CZM Coastal Community Resilience Grant Program

Chatham East-Facing Shoreline:

Coastal Resiliency and Management Assessment

Final

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Town of Chatham, MA

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1.0 INTRODUCTION

With assistance from the Massachusetts Office of Coastal Zone Management (MCZM) Coastal Resilience Grant Program, the Town of Chatham developed a quantitative analysis of coastal processes to support a detailed analysis of potential shoreline management techniques that could be utilized to sustain the east-facing Chatham shoreline over the next 20-to-30 years. As the inlets and channel positions migrate due to the natural Nauset Beach evolution process, the Town is focused on maintaining storm protection in an environmentally responsible manner. Previous work consisted of an extensive evaluation of the barrier beach migration process, including the influence of relative sea-level rise on the barrier beach and estuarine system. The quantitative analysis of coastal processes builds off of existing data and modeling tools; however, updated tidal information, bathymetric survey data, and expanded numerical modeling tools that incorporate tidal hydrodynamics, waves, and sediment transport were required to provide appropriate analysis tools for evaluating management options. The overall goal of the planning analysis was to produce a “roadmap” that the Town can utilize to proactively plan for projects to improve the resiliency along Chatham’s east-facing mainland.

Nauset Barrier Beach is a highly dynamic environment with two-centuries of well-documented changes of shifting shoals, inlet formation/migration, and variation in morphologic and hydrodynamic patterns throughout the Chatham Harbor/Pleasant Bay estuarine systems. Historical inlets to Pleasant Bay have migrated in a generally cyclical pattern that can be reasonably projected into the future. The overall goal of this assessment is to provide a planning analysis to help guide the Town to proactively plan for projects to improve resiliency and maintain storm protection capability of the shoreline between the Minister’s Point region and Morris Island (Figure 1.1) in an environmentally responsible manner. Although historical, and likely future, inlet migration is expected to follow a generally predictable pattern, the implications of these migration patterns to shoreline development are less certain. Specifically, the migration/formation of various inlets, shoals, and tidal channels alter coastal erosion and tidal flooding patterns, often on a storm-by-storm basis.

Tidal waters flowing between the ocean the Chatham Harbor/Pleasant Bay estuarine system and the developed uplands of southeastern Cape Cod have continually changed through history. At present, water between the estuary and the sea is exchanged through three discrete tidal inlets. North Inlet (formed in 2007) lies immediately south of the southern terminus of the long (and unbroken for more than 10 miles) stretch of east-facing barrier beach known as North Beach. Geographically, it is located in North Chatham in the vicinity of Strong Island and Minister’s Point. An approximate 2-mile long barrier island known as North Beach Island lies south of North Inlet and protects the area to the west known as Chatham Harbor. The second tidal inlet, South Inlet, formed in 1987. At present, it lies south of North Beach Island and north of the next section of the Nauset barrier system, referred to as South Beach. Up until 2017, the north end of South Beach was attached to the upland immediately south of the Chatham lighthouse; therefore, it demarcated the southern end of the estuary. The “April Fools Inlet”, or Fools Inlet, opened in April 2017, detaching South Beach from the Chatham mainland. Since the 1987 formation of South Inlet, the Chatham Harbor/Pleasant Bay estuarine system has experienced significant morphologic changes that have created flooding and coastal erosion concerns throughout the community. Although the historical and likely future inlet migration patterns generally follow a predictable pattern, the implications of these migration patterns to shoreline development are less certain. Specifically, the migration/formation of various inlets, shoals, and tidal channels has altered coastal erosion and tidal flooding patterns, often on a storm-by-storm basis.

Figure 1.1 The east facing shoreline of Chatham illustrating the approximate project limits from north of Minister's Point in Pleasant Bay to the southern tip of Morris Island. This area represents the most dynamic stretch of shoreline that is directly influenced by the evolution of the Nauset Barrier Beach and the series of tidal inlets.

Initially, formation of North Inlet brought an increased tide range and associated tidal flushing to the estuary. In general, this increased tidal flushing was viewed as positive change based on improved tidal flushing and water quality. However, the increased tidal flushing also allowed higher storm surge levels to propagate into the estuary, often leading to increased concerns over coastal armoring to protect upland development. Following initial formation of North Inlet, a colony of 10 beach cottages (camps) on North Beach, just north of the inlet, was destroyed by beach erosion as the inlet widened. Another colony, south of the inlet, resulted in the further loss of 9 of the 11 camps as North Beach Island continued to erode over the next few years. The ongoing widening of this inlet has led to substantial shoal formation within the estuary, as well as increased open ocean wave activity within the exposed area of the Chatham mainland shoreline, both to the north and south of Minister's Point. Migration of the main channel carrying flow into Pleasant Bay against the shoreline of Minister's Point has caused substantial scour, leading to undermining of coastal engineering structures.

Subsequent formation of Fools Inlet that separated South Beach from the mainland has further altered tidal flow pathways through the estuarine system. At present, three tidal inlets provide connections to the ocean. It is anticipated that the barrier beach system south of North Inlet will eventually break apart as North Beach and the associated North Inlet migrate south. The anticipated morphologic change described by the Provincetown Center for Coastal Studies (2017) through 2100 is illustrated in Figure 1.2. Over the next several decades, rapid changes to the barrier beach system and associated inlets/tidal channels likely will create conditions that exacerbate coastal erosion and tidal flooding to areas that may appear well-protected at the present time. At present, overall management of the mainland shoreline is being performed in a reactive manner, based on response to various coastal erosion and storm-induced flooding issues. However, the Town is focused on developing a proactive approach to overall shoreline management, rather than continuing the piece-meal approach to shore protection. With this in mind, the analysis focuses on engineering alternatives that not only address present concerns, but also include potential future issues related to additional flooding and erosion hazards, as well as climate adaptation techniques for the next 20-to-30 years.

Due to the rapidly changing morphology associated with the inlet dynamics, as well as the influence of typical nor'easters, the Chatham mainland shoreline between Minister's Point and Morris Island is experiencing both tidal current and storm wave conditions that have not been experienced within this region since the late 1800's. Development of the Chatham shoreline since this time-period has created a continually evolving situation that exposes different waterfront properties to coastal erosion depending on the position of the inlets. Over the early 2018 timeframe, areas in the Minister's Point region, as well as south of "Fools Inlet", experienced both erosion and coastal flooding not experienced over the past several decades. This flooding caused significant damage to coastal infrastructure and created a risk to public safety, as rapidly rising water levels inundated the entire Little Beach area. During the same storm event, elevated water levels and wave action resulted in overtopping and overwash of a recently nourished barrier beach adjacent to Minister's Point which closed the tidal connection to salt marsh landward of the beach and adversely impacted natural resources. All of this recent coastal storm damage can directly be attributed to the on-going morphologic changes associated with the Nauset barrier beach and inlet system.

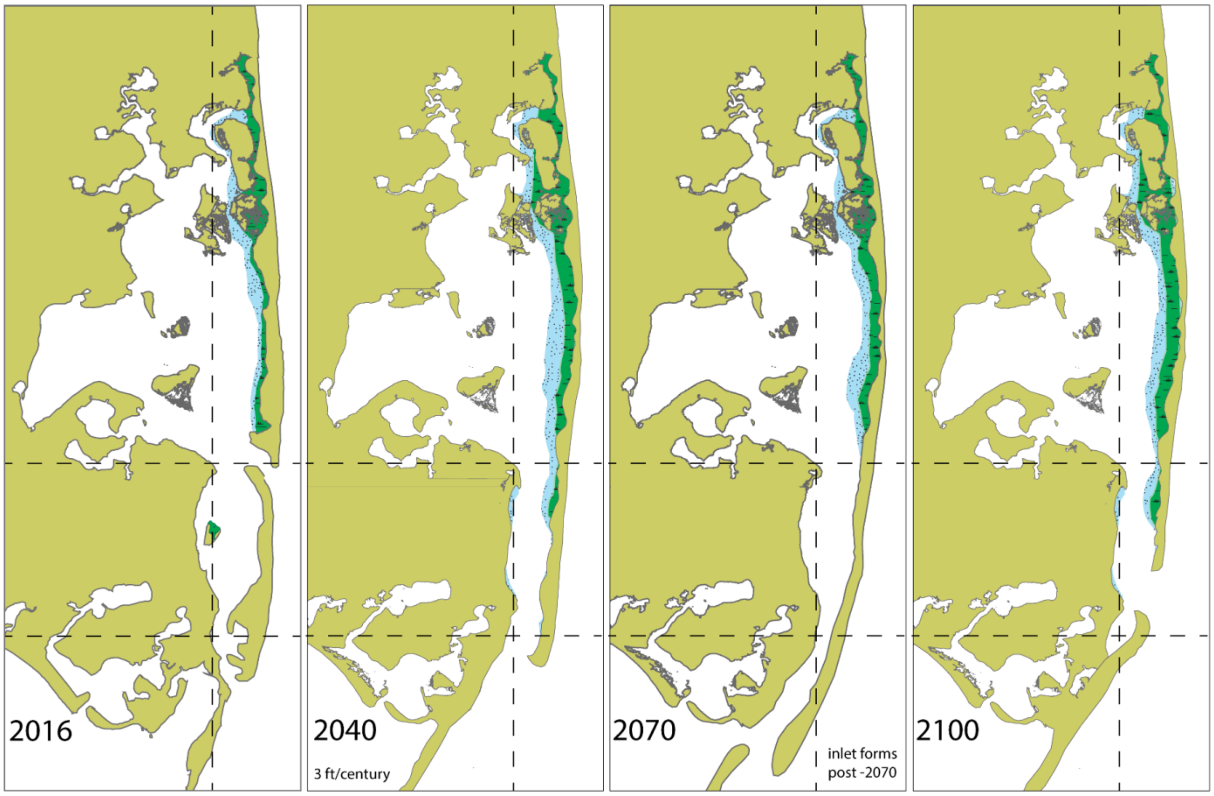


Figure 1.2 Time series for the 'high' sea level rise scenario (3 ft/century). The longest extent of Nauset Spit occurs around 2070. Inlet formation near Minister's Point will occur at some point in time between 2070 and 2100, likely closer to 2070 than 2100. This figure is focused on the changes to the barrier, which is to the right of the vertical dashed line. Changes to the inner shoreline will likely occur, but are not represented here (*courtesy of the Center*).

While the rapidly changing inlet and barrier beach morphology is the primary driver to flooding and erosion problems along the Chatham east-facing shoreline, sea level rise and associated impacts of higher storm surge levels will exacerbate potential risks to public safety, coastal infrastructure, and natural resources. The proposed assessment of shore protection needs is intended to improve coastal resiliency planning along the vulnerable Chatham east facing shoreline. The project is focused upon working towards alternatives to improve overall shoreline sustainability over the next 20-to-30 years, specifically by adapting more naturally to relative sea-level rise and the rapidly changing inlet morphology. In general, sustainable shoreline stabilization and flood protection are the primary goals, but it also is critical to ensure that any potential solution to stabilize the beach system continues to maintain a healthy littoral system and protects the natural function of the overall Chatham Harbor/Pleasant Bay shoreline. To this end, the analysis of shore protection alternatives focused on ensuring management of the regional littoral system.

To this end, the project provided a quantitative analysis of coastal processes to support a detailed analysis of potential shoreline management techniques that could be utilized to sustain the east-facing Chatham shoreline over the next 20-to-30 years. As the inlets and channel positions migrate due to the natural Nauset Beach evolution process, the Town is focused on maintaining storm protection in an environmentally responsible manner. Work performed to date consists of an extensive evaluation of the barrier beach migration process, including estimates of inlet positions over the next 80+ years and the likely influence of relative sea-level rise on the barrier beach and estuarine system. In addition, numerical hydrodynamic modeling of the Pleasant Bay estuary has been performed for conditions that existed in 2001 (post-1987 Breach single inlet system) and 2007 (post-2007 Breach two inlet system).

The quantitative analysis of coastal processes built off of the existing data and modeling tools; however, updated tidal information, bathymetric survey data, and expanded numerical modeling tools that incorporated tidal hydrodynamics, waves, and sediment transport were required to provide appropriate analysis tools for evaluating management options. The overall goal of the planning analysis iwas to produce a “roadmap” that the Town can utilize to proactively plan for projects that will improve the resiliency of the shoreline between the Minister’s Point region and Morris Island. The project incorporated the following components:

- Utilize existing tidal, bathymetric, coastal processes, and environmental information to inform development of the baseline models needed to support the project.
- Collect additional bathymetry and tidal data to support model development for the estuarine system as it exists in 2018.
- Incorporate historical and predicted information to develop anticipated migration of tidal inlets, tidal channels, and shoals to develop projected estuarine morphology over the next 20-30 years.
- Utilize numerical tidal hydrodynamic, wave, and sediment transport models to quantitatively evaluate coastal processes along the Chatham shoreline between the Minister’s Point region and Morris Island. This modeling will be performed for existing conditions, as well as for future conditions, based on projected estuarine morphology scenarios.
- Perform an analysis of various engineering and/or management alternatives that can be used to improve sustainability of the Chatham shoreline between the Bassing Harbor entrance and Morris Island
- Develop recommended alternatives for potential management options, focused on both long-term sustainability, as well as overall protection of the estuarine and coastal environment.

Laser altimetry (Light imaging, detection, and ranging, or LiDAR) was collected by the US Army Corps of Engineers (USACE) in the spring of 2018 and supplemented with bathymetric data collected in the fall of 2018 using a Phase-Measuring Sidescan Sonar (PMSS). These data were used to develop a three-dimensional surface for the model.

An Acoustic Doppler Current Profiler (ADCP) was stationed offshore between the 1987 and 2007 inlets for approximately 30 days (2 spring to neap tidal cycles) in approximately 30 ft of water in order to measure the open ocean tides unaffected by inlet processes.

Two ongoing tidal studies funded by the Town and the Pleasant Bay Alliance (PBA) have Center staff, led by Dr. Graham Giese, collecting and analyzing tidal data at Stage Harbor, Outermost Harbor, Meeting House Pond, and the Chatham Fish Pier. These data were critical to parameterize the model’s assessment of the complex tidal flow that moves through the three inlets at the present time. Data collection for these four tidal stations is ongoing and was provided to support the modeling effort.

The project team has been involved with the evaluation of inlet dynamics in Chatham since before the 1987 breach. The expertise of both Drs. Giese and Borrelli, and the coastal engineering staff at Applied Coastal, provided necessary scientific understanding of coastal sedimentary processes controlled by both wave action and tidal hydrodynamics. Specifically for the Chatham Harbor/Pleasant Bay estuarine system, the influence of the coastal sedimentary processes that govern inlet migration and evolution will be critical to understanding future management implications for the Chatham shoreline. Applied Coastal and the Center have worked well together in past efforts within Pleasant Bay and Chatham Harbor. The most recent project, funded by the Pleasant Bay Alliance, looked at future scenarios of coastal morphology with regards to sea level rise including inlet migration and evolution of Nauset Beach barrier island/barrier spit system through 2100. Building on that study, the project provided analyses at a more refined spatial and temporal scale needed to address short-term channel and shoal evolution (i.e. over the next 20-to-30 years).

This short-term refined analysis evaluated historical bathymetry throughout Pleasant Bay and Chatham Harbor. Based on a combined understanding of the previous inlet cycle (that began with a breach of the Nauset barrier directly east of Minister's Point in 1846) and the observed evolution of the present inlet cycle (initiated by the 1987 breach), predictions of channel and shoal evolution were developed and limits to those migrations were evaluated to the extent possible. Information based on this evaluation of historical information was combined with the results of the quantitative coastal processes evaluation described below to provide predictions for the next 20-to-30 years with regards not only to inlet evolution, but also to tidal channel and shoal migration. This understanding is aimed at assisting the Town with planning efforts for issues related to coastal flooding and coastal erosion potential.

The evaluation of recent and anticipated morphologic processes of the east-facing Chatham coastline was developed utilizing standard reference materials (maps, aerial photographs, and regional geologic data), as well as the team's knowledge regarding local coastal geology and its role in shaping this portion of the Massachusetts Coast. This evaluation also included how anthropogenic changes may have altered the natural sediment transport processes and the influence of sea-level rise upon the long-term stability of the regional coastline.

As part of the process for developing a predictive modeling tool that was utilized to assess shore/flood protection options for the Chatham mainland coast, a quantitative analysis of coastal processes was required to develop defensible 'baseline' conditions. The model utilized for evaluating tidal hydrodynamics, wave transformation, and sediment transport is the Coastal Modeling System (CMS), developed by the U.S. Army Corps of Engineers. CMS is ideally suited to evaluate the combined influence of currents and waves on sediment transport, as well as evaluating morphology change associated with changes in transport patterns.

The tidal hydrodynamics were calibrated using the long-term data sets developed by the Center, where the offshore Atlantic Ocean boundary conditions will be derived from the 30-day offshore ADCP deployment. A similar technique was utilized to calibrate previous hydrodynamic modeling efforts performed by Applied Coastal, most recently after the 2007 formation of North Inlet. Updated bathymetry based on the 2018 survey also was incorporated into the model grid, along with older bathymetry in portions of the estuary that have not been influenced by recent changes to the channel and/or shoal system.

Offshore wave conditions for the model were derived from the U.S. Army Corps Wave Information Studies (WIS). WIS provides 20-year historical records of wave height, period, and direction. The Chatham shoreline fronted by the Nauset barrier beach system tends to be protected during typical offshore wave conditions; therefore, for this evaluation the analysis of waves within CMS focused on more energetic conditions that allow propagation of waves to the mainland shoreline. Based on observations over the past several years, these higher energy wave conditions, typically associated with nor'easters, have the most pronounced effect on coastal erosion.

The CMS modeling tool was developed to assess the tidal and wave conditions that most strongly influence coastal erosion and flooding along the mainland shoreline. The model hydrodynamics were calibrated to existing conditions, and both prior conditions (2007) and future conditions (2045) were simulated. Morphology for the projected 2045 conditions was developed from (a) anticipated changes to the barrier beach, shoals, and channels based on historical trends from the previous cycle and (b) sediment transport trends described by the CMS model.. Once the overall CMS model was developed to simulate future channel and shoal alignments, the model was used to quantitatively evaluate anticipated changes to coastal flooding and erosion potential. This aspect of the modeling effort was critical for assessing the viability of potential shore protection alternatives. Within the context of ongoing coastal evolution, the influence of relative sea-level rise also was accounted for within the analysis. In this manner, quantitative information could inform the evaluation of engineering alternatives for appropriate time horizons.

Combining the results from the modeling and geomorphology analyses, an engineering analysis of potential shore protection options was developed separately for each identified shoreline 'reach'. As many of the impacts to coastal erosion are temporary (i.e. on the order of 10-to-20 years) prior to re-formation of the outer barrier beach, many of the strategies focused on providing stability to the shoreline on this short-term basis. Results from the sediment transport analyses also informed the viability of different shore protection strategies at meeting the long-term sustainability goals of the project. Specifically, the alternatives evaluation will assess the relative role of inlet position, as well as major channel and shoal locations, on the erosion/flooding potential for each reach. Shore protection strategies were evaluated for present conditions and for a time period approximately 20-to-30 years in the future. Understanding that the barrier beaches, shoals, and channels can migrate in both a gradual and episodic manner, the model simulations represent "end points" for the coastal processes evaluation, where the change in current and wave patterns progress from the observed present conditions to towards the projected 2045 conditions. As appropriate, suggested future management strategies change over time due to anticipated evolution of the inlet system.

For the future time period evaluated, the CMS modeling tool was utilized to assess the utility and long-term viability of the strategy for coastal resiliency. The evaluation considered erosion and/or flooding mitigation effects of the strategy, as well as potential environmental drawbacks (e.g. exacerbating downdrift erosion, impacts to environmental resources, etc.). Utilizing the coastal processes and engineering alternatives data developed, a series of shore protection concepts were evaluated for the shoreline extending from the Minister's Point region to Morris Island. Coastal resiliency issues also were addressed, as future shore protection expenditure planning will require that a sustainable outcome will be achieved based upon a 20-to-30-year planning horizon.

Due to a mixture of private and public property as well as sensitive environmental habitats along the waterfront of Chatham, cohesive, large-scale shoreline management efforts face an uphill battle for regulatory permitting and property easements. Many existing individual shoreline protection strategies were completed in a reactionary manner and could be enhanced by incorporating a better understanding of multi-inlet system dyanmics A more proactive approach to shoreline stabilization and management is warranted to ensure the long-term viability of the coastal resources and the critical roadway infrastructure along many portions of the shoreline. This effort is aimed at developing an overall coastal shore protection strategy over the next 20-to-30 years to improve the sustainability and resiliency of the Chatham shoreline. Although shoreline stabilization and flood protection are the primary goals, it also is critical to ensure that any potential solution to stabilize the beach system continues to protect the natural functions of the shoreline. To this end, the analysis of shore protection alternatives will be focused on ensuring management of the regional littoral system that benefits these public resources.

2.0 DESCRIPTION OF PROJECT AREA

At present, water between the estuary and the Atlantic Ocean is exchanged through three discrete tidal inlets, shown on Figure 2.1:

1. "North Inlet" (formed in 2007) is located in North Chatham in the vicinity of Strong Island and Minister's Point. The east-facing Nauset Barrier Beach system (continuous for over 10 miles) referred to in Chatham as "North Beach" lies to the north of North Inlet and an approximately 2-mile long barrier island known as "North Beach Island" lies south of North Inlet, protecting Chatham Harbor to the west. North Inlet opens to the Atlantic Ocean.

2. "South Inlet" (formed in 1987) lies south of North Beach Island and north of the next section of the Nauset barrier beach system, referred to as "South Beach". South Inlet opens to the Atlantic Ocean

3. "April Fools Inlet" or "Fools Inlet" (formed in April 2017) separates South Beach from the Chatham mainland. Prior to this inlet formation, the north end of South Beach was attached to the mainland and demarcated the southern end of the estuary up until 2017. Fools Inlet opens to the southern portion of historical Chatham harbor and Nantucket Sound.

In general, inlets to tidal estuarine systems exist as a result of the balance between the littoral drift and tidal flushing. In general, wave-induced currents along the open coast transport sediment along the shoreline causing inlet shoaling and/or migration in the direction of the dominant littoral drift. Water elevation differences between the ocean and the estuarine system create tidal flows that prevent inlet closure by providing sufficient water velocity to scour sediments from the main channel. For many natural inlet systems, a period of barrier spit elongation is followed by episodic breaching of the barrier beach, resulting in a more hydraulically efficient inlet channel.

Since the breach formation in 1987, South Inlet served as the only navigable passage between Chatham Harbor/Pleasant Bay and the open ocean. However, following the formation of North Inlet in 2007, South Inlet became increasingly shoaled while North Inlet increased in size and is presently (since 2018) the preferred inlet for marine traffic under most conditions. Initially, formation of North Inlet brought an increased tide range and associated tidal flushing to the estuary, generally considered a positive change due to improved water quality; however, increased tidal flushing also allowed higher storm surge levels to propagate into the estuary, often leading to increased concerns over erosion and flooding. In addition, this higher tide range and changes to shoaling patterns caused significant changes to other ecological resources including salt marshes and eel grass beds. Specifically, formation of the flood shoal in the vicinity of North Inlet (shown along the west side of North Beach just north of North Inlet on Figure 2.1) covered several acres of historical eel grass beds in Pleasant Bay. At the same time, improved water clarity has increased eel grass beds within upper portions of Pleasant Bay. In a similar fashion, shifting of sand due to increased currents and/or storm wave action has caused some salt marsh areas to be smothered; however, the increased tide range has led to a broader expanse of intertidal habitat for salt marsh plants. One example of a recent adverse impact to a salt marsh that has existed since the 1880s is landward of Linnell Lane Beach, where a historical tidal channel has been closed by recent storm overwash (Figure 2.2).

Due to the increased tide range and storm impacts, shorefront property owners throughout Pleasant Bay and Chatham Harbor have become increasingly concerned over shore protection needs. This has resulted in numerous requests for more extensive coastal armoring and other measures to protect upland development. The formation and eventual widening of North Inlet also lead to the destruction of a colony of beach cottages (or “camps”) on Nauset Beach. Ongoing widening of North Inlet has led to substantial shoal formation within the estuary, as well as increased open ocean wave activity within the exposed area of the Chatham mainland shoreline, both to the north and south of Minister’s Point over the last two-to-three years.

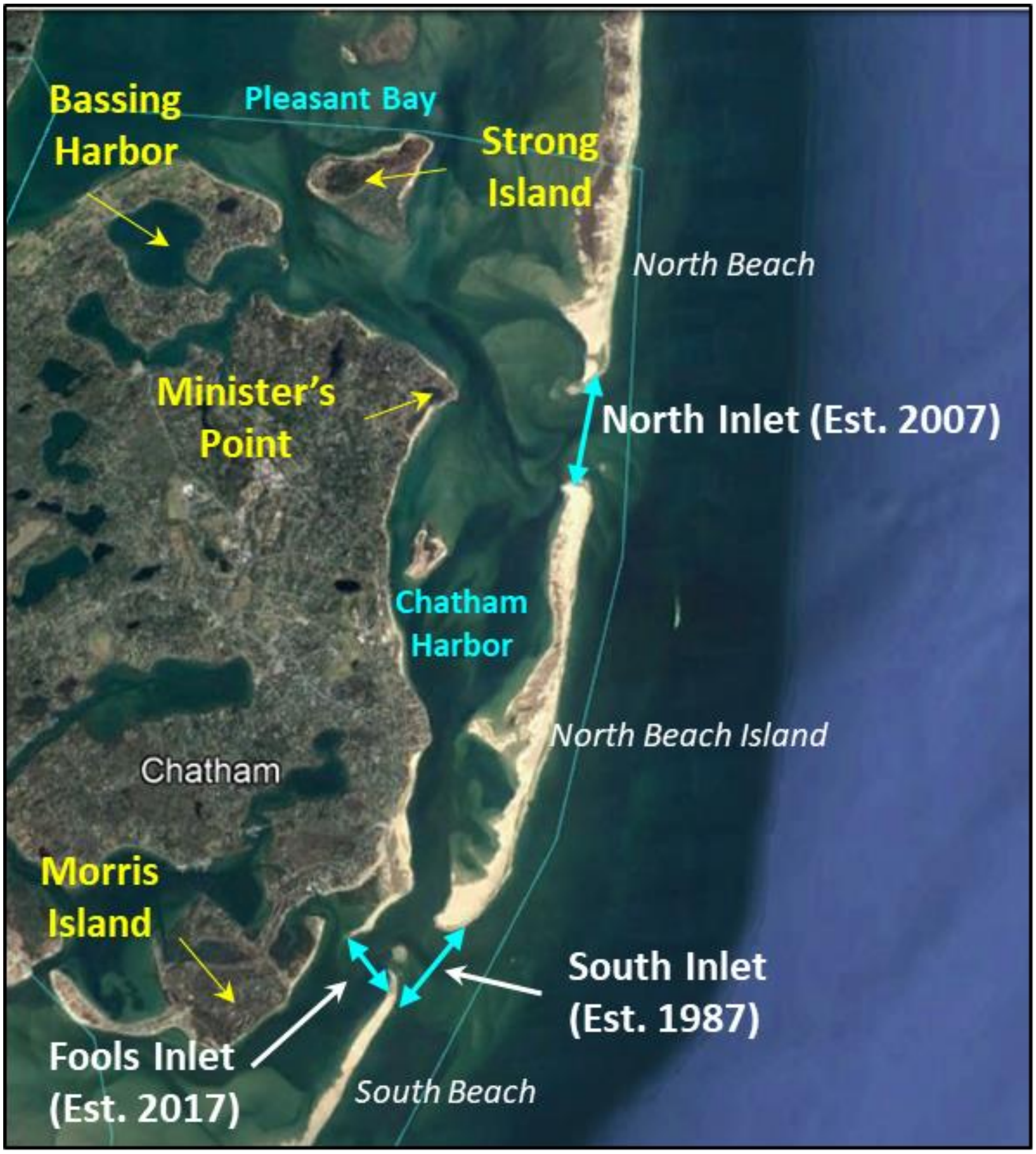


Figure 2.1 Aerial photograph from 2018 showing present three inlet configuration .

Figure 2.2 Linnell Lane Beach in March 2018 showing the ponded area landward of the barrier. The southern end of the ponded area (left), as well as a significant portion fringing the northern ponded area (right), contained salt marsh. However, overwash of the barrier beach led to closure of the historical inlet, which has become re-established adjacent to the revetment at the north end of the beach (*Image: courtesy of Spencer Kennard*).

2.1 Natural History

Approximately 5,000 years before present, local mean sea level was about 15-20 feet below the level existing today. As relative sea level increased to present levels, continued erosion of the coastal bluffs of the outer Cape shoreline provided sediment to downdrift beaches, modifying the form of the nearshore area. Nauset Beach formed from the erosion of these sandy bluffs. As relative sea-level continued to increase, the bluffs along the eastern shore of Cape Cod continued to erode and the barrier beach moved to the west. Nauset Beach has migrated to the west as a result of episodic overwashing by storm waves in a process referred to as barrier beach rollover. The “Halloween Storm” of 1991 (popularly the “Perfect Storm”) was an example of this rollover process, where the barrier beach was steepened on the oceanside and large volumes of sand were deposited into Pleasant Bay (Howes et al. 2006).

The Nauset Barrier Beach system experiences periods of southerly accretion followed by a destructional phase whereby the spit becomes segmented and portions of the barrier migrate onshore (McClennan, 1979; Giese, 1988). Segmentation is related to a gradual reduction in tidal exchange between Pleasant Bay and Chatham Harbor and the ocean, which is caused by a reduction in efficiency and increased resistance to tidal flow as the inlets move south during the decades-long cycle. This cycle of spit extension followed by barrier segmentation and destruction has a periodicity of approximately 140-150 years (Giese, 1988).

Giese et al (2009) formulated this cycle into a conceptual model (Figure 2.3) and used it to estimate future configurations. It describes inlet evolution in two phases:

1. *Inlet development phase* – Initiation of morphological cycle when a breach occurs in a barrier spit and southwest migration of southern barrier island follows. This cycle begins with an extended period of instability characterized by multiple inlets and changes in tides and tidal channels. This phase is considered “Tide-dominant” because inlet location and evolution is driven primarily by tidal forces, not alongshore littoral sediment transport.
2. *Inlet migration phase* – A continuation of the morphological cycle where the barrier spit re-grows and elongates to the south. Elongation produces an ever-increasing hydraulic head between the tide in the ocean and the estuary at the time of ocean high tide. This phase is considered “wave dominant” because it is primarily the wave climate in this region that controls the net southward alongshore transport of littoral sediment, and the southerly movement of the inlet. Historically, this cycle has occurred over approximately 150 years, based on documented inlet migrations. These are summarized in Figure 2.4 and discussed separately below.

