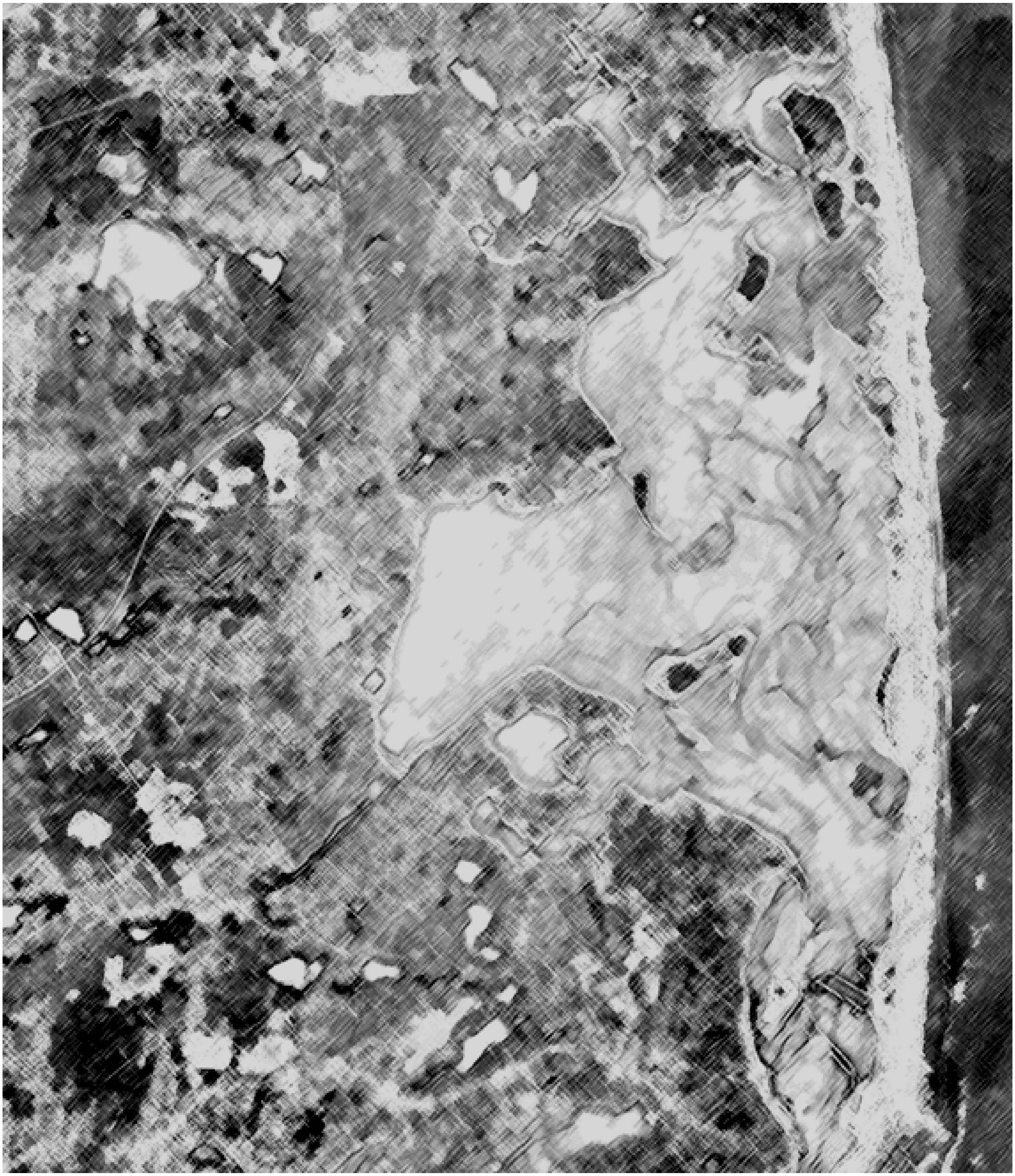
137 YEARS OF SHORELINE CHANGE IN PLEASANT BAY: 1868 TO 2005



A Report Prepared for the
Pleasant Bay Resource Management Alliance
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137 Years of Shoreline Change in Pleasant Bay: 1868-2005

PREFACE

In 2004 The Pleasant Bay Resource Management Alliance commissioned the author of this study to

> '...develop a GIS database of georeferenced aerial photographs of Pleasant Bay, which will then be used to document the morphodynamics and shoreline change in the study area'.

The first task was the compilation and digitalization of over 450 hardcopy vertical aerial photographs at high-resolutions, 600-1200 pixels per inch, for a total database size of 34 gigabytes. A subset of those aerial photographs was used in this study. The work of delineating a shoreline, within a Geographic Information Systems (GIS) environment was the next task, followed by the generation of rates of shoreline change. When the first set of rates was generated the expected results were observed. Along most of the mainland shoreline of Pleasant Bay the majority of the rates of shoreline change were within the range of uncertainty and thus little could be said about the nature of change in the bay. It was then that another approach to examine this area was developed.

The High Water Line is the most prevalent shoreline indicator used in peer-reviewed shoreline change studies, yet there was little evidence of change in Pleasant Bay over 137 years using this shoreline indicator. It seemed reasonable that more change had occurred over this time period, thus looking at shoreline change from a different perspective was investigated. Much of Pleasant Bay has a fringing salt marsh along the shoreline. It was this feature, the basinward edge of marsh vegetation, or 'marshline' that was developed, tested and used to document shoreline change in Pleasant Bay. After an extensive search of the peer-reviewed literature it was determined that there was no substantive discussion of this technique. This technical report represents two shoreline change studies: the first using the traditional shoreline indicator, the High Water Line; and the second using the marshline. At the time of writing a separate paper regarding the marshline is being developed for publication in the peer-reviewed literature and as such similar data, figures and other content will likely appear in both publications.

Note to reader: during the writing of this manuscript a new inlet formed over the Patriot's Day holiday in April 2007. The author suggests *Patriot's Inlet* to commemorate its formation (and refers to it as such herein), but more importantly to avoid unfortunate names such as *New Inlet* and the like. Appellations, fixed in time or space, for dynamic and ephemeral features such as tidal inlets can only lead to confusion. Though not always apparent, this seems to be the antitheses of scientific endeavor.

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EXECUTIVE SUMMARY

Low-energy coastal embayments, such as Pleasant Bay, are under increasing pressure from anthropogenic alterations. Unintended consequences from shoreline armoring, dredging activities and development can exacerbate impacts from storms, sea-level rise and climate change.

Coastal ecosystems, particularly salt marshes, are among the most biologically productive ecosystems in the world, but have not, in some instances, been well studied from a physical processes standpoint. For example, very little information is available relative to shoreline change in these types of environments. Shoreline change is fundamentally a manifestation of coastal sediment transport. This sediment constitutes the initial substrate within which biological activity occurs. Understanding sediment transport in this context was the impetus for a larger study, one aspect of which constitutes this report.

When conducting shoreline change studies the question of which shoreline indicator to map is critical. A shoreline indicator is the feature that is mapped on aerial photographs. More than a dozen shoreline indicators can been used in shoreline change studies, such as the wet/dry line, the wrack (debris) line, seaward edge of dune vegetation, etc. A shoreline proxy is a shoreline indicator that represents a known datum. The most prevalent shoreline proxy for open ocean, sandy beaches is the High Water Line (HWL) which represents the Mean High Water datum and will be discussed in detail below. The first part of this report is a traditional shoreline change study for Pleasant Bay using the HWL. After the rates of change using the HWL were examined the expected results were confirmed. The vast majority of rates of shoreline change were not statistically significant as they were within the range of uncertainty, or error. Therefore, little could be said of the nature of change in Pleasant Bay. Therefore, one hypothesis based on these data could state that, ‘little to no coastal change has taken place from 1868 to 2005 in Pleasant Bay’. This seemed counterintuitive based on the history of the bay including anthropogenic alterations such as erosion control structures and beach replenishment projects as well as the tidal inlets that have opened, migrated, closed and reopened.

In order to quantitatively disprove or support the above hypothesis a new shoreline indicator was used to calculate rates of shoreline change. Along the shoreline of Pleasant Bay, a coastal lagoon with fringing salt marsh, the basinward edge of marsh vegetation, or marshline, was used as a shoreline indicator to generate rates of shoreline change. The results using this new shoreline indicator were compared to results using the more traditional High Water Line (HWL) along shorelines where both shoreline indicators could be delineated. The marshline was shown to be superior to the HWL for documenting changes along marsh shorelines.

Rates of change along 25 miles (40 km) of shoreline where both the HWL and the marshline were delineated were documented and compared to one another. Less than 6.1 miles (9.8 km) of the HWL exhibited statistically significant shoreline change as compared to 14.0 miles (22.5 km) of the marshline for the same segments of the shoreline. Thus, 8.0 miles (12.8 km) of shoreline that saw no change using the HWL in fact, experienced erosion of the marshline-in some places up to 55 ft (16.7 m).

Changes in marsh vegetation below the HWL have implications for sediment transport, storm damage prevention and flood control that would not be otherwise quantifiable using most proxy-based shoreline indicators. Further, application of this method for tracking marsh change is useful not only for shoreline change studies, but also has potential applications for water quality, predator-prey relationships, ecosystem health and other science and/or management issues. The marshline allows the investigator to quantitatively assess changes in salt marsh habitat related to surface area, fringing marsh thickness, shoreline orientation and marsh disappearance and appearance. This technique also has implications for inlet formation as inlets are less likely to form in places with extensive salt marsh.

INTRODUCTION

Coastal areas are among the most populous and developed in the United States. Fifty percent of the U.S. population lives in counties that abut the coast, these counties represent 20% of the contiguous United States. Further, approximately 80% of the people in the U.S. live within one hour of the coast (Crossett *et al*., 2004). In addition, lands surrounding estuaries and lagoons are some of the most densely populated areas along the coast (NRC, 2007). There are over 850 estuaries and lagoons in the U.S. covering over 80% of the coastal regions along the Atlantic Ocean and Gulf of Mexico (Nordstrom, 1992).

Low-energy estuaries and lagoons are among the most biologically productive ecosystems in the world (Kennish, 2001; NRC, 2007) and include salt water wetlands, tidal flats, and mangrove forests. Salt marsh in particular provides: 1) habitat and refuge for finfish, shellfish, waterfowl and other wildlife; 2) flood protection; 3) storm damage prevention, 4) groundwater recharge; and 5) sequestration and filtration of contaminants (Kennish, 2001). A better understanding of sediment transport in these ecosystems would be of great value.

