

The Impact of Natural Waves and Ferry Wakes on Bluff Erosion and Beach Morphology in Boston Harbor, USA.

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ABSTRACT

HUGHES, Z.J., FITZGERALD, D.M. HOWES, N.C. and ROSEN, P.S., 2007. The impact of natural waves and ferry wakes on bluff erosion and beach morphology, Boston Harbor, USA. *Journal of Coastal Research*, SI 50 (Proceedings of the 9th International Coastal Symposium), 497 – 501. Gold Coast, Australia, ISSN 0749.0208

The Boston Harbor Island National Recreation Area is a unique environment resulting from the gradual inundation of a drumlin field. The resulting islands are diminishing in size due to rising sea level and coastal erosion. The island shorelines are dominated by bluffs composed of unconsolidated glacial sediment (till or reworked till). This study describes the morphology of the harbor shorelines and investigates the coastal processes effecting bluff erosion, including the relative contribution of locally generated waves and ferry wakes. Sea surface elevation data were collected using pressure sensors and a high frequency capacitance staff. DGPS shoreline mapping identified locations where bluffs were actively eroding and erosion rates were quantified through topographic surveys. Numerical wave modeling (SWAN) was used to assess the impact of locally generated waves in the absence of vessel wakes. Erosion rates vary from island to island, with a maximum of 1.9 myr^{-1} . Initial results indicate that the ferries wakes operate at a similar frequency to the locally generated wind waves (5Hz and 3.5Hz respectively). However, sea level elevation records indicate that waves and wakes only reach the bluff base during storm conditions and extreme high tides ($\sim 33 \text{ days/yr}$) when wind waves dominate the spectrum. Boat wakes are observed to increase wave energy reaching shorelines however the impact on bluff erosion is less conclusive.

ADDITIONAL INDEX WORDS: *SWAN model, sediment transport, drumlin erosion, vessel generated waves, salient*

INTRODUCTION

Changes in sea level associated with the end of the last glacial maximum continue to impact coastlines worldwide (DONNELLY, 2006). In particular, rising sea level in the Northeast of the United States has led to the inundation of terrestrial regions as well as the retrogradation of previously stable barrier systems and the ongoing transgression of others. Rising sea level changes sediment supplies, alters patterns of erosion and deposition, and modifies sediment transport pathways. Improved knowledge of these processes aids our understanding of coastal evolution and helps our prediction of future morphological changes. With global sea level rise predicted to increase from 2 mmyr^{-1} as presently observed, such knowledge becomes increasingly important. Over the past 100 yrs, an estimated 70% of the worlds sandy coastlines have retreated (BIRD, 1993), and the majority of research on these environments over the last 50 yrs has focused on open-coast beaches. Studies of more sheltered regions are much less common, particularly with respect to morphological response to sea level change.

In shallow or enclosed regions such as harbors, estuaries, bays and deltas wave-induced, erosion may be enhanced by the impact of vessel-generated waves (wakes) to the natural wave field (OSBORNE AND BOAK, 1999, PARNELL AND KOFOED-HANSEN, 2001). This is especially true in coastal waterways, e.g. within narrow estuaries and rivers, or between close-set islands. The

former has received an increasing amount of attention over the past 10 yrs in response to public concerns related to the escalating number of passenger ferries (e.g. PARNELL AND KOFOED-HANSEN, 2001; ELLIS *et al* 2006), while the latter is not widely studied. A maximum boat wake height of 0.3-0.35 m was previously determined as the threshold for significant erosion of a steep unconsolidated bank of sand (Gordon River, Tasmania; NANSON *et al*, 1994). Vessel wakes have been observed to increase suspended sediment in channels by an order of magnitude, above those produced by wind waves (SCHOELLHAMERR, 1996; PARNELL AND KOFOED-HANSEN, 2001). In studies of bank erosion by wakes, maximum wave height and the related energy have been determined to be the most important defining characteristics of the waves (ELLIS *et al*, 2002).

The research presented here examines morphological response to wave dynamics, natural and anthropogenic (wakes), in a sheltered harbor containing a complex system of islands.

Physical Setting

The Boston Harbor Island National Recreation Area, Massachusetts, is a unique environment resulting from the gradual inundation of a drumlin field during the past 8 ka (Figure 1). The resulting islands are diminishing in size due to rising sea level and coastal erosion (ROSEN and LEACH 1987; NEWMAN and MICKELSON, 1994; HIMMELSTOSS *et al*. 2005).

