Sea Level Rise:

Assessment of Impacts on Nauset Barrier Beach and Pleasant Bay

This report was prepared for the Pleasant Bay Alliance

by the Center for Coastal Studies of Provincetown

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Preamble from Pleasant Bay Alliance

Pleasant Bay is a 9,000-acre estuary located in the Towns of Orleans, Chatham, Harwich and Brewster, Massachusetts. Due to its unique and extensive environmental values, the Bay and its surrounding shoreline and connected wetlands were designated by the Commonwealth as an Area of Critical Environmental Concern (ACEC). The four towns that share the ACEC and Pleasant Bay watershed collaborated in developing a resource management plan for those areas, and formed an inter-municipal organization, the Pleasant Bay Alliance, to oversee implementation of plan.

Pleasant Bay provides nursery areas and habitat for a wide variety of fish, shellfish and other aquatic animals that make up the food chain for sustainable fisheries. The expansive marshes, beaches and tidal flats of the inner shoreline and outer beach provide food and habitat for shorebirds, migratory waterfowl and other terrestrial animals. The vitality and diversity of these resources rely on the coastal processes of tides, wind, waves and erosion that transport sediment and tidal waters throughout the system. The coastal landforms themselves provide other ecosystem services by helping to filter pollutants from run-off, providing flood and storm damage prevention and, in the case of salt marsh, absorbing carbon and other toxins that otherwise contribute to global warming.

The management plan recognizes the vital role of natural coastal shoreline processes in a healthy estuary. The Alliance regularly monitors changes in the inner and outer shoreline through tide gage monitoring, aerial imagery, and periodic assessments of those and other data sources with historic trends. The management plan also identifies the need for an assessment of potential changes in the Nauset barrier beach system and the Pleasant Bay inner shoreline and intertidal zone due to sea level rise. The potential change in sea level, coupled with increased potential for storm surge, could have significant effects such as loss of coastal habitat and resources, increased coastal erosion, loss of recreational resources such as beaches and landings, loss of public and private property and infrastructure, salt-water intrusion into wells and septic systems, elevated storm surge levels, and more frequent coastal inundation.

As a first step, the Alliance commissioned this study to (1) estimate the likely range of sea level rise in the vicinity of the barrier beach and inner shoreline; and (2) identify and quantify and characterize potential changes in the Nauset Barrier Beach and inner shoreline and intertidal zone of Pleasant Bay resulting from estimated changes in sea level. This information will provide an important foundation on which to begin to assess potential impacts to resources and infrastructure, and then develop management strategies and policies to address the challenges associated with sea level rise.

By assessing the system's response to sea level rise, this study also examines the role of natural sediment transport processes in the protection of waterfront property and the preservation of coastal resources and the values they provide, including habitat, pollution attenuation, and coastal storm resiliency. Hardening of the shoreline, while intended to help stem the process of erosion, may actually worsen the problem.

1 Introduction & Executive Summary

This study assesses the impacts of sea level rise on coastal resources found on the inner shoreline of Pleasant Bay and the portion of the Nauset Barrier Beach fronting Pleasant Bay. As described in detail below, the study finds that the impacts to coastal resources resulting from sea level rise are considerable, but vary depending on the estimated range of sea level rise that is expected to occur.

Using established models and best available climate science data, three sea level rise scenarios (low, mid and high) were developed for this study. These are conservative estimates of projected sea level rise for Nauset Beach/Pleasant Bay and range from one to three feet over the next 100 years. This magnitude of sea level rise would increase tide levels in Pleasant Bay by 1.2 to 2.9 ft by 2100. Regional sea level is a critical factor in assessing the sustainability of our coastal resources. By comparison, regional sea level has risen approximately 1 ft over the past century, the highest rate of sea level rise in almost 3,000 years.

Under any projected sea level rise scenario outlined in this study, the barrier beach and inlet system will remain intact, but with a different configuration and rate of inlet formation and evolution than has been exhibited over the past 150 years. Low-lying barrier beach areas will experience more overwash (typically during storms) with sediment being deposited in the back-barrier (bayside) environment. This is a vital process that allows the barrier to keep pace with rising sea levels. Wider areas of the Nauset Beach would be expected to experience a loss of ocean-side beach and intertidal zones resulting in lower dune heights.

Pleasant Bay may lose a quarter to a half of its 392 acres of landside intertidal resource area through the end of the century under the low (1ft/century) and mid (2ft/century) level rise scenarios, respectively. Intertidal coastal resources provide a variety of ecosystem services, include storm attenuation, pollution filtration and habitat. Public access, and low-lying infrastructure and property also would be adversely affected under any sea level rise scenario. Under the highest scenario, coastal intertidal resources would increase due to inundation of current upland areas. Installation of Coastal Engineering Structures to prevent the inland retreat of intertidal resources, such as salt marsh and tidal flats would lower the elevation of an eroding beach by denying sediment input and reflecting wave energy which increases the rates of erosion along the front and downdrift areas adjacent to these structures.

The assessment of sea level rise impacts to the barrier beach/inlet system and landside intertidal resources of Pleasant Bay provides a foundation for further study of specific impacts to natural resources, public access and public and private infrastructure and, subsequently, development of management strategies.

2 Sea level Rise: The Nauset Barrier Beach & Pleasant Bay

This chapter examines the anticipated rate of sea level rise for the region encompassing Pleasant Bay and the Nauset Barrier Beach.

Regional sea level is a critical factor in assessing the sustainability of our coastal resources.

Regional sea level has risen approximately 1 foot over the past century, the highest rate of sea level rise in almost 3,000 years.

In 2013 the Intergovernmental Panel on Climate Change (IPCC) estimated a range of possible increases to regional sea level rise in New York City. This measure of regional sea level also applies throughout southern New England.

An intermediate estimate of regional sea level ranges from an increase of .01 ft per year to .03 ft/yr. This value can be used to estimate local sea level for the Nauset Beach/Pleasant Bay region by applying the regional sea level increase to local tide measurements. The resulting increase in tide in the Pleasant Bay/Nauset region is 1.2 to 2.9 ft by 2100.

Ocean thermal expansion and glacier melting, which are byproducts of increases in greenhouse gasses, account for the major part of sea level rise acceleration.

Past and Present Regional Sea Level Change

The water's edge is one of our planet's most dynamic environments. Tidal flats, beaches, marshes, bluffs and dunes are all finely tuned to the levels of the tides, and as sea level changes, so do these coastal habitats and landforms. Geological processes driven by waves, winds and tides contribute to coastal change, but sea level provides the stage upon which these processes play. For example, in discussing barrier island migration, Berman (2015) illustrates how landward movement of barrier beaches is ultimately a response to rising sea level, regardless of the more immediate mechanism of change such as tidal inlet formation or storm wave overwash. Thus, in setting out to assess the impacts due to sea level rise on the shoreline of Nauset Beach and Pleasant Bay, it is essential to establish—to the extent possible—the expected behavior of sea level in the region of New England and Pleasant Bay.

When we speak of regional sea level, it is important to remember that we are speaking of *relative* sea level, that is to say the level of the sea surface with respect to level of the local land surface. The land surface of southern New England is undergoing long-term subsidence, or sinking, so both subsideneand a rising sea surface contribute to what we refer to as "sea level rise" in the region.

Thanks to the availability of tide records, the regional sea level history in southern New England during the 20th century is fairly clear. The NOAA tide record for Boston (Figure 1), which extends back almost 100 years, indicates a sea level rise trend of 2.8 mm per year (equivalent to about 1 foot per century). A similar rate of rise is shown by the even longer record for New York City (Figure 2). However, these recent rates represent a decided departure from regional sea level change rates in the past. Geological studies in southern New England (Donnelly et al., 2004) indicate that for many centuries prior to the mid-19th century, regional sea levels rose at a significantly slower rate. A similar acceleration beginning in the 19th century has been noted in global sea level; a recent study by Kopp, et al. (2016) reports that 20th century global sea level rose faster than during any of the previous 27 centuries.

Past and Projected Global Sea Level Change

While sustainability of local coastal resources is tied directly to regional and localsea level, the processes responsible for our regional as well as global sea level acceleration are global in nature. These processes, largely resulting from anthropogenic global warming, are discussed in the most recent (fifth) assessment of global climate change published by the International Panel on Climate Change (IPCC, 2013). Results from numerical models— “process-based” models incorporating both natural processes and anthropogenic increases in greenhouse gasses and aerosols—indicate that ocean thermal expansion and glacier melting account for the major part of the observed sea level acceleration (Church, et al., 2013). The process-based models also have been applied to project future sea levels, both global sea levels and regional sea levels.

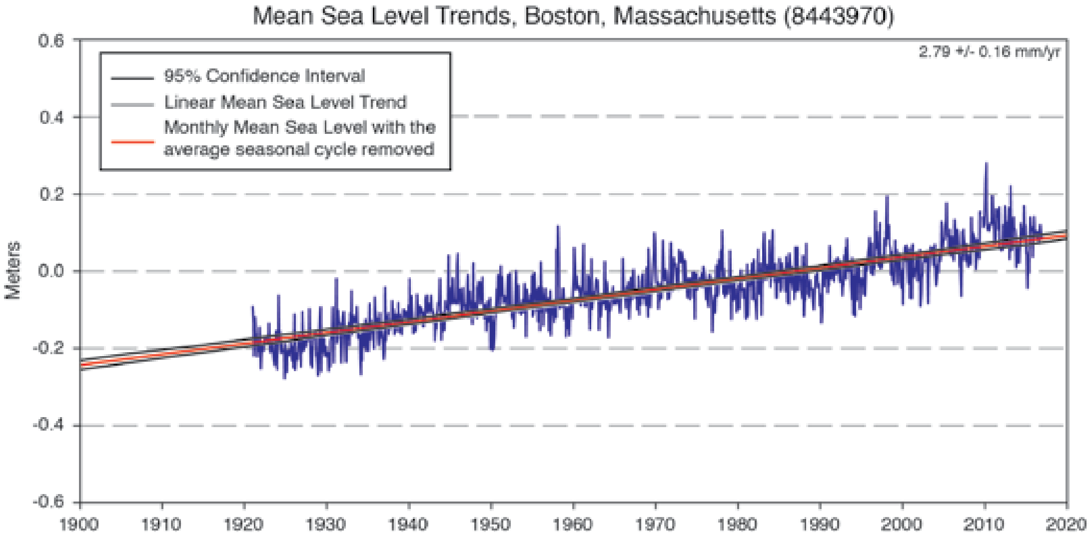

Figure 1. Monthly mean sea level at Boston (with the annual signal removed). The NOAA tide station data begin in 1921. The long-term mean sea level trend is 0.109 inches per year or 0.92 feet per century.

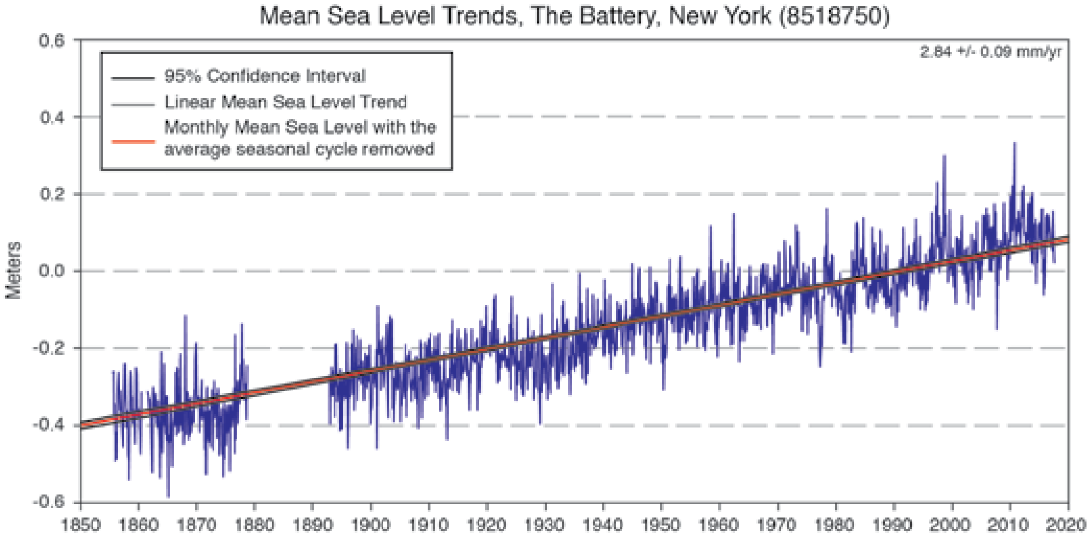

Figure 2. Monthly mean sea level at New York City (with the annual signal removed). The NOAA tide station data begin in 1856. The long-term mean sea level trend is 0.111 inches per year or 0.93 feet per century.

