Journal of Coastal Research	28	1A	20–33	West Palm Beach, Florida	January 2012

Coastal Hazard Vulnerability Assessment of Sensitive Historical Sites on Rainsford Island, Boston Harbor, Massachusetts

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ABSTRACT

MAIO, C.V.; GONTZ, A.M.; TENENBAUM, D.E., and BERKLAND, E.P., 2012. Coastal Hazard Vulnerability Assessment of Sensitive Historical Sites on Rainsford Island, Boston Harbor, Massachusetts. *Journal of Coastal Research,* 28(1A), 20–33. West Palm Beach (Florida), ISSN 0749-0208.

It has been well established that numerous coastal areas are threatened by sea-level rise and coastal flooding. Some of these vulnerable lands contain significant archeological sites and cultural resources. The accurate calculation of shoreline rates of change and identification of coastal hazard zones for areas containing cultural resources is crucial for the development of effective coastal zone management strategies that address resource conservation and preservation. This investigation employed geospatial and analytical statistical techniques to conduct a shoreline change study on Rainsford Island occurring from 1944 to 2008. The 4.45-ha island, located in Boston Harbor, Massachusetts, consists of two heavily eroded drumlins connected by a low-lying bar. Past archeological surveys have concluded that Rainsford Island has numerous historical sites and is an area of high prehistoric sensitivity. A recent geophysical survey mapped a Revolutionary War era cemetery on the island. Multiple data sources were integrated, including historical maps, aerial photographs, and airborne laser topographic data for shoreline delineation over various temporal and spatial scales. The Digital Shoreline Analysis System was used to determine rate-of-change statistics and distances, and to identify hotspot areas of erosion and accretion. The results show that the island eroded during the study period at a rate of 0.05 m/y on average, with erosion rates as high as −0.59 m/y. The bar has migrated SE resulting in erosion along the island's northern shoreline. Predictive modeling indicates that 26% of the island would become inundated with 1 m of sea-level rise including the area containing the cemetery.

ADDITIONAL INDEX WORDS: *Shoreline change, cultural resources, LIDAR, sea-level rise, erosion, coastal management.*

INTRODUCTION

Climate change will have widespread impacts on coastal areas and the socioeconomic and cultural resources that they contain (Kirschen *et al.*, 2007). The IPCC (2007) reports that there would be "major changes to coastlines and inundation of low–lying areas…" Presently, over 70% of the shorelines around the world are retreating landward, and on the eastern U.S. coast, nearly 86% of barrier beaches have experienced erosion during the past century (Galgano, Leatherman, and Douglas, unpublished data). As a result, numerous densely populated and developed cities rich in cultural and socioeconomic resources, such as New York and Boston, are highly vulnerable to coastal flooding and extreme erosional events (Clark *et al.*, 1998; Kirschen *et al.*, 2007).

It is expected that there will be approximately 1 m of sea-level rise (SLR) globally by 2100 (IPCC, 2007). An increased rate of SLR along the Massachusetts coast will have enormous environmental, socioeconomic, and cultural impacts (Kirschen *et al.*, 2007). These include the loss of ecologically important salt marsh habitat, increased height and penetration of storm surges into low-lying developed areas (Kirschen *et al.*, 2007), and the submergence and destruction of sensitive archeological sites and associated cultural resources (Shaw *et al.*, 1998).

In the past, coastal flooding in Massachusetts has resulted in enormous costs (Cooper, Beevers, and Oppenheimer, 2005). Kirshen *et al.* (2004) put the cost of coastal damages from the February "Blizzard of 78" at US$550 million, with emergency costs of US$95 million, mainly within the Boston metropolitan area. The "Halloween Nor'easter of 1991," also referred to as the "perfect storm," inflicted over US$1.5 billion in damages (Cooper, Beevers, and Oppenheimer, 2005).

To confront the challenges posed by SLR and storm surges along the Massachusetts coastline, there is a strong need for shoreline-change studies. Shoreline-change analysis is a tool that can be effectively employed to provide accurate and statistically robust information to coastal managers and policy makers, enhancing their ability to develop sound coastal zone

DOI: 10.2112/JCOASTRES-D-10-00104.1 received 12 July 2010; accepted in revision 1 November 2010.

management strategies (Chen and Rau, 1998; FitzGerald *et al.*, 2008; Gesch, 2009). The technique uses advanced geographic information systems (GIS) and analytical statistical methods to quantify, map, and predict coastal geomorphic trends (Boak and Turner, 2005; Leatherman, 1983; Moore, 2000). Through the analysis of erosion and accretion hotspot areas and lands susceptible to coastal flooding, a coastal hazard inventory can be developed (Gesch, 2009). Conducting these studies in Boston Harbor will be a key component to developing effective coastal zone management strategies and mitigation steps required to address future challenges associated with climate change (Dobson *et al.*, 2003; Ruggiero and List, 2009; Scavia *et al.*, 2002).

Shoreline-change analysis is of fundamental importance to numerous investigations carried out by coastal scientists, engineers, and managers (Boak and Turner, 2005). Effective coastal zone management strategies depend on an accurate determination of long term trends and rates-of-change statistics of the shoreline (Zeidler, 1997; Zuzek, Nairn, and Thieme, 2003). Because of the importance of robust and accurate rate calculations, these studies are no longer considered merely an academic exercise but a crucial objective of many coastal planning and management programs (Crowell and Leatherman, 1999; Moore, Ruggiero, and List, 2006).

Over the past decade, the methods employed in shoreline-change analysis have been dramatically improved by the capability to integrate data sets of differing spatial and temporal resolutions together within a GIS. Programs including ESRI's ArcInfo, Leica Geosystem's ERDAS Imagine, and the Digital Shoreline Analysis System (DSAS), an extension for ArcMap developed by the U.S. Geological Survey (USGS) have all been effectively employed in this endeavor (Thieler *et al.*, 2008). Combined, these technical advances provided an array of tools to assist in this investigation.

One of the most promising technological developments in shoreline-change analysis is the use of light detection and ranging (LIDAR) data (Harris *et al.*, 2005; Liu, Sherman, and Songgang, 2007; Moore, Ruggiero, and List, 2006; Robertson *et al.*, 2004). The increasing availability of LIDAR data over the past decade is revolutionizing the geospatial analysis of coastal features, and as its availability and temporal range increases, it will provide the foundation for many future shoreline change studies. LIDAR data are obtained from an aircraft- or vehicle-mounted instrument and provide the capability of producing high resolution digital elevation models (DEMs), which may effectively be integrated with local tidal data points to create mean high water (MHW) shorelines and flood hazard predictive maps (Liu, Sherman, and Songgang, 2007; Moore, Ruggiero, and List, 2006).

Study Site

The landform that now makes up Rainsford Island has been shaped and molded by dramatic environmental change for thousands of years and provides coastal scientists with an ideal natural laboratory in which to analyze historical shoreline change. Rainsford Island is currently owned and managed by the City of Boston and is 1 of 34 islands included in the Boston Harbor Islands National Recreation Area (National Park Service, 2009). The center of the small 4.45-ha Rainsford Island is 42°18′41.57″N, 70°57′14.74″W, and is located within Quincy Bay, Boston Harbor, Massachusetts (Figure 1). The island is made up of two heavily eroded drumlins connected by a low elevation sand and gravel bar (Figure 2). For its small size, Rainsford Island has a dynamic landscape that includes high steep bluffs, low elevation flat areas, steep sloping gravel beaches, and bedrock cliffs.

Geologic Framework

The geologic foundation for Boston Harbor consists of metasedimentary bedrock dating to the Precambrian and Paleozoic age, known as Cambridge Argillite (Kaye and Barchoorn, 1964). Rainsford Island exhibits two argillite outcrops on its south drumlin. During the numerous glacial advancements during the Pleistocene Period, the preexisting bedrock foundation was abraded and scoured into an irregular surface upon which glacial till was later deposited (Rendigs and Oldale, 1990). These later deposits are referred to as drumlin till, which is predominately composed of compact cobbles, boulders, and finer sediments scoured from the area during the period of the Wisconsin Glacial (Aubrey, 1994; Knebel *et al.*, 1993; Oldale and Coleman, 1992). Drumlin till forms the backbone of the landforms that today make up the Boston Harbor Islands; together they compose a drumlin archipelago, which is a unique geologic feature not seen anywhere else in the United States (Himmelstross *et al.*, 2006).

Land Use History

Boston Harbor has a rich and dynamic cultural past stretching back thousands of years. Many of the Harbor Islands have been systematically surveyed for archeological resources with approximately 60 sites identified as of 1999 (Luedtke, 2000). Although there are no documented precontact archeological sites on Rainsford Island, on neighboring Long Island, a single bifurcate projectile spear point was found dating to the early Archaic Period, approximately 11,000–8,900 YBP (Luedtke, 1984). The rapid inundation of the broad coastal plain during the early Holocene likely submerged much of the evidence for early prehistoric habitation within the Boston Harbor Basin (Aubrey, 1994; Bell, 2009).

The majority of documented archeological sites in the Harbor Islands date to the Middle or Late Woodland periods, approximately 1330–450 YBP (Luedtke, 2000). The abundance of Woodland sites within the harbor is likely a result of a slowing rate of SLR during this time, and estuarine habitats within the harbor had become well established, providing abundant marine resources that could be utilized by the local populations (Bell, 2009; Luedtke, 2000).