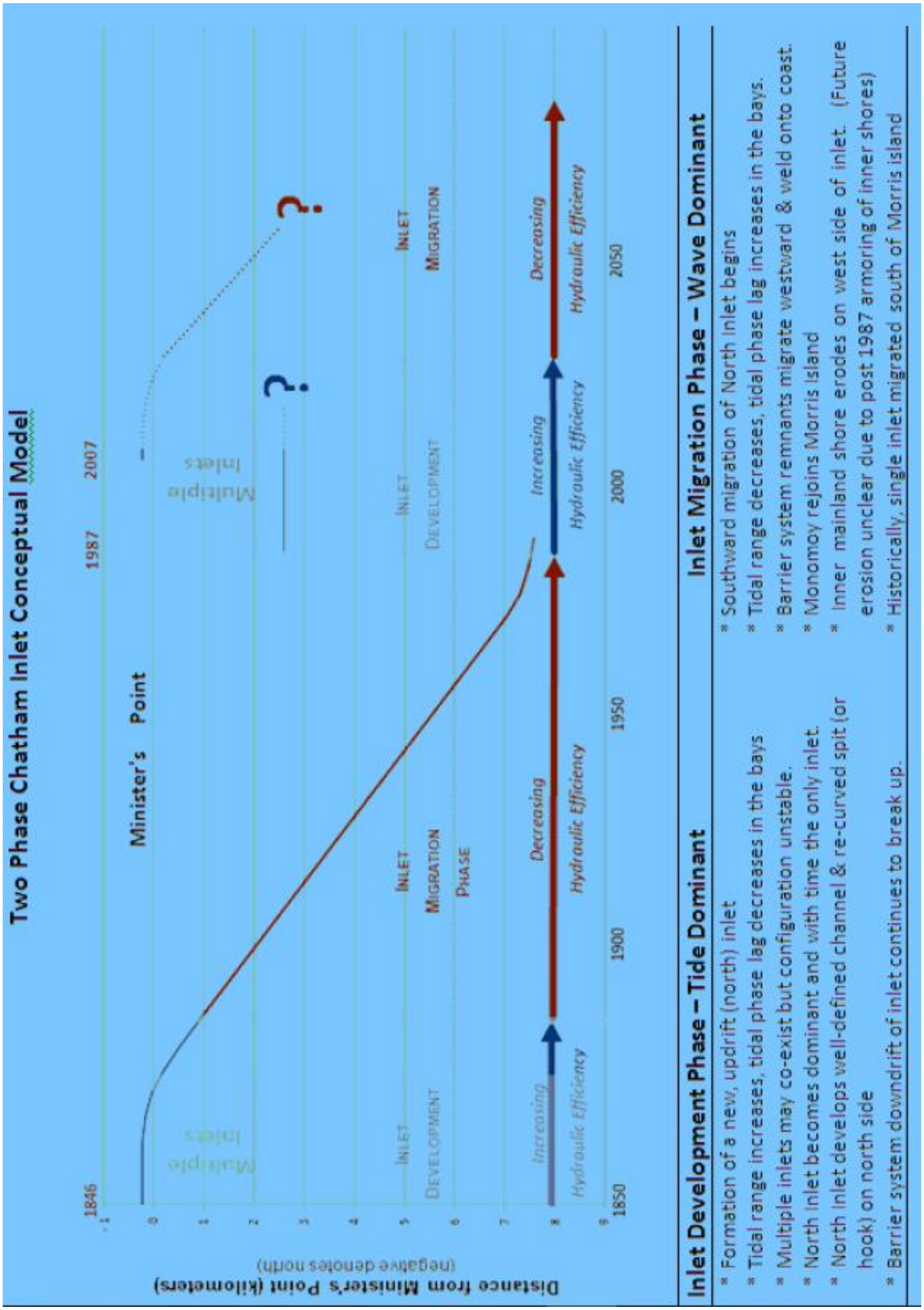


Figure 2.3 Phases of inlet evolution from Giese et al. 2009

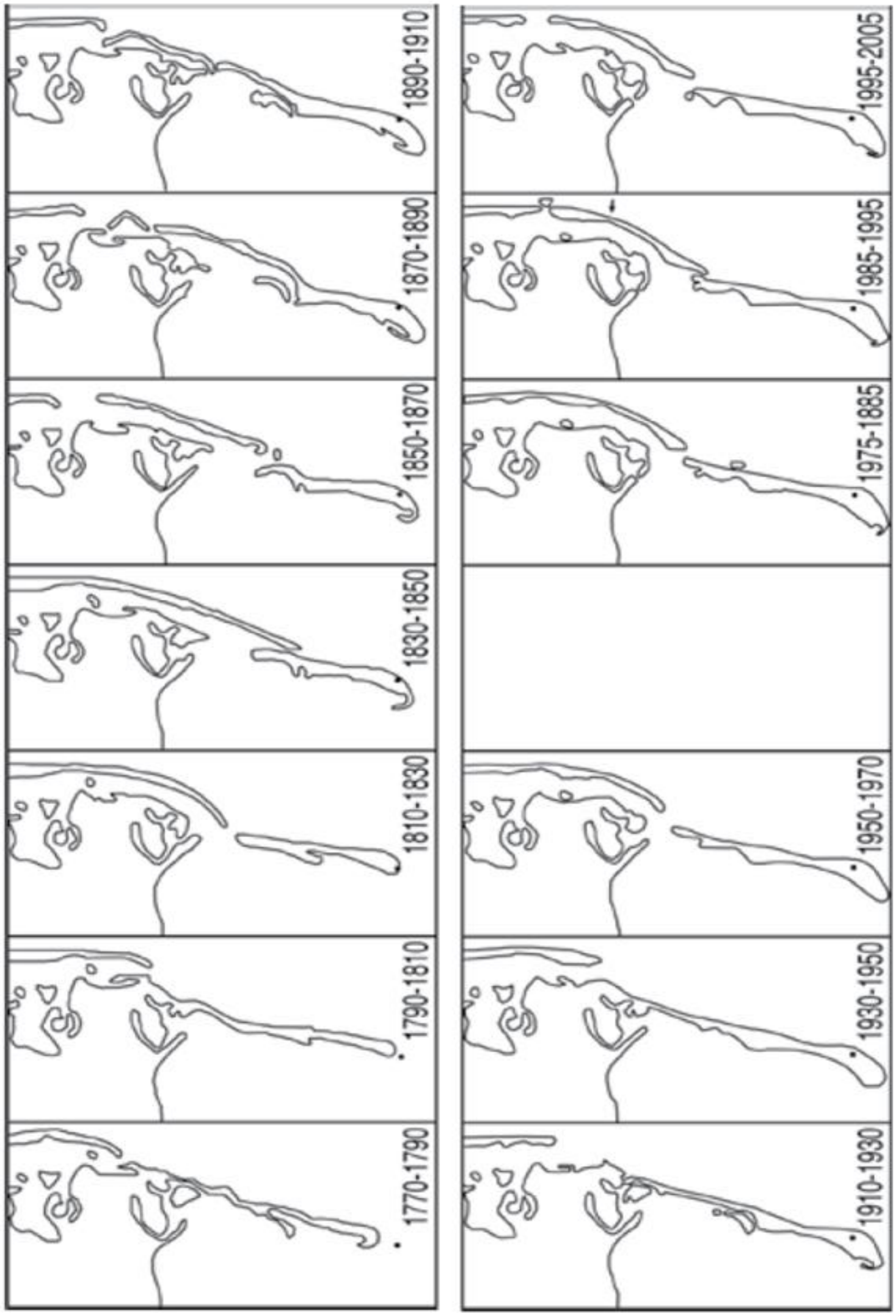


Figure 2.4 Historical changes in the Nauset Beach-Monomoy barrier system illustrated by generalized 20-year diagrams from 1770-1790 to 1950-2005 (from Giese, 1988).

2.1.1 1846 Breach

The 1846 breach is the oldest well-documented demonstration of the observed initiation of the inlet development phase available for the Nauset Barrier Beach system. This breach occurred opposite Minister's Point forming a new, but relatively small inlet into Pleasant Bay, initiating a new inlet cycle. The new inlet remained small until 1851, when Minot's Gale caused it to broaden and deepen.

After this formation, the system had two ocean inlets until the southern end of the detached end of Nauset Beach attached onto Monomoy Island approximately 20 years later. Nauset Beach did not migrate south until the remnant barrier to its south had undergone significant erosion and westward migration (Giese et al. 2009).

2.1.2 1987 Breach (South Inlet)

Nauset Beach was breached opposite Chatham Light during a moderate nor'easter on January 2, 1987. Factors leading to the breach included a long-term narrowing of the barrier, an approximate 1.5 ft storm surge superimposed on near perigean-perihelion-spring tide conditions (a "king tide"), restricted flow through the existing inlet well to the south causing large differences in tidal range and tidal phase between the ocean and Pleasant Bay. A decrease in sand supply to the downdrift barrier caused 300 to 1,000 feet of erosion to the barrier beach system immediately south of the inlet from 1990 to 2000. This decrease in sand supply was due to breaching of the hydraulically more efficient channels through the outer portion of the ebb delta (FitzGerald and Pendleton, 2002).

The formation of this inlet altered the hydrodynamics within the Pleasant Bay estuary, with an approximate 1 ft increase in tide range and a corresponding improvement to tidal flushing within the northern portions of the estuary. Following the 1987 breach, the beach system returned to a form similar to the 1846 pre-breach condition, indicating the start of the next cycle (Howes et al. 2006). As Nauset Beach continued to grow in a southerly direction, the estuarine system became less hydraulically efficient, and the phase lag between high tide in the Atlantic Ocean and high tide in the estuary became greater. Once the barrier spit reached a point where its hydraulic efficiency was significantly reduced, storm overwash conditions north of South Inlet could scour a more efficient channel that could eventually widen to an inlet.

2.1.3 2007 Breach (North Inlet)

On April 15-16, 2007 a spring northeast storm (the Patriot's Day Storm), with a peak storm surge that coincided with spring tides, caused the inundation and overwash of several sites along Nauset Beach. A breach in the barrier opposite Minister's Point gradually evolved into a persistent inlet, which grew slowly throughout the summer and expanding more rapidly in late winter 2008 to become North Inlet (Borelli et al 2016).

Applied Coastal studied pre- and post- breach hydrodynamic and water quality conditions of the whole of Pleasant Bay to evaluate how the system changed (2008). Overall, the modeling showed that the 2007 breach caused a general reduction in maximum tidal currents throughout Chatham Harbor and an increase in tidal exchange for the whole estuary. Within the vicinity of the new breach, the increase in tidal currents through the North Inlet throat led to the observed formation of well-defined flood and ebb shoals.

At the time, it was assumed that this inlet would eventually become the dominant and ultimately the single inlet for Pleasant Bay, as it was located more proximal to the main water bodies of Pleasant Bay and provides more efficient exchange (Keon and Kelley, 2011),.

2.1.4 2017 Breach (Fools Inlet)

The 2017 breach, or “Fools’ Breach” occurred in April of that year, detaching South Beach from the mainland south of Morris Island (Figure 2.1). Town officials have been concerned that a breach immediately south of South Inlet was imminent and that it would hasten the closure of South Inlet, thereby cutting off the Chatham commercial fishing fleet to the Atlantic Ocean, one of the largest and most active fleets in New England. There is concern that if Fools Inlet remains viable, it may divert flood tide flow into Nantucket Sound, thereby weakening tidal currents through South Inlet and causing it to shoal. Due to the increasing navigational risks associated with the passages between the open ocean and Chatham Harbor fishermen moved their vessels to Saquatucket Harbor in Harwich in the winter of 2018.

2.2 Present Conditions (2018)

At present, the Chatham coast is configured similarly to how it was in the time from the 1870s to the 1890s, following the 1846 breach. However, real estate development along the Chatham east-facing shoreline has increased significantly since the 1800s, specifically in some of the low-lying areas that are most vulnerable to coastal hazards (e.g. Little Beach and Andrew Harding’s Lane Beach). Therefore, as the inlet and barrier beach system continue to evolve, the changes will expose different waterfront properties to coastal hazards depending on the position of the inlets. Due to the rapidly evolving morphology of the barrier beach and inlets, as well as the influence of typical northeast storms, portions Chatham’s east-facing mainland shoreline between Minister’s Point and Morris Island is currently experiencing both tidal current and storm wave conditions that have not been experienced within this region since the late 1800’s.

During the 2018 winter storm season, areas in the Minister’s Point region the Little Beach region, located south of Fools Inlet, experienced erosion and coastal flooding not experienced for several decades. This flooding caused significant damage to coastal infrastructure and created a risk to public safety as rapidly rising water levels inundated the entire Little Beach area and prevented access to Stage and Morris Islands further south. Rapid coastal erosion of the beach system adjacent to Minister’s Point caused the closure of an adjacent salt marsh inlet channel, which lead to the marsh being continuously flooded. Changes in the shoal patterns and channel morphology within Chatham Harbor resulted in substantially increased current velocities at Minister’s Point leading to channel scour and resultant undermining and partial failure of a revetment at Minister’s Point. All of this recent coastal storm damage can be directly attributed to the on-going morphologic changes associated with the Chatham Harbor/Pleasant Bay estuary system.

2.2.1 Hydrodynamics

Circulation throughout Pleasant Bay is dominated by tidal exchange. In the present inlet configuration (2019), the Chatham Harbor/Pleasant Bay system, located within the Northeast Shelf, has hydraulic connections to the Gulf of Maine (via North and South Inlets) and to Nantucket Sound (via Fools Inlet), part of the larger Atlantic Bight, as shown in Figure 2.5Positioned at the boundary between the Gulf of Maine and the Mid-Atlantic Bight, tidal flow within Pleasant Bay is the result of the interaction of tides within these two distinct regions, which have different phasing and amplitudes.

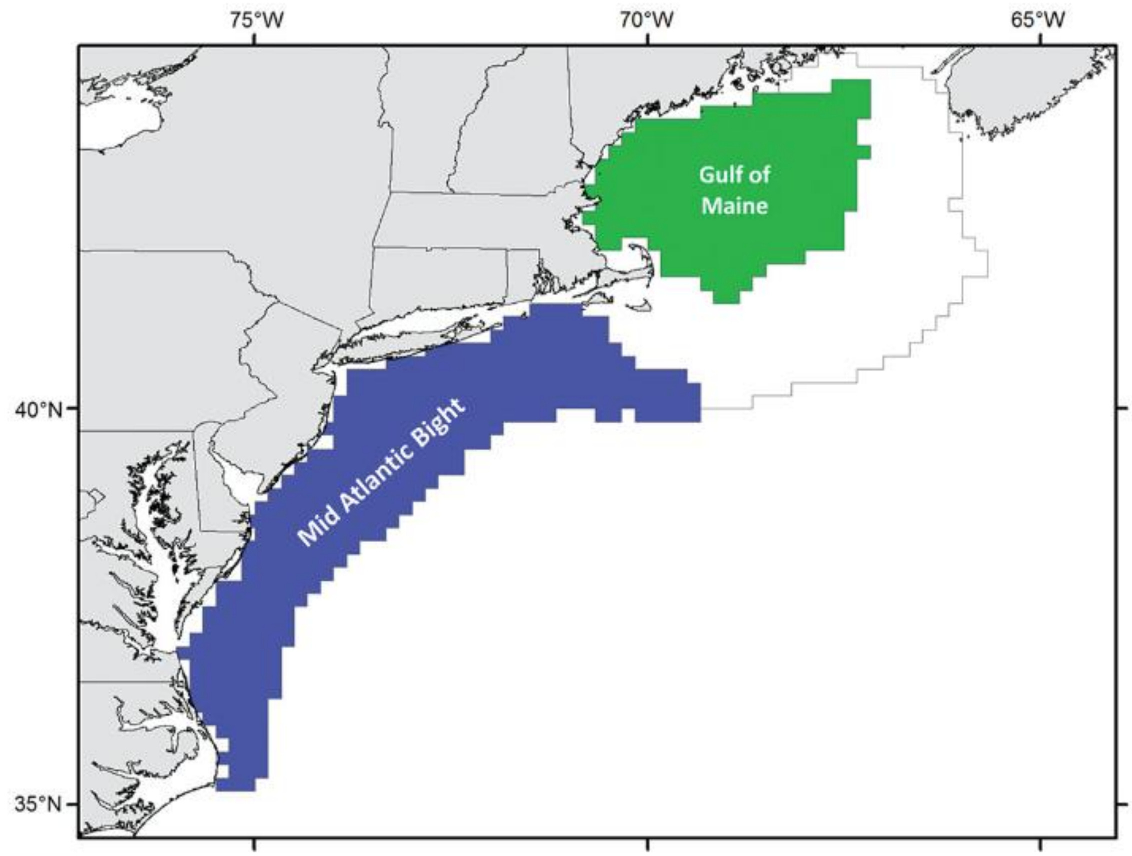


Figure 2.5 Map of the Northeast Shelf, which includes the Mid-Atlantic Bight and Gulf of Maine. The full extent of the Northeast Shelf region also include the area outlined in gray. From Gaichas et al. 2014.

Following the 2007 breach, tidal flows through North Inlet were dominated by incoming flood tides, and ebb flows from the main basin of Pleasant Bay were primarily directed through the south inlet (Giese and Legare 2019). A "turning point" in 2013 was suggested by Giese and Legare (2019) where the relative dominance of South Inlet decreased due to persistent shoaling and infilling of South Inlet and the North and South inlets began to "decouple" from each other. This is evident in the mean low water (MLW) elevation differences between Meetinghouse Pond and Chatham Fish Pier post-2013, indicating a decrease of flow through Chatham Harbor to South Inlet, and a corresponding increase in flow through North Inlet. The breakup of the northwest-trending spit on the landward side at the north tip of North Beach Island in June 2017 (Figure 2.6) followed the breach at Fools Inlet. The breakup of the spit improved the hydraulic efficiency of ebb and flood flow through North Inlet, which lead to a reduction of flow through South Inlet and Chatham Harbor. In March 2018, this ebb channel through North Inlet reconfigured into a distinct S-shape, shown in Figure 2.7 and the channel flowing into Pleasant Bay migrated landward towards Minister's Point.

Figure 2.6 Aerial photographs showing the breakup of the northwest-trending spit on North Beach island between June and October, 2017 (courtesy of T. Keon Town of Chatham) (Giese and Legare 2019)

Figure 2.7 Aerial photo from summer 2018 showing the distinct S-shaped channel connecting to North Inlet, highlighted by the dotted yellow line in the right panel (imagery May 2018, provided by Town of Chatham)

Following the formation of Fools Inlet in 2017, tidal flow pathways were altered within the estuary and exposed portions of Chatham's low-lying mainland south of the lighthouse to direct ocean wave exposure. This low lying area, known as Little Beach, located opposite Fools Inlet and the southerly migrating South Inlet, experienced substantial repetitive flooding during 2018 winter's series of northeast storms. Figure 2.8 shows the Chatham mainland relative to the 100-year storm still water level, where the majority of Linnell Beach and Little Beach/Morris Island (circled) are inundated.

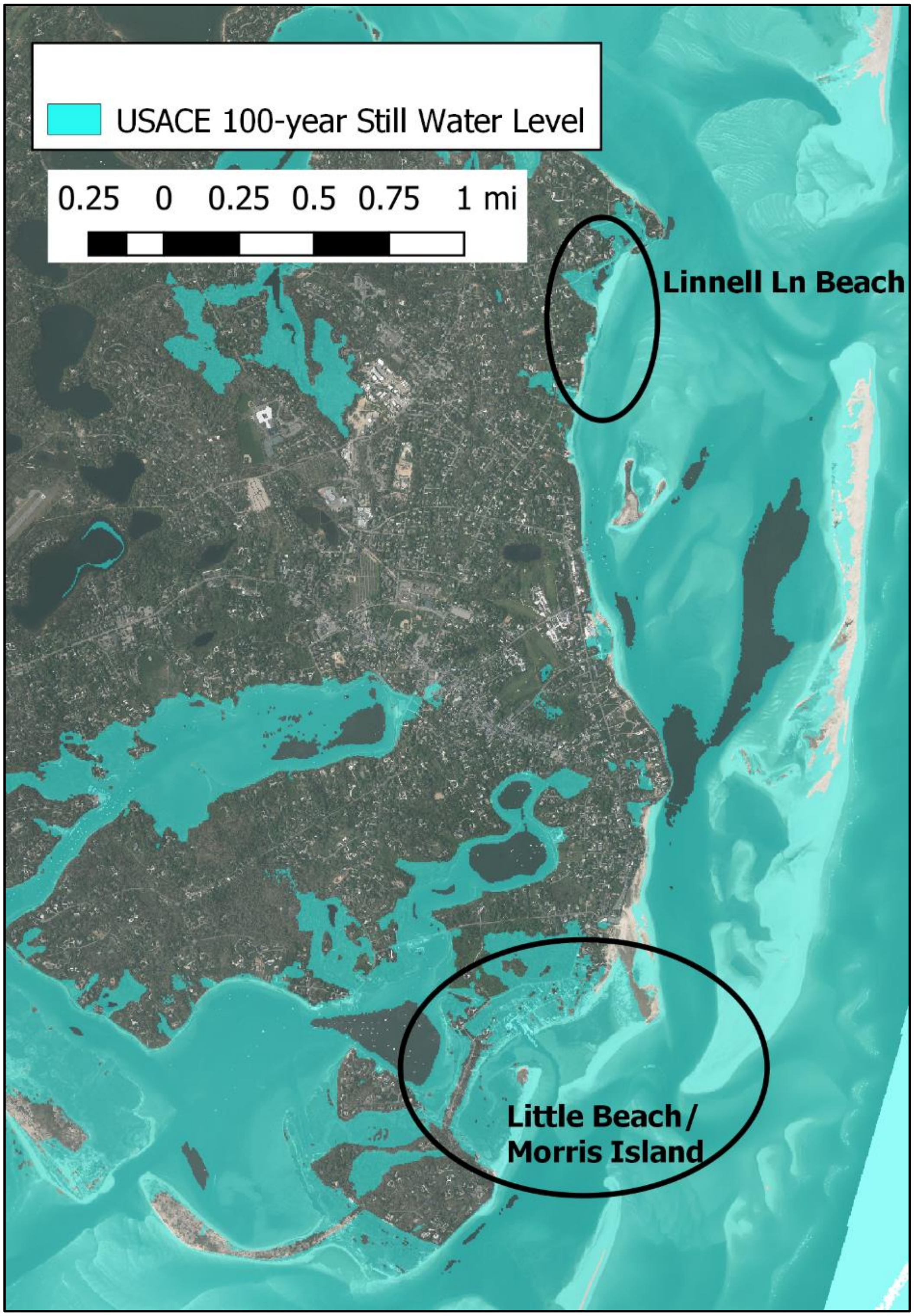


Figure 2.8 Still-water flooding that occurs during a 100-year storm (Nadal-Caraballo and Melby 2014, USACE 2015). Linnell Lane Beach and the Little Beach Area, both circled, have become particularly vulnerable to flooding following the southerly migration of North Inlet and development of Fools Inlet, respectively. (Imagery May 2018, from Town of Chatham)

2.2.2 Shoreline Stabilization Structures

Shoreline stabilization structures protect upland areas from erosion but by doing so, they eliminate the upland as a natural source of sediment, thereby starving down-stream beaches and increasing erosion in those areas. Figure 2.9 shows that shoreline stabilization structures extend along the majority of the mainland coast of Chatham. Historically, the coast has been armored reactively to erosion and increased energy from inlet formation and migration. In some cases, these structures may be more robust than needed to provide adequate protection under existing and future conditions.

Figure 2.9 Public and private shoreline stabilization structures, inventoried in 2009 and 2013, respectively. (Inventory Source: Mass GIS, Imagery Source April 2018, from USGS).

It is important to note that the conceptual model from Giese et al 2009 (Figure 2.3) specifies that future erosion is unclear due to increased shore armoring post-1987. Shoreline configurations from the 1868 and 1910, shown in Figure 2.10 and Figure 2.12, demonstrates patterns of spit formation along the mainland shoreline of Chatham Harbor during this time without shoreline armoring. An elongated spit extends off of Allen's Point, known today as Minister's Point in the 1868 chart, and Aunt Lydia's Cove is shown as an embayment of Chatham Harbor that is delineated by a spit that extends from the south in the 1910 chart (Figure 2.11).

Figure 2.10 The 1868 chart of North Chatham shows an elongate spit that extends off of Allen's Pt, now known as Minister's Pt. (Source: US Coast Survey)

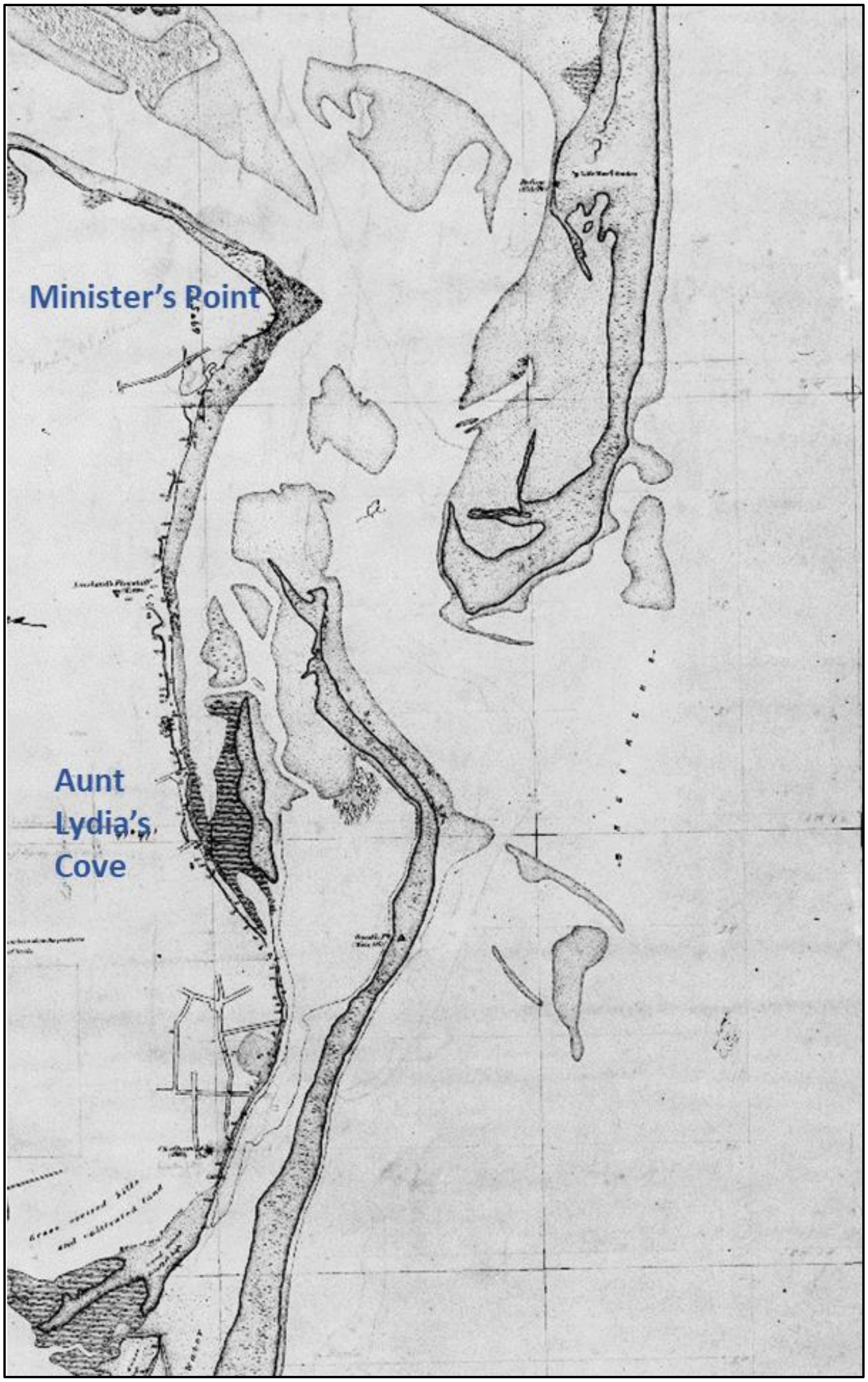


Figure 2.11 The 1886 chart of Chatham shows that the spit off of Allen's Pt/Minister's Pt has detached and possibly created shoals to the south; Aunt Lydia Cove as an actual cove due to transgressive barrier islands coming ashore

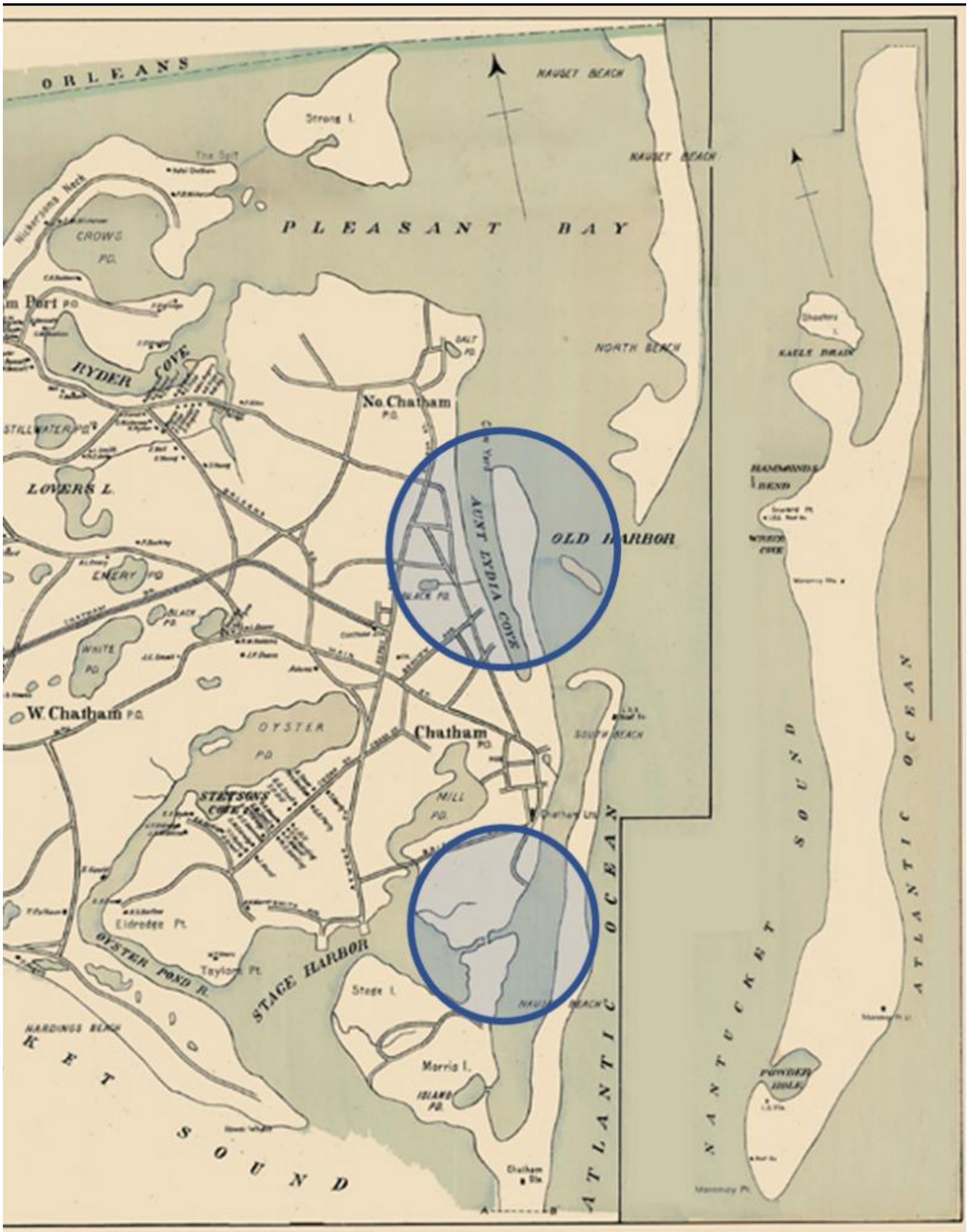


Figure 2.12 Detail of the 1910 chart of South Chatham shows Aunt Lydia's Cove as an actual cove and a hydraulic connection between Stage Harbor and Chatham Harbor.

2.3 Sea Level Rise Along the Chatham Coast

Most of the barrier beaches on Cape Cod are "transgressive," i.e., migrating landward and upward (in the long term) to cover the water body or salt marsh that lies behind it. This process is driven by sea level rise and occasional storm events; the barrier beach migrates to maintain equilibrium with the changing environment (Berman, 2015 Figure 2.13).