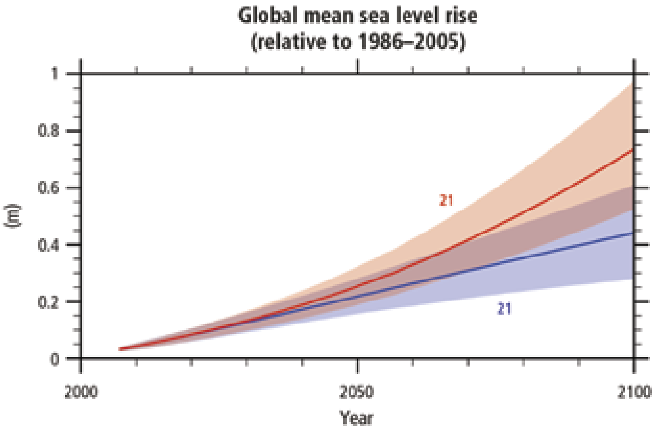

Figure 3. Projected global mean sea level rise over the 21st century from the IPCC fifth assessment of global climate change. Shaded areas show the likely ranges for the low input (blue) and high input (red) greenhouse gas emission pathways. The heavy blue and red lines indicate the median value of each range. Figure source: Church, et al., 2013.

The IPCC projections of 21st century global sea level change are shown in Figure 3 together with specific range estimates associated with two possible scenarios for greenhouse gas emissions inputs, referred to as "pathways". Only two of four scenarios, low and high, are shown. Since this figure represents a global average, it necessarily differs from the individual regional projections which reflect differing contributions due to regional climate modes, ocean dynamical processes, movements of the lithosphere, and changes in gravity due to water/ice mass redistribution (Church et al., 2013). [1]

Projected Regional Sea Level Change for the 21st Century

Benefiting from recent advancements, the fifth assessment of global climate change includes, for the first time, 21st century *regional* sea level change projections—projections have been made for nine representative coastal locations for which long tide records are available. One of those locations is New York City (NYC) and the IPCC projection for New York is shown in Figure 4. At the right hand margin of the figure are four colored vertical bars showing the range of NYC sea level projections for the year 2100 obtained from four groups of models, each using different input "pathways" for greenhouse gas emissions inputs. The projections for "low" input emissions are shown in dark blue, those for "low-intermediate" inputs in light blue, those for "high-intermediate" inputs in orange, and those for "high" inputs in red.

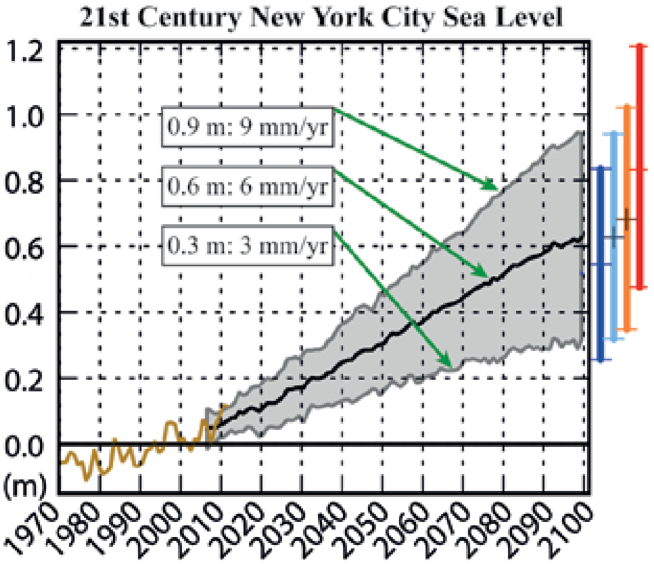

Figure 4. Observed and projected relative mean sea level change for New York City relative to MSL for 2000. Tide gauge record (since 1970) shown in brown. Shaded area indicates spread (5% to 95%) of results of 21 models using low-intermediate input "pathways." The black line shows the mean of the results. Vertical colored bars show 2100 MSL projections (5%, mean, 95%) of four groups of models with different input "pathways": low input (dark blue); low-intermediate input (light blue); high-intermediate input (orange); and high input (red). Figure adapted from Church, et al. (2013).

The grey, triangular shaded area in Figure 4 shows the spread of NYC sea level change projection results from the "low-intermediate" inputs group of models throughout the 21st century. The results of this group are reasonably similar to, and intermediate between, the results of the "low" inputs and "high-intermediate" inputs groups of models. The "high" inputs group results are not included because those projections result from the highest greenhouse gas emission pathways in the absence of climate change policies-such as those included in the Paris Climate Agreement of December, 2015. Figure 4 indicates a likely rise of regional sea level by 2100, relative to the 2000 level, from a low of about 1.0 ft (0.3 m) to a high of about 3.0 ft (0.9 m). The mean projected rise is approximately 2.0 ft (0.6 m).

Because the geophysical processes responsible for sea level changes for New York City are common to the entire southern New England/New York region, they will provide the basis for our assessment of impacts due to sea level rise on the Nauset Barrier Beach and inlet system (Task 2) and on the inner shoreline of Pleasant Bay (Task 3). Noting the linearity of the regional estimates in Figure 4, we annualize the IPCC results to project three 21st century sea level rise rates for the Pleasant Bay/Nauset Beach study area: a "low" rate of 0.01 ft/year (3 mm/year), a "mid" rate of 0.02 ft/year (6 mm/year), and a "high" rate of 0.03 ft/year (9 mm/year). The following table (Table 1) illustrates those rates applied to the contemporary (2015) annual

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[1] *It should be noted that these projected global sea level changes differ from, and are less extreme than, those presented in "Sea Level Rise: Understanding and Applying Trends and Future Scenarios for Analysis and Planning" (Massachusetts CZM, 2013). Drawing from contemporary technical information, including the then most recent (fourth) assessment of global climate change published by the International Panel on Climate Change (IPCC, 2007), that report presented projections of global and regional sea level change based on the most advanced research then available. Section 13.1.1 of the fifth assessment discusses the advancements since the fourth assessment that have led to revised projections such as those illustrated in Figure 3.*

mean sea level elevation at Chatham Fish Pier, 0.43 ft (0.13 m) **NAVD88**. It must be noted that while these *regional* sea level rise projections apply to the coastal waters of the southern New England/New York region, *local* sea level within individual systems such as bays and harbors will differ due to local circumstances and events. For example, tidal channel shoaling that elevates low tide levels, but not high tide levels, will result in local increased mean sea level.

Factors Influencing Estimates

Local sea level change in the Pleasant Bay area during the 21st century will be determined primarily by the rate of warming of the global climate system and by the rate of crustal subsidence. Crustal subsidence in our region results from a global process known as “glacial isostatic adjustment” (GIA), whereby our planet’s crust undergoes both uplift and subsidence in different regions as it adjusts to past glacial loading. The GIA contribution to southern New England sea level rise has been estimated to account for between 33–50% of the observed local mean sea level rise of 3mm/yr (e.g., Engelhart, 2010).

In contrast, the future contributions to regional sea level rise due to global warming will be affected by societal responses to the warming, and may well increase over the next few centuries (see, for example, Figure 3). Therefore, despite the linearity of the 21st century sea level change projections for the southern New England/ New York region indicated in Figure 4 and utilized for this study (e.g., Table 1), it is important to bear in mind that over extended time periods the contribution to regional sea level rise due to global warming is expected to increase, producing an increasing rate of regional sea level rise.

Regional sea level rise projections are influenced not only by uncertainties related to changes in global climate, but also to uncertainties related to regional geophysical responses to global climate change. For example, extensive collapse of ice shelves on the Antarctic Peninsula could lead to higher sea levels than presently projected. Closer to home, future changes in the distribution of global sea level rise throughout the oceans could affect regional sea levels, and regional changes in storm frequency and intensity could affect tidal inlets which, in turn, could affect sea levels as described above.

Estimated Mean Sea Level in Nauset Beach/Pleasant Bay under Low, Mid and High SLR Scenarios.

YEAR	LOW (3 mm/yr)	MID (6 mm/yr)	HIGH (9 mm/yr)
2040	0.20 m (0.7 ft)	0.28m (0.5 ft)	0.35m (1.1 ft)
2070	0.29 m (1.0 ft)	0.46m (1.5 ft)	0.62m (2.0 ft)
2100	0.38 m (1.2 ft)	0.64m (2.1 ft)	0.89m (2.9 ft)

Table1. Projected future annual mean sea levels (NAVD88) for the Nauset Beach/Pleasant Bay region for three representative years. Levels were calculated for three different rates of MSL rise (“low”, 3 mm/yr; “mid”, 6 mm/yr; “high”, 9 mm/yr) for the southern New England/New York region based on Church, et al. (2013) mean sea levelprojections for New York City. Local sea level within individual harbors and bays will differ from the regional, or “outside”, level (see text above).

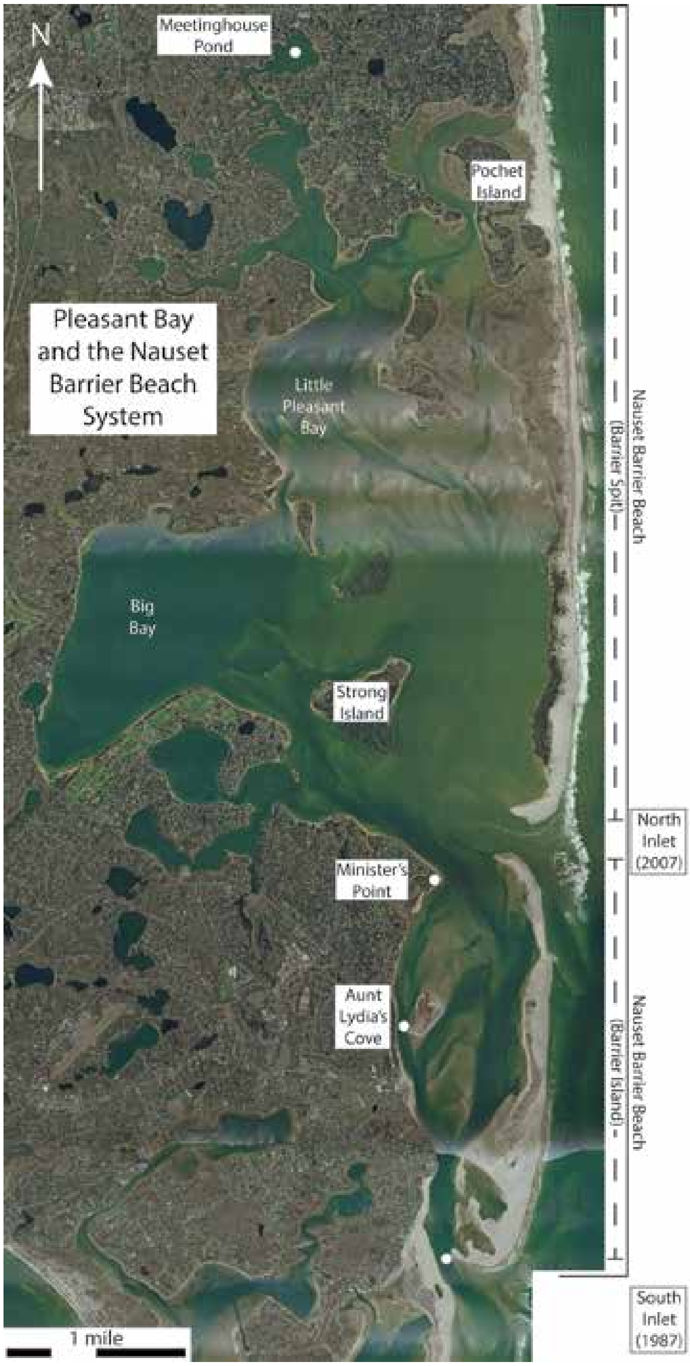


Figure 5. Pleasant Bay and the Nauset Barrier Beach System

3

Geomorphological Changes in the Barrier Beach & Inlet System

This chapter estimates changes in the Nauset Barrier Beach and Inlet system resulting from potential sea level rise scenarios.

