

SOUTH SHORE COASTAL HAZARDS CHARACTERIZATION ATLAS

DESCRIPTION OF VARIABLES



**Prepared for:
Massachusetts Office of
Coastal Zone Management**

**Prepared by:
Applied Coastal Research
and Engineering, Inc.**

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A. INTRODUCTION

The primary goal of the *South Shore Coastal Hazards Characterization Atlas* is to present information that can aid project review in areas where these projects may be vulnerable to coastal hazards. It is anticipated that the *Atlas* will assist local reviewers with the identification of technical information necessary to evaluate individual projects and implement sound coastal hazard mitigation strategies. Three major tasks were undertaken in the creation of the atlas: (1) compilation and review of existing data, (2) creation of a classification system for a range of coastal variables applicable to the entire coast of Massachusetts, and (3) preparation of GIS data layers and maps to present the information in a usable format.

Characterization of coastal hazards is not a new concept. Recently, the U.S. Geological Survey (USGS) developed relative coastal vulnerability assessments (e.g., Hammar-Klose *et al.*, 2003 and Thieler and Hammar-Klose, 1999). Although these large-scale assessments are useful, the unique geological and geographic setting of the Massachusetts coast requires a region-specific analysis. In addition, contemporary analysis techniques (e.g., GIS, rectified aerial photography, and digital topographic information) allow for more accurate delineation of coastal features, as well as other variables that help characterize local coastal hazards. It is noted that this analysis was performed for open coasts facing Cape Cod or Massachusetts Bays. In addition, the protected shoreline along Kingston Bay, Duxbury Bay, and Plymouth Harbor certain relevant variables were mapped (Shoreline Type, Shoreline Change Rate, and Repetitive Loss).

The unique geologic and geographic setting of the Massachusetts shoreline consists of a variety of shoreline types, ranging from bedrock outcrops to barrier beach systems. In addition, the geographic location of Massachusetts and the variable orientation of its shoreline make different portions of the coast susceptible to major damage from both tropical storms (hurricanes) and extra-tropical storms (northeasters). As indicated in Figure 1, the Massachusetts shoreline is characterized by glacial deposits, many forming high banks punctuated by areas of lower-lying beach. Massachusetts represents one of the few shorelines along the U.S. East Coast where glacial moraine or drumlin deposits dominate the regional sediment supply to beaches. Since the geologic and geographic setting of the Massachusetts coast governs how the shoreline changes over time, these characteristics need careful consideration in the assessment of coastal hazards.

Based on the unique characteristics of Massachusetts, and specifically the South Shore, the following is a list of variables used to characterize coastal hazards. The purpose for selecting these variables and the general method for evaluating each variable is described in the following sections of this guide.

- Tide Range
- Wave Climate
- Storm Susceptibility
- Properties with Multiple Federal Flood Insurance Claims
- Historical Shoreline Change Rate
- Littoral Cells
- Shoreline Type
- Dominant Coastal Processes
- Coastal Engineering Structures
- Beach Width Fronting Coastal Banks
- Relative Seal-level Rise

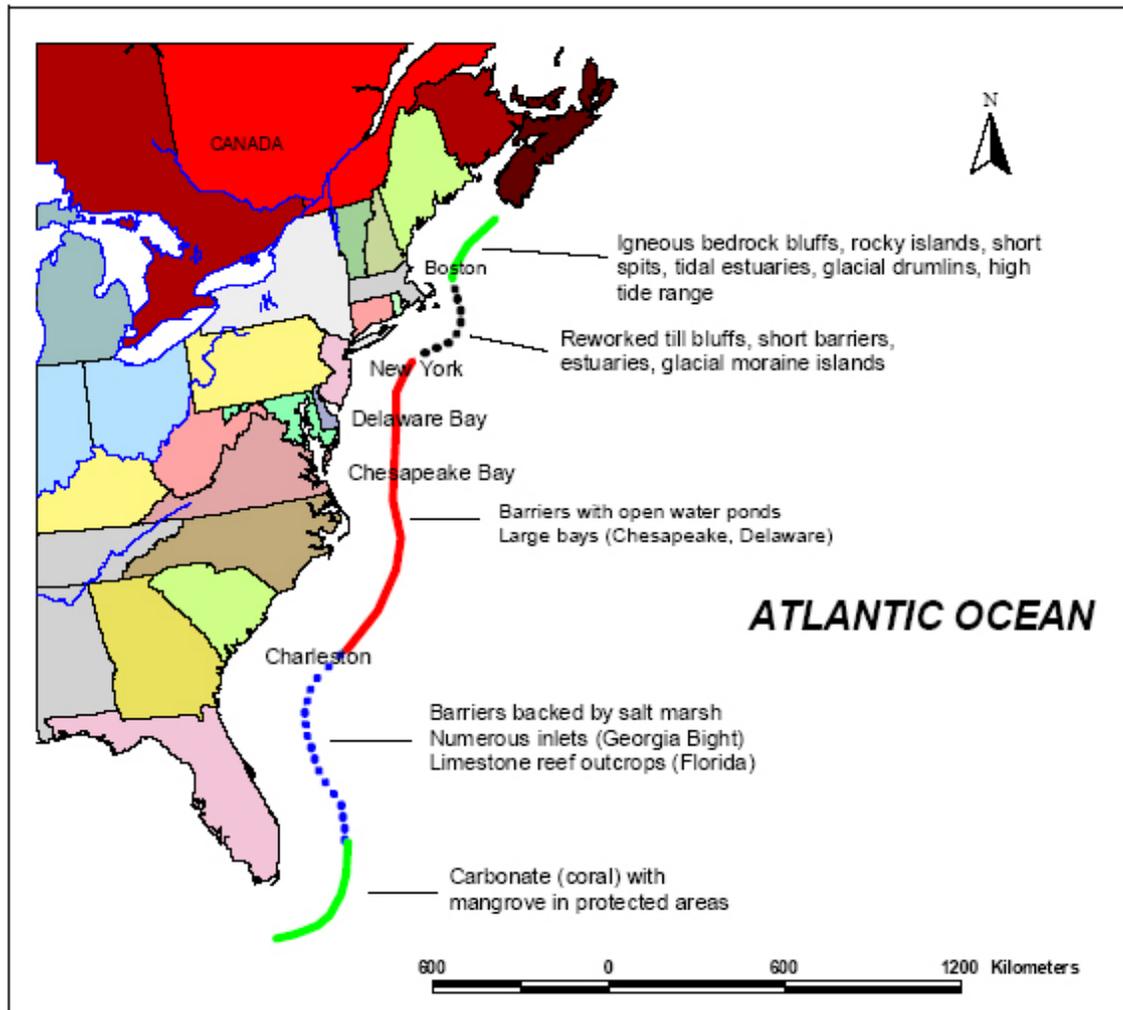


Figure 1. Atlantic coast characteristics (from the U.S. Army Corps of Engineers, 2002).

B. TIDE RANGE

Purpose: To illustrate the variations in tide range along the Massachusetts coastline.

Methodology: The tide ranges along the coast of Massachusetts were obtained from NOAA's Center for Operational Oceanographic Products and Services (CO-OPS). Tide range is defined as the difference between Mean Low Water (MLW) and Mean High Water (MHW).

The tides in Massachusetts are semidiurnal, meaning that in each period of 24 hours and 50 minutes (just over a day), there are two high and low tides. The tide range around the Massachusetts coast varies greatly, from less than 2 feet (0.6 m) near Woods Hole and Falmouth to greater than 9 feet (2.7 m) in Cape Cod and Massachusetts Bays (Figure 2). It is important to keep in mind that these ranges are for the astronomical tides only. Any contribution to local water level change due to storm or wave effects is not included. Furthermore, these tide ranges are averages, and the actual tide range for a given location changes gradually from day to day. During the new and full moons, the tide range will be the greatest, the so called "spring" tides. During a spring tide, a location with a 9 foot (2.7 m) average tide range can see a tide

range in excess of 12 feet (3.7 m). Between the full and new moons, when the moon is half full, the tide range is the smallest and this is referred to as the neap tide. So, throughout the month, the tide at a given location is in constant flux, either increasing towards the spring tide range or decreasing towards the neap tide.

