Land Loss Along New England Shores

by Philip L. Glover

B.Sc.
W'Q '44
Table of Contents

Abstract .................................................. 1
Introduction .............................................. 1
Factors in Coastal Erosion .......................... 2
Applied Coastal Geomorphology ................. 5
New England ............................................. 7
Community Reaction Case Studies............... 11
Conclusions ............................................. 13
References .............................................. 15
Abstract

Coastal erosion and sea level rise have been studied for quite some time. A variety of natural and man-made factors have resulted in the loss of property and life along the New England coast. An understanding of these factors and of applied coastal geomorphology, as well as local geology and previous attempts at shoreline management, are of utmost importance to planning authorities. Planning authorities so far have had mixed results in dealing with these problems. Some localities have been able to successfully deal with the encroaching sea, but most areas have either had mixed results or have suffered outright disaster.

Introduction

Since World War II a large portion of the United States' population has moved to coastal areas. The infrastructure of these areas is being threatened by a rise in sea level.

The National Research Council and the United States Environmental Protection Agency (EPA) have predicted that the shores of the US will be subjected to a rise in sea level of over 2m by the year 2100 (Hoffman, 1983). Much of the newly developed coastal areas is below the 2m contour line, and a 1m rise in sea level would result in the loss of about 36,260 square kilometers of land (Titus, 1988). The EPA estimates that it will cost up to $1.96 billion just to protect the developed areas.

As sea level rises, the 50- and 100- year flood zones will be pushed landward and flood protection structures built for a specific flood elevation will offer less protection. Saltwater intrusion would cause the quality of the drinking water to deteriorate in coastal areas that rely on surface drainage for drinking water. Saltwater intrusion would also damage estuarine habitats, and some shallow aquifers may become recharged by saltwater.

Airports of coastal cities are commonly built on bays with levees. A 1m sea level rise would force the relocation of these airports and disrupt air service. Sea level rise will also affect residential, business and industrial centers. Coastal engineering structures will be subjected to greater storm impacts and floods.

Landfills and waste disposal sites located in low areas near the coast would pose a public health hazard. If sea level rises, these sites would be subjected to flooding and erosion. Changes in the hydrology of groundwater movement could result in the dispersal of waste into the coastal zone.

The primary environmental impact of the predicted sea level rise would be the destruction of the nation's wetlands and barrier island systems. The EPA predicts between 22 and 56 per cent of the wetlands and barrier islands will be lost, depending on the amount of sea level rise (Pilkey, 1989).

Therefore, an understanding of the near-shore physical oceanography, coastal engineering, the economic and political aspects of shoreline management, and a basic knowledge of the biological system of the nearshore environment are important to the coastal geologist.

One of the basic principles of coastal geology is that each coastal type is different. Coastal processes important to one type of shoreline may be unimportant elsewhere. In this paper I discuss the natural factors of coastal erosion and the engineering structures and ideas used to counter them. The regional analysis of New England stands in marked
contrast to the rest of the US Atlantic coast, and is the focus of this paper. Examples of community action from Florida and Maryland are also presented.

Factors in Coastal Erosion

Natural Agents
Waves and Currents
The conversion of solar energy into the mechanical energy of the wind is subsequently converted into wave potential energy by the deformation of the sea surface. The wind waves that result possess potential energy, and waves are extremely efficient energy transporters. Waves do suffer energy loss, but this is mainly due to internal friction and the changes that continually occur between potential energy and kinetic energy.

As a wave enters shallow water, the depth of which is defined as being less than 1/20 of the wave length, it will undergo a transformation. As the water depth decreases in the nearshore environment, the wave length also decreases, and the water piles up until the wave breaks. These waves will also experience wave refraction -- the waves will touch bottom and bend to become parallel to the shore. Wave breaking is important to coastal erosion because the force generated is responsible for dislodging sediments and breaking up rocks.

Not all wave crests arrive parallel to the shore but arrive at a slight angle, and the momentum brought by these seas sets up a longshore current. The longshore velocity increases as the angle of wave approach and as the orbital velocity increases, which is controlled by wave height. These longshore currents affect the shoreline by transporting loose sediments from the site and depositing them elsewhere (Pethick, 1984).