Qualitative environmental criteria and anecdotal accounts suggest that Rainsford Island contains prehistoric sites, though many may be buried beneath historically reclaimed lands (Berkland, 2009). Only a small percentage of the island has been tested archeologically, leaving much of the island unsurveyed. Because of these factors, the 2002 Rainsford Island Archeological Survey concluded that the island was an

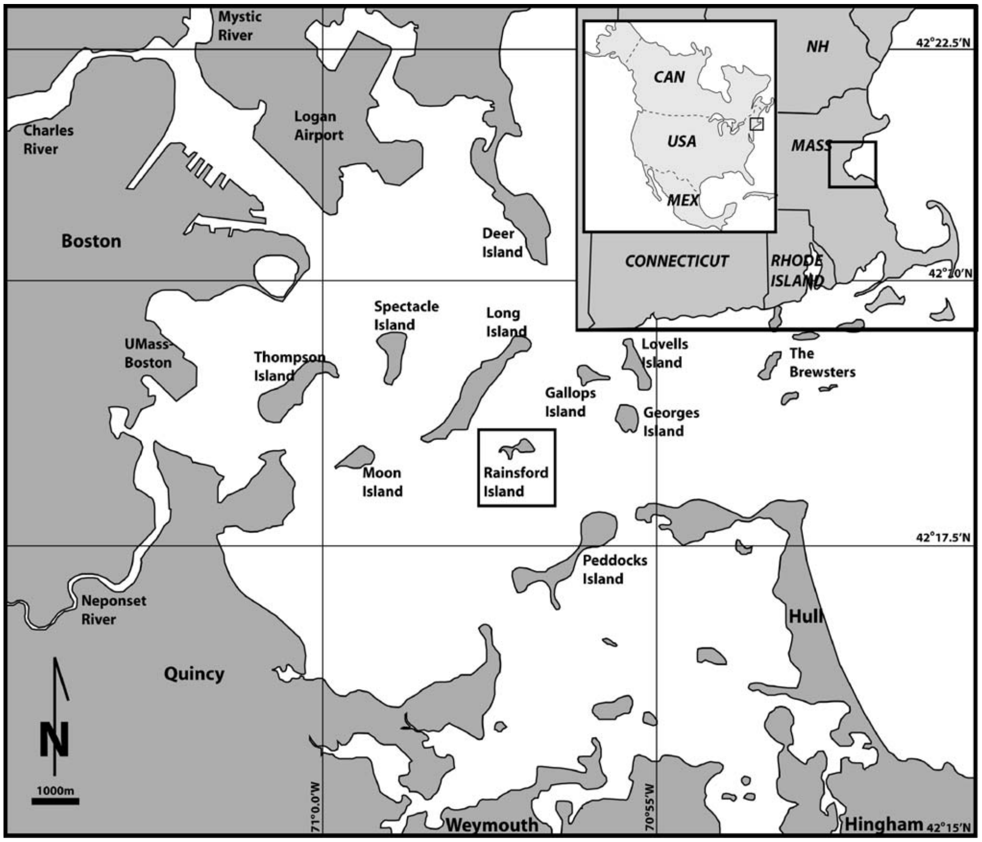

Figure 1. Rainsford Island is located within Quincy Bay, Boston Harbor, Massachusetts. The island is positioned between the larger Long and Peddocks Islands shown within the black lined square. Rainsford Island is currently managed by the City of Boston and is 1 of 34 islands included in the Boston Harbor National Recreation Area.

area of high prehistoric sensitivity (Claesson and Carella, 2002).

Rainsford Island has numerous culturally significant sites that provide a rich chronology of historical and environmental developments since the European colonization of North America. The island's namesake, Edward Raynsford, was the first European to inhabit the island in 1636. For the next 100 years, the island was used as a cattle pasture and fishing station (Claesson and Carella, 2002). Institutional use of the island began in 1737 and continued for nearly two centuries (National Parks Service, 2009). During this period, the island was predominately used as Boston's main quarantine station (Fenn, 1976). It also served as a veteran's hospital and alms house, reform school for boys, and the burial ground for many of its inhabitants (Boston Record Commissioners, 1907). The location and extent of the island's centuries-old cemetery was recently delineated through the use of ground penetrating radar (Gontz, 2008).

In 1996, the Boston Harbor Islands National Recreation Area was established by congressional mandate and encompassed Rainsford Island (National Parks Service, 2009). The recreation area was created to protect the Harbor Islands and their associated cultural and socioeconomic resources and to improve public knowledge and access (National Parks Service, 2009). Because of the numerous sensitive archeological sites and associated cultural resources on Rainsford Island, it remains under the management of the City of Boston and is closed to the general public (National Parks Service, 2009).

Study Intention

The goal of this investigation was to accurately map and quantify trends in the shoreline evolution on Rainsford Island occurring from 1944 to 2008 to assess the coastal hazard vulnerability of areas that contain sensitive archeological sites and associated cultural resources. The investigation used available data sources to identify past and present shoreline positions. Areas susceptible to erosion and flooding were identified as coastal hazard zones.

METHODS

Calculating shoreline change over time requires two main components: (1) the selection and definition of an indicator feature to use as a proxy to delineate the shoreline and (2) the detection and digitization of the indicator feature using available data sources (Boak and Turner, 2005). Despite

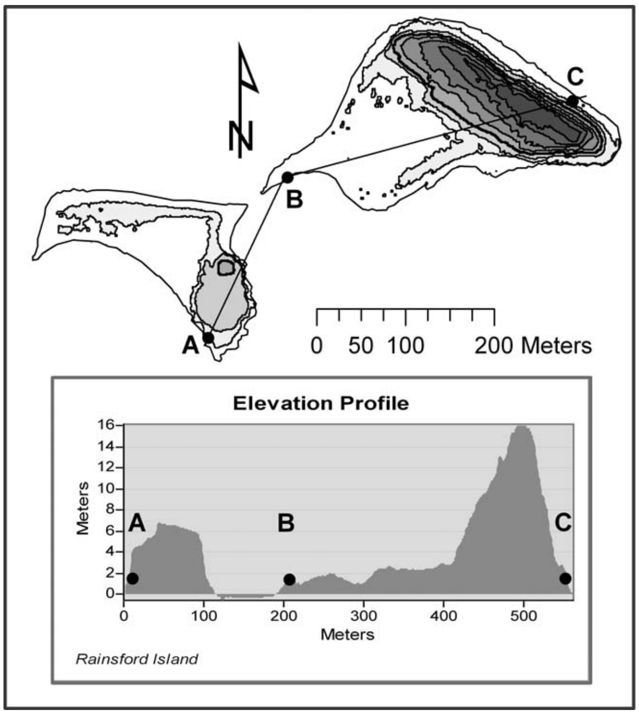

Figure 2. LIDAR-derived 1-m contour interval topographic map with elevation profile shown. The vertical profile was taken along the cross section shown with the black line proceeding from A to B to C. The black points indicate the corresponding locations of A, B, and C, on the topographic map and elevation profile. The heavily eroded north and south drumlins are connected by a low elevation sand and gravel bar. The north drumlin reaches a maximum height of 16.7 m, while the south has been eroded to a flat plain with a maximum relief of 6 m. The north portion of the island displays classic drumlin morphology that has been modified by erosion with high steep bluffs gently sloping downward toward the direction of ice flow.

breakthroughs in remote sensing technology and computer mapping techniques, all but the most recent shoreline change studies still rely heavily on manual visual identification and definition of an indicator feature (Boak and Turner, 2005; List and Farris, 1999; Robertson *et al.*, 2004).

Shoreline indicators usually fall into one of two categories: (1) visually discernable indicators such as coastal features that can be manually identified on aerial photographs and in the field, including the high water line (HWL), the vegetation line, and the storm debris line, and (2) elevation-based indicators such as those derived from the intersection of a coastal profile with a specific elevation taken from a statistically derived tidal datum including the mean high water (MHW) elevation (Boak and Turner, 2005; Harris *et al.*, 2005; Moore, Ruggiero, and List, 2006; Robertson *et al.*, 2004). MHW is a value derived from the average of all high tides occurring during the selected tidal datum epoch, which in this case is 19 years (Pugh, 1987).

Our study combined both visual and elevation proxies to examine the historical trends of the Rainsford Island shoreline. The visual proxy, the HWL, was extracted manually from high-resolution coastal aerial photography, and the elevation proxy, the data-derived MHW elevation, was projected onto the 2002 Boston Harbor LIDAR data. The HWL was defined in this study as the markings left on the beach face by the furthest extent of the last high tide. This feature is physically represented within the available data by the most seaward line of seaweed and debris.

There are numerous justifications for choosing the HWL as the indicator to delineate shoreline positions (Boak and Turner, 2005). The HWL is by far the most common indicator used in shoreline change analysis and is the official shoreline on historical maps and charts (Boak and Turner, 2005; Moore, Ruggiero, and List, 2006) This feature can also be accurately and consistently delineated on both low resolution historical aerial photographs and more modern high resolution orthophotographs.

The elevation proxy MHW shoreline was created from the linkage and integration of the 2002 MassGIS high resolution LIDAR-derived DEM and NOAA's statistically derived tidal data for Boston Harbor (MassGIS, 2003; NOAA, 2007). Statistically derived tidal data act as a benchmark height to measure local water levels and are based on long running tide gauge records. This linkage provides the ability to objectively create a shoreline based on statistically derived tidal elevation values, alleviating all uncertainties inherent in traditional shoreline change studies (Gesch, 2009; Liu, Sherman, and Songgang, 2007). The 2002 MHW shoreline was used as a baseline with which to model flood hazards associated with future SLR and storm surges and to visually assess coastal trends by overlaying it on historical maps. The MHW shoreline was also used to develop the two baselines necessary for the linear regression analysis of the HWL shorelines.

This investigation also used the vegetation line (vegline) as a visual indicator to delineate and quantify the change to the vegetated areas of the island. The vegline is an easily distinguishable coastal feature represented on the image data by a dramatic tonal difference between the light colored nonvegetated beach areas and the darker colored vegetative areas. This feature could be confidently identified on all of the aerial photographs used in this study.

The applicability of vegetation data may be limited, in some cases, because coastal geomorphic changes cannot always be correlated to changes in vegetation and vice versa. For example, a loss in vegetation during a particular year may be predominately a result of poor growing conditions rather than any coastal geomorphic shifts that may have occurred. On the other hand, a loss in vegetation may be evidence for a large storm surge resulting in the loss and/or burial of vegetation. Despite the difficulty in directly correlating vegetation change to shoreline-change, the confidence and accuracy in delineating this clearly discernable feature throughout the image data made it a very useful supporting tool with which to analyze the historical evolution of Rainsford Island's environments and assess the vulnerability of archeological sites and their associated cultural resources.