Embayment shorelines, like Pleasant Bay, represent the majority of eroding shorelines along the U.S. Atlantic and Gulf coasts (Morton *et al*., 2004; NRC, 2007), yet few studies have quantified rates of shoreline change in these areas. Conversely, shoreline change rates along open ocean shorelines have been determined for much of the United States at varying temporal and spatial scales (USACE, 1971; Crowell and Leatherman, 1999; Thieler *et al*., 2001; Byrnes *et al*., 2003). Currently, the U.S. Geological Survey (USGS) is quantifying shoreline change rates along the open ocean coast of the United States. The first regions to be completed include the: Gulf of

Mexico (Morton *et al*., 2004), southeast Atlantic coast (Morton and Miller, 2005), and sandy and cliff shorelines of California (Hapke *et al*., 2006; Hapke and Reid, 2007, respectively). However, none of these studies have included any significant embayment shorelines.

Delineating a shoreline from aerial photography along low-energy coastal embayments can be problematic. These shorelines are typically more complex and variable than corresponding stretches of open ocean in terms of shoreline type, energy regime, orientation, relief, etc. (Morton and Miller, 2005; NRC, 2007). It is assumed by the author that the exclusion of coastal embayment shorelines from the ongoing USGS study in particular and within the peer-reviewed literature in general is likely seen as a practical reality. First, delineating a defensible, repeatable and reliable shoreline from aerial photographs, and subsequently quantifying rates of shoreline change, can be extremely difficult and very time-consuming in these systems. Second, is the perceived likelihood that the majority of the rates of change generated would be so low as to not be statistically significant and are therefore seen as being of little use. However, any management decisions should be based on documented rather than perceived rates of change. For instance, being within the range of uncertainty itself yields a quantifiable number; if the uncertainty range is ±1 ft/yr then the erosion or accretion rate cannot be more than ±10 ft in 10 years or ±50 ft in 50 years, etc.

A New Technique

A new method of quantifying shoreline change in low-energy coastal embayments has been developed (Borrelli and Boothroyd (a), in prep). The need for, and lack of a method to quantify change in low-energy coastal embayments with fringing marsh in the peer-reviewed literature was the impetus for developing this new technique. The intent was to develop a defensible method of documenting change along these types of shorelines. In order to test the validity of this new shoreline indicator it was compared to the most prevalent proxy-based shoreline indicator in the peer-reviewed literature, the HWL. This method represents an interdisciplinary tool combining the techniques used to document shoreline change by coastal geologists with the GIS-based quantification of surface area change of salt marsh by ecologists.

Field Setting

Origin

Pleasant Bay is a coastal lagoon, though often referred to as an estuary, and is part of the Nauset Beach-Monomoy Island, barrier spit-barrier island complex (Figure 1). Nauset Beach here refers to the barrier spit that extends south from Nauset Inlet to the location of the 1987 inlet. The beach in Orleans will be referred to as the *Nauset barrier beach* similar to Adams and Giese (2008). Pleasant Bay proper and many of the sub-embayments in the lagoon are ice-block basins, or kettle holes. The Laurentide ice sheet advanced into southern New England in the late

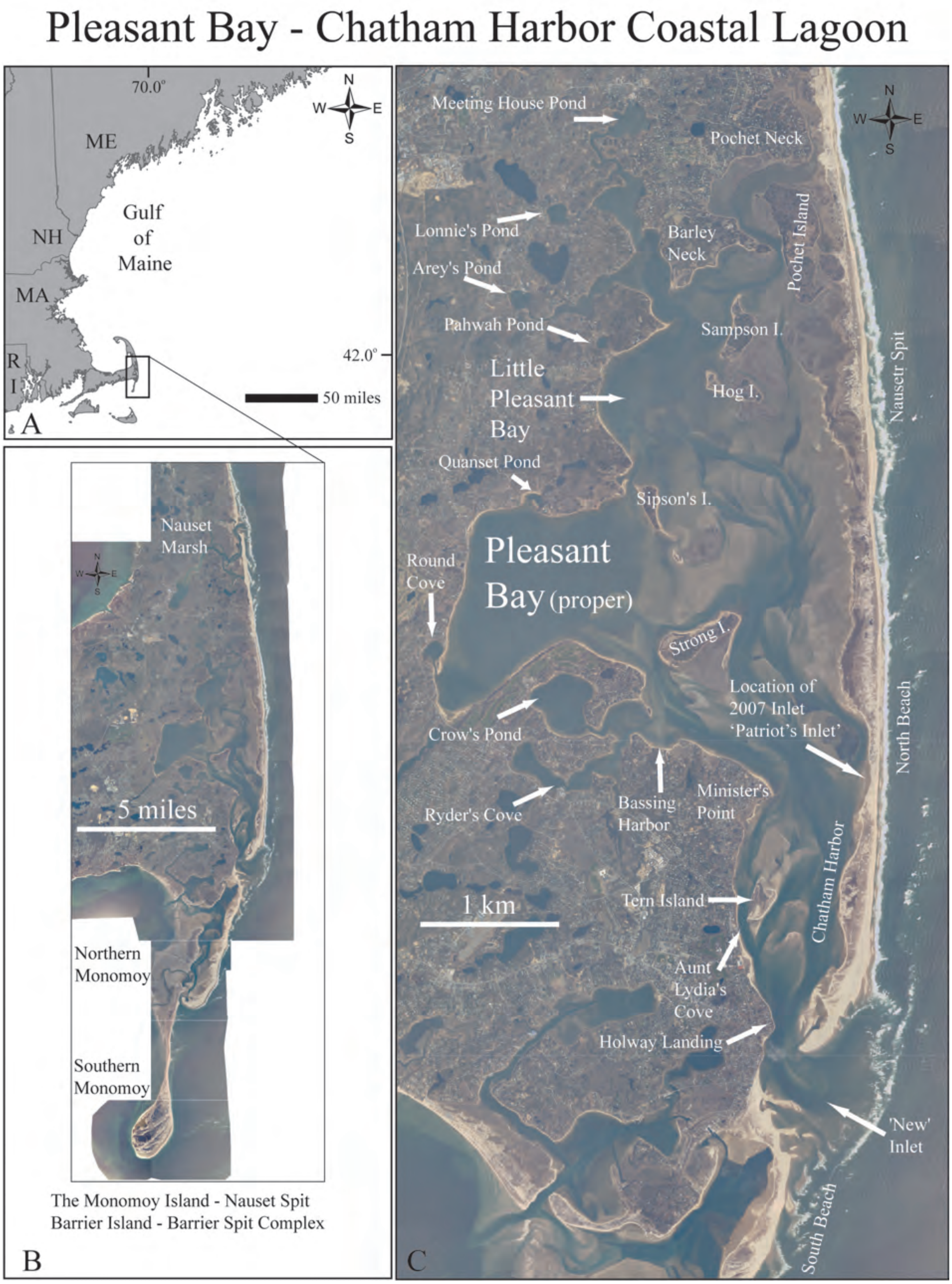

Figure 1: A) Southern New England; B) Nauset-Monomoy System; C) Pleasant Bay. 2005 aerial photograph.

Wisconsinan glacial stage, approximately 25,000 years Before Present (B.P.) and was at its maximum at 21,000 years B.P. (Stone and Peper, 1982). The glacial ice in the region during this time was approximately 0.30 miles (500 m) thick. From 21,000-18,000 years B.P. as temperatures increased and the ice-receded the bulk of the sediment that comprises Cape Cod was deposited (Oldale, 1982; Stone and Peper, 1982; Oldale and Barlow, 1986). As the rate of sea level rise began to decrease 6,000 years B.P. southeastern Cape Cod began to take on its characteristic morphology (Davis, 1896, Johnson, 1925; Fisher, 1987; Uchupi *et al*., 1996). Between 6,000-4,000 years B.P. barrier spits began to develop and subsequently small embayments were formed 4,000 years B.P. (Redfield, 1965, 1972; Orson *et al*., 1987; Kelley *et al*. 1988; Roman *et al*., 2000).

Recent Evolution

The present day Nauset Beach, the barrier spit that partially encloses Pleasant Bay, is a direct result of incoming ocean waves eroding the coastal bluffs to the north and entraining that material into the longshore sediment transport system in a predominantly southerly direction (Giese, 1978; McClennon, 1979; Giese, 1988). A recent study, however, has shown a possible shift in the dominant transport direction which would suggest that most of the material eroded from the bluffs is moving northward (Adams and Giese, 2007). This change could have far-reaching impacts to the Nauset Beach-Monomoy Island complex.

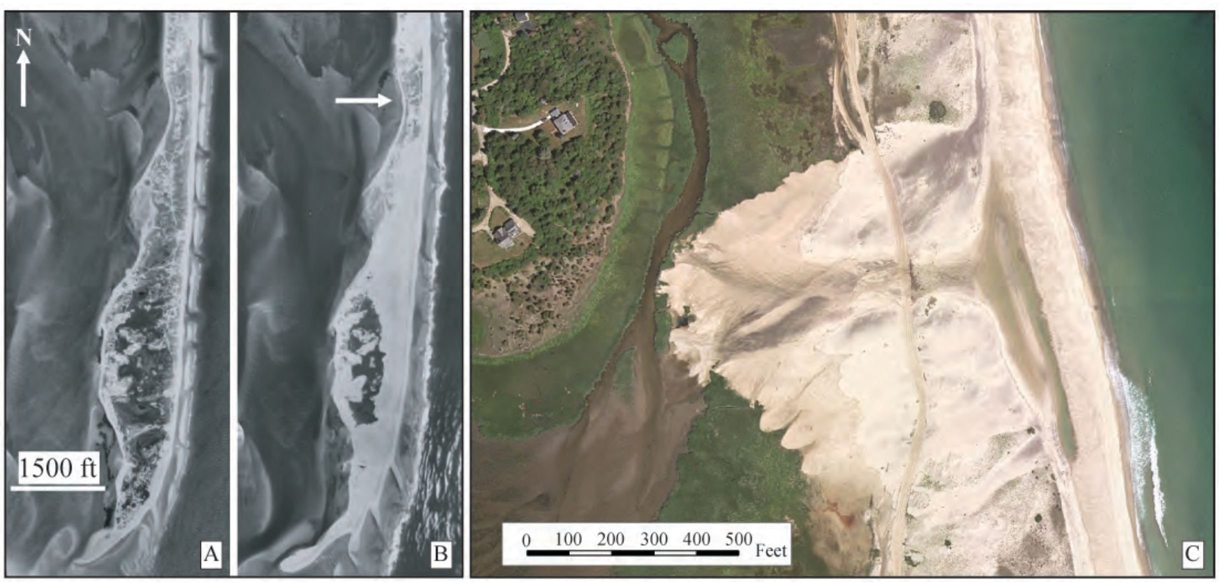

Figure 2. Post-storm washover fans along southern Nauset Beach. A. Aerial photograph from 22-FEB-91. B. Aerial photograph from 22-MAY-92. The only section along the southern 3.4 km of Nauset beach that was not significantly over washed during this storm was a 500 ft stretch of vegetated area that was the site of Patriot's Inlet noted by the white arrow (after Borrelli and Boothroyd (b), in prep) C. Example of washover fan immediately Seaward of Pochet Island.