Tides and Fluctuating Water Levels
The tide is actually a wave, with the crest and trough forming the high and low tide - a tidal wave has a length measured in hundreds of kilometers. Tidal waves are usually less than 0.5m high in the open ocean, but like wind waves they increase in height as they near the shore. The energy source for this type of wave is the gravitational pull of the Moon and the Sun as opposed to the wind.

A casual coastline observer, with the proper knowledge, usually can correctly determine whether the dominant coastal processes are tidal waves or wind waves. If the tidal range is less than 2m, it is assumed that wind waves provide the dominant coastal processes, and such an environment is said to be microtidal. A microtidal shoreline can be recognized by such features as beaches, spits and barrier islands. If the tidal range is greater than 4m, then the tide is assumed to provide the dominant coastal processes, and the environment is termed macrotidal. A macrotidal environment tends to have such features as tidal flats and salt marshes as its dominant features. In between these two extremes of tidal range lie coastal areas with intermediate tidal ranges whose landforms reflect both wind wave and tidal processes, and these areas are called mesotidal (Pethick, 1984).
Other Common Natural Factors

Other common natural factors include: rock type and sediment composition, vegetation, climate, coastal topography, and seasonal change. Sediment composition is important because the ease of sediment erosion depends on cohesiveness. The less cohesive a sediment is, the more easily it will be eroded. Obviously, hard crystalline rocks are very durable, and studies have shown that rocky coasts at middle and high latitudes have not changed substantially in recorded history (Shepard and Wanless, 1971).

The type and density of vegetation can influence coastal erosion by dissipating the energy reaching the shoreline, acting as a sediment binder that resists erosion, and even by encouraging the accumulation of sediment.

In humid tropical climates, however, deep chemical weathering causes the rapid decomposition of rocks and makes them more susceptible to erosion. In cold climates, frost wedging is an important mechanical weathering process which also leads to erosion (Pilkey, 1989).

Coastal topography is an important factor because the steepness of the nearshore topography affects the wave energy level at the shoreline. Waves undergo a transformation and eventually break in shallow water. So, if the nearshore topography is of a relatively gentle slope, waves will break further from shore, as they have had ample time to transform and break as the seafloor gradually becomes more shallow. If the nearshore topography is relatively steep, however, waves will break very close to, if not at, the shoreline, and the higher wave energy levels reaching the shoreline would be reflected by a higher rate of coastal erosion. The width of a beach along the shoreline also affects coastal erosion, as narrow beaches are relatively isolated and do not receive their sediment supply as readily as broad beaches. A beach that is deprived of its sediment supply undergoes coastal erosion in the same manner as sediment-supplied beaches, but their loss is not replaced by new sand from the littoral drift (Hill, 1991).

Variations in wave energy levels due to seasonal change are also reflected by the width and slope of local beaches. During the winter, when strong and high-energy waves are prevalent, the resultant beach is narrow and steep. During the summer, when wind and wave activity are diminished, the resultant beach is often wide and gently sloping (Hill, 1991).
Engineering Structures

Engineering structures interfere with the natural movement of material and water in the coastal environment. The impact of changing energy conditions on erosion and sedimentation is discussed below.

There are two main purposes for construction in the nearshore zone: to improve navigation and to hamper coastal erosion. When jetties, seawalls, or other structures are built in the nearshore area the natural equilibrium will be upset. Many of the most severe cases of coastal erosion can be attributed to this disturbance of nature's balance (Komar, 1976).

Jetties are built at the mouth of a river or tidal inlet in order to stabilize the channel, prevent shoaling by littoral drift, and to protect the channel entrance from storm waves. Jetties direct the stream or tidal flow to aid in the channel's self-scouring ability and to prevent immediate filling if dredging is used to scour the channel entrance. To prevent littoral drift from entering the channel, they usually extend out beyond the breaker zone. In doing so they also act as a dam to the longshore drift of sand in the nearshore zone. As a result, the sand accumulates on the updrift side of the jetties and the shoreline advances. On the downdrift side of the jetties the sand transport processes still operate and cause sand to drift away from the jetties, resulting in erosion and shoreline retreat.

Revetments, seawalls and bulkheads are built parallel or nearly parallel to the shoreline to prevent erosion and other damage due to wave action (Figure 1). When built on an eroding shoreline, erosion continues on adjacent shores.

