1 The Coastal Environment

Most Americans have visited the coast, and some are even fortunate enough to live in close proximity to the sea. In fact, nearly one in every two Americans is living within 80 km (50 mi) of a coastline (Owen and Chiras 1995). The word "coast" may bring up positive images of white sandy beaches, rocky shores, and headlands, or wetlands teaming with wildlife. The same word may also cause one to visualize inappropriate development (e.g., oversized hotels built down to the water's edge); overcrowding (e.g., wall to wall sunbathers on a too-small beach; motorhomes jammed together on a coastal parking strip), or higher risk development (e.g., nuclear power plants built on a fault zone). The coast, of course, is all of these things. For whatever reason, whether it be its sheer beauty, the unique aesthetic experience, or the abundance of natural resources, Americans are fascinated with the coastal environment. Perhaps better than any other, Rachel Carson (1983, p. 11) has captured the confrontation between land and sea:

> *The edge of the sea is a strange and beautiful place. All through the long history of Earth it has been an area of unrest where waves have broken heavily against the land, where the tides have pressed forward over the continents, receded, and then returned. For no two successive days is the shoreline precisely the same. Not only do the tides advance and retreat in their eternal rhythms, but the level of the sea itself is never at rest. It rises or falls as the glaciers melt or grow, as the floors of the deep ocean basins shift under its increasing load of sediments, or as the Earth's crust along the continental margins warps up or down in adjustment to strain and tension. Today a little more land may belong to the sea, tomorrow a little less. Always the edge of the sea remains an elusive and indefinable boundary.*

Americans are not alone in being drawn toward the coast. Two-thirds of the world's population lives near the coast. As humans increasingly inhabit coastal areas, they bring their houses, schools, agricultural systems, businesses, factories, and power plants, which in turn elevate the levels of coastal pollution and coastal areas used as dumping grounds for waste.

The very fact that so many people in the world live in coastal areas and use (and often abuse) their natural resources is reason enough to study coastal resource management. However, the coastal zone is important for other reasons as well, such as:

- *a habitat for wildlife* (e.g., the myriad of plants and animals that depend on coastal estuaries);
- *a natural filter* (e.g., wetlands that filter impurities from waters that pass through them);
- *a safety barrier* (e.g., barrier islands, beaches, dunes, and cliffs that buffer residents along the coast from high winds and seas);
- *a food source* (e.g., coastal fisheries that provide a food source for millions of people worldwide);
- *a recreation area* (e.g., open space for beach-combing, sunbathing, swimming, boating, fishing, and relaxing of whatever sort);

- *aesthetics* (e.g., inspiration for the painter, nature photographer); and
- *a source for psychological and spiritual renewal* (e.g., a mental "time-out" from the daily grind to regenerate one's soul).

Of course, all of these demands upon the coast take a heavy toll. Beaches, sand dunes, and elements within the coastal zone have a **carrying capacity** (population and impact limits) that must be respected. Just as you can only put so many cattle or sheep on a pasture before the grassland ecosystem deteriorates, there are limits to which coastal ecosystems can withstand natural impacts (e.g., winds, coastal storms, hurricanes, wave surge), and especially human impacts, such as population pressures (e.g., urban development, tourism, loss of open space), coastal pollution, offshore oil development, and ocean dumping. As will be illustrated throughout this book, determining the carrying capacity of a site is not easy, and, consequently, is open to much scientific and political debate.

There is no debate, however, that understanding the coastal environment—its major elements and how they interact—is the first step toward alleviating the pressures on the coastal zone and marine environment. Consequently, this opening chapter covers the following background information: *The Coastal Zone* provides a working definition of the coast, and identifies the five major issues facing America's coastal areas. *The Coastal System* introduces the reader to various ways to classify coastal types and processes, as well as major subdivisions of the coast. Natural processes affecting these coastal elements are also discussed, such as wind, coastal storms, and sediment transport. *Coastal Formations* identifies and briefly discusses the primary physical formations that can be found in the coastal zone, ranging from inland coastal mountains to open ocean habitats. Managing these phenomena, including their associated economic (e.g., fisheries, tourism) and cultural (e.g., shell middens & other archaeological treasures) resources, requires a new way of thinking, which is the theme of this book.

THE COASTAL ZONE

Defining the Coast

The **coast** refers to the area where land, water, and air meet. Most definitions of the coast merely have it beginning with the **shoreline** or **coastline** (the line of intersection of a water body with land) and extending inland to the limit of tidal or sea-spray influence, or to where the terrain shows signs of major change; but in this book, the term coast or **coastal zone** will also include the nearshore waters that extend from the shoreline to the outer limit of the continental shelf. The coast is of indefinite width (from several hundred feet to several miles) and varies with season and time. The coastal zone has the characteristics of mixing or adjustment, and change (Carter 1988). It is, in other words, where the terrestrial environment influences the marine or lacustrine (lake) environment, and vice versa. Hence, it is an **ecotone**—a transition area or border where two ecological communities meet.

In addition to defining the coast in physical or ecological terms, the coast or coastal zone can also be defined in terms of management or planning boundaries. For example, **coastal areas** (or coastal counties) in the United States are defined by political and cultural elements, as well as by physical features. According to definitions established by the Federal Coastal Zone Management Program, which is managed by the National Oceanic and Atmospheric Administration (NOAA), "coastal areas" of the United States include 30 coastal states (which includes those bordering the Great Lakes) and their 451 coastal counties.

The Federal Coastal Zone Management Act (CZMA), which created the Federal Coastal Zone Management Program, uses ecological, as well as political boundaries, to legally define the coastal zone. According to the act, the coastal zone encompasses the state's coastal waters and shorelands including "islands, transitional and intertidal areas, salt marshes, wetlands, and beaches" (CZMA 1994). The coastal zone also "extends inland from the shorelines only to the extent necessary to control shorelands, the uses of which have a direct and significant impact on the coastal waters, and to control those geographical areas which are likely to be affected by or vulnerable to sea level rise" (CZMA 1994). The coastal zone is further defined as the "connecting waters, harbors, roadsteads, and estuary-type areas such as bays, shallows, and marshes" of the Great Lakes, and in other coastal regions as "those waters, adjacent to the shorelines, which contain a measurable quantity or percentage of sea water, including, but not limited to, sounds, bays, lagoons, bayous, ponds, and estuaries" (CZMA 1994).

Meanwhile, political coastal zone boundaries extend "seaward to the outer limit of state title and ownership" as established by legislative action, such as the Submerged Lands Act enacted by Congress in 1953. This act allowed every coastal state to extend its boundaries to 4.8 km (3 mi) from its coasts. In the Great Lakes region, the states' coastal zone extends to the "international boundary between the United States and Canada" (Clark 1977).

States and territories subject to these definitions are those which are "bordering on, the Atlantic, Pacific, or Arctic Ocean, the Gulf of Mexico, Long Island Sound, or one or more of the Great Lakes," as well as "Puerto

Rico, the Virgin Islands, Guam, the Commonwealth of the Northern Mariana Islands, and the Trust Territories of the Pacific Islands, and American Samoa" (CZMA 1994). As indicated earlier, there are 30 states and 451 counties which are *directly defined* as "coastal areas." However, expanding upon these regions to include geographic areas that are "influenced" by the coast, 1,569 non-coastal counties, the District of Columbia, 23 boroughs or census areas in Alaska, and 42 independent cities in Virginia and Maryland, become "coastal areas" as well, as defined by the Coastal Zone Management Act.

To further complicate matters, individual state coastal management programs have sometimes modified the federal definition to suit their local political, economic, or cultural situation. However, local and state governments must have the same definition as the federal government, if they wish to participate in the Federal Coastal Zone Management program. For example, the California Coastal Act, the enabling legislation for California's coastal program, expands upon the coastal zone definition found in the Federal Coastal Zone Management Act. This definition specifies that the coastal zone includes inland areas "generally 1,000 yards from the mean high tide line of the sea." In addition, where "significant coastal estuarine, habitat, and recreational areas" exist, the coastal zone "extends inland to the first major ridgeline paralleling the sea or five miles from the mean high tide line of the sea, whichever is less." Furthermore, "in developed urban areas the zone generally extends inland less than 1,000 yards." Interestingly, California's Coastal Act also excludes an area, the San Francisco Bay, normally considered "coastal" by the Federal Coastal Zone Management Act, covering management of this region under a separate governmental authority known as the San Francisco Bay Conservation and Development Commission (California Coastal Act, Chapter 2, Section 30103).

Coastal Issues and Management Concerns

Coastal resource managers are faced with a number of pressing issues. Individual chapters in this book address the five major environmental concerns facing America's coastal areas: coastal hazards (Chapter 4), coastal pollution (Chapter 5), ocean dumping (Chapter 6), offshore oil development (Chapter 7), and disappearance of open space (Chapter 8). Recent (non-traditional) issues are integrated into the above chapters when appropriate. For example, the topic of "social equity" (i.e., the displacement of minority and/or poor residents by new coastal developments) will be discussed in the chapter on open space management. The "recent" coastal management concern—the need for integrated coastal and marine sanctuary management—is addressed throughout each of the major chapters.

- *Coastal hazards.* The prevention and mitigation of coastal hazards is a subfield of coastal resource management. It includes such problems, issues, and concerns as *storm hazard mitigation* (e.g., through warning systems and evacuation strategies; integrated coastal planning); *controlling shoreline erosion* (e.g., through traditional techniques and innovative strategies for erosion control protection; limits on permissible development); and *projecting and preparing for sea-level rise* caused by global warming (e.g., planning for inundation of coastal communities; coastal reinforcement or strategic retreat). The last issue may be the most crucial one facing coastal scientists today (Carter 1988).
- *Coastal pollution.* This category of concern includes all the types and sources of coastal pollution. For example, it requires understanding, minimizing, or mitigating concerns regarding *point source pollutants* (e.g., sewage outfalls, pollutants from marinas, industrial waste water), *nonpoint sources* (e.g., agricultural lands, urban areas, marine debris), and *physical and hydrological modifications* (e.g., harbor dredging, groundwater withdrawal, and dam construction and irrigation—all human activities that exacerbate saltwater intrusion).
- *Ocean dumping.* Though also a form of coastal pollution, "ocean dumping" is generally thought of as a separate subfield of coastal resource management. For over 100 years, America's coastal waters have been used as a dumping ground for the nation's waste materials, including *dredged materials, sludge, solid waste (garbage), industrial waste, military waste, nonmilitary radioactive wastes, and ocean incinerated wastes.* This subject area also includes the *deep ocean disposal debate* over whether or not to intensify the disposal of waste materials in deep ocean areas.
- *Offshore oil development and transport.* Developing coastal fossil fuel resources can also be a source of coastal pollution. In fact, many of the marine sanctuaries within the U.S. National Marine Sanctuary Program were established to prevent offshore oil development from occurring within the region. Coastal resource managers, local governments, and the average "coastal citizen" need to understand the components and associated impacts of offshore oil development, as they relate to exploration activities, offshore development and production schedules, subsea and onshore pipelines, vessel traffic, and oil spill response programs.
- *Open Space Preservation and Management.* This final major subfield of coastal resource management requires an understanding of human population demographics and how the urbanization process has impacted coastal areas, such as with the disappearance of coastal agricultural land, the loss of coastal wildlife habitats, declining

coastal recreational resources, loss of coastal village or small town character, and declining respect for coastal property. Coastal resource managers who are interested in this subfield may work on projects to sustain the productivity and diversity of coastal ecosystems (e.g., aquaculture, fisheries management), to reclaim wetland and estuary ecosystems, or to restore recreational opportunities (e.g., beach access) for coastal dwellers and visitors, and even cultural historic projects to help an area maintain its sense of place.

In order to move toward resolving the above issues, coastal resource managers will need to have a degree of scientific knowledge, an understanding of legal terms, an ability to help resolve conflicts, and skills within the arena of public education.

THE COASTAL SYSTEM

Coastal Types and Processes

Different coastal types are the result of various processes (e.g., tectonics, exposure to wind and waves, sediment supply and transport) working at varying geographic scales. These processes have been categorized in a hierarchy as first, second, and third-order processes. (See Table 1-1). Each of these classification scales will be discussed briefly in this chapter to give the reader a better understanding of how our coasts are formed and how susceptible they are to environmental changes such as global warming and sea level rise.

First-order processes. First-order processes are those which act at a *global* level, affecting coastal lengths of 1000 km (621 mi) or more (Inman and Nordstrom 1971). These processes include climate changes, sea level variation, and plate tectonics.

(a) Climate Changes

Global climate and temperature changes resulting from natural variations in atmospheric conditions (e.g., ice ages), or as a result of human interference (e.g., greenhouse warming), affect global sea level and influence second-order processes such as increased sediment deposition or erosion.

(b) Sea Level Variation

King (1972) and others have suggested that coasts can be classified according to sea-level change. During the Pleistocene, variations in sea level greatly influenced coastal forms. For example, a coast could be described in terms of *submergence* (e.g., a subaerial valley flooded by sea-level rise such as a **fjord**) or in terms of *emergence* (e.g., an uplifted, wave-cut platform such as a **marine terrace**). Many coasts, however, do not fit these generalizations (Hansom 1988). It is still important to understand the effect sea level changes have on processes shaping present day coasts.

Sea level oscillations can result from many environmental changes. These environmental changes range from short-term processes, such as atmospheric pressure changes which can last several months, to long term processes, such as advancing and retreating glaciation lasting millennia. (See Figure 1-1).

For example, the massive quantities of water locked in the world's ice sheets responds to environmental changes, releasing or decreasing the volume of water in the world's oceans. Today, sea level is also being affected through human extraction of fluids (e.g., oil, water, gas) and mass building on "soft" ground (e.g., coastal development in Venice, Italy; and Hawaii, USA). These

TABLE 1-1

The three major coastal scales

Order	*Dimensions*		*Controls*	*Results*
1st order	Length	c. 1000 km	Plate tectonics	Coastal plain and continental shelf
	Width	c. 100 km		
	Height range	c. 10 km		
2nd order	Length	c. 100 km	Erosion and deposition modifying 1st order features	Deltas, coastal dunefields estuaries
	Width	c. 10 km		
	Height range	c. 1 km		
3rd order	Length	1-100 km	Wave action and sediment size	Beaches longshore bars, mudflats
	Width	10 m-1 km		
	Height range	?		

Note: 1st and 2nd order factors define the coastal zone, 3rd order factors define the shore zone

Source: Viles & Spencer 1995, 20, adapted from Inman and Nordstrom 1971.

human impacts alone are causing sections of cities to sink below sea level (e.g., New Orleans) and thus require further intervention with artificial levees and pumps.

Sea level change also results from a change in volume of the ocean basins through oceanic plate spreading and continental uplift or lowering. One method by which the ocean basin volume is changing today is due to lifting or lowering of the earth's continents in response to the weight released from the last glacial melting. Areas once covered by glaciers are still rising in response to the removed weight, while surrounding areas previously bulging up around the weight of the glacier are now lowering (Davis 1994).

(c) Plate Tectonics

Given that the earth's crust is made up of continental and oceanic plates which are in constant motion with respect to each other, Inman and Nordstrom (1971) devised a method for the classification of coastal types dependent upon their position on a crustal plate. Using this method, they have categorized coastal areas as either leading-edge coasts, trailing-edge coasts, or marginal coasts.

i. Leading-Edge Coasts (active or collision coasts)

Definition: A leading-edge coast develops at the margin of a landmass, near the collision of active crustal plate margins (Davis 1994). (See Figure 1-2).

Characteristics: Leading-edge coasts are characterized by narrow continental shelves, deep ocean basins and trenches, rugged shores and sea cliffs, nearby coastal mountain ranges, and volcanic and earthquake activity. Because of the mountain slopes, the streams and small rivers flow relatively straight and fast, eroding their beds and dumping sediment directly into the ocean (Davis 1994). Of course, not all these characteristics occur in all leading-edge coastal areas.