The Nauset Beach barrier spit migrates landward primarily as a result of erosion on the open ocean shoreline and deposition on the backbarrier shoreline during overwash events (Leatherman, 1979). Washover fans are common along Nauset Beach particularly south of

Patriot's Inlet. Borrelli and Boothroyd (in prep-b) documented overwash on Nauset Beach during the 1991 Halloween Nor'easter along 116 acres (46.93 ha) of the 207 acres (83.95 ha), or 56% of the southern 2.1 miles (3.4 km) (Figure 2). The tidal range just offshore of Nauset Beach is 6.7 ft (2.0 m), in Chatham Harbor the tidal range is 4.6 ft (1.4 m) with a spring tidal range of 5.3 ft (1.6 m) (http://tidesandcurrents.noaa.gov). The significant wave height outside the bay is 4.9 ft (1.5 m) (http://www.ndbc.noaa.gov). This is a mixed-energy, wave-dominated coast according to the classification developed by Hayes (1979). Pleasant Bay is 3.1 miles (5.0 km) across at its widest point with mean and maximum depths of 6.6 ft (2.0 m) and 19.7 ft (6.0 m) respectively (Howes *et al*., 2006). Relative sea level rise along Cape Cod National Seashore is approximately 0.102 – 0.104/yr inches (2.59 - 2.65/yr mm) as reported by Hammar-Klose *et al*. (2003), approximately 14.3 inches (36 cm) of sea level rise from 1868 to 2005, the time span of this study. This is an approximate figure as the rates of sea level rise change through time.

Methods of Documenting Salt Marsh Change

Ecologists monitor salt marshes by conducting field studies to document changes in vegetation type and density, marsh elevation, soil salinity and other targeted processes or characteristics in order to better understand these ecosystems (Adam, 1990). Studies of large scale changes in marsh vegetation are also prevalent and are conducted by delineating the surface area of salt mash habitat and comparing change in area over time using historical aerial photographs. Several such recent studies of salt marshes in, or adjacent to, the study area, include Erwin *et al*., (2004) and Weishar *et al*., (2007). Erwin *et al*., (2004) documented large-scale marsh change in several east coast lagoonal salt marshes using aerial photography. Nauset Marsh, to the north of Pleasant Bay, saw a 19% loss of marsh habitat from 1947 - 1994. Causes of this loss were attributed to overwash processes and the conversion of salt marsh to open water areas. Weishar *et al*., (2007) looked at the change in fringing salt marsh from 1984 to 2005 in Ryder's Cove, a small sub-embayment in Pleasant Bay. From 1984 to 1994, a 14% decrease in fringing marsh was observed followed by a 5% and 12% increase in the following temporal periods. It was hypothesized in the study that a combination of increased tidal range 1.0 ft (0.30 m) due to the formation of the 1987 inlet and a concomitant increase in wave energy and subsequent erosion were the cause of the decrease. The ensuing increase in salt marsh, according to the authors, was the system re-equilibrating to the change in tidal range and recovering. The method of delineating the extent of the fringing marsh was not discussed.

Smith (2006) examined salt marsh dieback in study sites on Cape Cod and the areas that were most likely to be impacted were creekbanks in sheltered embayments. However, he saw no examples of dieback in Pleasant Bay. Smith discussed several potential causes of marsh loss including wrack accumulation, grazing by geese, ice rafting, and predation by insects and anthropogenic causes such as nutrient loading and eutrophication. He also observed that marsh regrowth can occur within several years. This regrowth was determined to be dependent on a number of factors including the presence of suitable substrate for marsh vegetation. The marshline technique could be a useful tool is assessing marsh dieback in applicable settings.

METHODS

Shoreline Change Analysis

The method typically used in shoreline change studies includes: 1) assembling a database of digital images from multiple sources and different media; 2) 'georeferencing' or assigning map coordinates to each image; 3) delineating a shoreline; and 4) quantifying rates of shoreline change and the associated range of uncertainty.

Assembling the Digital Database

The shorelines in this study have been delineated from selected vertical aerial photographs and topographic map sheets (T-sheets). The shoreline change analysis was further broken down into shoreline sections for clarity in interpretation, analysis and presentation including: 1) open-ocean; 2) backbarrier; 3) northern ponds; 4) pleasant bay(s); 5) southern ponds; 6) the mainland shoreline of Chatham Harbor; and 7) bay islands (Figure 3). For each year, or 'coverage', the

Table 1. Media and shorelines used for shoreline delineation and rate of change calculations.

Shoreline	Media	Years of Coverage	(n)	Shoreline Proxy (Indicator)
Open Ocean	Vertical aerial photographs and T-sheets	1868, 1886, 1938, 1951, 1978, 2001, 2005	7	HWL, (wet/dry line, high-marsh/low-marsh line)
Lagoon	Vertical aerial photographs and T-sheets	1868, 1938, 1978, 2001, 2005	5	HWL, (wet/dry line, high-marsh/low-marsh line)
Marshline	Vertical aerial photographs	1938, 2005	2	(Basinward edge of marsh vegetation)

entirety, or vast majority, of the shoreline would have to be included in the aerial photographs, or T-sheets, for shoreline delineation to be undertaken. For the open-ocean compartment, 7 shorelines were used (1868, 1886, 1938, 1951, 1978, 2001, 2005) to calculate rates of shoreline change. For the shorelines in Pleasant Bay, 5 shorelines were used (1868, 1938, 1978, 2001, and 2005). For the marshlines in Pleasant Bay, 2 shorelines were used (1938, 2005) (Table 1). More years of aerial photographs were available (Appendix A) but were not geo-referenced due to the quality of the images and/or time constraints; however all of the images were used to qualitatively assess the coastal morphodynamics of the area during the temporal span of the study. The digital database of raw (non-georeferenced) images for this study is over 34GB in size and contains approximately 450 high resolution vertical aerial photographs.

Three types of media were used in this study: hardcopy vertical aerial photographs, topographic sheets (T-Sheets) and digital orthophotographs. Hardcopy vertical aerial photographs and T-Sheets were collected from numerous sources including the Cape Cod National Seashore

(CCNS), The Town of Chatham (TOC), The Massachusetts Office of Coastal Zone Management (MCZM), and the MassGIS website. The hardcopy aerial photographs from CCNS and TOC were digitally scanned using a desktop scanner at high resolutions, typically 600-1000 pixels per inch (ppi) for color images and 1200 ppi for black and white images. Most of the images were 9 inches by 9 inches; however the desktop scanner used was 8.5 inches by 14 inches. Therefore,

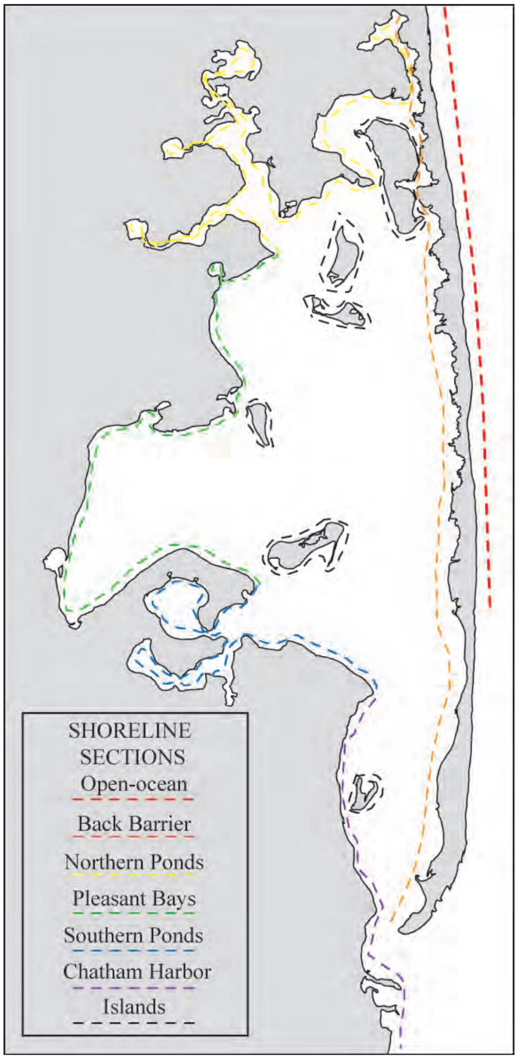

Figure 3: Shoreline sections for Pleasant Bay.

careful attention was required during scanning to determine which edge(s) would, or would not be included in the scan. Positive aspects of this kind of analysis include a quick, inexpensive and reliable digital data set. The drawbacks include the limits of desktop scanners and software compared to equipment in professional photogrammetric shops and altering the photo-center, the point directly below the camera, all of these can negatively affect the quality of the georeferencing process. The T-Sheets were obtained through MCZM. Three years of digital orthophotos (1994, 2001 and 2005) were downloaded from the Massachusetts Geographic Information Systems (MassGIS) website (http://www.mass.gov/mgis/).

Georeferencing Two-Dimensional Media

Georeferencing involves assigning map coordinates to a two-dimensional image that represents a location on a 3-dimensional surface, the earth. The process involves having a reference frame, in this case the 2005 orthorectified image from MassGIS, and the raw tiff image in the object frame. An orthorectified image includes 3-dimnesional information in the georeferencing process and thus is a more accurate representation on the earth's surface. The user identifies points common to both images and the software assigns 'real-world' coordinates from the image in the reference frame to the image in the object frame (Figure 4). This is a time-consuming process and the quality of the georeferencing is not known until the entire process is run and the georeferenced image is checked against the orthorectified image. If the displacement, or distance, between the same point in the reference image and the object image is too large the process is repeated. The scanned hardcopy vertical aerial photographs were georeferenced using Leica Geosystems' ERDAS Imagine© v8.7.