Nauset Barrier Beach and Inlet system currently evolves through a 150-year cycle of a tide-dominated inlet development phase followed by a wave-dominated inlet migration phase.

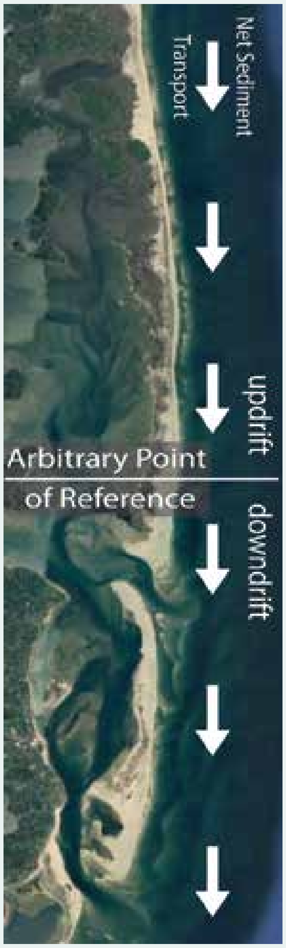
The 150-year cycle will remain intact under the current rate of sea level rise of 1 ft per century. However, if the rate of sea level rise increases, as anticipated, the 150-cycle will be shortened, and the barrier island will migrate, or move, toward the mainland (westward) more quickly.

Under any projected sea level rise scenario, the barrier beach and inlet system will remain intact, but with a different configuration. Low-lying barrier beach areas will experience more overwash with sediment being deposited in the back-barrier (bayside) environment. In wide areas, where some storm waves cannot completely washover the barrier into the bay, a loss of ocean-side beach and intertidal zones would likely occur along with a resultant lowering of dune heights.

Narrow, low-lying barriers slowly migrate landward as sediment is eroded from the ocean side shoreline, typically during storms, washes over the island and is deposited on the bayside shoreline. This is one of the ways barrier islands can keep pace with sea level rise.

Changes along the Nauset Barrier Beach System, particularly the open ocean shoreline, are driven by coastal processes (storms, winds, waves, tides, etc.) in conjunction with sea level rise. Estimates of future barrier beach configurations can be developed by quantitatively analyzing past cycles of tidal inlet development and evolution (Giese et al., 2009), projecting past and current three-dimensional barrier beach configurations into the future and coupling them with anticipated rates of sea level rise.

The Nauset Barrier Beach System is an interconnected configuration of **barrier islands** and **barrier spits** (Figure 5). Different forces are at work in shaping the portions of the barrier beach system **updrift** and **downdrift** (callout box 1) of the North Inlet formed in 2007. Sea level rise and coastal processes (storms, winds, waves, tides, etc.) are the main drivers of change along the barrier beach updrift of the North Inlet. Change along the barrier beach downdrift of the North Inlet is primarily caused by tidal inlet processes, with sea level rise playing a lesser role in the short-term. Tidal inlet processes are related to the semi-diurnal (twice daily) tides that move in and out of the tidal inlets in Pleasant Bay. Sand being carried along the open ocean shoreline either enters the inlet, bypasses the inlet and moves downdrift or is incorporated into a nearshore bar in and/or around the inlet. This sand is carried by waves and tidal currents and can have a significant influence on tidal inlet evolution.



Callout Box 1. Updrift and downdrift are similar to upriver and downriver. There is a direction of net movement of sediment along any stretch of shoreline for a given year, though sand can move as the wind and wave directions change. Along the Nauset Barrier beach that direction is from North to South.

The evolution of Nauset Beach has been documented as occurring in a 150-year cycle (Giese et al., 1988) as shown in Figure 6. Nauset Beach will lengthen as wave-transported material arrives from the north. As an inlet moves further south, the water's path from the open ocean to Pleasant Bay will become more circuitous and inefficient. Over time, given the right conditions a storm will open a new inlet and the cycle will repeat itself. Immediately after this point Pleasant Bar will have two inlets as it does at the time of this writing. If the rate of sea level rise seen during most of the 20th Century (~1 ft/century) continues, the 150-year cycle will remain relatively intact (Figure 78?).[2] An increase in the rate of sea level rise would be expected to alter the cycle of barrier beach and inlet development, as described below.

Based in part on analysis of historical cross sections of Nauset Beach done for the study area (Figure 8), relationships between the rate of sea level rise and barrier evolution were developed for the Nauset Barrier Beach System to estimate changes to the rate of landward migration of Nauset Barrier Beach and the inlet cycle time scale. Using the results of Figure 7 and those of the Massachusetts

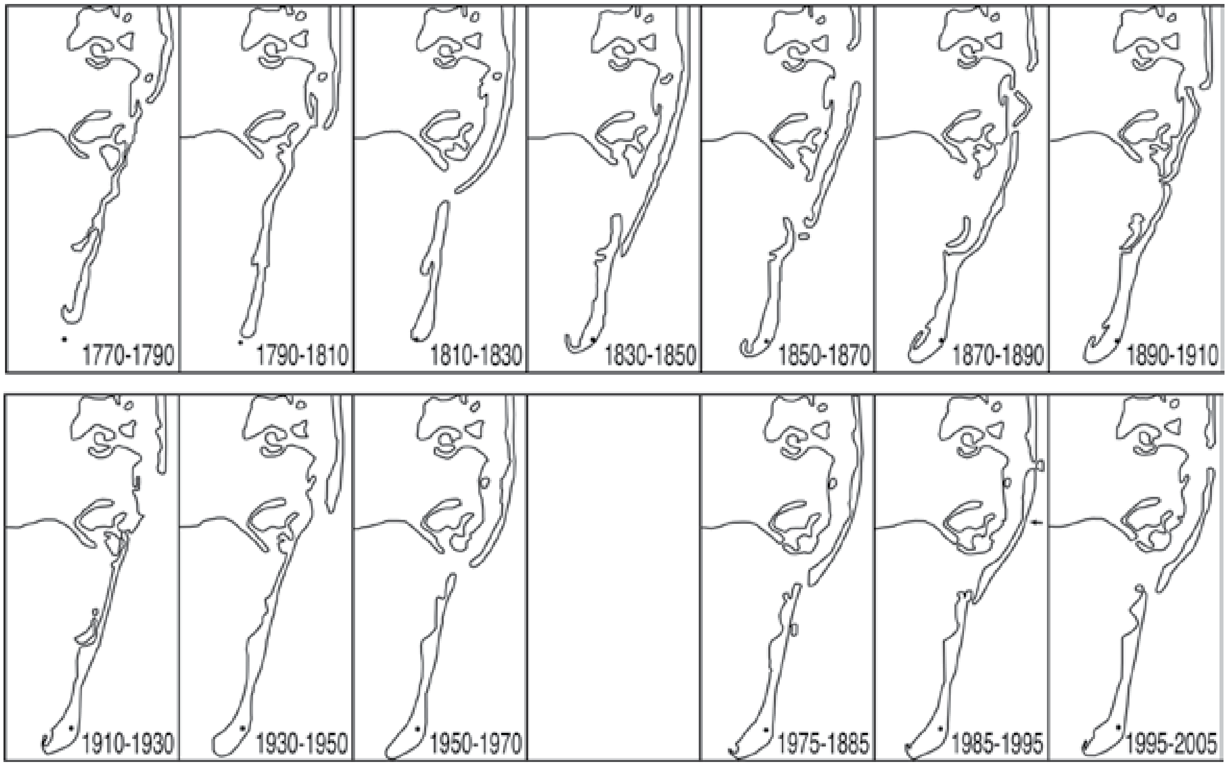


Figure 6. Historical changes in the Nauset Beach-Monomoy barrier system. From Giese, 1988. It is provided here to give historical context to the predictions of future shoreline positions.

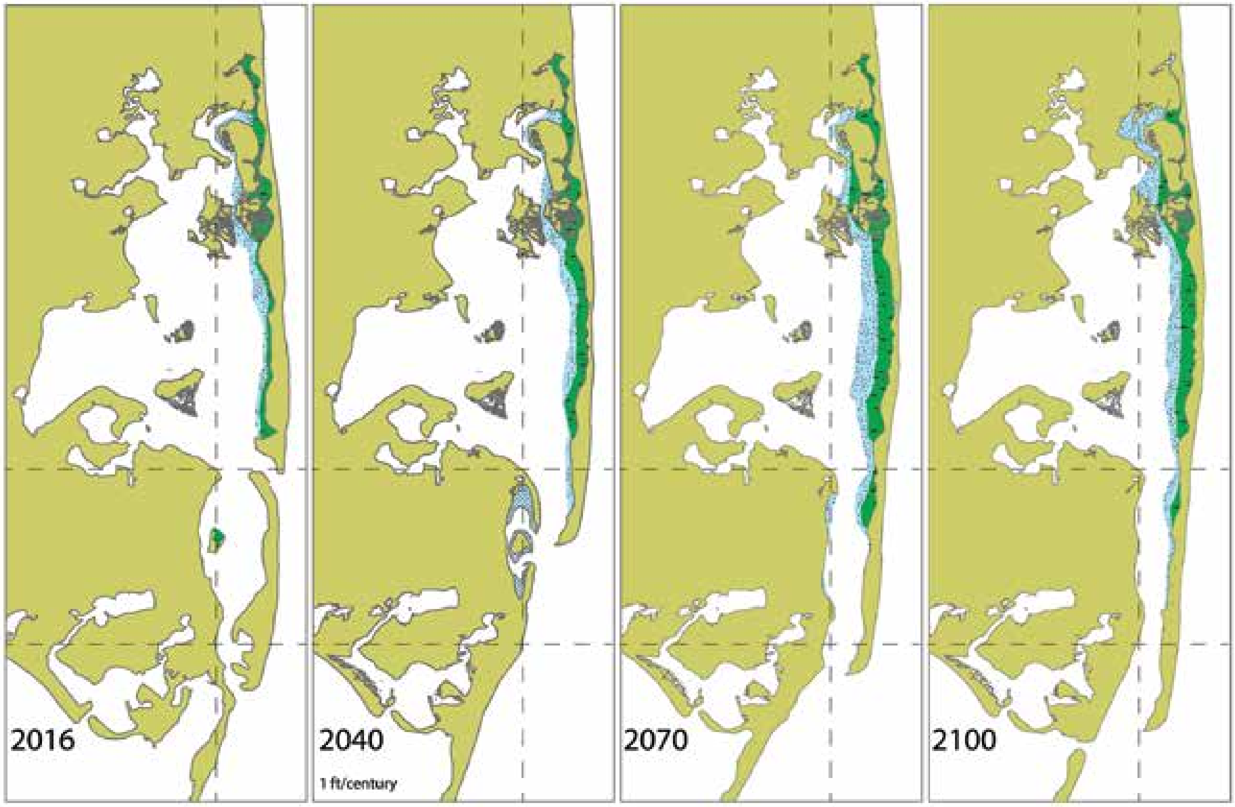


Figure 7. Time series for the 'low' sea level rise scenario (1 ft/century). The accretion around Minister's Point is basedon past shoreline configurations seen in this area (Giese, 1988) as well as anticipated changes to the tidal inlet. The material is largely removed by 2070 as the inlet migrates south less material is brought into the system and relatively consistent tidal currents will likely remove that material. This pattern is continued through 2100, though the Chatham Harbor area will likely start to see some deposition (shoaling) past 2100 due to the increasing inefficiency of the inlet as a result of increasing spit length. This figure is focused on the changes to the barrier, which is to the right of the vertical dashed line. Changes to the inner shoreline will likely occur, but are not represented here.

