Shoreline Erosion and Accretion of the Middle Atlantic Coast

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Introduction

Throughout history, people have been drawn to coastal areas for both economic and recreational purposes. In many places, development has taken place more rapidly than has our understanding of beach and barrier island processes. Processes affecting the shore zone span time scales from hours to decades and longer and include variations in the beach during a single 12-hour tidal cycle, periodic storm surges, shoreline recession in response to long-term changes in sea level, changes in storm tracks, and island-wide modifications associated with man's activities (fig. 1). Over the past several decades, much construction has taken place immediately inland from the shoreline, even though this location clearly introduces serious risks to both life and property (fig. 2). Understanding the natural dynamics is the key to recognizing and estimating both the short-term and long-term hazards of living in the coastal zone (Williams and others, 1991).

Coastal Geology and Geomorphology

The Atlantic Coastal Plain, from New Jersey to Florida, is relatively flat and slopes gently seaward to a wide submarine continental shelf. The shore zone, or interface between the land and sea portions of the coastal plain, consists of a series of barrier islands 2 to 20 mi (3 to 30 km) offshore. Most are low islands 1 to 3 mi (1.5 to 5 km) wide and 10 to 20 mi (15 to 30 km) long (fig. 3). The highest topographic features are sand dunes usually 10 to 20 ft (3 to 8 m) above sea level. In a few areas, such as Jockey Ridge near Nags Head, North Carolina, unvegetated dunes reach heights of 120 ft (40 m).

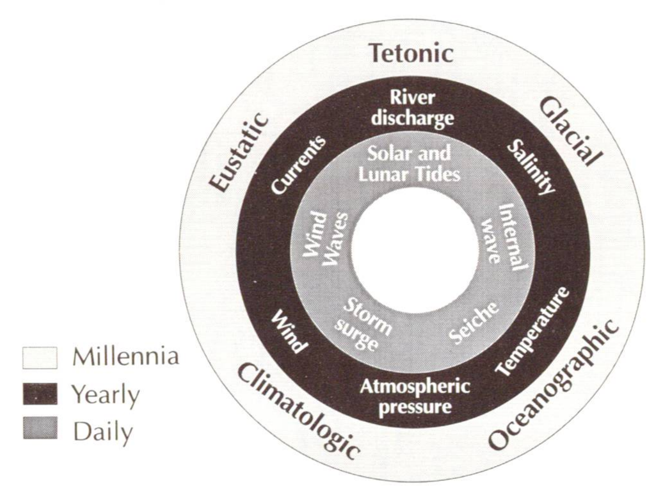

Figure 1. Coastal processes and periods of change.

In cross section, the Atlantic coast barrier islands are assemblages of sedimentary layers, each made up of particle sizes reflective of their sources and the processes responsible for their movements. These island deposits consist primarily of medium-grained quartz sand with a small percentage of heavy minerals, gravels, and shell fragments.

Beach material is carried and deposited by three dominant processes: inshore currents generated by waves and tides, storm surge and overwash, and transport by currents flowing through inlets. Bedded within the layers of beach material are units of well-sorted finer sands transported by wind. The interface between land and sea is a zone in constant motion (fig. 4). On sandy coasts, each variation in sea level alters the interface. Beach sands are transported offshore, onshore, and in the direction of prevailing longshore currents. In this way sandy coasts constantly adjust to accommodate different tide, wave, and current conditions. Periodic episodes of erosion and deposition are superimposed on a longer term trend of a rising sea level. This long-term rise submerges the beach, causes shoreline recession, and forces the barrier islands to migrate landward.

Figure 2. Impact of the Halloween storm of October 1991 on a northeast barrier island (Newsday).

Processes Which Control Shoreline Change

Coastal erosion and deposition are functions of three interrelated factors: (1) the amount and type of sediment within a coastal area; (2) the wave and tidal forces; and (3) changes in sea level (fig. 4). The shoreline recedes when the forces of erosion exceed the amount of sediment supplied to the system. The greater the deficiency of sand, or the higher the wave forces, the more rapid the rate of erosion. Any of the three factors (energy, sediment, or sea level) can vary through time and change the balance. Beach erosion is, however, a natural process and becomes a problem only when man's structures are placed in the path of shoreline recession.