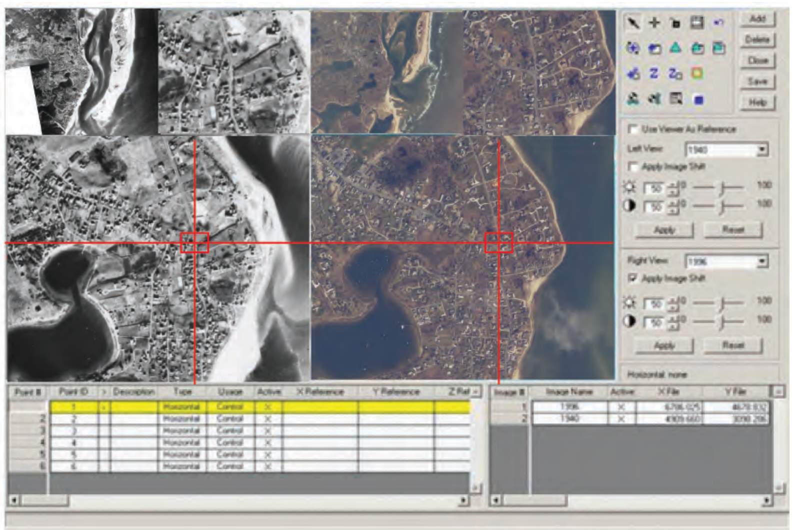

Figure 4. Screen capture of *ERDAS* Imagine**®** *v8.7.*The three color images on right are the reference frame image (April 2005 MassGIS) at different scales. Three black and white images on left are object frame being geo-referenced.

The aerial photographs that were georeferenced for this study have a pixel resolution of 1.6 ft (0.5 m) with an associated mean uncertainty of approximately ±16.4 ft (±5.0 m). The 2005 digital orthophotographs downloaded from MassGIS have a pixel resolution of 1.6 ft (0.5 m) and an associated uncertainty of ±9.8 ft (±3.0 m).

Delineating a shoreline

The shoreline is defined as, "The intersection of a specified plane of water with the shore or beach; it migrates with changes of the tide or of water level." (Jackson, 1997). The shoreline along any tidally-influenced coast varies continuously through time. The National Ocean Service (NOS), though not always under that name, has been delineating the coastline of the United States for mapping purposes since 1807.

In general, two types of shorelines are used in shoreline change studies: datum-based and proxy-based shorelines. Datum-based shorelines are based on three-dimensional data. Shorelines in the real-world are obviously three-dimensional, and for shoreline change analyses it would be preferable for each point along the shoreline to have horizontal coordinates (i.e. latitude/longitude) and a vertical elevation. An average of all the shorelines for a given period of time would also be desirable; for instance, all of the shoreline positions at high tide for an entire year. The Mean High Water (MHW) line is a common datum-based (tidal datum) shoreline. In Massachusetts Mean Lower Low Water (MLLW) is a tidal datum that has great significance as it is the seaward extent of private land ownership. MLLW is the average of the lower of the two daily low tides for a given time period. The MLLW datum was not used in this study as it very difficult to ascertain its position on aerial photographs and impossible if the photographs were not taken at very low tide. It is assumed that given a long enough time period other variables, such as: tidal phase, storm surge, wind events, beach state, etc., will become less and less significant and the datum-based shoreline will be the most accurate representation of the shoreline.

Collecting datum-based shorelines is not practical for large scale historical studies. The acquisition of datum-based shorelines for a given beach prior to the mid-1990s could only be done by going to a specific beach and conducting a survey in relation to a benchmark with a known elevation. Conversely, the wealth of historical vertical aerial photographs of coastal areas from the late 1930s to the present is extensive and T-sheets of sufficient quality date back to the mid-1800s. Vertical aerial photographs are two-dimensional thus extracting a datum-based shoreline is not possible, yet clearly a shoreline is present on all aerial photographs of the coast. The point of intersection between the water and land in an aerial photograph captures one moment in time. Although it is easily identifiable it cannot be used in shoreline change studies. Too many factors could be influencing the shoreline at the time the photograph was taken, including: wind events, tidal phase, seasonal variations, storm surge, and beach state.

Within the context of shoreline change studies that use aerial photographs a shoreline indicator is chosen that best represents the true shoreline. This shoreline indicator should also be easily identifiable, and its delineation repeatable by multiple operators. Most proxy-based shoreline change studies generally are attempting to find a proxy for the MHW tidal datum as it represents a datum that has been used to map shorelines for at least 200 years. The most prevalent proxy-based shoreline in the literature is the High Water Line. Shoreline indicators for the HWL include the: wrack line (debris line); wet/dry line and; change from low-marsh to high-marsh vegetation along marsh shorelines. Other proxies for shorelines include the: edge of the coastal bluff; seaward extent of dune vegetation; dune crest; dune toe and; beach scarp (Pajak and Leatherman, 2002). The wet/dry line is the shoreline indicator for the HWL used for shoreline delineation along sandy beaches in this study; and the change from low-marsh to high-marsh vegetation is the shoreline indicator for the HWL along marsh shorelines. The HWL was the preferred shoreline indicator for the surveys conducted by the NOS along open ocean shorelines when create T-Sheets (Leatherman, 2003) which allows for the use of these data for proxy-based shoreline change studies.

The Marshline

The basinward edge of marsh vegetation or 'marshline' is proposed as a proxy-based shoreline indicator along coastal embayment shorelines with fringing salt marsh. The marshline is readily discernible in aerial photographs (Figure 5) and has been developed solely to document change along coastal embayment shorelines with fringing marsh.

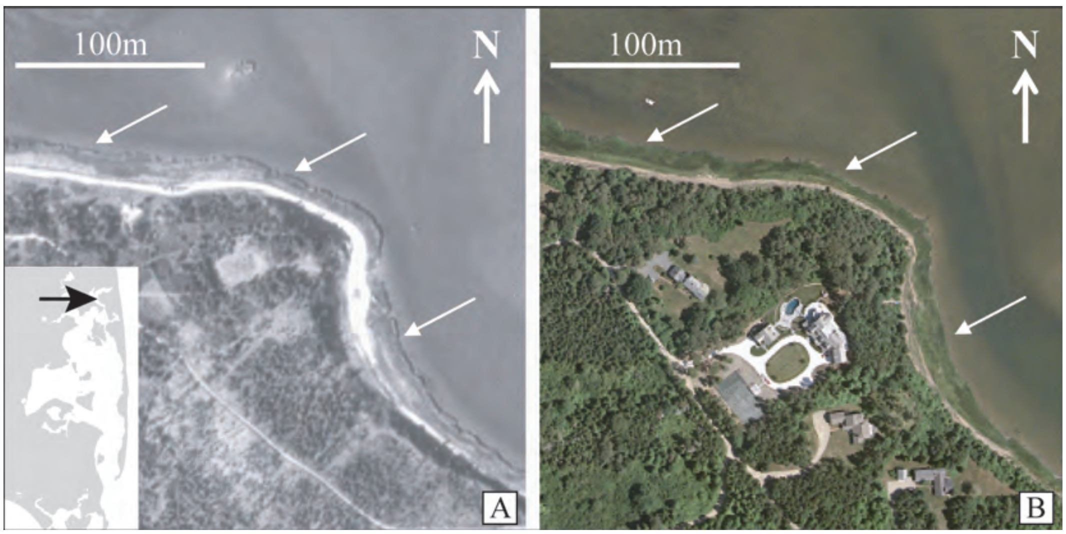

Figure 5: Comparison of 1947 and 2005 aerial photograph. The marshline is easily discernible in both images, as indicated by the arrows. Note that it is common for areas with fringing marsh to have intertidal sandy beaches landward of the marsh vegetation as seen above. (From Borrelli and Boothroyd (a), in prep).

Rates of Shoreline Change and Associated Uncertainty

The Digital Shoreline Analysis System (DSAS) (Thieler *et al*., 2005) extension for ARCGIS**®** was used to determine all rates of shoreline change. Transects were generated every 65.6 ft (20 m) along the entire shoreline and extend from a user-created, shore-parallel baseline. Transects were manually edited for proper placement and optimal orientation.

Information on rates of shoreline change can help investigators better understand the coastal sedimentary processes of a region as well as predict future shoreline positions (Crowell *et al*., 1991; Douglas *et al*, 1998). These data have also been widely used to establish building setbacks for state and local governments (Crowell and Leatherman, 1999**)**. The use of robust statistical analysis when calculating shoreline change rates can be a useful tool, if used properly.

An area of concern for investigators is the uncertainty associated with determining the shoreline change rates for a given area, often referred to as 'error'. These uncertainties, or errors, include random uncertainties and systematic uncertainties. Random uncertainties consist of: the misinterpretation of the shoreline proxy, errors in field surveying, errors associated with media (e.g. shrinking, fading of paper maps and/or aerial photographs) as well as digitizing and georeferencing aerial photographs. Random uncertainties do not uniformly affect the entire data set. Systematic uncertainties may include: timing of aerial photographs used in the database such as differences in seasonal changes, storm-induced erosion, and position in the tidal cycle. These uncertainties can affect the entire data set and the corresponding results. For example, the HWL along four beaches in North Carolina and Virginia migrated up to 6.6 ft (2.0 m) in one diurnal high water period (Dolan et al., 1980). Bosma and Dalrymple (1997) documented that seasonal changes of the HWL on sandy beaches in Delaware ranged from 16 - 66 ft (5 – 20 m). The south shore of Long Island, NY saw yearly changes in the HWL of up to 66 ft (20 m) (Smith and Zarillo, 1990). Zhang et al. (2002) document over 328 ft (100m) of change in the HWL as a result of large storms. Some investigators state that the storm shoreline lessens the statistical validity of future shoreline prediction and thus they treat storm shorelines as statistical outliers (Douglas et al, 1998; Galgano et al. 1998; Douglas and Crowell, 2000; Honeycutt et al, 2001), discarding valuable information needed to determine the dynamic nature of these shorelines.