Breakwaters protect a portion of shoreline area, providing a harbor shielded from incoming waves (Figure 2). They are usually attached to the coast at one or both ends, with a gap for a boat entrance, and extend out through the surf zone. This type of structure also has the drawback of being a sand trap and depriving adjacent beaches of their sediment supply.

A groin is a wall built nearly perpendicular to the shoreline (Figure 3) to trap a portion of littoral drift and thus build out the beach. This process helps to prevent further erosion of the existing beach, and since the beach helps protect coastal property, they also diminish the erosion of sea cliffs. Groins have the same effect as jetties of damming the littoral drift so that the shoreline builds out on the updrift side and erodes on the downdrift side. Therefore, the construction of one groin may force adjacent areas to construct groins. A series of groins is called a groin field. Once a groin is filled, it allows littoral drift to pass by its seaward end, so that it traps only a certain quantity of sand. Groins may be filled artificially by beach nourishment -- by trucking sand out to the beach (Komar, 1976). If this is done, littoral drift will continue to reach the downdrift beaches, thus allowing them to receive their sediment supply.

Currently there is interest in submerged offshore breakwaters. Submerged breakwaters extend roughly parallel to the shore and act to trip waves and cause premature breaking. This diminishes the wave energy to below that found under natural conditions, therefore reducing the rate of beach erosion.
Figure 1: Revetments (A) and seawalls (B) are built along the shoreline to protect against erosion and other damage due to wave action (U.S. Army Corps of Engineers pamphlet).
Figure 2: Breakwaters provide a harbor from incoming waves. When attached to the shoreline, they have the detrimental effect of acting as a sand trap and depriving adjacent beaches of their sediment supply. After Kerrio (1986).

Figure 3: Groins block the littoral drift of sediment, thus building out the beach on the updrift side. They also have the negative effect of depriving adjacent beaches of their sediment supply downdrift of the groins. After Kerrio (1986).
Applied Coastal Geomorphology

Coastal Types

The two main coastal types that undergo erosion, and with which coastal engineers concern themselves with, are beaches and cliffs.

Beaches

Beaches adjust very quickly to changes in wave energy levels and these energy levels may be extremely high. Beaches also react to changes in sediment type or its supply rate. They are not isolated systems, and a change in one area would be felt down the shoreline to the whole succession of beaches.

Cliffs

A lack of sand supply to the beaches would be reflected by serious cliff erosion. The same measures used to counter beach erosion may also be used for cliff erosion problems. However, most planning authorities believe that cliff erosion problems can always be solved by building a sea wall. This move often only exacerbates the problem. The reason for a beach defense structure is to dissipate wave energy out over a wide low-angle surface, and to dissipate the energy in the oscillatory movement of the sand grains. Vertical or slightly sloping sea walls create opposite conditions to this -- wave energy is concentrated and reflected. The reflected wave energy erodes sand from the nearshore zone and undermines the structure.

Recent thinking favors the use of submerged breakwaters. These structures cause waves to break prematurely, thus dissipating energy in internal friction which reduces shoreline erosion (Pethick, 1984).

Common Protection Measures

There are many types of protection measures used to protect beaches, but the most commonly used measures are the construction of groins and the implementation of beach nourishment. For other methods, refer back to the section entitled,"Engineering Structures".

Groins

The most common method for stopping beach erosion is to construct groins. Groins are wooden, metal, or rock fences constructed perpendicular to the shore. They are intended to stop the longshore transportation of sediments by trapping the sediment and extending the beach outwards. The main drawback of this measure is that beaches downdrift of the groins are deprived of their sediment supply.

Beach Renewal or Nourishment

Beach renewal is a method used to restore beach material without affecting downdrift areas. This method requires a thorough knowledge of the beach processes of
the area in question. For example, the size of the exotic sediment grains must be compatible with the desired beach slope, using the proper relation between beach-face slope, mean grain size and sorting (Figure 4). Also, the calculation of the height of the wave run-up must be matched with the desired beach slope for the selected material if the beach is to provide coastal protection. Calculations must also be made of the grain sizes likely to be transported away from the beach by wave action typical of the wave climate of the area, which will determine the minimum acceptable grain size to be used in the project. The main drawback of beach renewal is that it is very expensive.