The rate of Atlantic coast barrier island recession over the last 2,000 years undoubtedly varied as the rate in the rise of sea level changed and as the supply of sand diminished. Some of the eroded material has been lost into large offshore sediment sinks, such as Diamond Shoals off Cape Hatteras. Much of it, however, has remained within the barrier island sediment budget and has contributed to spit growth, inlet filling, dune building, and storm overwash deposits (Dolan and Lins, 1986).

Four types of sand movement are responsible for most changes occurring on barrier islands: (1) Movement of longshore sand along the shore zone occurs when waves approaching the coast at an angle set up sediment transporting processes called longshore currents. The direction and strength of longshore currents depends on the size and the direction of the waves approaching the coast. Over the course of the year, there is usually a net flow of water and sediment in one direction. (2) Movement of sediment across the shore zone occurs during storms when very high waves and tides result in water levels so high that the beaches and barrier islands may be overwashed. (3) Movement of fine-grained sand from the beach-face and sand flats occurs during periods of strong winds. And, (4) inlets also provide a means for sediment to be transported from the beach zone to the sounds and vice versa. Inlets are formed when storm surge and high waves drive water across the islands to the lower water levels of the sounds and bays. As the seawater moves across the island, usually into areas of progressively lower topography, channels form and may erode to depths that permit a reverse flow from sound to sea during ebb tide. Although most inlets that form during storms seal by natural processes within a relatively short time, some remain open for years, decades, and even centuries and, thus, become somewhat permanent features of the barrier islands. Inlet formation and closure are fundamental sediment transfer processes that move material from the ocean side to the sound side of the Atlantic barrier islands. The sand deposits that fill inlets represent a relatively large percentage of barrier island sediments, perhaps as much as 25 percent. The configurations of all middle Atlantic barrier islands respond, to a considerable degree, to the dominant processes — overwash and inlet formation.

Figure 3. Ocean City, Maryland, is in many places 0.5 mi (0.8 km) wide and less than 6 ft (2 m) high.

Storms and Waves

Hurricanes and winter extratropical storms, called "northeasters," have been the principal agents of geomorphic change for the middle Atlantic beaches and barrier islands since their formation. Landscape change occurs with the movement of sand by strong wind and wave activity. Hurricanes generate high storm surges in contrast to extratropical storms; however, northeasters are larger and generally of much longer durations and, thus, are more regional in their impacts.

Since 1900, more than 100 hurricanes have been recorded on the Atlantic and Gulf coasts. About one-half of these storms have been classified by the National Oceanic and Atmospheric Administration as "major," having winds greater than 90 mi/hr (150 km/hr) and storm surges of more than 9 ft (3 m) (Herbert and Taylor, 1979a and 1979b). The two most damaging hurricanes of this century killed more than 6,000 people in Galveston, Texas, in 1900 (Hughes, 1979) and 2,000 people in Florida in 1928. The five costliest hurricanes in terms of property losses were Frederick in September, 1979, which caused an estimated $700 million in damage along the Gulf Coast near Mobile, Alabama; Agnes in 1972, which caused $2 billion in damage; Camille in 1969, which destroyed $1.4 billion worth of property; Hugo, which resulted in over $6 billion in South Carolina in 1989; and by far the most costly in terms of property losses, Hurricane Andrew, which caused over $20 billion in damage in south Florida in 1992. Camille was also one of the most intense hurricanes since 1900, registering the maximum value of 5 on the Saffir/Simpson scale (Simpson and Riehl, 1981), with wind speeds of over 150 mi/hr (250 km/hr) and storm surges that raised the water more than 25 ft (8 m) above sea level (Herbert and Taylor, 1979a and 1979b).

Even though there appears to have been a decline in hurricane frequency over the past 25 years, rapidly increasing coastal populations mean that fewer than 20 percent of the current residents of Atlantic and Gulf coast barrier islands have experienced the impact of a strong storm.

Dolan/Davis Storm Classes and Coastal Impact

Storm Class	Beach Erosion	Dune Erosion	Overwash	Property Damage
Class 1 (Weak)	Minor changes	None	No	No
Class 2 (Moderate)	Modest	Minor	No	Modest
Class 3 (Significant)	Erosion	Can be significant	No	Loss of many structures at local scale
Class 4 (Severe)	Severe erosion	Severe dune erosion or destruction	On low profile beaches	Loss of structures at community scale
Class 5 (Extreme)	Extreme erosion	Dunes destroyed over extensive area	Massive in sheets and channels	Extensive regional scale: millions of dollars

TABLE 1. Dolan/Davis Rating Scale for Northeast Storms.