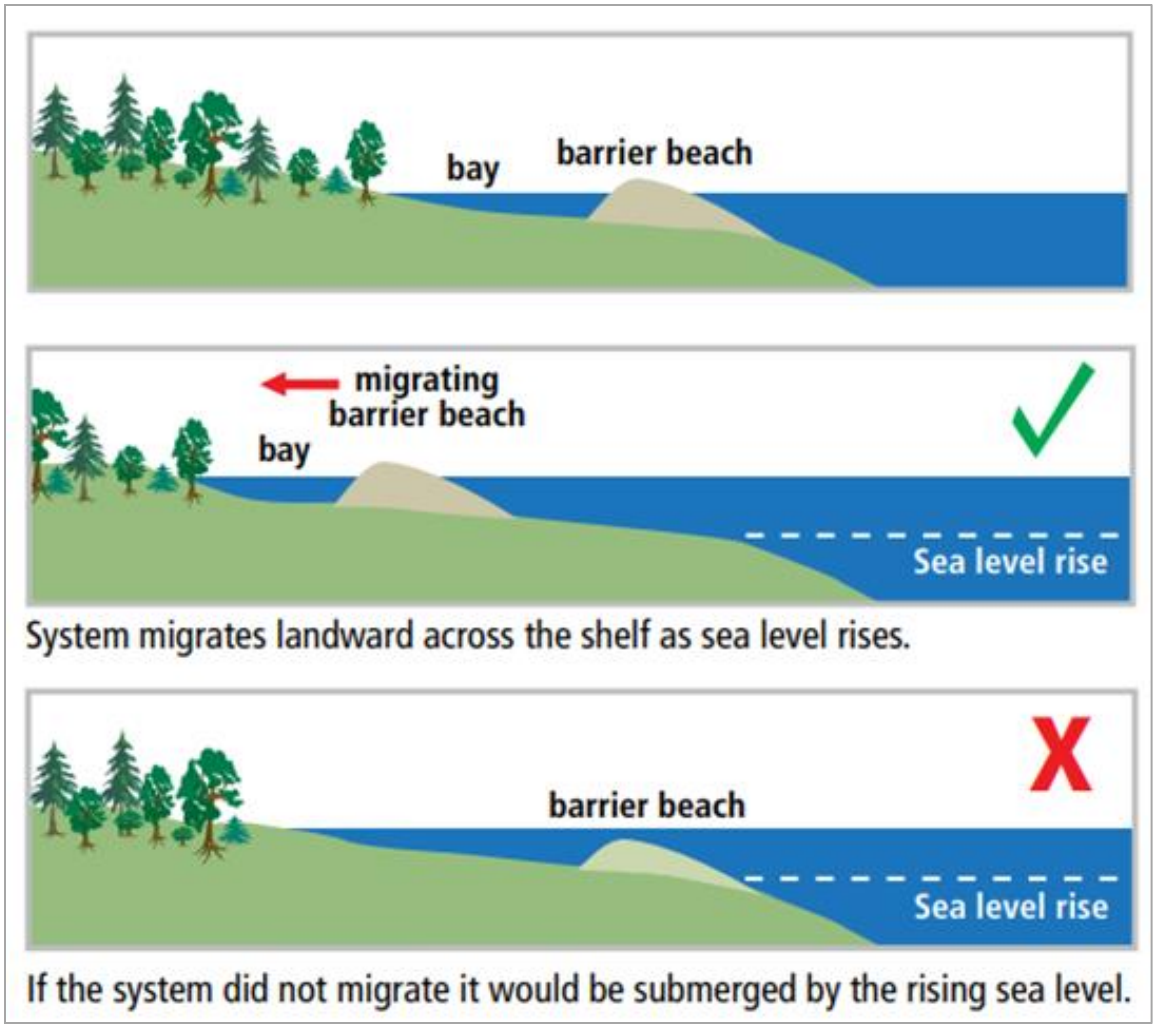


Figure 2.13 Barrier beaches on Cape Cod are "transgressive", migrating landward through natural coastal processes to avoid "drowning in place" (from Woods Hole Seagrant Program 2015).

Separate from the daily rise and fall of the tide, the average elevation of the ocean changes over time with respect to the land. This average position is called relative sea level and different geologic and atmospheric processes contribute to changes in relative sea level. Some of the causes include glacial ice melt, thermal expansion of the ocean as the global temperature increases, the velocity of the offshore Gulf Stream current, and the rising or sinking of the earth's crust itself. While the specific causes and future amounts of relative sea level ride (SLR) are the topic of much scientific debate, historical and present rates of SLR are well known for the region. A SLR trend of 2.8 mm per year (equivalent to about 1 foot per century) has been determined by NOAA for the tide record at Boston Harbor (Figure 2.14), which extends nearly a century to present.

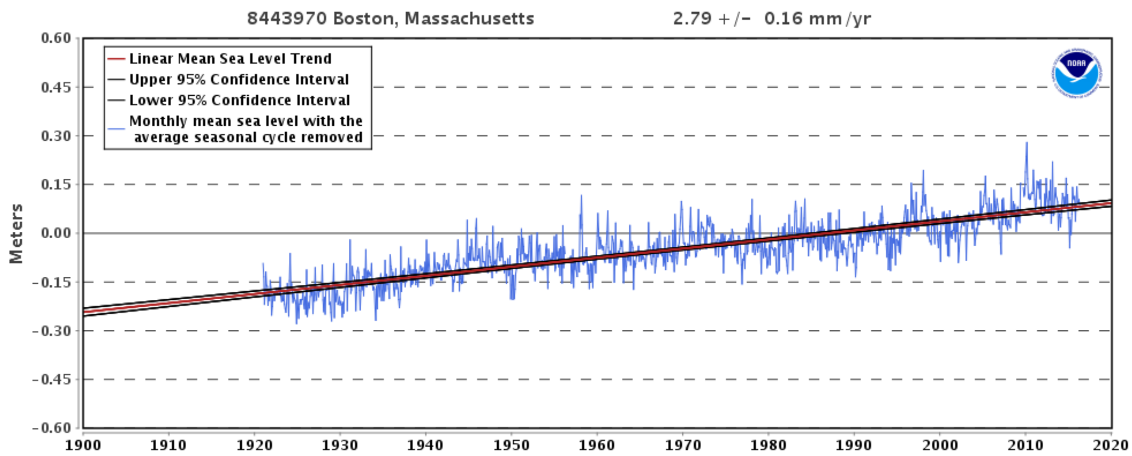


Figure 2.14 Long-term mean sea level data for NOAA Boston tide gauge station with linear trend and confidence interval.

The 2013 Intergovernmental Panel on Climate Change (IPCC) report benefits from recent advancements and includes for the first time regional sea level change projections. The report presents projections for nine representative coastal locations for which long tide records are available. One of those locations is New York City (NYC), which is used to represent the southern New England region, including Cape Cod.

The IPCC projection for NYC is shown in Figure 2.15. In this figure, 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 (Church et al. 2013, Borrelli et al. 2016).

The Pleasant Bay Alliance published a study in 2016 that annualized the IPCC results to project three 21st century sea level rise rates for the Pleasant Bay/Nauset Beach: 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) (Borrelli et al. 2016). Increased sea level rise could accelerate the migration of barrier beaches landward or even lead to their disappearance altogether if the rate of SLR outstrips the ability of the beach to react.

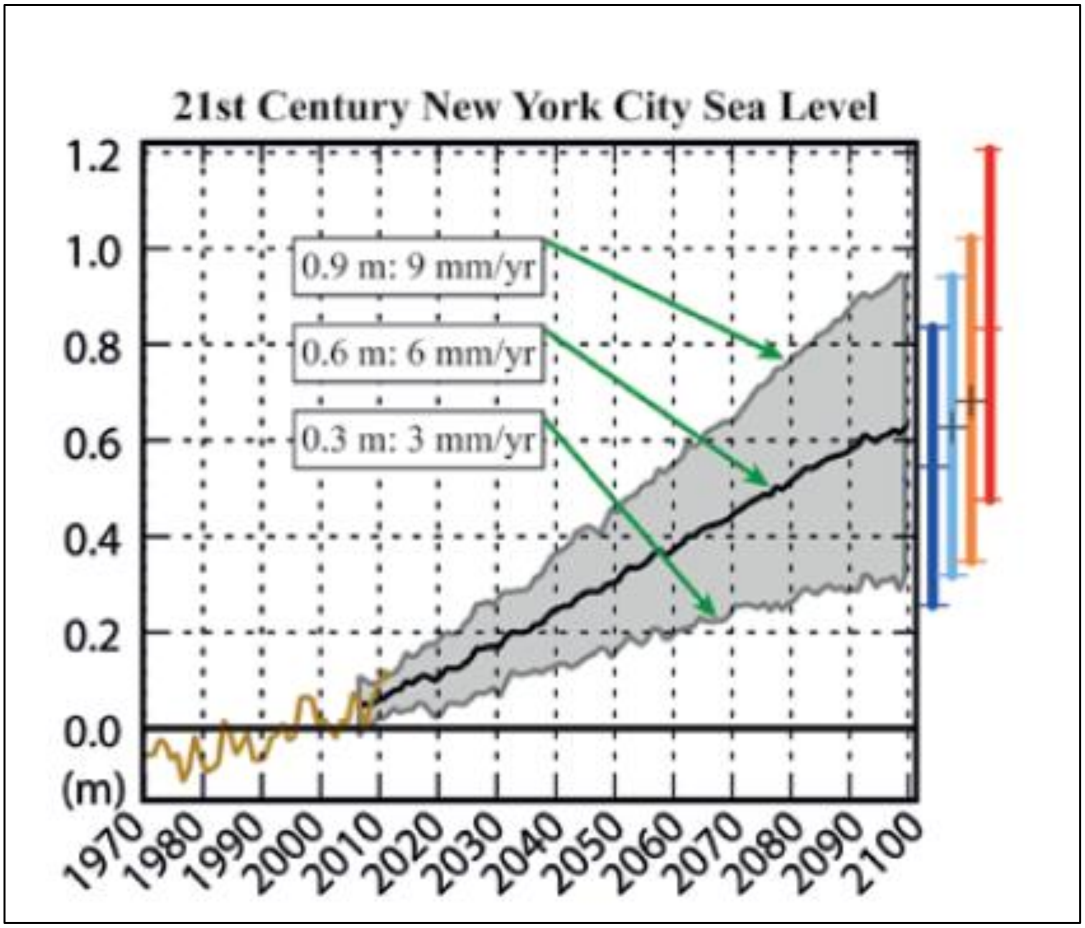


Figure 2.15 Observed and projected mean sea level change for New York City relative to MSL for 2000. Tide gauge record (since 1970) shown in brown. Shaded area indicates spread (5% to 95%) of results of 21 models using low-intermediate input "pathways". The black line shows the mean of the results. Vertical colored bars show 2100 MSL projections low input (dark blue); low-intermediate input (light blue); high-intermediate input (orange) and high input (red). Figure adapted in Borrelli et al (2016) from Church, et al. (2013).

The Massachusetts Office of Coastal Zone Management (MCZM) also published their own report in 2013 regarding future sea level rise projections along the Massachusetts coast based upon SLR projections developed by NOAA (Parris, *et al*, 2012). These projections utilized estimates for the historical linear trend, an "intermediate low" scenario, an "intermediate high" scenario, and a "high" scenario as shown in Figure 2.16. Utilizing the relatively conservative values associated with the "intermediate high" relative sea level rise projection for the region, the evaluation for future conditions assumed a 2-foot increase in relative sea level over the next 50 years.

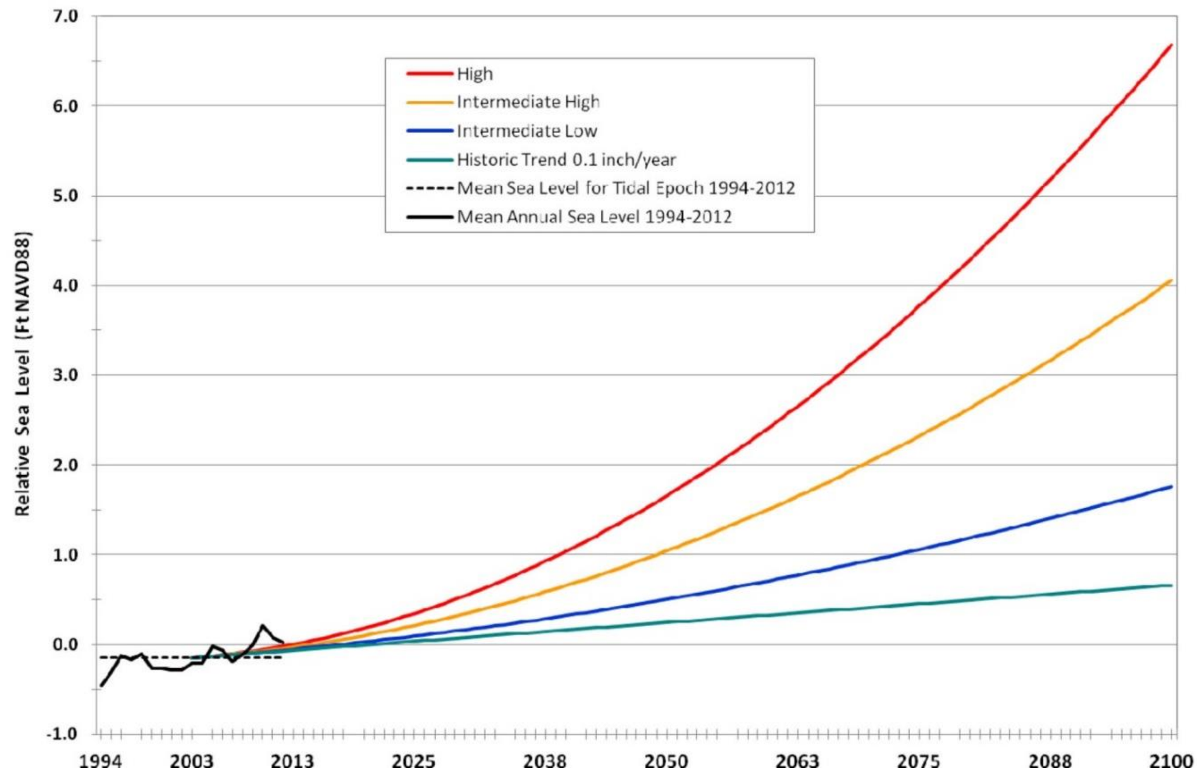


Figure 2.16 Relative sea level rise scenarios estimates (in feet NAVD88) for Boston, MA. Global scenarios from were adjusted to account for local vertical land movement with 2003 as the beginning year of analysis (*figure credit: MCZM, 2013*).

The Northeast Climate Adaptation Center published findings on changes in annual mean sea level, shown for Boston in Figure 2.17 (2018). Additional details on this can be found in their report available on resilientma.org.

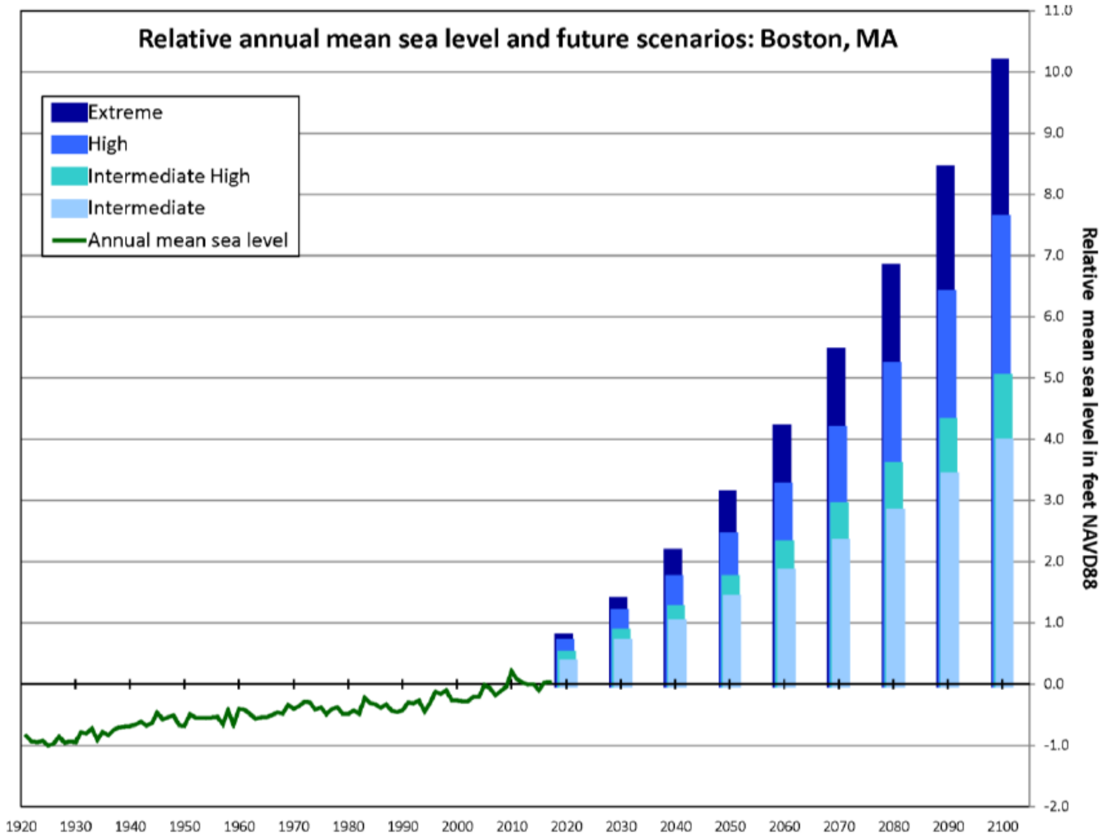


Figure 2.17 Relative annual mean sea level estimates (in feet NAVD88) for Boston, MA. (*figure credit: Northeast Climate Adaptation Center, 2018*).

3.0 DATA COLLECTION AND ANALYSIS FOR MODELING

The field data collection was performed by the Center for Coastal Studies (CCS). Field data are required to properly characterize the physical properties of any coastal system for which a numerical modeling analysis is undertaken. LiDAR and sidescan sonar bathymetry measurements were utilized throughout the system so that the complex network of channels could be represented accurately within the hydrodynamic model created for this study, which ultimately is used as the basis of the management analysis of Chatham Harbor and its inlets. Tide data also were collected at five gauging stations, as part of the field data collection effort. The tide data were used to force the circulation model from the Atlantic Ocean and Nantucket Sound, as well as to calibrate and corroborate its performance.

3.1 Bathymetry Data Collection

LiDAR bathymetry and topography data from the New England District of the USACE were made available from a survey flown in spring, 2018. These data were supplemented with additional sidescan sonar bathymetry collected by the Center for Coastal Studies in October 2018 and 2014. Supplemental bathymetry in the northern reaches of Pleasant Bay were available from past studies in the Pleasant Bay region, including for Bassing Harbor (Howes et al., 2003). All bathymetry data were tide corrected, and referenced to the North American Vertical Datum of 1988 (NAVD 88). Additional detail regarding collection and processing of bathymetry data collected by CCS is provided in Attachment 1.

The most recent bathymetry data show that the deepest point in the Pleasant Bay system is located proximate to Watch Hill, at -55 ft NAVD88 deep, at a point that has in recent decades been the location of the narrowest portion of the channel to South Inlet and Fools inlet. Other relatively deep spots occur at other channels to Chatham Harbor: the S-curve at North Inlet, Fools Inlet Channel, and the channel south of North Inlet that runs along the backside of the barrier island, with depths ranging from -21 to -23 ft NAVD88. Meetinghouse Pond, at the northern reach of Pleasant Bay, is a deep kettle pond with a maximum depth of -22 ft NAVD88.

3.2 Tide Data Collection and Analysis

CCS maintains tide gauges throughout the Pleasant Bay estuary as part of its long-term monitoring of the system. Tide data are collected with a 6-minute interval using HOBO temperature/pressure transducers. The pressure data recorded by the data loggers is later post-processed to corrected for atmospheric pressure, to determine the water elevation above the gauge. The transducers are inserted into a PVC pipe for protection and holes are drilled to allow the free flow of water. A tide staff was established at Meeting House Pond for a periodic visual check of calculated tide levels. The tide staff and tidal gauges were surveyed with offsets established to convert local tide staff readings to NAVD88 (in meters). Records from 1) Meetinghouse Pond, 2) Chatham Harbor at the Chatham Fish Pier, 3) Outermost Harbor, and 4) Stage Harbor were used in this study.

Tide data were also collected offshore from North Inlet using a stationary, upward-facing ADCP deployed from October 9 – November 13, 2018 (35 days). The ADCP collected water level data using a Keller pressure sensor with an accuracy of +/- 0.1% of FS plus a drift of +/- 0.11%. Data were downloaded from the ADCP using Teledyne *Velocity®* software. The pressure record from the gauge was converted to water depth above the gauge using atmospheric pressure changes recorded by a HOBO U20 pressure logger deployed at the Chatham Fish Pier. Additional details of ADCP deployment are provided in Attachment 1.

The locations of the tide gauge stations and ADCP deployment are shown in Figure 3.1. Tide data from all instruments were atmosphere-corrected to NAVD88 and are presented in Figure 3.2. Tide gauge data from Meetinghouse Pond, Chatham Fish Pier, and Outermost Harbor were used to calibrate this model; tide data from Stage Harbor were used as a boundary condition from Nantucket Sound (part of the Mid-Atlantic Bight); and tide data from offshore North Inlet were used as a boundary condition from the Gulf of Maine (Figure 3.2). All instrument data span longer than 29 days, the minimum required to record the monthly maximum and minimum astronomical tide ranges, and also to provide a record of sufficient length to perform a harmonic analysis to determine the 23 main tidal constituents at the instrument locations.

The loss of amplitude with distance from an inlet is described as tidal attenuation. Frictional mechanisms dissipate tidal flow energy, resulting in a reduction of the height of the tide. Tide attenuation is accompanied by a time delay (or phase lag) in the time of high and low tide (relative to the offshore tide), which becomes more pronounced farther into an estuary. Harmonic analysis and tide datums are analyses to evaluate the degree of tidal attenuation and frictional effects within an estuary.

The great degree of tidal energy attenuation across the inlets to Pleasant Bay gives an indication of the energy required to balance the pressure applied to the inlets from the large amount of littoral drift (sediment transport) along the shoreline of the outer Cape and Nauset Beach. The dissipated tidal energy works to oppose wave action acting on the open coast and the constant input of sand from Nauset Beach. However, the tidal and littoral dynamics are not in perfect balance at all times, as is evident by the cyclical nature of inlet migration and formation.

Figure 3.1 Locations of the four tide gauges (white triangles) and ADCP deployment (green triangle).

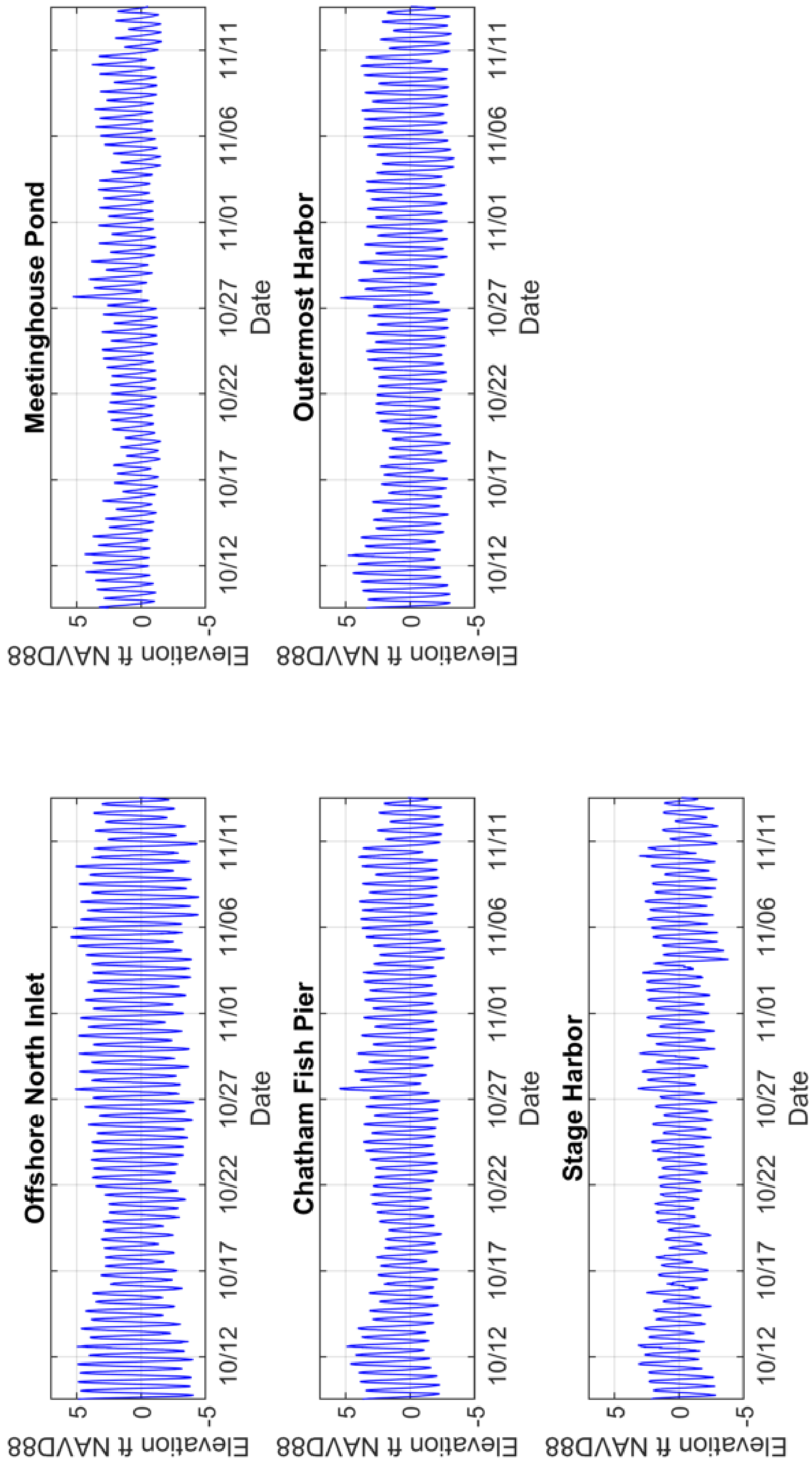


Figure 3.2 Measured tides during the October-November 2018 ADCP offshore gauge deploymentHarmonic Analysis

Tidal flows within the Pleasant Bay system are driven primarily by offshore water levels and are influenced by the hydrodynamic conditions of the inlets and flow paths within the estuary. A harmonic analysis was completed for each of the available tidal datasets to determine amplitude and phase of the major tidal constituents. This information was used to assess the propagation of tides though the system and the hydrodynamic ‘efficiency’ of the Pleasant Bay system.

Harmonic analysis is a mathematical procedure that fits sinusoidal functions of known frequency to the measured signal. The observed astronomical tide is therefore the sum of several individual tidal constituents, with a particular amplitude, period and relative phase. For demonstration purposes a graphical example of how these constituents add together is shown in Figure 3.3

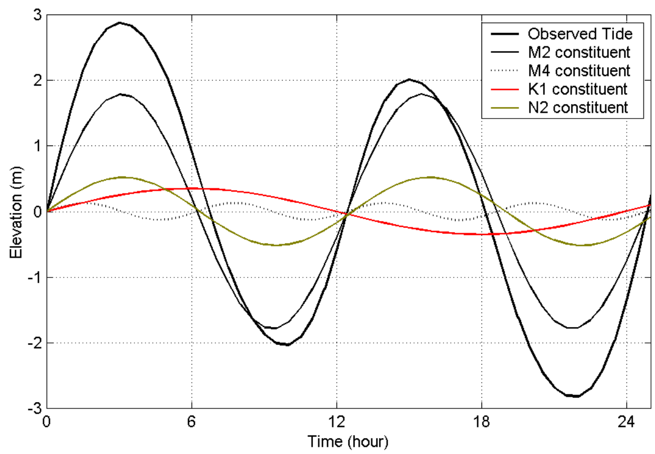


Figure 3.3 Example of an observed astronomical tide as the sum of its primary constituents.

Harmonic analysis was first conducted on each of the boundary condition datasets to determine how they influence tidal signals within the Pleasant Bays system. The measured tide data from each boundary condition dataset are presented in Figure 3.4 and Table 3.1 presents the amplitudes of eight tidal constituents for each of the boundary condition datasets and tide gauges in order of amplitude height, or energy.

Table 3.1 Major tidal constituents determined for each boundary condition dataset and tidal gauges during the 2018 offshore ADCP deployment in NAVD88 feet.

	Amplitude							
Constituent	M_2	N_2	S_2	K_1	O_1	M_{sf}	M_4	M_6
Period (hours)	12.42	12.66	12.00	23.93	25.82	354.61	6.21	4.14
Nantucket Boundary	1.87	0.42	0.23	0.31	0.26	0.11	0.13	0.07
Offshore Boundary	3.35	0.66	0.56	0.39	0.32	0.12	0.03	0.01
Outermost Harbor	2.66	0.49	0.39	0.32	0.26	0.21	0.22	0.06
Chatham Fish Pier	2.40	0.39	0.32	0.29	0.24	0.26	0.26	0.07
Meetinghouse	1.57	0.28	0.26	0.26	0.21	0.23	0.36	0.05

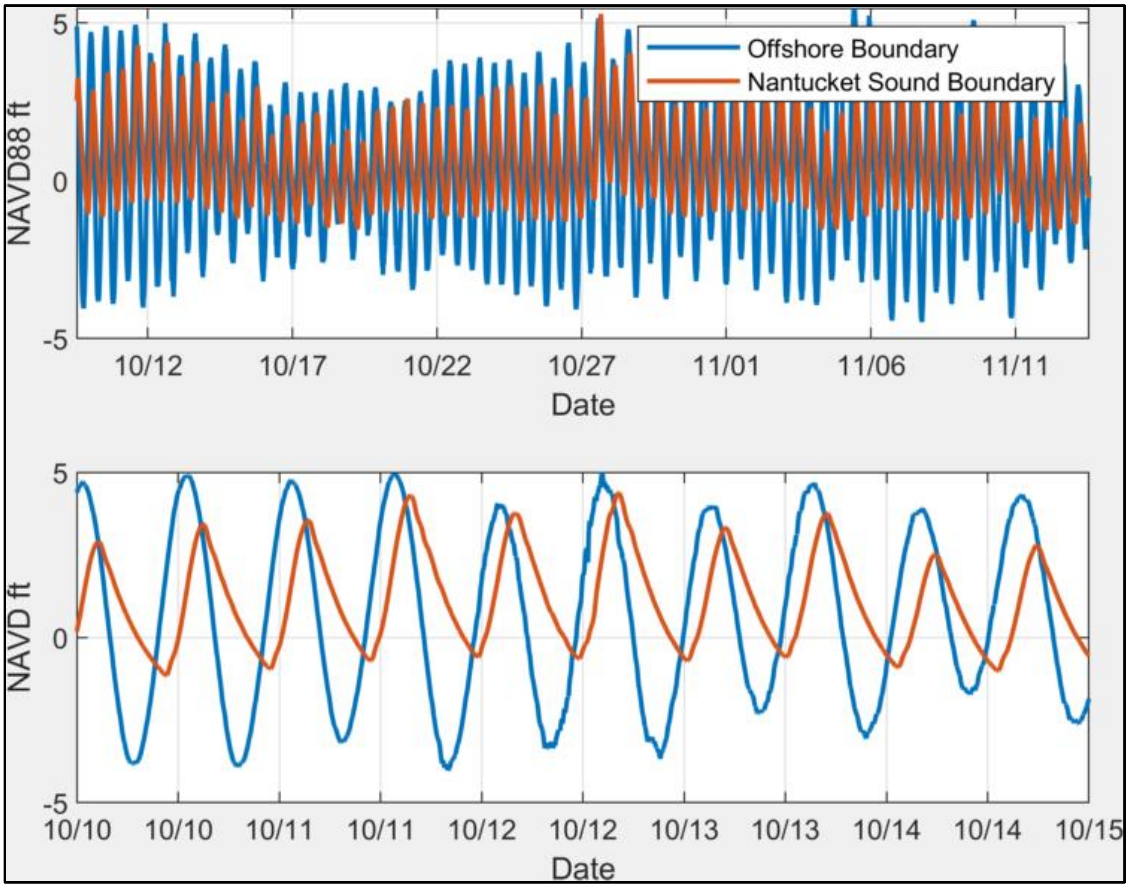


Figure 3.4 Tidal data from the offshore boundary condition and the Nantucket Sound boundary condition gauges. The top panel shows the full deployment (top) and the bottom panel shows a 5-day subset of deployment for finer detail.

The M_2, or the familiar twice-a-day lunar semi-diurnal tide, contributes the most energy to tides in Nantucket Sound and in the open ocean area offshore of Nauset Beach. However, the Nantucket Sound amplitude is 56% that of the Offshore M_2. This is caused by the differences in tide ranges in the Gulf of Maine and the Mid-Atlantic Bight. Chatham is located at the boundary of these two offshore regions, which can be seen in in Figure 3.5 (from the work of Chen *et al.,* 2011). This difference creates a hydraulic head that slopes down toward Nantucket Sound as tides pass from mid-flood to mid-ebb through high-slack water, and then reverses and slopes down toward the open Atlantic as the tide passes from mid-ebb to mid-flood though low-slack water.

The phasing of the tides in Nantucket Sound and offshore of Nauset Beach is similar, with the tide of high tide and low tide at both locations occurring at similar times, as can be seen in Figure 3.4. Results of the harmonic analysis show that the M_2 phase in the open Atlantic is approximately 25 minutes ahead of Nantucket Sound. If the tides in these two areas had a greater phase difference, larger head variances would result, and peak tide flows would be greater through Fools Inlet.

