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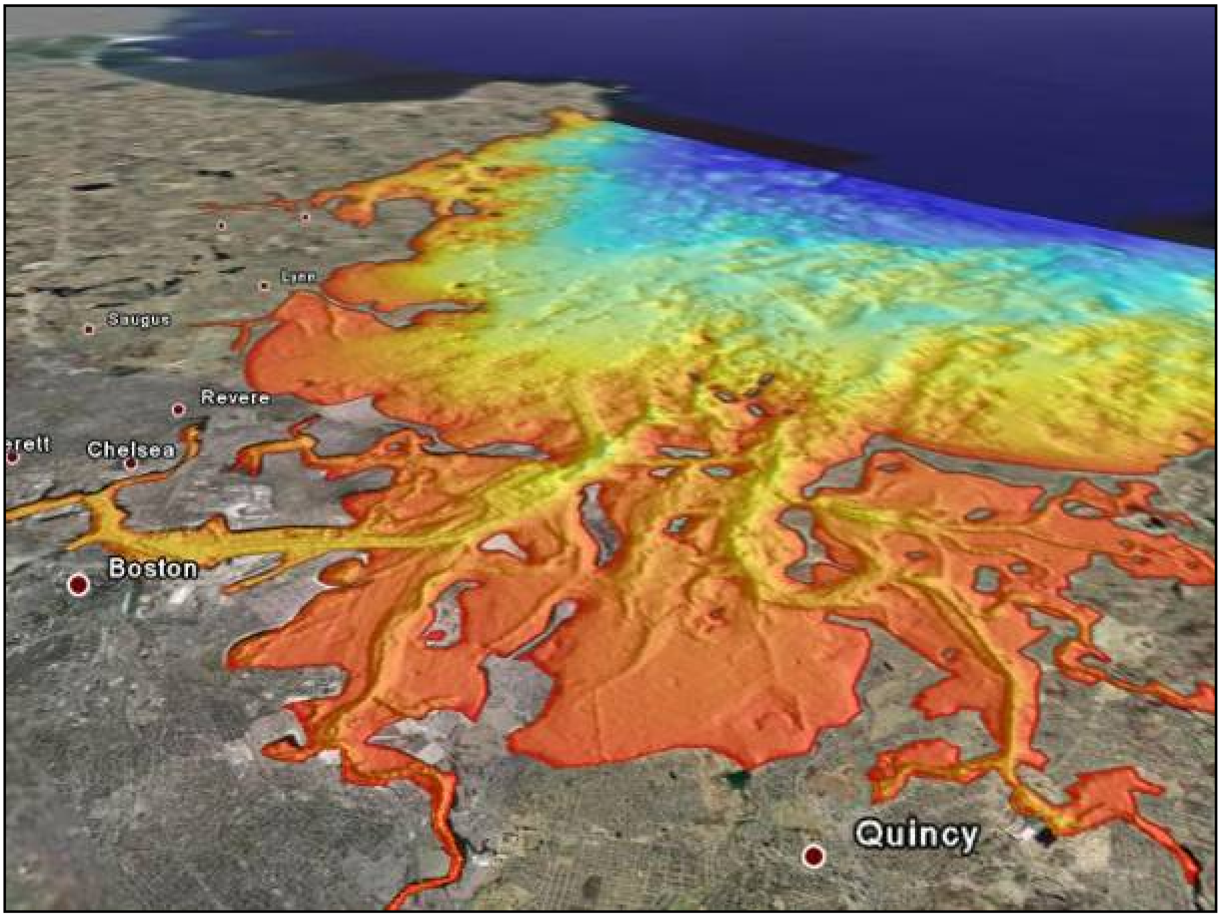
Boat Wake Impacts and their Role in Shore Erosion Processes, Boston Harbor Islands National Recreation Area

Natural Resource Report NPS/NERO/NRR—2011/403



ON THE COVER
Bathymetry of Boston Harbor, NOAA Estuarine Bathymetry (N170.kmz).
Image courtesy of Zoe Hughes, Department of Earth Sciences, Boston University.

Boat Wake Impacts and their Role in Shore Erosion Processes, Boston Harbor Islands National Recreation Area

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Introduction

Boston Harbor Islands National Recreation Area is a developing national park. Park managers are mandated to protect natural values of the islands while increasing visitor access and recreation opportunities. The Boston Harbor Island National Recreation Area is an exceptional natural resource. The islands are recognized as being the unique result (in the U.S.) of coastal and glacial processes resulting from Ice Age (Pleistocene) deposition of drumlins. The islands provide an exceptional opportunity for the public to experience Boston Harbor (Figure 1) and enjoy its dynamic coastal landscape. The park has prepared a General Management Plan, which states the purposes of the park as:

1. To preserve and protect a drumlin island system within Boston Harbor, along with associated natural, geologic, cultural, and historic resources.

2. To tell the islands' individual stories and to enhance public understanding and appreciation of the island system as a whole.

3. To provide public access to the islands and surrounding waters for the education and enjoyment of this and future generations.

Certain areas of the park are intensively visited, while other areas are sheltered and remote, offering an innate reserve for natural resources. There are also many examples of cultural resources due to both its long occupancy by Native Americans and European colonization, which have been declared significant by Congress. Today these islands are diminishing in size due to rising sea level and coastal erosion.

The park is known to provide habitat for nesting seabirds, harbor seals, more than 70 species of terrestrial birds, and state-listed plants. The configuration of the Boston Harbor Islands system, and the assemblage of natural, geologic, cultural, and historic features, (in addition to the proximity to a major metropolitan area), offers a resource that has no parallel in the United States.

Recently, large ferries have played a growing role in the transportation infrastructure for both island access and regional mass transit. This study is motivated by the need for improved monitoring and understanding of vessel wakes and their impact on the shoreline. Recently formed and rapidly retreating bluff scarps in low energy areas of the Boston Harbor Islands have become a public concern for resource stewardship and may indicate that boat wake traffic is responsible for erosion in areas unaffected by the natural wave climate. Unfortunately, the inferences have been neither verified nor quantified for the relative contribution of the anthropogenic role. Elsewhere however, there is growing evidence that ferry wakes can be the cause of significant erosion (Parnell and Kofoed-Hansen, 2001).

This study employs a variety of field studies and modeling techniques to identify and monitor sites of critical erosion along the Harbor Island shorelines; to quantify rates of shoreline retreat; and to assess the role of storms, boat wakes, and other short-term processes responsible for shoreline erosion. The work continues and expands upon a previous study of Boston Harbor shorelines (Permit BOHA-05514 ‘Baseline Study of Harbor Island Geomorphology and Retreat Rates of Selected Islands’). The project consists of three main sub-studies: 1) Shoreline Retreat and Bluff Erosion study - monitoring critically eroding sites on several of the islands through topographic surveys (Figure 1). 2) Mapping - undertaken on all islands in the Harbor. 3) Wave and Wake study- surface wave conditions and boat wakes are monitored using oceanographic instrumentation deployed on specially designed frames. Additional information has been obtained through numerical modeling of the wave climate. This report summarizes the research, the findings, and our dissemination activities.

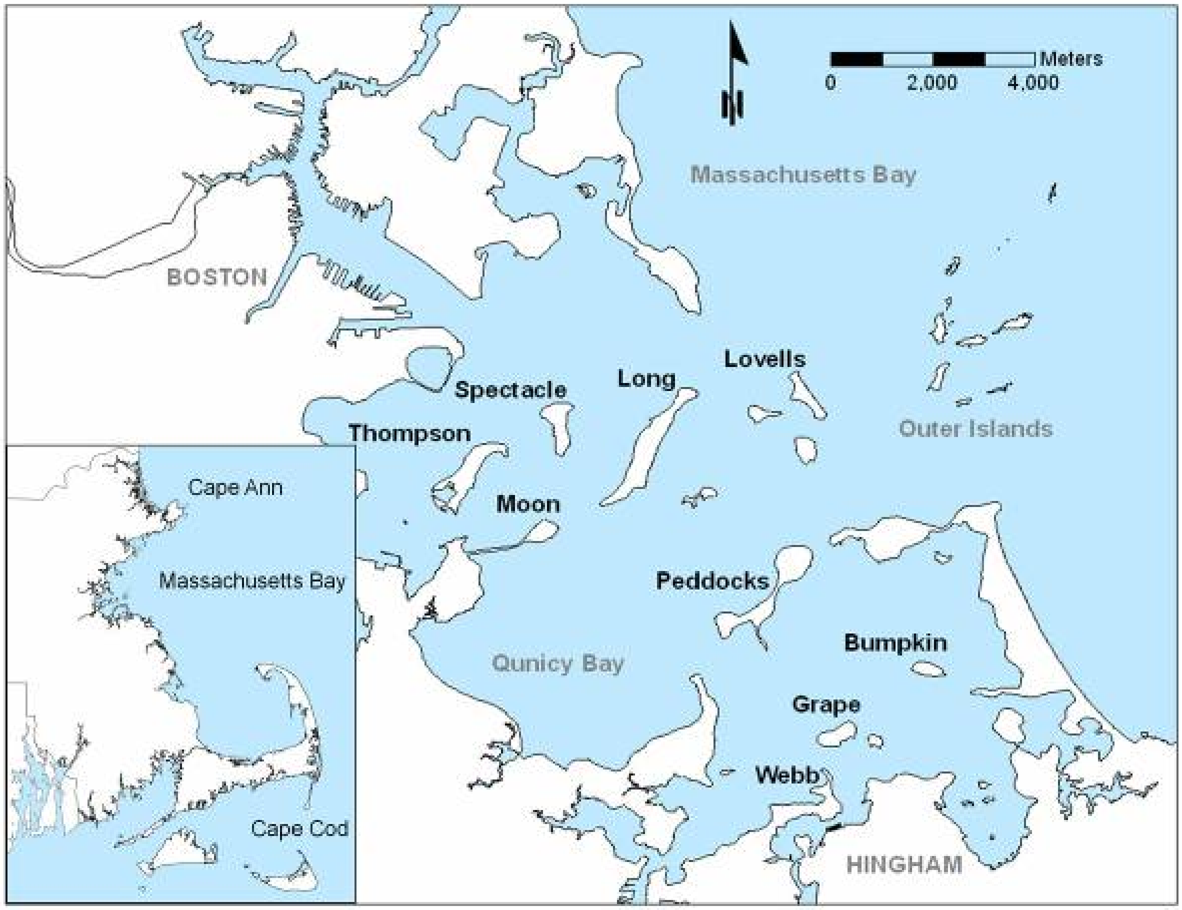

Figure 1. Location of Boston Harbor in the west of Massachusetts Bay below Cape Ann (inset). The Harbor Islands, the named islands were those included in the bluff retreat monitoring part of this study.

Background

Geologic Framework

Boston Harbor is situated within a topographic and structural lowland known as the Boston Basin (LaForge, 1932; Figure 2). This wedge-shaped, down-faulted body of sedimentary and volcanic rock is believed to have formed in the very Late Precambrian to Middle or Late Cambrian (approximately 500-600 million years before present; Kaye, 1982). The major unit is the Boston Bay Group consisting of fine-grained clastic rocks in the Cambridge Formation and the coarse-grained clastic rocks in the Roxbury Formation (Bailey, 2001). The Basin is bordered by thrust faults to the northwest and south (Billings, 1976). It is also bounded north and south by relatively competent plutonic rocks of the Cape Ann and Quincy granite, respectively. Long-term weathering and erosion of the less resistant Boston Bay rocks and their preferential erosion during the Pleistocene glaciation, formed a topographic basin and the reentrant of Massachusetts Bay (Kaye, 1976). Topographic relief of the bedrock surface is up to 90 m within the harbor (Kaye, 1982).

Subsequently, most of the Boston Basin was covered with deposits of glacial till, which includes deposits of two different ages. The older deposit (often referred to as the drumlin till) is probably Illinoisan in age (800,000 to 300,000 ybp; Newman *et al*, 1990). It is the primary component of drumlins that dominate the topography of Boston Harbor. The younger drift (the surface till) was deposited in late Wisconsinan time (up to 15,000 ybp). The late Wisconsinan sequence includes thin, discontinuous drift composed of gravel, sand, and till.

Sea Level Variation

Glacial ice retreat and marine submergence occurred simultaneously approximately 14,000 yr ago, and local relative sea level rose to about 18 m above present mean seal level (Kaye and Barghoorn, 1964; Oldale, 1985; Newman et al, 1990). The glacial deposits are overlain by relatively thick (up to 25 m) and areally extensive glaciomarine muds (Mencher *et al*, 1968; Rendigs and Oldale, 1990). These muds, known as the Boston Blue Clay, are a drape deposit and were laid down in coastal marine waters between 14,000 and 12,600 yr BP (Kaye, 1982).

Schnitker and Borns (1987) described the evolution of the Presumpscot Formation in Maine, which correlates with the Blue Clay to the south. In Maine, at approximately 11,600 yr BP, climatic warming resulted in relatively warm sea water intruding beneath the melting ice sheet and over the isostatically depressed land, causing glacial sediments to be deposited into a marine environment. As the glaciers retreated further and marine waters advanced, the mud was deposited inland of the present shoreline. The clay extends into the offshore zones of Massachusetts and Cape Cod Bays as well as Boston Harbor. The well-bedded clay, silt, and interbedded fine sand deposits reach a maximum thickness of 25 m beneath Boston Harbor (Kaye, 1982).

During the immediate post-glacial period, isostatic rebound caused the harbor area to emerge, and local relative sea-level fell to -22 m about 10,000 yr ago (Figure 3); Kaye and Barghoorn, 1964). The Back Bay region emerged as a poorly drained grassland with a few shallow ponds formed in closed depressions (Kaye, 1982). Soon after, the emergent land became vegetated (Johnson, 1949) as the sea level maintained a stable position for nearly 2,000 years.

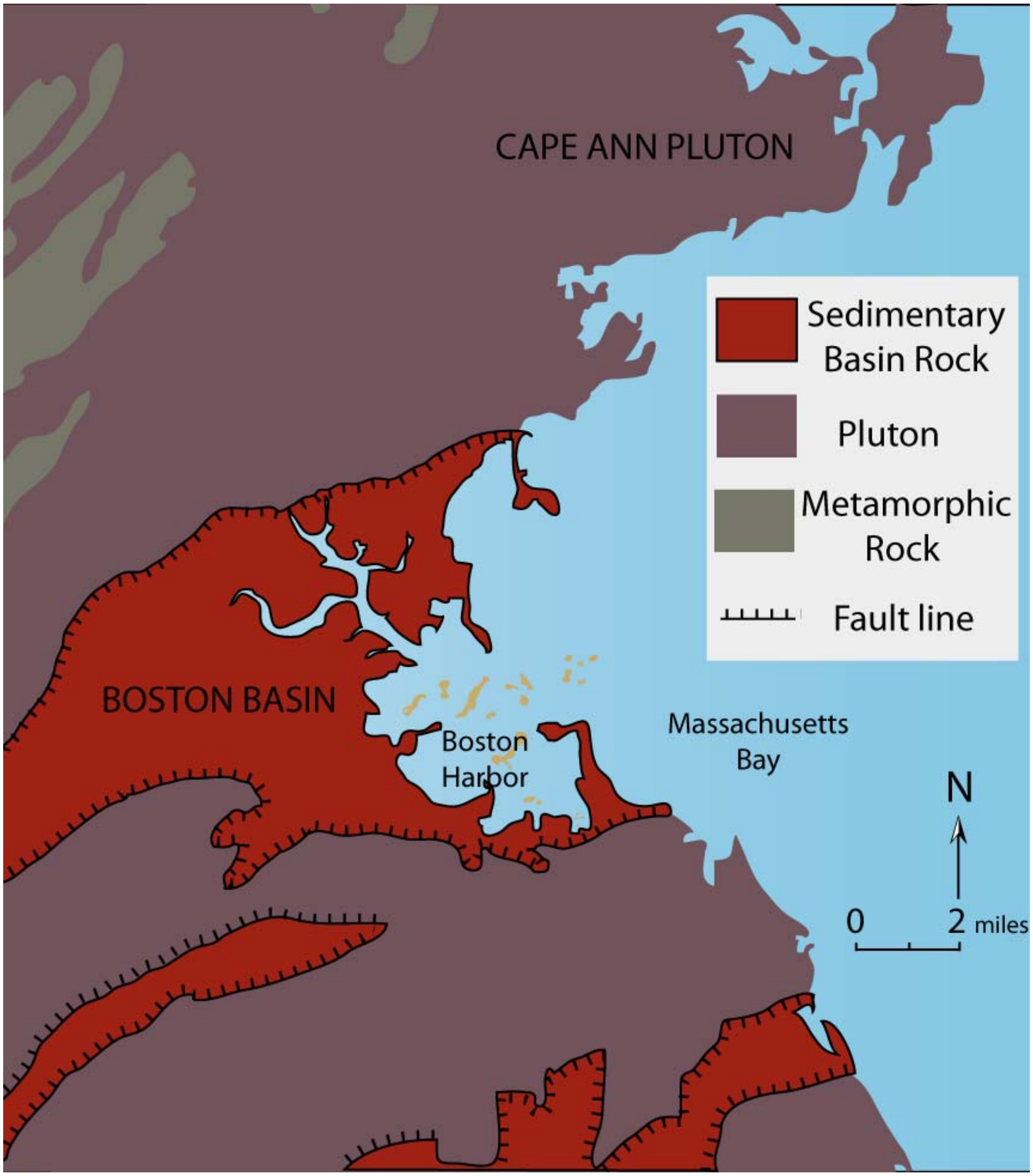

Figure 2. Major rock types and structural features of the Boston Region. Boston and the harbor are situated in a structural basin that contains meta-sedimentary rocks. Preferential erosion of the basin created the harbor.

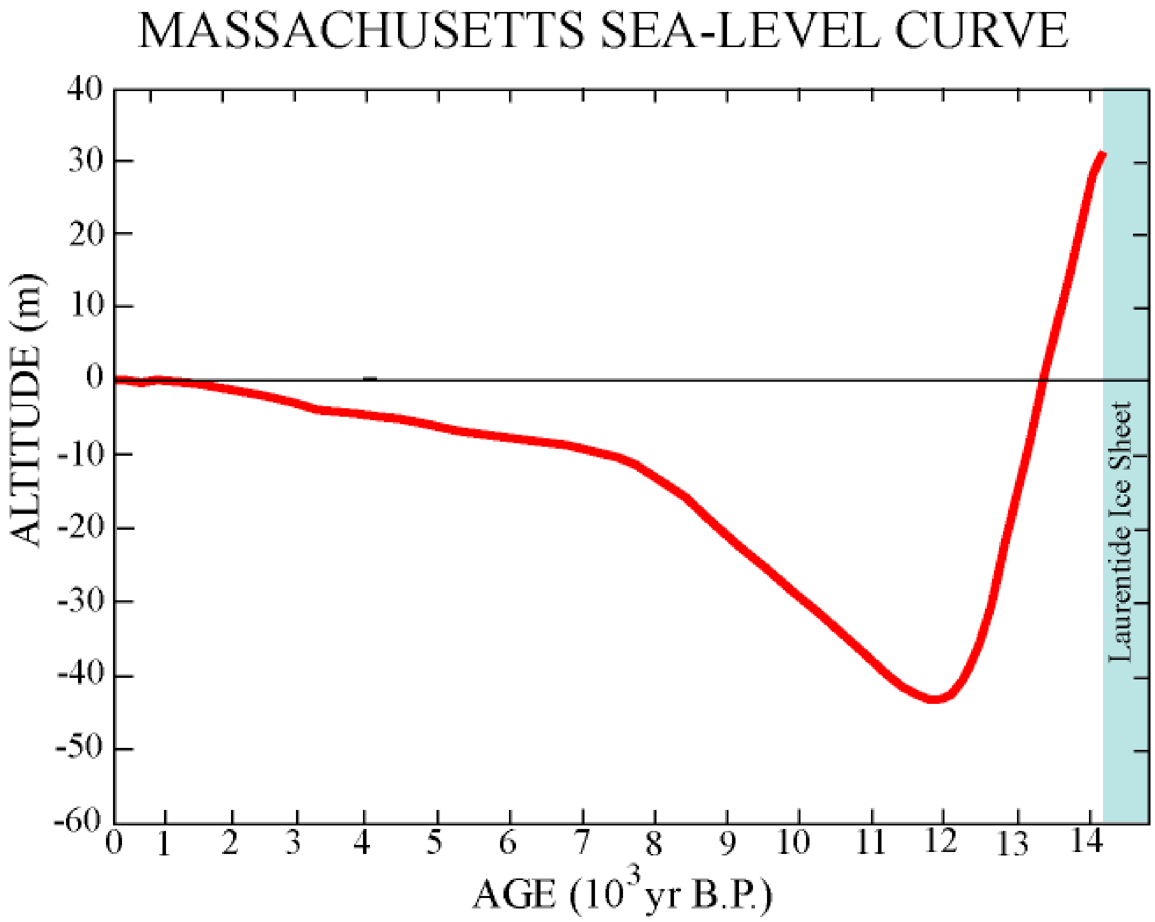

Figure 3. Massachusetts post-glacial sea-level curve (after Kaye and Barghoorn, 1964), showing a complex sea level history. Initially around ~14ka, land surface elevation was depressed by isostatic loading of the ice sheet, resulting in a shoreline at 30m above modern-day. The land rebounded rapidly with passage of the glacial fore-bulge, causing a sea-level low stand at ~10ka, followed by relatively rapid sea level rise as the fore-bulge moved further north and the ice sheets continued to melt, increasing eustatic sea-level. The rate of sea level rise slowed as the volume of water contributed from ice sheets decreased after 8ka.

The area was then resubmerged in response to ongoing eustatic rise of sea level and slowing of isostatic rebound. The shoreline reached - 3 m or less about 3,000 yr ago, when there was a sharp reduction in the rate of sea-level rise (Kaye and Barghoorn, 1964; Oldale, 1985). During the transgression, waves reworked the surface of older sediments, and localized deposits of marine clayey silts and sandy muds accumulated above the transgressive unconformity that now forms the harbor bottom (Rendigs and Oldale, 1990; Knebel et al, 1991).

Harbor Morphology and Processes
Boston Harbor is the flooded eastern part of the Boston Basin. The major topographic features in the harbor are the drumlins, which have been modified by wave energy as rising sea level brings waves against their margins.

There are many bedrock surface exposures, particularly outside of the harbor entrance. In other places the bedrock surface is buried by up to 90 m of glacial and glaciomarine sediments.

Harbor Bottom
The glaciomarine sediment, or the Boston Blue Clay, drapes most of the underlying features to form much of the harbor bottom. Only the tops of the drumlins and a few bedrock highs emerge above the cohesive clay. The Blue Clay is readily observable at many locations in the harbor, including Thompson Island salt marshes and Slate Island tidal flats. This clay creates the relatively flat surface of the harbor bottom, overlain by a relatively thin layer of reworked marine sediments (Figure 4; Knebel et al 1991). The deepest portions of the harbor coincide with the modern tidal channels, which are formed from preserved paleo-channels formed during periods of lower sea level (Newman et al, 1990).

Drumlins and Bluff Erosion
Boston Harbor is the only drowned drumlin field in the United States. Drumlins are asymmetrical elliptical hills consisting of till. The thick ice sheet that flowed across this region produced enormous hydrostatic pressure that infused water into the substrate plasticizing the till. The resulting drumlins that formed beneath the ice sheet exhibit a long axis parallel to the direction of ice flow, with a steeper side facing the flow direction and the longer, gradual slope in the down flow direction. The drumlins throughout the region are oriented in a northwest/southeast axis with a steeper slope facing northwest (Figure 5). The harbor drumlins are part of a larger drumlin field that extends throughout eastern Massachusetts and is composed of over 200 drumlins (LaForge, 1932). The drumlin field also extends at least 16 km seaward into Massachusetts Bay (Newman and Mickelson, 1984). The drumlins offshore were almost entirely reworked by wave action as the shoreline passed through during the Holocene transgression. Remnants of the eroded drumlins are manifested as low elliptical hillocks composed of a boulder lag deposit (Rosen, 1988). The harbor island shorelines have evolved as the drumlins have been submerged by rising sea level.

While bedrock comprises many of the islands outside of the harbor, the islands within the harbor have formed predominantly from the submergence and erosion of these drumlins, which provided sediment for connecting individual drumlins with spits and tombolos.

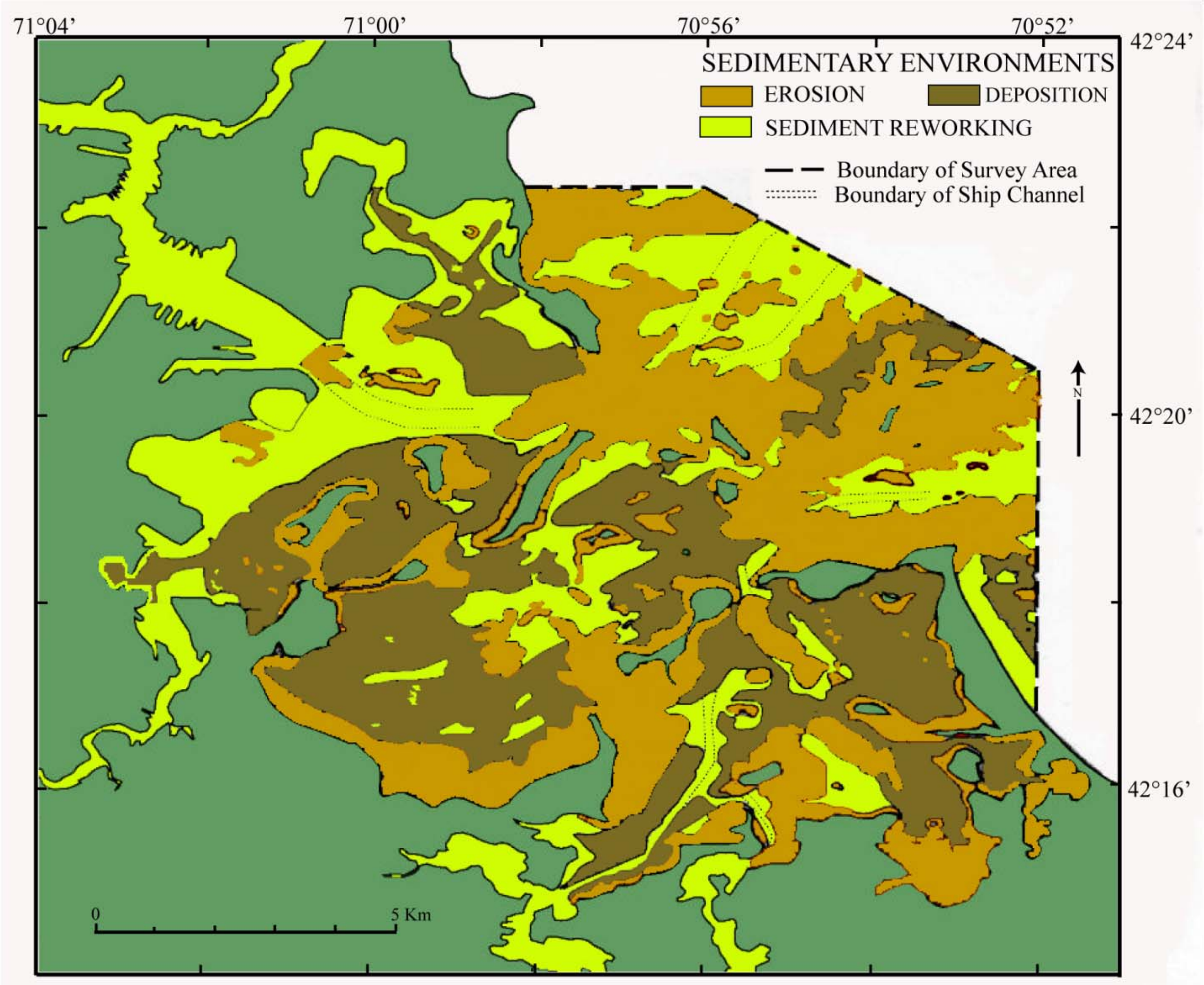

Figure 4. Sedimentary sea floor environments within Boston Harbor, where regions are defined by: erosion, deposition, or active reworking (Knebel 1991).

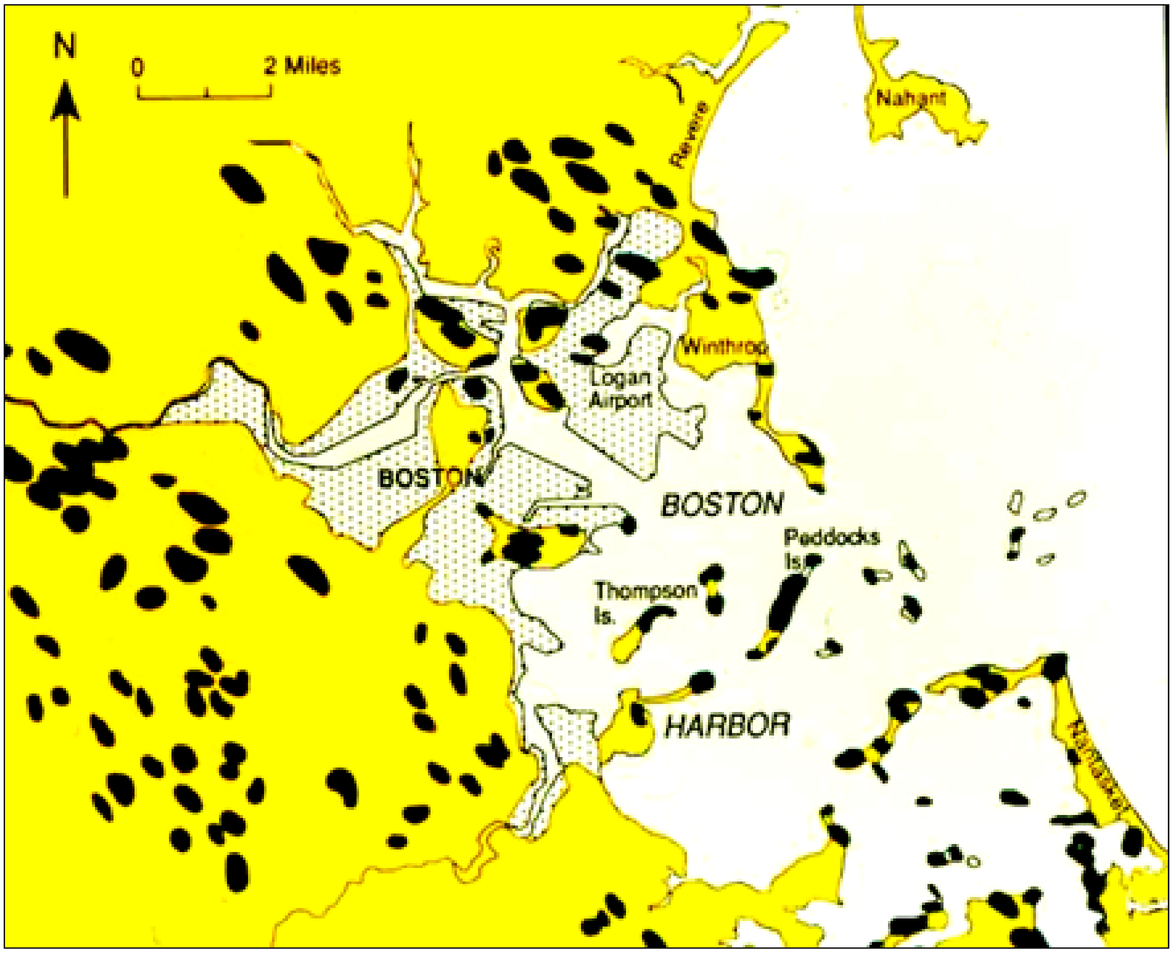

Figure 5. The location and orientation of drumlins and submarine valleys within Boston Harbor.

Drumlins within Boston Harbor have multiple exposures that are eroding and forming scarps or bluffs. Bluffs form at any orientation relative to the long axis of the drumlin, and often simultaneously erode from both ends. Himmelstoss et al (2006) proposed that the retreat of drumlin shorelines is the result of two major processes: 1) Wave attack oversteepens the bluffsand causes episodic slumping, forming planar bluff slopes, and 2) Sub aerial processes including runoff and seepage, which forms irregular slopes characterized by rills and gullies. Himmelstoss et al (2006), suggested that wave erosion and subsequent slumping are the dominant erosional processes in lower bluffs (<10m), as each slump event delivers a small amount of sediment to the base, which protects the slope from wave attack for a short period before oversteepening and slumping reoccur.

On higher bluffs (>10m), a slump event delivers a large volume of the sediment to the base, which shelters the slope from wave attack for a relatively long period of time. In this interval, runoff can form rills that evolve into deeply entrenched gullies. Once gullies form, the runoff is highly channelized on the slope, resulting in greater erosion. The volume of sediment delivered to the base of the slope by major gullies has protected the slopes from wave erosion and slumping for several decades on the higher slopes. These processes create a series of phases in the evolution of an eroding drumlin bluff. The initial formation of an erosional bluff on a drumlin will be a low slope, so oversteepening and slumping will dominate slope processes. As the erosion moves toward the crest of the drumlin, bluff height will increase and rills and gullies will dominate, and as the erosion proceeds past the crest, heights decrease and slumping again dominates the slope processes.

Retreat Terraces

These slope erosion processes move sediment to the base of the slope, where waves rework the sediment and redistribute it. Tills are composed of many different grain sizes from clay to boulders. The mud (clay and silt) is suspended by wave action and transported offshore where it is eventually deposited in the shallow harbor bottom or trapped in salt marshes to aid in forming peat.

The sand and smaller-sized gravel are typically transported alongshore to form beaches. In this low wave energy setting, the boulders are left as lag deposits known as boulder retreat terraces. These terraces overlie the tills below the level of wave attack and in some cases are overlain by the sand/gravel beach deposits. The boulder retreat terraces form a pavement that protects the underlying drumlin deposits from further wave attack. These lag deposits extend offshore to the original outline of the drumlin and define the final expression of the landform after erosion, as can be seen in submerged drumlins offshore.

Tombolos and Spits

Most of the drumlin shorelines have been modified by the evolution of connected spits, or tombolos, linking nearby drumlins. Up to five drumlins (i.e. Peddocks Island, Figure 6 and Figure 7) have been connected to form a single island. On most of the harbor islands, the connected spits do not necessarily have an orientation reflecting the wave regime. Within the harbor, however, each drumlin-tombolo island system is located within a single glacial till retreat platform.

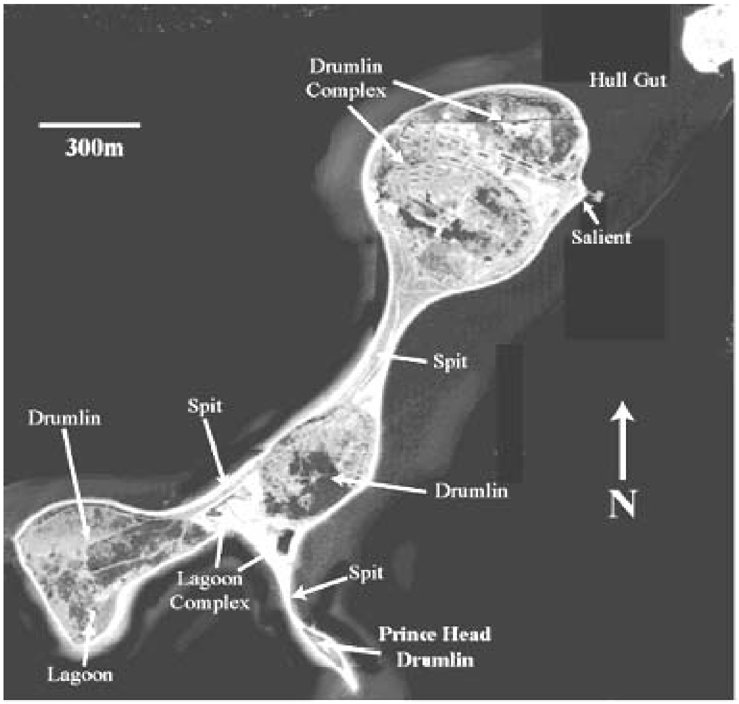

Figure 6. Aerial photo of Peddocks Island with major sedimentary features. The drumlins supply sediment, which is reworked into depositional sedimentary features: the spits and salients. Lagoons and marshes are located in low-lying regions bordered by spits.

Figure 7. Peddocks Island looking south from North Head across the tombolo with Middle Head in the background. Photo from the 1940's era shows the tombolo without the dense vegetation that dominates its western shore today.

The outline of the till platforms are delineated by the bottom sediment characteristics (Figure 4). Therefore, it appears that the position of these spits is influenced by pre-existing topography. As sea-level rose, sediment accumulated and spits formed on the drowned retreat platform of the glacial topographic highs. The relict post-glacial drainage system, which forms the bathymetric lows in the harbor, is largely unaltered by Holocene spit deposits (Figure 5). The inner harbor (the vicinity of the City of Boston) has been extensively land-filled over the past 1½ centuries (Rosen et al, 1993).

Seawalls and Other Coastal Structures

Engineering structures exist throughout the harbor, but none of the islands are completely surrounded by coastal structures. The major types of structures include the following:

1. *Seawalls*- vertical structures, which in Boston Harbor usually consist of cut granite blocks laid in courses that may or may not be further stabilized with iron pins. Many older seawalls were constructed on wooden platforms supported by pilings (Rosen and Vine, 1995). While retarding erosion of the land behind the wall, they promote vertical erosion of the beach.

2. *Revetments*- consisting of large boulders, commonly granite, 2 to 4 tons in weight, are placed roughly against an eroding slope to prevent erosion. In some instances the stones are placed in an interlocking pattern, which makes them more resistant to break-up during storms. Early revetments consisted of stone laid against the shoreline, which could gradually wash out causing back-cutting of the structure, while later revetments were laid on layers of gravel or fabric, which prove to be more stable.

3. *Groins*- structures constructed of rock, like seawalls, or consisting of vertical steel sheets or steel or wooden pilings. They are constructed perpendicular to the shoreline and extend into the surf zone. They trap the longshore transport of sediment, thereby building a beach. They may also prevent transport of sediment to the downdrift shoreline by trapping it, thereby promoting erosion.

4. *Breakwaters*- these structures extend offshore are built to protect a section of shoreline from exposure to wave energy, such as a beach or small harbor.

Many of the coastal structures within Boston Harbor date to the 1800's, and others were built when the islands were being fortified during WW1 and WW2. Since that time there have been numerous engineering projects that have rebuilt or extended the length of the existing structures along the shoreline.

Salients and Ridges

Holocene modification of the drumlins within the harbor typically includes the formation of salients (accumulations of sand extending seaward from an otherwise straight or uniform beach; e.g. Figure 6) formed at drift convergences or in areas of diminished wave energy and longshore sediment transport, typically in the lee of islands. The salients may form traveling forelands (Escoffier, 1954) where unequal wave energies from opposing longshore directions result in a landform which is migrating in a direction controlled either by dominant wave approach or greater longshore sediment supply. There is no regional direction of salient migration, since both sediment supply and wave climate are very localized within the harbor. Rates of migration of salients in Boston Harbor range from stable to 0.6 m/yr (Rosen et al, 2003).

Some of the salients in the harbor have preserved accretionary ridges composed of either sand (foredunes), gravel, or shell (storm ridges). In areas where these ridges are preserved, their form is similar: successive accretionary ridges parallel to one flank of the salient and truncated along the opposite flank (Fisher and Jones, 1982; Rosen and Leach, 1987).

Both salients, which have been historically stable, and traveling forelands have the same surface ridge pattern. Since the pattern indicates erosion on one flank and accretion on the opposite flank, stable salients most probably formed from a traveling foreland moving into a shoreline position where longshore processes are roughly balanced.

While most salients have rounded seaward ends, at least three of the features in Boston Harbor have a terminal bar projecting from the seaward end and extending several hundred meters into deeper water. In all of these cases the salients are stable. Their cuspate form is similar morphologically to cuspate spits reported in other areas (i.e., Rosen, 1975), where the terminal bar results from longshore drift convergence. The terminal bar on two of these features (Thompson Island South and Bumpkin Island) extends to other sub aerial headlands. As such, these features are a model for an early phase of formation of a tombolo. In both cases, the bars extend across areas of significant tidal flow, which may be the reason that these landforms remain as salients and have not evolved into tombolos.

Harbor Mouth Enclosure: Winthrop and Nantasket

Boston Harbor opens to the northeast into Massachusetts Bay. Flanking the harbor entrance on both sides are two drumlin connected-spit/barrier systems that extend from the glacial mainland into the harbor. These systems differ from most of the islands within the harbor largely due to a higher wave energy but less complex wave climate.Deer Island, Yirrell Beach, and Winthrop Head form the northern harbor enclosure.

This region contained an additional entrance to the harbor between Point Shirley and Deer Island called Shirley Gut. This inlet shoaled during the hurricane of 1938 and was subsequently completely closed by the U.S. Army Corps of Engineers (FitzGerald, 1981). The most prominent coastal feature along this shoreline is the Five Sisters Breakwater fronting Winthrop Beach, an offshore breakwater built in the 1930's. In recent decades, coarse gravel has accumulated as shore-connected bars behind the breakwaters and adjacent areas, probably resulting from landward transport of nearshore lag deposits (FitzGerald and Rosen, 1988). South of the harbor entrance is the Hull/Nantasket Beach complex that exhibits two very different barrier systems. The northernmost section, known as Stony Beach, forms a short, transgressive barrier between two eroding drumlins. Despite the proximity of the barrier to these eroding drumlin sediment sources, Stony Beach is narrow, sediment-starved, and backed by a continuous seawall that was built to prevent further shoreline recession. In contrast, Nantasket Beach is a long, wide, regressive sandy barrier beach anchored by at least five drumlins and a bedrock outcrop, and stable for at least the last 150 years. The evolution of this barrier was determined using relict drumlin scarp characteristics and preserved beach ridges in the pioneering study by Johnson and Reed (1910; Figure 8; see also Colgan and Rosen, 2001). The barrier form evolved around a series of drumlins that served as anchor points. As the drumlins eroded, sand was contributed to the barrier system, and when the drumlins were completely lost, the barrier moved rapidly onshore to another drumlin that could act as a pinning point. The Nantasket Barrier also received large quantities of sand from offshore sandy glacial deposits that have been added to the barrier

Climate

The coast of New England is susceptible to two types of cyclonic storms: infrequent hurricanes and more frequent extratropical storms. The most common extratropical storm is the "Nor'easter," which tracks east of Cape Cod and Nova Scotia, generating strong northeast winds and waves. This storm has maximum affect on easterly-facing shorelines such the Massachusetts Bay area. As Boston Harbor opens to the northeast, Nor'easters have the greatest impact at the mouth of and just inside Boston Harbor.

Nor'easters result in the highest coastal flood elevations in Boston Harbor. The 6-7 February Blizzard of 1978 coincided with spring high tides to produce the record tidal elevation of 1.72 m above the mean tide elevation inside Boston Harbor, which is the 100-year coastal flood in the region.

Hurricanes are rare along the New England coast. Commonly, by the time hurricanes reach New England much of their energy has dissipated. Most hurricanes that do make landfall in New England do so along the south coast (south Cape Cod/Rhode Island/Long Island), so winds are offshore in the Boston region.

Oceanographic Setting

There are more than 30 islands within Boston Harbor with an intricate network of narrow and shallow channels between them (Figure 9). The major inner harbor channels coincide with a paleo-drainage system that formed at lower sea levels during the Pleistocene (Newman and Mickelson, 1984; Figure 5).

Two major navigation channels, Presidents and Nantasket Roads, are maintained running from the mouth of the harbor (depth 20 m) to the ports of Boston and to Quincy Bay. Channels between other islands vary between ~4 – 10 m in depth; however, much of the inner harbor, toward Hingham and Quincy Bays, is shallow (3 m or less).

The mean tidal range in the Harbor is 2.9 m increasing to 3.4 m during spring tide conditions. The strength of tidal currents varies according to proximity to the opening to Massachusetts Bay and in constricted channels. For example, in the narrow waterways such as Hull Gut and the Narrows to the west of Lovell's Island tidal currents in excess of 1.0 m sec are common and well known to local fishermen and recreational boaters. The detailed measurements and analysis of the tides and tidal currents from this study are discussed later in this report.

Wave heights vary according to the seasonality of extra-tropical storms that occur more frequently during the late fall to early spring and to the changing prevailing winds that blow from the north and northwest during the fall and winter and from the southerly quadrant during the spring and summer. The correlation between the seasonal wind regime and wave energy is well represented by wave data in outer Massachusetts Bay. Twenty-nine kilometers east-northeast from the Harbor entrance, average wave heights are 2.0 m and 0.8 m during winter and summer, respectively (NOAA buoy 44013). Extreme winds accompany Nor'easter storms during late fall and winter. Inside the Harbor wave heights are much lower than those observed offshore as a result of shorter fetch (i.e. the distance over which the wind may blow while waves develop). These more sheltered areas receive a combination of local wind-generated waves and open ocean waves that propagate into Boston Harbor through Massachusetts Bay from the Gulf of Maine.

