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Original article

Assessing threatened coastal sites: Applications of ground-penetrating radar and geographic information systems

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ABSTRACT

Rainsford Island is an 11-acre island located in central Boston Harbor, Massachusetts. The proximity to the City of Boston resulted in the Island being used as a quarantine facility, poorhouse, veteran's hospital and school for wayward boys from 1737 to 1920. The Island consists of two linked topographic highs of glacial origin connected by a spit formed from reworked glacial material. The majority of the southern "high" is only slightly elevated above present-day sea level and was the site of a cemetery that serviced the quarantine facility, poorhouse and veteran's hospital. Historical research indicates that more than 1100 persons were buried on Rainsford during this time. The records for the cemetery have been lost through fire and only four sandstone posts presently mark the cemetery. Our team sought to (1) assess shoreline change on the southern portion of the Island; (2) map the boundaries of the unmarked cemetery using ground-penetrating radar and (3) determine the vulnerability of the cemetery to coastal erosion caused by long-term sea-level rise and episodic flooding. Shoreline change analysis indicates that the southern portion of the island has eroded on the north-facing beach at a rate of 0.2 m/yr while the south-facing beach has been stable. Topographic analysis of the landscape indicates that the central area of the southern portion is less than 1 m above sea level with a slightly elevated rim approximately 2 m above sea level. The ground-penetrating radar surveys indicated that the low-lying central portion exhibited evidence for burials. The results indicate that the cemetery is vulnerable to erosion and coastal flooding. A storm with a coastal storm surge of approximately 1 m will result in flooding of the cemetery. The northern edge of the cemetery is extremely vulnerable to erosion and the first mapped burial on the northern side will be impacted in approximately 10 years. The southern edge of the cemetery is protected by horizontal and vertical accretion. As a result, conservation resources should be concentrated on the northern edge of the cemetery.

1. Research aims

Ultimately, the aim of this project was to develop a methodology for a rapid, noninvasive assessment of the level of threat to cultural heritage sites that are proximal to the land–water interface. This technique is broadly applicable to sites on ocean coasts, riverbanks and lake shorelines. To adequately address the aim, two supporting goals of this project were identified. First, delineate the boundaries of an unexcavated or partially excavated site, in this case, the cemetery that was in use on Rainsford Island between ca 1737 and ca 1920. Second, evaluate the potential hazard to the culturally sensitive area by flooding and/or shoreline change. On Rainsford Island, flooding events are directly related to storm surge, while shoreline change is primarily the result of coastal erosion via wave action and longshore transport. Flooding and coastline change resulting from storm events are generally episodic events while shoreline change resulting from common wave climates and longshore transport are chronic in nature. Ultimately, the lowest areas will become threatened by passive inundation related to sea-level rise and represent a chronic threat to the area. The scope of the project did not include threats to the site from anthropogenic activities, as the Island has not seen significant anthropogenic pressures since prior to 1920, approximately 25 years before our first aerial photograph.

2. Experimental

2.1. Introduction

Rainsford Island is an 11-acre Island situated in central Boston Harbor, Massachusetts (Figs. 1 and 2) [1,2]. The Island is a complex of two modified glacially streamlined hills (drumlins) connected by

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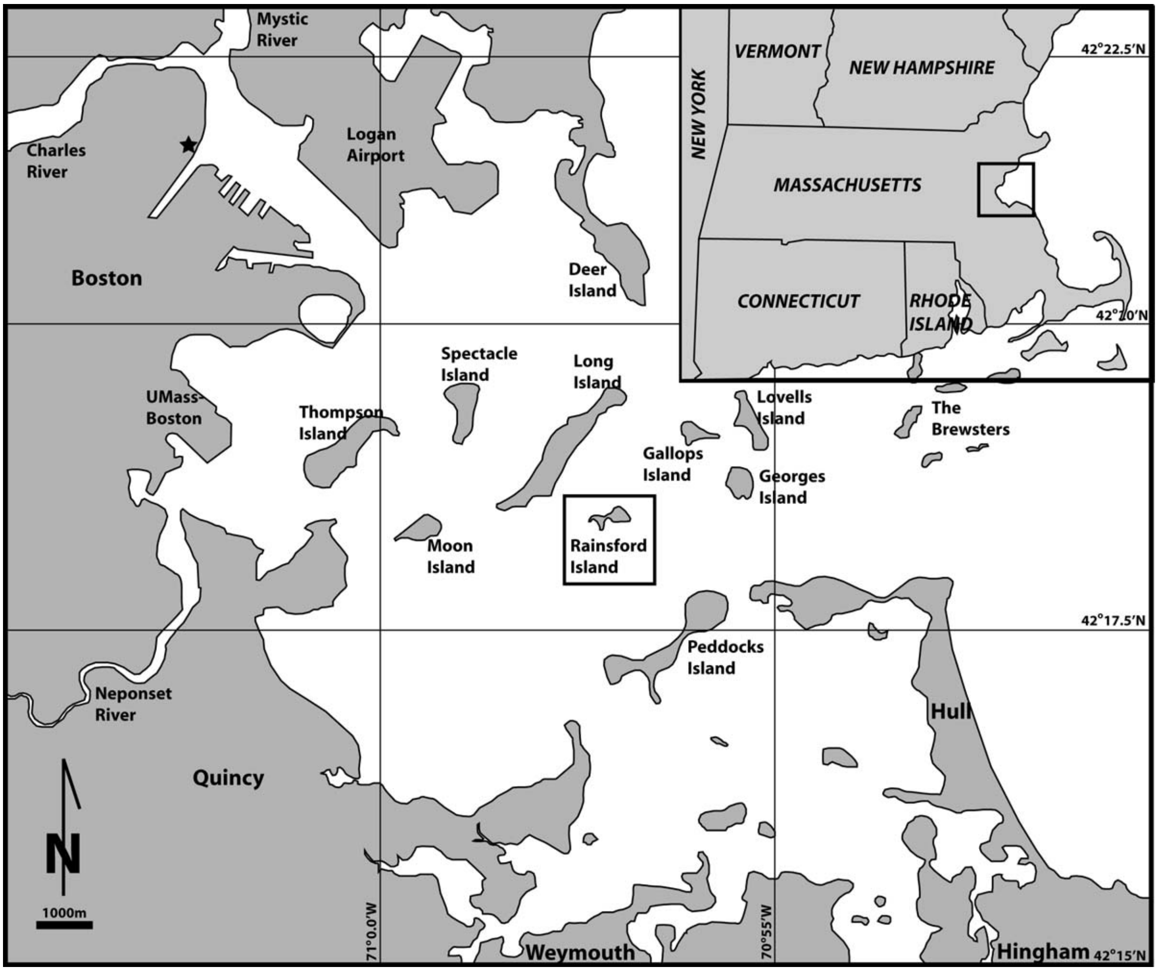