Measurements of any kind have a range of uncertainty and quantifying which results are statistically significant is critical to shoreline change studies. When calculating rates of shoreline change an equation to quantify the range of uncertainty must be developed to document the range of statistically significant erosion. Typically, all of the potential sources of uncertainty are quantified and a total range of uncertainty is generated. After which that number is divided by the number of years within the temporal span of the study. For example, in the case of Pleasant Bay if the range of uncertainty were determined to be ±137 ft over the course of this 137 year study (1868-2005), this would yield a yearly range of uncertainty of ±1 ft/year. Consequently, any rate of shoreline change <1 ft/yr whether positive (accretion) or negative (erosion) is not 'statistically significant' or statistically valid. Although those data can be used in other ways care must be taken. In a study of historical shoreline change in Massachusetts (Thieler, et al. 2001) 42% of the over 30,000 shore normal transects that were generated for mostly open ocean shorelines, were within the range of uncertainty (J. O'Connell, pers. com.) and therefore not statistically significant.

In order to calculate a range of uncertainty (Ur) for this study the following equation is used (Equation 1),

$$U_r = \sqrt{(U_g)^2 + (U_d)^2 + (U_t)^2 + (U_s)^2}$$

Equation 1. (after Hapke *et al*., 2006)

where U_g, U_d, U_t, U_s is the uncertainty associated with georeferencing, digitizing, T-sheet survey, and delineating the correct shoreline proxy, respectively. U_g represents the difference between the 'real world' coordinates of the image and coordinates assigned to the point during georeferencing. U_d is the difference between the point identified as the shoreline proxy and the actual one created by the user; more simply the inherent error in the movement of the mouse in any direction before clicking the mouse and assigning a point to it. U_t is the uncertainty associated with the original shoreline delineation during surveying conducted for creation of the original T-sheets. U_s is the difference between the actual HWL line and the one delineated on the image, this entails choosing the wrong shoreline proxy due to misinterpretation of the location of the shoreline proxy on the aerial photograph.

Calculating Rates of Shoreline Change: Linear Regression and End Point
Linear Regression Analysis (LRA) is used to find a line that best predicts the linear relationship between the independent variable (shoreline position) and the dependent variable (time). The better the fit of the trend line, the higher the confidence level is with regards to the future position of the shoreline. LRA requires a minimum of four data points or shorelines to yield statistically robust results. It is the most prevalent method for generating rates of shoreline change in the current literature (Crowell and Leatherman, 1999).

Though currently in the minority, the author believes a significant problem exists when using the LRA method-it assumes a linear process is driving shoreline change with respect to time. No supporting evidence of a linear physical process responsible for shoreline change could be found. Storms are the primary drivers of change along open ocean shorelines in the northeastern United States. On millennial time scales the episodic nature of storms maybe begin to approach linearity with respect to time, but for management purposes decadal time scales should be used. Even on centennial time scales storm activity has not been shown to approach linearity (Zhang *et al*., 2002). In addition, to improve the confidence interval of the regression, or r^2 value, some investigators contend that aerial photographs that were taken after a storm event should be discarded as it represents a shoreline out of equilibrium (Douglas *et al*, 1998; Galgano *et al*. 1998; Douglas and Crowell, 2000; Honeycutt *et al*, 2001, Zhang *et al*., 2002). This, in effect, removes the primary driver of shoreline change in order to better predict the rate of shoreline change; this seems counterintuitive.

Another method of calculating rates of shoreline change is the End Point (EP) method. This method simply calculates the distance between the earliest shoreline in the series and the most recent. If desired, that distance can be divided by the number of years separating the two shorelines to generate a rate of shoreline change per year. If there are multiple years then a rate could be generated for each interval, for example for 1868, 1938 and 2005 rates would be generated for 1868-1938, 1868-2005 and 1938-2005.

Using the marshline as a shoreline indicator limits the investigator to the temporal extent of available aerial photographs. Marsh extent was only mapped to an approximate location on historic T-Sheets (Shalowitz, 1964) and therefore cannot be used to delineate marsh extent. Only two suitable aerial photographic coverages were available for the fringing marsh along the

Pleasant Bay lagoon shoreline. The 1978 images did not cover the entire lagoon, the 1994 images were not of sufficient quality, and the 2001 images were deemed to close in time to the 2005 images to warrant inclusion in the marshline dataset. Having only two shorelines precludes the use of the LRA method for calculating rates of change and thus the EP method was used. Therefore, in order to compare the marshline and the HWL shoreline indicators, only rates generated using the EP method were used. In a larger study (Borrelli, 2008) shoreline change rates were generated using both LRA and EP for the HWL shorelines.

RESULTS AND DISCUSSION

The Pleasant Bay shoreline delineated from the 2005 aerial photographs, including the open ocean shoreline from south of Nauset barrier beach in Orleans to the northernmost point of South Beach near the 1987 inlet is 61.7 miles (99.3 km) long. Approximately 5000 shore-normal transects were generated for the 2005 shoreline. More than 298 miles (479 km) of shorelines were delineated for the entire study.

Sources and Range of Uncertainty

The mean uncertainty (U_g) for all the georeferenced hardcopy aerial photographs in the study was ±15.7 ft (±4.8m) (Table 2). The documentation of the HWL required delineation along coasts that ranged from medium- to coarse-grained, steep (reflective), open ocean beaches to finer grained, relatively flat (dissipative) low energy beaches. Computing shoreline variability (U_s) due to seasonal changes, beach state and tidal phase for each of these settings throughout the study area is beyond the scope of this study. Consequently we have taken estimates from other studies (Fletcher *et al*., 2003; Ruggerio *et al*., 2003; Morton *et al*., 2004; Morton and Miller, 2005; Hapke *et al*., 2006.) that quantified uncertainties and using a mean from those studies generated estimates for this study (Table 2).

Table 2. Sources of Uncertainty. Calculations for HWL and Marshline Shoreline Indicators. '*'denotes values determined by taking average values from other studies (Crowell *et al*. 1991, Moore 2000; Fletcher *et al*., 2003; Ruggerio *et al*., 2003; Morton *et al*., 2004; Morton and Miller, 2005; Hapke *et al*., 2006).

Source of Uncertainty	High Water Line (This Study)	High Water Line (Other Studies)	Marshline
Georeferencing (U_g)	±15.7 ft	± 10-13 ft	± 15.7 ft
Delineation of Proxy (U_d)	± 30 ft*	± 23-36 ft	± 3.0 ft
T-Sheet: Field Survey (U_t)	± 43 ft*	± 20-65 ft	N/A
Shoreline Variability (U_s)	± 50 ft*	± 32-65 ft	± 3.0 ft

This was also done for uncertainties related to T-Sheets (Crowell *et al*. 1991; Moore 2000 and references therein) and delineation of the shoreline proxy (Moore 2000; Ruggerio *et al*., 2003).

The range of uncertainty for rates of shoreline change from 1868 to 2005 is ±73.2 ft (±22.3 m) or ±0.53 ft/yr (±0.16 m/yr). The range of uncertainty using the HWL shoreline indicator from 1938 to 2005, the temporal span during which only aerial photographs were used, is ±59.7 ft (±18.2 m) or ±0.89 ft/yr (±0.27 m/yr). The range of uncertainty using the marshline shoreline indicator for 1938-2005 was ±16.7 ft (±5.1 m) or ±0.25 ft/yr (±0.08 m/yr) (Table 3). The range of uncertainty for the marshline calculations was lower than for the HWL, in spite of using the same aerial photographs. The marshline shoreline indicator eliminates several sources of uncertainty including tidal phase, seasonal beach changes, photographs taken post-storm, and misinterpretation of shoreline indicator (Table 2) see Borrelli and Boothroyd (b) (in prep) for details.

Table 3 Results of Uncertainty Calculations (MhL = marshline).

Time Period	Range of Uncertainty (U_r)	Uncertainty/yr (U_a)
1868-2005 (HWL)	±73.2 ft	±0.53 ft
1938-2005 (HWL)	±59.7 ft	±0.89 ft
1938-2005 (MhL)	±16.7 ft	±0.25 ft

It should be noted that detailed analysis on a scale smaller than shoreline sections is beyond the scope of this report. However, that analysis would be very useful for local resource managers and stakeholders.

Nauset Beach

Open Ocean-High Water Line

The open ocean shoreline from south of Nauset barrier beach to the area north of *Patriot's Inlet* (formed in 2007) which was also the approximate location of the 1846 inlet, is used as the southern extent of shoreline change analysis along the open ocean shoreline (Figure 3). Results further south are driven predominantly by inlet processes and as such significantly differ from other shoreline areas. Therefore, in order to compare similar stretches of shoreline through time the southern portion of Nauset Beach, such as North Beach, and South Beach, though analyzed, is excluded from the results below.

Along the 5.0 miles (8.1 km) of open ocean shoreline all 404 transects were erosional and outside the range of uncertainty. The mean rate of erosion from 1868 to 2005 along those transects was -4.9 ft/yr (-1.50 m/yr). The minimum and maximum rates of erosion were -2.9 ft/yr (-0.88 m/yr) and -7.5 ft/yr (-2.28 m/yr), respectively, using the EPR method. This is consistent with other studies. It should be noted that using LRA the mean rate is -4.7 ft (-1.42 m/yr) and the minimum and maximum rates of erosion were -2.5 ft/yr (-0.75 m/yr) and -6.7 ft/yr (-2.03 m/yr), respectively. These results are close to those documented using the Endpoint method.

Backbarrier-High Water Line

The backbarrier area along the bay side of Nauset Beach extends from the area behind Nauset barrier beach to just north of the location of the 1987 inlet at the time of formation (Figure 3). The stretch of shoreline south of Patriot's Inlet was included in the backbarrier analysis and not in the open ocean section for two reasons. First, the marshline work was conducted using the aerial photographs from 1938 to 2005, and second, in 1938 the area south of the future location of Patriot's Inlet was relatively stable as the 1846 inlet had migrated more than 5.0 miles (8.0 km) to the south by 1938.

Along 9.2 miles (14.7 km) of HWL shoreline only 70 transects out of 737, or 10.4% were erosional more than 605 transects were accretional (91.6 %) reflecting the landward migration of Nauset Spit. The mean rate of erosion from 1938 to 2005 along those transects was -5.3 ft (-1.16 m). The minimum and maximum rates of erosion were -0.92 ft/yr (-0.28 m/yr) and -12.5 ft/yr (-3.81 m/yr).