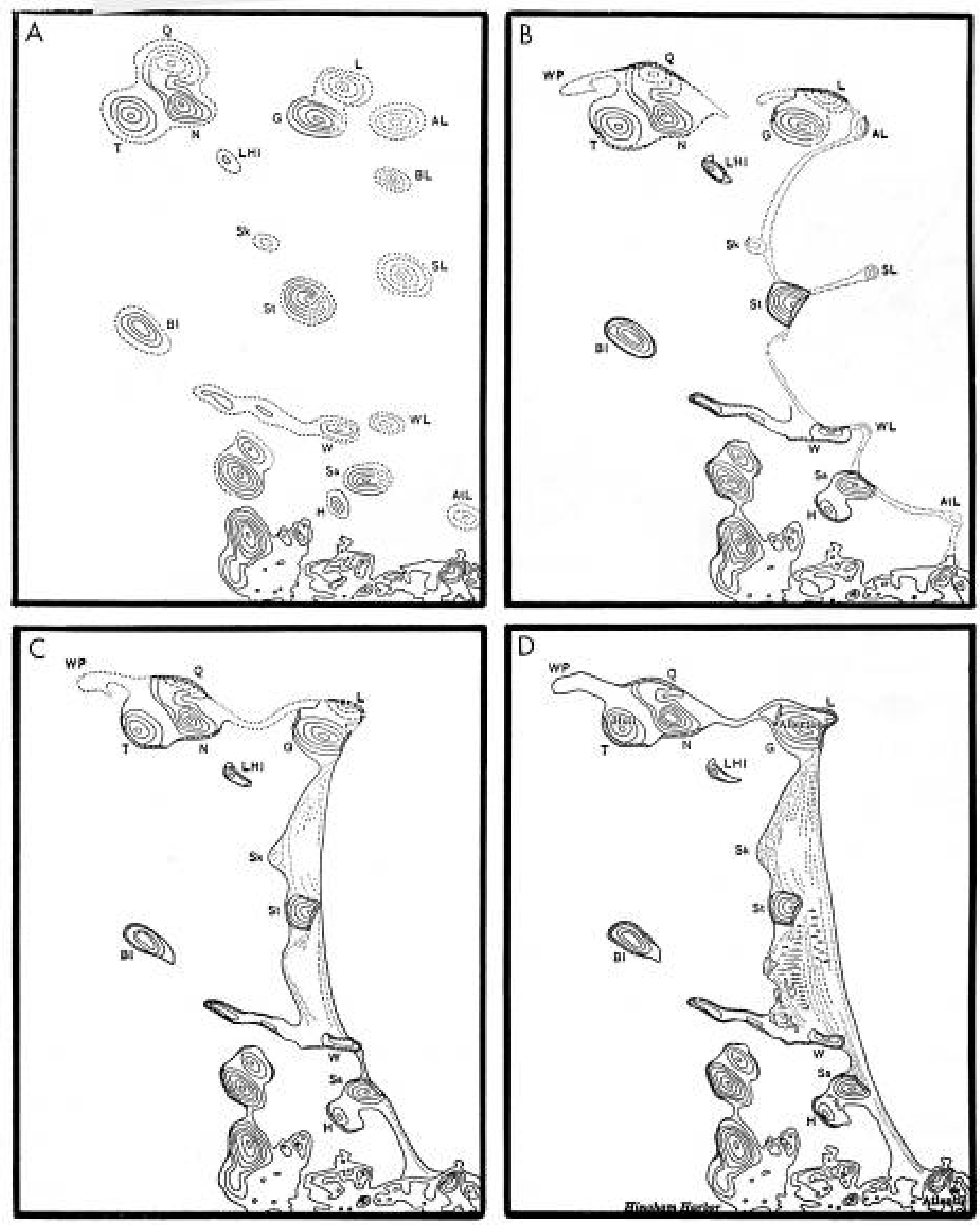

Figure 8. A conceptual model illustrating the formation of Nantasket Beach. Sediment from the drumlins is reworked by waves and transported by longshore currents, forming spits, which eventually link the drumlins. In the final stage, the beach progrades seaward (Johnson and Reed, 1910).

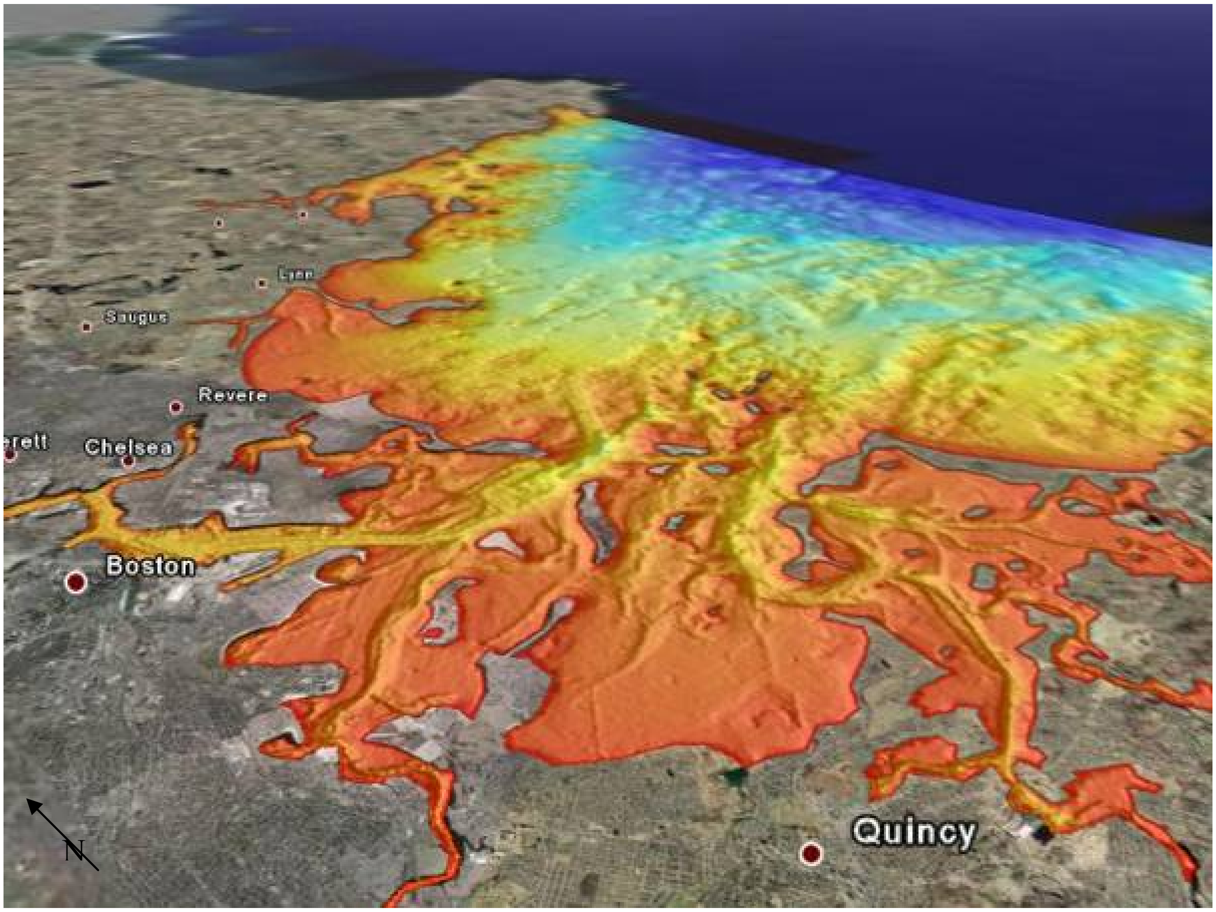

Figure 9. Bathymetry of Boston Harbor represented in color (orange = 2m, dark blue = 70m).

Vessel Wakes

The impact of vessel wakes in coastal areas is a subject of increasing public concern and, consequently, managerial interest. Many companies worldwide have adopted large high-speed ferries in order to maximize the efficiency of their passenger services. High-speed craft (HSC) are defined as those that have running speeds of approximately 50 knots. Passenger ferries operating at these speeds are between 40-100 m in length (Osborne and Boak, 1999; Parnell and Kofoed-Hansen, 2001; Soomere and Rannat, 2003). The higher speeds lead to the production of longer wakes and, because waves steepen and rise up as they shoal, a notable breaker at the shoreline. However, all boats produce a wake, and particularly within confined waters and other regions of low natural energy, heavy boat traffic can introduce a significant increase in energy from background conditions, which can impact the shoreline.

In many cases the replacement of ‘ordinary’ ferry services with HSC has led to a change or increase in energy regime causing the shoreline to reconfigure to reflect this new regime. The notable changes that this produces often lead to public concern (Parnell and Kofoed-Hansen, 2001). This has instigated a number of studies of the impact of vessel wakes at locations worldwide including San Francisco, California, Washington Sound, Denmark, Estonia, England

and New Zealand (Kofoed-Hansen and Mikkelsen, 1997; Osborne and Boak, 1999; Hammer, 1999; Stumbo et al, 1999; Parnell and Kofoed-Hansen, 2001; Soomere and Rannat, 2003;).

Wake effects are significant in areas of restricted depth and width, and where the distance between the vessel and the bank is small (of the order of a few hundred meters). Further, in very narrow channels (no more than a few multiples of the vessel length), such as those entering ports, large vessels often cause dramatic draw down (i.e. temporary lowering of the water surface followed by an oscillatory rebound). Impacts of boat wakes recorded in the literature include: bank and shoreline erosion, vegetation damage, adverse effects on biota, motions of moored vessels, increased stress on fixed and floating structures, changes in beach morphology, and landslides (Parnell and Kofoed-Hansen, 2001).

The study of vessel wakes began with the work of Froude in 1877 and Lord Kelvin in 1887. While there have been advances in our understanding of the physics and complexity of this type of wave, we still rely on this classical theory to describe the overall kinematics of wakes. Direct numerical simulations of vessel wakes exist and can produce a dynamic description of the waves. However, these are computationally demanding and limited in their calculations to a region within approximately five vessel lengths from the point of initiation (which for a ferry in Boston Harbor would be about 150 m). Thus for assessment and managerial decisions concerning boat wakes, we rely of a combination of field measurements and semi-empirical relationships.

Generated at the bow and stern of vessels, due to pressure gradients along the hull, wakes propagate away from the line of travel of the vessel, or the “sailing line”. Each vessel therefore produces two or more waves as it moves through the water. Multi-hulled vessels, such as catamarans, therefore produce four wakes - two wakes per hull. Consequently, they may potentially do more damage than an ordinary mono-hull vessel; however, this is dependent on the wave height and period of the wakes produced. Being dispersive in nature, vessel wakes become smaller with distance from vessel; approximately 50% of the energy is lost within 5 vessel lengths. In rivers and confined coastal waters this may still lead to a significant energy reaching the shoreline compared to natural conditions.

Wake characteristics are influenced by environmental parameters (water depth, seabed characteristics tidal flows, natural waves) and by factors related to the vessel producing them (water line length, displacement, trim, loading, velocity, method of propulsion course, rate or change of course etc). The behavior of the wakes once generated can also be complex, related to water depth. In shallow water they may shoal, refract, and diffract, based on small changes in topography.

Wakes are described based on two non-dimensional terms, the Length Froude (F_l) and the depth Froude (F_h) numbers.

$F_l = V / \sqrt{g L_w}$

(where g is the acceleration due to gravity ($9.81 m/s^2$) and L_w is the vessel length at the waterline).

Most normal vessels only have sufficient power to operate at $F_l = 0.4$; HSC operate in the range $F_l = 0.7$ or 8.

$F_h = V / \sqrt{g h}$

(where h is water depth).

This term is used in shallow water (i.e. water depth small compared to the wavelength), where the vessel wake is influenced by the seabed and is thus important in confined coastal waters such as harbors. When F_h is 'sub-critical', normally in the range 0.6-0.7, the wake generated by the vessel propagates away at an angle of about 19.5 degrees from the line of travel. The wake hits a critical value when $F_h = 1$. At this point energy is being continually added to the wakes and they propagate at 90 degrees to the sailing line. If $F_l \sim 0.5$ and $F_h \sim 1$, a 'hump speed' is reached, where maximum wake heights are produced (Stumbo et al, 1999). The leading wakes produced at critical and supercritical conditions have the most impact on the coastline. Greatest wake heights occur when $F_h \sim 1$.

As F_h increases from 1 to supercritical values the wake pattern changes again. The waves move more slowly than the vessel producing them. As a wave group is produced, long fast components waves move out from the vessel at a high angle to the sailing line, while short slow waves move parallel to the vessel travel line. Vessels traveling at supercritical (F_h) speeds in shallow water produce a smaller wake, than when traveling at the same speed in deeper water (subcritical values of F_h).

Previous field studies of boat wakes have assessed their impact based either on a height index or on an assessment of wave energy and period (through spectral analyses of time-series of surface elevation). In general there is a lot of unexplained variability in water surface records of boat wakes, due to among other factors, distance of measurement from travel line, local topography, and vessel speed and loading. Consequently, it is not possible to track individual vessels, rather to make a statistical assessment of the difference in energy reaching a certain point during the passage of a vessel wake and without wake.

In deep water (wavelength is greater than half the water depth), the wake period T can be related directly to the vessel speed:

$T = 0.27V$

(where V is velocity in knots).

Faster vessels produce longer period wakes; when a vessel operates at close to 50 knots, these have periods of around 9 s, which is equivalent to ocean swells. Slower smaller vessels produce shorter periods; for example a vessel traveling at 20 knots will produce a period of 5 s. This is much nearer to the period of locally generated wind waves in confined water bodies, which have periods up to 6 s but can be as short as 2 or 3 s.

As wakes shoal in shallow water, they steepen, shortening in wavelength and increasing in height. Thus long period waves that may be very small in deep water can produce very tall breakers. There have been reports in Europe, sadly some fatal, of these wakes from fast ferries overturning small fishing craft moored near shore (Marine Accident Investigation Branch, 2000; Kofoed-Hansen and Mikkelsen, 1997). Long waves can also produce shallow water depths in their troughs and lead to grounding of craft near shore.

Wakes produce an asymmetrical plunging breaker when they reach the shoreline; this produces a strong upwash but little backwash. As a consequence, previous studies have reported beach accretion and steepening due to vessel wakes, as sediment moved from offshore (e.g. Parnell, 1999; Stumbo et al, 1999). In some cases large pebbles and gravel, which normally are not moved by natural wave conditions, have been moved to the top of beaches and shorelines, blocking small streams and creating local ponding and flooding. A natural public reaction to the observation of increased wave heights and large breakers can be for the construction of shoreline defenses. However, these are often poorly designed and reflect wake energy resulting in the scouring of the region in front of defense structure, removing sediment and degrading the beach, a result that would not occur due to the wake alone (Parnell and Kofoed-Hansen, 2001). In other regions, breaking and propagating vessel wakes have been recorded to resuspend fine sediments for as long as several hours, thus impacting water quality and potentially biota.

Within Boston Harbor, there are concerns about the impact of ferry and boat wakes to the eroding drumlin bluffs and, more recently, to the beaches and marina of Spectacle Island. During spring high tides and other times of elevated water levels, waves created by boat wakes may break at the top of the beach, potentially steepening the bluffs. In other instances, boat wakes can augment wave attack along shorelines, which may accelerate shoreline erosion or accretion.

In order to consider the impact of vessel wakes in Boston Harbor we need to consider the natural wave conditions and the increase in energy due to the vessel wakes and assess their impact to the shoreline. In order to assess wave conditions without wakes we will employ a wave model based on local generation by winds. Field measurements of shorelines and water surface elevations will be made to assess the energy resulting from boat wakes and assess potential impacts.

Ferry Activity in Boston Harbor

There are several major ferry routes within Boston Harbor. The Massachusetts Bay Transport Authority runs regular ferries between Hull, Hingham, Quincy, and Inner Boston Harbor (Figure 10), the schedule varying seasonally. Other notable regular routes include the fast ferry service to Salem and Provincetown and the summer inter-island ferry run by the National Park Service. In addition to the ferry activity, the Harbor is subject to both commercial fishing and lobstering; and recreational boating.

The MBTA routes are the most frequent and constant of the ferry services operating within Boston Harbor year round. The ferries use three major paths as they navigate between the islands (Figure 10 shows the MBTA map of the routes). The ferries traveling from Boston to Hingham and Quincy are scheduled most frequently and also pass between many of the islands in the more sheltered regions in the west of the Harbor. These islands will receive less wave energy, as they have very limited fetch (distance over which a wave can be generated) and are some distance from the Harbor mouth (between Deer Island and Hull) through which ocean swells may propagate. There are also relatively narrow channels between certain islands, meaning that the vessels pass close to the shorelines in many places.

As part of this study, MBTA vessels were monitored and identified. There are a number of vessels in regular service, both catamaran and mono-hull, varying in length between 28-37 m. While official cruising speed of the vessels according to their manufacturing specifications is often up to 28 knots, maximum observed speed was 20 knots ($F_l \sim 0.5$) and ferries slowed down to 8 knots or less in the narrow channel between Webb State Memorial Park (Webb) and Grape Island. While larger and often faster than much of the commercial and recreational boat traffic, these vessels are smaller and slower than HSC. However, while it is unlikely that they produce long dangerous wakes, they may still significantly enhance the natural wave energy reaching the shoreline.

The Provincetown and Salem ferry services make use of larger vessels, catamarans of around 60 m in length, capable of cruising velocities up to 40 knots. However, these velocities are rarely reached within the Harbor, maximum speed being used once the vessels have reached open water. These vessels do fall within the category of HSC as used within the literature. The route they take through the Harbor is mainly confined to Presidents Roads, the deep major navigation channel from the Inner Harbor out to Deer Island. The vessels heading to Provincetown to the south often pass through Nantasket Roads, the slightly shallower, narrow channel between Lovell’s and Gallops Islands. This area would be the region most impacted by the vessels, however it should be noted that this is a region of high natural wave energy often exposed to maximum ocean swells; this will be discussed further within the report.

Approximately once or twice a day during the summer season (May-September) large whale watching cruises leave from the inner harbor of Boston. Vessels vary but tend to be catamarans of ~40 m in length. These also tend to take a route along Presidents and Nantasket Roads. Again velocities in excess of 20 knots are rarely reached within the Harbor.From June through September further ferries operate within Boston Harbor servicing the National Park itself. The vessels used vary annually; generally, a larger ferry similar to those used by the MBTA will take visitors from the docks in the Inner Harbor to one of the major ‘hubs’ either Spectacle Island or Georges. The route passes between Thompson and Spectacle Island, running south of Long Island between Long and Rainsford Islands to Georges Island, and/or using Presidents Roads to pass North of Long Island, passing either Gallops island on route to Georges Island. This ferry again does not exceed 20 knots.

The potential impact of each of these major routes and that of ambient boat traffic will be discussed specifically within the Synthesis section.

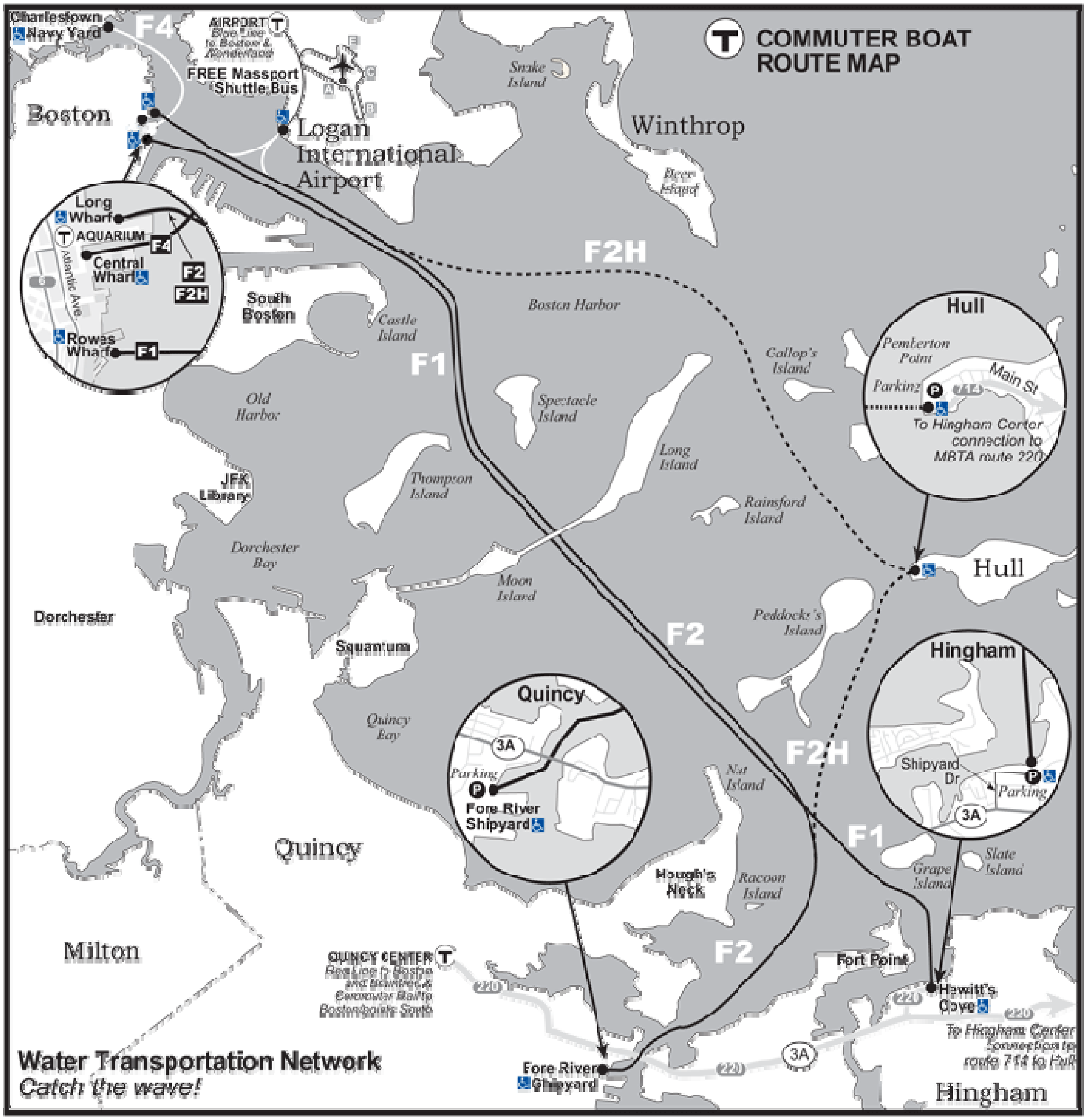

Figure 10. MBTA ferry routes in Boston Harbor, F1 and F2 being the most frequent.

Research Approach

Climatological Data

Surface hourly meteorological data were obtained from the National Climatic Data Center where available for the station at Boston Logan Airport and the historic station at Hull.

Hourly wind speed and direction data were grouped into sixteen directional bins and four wind speed bins using Matlab software. The percentage of the total time in each bin was calculated. These data were transformed into a windrose using a form set up in Excel. Windroses were determined for 10 year periods from 1974 to 2004 (inclusive).

Monthly precipitation and snow fall data from Logan Airport were combined to provide an annual total from the beginning of records in 1948 until 2007. Annual precipitation and peak monthly precipitation were compared to erosion rates. These data were further compared to natural climate signals, such as the El Nino Southern Oscillation (ENSO), for which data are readily available on line.

Bluff Retreat

Rates of retreat of the drumlin bluffs provide information concerning the amount of sediment released into the littoral system but also the loss of land.

In a previous study, Kaye (1982) monitored bluff retreat at one location in detail on the southwest end of Long Island. His study showed that most mass wasting occurred during spring thaw, when frozen saturated soil thawed. However, this study did not encompass major storms or wave impacts. The site of this study has been stabilized with fill and structures, so reoccupation of the site was not possible.

The geomorphic characteristics of retreating bluffs were described by Himmelstoss et al (2006). This study identified two suites of processes responsible for shore retreat, slope wash including runoff, direct precipitation, and groundwater outflow; and over-steepening of the slope by wave erosion at the base of the bluff, leading to slumping of the slope. The latter process delivered a volume of sediment to the base of the bluff, which protected the slope from further over-steepening and slumping for a period of time when slope wash processes could evolve. The dominance of these two processes was determined by bluff height. Bluffs greater than approximately 10 m in height were dominated by mass wasting processes, while lower height bluffs were dominated by slumping. Based on these observations, it was shown that higher bluffs deliver larger volumes of sediment to the base in an over-steepening/slumping cycle. This provided protection to the upper slope for longer periods of time, so slope wash processes (i.e. the mass-wasting processes caused by nonchanneled running water) could evolve. On lower slopes, the volume of sediment at the base was lower, so wave erosion over-steepened more rapidly, leading to more frequent slumping.

On higher slopes where slope wash dominated, gulleys evolved into large-scale, persistent channels on the slopes. Gulleys channel flow on the slope and efficiently erode material from the till surface. Once these larger gulleys form, they can deliver sufficiently large volumes of sediment to the base of the slope to avert slumping for long periods of time. Field observations have shown that gulleys have dominated high-bluff retreat over periods exceeding twenty five years (e.g. Long Island Great Brewster Island, Moon Island; Newman and Mickleson, 1984).

Data Collection

Profiles were established (and benchmarks installed) at 12 locations throughout Boston Harbor in 2004 (Figure 1 and 11). Station locations were selected in areas where active bluff retreat was observed so that the year-to-year dynamics of shore retreat could be recorded. The sites were chosen to represent a range of orientations, rates, and types of erosion (slumping or rilled). Certain sites were (approximately) reinstated following the studies of Himmelstoss (2003; Peddocks-1 on the west of Peddocks Island and Lovell's Island) and Kaye (1982; Long Island 2). Many of the bluff profile monitoring points were sited along the major MBTA ferry routes (Figure 10). The profiles were surveyed at least once annually; however several areas were surveyed multiple times in order to assess short-term variation over tidal cycles (both 12 hr and 28 day spring-neap cycle). Surveys were carried out with a Pentax total station survey lined perpendicular to the shoreline. The sites were marked using two fixed points placed approximately 1m and 2m respectively from the bluff edge, and change was measured relative to the position of the back stake as in certain cases the forestake was lost due to erosion. At Peddocks-1 the backstake was lost between 2005 and 2006, thus the forestake was used as the marker for estimates of relative position. An estimate of absolute height with respect to mean sea level (MSL) was made using the measured elevation of the water line taken during each survey and the observed tidal height at the NOAA tide gauge in the Inner Boston Harbor.

Analyses

The angles and heights recorded from the total station were manipulated in Microsoft Excel in order to provide a distance along the survey line (using the cosine rule) and elevation relative to the marker stake. Changes of the relative distance between the backstake and the bluff edge since 2004 have been calculated for each year. An average rate of erosion has been estimated using the 2008 positions.

Error on the total station between points is theoretically ± 0.001 m. However, on the heterogeneous rough surfaces of the bluffs and beaches in the Harbor, especially in windy weather, the use of the stadia rod cannot be as accurate. The error was estimated by taking three replicate readings at each point along a survey line location was found to be ± 0.02 m between points taken during the same survey. Again due to the heterogeneity of the survey surface and choice of rod placement, repeat surveys showed that error could be up to ±0.075 m horizontally between return surveys (with different total station placement and fractionally different choices in placement of the stadia at the two marker stakes). Error was reduced however by averaging over four years, thus errors in retreat rates in this report is ±0.02 m. A further error is introduced in the calculations of height due to the estimation of the total station height and the uneven, often bouldery substrate upon which it was placed. This has been estimated, based on repeat surveys as ±0.15 m. As such, retreat rates are stated based on horizontal changes.

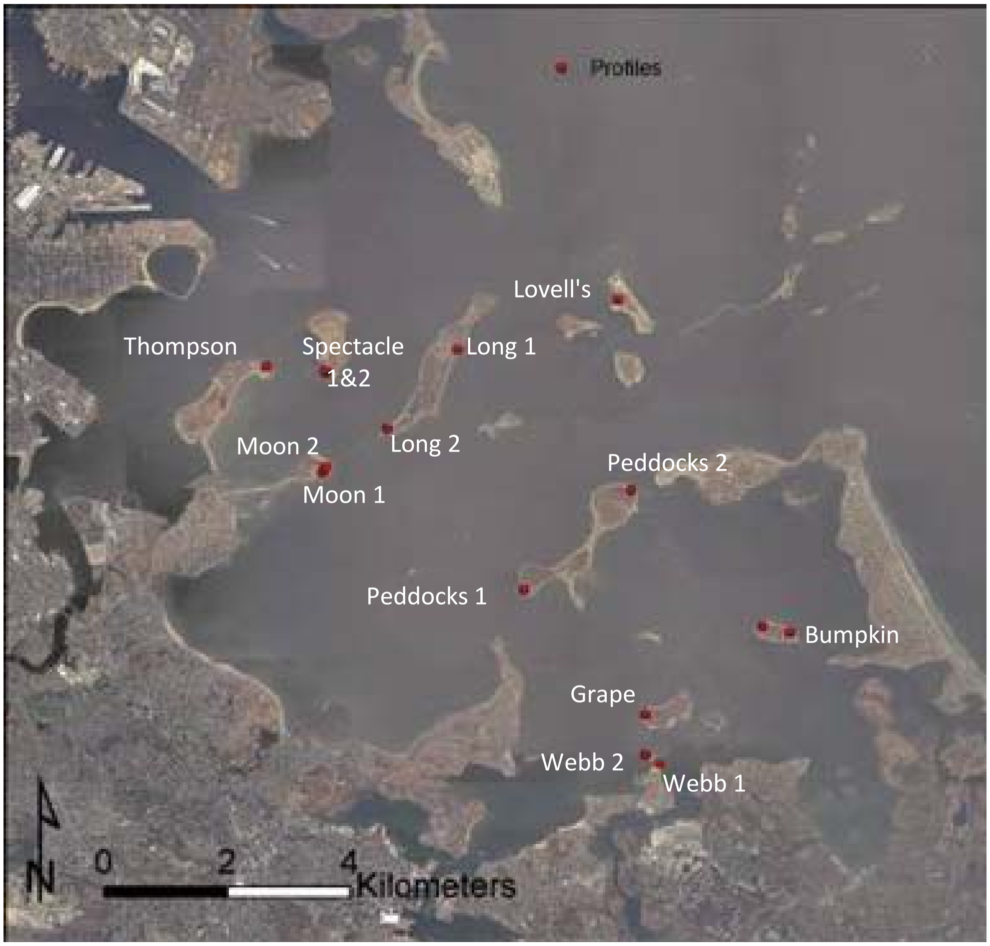

Figure 11. Positions of the bluff retreat monitoring stations. On Bumpkin island 2 profiles were initially set up in 2004, however the northwesterly station was abandoned after the first survey as on return in 2005 it was determined to have stabilized and had become partially vegetated.

Lovell's Island Sub-study

Data Collection

In order to try to better understand the transport pathways operating around an island, a series of sediment samples were collected from the region surrounding Lovell's Island. One of the most exposed of the drumlin islands (the outer islands being mainly bedrock), Lovell's is experiencing some of the highest rates of bluff retreat (Himmelstoss et al, 2005). It also exhibits notable accretionary features on its western shoreline, including a dune system, rare within the Harbor Islands. For this sub-study we concentrated on sand size particles only and considered only one island; it is therefore just a preliminary investigation into identification of sediment sources, sinks, and transport pathways within the harbor, and the viability of different methods of assessing these. Sediment samples were taken from exposed eroding bluff faces around the island and collected from inland sites including the dune system, the sandy beach and the salients on the western shoreline, and the mineralogy of certain grain sized compared. Ground Penetrating Radar (GPR) surveys were undertaken on the salients in order to investigate the stratigraphy of the accreting regions.

Analyses

Samples were analyzed in terms of the grain size using ½ phi interval sieving. Grain size, as well as assessments of the skewness and kurtosis of the cumulative grain size distribution, allows an assessment of sediment transport, indicating distance from the source and in some cases the direction moved. The mineralogy was assessed within the 3 and 1 phi samples. Several repeat counts were averaged for each sample in which 100 grains were identified as belonging to one of six categories (quartz, hornblende, feldspar, sphene, magnetite, and rock fragment) These data allow comparison among sites in order to determine the source of sediment.

Stability Analyses

The assessment of the stability of glacial bluffs based upon their vegetation and the fronting beach was described by Kelley and Dickson (2000). In this study the bluffs were mapped from the water, approximating the shoreline positions from the position of the boat and from aerial photographs. We have updated this method by assessing the bluffs from the shoreline using state of the art mapping equipment. In addition to mapping bluff stability and beach type, we were also able to record a number of other parameters in order to quantify and classify the nature of the Park shorelines.

Data Collection

Shoreline morphology and beach sediment type were mapped using a *Trimble Pathfinder Pro XRS* backpack system. The Trimble differential global positioning system (DGPS) consists of a backpack antennae unit and a hand-held computer. Data were logged using the Terrasync software through the construction of a data dictionary, which is used to classify the feature being mapped. The dictionary defined for the Boston Harbor mapping is shown in Figure 12. Features that have been recorded include bedrock outcrops, bluffs (according to height and stability), beach type, morphological features (such as salients and ridges), and the presence of shoreline protection and its condition. It was sometimes necessary to record both a primary and secondary beach type in order to capture the heterogeneity of the beach sediment. Detailed mapping of the islands was completed in 2006 although supplementary data were collected for comparison in 2007 (Table 1).

Analyses

The DGPS data were downloaded using the *Pathfinder* software and post-processed using the *ESRI ArcMap* software to produce a GIS, allowing spatial analysis of the observations. The post-processing included smoothing of the lines, offsetting of lines representing overlapping features, cleaning of lines to ensure all lines were assessed in the same direction (clockwise around each island), and the calculation of length and orientation of individual lines collected.

An assessment was also made of the maximum possible fetch in any direction for each line segment using the measuring tool in ArcMap. It should be noted that the fetch obtained does not take into account the probability of wave generation from that maximum fetch direction. These data, therefore, while illustrative of wave energy reaching the shoreline, will not provide as accurate an assessment as the wave model data, which is based upon the fetch and also the wind rose data and the offshore bathymetry. The data collected can be viewed as a map but also further analyzed using the GIS software (ESRI ArcMap and ArcCatalog). For this report data have been extracted to Excel in order to calculate relevant statistics concerning the distribution of sediment types; the erosion of bluffs; the amount of sediment being released at sites of bluff erosion; and correlations between erosion and orientation/bluff height/shoreline protection.

Hydrodynamic Measurements

Data Collection

Hydrodynamic measurements undertaken for this study concentrated on assessing wave and boat wakes, however some tidal current data have been also collected. Observations of wave height and length provide information about the amount of wave related energy arriving along a shoreline. To monitor the natural waves and the boat wakes, measurements were made using a combination of a capacitance wave staff and pressure transducer, the latter providing reliable data of a slightly lower vertical resolution (1 cm rather than 1 mm) that compliment observations from the staff. In alternative deployments several synchronized pressure gauges have been deployed simultaneously. The instrumentation has been used to collect data over various periods throughout 2004-2008. The deployments were made at a number of different sites concentrating on the area surrounding the ferry route from Rowes Wharf, in inner Boston harbor, to Hingham. Figure 13 shows the location of deployments. Data were collected at high frequency (10 Hz) in order to capture waves with periods as short as 1 s. To capture boat wake events it was important to record for as close to constantly as possible. The instruments require a short period to pass data from the cache memory into the permanent memory, thus measurements were taken for 55 minutes out of every hour. During the study we collected data during several Nor'easters and during fair weather, enabling a comparison between good and bad weather conditions.

A specially designed and constructed frame has allowed us to use the wave staff to investigate areas where there are no existing fixed vertical structures.

Concurrent evaluation of wave climate and boat activity allows us to determine certain frequencies at which wakes contribute to the incoming wave energy. Consequently, during deployments, vessels passing close to the unit were monitored and their size, approximate speed, and the behavior of their wake were recorded. These observations have allowed us to identify certain areas where bathymetry and ferry activity contribute to a higher potential for wake-related erosion (e.g. Webb State Memorial Park).

To further the investigation of sediment distribution, hydrodynamic data were collected to assess tidal circulation near to Lovell's Island. Two arrays, consisting of current meters (Nortek Aquadopp) and pressure gauges were deployed offshore for a 3-4 week period, collecting at 1 Hz for a 5 minute bursts every 30 minutes, on both the east and west of the island. These data will also provide calibration for hydrodynamic models of the region.

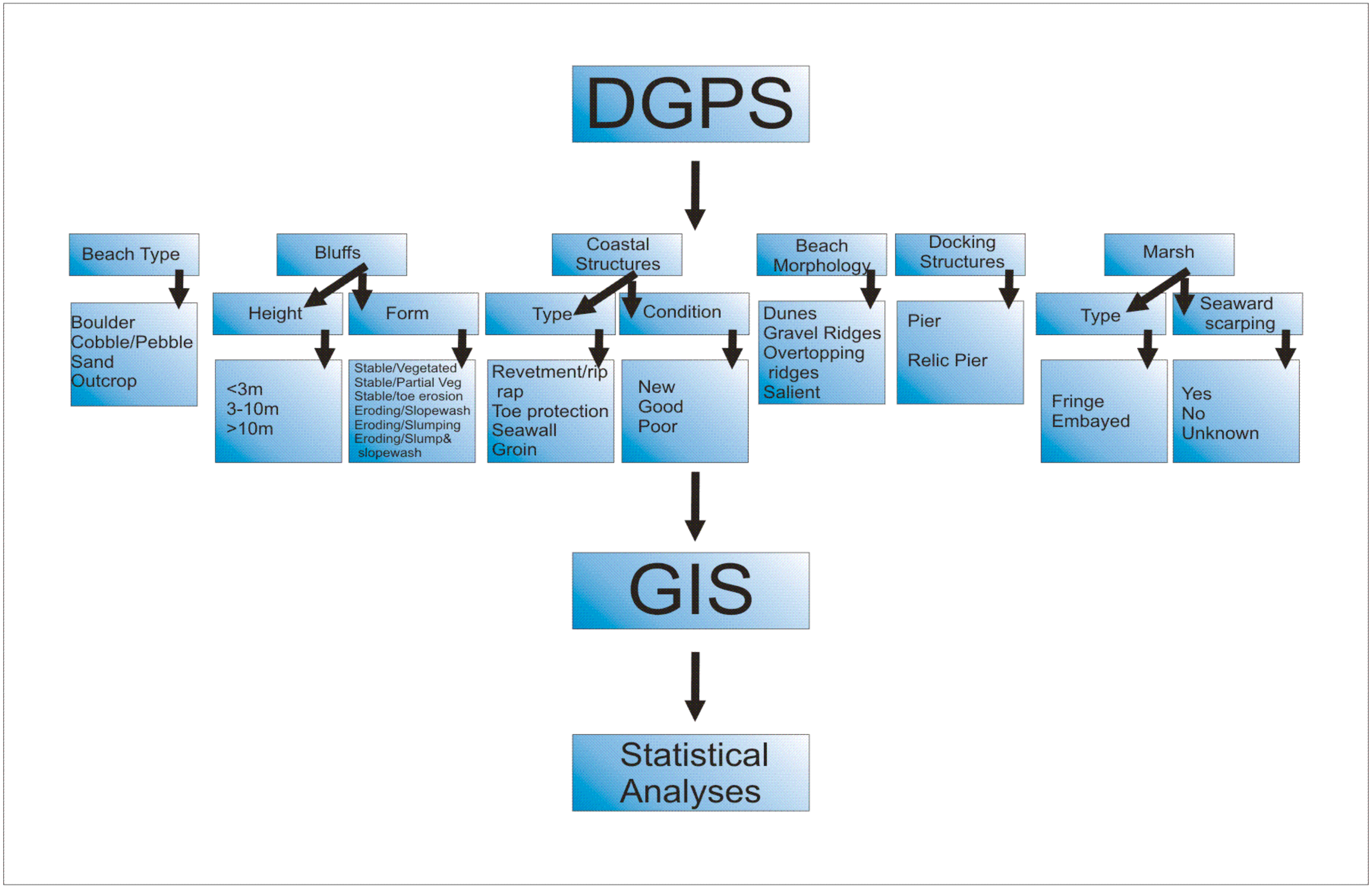

Figure 12. Trimble differential global positioning system data dictionary as set up for the Boston Harbor Islands.

Table 1. Schedule of GIS mapping on the Islands.

Island	Mapped
Bumpkin	6/28/2005
Button	9/9/2005
Calf	10/3/2005
Castle	8/11/2005
Deer	8/2006
Gallops	08/2007
Georges	7/14/2005
Grape	7/14/2005
Great Brewster	9/30/2005
Green	10/3/2005
Hangman	N/A
Langlee	9/9/2005
Little Brewster	10/3/2005
Little Calf	10/3/2005
Long	7/29/2005, 8/1/2007
Lovell's	8/20/2004
Middle Brewster	10/3/2005
Moon	8/11/2005
Nix Mate	10/3/2005
Nut	8/11/2005
Outer Brewster	10/3/2005
Peddocks	10/21/2004
Racoon	8/22/2005
Ragged	9/9/2005
Rainsford	8/22/2005
Sarah	9/9/2005
Shag Rock	N/A
Sheep	8/22/2005
Slate	8/22/2005
Snake	10/12/2006
Spectacle	8/4/2005
Spinnaker	8/24/2005
Thompson	6/17/2005
Webb Memorial State Park	8/11/2005
World's End	11/18/2005

Further deployments were made from Long Island, on the northern shore, close to the relic pier. The sensors were deployed from the beach, just beyond mean low low-water (MLLW) using specially designed frames to mount equipment in a stable fashion and close to the seabed. Exact heights above the bed are given in Table 2. The sensors were arranged in a linear transect, parallel to the shoreline with the ADV, OBS, and pressure transducer in the center, flanked on either side by an ADP (with a built in pressure transducer). The ADV, OBS, and pressure transducer collected burst data for 5 minutes every 30 minutes. The ADV and pressure transducers operated at a high-frequency (10Hz) providing surface elevation and velocity data capable of recording waves of short to long period (1 to 15 s).

A final deployment with current meters was made at Spectacle Island where a comparison was made between conditions inside and outside of the pier. Data were collected for 55 minutes out of every hour at 16 Hz using an ADV at each location. The instruments collected current velocities and pressure in order to determine the direction of wave propagation as well as tidal current averages. Two deployments were undertaken, one in February to characterize winter conditions and one in July to characterize summer conditions.

Analyses

Data from all of the instruments were assessed and corrected for drift, problems in resolution, excessive noise, spikes, and associated errors.

Mean resultant currents and their directions were calculated using the calibrated velocimeter data. For the current profilers at Long Island it was possible to examine the velocity over depth.

The data collected have been analyzed to determine the energy being transmitted to the shoreline by both waves and wakes. This is being achieved using spectral analysis of the data, the identification of the dominant frequencies operating throughout each deployment, and through integration of the spectra, an assessment of the energy transferred to the shore.

The mean water depth was calculated from calibrated pressure sensor data, allowing for the height of the sensor above the bed. Wave conditions are based upon shallow-water linear wave theory, using data from the pressure sensors.

Table 2. Details of instrument deployment.

Instrument	Burst sampling rate	Burst Period	Averaging period	Burst interval	Averaging interval	Height above bed	Blanking distance	Cell interval and number of cells
ADV	10 Hz	300s	300s	1800s	1800s	0.32 m	0.1 m	-
ADP	2 Hz	512s	180s	3600s	1800s	0.45 m & 0.435 m	0.2 m	0.15 m x 20 cells
OBS	2 Hz	300s	300s	1800s	1800s	0.47 m	-	-
PT	10 Hz	300s	300s	1800s	1800s	0.53 m	-	-

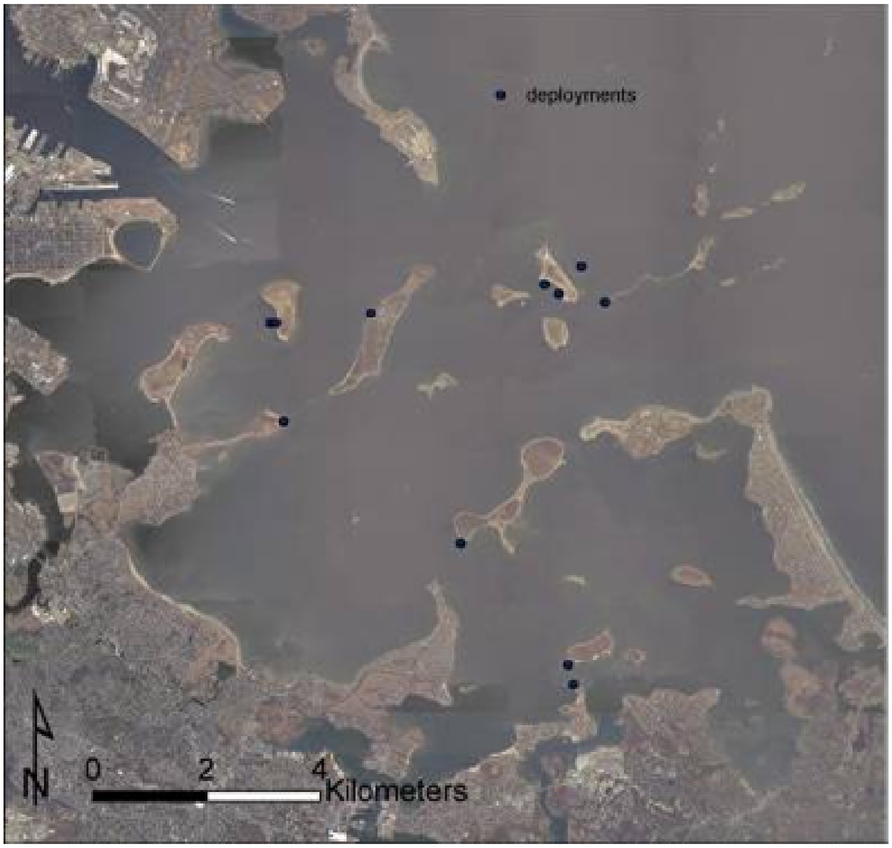

Figure 13. Aerial photograph of the Boston Harbor Islands, marked are the sites of instrumentation deployment (blue dot) and of the bluff profiles.

A correction for depth attenuation (*Kp*; Equation 1) was applied to the wave spectral density for frequencies lower than, and including, the wind wave frequency band (f <0.2; Bishop and Donelan, 1987; Tucker, 1991; Tucker and Hardcastle, 1996).

$$Kp = \frac{\cosh k(d+z)}{\cosh kd} \qquad \text{Equation 1}$$

where, in this case, z = depth of the sensor, below the surface of the water. The wave number (k) must be calculated from the solution of the dispersion relation (Equation 2). This was achieved utilizing the Newton Raphson method; this uses an iterative algorithm producing an answer to an accuracy $O(10^{-4})$ (Stapleton and Huntley, 1995).

$$\omega^2 = gk \tanh kd \qquad \text{Equation 2}$$

where ω is the radian frequency (i.e. $\omega = 2\pi/T$, and T is the wave period).

From calculated spectral moments, the following statistical parameters were calculated to provide information concerning the wave climate during each 5 minute burst.

Significant wave height:

$$H_s = 4\sqrt{m_0} \qquad \text{Equation 3}$$

where m_0 = zero moment of spectral density.

A zero-crossing period and a *mean period:*

$$T_{01} = m_0/m_1 \qquad \text{Equation 4}$$

where m_1 = the 1st moment of spectral density (Darras, 1987),

and *Orbital Velocity.*

$$U_w = \frac{\pi Hs}{T_p \sinh(kd)} \qquad \text{Equation 5}$$

These parameters are comparable to those calculated during the numerical modeling of waves (*see* Bluff Retreat section).

Calibration is required in order to correct the raw optical backscatter data from the OBS a laboratory. However, the relative intensity of backscatter is presented here as a proxy to the true sediment concentration. High levels of backscatter represent high levels of suspended sediment concentration.

Wave Modeling

Model Setup

A two-dimensional, third-generation wave model, SWAN (Simulating WAves Nearshore) has been used to evaluate the significant wave heights and periods of waves in the region of Long Island. The model accounts for generation by the wind, as specified by the user, and dissipation through white-capping, bottom-friction, and breaking, as well as wave-wave interactions. The model is based on wave energy balance equations and determines the propagation, refraction, shoaling and, on certain scales, diffraction of waves in complex bathymetries.