It should be noted that around the Chatham area there is a nodal point in the tides, where the average range changes significantly over a relatively small distance. Along the southern coast of Cape Cod, the average tide range increases gradually from less than 2 feet (0.6 m) at Falmouth, to about 3 feet (0.9 m) south of Cotuit to almost 4 feet (1.2 m) just west of Monomoy Island. A tide range of about 4 feet (1.2 m) is also seen on the ocean side of Monomoy Island but then jumps sharply to 6 feet (1.8 m) or more offshore of Chatham Harbor, which is only 10 miles (16 kilometers) or so north of Monomoy Point. From offshore of Chatham the tide range increases gradually from 6 feet (1.8 m) to more than 8 feet (2.4 m) northeast of Provincetown.

For the South Shore, typical northeast storms impacting the coastline have a duration longer than a tide cycle; therefore, tide range is not directly related to susceptibility to storm damage. Damage typically occurs during conditions of elevated water levels beyond the normal high tide levels (e.g. during periods of storm surge). However, for relatively short-duration tropical storms (e.g., hurricanes), a large tide range can decrease the storm impacts. Since hurricanes typically pass through Massachusetts in a matter of a few hours, a large tide range can prevent storm surge from causing flooding problems, if the storm passage is between low and mid-tide levels.

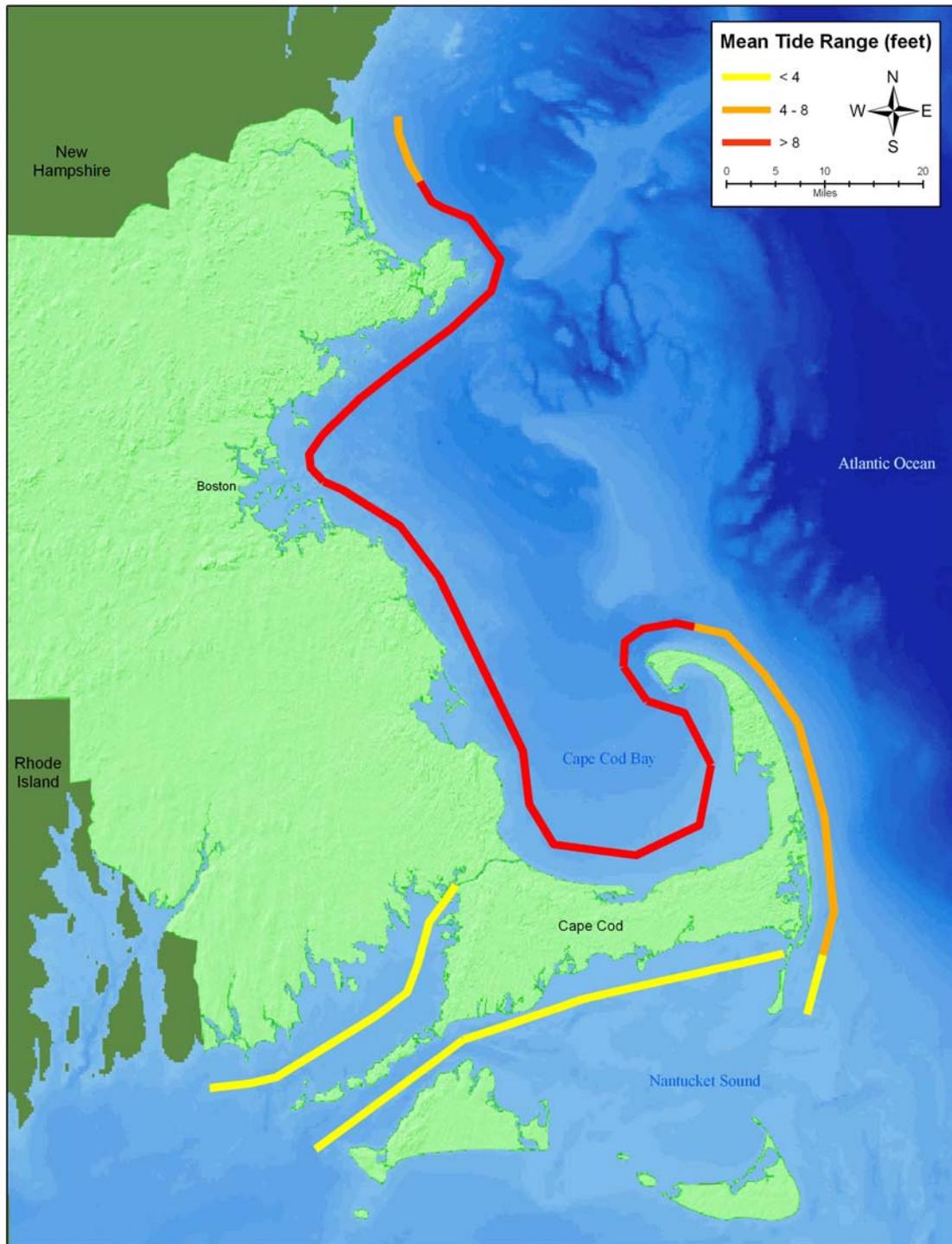


Figure 2. Tide Range - Mean tide ranges along the Massachusetts coast.

C. WAVE CLIMATE

Purpose: *To illustrate the direction and amount of wave energy that impacts the South Shore coast. This information can be used as a first step in determining the dominant driving force for moving sediment along the beaches of the South Shore.*

Methodology: *The U.S. Army Corps of Engineers Wave Information Study (WIS) provided the information for this variable. Wave height and direction information were summarized in a “wave rose” that indicates the percent occurrence and height of waves influencing the coast.*

The wave climate along the South Shore is dominated by waves from the east and northeast. The wave roses shown in Figure 3 are compiled from data taken from the U.S. Army Corps of Engineers Wave Information Study (WIS). This study uses historical meteorological data to calculate hourly wave conditions, which are then verified against measurements from wave buoys. The resultant data set is comprised of 20 years (1976-1995) of hindcast wave information, including significant wave height, peak period, and direction once each hour.

The wave roses in Figure 3 show the percentage of waves that arrive from a given directional band and the distribution of wave height within that direction band. The median direction of wave incidence for Station 94 is 79 degrees (east-northeast) and the average wave height of the highest 5% of waves is 12.4 feet (3.8 m). For Station 93 to the south, the median incident direction is 29 degrees (north-northeast), with the highest 5% of waves averaging 9.9 feet (3.0 m). These wave roses show that the coastline in the northern part of the study area is subject to more severe wave attack when compared with the southern portions of the study area. In addition, the northern section of the study area is impacted by waves primarily from the east and east-northeast directions, while the southern section is dominated by waves from the northeast. The difference in incident direction is an important factor to understand, as Cape Cod provides significant sheltering to the southern reaches of the study area. Cape Cod serves to block open ocean waves approaching much of the South Shore from the east, southeast, and south. The frequent occurrence of waves from the east and east-northeast at Station 94 is best explained by the lack of sheltering from Cape Cod. At this site, the dominant easterly waves from the North Atlantic Ocean are allowed to propagate unimpeded toward the shoreline.

A unique feature of the Massachusetts coast, north of the Cape Cod Canal is the series of rocky outcroppings interspersed with small pocket beaches. These outcroppings often provide sheltering for the neighboring beaches, but this protection is highly sensitive to the direction from which the waves are coming. For the narrow stretches of beach between such headlands, a change in wave direction of 10 or 15 degrees could have a major impact on storm damage for that portion of the shoreline. An open stretch of beach (e.g., Humarock) is much less sensitive to small changes in the angle of wave attack.