Although hurricanes cause extensive damage and sometimes loss of life, it is the winter extratropical storms, or northeasters, that cause most of the damage along the middle Atlantic coast. Unlike hurricanes, which form over the warm tropical waters of the Caribbean and the Atlantic, extratropical storms develop in the midlatitudes along weather fronts that separate cold, dry polar air from warm, moist tropical air. Each year between 20 and 30 such storms produce winds that generate waves of at least 5 ft (1.5 m) (Dolan and others, 1988). Dolan and Davis (1992a) developed a ranking system for northeast storms based on the wave heights and durations of the winds (table 1). The Lincoln's Birthday northeaster of February 12-13, 1973, one of the seven class 5 (most severe) northeasters to have occurred between 1942 and 1986, caused extensive erosion to the beaches from Long Island, New York, to Miami, Florida. The great Ash Wednesday storm of March, 1962, also a class 5 storm, produced waves more than 30 ft high (10 m) that were coupled with very high astronomical tides. This resulted in damage and destruction of coastal property along the entire middle Atlantic coast north of Cape Hatteras (Dolan and Davis, 1992b). More recently, millions of dollars in property damage occurred along the middle Atlantic coast (fig. 5) due to a series of severe winter storms, including another class 5 northeaster, the Halloween storm of October, 1991.

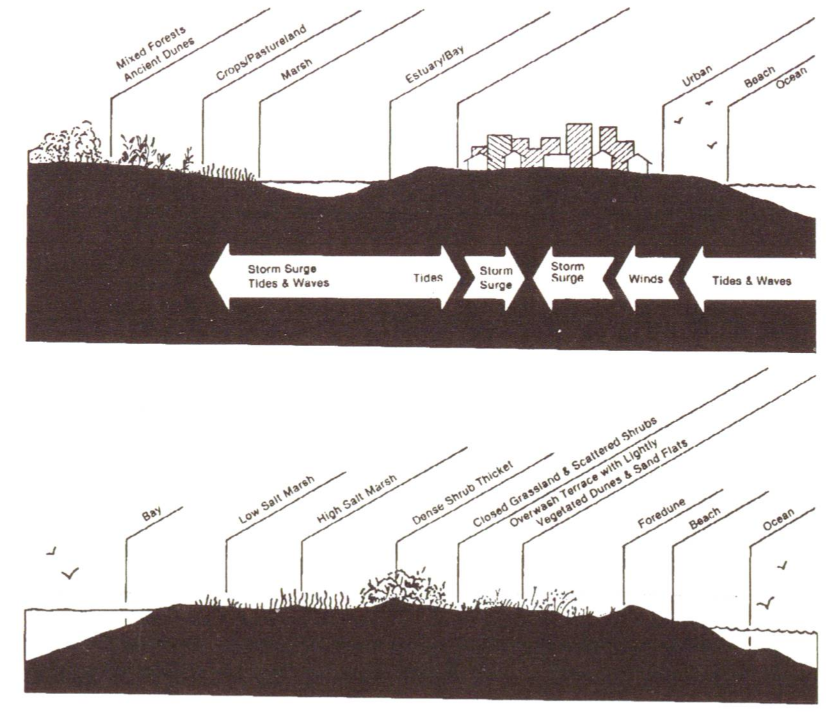

Figure 4. Cross section of a typical developed and undeveloped middle Atlantic coast barrier island. Most of the oceanfront development is in the pathway of powerful ocean processes.

Tides

Gradual variations in water level occur through tides, storm waves, storm surge, and long-term sea level fluctuations (fig. 6). Tidal action alone has little effect on sediment transport, but when storm surge and high waves are superimposed, the daily elevation and depression of the water level becomes a more important agent in sediment transport. The astronomical tides along the middle Atlantic coast are semidiurnal (12 hours and 25 minutes apart) with an average range of 3 to 4 ft (1 to 1.5 m). The highest spring tides occur twice each month when the Earth, Moon, and Sun are aligned, increasing the tidal range approximately 20 percent. As a result of the Moon's elliptical orbit, there is a minimal distance between the Moon and Earth once during each revolution. When this happens, higher tides, called perigean spring tides, are generated. Wood (1976) shows a strong coincidence between catastrophic storms and perigean spring tides. One hundred of the most severe coastal storms between 1635 and 1989, including the Ash Wednesday storm of 1962 and the March storm of 1989, occurred at the time of the perigean spring tides.