Data Sources and Integration

The ability to integrate and analyze multiple data sources at varying temporal and spatial scales within a GIS was an integral part of this investigation. ArcGIS version 9.2, designed by ESRI Inc., was used in this study for all data integration and geospatial analysis. Leica Geosystems ERDAS Imagine, a remote sensing and photogrammetric processing software package, was employed for the geoprocessing of all image data.

The shoreline data available for this study, beginning with the 1944 aerial photograph and ending with the 2008 MassGIS orthophotographs, cover over 60 years. This study included four unrectified aerial photographs dating from 1944, 1952, 1970, and 2002. These images required the application of geometric corrections and other geoprocessing before they could be integrated and used together within the GIS. Conversely, the three medium and high resolution digital orthophotos dating from 1992, 2005, and 2008, as well as the 2002 LIDAR data, were obtained through the Massachusetts Office of Geographic and Environmental Information (MassGIS) as georeferenced MrSID files. These files were downloaded and projected into the Massachusetts Mainland State Plane, NAD83 coordinate system and imported into the GIS (MassGIS, 2003, 2009).

A historic map of the island's infrastructure dating from 1904 was obtained through the Rainsford Island Archeological Survey data archives and integrated within the GIS (Claesson and Carella, 2002). This map required the application of geometric corrections and other geoprocessing before it could be integrated with the other data. Because of the poor alignment of the shoreline along portions of the large granite seawall, the map was not included in the shoreline analysis. The map was nonetheless very useful in identifying the general location of historical sites and coastal infrastructure, which allowed an assessment of how these sites have been affected by past coastal trends.

Shoreline Delineation and Digitization

The process of delineating and digitizing the HWL shoreline and vegline of Rainsford Island was carried out using ArcGIS software components. These coastal features were digitized using the Editor tools. For each image data set employed (georeferenced aerial photograph or orthophotograph), there were four shape files created from the HWL and vegetation features. For example, for the 2005 orthophotograph, the shape files included two polyline files representing the HWL and vegline, and two polygon files representing the surface area above the HWL and the surface area of the vegetated portions of the island. The polyline files were used to determine rate-of-change statistics, while the polygon files was used to approximate changes to surface area during the study period.

Digital Shoreline Analysis System (DSAS)

The DSAS, version 4.0, is an extension developed by the USGS for use with ArcGIS software (Thieler *et al.*, 2008). DSAS was designed to enhance the ability of coastal researchers to conduct historic shoreline-change studies using multiple historical shoreline positions. The DSAS extension casts perpendicular transects from a baseline and automatically calculates rate-of-change and associated statistics on the distance between the baseline and the multiple historic shoreline or vegline positions within ArcMap (Thieler *et al.*, 2008).

There were several steps required to prepare shoreline and vegetation data prior to using the DSAS extension. A detailed User Guide & Tutorial created by the USGS was used as a guide for the necessary tasks (Himmelstoss, 2009). These preparation steps included creating a baseline, setting shoreline field requirements, creating a geodatabase, and appending the shoreline and vegetation data so that a single file was developed for each data type (Thieler *et al.*, 2008).

The baseline is of fundamental importance to creating accurate rate calculations within DSAS (Himmelstoss, 2009). Because the digitized shoreline and vegline features were spatially unique and independent of one another, two separate offshore baselines were necessary to accurately determine rate-of-change statistics for each feature. The baseline used for the shoreline analysis was created by uniformly expanding or buffering the 2002 MHW shoreline 55 m seaward. This distance was necessary to include the wide variability in shoreline positions during the study period. The baseline was then manually edited to ensure the proper alignment of transects because best results are obtained when transects cross shorelines at a perpendicular angle (Thieler *et al.*, 2008).

The baseline for the vegetation analysis was created using similar procedures, by uniformly expanding the MHW shoreline 10 m seaward. Because there is no vegetation covering the low elevation gravel bar that connects the north and south drumlins, two separate baseline features were created during the editing session that together served as the vegetation baseline.

Transects were set at 100 m in length and spaced 10 m apart. Transects used in the shoreline analysis are referred to as T_s and transects used for vegetation analysis as T_v. There was a total of 232 shoreline transects (T_s) and 186 vegline transects (T_v). Individual transects were chosen to represent the different areas of the island based on two criteria. The first criterion was that transects were approximately centered within the geomorphic zone in which they were chosen to represent. The second criterion was that transects crossed the majority of shorelines perpendicularly. In some cases, more than one transect was chosen to represent a particular area because a single transect could not fulfill both criteria.

The DSAS extension was used to calculate numerous statistics for each transect based on the differences in measurements between shore and vegline positions through time. Statistics were calculated using a 90% confidence interval and include net shoreline movement (NSM), shoreline change envelope (SCE), linear regression rate (LRR), and the R-squared of linear regression (R^2) (Thieler *et al.*, 2008). All rates were reported in meters of change per year (m/y) along each transect, with negative values corresponding to areas of erosion.

Despite the numerous statistical methods available for calculating shoreline change within the DSAS extension, this study relied heavily on linear regression (LR) analysis for computing the change through time of the vegline and shoreline positions. Other statistics calculated were used as a reference but not reported in this paper. Douglas and Crowell (2000) report that the LR method of statistical analysis is one of the most effective statistical approaches to shoreline-change analysis because it minimizes potential random errors and short term variability. LR analysis also includes all of the available data and is an accepted method for calculating long-term rates of change (Crowell and Leatherman, 1999). LR analysis was therefore used as the primary method for statistical analysis.

2002 Mean High Water Shoreline

The first step in creating a tidal-data–LIDAR-derived MHW shoreline was to integrate the 2002 LIDAR DEM with the Boston Harbor tidal data. The National Oceanic and Atmospheric Administration/National Ocean Service (NOAA/NOS) Center for Operational Oceanographic Products and Services (CO-OPS) provide accurate statistically derived tidal data for the Boston Harbor area (NOAA, 2007). The 2002 MHW shoreline and LIDAR-derived DEM were used to create coastal flood hazard maps and to visually assess coastal trends occurring on the island. Because of the uncertainties associated with integrating LIDAR-derived MHW shorelines with those created using a visual proxy the 2002 MHW shoreline was excluded from the determination of rate-of-change statistics within DSAS. This elimination was necessary because there was only one LIDAR data set (2002), eliminating the option of comparing two objectively created shorelines. The regression analysis was therefore carried out exclusively on the seven visual proxy-derived HWL shorelines.

The flood hazard maps were based on a static sea-level model that does not take into account erosion or accretion, thus limiting their ability to depict shoreline response. They nonetheless offer an effective tool for visually identifying coastal hazard zones that are potentially vulnerable to the long term impacts of SLR and storm surge events. In the model, the elevation of the 2002 MHW shoreline is instantaneously raised by a user specified value (1 and 3 m) on the Rainsford Island LIDAR-derived DEM. Three separate areas were quantified and portrayed on the map, including the presently submerged areas, the newly inundated areas, and the undisturbed terrestrial areas.

Two flood hazard maps were produced, depicting the areas that may be submerged in response to a 1- and 3-m rise in sea-level or storm surge elevation. The 1-m elevation value was chosen to model the potential flood hazards associated with a 1-m rise in sea level, as predicted by the IPCC (2007). The 3-m elevation value was based on the approximate height currently set for the 100-year flood in the Boston metropolitan area (Kirschen *et al.*, 2008). These maps were produced within ArcMap using the Spatial Analyst tools. The division of the three classes was based on the North American Vertical Datum of 1988 (NAVD88) relative MHW elevation value of 1.319 m (NOAA, 2007). This value represents the elevation contour derived by taking the statistical mean of all high tides occurring over the 19-year tidal data epoch.

RESULTS

Rainsford Island was divided into eight geomorphic compartments based on the general characteristics of each area (Figure 3). One or two transects were chosen to represent each of these areas based on their centered position within the zone and the angle at which they crossed the shorelines. Statistics were obtained from each of the selected shoreline (T_s) and vegetation (T_v) transects. This division provided a more localized view of the coastal trends occurring on the dynamically shaped island. All LLR for shoreline and vegline results were graphed, showing change in shoreline–vegline position through time (m/y) and reported in their respective tables (Tables 1 and 2).

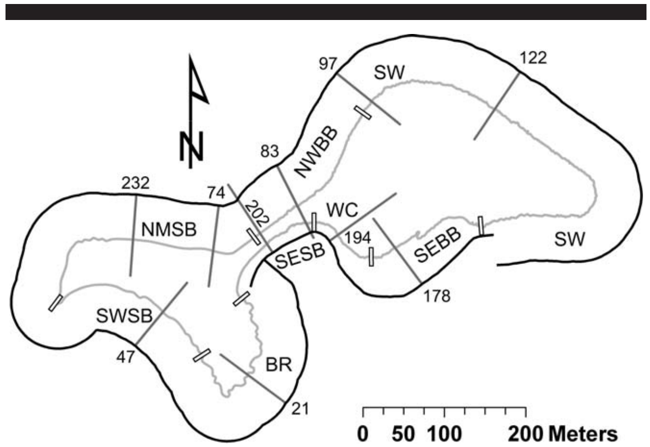

Figure 3. Shoreline compartments and representative transects on Rainsford Island. The dark line is the baseline created by displacing the 2002 LIDAR-derived MHW shoreline 55 m seaward. Transects 232 and 74 represented the north mixed sediment beach (NMSB); transect 83 represented the NW boulder beach (NWBB); transects 97 and 122 represented the seawall (SW); transect 178 represented the SE boulder beach (SESB); transect 194 represented the west cove (WC); transect 202 represented the SESB; transect 21 represented the bedrock areas (BR); and transect 47 represented the SW sand beach (SWSB). The elongated rectangles shown crossing the shoreline provide the location of beach divisions.