Fig. 1. The Boston Harbor region. Rainsford Island is an 11-acre island located in central Boston Harbor.

a low elevation sandy-gravelly spit that is vulnerable to flooding during astronomically high tides. The northern drumlin exceeds 17 m in elevation with an expansive low-elevation plain to the south. The southern drumlin is an eroding remnant bedrock core that rises to 6 m above sea level with a low-elevation plain to the south and west. The northern drumlin was armored in the 1860s to prevent continued erosion of the drumlin [3]. The seawall is still in place, but in poor state of conservation with numerous breaches. The high-relief portion of the southern drumlin consists of exposed bedrock that extends to the waterline on the southeast margin. With the exception of the seawall and bedrock drumlin core, the remaining coastline of the island consists of beaches of various textures ranging from predominantly gravel on the northern drumlin to predominantly mixed sand-sized particles on the southern drumlin. The gravel ranges in size from granules to boulders with diameters in excess of 1.5 m and shapes vary from very angular to well-rounded. The most angular of the boulders are most likely related to former infrastructure such as piers, seawall and buildings while the cobble and finer fraction is representative of material sourced from glacial deposits on the Island.

Not much information exists about the island before Colonial times. Archaeological evidence for Native American usage of the Boston Harbor Islands is known from neighboring Long Island [4], Thompson Island [5] and Spectacle Island [6]. A recent reconnaissance-level archaeological survey of the island did not indicate any precontact Native American sites. However, sites on neighboring islands suggest that there may have been precontact uses of the Boston Harbor Islands and associated resources [7,8].

The Island's proximity to the City of Boston ensured that the land use of the Island would be tied to the activities of the City of Boston [1]. The first Colonial usages of the Island were for farming from 1630 to 1737. In 1737, the City purchased the Island for use as a quarantine facility [2]. Rainsford Island also served to protect the City from various disease outbreaks such as yellow fever and small pox [1–3]. Numerous people quarantined on the Island died there. Estimates derived from historical accounts suggest that over 1100 persons were entombed on Rainsford Island between 1737 and 1920 [7]. During the time of City ownership, the Island saw various uses and infrastructure was developed. The remnants of piers, bulkheads and seawalls are evident on the Island's beaches and in the shallow subtidal areas. Of these structures, only the granite seawall, constructed during the 1860s, on the northern portion has remained relatively intact [7,8]. In the 1920s, a program was undertaken to exhume the remains of those on Rainsford Island and reinter the bodies in cemeteries elsewhere in the Boston area, including the Civil War Veteran's Cemetery on neighboring Long Island. It is unclear the number of graves exhumed and relocated [7,8]. Today, there are no tombstones on the low-elevation plain of the south drumlin. The only remnants of the cemetery are four 1 m-high brown sandstone posts at the corners of a 1.5 m × 2 m plot in the eastern section of the plain.

Changing shorelines have been studied with numerous techniques in an effort to quantify how any given shoreline changes over time. One of the most effective methods is the comparison of repeated aerial photographs [9]. Digitizing the high-water mark on aerial photographs at various time intervals results in the devel-