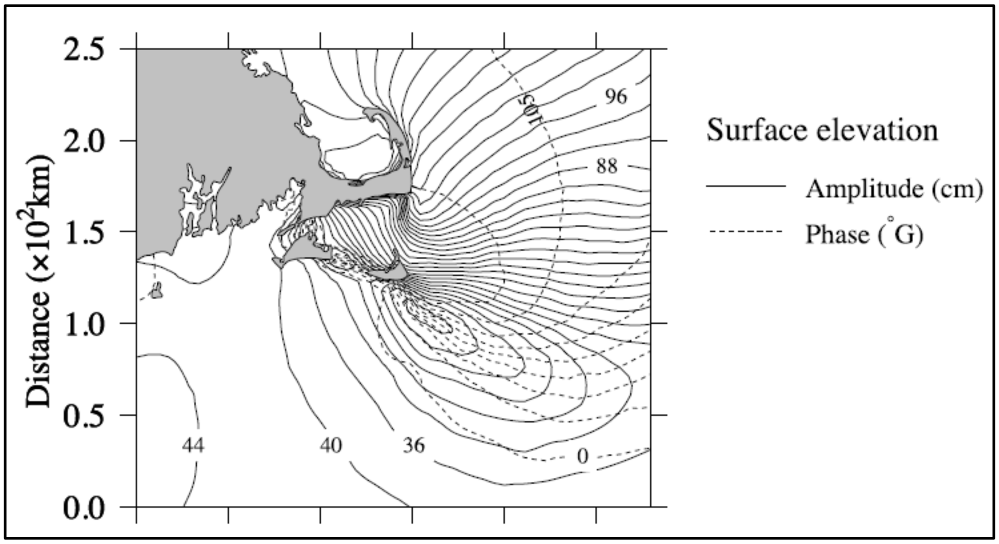


Figure 3.5 Distributions of the M_2 tidal amplitude (solid line) and phase (dashed line) over the New England shelf, Nantucket Sound/shoals, and east of Cape Cod for surface elevation. From Chen et al. 2011.

As the dominant boundary tide moves through the North or South inlet channel, the M_2 amplitude is reduced through hydraulic resistance. Of the inner Bay gauges, Outermost Harbor is closest to a boundary connection, presenting the least frictional attenuation of the gauges, and Meetinghouse Pond is the farthest from one, presenting the greatest attenuation. Even with its proximity to South Inlet, the M_2 amplitude at Outermost Harbor has been reduced to 2.66 ft, approximately 0.70 ft less than the Offshore amplitude. At the Chatham Fish Pier, the M_2 amplitude is further decreased to 2.40 ft, approximately one foot less than the Offshore amplitude, and at Meetinghouse Pond it is just 1.57 ft, barely 50% of the Offshore M_2 amplitude. The M_4 and M_6 tides are higher frequency harmonics of the M_2 lunar tide (exactly half the period of the M_2 for the M_4, and one third of the M_2 period for the M_6), results from frictional attenuation of the M_2 tide in shallow water. The M_4 has nearly a zero amplitude offshore, but grows to a maximum of 0.36 ft in Meetinghouse Pond in the northern extent of the system. The M_6 has a very small amplitude throughout the system.

The other major tide constituents also show similar variation between the offshore station and within the Bay. The diurnal tides (once daily), K_1 and O_1, show similar amplitude reductions with increasing distance from an inlet. Other semi-diurnal tides, the S_2 (12.00-hour period) and N_2 (12.66-hour period) tides (with offshore amplitudes of 0.23 and 0.42 ft respectively), also are attenuated though the inlet, resulting in maximum amplitude reductions of approximately 50% at Meetinghouse Pond as compared to offshore. The M_{sf} is a lunarsolar fortnightly constituent with a period of approximately 14 days, and is the result of the periodic conjunction of the sun and moon, and has an offshore amplitude less than 0.20 ft.

3.2.1.1 Tide Datums

Standard tide datums were computed from the available tide records and are presented in Table 3.2. From this table it is seen that there is a 26% reduction in the mean tide range (nearly 2 feet) from offshore the inlets to the fish pier. The two-day sample of tide elevations at three of the Pleasant Bay stations in Figure 3.6 visually demonstrates this reduction in range. A further reduction in mean tide range occurs between the fish pier and the upper-most reaches of the system in Meetinghouse Pond.

For most NOAA tide stations, these datums are computed using 19 years of tide data, the definition of a tidal epoch. For this study, a significantly shorter time span of data was available; however, these datums still provide a useful comparison of tidal dynamics within the system. The Mean High Water (MHW) and Mean Low Water (MLW) levels represent the mean of all the high and low tides of a record. The Mean Tide Level (MTL) is simply the mean of MHW and MLW. The calculated offshore tide range in Table 3.2 is 7 ft while the corresponding tide range in Meetinghouse Pond is 3.8 ft. Additionally, there is a noticeable reduction in MLW levels with increased distance from an inlet, as evidenced when comparing Outermost Harbor (-2.66 ft) to the Chatham Fish Pier (-1.94 ft) to Meetinghouse Pond (-1.05 ft). This suggests a significant attenuation of ebb tide with increased distance from the inlets. The tide lag is evident in Figure 3.6, with the greatest lag occurring at Meetinghouse Pond where low tide occurred 3.75 hours after low tide offshore.

Table 3.2 Tide datums computed using measured data collected in the Pleasant Bay system during 2018 offshore ADCP deployment. Datum elevations are given in feet relative to NAVD 88.

Tide Datum	Meeting-house Pond	Fish Pier	Outermost Harbor	Nantucket Boundary (Stage Harbor)	Offshore Boundary
Maximum Tide	5.28	5.48	5.41	3.22	5.48
MHHW	3.11	3.54	3.31	2.30	4.30
MHW	2.76	3.22	2.99	1.94	3.94
MTL	0.85	0.62	0.16	-0.13	0.43
MLW	-1.05	-1.94	-2.66	-2.17	-3.08
MLLW	-1.15	-2.10	-2.85	-2.46	-3.44
Minimum Tide	-1.61	-2.72	-3.44	-3.81	-4.46
Tide Range (MHW+MLW)	3.81	5.16	5.65	4.11	7.02

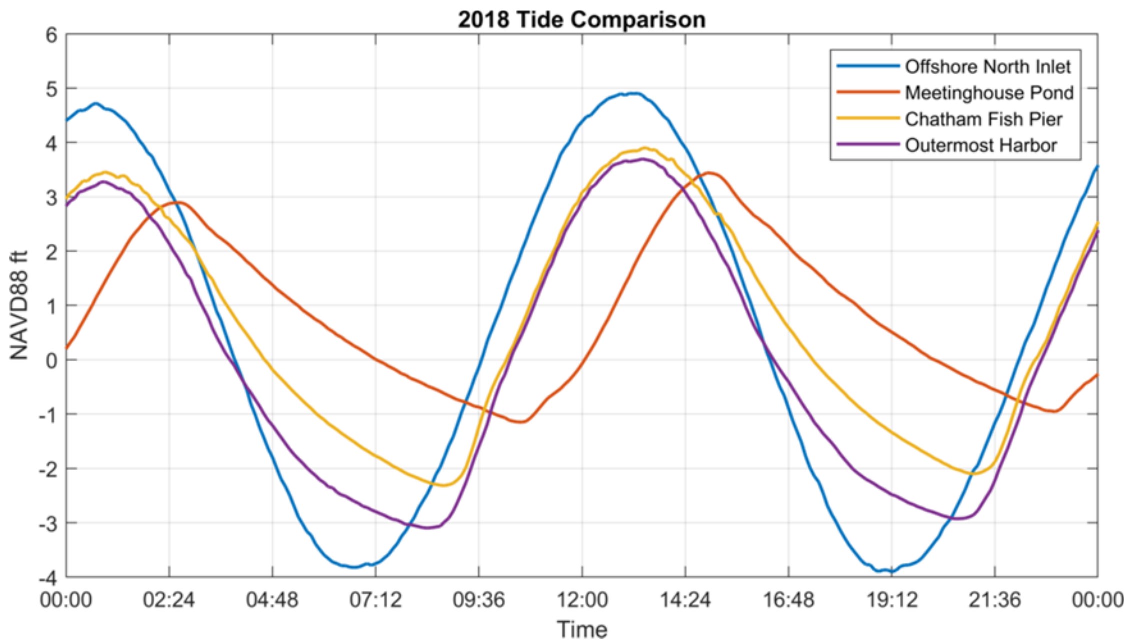


Figure 3.6 Plot showing two tide cycles tides for the dominant offshore boundary and three inner Bay stations plotted together in 2018. Demonstrated in this plot is the significant frictional damping effect caused by flow restrictions at the inlet channels. The damping effects are seen as a reduction in the range of the tide and a lag in time of high and low tides from the Atlantic Ocean. The time lag of low tide between the ocean and Meetinghouse Pond in this plot is approximately four hours.

3.3 Grain Size Analysis

Sediment samples were collected and analyzed by the Center for Coastal Studies in 2015 as part of their 2018 technical report. Figure 3.7 presents median grain sizes throughout the Pleasant Bay system. This figure shows that the dominant sediment type in the system is coarse sand greater than 250 microns, with finer grain sizes in deeper and/or distal areas of the system. Table 3.3 presents the sediment distribution used as input to the 2018 hydrodynamic model based on grain size sample results proximal to the inlets.

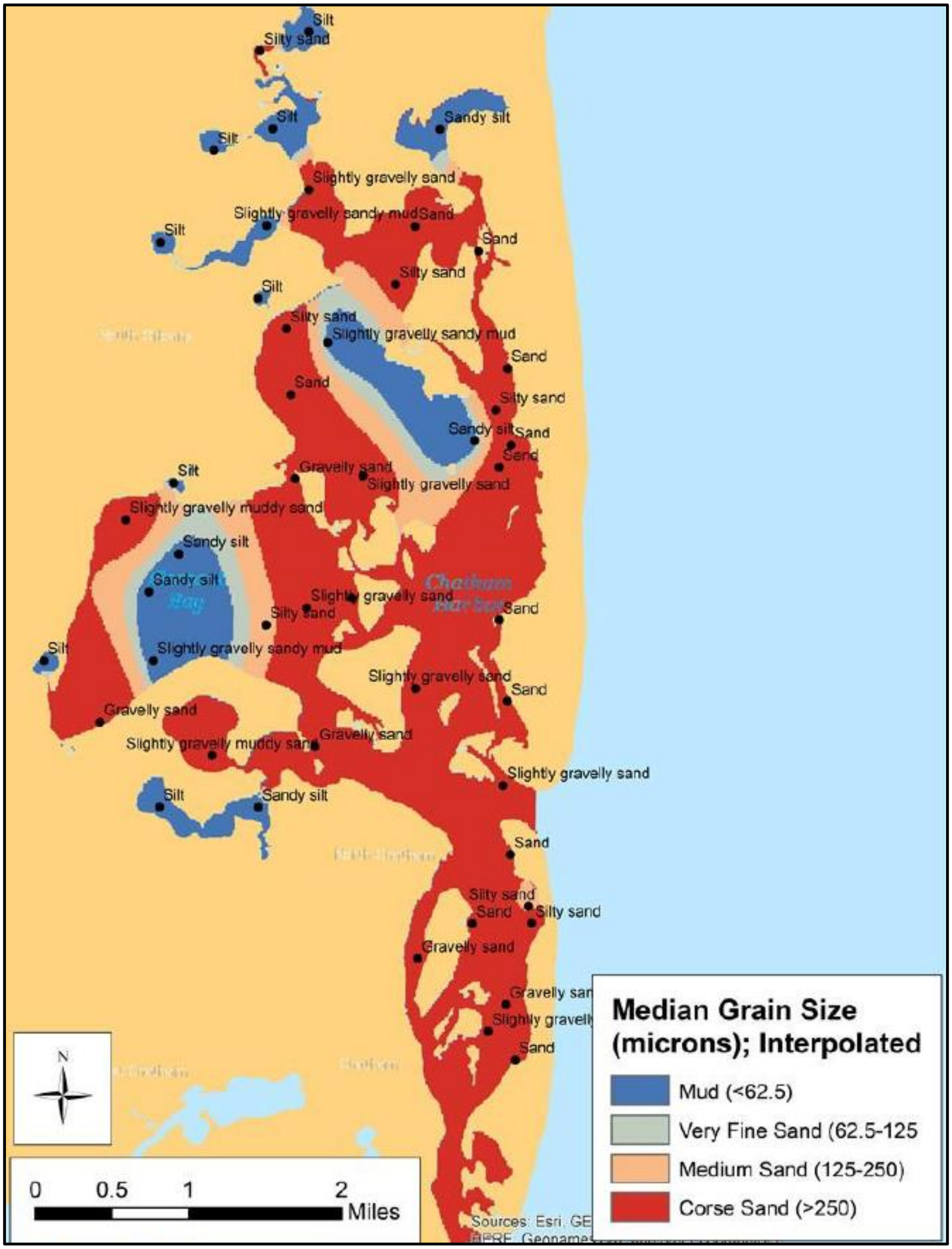


Figure 3.7 Median grain size in microns (interpolated) for Pleasant Bay. From Center for Coastal Studies 2018

Figure 3.8 Location of 6 sediment samples used to determine the grain size distribution for the 2018 model grid.

Table 3.3 Grainsize distribution used as input to model grid	
	(mm)
D_{10}	1.23
D_{50}	0.73
D_{90}	0.39

3.4 Wind and Waves

Wind and wave data were downloaded from the USACE wave information studies (WIS) hindcast database from station 63067. The WIS station is located 10 miles east of Chatham Light and has a record that spans the 33-year period between January 1980 and December 2012. The WIS data were used to develop offshore wave and wind conditions for the wave model. Each hourly WIS time step includes parameters that describe wave conditions (i.e., wave period, T_p; wave height, H_s; and direction, θ) and wind (direction and speed) at the station.

To determine wave and sediment transport patterns, the wave record was reduced to include only waves that affected sediment transport along the Chatham shoreline. Figure 3.9 shows a histogram of wave height occurrences that approach the 180-degree compass sector from 9 degrees (NNE) to 189 degrees (SSW), corresponding roughly to the seaward shoreline orientation of North Beach Island. This selected record was sorted by wave height and then divided into thirds. Each third was analyzed to determine the sum of the x and y components and resultant propagation direction and energy. The vector mean wave direction for the included compass sector is determined as:

mean x component of wave energy, $E_x = \sum H^2 \cos\theta$,
mean y component of wave energy, $E_y = \sum H^2 \sin\theta$,

$$\theta = \tan^{-1}\left(\frac{\sum E_x}{\sum E_y}\right).$$

The mean wave height for the included compass sectors is determined as:

$$H_{1/3} = \frac{\sqrt{\sum H^2}}{\mathrm{N}}$$

where $H_{1/3}$ is the significant wave height, θ is the vector mean wave direction, and N is the number of wave records

Table 3.4 Results of analyzing WIS data that approach the Chatham coastline from 9º to 189º

Wave Height	Vector Mean Wave Direction	Mean Significant Wave Height (ft)
Largest 1/3	82.50	6.69
Middle 1/3	117.50	3.05
Bottom 1/3	127.83	1.77

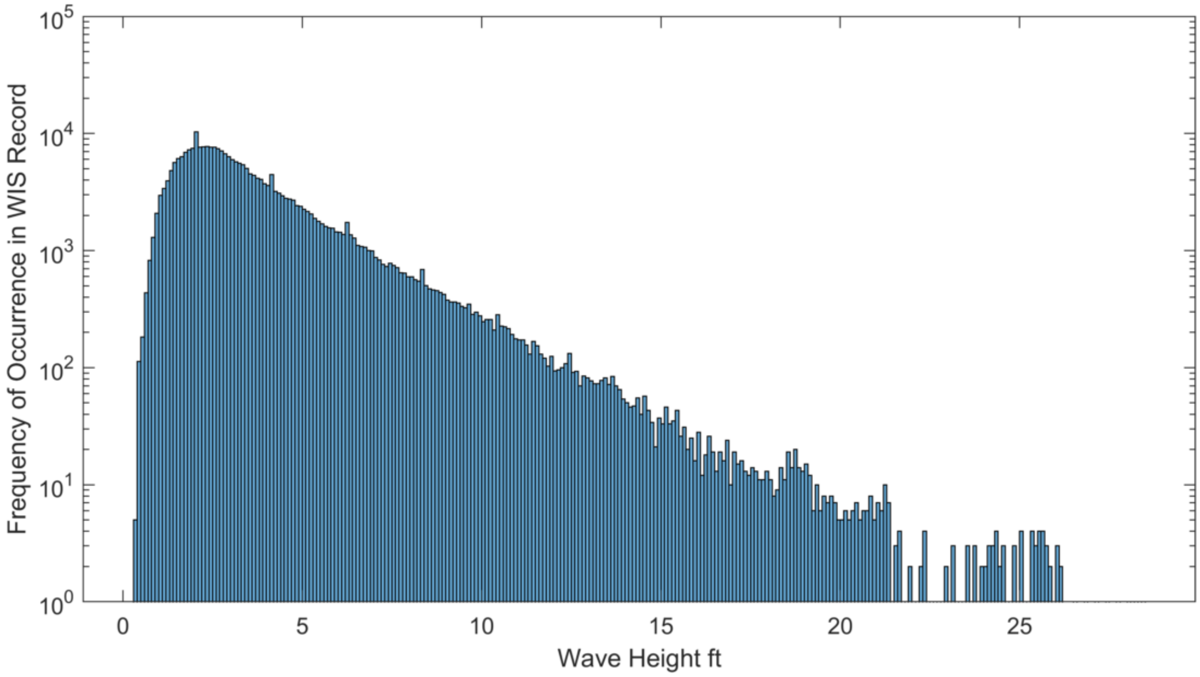


Figure 3.9 Frequency of wave height occurrence for waves that drive sediment transport along the Chatham coast (propagating from compass directions 9º to 189º).

Overall, the top 1/3 wave heights (largest waves) propagate from the ENE, the middle 1/3 wave heights propagate from the ESE and the bottom 1/3 wave heights (smallest waves) propagate from the SE.

Multiple storms were evaluated to determine offshore wave and wind conditions during severe northeastern storms as inputs for the wave model. Storm conditions for infrequent, severe northeast storms were used as inputs for the wave model. An offshore wave height of 25.5 ft propagating towards the shoreline from 82.5º and a wind speed of 40 miles per hour (mph) blowing from 70º were used as inputs.

4.0 MODEL DEVELOPMENT

The Coastal Modeling System (CMS) of the US Army Corps of Engineers (Sanchez, et al., 2014) was implemented to develop models that represent the past, present, and future hydrodynamic conditions of Pleasant Bay. CMS is well suited for meso-scale modeling (domains with dimensions of the order of 1 to 100 kilometers) and is a fully-featured morpho-dynamic modeling system that simulates two-dimensional sediment transport driven by the interaction of hydrodynamics and ocean waves. The final calibrated CMS morphological model of Pleasant Bay is a useful analysis tool that provides insight into the dynamic forces that are driving the evolution of the barrier system, its inlets and main channels. Morphological models like the one developed for this study greatly leverage the utility of measured data (i.e. bathymetry, tides, and currents) by providing and economical and scientifically based means of effectively expanding the regional and temporal reach of the collected data.

The work flow required to implement this model system has three main tasks which are discussed in detail in following sections:

- Grid generation
- Boundary condition specification
- Calibration
- Grid generation
- Boundary condition specification
- Calibration

The extent of each model grid was generated using the field data discussed in Section 3. Two time-varying water surface elevation boundary conditions (measured tide) were specified: one from the Atlantic Ocean based on the tide gauge data collected offshore Nauset Beach, and one from Nantucket Sound, based on the tide gauge data collected at Stage Harbor. Once the grid and boundary conditions were set, the model was calibrated to ensure accurate predictions of tidal flow and water surface elevations. Friction coefficients were adjusted to obtain agreement between measured and modeled tides. The calibrated model of present conditions provides an accurate portrayal of the hydrodynamics of the system conditions that existed at the time the different sources of data were collected, but does not account for further morphological changes that may have occurred since its completion.

The hydrodynamic circulation model CMS-Flow is a component of the Coastal Modeling System developed by the US Army Corps of Engineers Coastal and Hydraulics Laboratory. The model is a finite-volume numerical engine which includes the capabilities to compute hydrodynamics (water levels and current flow values under any combination of tide, wind, surge, waves and river flow), sediment transport, and morphology change. Cells are defined on a staggered, rectilinear grid and can have constant or variable side lengths.

4.1 Grid Generation

The CMS computational grid is a non-uniform Cartesian grid with rectangular mesh that provides additional refinement by implementing a telescoping mesh. The grid mesh cell size can be adjusted to allow for greater resolution in areas of focused interest or complexity. Local refinement is achieved by subdividing a cell into 4 equally-sized cells with a side length that is on-half of the original cell dimension.

The hydrodynamic grid for this study was created using the bathymetry data detailed in Section 3.1. These data were imported to the grid generation software SMS, and a grid mesh was created to represent the estuary. Bathymetry data were interpolated to the developed finite volume mesh used to represent the Pleasant Bay system. Within the Pleasant Bay estuary, the mesh grid size ranges from 10 m (32 ft) up to 160 m (524 ft) in Pleasant Bay. Offshore grid size is 320 m. Aerial photographs provided by the Town of Chatham were used to confirm grid accuracy.

The completed grid consists of 115,998 total 2-dimensional (depth averaged) rectilinear elements, and covers 33,553 acres. The completed grid mesh and grid bathymetry are shown in Figure 4.1.

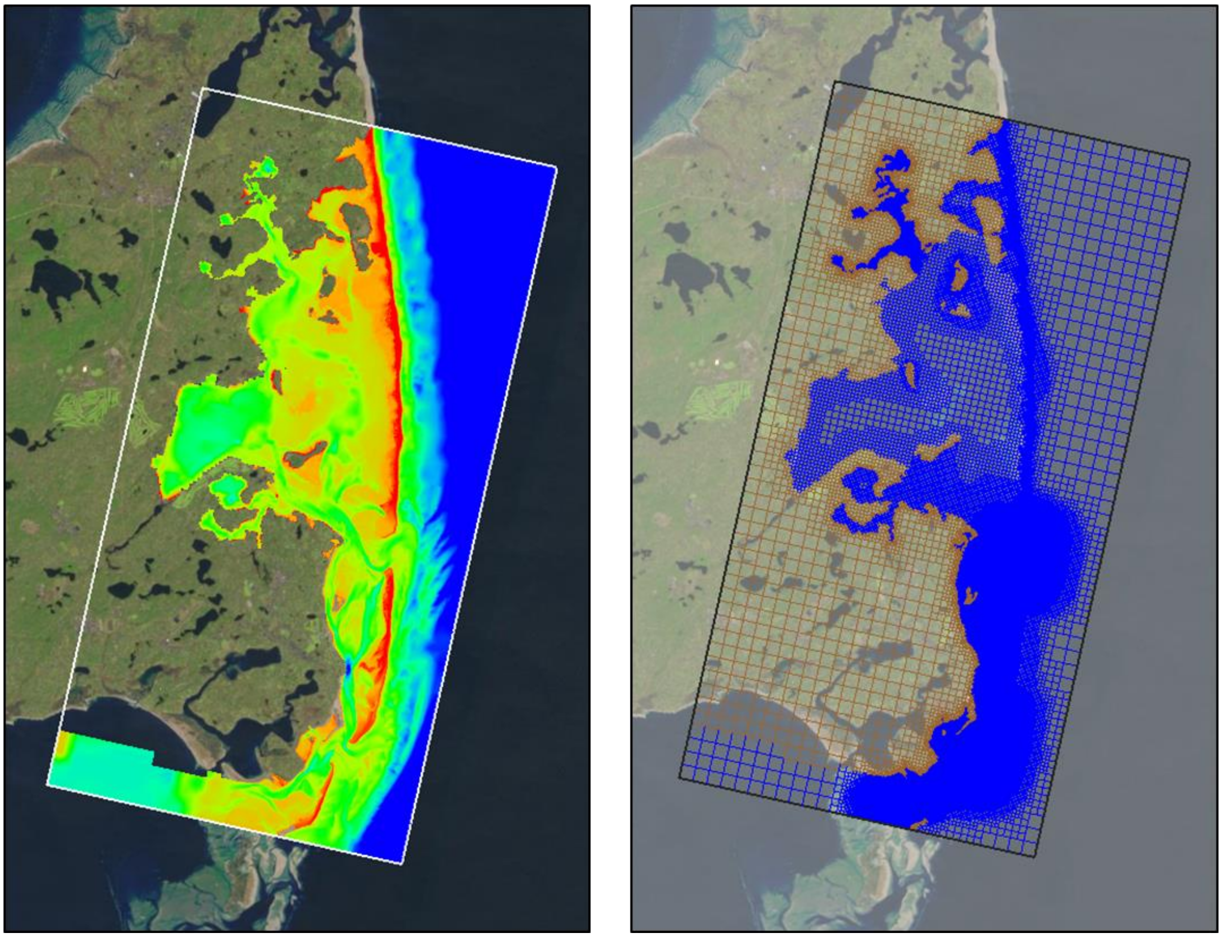


Figure 4.1 Hydrodynamic model bathymetry (left) and computational grid (right). In the computational grid, blue cells indicate water and brown cells indicate land.

The finite element grid for the system provided the detail necessary to accurately evaluate the variation in hydrodynamic properties throughout the system. The SMS grid generation program was used to develop rectilinear two-dimensional elements throughout the estuary. Grid resolution was governed by two factors: 1) expected flow patterns, and 2) the bathymetric variability of the system. Relatively fine grid resolution was employed where complex flow patterns were expected. For example, smaller node spacing in the main channels of Chatham Harbor was used to provide a more detailed analysis in these regions of rapidly varying flow (e.g., at the inlet channels). Widely spaced nodes were often employed in areas where flow patterns are not likely to change dramatically or less resolution was required, such as in the main basin of Pleasant Bay. Appropriate implementation of wider node spacing and larger elements reduced computer run time with no sacrifice of accuracy.

4.2 Boundary Condition Specification

The rise and fall of the tide in the larger basins that connect to the Chatham Harbor/Pleasant Bay System, the Atlantic Ocean and Nantucket Sound, are the primary driving forces for estuarine circulation in this system. Dynamic (time-varying) model simulations specified a new water surface elevation at the Pleasant Bay inlets every model time step of 6 minutes, which corresponds to the time step of the TDR data measurements

4.3 Hydrodynamic Calibration

After developing the computational grid, and specifying boundary conditions, the model for the Pleasant Bay system was calibrated. The calibration procedure ensures that the model predicts accurately what was observed in nature during the field measurement program. Numerous model simulations are typically required for an estuary model, specifying a range of friction and eddy viscosity coefficients, to calibrate the model. A Manning's friction coefficient value (Lindeburg, 1992) of 0.025 was used for the entire system.

Calibration of the hydrodynamic model required a close match between the modeled and measured tides in each of the sub-embayments where tides were measured. Initially, the model was calibrated to obtain visual agreement between modeled and measured tides. Once visual agreement was achieved, a five lunar-day period (10 tide cycles) was chosen to calibrate the model based on dominant tidal constituents. The five-day period was extracted from a longer simulation to avoid effects of model spin-up. Modeled tides for the calibration time period were evaluated for time (phase) lag and height damping of dominant tidal constituents.

The calibration was performed for an eight-day (200-hour) period beginning October 9, 2018 13:00 EST. This representative time period begins just prior to highest the spring tide range of the tide gauge deployment period, when tidal currents are greatest, and model numerical stability is often most sensitive.

Figure 4.2 through Figure 4.6 illustrate the five-day calibration simulation along with a 50-hour sub-section. Modeled (solid line) and measured (dotted line) tides are illustrated at each model location with a corresponding TDR.

Although visual calibration achieved reasonable modeled tidal hydrodynamics, further tidal constituent calibration was required to quantify the accuracy of the models. Calibration of M_2 (principle lunar semidiurnal constituent) was the highest priority since M_2 accounted for a majority of the forcing tide energy in the modeled systems. Due to the duration of the model runs, four dominant tidal constituents were selected for constituent comparison: K_1, M_2, M_4, and M_6. Table 4.1 compares tidal constituent amplitude (height) and relative phase (time) for modeled and measured tides at the tide gauge locations. The constituent phase shows the relative timing of each separate constituent at a particular location, and also the change (or phase lag) in timing of a single constituent at different locations in an estuary.

The constituent calibration resulted in agreement between modeled and measured tides. The largest errors associated with tidal constituent amplitude were on the order of 0.34 ft, which is consistent with the order of accuracy of the tide gauges ($\pm$0.13 ft). Time lag errors were typically equivalent to the time increment resolved by the model (6 minutes), indicating good agreement between the model and data.

Table 4.1 Tidal constituents for measured tide data and calibrated model output, with model error amplitudes, for the Pleasant Bay system, during modeled October 2018 200-hr calibration time period (9-17 October 2018).

Location	Constituent Amplitude (NAVD88 ft)				Phase (deg)	
Model Calibration Run						
Location	Constituent Amplitude (NAVD88 ft)				Phase (deg)	
	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Offshore	3.39	0.06	0.02	0.46	-13.6	79.69
Stage Harbor	1.91	0.13	0.07	0.36	2.61	115.00
Chatham Fish Pier	2.78	0.16	0.09	0.37	-0.88	-81.13
Meetinghouse	1.95	0.45	0.09	0.29	46.81	37.59
Outermost Harbor	2.91	0.10	0.08	0.40	-6.34	-96.90
Measured Tide During Calibration Run						
Location	Constituent Amplitude (NAVD88 ft)				Phase (deg)	
	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Offshore	3.39	0.06	0.02	0.46	-13.64	79.69
Stage Harbor	1.91	0.13	0.08	0.36	2.62	114.79
Chatham Fish Pier	2.44	0.25	0.08	0.33	3.33	-68.51
Meetinghouse	1.71	0.40	0.06	0.31	54.54	48.24
Outermost Harbor	2.76	0.21	0.08	0.37	-3.54	-69.35
Error (measured-modeled)						
Location	Constituent Amplitude (NAVD ft)				Phase (deg)	
	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Offshore	0.00	0.00	0.00	0.00	-0.06	0.69
Stage Harbor	0.00	0.00	0.01	0.00	0.03	-0.22
Chatham Fish Pier	-0.34	0.09	-0.01	-0.04	8.74	13.06
Meetinghouse	-0.24	-0.05	-0.03	0.02	16.02	11.02
Outermost Harbor	-0.15	0.11	0.00	-0.03	5.81	28.51

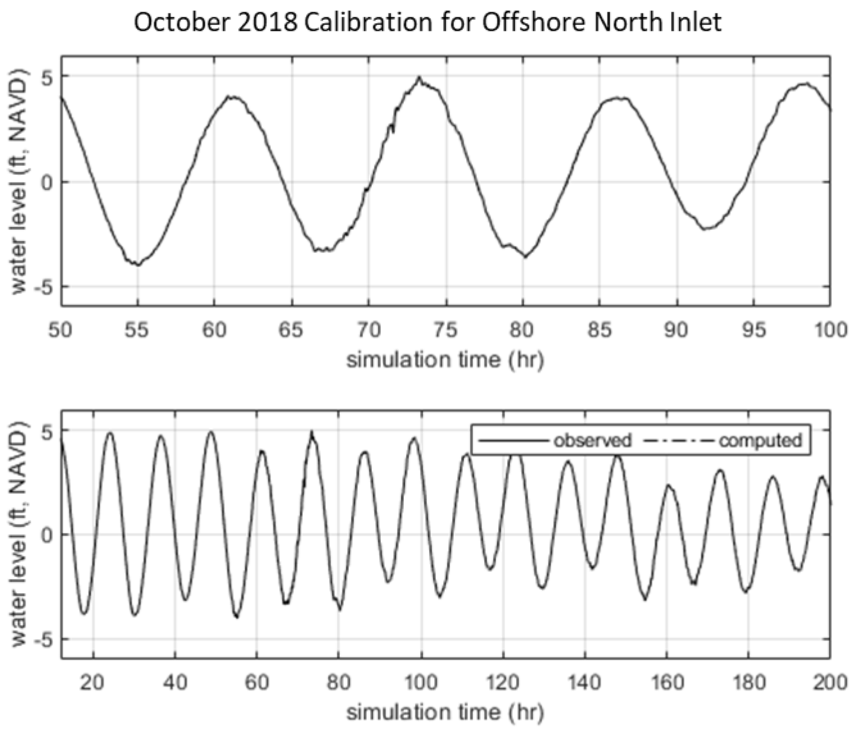


Figure 4.2 Comparison of model output and measured tides for the ADCP data located Offshore North Inlet. The top plot is a 50-hour sub-section of the total modeled time period, shown in the bottom plot.