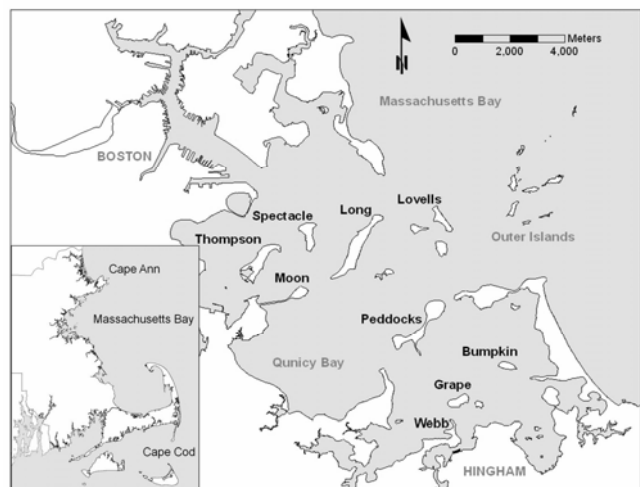


Figure 1. Boston Harbor, Massachusetts, USA. Nine of the 30 drumlin-pinned islands were monitored as part of this study (bluff profiling and nearshore wave measurements).

There are more than 30 islands within the harbor (including the outer islands) with an intricate network of narrow and shallow channels between them. The mean tidal range in the harbor is 3.1 m. Two large navigation channels are maintained running from the mouth of the harbor (depth 20 m) to the port of Boston and to Quincy Bay. In the deep, narrow channels around Lovell's and Peddocks Islands (13 m and 14 m, respectively) the tidal currents reach 1.5 ms^{-1} . Much of the inner harbor, toward Hingham and Quincy Bays, is shallow (3 m or less). Wave heights vary seasonally. In Massachusetts Bay, 29 km ENE of the harbor, wave heights average 2 m and 0.8 m during winter and summer, respectively (NOAA buoy 44013).

The island shorelines are dominated by bluffs composed of unconsolidated glacial sediment (NEWMAN and MICKELSON, 1994). The short-term rate of erosion and shoreline recession is a function of incident wave energy (dependant on fetch), extent of coastal vegetation, nearshore bathymetry, sediment composition, and precipitation. Erosion rates vary from island to island. Assessing shoreline retreat using historical charts and photographs, HIMMELSTOSS *et al.* (2005) observed that the seaward islands tend to erode in the northeastern quadrant, whereas deposition occurs along southwest shores, in line with the dominant NE swell wave climate. In certain areas of the harbor, high rates of bluff erosion occur along shorelines subjected to only moderate waves, such as Thompson Island, which experienced a loss of 18m (1938-1977) on the NW shore. It has been suggested that this erosion is in part related to ferries wakes, produced by the 30 m vessels servicing the Boston to Hingham route. At high tide these waves may reach 0.3 to 0.6 m. The anthropogenic contribution to the erosion of the Boston Harbor Islands has yet to be quantitatively assessed.

The sediment comprising the shorelines of Boston Harbor is derived from the erosion of the bluffs (ROSEN and LEACH, 1987). These sediments range in size from clay to boulder-sized gravel. As a consequence, the beaches within the harbor vary greatly in terms of sediment size, often being mixed. To date, no one has mapped the distribution of beach types, however, eroding bluffs

are generally fronted by boulder (-lag) beaches. In several regions large sedimentary deposits can be observed, most notably a system of dunes and sandy salients on the western shore of Lovells and an extensive region of low lying gravel, sand and mud on the SE shore of Peddocks Island.

METHODS

A combined program of field observations and modeling was conducted within the harbor, focusing on nine islands, with either one or two survey points on each island (Figure 1 and Table 1). The islands were chosen to represent a range of environments throughout the harbor. In addition, sub-population of these was chosen within the inner harbor in order to investigate areas where bathymetry and ferry activity produce a higher potential for wake-related erosion (e.g. Thompson, Moon and Grape Islands which fall along the ferry route).

Shoreline morphology and beach sediment type were mapped using a Trimble Pathfinder Pro XRS backpack DGPS system. These data were downloaded and post-processed using the ESRI ArcMap software to produce a GIS, allowing spatial analysis of the observations.