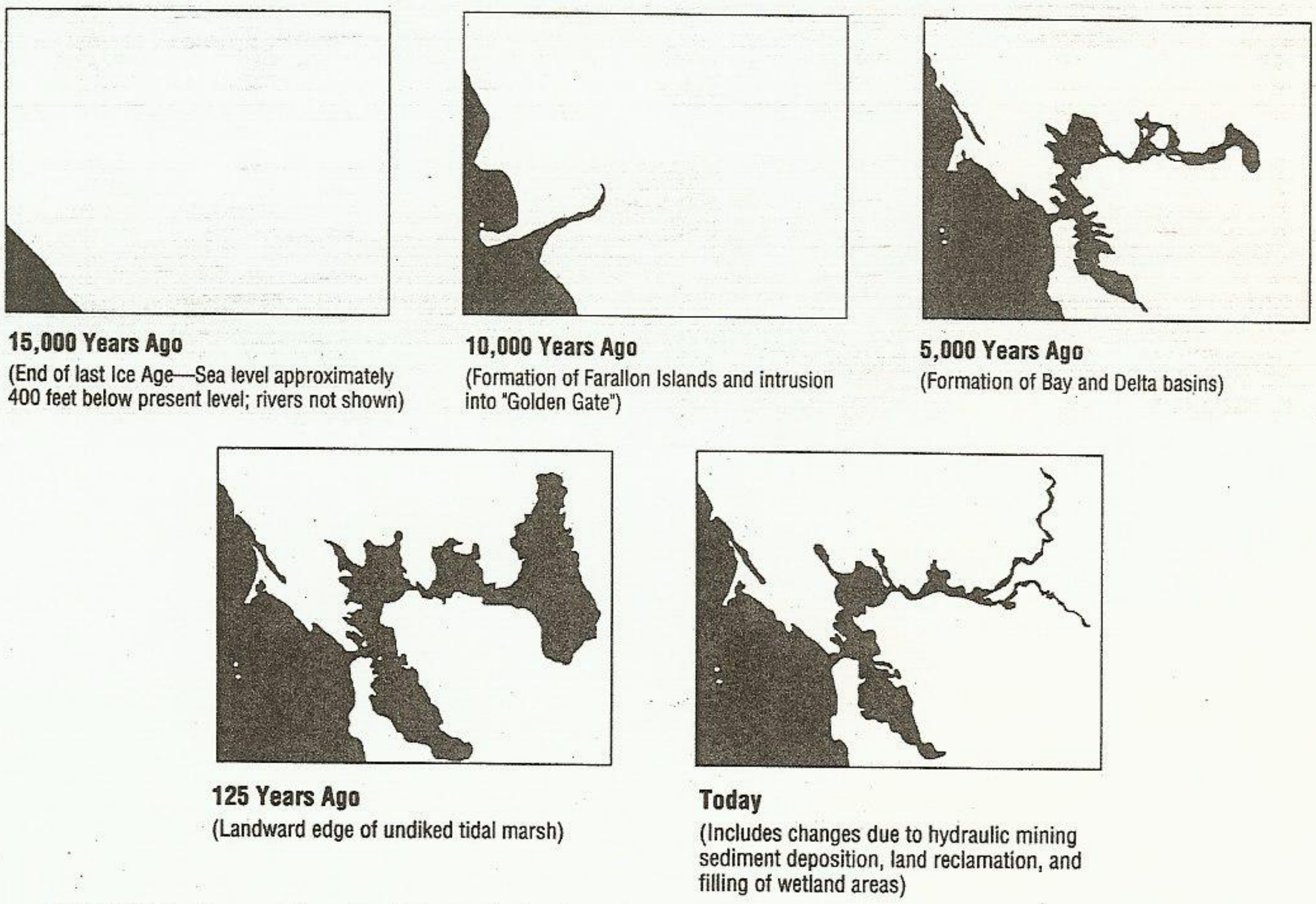


FIGURE 1-1 Sequential sea level rise in the San Francisco Bay/delta estuary. (*Source:* Association of Bay Area Governments 1992, 12–13)

Examples: West coast of U.S.; Andean coast of South America; East and West Indies (Davis 1994). (See Figure 1-3).

ii. Trailing-Edge Coasts (passive or plate-imbedded coasts)

Definition: Trailing-edge coasts are formed on the edge of a land mass, moving with a crustal plate away from the divergent plate margin, and situated very far from a plate margin (i.e., in a very tectonically stable portion of the plate).

Characteristics: Trailing-edge coasts typically have broad continental shelves without ocean trenches. Their coastal plains are wide, have shallow waters, and often contain low-lying lagoons and barrier islands. Erosional forces are slow during normal wave activity due to the shallow water and resulting weak wave action (Davies 1980). (Of course during the hurricane season, erosional forces are much greater). Sub-categories of trailing-edge coasts exist, depending on the time since the plate separated from it's prehistoric neighbor; or stated differently, depending on the maturity of the coastline and shelf width (Davis 1994).

Examples: East coast of U.S., particularly the coasts of North and South Carolina; the Gulf of California; Greenland; the Bay of Bengal.

iii. Marginal-Sea Coasts (also plate-imbedded)

Definition: Marginal-sea coasts develop along shores of a sea, enclosed by continents and island arcs which further protect it's shores and continental shelves from wave action (Davies 1980).

Characteristics: Marginal coasts typically have wide continental shelves with shallow seas to break incoming waves. The coastal plains vary in width but are often bordered by hills and small mountains. The rivers are

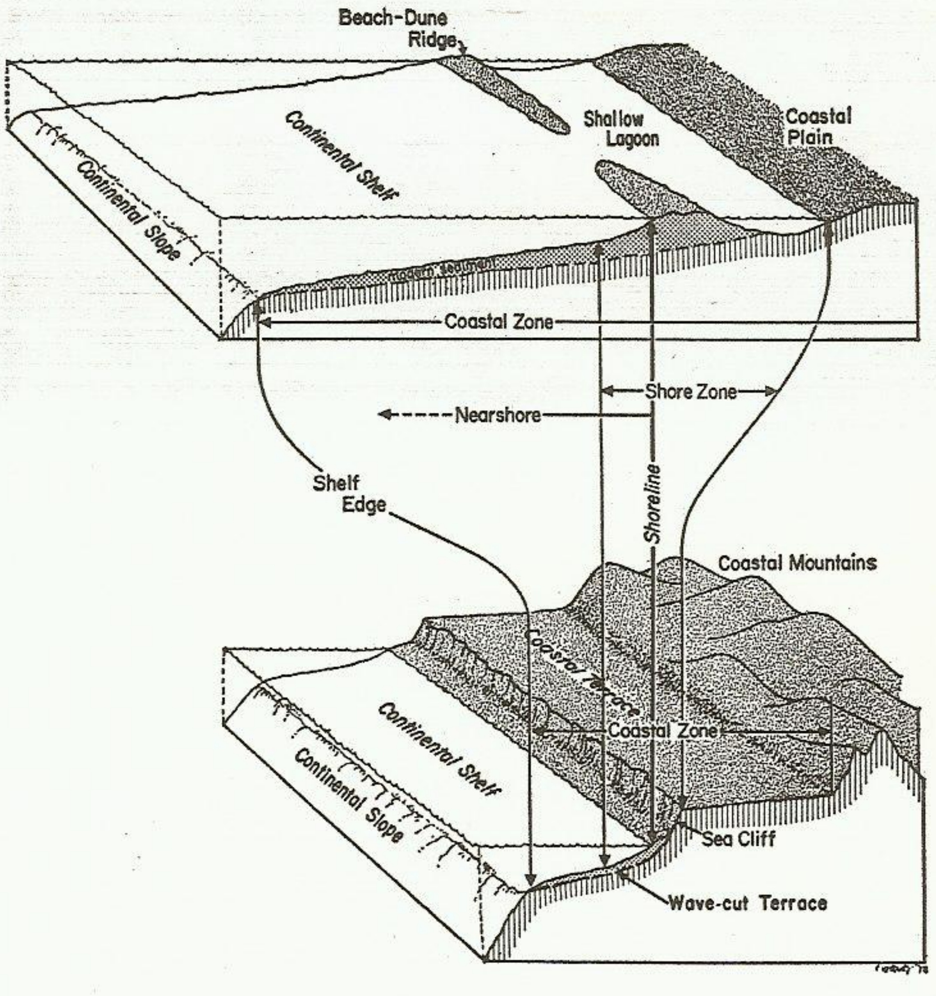


FIGURE 1-2 Coastal classification based on tectonic situation. Wide-shelf plains coast (upper) characteristic of the U.S. east coast (trailing edge), and narrow-shelf mountainous coast (lower), characteristic of the U.S. west coast (collision or leading edge), based on Douglas l. Inman and Brush 1974. (*Source: Coastal Ecosystems Management* by Clark © 1977, reprinted by permission of John Wiley & Sons, Inc.)

often large and carry huge sediment loads, resulting in large deltas at the river mouths.

Examples: the South China Sea protected by the Philippine Islands; the Gulf of Mexico protected by the volcanic area of Central America and the adjacent Caribbean island arcs.

Second-order processes. Second-order processes are those which act at a more local level, effecting coastal lengths of 100–1000 km (62–621 mi) (Refer back to Table 1-1). These processes include erosion, **biogenic** activity (e.g., coral reef building), **cryogenic** activity (e.g., seasonal carving of ice-laden coasts), and deposition forces which result in large local features like deltas, dunefields, coral reefs, and ice fields of arctic coasts. Taking these second-order processes into consideration with the tectonic first-order classifications, Inman and Nordstrom (1971) further defined subclassifications for coastal areas as shown in Table 1-2.

Third-order processes. Third-order processes are those that give classifying features to a local length of shore. These processes (e.g., wind, waves) react with land formed by the previous first- and second-order processes (e.g., sea level, sediment deposition, tectonics) (Viles and Spencer 1995). Wave action is considered the most significant third-order process shaping our shore zones today.

Because of the importance of wave action, Davies (1972) even suggested a separate classification scheme which grouped coasts according to three types: (a) protected sea environments; (b) storm wave environments; and (c) swell wave environments. (See Figure 1-4).

His classification is actually a grouping of the world's coastal areas by their wave environment, or degree of exposure to wave energy. Given that wave heights are controlled by wind speed, direction, duration, and the distance the wind blows (i.e., fetch), this diagram of wave patterns and intensity can help in predicting coastal features at local levels (Viles and Spencer 1995). Note that these factors will cause local waves to have predominant directions, with deviations occurring during events such as storms and typhoons.

It is important to note that *all scales of classification must be considered when studying a local coastal area.* Steep cliffs and narrow beaches, though appearing to be a first-order leading-edge coast, may in fact be a trailing-edge coast which has been greatly impacted by second- and third-order processes. This is the case regarding the southern coast of Australia (Davis 1994). In addition, one

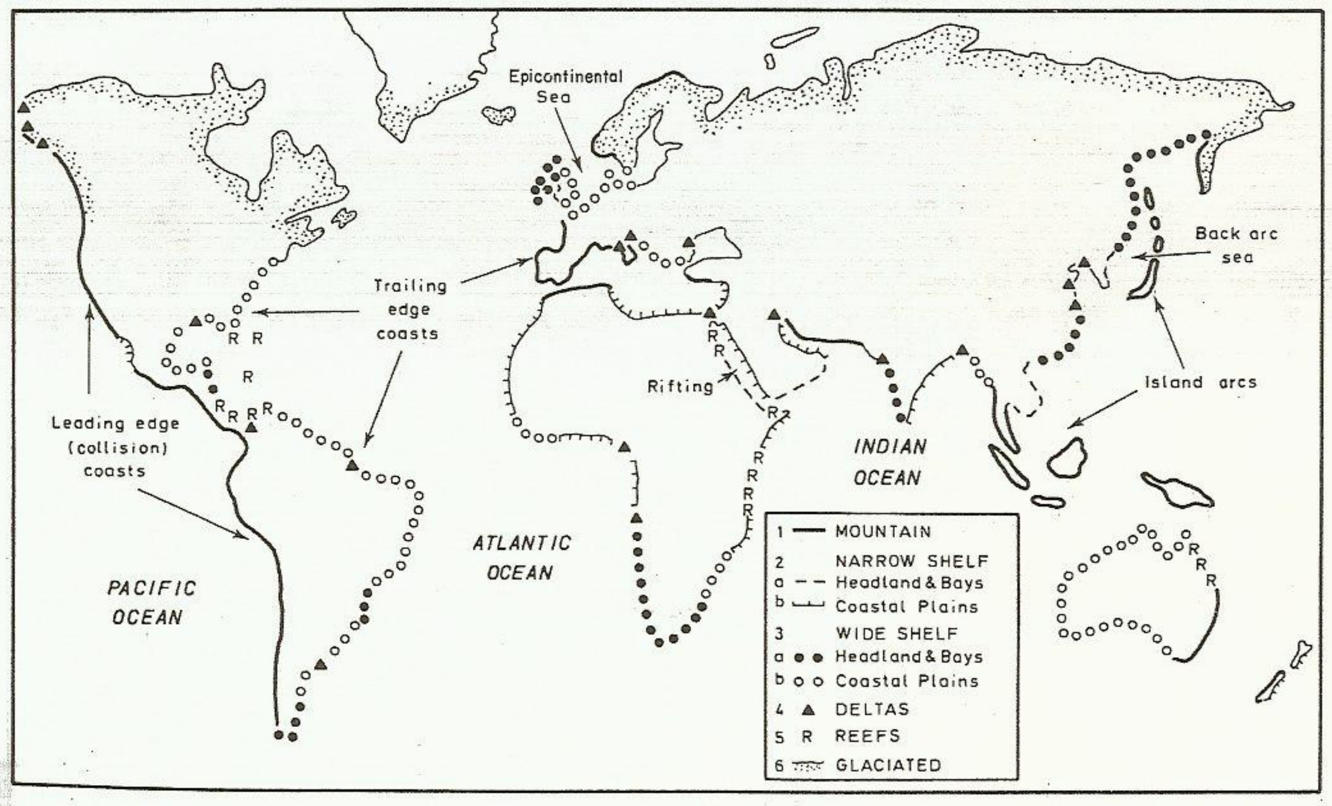


FIGURE 1-3 The tectonic classification of the world's coastlines, based on the work of Inman and Nordstrom 1971. (*Source:* Reprinted from *Coastal Environments,* 1988 by Carter, by permission of Acadmic Press Limited, London)

must not assume that if you find a trailing-edge coast on one side of a continent, you will find a leading-edge coast on the other. Coasts have features of different size and scale, and all three orders of coast-forming processes must be considered before any conclusions of origin are drawn.

Subdivisions of the Coast

Hansom (1988) has identified common nomenclature for the subdivisions of the coast based on wave process zones. There are three major zones—backshore, nearshore, and

TABLE 1-2
Morphological classification of coasts

Coast type	*Characteristics*
Mountainous coast	Shelf < 50 km wide, coastal mountains > 300 m high, rocky shore zone with pocket beaches. Mainly on collision coasts
Narrow-shelf hilly coast	Shelf < 50 km wide, coastal hills c. 300 m high or less, occasional headlands and beaches, some barriers
Narrow-shelf plains coast	Shelf < 50 km wide, low-lying coastal plains, barrier beaches, occasional low cliffs
Wide-shelf plains coast	Shelf > 50 km, low-lying coastal plains and wide shore zone, often with barrier beaches
Wide-shelf hilly coast	Shelf > 50 km wide, coastal hills c. 300 m or less, barrier beaches and occasional headlands and cliffs
Deltaic coast	Sediment deposited where river enters sea; low-lying coastal bulge
Reef coast	Organic origin, resistant; fringing or barrier type
Glaciated coast	Coastal features dominated by erosional effects of glaciers, precipitous cliffs and fjords common

Source: Viles and Spencer 1995, 22, adapted from Inman and Nordstrom 1971.