The model was run using a 30 m linear grid domain covering the full extent of Boston Harbor and offshore, allowing sufficient distance to the boundary. This resolution was used as it was possible to model the entire Harbor simultaneously while keeping within reasonable computation time and file-size limitations for the runs. Bathymetry was obtained from the United States Geological Survey (30 m horizontal resolution, Figure 14), and thus no sub-sampling or averaging was necessary to produce the grid, meaning that the bathymetry data used were of the highest accuracy possible with the available data. This resolution also allowed a large number of points along each shoreline (shorelines vary in length), providing a reasonable comparison to the field data.

Model Runs

The average and extreme climatic conditions have been used to determine the corresponding wave conditions in Boston Harbor. The model has been run in two modes: 1) Stationary allowing the sea to fully develop under a given condition (i.e. reach an equilibrium where waves are no longer growing); and 2) Non-stationary, where conditions are run for a certain length of time. After this period the run may stop or conditions may change, however the sea may not yet have come into equilibrium with the forcing conditions. For assessments of storm conditions and for validations, the model has been run in non-stationary modes. To allow average assessments the model has been run in stationary mode. The following studies have been undertaken:-

1. Non-stationary allowing hindcast simulations for validation using both wave buoy data and wind data obtained from the National Oceanographic and Atmospheric Administration and from NCDC.

2. Stationary runs for 16 wind directions and 4 wind speeds. A time average was determined for significant wave heights, direction, period and orbital velocity fields calculated in the model runs. Each contribution to the average was normalized according to the percentage that each wind speed-direction combination occurred over the period 1994-2005. This method allows an assessment of the cumulative impact of the locally generated wind field.

Validation and Comparison with Observation

The model has been validated previously using data collected from a pressure transducer located offshore from Lovell's Island (Hughes et al, 2007) and is further compared herein to the data recently collected offshore of Long Island. Conditions measured during the September field deployment showed wave heights very similar to the model conditions predicted at the field site.

Winds were from the west and less than 5 m/s during the study. The data presented here are for a stationary run (i.e. sea allowed to fully develop) based upon the 26th to the 28th of September when winds from the southwest (232°) at 4.6 m/s were sustained for three days. The modeled data are within the measured ranges and in the case of the wave height modeled wave height is within 1.6 cm or 14 % of the measured heights. It is possible that the period of the waves is being slightly underestimated (Table 3).

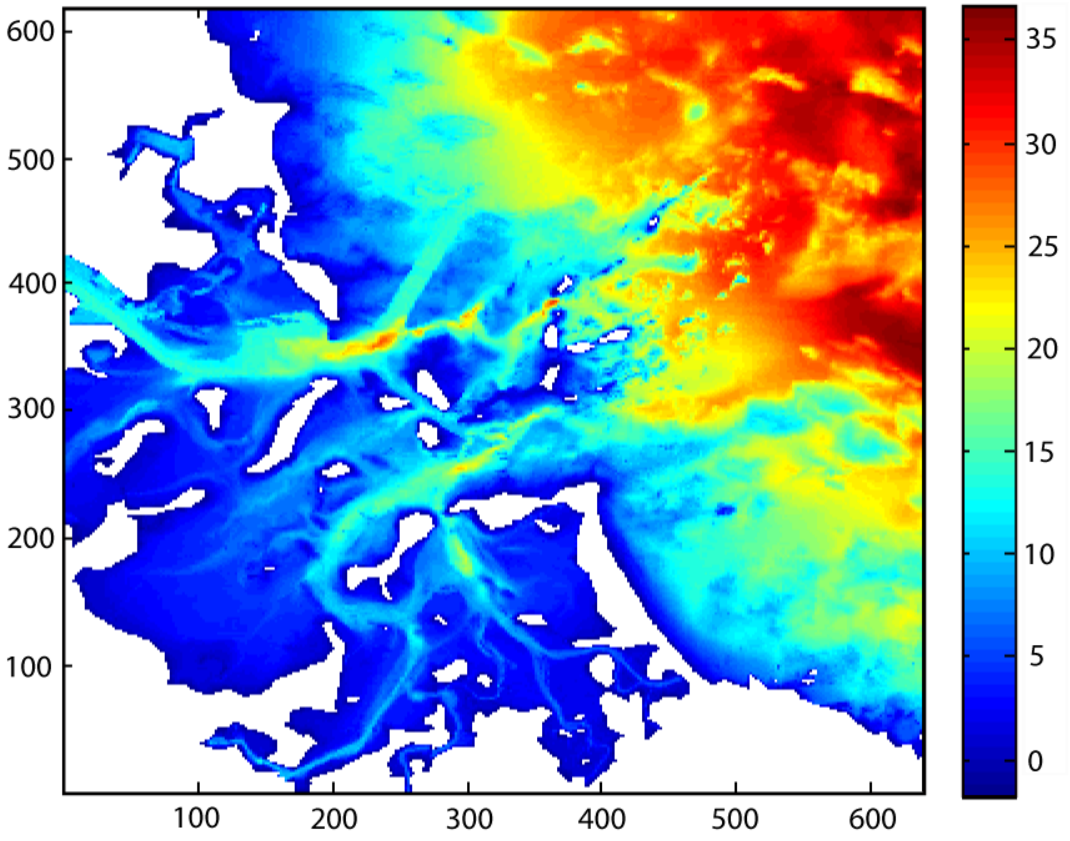

Figure 14. Bathymetry 30 m resolution Harbor wide wave model. The region was extended a distance offshore to avoid boundary influences.

Table 3. Model (average of 3 points surrounding instrument deployment site) and observation comparison.

	Wave Height (m)	**Range**	**Peak wave Period (s)**	**Range (s)**
26-28th Sept 07	0.112	0.05-0.2	2.3	1- 4
Modeled data	0.1283		1.6	

Data Summary

Climate

The total annual precipitation in Boston has a rough inverse relationship with the El Nino southern oscillation index (Figure 15). Thus, periods of high precipitation are cyclic in the Boston region on a multi-yearly level. On an annual basis, Boston averages 430 cm of precipitation a year (1948-2007). July is the driest month with an average of 29.1 cm of precipitation, and November is the wettest month with 41.7 cm. The seasonal variability of precipitation is relatively low. This impacts the bluff stability and erosion rates as prolonged periods of precipitation weaken the till and encourage slumping, and surface run off causes slopewash.

The prevailing winds in coastal Massachusetts are generally from the westerly directions (Figure 16). Typically, winds are from the southwest in the spring and summer, and the highest frequency of calm weather also occurs during this period, although the occasional strong storm can occur at the end of the summer. Prevailing winds in the fall and winter are from the northwest.

The dominant (strongest) winds are from the northeast and are associated with the passage of extratropical storms that track east of the Gulf of Maine. They have their greatest frequency during the fall and winter. During the winter, strong winds also blow from the northwest when polar air masses move across the continent. These northwest storms gain in intensity with distance offshore, probably due to turbulence as the wind blows over land areas.

Bluff Retreat

Permanent shore retreat monitoring stations were established in 2004 at 12 locations throughout the harbor islands (Figure 11). Station locations were selected in areas where active bluff retreat was observed so that the year-to-year dynamics of shore retreat could be recorded.

Overlays of the annual surveys are shown in Figures 17–30; the vertical elevations are given with reference to the landward benchmark on each profile (the positions of these benchmarks are provided in Table 4). GPS fixes of the forward stake in each profile is shown in Table 4, and cumulative retreat since 2004 and the final average value of retreat are shown in Table 5.

Long Island Profile 1 shows a four year progression of slump material at the base of the bluff being gradually steepened; it is likely that the toe is being eroded by wave action. The talus (toe of slumped material) extends from the bluff lower down the beach. This area is more likely to experience wave action. At a site close to an active ferry route, the sediment in the talus may potentially also be redistributed by wakes, if high tide coincides with periods of boat activity. However, Profile 1 on Long Island is not close to a ferry route. Furthermore, wakes are likely to transport sediment up a beach so it is unclear as to how redistribution of sediment by wakes might occur. During the period of observation, the upper slope has been protected, and the upper slope has been stable. However, the base of the slope is progressively steeper, leading to a potentially unstable situation relative to slumping in upcoming years. Long Island Profile 2, close to the bridge with Moon Island, however, shows no change at the upper slope, and little significant change at the base of the slope. From visual inspection, however, we would note that the base of the bluff is retreating from the stone toe stabilization placed in 2003-2004.

Bumpkin and Grape Island show very little retreat over the four year observation period, with both sites showing an increase in slope vegetation during the study.

This retreat is occurring through a combination of slumping and wash of unstabilized sediment placed behind the toe protection. No wave cutting was observed. Ultimately this removal of the toe slope will lead to steepening of the bluff and lowered stability.

Lovell's Island Profile shows continuous parallel slope retreat, with several meters of retreat at the base over four years and almost 3 m at the bluff top. This is the highest retreat observed in the study area. The profiles record periods when there was protection at the toe (i.e. 2008, 2004) and periods of overall steepened slopes (2007). The Lovell's profile is located on a northwest-facing shoreline, and the seaward position of this island and the sandy composition of this till may influence these data.

The Moon Island Profile 1 is located on the east-southeast facing shoreline of the island but is exposed to large fetches across Quincy Bay. The bluff has retreated by over 1 m over the monitoring period. The lower bluff retreated significantly between 2004 and 2005, and the protective debris at the base of the profile was diminished in the same period.

Subsequently the profile has been relatively steep, leading to instability. Moon Island Profile 2 has remained relatively unchanged over the four year interval. This profile is also on the flank of a gulley, but the toe of this bluff is partly bedrock and has remained sufficiently stable to prevent rapid change.

Peddocks Island Profile 1 is a lower bluff in the middle of a drumlin complex (on the western shoreline of the island). The top of the bluff has been stable over the study period. In this area, littoral and landward transport of gravel has built a major berm at the backbeach to protect the toe of the bluff in 2008. It appears that this input of sediment is related to sediment transport from a proximal offshore location or along shore, perhaps resulting from a major Nor'easter in 2007. This sediment will, however, not have been able to have pass across the deeper navigation channels that separate the Peddocks from other islands due to the strength of currents and the weaker influence (on the bed) of waves in deeper water. Peddocks Island Profile 2 is on the east side of the northern drumlin. It is exposed to higher winds and waves approaching from Massachusetts Bay to the northeast. The top of the bluff has remained relatively stable, while the lower bluff shows variable changes, however this is likely to be the results of tracking slightly different lines down the bluff, which is gullied, leading to slightly wider bluff measurements in 2005 and 2007. In order to avoid this error, certain benchmark positions were chosen at which to repeat the measurements along the annual transect, however it was not always possible (due to mass movement of sediment or vegetation growth) to accurately repeat the same points each year. This is most likely to cause notable variations on bluffs, which are either high or heavily gullied (conditions which naturally coincide), thus we expect the impact to be greatest at this profile and that at Moon Island profile 1. However, as all retreat calculations have been made using the fixed benchmark and the bluff edge and not using any of the 'on slope' measurements, this will not introduce any error into the quantification of retreat rates. Visual inspection however shows that, while partially vegetated, this bluff is losing fine sediment through wash, producing a wide flat fan at the bluff base.

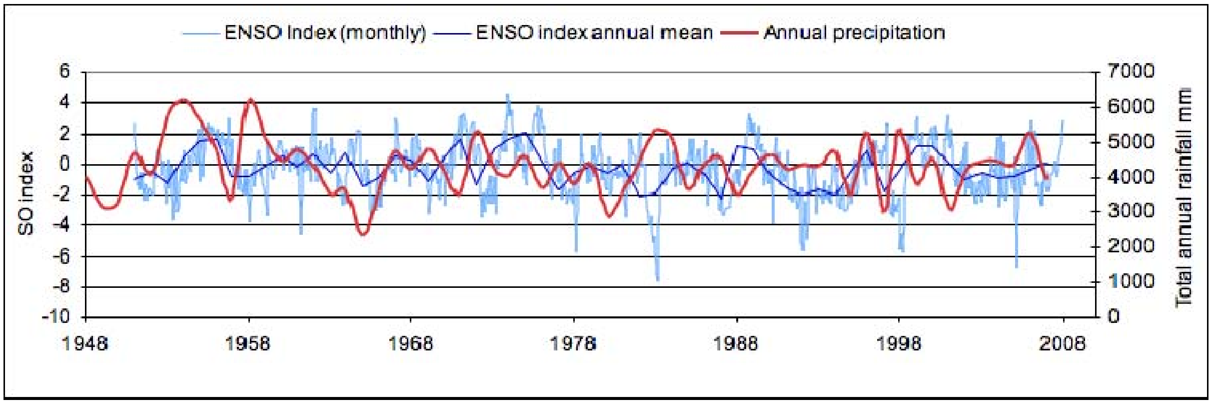

Figure 15. Total annual precipitation at Boston Logan Airport and El Nino Southern Oscillation index, showing an approximate inverse relationship between ENSO and rainfall. A low ENSO indicated a high annual rainfall. Thus high precipitation is cyclic at Boston.

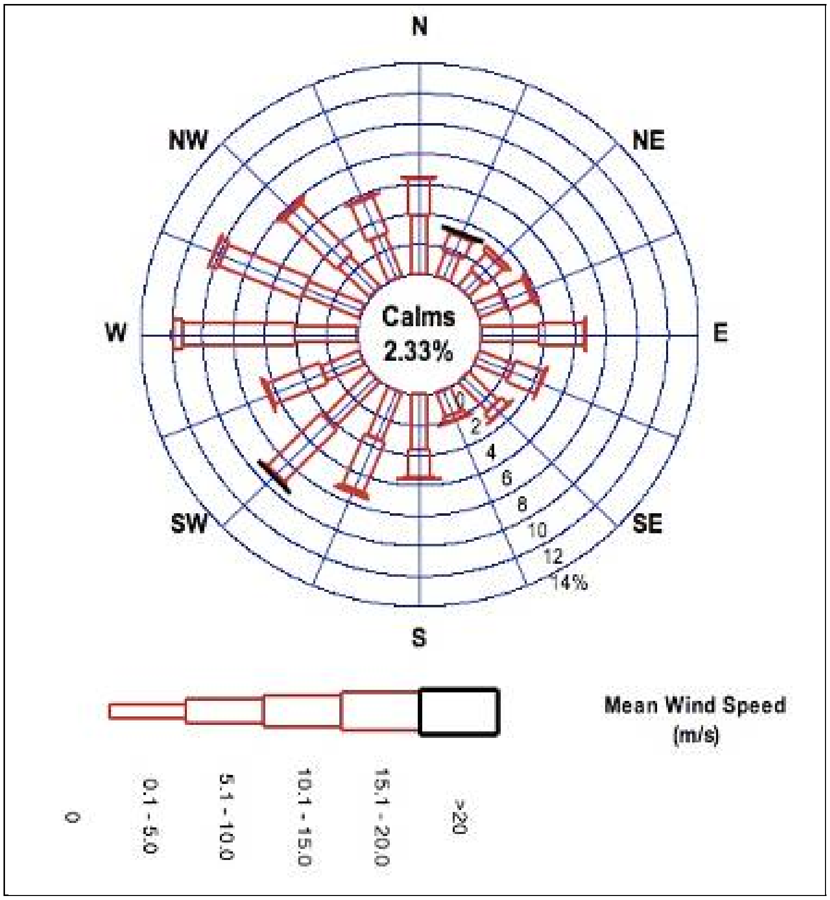

Figure 16. Wind rose for data 1994-2005 showing frequency and mean speed for 16 compass points.

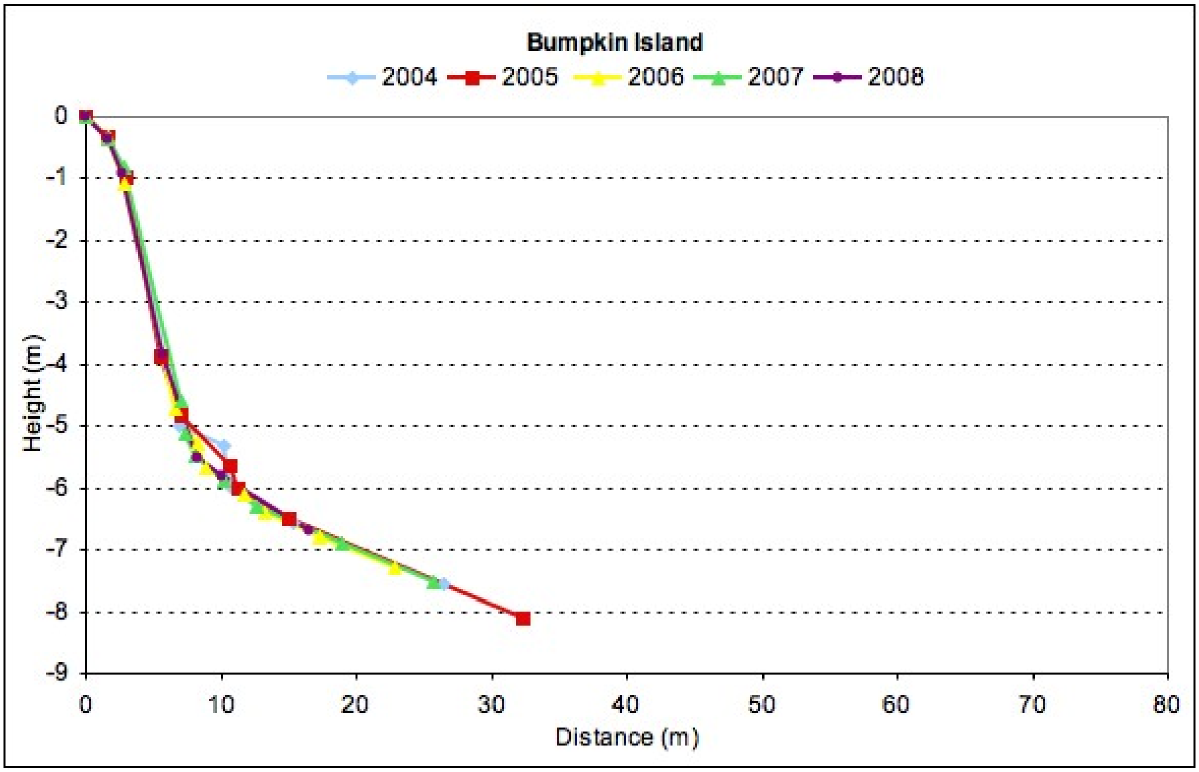

Figure 17. Overlay of annual bluff surveys on Bumpkin Island.

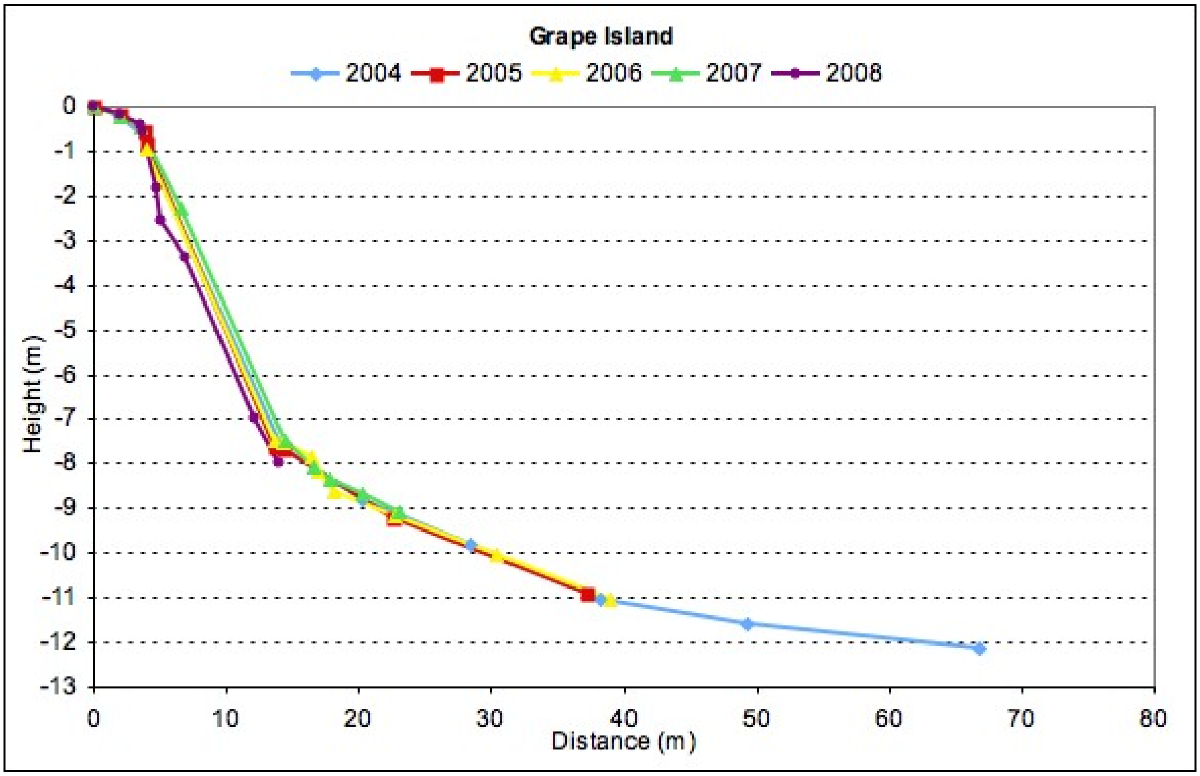

Figure 18. Overlay of annual bluff surveys on Grape Island.

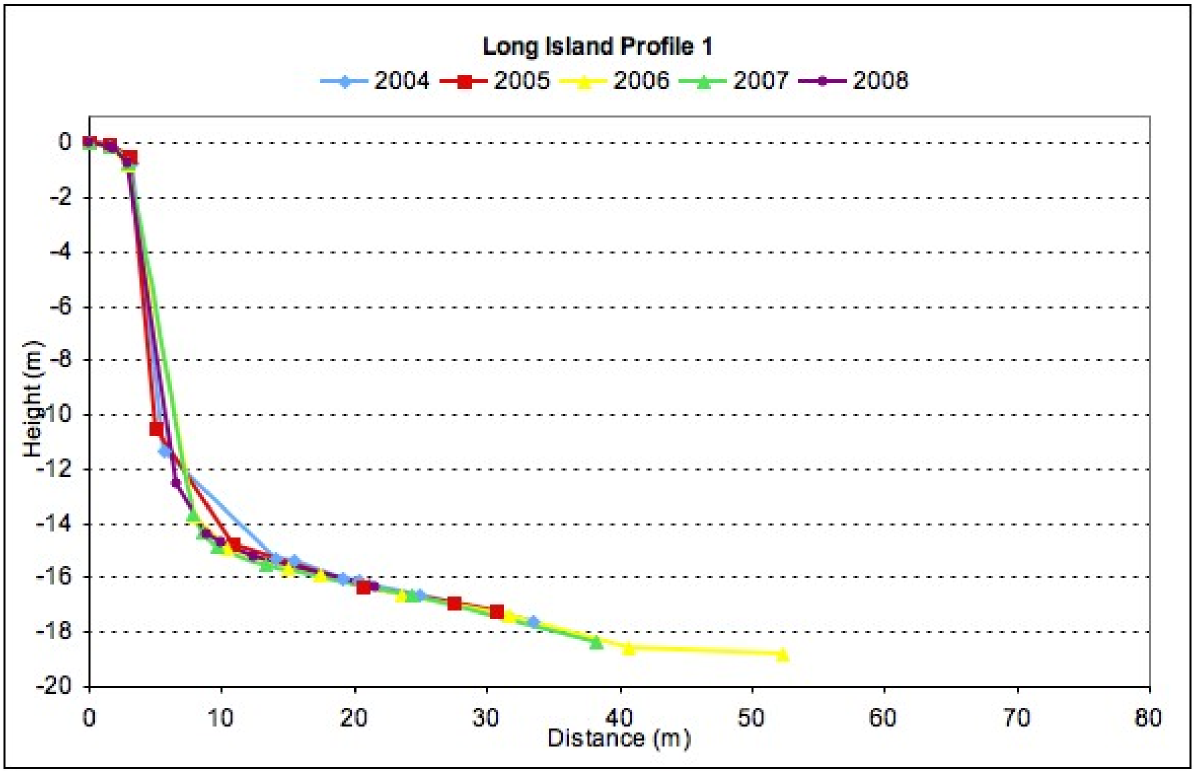

Figure 19. Overlay of annual bluff surveys on Long Island Profile 1.

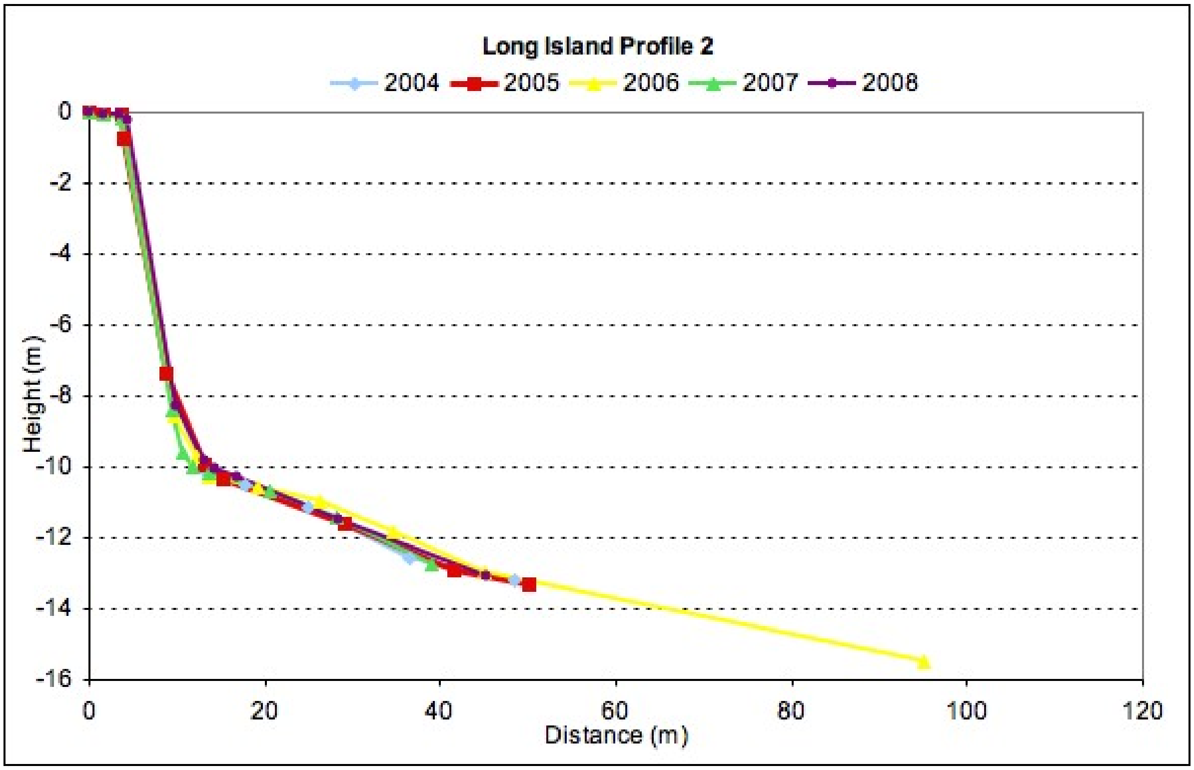

Figure 20. Overlay of annual bluff surveys on Long Island Profile 2.

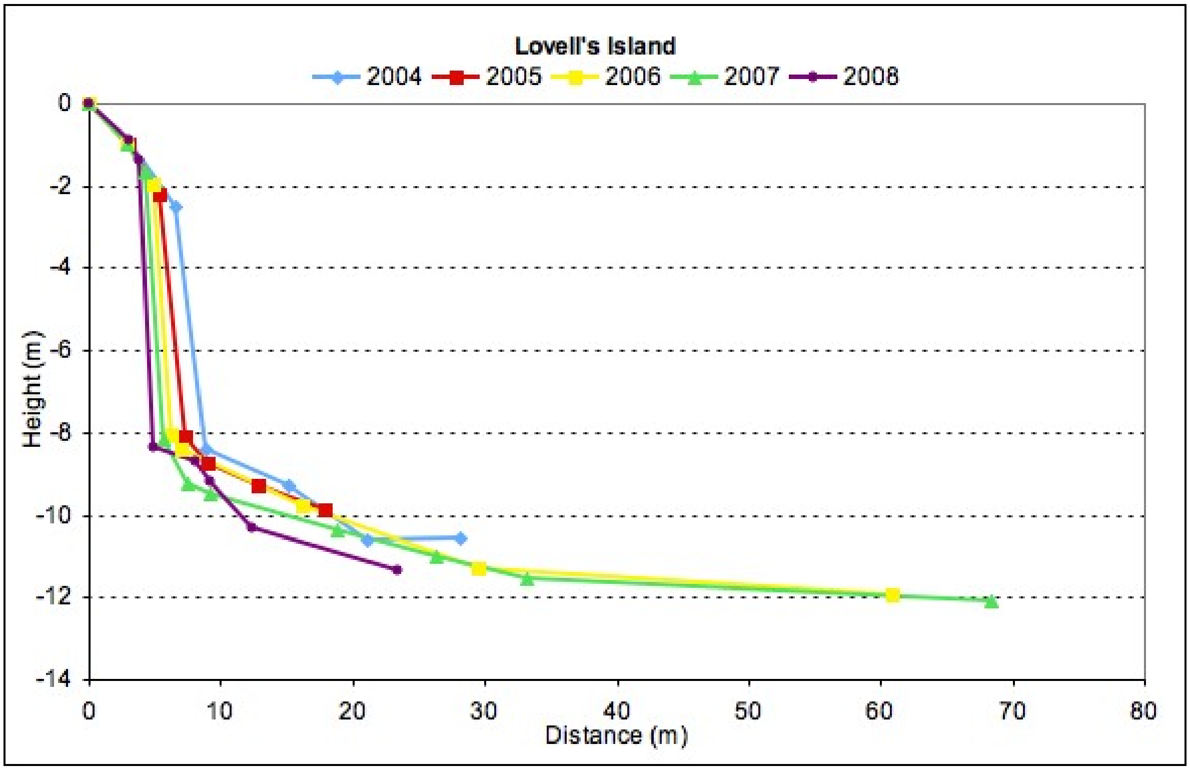

Figure 21. Overlay of annual bluff surveys on Lovell’s Island.

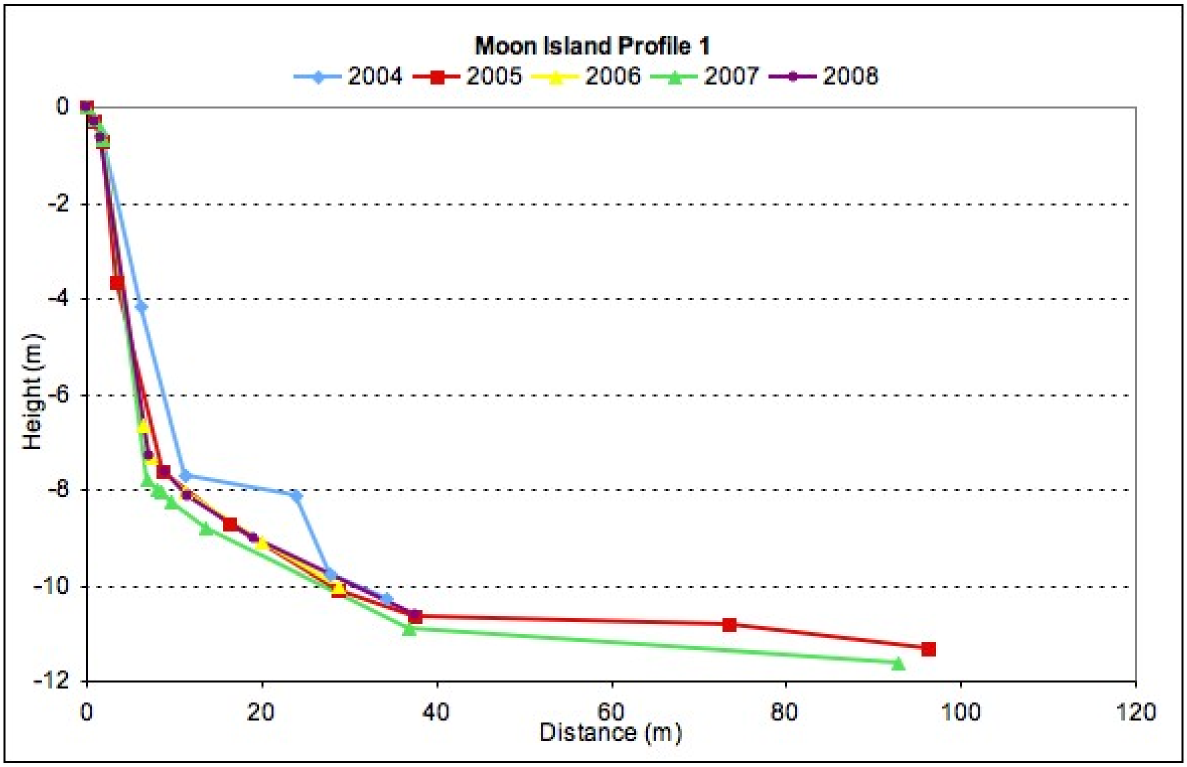

Figure 22. Overlay of annual bluff surveys on Moon Island Profile 1.

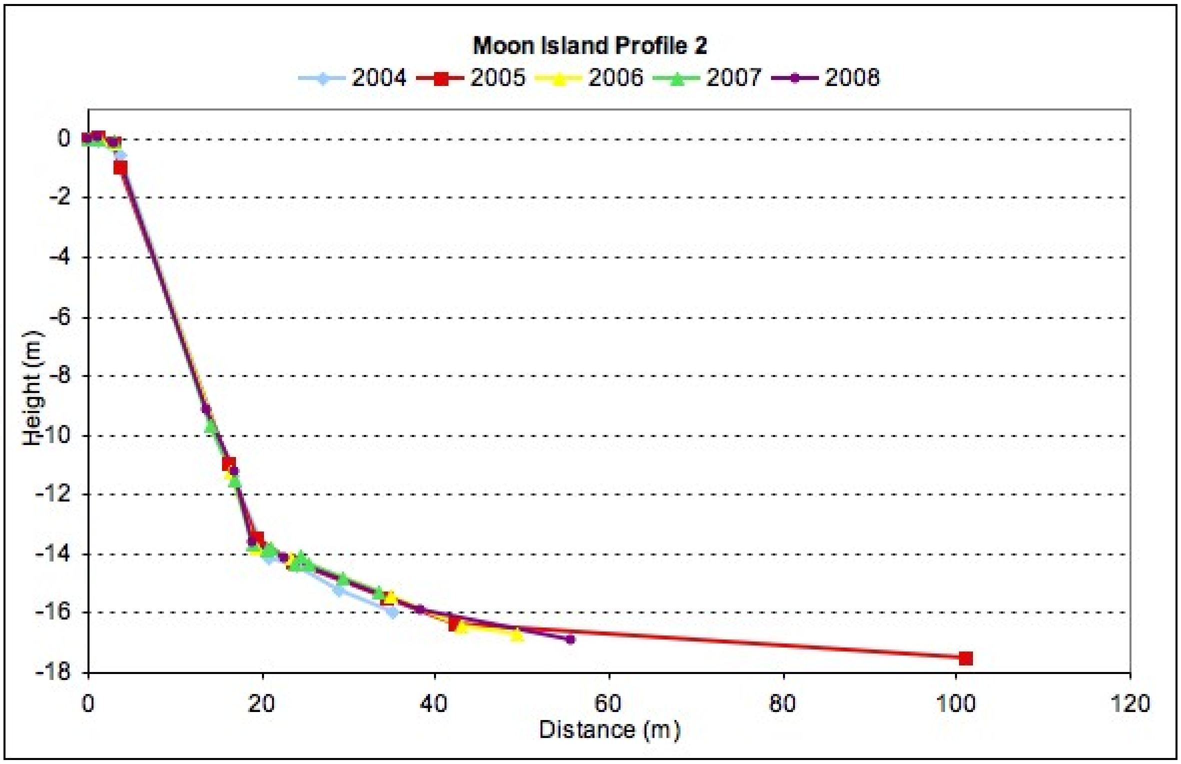

Figure 23. Overlay of annual bluff surveys on Moon Island Profile 2.

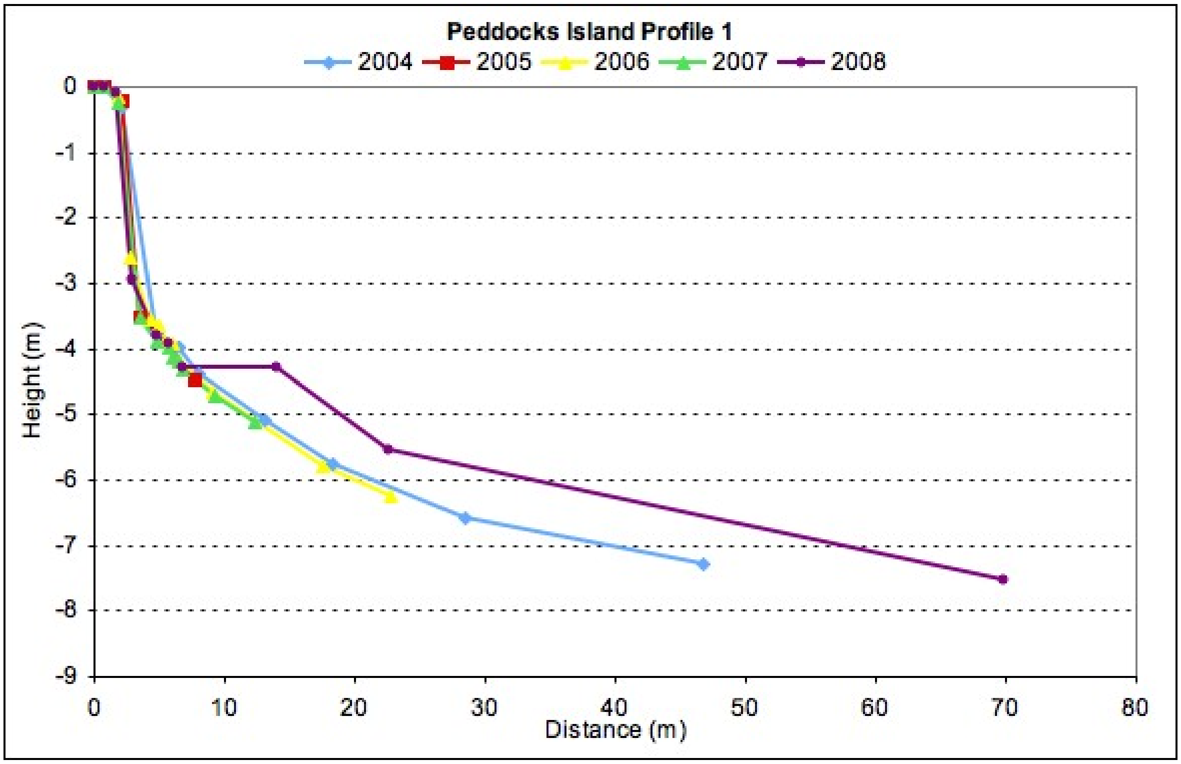

Figure 24. Overlay of annual bluff surveys on Peddocks Island Profile 1.

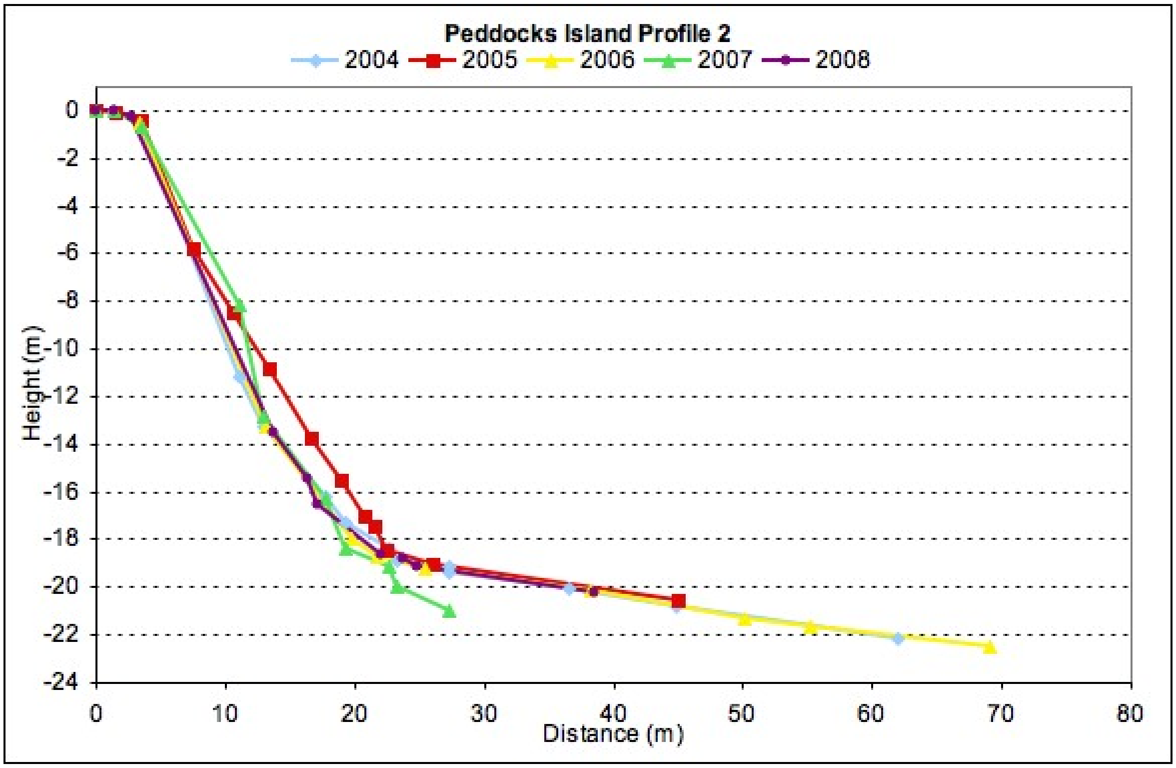

Figure 25. Overlay of annual bluff surveys on Long Island Profile 2.

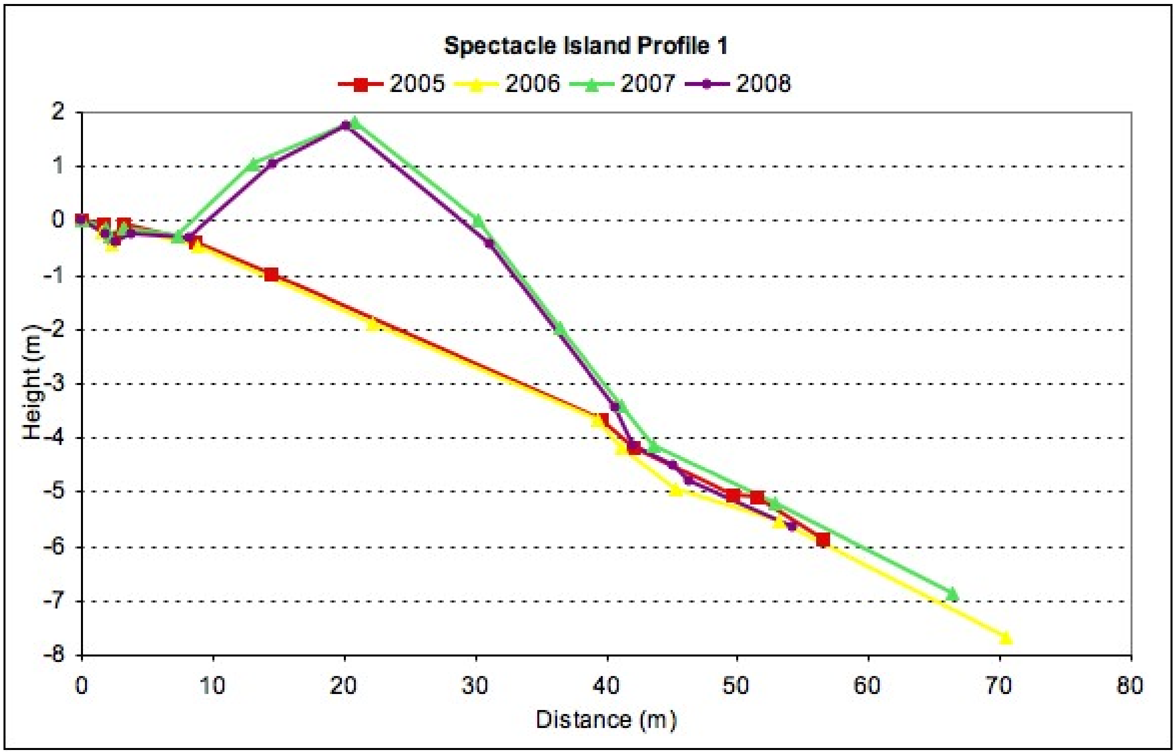

Figure 26. Overlay of annual bluff surveys on Spectacle Island Profile 1.

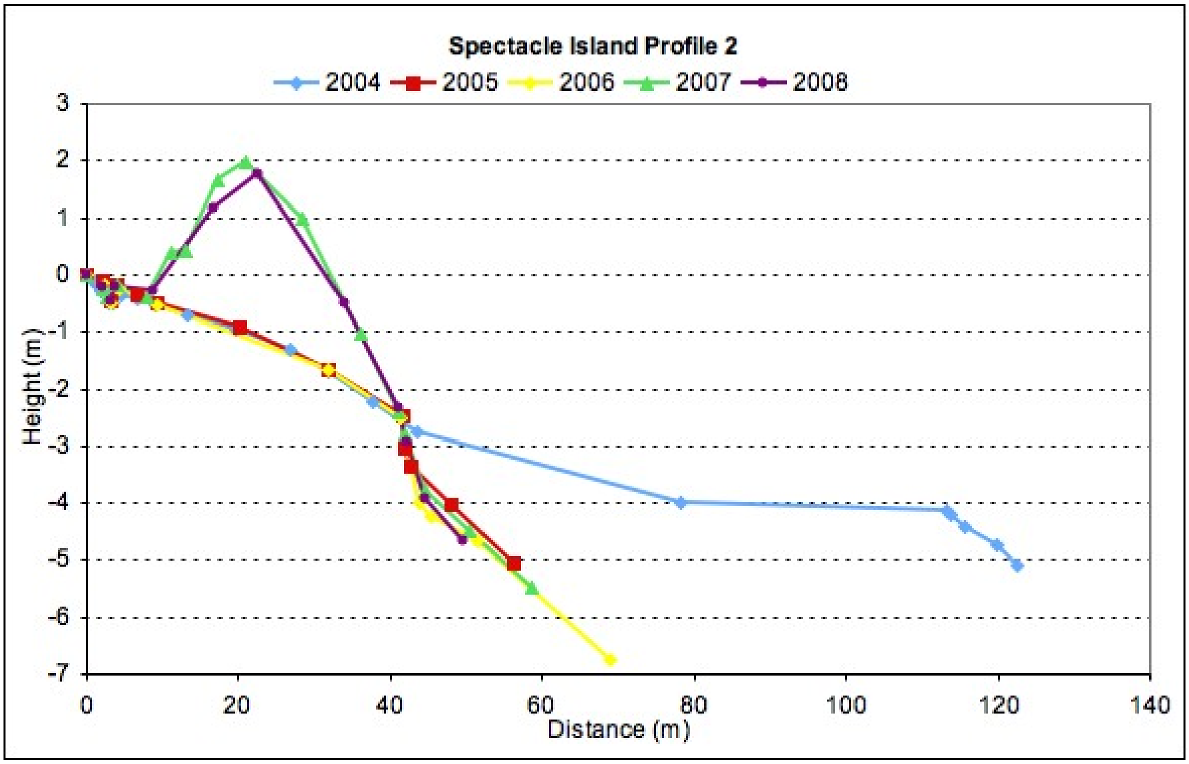

Figure 27. Overlay of annual bluff surveys on Spectacle Island Profile 2.