Sea Level Fluctuation

Eustatic Mechanisms

The changes in ocean water volume due to its transfer as ice onto the land surface during glacial periods is referred to as glacio-eustasy. In this process, sea water is progressively lost, via precipitation as snow. The water accumulates as ice on the land surface and sea level falls. During interglacials the reverse occurs: the ice melts and sea level rises.

Local Mechanisms

Tectonic activity can result in the steady uplift of the land surface relative to the sea so that a series of terraces can form that mark former sea levels. Since uplift is one-directional, the highest terrace will be the oldest. This process is called tectonic uplift.

The transfer of water from the oceans to the land surface did not only result in the lowering of eustatic sea level - the weight of the ice caused the land mass to depress in the area of the glaciers and ice sheets. The amount of depression was about 1/3 of the maximum ice thickness. If this depression of the land coincided with the fall of eustatic sea level the resultant coastline would have remained stationary, but this was rarely the case. In most cases, there was a substantial time lag before the full effects of the isostatic depression took place, so that a range of coastal positions would have resulted.

Once the glaciers retreated, the land was given a chance to regain equilibrium in a process called isostatic rebound. Again, there was a time lag in this process, so that there a range of coastal positions can be seen (Pethick, 1984).

Predicting Sea Level Change

The best indicator of the future behavior of a system usually is its past record. Current trends suggest a eustatic rise of about 1 - 1.3mm per year. However, one factor suggests that the past record is not an accurate indicator of future sea level rise: the warming of the Earth caused by the introduction of carbon dioxide and other gases into the atmosphere (Pilkey, 1989).

Carbon dioxide, methane, and other gases are contributors to the Earth's surface temperature because they allow solar energy to reach the Earth's surface but trap infrared radiation in the atmosphere. There is abundant evidence that the concentration of carbon dioxide in the atmosphere has increased from an estimated 290ppm in 1880 to a measured 315ppm in 1958 to 340ppm in 1980 as a result of burning fossil fuels and clearing
Figure 4: Sediment sorting and mean grain size determines beach face angle (in Komar, 1976, after McLean and Kirk, 1969).

<table>
<thead>
<tr>
<th>Scenario (centimeters)</th>
<th>2000</th>
<th>2025</th>
<th>2050</th>
<th>2075</th>
<th>2100</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>17.1</td>
<td>54.9</td>
<td>116.7</td>
<td>241.5</td>
<td>345.0</td>
</tr>
<tr>
<td>Mid-range high</td>
<td>13.2</td>
<td>39.3</td>
<td>78.9</td>
<td>136.8</td>
<td>216.6</td>
</tr>
<tr>
<td>Mid-range low</td>
<td>8.8</td>
<td>26.2</td>
<td>52.6</td>
<td>91.2</td>
<td>144.4</td>
</tr>
<tr>
<td>Low</td>
<td>4.8</td>
<td>13.0</td>
<td>23.8</td>
<td>38.0</td>
<td>56.2</td>
</tr>
<tr>
<td>Current trends</td>
<td>2.0-3.0</td>
<td>4.5-6.8</td>
<td>7.0-10.5</td>
<td>9.5-14.3</td>
<td>12.0-18.0</td>
</tr>
</tbody>
</table>

Table 1: Various projected sea level rise scenarios to the year 2100 (Hoffman, 1983). Hoffman believes that the most likely sea level rise will be between the two mid-range scenarios.
forests. The National Academy of Sciences has estimated that the predicted doubling of carbon dioxide levels over the next 100 years will lead to an increase in surface temperature of 1.5 to 4.5 degrees celsius during that period (Pilkey, 1989). There are currently many unknowns in the models now in use, but Hoffman (1983) believes that the most likely sea level change will be between the two middle estimates (Table 1).

**New England**

The shoreline of the east coast of the United States is, from Florida up through New Jersey, a barrier island shoreline. Except for a few, mostly Pleistocene rock outcrops, it is an unconsolidated shoreline and is almost entirely in a state of erosion and sedimentation.

The geomorphology of barrier islands is complex. Barrier island morphology seems to depend on whether the wave regime is tide-dominated or wind-wave dominated, or somewhere in between (Williams and Leatherman, 1993).