Regular topographic surveys, using a Pentax Theodolite, were taken across the bluffs and the beaches in front of them. Frequency of surveys varied between sites. Webb and Grape were selected for more intense surveying, allowing assessment of short term (quarterly) and very short term (over a lunar tidal cycle) erosion. Other sites were surveyed annually or bi-annually over the period April 2004 – October 2006.

A suite of instruments, including pressure transducers (Coastal macrologger) and a capacitance wave staff (Ocean Sensor Systems) was deployed from the beach, just beyond mean low water, at a number of sites during 2004 and 2005 (Moon, Webb, Grape, Peddocks and Lovells Islands). Deployments made use of a specially designed frame to support the wave staff and lasted for 3-10 days depending on security at the site. The sensors collected near-continuous (55 min burst) high-frequency (10Hz) surface elevation data capable of describing waves of periods as short as 1 s. During deployments, size, estimated speed and wake behavior of vessels passing the sensors were noted. The time-series of sea surface elevation, in conjunction with observations of passing ferries, provide a comparison of the period and amplitude of both the ferry wakes and locally generated wind waves.

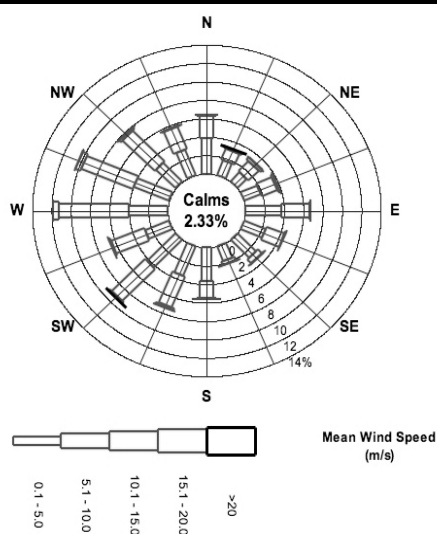


Figure 2. Wind Rose for Boston Harbor 1994-2005. Note the predominant winds from the W and SW and the strongest winds operate from both the SW and the NNE.

Calculations of the wave energy spectra, using Fast Fourier Transforms (TUCKER, 1991), were used to determine the frequencies at which wakes contribute to the wave energy impacting the shoreline. Concurrent evaluation of wave climate and boat activity allows the determination of the relative magnitude of the anthropogenic and natural wave components comprising the energy spectra.

The observed wave data have been augmented with results from a numerical model (Simulating WAVes Nearshore) of Boston Harbor. This allows a comparison between the observations and the less complex modeled scenario where wind waves are generated locally in the absence of boat traffic. The modeling also produced 2-dimensional vector fields, which provide insight into the potential wave-related erosion and sediment transport pathways in the harbor.

The model was run using a 90 m linear grid domain covering the largest possible extent of the harbor given grid size restrictions. Bathymetry was obtained from the United States Geological Survey (90 m horizontal resolution). SWAN was run in stationary mode for 16 wind directions and 4 wind speeds. The model was validated using data collected using a pressure transducer offshore from Lovells Island. The model showed a good agreement at two sites (not shown here). 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 (Figure 2). This method allows an assessment of the cumulative impact of the locally generated wind field.

Sea surface elevation data collected within Boston Harbor (NOAA Stn# 8443970), were analyzed statistically and compared to tidal predictions over a 10 yr period in order to determine the frequency and extent of deviations from the tidal curve. Variations above the predicted tidal elevation are assumed to be associated predominately with meteorological events.

Hourly wind data were obtained from the National Climatic Data Centre for Logan Airport (WMO ID 72509) within the harbor. Data were analyzed in 10 yr increments over the period 1975 to 2005. These data were used to produce an up-to-date wind rose for the harbor (Figure 2).

RESULTS AND DISCUSSION

Bluff erosion

The observed rates of erosion over the period of observation vary widely from site to site, and for each site. The greatest retreat rates were recorded at Moon Island and Lovells Island. A general patchiness of the lateral variation in erosion was observed in the field. For example the bluff profile on NW shore of Webb State Park showed no erosion, yet ~1m along the bluff a large incision developed in the top of the bluff due to precipitation run-off. However the data collected as part of this study supplies values of retreat over a short time-scale that would not be possible with a longer-time scale observations. This provides information concerning the manner of erosion at each site. Erosion rates were closely linked to the type of erosive process (slumping or slope-wash), high values on Moon Island relate to a slumping event in the region of the profile.