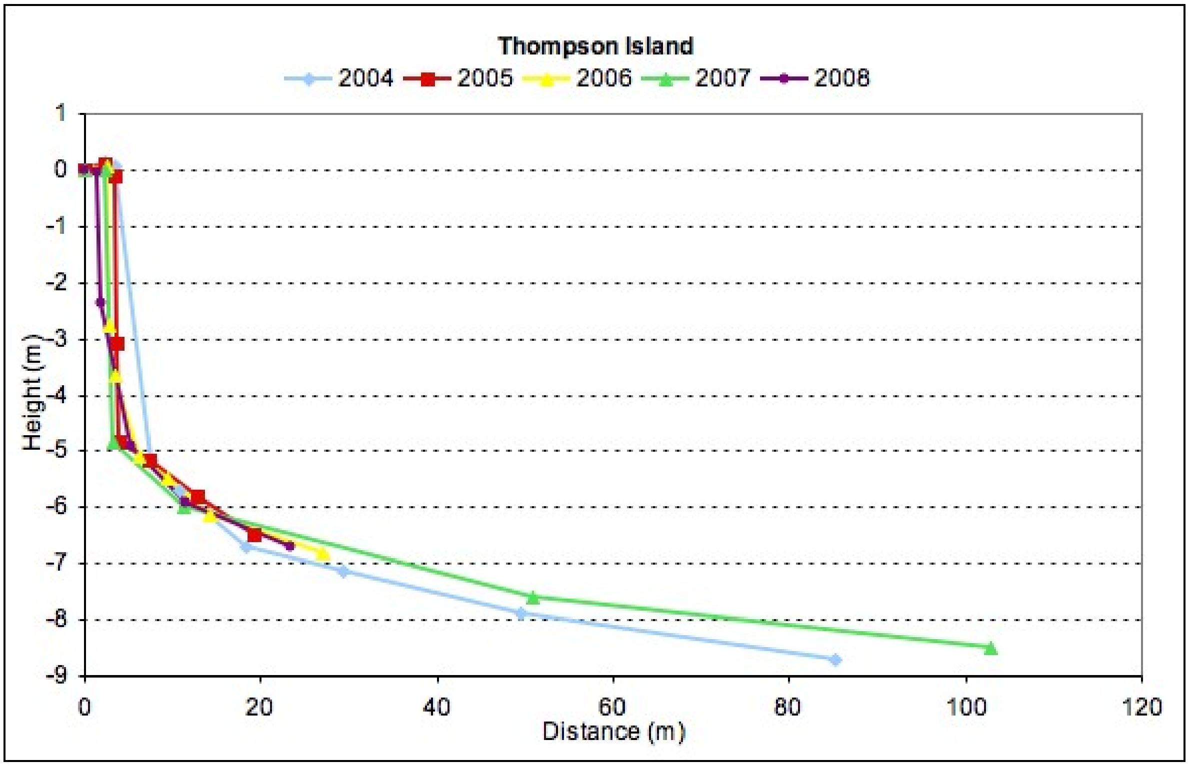

Figure 28. Overlay of annual bluff surveys on Thompson Island.

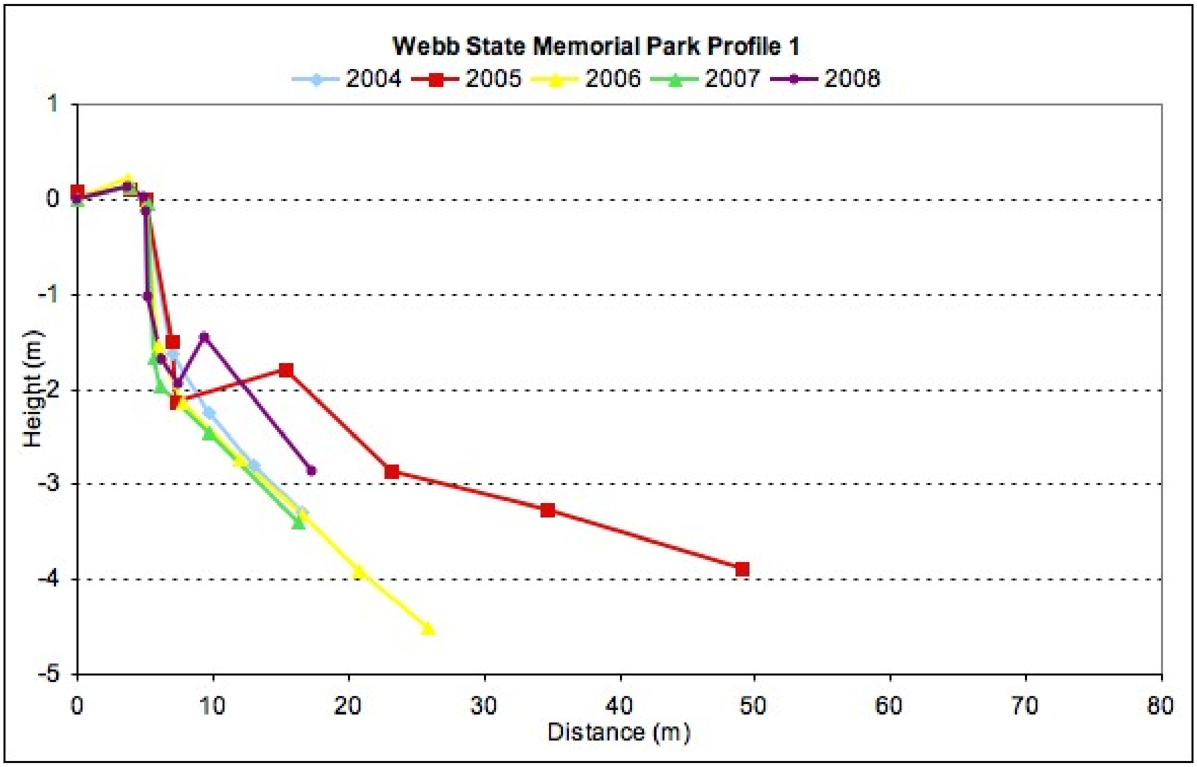

Figure 29. Overlay of annual bluff surveys on Webb State Park Profile 1.

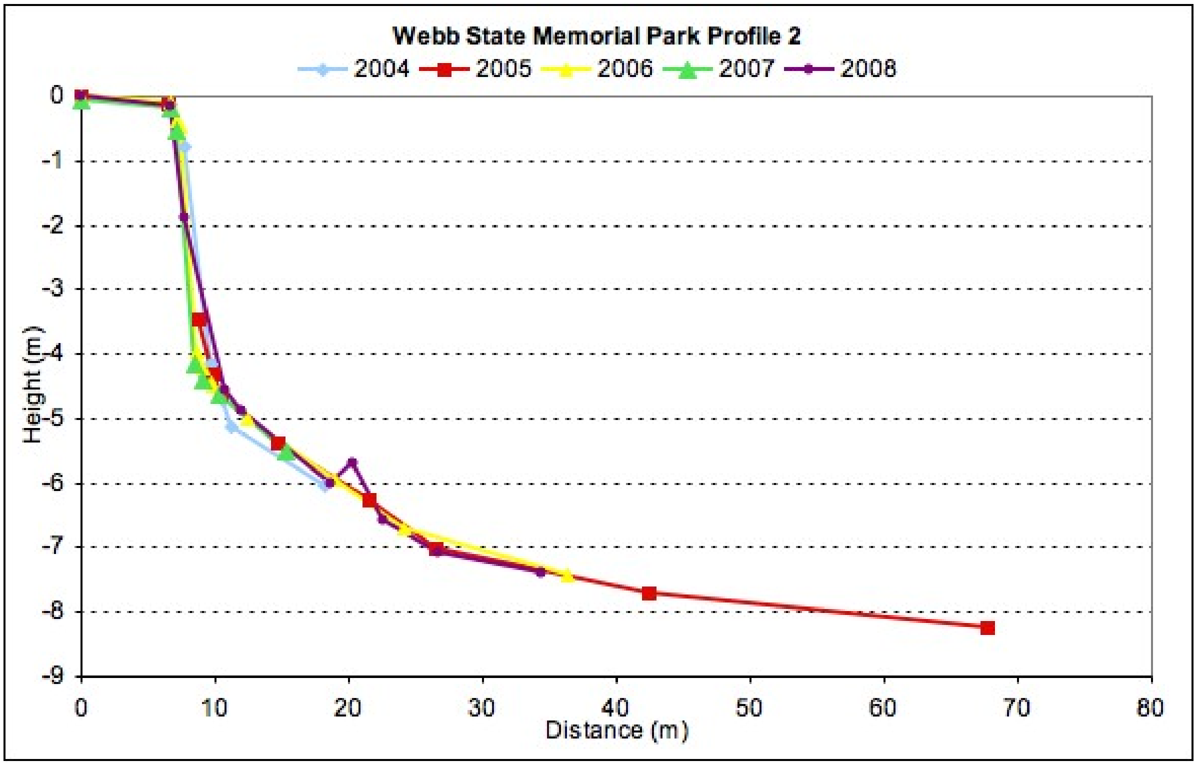

Figure 30. Overlay of annual bluff surveys on Webb State Park Profile 2.

Table 4. GPS locations of the backstake positions for the monitoring profiles.

Location	N	W
Peddocks 1	42 17'25.4"	70 56' 93.6"
Peddocks 2	42 18' 7.7"	70 55' 40.0"
Lovell's 1	42 19' 48.2"	70 55' 48.9"
Moon 1	42 18' 17.8"	70 59' 18.6"
Moon 2	42 18' 20.8"	70 59' 16.6"
Long 1	42 19' 22.5"	70 57' 42.3"
Long 2	42 18' 40.6"	70 58' 32.4"
Thompson 1	42 19' 14"	70 59' 57.9"
Bumpkin 2	42 16' 52.0"	70 53' 48.1"
Webb 1	42 15' 48.1	70 55' 31.5"
Webb 2	42 15' 43.4"	70 55' 21.4"
Grape	42 16' 09.3"	70 55' 31.3"
Spectacle 1	42 19' 10.9"	70 59' 14.9"
Spectacle 2	42 19' 11.3"	70 59' 16.8"

Table 5. Cumulative bluff retreat since 2004 and the final average annual retreat at bluff monitoring stations. NB Long island 1 had a notable overhang, when this was 'removed' from the final profile the 2008 change was 1.38m giving a retreat rate of 0.35 m.

Location	2005	2006	2007	2008	Average change ±0.02 m	No of years
Peddocks 1	0.04	0.23	0.25	0.45	0.11	4
Peddocks 2	0.00	0.13	0.15	0.62	0.16	4
Lovell's 1	1.27	1.70	2.30	2.76	0.69	4
Moon 1	0.85	0.89	0.97	1.14	0.28	4
Moon 2	0.55	0.63	0.74	0.76	0.19	4
Long 1	0.23	0.38	0.38	0.43	0.11	4
Long 2	0.17	0.13	0.26	0.34	0.09	4
Thompson 1	0.00	0.94	1.25	2.04	0.51	4
Bumpkin 2	0.01	0.10	0.18	0.27	0.07	4
Webb 1	0.00	0.00	0.00	0.09	0.02	4
Webb 2	0.06	0.36	0.53	1.02	0.26	4
Grape	0.13	0.32	0.34	0.38	0.09	4

The Spectacle Island Profiles (1 and 2) were established at the northeast end of the island where there was a natural drift convergence forming a gravel salient prior to engineering changes on the island. In 2004, very shortly after the construction of the pier and wave blocks, the shallow beach extended some distance offshore. By 2005 the beach face had become much steeper, as sediment was removed from the region. In 2006, a large sand berm was emplaced in this area, planted with Ammophila and treated as a "dune." This berm has been stable overall, however retreat along the top of the beachface has continued. The steep beach face has remained.

The Thompson Island Profile is located on the northwest side of the northern drumlin. This profile has also demonstrated parallel retreat, with retreat at the top of the bluff as well as the base. This profile also shows slumping and accumulation of sediment at the base of the bluff following the 2007 Nor'easter. While this increased toe slope suggests limited removal of sediment at the bluff base by waves, visual inspection shows that less than 10 m to the south of the profile location, a significantly lowered portion of beach face does allow sea level to reach the bluff face during extreme spring tides and storms. This is one of the only bluff sections in the harbor that has regularly been observed in contact with the waterline and thus wave throughout the period of study. Multiple visits during equinoxial and storm tides demonstrated repeatedly that the water line remained significantly lower than the bluff base at most sites.

Webb State Park Profiles are located in the inner portion of the harbor, although profile 2 faces due northeast across an open bay towards Peddocks Island. Both profiles are adjacent to a major navigational channel used by commuter ferries, so their wake may impact the bluffs, however ferries were observed slowing down notably before entering this channel. The top of the bank in profile 1 has remained stable over the study period. The base of the bank has fluctuated, with some periods (2008, 2005) where the beach has developed high berms protecting the bluff, and other years when there was exposure to direct wave impact.

Profile 2 remained stable at the top of the bluff throughout most of the study, until 2008 where a rapid retreat was observed. Little change was observed at the base, except in 2008 a significant toe had developed, likely the product of slumping at the bluff top, probably resulting from the 2007 Nor'easter.

In summary, the form of slope retreat viewed in profile clustered as bluffs showing little change over four years (Bumpkin, LI 2, Moon 2, Peddocks 1, Webb 1) and bluffs showing parallel retreat (LI 1, Lovell's, Moon 1, Thompson). Of the parallel retreat sites, Lovell's and Thompson sites showed significant retreat of the top of the bluff, while most others showed minimal change at the top. The areas of parallel retreat included both areas dominated by mass wasting by slumping and by gulley processes. Webb profile 2 demonstrates a rapid retreat between 2007 and 2008 at the top of the bluff, with the sediment being deposited at the base. Kaye's observation that most change takes place during spring corresponds to the dramatic changes observed in spring, 2008, following the 2007 Nor'easter when precipitation was high. The formation of accretionary berms on the beach at two sites, Lovell's and Webb 1, also played a role in slope processes.

Relationships between retreat rates and both the bluff height and the elevation of the bluff base above mean sea level are investigated in Figures 31 and 32. No clear relationship can be seen with either parameter.

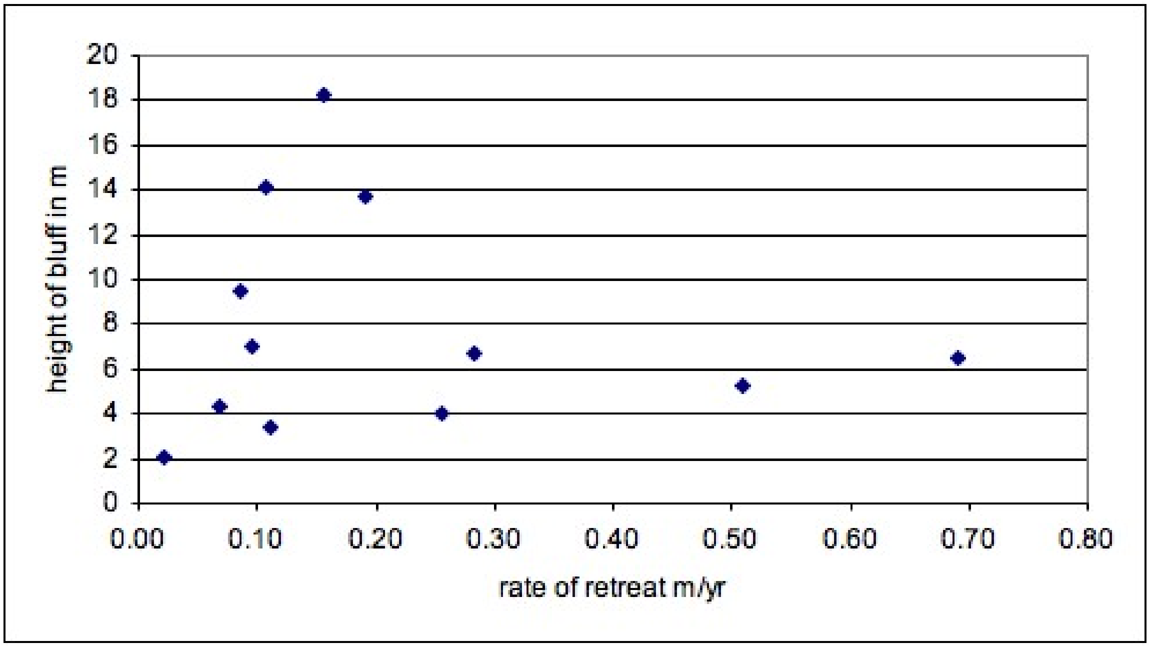

Figure 31. Height of bluff compared to retreat rate.

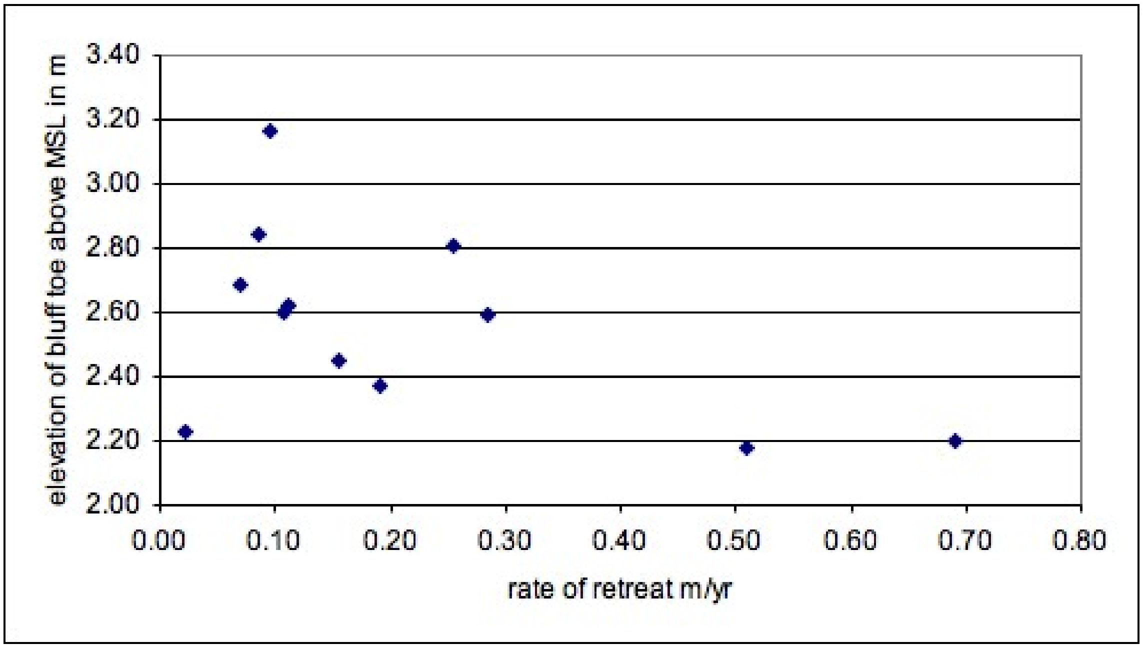

Figure 32. Height of toe of bluff compared to retreat rate.

The bluff retreat data indicate that Himmelstoss' model, which stands as the benchmark work on slopes in Boston Harbor, may be refined by other secondary controlling factors, including seasonality of slumping and impact of local littoral processes.

GIS and Stability Studies

In total over 60 km of shoreline were monitored during the surveys of shoreline and bluff condition. Figure 33 shows the extent of the survey, which included all of the Harbor Islands and the mainland shorelines considered either as within the Recreational Area or drumlin promontories.

Figures 34 to 41 provide example summary figures of the GIS for a number of the islands in the Harbor. The islands exhibit a variety of different beach types, bluff heights, bluff condition, and morphological features. Within the GIS these features are fully interactive and the user can choose to select individual categories from the data dictionary (Figure 11). These data can be used as a baseline for future studies, particularly for features that may alter significantly over time such as the percentage eroding bluffs, the position of overtopping ridges, or the extent of fringe marshes. The GIS also allows statistical analysis of the data.

Beach Type

Unlike many shorelines along the East Coast of the United States, the Boston Harbor Islands have heterogeneous mixed sediment shorelines, due mainly to the varied make up of the drumlins that are the source of the beach sediment (Figure 42).

The most common beaches in the Harbor are pebble/cobble (42%), however even within this classification there are still cross beach variations, with upper beaches in the Harbor often giving way to flat boulder lag or to mud flats below mean low water (Figure 43). Boulder and sandy beaches are only slightly less common (30% and 28% respectively). All of the Islands have some boulder lag and pebble beach, while only some have sand beaches, notably Long, Lovell's, Moon (due to the sheltered sandy beaches along the land bridge to the mainland), Peddocks, and Thompson Islands (Figure 44).

Boulder beaches, which are left behind as drumlins erode (and are often referred to as boulder 'lag') are most common in the north and northwest quadrants; this coincides both with high energy storm directions and with the orientation of the steepest, highest drumlin faces (Figure 45). The drumlins in the Harbor are oriented with the steep face facing the northwest and a shallower slope to the southeast. Interestingly, there is no domination by boulder lag in the northeast, the direction from which many storms originate in this region. Sand beaches dominate sheltered southerly shorelines.

Figure 46 illustrates the spatial distribution of boulder beaches throughout the Harbor, classifying them according to fetch. Very few boulder beaches have fetches less than 1500 m, confirming that these are high energy environments, which exist as lag after the sand, muds, and gravels have been removed from the glacial till. The boulders beaches close to the mouth of the harbor have extremely high fetches.

In general, regions with high fetch are more likely to have a boulder beach, whereas regions of lower fetch are more likely to have pebble/cobble beaches (Figure 47). Interestingly, all fetches are about equally likely to have a sandy beach.

Coastal Protection

Within the harbor there are over 10 km of seawall, 8.5 km of revetments, 6 groin, and 400 m of toe protection (Figure 48). Spectacle Island has the greatest length of seawall, protecting the landfill within it. Moon Island has the next longest sections of seawall, which protect much of the land bridge to the mainland (Figure 49).

As part of this study, the condition of the seawall was also assessed (Figure 50). Approximately 85% of the seawalls are in good condition (Figure 51).

The sections that are in poor conditions occur on Peddocks, Rainsford, Georges, Gallops, and Great Brewster Islands (Figure 50 and 52). These islands are notably positioned towards the mouth of the Harbor and have large fetches, confirming heaving wave action is responsible.

Revetments in the Harbor are mostly in good condition (93%; Figure 53). Regions of poor condition again occur on the more exposed islands of Great Brewster, Georges, and Rainsford. However, Sheep and Thompson Islands also have some sections of their revetments in poor condition (Figure 54).

Of the six areas, which have groins in the Harbor, 83% are in good condition (Figure 55). The majority of groins, by length, occur on Lovell's and Georges Islands, where the groins were professionally constructed and are in good condition (Figure 56). Several groins have been put in on Peddocks, Worlds End and Bumpkin Islands; these are not in good condition and in most cases seem to have been constructed by hand by visitors or property owners. It is likely these were never in ‘good condition’ but were poorly constructed in the first place.

In some areas, specifically Worlds End and Long Island, the toe of bluffs has been protected with a single line of small boulders. This toe protection only covers 400 m approximately and 80% is in good condition (Figure 57). These results are summarized in Table 6.

Docks

There are 13 active docks within the Boston Harbor Islands, and 2 relic piers that have been partially destroyed but are still standing (Figure 58). Most of these docks are maintained regularly and are in good condition.

Historic charts and photographs (e.g. Figure 7) show that docks once existed in other regions; these are no longer identifiable.

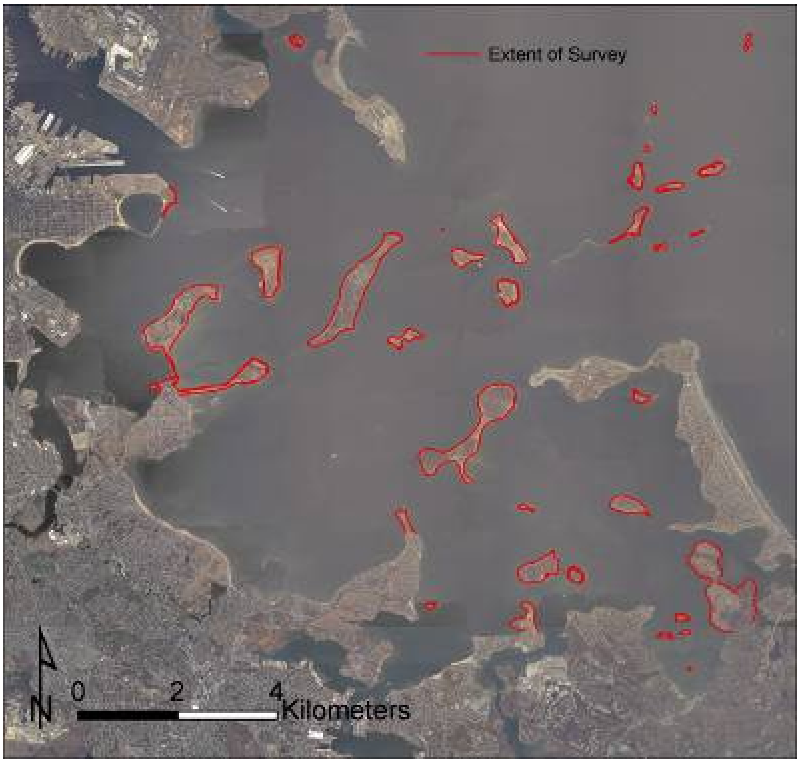

Figure 33. Extent of survey of shoreline characteristics.

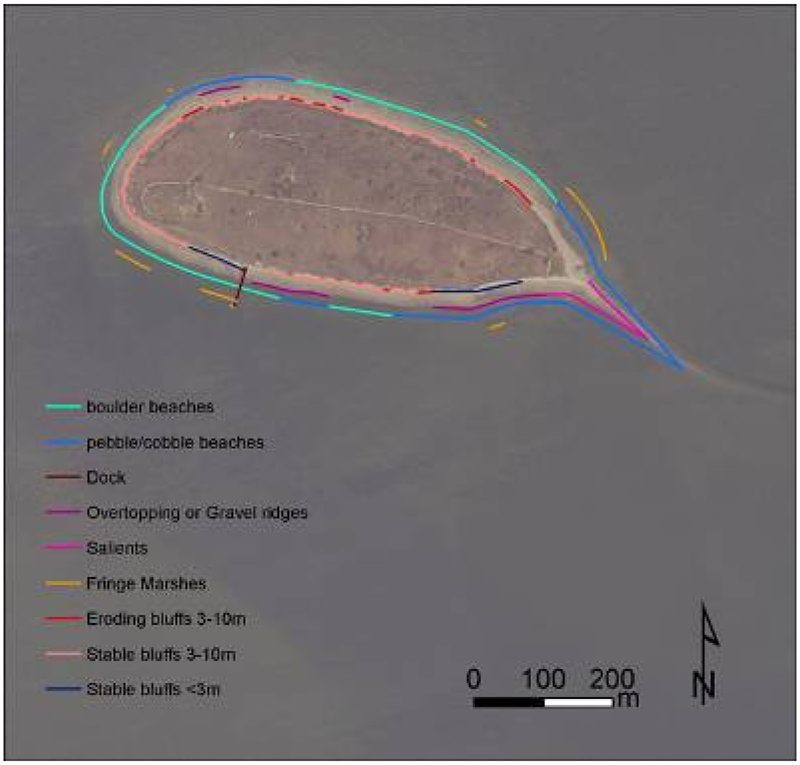

Figure 34. Shoreline characteristics on Bumpkin Island.

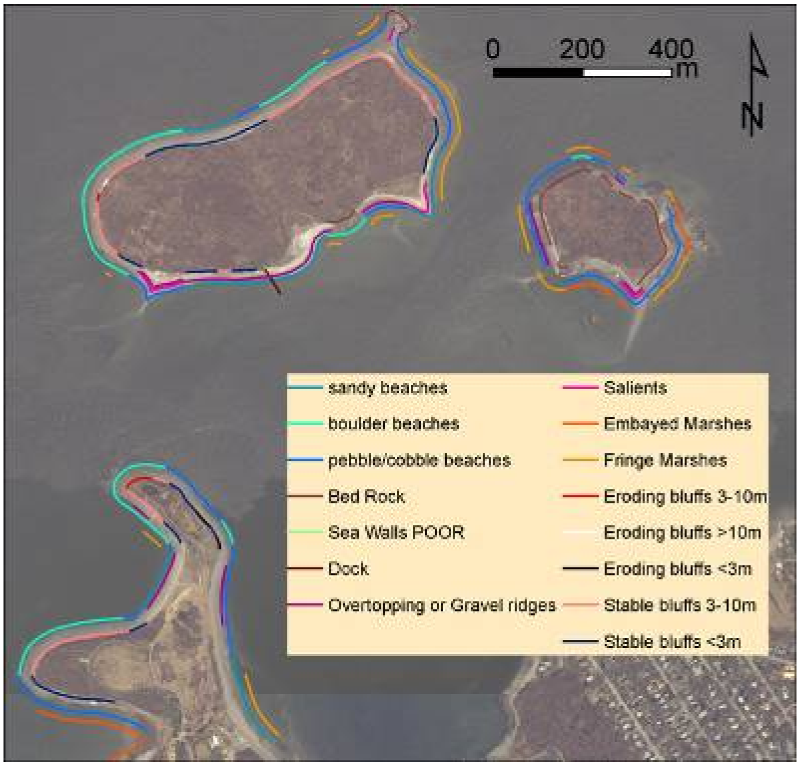

Figure 35. Shoreline characteristics on Grape and Slate Islands and Webb state Park.

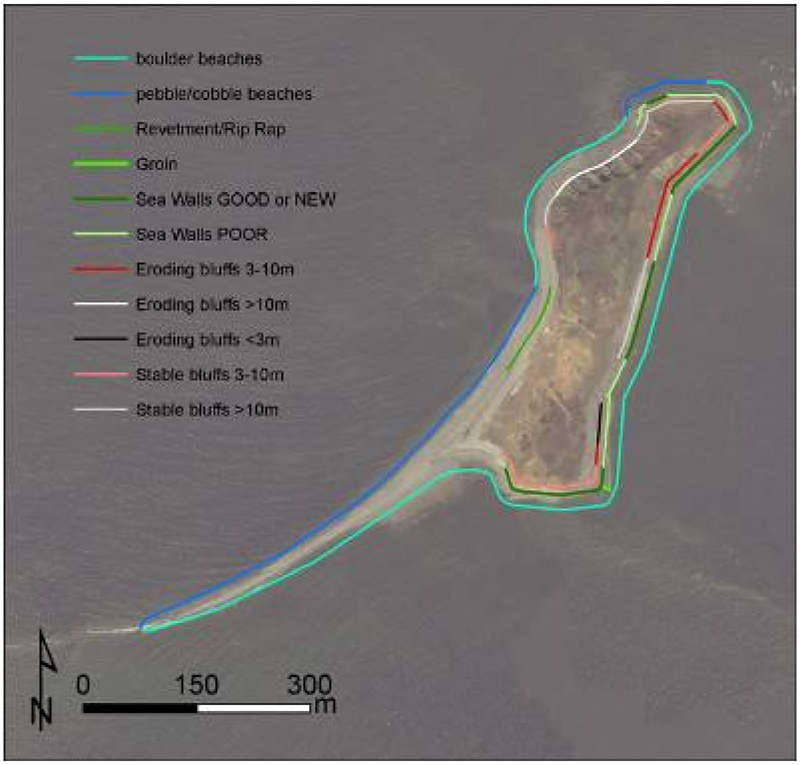

Figure 36. Shoreline characteristics on Great Brewster Island.

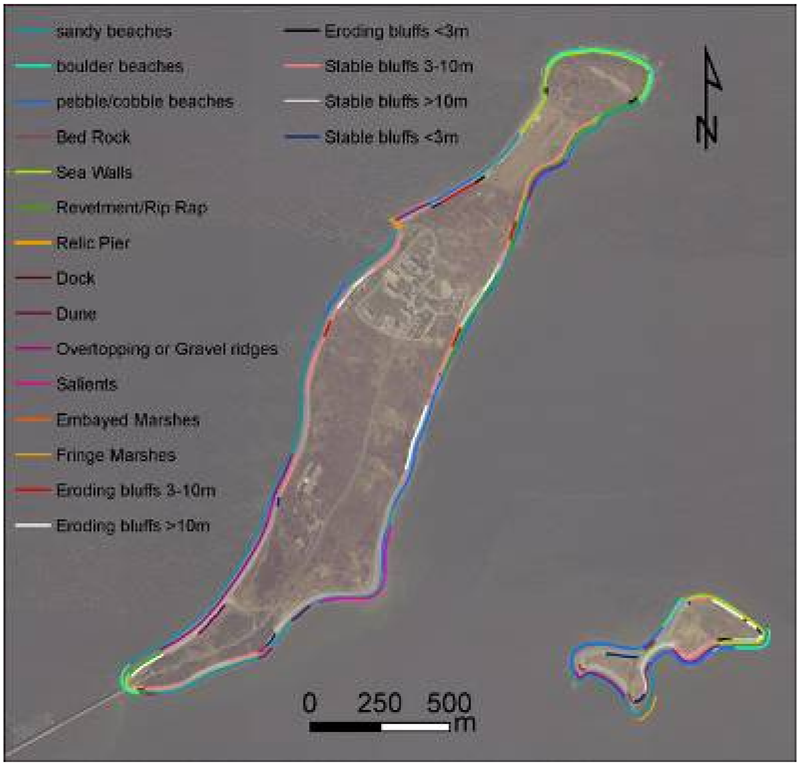

Figure 37. Shoreline characteristics on Long and Rainsford Islands.

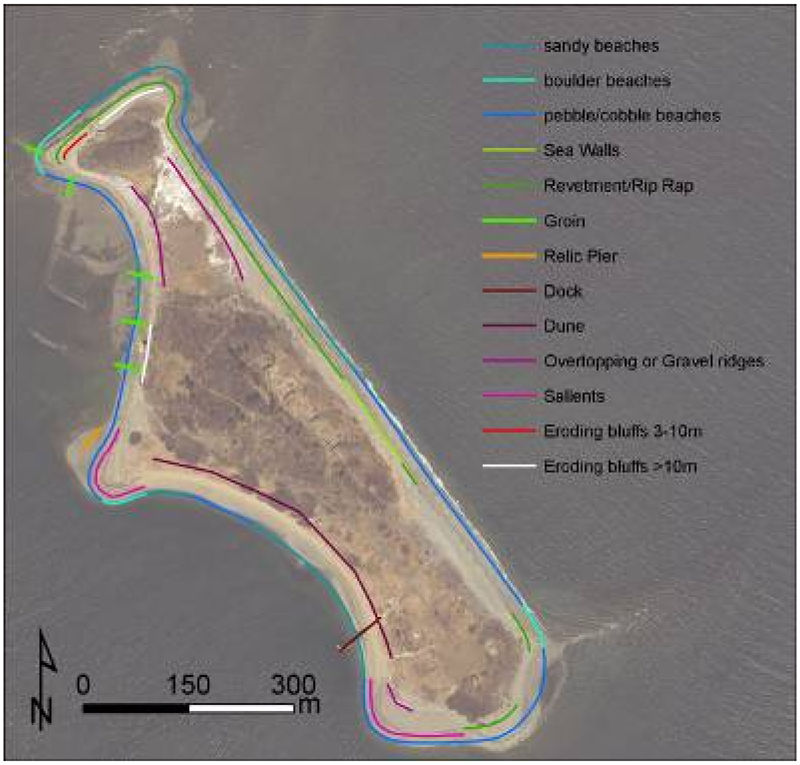

Figure 38. Shoreline characteristics on Lovell’s Island.

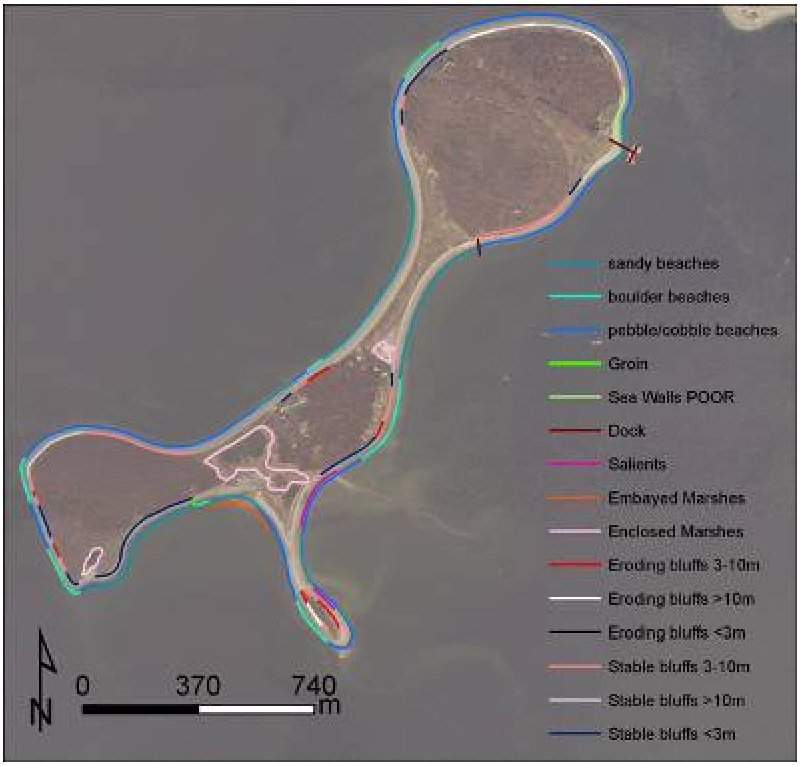

Figure 39. Shoreline characteristics on Peddocks Island.

Figure 40. Shoreline characteristics on Thompson, Moon, and Spectacle Islands.

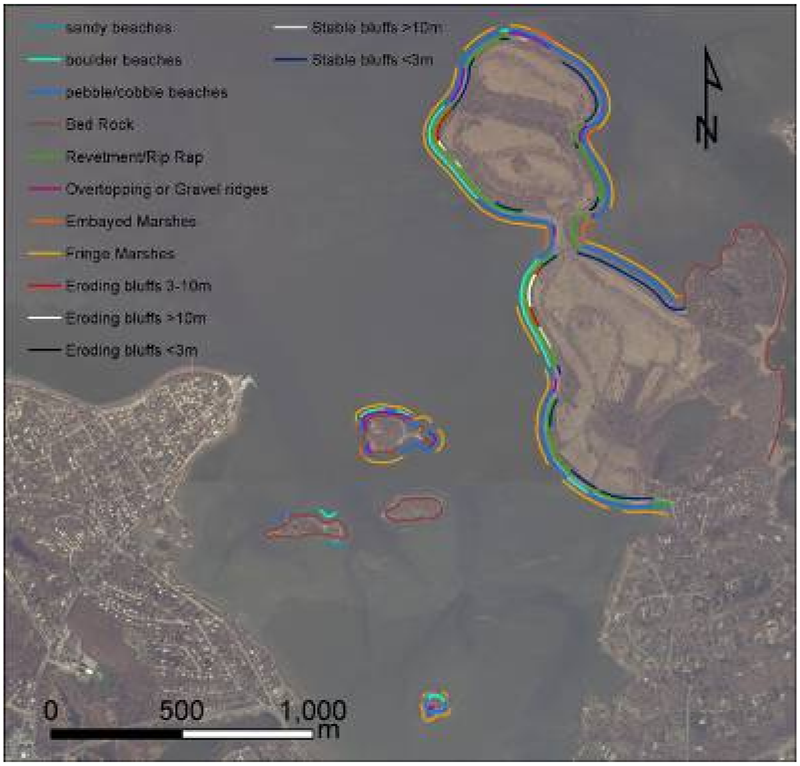

Figure 41. Shoreline characteristics on World's End and Ragged, Sarah, and Langlee Islands.

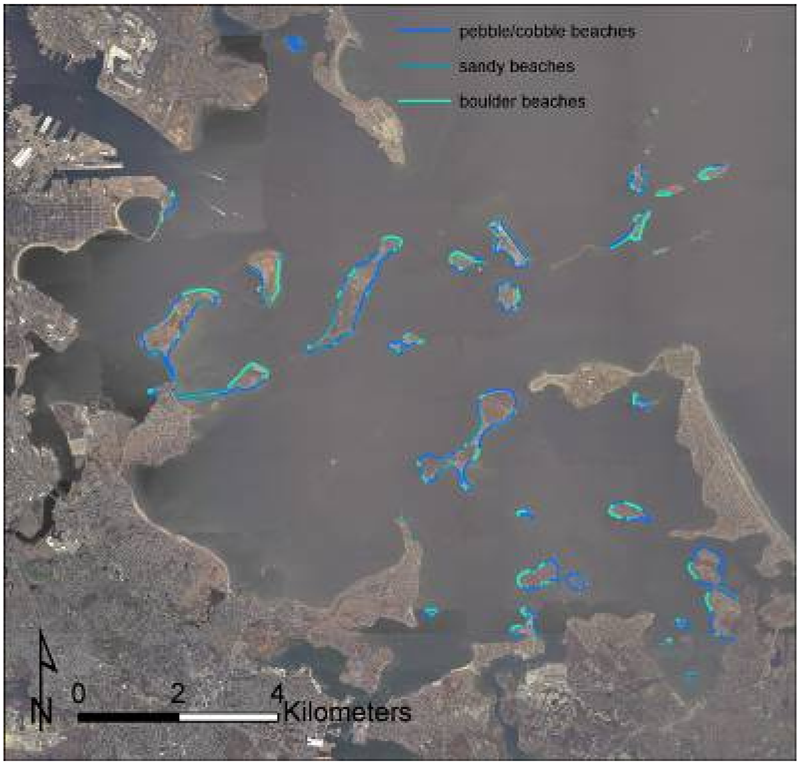

Figure 42. Distribution of beach sediment types in Boston Harbor.

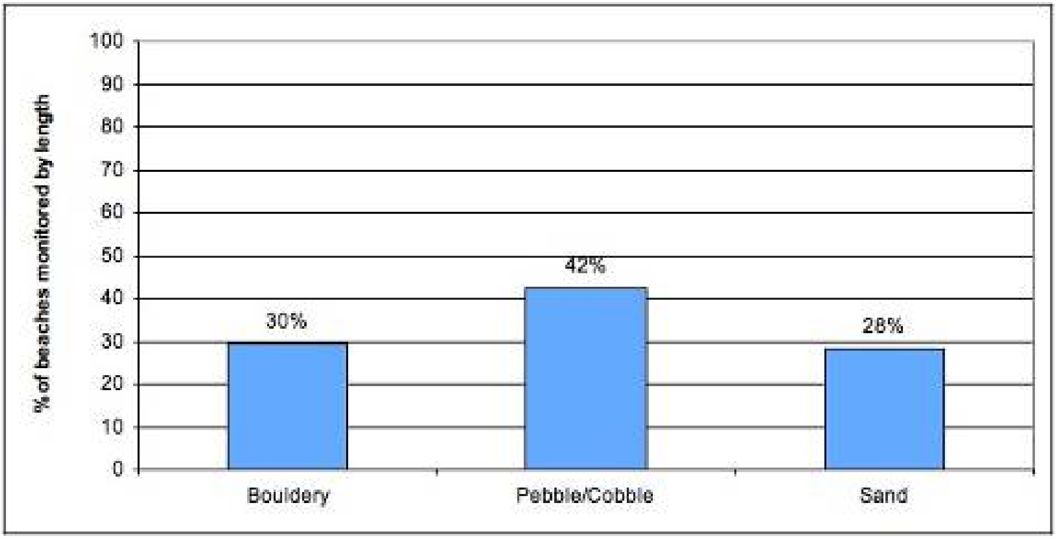

Figure 43. Frequency of occurrence of beach sediment types on Boston Harbor beaches.

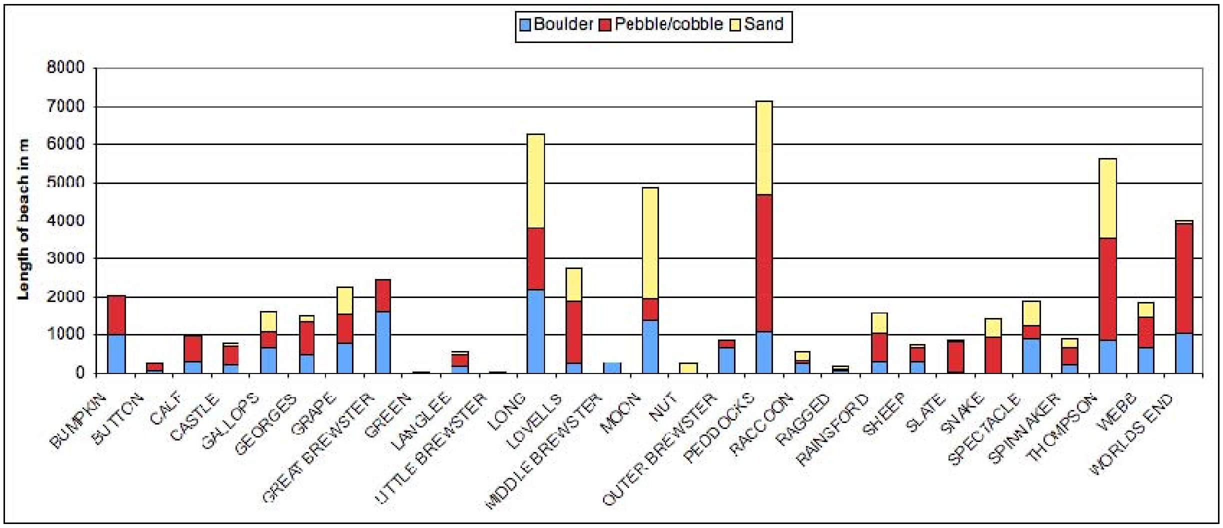

Figure 44. Occurrence of beach sediment types on each island or shoreline reach in Boston Harbor.