New England's geology and climate are unique compared to the remainder of the Atlantic Coast. Instead of the low-relief interior composed of Cenozoic coastal plain sediments, this area is dominated by a high, rocky interior and an irregular shoreline. Since New England was so recently glaciated, its record of sea level change during the Late Quaternary is very different from other locations along the coast. Also, New England's coast is mantled with glacial deposits and modern littoral sediments derived from other areas. The sheltering effect of its wide continental shelf and numerous islands and peninsulas creates a wave, tide, and storm environment different from the rest of the US east coast (Pilkey, 1989).

**Bedrock Framework**

Except for the glacial deposits which form the area around Cape Cod, the lithology and structure of New England's bedrock framework primarily controls the overall shape of the coast (Kelley, 1987). Crystalline bedrock in the area trends to the north or northeast and nearly parallels the shore. Most of the rocks in New England were metamorphosed and intruded by granite during the Paleozoic and Mesozoic eras. Failed rift basins occur in southern Connecticut, the Gulf of Maine, and in the Bay of Fundy, and these are composed of clastic terrestrial or basaltic rocks.

Because of its bedrock structure and varied erosion resistance, New England's coastline is composed of a series of distinctive sections. The straight cape of the northeast compartment is formed by two orthogonal fault systems -- one parallel to the Atlantic Coast and the other forming the border with Canada. The metavolcanic rocks
that outcrop here form high linear cliffs (#1, Figure 5). Southeast of this section is an extensive region dominated by plutonic rocks that form high headlands and islands because of their resistance to erosion. This area is known for its broad embayments with many sheltered harbors and an undeveloped shoreline (#2, Figure 5). The "indentured shoreline" consists of numerous peninsulas and island chains held up by metamorphic rocks that separate narrow estuaries (Kelley, 1987) (#3, Figure 5). Headlands of erosion resistant plutonic rocks with intervening embayments of metamorphic rocks shape the adjacent section into a series of "arcuate embayments" (#4, Figure 5). Bedrock is commonly exposed only at headlands here, and sandy beaches border the bays. From northern Massachusetts to western Rhode Island a section is dominated by outcrops of plutonic rocks with two major bays (Narraganset Bay and Boston Bay), which are carved from metasedimentary rocks of similar lithology. (#5, Figure 5). This section is broken by Cape Cod, which consists mainly of glacial Cenozoic sediments overlying all outcrops of rock (#6, Figure 5). Finally, the linear Connecticut coast marks the southern end of bedrock and the northern end of the coastal plain sediment. Long Island Sound is a glacially and fluvially carved lowland of Cenozoic sediment, and the fluvially carved outcrop pattern apparently shapes the straight coastline. Even though bedrock trends normal to the coast here, the coastline has few major indentations except where a Mesozoic Basin is exposed (Pilkey, 1989) (#7, Figure 5).

Bedrock not only shapes the New England coast, it also helps protect it from erosion. Most of the crystalline rocks of New England are not actively eroding (Shepard and Wanless, 1971). Sea stacks, arches, and caves exist only in places where differential rock resistance occurs in an outcrop because of a high fracture density, dikes or xenoliths. There are few places in New England where bedrock is eroding and causing property damage except in the Bay of Fundy. The bedrock's great erosion resistance also protects bluffs overlying the rock. Only when New England's beaches and bluffs are within the intertidal zone does significant erosion occur.

Coastal outcrops of rock refract waves. Along a sediment-starved coast like New England's, wave energy tends to permanently remove sand from exposed beaches. Although bedrock as a natural breakwater is only temporary in a geologic time frame, it is quite sufficient for sheltering beaches for the lifetime of a building. The refraction of waves produces complex patterns of wave convergence and divergence. Such wave refraction has shaped the numerous pocket beaches found in New England.
Figure 5: Map of New England and locations of the region's distinctive sections. Modified from Pilkey (1989).
Quaternary Events

There is evidence for two glaciations in New England, and a detailed record of only the last glaciation in the Quaternary (Schafer and Hartshorn, 1965). The primary effects of the glaciation include the removal of preglacial soils or sedimentary rocks, the rounding of slopes and the deepening of the northwest-southeast aligned valleys, the filling of many preglacial valleys reworking of existant drainage patterns, and the deposition of unconsolidated glacial sediments. (Pilkey, 1989).