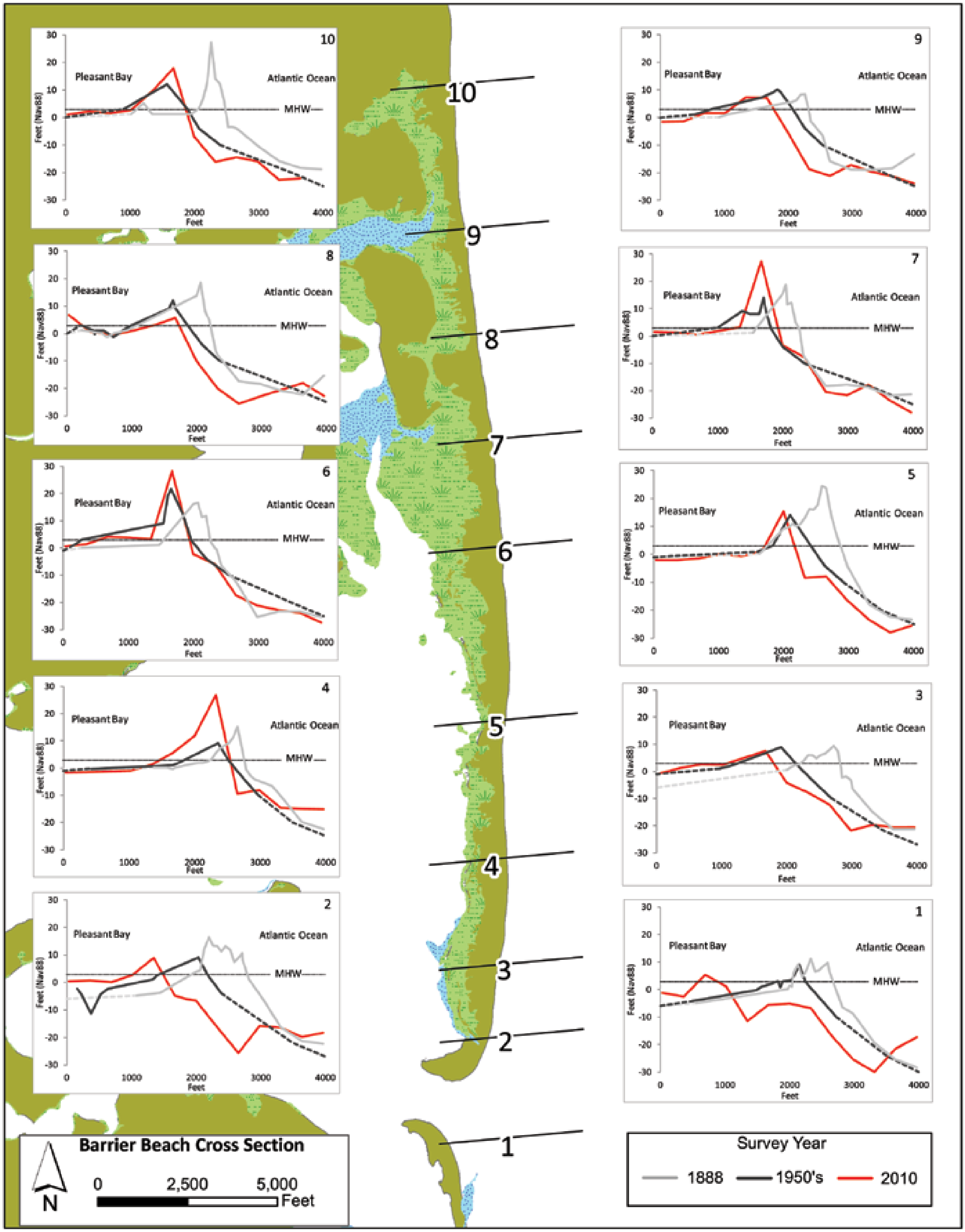


Figure 8. Barrier Beach Cross Sections. The above cross sections were taken from profiles collected in 1888 (Marindin, 1890), topographic and hydrographic surveys conducted in Pleasant Bay in the 1940-50s and the topographic/bathymetric lidar collected by the US Army Corps of Engineers in 2010. Dotted lines in profiles represent extrapolated data estimated by the authors.

Coastal Zone Management's (CZM) Shoreline Change Project, the long- term retreat rate for the barrier beach north of the inlet was determined to be approximately 4.5 feet/year (1.3 m/yr). Interestingly, in the later part of the 19th century Henry Mitchell, of the U.S. Coast Survey, determined that the southerly section of the barrier beach was then migrating west at a rate of approximately 4 feet/year (1.2 m/yr) (Marindin, 1890; Mitchell, 1871, 1873). Based on the above analysis, and assuming a simplified yet widely accepted linear relationship between coastal retreat and sea level rise, rates of 4.5 feet/year (1.3 m/yr), 9 feet/year (2.7 m/yr), and 13.5 feet/ year (4.1 m/yr) were calculated for the "low", "mid", and "high" scenarios developed in Task 1.

Recognizing that the time scale will be accelerated in response to sea level rise, the durationd of the inlet cycle was adjusted to reflect the "low", "mid", and "high" scenarios developed in Task 1. Although a linear relationship with sea level rise and coastal retreat was assumed above, a nonlinear relationship in which the time scale was adjusted by factors of 1, 2, and 3 was determined to best fit potential inlet cycle scenarios. Application of this relationship yields inlet cycle estimates of 150 years (the present or "low" scenario), 100 years (the "mid" scenario), and 75 years (the "high" scenario) (callout box 2), illustrating the shortened cycle of inlet evolution in the Nauset Barrier Beach System.

Figure 9 depicts a time series estimate of the "mid" sea level rise scenario where the rate of sea level rise is 2ft/century and the cycle shortens to approximately 100 years. North of the inlet(s) barrier widths will vary depending on pre-existing conditions, i.e. narrow, low-lying areas will experience more frequent overwash (assuming other variables remain unchanged) and more deposition in the backbarrier environment, which may help these areas keep pace with sea level rise for a period of time. Conversely, wider areas will have less beach (**intertidal** and **supra-tidal** areas) which will result in less wind-blown sand and lower dunes. Again, overwash can be expected; although this overwash will likely not be deposited on the backbarrier shoreline as it would be unlikely for the water

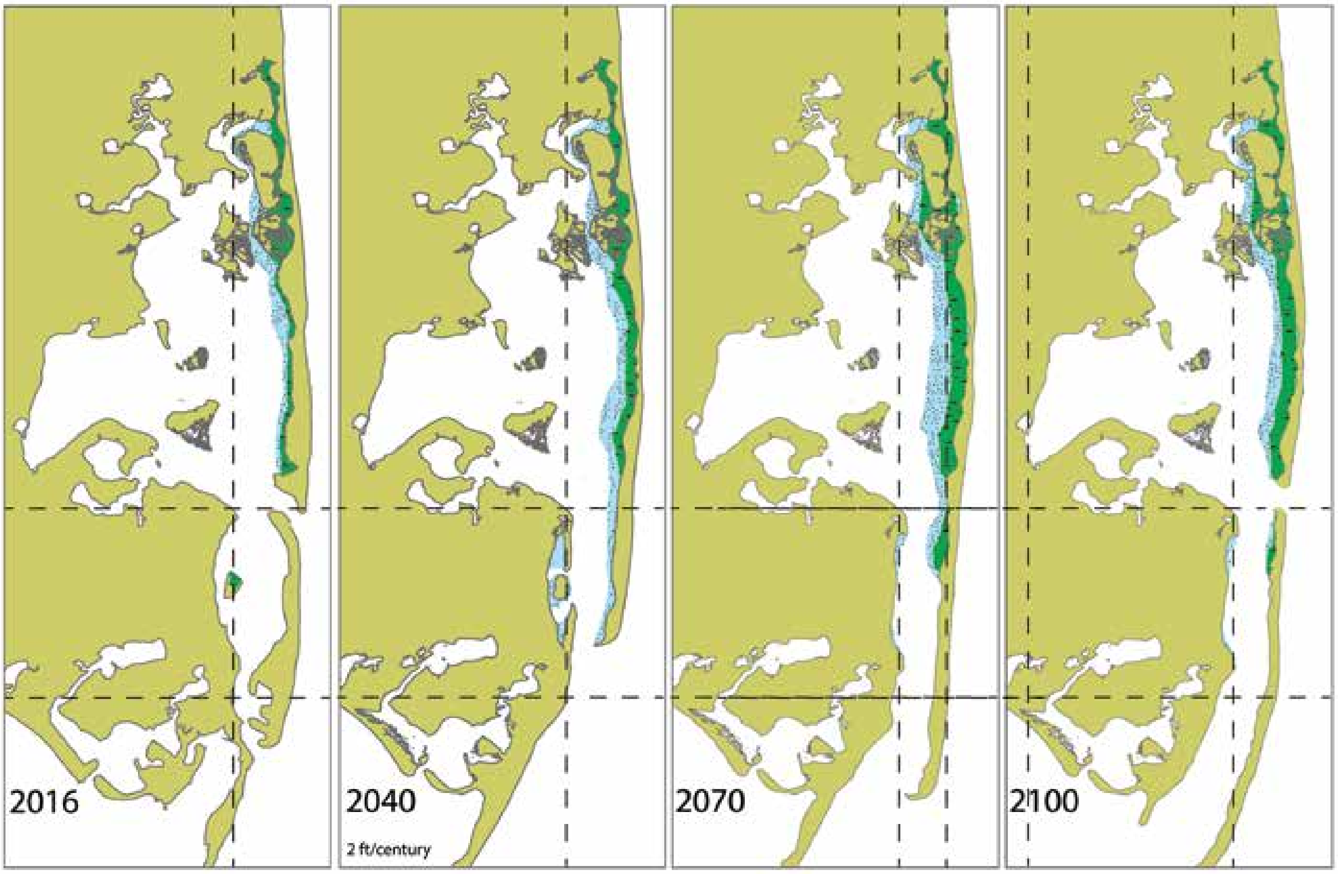


Figure 9. Time series for the 'mid' sea level rise scenario (2 ft/century). This figure is focused on the changes to the barrier shorleine, which is to the right of the vertical dashed line. Changes to the inner shoreline will likely occur, but are not represented here.

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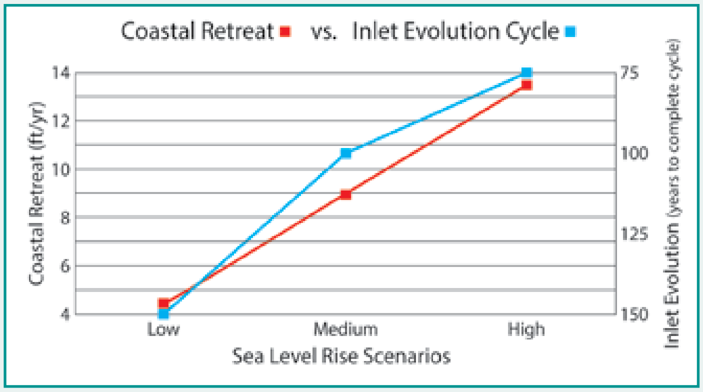
1 The cycle can be influenced by human-induced changes that alter the system. Such changes could include placement of erosion control structures, large-scale dredging and other alterations that may impact tidal currents or sediment transport. Any of these changes could alter the 150-year cycle in duration and inlet formation, migration, and evolution. Other changes such as storm frequency and intensity are important but outside the scope of this work.