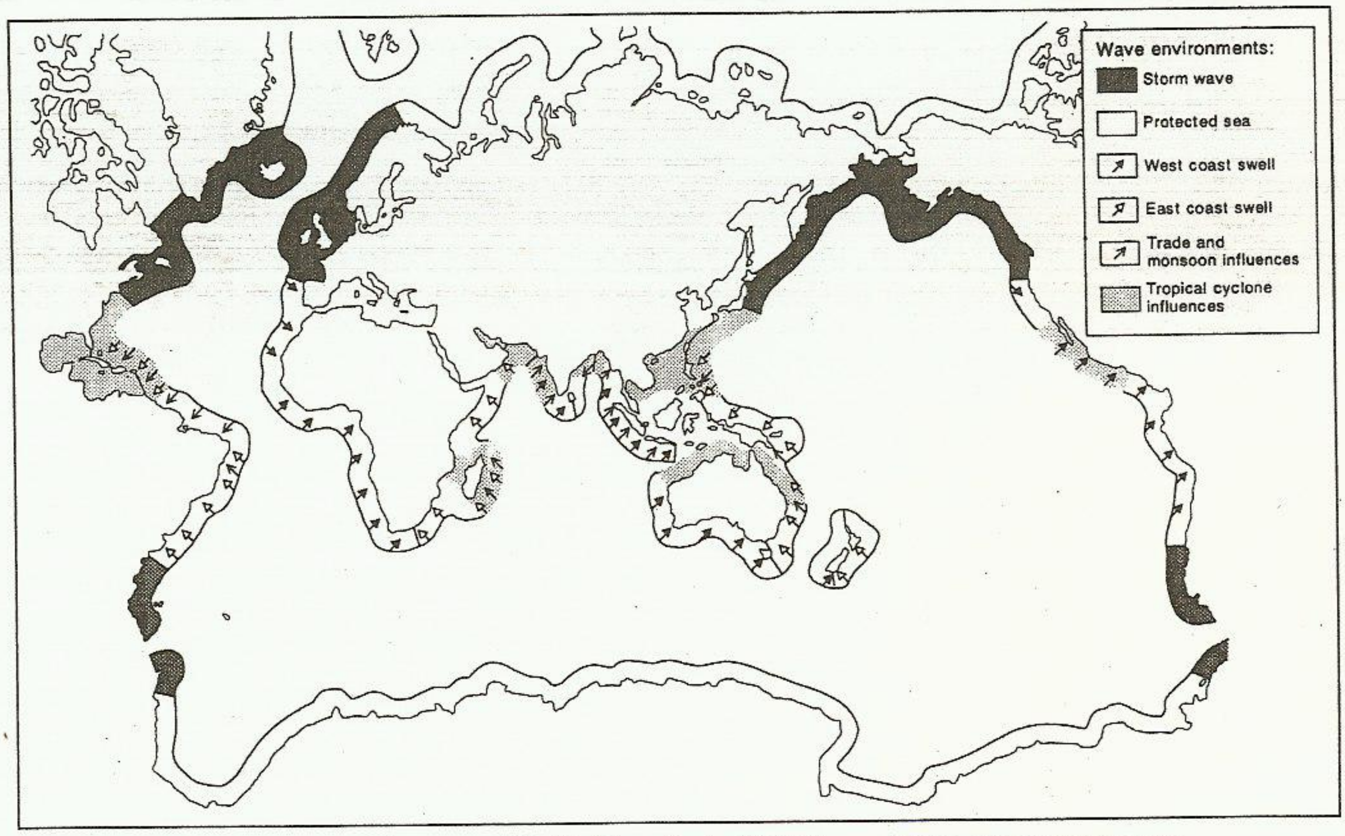


FIGURE 1-4 World wave environments. Modified from Davies 1972. (*Source:* Viles and Spencer 1995, 27)

offshore, each of which can be further subdivided. (See Figure 1-5).

The **backshore zone** extends from sand dunes or beach ridges down to the high water mark (HWM). This is an area that generally lies above the level of wave reach, except during heavy storms.

The **nearshore zone** extends from the HWM to the offshore zone. This is the area that is affected most by waves and where sediment movement occurs. The nearshore zone has three subdivisions: the swash zone; the surf zone; and the breaker zone. The **swash zone** is the area of the shore that is alternately covered by swash (wave uprush) and backwash (wave recession). Of course, the location of the swash zone changes with the level of the tide. The **surf zone** is where over-steepened waves topple; here, broken waves travel towards the shore, depositing (and removing) sediment in the process. The third subdivision, the **breaker zone,** is the most seaward area where the tallest breaking waves occur.

The **offshore zone** extends beyond the breaker zone out to sea, where water depths are greater than half the wave length of the incoming waves. In this zone, wave-induced sediment movement is limited.

Coastal Dynamics

The coastal zone is under constant change due to three major groups of natural factors: (1) terrestrial factors; (2) marine factors; and (3) biological factors (Hansom 1988), in addition to anthropogenic factors, discussed later.

Terrestrial factors. The *geologic structure* of the site is a primary terrestrial factor. As indicated earlier, tectonic forces that determine whether a coast is a collision coast, trailing edge coast, or marginal sea coast have an impact on the nature of the structural base upon which the coastal features develop. For example, a coastal outline may have the appearance of a drowned valley landscape because of large-scale folding in its geological past, or it may have a very straight coastline due to geological faults in the area. It could also have a fjord coastline caused by the erosional forces of glacial activity and sea level changes.

According to Hansom (1988), the *climatic regime* is also another terrestrial factor that impacts coastal areas in three primary ways: (1) The climate of an area affects temperature and rainfall amount and intensity, vegetation type, and consequent discharge of *fluvial sediment* from the coastal **hinterland**—the "uplands" away from the coast, such as watersheds, water courses, plains, and hills (Clark 1996). (2) Climate also affects such *geomorphic processes* as weathering, mass movement, erosion, as well as biological processes in the zone between the shore and the coastal hinterland. (3) Finally, the present atmospheric climate directly affects *shore processes* themselves, such

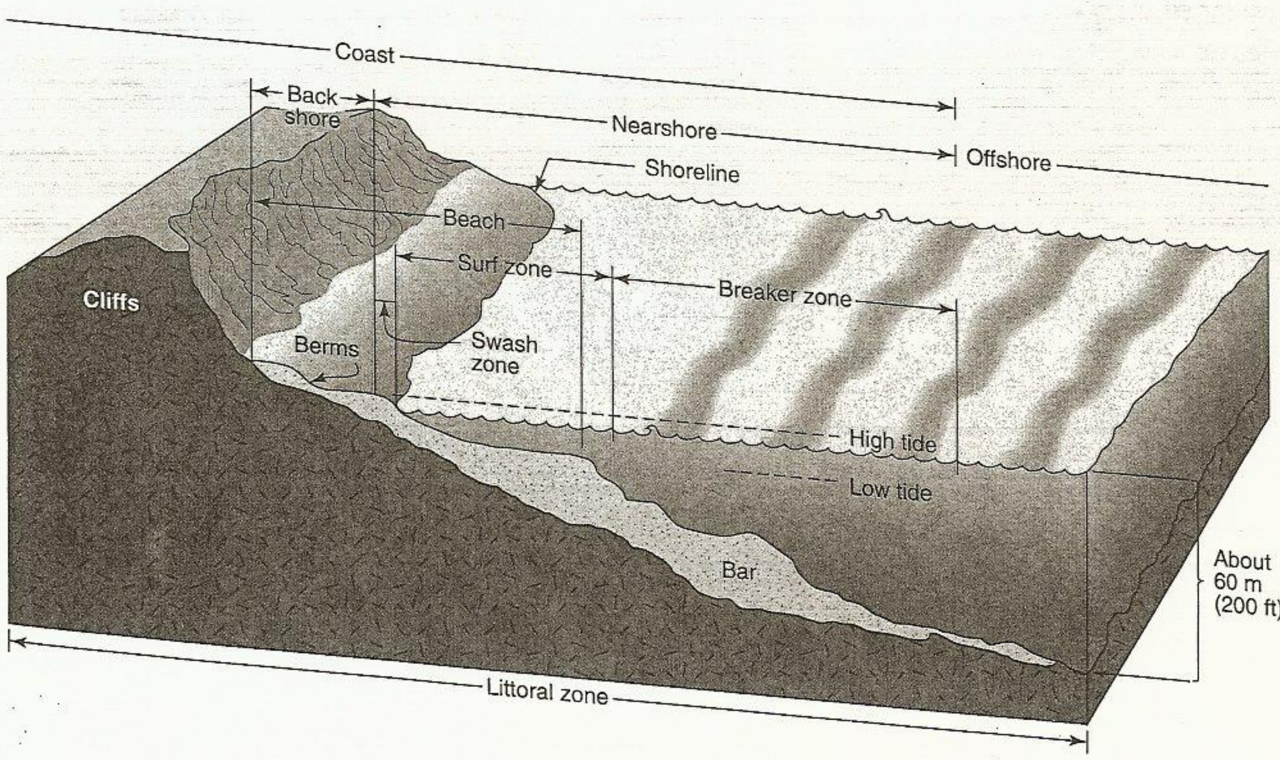


FIGURE 1-5 Coastal wave zones and beach features. (Diagram by Heather Theurer)

as platform weathering and dune building (Davies 1980). One can easily see why a coastal resource manager must have a good understanding of the *coastal hydrologic cycle,* particularly rates of precipitation and evapotranspiration, surface water flow, percolation and infiltration, groundwater flow, saltwater intrusion, and so on. (See Figure 1-6).

Marine factors. The coastal zone is also affected by marine factors, such as tides, storm surges, waves, tsunamis, currents, upwelling, and sea level rise.

Tides (the daily oscillations in sea level resulting from the physical relationships of sun and moon) are a major marine factor affecting coastal dynamics, as well as such human economic activity as traditional food gathering, commercial fishing, recreational tide-pooling, and, more recently, generating electricity by harnessing tidal power. Every day, many coastlines experience two high tides (rising tides, known as **flood tides**) and two low tides (falling tides, known as **ebb tides**). All sites have a **tidal range**—the difference between high and low tides. The greatest tidal range on Earth exists at the Bay of Fundy in Nova Scotia, where the maximum tidal range reaches 15.4 m (51 ft) (Viles and Spencer 1995). The lowest tidal range exists in Lake Superior in the United States, with a tidal variation of only approximately 5 cm (2 in) (Christopherson 1997).

The tidal range for the Santa Cruz harbor on the shores of the Monterey Bay National Marine Sanctuary reaches only a maximum of 2.4 m (8 ft). Tidal prediction is especially important to deep-hulled commercial ships. In some cases, passage in and out of a commercial port is possible only during high tide. Extreme high tides, when linked with storm surges, can lead to flooding, property damage, and loss of life.

Waves are another marine factor affecting coastlines. **Waves** can be defined as undulations of water that generally result from wind friction on the surface of an ocean or bay. As mentioned earlier, coastlines are sometimes classified as either *storm wave coastlines* (short high waves from various directions), *swell wave coastlines* (long and low waves from a consistent direction), or *protected coastlines* (no significant wave action) (Davies 1980). One type of wave that greatly influences coastlines is the tsunami. Rather than being generated by wind friction on the surface of the ocean, a **tsunami** is the result of an undersea disturbance due to seismic activity (e.g., a submarine fault movement). *Tsunami* is a Japanese word meaning "harbor wave," so named because of its devastating effect on harbors. Further details about this highly destructive type of wave are given in Chapter 4, *Coastal Hazards.*

When normal (non tsunami) waves enter shallow waters close to the beach, the wave height increases rapidly, reaches a point when its height exceeds its vertical stability, and the wave then falls into a characteristic **breaker** crashing on the beach. There are four types of breaking waves: spilling, plunging, collapsing, and surging. *Spilling breakers* occur when steep waves meet flat beaches; *plunging breakers* are associated with steep beach-

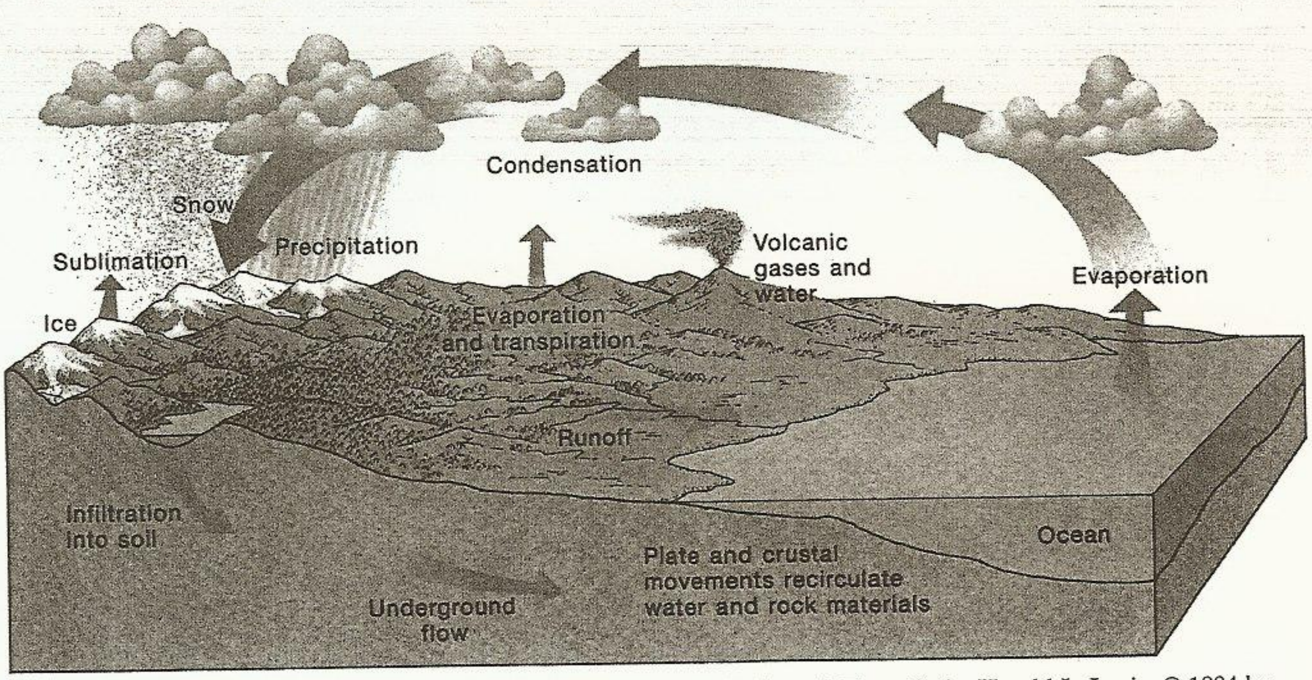


FIGURE 1-6 Coastal hydrologic cycle. (*Source:* From *The Earth Through Time* 4/e, by Harold L. Levin, © 1994 by Saunders College Publishing, reproduced by permission of the publisher)

es that cause the leading edge of a wave to become almost vertical prior to the top curling over and plunging forwards; *collapsing breakers* occur when swell waves break on steep beaches, causing the leading edge of the wave to collapse before it can form a curl; and *surging breakers* occur when waves of low steepness approach very steep beaches (Davis 1994). (See Figure 1-7).

When waves approach the surf zone and shallower water at an oblique angle, a longshore current can result. (See Figure 1-8). This current works in combination with

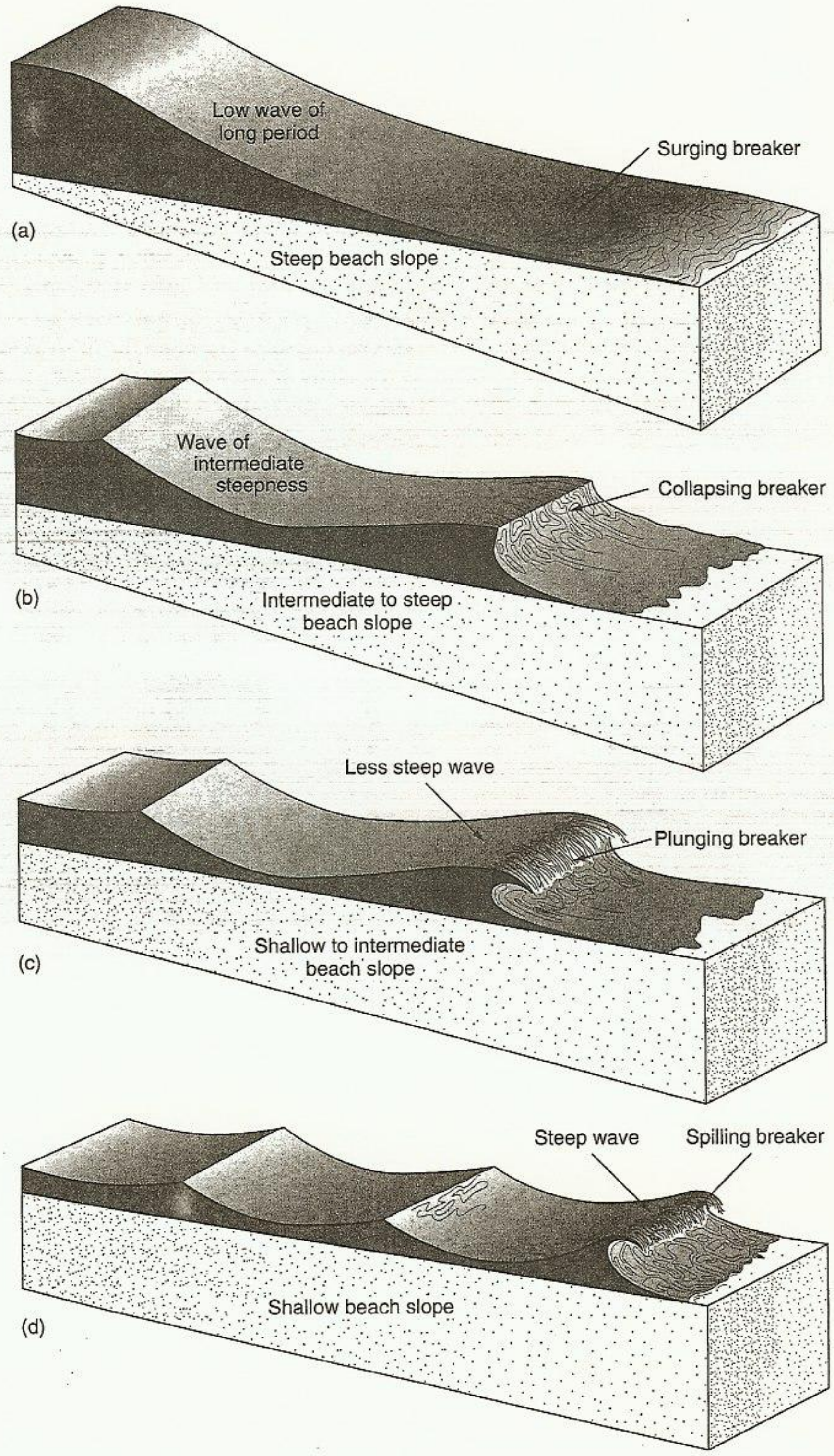


FIGURE 1-7 Types of breaking waves and the beaches on which they commonly occur. (a) surging breaker, (b) collapsing breaker, (c) plunging breaker, (d) spilling breaker. (*Source:* Diagram by Heather Theurer. Adapted from Davis 1994.)

wave action to create **littoral drift**—the transport of large amounts of sand, gravel, sediment, and debris along the shore. With each *swash* and *backwash* of surf, **beach drift** may also occur—the movement of sand particles on the beach in the direction of the littoral drift. In other words, waves can move sediment on the beach as well as within a longshore current. These transported sediments can represent a significant volume, filling inlets and harbors.