Glacial Sediment

Till is one of the most common glacial deposits along New England's coast. In central and eastern New England, it is found as moraines of boulders and clay that produce coarse-grained flats as they erode. To the south the till is often found as drumlins and is sandy enough to form beaches along the base of eroding bluffs. Erosion of the exposed moraine systems of Cape Cod and Rhode Island has produced numerous beaches.

Sandy glaciofluvial deposits are the most important sources of beach sand in New England. Glaciofluvial deposits dominate the exposed and eroding shore of Cape Cod and its nearby islands. Bluffs composed of this material 40m high are eroding at the rate of 1m per year on the outer portion of Cape Cod and are producing the sands that make up Cape Cod's curved end (Pilkey, 1989).

Large sandy deltas were deposited in water 30 - 60m deep at the time of low sea level in the western Gulf of Maine (Belknap, 1987), and wave reworking of these glaciofluvial sediments provides sand for beaches near the mouths of the Kennebec and Merrimack Rivers.

Emergent glaciomarine sediment is commonly found only along Maine's coast. Unlike coarser-grained glacial deposits, bluff erosion of this sediment tends to produce intertidal salt marshes and mudflats. This muddy material usually erodes slowly, but catastrophic landslides have occurred (Kelley, 1987).

Sea Level History

During the retreat of the Laurentide ice sheet, which began around 20,000 years BP, ocean volume increased rapidly, and the shoreline of the late Pleistocene moved landward from the shelf break. Isostatic depression of the land due to ice loading flooded low coastal areas from 13,000 to 12,000 years BP along New England's eastward-facing coast (Belknap, 1987).

In central Maine, at about 9500 years BP, sea level was 65m lower than it is today. During the same time, however, sea level was much shallower (30m or less) south of
Boston. After reaching its lowest point, sea level began rising rapidly in New England due to continuing eustatic rise and local submergence (Pilkey, 1989).

At the beginning of the Holocene sea level may have risen up to 15mm per year. Radiocarbon dating of basal salt marsh peats have shown that from 4500 years to 2,000 years BP the sea level rise had slowed to between 1 - 4mm per year (Belknap, 1987).

At present, sea level change in New England exceeds 0.5mm per year, and there has been a clear trend of accelerated sea level rise from Boston to the Bay of Fundy (Figure 6).

Present State

The primary factors influencing New England's coast on a daily basis are the waves and tides. Tide ranges are mesotidal along the western Gulf of Maine, to macrotidal near the Bay of Fundy, to microtidal along most of Long Island Sound and along the southern coast Rhode Island and Massachusetts. New England's shores are usually viewed (FitzGerald, 1987) as being tide-dominated or as a mix of wave and tide factors. The tide-dominated nature of New England is a major factor in the stability of its coasts because storm damage is usually minimal in areas with large tidal ranges.

New England is often subjected to two major types of storms: Extratropical and tropical storms. Extratropical storms usually occur between November and April and last longer and cover a wider area than tropical storms, increasing the chances that they will occur during high tide. The winds from these storms come from different directions and affect beaches differently, depending on the beach orientation. Tropical storms are rare but are very destructive to southern New England. These storms are important to southern New England because their approach to that coast is more direct than to other New England shorelines and the storm's strongest area often strikes land (Pilkey, 1989) (Figure 7).

Recent Coastal Change

Except for a few locations at the mouths of large rivers, New England's beaches acquire their sediments from eroding bluffs (FitzGerald, 1987). At Cape Cod, barrier islands are common, but are not usually found in other areas of New England. Most New England beaches connected by an eroding bluff to the mainland and are found as barrier spits, tombolos, or pocket beaches. Complex wave refraction around islands of unconsolidated sediment or bedrock knobs help form the variety of beach morphologies found in New England.
Figure 6: Tide gage locations and present rates of sea level rise in New England (Pilkey, 1989).

Figure 7: Hurricane tracks and dates through New England (Pilkey, 1989).
Models for Coastal Erosion

D.B. Scott presented a model that requires sea level to rise for new sediment sources to be used. This model shows an episodic retreat of barrier islands in response to rising sea level. As the sediment supply for a particular beach is depleted, the beach shape changes and the beach area jumps landward to new source. J.A. Walsh's work in Maine has shown a long-term correlation between spit growth, bluff retreat, and sea level rise (Pilkey, 1989). Most of New England's coast is not composed of beaches, but of other unconsolidated material like salt marshes, bluffs, and tidal flats, or of bedrock. New England's bedrock is unaffected by rising sea level, but its "soft coast" is affected as sea level rises, and most of New England's beaches are retreating to a measurable degree (Figure 8).