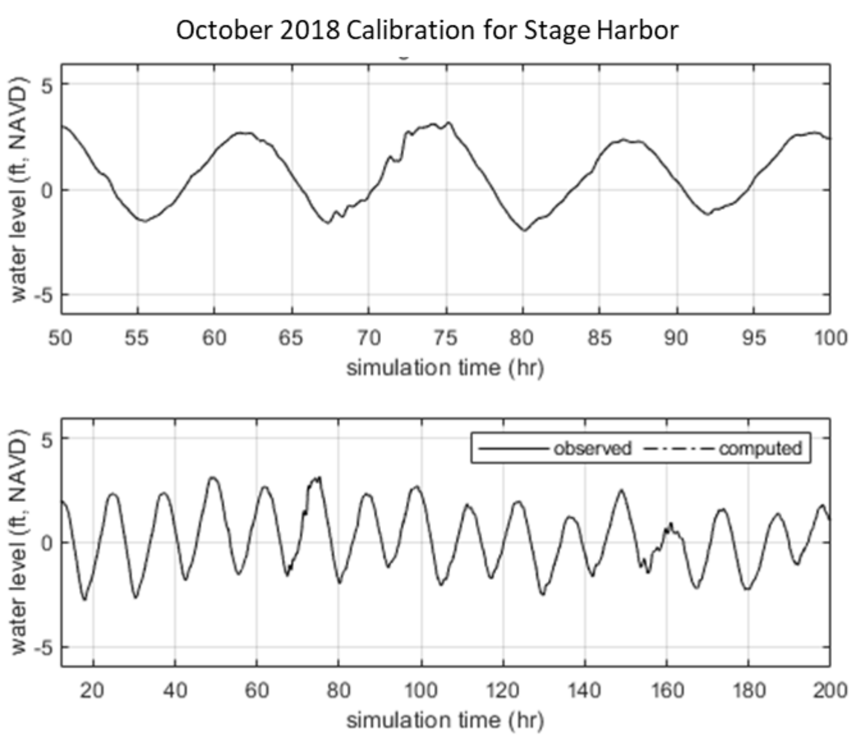


Figure 4.3 Comparison of model output and measured tides for the Stage Harbor tide gauge. The top plot is a 50-hour sub-section of the total modeled time period, shown in the bottom plot.

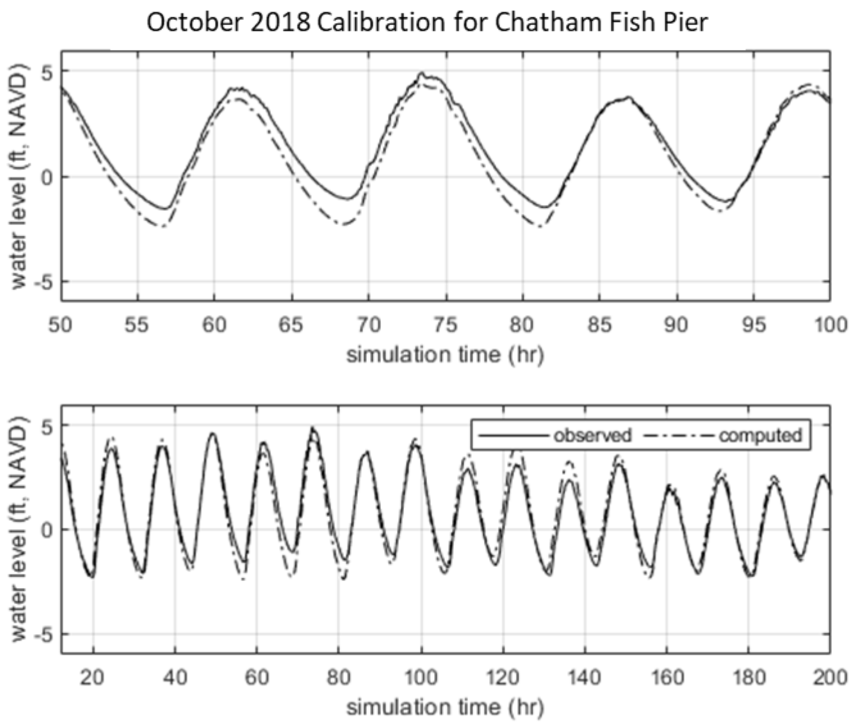


Figure 4.4 Comparison of model output and measured tides for the Chatham Harbor tide gauge. The top plot is a 50-hour sub-section of the total modeled time period, shown in the bottom plot.

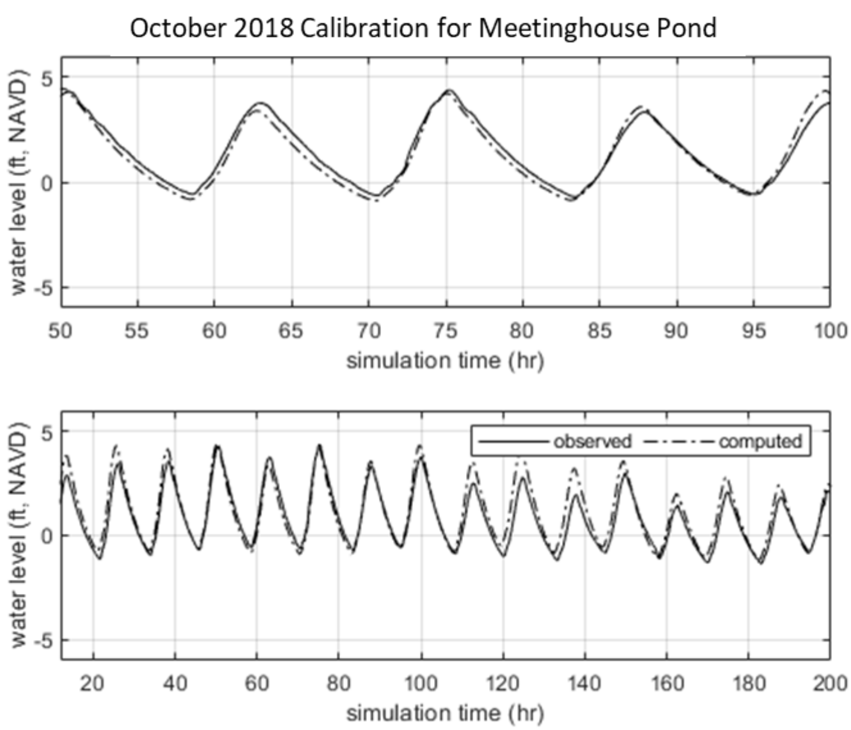


Figure 4.5 Comparison of model output and measured tides for the Meetinghouse Pond tide gauge. The top plot is a 50-hour sub-section of the total modeled time period, shown in the bottom plot.

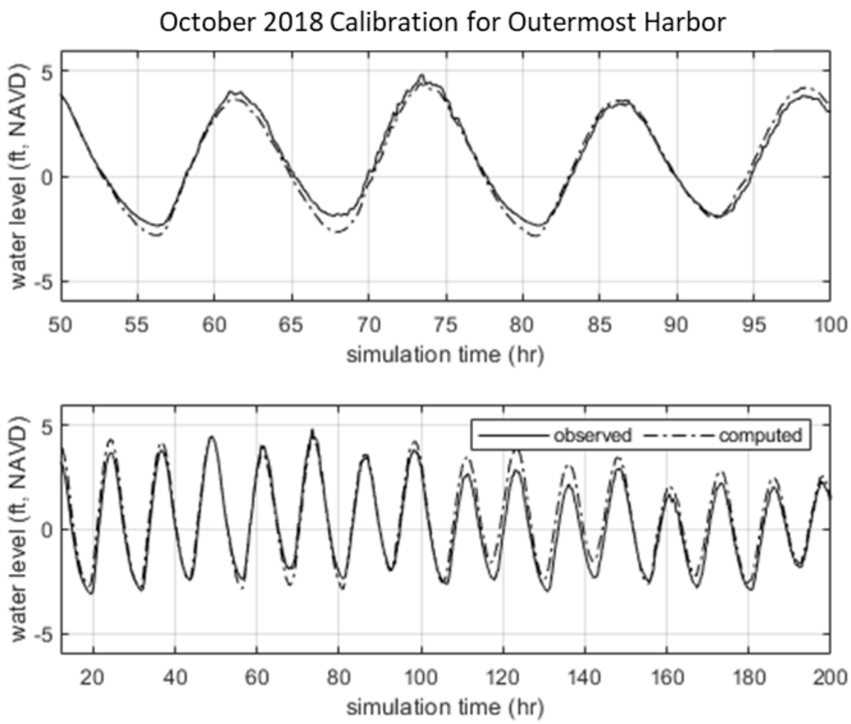


Figure 4.6 Comparison of model output and measured tides for the Outermost Harbor tide gauge. The top plot is a 50-hour sub-section of the total modeled time period, shown in the bottom plot.

The calibrated hydrodynamic model is a useful tool that is an extension of the physical data used in its development. The model can be used to examine the hydrodynamic characteristics of the system in areas or for times where no physical data exist.

4.4 Hydrodynamic Validation

Once calibration was achieved, an additional validation run was completed to evaluate a period of time that was independent from the calibration period. The validation was performed for a 160-hour period beginning October 23, 2018 11:00 EST.

Figure 4.7 through Figure 4.11 illustrate the five-day calibration simulation along with a 50-hour sub-section. Modeled (solid line) and measured (dotted line) tides are illustrated at each model location with a corresponding TDR.

The same four dominant tidal constituents were selected as was done for the calibration period for constituent comparison: K_1, M_2, M_4, and M_6. Table 4.2 compares tidal constituent amplitude (height) and relative phase (time) for modeled and measured tides at the tide gauge locations.

The constituent validation resulted in agreement between modeled and measured tides. The largest errors associated with tidal constituent amplitude were consistent with those from the calibration period, on the order of 0.3 ft, which is consistent with the order of accuracy of the tide gauges. Time lag errors were typically equivalent to the time increment resolved by the model (6 minutes), indicating good agreement between the model and data.

Table 4.2 Tidal constituents for measured tide data and calibrated model output, with model error amplitudes, for the Pleasant Bay system, during modeled October 2018 200-hr validation time period (23-28 October 2018).

Model Calibration Run						
Location	Constituent Amplitude (NAVD88 ft)				Phase (deg)	
	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Offshore	3.65	0.00	0.00	0.52	4.52	109.56
Stage Harbor	1.99	0.15	0.08	0.46	19.61	146.08
Chatham Fish Pier	2.89	0.23	0.08	0.45	17.55	-38.13
Meetinghouse	1.90	0.44	0.07	0.41	66.70	74.93
Outermost Harbor	3.06	0.16	0.08	0.46	12.24	-47.50
Measured Tide During Calibration Run						
Location	Constituent Amplitude (NAVD88 ft)				Phase (deg)	
	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Offshore	3.65	0.00	0.00	0.52	4.49	110.24
Stage Harbor	1.99	0.15	0.08	0.46	19.63	145.89
Chatham Fish Pier	2.58	0.28	0.08	0.45	23.09	-17.31
Meetinghouse	1.76	0.40	0.05	0.42	73.00	86.36
Outermost Harbor	2.91	0.24	0.08	0.48	15.41	-11.24
Error (measured-modeled)						
Location	Constituent Amplitude (NAVD88 ft)				Phase (deg)	
	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Offshore	0.00	0.00	0.00	0.00	-0.03	0.71
Stage Harbor	0.00	0.00	0.00	0.00	0.04	-0.20
Chatham Fish Pier	-0.31	0.05	0.00	0.00	11.47	21.55
Meetinghouse	-0.14	-0.04	-0.02	0.01	13.04	11.84
Outermost Harbor	-0.15	0.08	0.00	0.02	6.55	37.52

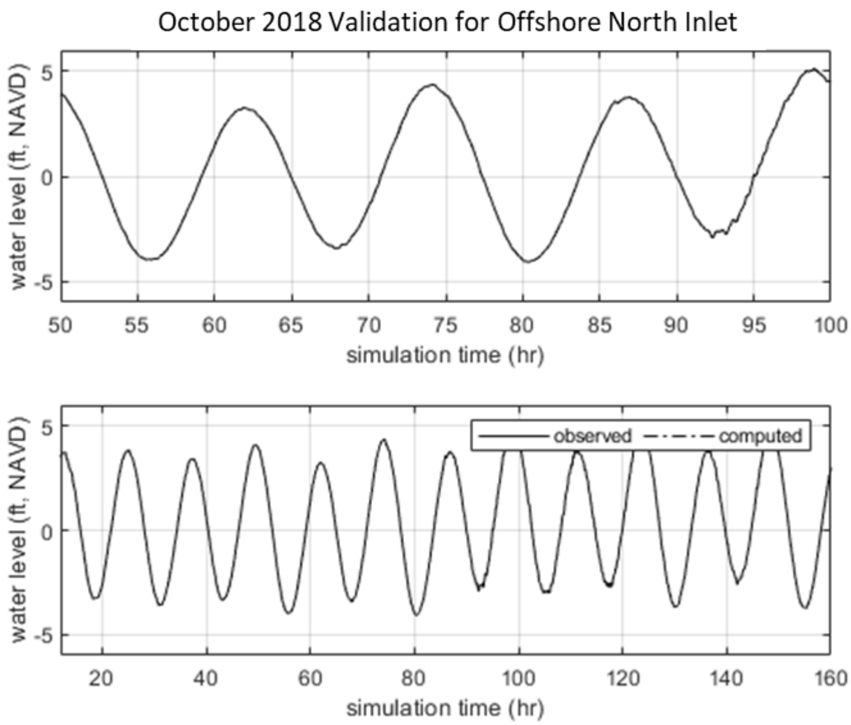


Figure 4.7 Comparison of model output and measured tides for the North Inlet Offshore tide gauge during the October 2018 validation period. The top plot is a 50-hour sub-section of the total modeled time period, shown in the bottom plot.

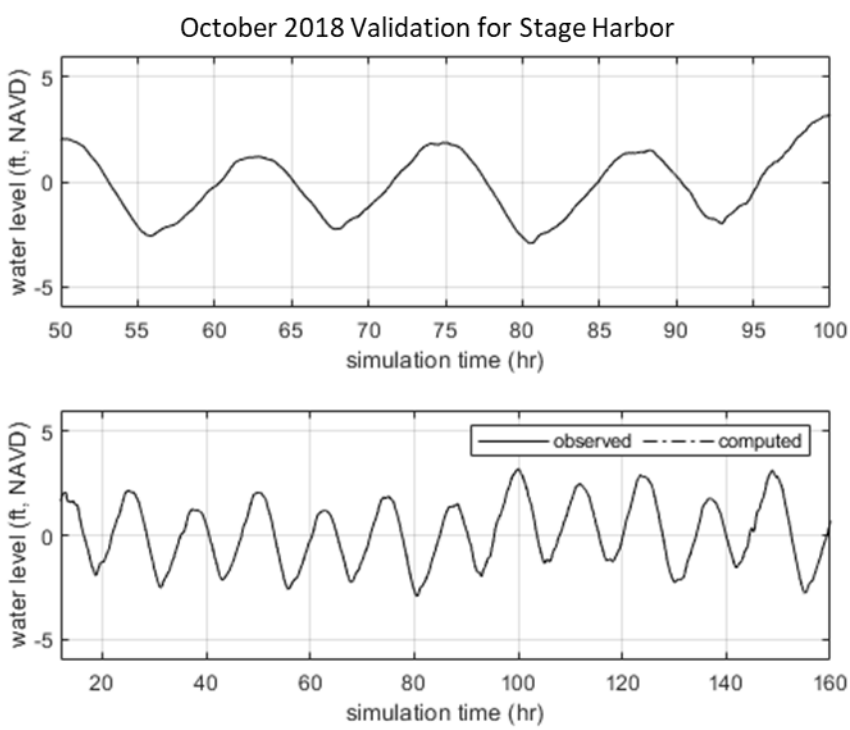


Figure 4.8 Comparison of model output and measured tides for the Stage Harbor tide gauge during the October 2018 validation period. The top plot is a 50-hour sub-section of the total modeled time period, shown in the bottom plot.

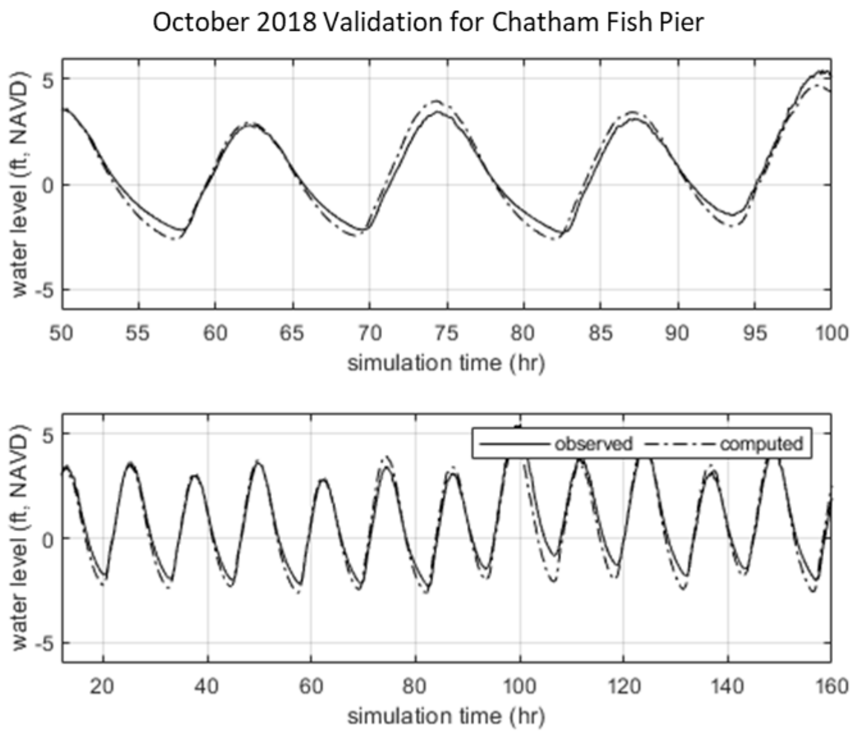


Figure 4.9 Comparison of model output and measured tides for the Chatham Fish Pier tide gauge during the October 2018 validation period. The top plot is a 50-hour sub-section of the total modeled time period, shown in the bottom plot.

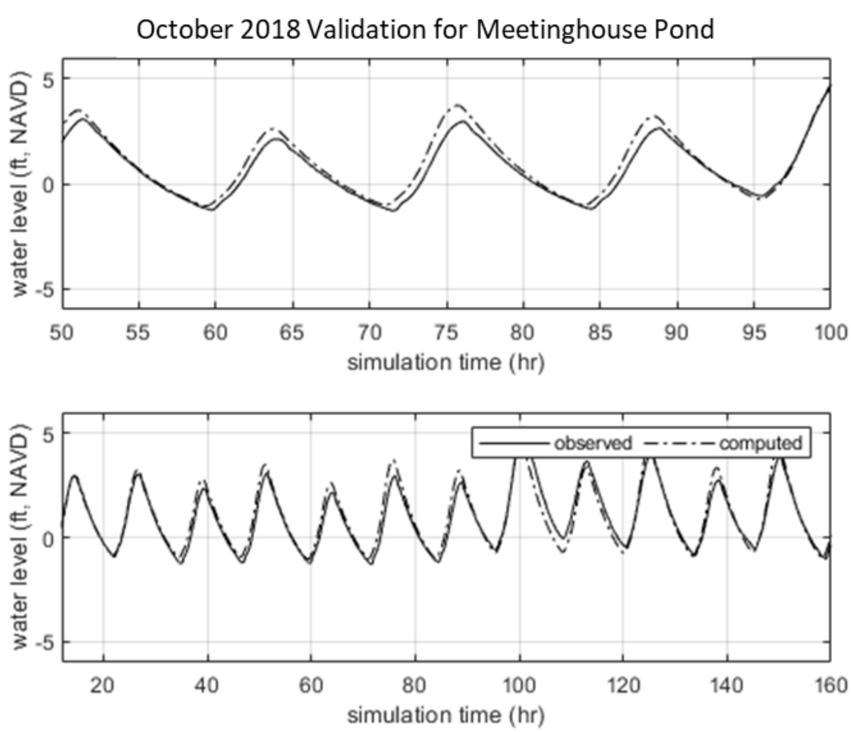


Figure 4.10 Comparison of model output and measured tides for the Meetinghouse Pond tide gauge during the October 2018 validation period. The top plot is a 50-hour sub-section of the total modeled time period, shown in the bottom plot.

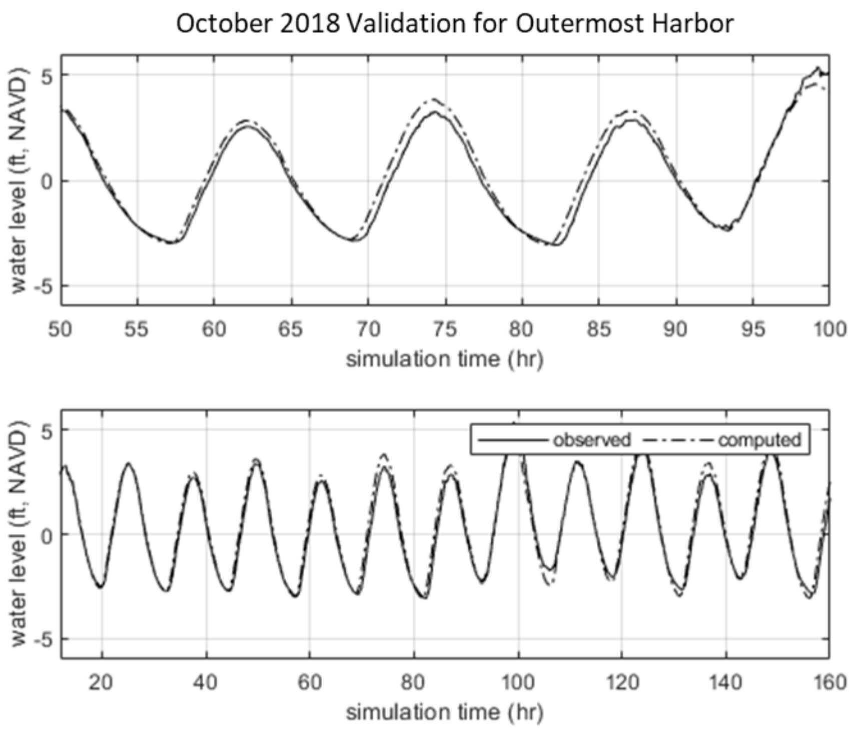


Figure 4.11 Comparison of model output and measured tides for the Outermost Harbor tide gauge during the October 2018 validation period. The top plot is a 50-hour sub-section of the total modeled time period, shown in the bottom plot.

4.5 Past Hydrodynamic Modeling of Single- and Two-Inlet Configurations

A hydrodynamic analysis of the Pleasant Bay system was conducted as part of the Massachusetts Estuaries Project (MEP) in 2004. This model evaluated the single inlet configuration that existed at the time of the analysis, using data collected in 2004 (Howes et al., 2006). A follow-up analysis was done in 2008 to evaluate changes in the system that occurred with the formation of the new inlet in April 2007 (Applied Coastal, 2008). The original MEP and post-breach analyses utilized the RMA-2 hydrodynamic model. The bathymetry and boundary condition data from the 2007 RMA-2 model were used to develop a CMS-flow model of 2007 post breach conditions. The performance of this model was corroborated using the available 2007 tide data.

Once completed, the separate CMS models that represent 2007 and 2018 configurations of Pleasant Bay and Chatham Harbor were used to compare current patterns and the distribution of flows through the system channels and inlets of these two time periods.

4.6 Wave Grid

CMS-Wave is a phase-averaged model for propagation of directional waves over complicated bathymetry and nearshore regions where wave re-fraction, diffraction, reflection, shoaling, and breaking simultaneously act. Wave diffraction terms are included in the governing equations following the method of Mase et al. (2005). The wave-current interaction is calculated based on the dispersion relationship and includes wave blocking by an opposing current (Larson and Kraus 2002). Bottom friction loss is estimated from the classical drag law formula (Collins 1972, as described in the CMS User manual)

The CMS-Wave model developed for the shoreline study used a coarse grid with 200 meter spacing for the region including the offshore region between the Chatham shoreline and the location of the WIS hindcast station (Figure 4.12) and a fine mesh with a 50 meter (164 ft) spacing that covers the study area in higher resolution (Figure 4.12). The National Ocean Service GEODAS database (NOS, 1998) was the main source of offshore bathymetric data used to create the coarse grid. The same bathymetry set developed for the CMS-Flow hydrodynamic grid was used to specify elevations in fine-scale nearshore wave grid. All bathymetry data were rectified to the NAVD88 datum.

The coarse grid was used to propagate the offshore wave conditions, developed from the analysis of the WIS hindcast record, to the nearshore. The fine mesh grid was nested within the domain of the coarse grid. This means that the input wave conditions along the open boundary of the fine grid is spatially varying output from the coarse grid (i.e., the fine grid open boundary waves are output from the coarse grid). This technique allows fine resolution of the model grid in areas where it is needed, but also allows larger grid spacing where the fine resolution is not needed, and as a result, minimizes computational requirements, without sacrificing accuracy.

The coarse grid is made up of 37,180 computational cells with a spacing of 200 meters (656 ft). The x-axis of the grid is 13.7 miles or 110 cells long. The y-axis of the grid is 42 miles or 338 cells long. The greatest depth in the coarse grid domain is -152 m NAVD88, which occurs at the northeast corner of the coarse grid. The nearshore fine mesh is made up of 54,116 computational cells with a spacing of 50 meters. The x-axis is made up of 166 cells, for a total length of 5.2 miles. The y-axis is made up of 326 cells for a total length of 10.1 miles.

Each hydrodynamic model was nested within this wave grid and run for the same northeast storm conditions to evaluate wave heights and current pattern changes during storms. A wave model timestep of one hour was used, which corresponds to the time step of the WIS hindcast data record.

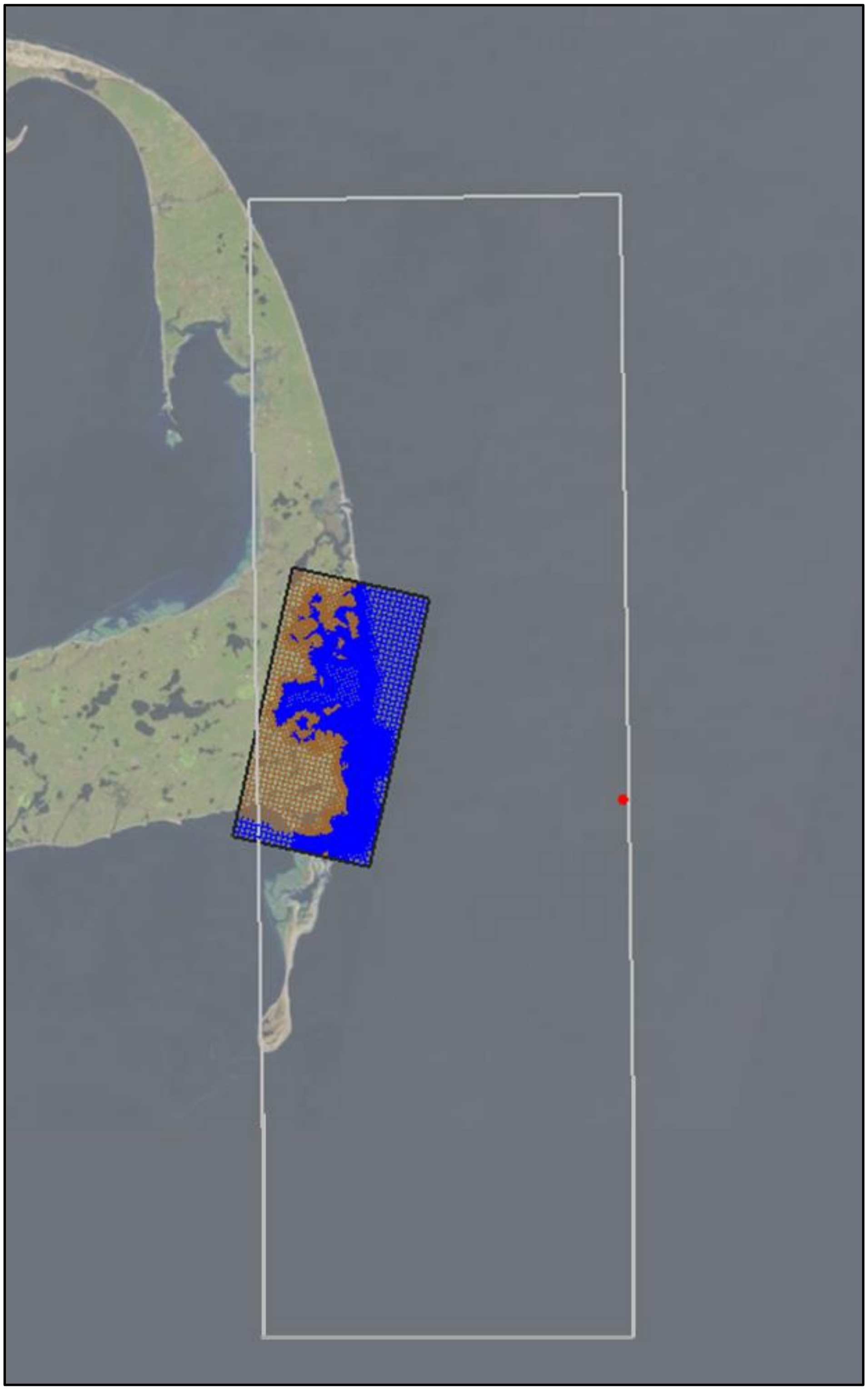


Figure 4.12 The extents of the coarse wave grid, used to propagate offshore wave conditions, are indicated by the gray outline, with the WIS station represented by the red circle. The fine wave grid model is fully nested within the coarse wave grid with the open boundary located along the eastern edge.

5.0 QUANTITATIVE ANALYSIS OF COASTAL CHANGE AND SEDIMENT TRANSPORT PROCESSES: PAST TO PRESENT

A direct comparison of 2007 and 2018 hydrodynamic conditions in Pleasant Bay was done by running model grids that represent these two time periods, while using the same offshore tidal open boundary condition. By driving both models with the same offshore tide, biases in the measured data that occur because of time period differences are eliminated. This is a powerful utility of hydrodynamic models, since this is not a possibility with the real physical system.

Six reference locations were selected for detailed comparison that each represent areas of rapid change from 2007 to 2018. These locations are shown in Figure 5.1 and are used as reference points to discuss changes in the system. Reference Location 1 is at the entrance to Pleasant Bay proximate to Minister's Point, where residents have reported swift currents and increased erosion following the widening of North Inlet. Reference Locations 2 through 4 continue south along the western edge of Chatham Harbor to Watch Hill, which was where South Inlet was located in 2007, but presently is protected by the southern elongation of North Beach Island. Reference Locations 5 and 6 represent the eastern side of Chatham Harbor.

5.1 Bathymetric Change

Prior to analyzing hydrodynamic changes, it was important to investigate larger-scale physical changes that have occurred from 2007 to 2018.

Figure 5.1 shows water depths in 2007 and 2018. In 2007, there was a deep channel offshore from Minister's Point (Reference Location 1) that connected into a channel of similar depth and continued N-S through Chatham Northeast (Reference Location 6), Chatham Southeast (Reference Location 5), and Watch Hill (Reference Location 4), and then exited the system through South Inlet. In the 2018 panel of

Figure 5.2, it is evident that this channel has shoaled in immediately south of North Inlet, severing the hydraulic connection that dominated flow in 2007. This shoaling increased the sinuosity and decreased the efficiency of this channel. By 2018, the main channel had migrated landward toward Minister's Point. Figure 5.1 also shows a secondary, slightly shallower, channel across from Minister's Point that runs along the backside of the barrier island. By 2018, this channel has become dead-ended as the southern end of Nauset Beach has moved into the channel and cut it off from the inlet.