Figure 10. Example of overwash events at Pochet Island. The white arrow is provided to reference change in washover fan through time. This is also one of the ways that barrier islands keep pace with sea level rise. When overwash occurs the island increases in elevation in that area.



Callout Box 2. Coastal retreat (linear) vs. Inlet Evolution Cycle (nonlinear).

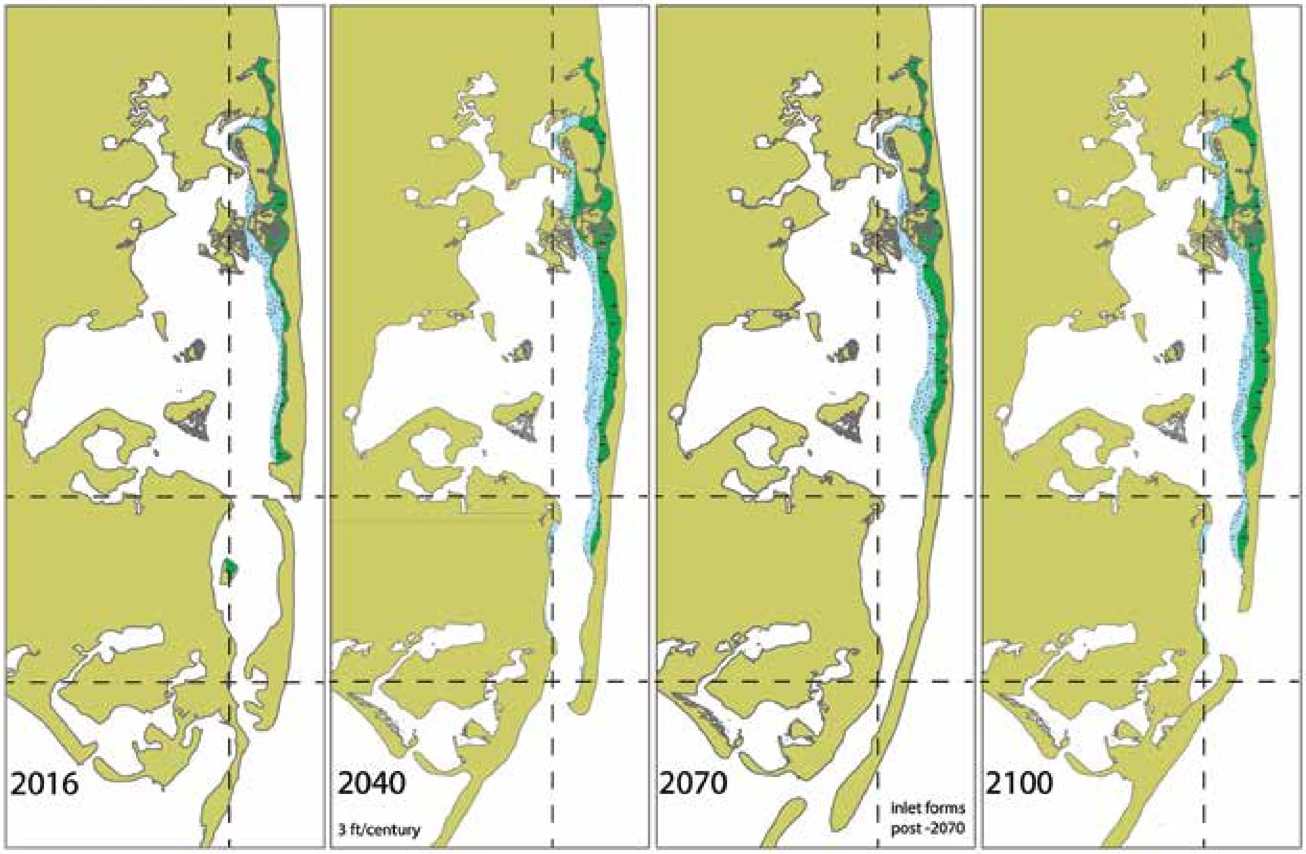


Figure 11 . Time series for the ‘high’ sea level rise scenario (3 ft/century). The longest extent of Nauset Spit occurs around 2070. Inlet formation near Minister’s Point will occur at some point in time between 2070 and 2100, likely closer to 2070 than 2100. This figure is focused on the changes to the barrier, which is to the right of the vertical dashed line. Changes to the inner shoreline will likely occur, but are not represented here.

to flow across a wide sandy area. In time this could result in the overall narrowing of barrier beach in these areas. The steepness of these areas is a critical factor when considering overwash, inundation and other processes and changes driven by flowing water.

This cycle of barrier islands narrowing followed by overwash during storm events and back barrier deposition and subsequent widening of the barrier is one way barrier islands keep pace with sea level rise and is commonly called “rollover” (Berman, 2015). This is actively occurring along the Nauset Barrier Beach System in places such as Pochet Island (Figure 10) and will prevent the islands and spits from ‘drowning in place’ or disappearing due to sea level rise. Increasing inundation has recently been shown to aid certain salt marshes along backbarrier shorelines in keeping pace with sea level rise provided there is sufficient sediment supply (Kirwan et al., 2016). It is likely with continued overwash much of the salt marsh along the backbarrier shoreline in the Nauset Barrier Beach System will keep pace with the rates of sea level rise discussed herein. Fringing salt marsh along the mainland shoreline however, will likely decrease as this salt marsh has little place to migrate due to development, infrastructure and shoreline hardening (Borrelli, 2009).

If the rate of the sea level rise accelerates to 3 ft/century the cycle will take approximately 75 years to complete (Figure 11). In this scenario it is possible that the 1987 southern inlet will close quickly, followed by rapid southern migration of the single 2007 inlet and a new inlet formation in approximately 2070. This would represent an increasing dynamic system and the uncertainty associated with future predictions on coastal evolution would in turn increase accordingly.

Understanding that both sea-level rise and the barrier beach geomorphology influence water levels within the Chatham Harbor/Pleasant Bay system, it was critical to assess the combined influence to provide the most accurate prediction of future water level conditions within the estuary. To accomplish this assessment, a previously developed model of flow characteristics within the Pleasant Bay estuarine complex (Howes, *et al*., 2006) was updated with the existing post-2007 breach information, as well as a future sea level rise predictions presented previously, where the estimated sea level rise of 1.2 feet (0.38 meters) was added to the 2007 offshore tide. This estimate was derived from the mid-range rate of 6 mm/year (~1/4 inch per year) determined for Pleasant Bay, based on IPCC (2013) projections for New York City. Figure 12 provides

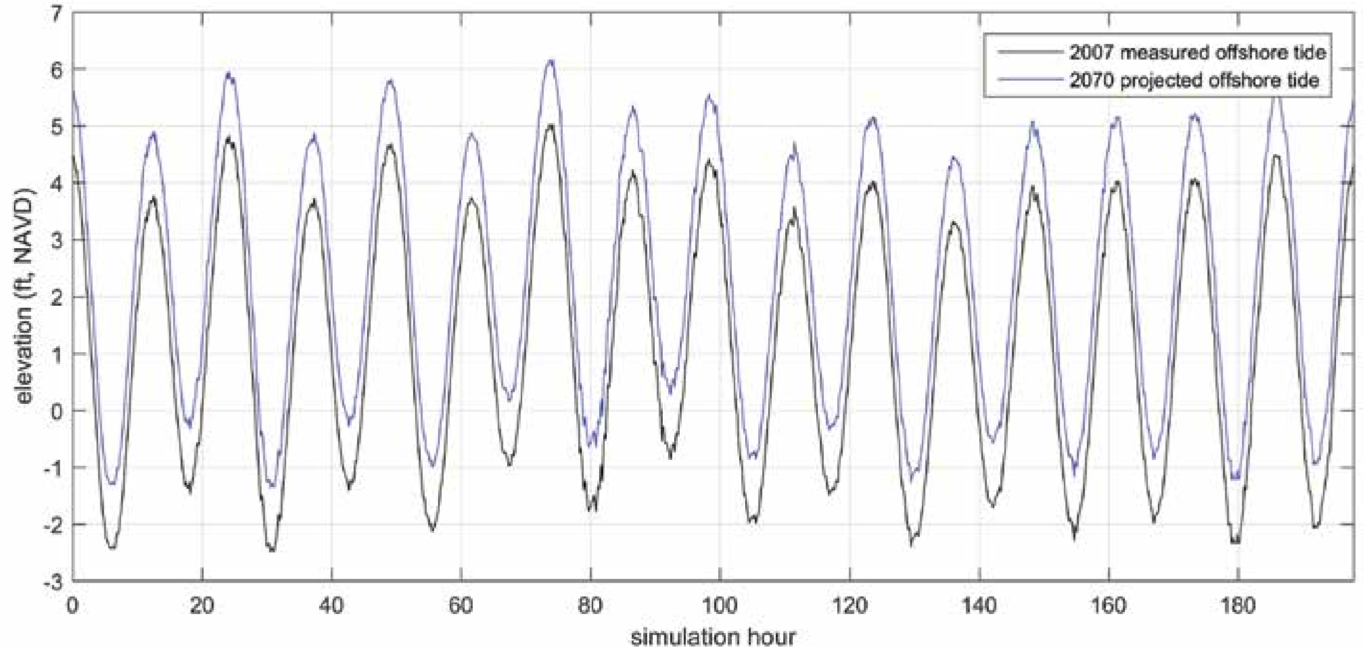


Figure 12. Comparison of measured 2007 tide from offshore of Pleasant Bay during the model simulation duration, and the projected 2070 tide, including the sea level rise estimate of 1.2 feet for the period between 2007 and 2070.

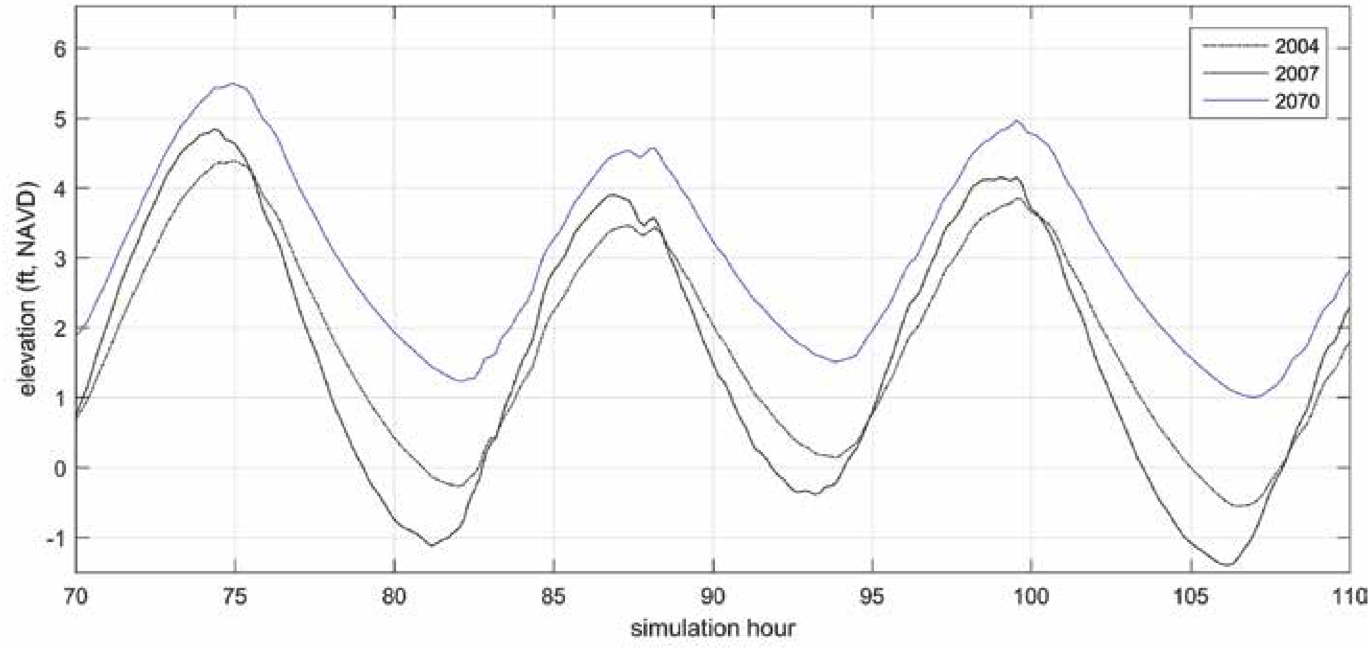


Figure 13. Comparison of tides at Chatham Harbor, for thee model scenarios, including 2004 pre-breach conditions, 2007 post-breach conditions, and estimated 2070 system morphology with projected SLR.