Table 1 compares long-term bluff retreat rates (HIMMELSTOSS *et al*, 2005), calculated from aerial photos (AP); averaged retreat rates observed (obs) over the three years of study and the elevation of the bluff base above mean sea level (MSL). While there are no clear relationships between the base elevation and the actual rate

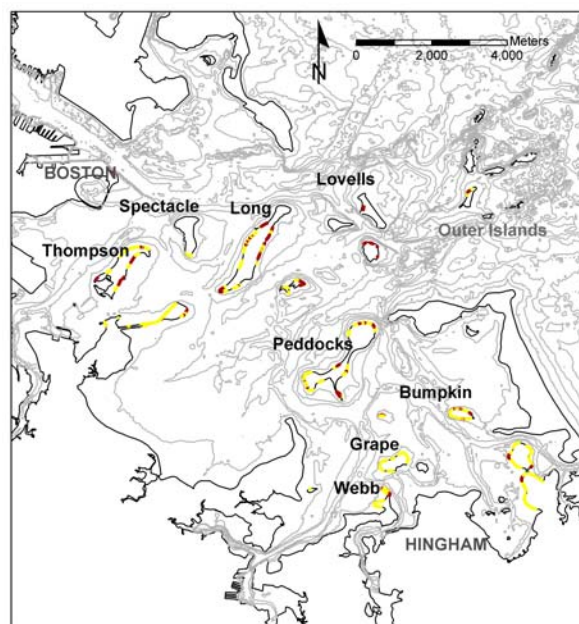


Figure 3 The spatial distribution of bluffs throughout Boston Harbor, both actively eroding (dark grey) and stabilized bluffs (light grey) are shown. NB the northeastern tip of Long Island is protected by a sea wall, like wise the NE tip of Moon island. Bathymetry to MSL.

of retreat, little or no retreat is seen on bluffs with bases greater than 2.62 m above MSL. This indicates that, although no clear relationship can be drawn between the exposure to waves and retreat rate, it is likely that exposure of the bluff toes to waves is a condition for erosion of a significant and measurable rate to occur.

All of the islands surveyed during the shoreline mapping exhibited bluffs, except Spectacle island, which has been modified as part of a landscaping project (Figure 3). While many eroding bluffs face the NE, an equally large number face W (e.g. Long, Peddocks, Grape, Webb and Lovells Islands exhibit W, NW or SW facing eroding bluffs). This suggests that locally-generated wind waves play a significant role in bluff erosion, in addition to NE swells (HIMMELSTOSS *et al*, 2005).

Table 1: Retreat rates from aerial photos (1938-1995; HIMMELSTOSS *et al*, 2005) and average observed through topographic profiling, bluff height and height of the base above MSL. Little erosion is seen at sites greater than 2.65m above MSL.

Island	Retreat (AP) m/yr	Retreat (obs) m/yr	Height m	Base wrt MSL m
Thompson	0.21	0.4	4.73	2.22
Webb SE		0.5	1.99	2.23
Moon SE		1.9	6.65	2.37
Lovells	1.06	0.84	6.45	2.45
Peddocks E	0.11	2	18.29	2.45
Moon E		0.4	13.7	2.59
Long S	0.42	0.05	14.12	2.60
Peddocks W	0.26	0.9	3.45	2.62
Bumpkin		0	4.34	2.68
Long W		0	9.5	2.84
Grape	0.07	0	7.05	3.16
Webb NW		0	3.9	3.33

Wind waves versus wakes

Observed boat wakes typically displayed a sequence of propagating waves (Figure 4), initially led by a low amplitude, low frequency (10s) wave, followed by one or more higher frequency groups of larger amplitude (0.3-0.5 m).

Observations of boat wakes on calm days in Boston Harbor indicate that majority of wave energy being transferred to the

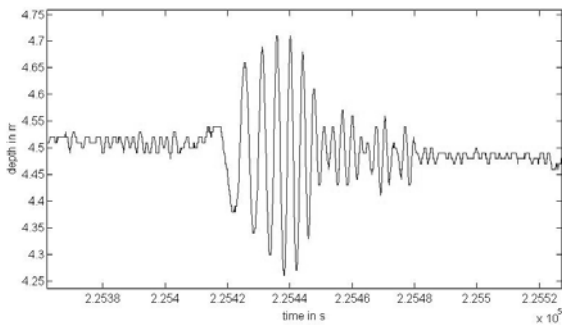


Figure 4. Example of a wake signal from observations of sea surface elevation; a low amplitude, long period wave arrives before at least one train of increasingly shorter period waves. Maximum wave heights observed here are 0.5 m.