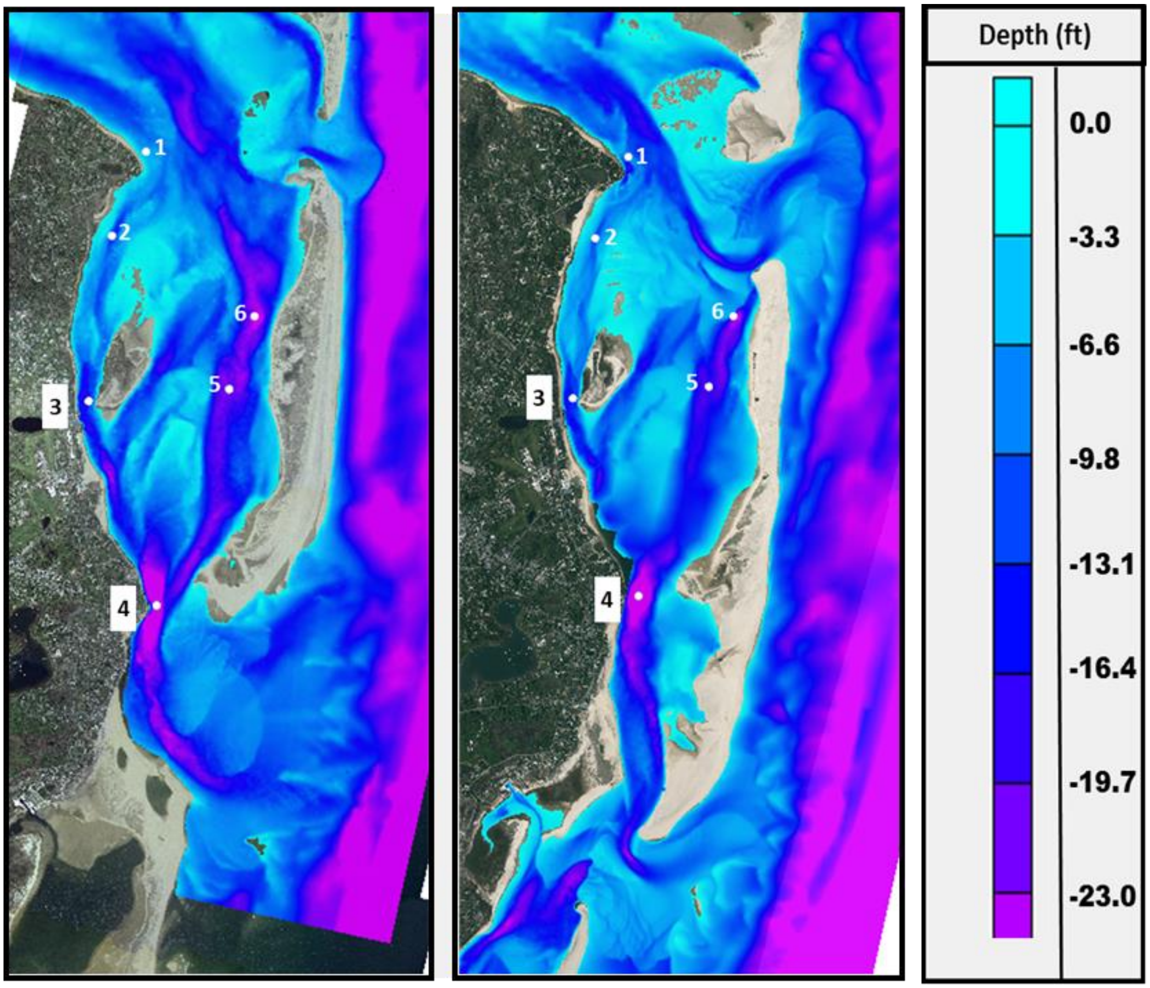


Figure 5.1 LiDAR data showing water depth from 0 to -23 ft NAVD88; 2007 inlet configuration on left, 2018 inlet configuration in middle, scale on right. Six reference locations were selected to directly compare water elevation and current speeds between 2007 and 2018 models: 1. Minister's Point; 2. North Chatham Channel; 3. Chatham Fish Pier; 4. Watch Hill; 5. Chatham Southeast; 6. Chatham Northeast.

Figure 5.2 and Figure 5.3 provide additional bathymetric details of changes near Minister's Point and at the northern entrance to Chatham Harbor, respectively. The x-axis starts at the mainland coast and extends to the east, ending at the barrier island. The vertical black lines indicate reference points shown in Figure 5.1. From 0 to 2,500 ft offshore of Minister's Point in Figure 5.2, it is evident that the thalweg of the dominant channel in 2007 has shallowed by 8 ft and migrated shoreward. From 2,500 to 5,000 offshore of Minister's Point, the secondary channel visible in the 2007 bathymetry is fully filled in. The 2018 transect shows that the highest point of the barrier beach migrated shoreward approximately 1,300 ft. Figure 5.3 shows little bathymetric change in the 0 to 2,500 ft offshore of N Chatham Channel; however, it does show that the large 2007 channel on the backside of the barrier island has narrowed by approximately 650 ft and shallowed by approximately 3.3 ft in 2018.

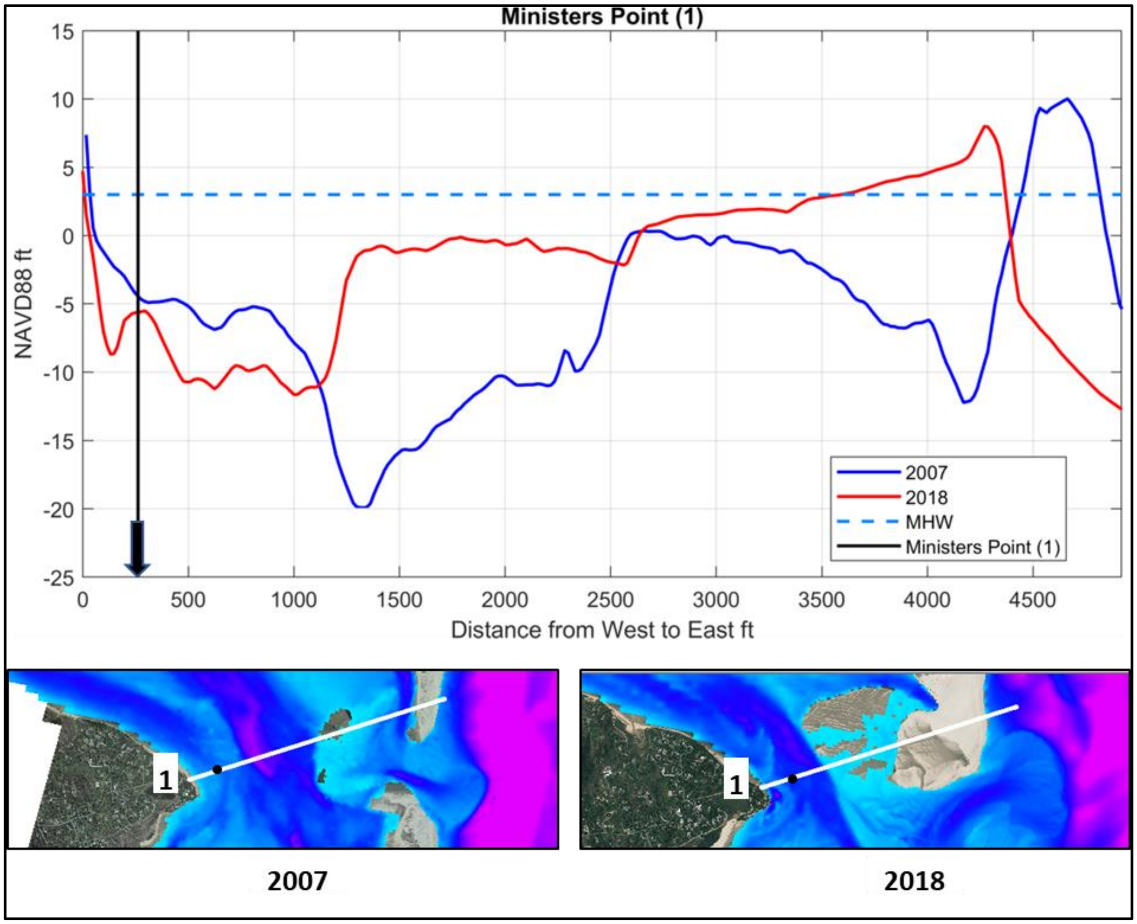


Figure 5.2 Elevation along a transect from Minister's Point (Location 1) in map view (lower panel) and cross-sectional view (upper panel) for 2007 and 2018.

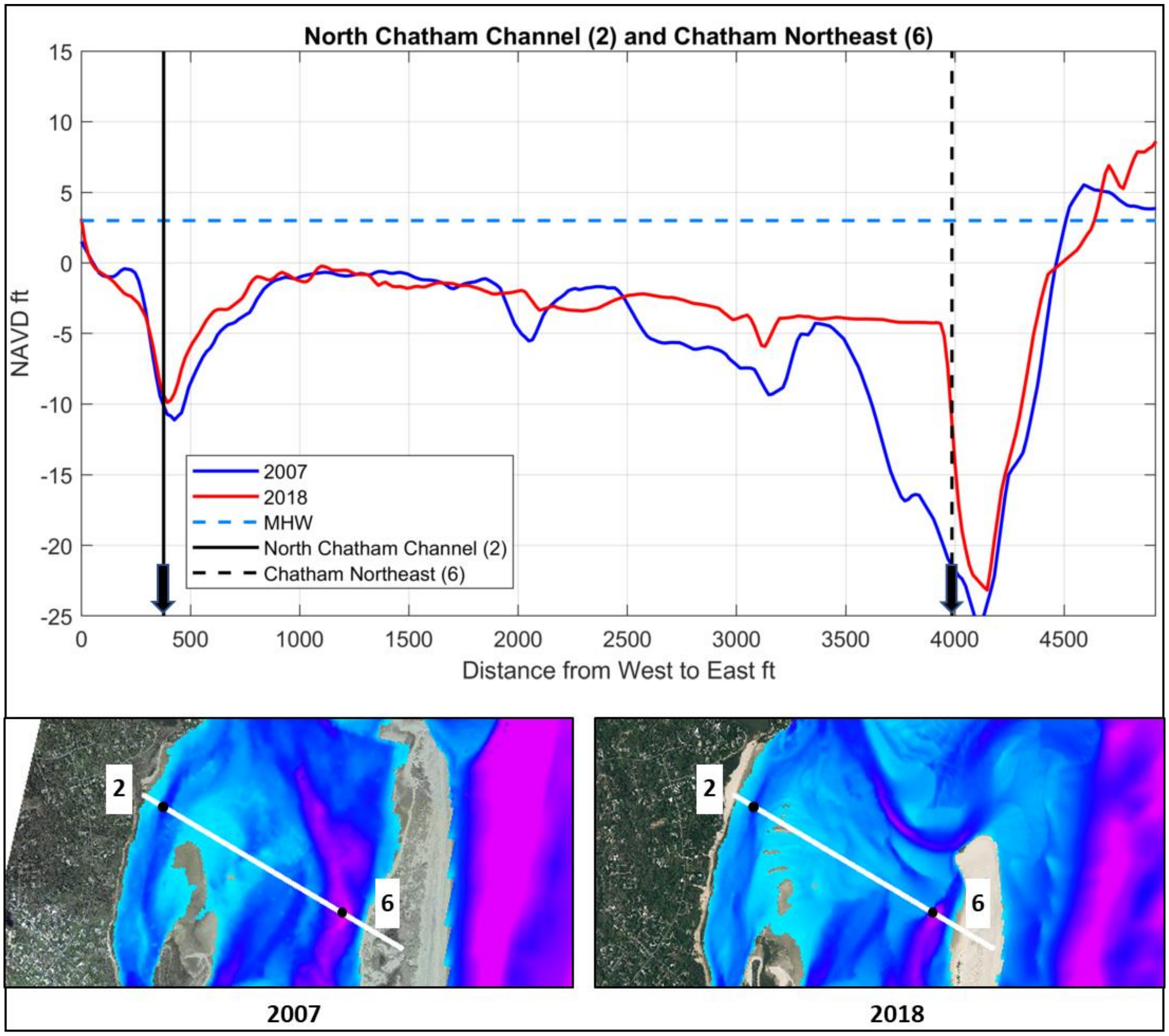


Figure 5.3 Elevation along a transect from Chatham North Channel (Location 2) to Chatham Northeast (Location 6) in map view (lower panel) and cross-sectional view (upper panel) for 2007 and 2018.

5.2 Tidal Currents

The bathymetric and morphologic changes that have occurred from 2007 to 2018 can be correlated to changes in the hydrodynamics. Section 3.2.1.2 discussed the tide ranges in the system for 2018. Modeled water elevations were compared for 2007 and 2018 to evaluate changes. Meetinghouse Pond, Chatham Fish Pier, and Watch Hill were selected for comparison as they are representative of the range of changes that occurred between the two modeled time periods. Water elevation comparisons for these three locations is presented in Figure 5.4, Figure 5.5, and Figure 5.6. These plots show that the tide range in Meetinghouse Pond has decreased by approximately one foot while the tide ranges at Chatham Fish Pier and Watch Hill have decreased by approximately a half-foot.

Most of the change in ranges have occurred due to an increase in low water elevation, from 2007 to 2018. This suggests that the 2018 inlet configuration is less efficient than the 2007 configuration. Giese (2012) noted a 5-year trend of increasing mean low water elevations at Meetinghouse Pond from 2008 to 2012 and attributed this to shoaling in the channel that lies east of Strong Island and north of the inlet, which is the same channel shown in Figure 5.2 that likely filled in due to the southerly migration of Nauset Beach. The overall narrowing of channels across Chatham Harbor shown in Figure 5.3 also reduces flow efficiency, which would explain the smaller ranges at both Chatham Fish Pier and Watch Hill.

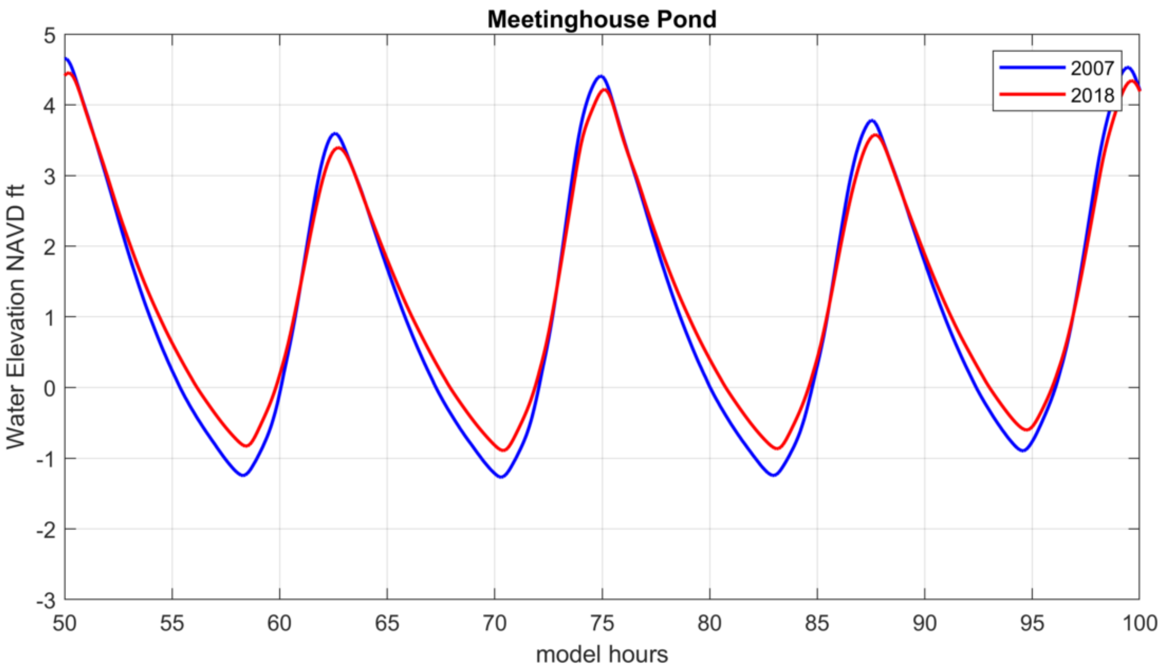


Figure 5.4 Modeled water elevation (NAVD88 ft) at Meetinghouse Pond using the same October 2018 offshore tides for the 2007 model (blue) and 2018 model (red).

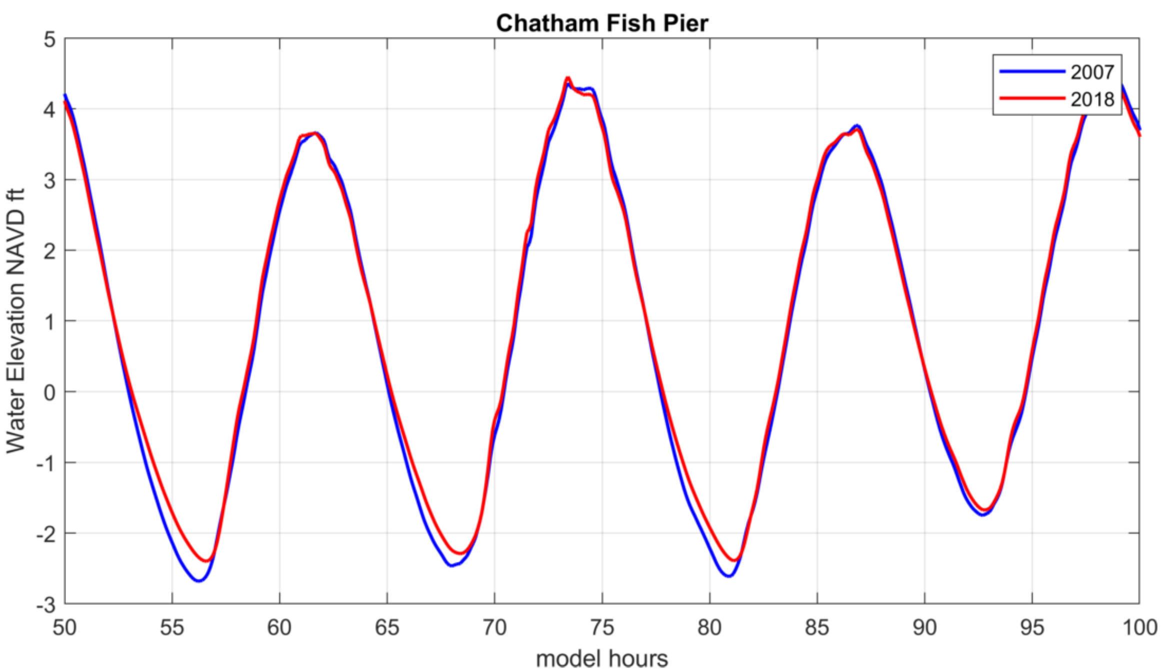


Figure 5.5 Modeled water elevation (NAVD88 ft) at Chatham Fish Pier using the same October 2018 offshore tides for the 2007 model (blue) and 2018 model (red).

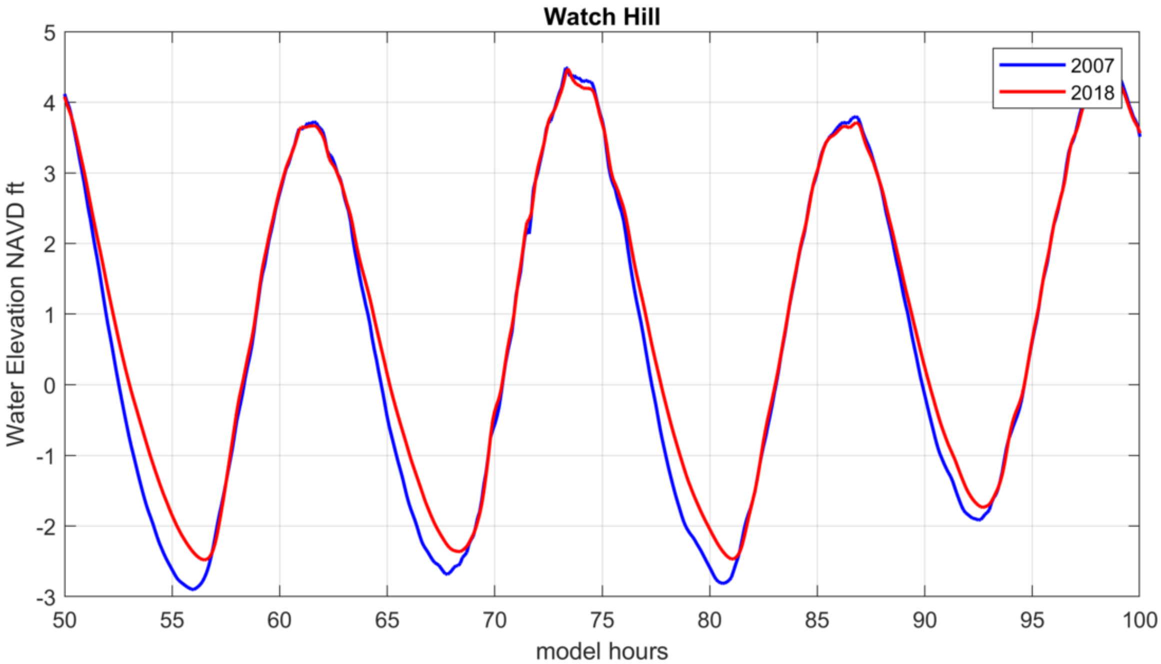


Figure 5.6 Modeled water elevation (NAVD88 ft) at Watch Hill using the same October 2018 offshore tides for the 2007 model (blue) and 2018 model (red).

Figure 5.7 and Figure 5.8 show contour maps of modeled depth averaged velocities at the point of maximum ebb and flood currents, respectively, for 2007 and 2018 inlet configurations. Each of the plots represent the same model time step. In the northern part of the system, the area where max flood and ebb currents above 4 ft/sec occur has increased. In 2007, the highest currents were confined within the relatively narrow North Inlet channel and then became reduced as they moved into or out of Pleasant Bay due to the two channels that carried flow. In 2018, there is only the single channel that has migrated landward since 2007, which forces flow closer to the mainland coast. Because of this, the flood and ebb currents remain high due to the shoaled condition of the channel.

South Inlet has migrated in a southerly direction and Fools Inlet is open in 2018. Figure 5.7 shows high ebb current speeds at South Inlet in 2018 similar in magnitude to those experienced at its previous location in 2007, and very low ebb currents at Fools Inlet. Figure 5.8 shows equally high flood current speeds at both Inlets.

Figure 5.7 and Figure 5.8 each show that flow through Chatham Harbor has decreased greatly from 2007 to 2018, particularly along its eastern side. These results support an analysis presented in Giese (2019) that suggests that North Inlet and South Inlet are hydrodynamically “decoupling” from each other based, resulting in an inlet configuration where most of the tide prism of Pleasant Bay passes through North Inlet, with little contributed from the South and Fool’s inlets.

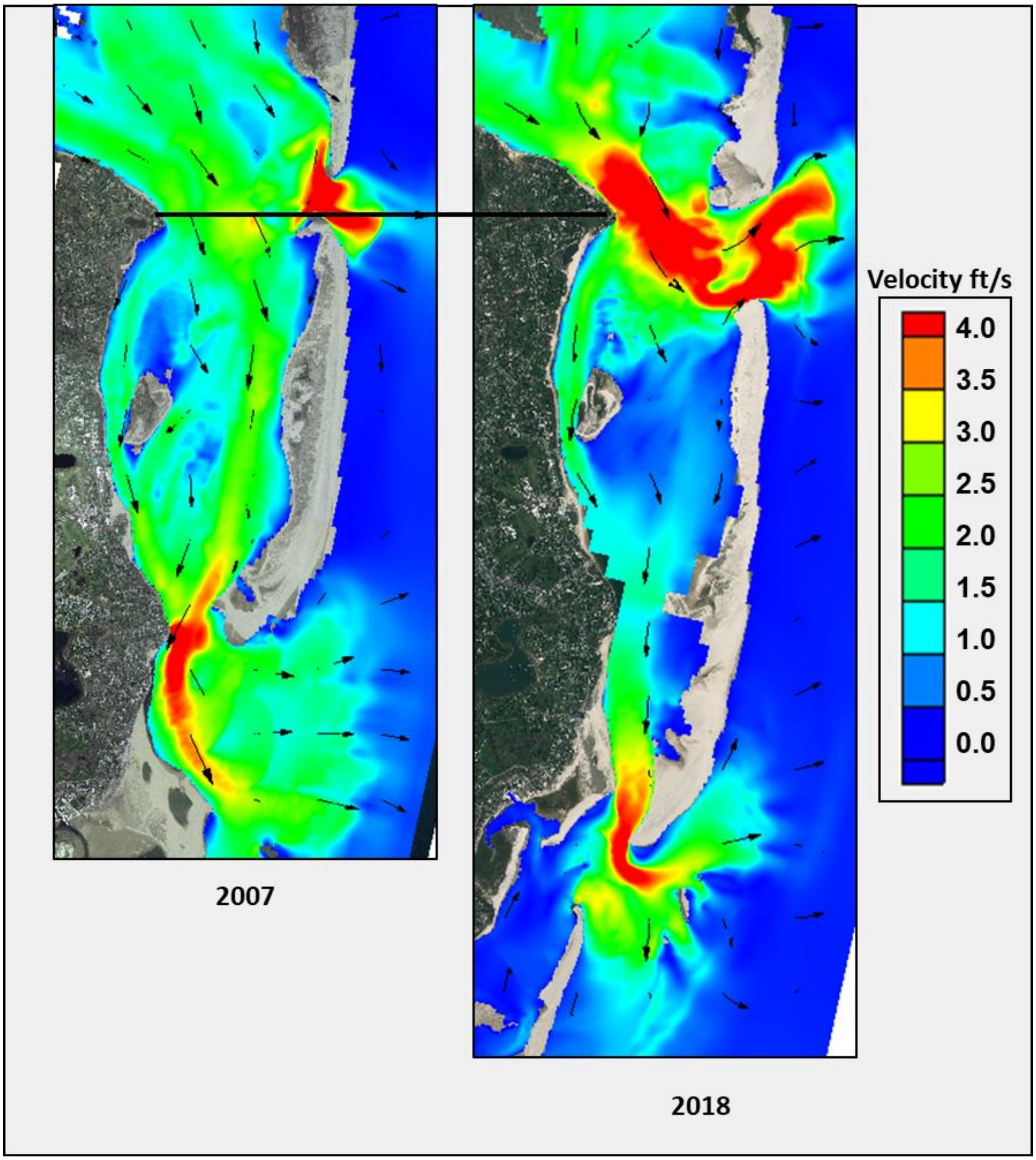


Figure 5.7 Contour plots of depth-averaged maximum ebb currents from 2007 and 2018 at the same timestep.

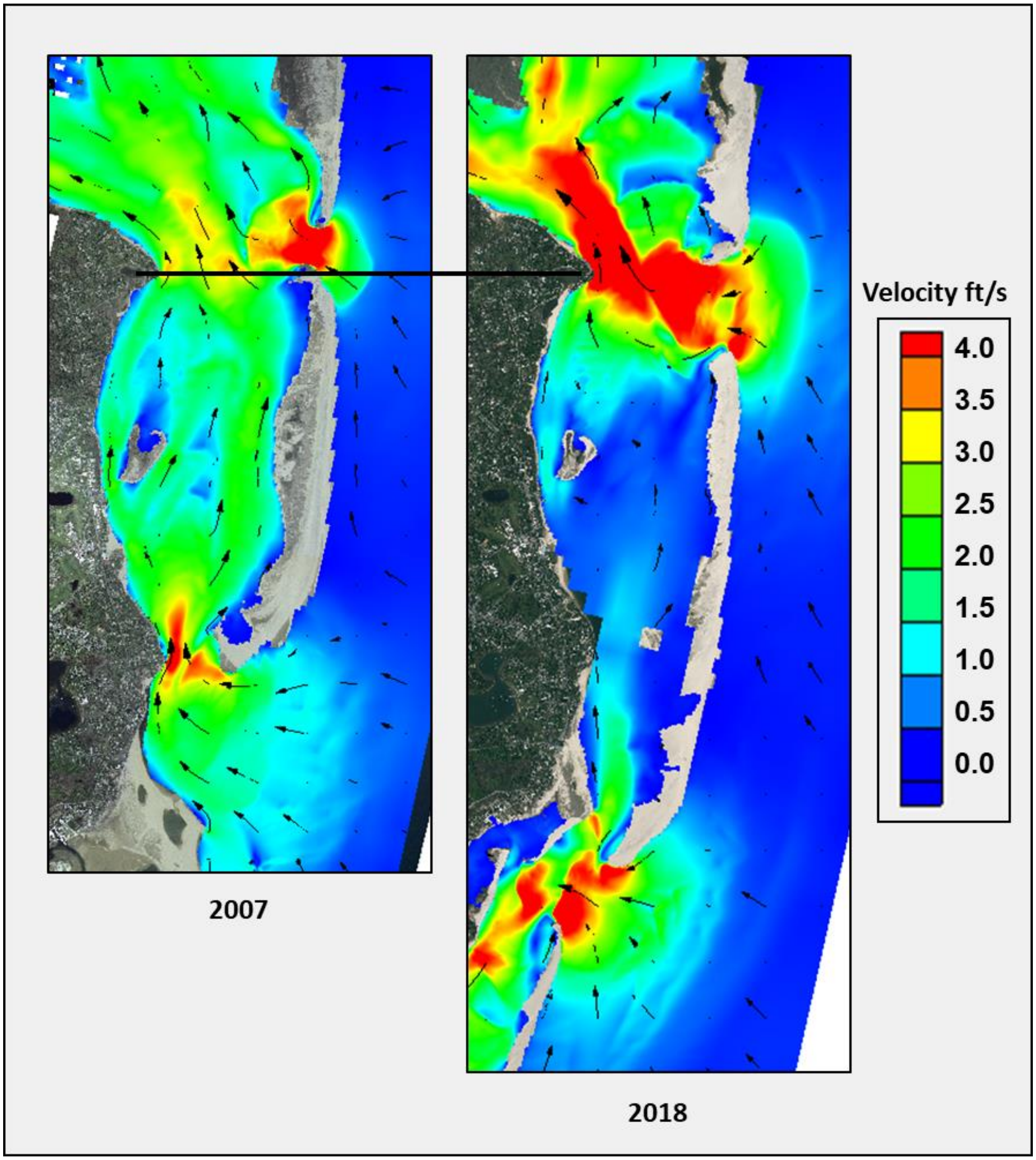


Figure 5.8 Contour plots of maximum flood currents from 2007 and 2018 at the same timestep.