Sea Level

Sea level has oscillated several times during the past half-million years (Emery and Aubrey, 1991). During the cooler glacial periods, water was withdrawn from the seas, stored on land as glacial ice, and the shoreline advanced seaward. When the ice melted during warmer interglacial periods, the ocean basin refilled and coastlines retreated across the continental shelves. This process involved great quantities of seawater, enough to move the shoreline across 100 mi (160 km) of middle Atlantic Continental Shelf.

When the last period of glaciation, the Wisconsin, came to an end about 20,000 years ago, sea level was approximately 350 ft (100 m) lower than it is today, and the shoreline of the Atlantic coast was 25 to 100 mi (50 to 150 km) seaward of its present position. With the change from glacial to interglacial, the sea started to rise rapidly and continued to rise for 15,000 years, reaching within 10 to 15 ft (3 to 5 m) of the present level about 4,000 years ago. Although sea level remained fairly stable following the initial rise during the post-Wisconsin period, sea level has risen several feet over the past 2000 years. This slow rise has resulted in the recession of the shoreline and the enlargement of bays and sounds. Over the past 100 years, the rise has been approximately 12 in (30 cm) on the Atlantic coast (Hicks and others, 1983). The average "relative" rise in sea level (actual rise in sea level plus land subsidence or uplift) for the middle Atlantic coast is currently estimated to be between 0.5 and 1.5 ft (15 to 40 cm) per century (Emery and Aubrey, 1991).

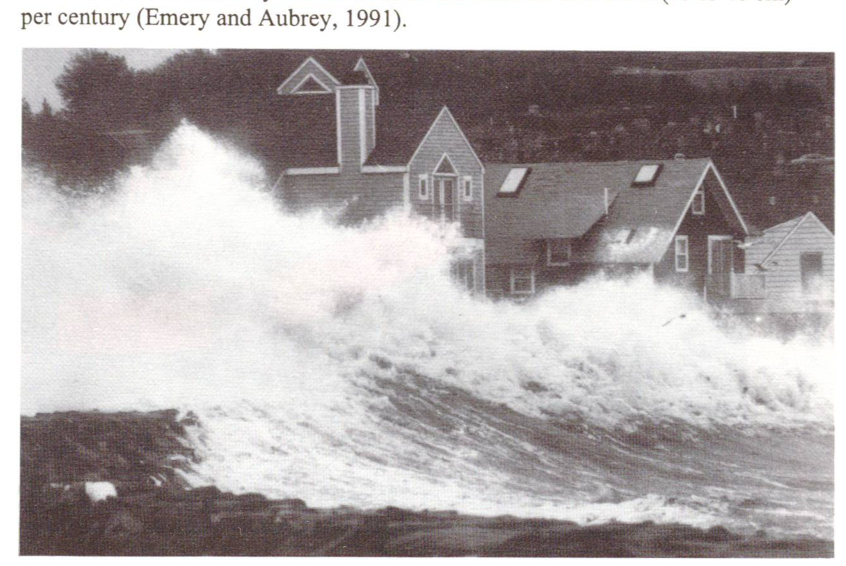

Figure 5. High waves, storm surge, and flooding caused by the Halloween storm of October 1991 (Boston Globe).

Measurement of Shoreline Change

Marine scientists, managers, and engineers have long recognized the shoreline and beach face as elements of a highly dynamic physical system. What is needed for knowledgeable and competent planning is reliable information about the rates of shoreline change through time. Information of this type can be obtained from ground surveys, maps, charts, and aerial photographs. Ground survey methods, or direct measurements, provide data of the highest accuracy and reliability, but opportunities for detailed historical comparisons are lacking for most coastal areas, and the generation of new surveys is expensive and time-consuming. Therefore, with the exception of a few scattered sites, direct ground-level measurements are generally unavailable. On the other hand, maps and charts are available for most coastal locations and frequently date from the mid-1800's.