RESOURCE AREA	AREA (ACRES)	TOTAL PERCENT
Beach	71.3	18%
Salt Marsh	257.1	66%
Tidal Flat	63.9	16%
TOTAL	**392.3**	**100%**

Table 2. Wetland Resource Areas, Mainland Pleasant Bay

YEAR	LOW	% CHANGE	MED	% CHANGE	HIGH	%CHANGE
2016	392.3		392.3	392.3		
2040	323.1	-18%	362.7	-8%	345.3	-12%
2070	340.2	+5%	348.8	-4%	358.0	+4
2100	302.4	-9%	208.9	-40%	370.0	+3%
	Total	**-23%**		**-47%**		**+6%**

Table 3. Change in Acres of Intertidal Area under Low, Medium and High SLR Scenarios

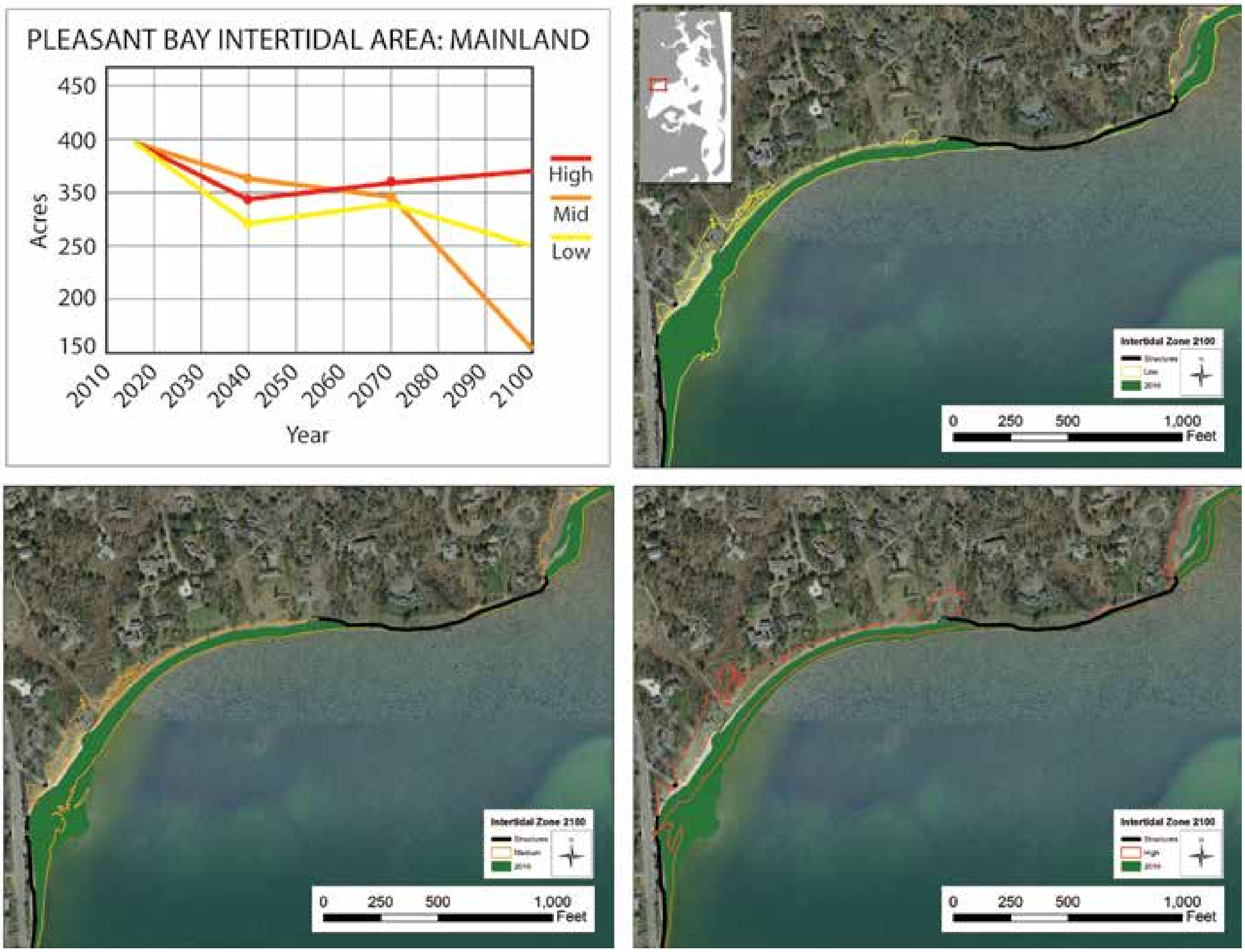


Figure 14. Impact of Coastal Structures. Upper Left: change in intertidal area along the mainland shoreline in Pleasant Bay by 2100. The present day intertidal zone (solid green) overlain by future estimated intertidal zones based on three sea level rise scenarios: Upper Right: Low scenario (Yellow). Lower Left: mid-scenario (Orange). Lower Right: high-scenario (Red). Coastal structures are highlighted in black. Note the relationship between the intertidal zone and the presence or absence of structures.

Callout Box 3. Approximate demarcation for this study of inner shoreline and barrier shoreline.

a plot of the estimated upward shift in offshore tidal elevations, assuming the anticipated increase in mean sea level.

To simulate the influence of both the different inlets (i.e. barrier beach geomorphology), as well as sea level rise on water elevations within the Pleasant Bay system, a series of model runs were performed based on (a) different inlet configurations, and (b) different offshore tidal elevations associated with future sea level rise. Model runs were made using the 2004 single inlet morphology, the 2007 post-breach multiple (2) inlet morphology following the creation of the North Inlet, and the projected 2070 single inlet system configuration including the anticipated 1.2 feet of additional sea level rise.

Figure 13 illustrates the modeled tide ranges for the three simulations. While the tidal range (the difference between high tide and low tide) for 2004 and 2070 is similar, both being single inlets systems, the increased high tide (and low tide) elevation is due to the increase in sea level (Figure 12). As shown in Figure 13, the tide range with the multiple inlet system (2007) is between 1.2 and 1.6 feet greater than with the single inlet system in 2004 and 2070, respectively. In addition, this recent multiple inlet system is responsible for the approximate 0.5 foot increase in Mean High Water elevation within Chatham Harbor after the opening of the 2007 inlet. This recent increase in tide range also corresponds to improved tidal flushing within the Pleasant Bay system. Due to the projected location of the inlet in 2070, it is anticipated that the tide range will be significantly

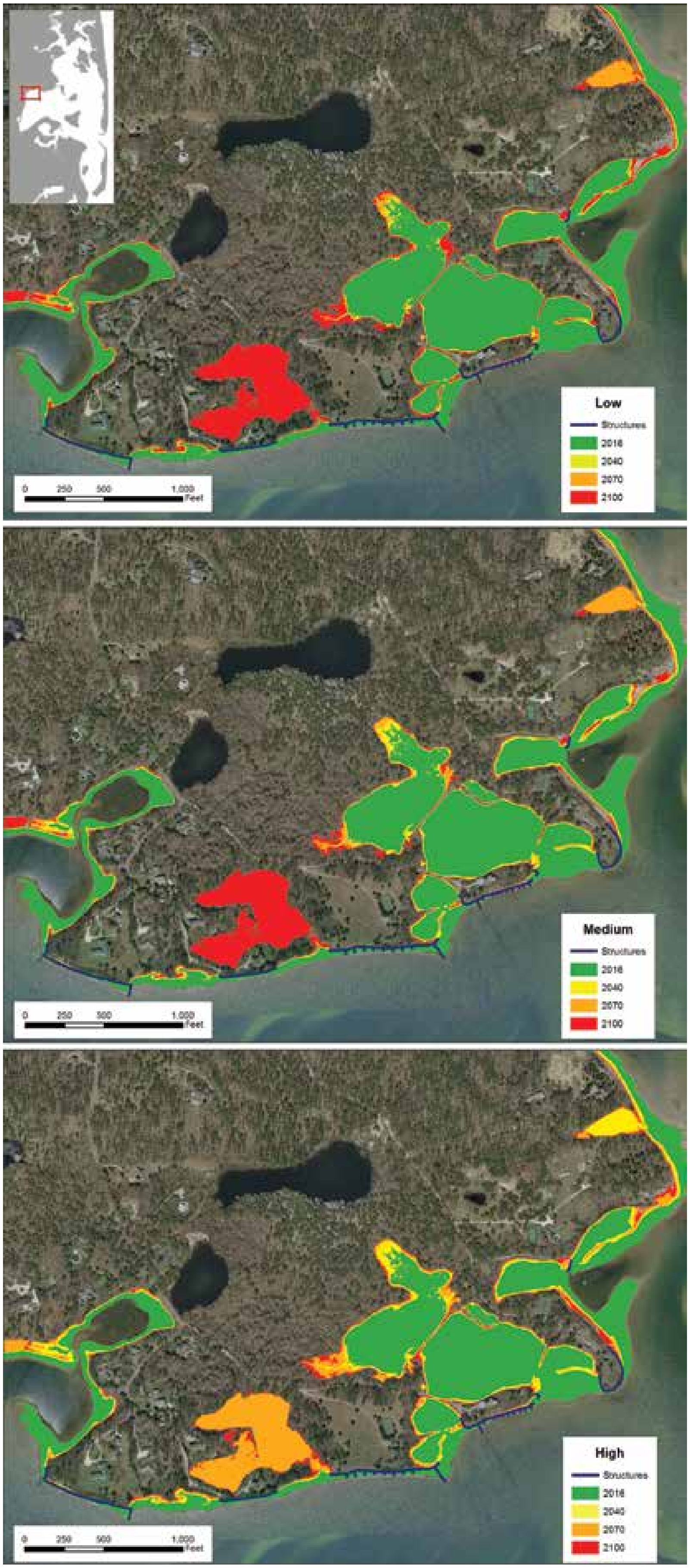


Figure 15. Example of changes to intertidal areas in subset of Pleasant Bay based on different sea level rise scenarios

reduced from the existing multiple inlet system and is already showing a decreasing trend as measured by tide range data (Legare and Giese, 2016). Mean High Water can be anticipated to be approximately 0.7 feet higher in Chatham Harbor than it was in 2007. It should be noted that this increase in local Mean High Water is only about 60% of the increase in projected offshore sea levels by 2070.

The formation of new tidal inlets in Pleasant Bay is dependent on many factors. Perhaps most important are suitable topographic and bathymetric conditions necessary for initial formation and subsequent maintenance by natural processes. For example, an inlet would not be able to form near Pochet Island because a suitable basin of water of sufficient depth and/or volume in close proximity to the backbarrier shoreline does not exist. Typically, when a new inlet forms storm waves overwash a barrier making a connection between the ocean and bay. This happens occasionally at Pochet Island as can be seen by the frequent overwash fans there (Figure 10). However, for an inlet to stay open, water from the Bay needs to flow back to the ocean and the water in this area is not deep enough to sustain substantial "bay-to-ocean" flow. In fact, one of the reasons inlets form just north of Minister's Points is due to the deeper waters in the areas to the east and south of Strong Island.