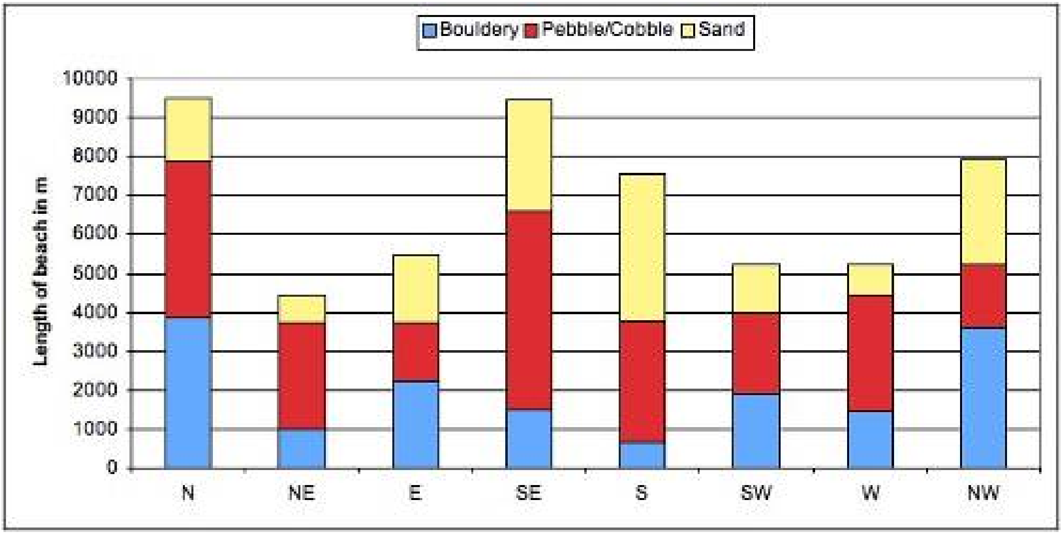

Figure 45. Distribution of sediment types on beaches with varying exposures in Boston Harbor.

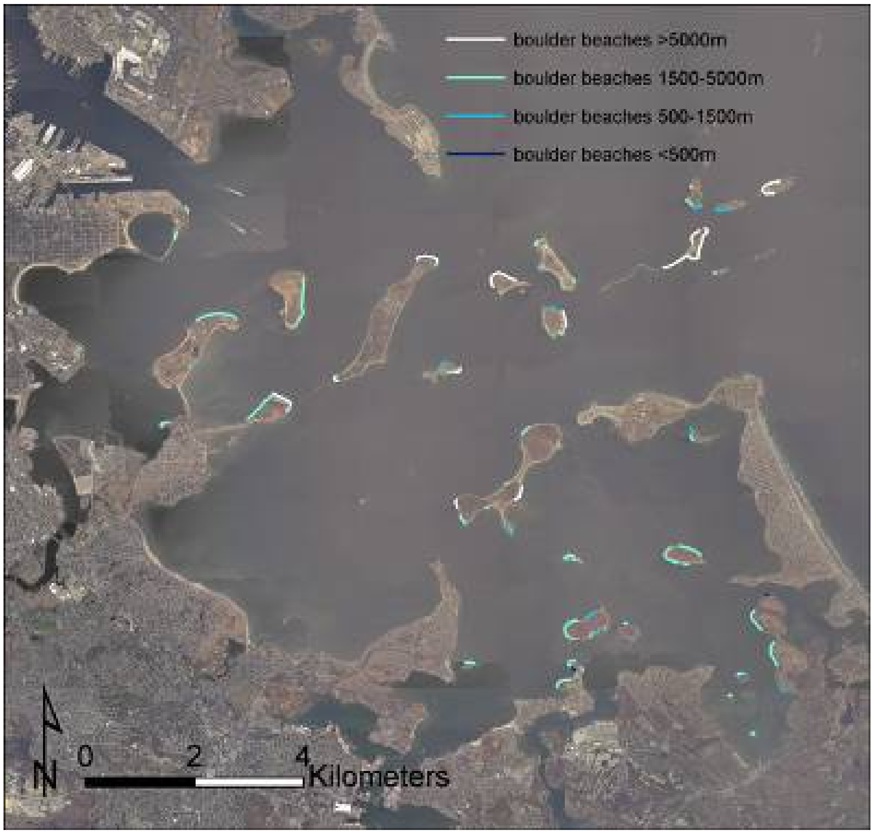

Figure 46. Distribution and length of boulder beaches, Boston Harbor.

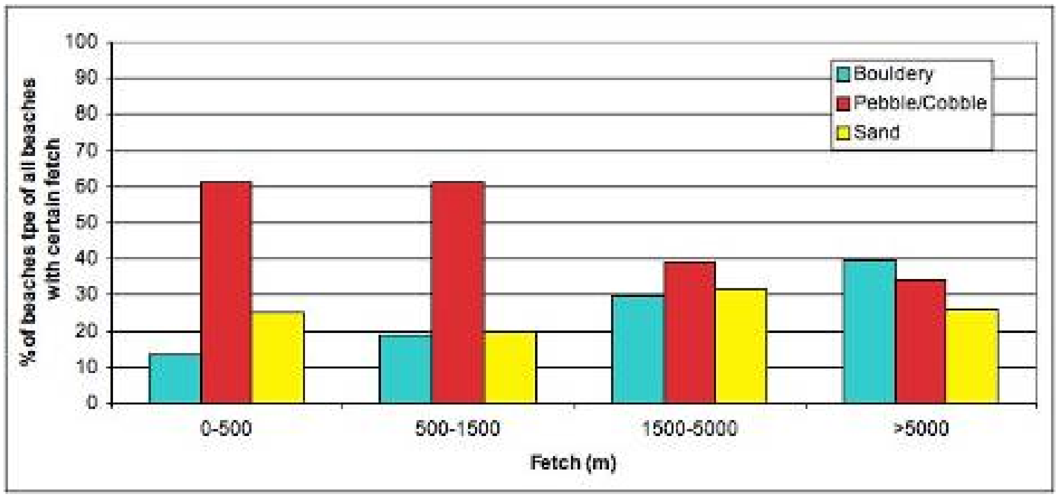

Figure 47. Beach types compared to fetch distances, Boston Harbor.

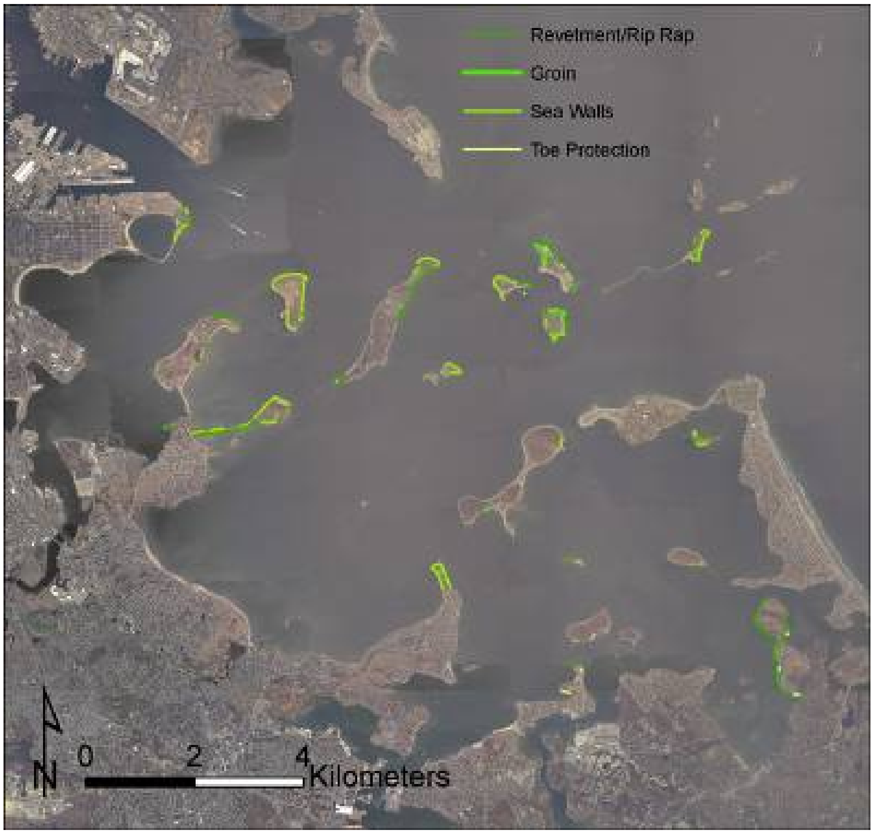

Figure 48. Distribution of coastal engineering structures in Boston Harbor.

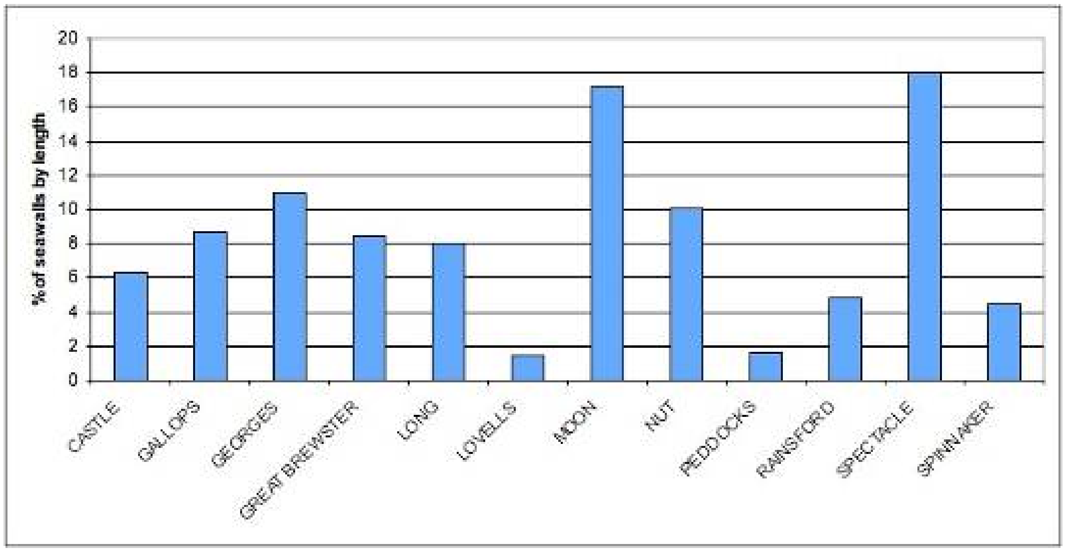

Figure 49. Percent of island shorelines protected by seawalls in Boston Harbor.

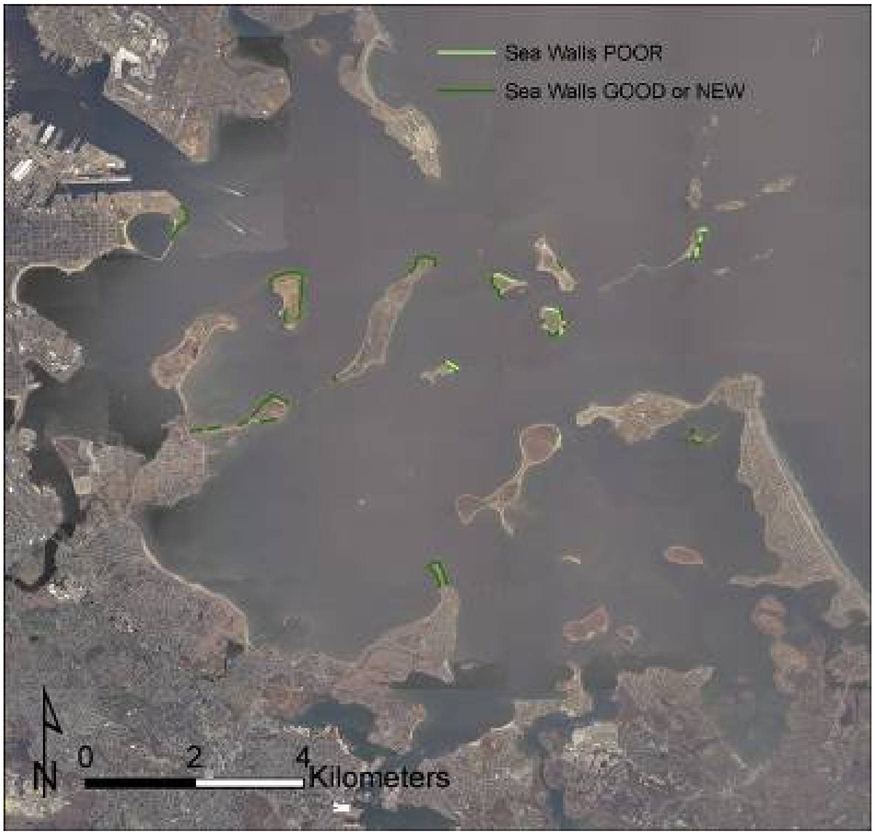

Figure 50. Condition of seawalls, Boston Harbor.

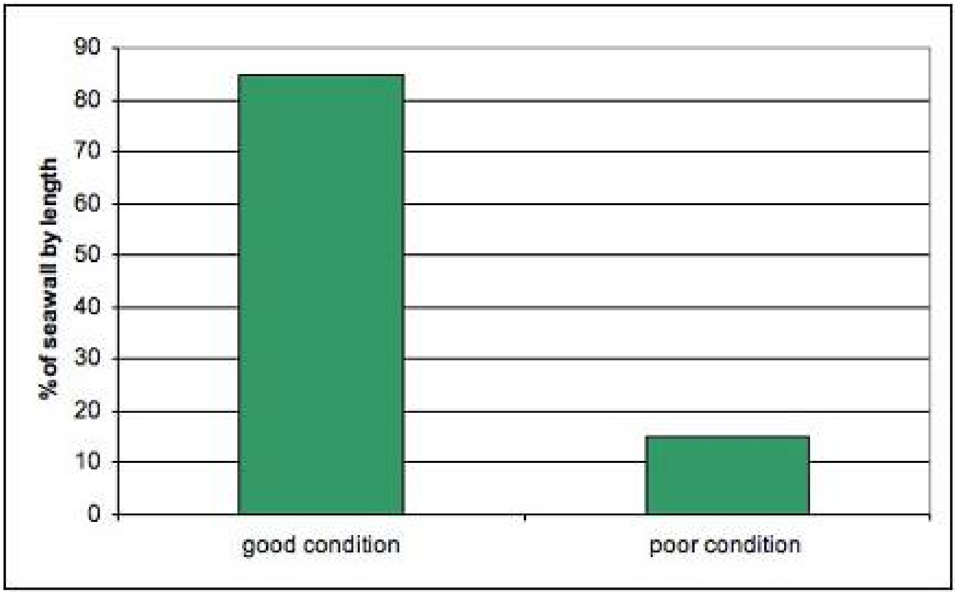

Figure 51. Summary of condition of seawalls, Boston Harbor.

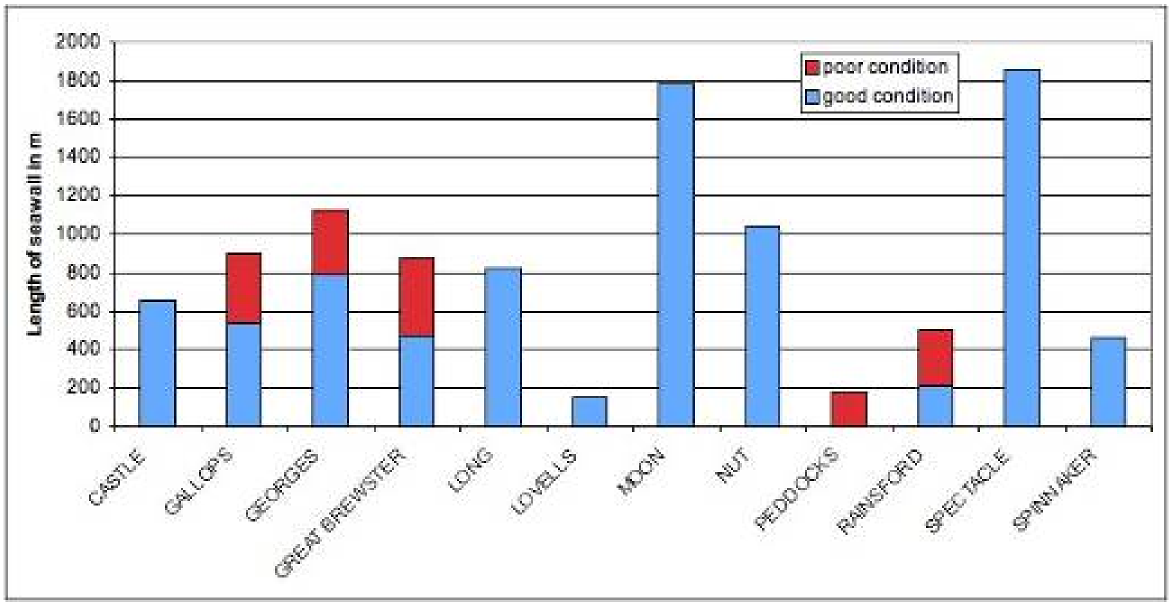

Figure 52. Length of seawalls and condition on each island, Boston Harbor.

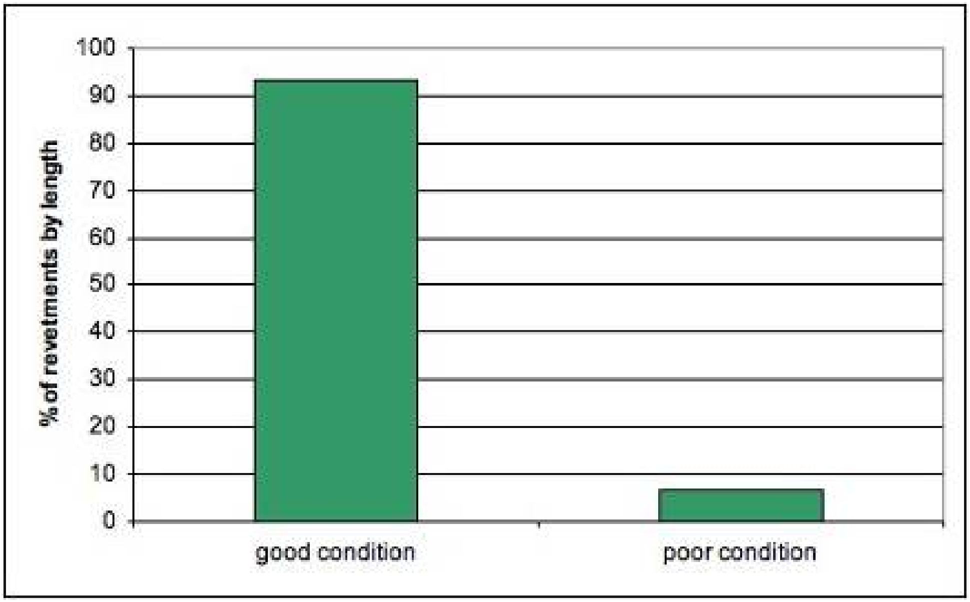

Figure 53. Summary of condition of revetments, Boston Harbor.

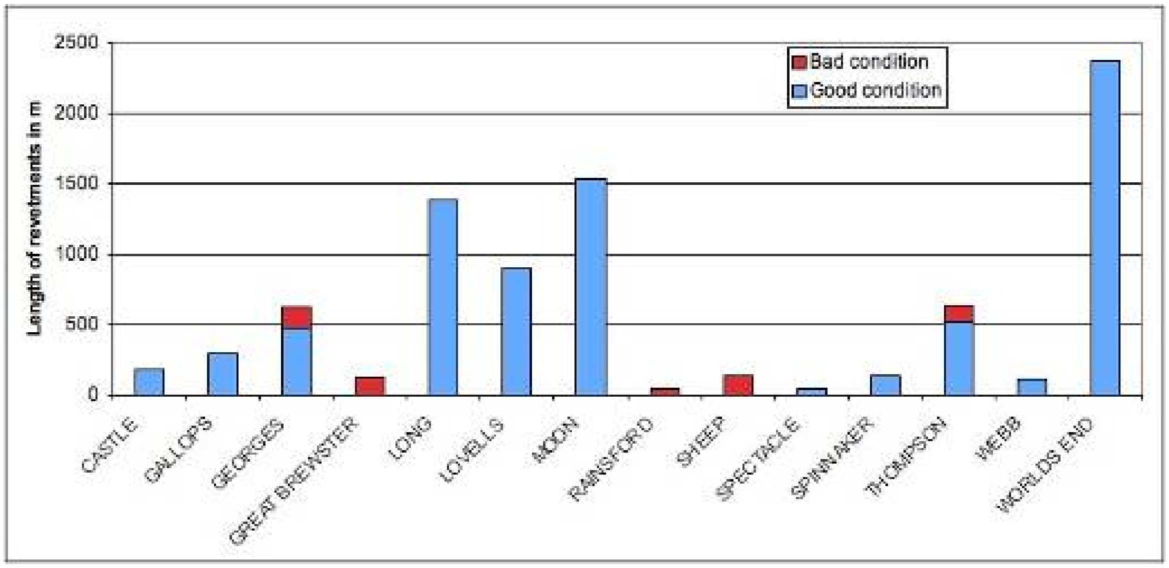

Figure 54. Length of revetment and condition on each island, Boston Harbor.

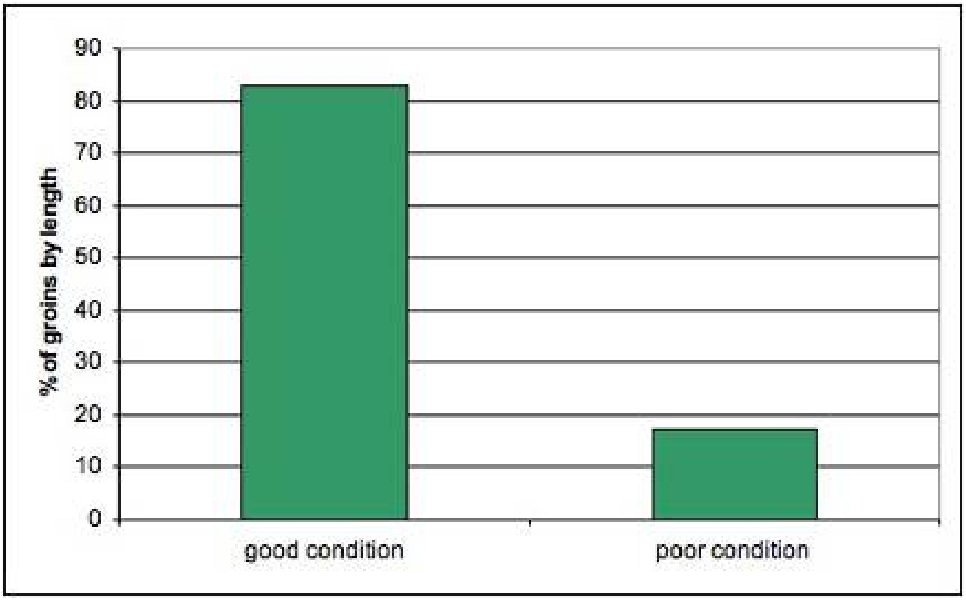

Figure 55. Summary of condition of groins, Boston Harbor.

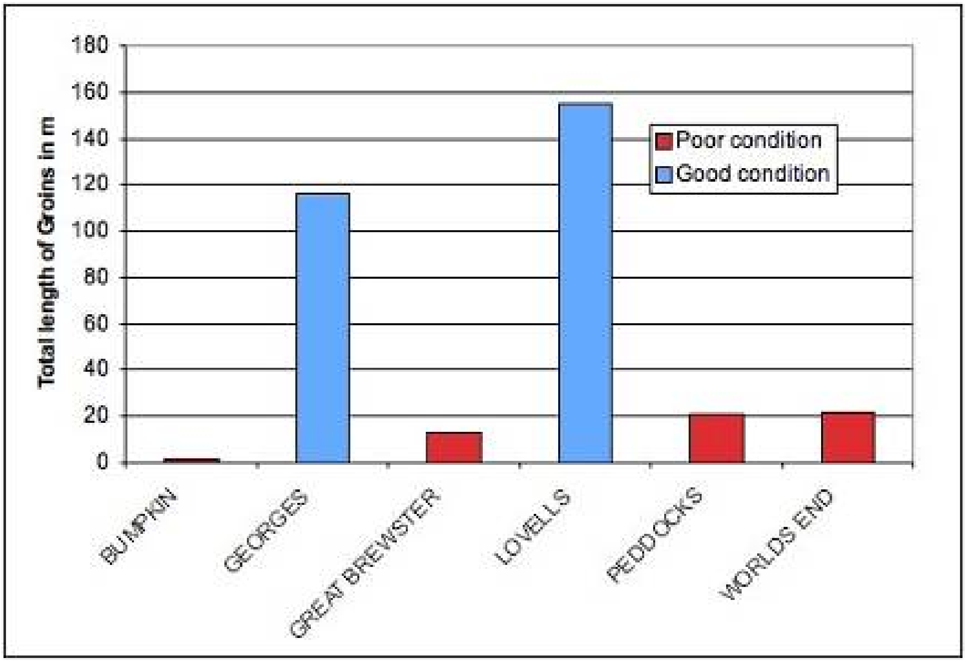

Figure 56. Length of groins and condition on each island, Boston Harbor.

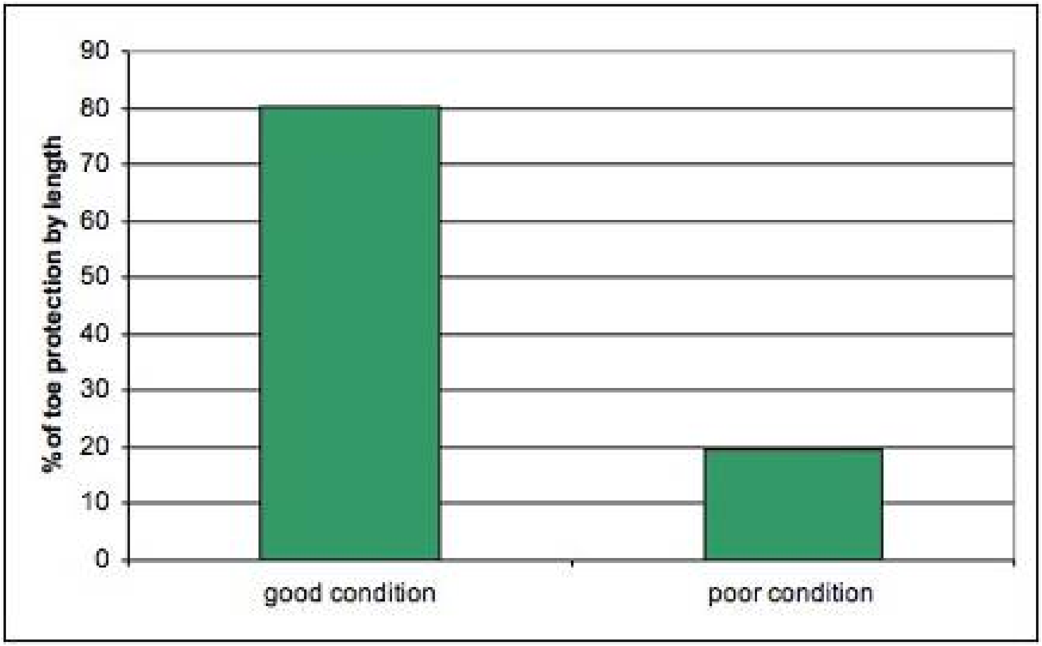

Figure 57. Summary of condition of toe protection, Boston Harbor.

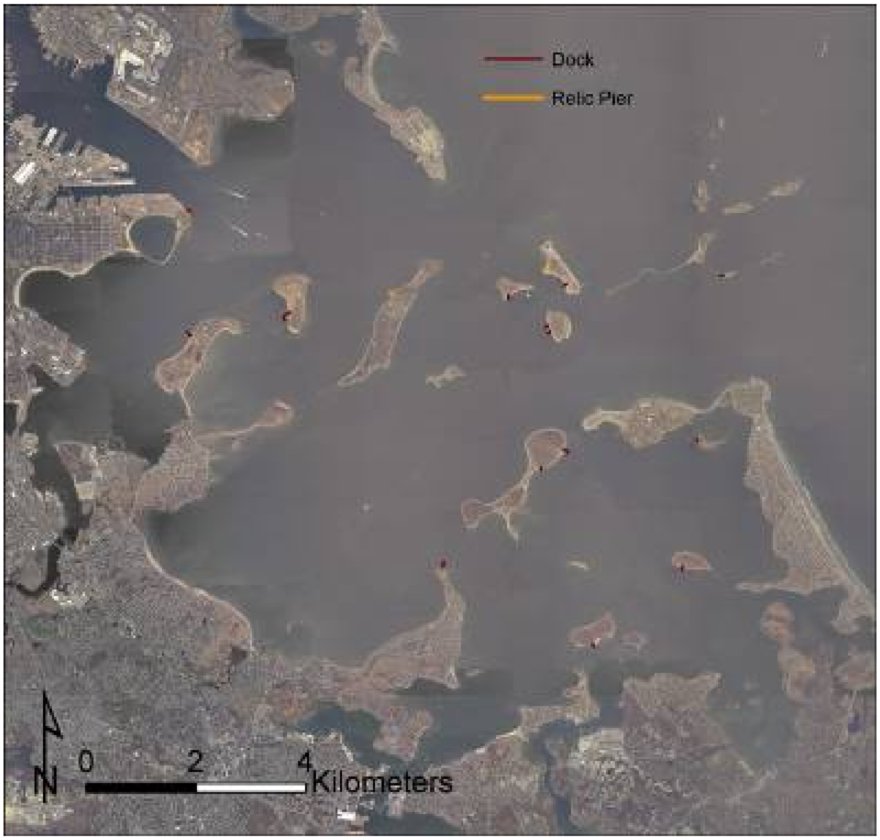

Figure 58. Distribution of docks and piers in Boston Harbor.

Table 6. Coastal structures observed and assessed within the Boston Harbor Islands National Recreation Area.

	Total length in m	% good	% poor
Groin	327	83	17
Revetment	8542	93	7
Seawall	10345	85	15
Toe protection	402	80	20

Bluffs and Bedrock

The outer islands are dominated by bedrock with very little drumlin till (Figure 59), however islands in the south of the Harbor also commonly exhibit exposed bedrock, including Slate and parts of Worlds End.

Over 23.5 km of glacial bluffs are distributed throughout the Harbor. While the outer islands are dominated by bedrock exposures, there are a few regions of drumlin bluffs, most notably Great Brewster Island, which has the highest bluffs in the Harbor (Figure 60). The morphology of a drumlin, being shaped like an upside down spoon, means that as the perimeter erodes there is potential for variation in bluff height around an individual drumlin; this can be seen in Figure 60. However, the majority (61%) of bluffs fall into the 3-10 m range, with only 24% being less than 3 m and 15% being over 10 m (Figure 61).

The bluffs were assessed for their condition, in terms of both amount of vegetation, if stable, and by which process they are eroding, if they are not stable (Figure 62). The majority of bluffs are stable and either vegetated or partially vegetated (Figure 63 and 64). Eroding bluffs are unvegetated and may be eroding either by slumping, slopewash (which in extreme cases, creates rills and gulleys that spread from the base of the bluff upwards), or a combination of the two (Figure 62).

The greatest length of bluffs occurs on the larger islands, Long, Peddocks, and Worlds End (Figure 65). Moon Island has high lengths of bluff, however not all of this is drumlin bluff. Instead a large portion lies along the man-made land bridge between the island and the mainland. Much of this land bridge is seawalled; however some sections are eroding by slumping (Figure 64 and 65).

In total, 80% of the bluffs are classified as stable and 20% as eroding, the dominant process being slumping (Figure 66). Figure 67 shows the distribution of bluff processes throughout the Harbor. Certain Islands show more bluff erosion than others, notably Great Brewster, where almost half of the bluffs are eroding, Long, Peddocks, and Thompson Island. Almost all of the slopewash or erosion by combined slopewash and slumping occurs on bluffs over 10 m (Figure

68 and 69). Additionally, bluffs over 10 m are more likely (46%) to be eroding than either bluffs 3-10 m (16%) or bluffs less than 3 m (13%). These results are summarized in Table 7.

Figures 70 and 71 give an estimate of average, maximum, and minimum fetches associated with erosion process and bluff height. Higher minimum and average fetches are associated with bluffs eroding by slopewash or combined slumping and slopewash. This is counter-intuitive as slumping would more likely be associated with wave notching, if it were occurring. Figure 71 shows that taller bluffs also tend to have higher fetches.

Peddocks, Long, Rainsford, Great Brewster, and Lovell's Islands have a high percentage of tall bluffs (Figure 72). This may be a consequence of initially higher drumlins but is also likely to be the consequence of greater lateral erosion into the drumlin. Again, bluffs on Moon Island are skewed by the inclusion of the long section of man-made bluffs which line the land bridge between the Island and the mainland. Some evidence of erosion of these man-made till features is observed in areas where no sea wall or armoring protects them.

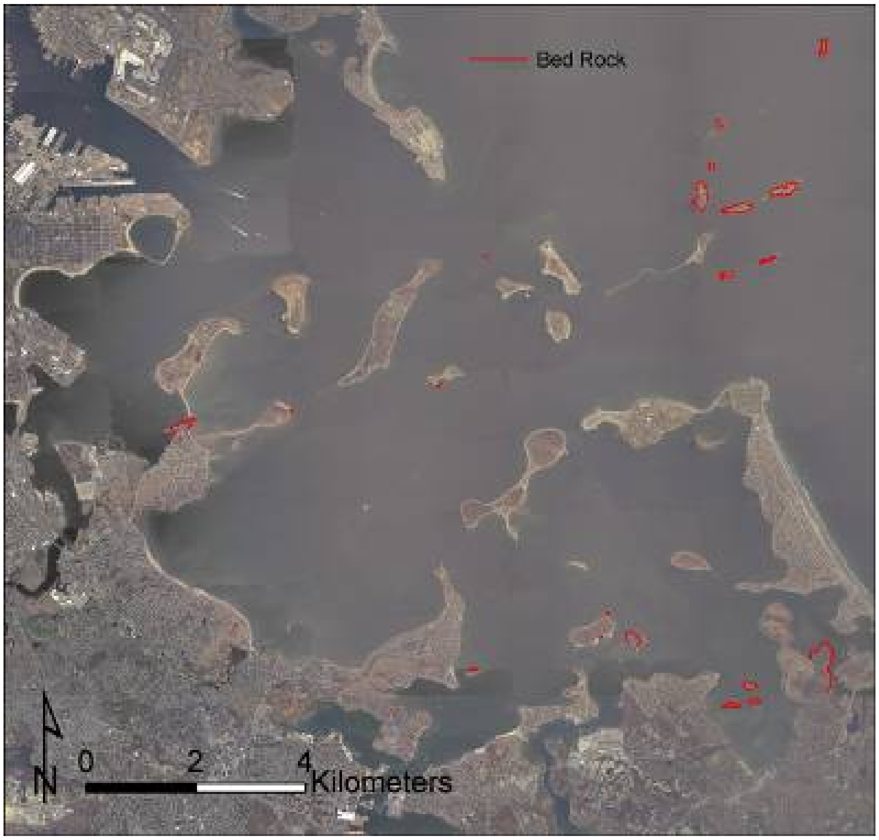

Figure 59. Exposures of bedrock along shorelines in Boston Harbor.

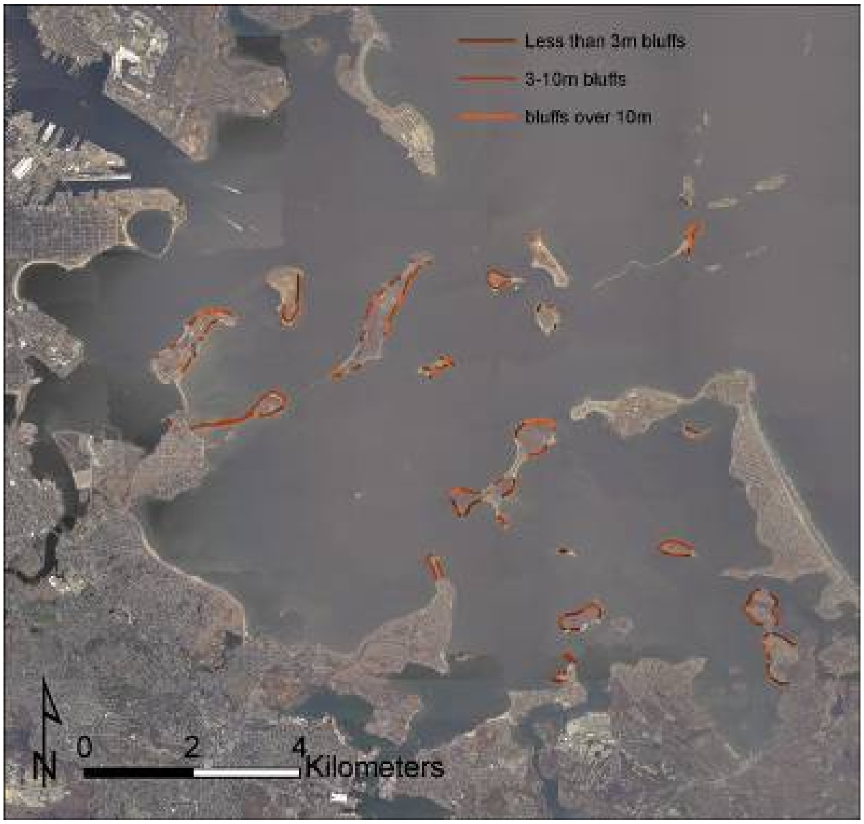

Figure 60. Distribution of bluff heights in Boston Harbor.

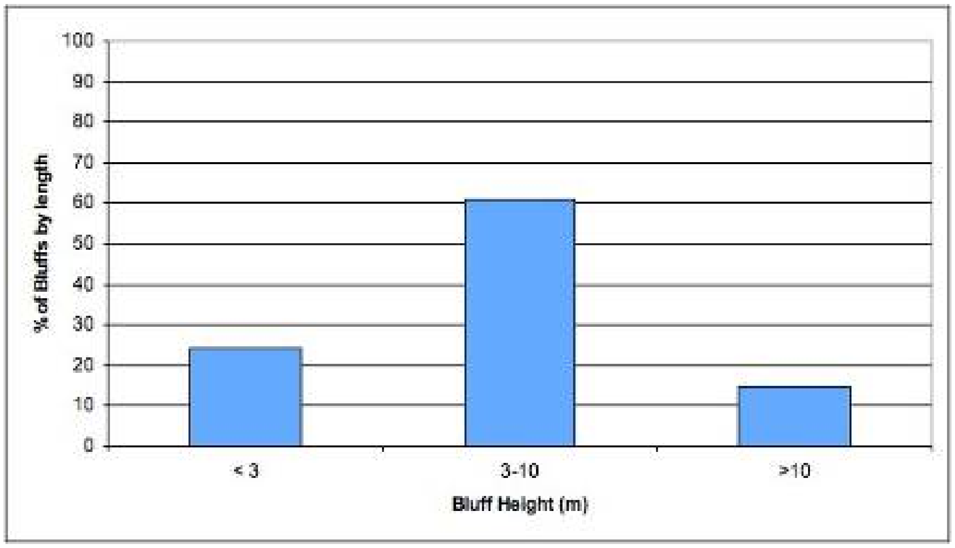

Figure 61 Frequency of bluff heights in Boston Harbor.

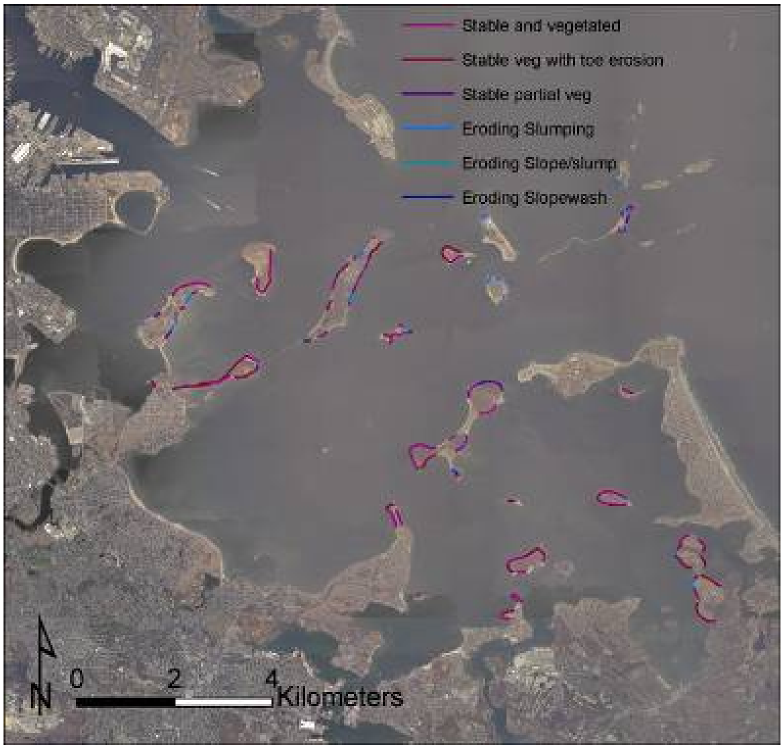

Figure 62. Major slope processes on Boston Harbor bluffs.

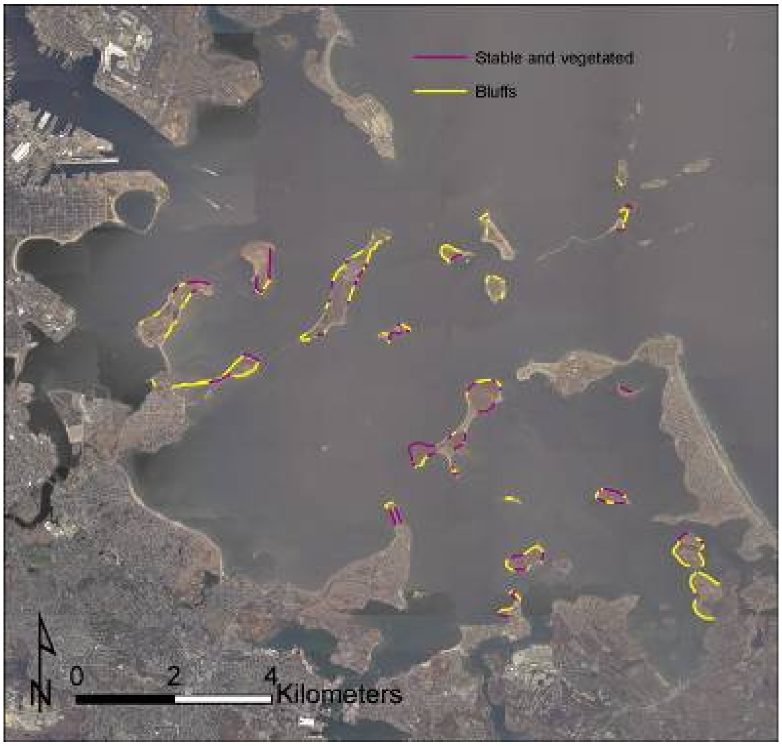

Figure 63. Position of the bluffs in the Harbor stabilized by vegetation (purple) and all bluffs (yellow).

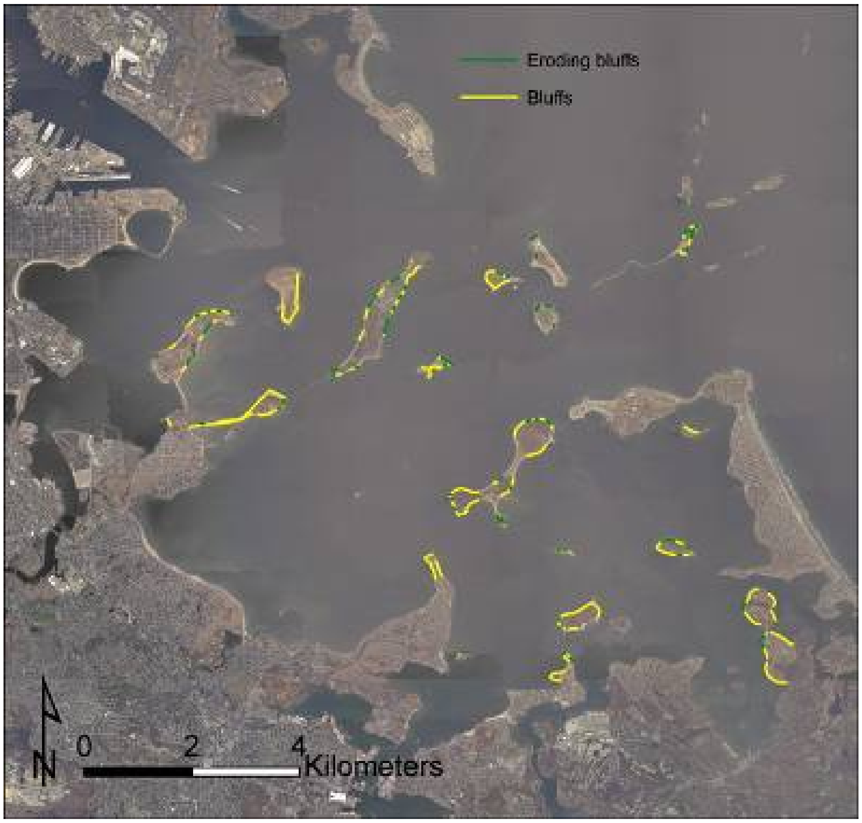

Figure 64. Positions of eroding bluffs in Boston Harbor (green) and all bluffs (yellow).