Aerial photographs are accessible for most coastal sites in the United States. The earliest photographs date from the 1930's and images for subsequent decades are generally attainable. Aerial photographs have many advantages over the other types of information in coastal mapping. In a matter of hours hundreds of miles of coast can be photographed, providing an "instantaneous" record rather than a survey spanning months or years. Photographs include a measure of detail over extended areas unavailable with any other information base; furthermore, photographs are permanent and easily duplicated.

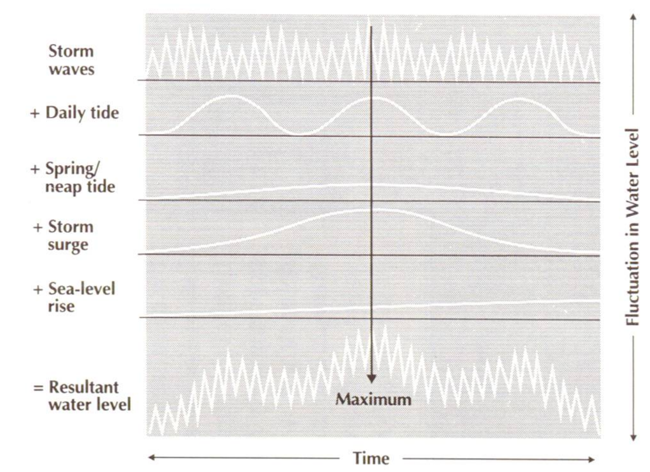

Figure 6. Conceptual relationships in processes responsible for water level differences.

Data Collection

The data used for the open-ocean coastline of the Middle Atlantic Coast Map were obtained from two high-spatial-resolution data sets: one was generated from aerial photographic analysis (1940's to 1980's) at the University of Virginia (Dolan and others, 1978), and the second was compiled from maps and charts (1850's to 1980's) by the coastal research group at the University of Maryland (Crowell and Leatherman, 1989). The University of Virginia data were used for the shorelines of North Carolina, Virginia, and Maryland; the University of Maryland data were used for New Jersey and Delaware. Both of these data bases provide shoreline erosion rates at 150-foot (50-m) intervals along the coast. Several smaller data sets were used for the summaries of erosion and accretion along the shorelines of Chesapeake Bay and Delaware Bay.

Because the minimum mapping unit (along the coast) for a map of 1:2,000,000 scale is about 3 mi (5 km), considerable smoothing and generalization were required to reduce the more than 20,000 individual values in these two data sets to obtain the patterns shown on the map. The data used to compile this map were collected using different methods and span different periods of time.

Selection of Erosion and Accretion Categories

Once the shoreline change data were assembled for the five middle Atlantic states, the data were smoothed and grouped into the color patterns shown on the map. Smoothing was a two-step process. First, the individual units of erosion rate data were replaced by a running average along the coast. Second, the running averages were then divided into the nine discrete categories, ranging from severe erosion to significant accretion.

The smoothed rate of each of the 20,000 transects was then assigned to one of these categories, resulting in color-coded units on the map that parallel the coast. Each segment encloses a minimum mapping unit of at least 3 miles, the least discernible unit for a 1:2,000,000-scale map. Therefore, the color patterns shown on the Middle Atlantic Coast map are highly generalized averages. A supplemental report is available for a complete tabulation of the original raw data used (Dolan and Peatross, 1992).

Dividing a continuous pattern of along-the-coast erosion and accretion into discrete categories necessitates some subjective interpretation. The authors' purpose was to establish a useful number of meaningful divisions to show the regional scale trends of shoreline change. Selecting these specific nine categories was based on an analysis of the overall clustering and range of the rates, a review of the literature used in selected data sets, and the experiences of the authors.