Sediments come to rest in four main sorts of situations—reentrant trap; salient trap, equilibrium trap, or deep sink (Davies 1977). (See Figure 1-9). *Trap* refers to the temporary escape of sediments from the transport system (e.g., littoral drift). In other words, some if not most of the sediment may eventually get freed and remobilized back into the transport system. Sediment lost into a "sink" (e.g., the submarine canyon of Monterey Bay, California; the submarine canyon of southern California) is removed permanently from the transport system, at least until the present day sea level changes. In a *reentrant trap* situation, sediments are trapped in a bay or other reentrant where land jutting seaward prevents the sediment from moving further along the coast. *Salient traps* can occur where the shore suddenly trends landward, producing a spit or tail like sand bar extending into deep water. Where approximate equilibrium of forces occur, sediment accumulates in an *equilibrium trap.* (See Figure 1-10).

Coastal storms and hurricanes are also major marine factors that alter the coastal environment. Certain ge-

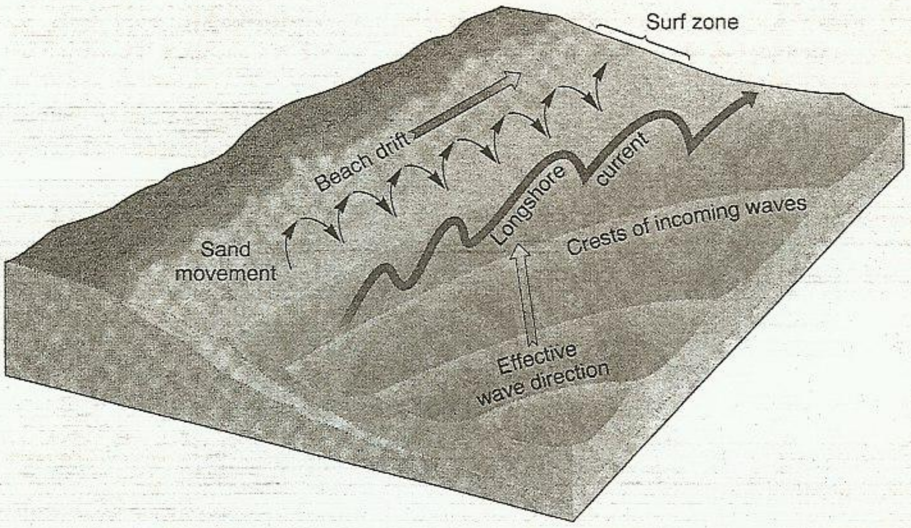


FIGURE 1-8 Diagram of longshore current and beach drift. (*Source: GeoSystems* 3/e by Christopherson ©1997, 492. Reprinted by permission of Prentice Hall, Inc.)

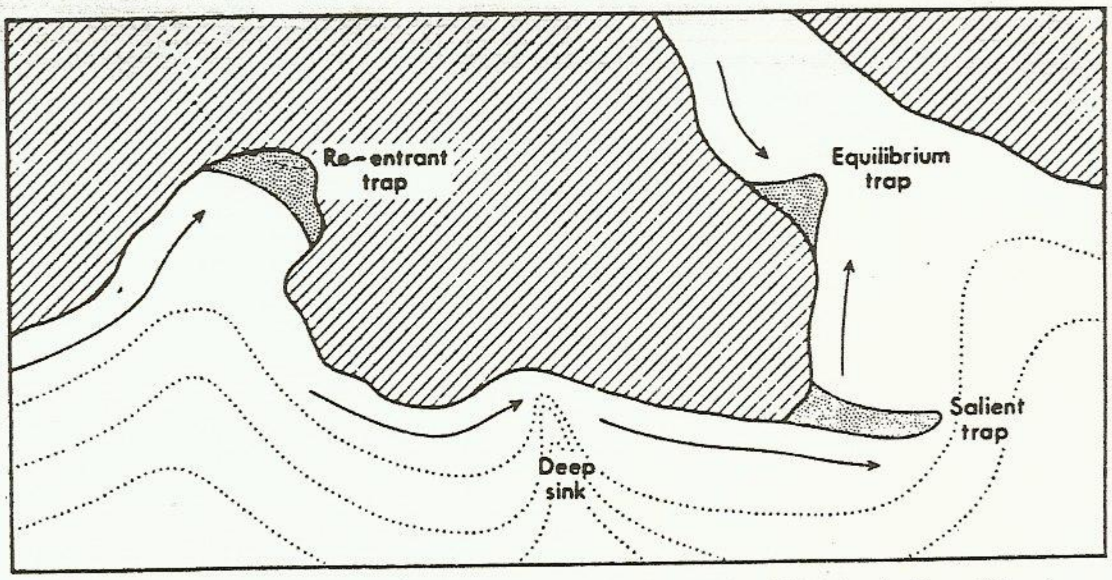


FIGURE 1-9 Sediment traps and sinks. (*Source:* From *Geographical Variation in Coastal Development* by Davies, 1977. Reprinted by permission of Addison Wesley Longman, Ltd.)

ographic regions are more prone to *landfalls* (the system reaching the land) than others. Along America's shores, Florida has received the greatest number of hits by hurricanes. In 1992, for example, Hurricane Andrew struck Southern Florida, altering shorelines, local ecosystems, and devastating homes. Some 75,000 homes were destroyed, leaving 250,000 people homeless. Texas, Louisiana, and North Carolina are also heavily hit by hurricanes, **storm surges** (heightened wave action due to hurricanes and coastal storms) and **storm flooding** (heightened flooding due to hurricanes and coastal storms). It is easy to visualize how coastal storms or hurricanes (which have a minimum sustained wind speed of 75 mph) can erode shorelines (or cause new beaches), create or close inlets, damage coastal vegetation, and affect already endangered wildlife species (See Chapter 4, *Coastal Hazards,* for further details).

Finally, *sea level change* is a major marine factor that must not be overlooked. Over geologic time, fluctuations in sea level have exposed a great range of coastal landforms to wave and tidal processes. Relative sea level change results from either *tectonic forces* that lower or raise coastlines, or from *glacio-eustatic processes* that alter the amount of water locked up in ice. Throughout most of the recent geologic epoch (the last 10,000 years, known as the Holocene), the sea level has been rising. Today, most scientists believe that global temperatures are increasing, which will further melt glacial ice, thereby further raising sea levels worldwide. Although it is generally believed that the rise in sea level will be less than 2 m (6.5 ft), a rise of only 0.3 m (1 ft) would cause shorelines worldwide to move inland an average of 30 m (100 ft) (Christopherson 1997). Planning for such a change to coastlines will be a political and economic nightmare, especially when scientists continue to debate about the degree of sea level change that might occur.

Biological factors. In addition to terrestrial and marine factors, there are biological factors that affect coasts. They are commonly divided into two types: plant and animal. The impact of humans on the coast will be summarized at a later point in this chapter.

Vegetation affects coasts by either enhancing the depositional process or as one of many factors in the erosional process of a coastal landform. Marram grass (*Ammophilia arenaria*) and other salt-tolerant species that are the first colonizers of a sandy beach or sand dune help in the build-up of these landforms; their horizontal and vertical shoots or rhizomes act as a net that helps hold the landform in place. Marsh samphire (*Salicornia spp.*) and other salt-marsh plants perform a similar function in promoting deposition and stabilization in mudflat environments in the middle latitudes, as do mangrove trees in the hot and wet tropical regions. Vegetation can also perform the opposite function by enhancing erosion (e.g., blue-green algae that erode rock by secreting oxalic acid which dissolves calcium carbonate) or by "pulling down" coastal cliffs (e.g., as does the heavy hottentot fig on a bluff).

Animals are also an important factor affecting coasts. Like vegetation, animals can either be a constructive or erosional force. Coral polyps are one of the most constructive marine organisms on the planet. By taking up

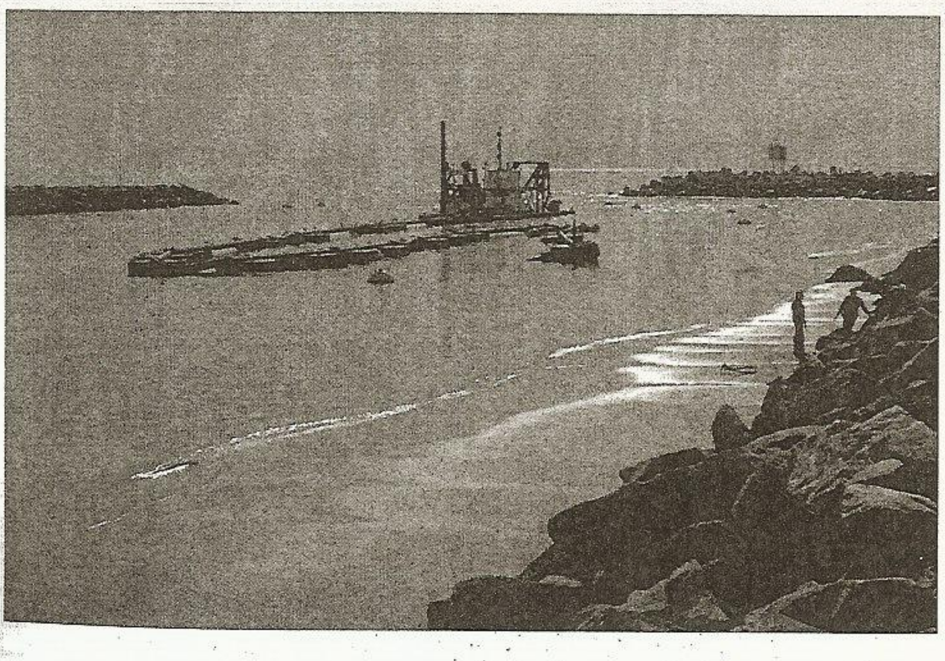


FIGURE 1-10 Equilibrium trap at west jetty of the Small Craft Harbor Santa Cruz, CA. In the right corner, two police officers are dislodging the body of a lost fishermen that also drifted into the equilibrium trap. In the center of the inlet is the harbor district's main dredge. (*Source:* Photo by author)

calcium carbonate from the sea water and secreting it into various hard skeletal structures, coral polyps have built impressive coral reefs on coasts around the world. For example, the Great Barrier Reef on Australia's eastern coast extends for approximately 1,750 km (1087 mi). Coral reefs are generally classified as either a **fringing reef** (coral rock platforms that adjoin the coast; e.g., Hawaii Island, Hawaii); a **barrier reef** (coral rock platforms that lie offshore, generally surrounding a lagoon; e.g., Chuuk [formerly Truk] or Belau [formerly Palau], Micronesia); or an **atoll** (circular or ring-shaped coral rock platforms that encircle a lagoon, e.g., Bikini atoll, Micronesia). These reefs not only represent organic deposition but their presence also helps to protect the shore against storm waves and strong currents.

Marine organisms can also be an erosional force affecting coasts. For example, several types of mollusks, such as the piddock (*Pholas dactylus*) and the wrinkled rock borer (*Hiatella arctica*), bore into coastal rock for shelter. Riddled with bore holes, the coastal rocks become more susceptible to erosion. Other intertidal and subtidal mollusks browse on algae that inhabit rock surfaces. In the process of browsing, the marine animals accidentally remove rock in the process (Hansom 1988).

COASTAL FORMATIONS

The U.S. coast includes a varied terrain that includes mountain ranges, rivers and streams, marine terraces, estuaries and bays, bluffs and headlands, rocky intertidal shores, coastal sand dunes, sandy beaches, nearshore waters, islands, and offshore rocks. What follows is a brief introduction to these terrain types. Entire books have been written about each formation type, and where appropriate, references for more detailed information are cited. (See Figure 1-11).

Coastal Mountains and Watersheds

Coastal mountains. Coastal ranges have many effects: They can serve to separate one geographic region from another. For example, California's Coast Ranges separate the state's coastal areas from the Great Central Valley and the deserts of the interior. Second, coastal ranges can separate one climatic region from another. These same coastal barriers dramatically affect California's climate: Pacific storms bring rain to the western or windward slopes of California's Coast Ranges, while the leeward

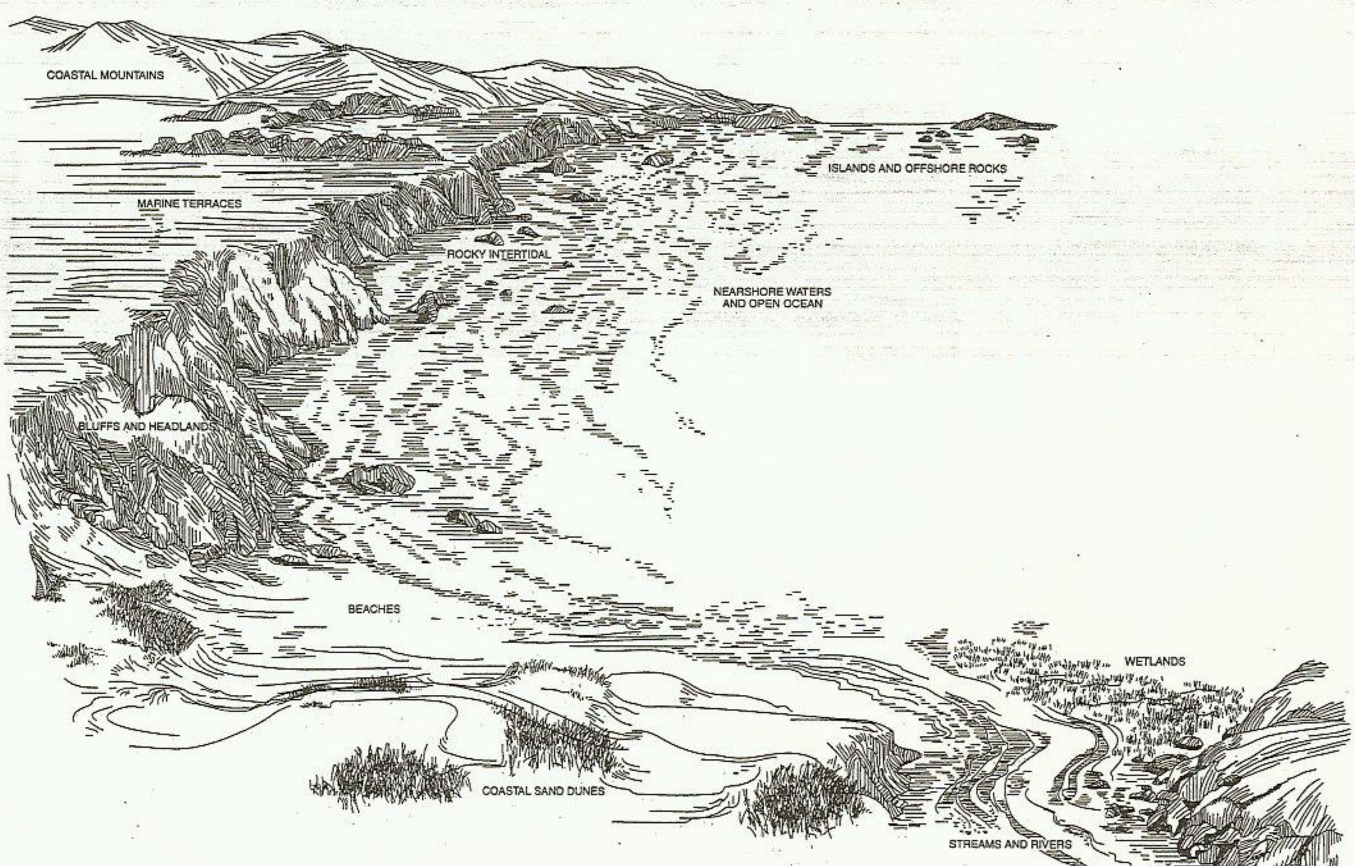


FIGURE 1-11 Diagram of major coastal habitats. (*Source:* Adapted from California Coastal Commission 1987, 13–14)

slopes remain relatively dry. Third, mountains mean dramatic variations in elevation and climatic zones, which in turn, result in a diversity of plant life. This explains why the windward slopes of California's Northern Coast Ranges are cloaked with redwood and Douglas fir trees. The heavy winter rains, summer fog, and moderate temperatures in this area have produced redwood groves where 2,000-year-old trees tower more than 91 m (300 ft). By contrast, the drier regions of the Southern Coast Ranges are vegetated with oaks, pines, and drought-resistant chaparral species (e.g., manzanita, chamise, and sage). Fourth, coastal mountains provide an aesthetic wonderland. It would be hard to imagine California's famous Big Sur Coast on the shores of the Monterey Bay National Marine Sanctuary without the back drop of the Santa Lucia Mountains, nor Highway 1 in San Mateo County, California, without the problems of Devil's Slide (See Chapter 4, *Coastal Hazards,* for further details).