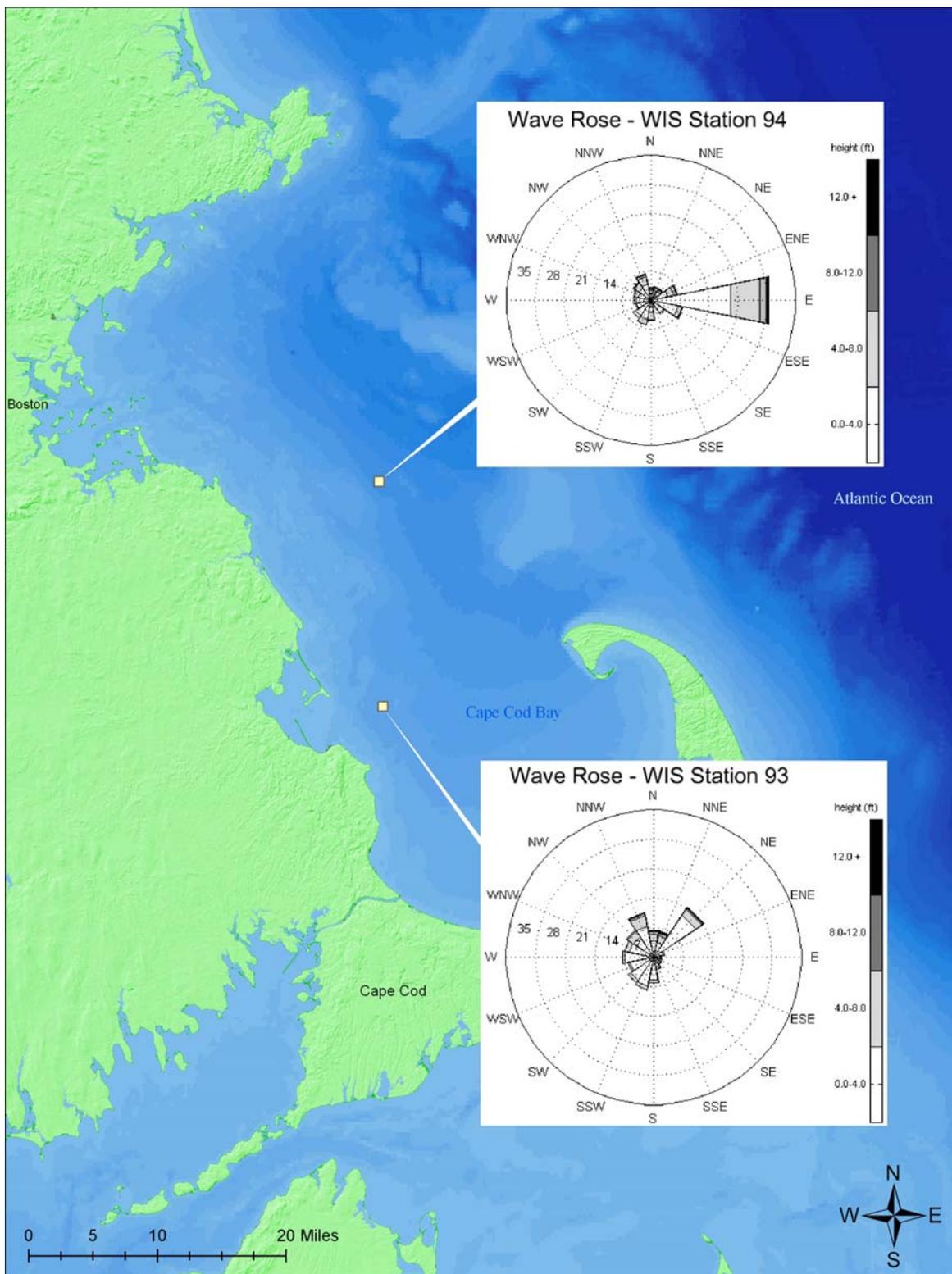


Figure 3. Wave Climate - Wave roses for two offshore wave hindcast stations showing the east-dominated wave conditions for the open ocean (Station 94) and more northeast dominated wave conditions for shorelines sheltered by Lower Cape Cod (Station 93). The wave roses divide wave data into direction bands and color code by wave height. The data is plotted radially by percent occurrence, which is labeled in the left portion of the rose. The wave data is from 1976-1995.

D. STORM SUSCEPTIBILITY

Purpose: *To illustrate the relative magnitude of surge elevations relative to different return-period events. This variable indicates that Massachusetts shorelines influenced predominantly by relatively frequent northeasters are more susceptible to storm damage on an annual basis than shorelines influenced predominantly by less frequent hurricanes.*

Methodology: *The 1-year and 100-year return period still water storm surge levels were determined from the 1988 U.S. Army Corps of Engineers Flood profiles. These 1-year and 100-year return period events were selected to illustrate the relatively large difference in storm susceptibility between coastlines dominated by northeast storm events (including the South Shore) and those dominated by tropical storm events (e.g. hurricanes).*

Due to the unique geographic location of Massachusetts, both tropical (originate in the tropics) and extra-tropical (originate in mid-latitudes) storm events are important to the characterization of potential coastal hazards. For the shorelines in Buzzards Bay, as well as along the south shore of Cape Cod, Martha's Vineyard, and Nantucket, hurricanes typically are considered the storms of record. However, storm damage along the remainder of the Massachusetts coast is dominated by extra-tropical storm events (northeasters). Tropical storms and hurricanes generally move across Massachusetts rapidly (often in a few hours); however, their storm surge can be substantial, especially in large semi-enclosed basins oriented toward the direction of storm approach (e.g., Buzzards Bay). In addition to their rapid passage, significant hurricane events are relatively infrequent, with only two Category 1 Hurricanes making official landfall (where the center of the Hurricane eye crosses the shoreline) in Massachusetts during the past 100 years (1916 and 1954). Hurricane landfalls in the Massachusetts region are shown on Figure 4. However, extensive damage has been caused by more powerful hurricanes that made landfall west of Massachusetts, including hurricanes in 1991 (Bob), 1944, and 1938. In contrast, northeast storms typically occur several times per year, generally between late October and April. Although the sustained winds are typically less than hurricane-strength, the duration of these storms can be problematic, causing coastal flooding situations for upwards of two-to-three days for severe storms. Although storm surge elevations associated with northeast storms are not as severe as major hurricanes, their relatively frequent occurrence and duration create significant coastal hazards along the South Shore. To evaluate the susceptibility of the South Shore to these storms an analysis of storm surge elevations and storm frequency was performed.

Figure 5 illustrates the 100-year storm surge levels along the Massachusetts coast. Due to the limited data available, it is not possible to determine an accurate 100-year storm surge level along the undeveloped shoreline of outer Cape Cod, or along the south shores of Martha's Vineyard or Nantucket. The 100-year storm surge elevation represents the Stillwater elevation without the local influence of waves. The highest storm surge levels experienced in Massachusetts occur in Buzzards Bay, where the 1938 hurricane caused a storm surge in excess of 14 feet NGVD. However, it should be noted that most of the Massachusetts coast has 100-year storm surge levels in excess of 10 feet NGVD.

As shown in Figure 6, for the shorelines of Buzzards Bay and the south shore of Cape Cod, the difference between the 1-year and 100-year storm surge elevations is generally between 6-8 feet (1.8-2.4 m), with areas where the difference is greater than 8 feet (2.4 m) in the upper reaches of Buzzards Bay. This indicates quite clearly that the annual winter storms of the region result in storm surge elevations significantly lower than those associated with a rare, severe tropical storm, such as a hurricane. In short, a severe hurricane impacting the area will be accompanied by historic flooding and associated damage. Although hurricane's can cause damage along the entire Massachusetts Coast, areas most susceptible to this damage are the

south-facing shoreline including the Buzzards Bay coast, the southern shore of Cape Cod, Nantucket, and Marthas Vineyard.

In contrast to the expected relation between storm severity and storm surge elevations along the south facing coast of Massachusetts, the Massachusetts Bay and Cape Cod Bay shorelines show quite a different trend. For this section of the coast, the difference between the 1-year and 100-year storm surge elevations is only 2-4 feet, except for a small area on either side of the Cape Cod Canal, where the difference is just over 4 feet. This indicates that the storm surge elevations associated with typical northeasters experienced on an annual basis produce almost as much flooding as the epic storm which has a 1% chance of occurring in any given year. Therefore, shorelines dominated by northeast storms experience storm surge elevations that cause flood damage nearly every year. Although not evaluated, the impact of these northeast storms often is related as much to duration as the ultimate elevation of the storm surge.