shoreline is associated with waves having 5 second periods (Figure 5). In comparison measured and modeled natural waves predominantly occur at around 2-4 s periods (Figure 5). Thus, boat wakes operate at a slightly higher frequency than the natural waves. This frequency and their groupiness would imply a greater ability to resuspend sediment than the locally generated wind waves (OSBORNE and BOAK, 1999), such that that boat wakes may

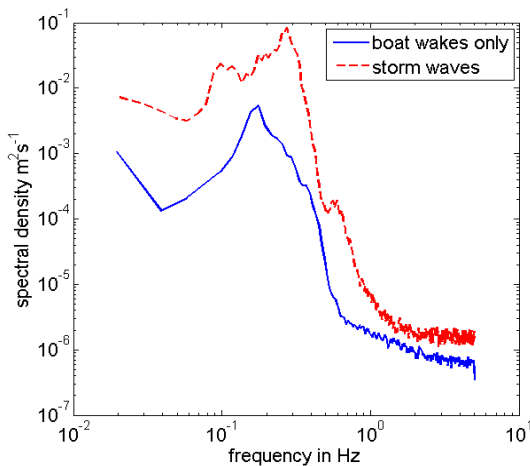


Figure 5. Energy spectra for the boat wakes in calm water collected Webb State Park, July 2005 (solid line) and combined wakes and natural waves during a moderate Nor'easter, Moon Island May 2005 (dashed line), peak energy occurring at 3.6 s, implying local generation and agreeing with model data described below.

significantly affect the transport of sediment within waters of the harbor.

Figure 6 summarizes the results of the wave modeling. Although strong winds operate from the NE, the impact of the

predominant SW winds can be seen in the results. Regions of low wave activity correspond with areas of deposition and fine sediment deposition, e.g. SE of Peddocks Island. Many islands demonstrate a response to a particular wind direction. Winds from the NE greater than 10 ms⁻¹ produce modal wave heights of over 0.8m. Due to refraction these waves focus on the tip of Moon Island where high retreat rates have been recorded. Lovells Island morphology is likely a result of the strong SW winds. These winds may be responsible for the formation of the dune system and model results indicate that the islands to the west of Lovells act as breakwaters potentially explaining the existence of salients at both ends of its SW shoreline. The modeled locally generated waves reflect the patterns of deposition within the harbor, demonstrating that much of the morphology of the islands can be explained due to local wave-generated sediment transport. Rates of bluff erosion seem to respond to wind wave 'events' rather than a cumulative mean. This supports observations above concerning the short-term erosion patterns related to the type of erosive process, suggesting, for example, that a single storm event can trigger a slumping event. However, the rate of erosion will be related to other longer-term factors not studied here e.g. precipitation, saturation of the till, variations in sediment composition or vegetation cover.

Sea surface elevation and bluff erosion

The observation was often made in the field that sea level rarely reached the base of the bluff. For waves to erode the toe of the bluff the following condition must be met.

$$\eta + \zeta > \beta \quad 1$$

Where β = the height of the bluff base above MSL, ζ = predicted tidal elevation above MSL and η = wave amplitude at the shoreline. Based upon the observations in Table 1, assuming no deviation from the theoretical tidal elevation we will compare the base elevation of Lovells (2.45 m) and Peddocks W (2.62) bluffs. To satisfy Equation 1 during an average high tide (range=3.1 m) these values become $\eta=1.07$ m and $\eta=0.90$ m, Peddocks and Lovells. During respectively an equinoxial high tide (range=4.49 m) requires $\eta=0.38$ m at Peddocks and $\eta=0.21$ m at Lovells. Given the observed and modeled wave heights in the harbor of around 0.4 m, (Figure 4 and 6), waves would only reach the Lovells bluff at the high equinoxial tide, and would not reach the Peddocks bluff at all. It is normal, however, for sea level to fluctuate from the predicted and it should be noted that waves breaking near the bluff will be steeper than those observed offshore; that waves in the harbor can reach over 0.5 m during storm events (Figure 6); and that localized wave set up on beaches may increase the sea surface elevations. We therefore examined the time series of actual sea surface elevation and considered two cases: when observed sea level exceeds the predicted tidal height by 0.2 m; and by 0.5 m. The frequencies of these events are 33 and 3 days/yr, respectively.