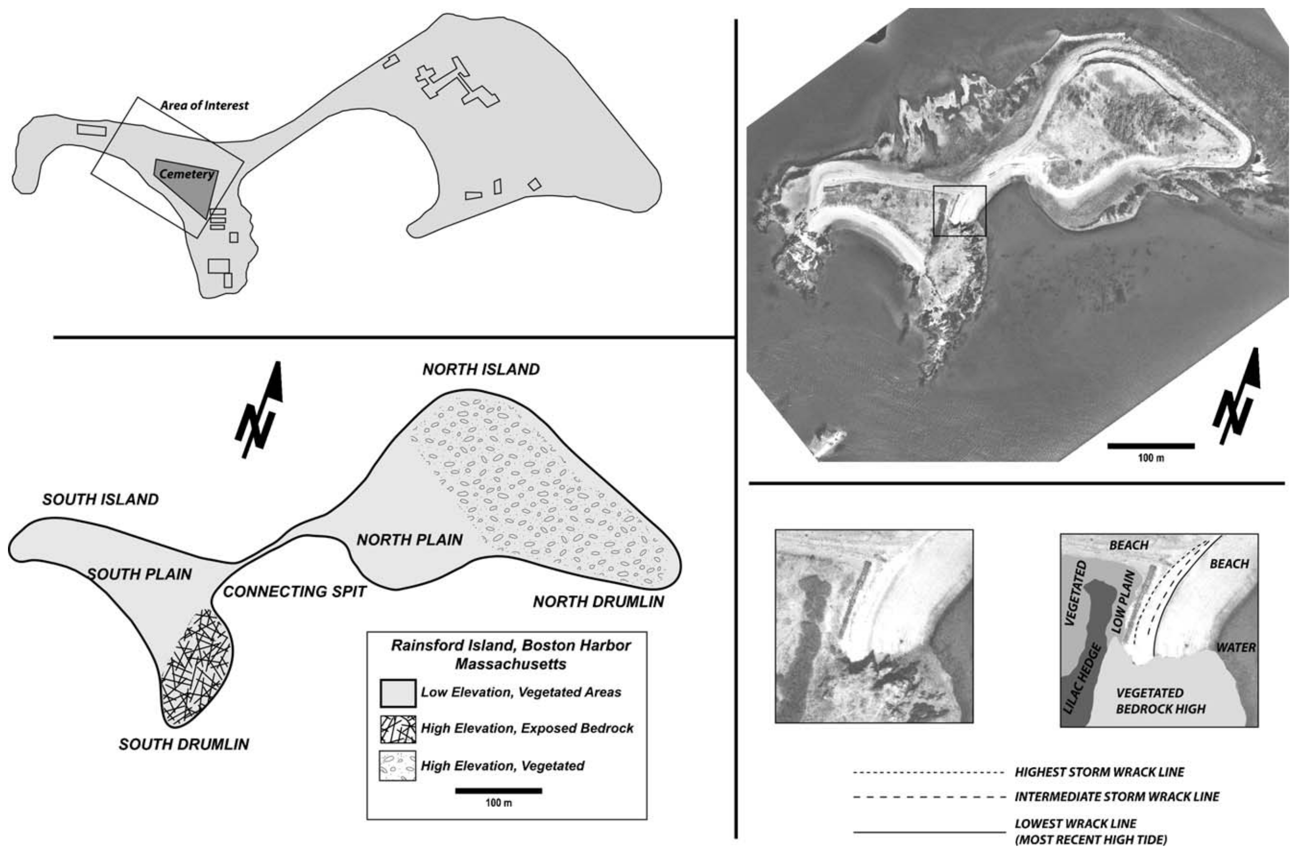

Fig. 2. 1904 Map of Rainsford Island and modern environments. Panel A - The 1904 map of Rainsford Island shows the location of numerous buildings and a pier. The approximate boundaries of the cemetery are shown on the map and formed the basis for selection of the study area. After City of Boston Map, from Massachusetts Office of Geographic Information Systems. Panel B–Interpreted modern imagery of Rainsford Island show very little of the infrastructure from 1904. Scattered foundations and four sandstone bollards are all that remain. Panel C–2002 digital orthophoto quad of Rainsford Island. Note the dense low vegetation on the southern portion of the Island, the location of the survey. Panel D–close up of a segment of the Rainsford Island shoreline showing the lowest wrack line, which was used as an indicator of high tide.

opment of a spatial and temporal dataset capable of accurately representing landward and seaward movement of shorelines, as well as calculating changes in the total area of the island. When compared to sea-level changes and storm frequencies over the period of photographic coverage, simplistic shoreline migration models can be developed and used for planning and hazard mapping [10].

Ground-penetrating radar (GPR) has been shown to be an effective tool for mapping unmarked gravesites in modern [11,12] and historic cemeteries [12]. In addition, imaging the stratigraphy of the area with GPR provides the information required to elucidate the connection between sedimentary deposits and the geologic processes that created them. Such an analysis is extremely useful in determining the potential impact of geologic processes on buried cultural heritage sites [13].

The central portion of the southern drumlin comprised the study area. While the Island hosted numerous buildings and other cultural sites [1–3], the feature of greatest interest for this study was the cemetery. A 1904 map of Rainsford Island depicts the cemetery on the southern portion of the Island (Fig. 2). We expanded the area to conduct a detailed ground-based geophysical survey where vegetation permitted and examined LiDAR coupled with repeat aerial orthophotographs to determine the boundaries of the cemetery and the level of threat from coastal processes.

2.2. Methodologies

The project integrated two methodologies to assess the cultural and environmental vulnerability of the Island. Aerial photographic analyses were used to identify and quantify shoreline change, while GPR was used to map the cemetery and assess environmental change.

2.2.1. Aerial Photography, LiDAR & GIS

The geographic information systems (GIS) dataset consisted of aerial photographs, surface topography derived from light detection and ranging technology (LiDAR) and interpreted geophysical data. Two orthophotographs collected in 1944 and 2008 were selected for analysis based on photographic resolution. The photos were acquired from the Massachusetts Office of Geographic Information Systems (MassGIS) in MrSID format. The LiDAR dataset was collected during the summer of 2002 and acquired from MassGIS in raster format. Aerial photographs and LiDAR were spatially referenced in Massachusetts State Plane projection. Geophysical interpretations were derived from the GPR system described below and spatially referenced in Universal Transverse Mercator (UTM) Zone 19 N projection.