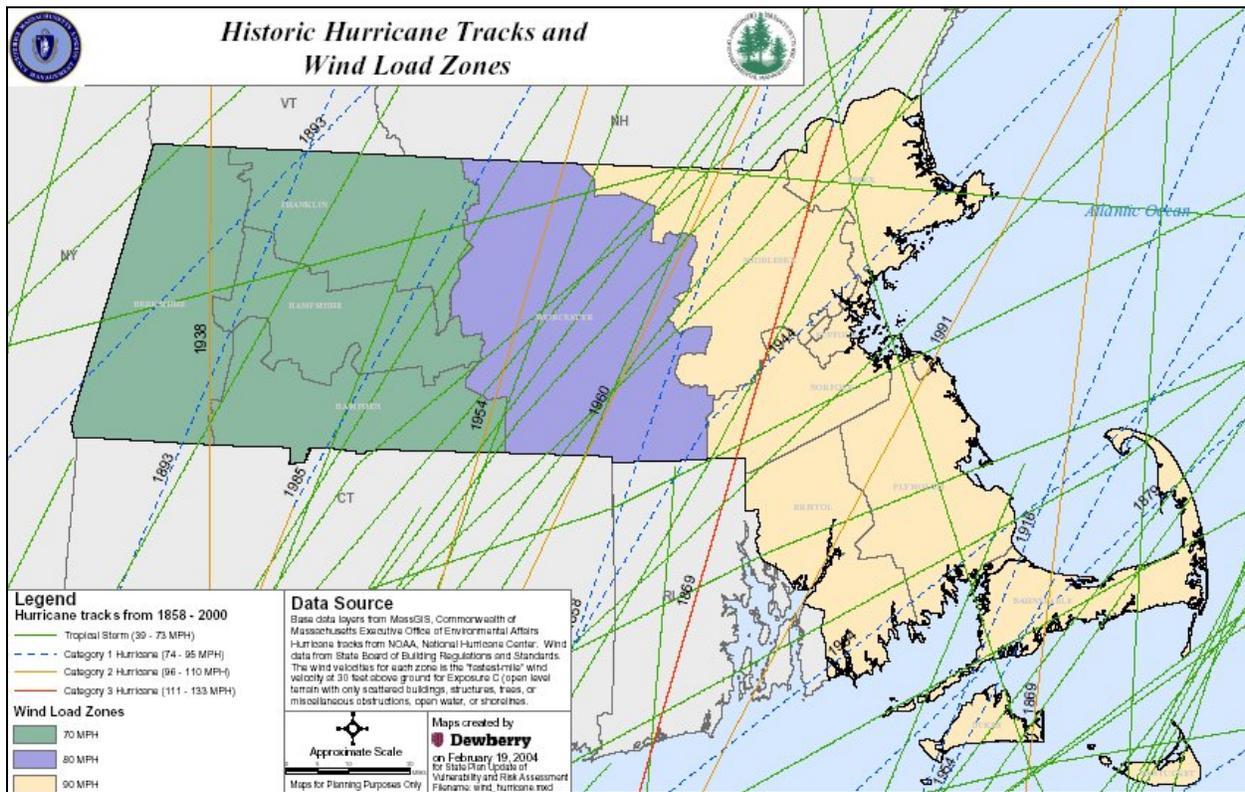


Figure 4. Historical hurricane tracks impacting Massachusetts from 1858 to 2000.

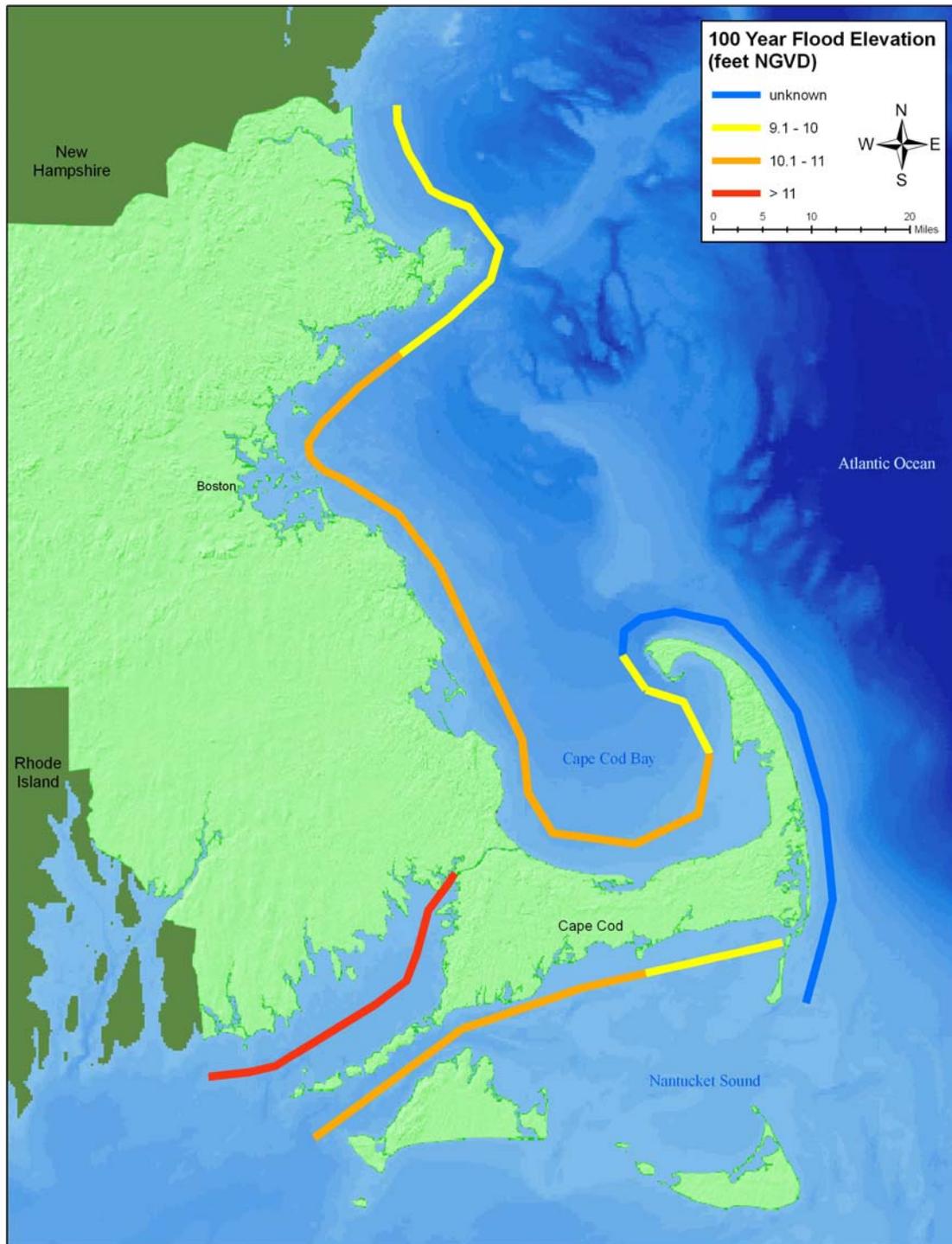


Figure 5. 100-year coastal storm surge elevations along the Massachusetts shoreline (derived from Tidal Flood Profiles, New England Coastline. U.S. Army Corps of Engineers, New England Division, September, 1988).