Thus, the elevation of the base of the bluff with respect to sea level is very important in terms of wave erosion. It is likely that wave erosion is enhancing the bluff retreat only at the lower sites. Waves will only be active in bluff erosion during exceptionally high tides or during elevated sea surface events, which often coincide with low pressure systems and storms. During these periods locally wind-generated waves dominate the energy spectra (Figure 4) and thus, boat wakes will not have a significant impact on the bluff erosion. This conclusion supports observations from the hydrodynamic models that events rather than cumulative wave impacts are reflected in the spatial distribution of eroding bluffs. However, certain regions may be more or less susceptible

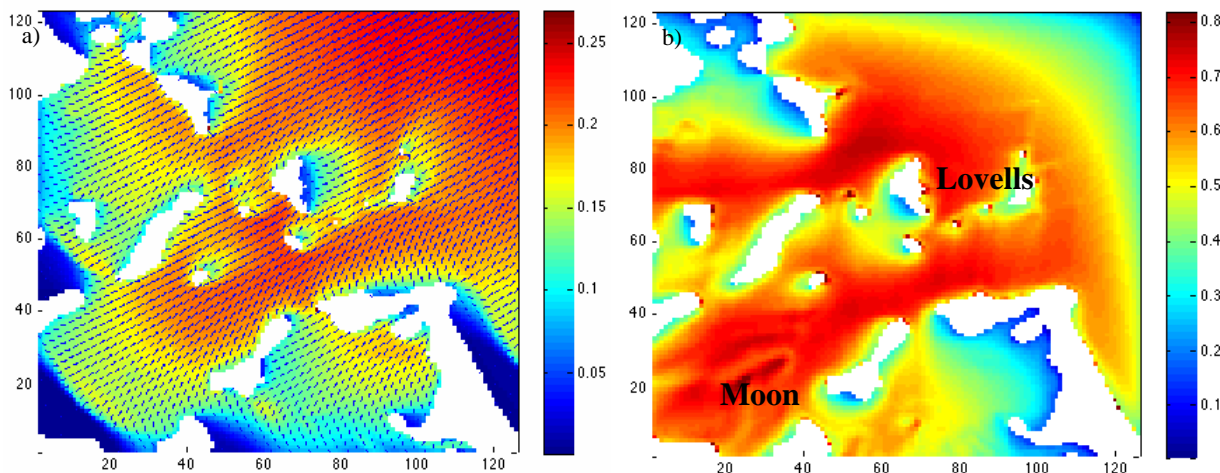


Figure 6. a) Wind Rose normalized means in direction and significant wave height calculated using the SWAN model. Vectors length normalized by local wave height. Some wave sheltering can be seen west of Lovell's (the shape of Lovell's relates to a very shallow boulder lag which is exposed at low tide to the N of the island) b) An event from the NE, winds 15 m h^{-1} , large waves impact the bluffs on Moon Island.

due to the state of the bluff in (saturation, vegetation and sediment composition).

CONCLUSION

The results of this study indicate that variations in the local wind wave field correlate with erosional and depositional patterns and the resulting island coastal morphology in Boston Harbor. For example, sheltered regions are associated with sites of sand deposition and salient formation. Wakes increase the level of wave energy reaching the shoreline and may contribute significantly to the beach morphology and redistribution of fine sediment in the sheltered regions of the inner harbor. Although our data demonstrate no clear relationship between the rate of bluff erosion and the sea level elevation or the local wave field, a threshold height value of bluff base above MSL was identified, bluffs with bases below this threshold may be reached by waves during storm events. This enhances their erosion rates significantly. Exposure to the natural wave field, which varies according to orientation and elevation above mean sea level, can therefore play an important role in bluff erosion. However, waves reach the bluff only during high water elevations normally associated with storms, when boat wakes are unlikely to contribute significantly to the wave energy spectra. Thus boat wakes are unlikely to influence the erosion of bluffs in Boston Harbor. Ultimately, as the rate of sea level rise accelerates, the drumlin bluffs will be increasingly exposed to wave erosion, resulting in higher rates of land loss.

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ACKNOWLEDGEMENTS

This project was funded by NPS grant BOHA-05514 'Boat Wake Impacts and their Role in Shore Erosion Processes, Boston Harbor Islands National Recreation Area.