All geospatial data were integrated into one database using ArcGIS 9.3 and transformed from their native projections to UTM. Shorelines were digitized as polygons on each aerial photograph using the lowest wrack line, a common indicator of the most recent high tide [9]. Area above the high water line for each year was calculated in ArcGIS. Areas were compared to determine the overall net gain or loss of the island. In addition, 274 transects spaced 10 m apart were constructed perpendicular to the 2008 shoreline to determine the overall direction and magnitude of shoreline movement along the southern drumlin. Representative transects were selected in zones based on the shoreline orientation and sediment texture. The transects were used to represent the changes to each zone [14].

A digital shoreline elevation was extracted from the LiDAR dataset that represented the still-water high tide elevation in 2002 based on tide gauge records from the National Oceanographic and Atmospheric Administration (NOAA) [10,15]. ArcGIS was then used to alter the still-water elevation to simulate storm surge elevations. Storm surge simulations did not include wave heights or wave-based processes. Storm surge elevations of 1.0 and 3.0 m were selected as representative of the magnitude of storms that have occurred in Boston Harbor since 1944 [10,16]. Areas were shaded based on their level of inundation.

2.2.2. Ground-penetrating Radar

The team employed a MALA GeoSciences Pro-Ex GPR system with a 500 MHz antenna to image the subsurface. The GPR system was coupled to a Hemisphere VS100/R100 real-time kinematic global positioning system (RTKGPS) to provide subdecimeter geospatial information, which was digitally integrated into the record at time of acquisition. A field laptop was used to log data and view real-time data during acquisition. Real-time visualization coupled with integrated RTKGPS allowed for modification of survey lines during acquisition. Postprocessing was accomplished using GPR Slice v6 developed by Geophysical Archaeometry Laboratory and consisted of bandpass filtering, application of user-defined gains, topographic correction, and conversion from time to depth sections. Island topography was extracted from the 2002 Boston Harbor LiDAR.

The GPR data were examined to determine the subsurface geology, depositional history [13] and anthropogenic disturbances consistent with gravesites [11,12]. Specific GPR responses related to gravesites include: (1) small-scale disruption and truncation of stratigraphy; (2) hyperbolic reflections at the base of disturbed stratigraphy; (3) scale and orientation of disturbed stratigraphy; and (4) the overall pattern of disturbances over large areas [11]. Considering the area has not been redeveloped since the abandonment in the 1920s [7], the expected stratigraphy should represent deposition of geologic materials or erosion of those materials by natural agents or disruption of those materials by anthropogenic activities at the cemetery. The geographic coordinates and depths to features interpreted as anthropogenic were located and digitized from GPR data and integrated into the GIS dataset for spatial analysis and comparison to inundation maps and the rates of island erosion. Distances from burial sites to the 2008 shoreline were calculated and the rate of shoreline migration applied to estimate the time for the shoreline to intersect the seaward-most gravesites. This portion of analysis did not account for storm-generated flooding.

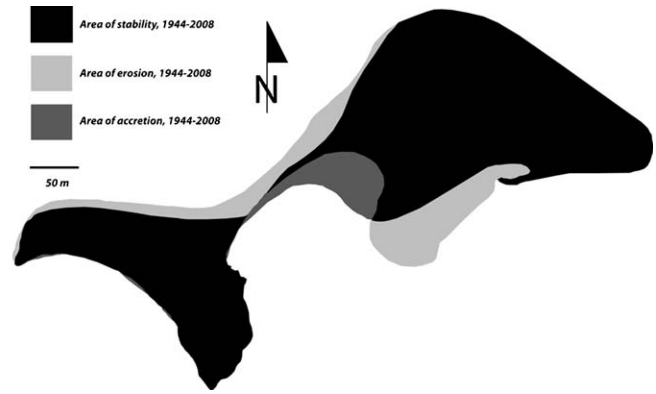

Fig. 3. Comparison of the 1944 and 2008 shorelines. Base image is the 2008 air photograph of Rainsford Island. The solid black line indicates the 2008 shoreline and the pale gray filled area indicates Rainsford Island in 1944. The Island shows significant shoreline erosion on the north-facing beach and a stable south-facing beach. Base aerial photographs from Massachusetts Office of Geographic Information Systems.

2.3. Experimental data

2.3.1. Aerial photography & LiDAR

The project analyzed two series of aerial photography of Rainsford Island. The first series was acquired in 1944 and the second in 2008. Mean high water indicators were digitized on each photograph and compared (Fig. 3). The methodology for shoreline identification of Boak and Turner [17] was followed, using the seaward-most wrack line as an indicator for the most recent high tide. Digitized shorelines were compared and analyzed for net shoreline change and rate of shoreline change.

The LiDAR dataset was analyzed for the 2002 shoreline position based on elevation from the Boston Harbor tide gauge station. The high tide elevation was extracted from the LiDAR and increased 1.0 and 3.0 m to simulate flooding resulting from coastal storms. The increased high-tide level represented static water level and did not include wave action (Fig. 4).