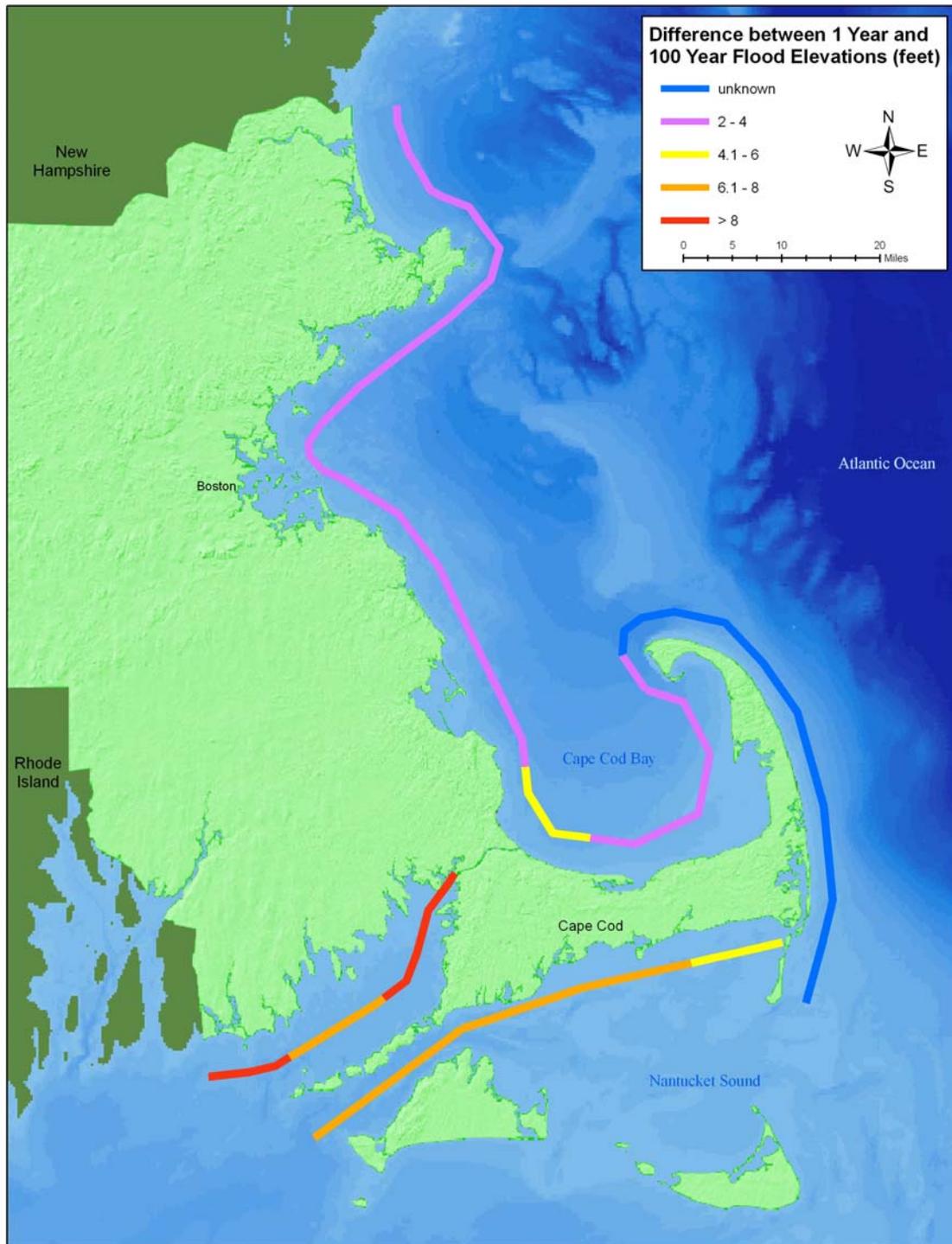


Figure 6. Difference between 1-year and 100-year coastal storm surge elevations along the Massachusetts shoreline (derived from Tidal Flood Profiles, New England Coastline. U.S. Army Corps of Engineers, New England Division, September, 1988).

E. PROPERTIES WITH MULTIPLE FEDERAL FLOOD INSURANCE CLAIMS

Purpose: *To illustrate the distribution of past storm damage resulting in flood insurance claims by property owners.*

Methodology: *The information for this variable was derived from the existing MCZM database summarized in the report “Analysis of Massachusetts Repetitive Loss Damages: 1978 to 2002. As noted, the maps represent the general distribution of properties with multiple flood insurance claims and do not reflect exact locations (per Privacy Act).*

For the purpose of this study, this variable represents repetitive loss properties, defined by the Federal Emergency Management Agency (FEMA) as any property that has sustained two or more claims in excess of \$1,000 over a rolling 10-year period. Some of these insured properties have sustained multiple losses since 1978, while others have recorded only the minimum of two losses within a given 10-year period. The approximate location of each repetitive loss property is shown as a red dot on the maps. Since this variable only represents properties where claims were made to FEMA as part of the National Flood Insurance Program, it does not represent damage to all coastal properties.

F. HISTORICAL SHORELINE CHANGE RATE

Purpose: *To illustrate a site-specific understanding of the historical rate of shoreline change along each section of the coast. This information can be used for regional planning efforts, as well as for evaluating the potential impact of coastal projects on the regional shoreline system. Since a majority of shoreline armoring within this region was constructed between the early to mid 20th century and the present, the shoreline change analysis represents rates associated with the existing condition of the coast.*

Methodology: *The 1938 and 1950’s shoreline locations were derived from “Massachusetts Shoreline Change Project: 1800’s to 1994”, which were previously digitized from NOAA T-sheets. The 2001 shoreline was created from the 2001 aerial photographs, supplemented with the 2000 LIDAR data used to help resolve uncertainties. In addition, differential GPS surveyed shorelines in the Towns of Hull, Scituate, and Plymouth were utilized to ground-truth the 2001 shoreline location. Using these temporal endpoints, the net change in shoreline position and resultant shoreline change rate were calculated.*

Many of the coastal engineering structures that influence sediment transport and shoreline change along the South Shore were constructed over the past 50 to 75 years. As a result, the 1950/52 to 2001 time period has been selected as the most appropriate representation of recent shoreline change. The lone exception is in the Nantasket area, where no data were available from the 1950’s and so data from 1938 and 1978 were used to compare to 2001. Shoreline change rates during this period represent shoreline response following construction of most coastal engineering structures along the Massachusetts South Shore.

Using these temporal endpoints, shoreline change rates were calculated every 131 feet (40m) for the entire length of the study area. The shoreline change rate is indicated by both the length and color of the transect lines along the coast. The length of the transect line shows relative magnitude of the change rate. The greens and blues indicate accretion while yellows and reds show erosion. Each map legend shows a small area of black near the center of the color bar. This region indicates that the value of the shoreline change rate for that transect is within the statistical uncertainty of the analysis itself and not that the change rate was calculated to be zero. If a transect’s change rate falls within this uncertainty, it is shown on the map with a

small length to increase its visibility. As a result, these black colored transects are the lone case where the transect length does not indicate the relative magnitude of the change rate.

A separate technical report, *South Shore Shoreline Change Analysis: Hull to the Cape Cod Canal, MA*, describes in detail the methodology used to develop the historical shoreline change rates for the South Shore coastline.

G. LITTORAL CELLS

Purpose: *To delineate boundaries that serve to inhibit movement of sediment along the shoreline. Littoral cells can be used to evaluate the potential adverse impacts of coastal construction projects on a regional basis.*

Methodology: *Applied Coastal utilized available literature, aerial photography, and professional judgment to determine the appropriate boundaries of littoral cells within the study area. Literature consisted of scientific papers and reports associated with regional and sometimes local wave climate, coastal geologic processes, and/or coastal engineering design. Review of aerial photography combined with knowledge of coastal processes was used to refine littoral cell boundaries in some areas. In addition, local knowledge derived from coastal project experience provided information regarding littoral cell limits.*

For the purposes of this study, a littoral cell is defined as a section of shoreline where longshore sediment transport occurs without interruption. The boundaries of the cell are delineated by some feature (typically a headland or inlet) that inhibits sediment from continuing to travel along the shoreline. In this sense, the littoral cells can be a tool for initially evaluating the area of impact associated with a given project. For the series of maps presented in the *South Shore Coastal Hazards Characterization Atlas*, the littoral cell boundaries are shown as shore-perpendicular dashed lines on the maps. Where possible, entire littoral cells are shown on a single map, since the initial step in evaluating a coastal development project is to view the project in a regional context. The mapping of the chosen littoral cells should not be taken to mean that there is no transfer of sediment from one cell to the next. Sediment transport occurs over a large range of spatial and temporal scales; therefore, each of the cells mapped in the *Atlas* are themselves part of the larger littoral system. Large-scale processes such as sediment transport across the inner continental shelf can be responsible for transport between littoral cells. In addition, storms can cause inter-littoral cell movement by transporting material beyond the limits of the typical surf zone.

Development of littoral cell boundaries was based on a thorough review of available data, as well as local and regional knowledge developed over the past 15 years of working on coastal-related issues in Massachusetts. In addition, James O'Connell, Coastal Processes Specialist with the Woods Hole Oceanographic Institution's Sea Grant Program provided feedback regarding the selected littoral cell boundaries, specifically in the Towns of Marshfield and Duxbury.