North Mixed Sediment Beach (NMSB)

The results for the NMSB were obtained from the analysis of T_s 74 and T_s 232 and provide the first example of an erosional hotspot on Rainsford Island. The analysis of T_s 74 provided an LRR of -0.19 m/y, and an R^2 value of 0.82. During this period, the shoreline moved landward 12 m. Between 1944 and 1970 there was no change in shoreline position. The largest change came between 1970 and 1992 when the shoreline moved landward 10 m. The analysis of T_s 232 provided an LRR of -0.1 m/y with an R^2 value of 0.69. The shoreline moved landward 8 m. The shoreline results from the analysis of T_s 232 and T_s 74, which lay approximately 30 m apart, are consistent, showing a slow rate of erosion. The vegetation analysis of T_v 176 also showed a linear trend of loss. The LRR was -0.15 m/y, with an R^2 value of 0.65. The vegline moved landward 8 m.

There was a strong positive correlation between the shoreline and vegline data sets for the NMSB, indicating that both have retreated landward during the study period. The statistical analysis indicates that if the coastal processes that produced these rates of erosion remain the same, the NMSB will likely continue to retreat during the next decade.

Table 1. *Shoreline results obtained through the DSAS. Positive NSM and LRR indicate progradation, negative NSM and LRR indicate landward movement. Rates are reported in meters per year (m/y) and distances in meters (m).*

Transect Number	Shoreline Location	Linear Regression Rate (LRR), m/y	R^2	Net Shoreline Movement (NSM), m
232	NMSB	−0.10	0.69	−8
74	NMSB	−0.19	0.82	−12
83	NWBB	−0.34	0.80	−20
97	SW	−0.08	0.91	−5
122	SW	−0.30	0.41	0
178	SEBB	−0.59	0.96	−43
194	WC	0.83	0.90	50
202	SESB	0.33	0.85	20
21	BR	0	0	1
47	SWSB	0.05	0.47	2

Table 2. *Vegline results obtained through DSAS. Positive values correspond to progradation, while negative values correspond to landward movement. Rates are reported in meters per year (m/y) and distances in meters (m).*

Transect Number	Vegline Location	Linear Regression Rate (LRR), m/y	R^2	Net Shoreline Movement (NSM), m
176	NMSB	−0.15	0.65	8
27	NWBB	−0.13	0.53	−12
43	SW	0.27	0.73	−16
83	SEBB	0.23	0.88	−15
99	WC	−0.41	0.66	−19
117	BR	0.82	0.76	54
141	SWSB	0.2	0.86	14
176	NMSB	−0.15	0.65	8
27	NWBB	−0.13	0.53	−12
43	SW	0.27	0.73	−16

Northwest Boulder Beach (NWBB)

Analysis of T_s 83 provided the results for the NWBB, which is also an erosional hotspot (Figure 4). This coastal compartment contains part of the low-lying bar connecting the two drumlins and showed an LRR of −0.34 m/y with an R^2 value of 0.80. The greatest net shoreline movement (NSM) came between 1970 and 1992 when the shoreline retreated by 20 m. The vegetation data mirrors the trend of loss in the shoreline analysis with an LRR of −0.13 m/y along T_v 27. Between 1944 and 2008, the vegetation retreated landward by 12 m.

Southeast Boulder Beach (SEBB)

T_s 178 was used for the analysis of the SEBB, which showed a rapid rate of erosion of −0.59 m/y, with an R^2 value of 0.96 and an NSM of −43 m (Figure 4). According to the results, this area has experienced a significantly higher rate of erosion than other areas of the island. Vegetation analysis of T_v 83 along the SEBB showed a loss of vegetation at the slower rate of −0.23 m/y, with a total landward retreat of 15 m. This area once contained the island's main wharf and docking facilities, which have all been destroyed during a century of erosion (Claesson and Carella, 2002).

Seawall (SW)

The high bluffs of the north drumlin have been buffered from wave attack and erosion by the large granite seawall constructed in 1836 (Claesson and Carella, 2002). Even though the seawall has been breached and collapsed in some areas, it still is largely intact and has likely limited the rate of erosion in the areas that remain armored. The combined shoreline and vegetation results indicate that this area has been relatively stable and has experienced a lower rate of erosion than the other areas of Rainsford Island (excluding the bedrock outcrops).

The analysis of T_s 97 provided an LRR of −0.08 m/y, with an R^2 value of 0.91 (Figure 5). The analysis of T_s 122 provided an LRR of −0.3 m/y and an NSM of −0.33 m/y. The analysis of the vegetation data along the SW was carried out using T_v 43. The results show a more significant rate of loss compared with the erosion of the shoreline. The LRR was −0.27 m/y with the vegetation retrograding landward by 16 m. This was more than three times that of the distance of the shoreline. These processes are closely related to the geologic framework of the bluff and amount of precipitation, while the shoreline position is controlled by the buffering capacity of the seawall.

The observed change in vegetation position along T_v 43 is likely the result of bluff-top erosion and mass wasting events, resulting in the burial and loss of vegetation along this portion of the bluff. Because the vegetation serves to stabilize the steep bluff, its loss serves as a positive feedback mechanism for further instability and erosion.

Bedrock (BR)

The steep bedrock shoreline on the southern end of the south drumlin has remained stable throughout the study period. Results from T_s 21 provided an LRR of 0 m/y, with an R^2 of 0 (Figure 5). Early settlers were likely attuned to the stability of this portion of the island, choosing it for the site of the large stone hospital built in the 1800s (Claesson and Carella, 2002). The vegline results were obtained from T_v 117, which provided an LRR of 0.85 m/y, with a net vegetation movement (NVM) of 54 m. The hospital's large granite foundation still remains in this area but has been overgrown by vegetation, which may be the major factor behind the rapid advancement of the vegetation in this area.

Southwest Sand Beach (SWSB)

The analysis of T_s 47 provided an LRR of 0.05 m/y and an NSM of 2 m, indicating this area is stable. The regression line had a relatively low correlation with the data points, with an R^2 value of only 0.47. Most of the accretion in this area occurred prior to 1970 because between 1970 and 2005 the beach remained relatively stable. The vegetation analysis was carried out using T_v 141. The results show a trend of vegetation gain, with some small periods of loss. The LRR of 0.20 m/y was over three times greater than that of the shoreline analysis. Between 1944 and 2008, the vegetated areas along this transect advanced seaward by 14 m.

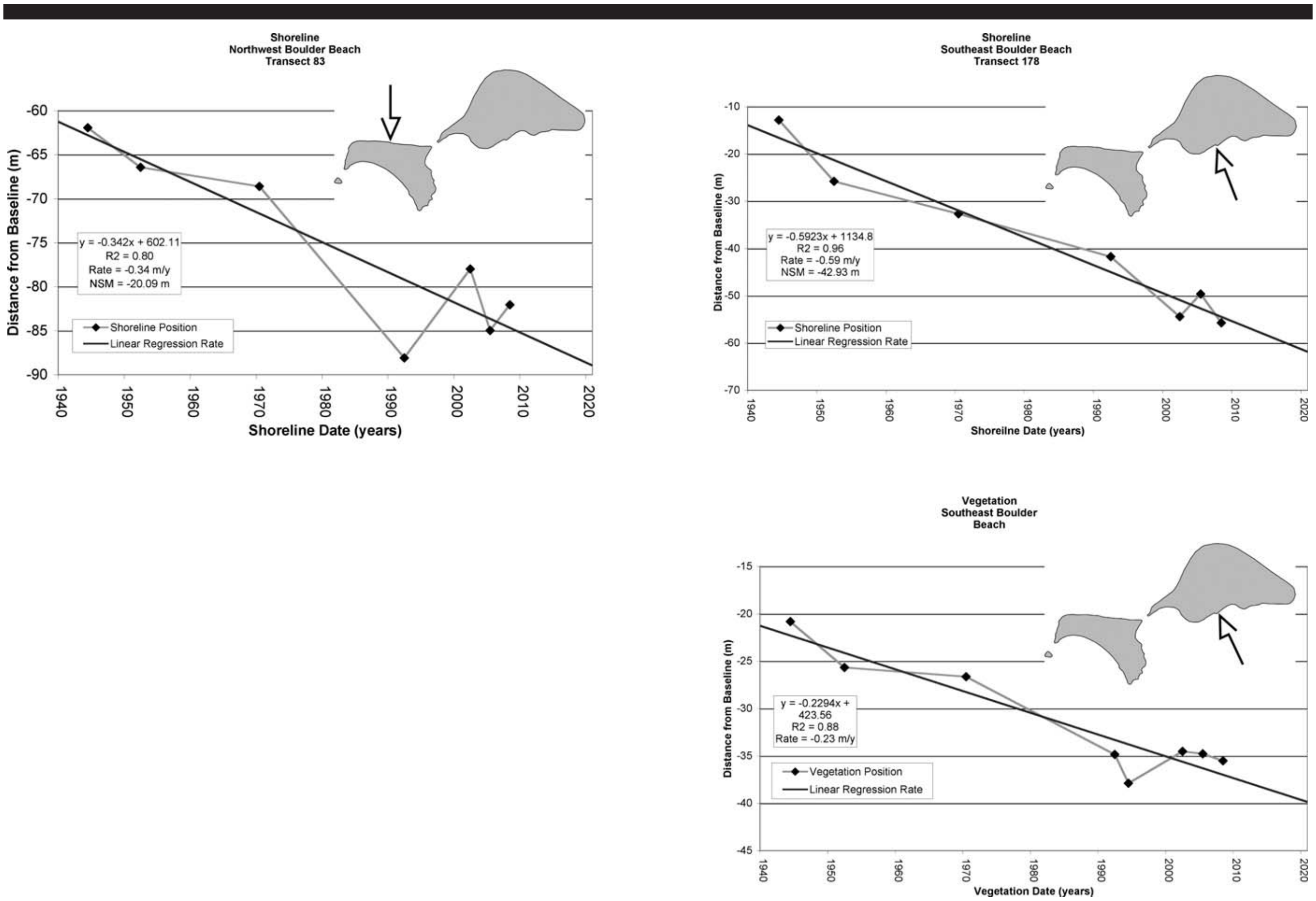

Figure 4. Graphed results of two erosional areas on Rainsford Island including the NWBB and SEBB.