During storm events material is eroded from the ocean shoreline and elevated water levels carry sand across the barrier. Some of that material is transported to the bayside of the barrier during this 'overwash' event. The resulting landforms, the flat, broad areas of sandy deposits, are called 'washover fans'. Interestingly, the process is termed overwash and the resulting landforms are called washover fans, much to the chagrin of those studying coastal processes. Washover fans are prime habitat for endangered species of shorebirds, including the Piping Plover.

The mean rate of accretion from 1868 to 2005 along the 605 transects was 7.2 ft/yr (2.2 m/yr) using the EPR method. The mean bayside accretion rate is almost 2 feet less than the ocean side erosion rate. This is an indication that the barrier is becoming narrower, which has been corroborated by an analysis of barrier width through time (Borrelli and Boothroyd (b) in prep). Barrier width is a critical factor in protection against inlet formation. Further analysis of these data would document specific areas of the barrier that may be thinning more rapidly than others.

Backbarrier-marshline

There are 5.5 miles (8.86 km) of marshline along the backbarrier as compared to 9.2 miles (14.8 km) of total backbarrier shoreline. This is a function of sections of shoreline without salt marsh. A total of 202 transects out of 443, or 45.6% were accretional with only 29 erosional transects. The mean rate of accretion is 6.46 ft/yr (1.97 m/yr). The accretion is mainly due to the creation of salt marsh resulting from washover fans and sub-tidal storm surge platforms (sub-tidal washover fans) becoming colonized by vegetation.

More than 52% of backbarrier marshline transects were outside the range of uncertainty compared to 91.6% of backbarrier HWL transects. This is indicative of a rapidly migrating backbarrier HWL as mentioned above and a salt marsh community that cannot keep pace with that change. This inability of the marshline to maintain its position relative to the backbarrier HWL may be a result of several factors including: sea level rise, eutrophication, lack of sediment or substrate upon which to grow as it relates to inlet processes and migrating tidal channels. An example of the latter occurring in Pleasant Bay is discussed in Borrelli and Boothroyd (b) in prep).

Mainland Pleasant Bay

Northern Ponds-High Water Line

The Northern Ponds shoreline extends from the transition of the backbarrier shoreline behind the parking lot at Nauset barrier beach in Orleans to Namequoit Point where the Little Pleasant Bay shoreline begins (Figure 3). This shoreline sections includes: Arey's Pond; Lonnie's Pond; and Meeting House Pond. The Northern ponds shoreline is 13.9 miles long (22.4 km) with 1122 transects. More than 85% of the HWL transects were within the range of uncertainty so little can be said about shoreline change in those areas. Of the 171 transects outside the range of uncertainty 52% were erosional and 47% were accretional (or 8% and 7% of the total 1122 transects, respectively). Interestingly, the mean rate of change for all of the 1122 transects was 0.0 ft, this is indicative of a relatively static HWL. The mean rate of change along the erosional transects was 1.41 ft/yr (0.43 m/yr). This mean rate of erosion seems high until a standard deviation of 2.79 ft/yr (0.85 m/yr) is noted. The reason for this, 16 transects with erosion rates of between 1.84 ft/yr (0.56 m/yr) and 5.91 ft/yr (1.80 m/yr) and the remaining transects having values between 0.26 ft – 0.82 ft/yr (0.08m/yr – 0.25m/yr). Transects exhibiting high rates of change are somewhat anomalous and represent naturally dynamic areas of change (Figure 6). The mean accretional rate was 1.18 ft/yr (0.36 m/yr).

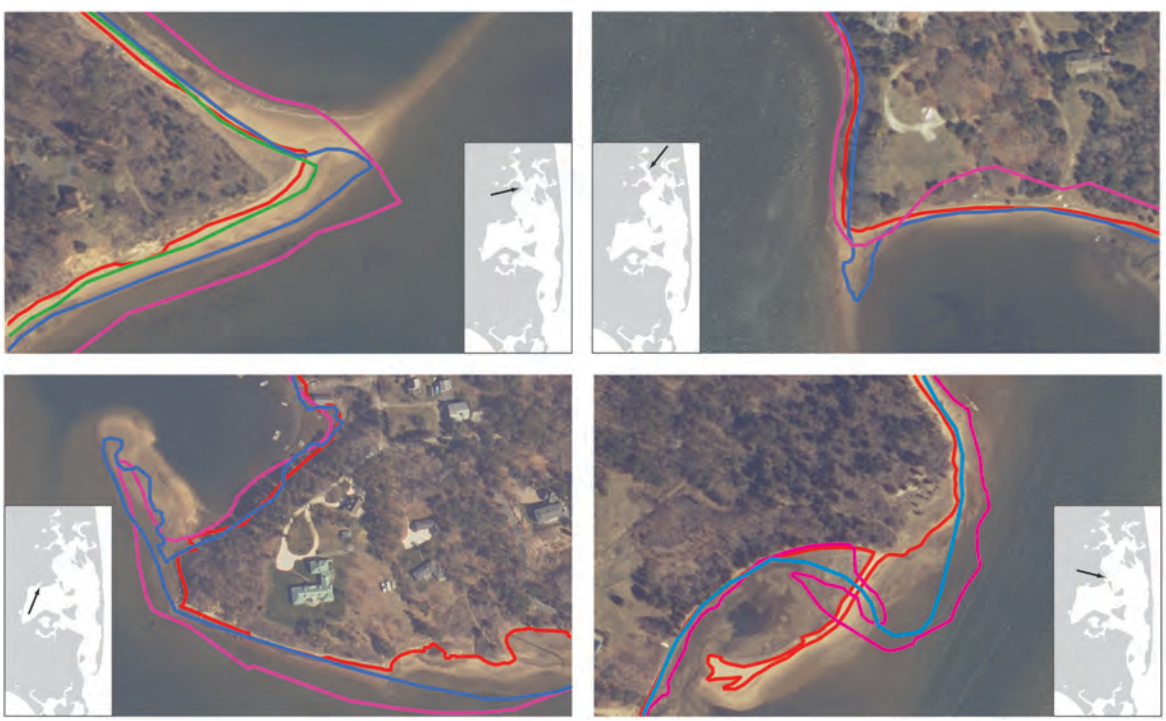

Figure 6. Examples of areas where most of the change occurred along the mainland shoreline of Pleasant Bay. Pink is 1868, Blue is 1938, Green is 1978 (upper left only) and Red is 2005.

Northern Ponds-marshline

Almost all of the shoreline in this area has fringing salt marsh. The Northern Ponds marshline is 13.7 miles (22.0 km) or 98% of the HWL. Of the 1100 marshline transects 332 transects (30.2%) were outside the range of uncertainty, twice the number of HWL transects. More than 91% of these transects (256) were erosional with a mean rate 0.75 ft/yr (0.23 m/yr). There does not seem to be a direct correlation between the presence of fringing salt marsh and lower rates of erosion. This is likely a result of several factors contributing to salt marsh loss some of which may not be related to increasing energy levels commonly associated with erosion. However, it has been well-documented that salt marsh vegetation will dampen low levels of wave energy that would likely have eroded fine-grained sediment backing the areas of fringing salt marsh. The mean rate of accretional transects (n=24) was 0.46 ft/yr (0.14 m/yr).

Pleasant Bay(s)-High Water Line

This section of shoreline is named Pleasant Bay(s) with the 's' in parentheses as to denote the inclusion of the mainland sections of Pleasant Bay proper and Little Pleasant Bay (Figure 3).

This section saw more change along the mainland embayment shoreline using the HWL than any other area outside of Chatham Harbor; it also had less marshline than any other shoreline section. Both of these conditions are indicative of shorelines with relatively high levels of wave energy. This shoreline section is dominated by east facing shorelines, has the largest sub-embayments fronting those shorelines and some of deepest water in Pleasant Bay. These factors will allow more wave energy to reach these shorelines, allowing storm events to erode more material, removing the substrate needed for salt marsh creation. Also, the increased wave energy may decrease the likelihood of new salt marsh vegetation taking hold which would provide much needed wave attenuating benefits.

Of the 698 transects in this area 300 (43%) were outside the range of uncertainty along the 8.67 miles (13.9 km) of HWL shoreline. Coincidentally, exactly 50% of those transects were erosional and 50% were accretional. The mean rate of erosion was 1.31 ft/yr (0.40 m/yr) and the mean rate of accretion was 1.80 ft/yr (0.55 m/yr). The east facing shoreline of Little Pleasant Bay had the longest continuous stretches of erosional transects.

Pleasant Bay(s)-marshline

Only 4.1 miles (6.54 km) or 47% of this shoreline section has fringing salt marsh yielding 327 transects. More than 51% of those transects were outside the range of uncertainty. However, unlike the HWL transects more than 98% of those 168 transects are erosional with a mean rate of 0.82 ft/yr (0.25 m/yr). The fringing salt marsh along this section of Pleasant Bay is clearly decreasing. As mentioned above this is likely a result of greater water depths, shoreline orientation and fetch contributing to the increase of wave energy experienced along this shoreline.

Southern Ponds-High Water Line

The Southern Ponds shoreline extends from Fox Hill Island to Allen’s Point (known locally as Minister’s Point) and includes Crow’s Pond, Ryder’s Cove and Bassing Harbor. Along the 7.3 miles (11.9 km) of HWL shoreline 246 transects out of 593, or 41.5% were outside the range of uncertainty and of those 246 transects 114 (46.3%) were erosional and 132 (53.7% were accretional. The mean rate of erosion was 0.72 ft/yr (0.22 m/yr) and accretion 0.79 ft/yr (0.24 m/yr).

Southern Ponds-marshline

There are 6.7 miles (10.7 km) of marshline along the shorelines of the Southern Ponds. This yields 535 transects of which 292 (54.2%) were outside the range of uncertainty. More than 98.6% (286) of those transects are erosional. The mean rate of erosion was 0.82 ft/yr (0.25 m/yr). Given that the HWL change numbers were nearly equal in the distribution between erosional and accretional transects and the overwhelming majority of marshline transects were erosional it is clear that processes are working throughout the entire sub-embayment that are negatively impacting the salt marsh in these areas. A more thorough analysis would be needed to ascertain potential causes of this phenomenon.