H. SHORELINE TYPE

Purpose: To illustrate the dominant shoreline landform that governs coastal geological processes. Understanding shoreline type can aid in project review by indicating which shoreline areas are potential sediment sources for downdrift beaches. In addition, it is important to understand that areas delineated as barrier beaches typically are susceptible to storm overwash; therefore, natural landward migration of these features should be anticipated.

Methodology: In general, the existing shoreline type classification from “Patterns of Repetitive Loss in the Massachusetts Coastal Zone” provided the basis for this variable; however, both refined delineation of shoreline type and modifications to the definitions were performed by Applied Coastal. “Patterns of Repetitive Loss” delineated shoreline type on a 1000 meter grid. For the South Shore Coastal Hazards Characterization Atlas, delineation of the shoreline type was refined through review of the 2001 aerial photography, site-specific knowledge, and consultation with CZM’s Coastal Geologist, Rebecca Haney. James O’Connell, Coastal Processes Specialist with the Woods Hole Oceanographic Institution’s Sea Grant Program, provided additional feedback regarding the selected shoreline type boundaries, specifically in the Towns of Marshfield and Duxbury. Definitions of shoreline type were modified to more accurately represent coastal features along the Massachusetts shoreline. Specifically, naturally erosion-resistant coastal banks were separated from coastal banks as a result of input received. The separation was performed because the glacially-derived shorelines contain significant areas where glacial till slows the natural coastal erosion processes. Delineation of these areas was based upon site-specific knowledge, as well as aerial photographic analysis.

The shoreline type variable indicates the major geomorphology that governs how the natural shoreline responds to the various wave and tide forces experienced along the coast. The classification of shoreline types include the following:

- **Port and Industrial Shorelines** – Shorelines of this type were characterized by large-scale industrial or port developments containing bulkheads, retaining walls and seawall. It is typical that such construction has permanently altered the surrounding landforms in a manner that makes identification of the previous natural landform problematic. For the South Shore area evaluated, only Plymouth Harbor and the Pilgrim Nuclear Power Station were designated as this shoreline type.
- **Sandy, Barrier, and Cobble Beaches** – These are reaches of sandy, cobble or mixed beach which are not backed by coastal banks. Although beach grain size varies dramatically along the South Shore, ranging in size from fine sand to cobble, all beach systems were classified as the same shoreline type. Beach shorelines, regardless of grain size characteristics, perform in a similar fashion to both average daily wave conditions and higher-energy storm conditions. Typical examples of barrier beaches along the South Shore include Nantasket Beach, Humarock, Duxbury Beach, and Plymouth Long Beach. In addition to the major beach systems along the South Shore, a number of pocket beaches also exist. A pocket beach is a relatively short length of sand or cobble shoreline which is located between two headland features.
- **Estuaries, Lagoons, Mud Flats, Salt Marshes** – This category encompasses the perimeter of protected waters along the South Shore whose shorelines are characterized by low lying mud flats or salt marshes. These more quiescent estuarine shorelines are generally less susceptible to wave erosion; however, the effects of flooding from storm surge may still cause them to be considered high hazard areas. These shorelines can be found inside of all inlet systems along the South Shore, with a majority of the area contained within Duxbury Bay and Plymouth Harbor.

- **Naturally Erosion Resistant Coastal Banks** – These are coastal banks consisting of consolidated glacial till that are typically fronted by large stone and boulders that have eroded from the bank itself and now help reduce wave impact at the base and protect the bank from erosion. Due to the glacial origins of the Massachusetts shoreline, coastal banks can consist of a variety of sediment types, ranging from clay to house-sized boulders. Because of these sediment characteristics, some of the coastal bank deposits are more resistant to erosion than others. Typically, these naturally erosion-resistant shorelines appear as headlands or promontories. For the South Shore analysis, a combination of site-specific knowledge, the 2001 aerial photography, and nautical charts published by the National Oceanic and Atmospheric Administration (NOAA) were utilized to delineate erosion-resistant coastal banks. Both the aerial photography and NOAA charts were helpful in delineating nearshore boulder fields that are indicative of an erosion-resistant coast. Shorelines of this type can be found from Hull to Plymouth (e.g., Point Allerton, Gurnet Point, and Rocky Point).
- **Coastal Banks** – Coastal banks of soil that were not defined as “naturally erosion resistant” were classified as coastal banks. The banks in this shoreline type consist primarily of sediment ranging in grain size from clay to cobble, with little or no boulders. Significant stretches of coastal banks exist in Marshfield and Plymouth (e.g., Nameloc Heights and White Cliffs).
- **Rocky Coast** – Although much of the Massachusetts shoreline consists of glacial sediments, major portions of the North Shore and some sections of the South Shore consist of bedrock outcrops, classified here as rocky coasts. A majority of this shoreline type is found in Cohasset, where pocket beaches have formed between the jagged outcrops. These shorelines were identified through site-specific knowledge in addition to the 2001 aerial photography.

I. DOMINANT COASTAL PROCESSES

Purpose: *To illustrate the fundamental processes that influence sediment movement along the South Shore. Although all, or at least most, coastal processes influence sediment movement in every region, only the dominant processes are presented in the Atlas.*

Methodology: *The dominant coastal processes were developed from a review of shoreline type, as well as extensive regional and local knowledge of factors that influence littoral processes (e.g. waves, tides, storm surge, wind, etc.). Dominant coastal processes are only delineated in areas where sediment movement is important, i.e. shorelines exhibiting active movement of nearshore sediments.*

Along most areas of the Massachusetts coast, waves provide the primary force for reshaping the shoreline. However, the glacially derived sediments of Massachusetts do not form a straight smooth shoreline, but rather a jagged coast punctuated with rock outcrops and ancient drumlin deposits (consisting of sediment ranging from clay to house-sized boulders). Due to long-term coastal erosion (the reworking of glacial deposits), beaches have formed between or adjacent to these naturally erosion-resistant features. The natural variability in shoreline type influences the coastal processes that dominate how a particular shoreline stretch responds to the long-term effects of waves and tides, as well as the infrequent short-term influence of storm waves and surge. Based on the regional geomorphology and exposure of the coast to open ocean wave conditions, it was possible to assess the dominant coastal processes governing the various shoreline regions of the Massachusetts South Shore.

This series of maps provides information regarding the dominant processes controlling sediment transport and the shoreline stability. As described in the map legend, the primary

coastal process is drawn nearest to the shoreline. Other important coastal processes that influence local sediment transport are shown seaward of the dominant process. It should be noted that most or all of the coastal processes might influence a particular stretch of shoreline; however, only processes that have an impact on long-term shoreline evolution for a majority of the shoreline being considered are presented on the maps.

- **Longshore Sediment Transport** - When waves break in the surf zone, much of their energy is released in the form of a current that flows parallel to the shoreline. This wave-driven current moving along the coast is called the longshore current. If the waves have sufficient energy, they can mobilize sediment into the water column (e.g., due to wave breaking). This sand will be carried by the longshore current, moving it down the beach. This process of suspended sand being carried along the coast by the longshore current is referred to as longshore sediment transport.

This process should not be thought of as sand flowing along the coast at a steady rate at all times. Rather, longshore sediment transport is better understood as an episodic event related to periods of high wave energy. With larger waves there is a wider surf zone, stronger longshore currents, and an increase in the amount of sand that is suspended in the water column. As a result, large amounts of sand can be moved over the course of a single storm while very little sand might be moved during a calm period of several weeks or months.

Along a majority of the South Shore, the dominant direction of longshore sediment transport is from north to south. However, any shoreline can experience periods of reversal and certain beaches may experience net longshore transport from south to north due to sheltering from neighboring landmasses.

Where appropriate, the long-term direction of longshore sediment transport (or littoral drift) has been depicted as arrows on the Dominant Coastal Processes maps. These arrows only indicate net direction of transport and do not indicate the relative magnitude of transport. The direction of longshore sediment transport was delineated only where sufficient information was available to determine the net direction of sediment movement.