West Cove (WC)

The analysis of T_s 194 within the WC provided results that show the area rapidly accreted at an LRR of 0.83 m/y, with an R^2 value of 0.90 (Figure 6). Between 1970 and 1992 over 50 m of accretion occurred. In contrast to the shoreline, the vegline was retreating at an LRR of −0.41 m/y along T_v 99. The NVM was −19 m, indicating a landward retreat between 1944 and 2008. However, the vegline change envelope, which is a measure of the total distance the vegline has moved regardless of the temporal scale, was 34 m. This indicates the vegetation within the WC has both advanced and retreated during the study period.

Southeast Sand Beach (SESB)

The analysis of T_s 202 along the SESB shows a steady seaward movement of the shoreline with an LRR of 0.33 m/y, with an R^2 of 0.85 and a seaward progradation of 20 m (Figure 6). The high linear correlation between the data points provides strong evidence that the SESB will likely continue its trend of accretion during the next decade. Because there is no vegetation on the low-lying bar, the vegetation analysis was not carried out in this location.

Flood Hazard Maps

The predictive map displaying the possible inundation in response to a 1-m rise in sea level or storm-surge event indicated that 26% of Rainsford Island would become flooded under this scenario (Figure 7). The bedrock and seawalled portions of the island appear to be resistant to a 1-m SLR or storm surge event and remain stable. This is a direct result of the vertical to near vertical slope of the coastline in these areas preventing inundation. The submergence of the narrow low-lying areas of the bar results in the north and south drumlins detaching under a 1-m scenario. Large portions of the WC, SEBB, NWBB, and NMSB also become inundated.

In addition to the flooding that takes place along the shoreline, other low-lying inland areas also become inundated. These areas contain sensitive historical sites, including the cemetery, which is considered a significant cultural resource. The inundated triangular area on the south drumlin coincides closely with the borders of this extremely sensitive site.

Under a scenario where there is a storm surge or SLR of 3 m, over 67% of the island would be inundated (Figure 8). The erosion that would follow a 3-m event would be primarily dependent on the geologic framework of the island, with the

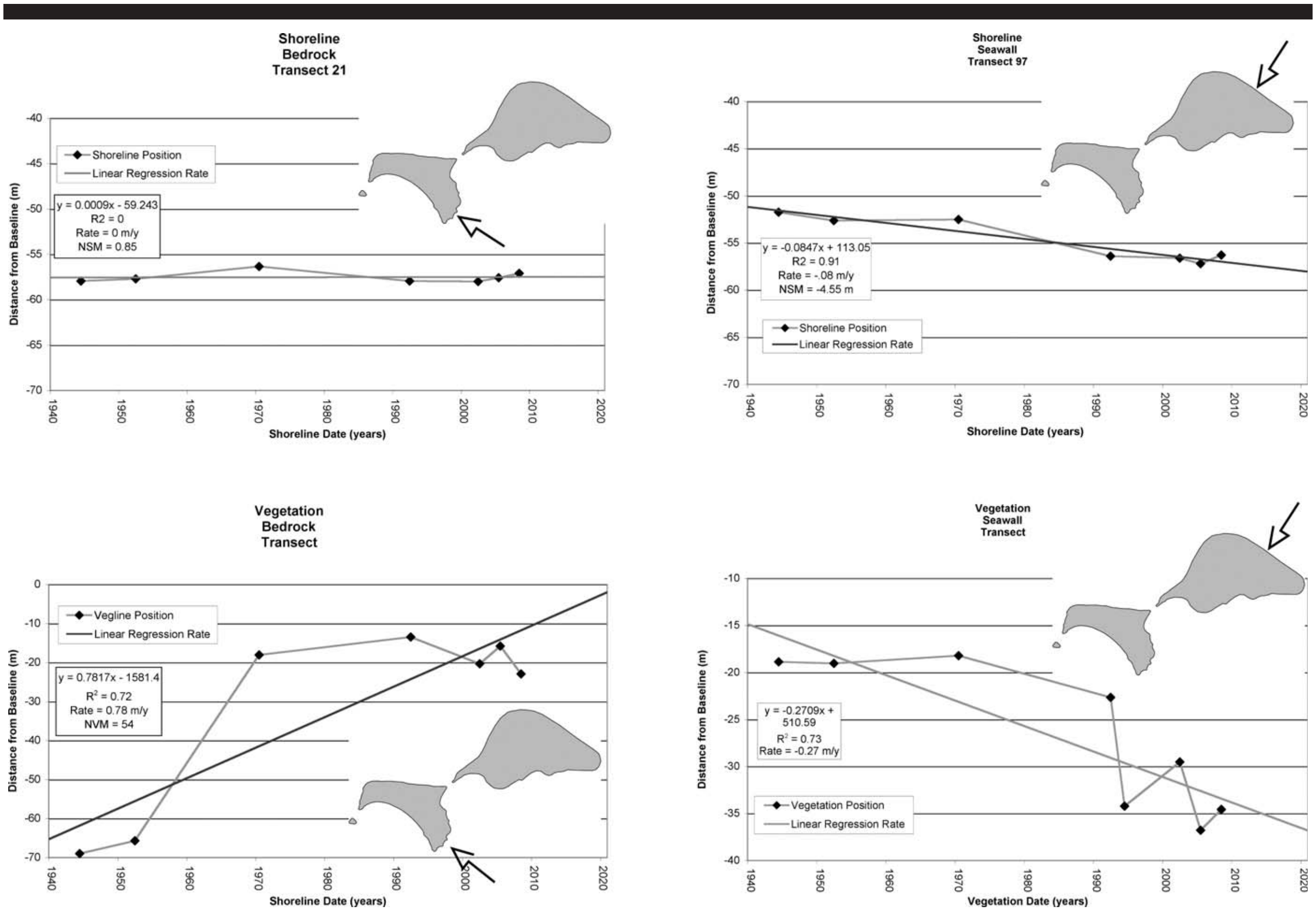

Figure 5. Graphed results of stable areas on Rainsford Island including the SW and BR areas.

unconsolidated sediments that make up the beaches and low-elevation plain rapidly eroding, while the bedrock outcrop remains intact.

The seawalled areas of the island that had remained relatively stable in response to a 1-m flood became inundated under the 3-m scenario. Once the elevation of the vertical to near-vertical shoreline in these areas is overtopped, the landward areas, once protected, become inundated. This inundation would likely result in the bluffs becoming undercut by wave attack at their base, leading to mass wasting events and further erosion. Overtopping of the seawall could also result in failure of the structure and development of erosive hotspots. Despite our inability to account for erosional processes on the flood hazard maps, they clearly identify lands that may be permanently lost as a result of long term SLR.

DISCUSSION

Coastal Geomorphic Implications

This study was made difficult because Rainsford Island has a relatively small and dynamic shoreline that rapidly responds to natural forcing mechanisms. As a result of the dynamic nature of the island's shoreline, the HWL feature that we were attempting to identify and delineate has been in a state of constant geomorphic change throughout the study period. Major factors that influence the position of the Rainsford Island coastline include seasonal fluctuations in wind and wave energies, changes to relative sea level, and extreme storm events such as Nor'easters and hurricanes. The powerful winter storms, which for centuries have battered the New England coastline, play a significant role in coastal change and may pose the greatest threat to the cultural resource located on the island (Ashton, Donnelly, and Evans, 2007; Besonen *et al.*, 2008; Zhang, Douglas, and Leatherman, 2000).

One of the most striking coastal geomorphic trends identified in this study was the southeast migration of the sand and gravel bar that connects the two drumlins. Between 1944 and 2008, the bar steadily migrated SE. The regression analysis quantified this migration, providing a strong negative correlation between the NWBB and SESB shoreline results with 20 m of erosion and 20 m of accretion, respectively. The LRR for the two beaches follow this trend at 0.33 and −0.34 m/y for NWBB and SESB, respectively.

The coastal processes that led to the migration of the bar also influenced other nearby areas, including the two accretion hotspots, the WC and SESB. The highest rate-of-change