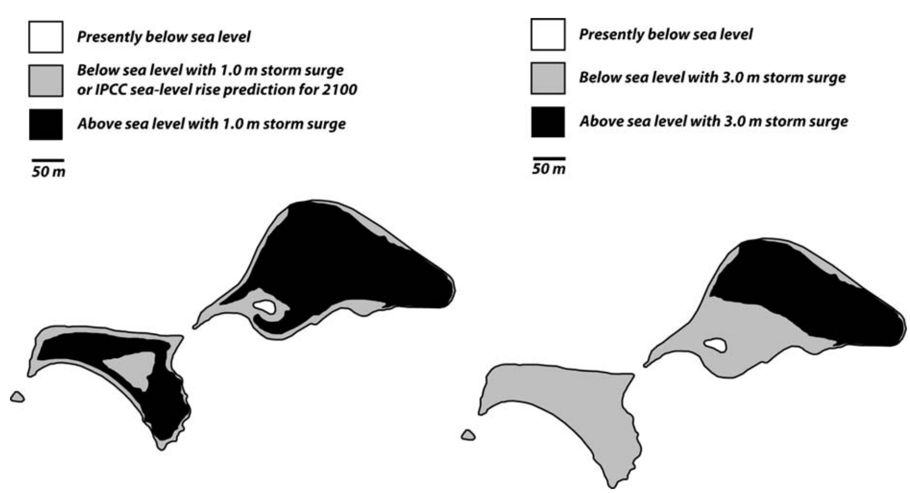

Fig. 4. LIDAR dataset with mean high water, 1.0 m and 3.0 m storm surges. Black line indicates the present coastline, light gray indicates areas submerged and dark gray indicates areas above selected water elevation. Note that at 1.0 m storm surge, the central portion of the southern drumlin is submerged and at the 3.0 m storm surge, the entire low elevation plain on the southern drumlin is submerged.

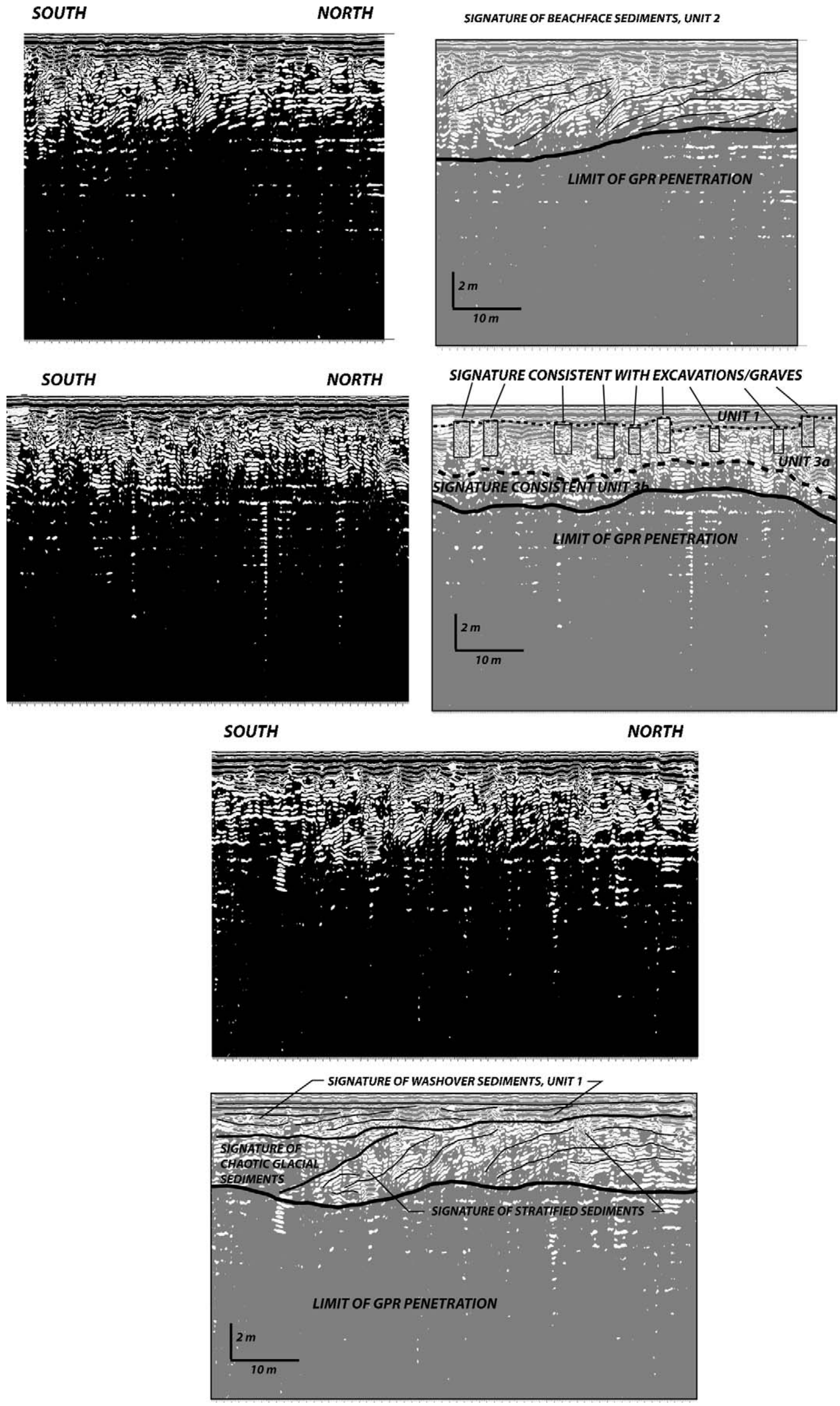

Fig. 5. Ground-penetrating radar images from Rainsford Island. Various excerpts from lines acquired with the MALA GeoSciences 500 MHz ground-penetrating radar showing common features and patterns observed during the Rainsford Island Survey. TOP shows a series of dipping reflectors commonly observed on/near accreting shorelines, suggesting progradation. MIDDLE shows a series of shallow disturbances in stratified sediments that were observed in the central portion of the southern island suggesting excavations and interpreted as graves. BOTTOM shows a series of parallel reflectors thinning away from the shoreline and burying underlying stratigraphy that were observed inland from shorelines and interpreted as sediments deposited as storm surges washed over the island.