Model outputs from the six reference locations shown in Figure 5.1 were evaluated to better quantify tidal current changes throughout the system. Tidal current plots were plotted (Figure 5.9) with an initiation of sediment motion threshold of 0.6 m/s (2 ft/s), based on Van Rijn (1993). Insipient sediment motion occurs when bed-shear stress exceeds a threshold value, θ_{cr}, which is dependent on the factors including hydraulic conditions near the bed and the particle size. The hydraulic conditions near the bed can be expressed by the Reynolds number

$Re_* = u_* d / v$, where

u_* = bed shear velocity,

d = grain diameter,

v = kinematic viscosity ($\sim 10^{-6}$)

Thus: $\theta_{cr} = F(Re*)$

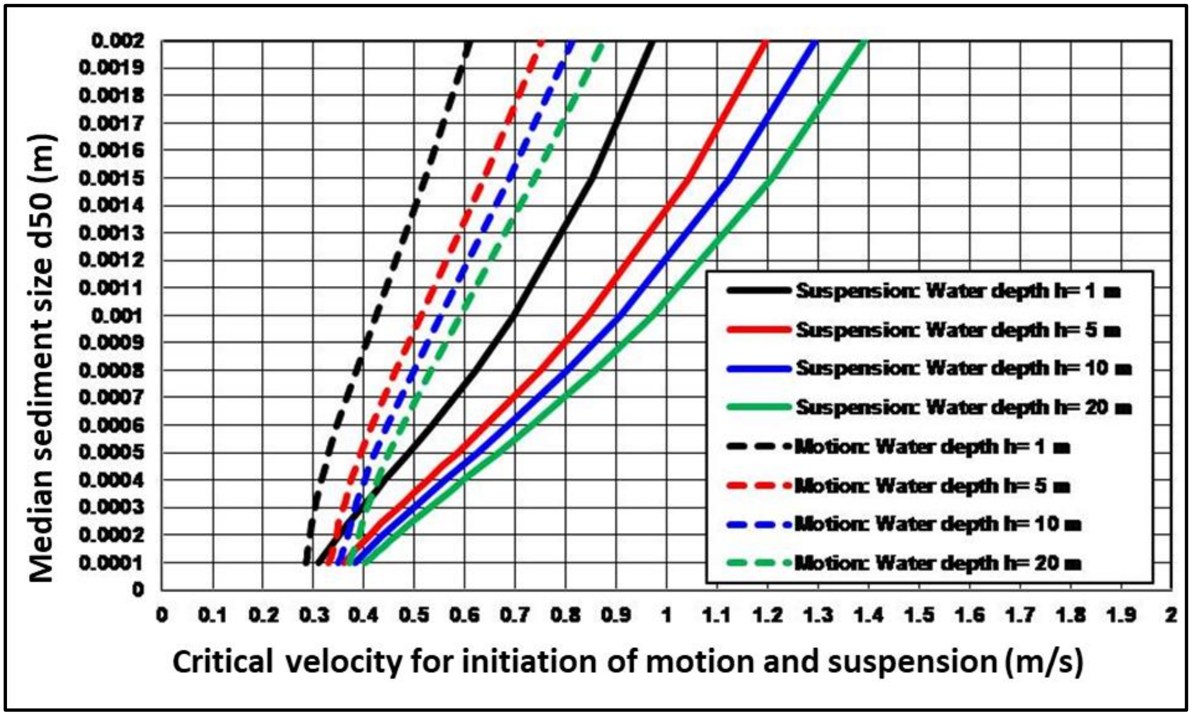


Figure 5.9 Critical depth-averaged velocities at initiation of motion and suspension for sediment with $d50$ between 0.1 and 2 mm (from Van Rijn 1993)

Tidal current plots for each model year are shown by location in Figure 5.10 through Figure 5.14. Table 5.1 summarizes changes in flood and ebb average max speeds at each of the six reference locations and Table 5.2 summarizes changes in duration of flood and ebb between the two time periods for each of the reference locations. Overall, from 2007 to 2018, flood and ebb currents have increased proximate to and north of North Inlet: Minister's Point (Reference Location 1) and North Chatham Channel (Reference Location 2); and decreased in areas south of North Inlet: Watch Hill (Reference Location 4), Chatham Southeast (Reference Location 5), and Chatham Northeast (Reference Location 6). Along the western side of Chatham Harbor at Chatham Fish Pier (Reference Location 3), ebb (south-flowing) currents have increased and flood currents (north-flowing) have decreased from 2007 to 2018.

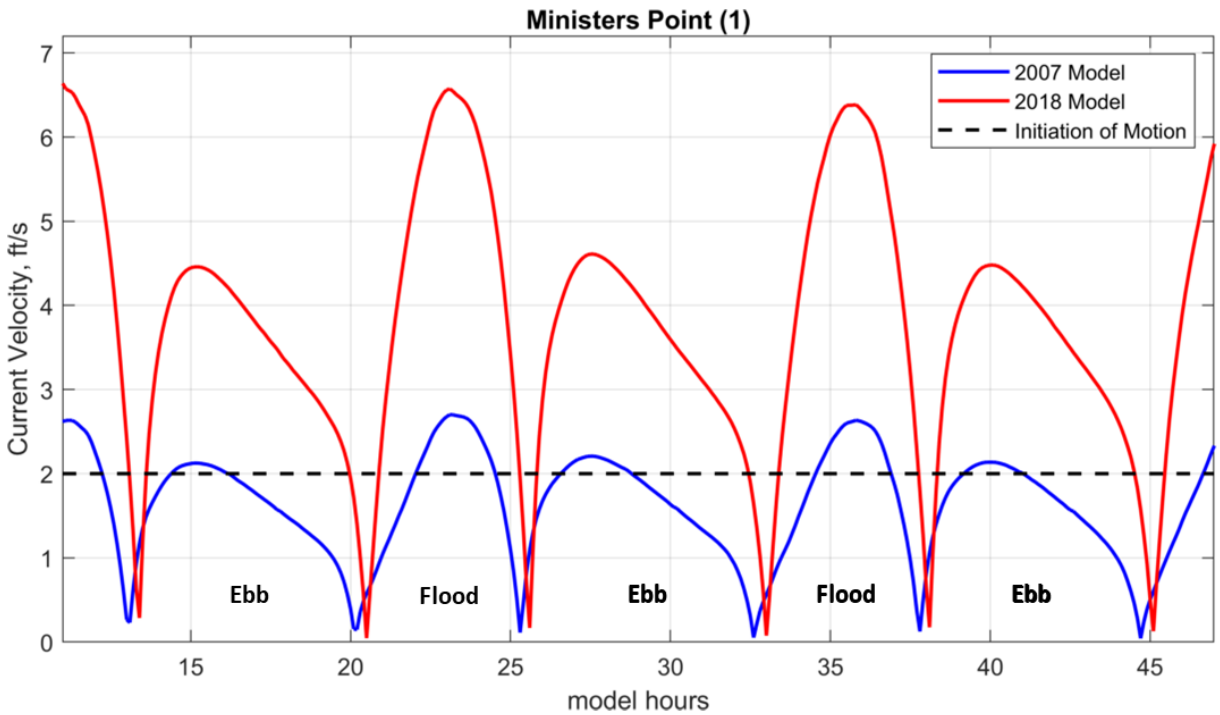


Figure 5.10 Modeled current speed using October 2018 offshore tide at Minister's Point (Location 1) from the 2007 model (blue) and 2018 model (red). Solid black line indicates flood (positive, northward) and ebb (negative, southward) flows. Horizontal dotted lines indicate approximate initiation of sand motion.

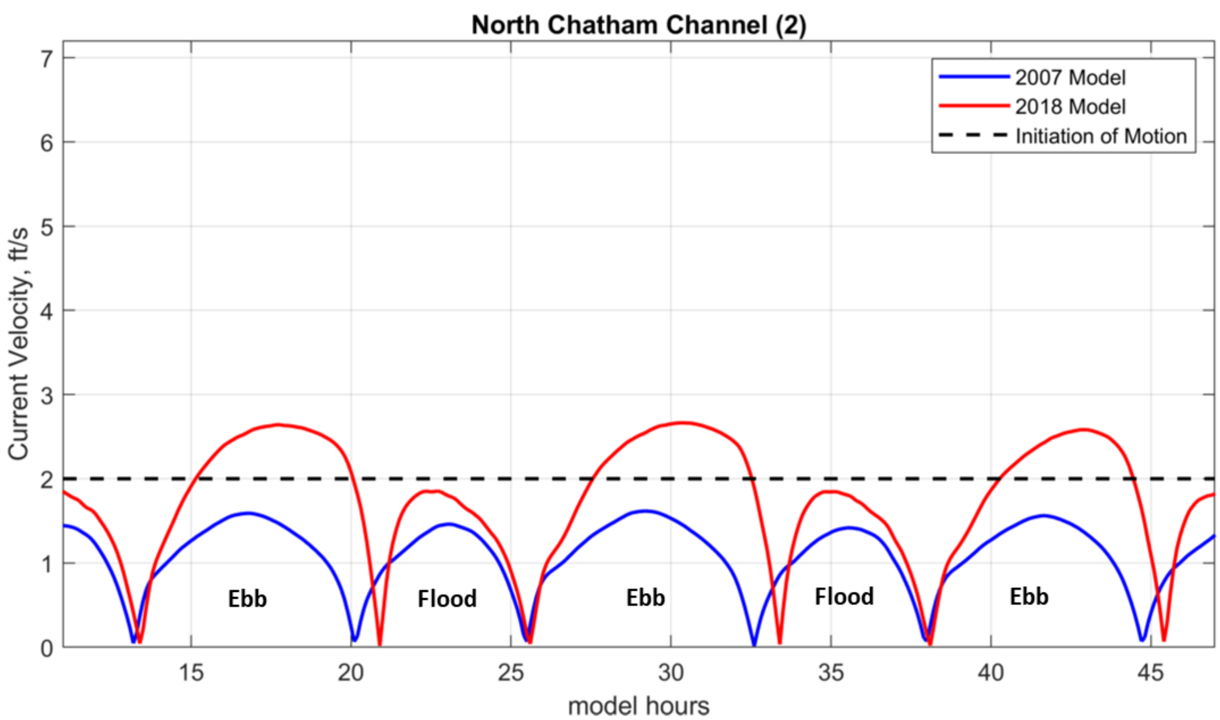


Figure 5.11 Modeled current speed using October 2018 offshore tide at North Chatham Channel (Location 2) from the 2007 model (blue) and 2018 model (red). Solid black line indicates flood (positive, northward) and ebb (negative, southward) flows. Horizontal dotted lines indicate approximate initiation of sand motion.

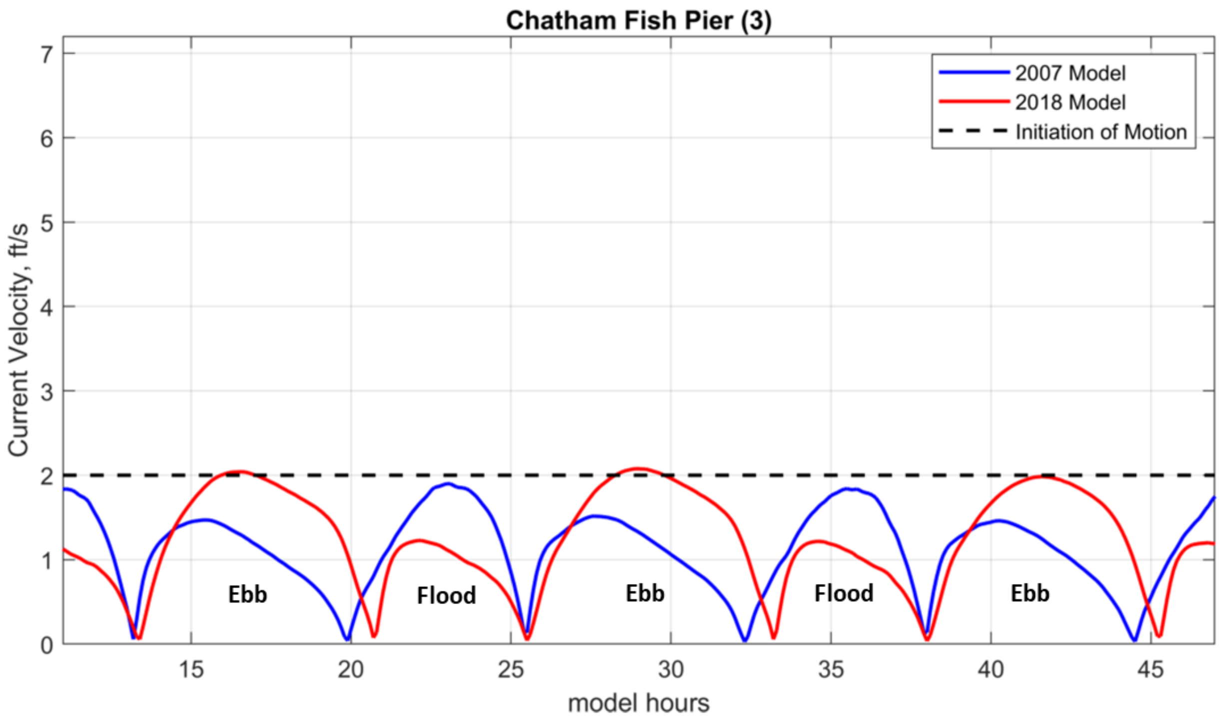


Figure 5.12 Modeled current speed using October 2018 offshore tide at Chatham Fish Pier (Location 3) from the 2007 model (blue) and 2018 model (red). Solid black line indicates flood (positive, northward) and ebb (negative, southward) flows. Horizontal dotted lines indicate approximate initiation of sand motion.

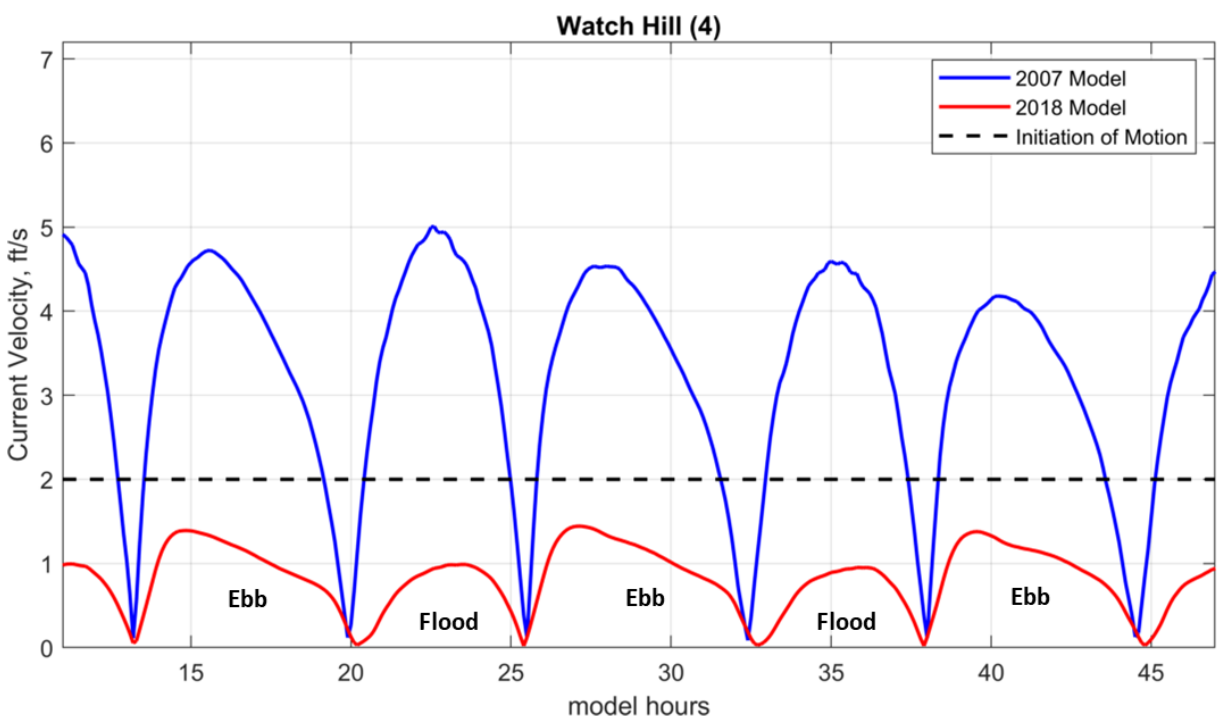


Figure 5.13 Modeled current speed using October 2018 offshore tide at Watch Hill (Location 4) from the 2007 model (blue) and 2018 model (red). Solid black line indicates flood (positive, northward) and ebb (negative, southward) flows. Horizontal dotted lines indicate approximate initiation of sand motion.

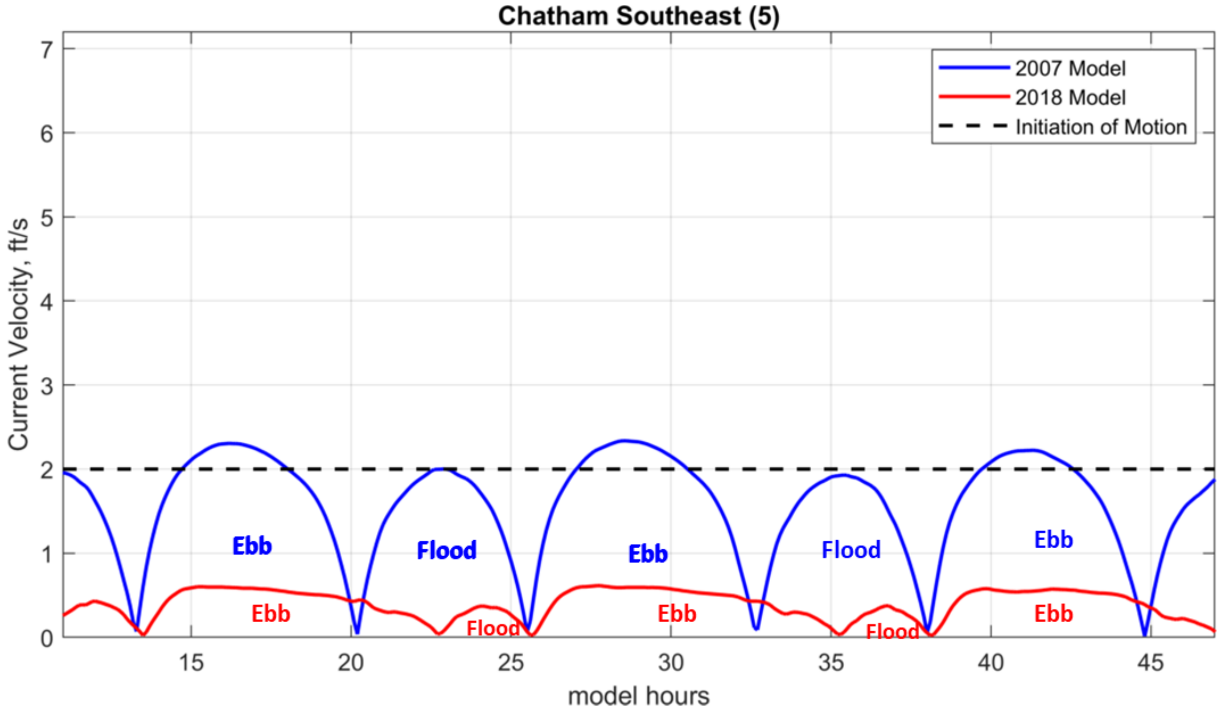


Figure 5.14 Modeled current speed using October 2018 offshore tide at Chatham Southeast (Location 5) from the 2007 model (blue) and 2018 model (red). Solid black line indicates flood (positive, northward) and ebb (negative, southward) flows. Horizontal dotted lines indicate approximate initiation of sand motion.

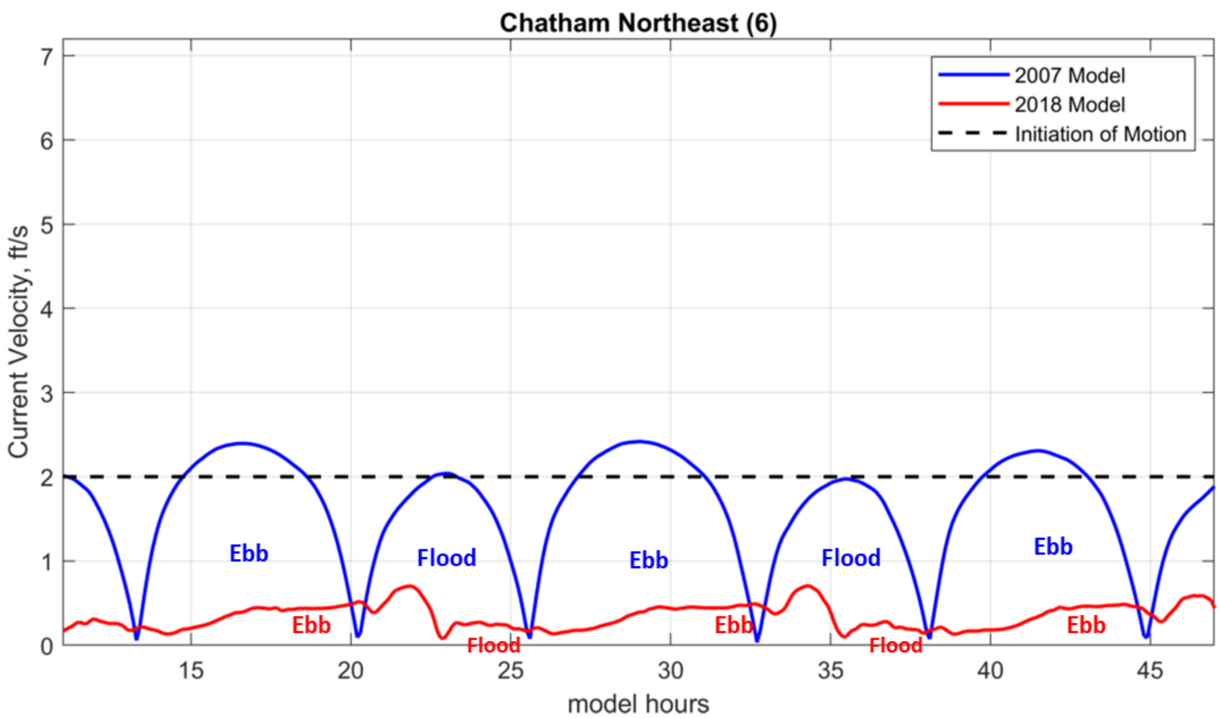


Figure 5.15 Modeled current speed using October 2018 offshore tide at Chatham Northeast (Location 6) from the 2007 model (blue) and 2018 model (red). Solid black line indicates flood (positive, northward) and ebb (negative, southward) flows. Horizontal dotted lines indicate approximate initiation of sand motion.

Table 5.1 and Table 5.2 summarize changes between 2007 and 2018 average flood and ebb current speeds and durations, respectively. Overall, it can be seen that both ebb and flood current speeds at Minister's Point and North Chatham Channel have increased by greater than 40% from 2007 to 2018 while ebb and flood current speeds at Watch Hill, Chatham Southeast, and Chatham Northeast have decreased by greater than 50%. At the Chatham Fish Pier, flood currents have increased while ebb currents have decreased.

Table 5.1 Computed average flood and ebb tide current speeds (in feet per second) for the same six reference locations in the 2007 model and 2018 model, each run with the same October 2018 tide.

	2007		2018		% change	
	Mean Max Speed (ft/s)		Mean Max Speed (ft/s)			
	E	F	E	F	E	F
Minister's Point (1)	1.94	2.33	3.97	5.64	+105	+142
North Chatham Channel (2)	1.41	1.25	2.32	1.77	+65	+42
Chatham Fish Pier (3)	1.28	1.57	1.77	1.15	+39	-27
Watch Hill (4)	3.51	3.77	1.15	0.85	-67	-77
Chatham Southeast (5)	1.97	1.67	0.52	0.30	-73	-82
Chatham Northeast (6)	2.03	1.71	0.56	0.24	-73	-86

Changes to the duration of flood and ebb phases of the tide have not been as large as tidal current speed changes from 2007 to 2018. Minister's Point, North Chatham Channel, Chatham Fish Pier, and Watch Hill have each had minimal changes (12% or less) in flood and ebb duration. Chatham Southeast has experienced slightly larger changes, with a 30% increase in ebb duration and 39% decrease in flood duration. Chatham Northeast has experienced the greatest change with a 53% decrease in ebb duration and a 54% decrease in flood duration.

Table 5.2 Computed average flood and ebb tide duration (in hours) for the same six reference locations in the 2007 model and 2018 model, each run with the same October 2018 tide.

	2007 Mean Duration (hrs)		2018 Mean Duration (hrs)		% change	
	E	F	E	F	E	F
Minister's Point (1)	7	5.3	7.1	5.3	1.4	0.0
North Chatham Channel (2)	6.9	5.5	7.5	4.9	8.7	-10.9
Chatham Fish Pier (3)	6.6	5.8	7.3	5.1	10.6	-12.1
Watch Hill (4)	6.7	5.7	7.1	5.3	6.0	-7.0
Chatham Southeast (5)	6.9	5.5	9	3.35	30.4	-39.1
Chatham Northeast (6)	6.9	5.5	3.25	8.5	-52.9	54.5

5.3 Flow Characteristics

A residual analysis of tidal flows for the 2007 and 2018 models was performed to determine how flows are distributed between the two inlets during the flood and ebb portions of the tide cycle, again using the October 2018 tide in each to allow for direct comparison. The 2007 inlet formation and its effect on hydrodynamics on Pleasant Bay with the transition from a one-inlet to a two-inlet configuration was previously analyzed by Applied Coastal in 2008. For this present study, an analysis was conducted to evaluate efficiency of flow through each of the hydraulic connections following the 2018 breach at Fools Inlet to better determine their contributions to the estuarine tidal patterns in 2018. This analysis demonstrate that flows through fools inlet from Nantucket Sound contribute minorly to the Pleasant Bay system on whole; this connection has almost unilateral southern flow from the open Atlantic, through South Inlet (details provided in Section 3.2). Therefore, the tides in the Pleasant Bays system are still dominated by Atlantic Ocean tides, as they were in 2007.

The flood and ebb tide prisms were computed for each inlet in each model and averaged over the 15 tide cycles of the calibration period. These calculations are based on flow rates taken from transects placed across the inlets. The flood (+) and ebb (-) prisms where added together to determine the average tidal residual for the simulation period. As suggested by Giese (2019), these results also indicate that North Inlet and South Inlet are hydrodynamically “decoupling” from each other in 2018 as there is little exchange between the two of them through Chatham Harbor. This was determined using three transects for 2007 and 2018 in the vicinity of north inlet (Figure 5.16) and two transects for 2007 and three transects for 2018 at the south end of Chatham Harbor (Figure 5.17).

Pleasant Bay is the receiving basin for northerly-directed flood tide flow out of Chatham Harbor. Based on the 2018 residual analysis, Pleasant Bay receives the majority of its flood tide prism volume directly from North Inlet (more than 95%) with the remaining coming from Chatham Harbor. In contrast, Pleasant Bay received approximately 55% of its flood tide prism from Chatham Harbor in 2007, as shown in Figure 5.18 and summarized in Table 5.3. Figure 5.18 shows that flood flows begin first in the North Inlet while Pleasant Bay is still ebbing. For a short period after the bay begins to flood (e.g., at hour 21 of Figure 5.18) flows across the northern Chatham Harbor transect is still flowing to the south, away from Pleasant Bay, indicating that incoming flow from North Inlet is split during this time between Pleasant Bay and Chatham Harbor. Table 5.3 shows that the 2018 residual volumes for North Inlet and Chatham Harbor North are approximately equal and opposite each other, suggesting that the residual flood volume from North Inlet flows south into Chatham Harbor.

At the south end of Chatham Harbor, the 2018 residual analysis shows that most of the flow entering through the south inlet (typically more than 98%) exits to Nantucket Sound via Fool's Inlet while Pleasant Bay is flooding. Figure 5.19 shows that Fools Inlet has nearly unidirectional flow with very little flow directed toward Chatham Harbor. When the tide ebbs through the south inlet, most of the flow is coming from Chatham Harbor (more than 90%), with a small contribution from Fool's Inlet. Table 5.4 indicates that the residual flow through Fool's Inlet is equal to the sum of the residual through the south inlet and the residual from Chatham Harbor. Therefore, Fool's Inlet captures most of the flood flow through the south inlet. Although the flood prisms of the north and south inlets are roughly the same, the south inlet contributes only about 10% of the total prism of Pleasant Bay proper.

Figure 5.16 Transects used to analyze flow characteristics in North Chatham for the 2007 and 2018 inlet configurations. Flood tide was defined as positive flow to the north.

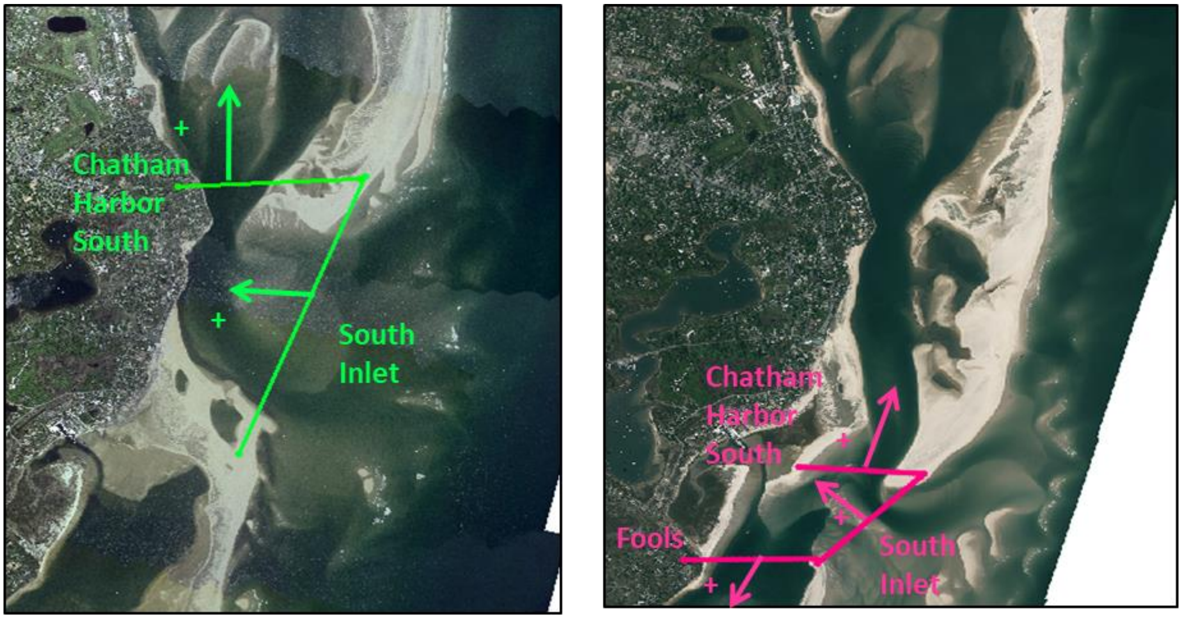


Figure 5.17 Transects used to analyze flow characteristics in South Chatham for the 2007 and 2018 inlet configurations. Flood tide was defined as positive flow.

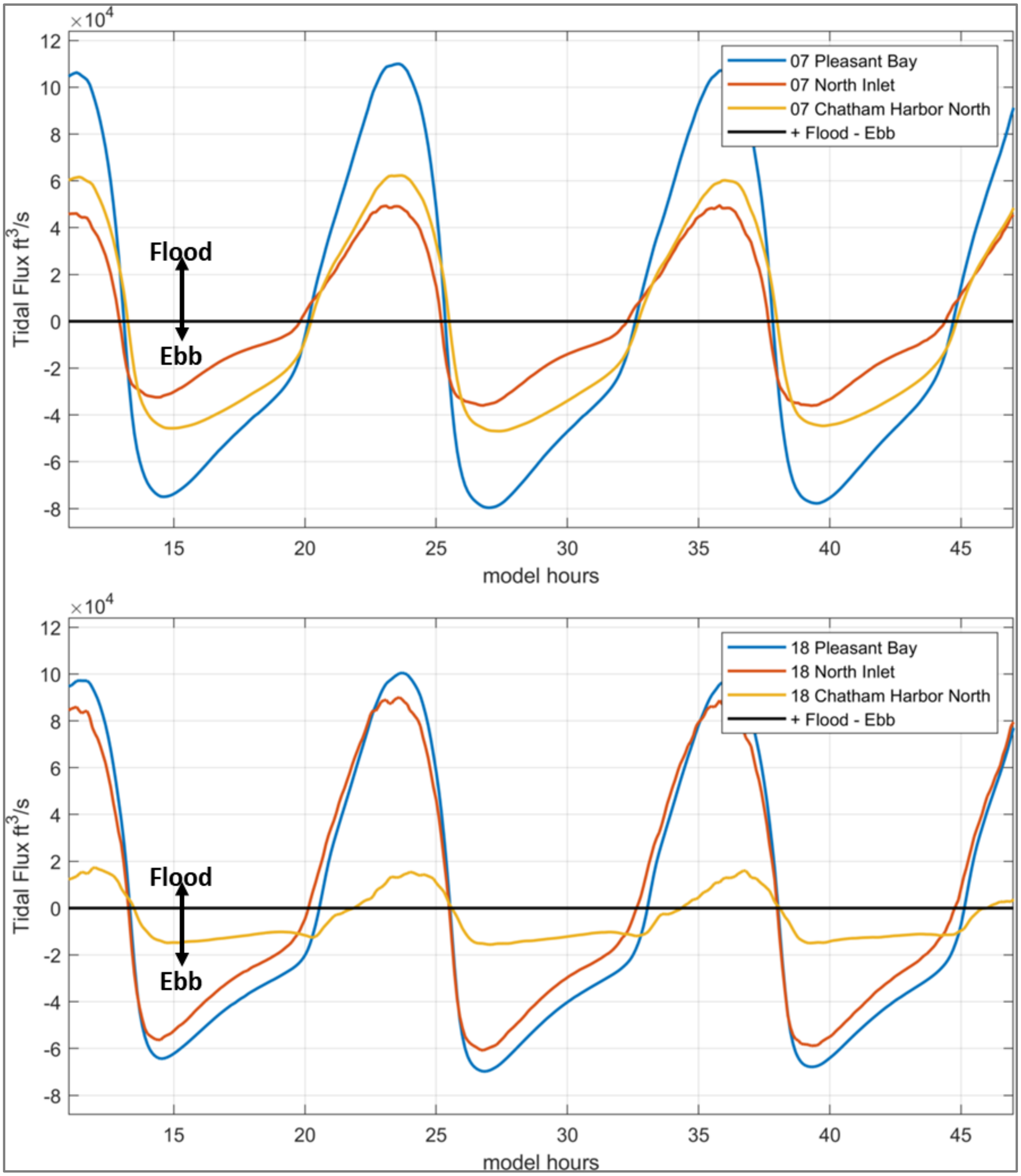


Figure 5.18 Calculated average tidal flux from each of the transects in North Chatham for 2007 (top) and 2018 (bottom).