Kelley (1987) also presented a model for coastal change in New England. His shows the processes in a typical Maine embayment that can be extrapolated to most of New England (Pilkey, 1989). In the outermost, microtidal area, storm waves strip most of the shoreline of its unconsolidated sediments, leaving only exposed ledge and high-energy gravel or sand beaches. In the innermost fluvial or macrotidal area, bluffs have not begun to erode because they are protected by salt marshes and tidal flats. Sediment for the intertidal environments are acquired from nearby rivers or the center of the embayment. As sea level rises, these environments usually extend across the mainland. The center of the embayment is affected partly by both waves and tides. At this point all the bluffs are eroding. Depending on the texture of the bluff, low-energy beaches or salt marshes form after marked bluff erosion. These environments survive for only a brief period, because during the time they protect a bluff from further erosion they lose their own supply of sediment. A cycle of bluff erosion, beach or marsh growth or erosion, followed by renewed erosion is established. The length of such a cycle depends on several factors, but in most places lasts less than 100 years (Figure 9).

Community Reaction Case Studies

Rhode Island Coast

The beaches of Rhode Island acquire their sediment from the erosion of bluffs of glacial till. This shoreline is located near several urban centers and has been constructed as a coastal resort (Figure 10). On September 21, 1938, a hurricane brought in a surge of over 4m, owing to the spring high tide. The area was completely destroyed, having cost
Figure 8: D. B. Scott's model for an episodic retreat of barrier beaches as a result of rising sea level in Nova Scotia and New England (Pilloy, 1989).
Figure 9: Kelley's model for coastal change in Maine in which a cycle of bluff erosion, beach or marsh growth or erosion, followed by renewed erosion is established (Kelley, 1987).
Figure 10: Southern Rhode Island coast. In 1938, a hurricane completely destroyed the area, leaving

caused at least $250 million in damage.
at least $250 million in damage. Most of the destroyed property was located on flat
barrier beaches, which were completely overwashed.

Significant development did not return to the area until 1963. Rhode Island permits
construction in high-velocity flood zones if the first floor is constructed on storm-resistant
pilings at least 0.45m above the predicted storm wave crests. A growing infrastructure
precludes the area's inclusion into the Coastal Barrier Resources System, and as the
memory of the previous disaster fades, total development of the area may yet occur
(Pilkey, 1989).

_Popham Beach, Maine (Natural Processes)_

Popham Beach is located at the mouth of the Kennebec River. The beach derives
its sand from the reworking of submerged Pleistocene deltaic deposits and from fluvial
sediments. Significant shoreline erosion may have deterred early development, and some
houses were moved in 1896 due to the threat of erosion. By 1942, the beach had
accreted as much as 150m, and housing construction became widespread.

By 1976, temporal variation in the sand supply and frequent storms had caused the
beach to recede to the 1896 shoreline. Forty properties were either destroyed by storms
or removed by 1977, when a new period of accretion began (Figure 11).

In 1979, the Maine legislature added the Sand Dune Amendment to the state's
Wetland Act. Under this law, individuals were allowed to rebuild on sites of properties
destroyed in 1978 for up to one year, then no construction that unreasonably damaged the
dune systems or was subject to unreasonable flood hazards was allowed. In 1983, the
state's environmental jury, the Board of Environmental Protection, added rules that better
defined "unreasonable", since no construction permits had yet been denied (FitzGerald,
1987).

In the late 1980's, due to the dwindling number of houses, Popham Beach was
included in the federally designated Coastal Barrier Resources System. This designation
precludes federal flood insurance to any new houses, and allows the island to revert to its
natural state as the sea level rises.