Chatham Harbor-High Water Line

The Chatham Harbor shoreline includes only the mainland shoreline from Minister’s Point to the northernmost point of South Beach near the location of the 1987 inlet as of 2005. Along 2.5 miles (4.0 km) of HWL shoreline 137 transects out of 202, or 67.8% were outside the range of uncertainty. Erosion was documented along 64 transects (46.7%) and 73 transects (53.3%) were accretional, with maximum rates of 1.87 ft/yr (0.67 m/yr) and 2.20 ft/yr (0.57 m/yr), respectively. This is a particularly complex area. In 1868, only 20 years after an inlet formed across from Minister’s Point (in the same place as Patriot’s Inlet) the mainland shoreline was susceptible to much higher wave energy than prior to the 1846 inlet formation. In 1938 Chatham Harbor was fronted by Nauset Beach and over the next 50 years Nauset Beach extended further south reducing the tidal range and wave energy that reached the shoreline. In 1987 after the new inlet formation increased tidal range, wave energy and tidal currents erosion in many parts of the harbor was evident. These rates reflect the low energy period from 1938 to 1986 and the higher energy periods from 1868 to 1886 and 1987 to 2005. A more detailed study would be needed to document the processes responsible for shoreline change seen during these time periods.

Chatham Harbor-marshline

There are 0.78 miles (1.3 km) of marshline along the mainland shoreline of Chatham Harbor. A total of 56 transects out of 63, or 89.9% were erosional with a mean rate of 1.18 ft/yr (0.36m /yr). This would likely be related to the increase in tidal currents and wave energy resulting from the 1987 inlet formation.

The Islands

Islands-High Water Line
The total HWL shoreline in the islands shoreline section in Pleasant Bay is 10.9 miles (17.54 km). The six islands mapped include: Pochet (4.2 miles); Sampson (1.2 miles); Hog (1.1 miles); Sipson (0.7 miles); Strong (2.8 miles; and Tern (0.9 miles). Of the 875 transects, only 181 (20.6%) were outside the range of uncertainty, of those transects 155 (85.6%) were erosional. The mean erosion rate for those transects is 1.02 ft/yr (0.31m/yr).

Islands-marshline
The 6.3 miles (10.2 km) of marshline yields 512 transects, of which 59.4% are outside the range of uncertainty. More than 89% of those transects are accretional with a mean rate of accretion of 0.79 ft/yr (0.24m/yr). This coupled with the fact that the majority of the HWL transects are erosional would suggest that while landward migration of the HWL is occurring as a result of erosion or sea level rise, for example, the salt marsh is colonizing new areas associated with the islands. Again, however, more analysis would need to be undertaken to document the controlling factors.

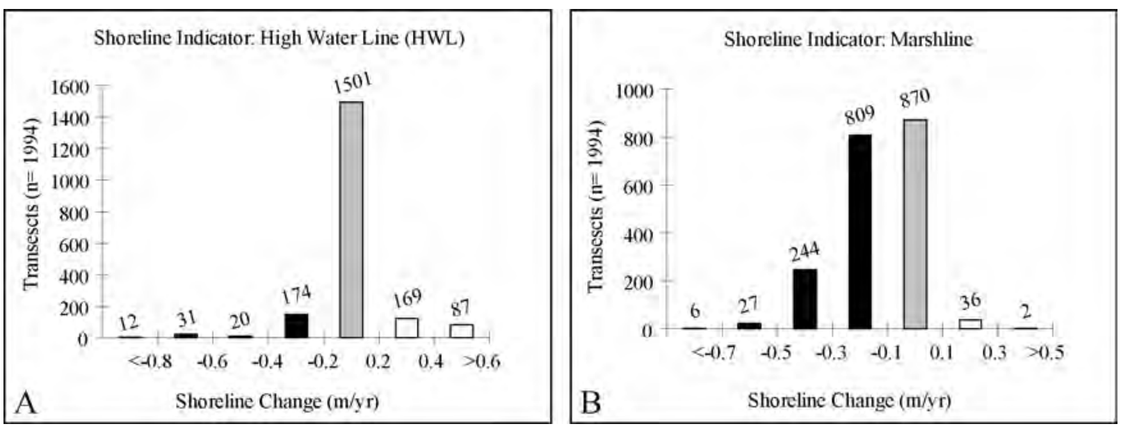

Figure 7. Comparison of shoreline change based on different shoreline indicators along the same stretches of low-energy bay shoreline. (A) HWL transects and (B) marshline transects. Black is erosional, white accretional and gray represents transects within the range of uncertainty

The High Water Line vs. the Marshline

The mainland lagoon shoreline is miles 45.5 miles (73.2 km) long, 24.8 miles (40.0 km) of which has extant fringing marsh. Over 14 miles (22.5 km) of marshline exhibited statistically significant change compared to 6.1 miles (9.8 km) of the HWL for the same segments of the shoreline (Figure 7). The change seen along these stretches of marshline illustrates an active coastal sedimentary environment not seen in the corresponding HWL proxy.

Assessing risk in these areas based on changes in the HWL may not be suitable. Along these stretches of shoreline the HWL has not moved significantly during the time period of this study but changes have occurred (Figure 8). The properties in figure 8 have seen a decrease in marsh vegetation that could have provided flood protection and storm damage prevention. Further, while the HWL has not migrated significantly these changes seen in the marshline may be indicative of future trends. Erosion seen along the 7.9 miles (12.7 km) of marsh shorelines with little or no change in the HWL indicates either marsh die-off and subsequent erosion of the substrate or forces working to erode healthy marsh vegetation and its substrate in situ.

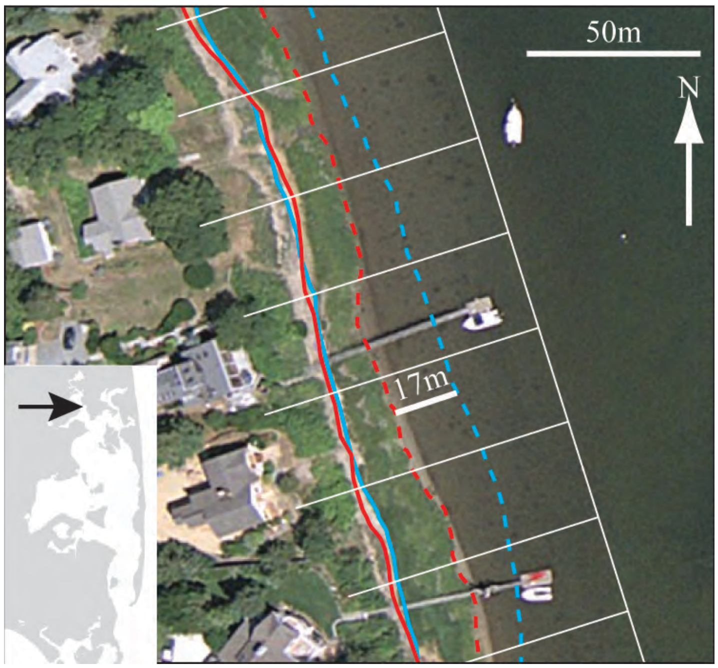

Figure 8. Changes in Marshline and HWL. Inset shows location within Pleasant Bay. The dashed lines are the marshlines (blue = 1938, red = 2005). The solid lines are the High Water Lines. The shore-perpendicular white lines are transects and the shore-parallel white line is a baseline generated by the software used to calculate rates of shoreline change (From Borrelli and Boothroyd (a) in prep).

CONCLUSIONS

Pleasant Bay and similar low energy coastal embayments do not exhibit significant rates of shoreline change using traditional shoreline indicators. However, the marshline, as outlined above, can provide managers and other stakeholders with critical information regarding changes to fringing salt marsh. In areas where both the marshline and the HWL could be delineated the former was shown to be superior for documenting change.

The marshline delineation was more objective, repeatable and reliable than the HWL delineation in Pleasant Bay. Thus, rates of shoreline change generated using the marshline are more scientifically defensible than those generated with the HWL. Physical processes related to shoreline change in salt marshes are not well understood and the marshline can be used to improve our understanding of coastal sediment transport in these low energy systems.

The marshline documented erosion, up to 55 ft (16.7 m) in some cases, along 8.0 miles (12.8 km) of shoreline in Pleasant Bay that was not detected using the HWL. More than 25 miles (40 km) of shoreline where both the HWL and the marshline were delineated were compared to one another. Less than 6.1 miles (9.8 km) of the HWL exhibited statistically significant shoreline change as compared to 14.0 miles (22.5 km) of the marshline for the same segments of the shoreline.

Changes not otherwise quantifiable using most proxy-based shoreline indicators can be generated using the marshline. Marsh vegetation below the HWL has implications for sediment transport, storm damage prevention and flood control. The marshline can be used to assess changes in salt marsh habitat related to surface area, fringing marsh thickness, shoreline orientation and marsh disappearance and appearance. In addition, the marshline has potential applications for water quality, predator-prey relationships, ecosystem health and other science and/or management issues. This technique may also have implications for inlet formation as inlets are less likely to form in backbarrier locations with extensive salt marsh.

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REFERENCES

Adam, P., 1990, Saltmarsh ecology, Cambridge, Cambridge University Press. p. 461.

Adams, M., Giese, G.S., 2008, Nauset Beach Breach and Inlet Formation, 2007-2008 Cape Cod, Chatham MA. Technical Report for the U.S. National Park Service. pp. 28.

Borrelli, M., 2008, Sediment transport in a dynamic, tidally-influenced coastal embayment exemplified by Pleasant Bay and Chatham Harbor, Cape Cod, Massachusetts. Unpub. Ph.D. Thesis, University of Rhode Island, RI, 154p.

Borrelli, M., and Boothroyd, J.C., *in preparation* (a), Calculating Rates of Shoreline Change along a Low-energy Coastal Embayment with Fringing Salt Marsh: The High Water Line vs. A New Proxy-based Shoreline Indicator.

Borrelli, M., and Boothroyd, J.C., *in preparation* (b), Effects of minor anthropogenic alterations in a highly energetic tidally-influenced system: New inlet formation and management practices adjacent to Cape Cod National Seashore, Massachusetts

Bosma, K.F., and Dalrymple, R.A., 1997. Beach Profile Analysis Along the Delaware Atlantic Coastline. University of Delaware, Center for Applied Coastal Research, Research Report No. CACR-97-05, 165 p.

Byrnes, M.R., M. Crowell, and C. Fowler., 2003, eds., Shoreline Mapping and Change Analysis: Technical Considerations and Management Implications. *Journal of Coastal Research*, Special Issue 38, pp. 1-4.