- **Cross-Shore Sediment Transport** - In addition to sand moving parallel to the coast, there is also a component of transport that moves sediment onshore and offshore. A familiar example of this is the formation of a winter beach profile, where sand is moved from the dry beach to shallow water areas offshore, typically forming a nearshore bar. Offshore sand migration typically occurs during the winter months and in the summer months this sand is returned to the beach. In general, steeper, high-energy waves during the winter months cause sediment to move seaward and the milder late spring through fall wave climate causes sand to migrate back onto the beach face. The movement of sand back and forth perpendicular to the shoreline is called cross-shore sediment transport. This process is dominant on pocket beaches (relatively short beaches between sections of rocky or erosion-resistant coast), where there is little opportunity for a strong longshore current to be generated. Cross-shore sediment transport is often dominant on cobble beaches, where long-term lower energy longshore processes cannot mobilize the gravel and cobble material.
- **Aeolian Transport** - Under strong enough winds, the sand along the dry beach can be mobilized and carried away from its original location. This transport of dry sand by wind forces is called aeolian transport. Any impediment to the sand's movement along the

beach can serve to limit windblown transport. Fencing and beach grass planting are common examples of such efforts to limit aeolian transport and/or encourage the deposition of wind blown sands in specific locations such as on an existing dune.

- **Tidally Induced Transport** - At most inlets, the currents due to the tide are strong enough to suspend and move sediment. For this reason, these inlets can remain open without significant dredging requirements. Tidal currents alone can be strong enough to shape those sections of beach immediately adjacent to the inlet. For the purpose of this map series, the migration of sand due to tidal currents is referred to as tidally induced transport. Due to the relatively large tide range along the South Shore, inlet tidal currents typically are strong and have a large influence over sediment transport in the vicinity of inlets.
- **Bank Erosion** - The banks on the South Shore consist of a wide range of sediments including glacial till and sandy outwash material. Coastal bank erosion provides an important source of material to beaches, tidal flats, and salt marshes. In general, the erosion of banks can be attributed to direct wave impact at the base, which removes material. Following the erosion at the base of the bank, the upper portions collapse under their own weight, falling to the beach below. Other mechanisms that can play a role in bank erosion include upland runoff, groundwater seepage through the bank face, freezing and thawing cycles, and direct erosion from wind and rain.

It should also be noted that bank erosion is largely an episodic event, corresponding to storm conditions with high water levels and large waves. This episodic erosion should be kept in mind when considering average erosion rates for banked shorelines.

- **Barrier Beach Overwash** - Overwash is the flow of water and sediment over a beach and/or dune crest that does not directly return to the ocean. Overwash begins when the runup level of waves, usually coinciding with a storm surge, exceeds the local beach or dune crest height. As the water level in the ocean rises to a level where the beach or dune crest is over-topped, a steady sheet of water and sediment runs over the beach system. Along barrier beach systems, sand derived from the beach face overwashes into the bays or harbors backing the barrier. On undeveloped barrier beaches (e.g. Duxbury Beach), overwash and aeolian transport are the mechanisms by which the barrier migrates in response to sea-level rise. As a result of major storms, dunes can be destroyed or weakened along barrier beaches. Barrier beach weakening typically is temporary, as natural coastal processes rebuild the barrier. Regions starved of natural littoral sediments may experience long-term weakening of the beach's natural storm-protection function.

J. COASTAL ENGINEERING STRUCTURES

Purpose: *To illustrate the location and extent of coastal engineering structures along the South Shore.*

Methodology: *The existing MCZM Coastal Structures Inventory was verified using information from various Town reports, regional knowledge, and review of the 2001 aerial photographs and the 2000 LIDAR data.*

Coastal engineering structures along the South Shore were mapped using site-specific knowledge, coastal structures inventories performed for various towns, the MCZM coastal structures inventory (compiled 2002-2003), and the 2001 aerial photographs. The mapping

includes man-made shore protection structures constructed along the beach and bluffed shorelines for the purpose of altering the natural movement of beach material and/or preventing landward migration of the shoreline. Structures that were buried and not visible for the ground surveys or in the aerial photographs are not depicted. This category includes structures that are both parallel and perpendicular to the shoreline such as: groins, jetties, bulkheads, vertical seawalls, revetments, and breakwaters. These maps provide a good understanding of the amount of coastal armoring that exists along the South Shore, within the limitations mentioned above. Based on this analysis approximately 26 miles (or ~30%) of the South Shore shoreline is fronted by coastal engineering structures, not including regions that may be protected by shore-perpendicular structures (e.g., groins and jetties). Prior to construction of these shore protection structures, sediment contained in the coastal banks and beaches was available to downdrift shorelines.

K. BEACH WIDTH FRONTING COASTAL BANKS

Purpose: *To assess the amount of potential protection afforded coastal banks by the fronting beach as an indicator of relative coastal bank stability. Based on local and regional observations of beach width fronting coastal banks, Applied Coastal developed this variable as a guide for assessing how beach width can be related to susceptibility of a coastal bank to storm wave attack and the related stability.*

Methodology: *The beach width was calculated as the distance between the newly developed 2001 shoreline and the 15' NAVD contour. The 15' contour is used to represent the location of the toe of bank based upon a comparison of differential GPS surveyed locations overlain on the LIDAR contour data. The 15' NAVD contour is specific to the tide range and wave condition characteristics of the South Shore.*

The Massachusetts coast is somewhat unique in that it features a significant amount of coastal bank shoreline comprised of glacially-derived erodible sediments. There are many variables that play a role in bank erosion including rainwater runoff, groundwater seepage through the bank face, freezing and thawing cycles, and direct erosion from wind and rain. However, the foremost contribution is from direct wave attack and the removal of material at the toe of the bank. When enough material is removed, the higher elevations of the bank collapse to the beach below and the fallen material is soon removed by wave action, causing landward retreat of the shoreline. If no cohesive sediments exist within the coastal bank (i.e., clay and silt), the stable slope for coastal banks (angle of repose) is approximately 1:3 (vertical:horizontal) or about 30°. If erosion at the toe of the slope causes the bank to be steeper than this, the bank will eventually equilibrate (or collapse) to its more stable slope.

Observations along the South Shore reveal that certain sections of bank coast are well vegetated and others are completely denuded (void of vegetation). The presence of natural vegetation (i.e. not supplemented by planting) on the sloped face of the bank is a clear indication that it hasn't suffered any significant erosion in the past few years. In contrast, the denuded banks have been eroded recently and have not been stable long enough to allow plants to establish a stable base naturally. However, planting on a denuded bank is one potential way to slow erosion.

The width of the beach fronting the banks can be an indicator of whether the bank face is stable. To be precise, the beach *volume* in front of the bank is the dominant variable, but the beaches fronting the bluffed shorelines along the South Shore have similar slopes and most bank shorelines lacking fronting dune systems. The beaches typically consisted of a steady mild slope from the waterline back to the toe of the bank. Because of this, beach width provides a good indicator of beach volume.

The beach width displayed on the maps was calculated as the distance between the newly developed high water line (discussed in section F above) and the 15 ft contour (NAVD 88) taken from NOAA's 2000 LIDAR data. LIDAR (Light Detection And Ranging) is an active sensor, similar to radar, that transmits laser pulses to a target and records the time it takes for the pulse to return to the sensor receiver. This technology has been used by NOAA for high-resolution topographic mapping along the coast of Massachusetts.

To ground-truth the base of bank location, 1.7 miles of Global Positioning System (GPS) data was collected by walking the base of bank line along the White Cliffs and Ellenville regions of Plymouth. These field data were then overlaid with the NOAA 2000 LIDAR data. Based on comparisons between the GPS survey data and the NOAA 2000 LIDAR data for areas exhibiting relatively stable coastal banks, the 15 ft contour was selected as the best elevation to represent the base of bank for this region. The 15 ft contour value also indicated good agreement with the interpreted location of the bank base as judged visually from the aerial photos.

L. RELATIVE SEA-LEVEL RISE

Purpose: *To illustrate the predicted rise in relative sea-level along the South Shore, as well the width of beach that would be lost due to that change, based upon various beach slopes. Where historical shoreline change has been significant, the influence of relative sea-level rise on coastal change will be relatively small. In contrast, areas with historically limited shoreline change will see a relatively large impact from the future rise in sea-level.*

Methodology: *Published relative sea-level change rates for Boston and Cape Cod Canal were averaged to determine an appropriate rate for the South Coast.*

Separate from the daily rise and fall of the tide, the average elevation of the ocean changes over time with respect to the land. This average position is called relative sea-level (RSL), and different geologic and atmospheric processes contribute to changes in RSL. Some of the causes include glacial ice melt and the rising or sinking of the earth's crust itself. While the specific causes of RSL change are the topic of much scientific and political debate, they are of secondary concern to coastal planners and homeowners who are interested simply in the current rate of change itself, whatever the cause.