Watersheds, rivers, and streams. Coastal rivers, streams, and creeks flow through the canyons and valleys of coastal mountains until they reach the sea. These drainage ways transport oxygen, nutrients, and sediments through the watershed, giving life to the area. Riparian woodlands and associated wildlife develop along stream banks and floodplains, while wetlands and estuaries form where these drainage ways meet the sea. Without coastal waterways, anadromous fish such as steelhead and salmon could not migrate to well-oxygenated fresh water streams and gravel streambeds that they need for spawning.

Coastal rivers play other crucial roles, such as depositing the sediments that form broad floodplains. These floodplains contain rich, deep soils for agriculture (e.g., the Salinas River floodplain in CA), and have often been the sites of urban development (e.g., the Los Angeles Basin which was formed by the deposition of sediment from the Los Angeles, San Gabriel, and Santa Ana rivers). Coastal rivers also replenish sand lost from beaches, unless of course, these rivers have undergone dam construction, channelization, or some other form of water diversion for agricultural irrigation or the increased water demands of a growing urban population.

Marine Terraces, Coastal Bluffs, and Rocky Headlands

One of the most distinctive differences between the Atlantic and Gulf coasts versus the Pacific coast of North America, is that the former have gently sloping seashores—the result of gradual *submergence* of the continent's edge, whereas the Pacific coast has elevated marine terraces, coastal bluffs, and rocky headlands—the result of *emergence,* specifically abrupt faulting and uplift in combination with the erosive power of waves, winter rainstorms, and wind.

Between the coastal mountains and the sea cliffs on America's western shores, one may find marine terraces. Marine terraces are seaward-sloping wave-cut benches or platforms that have been uplifted above sea level. (See Figure 1-12).

It is possible to have several terrace levels at one coastal site where geologic processes have been at work for millions of years. Along the California coast, for example, the oldest and highest terraces were created by the same processes that forced up the Coast Ranges some 1–2 million years ago. A terrace 396 m (1,300 ft) above sea level can be found along the sides of the Palos Verdes Hills in Los Angeles County, and twenty stepped terraces have developed along the coast of San Clemente Island, California. Along the shores of the Monterey Bay National Marine Sanctuary, marine terraces are visible just north of the city of Santa Cruz. Terrace soils are composed of rock debris, shells, and other marine fossil fragments that were deposited on the once-submerged terrace. Once emerged from the sea, coastal streams and rivers cross the terraces depositing a thick layer of nutrients, sand, and gravel, making them excellent areas for coastal agriculture.

The seaward edge of a marine terrace is known as a **coastal bluff.** Coastal bluffs are steep coastal slopes shaped by the erosive power of waves at its base, and uplifted from the ocean floor. They are often prone to erosion, since many are composed of highly erodable material (e.g., sandstones, shale, siltstones, and mudstones). Moving up the California coast, examples of sedimentary coastal bluffs are the shale cliffs of Point Loma in San Diego County, the alluvial cliffs of La Jolla, and the sandstone bluffs of Santa Cruz. Some coastal bluffs are eroded to the point where arches have been created, and have later fallen due to further erosion (e.g., Natural Bridges State Beach, Santa Cruz, California). However, not all coastal bluffs are made up of highly erodable material, such as the highly resistant granite bluffs of the Monterey Peninsula, California.

Development on coastal bluffs has increased the rate of coastal erosion. Everything from drain pipes and septic tanks that saturate soils with runoff, to lawns and gardens that are over-irrigated, to road construction too close to the water's edge have added to nature's own rate of eroding coastal bluffs.

Rocky headlands occur on high-energy coasts where mountains meet the sea. They are composed of igneous rocks (e.g., granites and basalts) that are resistant to wave erosion. On the highly active tectonic California coast, an example of a *granitic headland* can be found at Point Reyes headland in Marin County, California. Along California's shores, one can also find examples of *basaltic lava headlands,* such as at Morro Rock in San Luis Obispo County, and Point Sur in Monterey County.

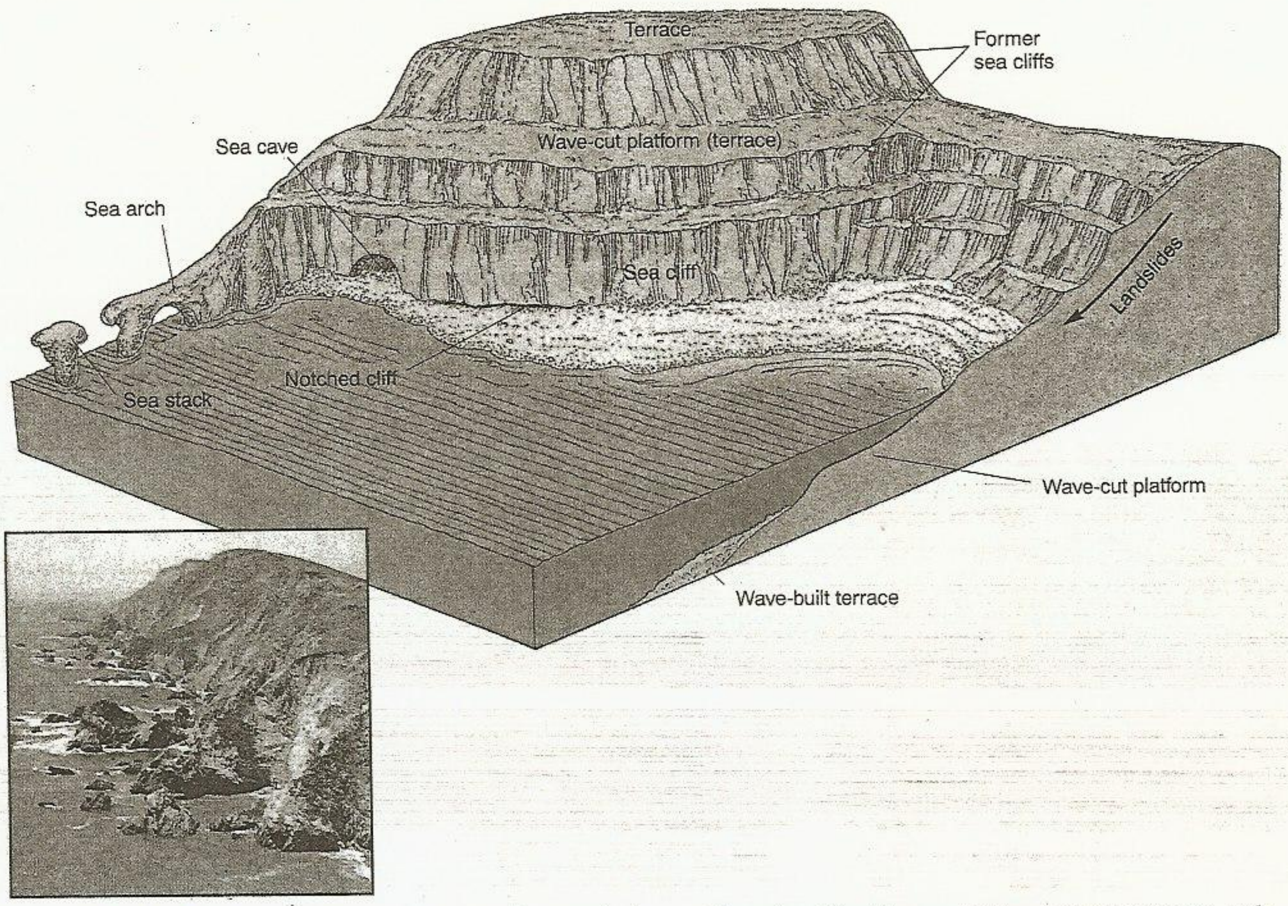


FIGURE 1-12 Erosional coastal features. Characteristic coastal erosional landforms: platforms, terraces, caves, arches, and stacks. (*Source: Geosystems* 3/e, by Christopherson 1997, 494) The photo shows the California coast, a typical erosional coastline. (*Source:* photo by Robert Christopherson, in *Geosystems* 3/e, by Christopherson 1997, 494. Reprinted by permission of Prentice Hall, Inc.)

Coastal Sand Dunes

Sand dunes are among the more interesting, dynamic, and fragile coastal ecosystems. They are classified as aeolian contour bedforms which can be defined as mounds, ridges, or hills of loose sand that have been heaped up by the wind (Griggs and Savoy 1985). Dunes can be formed from both beach sand blowing inland and land sand blowing seaward. Dunes shift over time until a veil of pioneer plants stabilizes the drifting sand. Even after that occurs, however, the dunes still change form under the stress of wind, storm waves, and the traffic of human activity.

Distribution, formation, patterns. Coastal sand dunes occur worldwide, though they are most common in temperate climates, especially along those coasts that have strong onshore winds and a plentiful supply of sand-sized sediment (Carter 1988). Sediment deposited at the mouths of rivers and offshore sandbars provides an important source of material for dune building. The littoral current carries the sediment along the shore until the particles are deposited on a beach by wave action. The dry sand particles on the beach are then blown landward from the beach until driftwood and plants interrupt the wind flow. The drift gradually builds up to a sizable mound. Coastal dune fields may take several shapes, such as *transverse ridges* (parallel ridges perpendicular to the prevailing winds; e.g., Northern California coast), or *parabolic or conical ridges* (U-shaped dunes with the concave side facing the prevailing wind; e.g., Pismo Beach in Central California). The most recently formed dune near the beach is known as the *primary* or *foredune,* whereas the older, more vegetated and thus stabilized dune is called the *backdune or stable dune.* Some backdunes may be as much as 18,000 years old.

Function of sand dunes. Coastal sand dunes have several functions. (See Figure 1-13). First and foremost, they buffer the shore against extreme winds and waves. Second, they replenish beaches and nearshore areas that have had their sand supply depleted during and after heavy storms. The sands eroded from dunes and beaches during winter

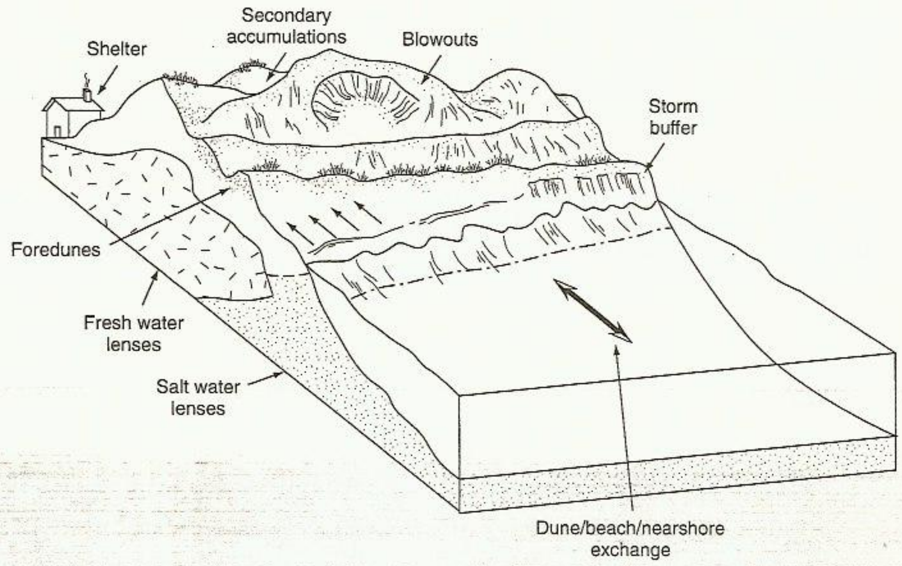


FIGURE 1-13 The coastal sand dune system. (*Source:* Diagram by Heather Theurer.)

storms often form a sandbar offshore. During the calm summer season, the sand is gradually returned to the beach. Third, coastal dunes shelter inland residences and settlements. Fourth, they help in keeping salt-water intrusion from contaminating fresh water lenses (underground freshwater supplies). Coastal dunes are habitats for wildlife (e.g., gray foxes, striped skunks, and mule deer). Finally, they are recreation areas for humans.

Human impact. According to Carter (1988), sand dunes have suffered the greatest degree of human pressure of all the coastal ecosystems. Humans impact dunes by building dams on rivers that trap river sediment, thereby depleting the sand supply to the dune field. Humans also construct groins, jetties, and seawalls that disrupt the natural sediment flow in the littoral drift as well as the recycling of sand from sandbar to beach. Foot traffic, horses, and off-road vehicles damage the dune plants that act as a protective veil; the result often becomes wind erosion and **blowouts**—wind hollows or basins within dunes. Development on our nation's coastal dunes has brought severe damage, particularly to the vulnerable foredune where development should never occur.

Beaches

Of all the coastal formations associated with a depositional coastline, the most familiar is the beach. Most people think of the beach as merely that sandy area on the shore where they sunbathe, picnic, or play in the surf. Technically, however, a **beach** is that area of the shore, on average, from 5 m (16 ft) above high tide to 10 m (33 ft) below low tide (Christopherson 1997), and is composed of sand or pebbles (Refer back to Fig. 1-5). [It should be noted, however, that *coastal scientists often disagree as to the exact definition of the beach area, as well as other subdivisions of the coast.* Consequently, Schwartz (1982, p. 140) maintains, "the best working definition of a beach is the accumulation of unconsolidated sediment that is limited by low tide on the seaward margin and by the limit of storm wave action on the landward side."]

Regardless, more of "the beach" can be underwater than visible to the person strolling along its shore. Seasonal cycles determine the appearance of the visible beach. In summer, beaches are generally wide and gently sloping; they become steep-fronted and narrow from winter storms. With violent storm waves, beaches may be stripped of all their sand, exposing larger rock particles or rock pavement. The sand that is removed from beaches in the winter is deposited in offshore sandbars. During mild summer months, gentle swells push the offshore sediment back to the exposed shore.

Source and type of sediment. The beach is an area where sediment is in motion. Constructive action is from the **swash** of the wave, while destructive action occurs from its **backwash.** Sediment is deposited by breaking waves, often with the aid of littoral drift. The sand, pebbles, and fragmented shell originate from several sources, including sediment from rivers entering the sea, erosion of cliffs, and debris recycled from other beaches. In some California sites, river sediments are the source of 80 to 90 percent of beach sand (California Coastal Commission 1987).

The color of the sand gives a clue to its mineral content, as well as to the origin of the eroded sediments that make up the sand supply. Some of the world's beaches are stark white, dominated by sands of quartz and feldspar minerals, such as at Carmel Beach, California, which is located on the shores of the Monterey Bay National Marine Sanctuary. Other "white sandy beaches" are actually more amber-colored. For example, close inspection of the beach at Sand City just a few miles north of Carmel Beach reveals the presence of iron minerals; pale quartz grains; flecks of black mica; and green, pink, or white feldspar. In volcanic areas, such as Hawaii and Iceland, wave-processed lava creates black-sand beaches. On some shores, beaches are almost nonexistent, such as on the coast of Maine, portions of the Atlantic provinces of Canada, and the southern coast of Monterey Bay, California. Here, the scenically rugged shores are dominated by resistant granite rock, rather than long and wide sandy beaches.

Function. A beach has several functions, but the primary one is to stabilize a shoreline by absorbing wave energy. It can do this because of two principal features: First, the *sloping surface* of a beach gradually dissipates the energy of a wave as the wave makes its way up shore. Second, the fact that a beach is *made of sand* allows it to be flexible, changing its slope and contour as the waves change.