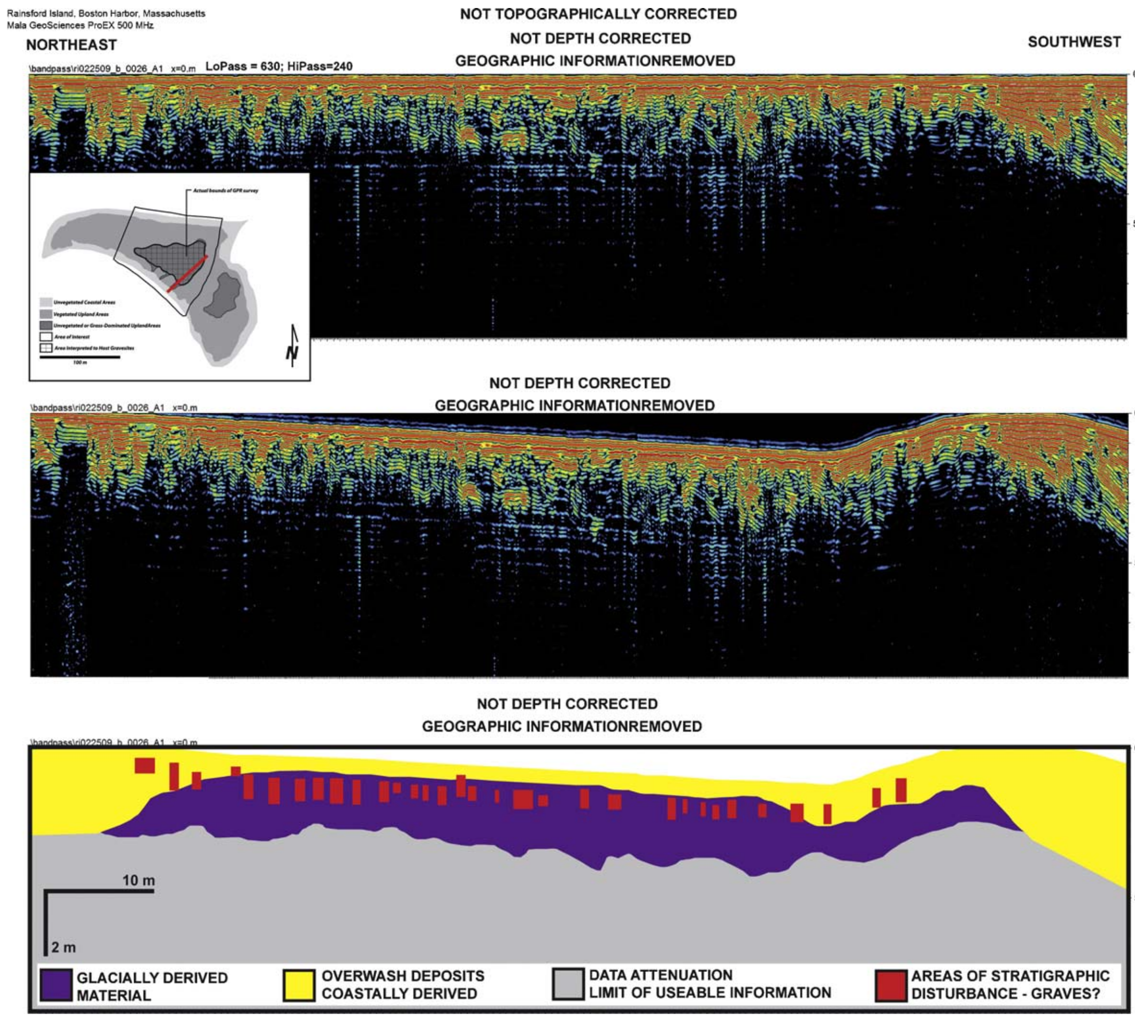

Fig. 6. Ground-penetrating radar line 26. The GPR survey was able to image closely spaced disturbances in the subsurface (red). These disturbances were interpreted as either graves or post burial re-excavation for burial removal. Stratigraphic disturbances consistent with burials were located nearly everywhere the GPR survey was conducted.

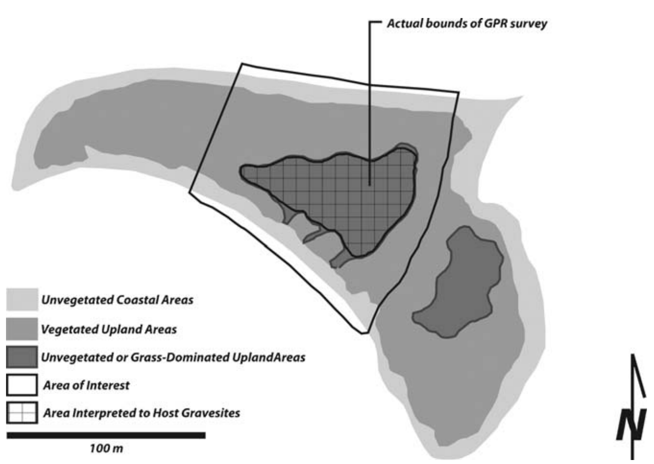

Fig. 7. Cemetery boundaries. The GPR surveys all open areas on the south plain. Dense vegetation consisting of sumac and other shrubs prevented surveying the entire area of interest. GPR data indicate that entire area (HATCHED) that was surveyed shows anomalies consistent with shallow excavations, approximately 1–2 m in width and 2–2.5 m in length spaced approximately 0.5–1 m apart.