Figure 7 shows tide gauge records over the past century for stations located along the northeastern coast of the United States. Note that in Figure 7, the rate of change is given for relative land level, hence the rates are negative. Of particular interest to the South Shore are the average rates of RSL change determined for the Boston and the Cape Cod Canal tidal records. It can be seen that the average rate for the Boston data shows RSL rising by 2.9 mm/yr (0.11 inch/yr), while the Canal data shows a rise of 2 mm/yr (0.08 inch/yr). In order to find a value applicable across the whole study area, an average of the two rates was chosen. Based on these data, a single RSL rise rate of 2.45 mm/yr (0.96 inches per decade) will be used to estimate future change along the South Shore. This rate is in good agreement with mean sea-level trends determined in 2001 by NOAA based on tide gauge data.

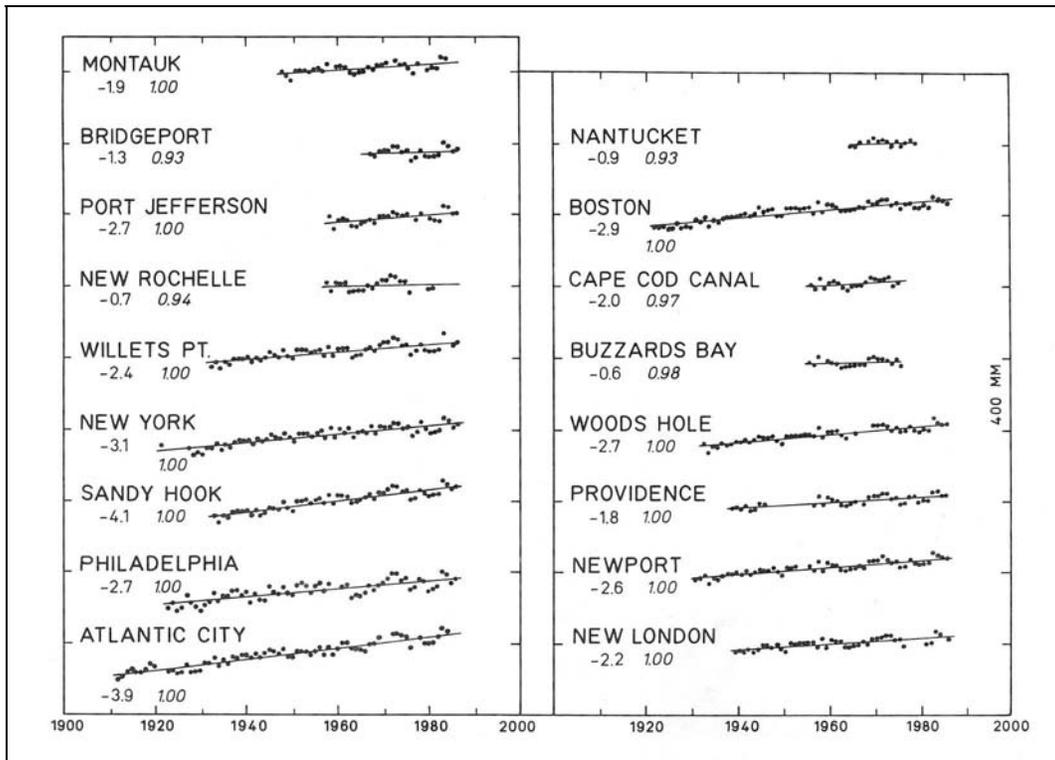


Figure 7. Plots of mean annual relative land levels. Beneath the station names are the mean annual change of relative land level in mm/yr, and the confidence interval of the regression line, which has been drawn through the data points. From Emery and Aubrey (1991).

While a rise in RSL means that future storm surge, wave setup, etc. will be that much higher vertically, a higher relative water level also has a horizontal component that can be significant, especially on a mildly sloped shoreline. Table 1 shows the estimated vertical change in water levels over the next 100 years, as well as the horizontal land that would be covered based on three representative beach slopes. For example, a typical beach profile is shown in Figure 8. This data from a beach in Plymouth shows a slope of approximately 1/10. In 2030 the RSL is expected to rise by 61 mm which is equal to 2.4 inches. On a shoreline with a 1/10 slope, this 2.4 inch rise in RSL would result in 2 feet of land width being lost.

Year	Vertical Rise		Horizontal Displacement (feet)		
	mm	inches	1/10 slope	1/50 slope	1/100 slope
2005	0	0	0.0	0.0	0.0
2010	12	0.5	0.4	2.0	4.0
2015	25	1.0	0.8	4.0	8.0
2030	61	2.4	2.0	10.0	20.1
2055	123	4.8	4.0	20.1	40.2
2105	245	9.6	8.0	40.2	80.4

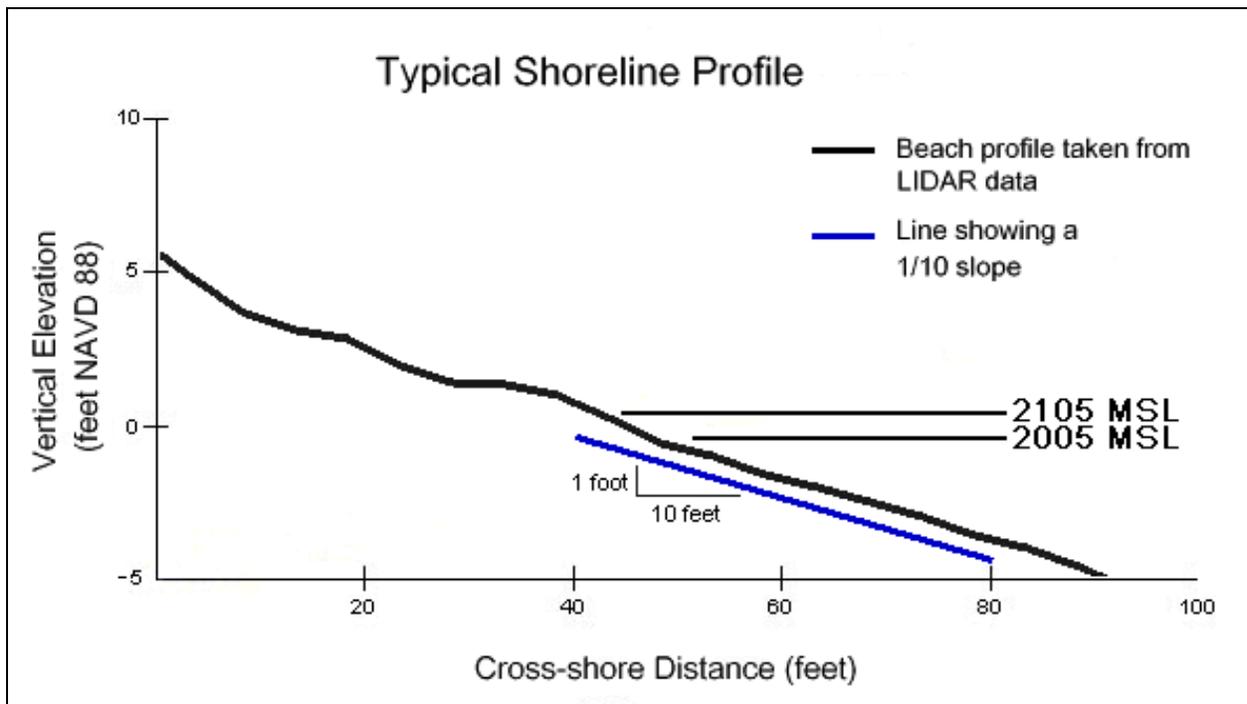


Figure 8. Beach profile plotted from LIDAR data in Plymouth showing a beach slope of approximately 1/10. The Mean Sea-level (MSL) for 2005 and 2105 (predicted) are shown for reference.

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M. REFERENCES

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