Types of sandy beaches. There are three major types of sandy beaches: mainland, pocket, and barrier. **Mainland beaches** stretch unbroken for several miles along the edges of a "mainland," or major land mass. They are generally low standing, prone to flooding, and are often backed by steep headlands. Sediment arrives from nearby rivers and eroding bluffs.

Examples of mainland beaches can be found in southern California, northern New Jersey, and the coasts of the Great Lakes. **Pocket beaches** are found in "pockets"—small bays or alcoves protected by surrounding rocky cliffs or headlands. The coasts of New England and the Pacific Northwest have numerous pocket beaches. By contrast, one would look along the east and southeast coast of the U.S., the Gulf of Mexico, and much of Alaska to find examples of barrier beaches. **Barrier beaches** are part of a complex integrated system of beaches, dunes, bays, marshes, tidal flats, and inlets. **Barrier islands** and associated beaches will be discussed in greater detail below.

Ecological habitat and human impact. One often forgets that a beach is an ecological habitat for numerous organisms, as well as a place for humans to sunbathe, swim, surf, picnic, and fish. For example, beaches are inhabited by numerous invertebrates and insects: Crustaceans, bivalve mollusks, and tube-building worms exist in the surf zone; sand crabs scavenge in the sun-dried kelp inland from the surf zone; beetles and pesty kelp flies roam the beach foreshore; and air-breathing pill bugs and beach hoppers inhabit the dry upper beach.

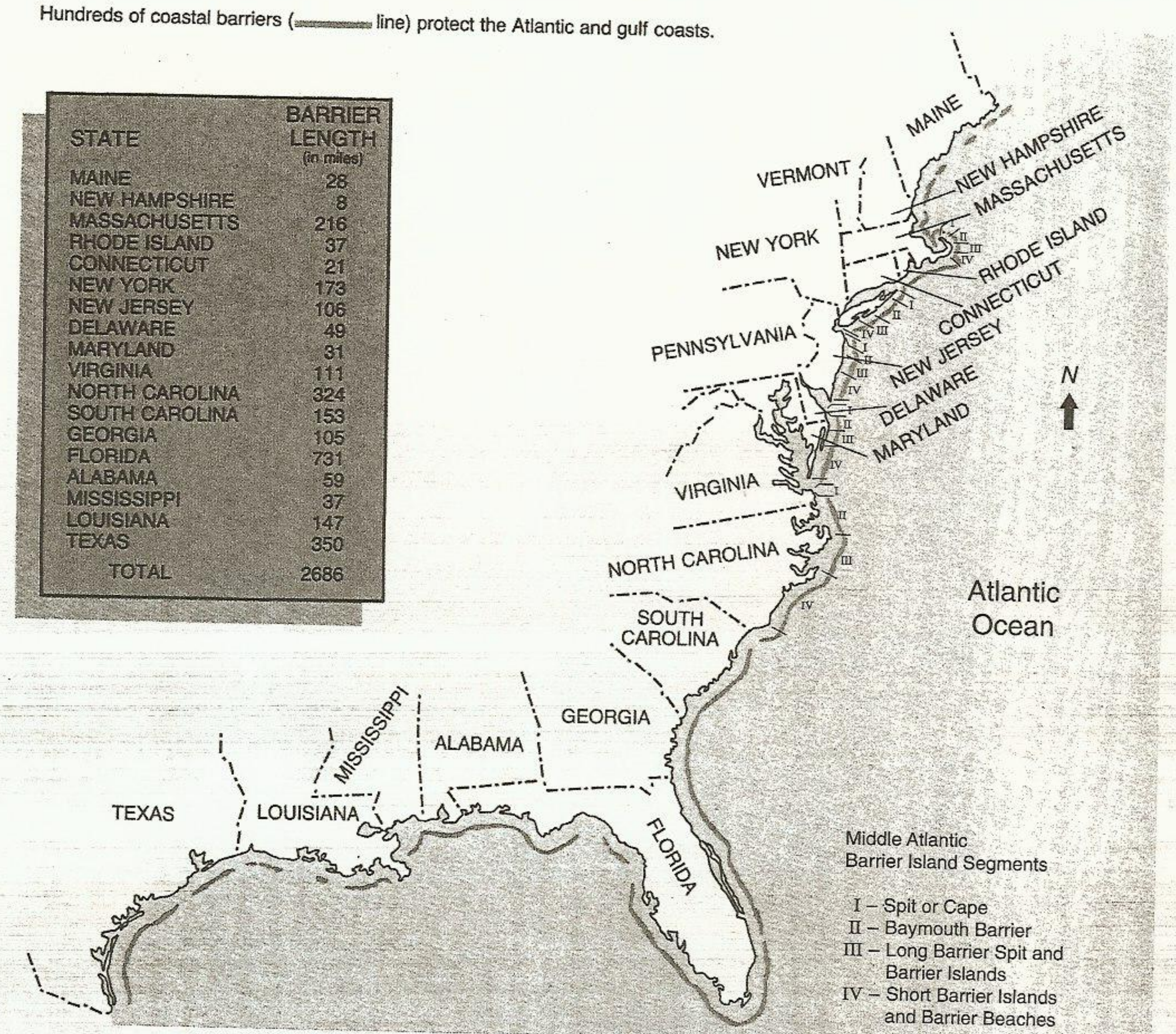
Beaches, especially the sandy ones, are of considerable importance to humans. They are obviously a major tourist and recreational resource. Imagine the economic consequences to such beach cities as Miami Beach, Florida or Waikiki Beach on Oahu in Hawaii, if there were no beaches. Unfortunately, humans have impacted this coastal habitat in a variety of ways, including the discharge of raw domestic sewage; oil pollution from offshore drilling rigs or tanker spills; industrial effluent; and the disruption of sediment flow by sand mining, or the construction of such items as jetties, groins, and breakwaters. All of these negative impacts can result in lost or closed beaches, sediment filled (and thus closed) harbors, falling coastal highways, and condemned beach houses.

Coastal Barriers

Another coastal formation is the coastal barrier. A **coastal barrier** is a natural geomorphic feature that forms offshore roughly parallel to the coast. It acts as a barrier, taking the brunt of storm energy, thereby protecting the mainland. These protective coastal features can be found along 4,345 km (2,700 mi) of our nation's shoreline, from the rocky headlands of Maine to the arid salt flats of south Texas. (See Figure 1-14). Coastal barriers are composed of sand and other sediments that are supplied by longshore currents, tides, and waves.

Types of coastal barriers. There are three major types of coastal barriers: barrier spits, bay barriers, and barrier islands. A **barrier spit** is an elongated depositional sand barrier attached to a headland that partially crosses the mouth of a bay, creating a **lagoon**. An example of this is Siletz Spit on the Oregon coast. (See Figure 1-15).

When a bank of sand or shingle extends all the way across a bay from headland to headland, a **bay barrier** has developed. In this case, the bay is cut off completely from the ocean. The barrier at Edgartown Great Pond on the Martha's Vineyard coast is an excellent example of a barrier. Some bay barriers may have been formed by the convergence of spits, growing in opposite directions from each end of the bay. Bay barriers may also be the result of onshore migration of offshore bars, with the aid of a rising sea level. Regardless, what is characteristic of bay barriers is that they connect headlands and occur in shallow waters. Other terms are also used for bay barriers, such as *bay bars* or *baymouth bars*. If the sandy bar is in the form of an island—not attached to a headland, nor spanning headlands—it is called a **barrier island.** The often used example of a barrier island chain is that which is found along the North Carolina coast, from Virginia Beach in the north to Cape Lookout in the south. (See Figure 1-16). This area includes Kitty Hawk where the Wright Brothers gave flight to their first aircraft, as well as Cape Hatteras—one of three local na-



STATE	BARRIER LENGTH (in miles)
MAINE	28
NEW HAMPSHIRE	8
MASSACHUSETTS	216
RHODE ISLAND	37
CONNECTICUT	21
NEW YORK	173
NEW JERSEY	106
DELAWARE	49
MARYLAND	31
VIRGINIA	111
NORTH CAROLINA	324
SOUTH CAROLINA	153
GEORGIA	105
FLORIDA	731
ALABAMA	59
MISSISSIPPI	37
LOUISIANA	147
TEXAS	350
TOTAL	2686

FIGURE 1-14 Coastal barriers along the Atlantic and gulf coasts, illustrating middle Atlantic barrier island segments. (*Source:* Adapted from Wells and Peterson, undated; 4)

tional seashore reserves managed by the National Park Service.

Barrier islands. Barrier islands are the most complex of the various coastal barriers, since they include all of the environments also found in other coastal barriers, and they have been the most used (and abused) by humans. Approximately 12–15 percent of the Earth's outer coastline has barrier islands, ranging from the north slope of Alaska to the tropics of South America and Australia (Davis 1994). In order to form, barrier islands need three key ingredients—*sediment* (an abundant supply of sand); *a transport agent* (wind, waves, and currents to carry the sediment), and *an accumulation site* (a gently sloping continental shelf where the sediment can accumulate). All three ingredients are found on stable, trailing edge coasts. Consequently, the Atlantic coast of the United States—a classic example of a trailing edge coast, is basically one continuous barrier island system. For a discussion of various theories on barrier island formation, see Davis 1994.

Value of coastal barriers. As mentioned earlier, coastal barriers protect the mainland from storm waves and surge. However, this *buffering service* against wave energy provides another value—*habitat formation.* In other words, coastal barriers allow marshes, estuaries, and other ecological habitats to develop. For example, a well

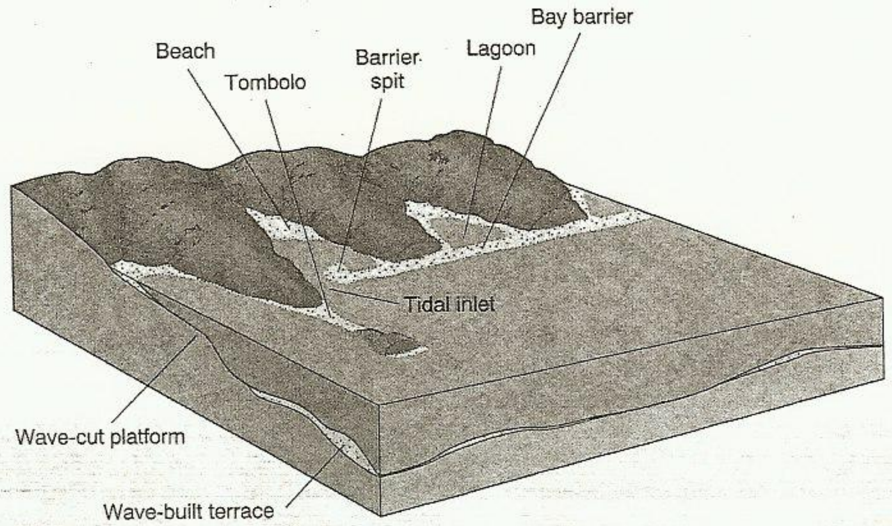


FIGURE 1-15 Characteristic depositional coastal features (*Source: Geosystems* 3/e, Christopherson 1997, 495. Reprinted by permission of Prentice Hall, Inc.)

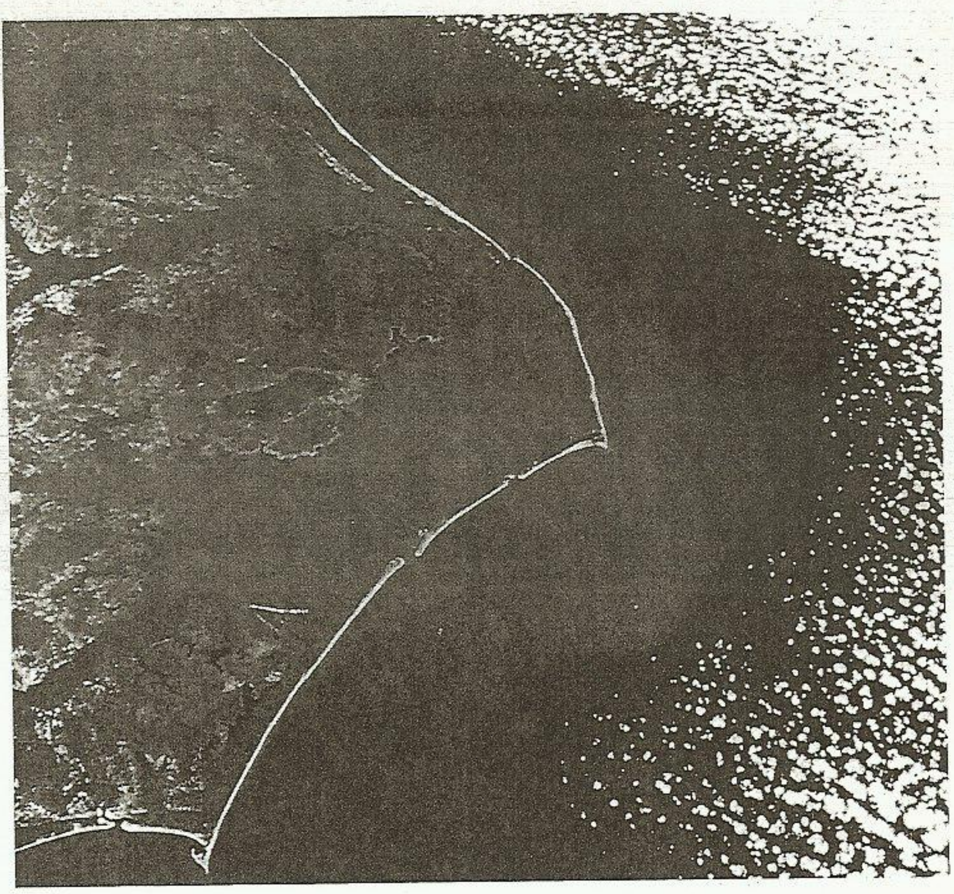


FIGURE 1-16 *Landsat* image of barrier island chain along the North Carolina coast. Hurricane Emily swept past Cape Hatteras in August 1993, causing damage and beach erosion. (*Source:* Image from NASA.)

developed barrier island and nearby mainland has six major coastal ecosystems: (1) a *coastal marine ecosystem,* which includes the intertidal and subtidal zone, as well as the beach; (2) a *seaward maritime ecosystem,* which includes the dune field, shrub thicket and maritime forest on the ocean side of the island; (3) a *freshwater ecosystem,* which contains rivers, lakes, and associated marsh or swamps; (4) *a landward maritime ecosystem,* containing a maritime forest; (5) an *estuarine ecosystem,* which contains marsh or mangroves on its seaward side, and seagrass beds, sand and mud flats, and oyster reefs in the center and landward side; and (6) a *mainland ecosystem,* which is the upland habitat adjacent to barrier islands. (See Figure 1-17).