2.4. Ground-penetrating radar

A total of 5 km of 500 MHz GPR-coupled RTKGPS data were acquired over the course of two surveys of southern Rainsford Island. Heavy vegetation significantly restricted our ability to identify the boundaries of the cemetery and did not allow for imaging of the entire area of interest. Of specific note, in terms of limiting the survey, were the dense shrubs and small trees that prevented the survey lines from extending to beach on the north-facing shore and the 10 m thick lilac hedge on the eastern margin of the area of interest (Fig. 4). As Rainsford Island is a component of the Boston Harbor Island National Park Area, removal of small trees and shrubs was not permitted. Real-time visualization of the GPR data suggested that boundaries of the cemetery were somewhere between the shoreline and the area covered by trees and shrub on the northern side; and beneath the lilac hedge on the eastern side. The unsurveyed area on the northern edge varied from a few meters to 15 m wide; on the southern edge, it was generally less than 5 m. The east and west margins presented the largest uncertainty as the lilac hedge exceeded 10 m over its entire length and the vegetation thickened to the west resulting in an unsurveyed area range from 10 to 35 m in width. The inability to survey the entire low lying plain with the GPR prevented accurate delineation of the boundaries of the cemetery.

2.5. Results

2.5.1. Aerial photography & LiDAR

Over the 64-year period of study, sea level rose at 2.9 mm/yr as determined from the Boston Harbor tide gauge station [17]. If the calculated rate of sea-level rise is applied to the study period, a total rise in the sea surface elevation of 0.184 m results. Presently, the area of the cemetery is generally slightly less than 1 m above mean high water, as determined from the LiDAR dataset. If the rate of sea-level rise continues, the Cemetery will submerge in 2347, 345 years from the collection of the LiDAR dataset. However, the Intergovernmental Panel on Climate Change suggests increasing rates that result in a rise of upwards of 1.0 m by 2100, suggesting that the cemetery would be submerged by then [18].

In addition to chronic inundation generated by sea-level rise, this 64-year period experienced several intense winter storms, including the Blizzard of 1978 and the Perfect Storm of 1991 [10,16]. These individual events produced storm surges in excess of 2 m at the tide gage in downtown Boston [10].

The analysis of the 1944 and 2008 aerial photographs indicate that the island has lost a total of 11,077 m^2 or 11% of its land area over the 64-year period [14]. Closer examination of the 1944 and 2008 shorelines on the southern drumlin indicate that the north facing shoreline has eroded, migrating south-southeast at a rate of 0.20 m/yr and the south-facing beach has remained nearly stable or accreting slightly, migrating southward at 0.05 m/yr. Scarps and sharp vegetation lines on aerial photographs (Fig. 2) verify erosion on the north-facing beach while the washover sediments, lack of scarps and an undulating vegetation line are supportive of the nearly stable to slightly accreting shoreline of the south-facing beach.

The LiDAR analysis shows that during a storm surge of 1.0 m, the central portion of the low elevation plain on the southern drumlin submerges without a connection to the open waters of the harbor. The isolated ponding suggests that the elevated berms surrounding the low-elevation plain provide a degree of protection. Once flooded, channels or breaches through the berm will be created as the water attempts to return to the open harbor during the waning phases of the flooding event [19,20]. During a 3.0 m storm surge, the entire low-elevation plain on the south drumlin submerges. The topographically-elevated berms are vulnerable to breaching during the rising and/or retreating surge [19,20] (Fig. 3).

2.5.2. Ground-penetrating radar

The GPR data suggested the presence of several geophysically-distinct units (Figs. 4 and 5). Units were characterized based on the character of internal reflections, relationship of the internal reflections with the upper and lower bounding surfaces and the geometry of the bounding surfaces [21]. Unit 1 was characterized by parallel to subparallel internal reflections. Internal reflections dipped slightly north or south depending on the location of the survey line. Unit 2 was characterized by strongly dipping parallel to subparallel internal reflectors that were often truncated by other dipping reflectors. Internal reflections dipped north or south, depending on the line orientation and position. Unit 3 was characterized by weakly parallel to subparallel or weakly chaotic internal reflectors. Hyperbolic point reflectors were frequent as were stratigraphic interruptions. Unit 4 was characterized by strongly chaotic internal reflectors and/or signal attenuation.

Unit 1 was interpreted as sediments that were deposited as washover fans, formed when waves wash over the area during periods of intense storms. Unit 2 was interpreted as beachface deposits from wave and longshore transport of sediments along the beach during the development of the connecting spit and reworking of glacial and nearshore sediments. Unit 3 was subdivided into Unit 3a and Unit 3b. Unit 3 is interpreted as weakly stratified glacial outwash sediments and/or unstratified glacial till. Hyperbolic point reflections originate from large out-sized clasts common in outwash sediments (dropstones and ice-rafted debris) and/or the coarse component of till [20,22]. Unit 3a contained stratigraphic interruptions with variable lower bounding surfaces and were interpreted as the result of anthropogenic excavations such as burial sites or exhumed burial sites [11,12]. Unit 3b did not contain stratigraphic interruptions. Some of these interruptions had slight hyperbolic reflections at their base, but most did not (Figs. 4 and 5). Unit 4 was interpreted as geophysical basement represented by bedrock, glacial till and/or interstitial salt that attenuated the radar signal. Based on the GPR data, we interpret Unit 3a as the unit containing the cemetery and Unit 3b as a correlative unit without anthropogenic disturbances, or outside the bounds of the cemetery.