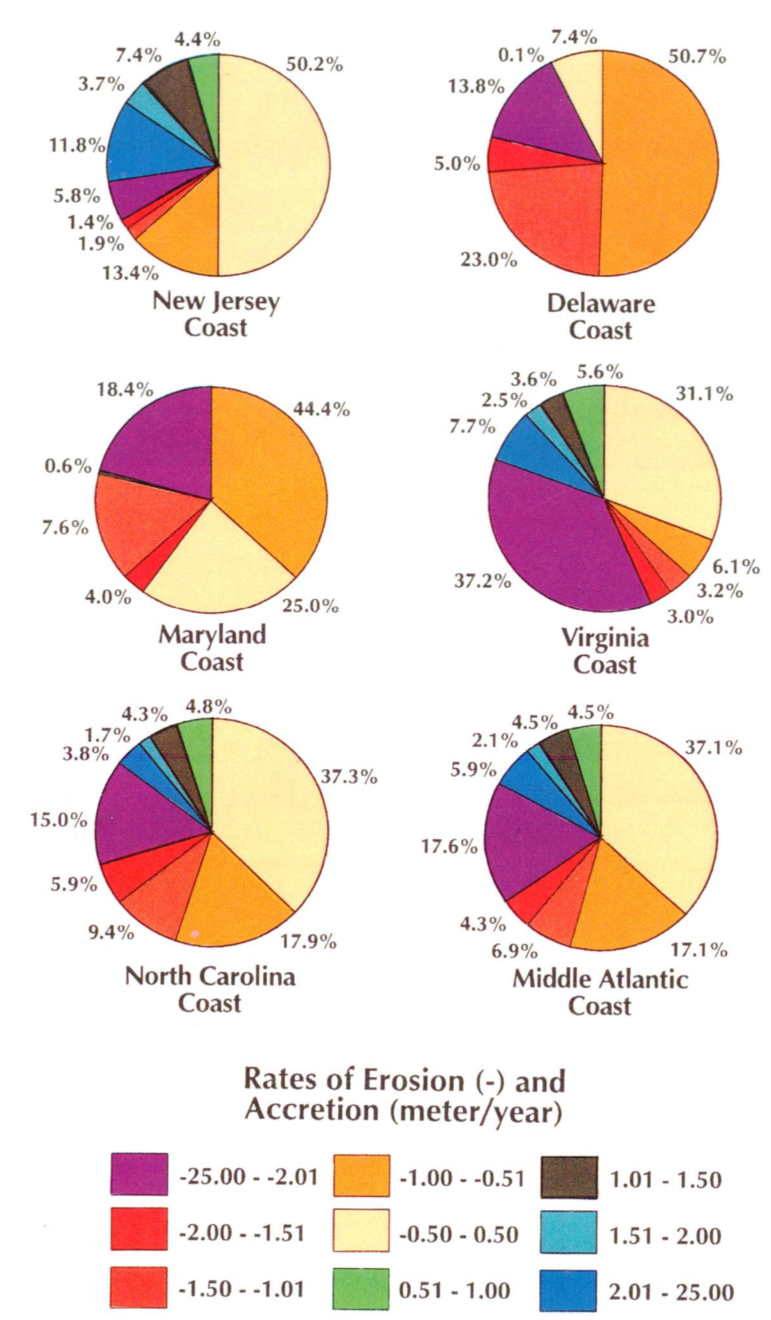

Figure 7. Statistical summaries of erosion rates for the middle Atlantic states.

As in the previously published Coastal Erosion and Accretion map (1:7,500,000) of the National Atlas map series (U.S. Geological Survey, 1985), the Middle Atlantic Coast Map includes four erosion categories and four accretion categories. A stable category, +/- 0.5 m/yr (1.5 ft/yr), was used for locations with rates that were considered to be within the margin of error for the original data. The authors recognize that an annual erosion rate of 1 to 2 ft (0.3 to 0.6 m) in a developed area can be a more serious problem than an annual rate of 10 ft (3 m) on an undeveloped barrier island. Therefore, the terms associated with each category must be considered only as a convenient nomenclature.

Overview of Rates of Shoreline Change for the Middle Atlantic Coast

Figure 7 is a series of diagrams that summarize the shoreline erosion and accretion rates for the middle Atlantic states, from North Carolina to New Jersey. Overall, 44 percent of the shorelines on this map is eroding at rates greater than 2.0 ft/yr (0.6 m/yr) and 17 percent is accreting. Ninety-three percent of the Delaware coast is eroding; 74.5 percent of Maryland's coastline is eroding, and 49.5 percent of Virginia's shoreline is eroding. Forty-two percent of the coast of North Carolina is eroding; 20.9 percent at a rate greater than 6 ft/yr (2 m/yr). Chesapeake Bay and Delaware Bay have highly complex patterns of shoreline erosion and accretion; therefore, statewide statistics are of limited value. Nevertheless, based on the data available to compile this map, the average rate of bay shoreline erosion is 5.2 ft/yr (1.6 m/yr) for the Chesapeake Bay and 3.6 ft/yr (1.1 m/yr) for Delaware Bay.