Crossett, K. M., Culliton, P.C., Wiley, T. R., and Goodspeed, B.L., 2004, Population trends along the coastal United States: 1980-2008, Coastal Trends Report Series. National Oceanic and Atmospheric Administration, National Ocean Service, Management and Budget Office, Special Projects. p. 86.

Crowell, M., and Leatherman, S.P., eds., 1999, Coastal erosion mapping and management: *Journal of Coastal Research*, Special Issue 28, 196 pp.

Crowell, M., Leatherman, S.P., Buckley, M.K., 1991, Historical shoreline change; Error analysis and mapping accuracy: *Journal of Coastal Research*, v. 7, p. 839-852.

Davis, W.M., 1896. The outline of Cape Cod. *Proceedings of the American Academy of Arts and Sciences.* 31, 303-332.

Dolan, R., Hayden, B., May, P., May, S., 1980. The reliability of shoreline change measurements from aerial photographs. *Shore and Beach***,** 48, p22-29.

Douglas, B.C., Crowell, M., and Leatherman, S. P., 1998. Considerations for shoreline position prediction. *Journal of Coastal Research*, 14(3), 1025–1033.

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

Everts, C.H., Battley, J.P., Gibson, P.N., 1983, Shoreline Movements: Cape Henry, Virginia, to Cape Hatteras, North Carolina, 1849-1980, Report 1.

Fisher, J. J., 1987. Shoreline development of the glacial Cape Cod coastline, *in* FitzGerald, D.M., and Rosen, P. S., eds., *Glaciated Coasts*: San Diego, Academic Press Incorporated, p 279-305.

Fletcher, C., Rooney, J., Barbee, M., and Lim, S., 2003. Mapping shoreline change using digital orthophotogrammetry on Maui, Hawaii. *Journal of Coastal Research*. Special Issue No. 38, 106–124.

Galgano, F. A. 1998, Geomorphic analysis of modes of shoreline behavior and the influence of tidal inlets on coastal configuration, U.S. East Coast [Ph.D. Thesis]: University of Maryland, 178 p.

Giese, G. S. 1978. The barrier beaches of Chatham, Massachusetts. Provincetown Center for Coastal Studies, Technical Report 78-21, p. 38.

Giese, G. S., 1988, Cyclical behavior of the tidal inlet at Nauset Beach, Chatham, Massachusetts, *in* Aubrey, D.G., and Weishar, L.L., eds., Hydrodynamics and sediment dynamics of tidal inlets: Berlin, Springer-Verlag, p. 269-283.

Hapke, C.J., and Reid, D., 2007, National Assessment of Shoreline Change, Part 4: Historical Coastal Cliff Retreat along the California Coast: *U.S. Geological Survey Open-file Report* 2007-1133.

Hapke, C.J., Reid, D., Richmond, B., Ruggiero, P. and List, J., 2006, National Assessment of Shoreline Change Part 3: Historical Shoreline Change and Associated Land Loss Along Sandy Shorelines of the California Coast, *U.S. Geological Survey. Open-file Report* 2006-1219.

Hammar-Klose E.S., Pendleton, E.A., Thieler, E.R, Williams, SJ., 2003, Coastal Vulnerability Assessment of Cape Cod National Seashore (CACO) to Sea-Level Rise, *U.S. Geological Survey, Open-file Report* 02-233.

Hayes, M.O., 1979, Barrier island morphology as a function of tidal and wave regime, in Leatherman, S.P., ed., *Barrier Islands: From the Gulf of St. Lawrence to the Gulf of Mexico*: New York, Academic Press, p. 1-27.

Honeycutt, M., Crowell, M., Douglas, B. 2001, Shoreline position forecasting: Impact of storms, rate-calculation methodologies, and temporal scales: *Journal of Coastal Research* v. 17, n3, p. 721–730.

Howes, B., Kelley, S.W., Ramsey, J.S., Samimy, R., Schlezinger, D., Eichner, E., 2006, Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for Pleasant Bay, Chatham, Massachusetts: Massachusetts Estuaries Project, Massachusetts Department of Environmental Protection. Boston, MA.

Jackson, J. A., 1997. Glossary of geology. American Geological Institute, 4th ed., Alexandria, VA, 769 pp.

Johnson, D.W., 1925, The New England-Acadian Shoreline: New York, John Wiley and Sons, p. 608.

Kennish, M.J., 2001, Coastal Salt Marsh Systems in the U.S.: A Review of Anthropogenic Impacts: *Journal of Coastal Research*, v. 17 no. 3, p. 731–748.

Leatherman, S.P., 1979, Overwash processes on Nauset Spit, *in* Leatherman, S.P., ed., *Environmental Geologic Guide to Cape Cod National Seashore*: Society of Economic Paleontologists and Mineralogists, Eastern Section p.171-192. Leatherman, S.P., 1983, Shoreline mapping: A comparison of techniques, Shore and Beach, v.51, p. 29-33.

Leatherman, S.P., 1983, Shoreline mapping: A comparison of techniques, *Shore and Beach*, v.51, p. 29-33.

Leatherman, S.P., 2003. Shoreline Change Mapping and Management along the U.S. East Coast. *Journal of Coastal Research*, Special Issue no. 38: 5-13.

McClennen, C. E., 1979, Nauset Spit: Model of cyclical breaching and spit regeneration during coastal retreat, *in* Leatherman, S. P., eds., Environmental Geologic Guide to Cape Cod National Seashore, p. 109-118.

Moore, L.J., 2000, Shoreline mapping techniques: *Journal of Coastal Research*, v. 16, p. 111-124.

Moore, L.J., Ruggerio, P., List, J., 2006, Quantifying Shoreline Change Using Mean High Water and High Water Line Shorelines: Should Proxy-Datum Offsets be Incorporated: *Journal of Coastal Research* v.22, n4, p. 894-905.

Morton, R.A., Miller T.L, and Moore, L.J., 2004, National Assessment of shoreline change: Part 1, Historical shore-line changes and associated coastal land loss along the U.S. Gulf of Mexico, U.S. Geological Survey Open File Report 2004-1043, 44 pp.

Morton, R. A., J. C. Bernier, J. A. Barras, and N. F. Ferina, 2005, Rapid subsidence and historical wetland loss in the Mississippi delta plain: Likely causes and future implications, *U.S. Geol. Surv. Open File Rep.*, 2005-1216, 116 pp.

Morton, R.A., Miller, T.L., 2005, National Assessment of shoreline Change: Part 2: Historical shoreline change and associated land loss along the U.S. South East Atlantic Coast: *U.S. Geological Survey Open-file Report* 2005-1401.

National Research Council. 2007, Mitigating Shore Erosion Along Sheltered Coasts: Washington, D.C., National Academies Press, p. 188.

Nordstrom, K.F., 1992, Estuarine Beaches: London, Elsevier Science Publishers, p. 225.

O'Connell, J.F, 1997, Historic Shoreline Change Mapping and Analysis Along the Massachusetts Shore, *Proceedings of the Tenth Symposium of Coastal and Ocean Management, Coastal Zone '97*, Boston, MA.

Oldale, R.N., 1982. Pleistocene stratigraphy of Nantucket, Martha's Vineyard, the Elizabeth Islands, and Cape Cod, Massachusetts, *in*: Larson, G.H., and Stone, B.D. (eds.), *Late Wisconsin Glaciation of New England*. Dubuque, Kendall/Hunt, p. 1-34.

Oldale R.N., and Barlow, R.A., 1986, Geologic map of Cape Cod and the islands: U.S. Geological Survey Miscellaneous Investigations Series Map I-1763, 1 sheet, scale 1:100,000.

Pajak, M. J., Leatherman, S., 2002, The high water line as shoreline indicator. *Journal of Coastal Research*. v18. p. 329–337.

Redfield, A.C., 1965, Ontogeny of a salt marsh estuary: Science, v. 147, p. 50–55.

Roman CT, Jaworski N, Short F.T,, Findlay S, Warren. S.R., 2000, Estuaries of the Northeastern United States: Habitat and Land Use Signatures. *Estuaries*: Vol. 23, No. 6. pp. 743–764.

Ruggiero, P., Kaminsky, G.M., and Gelfenbaum, G., 2003, Linking proxy-based and datum-based shorelines on a high-energy coastline: Implications for shoreline change analyses: *Journal of Coastal Research* Special Issue 38, p. 57-82.

Shalowitz, A.L., 1964. Shore and sea boundaries; Volume 2, Interpretation and use of coast and geodetic survey data: Publication 10-1, U.S. Dept. of Commerce, Coast and Geodetic Survey, 749 pp.

Smith, S., 2006. Draft report on salt marsh dieback on Cape Cod: United States National Park Service, Cape Cod National Seashore. 76 pp.

Smith, G.L., and Zarillo, G.A., 1990. Calculating long-term shoreline recession rates using aerial photographic and beach profiling techniques. *Journal of Coastal Research*, 6 (1), 111-120.

Stone, B. D., and Peper, J. D., 1982, Topographic control of the deglaciation of eastern Massachusetts: ice lobation and the marine incursion, *in*: Larson, G.H., and Stone, B.D. (eds.), *Late Wisconsin Glaciation of New England*. Dubuque,Kendall/Hunt, p. 145-166.

Thieler, E.R., O'Connell, J.F., and Schupp, C., 2001, The Massachusetts shoreline change project: 1800s - 1994 *Technical Report, United States Geological Survey*, Administrative Report, Woods Hole, Massachusetts. p. 39.

Thieler, E.R., Himmelstoss, E.A., Zichichi, J.L., and Miller, T.L., 2005, Digital Shoreline Analysis System (DSAS) version 3.0; An ArcGIS© extension for calculating shoreline change: *United States Geological Survey Open-File Report* 2005-1304.

Uchupi E, Giese G.S., Aubrey, D.G., Kim, D.J., 1996, The Late Quaternary construction of Cape Cod, Massachusetts: A reconsideration of the W. M. Davis model. Special Paper, V. 309, p. 69.

United States Army Corps of Engineers, 1971, National Shoreline Study: Shore Protection Guidelines. Department of the Army, Corps of Engineers, Washington, DC.

Zhang, K., Douglas, B.C., and Leatherman, S., 2002, Do storms cause long-term erosion along the U.S. east barrier coast? *Journal of Geology*, 110(4).