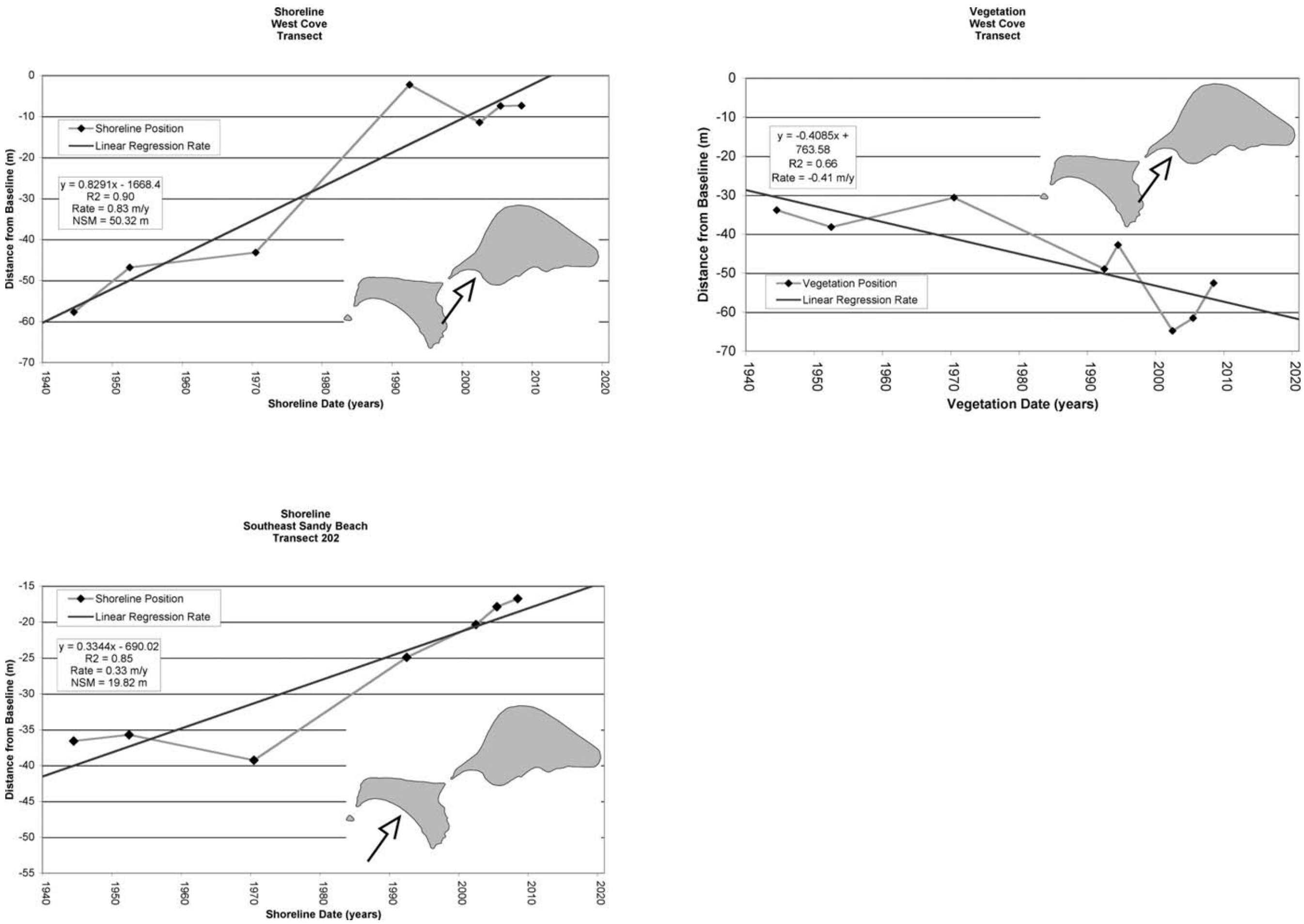

Figure 6. Graphed results of accretion areas on Rainsford Island including the WC and SESB.

statistic in the study was obtained from the regression analysis of the WC data. Once open to the sea and used as a mooring lagoon for visiting boats prior to 1952, the small lagoon rapidly accreted at a rate of 0.83 m/y (Claesson and Carella, 2002). As a result of the rapid filling, there was over 50 m of shoreline progradation in this area. The accretion can clearly be observed by overlaying the 2002 MHW shoreline on the 1944 georeferenced aerial photograph (Figure 9). The second accretion hotspot on Rainsford Island was along the SESB, which is in close proximity to the WC. In conjunction with the filling of the WC and the migration of the bar, this beach advanced seaward 20 m. It is difficult to project whether these areas will continue their trend of accretion as indicated by the regression analysis because part of the bar presently sits below MHW.

The NWBB and the NMSB are located on the NW side of the island and encompass one side of the bar. While the WC and the SESB were accreting, this area experienced a high rate of erosion. The strong linear correlation in the regression analysis and the results from the flood hazard maps indicate that if coastal processes remain the same, this area will continue its trend of erosion during the next decade, further decaying the integrity of the cultural resources inland from these locations. Because of these factors, the NWBB and the NMSB have been identified as coastal hazard zones (Figure 10).

In the near future, coastal flooding resulting from a storm surge would likely inundate much of the island's shoreline and other low elevation areas above the HWL. While the shoreline would only be flooded during the duration of the storm event because of the steep seaward slope of the beaches, inland the low elevation topographical depressions on the north and south drumlins could potentially remain flooded for a longer period. The low-lying inland area of the south drumlin, which contains the burial ground, is highly vulnerable to flooding and erosion and has therefore been identified as a coastal hazard zone (Figure 10).

The SEBB has also been identified as a coastal hazard zone (Figure 10). The regression analysis shows a strong linear correlation and a likely continuation of the erosional trend during the next decade. This area is also vulnerable to coastal flooding as indicated by the 1-m flood hazard map. Erosion and flooding in these areas has already resulted in the loss of historical sites, including the main wharf and numerous other buildings. These changes can clearly be observed by overlaying the 2002 MHW shoreline on the 1904 historical map (Fig-

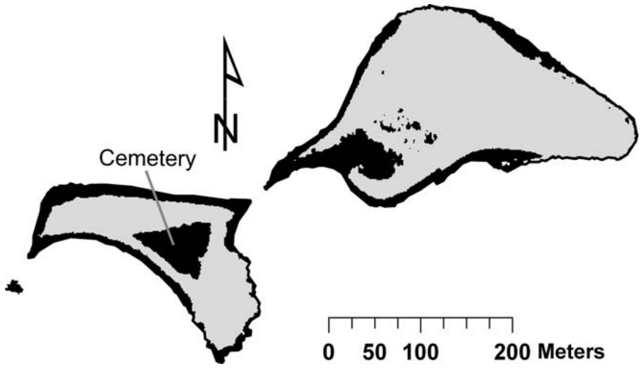

Figure 7. Flood hazard map of Rainsford Island showing the possible shoreline response to a 1-m rise in sea level or to a storm surge event. Inundated areas are shown in black while stable areas are shown in gray. Under this scenario much of the island's shoreline would likely experience some degree of erosion except for areas buffered by the seawall and bedrock outcrops and those areas that have shown long term trends of accretion such as in the west cove. The triangular-shaped inundated area on the south drumlin is the precise location of the Rainsford Island Cemetery, a highly sensitive archeological site.

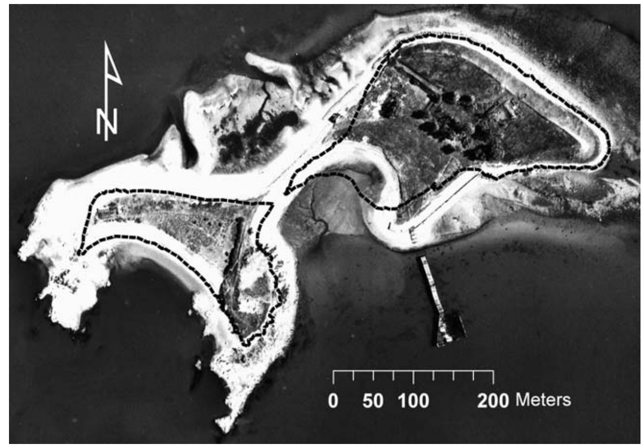

Figure 9. 1944 orthorectified aerial photograph with the 2002 MHW shoreline. The black dashed line represents the 2002 MHW shoreline. The dramatic accretion that occurred within the WC between 1944 and 2002 is clearly observable. The southeast migration of the low elevation bar connecting the two drumlins is also evident, while other areas of the island, including those buffered by the seawall, have remained relatively stable.

ure 11). Other sites positioned on or slightly inland of the 2002 MHW will likely be lost in the coming decades if the trend continues. However, this area may become buffered to increased or continued erosion as the WC continues to accrete.

The greatest period of coastal geomorphic change on Rainsford Island occurred between 1970 and 1992, with most of the erosion during this period occurring in areas associated with the bar migration (Figure 12). In addition, the majority of the southeast migration of the bar and the filling of the WC occurred during this 22-year period. It is unclear whether the mechanism behind these dramatic coastal changes was related to the "Blizzard of 78" or the "perfect storm." Both major storm systems occurred during the 1970–1992 period and high-quality aerial photography is not available between 1978 and 1992 to assess the influence of the events individually. Further temporal data coverage and geophysical evidence would be required to conclusively draw these linkages because only anecdotal accounts exist presently.

Cultural Resource Implications

The numerous coastal archeological sites located on the Boston Harbor Islands face a heightened risk of coastal hazards because of an accelerated rate of SLR along the Massachusetts coastline (FitzGerald *et al.*, 2008). Based on tide gauge records in Boston Harbor, Donnelly (2006) reports the average rate of

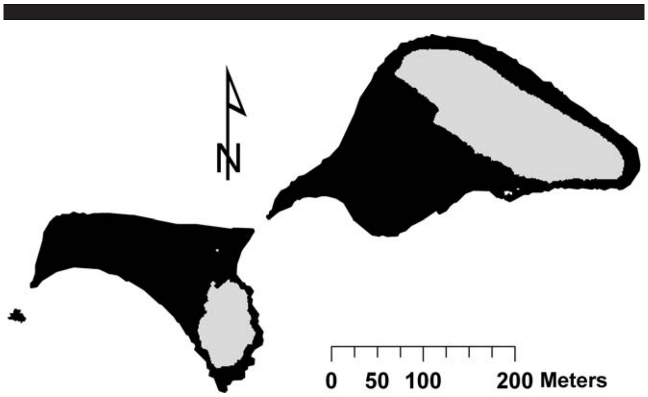

Figure 8. Flood hazard map of Rainsford Island showing the possible shoreline response to a 3-m rise in sea level and or storm surge event. Inundated areas are shown in black, while stable areas are shown in gray. This scenario displays the possible implications of the predicted increase in elevation and reoccurrence of the 100-year flood event, which is currently set at 3 m. A storm surge of this elevation would result in the almost complete inundation of the island and the loss of numerous sensitive historical and archeological sites.

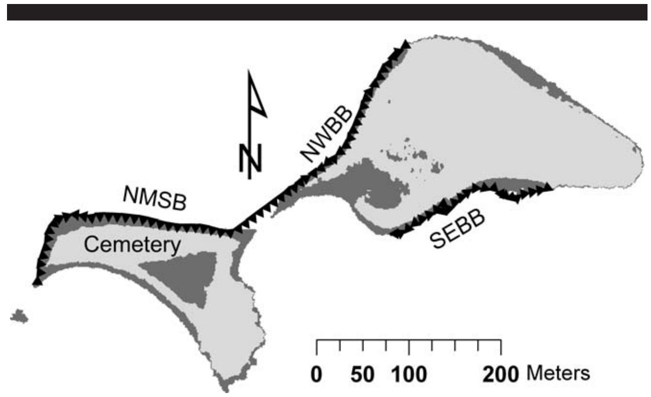

Figure 10. Coastal hazard map. Areas that are vulnerable to flooding resulting from storm surges and SLR are shown in dark gray. Areas that are vulnerable to erosion are shown by the connected black triangles and include the north mixed sediment beach (NMSB), the northwest boulder beach (NWBB), and the southeast sand beach (SEBB). The cemetery is identified on the map as being vulnerable to coastal flooding.