There are also significant differences in shoreline erosion within states. When the coast of Virginia is separated into two geographic regions, the barrier island section north of Chesapeake Bay shows an erosion rate of 7 to 80 ft/yr (2.1 to 25 m/yr) over the 40 years of record; whereas, the continuous beach strand south of the Bay is eroding at a rate of less than 3 ft/yr (1 m/yr).

The overall erosion rates for the ocean-facing shorelines of Virginia are the highest of the middle Atlantic states. One reason for this is that the 11 barrier islands located along the coast north of Chesapeake Bay have erosion and accretion rates that exceed those of any other coastal area in the nation other than the barrier islands off the coast of Louisiana (Louisiana Geological Survey, 1991).

Most of the Virginia barrier islands have a very distinct erosion and accretion pattern. Figure 8 shows this rotation trend on Hog Island, Virginia, which is typical for the chain of islands. The northern end of most of the islands is either stable or accreting; whereas, the southern parts are eroding at very high rates (in some places there are erosion rates in excess of 25 ft/yr (9 m/yr). The complete loss of Broadwater, Virginia, due to rapid shoreline erosion is an example of development in the wrong place. Over the past century, rapid erosion, and the attendant land loss, destroyed this entire community on Hog Island (fig. 8). Before its citizens, their homes, and their church, were evacuated and the area finally abandoned (1934-39), Broadwater included a population of several hundred, with a school, hotel, lighthouse, general store, and a cemetery (Marstad, 1985). Today the site of the village is located more than a mile offshore from the present coastline (fig. 8).

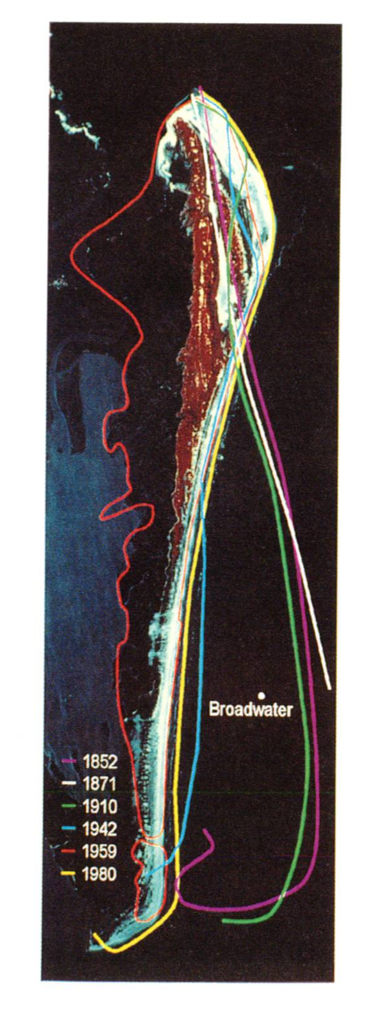

Figure 8. Historical shoreline changes of Hog Island.

Human Impact

About 70 of the 295 barrier islands that rim the Atlantic and Gulf coasts of the United States are to some degree developed (Lins, 1980), and about 80 other islands have been bought by state and local governments for recreation areas and nature preserves. Fifteen of the largest islands have been acquired by the Federal Government for wildlife refuges and national seashores and more than 100 islands are privately owned and largely undeveloped.

The development of North Carolina's Outer Banks typifies what has happened on many of the middle Atlantic coast barrier islands. Even though the dynamic nature of the beaches and dunes has always been part of the aesthetic and recreational appeal of the Outer Banks, the islands remained remote and were seldom visited until the first bridges from the mainland were built in the 1930's. Soon thereafter, a plan was implemented to build a road running the length of the Outer Banks with barrier dunes to prevent storm surge and overwash (Dolan and Lins, 1986).

Thirty years of artificial dune stabilization have altered the ecology and geology of the Outer Banks. Viewed from the air, the most striking difference between the natural and altered barrier islands, other than the artificial barrier dune, is a marked difference in beach width. The unaltered islands have beaches from 350 to 600 ft (100 to 200 m) wide, whereas on Hatteras Island the beach has been reduced to 100 ft (30 m) or less.