The natural movement of sand, erosion and accretion, is part of a cycle needed to sustain this system. With regard to the natural resources in Pleasant Bay, erosion (and accretion) is a natural phenomenon that is part of the sediment transport process which is vital to the ability of the system to evolve and keep pace with sea level rise. Erosion in one area leads to accretion, and preservation or creation of important coastal resources, in another. Toward that end, the policy of Cape Cod National Seashore is to allow the natural process of erosion to take place within park boundaries. The sediment that erodes from the coastal bluffs and beaches to the north of the Nauset Barrier Beach system is within park boundaries and will help maintain the Nauset barrier fronting Pleasant Bay up to and past 2100. If the erosion that takes place north of the Nauset Barrier Beach system were prevented, the width and elevation of the barrier would rapidly decrease and its persistence into the near future would be in question. Even preventing seemingly small amounts of erosion along the bluffs within the Bay itself can have substantial negative impacts when viewed cumulatively.

Figure 16: Stone revetment along the Pleasant Bay shoreline illustrating the loss of fronting beach, as passive erosion continues beyond the limits of the structure.

4

Future Geomorphological Changes to Intertidal Coastal Resources in Pleasant Bay

This section estimates the effects of sea level rise on the landside intertidal resource areas of Pleasant Bay.

Pleasant Bay today has approximately 392 acres of intertidal coastal resources that provide a variety of **ecosystem services**.

Pleasant Bay may lose a quarter to a half of its intertidal resource areas through the end of the century under the low and medium sea level rise scenarios, respectively. The loss of intertidal areas is exacerbated by the presence of Coastal Engineering Structures which prevent the inland retreat of intertidal resources, such as salt marsh and tidal flats. Public access, and low-lying infrastructure and property also would likely be adversely affected.

Under the high sea level rise scenario, and assuming nothing is done to prevent inundation, the amount of intertidal area increases 6% by 2100. This scenario does not depict the preservation of existing intertidal areas, but rather represents the inundation of upland areas previously not within the intertidal zone.

The changes anticipated in Pleasant Bay along the intertidal areas on the inner shoreline (callout box 3) as a result of sea level rise can be illustrated by examining the evolution of the intertidal zone through time. Here the intertidal zone is defined as the area between **Mean Low Water** and Mean High Water.

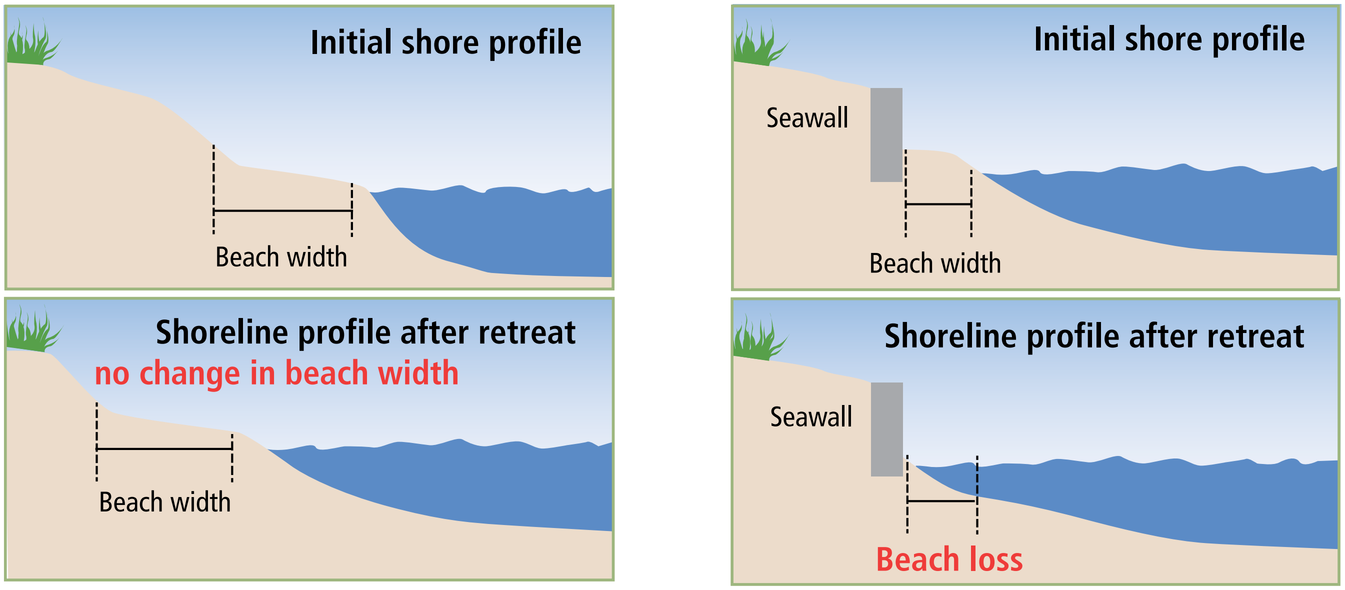
The intertidal zone contains significant coastal resources such as salt marsh and intertidal flats that provide critical ecosystem services. These services include storm damage prevention, flood protection, shellfish habitat, and juvenile finfish refuge and nursery. These areas are vital habitat and feeding areas for many species of vertebrate and invertebrate animals ranging from shellfish to finfish and crabs to birds. Birds in particular, both local and migratory, use these areas to feed, nurse and nest. Salt marsh and eelgrass are critical areas for predator avoidance, nurseries, as well as locking in sediment with root matter to reduce erosion and attenuate (dampen) wave energy. Salt marsh and eelgrass and other vegetation can sequester toxins and also carbon that could otherwise contribute to global CO^2 levels further increasing global warming. To a lesser degree unvegetated intertidal flats themselves dampen wave energy that would reach the shore thereby reducing coastal erosion.

Three sea level rise scenarios have been developed for Pleasant Bay based on both global and regional sea level rise projections. These three sea level rise scenarios (low, medium and high) were then used to develop three snapshots of the mainland shoreline within Pleasant Bay in 2040, 2070 and 2100. First, the extent of the 2016 intertidal zone was documented based on data from the Chatham tide gauge data and recent and ongoing tidal studies commissioned by the Pleasant Bay Alliance (Giese, 2012; Giese and Kennedy, 2015). These data were used to develop an elevation for MHW and MLW and the area between these elevations were extracted from existing elevation data and represented spatially within a GIS environment. The existing data layers for wetlands resources for Pleasant Bay were downloaded from the MassGIS website and were overlain onto the present day intertidal zone. Resources in the intertidal zone were extracted based on general wetland category (Table 2). The intertidal zone for 2016 was then altered to reflect changes to the MHW and MLW based on the three sea level rise scenarios developed for this study. The projected changes represent the intertidal zone as a whole. Changes to distinct resource types (such as beach, flats, salt marsh) in the intertidal zone could not be determined due to the uncertainty associated with how these resource types would respond to not only increases in water levels, but also the variable natural processes and human alterations that would occur. However, the changes to the intertidal zone in total were documented in several ways.

First, a three-dimensional data layer based on the 2016 intertidal zone was used to map the extent of the intertidal zone based on the present day topography of Pleasant Bay and the 3 sea level rise scenarios for 2040, 2070 and 2100. Tabular data on four time periods were calculated: 2016, 2040, 2070 based on the above-mentioned GIS data layers (Table 3). Interestingly, the changes in intertidal zone along the mainland of Pleasant Bay vary considerably (Figure 14), particularly from 2070 to 2100. For instance, in the "low" scenario the intertidal zone decreases by 18% in area from 2016 – 2040, but increases 5% from 2040 – 2070, while finally decreasing 9% from 2070 to 2100. The overall loss for the "low" scenario is 23% from 2016 – 2100.

The "mid" scenario sees the highest overall decrease in intertidal zone from 2016 to 2100. The intertidal zone decreases for all time periods for the "mid" scenario: 8% from 2016 – 2040, 4% from 2040 – 2070, and 40% from 2070 to 2100. The "mid" scenario is the only scenario where there is a steady decline in intertidal area.

The intertidal zone in the "high" scenario decreases by 12% in area from 2016 – 2040, but increases 4% to acres from 2040 – 2070, and increases a further 3% from 2070 to 2100. The change from 2016 to 2100 for the "high" scenario is an increase of 6% in intertidal area. This is due to increasing inundation of areas heretofore not reached by tidal waters (Figure 15). None of the scenarios assume any alteration to the shoreline and/or inundation prevention actions. It is likely that human intervention to prevent future flooding of existing low lying upland areas



Beaches on chronically eroding shores can maintain their natural width as they slowly retreat landward.

Beach loss eventually occurs in front of a seawall where there is chronic erosion.

Figure 17. Chronic beach erosion on unhardened shores (left) and with seawalls in place (right) (image credit: U.S. Army Corps of Engineers).

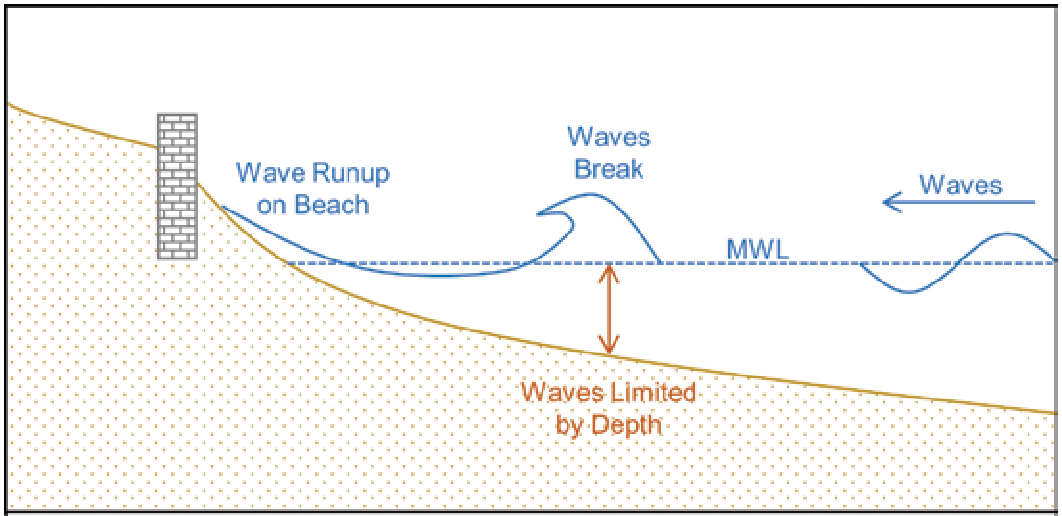
may alter (lower) the predicted increase in intertidal areas under the high sea level rise scenario.