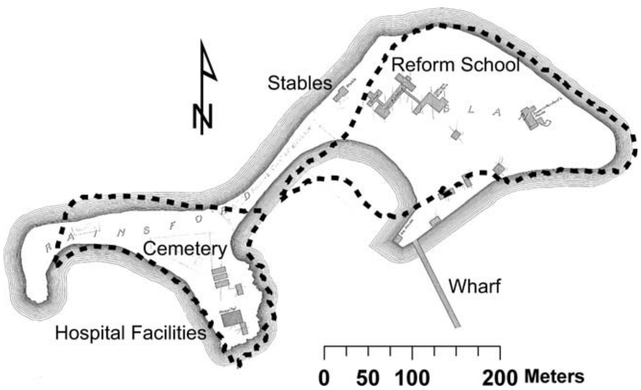

Figure 11. Historical 1904 georeferenced map of Rainsford Island with 2002 MHW shoreline represented by the black dashed line. This map provides the locations of the historically sensitive sites on Rainsford Island. Numerous buildings and coastal infrastructure can be seen seaward of the MHW shoreline indicating that they have been lost to erosion. Other sites currently located along the dashed line are highly vulnerable to future erosion.

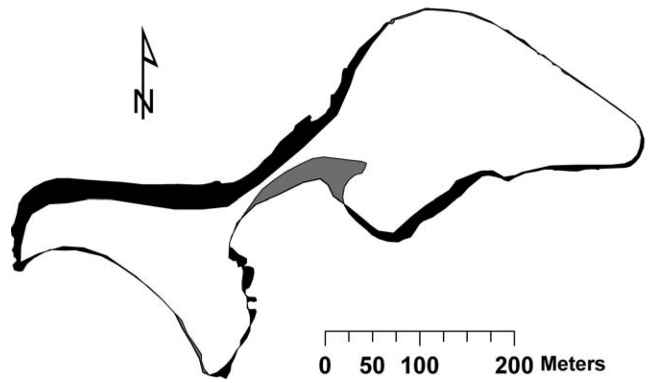

Figure 12. Map of Rainsford Island showing shoreline change occurring between 1970 and 1992. The areas of accretion are shown in gray, areas of erosion in black, and area of stability in white. During this period, over 9385 m^2, or 11% of the island's surface area, was lost, most of which occurred on the island's northern beaches.

SLR over the past 80 years is 2.8 mm/y. A recent report written by Yin, Schlesinger, and Stouffer (2009) projects that because of human-induced climate change, the heavily populated northeastern coast of the United States will experience a considerably faster and larger increase in the rate of relative SLR compared with the global mean.

SLR is closely correlated to an increased height, recurrence interval, and penetration of storm surges (FitzGerald *et al.*, 2008; Kirshen *et al.*, 2008). Kirshen *et al.* (2008) showed that the predicted increases in SLR under higher emissions scenarios would result in increased reoccurrence and height of future 100-year flood events in the Boston Harbor area. The 100-year flood event refers to the flood height that on average will be met or exceeded every 100 years or that has a 1% chance of occurring each year (Pugh, 1987). Kirshen et al. (2008) reports that within a half-century, the elevation of the 2005 100-year flood event may be equaled or exceeded every 30 years.

Ashton, Donnelly, and Evans (2007) report that not only does SLR increase the hazards associated with coastal flooding but also dramatically alters wave and tide regimes leading to a loss of land that is orders of magnitude greater than flooding alone. These compounding factors dramatically increase the coastal hazards within Boston Harbor and have a potentially devastating impact on the preservation potential of historical sites and associated cultural resources located on Rainsford Island.

Coastal Zone Management and Policy Implications

The potential destruction of historical sites and the associated cultural resources located on Rainsford Island presents enormous challenges to local decision makers, scientists, and the general public. The burials within the cemetery include numerous victims of the devastating eighteenth century smallpox epidemic as well as veterans of the Revolutionary War, the War of 1812, and the Civil War (Claesson and Carella, 2002). The environmental, societal, and political repercussions of the remains of American war veterans and smallpox victims being eroded from the substrate and transported into the marine environment cannot be overstated.

When considering what type of management strategy will be most effective at confronting these challenges, it is important to acknowledge both the long and short term hazards associated with climate change. On a decadal time scale, there are threats associated with the increased height and recurrence interval of storm surges and storm waves potentially leading to catastrophic erosional events. These events, often resulting from winter Nor'easters or hurricanes, can completely transform a coastline in only a few hours and currently pose the greatest threat to Rainsford Island (Fitzgerald *et al.*, 2008). On a longer, multidecadal to centennial time scale, there is the more subtle, but nonetheless significant, threat posed by the steady rise in global ocean levels. Even though these changes are difficult to observe from year to year, the continued increase in global eustatic sea level will completely transform the shoreline as we know it and undoubtedly lead to the permanent loss of coastal lands and estuarine ecosystems (Klein and Nicholls, 1999; IPCC, 2007).

An effective coastal zone management plan will take into account both the long and short-term coastal hazards associated with climate change (Klein and Nicholls, 1999). In regards to the Rainsford Island cemetery, a plan to permanently armor and maintain the full integrity of the cemetery would require a significant input of public resources and would likely prove ineffective. A more appropriate strategy could be the temporary protection of the NWBB to provide a temporal window allowing for a thorough archeological survey, scientific documentation, and inventory of the site. The proper removal and reinterment of human remains may also be necessary. This strategy could prove effective because it mitigates the immediate threats posed by erosional events, preserves the cultural resource through documentation and reinterment, and, most importantly, acknowledges and adapts to the long-term reality that the cemetery will, in all likelihood, be permanently submerged in the coming century.

CONCLUSIONS

Rainsford Island is exhibiting signs of significant geomorphic response to the coastal processes operating in Boston Harbor. The island is eroding on the northwest side, roughly stable to slightly accreting on the southeast side, and stable because of armoring on the northeast side. As a result, the island is thinning.

The WC area saw the most significant change with respect to accretion. This area is down drift from the location of the stone and timber wharf that was destroyed during the Portland Gale of 1898 (E. Berkland, City of Boston, Archeologist, personal communication). The accretion could be the result of the removal of this barrier to alongshore sediment transport. The connecting bar between the N and S drumlins is migrating southeast. The combination of the bar migration and erosion on the NW beaches suggests the greatest energy is associated with waves from the west through north quadrants.

Sea level rise within Boston Harbor is already having enormous environmental, cultural, and socioeconomic impacts. On Rainsford Island, documented historical sites have already been destroyed, including a century-old school house and officer's quarters. The results of this study show that the island's burial ground is under threat from coastal flooding and erosion as the NWBB continues to retreat landward.

The Rainsford Island cemetery is a highly sensitive historical and cultural site containing the graves of individuals that provide a rich chronology of events that led to the establishment of the United States of America. If the current geomorphic trends identified in this investigation persist, the cemetery could be directly affected in as little as 10 years (Gontz, 2008). To preserve the integrity of this site, we must take immediate action.

The Rainsford Island shoreline change study successfully integrated multiple data sources of varying spatial and temporal resolutions within a GIS and developed new methods and techniques to enable the geospatial analysis of the integrated data. Through this successful integration and analysis, the investigation accurately mapped the shoreline, calculated rate-of-change statistics, located accretion and erosion hotspots, and identified coastal hazard zones that contain sensitive archeological sites and associated cultural resources vulnerable to flooding and erosion. This investigation also provided robust statistical-based results that will benefit future coastal zone management decisions and provide a baseline for future shoreline studies on Rainsford Island.

ACKNOWLEDGMENTS

The research team would like to express their gratitude to Captain Russ Bowles and crew from the University of Massachusetts-Boston, Division of Marine Operations, for providing transport to and from Rainsford Island. We also would like to thank the City of Boston Environment Department for supplying labor to clear brush; the Massachusetts Office of Geographic and Environmental Information (MassGIS) for facilitating acquisition and preprocessing of geospatial data; Chris Wastson for his assistance with LIDAR data analysis; and Professor Curtis Olsen for his continued guidance and support. Special thanks for the anecdotal accounts provided by "Mayor Tom," unofficial caretaker of Rainsford Island. The University of Massachusetts-Boston provided funding for the project.

LITERATURE CITED

Ashton, A.D.; Donnelly, J.P., and Evans, R.B., 2007. A discussion of the potential impacts of climate change on the shorelines of the northeastern USA. *Mitigation and Adaptation Strategies to Global Change,* 7(13), 719–713.

Aubrey, D.W., 1994. Geomorphology of Spectacle Island and Boston Harbor, Massachusetts, 10,000 years B.P.–present. *In:* Aubrey, D.W., Kaplan, L., Largy, T. and Dirrigle, F.F. (eds.), *The Spectacle Island Site: Middle to Late Woodland Adaptations in Boston Harbor, Suffolk County Massachusetts, Central Artery/Tunnel Project*, Vol. 2. Boston, Massachusetts: Timelines Inc.

Bell, E.L., 2009. Cultural resources on the New England coast and continental shelf: research, regulatory, and ethical considerations from a Massachusetts perspective. *Coastal Management*, 37, 17–53.

Besonen, M.R.; Bradley, R.S.; Mudelsee, M.; Abbot, M.B., and Francus, P., 2008. A 1,000-year annually-resolved record of hurricane activity from Boston, Massachusetts. *Geophysical Research Letters*, 35(L14705).

Boak, E.H. and Turner, I.L., 2005. Shoreline definition and detection: a review. *Journal of Coastal Research*, 21(4), 688–703.

Boston Record Commissioners, 1907. Boston Record Commissioners Report, Boston Registry Department, Records Relating to the Early History of Boston, Vols. 1–39. Rockwell and Churchill City Printers, Boston. 1876–1907.

Chen, L.C. and Rau, J.Y., 1998. Detection of shoreline changes for tideland areas using multitemporal satellite images. *International Journal of Remote Sensing*, 19(17), 3383–3397.