Coastal Engineering Measures

There are four basic methods used by coastal engineers to mitigate for shoreline erosion (fig. 9). Structures designed to trap sediment in areas that are eroding (groins); structures that reduce the wave forces reaching the coast (breakwaters); structures that provide direct protection from wave action and storm surge (sea walls and revetments); and finally, an approach that has become known as "soft" engineering, the replacement of beach sands that are lost to erosion (beach nourishment).

Groins are hard structures (wood, steel, or concrete) that are constructed perpendicular to the beach, and extend out into the surf-zone. The purpose is to impede the longshore transport of sand, thus expanding the beach in the updrift side of the groin. However, groins commonly lead to severe erosion on the downdrift sides, so there is an important trade-off that must be considered in using these structures.

Breakwaters are usually constructed in the pathways of approaching waves in order to impede or alter the shoaling and breaking process, thus reducing the level of wave energy reaching the beach. The usual assumption in the design of these structures is that by reducing the level of wave energy reaching the beach, the forces responsible for erosion will also be reduced. As with groins, one of the most common problems with breakwaters is that sand gained behind the breakwater is sand lost at some adjacent site.

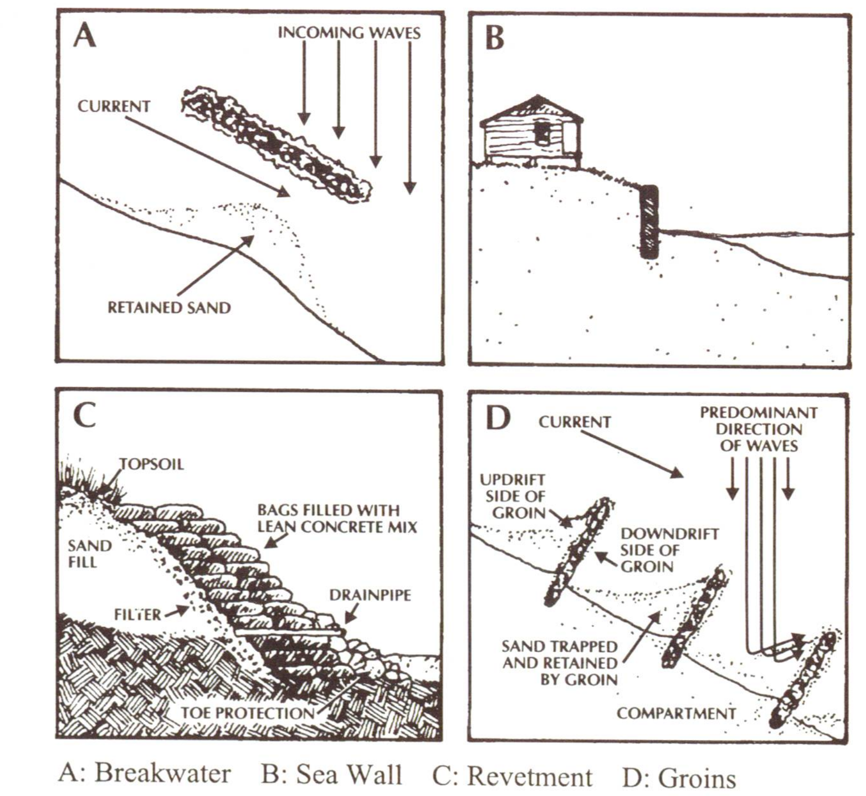

Figure 9. Basic engineering approaches to mitigate shoreline erosion and coastal land losses.

Sea walls and revetments are designed to protect coastal property by providing a structural barrier of wood, rocks, concrete, or steel that is strong enough to absorb and divert waves and storm surge. If severe erosion is the problem for a site under consideration for a sea wall, the design must include the eventual disappearance of the beach in front of the structure, leaving the sea wall exposed to the direct forces of waves and storms. From this standpoint, sea walls and revetments must be considered temporary solutions in areas of rapid erosion.

Beach nourishment, like sea walls, is not a permanent solution to beach erosion. This approach is simple: sand from an alternative location, preferably where it is not needed, is used to replace sand lost due to erosion (fig. 10). Sources for beach replenishment sands range from navigational channels in inlets to offshore shoals. The most limiting aspects associated with beach nourishment include the high costs per mile of beach, the lack of inexpensive sand sources, and the vulnerability of the soft engineering structure to severe and unpredictable storms.

Figure 10. A large-scale beach replenishment project at Cape Hatteras, North Carolina, in 1973.

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