Maine's latest sand dune rules require the removal of any structure at least 50%
destroyed by a storm, and no further development is permitted on the site
to recede to its 1896 shoreline (Pilkley, 1989). By 1976, the shoreline had moved further inland, likely due to changes in sediment supply and the effects of frequent storms. The black lines in the diagram represent the shoreline changes at Popham Beach, Maine. The white areas indicate the extent of shoreline change.
**Miami Beach, Florida (Beach Renewal)**

On September 17, 1926 a hurricane hit Miami Beach. By midnight the storm had driven the surf over most of the island, destroying beach front property. The storm hospitalized 854 and left 25,000 people homeless.

The city council moved to protect beachfront homes by building a groin field and declaring a bulkhead line at the high-tide mark.

In 1967, the US Army Corps of Engineers offered a plan of beach renewal. The beach would be seven miles long with an eleven-foot high dune in front of the hotels. The shoreline was to be expanded 300 feet seaward from the old bulkhead line. The $35 million construction cost did not include the cost of annual sand replacement. This new beach costs $1 million per year to maintain and it loses 211,000 cubic yards of its new sand each year (Kaufman and Pilkey, 1979).

**Ocean City, Maryland (Coastal Construction)**

In 1935 the Corps of Engineers built jetties on both sides of the Ocean City inlet - one at Ocean City, the other across the inlet on the northern end of Assateague Island. The northern jetty trapped sand from the southerly flowing longshore currents, and Ocean City's island grew so much that by 1955 the beach had expanded almost to the end of the city's pier.

South of Ocean City and downdrift of the jetties, sediment-deprived Assateague Island eroded. By 1962 the jetty on its side was separated from the island by a gap of almost 240m, and another gap was opened by a storm that was over 1km in width, 2.5km south of the jetties. The northern end of the island was reconnected to the jetty by dredged-up fill. Since the jetties' construction, the islands shoreline has retreated over 540m (Komar, 1976).

**Conclusions**

As demonstrated in this paper, coastal erosion and sea level rise are by no means a new phenomenon. I have listed a very brief summary of the factors of coastal erosion and sea level rise below:

a) waves and currents: waves and currents break up the shoreline material and longshore currents transport this material away from the shoreline.

b) tides: a macrotidal environment is less affected by storms because of the resistant nature of the associated landforms (salt marshes and tidal flats).
c) Other factors such as rock type and sediment composition and cohesion, vegetation, climate, coastal topography, and seasonal change also affect shoreline erosion rates within the context of the surrounding wave, tide, and storm regime.

d) Engineering structures often have negative impacts when not properly employed. However, where other alternatives are not feasible, a properly designed and engineered structure can have a positive impact if sediment transport is allowed to adjacent areas (Levels Reference Study Board, 1993).

e) Glacio-eustasy: the freezing and melting of ice sheets affects sea level directly, as water is added or subtracted from the world ocean.

f) Isostasy: ice loading of the land causes the land to depress and ice unloading in turn allows the land to rebound, thus affecting the relative sea level in a certain area.

g) Greenhouse effect: carbon dioxide levels in the atmosphere will lead to the warming of the Earth, which will lead to an increase in ocean volume.

Applied coastal geomorphology uses our understanding of landform types and other factors described above, to take appropriate action for coastal zone management. Knowledge of the region's geologic history, bedrock framework, sources of sediment, recent coastal change, and an understanding of the results of past attempts at coastal management are all very helpful.

In the context of New England, the geologically distinct sections should first be considered one at a time, and then altogether to make sure that a course of action taken in one area does not adversely affect another. Actions taken in various localities provide helpful lessons to planning authorities. In some localities, as exemplified at Popham Beach, wise ecologically-minded planning has allowed the area to establish a natural equilibrium. In other areas, such as the Rhode Island coast, past lessons have been forgotten and the relatively unregulated coastal development may be a recipe for future disaster.

The Levels Reference Study Board (1993) has suggested a policy in reference to the Great Lakes region and the St. Lawrence River, and this policy could be extrapolated to other areas. Their policy first suggests the removal of structures from hazard areas, the flood-proofing of existing structures, the use of non-structural shore protection, and the use of engineering structures where other means are inappropriate.

Coastal abandonment policies are among the most sound, but where there is development there is also money and power, and developed areas will probably opt for an engineered coastline. The probable evolution of New England's coast could result in an engineered coastline extending from Rhode Island up to Maine, with an undeveloped,
natural shoreline extending north from there. However, other shoreline management approaches might be taken.

References