Claesson, S.H. and Carella, E., 2002. Rainsford Island Archaeological Reconnaissance and Management Plan. Boston: Boston Landmarks Commission.

Clark, G.; Moser, S.; Ratick, S.; Dow, K.; Meyer, M.; Emani, S.; Jin, W.; Kasperson, J.; Kasperson, R., and Schwarz, H., 1998. Assessing the vulnerability of coastal communities to extreme storms: the case of Revere, MA, USA. *Mitigation Adaptation Strategies Global Change*, 3, 59–82.

Cooper, M.; Beevers, M., and Oppenheimer, M., 2005. *Future Sea Level Rise and the New Jersey Coast, Assessing Potential Impacts and Opportunities*. Princeton, NJ: Woodrow Wilson School of Public and International Affairs, Princeton University Press.

Crowell, M. and Leatherman, S.P., 1999. Coastal erosion mapping and management. *In:* Crowell, M. and Leatherman, S.P. (eds.), *Coastal Erosion Mapping and Management*. Journal of Coastal Research, Special Issue No. 28, 196 p.

Dobson, J.E.; Bright, E.A.; Ferguson, R.L.; Field, D.W.; Wood, L.L.; Haddad, K.D.; Iredale, H., III; Jensen, J.R.; Klemas, V.V.; Orth, R.J., and Thomas, J.P., 2003. NOAA Coastal Change Analysis Program (C-CAP): guidance for regional implantation, NOAA Technical Report, NMFS 123–1995.

Donnelly, J.P., 2006. A revised late Holocene sea-level curve for northern Massachusetts, USA. *Journal of Coastal Research*, 22, 1051–1061.

Douglas, B.C. and Crowell, L.M., 2000. Long-term shoreline position prediction and error propagation. *Journal of Coastal Research*, 16(1), 145–152.

Fenn, E.A. 1976. *Pox Americana: the Great Smallpox Epidemic of 1775–82*. New York: Hill and Wang.

FitzGerald, D.M.; Fenster, M.S.; Argow, B.A., and Buynevich, I.V., 2008. Coastal impacts due to sea-level rise. *Annual Review of Earth and Planetary Sciences*, 36, 601–647.

Gesch, D.B., 2009. Analysis of lidar elevation data for improved identification and delineation of lands vulnerable to sea-level rise. *In:* Brock, J.C. and Purkis, S.J. (eds.), *The Emerging Role of Lidar Remote Sensing in Coastal Research and Resource Management*. Journal of Coastal Research, Special Issue No. 53, pp. 49–58.

Gontz, A., 2008. The Suitability of Ground Penetrating Radar for Assessment of the Rainsford Island Cemetery and Applications toward Its Use in Developing a Conservation Plan. Boston, Massachusetts. Report submitted to City Archaeology Program, The Environment Department, City of Boston, 17p.

Harris, M.; Brock, J.; Nayegandhi, A., and Duffy, M., 2005. Extracting Shorelines from NASA Airborne Topographic Lidar-Derived Digital Elevation Models. USGS Open-File Report, 39, 1427–2006.

Himmelstoss, E.A., 2009. DSAS 4.0 Installation Instructions and User Guide. *In:* Thieler, E.R.; Himmelstoss, E.A.; Zichichi, J.L., and Ergul, A. (eds), Digital Shoreline Analysis System (DSAS) version 4.0—An ArcGIS Extension for Calculating Shoreline Change. USGS Open File Report 1278-2008.

Himmelstoss, E.; FitzGerald, D.M.; Rosen, R., and Allen, J.R., 2006. Bluff evolution of coastal drumlins; Boston Harbor Islands, Massachusetts. *Journal of Coastal Research*, 22(5), 1230–1240.

IPCC (Intergovernmental Panel on Climate Change), 2007. *Summary for Policy Makers: Working Group I (WGI) Fourth Assessment Report (AR4)*. New York: Cambridge University Press.

Kaye, C.A. and Barchoorn, E.S., 1964. Late Quaternary sea-level change and crustal rise at Boston, MA, with notes on autocompaction of peat. *Geological Society of America Bulletin*, 75, 63–80.

Kirshen, P.; Ruth, M.; Anderson, W., and Lakshmanan, T.R., 2004. Infrastructure Systems, Services and Climate Change: Integrated Impacts and Response Strategies for the Boston Metropolitan Area. Final Report to U.S. EPA ORD, EPA Grant Number: R.827450–01.

Kirshen, P.; Watson, C.; Douglas, E.; Gontz, A.; Lee, J., and Tian, Y., 2008. Coastal flooding in the northeastern United States due to climate change. *Mitigation and Adaptation Strategies for Global Change,* 13, 437–451.

Klein, J.T. and Nicholls, R.J., 1999. Assessment of coastal vulnerability to climate change. *Royal Swedish Academy of Sciences, Ambio*, 28(2), 32–37.

Knebel, H.J.; Rendigs, R.R.; Oldale, R.N., and Bothner, M.H., 1993. Sedimentary framework of Boston Harbor, Massachusetts. *In:* Fletcher, C.H., III, and Wehmiller, J. (eds.), *Quaternary Coasts of the United States: Marine and Lacustrine Systems, SEPM Special Publication,* vol. 48, pp. 35–43.

Leatherman, S.P., 1983. Shoreline mapping; a comparison of techniques. *Shore & Beach*, 51(3), 28–33.

List, J.H. and Farris, A.S., 1999. Large-scale shoreline response to storms and fair weather. *Proceedings of the Coastal Sediments*, (1999), 1324–1337.

Liu, H.; Sherman, D., and Songgang, G.U., 2007. Automated extraction of shorelines from airborne light detection and ranging data and accuracy assessment based on Monte Carlo simulation. *Journal of Coastal Research*, 23(6), 1359–1369.

Luedtke, B.E., 1984. Preliminary Report on an Archaeological Survey of the Southern Half of Long Island, MA. Report Submitted to the Massachusetts Historical Commission.

Luedtke, B.E., 2000. Archaeology on the Boston Harbor Islands after 25 years. *Bulletin of the Massachusetts Archaeological Society*, 61(1), 2–11.

Martinez, M.L.; Intralawan, A.; Vazquez, G.; Perez-Maqueo, O.; Sutton, P., and Landgrave, R., 2007. The coasts of our world: ecological, and social importance. *Ecological Economics*, 63, 11–23.

MassGIS, 2003. Boston Harbor LIDAR Metadata. Boston, Massachusetts: Executive Office of Environmental Affairs, http://www.mass.gov/mgis/ (accessed March 7, 2009).

MassGIS, 2009. Download Free Data. Boston, Massachusetts: Executive Office of Environmental Affairs, http://www.mass.gov/mgis/download.htm (accessed February 9, 2009).

Moore, L.J., 2000. Shoreline mapping techniques. *Journal of Coastal Research*, 16(1), 111–124.

Moore, L.J.; Ruggiero, P., and List, J.H., 2006. Comparing mean high water and high water line shorelines: should proxy-datum offsets be incorporated into shoreline change analysis? *Journal of Coastal Research*, 22(4), 894–905.

National Park Service, 2009. Island Facts: Rainsford Island. Boston: Boston Harbor Islands National Recreation Area. http://www.nps.gov/boha/index.htm (accessed May 5, 2008).

NOAA (National Oceanic and Atmospheric Administration), 2007. National Oceanic and Atmospheric Administration, Center for Operational Oceanographic Products and Services. Tides and Currents. http://tidesandcurrents.noaa.gov/ (accessed April 1, 2008).

Oldale, R.N., and Colman, S.M., 1992. On the age of the penultimate full glaciation of New England. *Geological Society of America*, SP(270), 317–326.

Pugh, D.T., 1987. *Tides, Surges and Mean Sea Level*. Chichester, UK: John Wiley and Sons, 472, OSTI ID(5061261).

Rendigs, R.R. and Oldale, R.N., 1990. Maps Showing the Results of a Subbottom Acoustic Survey of Boston Harbor, Massachusetts. USGS Miscellaneous Field Studies, 1990.

Robertson, W.; Whitman, D.; Zhang, K., and Leatherman, S.P., 2004. Mapping shoreline position using airborne laser altimetry. *Journal of Coastal Research*, 20(3), 884–892.

Ruggiero, P. and List, J.H., 2009. Improving accuracy and statistical reliability of shoreline position and change rate estimates. *Journal of Coastal Research*, 25(5), 1069–1081.

Scavia, D.; Field J.C.; Bosesch, R.W.; Buddemeier, R.W.; Burkett, V.; Cayan, D.R.; Fogarty, M.; Harwells, M.A.; Howarth, R.W.; Mason, C.; Reed, D.J.; Royer, T.C.; Sallenger, A.H., and Titus, J.G., 2002. Climate change impacts on U.S. coastal and marine ecosystems. *Estuaries*, 25(2), 149–164.

Shaw, J.; Taylor, R.B.; Solomon, S.; Christian, H.A., and Rorbes, D.L., 1998. Potential impacts of global sea-level rise on Canadian coasts. *The Canadian Geographer,* 42(4), 365–379.

Thieler, E.R.; Himmelstoss, E.A.; Zichichi, J.L., and Ergul, A., 2008. Digital Shoreline Analysis System (DSAS) version 4.0—an ArcGIS extension for calculating shoreline change. USGS Open-File Report, 1278-2008.

Yin, J.; Schlesinger, M.E., and Stouffer, R.J., 2009. Model projections of rapid sea-level rise on the northeast coast of the United States. *Nature Geoscience*, NGEO(462), 10.1038.

Zeidler, R.B., 1997. Continental shorelines: climate change and integrated coastal management. *Ocean and Coastal Management*, 37(1), 41–62.

Zhang, K.; Douglas, B., and Leatherman, S.P., 2000. Twentieth-century storm activity along the U.S. east coast. *Journal of Climate*, 13, 1748–1761.

Zuzek, P.J.; Nairn, R.B., and Thieme, S.J., 2003. Spatial and temporal consideration for calculating shoreline change rates in the Great Lakes Basin. *Journal of Coastal Research*, 38(1), 125–146.