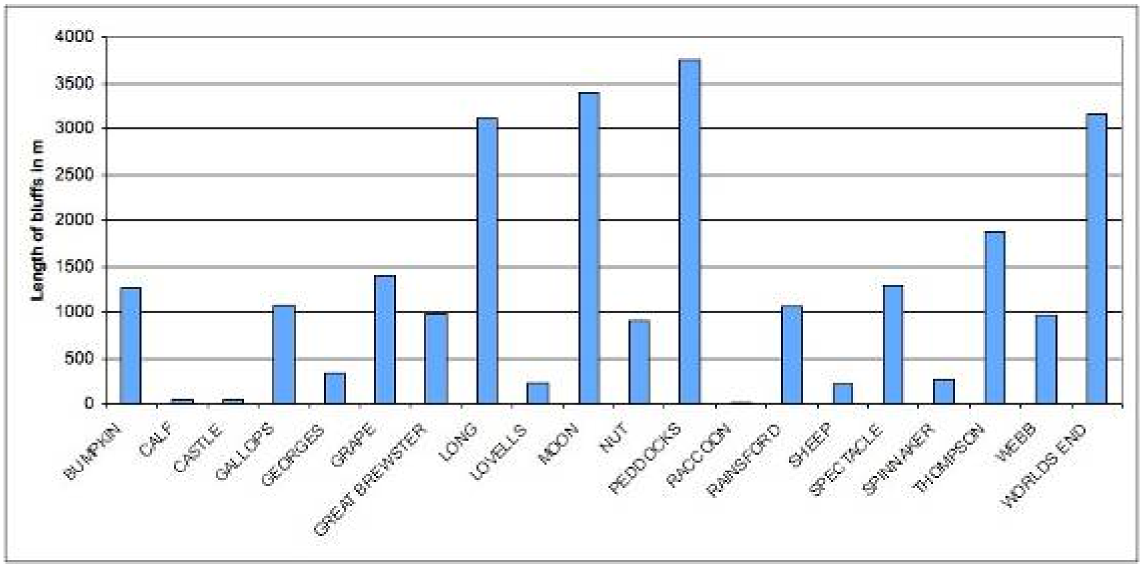

Figure 65. Lengths of bluffs on islands, Boston Harbor.

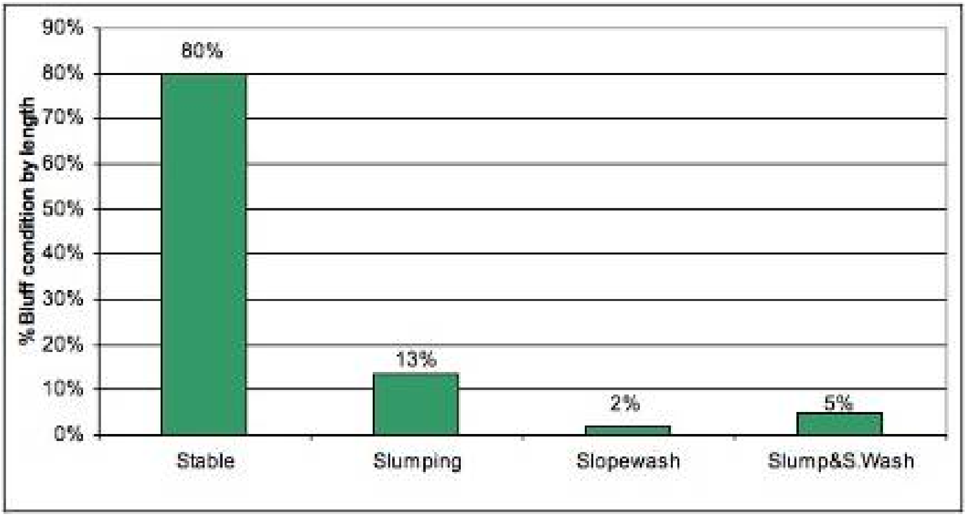

Figure 66. Frequency of bluff processes by overall length, Boston Harbor.

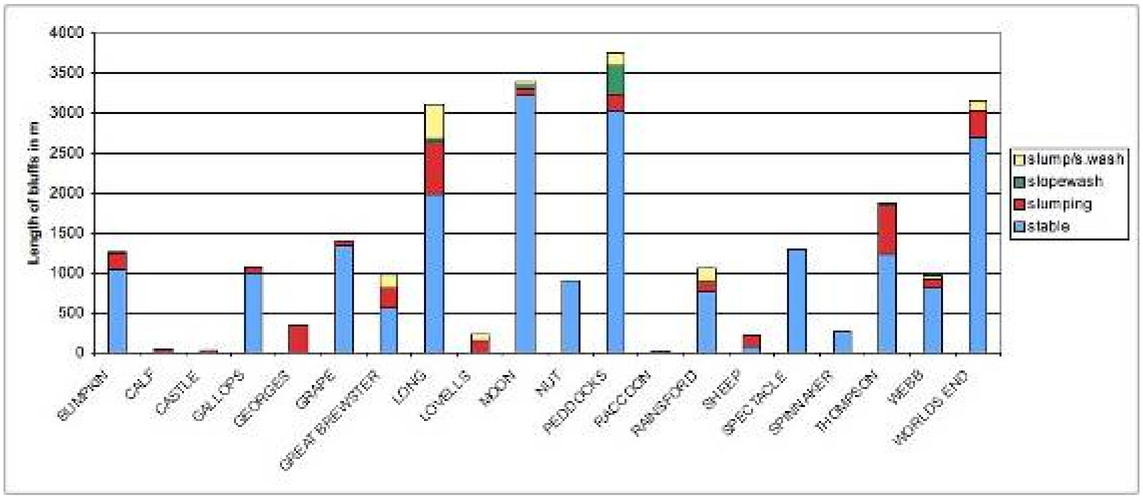

Figure 67. Distribution of bluff processes on islands, Boston Harbor.

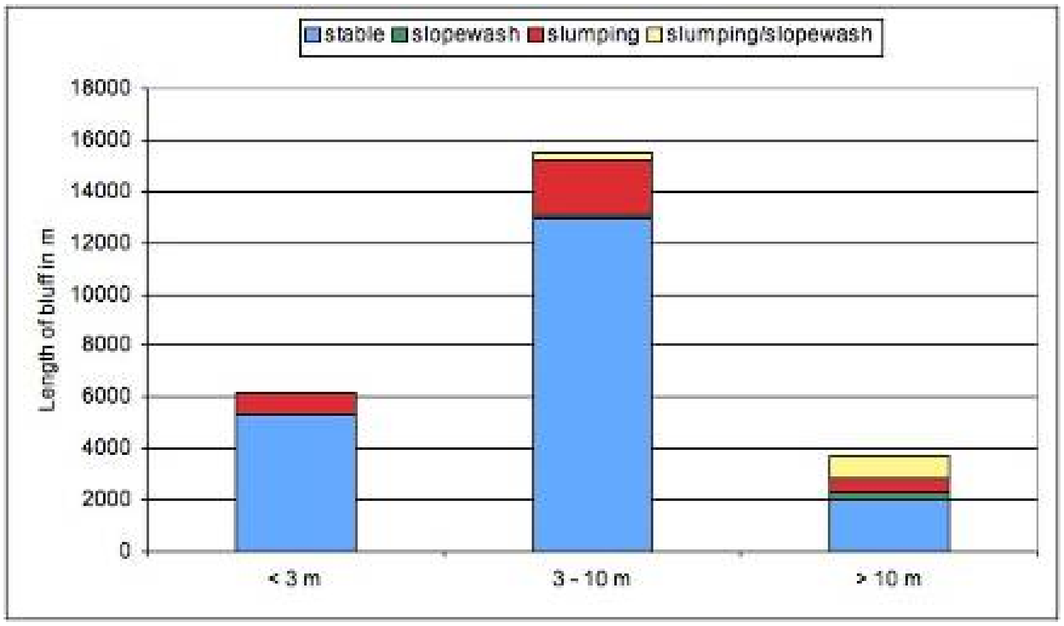

Figure 68. Distribution of bluff processes based on bluff length, Boston Harbor.

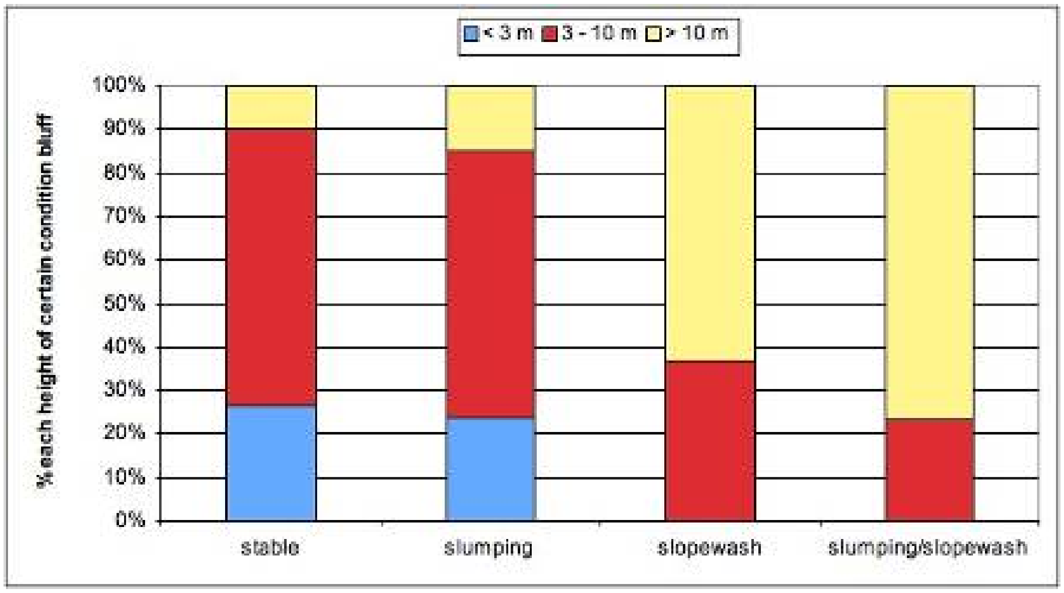

Figure 69. Bluff form compared to bluff heights, Boston Harbor.

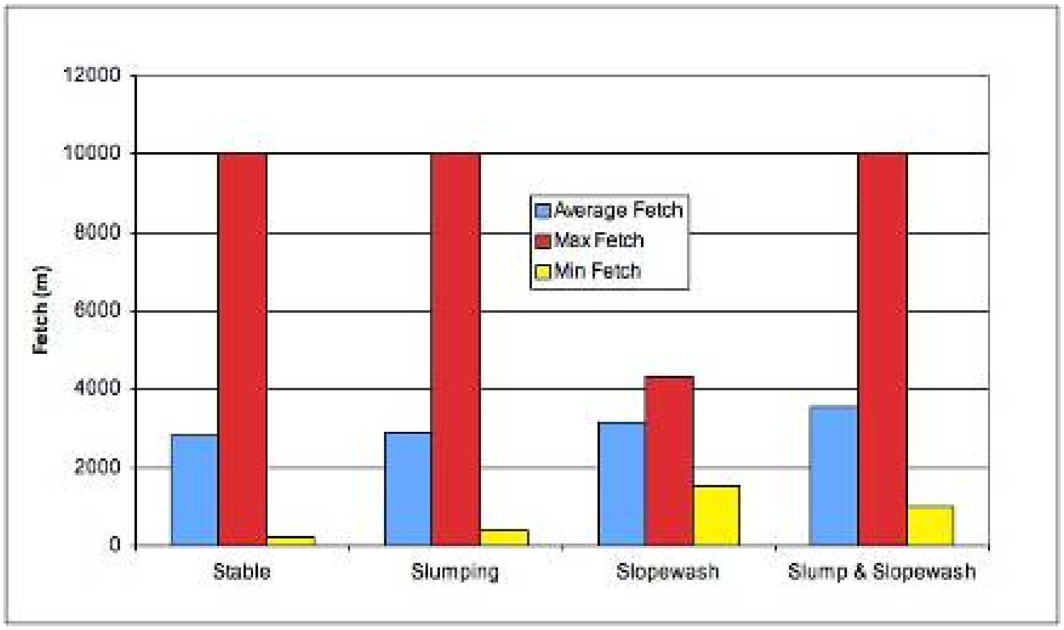

Figure 70. Bluff forms compared to fetch distances.

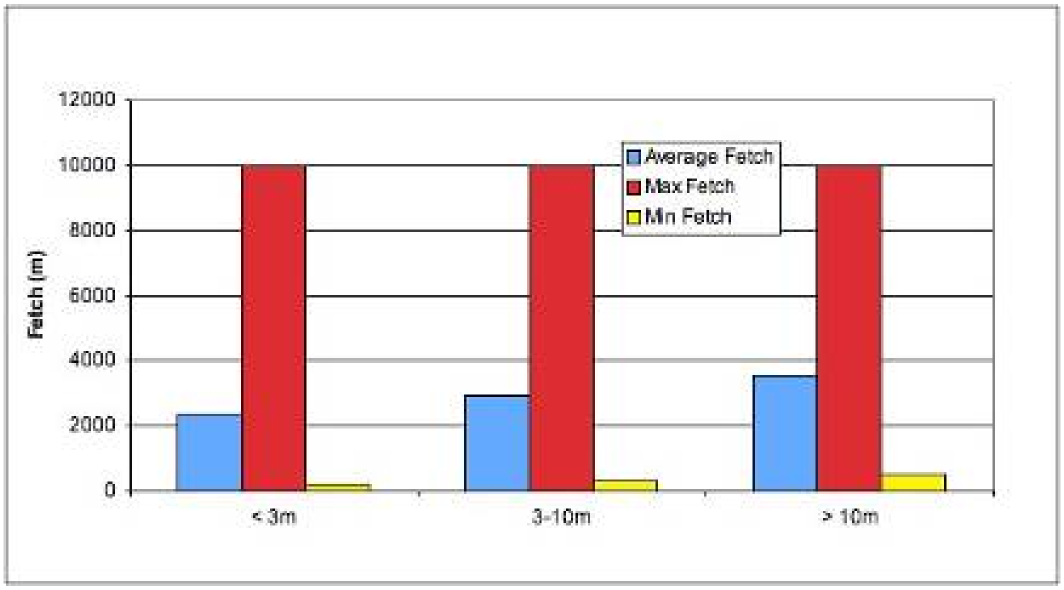

Figure 71. Bluff heights compared to fetch distances.

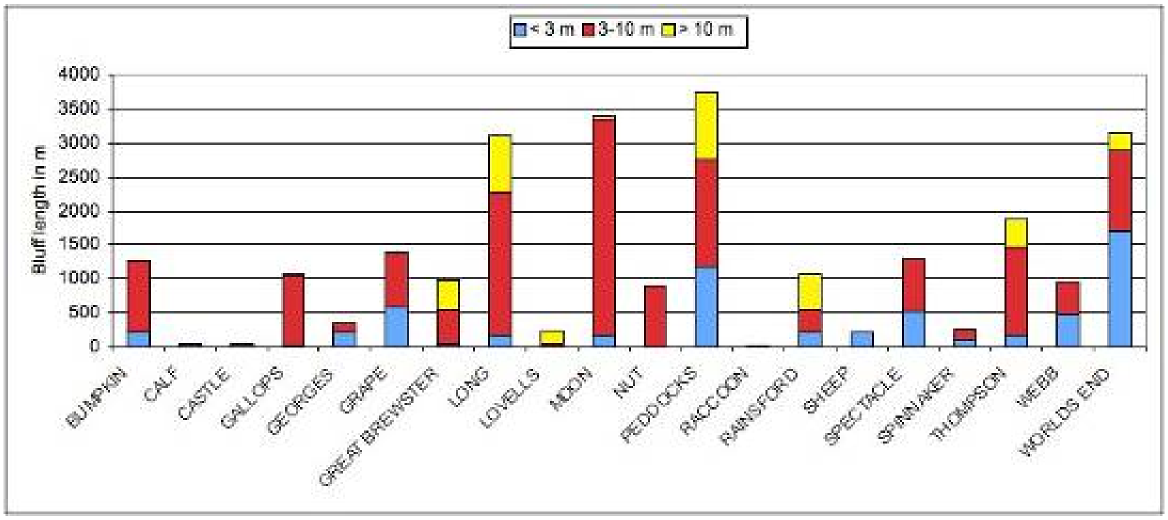

Figure 72. Bluff height distribution on each island, Boston Harbor.

Table 7. Summary of bluff length and processes for each island, Boston Harbor.

	Total length (m)	% <3 m	% 3-10 m	% >10 m	% stable	% eroding	% slumping	% slopewash	% slumping/ slopewash
Bumpkin	1260	17	83	0	83	17	16	0	1
Calf	53	100	0	0	0	100	100	0	0
Castle	39	100	0	0	0	100	100	0	0
Gallops	1077	2	94	4	93	7	7	0	0
Georges	342	66	34	0	0	100	100	0	0
Grape	1405	42	57	1	96	4	4	0	0
Great Brewster	978	5	50	45	58	42	25	0	17
Long	3104	6	68	27	64	36	21	2	13
Lovells	236	0	21	79	0	100	65	0	35
Moon	3395	5	94	1	95	5	2	1	2
Nut	907	0	100	0	100	0	0	0	0
Peddocks	3748	30	45	25	81	19	6	10	4
Raccoon	16	100	0	0	100	0	0	0	0
Rainsford	1061	20	32	48	73	27	12	0	15
Sheep	218	100	0	0	37	63	63	0	0
Spectacle	1290	45	55	0	100	0	0	0	0
Spinnaker	263	64	36	0	100	0	0	0	0
Thompson	1874	10	68	22	66	34	33	0	1
Webb	970	50	50	0	84	16	11	0	4
Worlds End	3152	54	38	8	86	14	11	0	4
Harbor	**25386**	**24**	**61**	**15**	**80**	**20**	**13**	**2**	**5**

Bluff orientation is compared to the process of erosion in Figure 73, which shows that less erosion occurs in the south and more occurs in the northern sectors. The high rates of slopewash that occur in the northwest, compared to other directions, suggest that this is related to the high percentage of bluffs (>10 m) which have this orientation, which, in turn, is likely because of drumlin orientation. High rates of slumping are seen in the east.

Marshes

Shoreline marshes mostly occur within the sheltered inner regions of the Harbor (Figure 74), some of which fringe exposed shorefaces and some of which occur in sheltered embayments and coves. A further 4 km (by perimeter) of marshes occur inland (Figure 75). These marshes and their ability to survive as sea level rises will be the subject of a future study.

Over 2 km of shoreline marsh was observed in sheltered embayments, bays or coves around the harbor islands (Figure 75 and 76). These areas of marsh were more protected and exhibited very little edge erosion. The largest regions of embayed marsh occur on Worlds End.

Almost 10 km of fringe marsh, i.e shoreline marshes on straight and/or exposed shores, was observed during the survey period (Figure 77). Surveys were performed during all tidal water levels, rather than being limited to just low water, which meant that the edges of marshes could not always be observed as they were submerged. However, of the 59% which could be assessed, 34% were observed to be scarping i.e. undergoing active erosion at the edge **(**Figure 78). Fringe marshes occur on many islands, however greater lengths of this type of marsh are observed on sheltered shorelines of the inner Harbor (Worlds End).

A total of six enclosed saltmarshes can be found within the Harbor Islands, with a perimeter totaling over 4 km. Three of these marshes occur on Peddocks Island, two on Thompson, which also exhibits a large amount of embayed and fringe shoreline marsh, and one on Calf Island in the outer Harbor east of Lovell’s Island (Figure 75 and 79).

Beach Morphology

During the survey over 7 km of overtopping ridges (gravel or shell) were observed. While these are not permanent features they may remain for several years or more in a given location and demonstrate the regions that experience high wave conditions during storms (Figure 80 and 81).

Long and Thompson Island exhibit the greatest *length* of ridge monitored (Figure 81). These data, however, do not give an estimate of the height of the ridge. Ridges on Lovell's are notably tall and extend a great distance inland.

By length, 884 m of dunes were measured throughout the Harbor, 78% of which are naturally occurring (the rest incorporating the Spectacle Island man-made dune). Of the natural dunes, almost 70% occur on Lovell’s Island, which contains an exceptional amount of sand in comparison to the other islands (Figure 82).

There are six islands with one or more salients; both Grape and Lovell’s island exhibit two salients. The largest salient is that on Thompson Island (Figure 83).

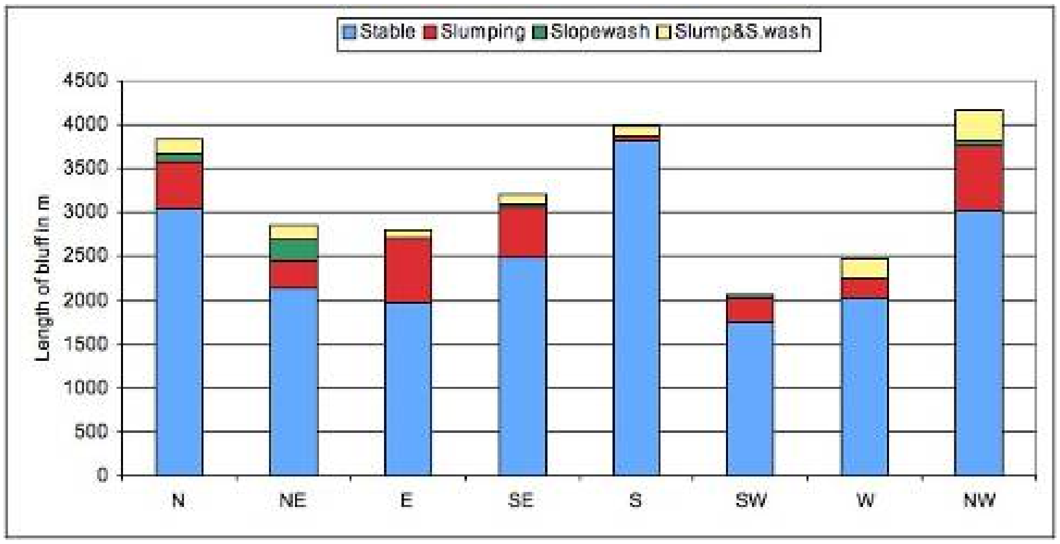

Figure 73. Bluff processes compared to exposure, Boston Harbor.

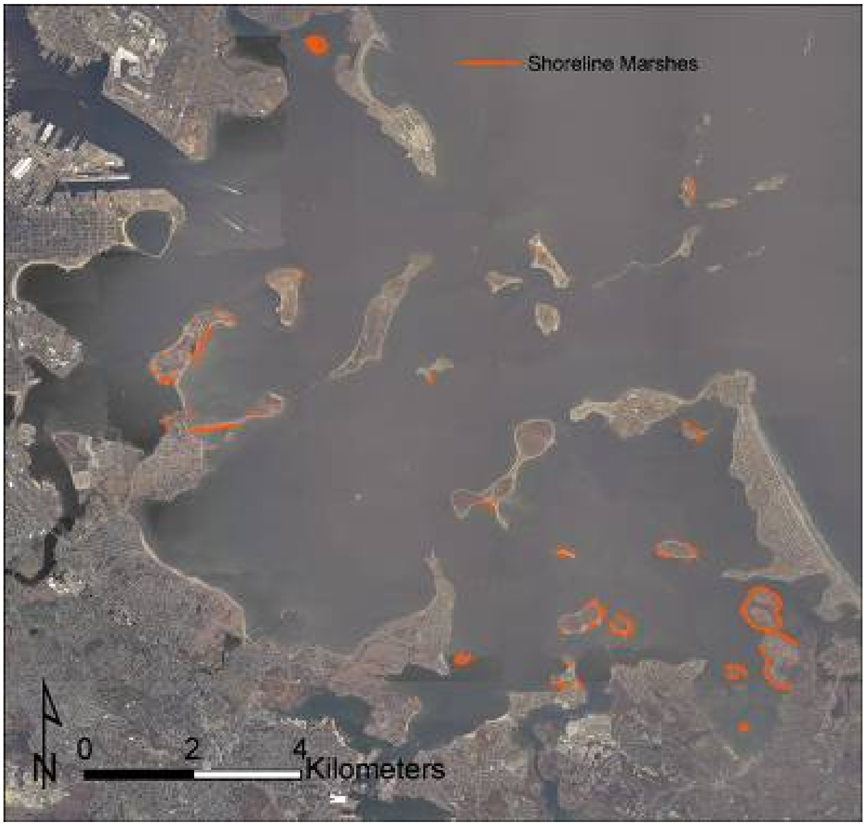

Figure 74. Distribution of salt marshes along shoreline, Boston Harbor.

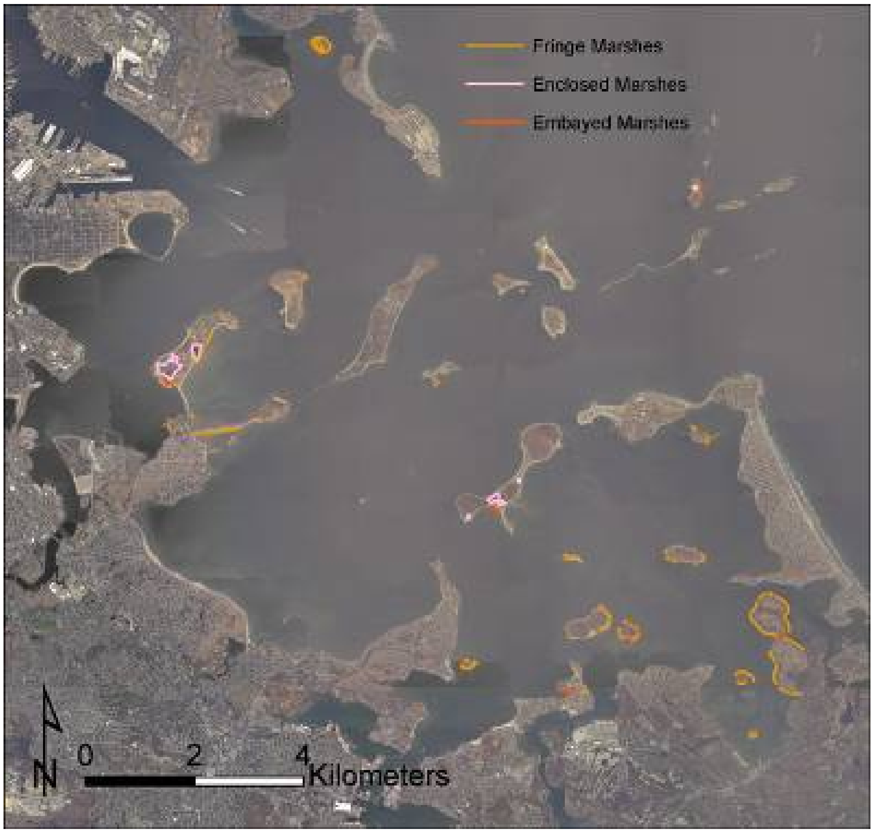

Figure 75. Distribution of salt marsh by types, Boston Harbor.

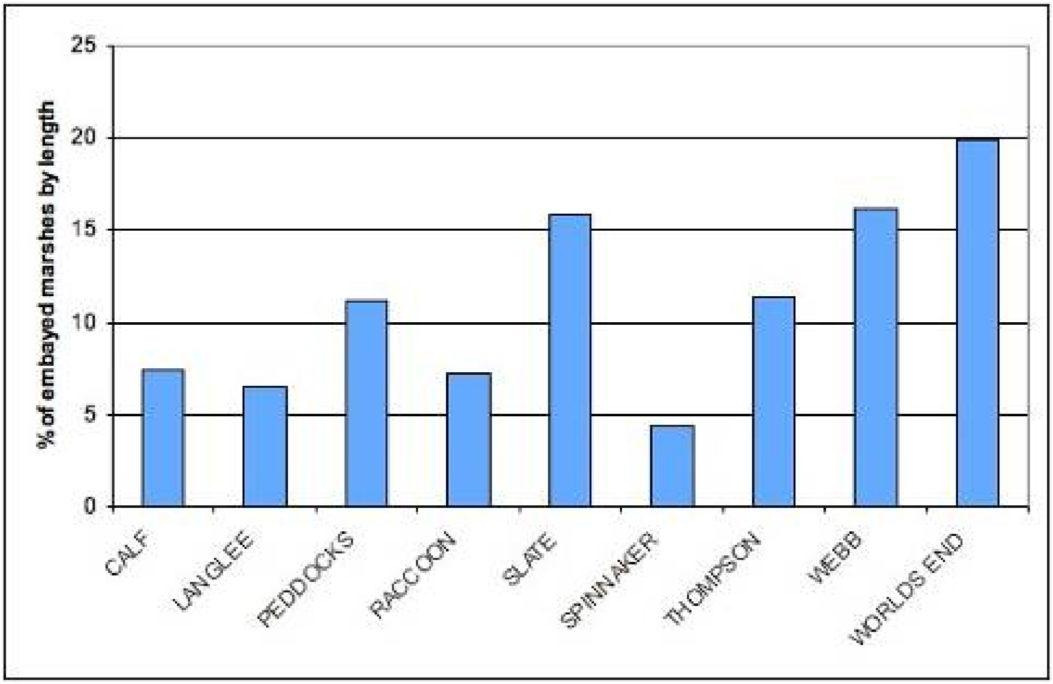

Figure 76. Distribution of embayed marshes across islands, Boston Harbor.

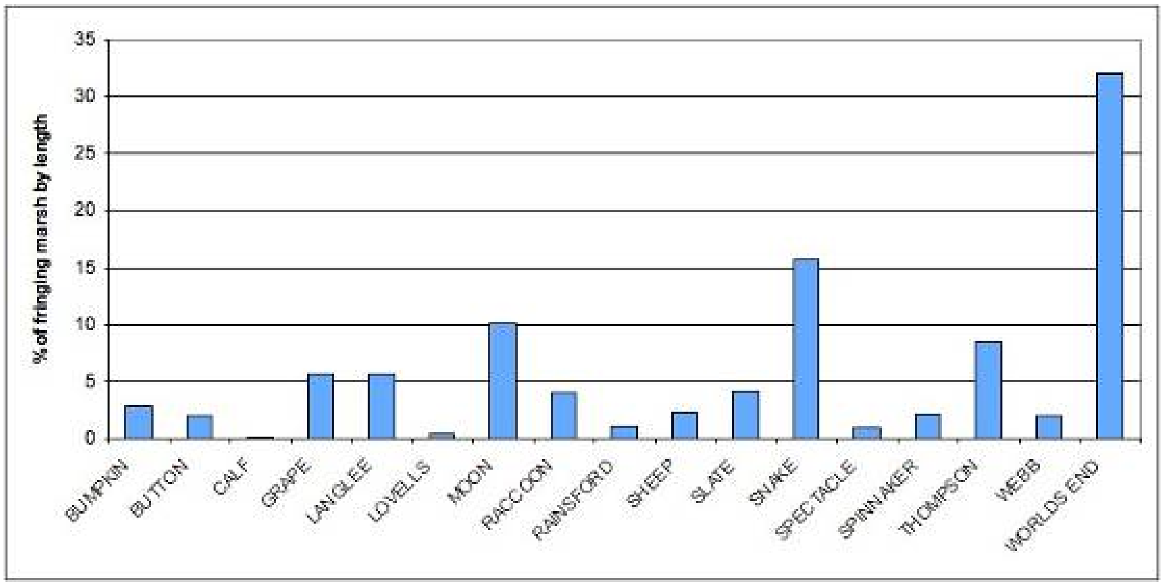

Figure 77. Distribution of fringing marshes across islands, Boston Harbor.

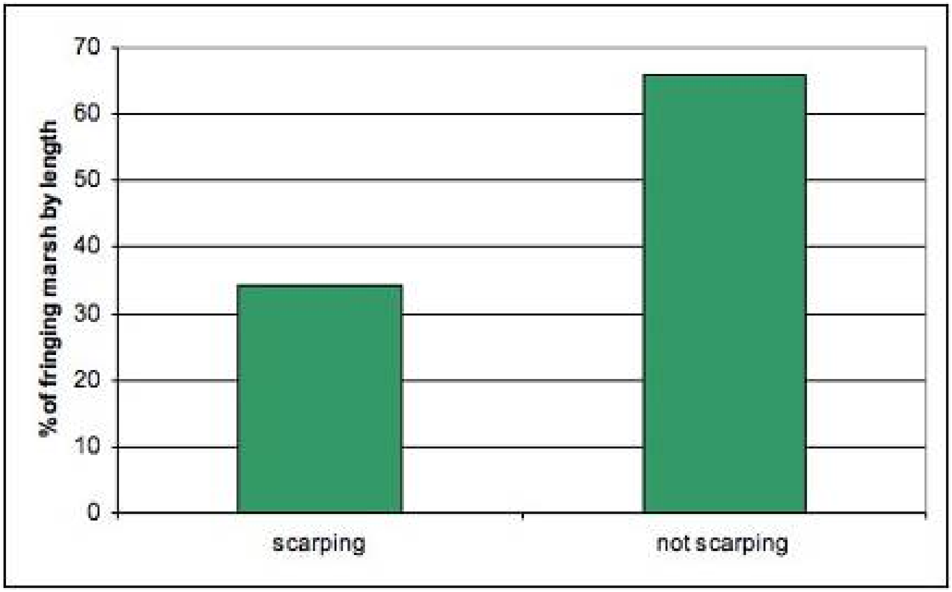

Figure 78. Frequency of scarped and non-scarped fringing salt marshes, Boston Harbor.

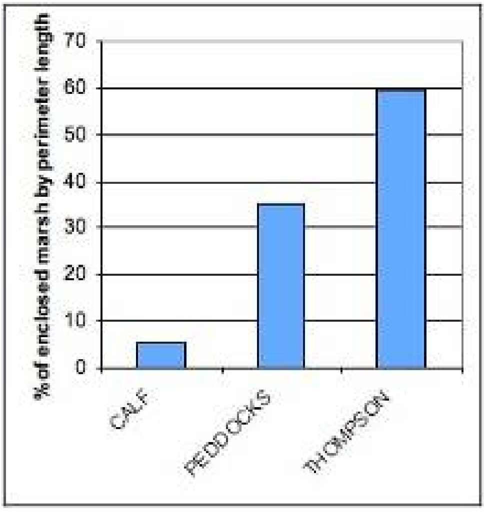

Figure 79. Distribution of enclosed marsh perimeter by islands, Boston Harbor.

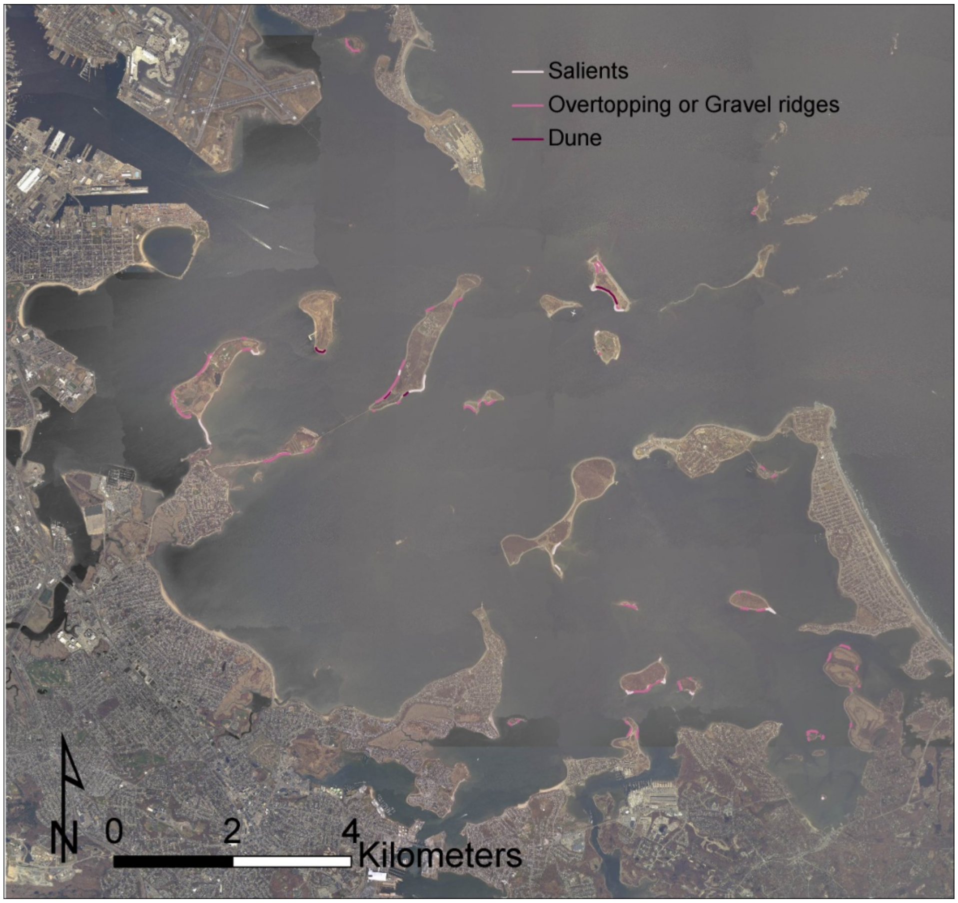

Figure 80. Distribution of certain coastal forms: salients, overtopping gravel ridges and dunes, Boston Harbor.

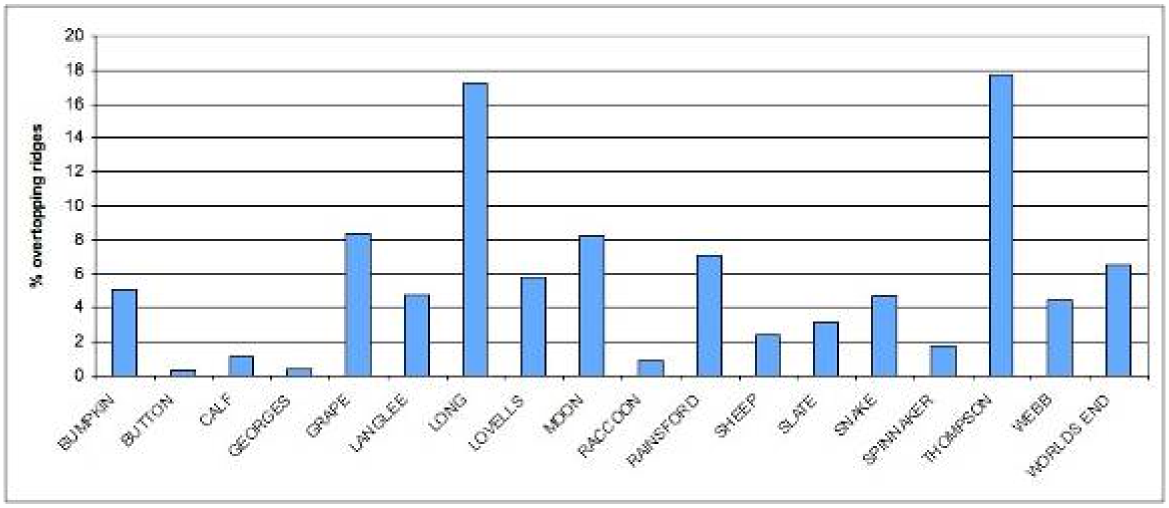

Figure 81. Distribution of overtopping ridges by island, Boston Harbor.

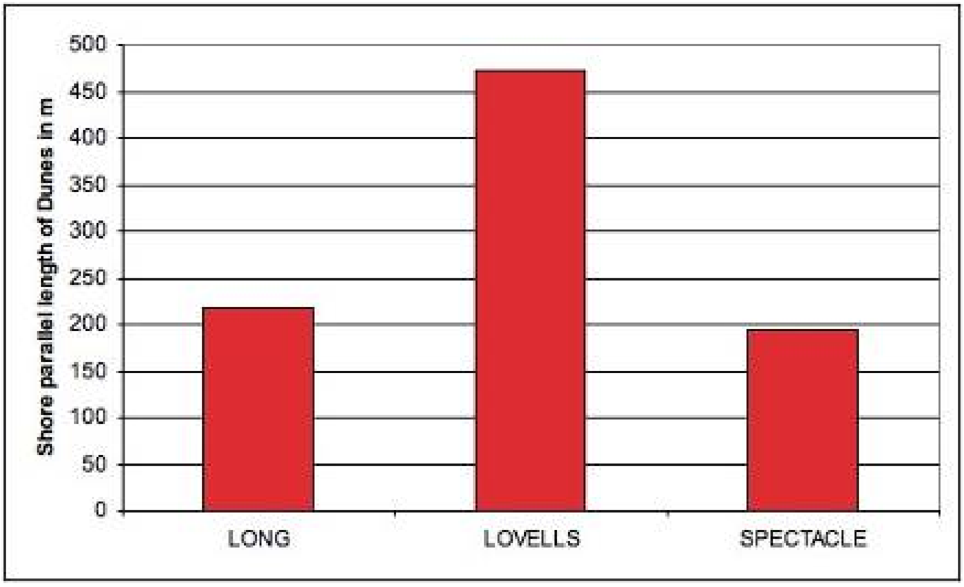

Figure 82. Length of sand dunes by island, Boston Harbor.

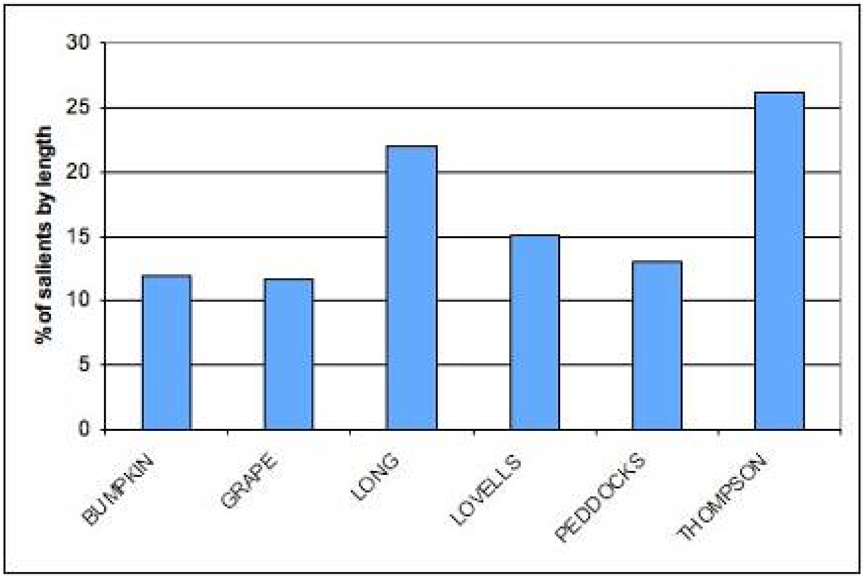

Figure 83. Distribution of salients by length of shoreline and island, Boston Harbor.

Lovell's Island Sub-study

All of the harbor islands have undergone extensive changes during the past 4 to 5,000 years due to bluff erosion and wave reworking of drumlin sediments, which have resulted in the formation of spits, bars, beaches, and lagoons. The geometry of drumlins, the pre-existing topography controlling spit growth, and large range of materials and wave energies result in a complex evolution for many of the island systems. Lovell’s Island is one of the outer islands located at the entrance to Boston Harbor. Due to its exposure to northeast storm wave climate, Lovell’s has experienced greater morphological changes and higher erosional and depositional sedimentation rates than some of the inner, more protected islands. Sediments on the island, both in the beaches and dunes, were found to be immature (close to the source) and mineralogically similar to those of the bluffs (Figures 84 to 86).

The sea-level curve for the region (Figure 3), bathymetry around the island, surficial bottom sediments in the vicinity of the island, geophysical and sedimentological data (Figure 87), and present geomorphology of Lovell’s are used to reconstruct a conceptual model of Lovell Island’s evolution (Figure 88). Of particular interest is the development of numerous scarps, existence of a paleo-scarp, formation of salients, and erosion and reworking of a former drumlin.

Time 1. 4-5,000 years BP

Rising sea level floods Boston Harbor. Lovell Island consists of a cluster of attached and isolated drumlin islands. Erosion commences.

Time 2. 2-3,000 years BP

Extensive erosion of Rams Head located northwest of Lovell’s occurs due to its exposure to open ocean conditions. Much of the sediment eroded on the seaward side of Rams Head forms a southwesterly-trending, mostly sub-tidal spit that connects with the northern drumlin of Lovell

Island. During the same period, the southwesterly-facing central drumlin complex erodes by local wind-generated waves in Boston Harbor, particularly during Southwesters. A bluff 3 to 7 m high develops along this shoreline (see dashed line in Figure 87).

Time 3. 1-2,000 years BP

Continued erosion of Rams Head reduces the former island to a boulder retreat lag. The sand and fine gravel eroded from Rams Head as well as the sediment comprising the sub-tidal spit are transported southward toward Lovell Island. This process results in the development of two spits that connect the northern drumlin to the central drumlin complex. These spits enclose a small embayment eventually forming a fresh to brackish water pond and marsh system.

Time 4. 1,000 years BP to the Present

Due to its open-ocean exposure, the northern and northwestern ends of the island continue to erode, releasing sediment that moves southward by storm waves and southeastward by the prevailing northwesterly wind-generated waves. Ultimately, much of the sand in the system is transported to the leeward side of the island and is redistributed by local wave regimes. Sand accumulates in front of the former active bluff, dunes are formed, and salients are developed along the southwest side of the island (Figure 87). Gravel arrives to the backside of the island at a ater time and mantles some of the sandy accretionary shoreline features. Steep gravel beaches develop along the eastern side of the island.

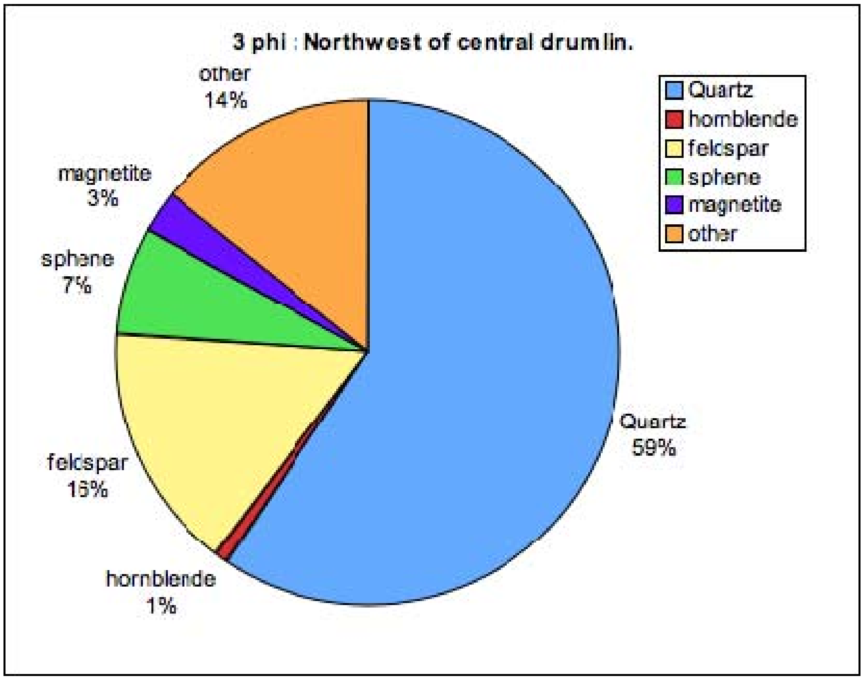

Figure 84. Mineralogy of the 3 phi sample from the central drumlin, northwest bluff on Lovell's Island.