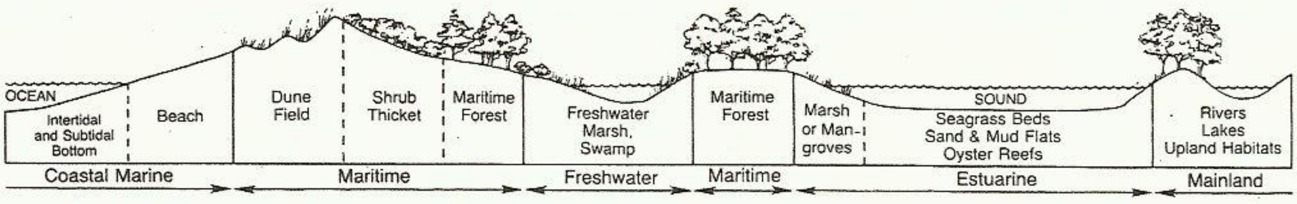


FIGURE 1-17 Cross section of typical barrier island and nearby mainland. (*Source:* Wells and Peterson [undated])

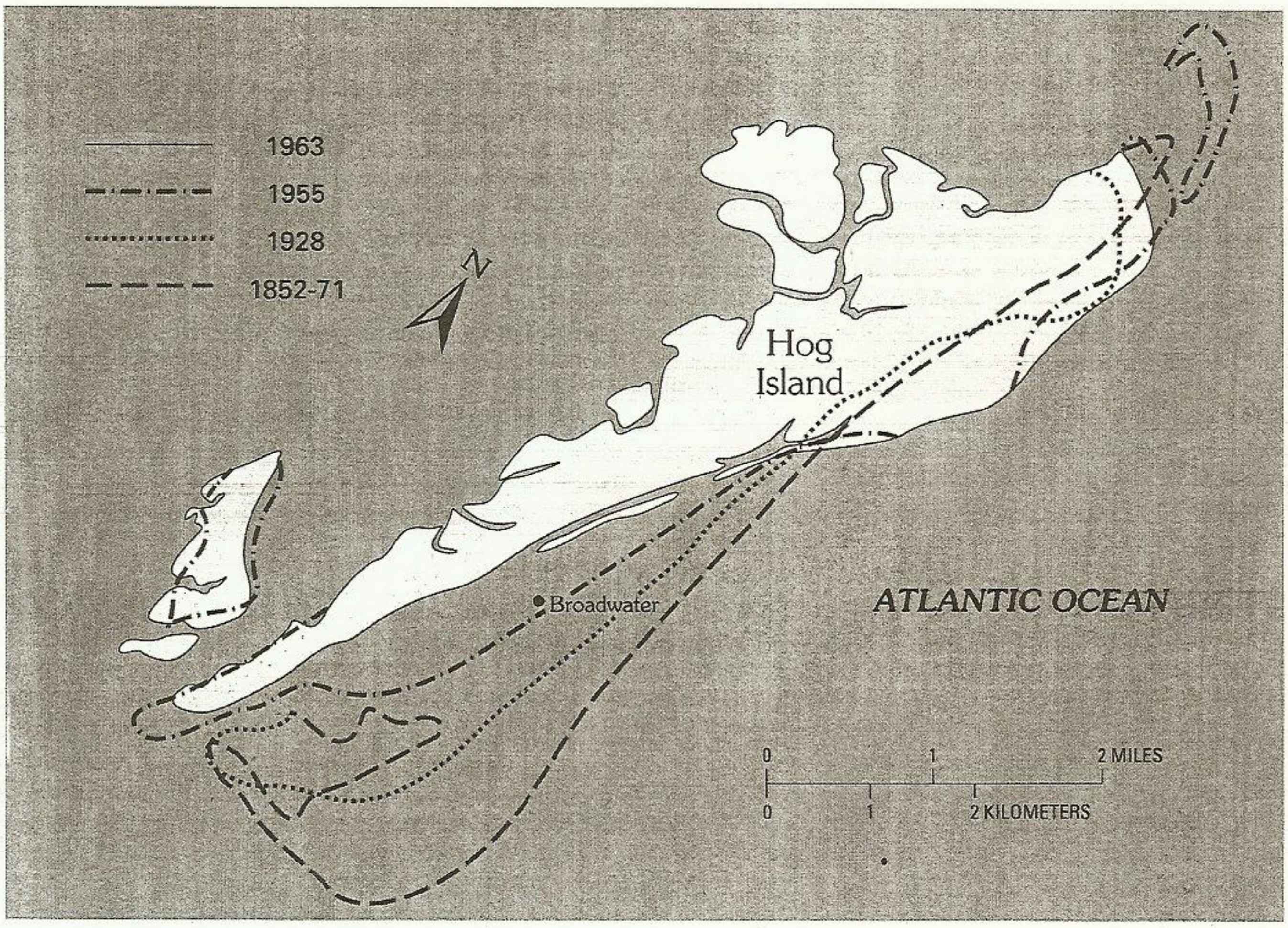


FIGURE 1-18 Hog Island, Virginia—A changing barrier island. (Modified from *Ecosystem Description,* Vol. 1, part B, of Virginia Coast Reserve Study conducted by the Nature Conservancy, [*Source:* Adapted from Williams, et al., 1990])

These habitats are important to shorebirds, water birds, and other waterfowl for their breeding and migration cycles. Many of our nation's endangered and threatened species, such as the loggerhead sea turtle and the whooping crane, make use of these areas. Coastal barriers are also valuable to humans for recreation purposes (e.g., nature walks, birdwatching, photography) as well as the economic benefits of tourism to local coastal communities.

Human impacts on coastal barriers. Coastal barriers are constantly migrating because they are exposed to severe storms. Consequently, these ever changing "ribbons of sand" are an unwise choice for homesites or commercial building. Yet, humans continue to build on these unstable structures. Many of the coastal barriers along Florida's coast have been so overdeveloped that they are a mere sea of roads, hotels, condominiums, and shopping centers. Someday, in fact, they may be literally "returned to the sea." Even the slightest development on a barrier island can provide a dangerous scenario. A case in point is the barrier island called Hog Island off the coast of Virginia. (See Figure 1-18).

In the 1800s, hunting and fishing clubs were established in the pine forests on Virginia's barrier islands.

One of the largest clubs was at Broadwater near the middle of Hog Island—an island of 300 people, 50 houses, a lighthouse, a school, a church, and a cemetery. By 1930, erosion brought down the lighthouse, and a hurricane in 1933 destroyed the protective pine forest and devastated the town. By 1940, most of the inhabitants gave up and left the island. Today, the former site of Broadwater is hundreds of meters offshore, under several meters of water.

Coastal Inlets—Lagoons, Deltas, and Estuaries

Coastal inlets are another form of coastal formation. A **coastal inlet** can be defined as a small indentation in a coastline, and is usually a relatively narrow channel or pocket of water that leads inland. Davies (1977) identifies three broad classes of coastal inlets—lagoons, estuaries, and deltas.

Lagoons. At one end of the spectrum are **lagoons**—long, shallow bodies of water with very restricted exchange with the sea, minimal tidal flux, and no significant freshwater inflow. Consequently, variations in salinity are due primarily to seasonal fluctuations in precipitation and evaporation. Lagoons form wherever sandbars or barriers separate a section of the sea from the mainland. In terms of a habitat for wildlife, lagoons typify that of a hypersaline environment—few species but large populations (Davis 1994).

Deltas. At the other end of the spectrum are **deltas**—land masses formed from alluvial deposits of sand, silt, mud, and other particles at the mouth of a river. Delta shapes are most often explained and classified according to the relative influence of the three major factors affecting their development: the river, waves, and tides. In 1975, William Galloway—a geology professor at the University of Texas at Austin—originated the triangular classification scheme for river deltas. (See Figure 1-19).

River-dominated deltas, such as the Mississippi River delta on the Gulf of Mexico, characteristically have (a) a good freshwater and sediment supply from the drainage

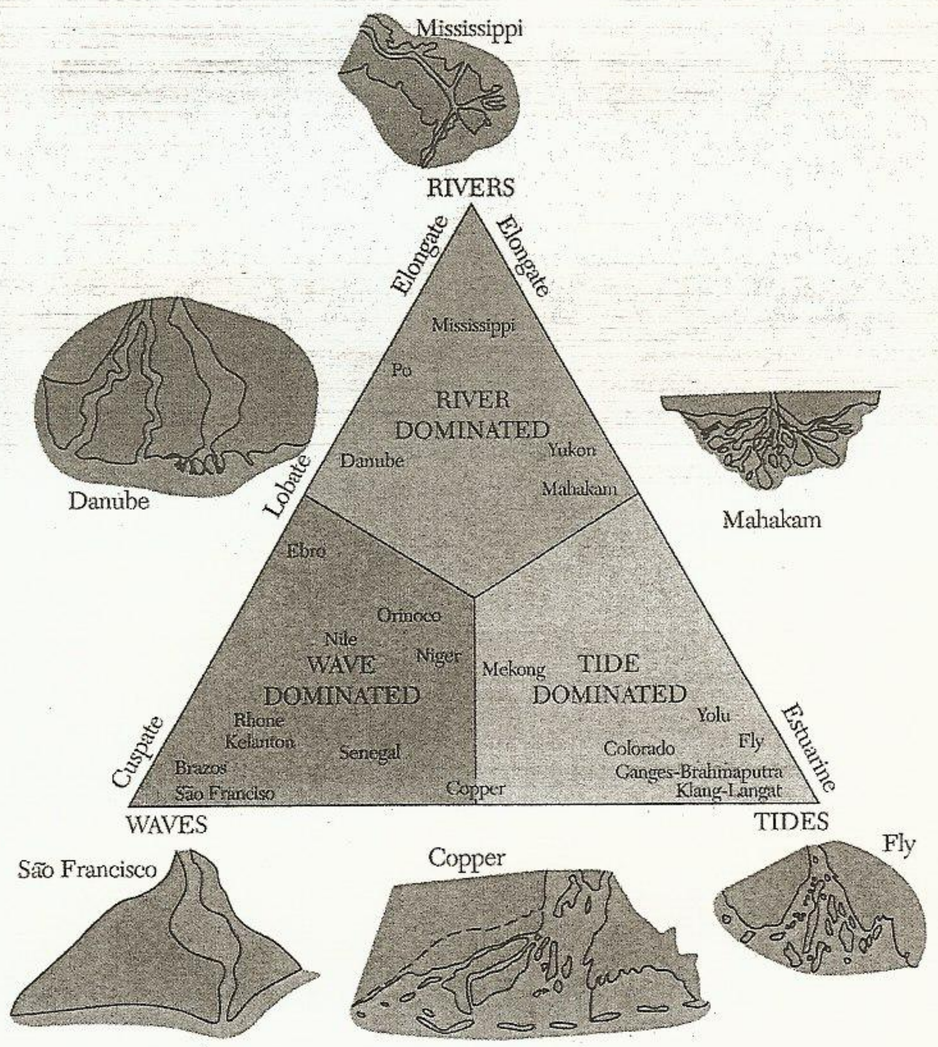


FIGURE 1-19 River delta systems according to William Galloway's triangular diagram classification system. (*Source:* Adapted from L. D. Wright and J. M. Coleman, AAPG ©1973, reprinted by permission of the American Association of Petroleum Geologist)

basin; (b) a well-developed (elongated) delta plain; (c) several tributaries projecting seaward, giving them a "bird's-foot" configuration; and (d) a placid receiving basin—one that has small waves, a small tidal range, and a tectonically stable coast. Although the Mississippi delta is in the path of hurricanes and storm surges that cause accelerated erosion, this activity does not impact overall delta configuration (Davis 1994).

Tide-dominated deltas, such as the Fly River in Papua, New Guinea, generally have (a) strong tidal currents that overpower the freshwater discharge; (b) weak longshore currents; (c) more sediments carried inland by strong tidal currents than river sediment discharge; and (d) salt marshes that rim the intertidal flats. Because of their tidal flats and salt marshes, tide-dominated deltas have a tendency to resemble estuaries.

Wave-dominated deltas, such as the São Francisco River delta on the southern coast of Brazil, characteristically have (a) only one river channel, or just a few distributaries; (b) river and sediment flow is only moderate compared to the stronger distributing power of the waves; (c) weak tides; and (d) well-developed beaches and dunes on the outer delta. Wave-dominated deltas are generally smaller than the other two types, because the waves striking the delta front are more powerful than the river's ability to replace the area with sediment.

Estuaries. Estuaries are a third type of coastal inlet. Whereas lagoons are quiet saline bays with no regular freshwater influx, an **estuary** is the area where the mouth of a river enters the sea and freshwater and seawater intermix. Since it is a place where tides ebb and flow, it is often more turbulent than a lagoon. Another way of thinking about estuaries is that they are "arms of the ocean" that have been thrust into the mouth and lower course of rivers as far as the tide will take them. All estuaries have three parts: (1) the *head* (the inland areas where the river enters); (2) the *main estuary* (the middle or fully estuarine area); and (3) the *mouth* (the seaward end or indentation of the coastline). (See Figure 1-20).

Estuaries are generally classified according to geologic origin and geomorphology, or according to characteristic circulation patterns. When classified according to origin, there are four types: coastal plains estuaries; fjord estuaries; bar-built estuaries; and tectonic estuaries. *Coastal plains estuaries* (also commonly known as "drowned river valley estuaries") are the result of the drowning of a river valley. Many of the estuaries of the eastern United States are of this type, including the Chesapeake and Delaware bays, and the estuaries of the Mississippi, Hudson, and Savannah rivers. *Fjord estuaries* are the result of the drowning of a valley gouged out by glaciers. These estuaries are generally deep, narrow, and u-shaped in cross section. The largest fjord estuaries can be found in Greenland, British Columbia, Scandinavia, and Chile. Estuaries may also result from the development of an offshore barrier, such as a line of barrier islands, a reef formation, a beach strand, or a line of marine debris. Examples of these bar-built estuaries include: Laguna Madre, along the Texas coast; Barataria Bay and Mississippi Sound, along the Gulf of Mexico; and Pamlico and Albemarle sounds in North Carolina. Tectonic processes may also result in the origin of *tectonic estuaries,* such as San Francisco Bay, that resulted from slippage and land subsidence along fault lines.

The above classification of estuaries by geologic origin is useful, especially to physical geographers and geologists, but physical oceanographers choose to classify estuaries according to circulation patterns. According to this classification system, there are three types of estuaries: salt-wedge estuaries; partially mixed estuaries; and fully mixed estuaries. (See Figure 1-21).

Salt-wedge estuaries are referred by some as "stratified estuaries" since the saltwater and freshwater masses are almost completely separate, with no significant amount of mixing occurring. These estuaries are river dominated, with a weak marine inflow due to a small tidal range. The Mississippi River estuary is a good example of

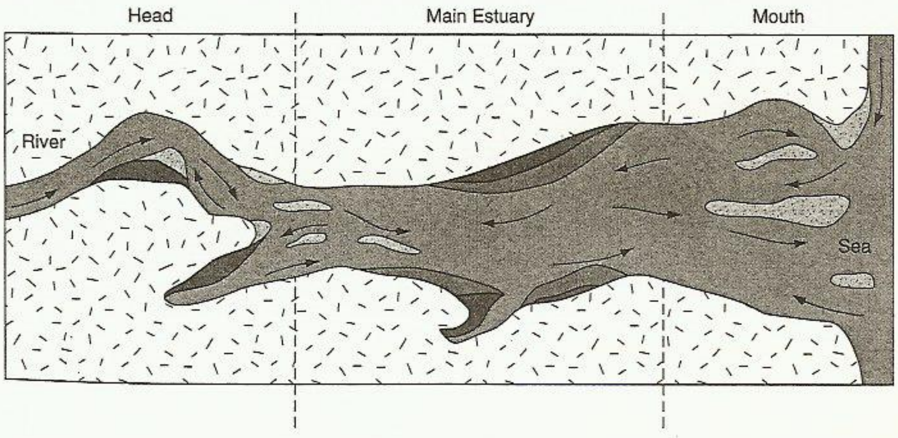


FIGURE 1-20 Three major parts of a typical estuary—Head, Main Estuary, Mouth. (*Source:* Diagram by Heather Theurer.)

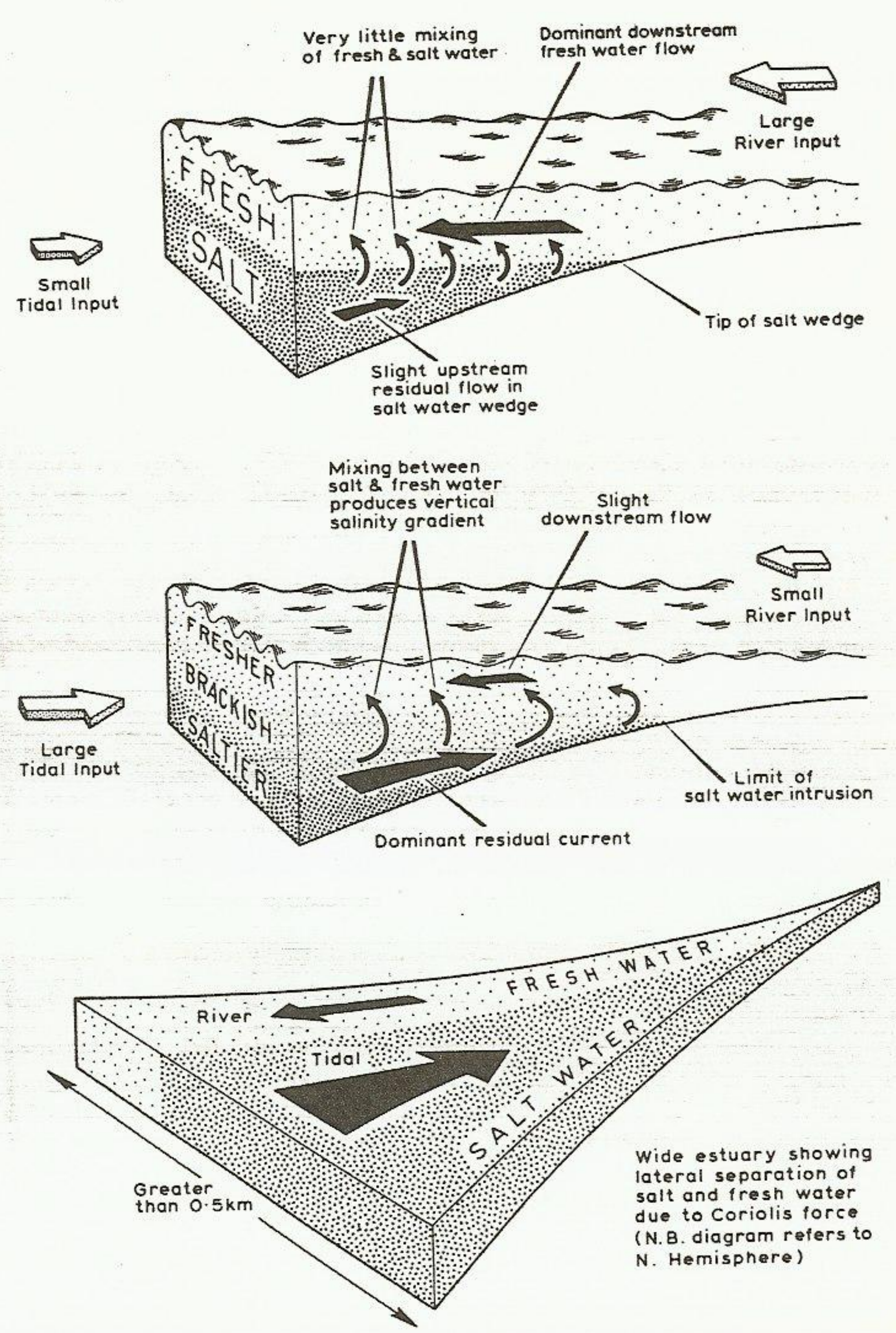


FIGURE 1-21 Three major types of estuaries—Salt-wedge; Partially-mixed; Fully-mixed. (*Source:* Adapted from Pethick 1984, 179–181)

a salt-wedge estuary. On the other hand, the Chesapeake Bay is a good example of a *partially mixed estuary.* In this type of estuary, tidal current, not a river, is the dominant factor in circulation. Consequently, a mixing of salt water and fresh water occurs. Salinities in partially mixed estuaries may range from 0 for fresh water to 35 parts per thousand for undiluted seawater (Davis 1994). *Fully mixed estuaries* may have either vertically homogenous water profiles [i.e., the salinity is the same from the surface to the bottom of the water body (Davis 1994)], or have lateral flow and salinity separation [i.e., the net salt water and fresh water flow are moving in opposite directions (Pethick 1984)]. In any case, these estuaries characteristically have weak river flow, strong tidal flows, and are generally wider than about 0.5 km (0.3 mi) (Pethick 1984). It is important to remember, however, that these circulation patterns may also shift with the seasons. For example, the variation in wave action between summer and winter may cause an estuary to vary from stratified to partially mixed. However, some funnel-shaped resonating estuaries like the Bay of Fundy in Nova Scotia, Canada, have such strong tidal currents that they remain fully mixed throughout the year (Davis 1994).