The GPR survey suggests that the low-elevation plain contains evidence of use as a cemetery, but not the topographically higher berm immediately adjacent to the south-facing beach (Fig. 6). Dense vegetation prevented the survey from imaging the entire southern portion of the island and thus, the boundaries of the cemetery remain unknown. Complete surveying of the area of interest would require large-scale removal of the dense vegetation and not within the scope of this investigation (Fig. 7).

3. Conclusions

Sea level has been rising slowly along the North Atlantic US coasts at variable rates since the end of the last glacial period [20]. The predicted rise for the year 2100 is approximately 1.0 m [18] and storm frequencies are predicted to increase [10,16]. The response of unconsolidated sediment coastlines is strongly controlled by the interplay of episodic events and long-term sea level rise [19] and an accurate assessment of the hazards posed by these processes is required in order to adequately protect and manage coastal sites from these threats [20]. Predictions such as these are realized in the near future, the result will be the ultimate flooding, potential destruction through erosion and loss of the cultural heritage site located on Rainsford Island in Boston Harbor.

The combined application of field and spatial analysis of aerial photography and LIDAR enabled an interpretation of historical geologic processes and responses within a site of cultural heritage and produced threat assessments of that site. For example, Unit 1 suggests that the low-lying areas of the cemetery flooded and experienced storm wave-generated washover deposition subsequent to the cemetery abandonment.

In the case of Rainsford Island, the northern edge of the cemetery is under the greatest threat from prolonged coastal erosion. At the present rate, the retreating shoreline and vegetation line will cross the northern-most mapped burial in about 10 years. The southern burials are less threatened due to the stable and slightly prograding shoreline. In fact, the southern portions of the cemetery are receiving more sediment, which results in progressive grave burial. The entire cemetery is threatened by coastal flooding. With a minor storm surge of 1.0 m above mean high water, the entire cemetery has the potential to flood and has flooded in the recent past (Fig. 3). While no anecdotal evidence or documentation exists, the GPR data indicate that washover sediments are thickest on southern ends and thinnest toward the center of survey lines and cap disturbances associated with grave excavation (Fig. 4). These stratigraphic relationships suggest that flooding has occurred.

Natural coastal processes pose imminent threats to the cultural sites on Rainsford Island (Fig. 8). If the trends identified in this study continue as they have for the past 64 years, the cemetery site on Rainsford Island may experience significant damage with exhuma-

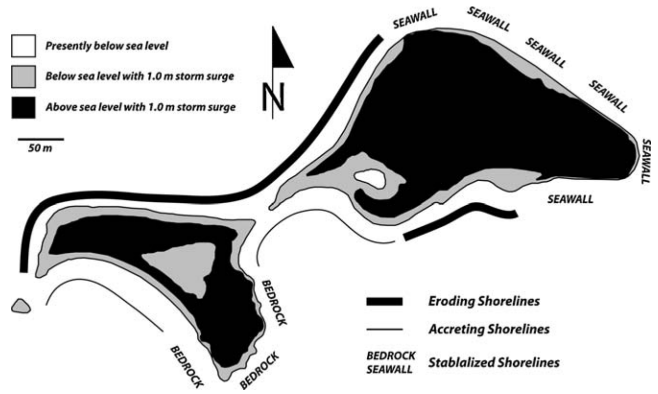

Fig. 8. Coastal hazard map of Rainsford Island. Based on the aerial photography analysis, areas of vulnerability to flooding and coastal erosion are identified. Back areas indicate areas above sea level with a 1.0 m storm surge while gray areas are flooded. The heavy black line offset from the shoreline indicates areas of coastal erosion, while thin lines indicate stable or accreting shorelines and BEDROCK or SEAWALL indicate stabilized shorelines. The large are of inundation on the southern portion of the island hosts the cemetery.

tion of the northern-most grave site within approximately 10 years. Episodic flooding does not significantly impact the survivability of the cemetery site, but chronic flooding would ultimately submerge the site. By far the greatest threat is through erosion associated shoreline change, which can destroy the site.

While the graves were reportedly excavated and removed from the island [7,8], no documentation remains. The GPR surveys and coupled LIDAR and aerial photography provided a framework for future research to conduct targeted ground truthing along the northern edge of the cemetery site to determine if the reports are true. The ground truthing was beyond the scope of this project and not scheduled to occur in the near future based on concerns with respect to potential human remains.

While Rainsford Island represents a unique and site-specific analysis, broad lessons were learned from this study. Coastal scientists, archaeologists, resource planners and managers are aware of the numerous different technologies that are capable of mapping the surface and subsurface over various temporal scales. GPR, LIDAR and aerial photography are just three, that when integrated, provide a process-based framework with a temporal-based assessment of the impacts of the processes. The combined application of GPR with LIDAR and remote aerial imagery shows that sensitive areas can be assessed without disturbing cultural heritage sites and identify vulnerable areas that require immediate attention to avoid damage or destruction.

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