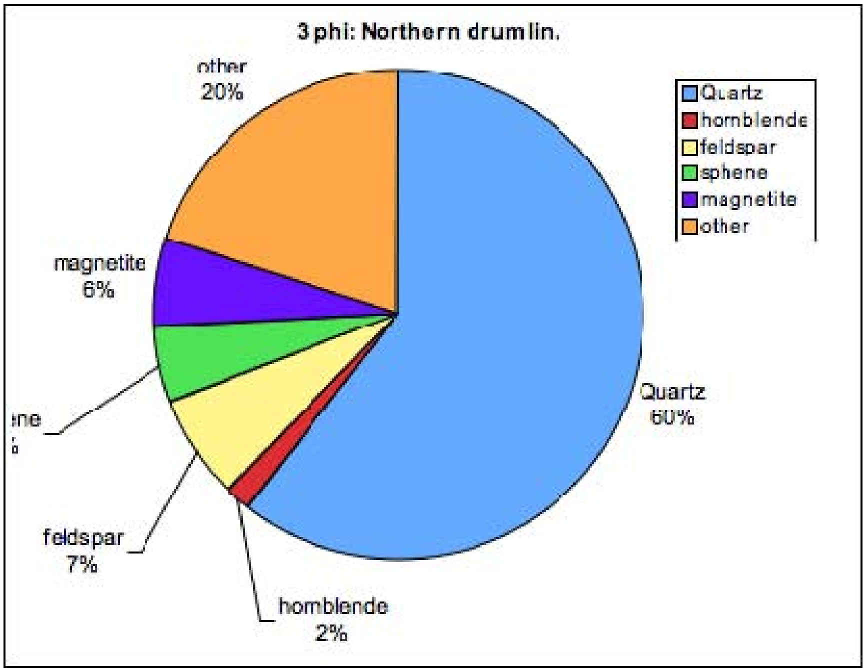

Figure 85. Mineralogy of the 3 phi sample from the drumlin bluff at the north of Lovell's Island.

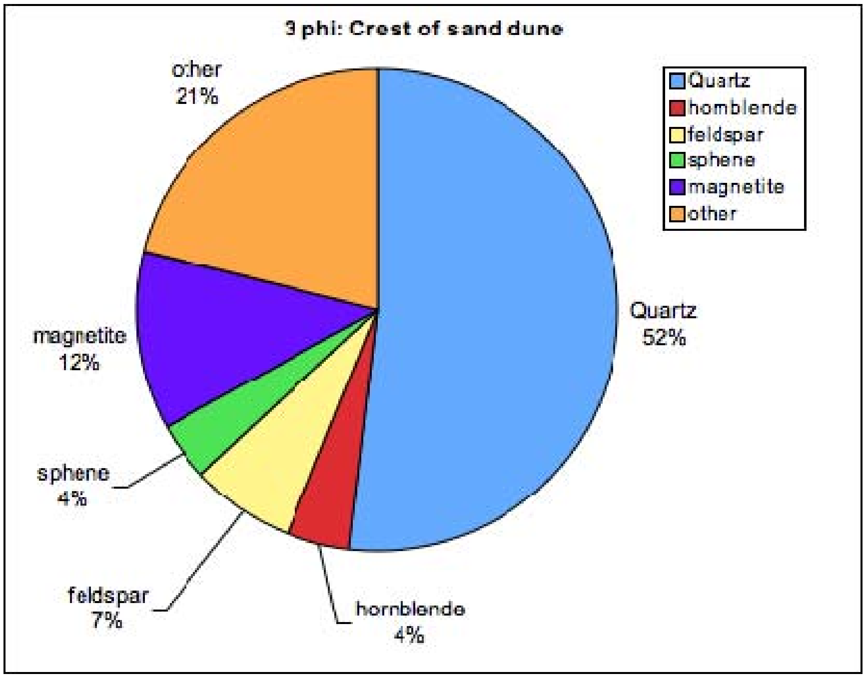

Figure 86. Mineralogy of the 3 phi sample from the dune crest on Lovell's Island.

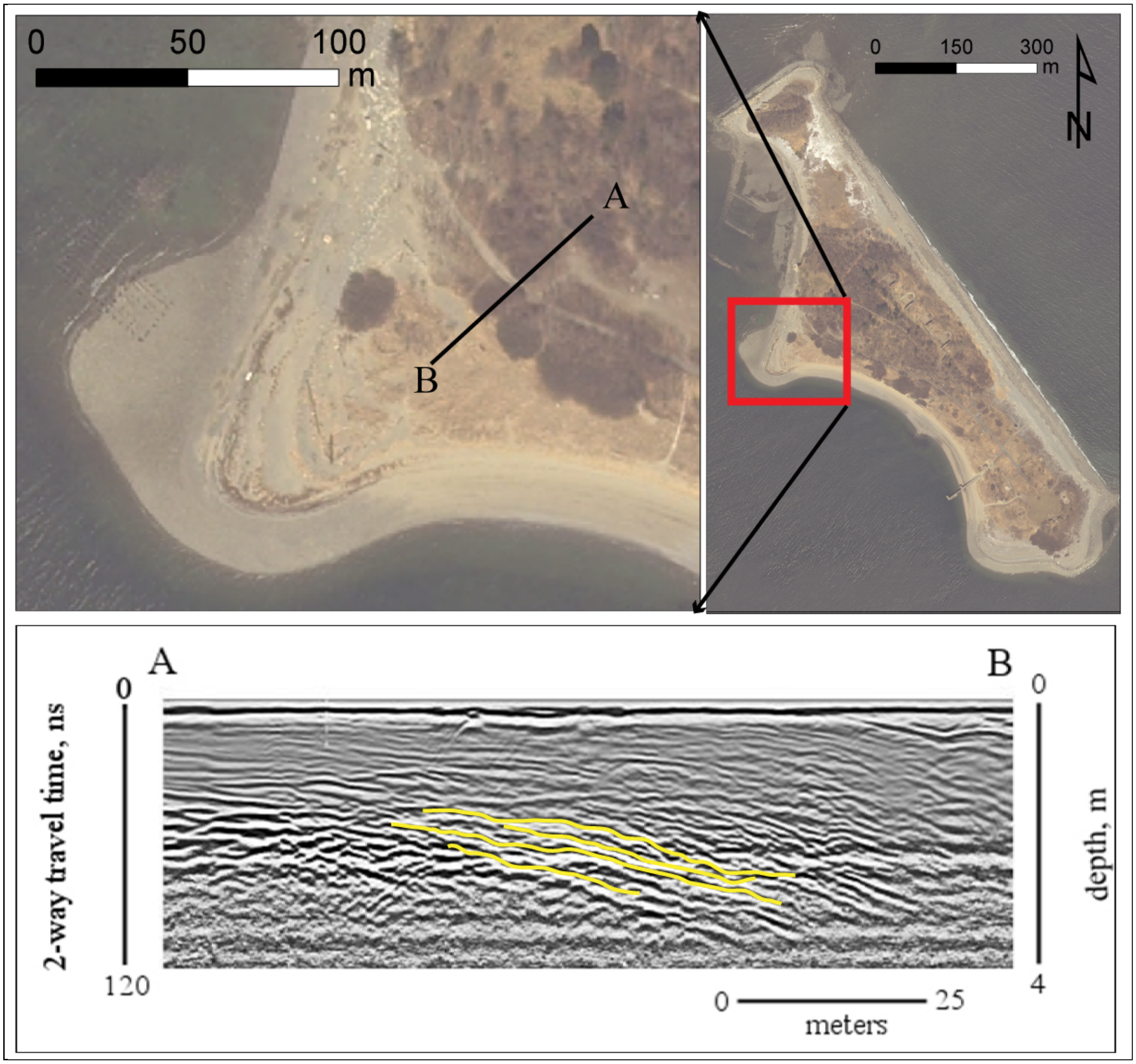

Figure 87. Lovell's Island showing the salient (zoomed image) and the Ground Penetrating Radar transect (above); the GPR data showing prograding shorelines as the beach extends seaward over time (highlighted in yellow) (below).

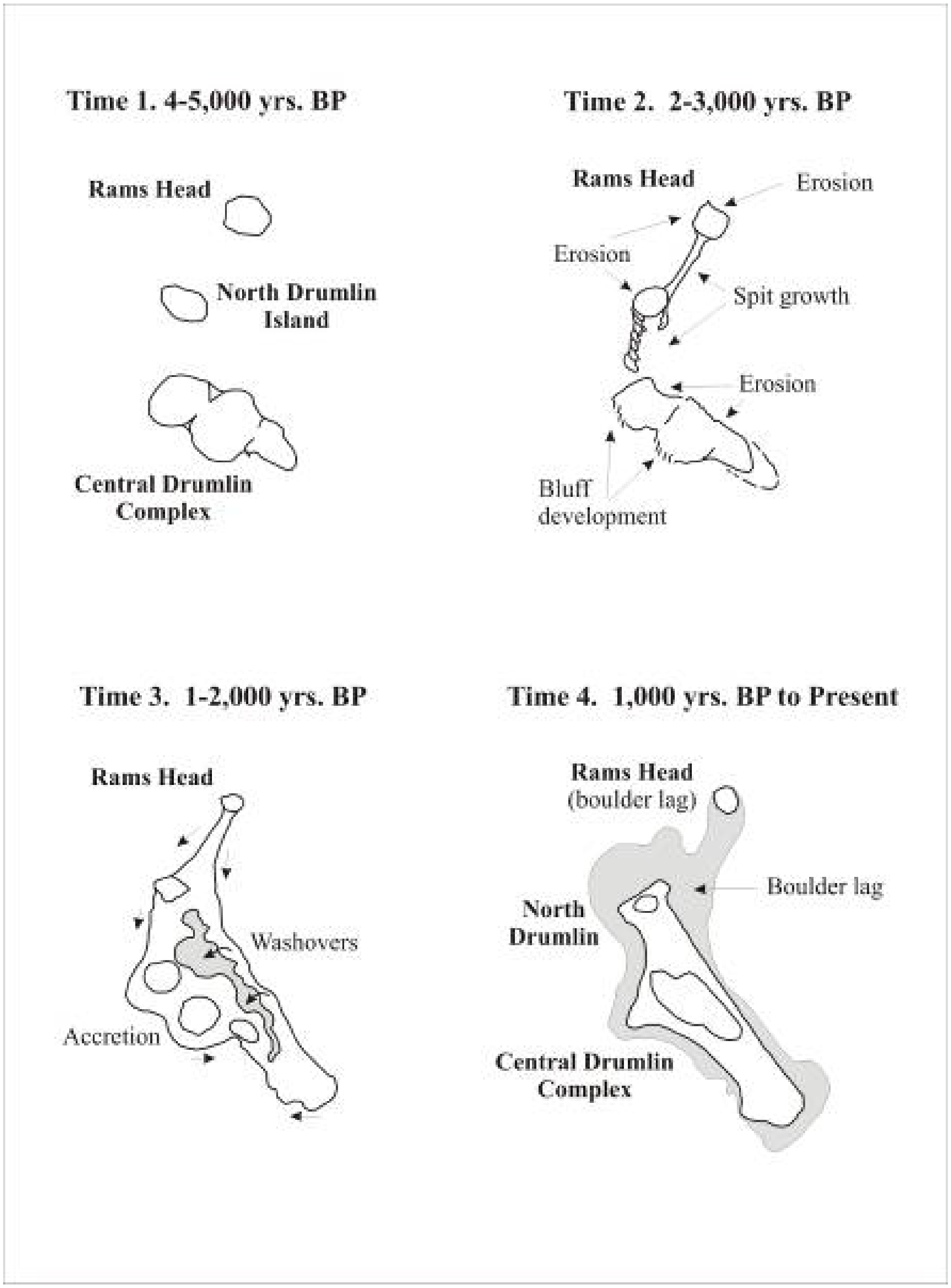

Figure 88. Conceptual model of the formation of Lovell's Island.

Current Observations

The velocity and direction of tidal currents were monitored on three occasions during the period of the study. Examples of such measurements, taken on Long Island in the middle of the northern shore, between Spectacle and Long Island, are shown in Figures 89, 90 and 91. These observations included measurements of waves, currents and a measure of suspended sediments. Further measurements have been collected at Lovell's Island (2005) and Spectacle Island (2008).

Tidal currents in the north west of the Harbor are notably dominated by ebb currents, with flood currents being extremely low at both Spectacle and Long Island (Figure 89 and 90). In the channel between Long and Spectacle Island, the currents flow from east to west during the ebb, and along the southern western shore of Spectacle Island the ebb flows from the north to the south. The velocities in these regions rarely exceed 15 cm/s near the bed (Figure 89 and 91). Higher in the water column (Figure 91), currents reach no more than 40 cm/s, high currents being generated by local gusts of wind operating on the surface of the water. These velocities are not sufficient to suspend sediment, but may be able to move sediment that has been resuspended by waves.

Suspended sediment concentrations are high during periods when the water depth is very shallow and the currents are small, as at low water slack tide. This is likely because the sediment is being suspended by small breaking waves. Wave heights (Figure 91) are less than 10 cm; some spikes due to boat wakes can be seen in the data, as can enhanced wave heights due to a storm on the 24th Sept. Wave data from this deployment, as the location was considered distant from the main ferry route and sheltered from major navigation channels, are used to validate the wave model.

Velocities in the narrows behind Lovell's Island were observed in excess of 1 m/s at 1 m above the bed. These velocities are sufficient to move sediment, and to prevent transport of sediment across the Narrows channel.

Wake Observations

Boat wakes were detected at all monitored sites. Figure 92 and 94 show examples of a typical ferry boat wake produced by a mono-hull vessel traveling at super critical speeds with respect to depth in the channel between Spectacle and Thompson Islands. A low amplitude, long period wave precedes shorter period waves of greater amplitude. Ferries pass the islands regularly; during peak commuting hours this can be up to six or more boats passing per hour (Figure 93). However, our observations show no asymmetry in the number of vessels traveling in each direction (50% moving north, 50% moving south; see example records in Appendices). In the example boat wake, the crest of the wave is moving from the south to the northeast (Figure 94), suggesting that it will transport sediment to the north as it transfers its energy to the shore. The dynamics of boat wakes also suggest that sediment may be moved onshore.

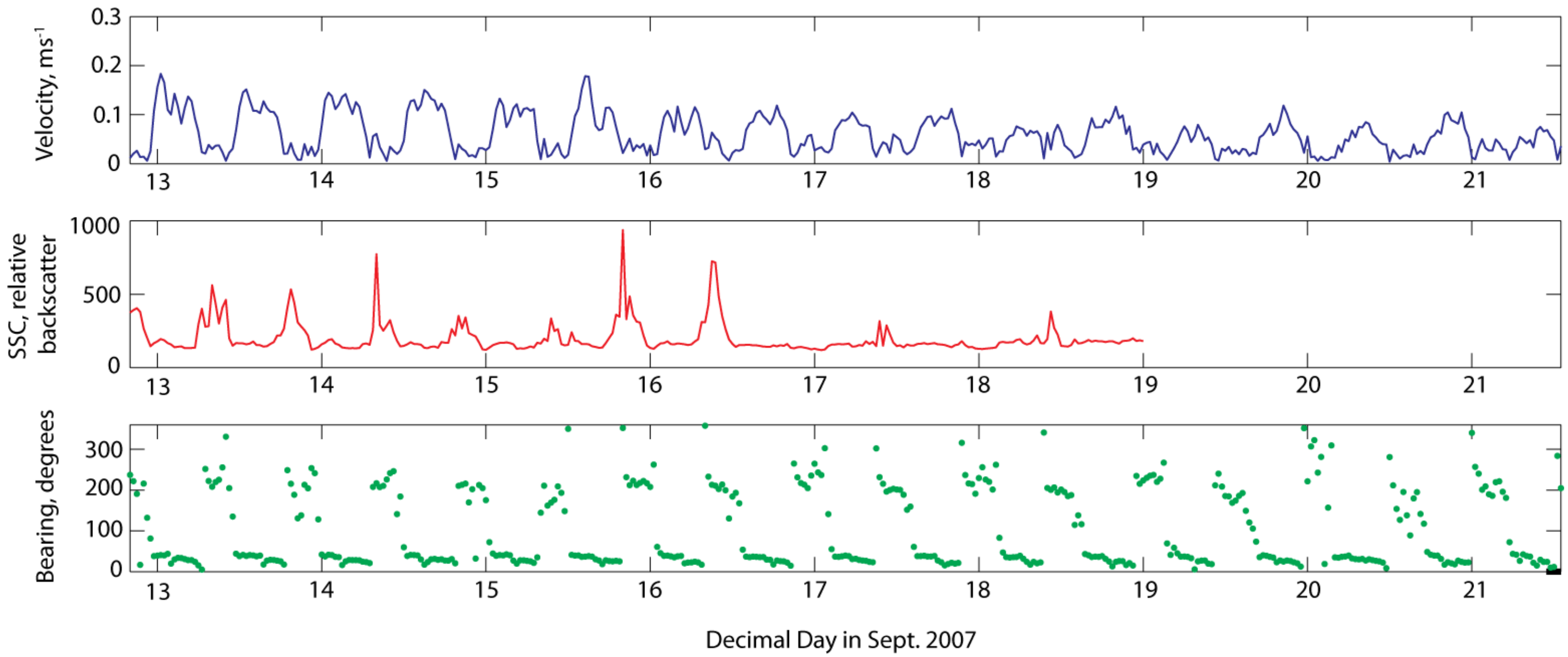

Figure 89. Current speed, suspended sediment concentration and current direction on the north shore of Long Island, September 2007.

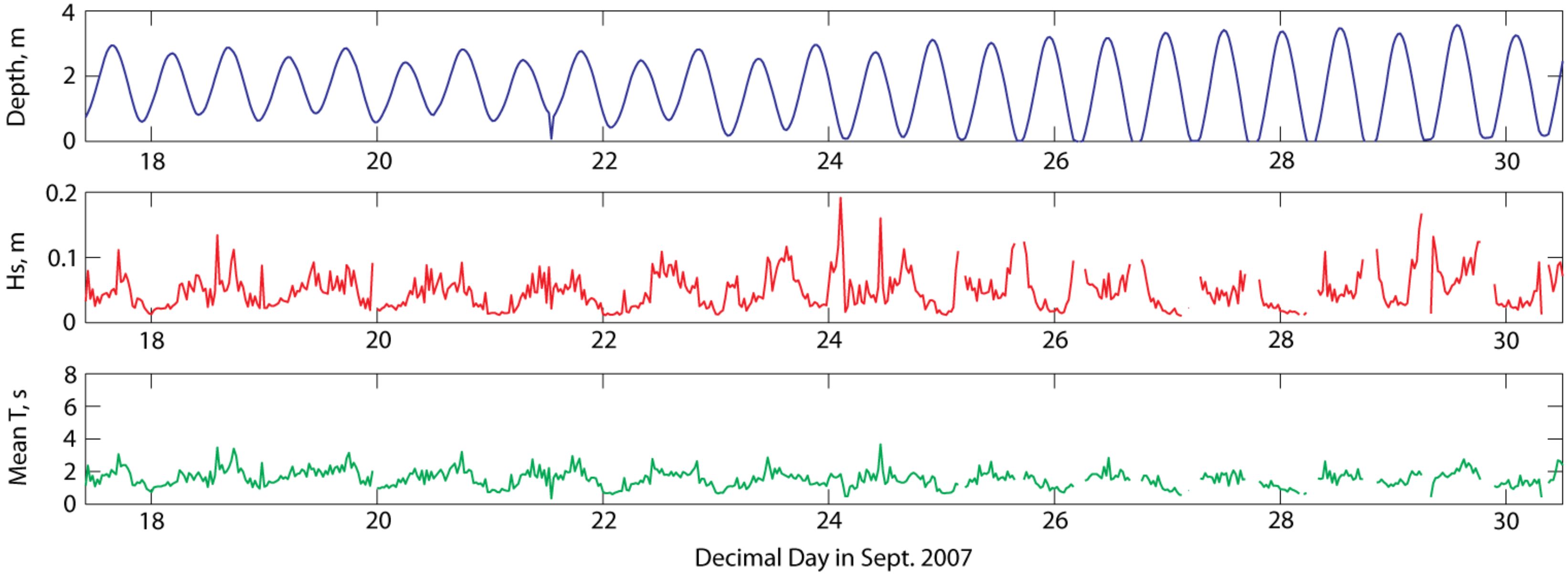

Figure 90. Water depth, wave height and wave period from the north shore of Long Island in September 2007. These data are used to validate the wave model. A small storm event occurs on the 24th September. Small spikes in wave height are due to boat wakes.

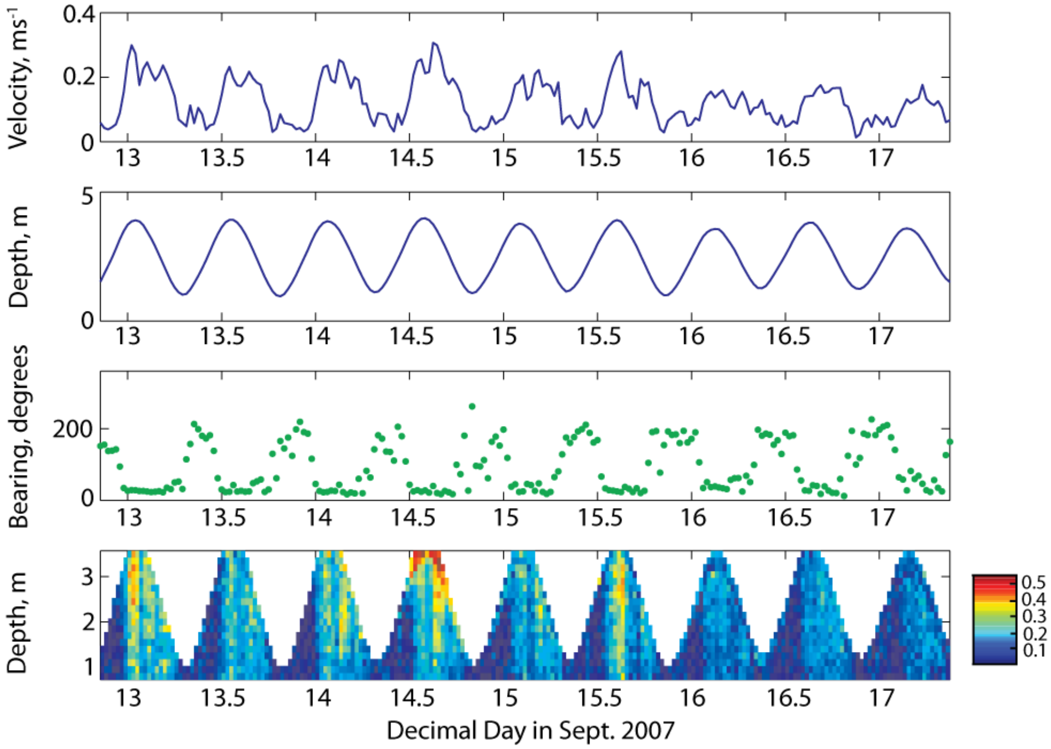

Figure 91. Current speeds, water depth, current direction and velocity profiles over depth on the north shore of Long Island, between Spectacle and Long Island.

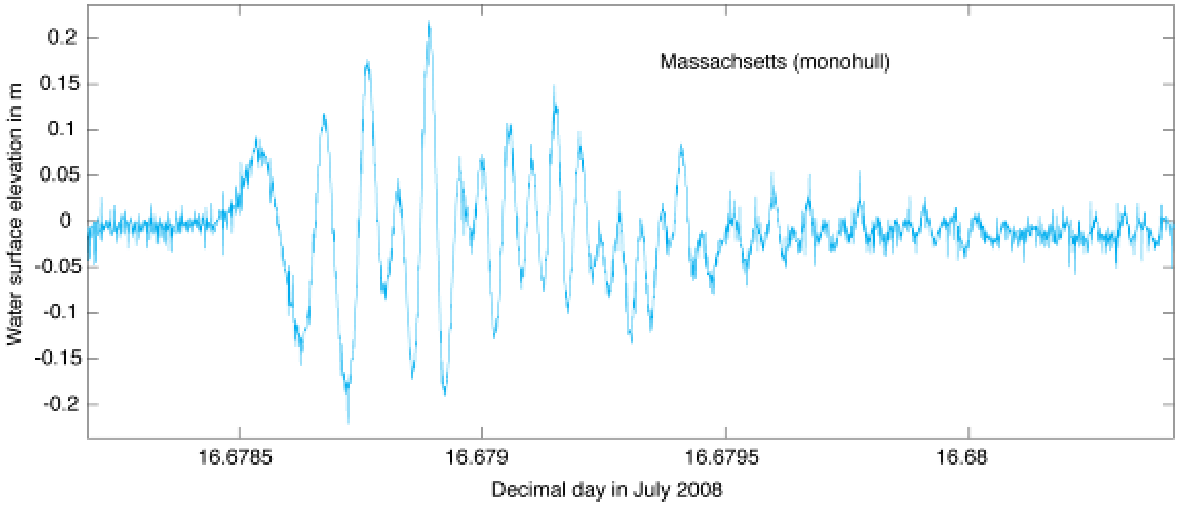

Figure 92. Example of a boat wake from the Massachusetts a mono-hull ferry. The maximum wave height is ~40 cm. The initial wave is a longer period wave followed by shorter period waves of greater height.

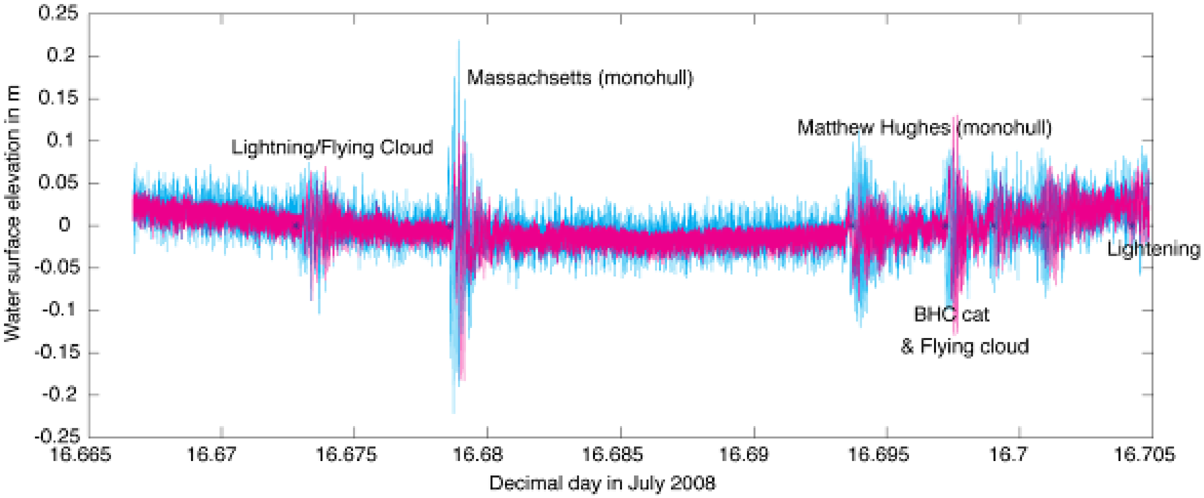

Figure 93. One burst (55 minutes long) from Spectacle Island both inside the marina (pink) and outside the marina to the north of pier (blue) observed during summer. Six vessels passed the monitoring point. The largest wake was produced by the Massachusetts, approximately 4 times greater in height than the natural waves and consequently introducing at least 16 times the energy.

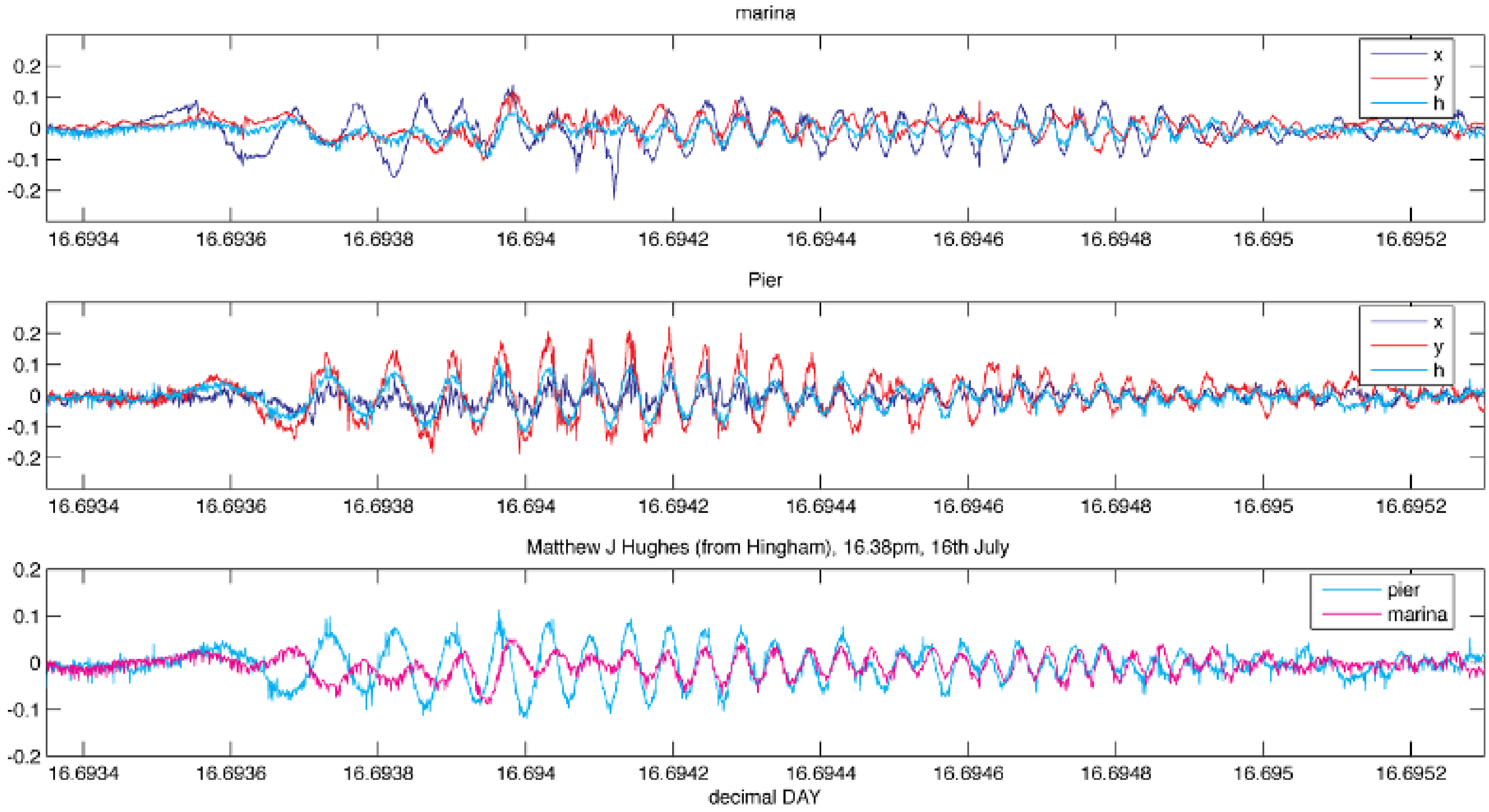

Figure 94. Current speeds in m/s (+ve x = to east, -ve x= to west, +ve y= to the north and –ve y to the south) water depth in m (h) inside the marina and outside the pier at Spectacle Island during the passage of boat wake. The wake crest is moving to the northeast, thus caused by a boat moving from Hingham towards Boston. Lower figure: water depth showing time delay between the wake arriving at the offshore pier site and the onshore marina site.

Maximum ferry wake heights vary based on a large number of parameters (e.g. distance from measurement position of the sailing line, local bathymetry, vessel speed, loading, and variation in course); however they generally fall into the range of 0.2 m to 0.5 m. Of the ferries operating in the harbor, the mono-hull vessels produce significantly larger wakes. At the sites monitored no HSC were observed or recorded.

Boat wakes contribute significantly to energy reaching the shoreline, introducing larger waves and an order of magnitude increase in energy at the shoreline than the natural wave climate. This period of influence is limited to daytime when the ferries are operating and during periods when natural wave and winds are low (Figure 95). During the night and at weekends, the influence of waves is reduced, mostly dropping to zero between the hours of midnight and six in the morning (Figure 95). During storm conditions, however, particularly at more exposed locations such as Moon Island, which has relatively large fetches to the east, the natural wave energy is much higher and the wake impact is less significant (Figure 96).

In summary, boat wakes may introduce a significant increase in wave energy to the shoreline during calm weather. In more exposed regions or during storms and increased natural wave energy, wake-enhanced energy is not as significant.

Wave Modeling

Mean wave direction is from the west to the east (Figure 97). Mean significant wave heights are less than 0.40 m in the majority of the Harbor, except near the mouth of the Harbor. Thus boat wakes along the ferry routes, which range between 0.2 and 0.5 m, are larger than the natural waves occurring due to wind waves.

In the region near the mouth of the Harbor mean wave heights from locally generated winds are much larger than those associated with boat wakes; in addition, this region experiences swells from offshore. Consequently in areas such as the north shores of Rainsford, Lovell's, Gallops, Long, and Georges Islands, shorelines will experience less impact by boat wakes. Nevertheless, they are exposed to large waves and consequently liable to high rates of bluff retreat and damage to seawalls (*see* GIS and Stability Studies section).

Maximum wave heights in many regions of the Harbor are larger than boat wakes (Figure 98). The direction associated with these maximum wave heights is significant for the morphology of the Harbor shorelines; directional vectors can be seen to focus on salients on Long, Lovell’s, Thompson, and Bumpkin Island. In the most part this is due to sheltering by nearby Islands. In the westerly Harbor, maximum wave heights are associated with northeasterly and easterly waves, thus east and northeast facing shorelines will be impacted by larger waves than westerly facing shorelines.

The south of the Harbor is exposed to maximum wave heights and energy from the northwest. The direction of maximum wave energy can also be seen to focus on several of the salients, including those on Lovell's and Long island.

Full modeling results can be found in the appendices.

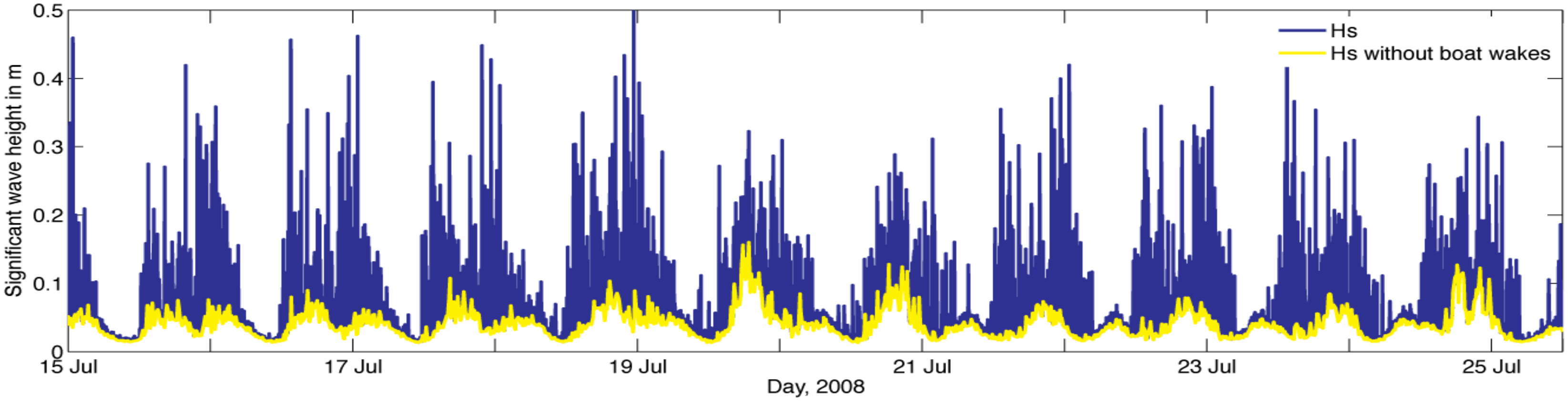

Figure 95. Significant wave heights offshore of Spectacle Island. The boat wakes appear as large spikes overlying the natural waves. Natural waves vary during the day due to sea breezes set up by temperature differences between land and sea. The boat wakes are up to 5 times the size of natural waves. July 20 and 21 are weekend days, when the ferry schedule is less frequent and smaller boat traffic influences the wave height. During the hours midnight to 6 am very few wakes are seen overlying the natural waves.

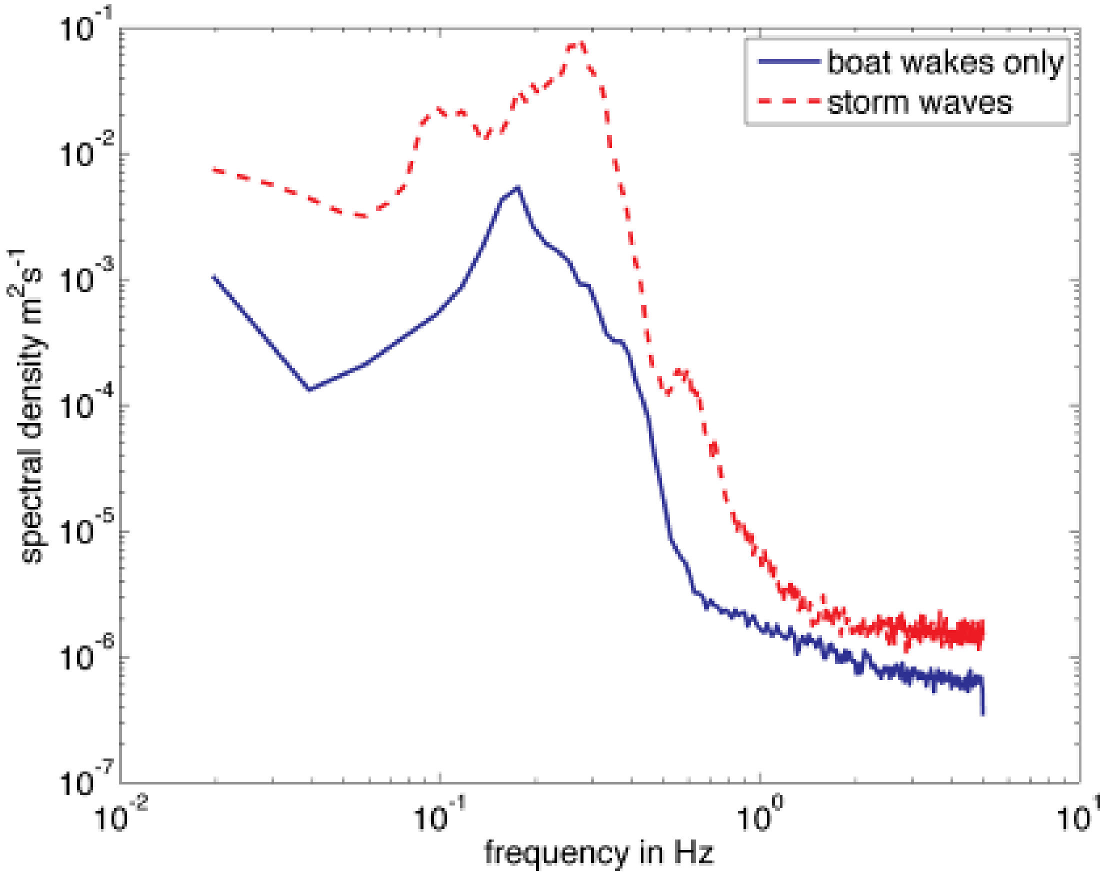

Figure 96. A comparison of energy spectral density over a two minute period during a Nor'easter and over a two minute period during the passage of a boat wake at Moon Island.

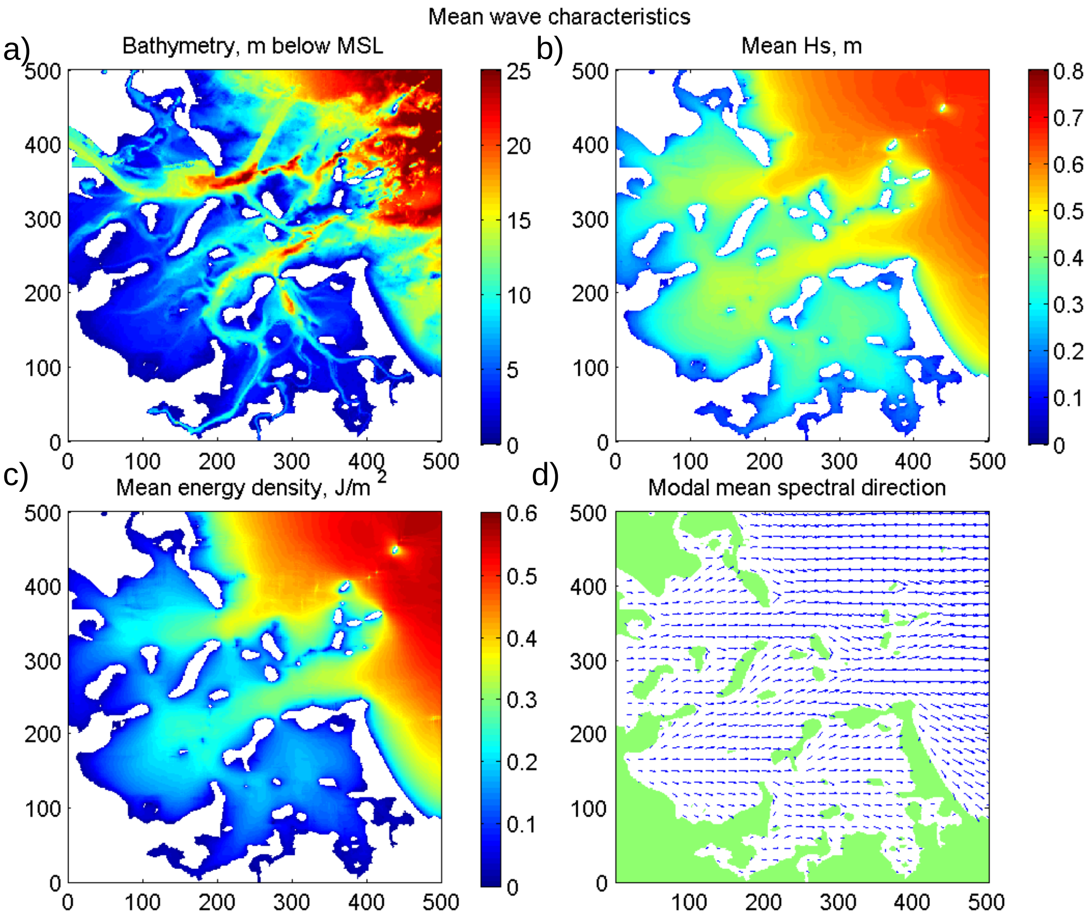

Figure 97. Wave characteristics determined from cumulative modeling of local wind-generated waves: a) the bathymetry; b) the average significant wave height (Hs) experienced at each point in this region (weighted according to the observed wind climate); c) the average energy density experienced at each point in this region; and d) the direction of propagation associated with the modal significant wave heights (scaled to Hs). The modal wave direction throughout the harbor relates directly to the prevailing westerly wind conditions in Boston Harbor, although modal wave heights are less than 40 cm in the western Harbor, but higher close to mouth and in the outer Harbor.

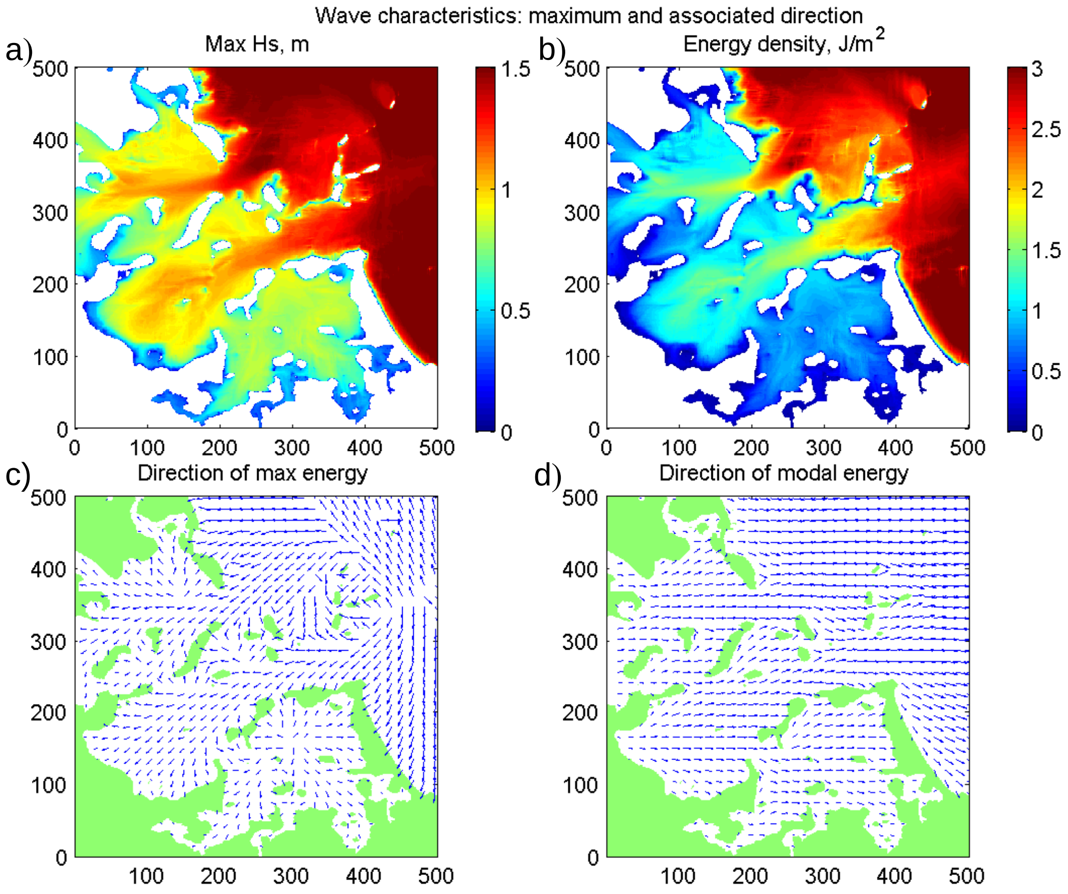

Figure 98. Wave characteristics determined from cumulative modeling of local wind-generated waves: a) maximum significant wave height experienced at each point in this region; b) the maximum energy density experienced at each point in this region; c) the direction of propagation associated with the maximum significant wave heights, and d) for comparison the direction of model energy for each point. (NB directional vector plots are scaled to wave height and sampled every 20th model cell).

Synthesis

Wake Influence on Shorelines

The wakes from vessels introduce significant energy to the shoreline during calm weather conditions. The impact of this increase of energy, however, must be put into context with the total wave regime of harbor and the effect it has on erosion and sediment transport.