Coastal Wetlands

Coastal wetlands are another type of coastal phenomenon. Coastal wetlands can be simply defined as wet vegetated areas along the coast. Wetlands have three components: (1) presence of water at the surface or within the root zone; (2) soil conditions that are different from adjacent uplands; and (3) vegetation adapted to wet conditions (*hydrophytes*) (Mitsch and Gosselink 1993). These components are all a part of the major habitats associated with estuaries: salt marshes, freshwater marshes, and mangrove swamps.

Salt marshes. A salt marsh is a "natural or semi-natural halophytic grassland and dwarf brushwood on the alluvial sediments bordering saline water bodies whose water level fluctuates either tidally or non-tidally" (Beeftink 1977). Salt marshes predominate in mid to high latitudes along intertidal shores throughout the world. In the lower tropical and subtropical regions (between 25 degrees N and 25 degrees S), they are replaced by mangrove swamps along coastlines. A cross-section of a salt marsh shows the subenvironments and distribution of different marsh grasses. (See Figure 1-22). Generally, cordgrass (*Spartina*) can be found closest to the tidal creek, while the higher marsh is covered in various varieties of needle rush (*Juncus*).

Freshwater marshes. Freshwater coastal marshes combine many of the features of saline coastal marshes and freshwater inland marshes, yet they remain unique ecosystems. Freshwater marshes reflect greater biotic diversity, as a result of the reduction of salt stress found in salt marshes. Because plant diversity is higher, more birds use this type of marsh than any other marsh type. Freshwater marshes require adequate river flow or rainfall to maintain fresh conditions, a relatively flat gradient from the shoreline inland, and a substantial tidal range. This set of conditions occurs along the middle and south Atlantic shores of the United States. There is not always a clear-cut distinction between tidal and inland freshwater marshes since on the coast they form a continuum. (See Figure 1-23). It is safe to say, however, that tidal freshwater marshes experience tides but are above the salt boundary, whereas inland freshwater marshes experience neither salt nor tides. Since urban centers are generally located further inland from the more saline portions of the estuary, these freshwater coastal marshes are usually more susceptible to human impact than coastal salt marshes.

Mangrove swamps. In tropical and subtropical estuaries and bays throughout the world, the mangrove wetland replaces the salt marsh as the dominant coastal ecosystem. **Mangroves,** commonly called swamps but actually *mangles,* are thick tangles of woody shrub and tree roots of various taxonomic groups. (See Figure 1-24). All the dominant plant species are known for their ability to adapt to the saline wetland environment (e.g., salt exclusion, salt excretion, pneumatophores, and the production of viviparous seedlings). Mangroves are most noted for their spectacular display of prop (above ground) roots, especially the red mangrove (*Rhizophora mangle*) and the black mangrove (*Avicennia germinans*). These massive root systems provide physical stability to shorelines by creating dense sediment-stabilizing mazes. Scientists have also established that mangroves serve as sinks for nutrients and carbon, protect inland areas from severe damage during tidal waves and hurricanes, and export organic matter to adjacent coastal food chains.

These "tropical buffer zones" are limited geographically to the frost free zone of 25 degrees N to 25 degrees S latitude. (See Figure 1-25). In the United States, mangrove wetlands are limited to the southern extremes of Florida and to Puerto Rico. In Florida, the best development of mangroves is along the southwest coast, where the Everglades and the Big Cypress Swamp drain to the sea. This is the area of Florida's Ten Thousand Islands—one of the largest mangrove swamps in the world. The predominant species of mangrove here is the white mangrove (*Laguncularia racemosa*). Development pressures, however, have eliminated a significant portion of these original mangroves. For example, Patterson (1986) estimates that 24 percent of the mangroves were removed from Marco Island—one of the most developed islands in the region. Today, Florida's mangroves are protected against such devastation.

Importance of estuaries and coastal wetlands. In the past, estuaries and their associated wetlands (saltwater marshes, freshwater marshes, mangroves) were considered swampy wastelands. Today, because of scientific findings and changing public perception, these so-called wastelands are taking on new value. We now know that estuaries and wetlands can function as:

- *Wildlife habitats.* They provide shelter, migration rest stops, breeding sites, and food for millions of waterfowl, fishes, invertebrates, and fur-bearing animals. In fact, several endangered species live only in estuaries and their associated wetlands.
- *Fish nurseries.* They provide a breeding ground for large numbers of fishes, including commercially important species. According to Owen and Chiras (1995), 60 percent of the marine fish harvested by America's fishing

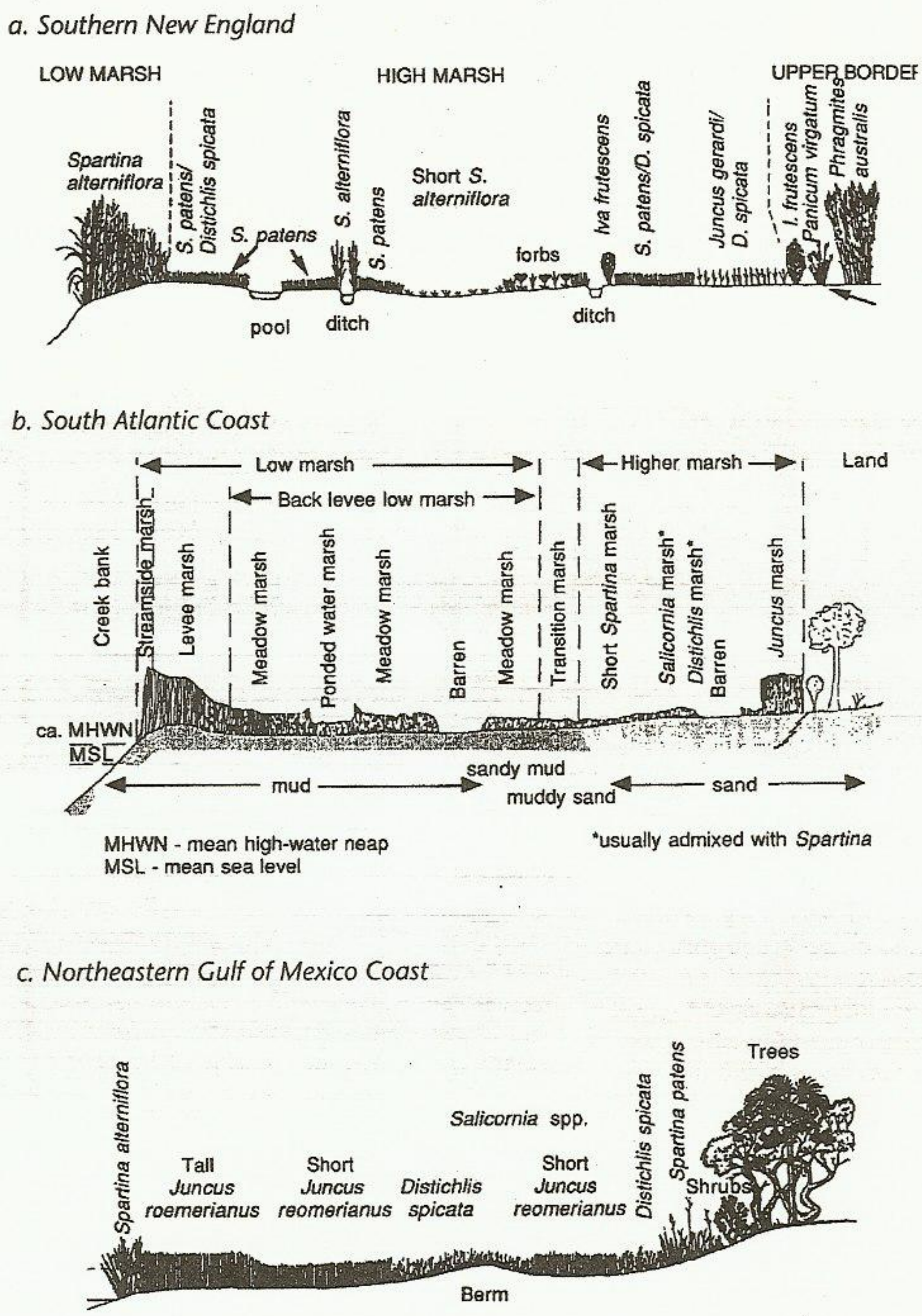


FIGURE 1-22 Zonation of vegetation in typical North American salt marshes. (a. after Niering and Warren, 1980; b. after Wiegert and Freeman, 1990; c. from Montague and Wiegert, 1990. [*Source: Wetlands*, 2/e by Mitsch and Gosselink, © 1993. Reprinted with permission of John Wiley & Sons, Inc.])

industry spend part of their life cycle in estuaries. In the Gulf of Mexico, for example, 98 of every 100 fish that are taken are estuary and salt marsh dependent.

- *Fisheries.* Estuaries provide fish and shell fish as a valuable food resource.
- *Natural farms.* They grow green material (more than our best-managed farms) that feeds a complex food web.
- *Flood and erosion controls.* They provide an important role in flood control, by absorbing the shock of storm-driven waves before they rush inland and cause destruction of property and human life.
- *Natural pollution-filtering systems.* They help cleanse the water of industrial and domestic sewage delivered to the estuaries by rivers. For example, just 5.6 hectares (14 acres) of estuary has the same pollution-reducing ability as a $1 million waste treatment plant (Owen and Chiras 1995).
- *Air purification systems.* They, like any large expanse of green plants, absorb carbon dioxide from the air and release oxygen.
- *Environmental education centers.* They provide "living laboratories" for schools, recreation centers, and mental health retreats.

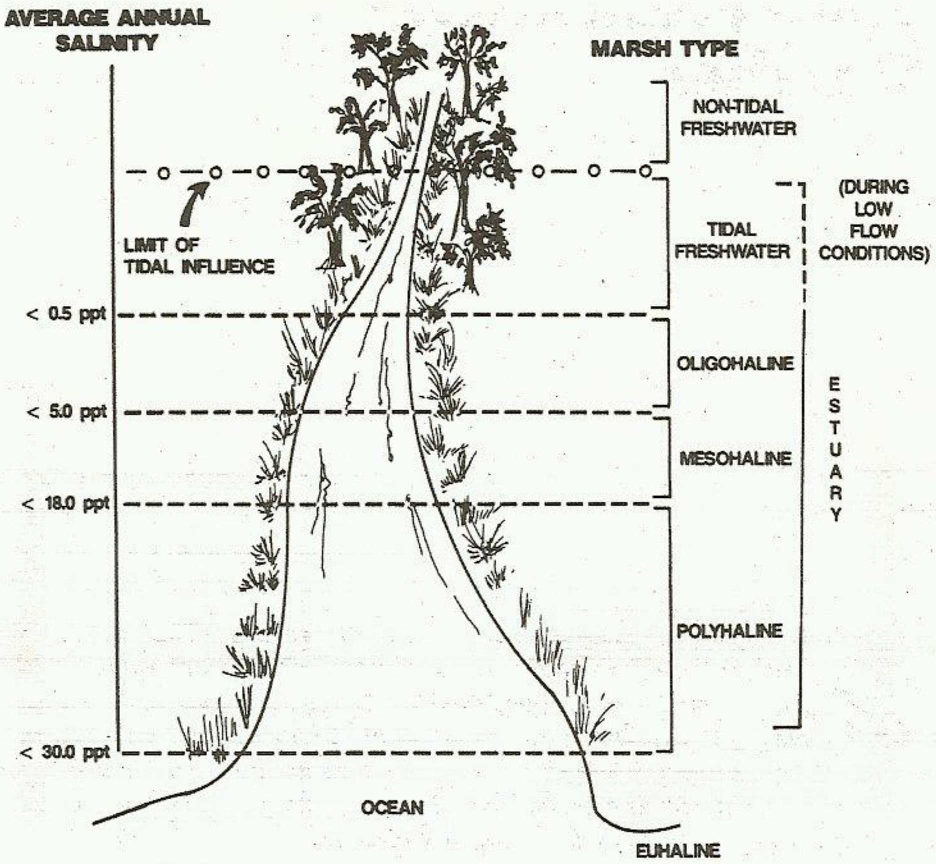


FIGURE 1-23 Coastal marshes lie on gradients of decreasing salinity from the ocean inland. (From W.E. Odum et al., 1984. [*Source: Wetlands,* 2/e by Mitsch and Gosselink, © 1993. Reprinted by permission of John Wiley & Sons, Inc.])

- *Job centers.* They provide jobs for fishermen, wetlands ecologists, marsh managers, tour guides, and nature or recreational store owners.
- *Tourist attractions.* They attract millions of visitors, such as birdwatchers, anglers, hunters, and boaters. The local economy is also supported when these same people "support their sport" by spending money in local nearby towns.

If you add up all the values of a particular estuary and/or its associated wetland, the site that may have once been considered a "muddy wasteland" may be more valuable to society in the long run than if the site were developed for short-term profit.

Destruction of estuaries and coastal wetlands. Despite their importance, our nation's estuaries and associated wetlands are annually dredged to deepen channels for navigation and filled to form solid land for agriculture or construction sites. The economic value of wetland development is an important force causing this change. In the early 1980s, more than 180,000 hectares (450,000 acres) of U.S. wetlands (much of it in estuaries) was destroyed annually (Owen and Chiras 1995). Most of this occurred on the coasts of New Jersey, Florida, Louisiana, Texas, and California. However, efforts are beginning to reverse some of this destruction. There is a growing interest in estuarine and coastal wetland restoration, though most mitigation projects to date have not been very successful. For example, the U.S. Army Corps of Engineers is now beginning to use sediment dredged from rivers to create new marshes. But compared to the current rate of destruction, their efforts are still minuscule.

Nearshore Waters and Open Ocean (including Marine Sanctuaries)

The final major coastal habitat is a combination of the nearshore zone (swash zone, surf zone, and breaker zone) and the offshore zone. Here, on the gently sloping continental shelf, one finds vast numbers of marine organisms, algae, invertebrates, fish, seabirds, and mammals that inhabit these shallow waters. It is also here that one finds tide pools (in the intertidal), kelp forests, sea mounts, and submarine canyons that provide a diversity of ecological habitats for wildlife. It is also within this zone that our nation has its national marine sanctuaries—the oceanic equivalent to our terrestrial national park system. An entire chapter, Chapter 3, will be devoted to discussing these marine and coastal protected areas.