Coastal Engineering Structures and Pleasant Bay

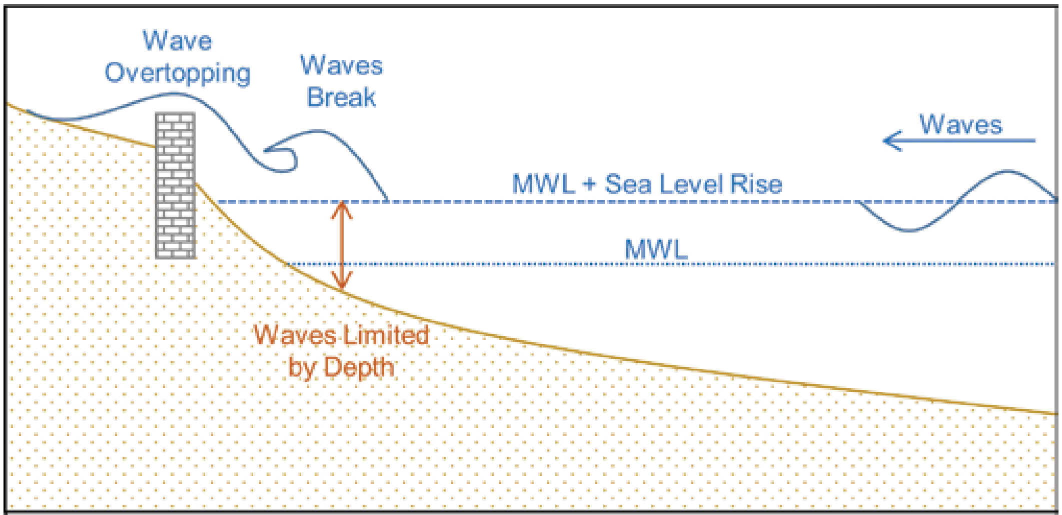
A natural shoreline undergoing long-term erosion in response to a sediment deficit and/or sea-level rise will exhibit landward migration of the high water line. This natural **passive erosion** process can be exacerbated by the introduction of shoreline armoring (e.g. revetments and/or seawalls), where the structure may prohibit material from eroding from the upland, thereby increasing the sediment deficit to both downdrift and fronting beaches. In addition, if a revetment or seawall is constructed to halt erosion, the shoreline becomes essentially fixed at that location as sea level rises. As sea level rises, adjacent natural landforms (e.g. beaches, dunes, and coastal banks) will continue to erode and retreat landward; therefore, the coastal armoring creates an artificial headland. In these cases, the typical effect is loss of beach and/or salt marsh fronting the coastal armoring structure (see Figure 16 for an example) as well as accelerating erosion along adjacent shorelines due to wave focusing and sediment loss. Many other types of structures and/or alternatives exist when addressing coastal erosion, with differing levels of impact and permanence (Berman, 2015).

Historically, stone revetments have been the primary form of shore protection in Pleasant Bay. Stone revetments can provide increased wave dissipation, reduced wave overtopping, and increased storm protection. This storm protection is not permanent because seawalls, and to a lesser extent revetments, can cause accelerated lowering of the fronting beach over time, which will eventually destabilize these structures. This lowering of the beach is caused by a lack of sediment input and increased wave reflection of the vertical or steeply sloping face of the structure relative to the natural beach. A lower beach elevation results in waves breaking closer to the shoreline with increased overtopping potential. Seawalls and revetments only protect the land directly behind them. Figure 17 shows that if there is no shore armoring in place, the eroding beach will move landward to maintain the width of the beach. With a seawall or revetment in place, the fronting beach becomes narrower with continued erosion, as the beach cannot migrate landward due to the presence of the seawall.

During normal wave and tide conditions, the waves may run-up on the narrow fronting beach. However, as shown in Figure 18, the waves break further inland during higher water elevations that could be caused by episodic storms conditions and/or the influence of sea-level rise. Without sufficient beach width to dissipate the wave energy, the waves will tend to overtop the seawall or revetment and cause lowering of the fronting beach. This beach lowering is due to the magnified erosion/scour force of the waves as they reflect from the structure, and to the deficiency of bank sediment protected by the wall that otherwise could help replenish the fronting beach (Silvester and Hsu, 1993).



Waves break further from shore and dissipate over the beach.



Waves break closer to shore and have less room to dissipate, resulting in waves overtopping the seawall, beach lowering and inland damage.

Figure 18: A schematic diagram showing the influence of increased water levels and structure interaction with the natural wave environment.

Along an eroding shoreline, a seawall or revetment may accelerate the erosion rates of adjacent beaches (USACE, 1984). Erosion in the form of scour along the entire length of the structure including the ends or edges may threaten the structure itself as erosion continues. While the designed revetment may provide storm protection to adjacent upland, the lack of high tide beach and low sediment supply along much of the Pleasant Bay shoreline will likely lower the profile in front of the revetment, eventually causing stones to slump and loosen. Therefore, revetments do not represent a permanent shore protection solution in these environments, as they generally require regular maintenance and repairs to maintain their effectiveness. Long-term erosion can often lead to catastrophic failure of the structure. Structural failure typically will occur during a significant storm surge event and can be exacerbated if the structure and/or beach are not maintained. Unlike most "soft" shore protection measures, revetments often do not exhibit signs of structural inadequacy, which can lead to a "false sense of security" for property owners in areas fronted by these "hard" shore protection measures.

Specific to Pleasant Bay, recent geomorphic changes to the multiple inlet system appear to indicate that both the high tide elevation and the tide range are decreasing subsequent to the formation of the 2007 over the past few years (Legare and Giese, 2016). While the formation of both the 1987 and 2007 breaches through the Nauset Barrier Beach system initially led to significant shoreline erosion pressures due to increased tide range, and wave exposure in some cases, much of this influence has begun to moderate. It appears that the continuation of the long-term Nauset Beach growth cycle will lead to a decreased tide range and the associated return to a more stable inland shoreline in the coming years. However, this process will be gradual and occur over a period of decades. Significant nor'easters will continue to create erosion pressures that likely will need to be evaluated on a site-by-site basis. In the short-term (i.e. the next 20-to-30 years), the influence of the Nauset Barrier Beach system on water levels in Pleasant Bay will likely be more significant than the influence of long-term relative sea-level rise. Overall, the recent tide data within the Pleasant Bay and Chatham Harbor system, as well as future predictions of the geomorphic migration of the fronting barrier beach system, support the hypothesis of continued future reduction in Pleasant Bay high tide elevations. These reductions in tide elevations, along with westward movement of barrier beach sediment leading to possible inner shoreline beach accretion along some sections of the mainland, likely will significantly reduce or perhaps eliminate the need for more large-scale armoring of the estuarine shoreline.

Areas in proximity to coastal engineering structures, particularly those structures designed to prevent erosion behind them are most impacted by sea level rise. Consequently, the intertidal areas fronting those structures are among the most vulnerable to increases in sea level. Coastal engineering structures prevent these areas from migrating landward and keeping pace with sea level rise. Ironically, the more effective these structures are at preventing erosion, the greater the adverse effects from an ecosystem perspective. Erosion that is prevented in these areas would have supplied sediment to downdrift areas. In response, homeowners downdrift of these structures often install their own structures, which will in turn starve additional downdrift areas of needed sediment. Naturally evolving coastal areas are superior to those with engineering structures with regards to providing ecosystem services as well as responding to future storm events and ongoing sea level rise.

5 Conclusions

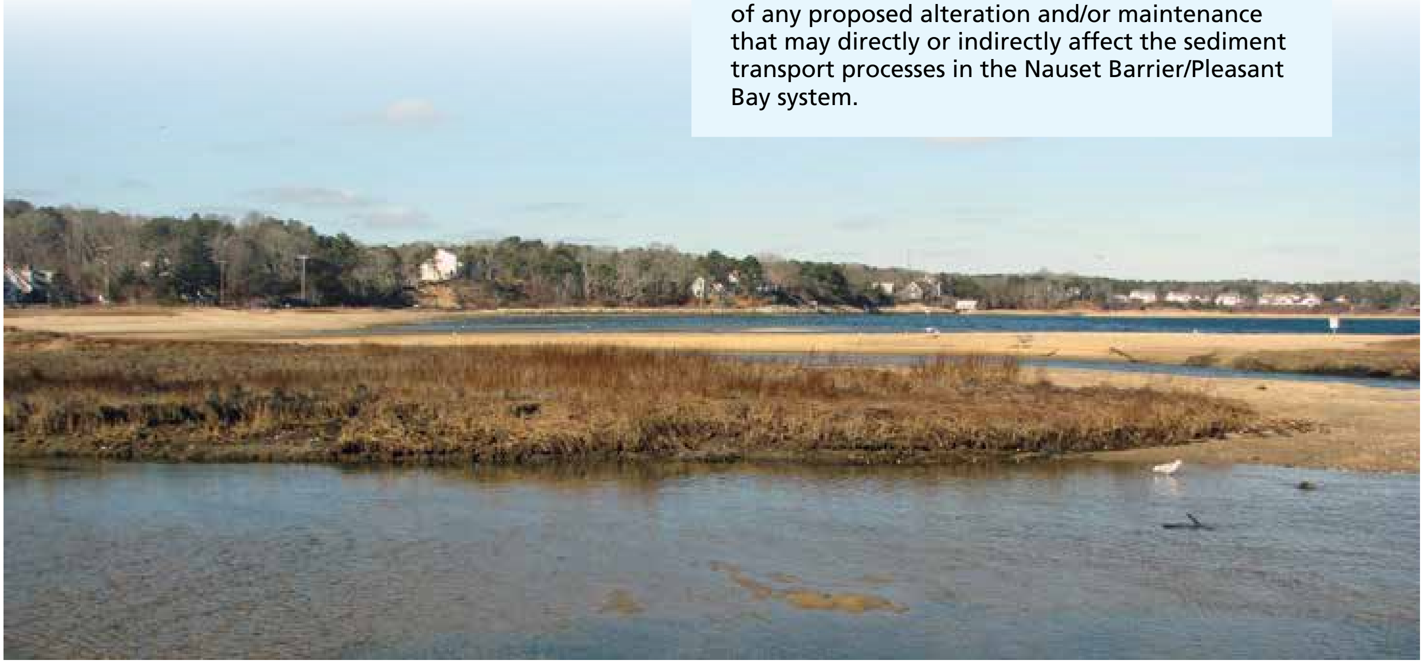
The impacts to the inner shore of Pleasant Bay and that portion of the Nauset Barrier Beach fronting Pleasant Bay were shown to be directly related to ongoing natural process, human alterations and sea level rise. Sea level in and around Pleasant Bay is rising and the rate of sea level rise is also increasing. In the last century it rose at a rate of 1ft/century and future projections forecast a further increase in that rate.

Changes to landside intertidal coastal resources of Pleasant Bay north of Ministers Point will include mostly losses, and some gains in resource areas. In the Chatham Harbor area, westward movement of sediment from the barrier beach and barrier island may create shoaling and possible accretion of beaches along some sections of the mainland as noted in Figures 7, 9, and 11 as well as observed historically and most recently following the 1987 break. Amounts and duration of any potential accretion have not been calculated. Because the Chatham Harbor area is so geologically dynamic and has the highest variability in the system, any projection carries uncertainty.

Human actions to prevent erosion, such as installation of coastal engineering structures, in one place will accelerate erosion of the fronting beach and adjacent areas.

Long-term preservation of sediment transport processes and the coastal resources they support will require balancing preservation of natural resources with protection of public and private property, infrastructure, and access points.

All management activities should take into consideration the short-, mid- and long-term impacts of any proposed alteration and/or maintenance that may directly or indirectly affect the sediment transport processes in the Nauset Barrier/Pleasant Bay system.



GLOSSARY

Barrier Islands: A detached portion of a barrier beach between two inlets.

Barrier Spits: A barrier beach attached to the mainland that extends into open water at the other end.

Coastal Engineering Structures: any structure that is designed to alter wave, tidal or sediment transport processes in order to protect inland or upland structures from the effects of such processes.

Downdrift: In the direction of longshore sediment transport.

Ecosystem Services: Any positive benefit that wildlife or ecosystems provide to people.

Intertidal: The area of the shore that lies between the highest astronomical high tide and the lowest astronomical low tide.

Mean High Water: The average of all the high water heights observed over a period of time.

Mean Low Water: The average of all the low water heights observed over a period of time.

Mean Sea Level: The average of sea level heights over a period of time.

NAVD 88: North American Datum of 1988. A fixed vertical reference surface adopted as a standard geodetic datum. The datum was derived from a general adjustment of elevation data for the United States, Canada, and Mexico. NAVD 88 should not be mistaken for Mean Sea Level.

Passive Erosion: After a hard structure is built along an eroding coastline, the shoreline will eventually migrate landward on either side of the structure.

Sequester: To isolate or store away from interaction with surrounding areas or processes.

Supra-tidal: The area of the shore that lies above the highest astronomical high tide inundated only during exceptional tides and/or storm surges.

Updrift: In the opposite direction of longshore sediment transport.

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