There are no clear spatial links between the major MBTA ferry route and bluff erosion or seawall failure (Figure 99). Additionally, much of the route where ferries travel are lined with coarse sediment, especially cobble and boulders beaches, which are unlikely to be altered by the boat wakes. The region has historically been characterized by cobble and pebble beaches, and, as discussed in the Vessel Wakes section, boat wakes tend to move sediment up the shore, steepening the beach, rather than off- or along-shore. No sandy deposits have been found on the upper beach suggesting that the beach configuration is natural and not a result of wake action.

The sand shorelines of Spectacle Island and the south of the Webb State Memorial Park promontory may be impacted by wake energy.

Erosion of bluffs is related to bluff height, presence of vegetation, and precipitation. There is little evidence of undercutting; in fact, there are many sites where alluvial fans and sediment ‘toes’ (akin to screen slopes consisting of eroded sediment) occur and persist at the base of eroding bluffs for several years. Elevated water levels normally occur during storm surges produced by low-pressure systems. Also associated with storms are higher than normal waves and wave setup. Thus, during the periods when wakes reach shorelines, storm-generated waves will be much larger than the boat wakes and will contribute much greater energy to the system. The bluff base elevation data relate to only 12 sites monitored within this study. Thus, it is possible that other regions of bluff may sit lower with respect to mean sea level; however, 100% of those observed in this study seem to experience wave attack only during extreme storm conditions, e.g. Lovell's Island. Consequently, we conclude that boat wakes are not likely to impact drumlin bluff erosion in the same way that it may influence beaches. This is in accordance with the findings of Jones et al (1992), who suggested that bluff retreat is a function of sediment composition.

The impact of wakes is most notable when the boat conditions change. Notably, in the literature this is often due to the introduction of High-speed Craft, which are usually larger as well as faster than traditional ferries (Parnell and Kofoed-Hansen, 2001). The ferry activity in the Harbor has been relatively constant for the last decade. As such, it is likely that the shorelines have achieved an equilibrium with the wave energy (i.e. some steepening of sandy shorelines, or movement of fine sediments up the shoreface would have initially been expected when ferries first began to operate). However, alterations in ferry activity or shorelines may upset any existing balance. The introduction of the pier and wave blocks at Spectacle Island are examples of this. Spectacle Island receives wake energy from an equal number of vessels moving in opposite directions; however, the marina is infilling with sediment moving along shore into the marina. The marina is a sediment sink due to the low wave energy.

Shoreline Stability and Evolution

Evolution of the islands is a function of sediment supply from the drumlins and the distribution of wave energy. Tidal currents are very low in many areas of the Harbor, thus wave action is the dominant hydrodynamic force acting to move sediments and shape the coastline. Directions of maximum wave energy from the wave model imply that salients are formed and evolve based on storm events and sheltering by nearby islands.

Seawalls and bluffs exposed to ocean swells and large fetches are likely to be damaged or to retreat at more rapid rates than those sited in more sheltered regions of the Harbor. Marshes occur in sheltered regions of the harbor; again, the likely source of the inorganic sediment is the drumlin bluffs.

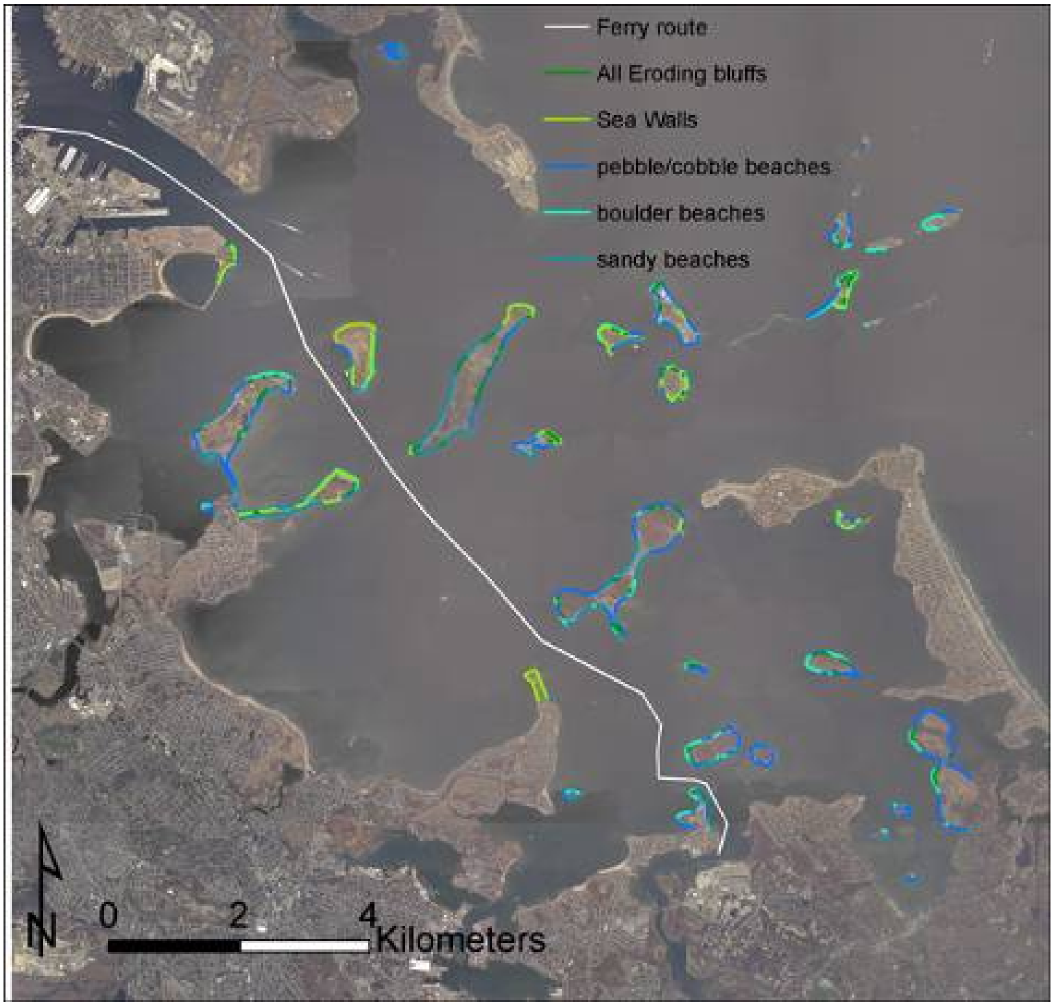

Figure 99. Summary of beach type, eroding bluff position, and seawalls along the major MBTA ferry route.

Conclusions

This report focuses on the impact of boat wakes and local wind-generated waves along the shorelines, and specifically the erosion of drumlin bluffs.

Bluff retreat: There is no clear relationship between bluff erosion and bluff height, fetch, or elevation of bluff toe with respect to mean sea level. Retreat rates vary between 0.02 and 0.7 m/yr, with up to 1.25 m lost in a single year. Lovell's and Thompson Islands are undergoing the fastest rates of bluff retreat (Table 5), followed by the Moon Island and Webb State Park. Webb State Park and Thompson Island both had rapid repeat events in 2008; it is suggested that this is related to the Nor'easter in late spring 2007 which may have weakened the bluff through either wave action or high levels of precipitation and slumping occurring after the spring thaw produced a notable toe at the bluff base.

Shoreline quantification: The shoreline of the Boston Harbor National Recreation Area is extremely diverse with more than 50 km of beaches, 42% of which are pebble or cobble, 30% boulder and 28% sand, and 25 km of bluffs, 61% of which are between 3 – 10 m in height, and only 15% of which are over 10 m high.

General Stability: We have shown that 80% of the bluffs in the Harbor are stable, whereas 20% are actively eroding. Erosion occurs mostly by slumping. Slope wash is limited to bluffs over 3 m high but can play a significant part in the erosion of bluffs over 10 m. Erosion is more likely to occur at bluffs over 10 m high, and facing northwest, which is likely a function of the shape and original orientation of the drumlins, although storm events may also play a part in this alignment on certain islands.

Wave versus wake energy within Boston Harbor:

Wakes on bluffs: While basal wave attack does occur at drumlin bluffs, it is unlikely in most cases to be related to boat wakes or ferry activity. The exception being Thompson Island, which is both experiencing high retreat rates and potentially enhanced wave energy related to boat wakes.

Wakes on shorelines: The navigation channels in the sheltered, low natural wave energy regions in the western Harbor are, for the most part, lined by cobbled and/or boulder beaches and retreat lags. Some areas such as much of Moon and Nut Islands and the tip of Long Island are stabilized with seawalls. The exceptions are parts of Grape Island and Webb State Memorial Park and the western shore of Spectacle Island. The shorelines of Grape and Webb have been exposed to ferries for long enough to have reached a state of equilibrium with the increased energy regimes. A change in ferry activity, such as faster traveling speeds or construction of coastal engineering structures, would likely cause morphological changes to these beaches and a potential degradation of the beach (Parnell and Kofoed-Hansen, 2001). This is the case at Spectacle, which is experiencing sediment shoaling within the Marina at the expense of the beaches on either side. The volume of sediment transport related to boat wakes is likely to be symmetrical due to the nature of the ferry schedules, with as many ferries traveling to Hingham from Boston as there are returning.

Recommendations

Based on the findings of this report several sites warrant consideration for remediation: Thompson Island eastern shore and bluff, Spectacle Island western shore, and Lovell's' Island northeastern bluff.

Thompson and Spectacle Island experience higher levels of wave energy than natural conditions would suggest, due to the high boat traffic in the region and the narrow channel. This boat activity and increased energy have been constant for many years and the shorelines (i.e. the beach face) may have reached equilibrium with this enhanced wave forcing. However, on Thompson Island the composition of the bluff (consisting of outwash/till combination) and the low bluff-base position with respect to mean sea-level suggest that it is more susceptible to erosion. Waves have been observed to reach parts of this bluff and thus, the addition of boulders to the existing cobble and boulder beach fronting the bluff may reduce wave energy sufficiently to slow bluff retreat. However, the bluff will still be highly susceptible to slope failures related to rainfall, ensuing slumping, or slope-wash erosion. Other bluff sites in the harbor may experience some redistribution of the talus (slumped sediments at the bluff toe) either by natural waves or, in areas along the ferry route, by wakes, during high astronomical and meteorological tides. This occurs when the volume of the talus is large enough to come into contact with sea level (i.e. after large or cumulative slumping or slopewash events). This provides a natural input of sediment to the beach. The contribution of wakes versus waves will depend upon the probability of high water levels occurring during periods of high ferry activity. Theoretically, wakes are more likely to move sediment up a beach than along it, thus natural wakes will be more effective than wakes at removing sediment from a talus.

Spectacle Island marina is experiencing infilling because of an interruption in sediment transport caused by sheltering by the waves screens in one direction. Engineering solutions that are presently being undertaken by the City of Boston and Massachusetts Coastal Zone Management (contract to Applied Coastal Ltd should be based on these observations).

The exposed bluff on the northwest shore of Lovell's Island is undergoing rapid erosion and the fastest retreat rates measured in Boston Harbor; this is likely a function of the long fetch and large waves to which this area is exposed. Beach nourishment of this site would likely be ineffective, due to potentially high sediment transport rates. Groin structures are already in place and have little impact on erosion because the area in which they are situated is sediment starved. Additionally, this shoreline has retreated inland of its original position since construction. This site might be suitable for a breakwater structure offshore, however a thorough investigation into the impacts of such a structure on the sandy sediments of the northwestern and western shores is advised. A system that reduces wave energy without removing all long shore transport would be the aim.

We recommend that managers consider the impact of both natural and boat wake energy when planning coastal structures. Docks and piers may impact the direction of both natural and wake-related transports. The interruption of wave energy often leads to the sequestration of sediments behind the obstruction. This is likely the case at Spectacle Island.

Speed restrictions could be applied to ferries and large pleasure craft in narrow channels and when passing close to shorelines. However, the requirement to slow will only be effective if:

- Vessels travel below the critical speed ($F_h=1$) as they passes the focus location; and
- Reduced speed is accomplished well in advance of the focus location to avoid passing through the “hump speed’ which occurs at $F_h=1$, as $F_l \sim 0.5$ for most of the Harbor ferries.

In areas considered highly impacted by wakes (i.e. the channel between Thompson Island and Spectacle Island), the most effective solution would be the introduction of a ‘no-wake” zone.

General Notes on Management of Bluff Erosion.

Vegetation is the most effective means of stabilizing bluffs, and it should be encouraged both on the slope and above the bluff. Vegetation decreases erosion due to slopewash by reducing overland flow caused during high precipitation events. The root structures of plants also add integrity to the slope. *We recommend the conservation of vegetation on and above all bluffs.* Certain regions may also benefit from revegetation such as the prominence in Webb State Memorial Park. As bluff erosion relates to height and often precipitation rather than exposure to wave action, toe stabilization is unlikely to be an effective measure in shore protection in most cases. Bluff height and conditions are heterogeneous and the rate of erosion exhibits variability both spatially and temporally, thus erosion issues need to be considered on a case-by-case basis.

In areas identified as at risk from wave or wake erosion, we recommend raising the level of the natural beach fronting the bluff through nourishment. Most eroding bluffs are fronted by boulder beaches, and thus we recommend building up the elevation of the beach through establishment of boulder and cobble beaches to reduce bluff erosion in areas of critical importance.

Managers should also consider that the drumlin bluffs are the sole source of sediment to the shorelines within the Harbor. Without contributions from eroding bluff, proximal sites may experience reduction in beach widths and/or alterations in beach substrate, specifically trending toward coarser sediment. *We recommend that aggressive stabilization actions such as the construction of seawalls should be applied only in regions:*

- *Where erosion or further erosion may cause damage to structures or sites of archaeological value or risk environmental hazards such as the release of landfill or asbestos (e.g. Gallops or Spectacle Islands).*
- *That have been previously seawalled and have no proximal beach that would provide protection against wave attack or to be impacted by a reduced sediment supply (e.g. western shoreline of Rainsford Island).*

Broader impacts

Internships

All internships were separately funded by the J.R. Allen Research & Education Fund.

Internships 2005

Alexandra Giese, Harvard University	June 1st – September 1st, 2005
Nick Howes, Boston University	June 1st – September 1st, 2005

Alexandra, a freshman, and Nick, a junior, were involved in all aspects of the project during their internships. Over the summer 2005 they mastered the use of various instruments and survey equipment including a Trimble backpack differential global positioning system, a Pentax total station, pressure transducers and Coastal macro-loggers, Nortek Aquadopp current profilers and all the associated software. In addition to assisting with general fieldwork and data collection, the interns were given individual directed studies to work on during the three months that they were at Boston University, Alexandra concerning the erosion of glacial bluffs over neap-spring tidal cycles and Nick using GIS software to analyze the DGPS data. The culmination of each project involved the presentation of a poster at the Boston Harbor Island Award Dinner in November 2005.

Internships 2006

Abbey Steffens, Newton High School	June 1st – September 1st, 2006
Nick Howes, Boston University	June 1st – September 1st, 2006

Nick Howes presented a poster at the Northeastern meeting of the Geological Society of America in March 2006. He repeated the internship in the summer of 2006, continuing to assist with mapping and monitoring fieldwork. Nick's focus study continued to be the compilation of the Harbor GIS. In summer 2006, we were joined by Newton High School senior Abbey Steffens. In addition to assisting with the mapping and monitoring fieldwork, Abbey undertook a study focused on the sediment transport pathways around Lovell's island. Abbey learned to use various survey equipment including a Trimble backpack, a differential global positioning system, and a Pentax total station and learned laboratory techniques to analyze sediment size. Abbey wrote her study up as a paper and submitted it to the Intel Science Talent Search.

Internships 2007

Abbey Steffens, Ohio State University	June 1st – September 1st, 2007
Alexis Sabine-Mathos, Northeastern University	June 1st – September 1st, 2007

Abbey returned to work with us in the summer of 2007 before matriculating into Ohio State University. She continued her field and laboratory studies, examining sediment from both Lovell's and Long islands. This year we were joined by Alexis Sabine-Mathos, a junior at Northeastern University. Alexis assisted with the continued monitoring of the Harbor. However, the focus of role was formatting the GIS and extracting statistics to examine coastline stability. Alexis continues to be involved and will be a co-author of a paper concerning the stability of shorelines in Boston Harbor that is presently in preparation.

Graduate Studies

In fall 2007, we were joined by Ashley Bolbrook, who is undertaking her Masters research at Boston University. Ashley is extending the present studies of wave modification of shorelines and expanding our modeling efforts. She will be concentrating on the formation of salients, such as those observed on Long and Lovell's Islands. Ashley will be finishing her studies in Spring 2009.

Undergraduate Studies

The following 15 undergraduate students have been involved with the project as part of their studies:

Student	University	Year/Type of Study	Description
Tobias Hatten	Boston University	2005, Senior Thesis	In-depth study of the sedimentology of Lovell's Island including hydro- and sediment transport studies, mineralogical analyses and investigations into the source of sediment
David Waxman	Boston University	2005, Class project as part of ES331: Sedimentology	Studying the mineralogy and sediment distribution around Lovell's Island
Danielle Best	Boston University	2005, Class project as part of ES331: Sedimentology	Studying the mineralogy and sediment distribution around Lovell's Island
Nikki Gorin	Northeastern University	2005, Summer Advanced Topics course	Using Coastal Zone Management data to investigate GIS
Brian Bais	Northeastern University	2005, Directed study	Sampling and surveying techniques
Jennifer Lovett	Northeastern University	2005, Directed study	Sampling and surveying techniques
Hillary Boone	Northeastern University	2005, Directed study	Sampling and surveying techniques
Claire Connolly	Boston University	2006, Class project as part of ES331: Sedimentology	Studying the mineralogy and sediment distribution around Lovell's Island
Craig Nale,	Boston University	2006, Class project as part of ES331: Sedimentology	Studying the mineralogy and sediment distribution around Lovell's Island
Jenny Leung	Boston University	2006, Class project as part of ES331: Sedimentology	Studying the mineralogy and sediment distribution around Lovell's Island
Casey Bartlet,	Northeastern University	2006, Directed study	GIS analyses
Andrew Knott	Boston University	2007, Class project as part of ES331: Sedimentology	Studying the mineralogy and sediment distribution around Long Island

Joseph Pike	Boston University	2007, Class project as part of ES331: Sedimentology	Studying the mineralogy and sediment distribution around Long Island
Meridith Anderson	Boston University	2007, Class project as part of ES331: Sedimentology	Studying the mineralogy and sediment distribution around Long Island
Mike MacDonald	Northeastern University	2008, Directed study	Bluff erosion throughout the harbor, sampling and surveying techniques

Awards

Duncan FitzGerald, *Undergraduate Mentor of the Year, 2006,* Awarded by Undergraduate Research Opportunities Program, Boston University.

Presentations

Hughes, Z. J., Geophysical Processes of Boston Harbor: past and future evolution of the Islands. Boston Harbor Islands Science Symposium, University of Massachusetts, Boston, October 3, 2008.

Hughes, Z. J., N. C. Howes, D M FitzGerald and P. Rosen. The impact of natural waves and ferry wakes on the erosion of bluffs, Boston Harbor, US. International Coastal Symposium 2007, Gold Coast, Queensland, Australia, 16-20 April 2007.

Hughes, Z. J., D M FitzGerald and P. Rosen, Assessing the impact of ferry boat wakes on shoreline erosion in Boston Harbor, Massachusetts. Proceedings of the International Conference of Coastal Engineering San Diego, CA, Sept 4-8 2006.

Hughes, Z. J. Wave measurements nearshore, Boston Harbor, Invited lecture at the 1st Advisory Meeting for the Center for Environmental Sensing Networks, University of Massachusetts, Boston, Aug 16, 2006.

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Appendix A: Wake observations from shore

Example of observations made from shore during deployment on Spectacle Island. Number of vessels moving Hingham to Boston = 112 (48.8%), number of vessels moving Boston to Hingham 113 (50.2%).

Date	Time	Boat	Long Wave	Short Wave	Direction	Notes
7/15/08	9:32	Flying Cloud	9:36:45	9:37:18	Boston to Hingham	Very slow, far
	10:13	Matthew J Hughes	10:17:27	10:18:19	Boston to Hingham	Approached Fast, Slowed at Green Chan. Marker (right off of Thomson Island), midway offshore sped up after pier.
	10:15	Lightning	10:16:55	10:18:19	Hingham to Boston	fast, mid
	10:19	Island Discovery (Harbor Island Express Cat Boat)	10:20:27	10:20:54	Boston to Hingham	slow, close, docked at marina.
	10:27	Flying Cloud	10:29:36	10:30:55	Boston to Hingham	fast, mid
	10:52	Lightning	10:55:36	10:56:03	Boston to Hingham	Approached slow, far, sped up past Green Chan. Marker off of Thomson Island
	11:12	Virginia C.II (Large Single hull Ferry)	11:12:39	11:12:50	Boston to Hingham	Very Slow, Very Close
	11:14	Flying Cloud	11:16:53	11:17:03	Hingham to Boston	slow, close
	11:21	Matthew J Hughes	n/a to choppy	n/a to choppy	Hingham to Boston	approached slow, mid, sped up past channel marker off of thomson island
	11:50	Island Expedition (Harbor Isand Express Cat Boat)	11:51:22	11:51:30	Hingham to Boston	Very Slow, Very Close
	11:51	Flying Cloud	11:54:06	11:54:52	Boston to Hingham	Slow, Mid, increased speed past marina
	12:25	Island Expedition (Harbor Isand Express Cat Boat)	12:26:04	12:26:25	Boston to Hingham	slow, close, docked at marina.
	1:46	Large Single Hull Ferry	1:47:58	1:48:27	Boston to Hingham	Fast, mid

Date	Time	Boat	Long Wave	Short Wave	Direction	Notes
7/15/08	1:49:37	Freedom (Large Cat Boat)	n/a to choppy	n/a to choppy	Boston to Hingham	Slow, Mid
	1:55:30	Island Expedition (Harbor Isand Express Cat Boat)	1:56:21	1:56:30	Hingham to Boston	Slow, close, left marina
	2:10:24	Flying Cloud	2:13:13	2:13:47	Hingham to Boston	Fast, Far
	2:30:52	Island Expedition (Harbor Isand Express Cat Boat)	2:31:26	2:31:42	Boston to Hingham	Slow, Close, docked in marina
	2:51:58	Matthew J Hughes	2:53:38	2:53:57	Hingham to Boston	approached fast, slowed at our southern buoy, mid distance, sped up at our northern buoy
	3:30	Flying Cloud	3:32:33	3:33:06	Hingham to Boston	Fast, Mid
	3:44:02	Matthew J Hughes	3:46:20	3:46:45	Boston to Hingham	Fast, Mid
	4:00:41	Island Expedition (Harbor Isand Express Cat Boat)	4:01:16	4:01:16	Hingham to Boston	slow, close
	4:05:52	Flying Cloud	4:07:53	4:08:07	Hingham to Boston	Fast, Mid
	4:07:19	Lightning	4:08:41	4:09:11	Boston to Hingham	Fast, Close
	4:13:22	Massachusetts (Large single hull ferry)	4:17:02	n/a	Boston to Hingham	Fast, Far
	4:37:07	Matthew J Hughes	4:38:32	4:38:51	Hingham to Boston	Fast, Mid
	4:39:55	Boston Harbor Cruises CAT Boat	4:41:03	4:42:07	Boston to Hingham	Fast, Mid
	4:40:51	Flying Cloud	4:43:26	4:43:57	Boston to Hingham	Fast, Mid
	4:54:47	Lightning	4:58:06	4:58:29	Hingham to Boston	Fast, Far
	4:58:37	Island Expedition (Harbor Isand Express Cat Boat)	n/a	n/a	Hingham to Boston	Slow, Close
	5:06:00	Massachusetts (Large single hull ferry)	5:09:20	5:10:30	Hingham to Boston	Fast, Far

Date	Time	Boat	Long Wave	Short Wave	Direction	Notes
7/15/08	5:15:51	BHC CAT Boat "Nora Victoria"	5:17:00	5:17:46	Hingham to Boston	Approached Fast, Slowed at Southern Buoy, sped at N. Buoy. Close
	5:16:29	Matthew J Hughes	5:17:00	5:17:46	Boston to Hingham	Fast, Mid, *Huge Wake
	5:30:09	Flying Cloud	5:31:45	5:33:14	Hingham to Boston	Fast, Mid
	5:32:47	BHC CAT Boat	5:34:08	5:36:05	Boston to Hingham	Fast, Far
7/16/08	9:33:00	Flying Cloud	9:34:40	9:35:49	Boston to Hingham	Fast, Mid
	10:14:15	Matthew J Hughes	10:16:31	10:16:40	Boston to Hingham	Slow, Close
	10:20:36	Flying Cloud	10:22:42	10:23:08	Hingham to Boston	Fast, slowed at our S. Buoy, sped up at Green channel marker off thomson island, mid distance.
	10:24:54	Lightning	10:26:59	n/a	Boston to Hingham	Approached Fast, slowed for construction barge near N. Buoy, sped up at Green Channel marker off thomson island
	10:56:12	Flying Cloud	10:57:54	10:58:49	Boston to Hingham	Fast, Mid
	11:07:50	Virginia C.II (Large Single Hull Ferry)	11:09:15	11:09:45	Boston to Hingham	Very slow, Mid
	11:22:00	Matthew J Hughes	11:27:54	11:28:16	Hingham to Boston	Slow, Far
	11:46:43	Lightning	11:51:03	11:52:18	Boston to Hingham	Approached Slow, sped to fast at Green Channel Marker, Far
	12:21:46	Island Expedition	12:22:21	12:23:15	Boston to Hingham	Slow, Close
	1:30:28	Flying Cloud	1:34:02	1:34:35	Hingham to Boston	Fast, Mid
	1:44:05	Matthew J Hughes	n/a	n/a	Boston to Hingham	Slow, far
	1:47:37	Island Expedition	1:48:06	1:48:26	Hingham to Boston	Slow, Close, Left marina
	2:10:34	Virginia C.II (Large Single Hull Ferry)	2:11:13	n/a	Hingham to Boston	Slow, Close
	2:20:24	Island Expedition	2:21:39	2:21:58	Boston to Hingham	Slow, Close, Docked in Marina

Date	Time	Boat	Long Wave	Short Wave	Direction	Notes
7/16/08	2:51:58	Matthew J Hughes	2:55:33	2:56:03	Hingham to Boston	Fast, Mid
	3:30:20	Flying Cloud	3:34:12	3:34:38	Hingham to Boston	Fast, Far
	3:42:59	Matthew J Hughes	3:45:43	3:47:15	Boston to Hingham	Fast, Mid
	4:05:30	Flying Cloud	4:07:38	4:09:32	Boston to Hingham	Fast, Far
	4:05:48	Lightning	4:07:31	4:09:19	Hingham to Boston	Fast, Mid
	4:13:23	Massachusetts	4:14:55	4:17:26	Boston to Hingham	Fast, Far
	4:35:05	Matthew J Hughes	4:36:22	4:38:28	Hingham to Boston	Fast, Mid
	4:40:17	BHC CAT Boat Nora Victoria	4:41:40	4:44:25	Boston to Hingham	Fast, Mid
	4:42:40	Lightning	4:43:32	4:46:20	Boston to Hingham	Fast, Far
	4:57:25	Island Expedition	4:58:23	n/a	Hingham to Boston	Slow, Clost, left marina
	5:05:15	Massachusetts	5:06:42	5:08:45	Hingham to Boston	Fast, Mid
	5:14:55	Matthew J Hughes	5:16:32	5:18:37	Boston to Hingham	Fast, Mid, Huge Wake
	5:17:00	BHC CAT Boat Nora Victoria	5:18:04	5:19:06	Hingham to Boston	Fast, Close, Huge Wake
	5:29:19	Lightning	5:30:25	5:32:26	Hingham to Boston	Fast, Mid
	5:31:06	BHC CAT Boat Nora Victoria	5:31:52	5:35:00	Boston to Hingham	Fast, Mid
7/17/08	9:23:34	Island Discovery	9:24:37	9:26:07	Hingham to Boston	Fast, Close
	10:14:00	Matthew J Hughes	10:16:44	10:19:32	Boston to Hingham	Slow, far
	10:26:59	Flying Cloud	10:27:47	10:28:37	Boston to Hingham	Fast, Close
	10:51:51	Lightning	10:52:55	10:55:48	Boston to Hingham	Fast, Far
	11:03:40	Virginia CC.II	11:04:20	11:06:49	Boston to Hingham	Very Slow, Mid
	11:17:33	Flying Cloud	11:18:10	11:20:30	Hingham to Boston	Fast, Mid, slowed at green channel marker
	11:42:31	Island Expedition	11:43:12	n/a	Hingham to Boston	Slow, Close, left marina
	11:54:00	Flying Cloud	11:55:42	11:57:25	Boston to Hingham	Fast, Mid
	12:14:03	Island Expedition	12:15:00	12:15:30	Boston to Hingham	Slow, close, docked in marina

Date	Time	Boat	Long Wave	Short Wave	Direction	Notes
7/17/08	12:41:35	Flying Cloud	12:42:45	12:44:15	Hingham to Boston	Fast, Mid
	1:44:05	Matthew J Hughes	1:45:25	1:49:22	Boston to Hingham	Slow, Far
	2:12:55	Flying Cloud	2:14:28	2:16:15	Hingham to Boston	Fast, Mid, slowed at green channel marker
	2:14:40	Virginia CC.II	2:15:22	n/a	Hingham to Boston	Slow, Close, left marina
	2:37:59	Island Expedition	2:38:55	2:39:38	Boston to Hingham	Slow, close, docked in marina
	2:50:46	Matthew J Hughes	2:53:25	2:54:35	Hingham to Boston	Slow, far, sped up at green channel marker
	3:30:00	Lightning	3:31:15	3:32:54	Hingham to Boston	Fast, Mid
	3:42:59	Matthew J Hughes	3:44:01	3:46:50	Boston to Hingham	Fast, Far
	4:07:04	Lightning	4:08:33	4:11:00	Boston to Hingham	Fast, Far
	4:07:30	Flying Cloud	4:08:49	4:11:00	Hingham to Boston	Fast, Mid
	4:13:00	Massachusetts	4:14:41	4:17:05	Boston to Hingham	Fast, Far
	4:38:25	Matthew J Hughes	4:39:08	4:40:35	Hingham to Boston	Fast, Close, slowed at southern tip of pier, sped up past northern tip
	4:41:29	BHC CAT Boat	4:43:00	4:43:50	Boston to Hingham	Slow, Mid
	4:43:12	Flying Cloud	4:44:43	4:47:29	Boston to Hingham	Fast, Mid
	4:53:31	Lightning	4:54:47	4:57:17	Hingham to Boston	Fast, Mid
	5:07:40	Massachusetts	5:08:23	5:09:45	Hingham to Boston	Fast, Close
	5:14:08	Matthew J Hughes	5:15:45	n/a	Boston to Hingham	Slow, far, sped up at green channel marker
	5:20:31	BHC Nora Victoria CAT Boat	5:21:07	n/a	Hingham to Boston	Slow, Mid
	5:30:54	BHC CAT Boat "Aurora"	5:32:15	5:33:43	Hingham to Boston	Fast, Mid
	5:31:00	Flying Cloud	5:33:02	5:34:26	Hingham to Boston	Fast, Mid
	6:03:22	Matthew J Hughes	6:05:08	6:06:06	Hingham to Boston	Fast, Mid
7/18/08	10:13:35	Matthew J Hughes	10:14:53	10:17:36	Boston to Hingham	Fast, Far
	10:16:42	Flying Cloud	10:17:29	10:20:01	Hingham to Boston	Fast, Mid

Date	Time	Boat	Long Wave	Short Wave	Direction	Notes
7/18/08	10:28:54	Lightning	10:30:24	10:31:27	Boston to Hingham	Fast, Mid
	10:33:24	Large Umass Ferry, Single Hull	10:33:33	10:34	Boston to Hingham	Slow, Close
	10:39:28	Island Expedition	10:39:50	10:46:59	Hingham to Boston	Slow, Close
	10:50:35	Flying Cloud	10:51:56	10:54:17	Boston to Hingham	Fast, Mid
	11:15:35	Lightning	11:16:49	11:18:19	Hingham to Boston	Fast, Mid
	11:22:21	Matthew J Hughes	11:23:45	11:26:31	Hingham to Boston	Slow, Mid
	11:26:11	Island Expedition	n/a	n/a	Boston to Hingham	Slow, Close, docked in marina
	11:48:47	Lightning	11:50:11	11:52:25	Boston to Hingham	Fast, Mid
	12:14:01	Island Expedition	12:14:58	n/a	Boston to Hingham	Slow, Close, docked in marina
	12:35:08	Lightning	12:36:05	12:37:29	Hingham to Boston	Fast, Close
	1:43:06	Matthew J Hughes	1:44:45	1:46:59	Boston to Hingham	Approached fast, slowed at Green chan marker, far
	2:03:42	Lightning	2:04:56	2:06:13	Hingham to Boston	Fast, Mid
	3:29:36	Flying Cloud	3:30:47	3:32:39	Hingham to Boston	Fast, Mid
	3:42:28	Matthew J Hughes	3:44:26	3:46:30	Boston to Hingham	Approached fast, slowed at Green chan marker, far
	4:05:02	Flying Cloud	4:05:58	4:08:30	Boston to Hingham	Fast, Mid
	4:05:14	Lightning	4:05:45	4:07:49	Hingham to Boston	Fast, Close
	4:12:48	Massachusetts	4:13:46	4:15:37	Boston to Hingham	Fast, Mid
	4:34:48	Matthew J Hughes	4:35:44	4:38:40	Hingham to Boston	Slow, Mid
	4:39:30	BHC CAT Boat	4:40:15	4:41:50	Boston to Hingham	Fast, Close
	4:41:50	Lightning	4:41:50	4:44:40	Boston to Hingham	Fast, Mid
	4:48:00	Flying Cloud	4:48:59	4:51:30	Hingham to Boston	Fast, close
	5:06:37	Massachusetts	5:07:25	5:08:45	Hingham to Boston	Fast, close
	5:13:45	Matthew J Hughes	5:15:14	5:17:06	Boston to Hingham	Fast, Mid

Date	Time	Boat	Long Wave	Short Wave	Direction	Notes
7/18/08	5:17:23	BHC CAT Boat	5:18:20	5:19:43	Hingham to Boston	Fast, Close
	5:26:18	Lightning	5:27:16	5:29:15	Hingham to Boston	Fast, Mid
7/19/08	10:12:19	BHC CAT Boat	10:13:21	10:14:56	Hingham to Boston	Fast, Mid
	10:28:38	Large CAT Boat "Freedom"	n/a	n/a	Boston to Hingham	Slow, Close, docked at pier
	11:03:53	Lightning	11:05:19	11:06:48	Boston to Hingham	Fast, Mid
	11:22:50	Island Discovery	12:23:37	12:23:52	Boston to Hingham	Slow, close, docked at marina
	12:24:55	Flying Cloud	12:25:41	12:27:34	Boston to Hingham	Slow, close, docked at marina
	12:37:32	Island Discovery	12:37:43	12:38:32	Boston to Hingham	Slow, close, docked at marina
	1:11:30	Flying Cloud	1:12:39	1:14:05	Hingham to Boston	Fast, Mid
	1:53:58	Flying Cloud	1:55:04	1:56:44	Boston to Hingham	Fast, Mid
	2:30:13	Island Expedition	2:30:57	2:31:39	Boston to Hingham	Slow, close, docked at marina
	2:38:39	Flying Cloud	2:39:32	2:40:35	Hingham to Boston	Fast, Close
	3:23:00	Island Expedition	n/a	2:23:45	Boston to Hingham	Slow, close
	3:35:46	Island Expedition	n/a	3:36:35	Hingham to Boston	Slow, close, left marina
	4:15:10	Flying Cloud	4:16:30	4:19:16	Hingham to Boston	approached fast, slowed at southern buoy, sped up at southern tip of pier, close
	4:28:51	Island Expedition	4:29:35	4:30:05	Boston to Hingham	Slow, close, docked at marina
	5:27:40	Lightning	5:28:49	5:31:09	Hingham to Boston	Fast, Mid
	6:15:00	Flying Cloud	6:16:59	6:18:48	Hingham to Boston	Fast, Mid
7/21/08	9:30:11	Flying Cloud	9:31:22	9:33:29	Boston to Hingham	Fast, Mid
	9:31:53	BHC CAT "Aurora"	9:31:53	n/a	Hingham to Boston	Slow, Close
	10:13:25	Matthew J Hughes	10:15:00	10:16:52	Boston to Hingham	Fast, Mid
	10:14:20	Flying Cloud	10:15:20	10:16:09	Hingham to Boston	Fast, Close
	10:17:04	Island Expedition	n/a	10:17:46	Boston to Hingham	Slow, Close

Date	Time	Boat	Long Wave	Short Wave	Direction	Notes
7/21/08	10:26:26	Island Discovery	10:27:59	10:29:45	Boston to Hingham	Fast, Mid
	10:48:38	Flying Cloud	10:15:13	10:52:06	Boston to Hingham	Fast, Far
	11:25:00	Matthew J Hughes	11:26:10	11:29:20	Hingham to Boston	Slow, close
	11:38:59	Island Expedition	11:39:39	11:40:47	Hingham to Boston	Approached fast, slowed to dock at marina, close
	11:54:26	Island Discovery	11:55:05	11:59:52	Boston to Hingham	Fast, Far
	12:45:40	Island Expedition	12:47:25	12:49:10	Hingham to Boston	Fast, Mid
	1:26:19	Island Expedition	1:28:13	n/a	Hingham to Boston	Fast, Mid
	1:29:55	Lightning	1:30:52	n/a	Hingham to Boston	Fast, Mid
	1:40	Island Expedition	1:41:05	n/a	Hingham to Boston	Slow, close, docked
	1:45:44	Matthew J Hughes	1:47:07	1:50:15	Boston to Hingham	Slow, far
	2:51:59	Matthew J Hughes	2:54:44	2:54:44	Hingham to Boston	Slow, Mid
	3:30:02	Lightning	3:31:27	3:34:54	Hingham to Boston	Fast, Mid
	3:44:23	Matthew J. Hughes	3:45:35	3:48:09	Boston to Hingham	Fast, Far
	3:46:05	Island Discovery	3:46:46	n/a	Hingham to Boston	Slow, close, docked
	4:03:29	Flying Cloud	4:05:00	4:07:53	Boston to Hingham	Fast, Mid
	4:06:10	Lightning	4:07:32	4:10:25	Boston to Hingham	Fast, Mid
	4:42:31	Massachusetts	4:13:20	4:16:00	Boston to Hingham	Fast, Mid
	4:35:16	Matthew J. Hughes	4:36:30	4:38:30	Hingham to Boston	Fast, Far
	4:38:32	BHC CAT Nora Victoria	4:39:55	4:42:30	Boston to Hingham	Fast, Mid
	4:39:00	Flying Cloud	n/a	n/a	Boston to Hingham	Fast, Mid
7/22/08	9:29:50	Flying Cloud	9:31:14	9:33:16	Boston to Hingham	Fast, Mid
	9:30:23	BHC CAT Aurora	9:31:28	9:33:16	Hingham to Boston	Fast, Close
	10:13:59	Island Discovery	10:14:31	10:16:00	Boston to Hingham	Slow, Close
	10:15:01	Matthew J Hughes	10:16:33	10:18:47	Boston to Hingham	Fast, Mid

Date	Time	Boat	Long Wave	Short Wave	Direction	Notes
7/22/08	10:15:54	Flying Cloud	10:16:33	10:18:41	Hingham to Boston	Slow, Close
	10:26:19	Lightning	10:27:45	10:30:39	Boston to Hingham	Slow, Close
	10:50:22	Flying Cloud	10:52:12	10:53:56	Boston to Hingham	Fast, Mid
	11:16:21	Lightning	11:17:45	11:19:15	Hingham to Boston	Fast, Mid
	11:22:49	Matthew J Hughes	11:24:17	11:26:55	Hingham to Boston	Fast, Mid
	11:53:00	Lightning	11:54:12	11:57:00	Boston to Hingham	Fast, Mid
	12:41:50	Lightning	12:42:37	12:43:57	Hingham to Boston	Fast, Mid
	1:30:06	Flying Cloud	1:30:56	1:32:13	Hingham to Boston	Fast, Close
	1:43:30	Matthew J Hughes	1:45:01	1:50:20	Boston to Hingham	Fast, Far, slowed at G channel marker
	2:13:18	Lightning	2:14:22	2:16:00	Hingham to Boston	Fast, Far
	2:52:30	Matthew J Hughes	2:53:13	2:55:30	Hingham to Boston	Slow, Mid
	3:46:13	Matthew J Hughes	3:47:30	3:49:50	Boston to Hingham	Fast, Far
	4:07:12	Lightning	4:07:39	4:09:55	Hingham to Boston	Fast, Mid
	4:17:00	Massachusetts	4:18:22	4:20:53	Hingham to Boston	Fast, Mid
	4:39:09	Matthew J Hughes	4:40:17	4:41:53	Hingham to Boston	Fast, Mid
	4:39:40	BHC CAT Aurora	4:40:17	4:43:37	Boston to Hingham	Fast, Far
	4:40:31	Lightning	4:41:26	4:44:14	Boston to Hingham	Fast, Far
	4:49:48	Island Discovery	n/a	4:50:05	Hingham to Boston	Fast, Close
	4:49:48	Flying Cloud	4:51:10	4:53:27	Hingham to Boston	Fast, Far
	4:55:07	Island Discovery	n/a	n/a	Hingham to Boston	Fast, Close
	5:06:06	Massachusetts	5:07:16	5:09:09	Hingham to Boston	Fast, Mid
	5:15:30	Matthew J Hughes	5:16:45	5:18:22	Boston to Hingham	Fast, Mid
	5:19:35	BHC CAT Aurora	5:20:48	5:22:28	Hingham to Boston	Fast, Mid
	5:26:09	Lightning	5:27:26	5:30:00	Hingham to Boston	Fast, Mid

Date	Time	Boat	Long Wave	Short Wave	Direction	Notes
7/22/08	5:31:30	Provincetown Fast Ferry "Salacia" Large CAT Boat	5:32:14	5:33:40	Boston to Hingham	Fast, Close
	5:33:57	BHC CAT Nora Victoria	n/a	5:36:58	Hingham to Boston	Slow, Mid
7/23/08	9:29:09	BHC CAT Aurora	9:30:11	9:32:00	Hingham to Boston	Fast, Close
	9:29:56	Lightning	9:31:10	9:33:58	Boston to Hingham	Fast, Far
	10:09:08	BHC CAT Aurora	10:09:17	10:19:28	Boston to Hingham	Fast, Mid
	10:15:54	Lightning	10:17:20	10:19:28	Hingham to Boston	Fast, Mid
	10:24:24	Flying Cloud	10:25:55	10:28:21	Boston to Hingham	Fast, Mid
	10:50:28	Lightning	10:51:44	10:54:36	Boston to Hingham	Fast, Far
	11:46:56	Flying Cloud	11:48:22	11:50:34	Boston to Hingham	Fast, Far
	12:17:20	Island Expedition	12:18:04	n/a	Boston to Hingham	Slow, Close
	12:32:52	Flying Cloud	12:34:01	12:35:55	Hingham to Boston	Fast, Mid
	1:05:39	Flying Cloud	1:06:55	11:10:43	Boston to Hingham	Fast, Far
	1:18:10	Island Expedition	1:19:55	1:23:17	Boston to Hingham	Fast, Mid
	1:32:45	Lightning	1:34:46	1:37:45	Hingham to Boston	Slow, Mid
	1:44:17	Island Discovery	1:44:37	n/a	Hingham to Boston	Slow, Close
	1:55:34	Matthew J Hughes	1:56:50	2:00:49	Boston to Hingham	Slow, Far
	2:06:50	Flying Cloud	2:07:37	2:08:53	Hingham to Boston	Fast, Close
	2:53:45	Matthew J Hughes	2:54:55	2:57:15	Hingham to Boston	Slow, Mid
	3:30:17	Lightning	3:31:53	3:33:45	Hingham to Boston	Fast, Mid
	3:44:40	Matthew J Hughes	3:45:27	3:49:27	Boston to Hingham	Slow, Far, Sped up at southern end of pier
	4:07:03	Flying Cloud	4:07:46	4:09:40	Hingham to Boston	Fast, Far
	4:07:03	Lightning	4:07:46	4:09:40	Boston to Hingham	Fast, Far
	4:15:52	Massachusetts	4:15:20	4:17:47	Boston to Hingham	Approached Slow, sped up at green chan marker, mid

Date	Time	Boat	Long Wave	Short Wave	Direction	Notes
7/23/08	4:37:15	Matthew J Hughes	4:38:28	4:40:35	Hingham to Boston	Slow, Mid
	4:39:30	BHC CAT Aurora	4:40:38	4:40:35	Hingham to Boston	Slow, Mid
	4:41:50	Flying Cloud	4:42:41	4:44:38	n/a	n/a
7/24/08	9:28:31	BHC CAT Aurora	9:29:22	9:31:35	Hingham to Boston	Approached fast, slowed at southern end of pier, close.
7/25/08	10:25:05	Flying Cloud	10:25:59	10:27:52	Boston to Hingham	Fast, Mid
	10:50:15	Lightning	10:51:46	10:54:39	Boston to Hingham	Fast, Mid
	11:12:05	Flying Cloud	11:13:37	11:15:45	Hingham to Boston	Fast, Far
	11:47:18	Flying Cloud	11:48:49	11:51:10	Boston to Hingham	Far, Far
	12:19:52	Island Expedition	12:20:19	12:22:10	Boston to Hingham	Slow, Close, docked in Marina
	12:34:33	Flying Cloud	12:35:51	12:37:35	Hingham to Boston	Fast, Mid
	1:31:28	Lightning	1:32:29	1:34:49	Hingham to Boston	Fast, Far
	1:44:12	Matthew J Hughes	1:45:55	1:47:54	Boston to Hingham	Slow, far, sped up passed G channel marker
	2:08:26	Flying Cloud	2:09:30	2:11:10	Hingham to Boston	Fast, Mid

Appendix B: Full model results

Wave characteristics determined from modeling of local wind-generated waves Model was run for 16 wind quadrants for 4 wind speeds (relating to windrose, Figure 16).

Figures are laid out as follows:

Top left image a) the bathymetry;

Top right image b) the average significant wave height (Hs) experienced at each point in this region (weighted according to the observed wind climate);

Bottom left image c) the average energy density experienced at each point in this region; and

Bottom right image d) the direction of propagation associated with the modal significant wave heights (scaled to Hs). The modal wave direction throughout the harbor relates directly to the prevailing westerly wind conditions in Boston Harbor, although modal wave heights are less than 40 cm in the western Harbor, but higher close to mouth and in the outer Harbor.

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