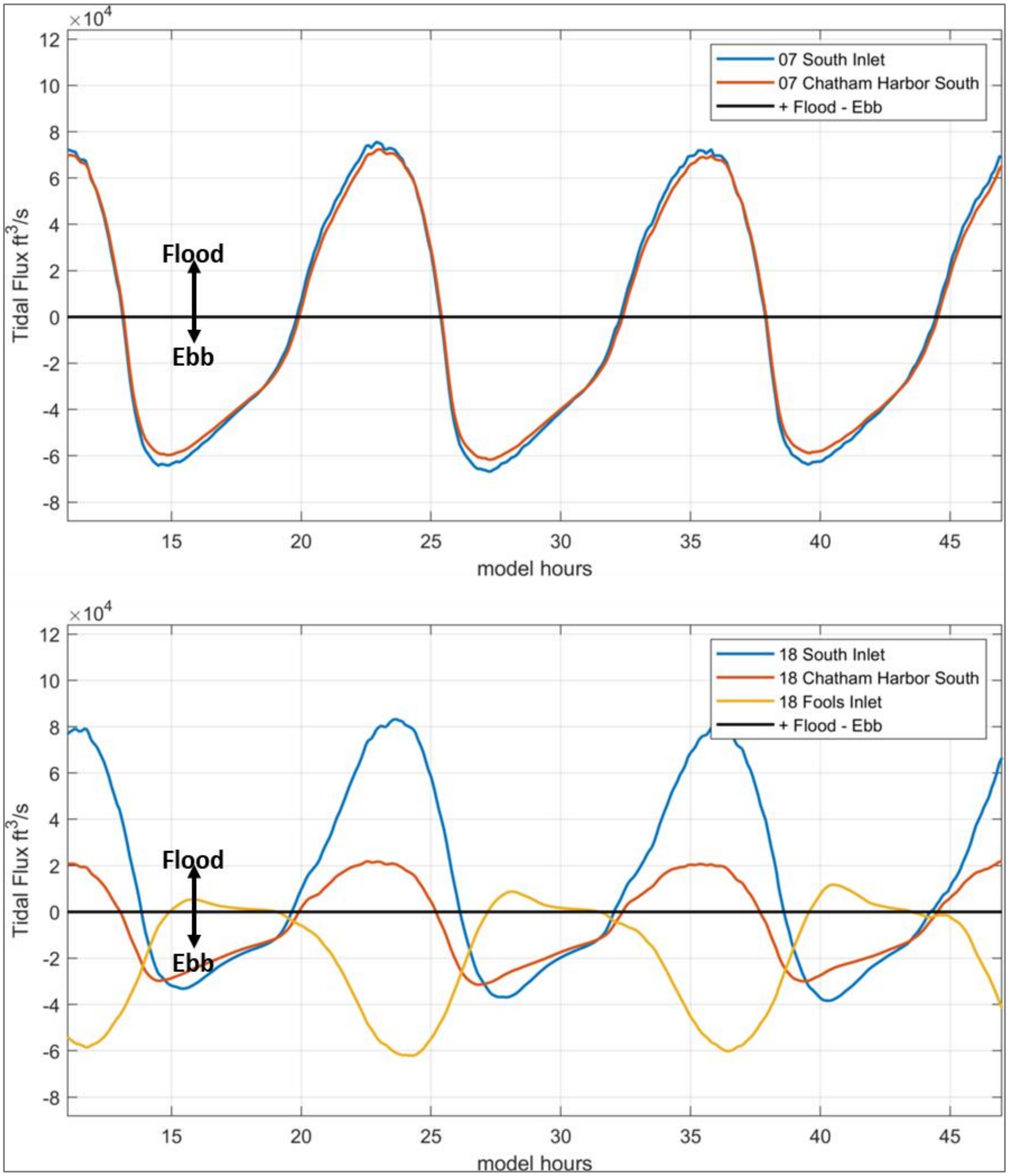


Figure 5.19 Calculated average tidal flux from each of the transects in North Chatham for 2007 (top) and 2018 (bottom).

Table 5.3 Computed average flood and ebb tide prisms and residual flows (in cubic feet) for North Chatham for the 2007 and 2018 inlet configurations using the same October 2018 tide. F is average flood tide, E is average ebb tide, and R is residual, calculated as flood minus ebb.

	North Inlet		Pleasant Bay		Chatham Harbor North	
	2007	**2018**	**2007**	**2018**	**2007**	**2018**
F	555,000,000	986,000,000	1,149,000,000	1,020,000,000	636,000,000	111,000,000
E	-507,000,000	818,000,000	-1,154,000,000	-1,020,000,000	-685,000,000	-273,000,000
R	48,000,000	168,000,000	-50,000,000	177,000	-49,000,000	-162,000,000

Table 5.4 Computed average flood and ebb tide prisms and residual flows (in cubic feet) for South Chatham for the 2007 and 2018 inlet configurations using the same October 2018 tide. F is average flood tide, E is average ebb tide, and R is residual, calculated as flood minus ebb.

	South Inlet		Fools Inlet		Chatham Harbor South	
	2007	**2018**	**2007**	**2018**	**2007**	**2018**
F	836,000,000	973,000,000	--	777,000,000	794,000,000	243,000,000
E	-885,000,000	-440,000,000	--	-90,000,000	-842,000,000	-404,000,000
R	-49,000,000	533,000,000	--	687,000,000	-48,000,000	-161,000,000

5.4 Barrier Beach Coastal Change

Barrier beaches are dynamic features that adjust rapidly in response to multiple environmental factors and are therefore helpful indicators to monitoring changes in the balance of energetic processes at play in the coastal zone. Two processes, rollover and erosion, are apparent between the 2007 and 2018 inlet configurations and are discussed below.

Barrier beach rollover is a landward migration process driven by overtopping and overwashing of barrier beaches and spits. Overwashing occurs when storm waves over-top low-lying sections of the beach removing sand from the beach face and depositing it in the marsh or lower-energy side of the barrier behind the dune. In this process, the sand volume of the barrier beach remains relatively constant for a given stretch of coastline. Rates of rollover vary and are dependent primarily on sediment availability, as well as rate of sea level rise, storm frequency and intensity in relation to typical conditions, sediment characteristics and the geometric and volumetric properties of the barrier (Stripling et al 2008, Bradbury and Powell 1992, Bradbury 1998; Carter et al. 1987, Orford et al. 1991a). Rollover is evident along North Beach and the northern extent of North Beach Island, as shown in Figure 5.21 and Figure 5.20, respectively. In these locations, the highest elevation of the barrier beach has migrated landward from 2007 to 2018, and the total volume of beach above the tidal range remains relatively consistent through time.

Erosion of barrier islands occurs when the sand budget in a given area decreases through time. This is typically seen when islands narrow over time due to lack of sediment availability. The southern extent of North Beach Island has narrowed from 2007 to 2018, as shown in Figure 5.22. The mainland side of the barrier has retained the same elevation and morphology from 2007 to 2018 while the offshore side of the barrier has decreased in elevation, decreasing the overall volume of elevation above the tidal range. This suggests that sediment is not reaching this section of North Beach Island but instead is being eroded away. Longshore sediment transport in this area is southerly; therefore, it is expected that the material lost from this area of North Beach Island is being transported south.

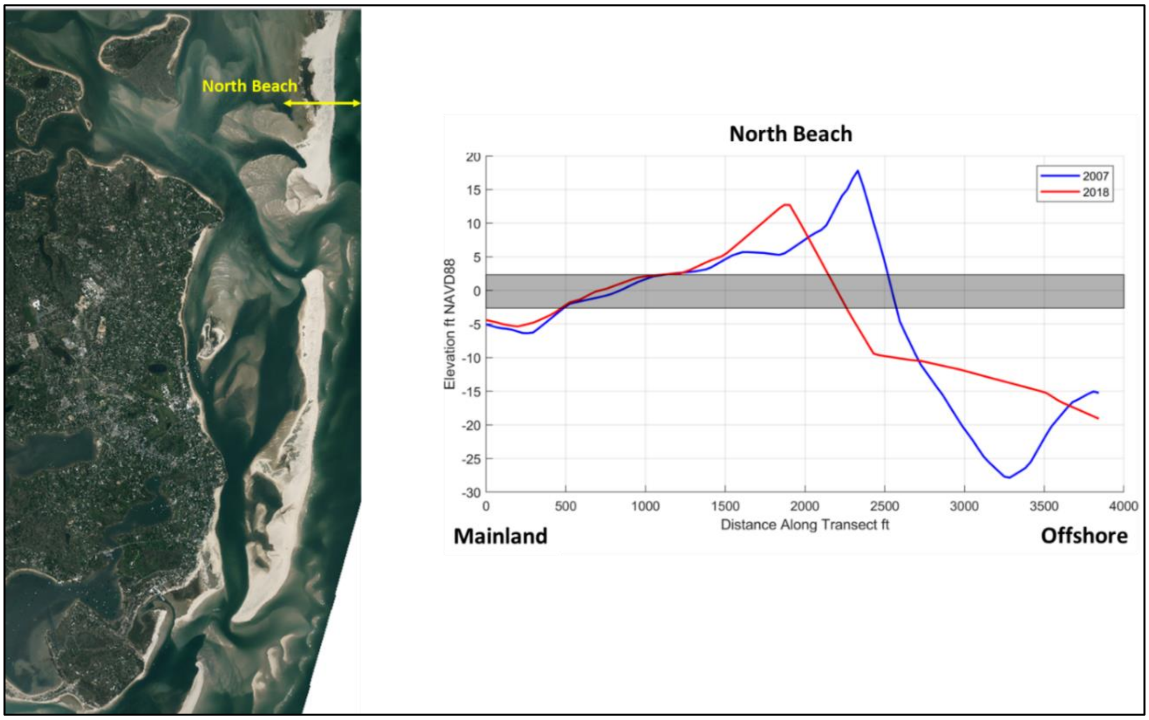


Figure 5.20 LiDAR data from 2007 and 2018 with tide range in gray, on right panel, along a transect on North Beach, shown in yellow in the left panel. LiDAR data show that the highest point of elevation on the barrier beach has lowered and land above the tide line has lowered and moved towards the Mainland.

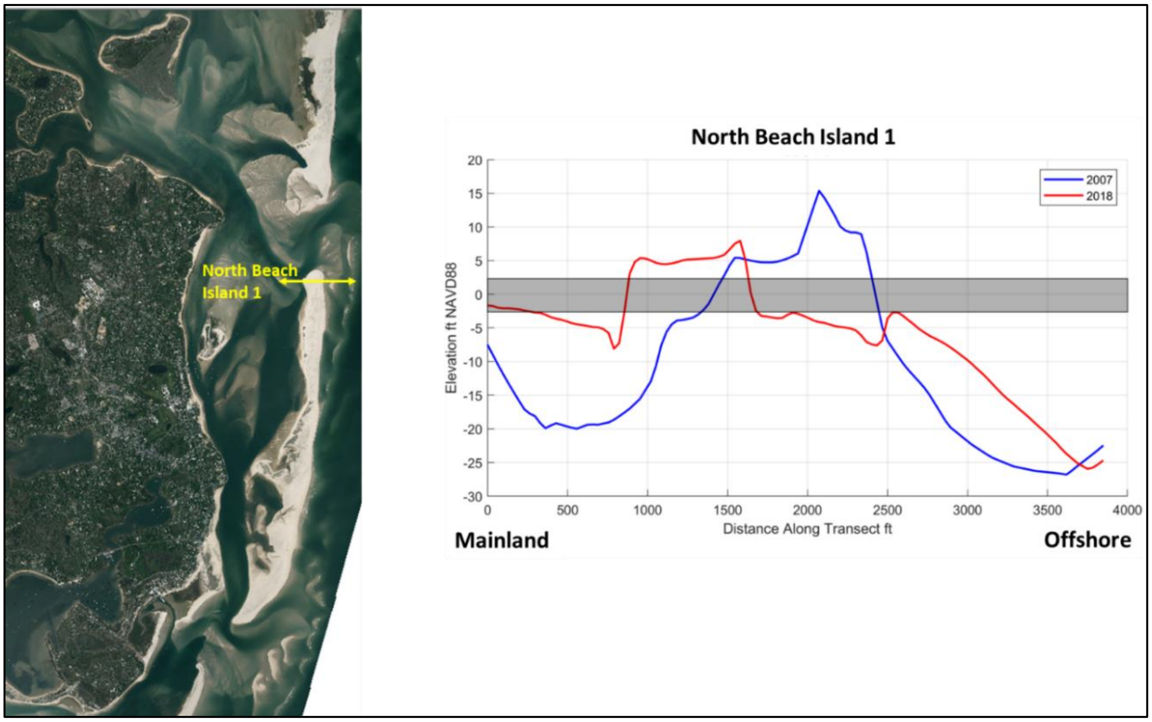


Figure 5.21 LiDAR data from 2007 and 2018 with tide range in gray, on right panel, along a transect on North Beach Island, shown in yellow in the left panel. LiDAR data show that the highest point of elevation on the barrier beach has lowered and land above the tide line has lowered and moved towards the Mainland.

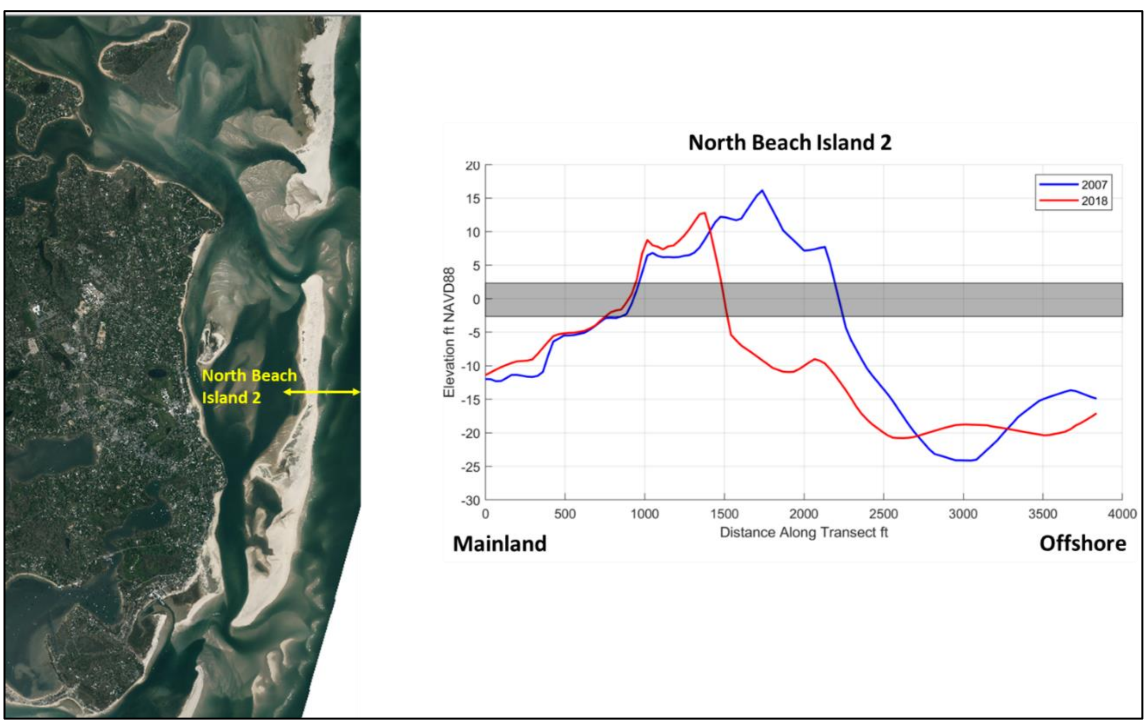


Figure 5.22 LiDAR data from 2007 and 2018 with tide range in gray, on right panel, from a transect on North Beach, shown in yellow in the left panel. LiDAR data show that the highest point of elevation on the barrier beach has lowered and land above tide line has narrowed by approximately 800 feet.

5.5 Storm Patterns

The models representing 2007 and 2018 morphological conditions of Pleasant Bay and Chatham Narbor were run with northeast storm conditions, with severe wind and waves approaching the coast. Results from the two time periods using the same storm conditions help to inform where storm energy has the greatest impact on the mainland coast for each inlet configuration and whether energy reaching the coast has changed in magnitude over time.

5.5.1 Wave Heights

Modeled wave heights are shown at high tide in Figure 5.23 and at low tide in Figure 5.24. In both models, large waves do not propagate as far into the estuary during low tide as during high tide. In 2007, the mainland area receiving the highest wave energy was the area near Watch Hill, area number 4 shown in Figure 5.23. In 2007, this area had little to no barrier island fronting it and was therefore exposed to open ocean wave conditions. In the northeast storm conditions modeled, Watch Hill experienced wave heights of 3-4 ft and the area immediately south of it experienced waves as high as 5-6 ft. In 2007, the other mainland area to experience relatively high wave energy was the north side of Minister's Island, near area 1 in Figure 5.23. Location 1 experienced approximately 2-ft wave heights during the modeled northeast storm conditions. In 2018, the change in inlet configuration shifted areas of high wave energy. Figure 5.23 shows two areas with high wave energy: the area south of Minister's Point in the vicinity of location 2, and south of location 4, near the Little Beach vicinity. The mainland in each of these areas experienced wave heights of 3-4 ft. As North Inlet has widened and migrated south, its associated window of mainland impacts has moved south and expanded with it. Additionally, as discussed in Section 5.4, the channels offshore from Minister's Point have shifted landward, directing flow closer to the mainland. Wave heights reaching the mainland have increased in height and extent from 2 ft north of Minister's Point in 2007 to four to five feet from Minister's Point (Reference Location 1) to North Chatham Channel (Reference Location 2) in 2018, a distance of approximately ½ mile.

The southern elongation of North Beach Island now protects Watch Hill and the area that was exposed during 2007. The southern focus for wave energy in the 2018 configuration is in the Little Beach Area, located opposite South Inlet's present location. South Inlet has therefore migrated approximately one mile from 2007 to 2018, the distance between Watch Hill and Little Beach. In 2018, it is now Little Beach that is mostly exposed to open ocean wave conditions, although there is limited protection from low-elevation sand shoals.

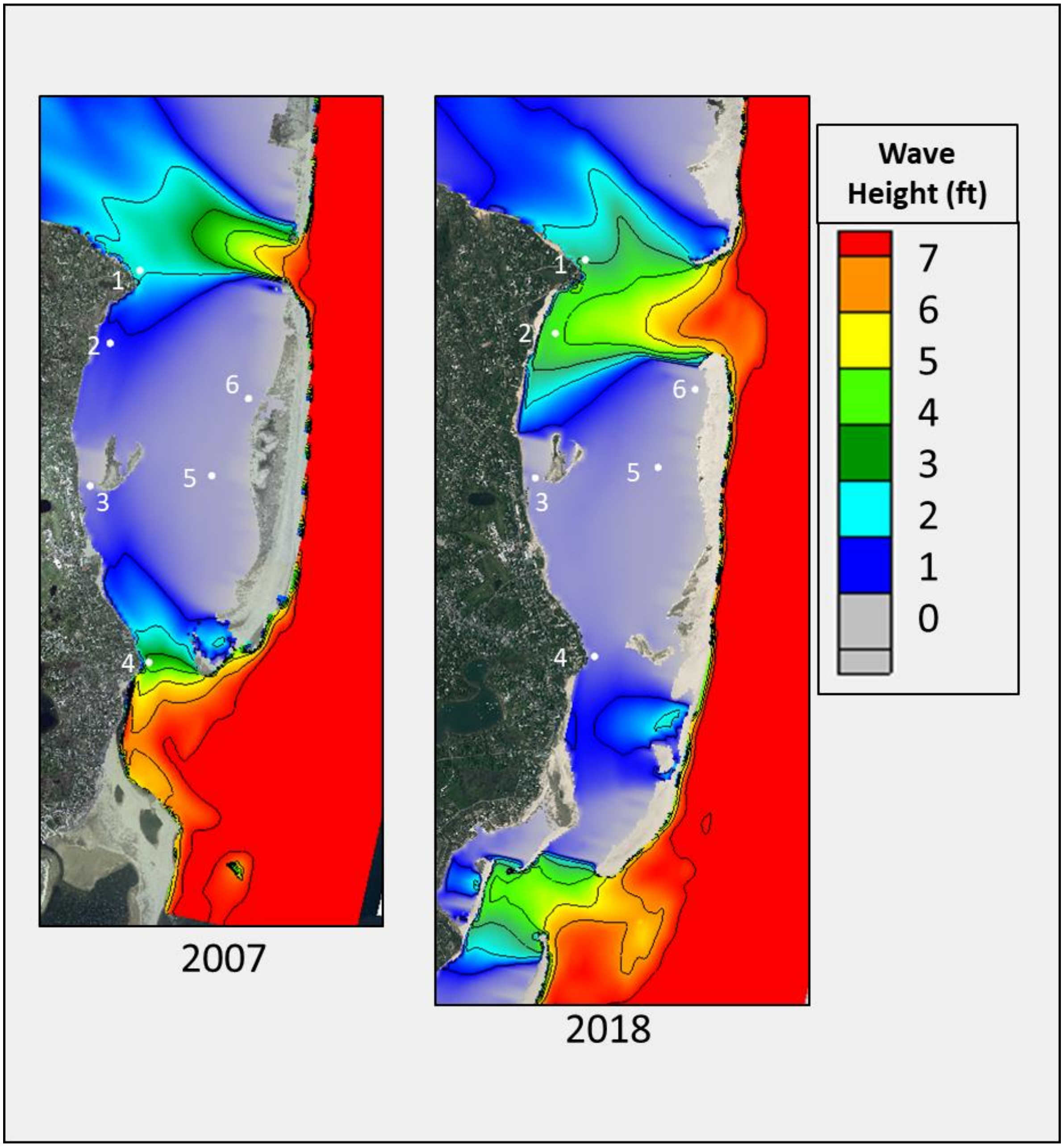


Figure 5.23 Modeled wave heights at high tide using the same October 2018 offshore and Nantucket sound tides. The same 6 reference locations are shown for reference 1 – Minister's Point; 2 – Chatham Channel North; 3 – Chatham Fish Pier; 4 – Watch Hill; 5 – Chatham Southeast; 6 – Chatham Northeast

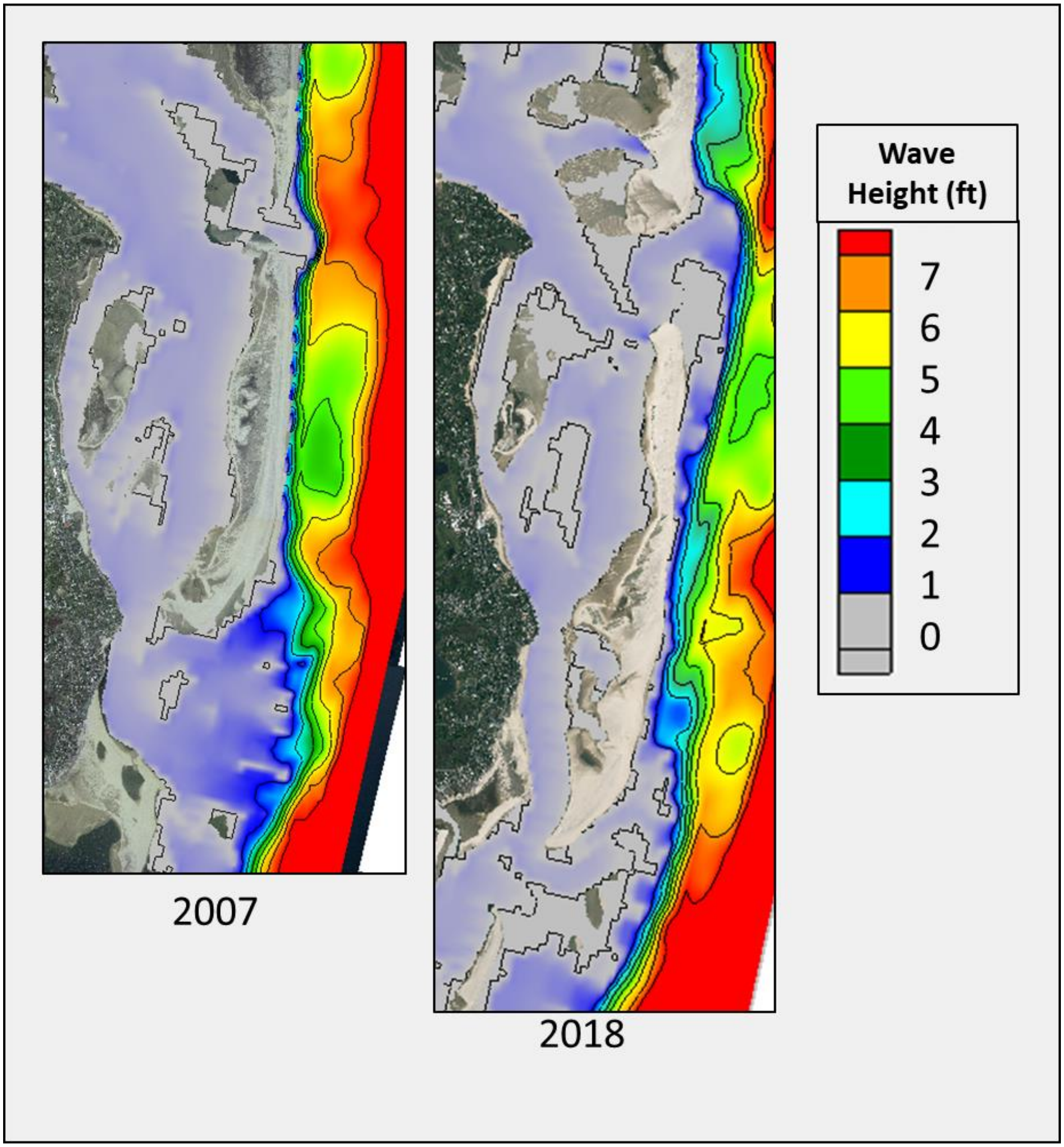


Figure 5.24 Modeled wave heights at low tide using the same October 2018 offshore and Nantucket sound tides

5.5.2 Sediment Transport

Sediment transport flow patterns and magnitude were evaluated at the inlets and channels immediately proximate to the inlets to compare results between daily conditions and storm conditions in order to determine the dominant driver of morphology changes in the system.

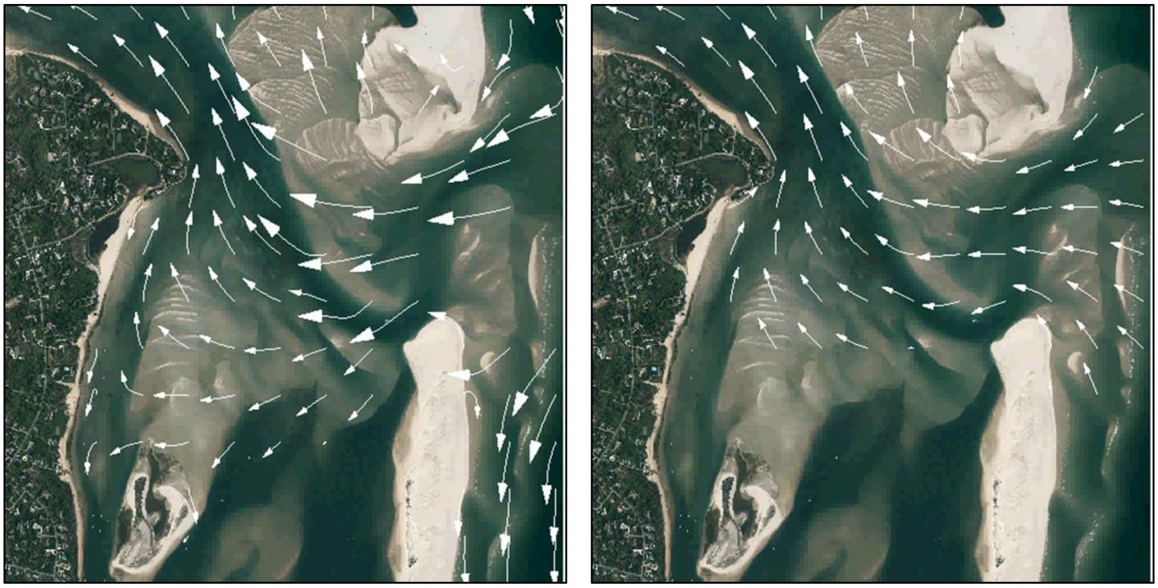
Model results suggest that storm conditions increase southern directed sediment transport on both the bayside and oceanside of the barrier islands. Additionally, storm conditions increase sediment mobility and the magnitude of sediment transport occurring throughout the estuarine system. Figure 5.25 shows differences in sediment transport flow patterns proximate to North Inlet during high tide for daily conditions and storm conditions. There is a shift of sediment transport further south into Chatham Harbor, reaching the northern tip of Tern Island, due to increased wave energy from the northeast during storms. Waves refract as they travel over the shallow depths of Tern Island Flats which sets up southerly-directed sediment transport along the mainland coast, causing erosion along the mainland during storms. Figure 5.27 shows that the magnitude of sediment transport more than doubles at North Inlet during storm conditions, increasing from 7.5-9 pound-mass per second (lbm/s) just inside North Inlet during daily conditions to 14-19 lbm/s during storm conditions. It also shows that the extent of the most active areas of sediment transport extends further south during storm conditions: the southernmost extent of sediment transport during daily conditions is approximately 1/5 mile north of Tern Island whereas storm conditions reach Tern Island. There is minimal sediment magnitude increase at Minister's Point during storm conditions.

Storm condition sediment transport patterns during an ebb tide at North Inlet are shown in Figure 5.27 and also indicate increased southern transport along the mainland coast as compared to daily conditions, with less sediment transported out of the system through North Inlet than typically occurs during daily conditions. This is observed also in the plot of sediment transport magnitude shown in Figure 5.26, where maximum magnitudes exiting through North Inlet during daily ebb tides reach 14 lbm/s as compared to storm maximum magnitudes of 9 lbm/s. This suggests that northeast storm conditions decrease sediment transport out of the system and increase transport south into Chatham Harbor.

Storm condition sediment transport flows during flood tide at the southern inlets are shown in Figure 5.29 and indicate similar patterns to those seen at North Inlet at both the bayside and oceanside of the barrier islands. At the southern inlets, storm conditions during flood tides decrease sediment transport north into Chatham Harbor and increase sediment transport in a southerly direction on the bayside and oceanside of the barrier islands. This is quantified in Figure 5.30, where sediment transport magnitudes occur further north towards Chatham Harbor during daily conditions as compared to storm conditions. Additionally, maximum magnitudes entering at South Inlet reach 14 lbm/s during daily conditions and increase to 19 lbm/s during storm conditions.

Storm condition sediment transport flows during ebb tide at the southern inlets are shown in Figure 5.31. For daily conditions, sediment transport during ebb tides splits between South Inlet and Fools Inlet. During storm conditions, very little sediment transport is directed through South Inlet and almost all is directed to Fools Inlet. This is also shown in Figure 5.32, where there are higher magnitudes of sediment transport offshore from South Inlet and increased sediment transport through Fools Inlet as compared to during daily conditions.

Throughout the system, it is evident that the modeled storm conditions increased southerly sediment transport on the bayside and oceanside of the barrier islands and decreased sediment transport exiting through North and South Inlets. This suggests daily tidal currents maintain inlet channels while northeast storm energy dominates southerly inlet migration and barrier beach southerly elongation.



Storm Conditions **Daily Conditions**

Figure 5.25 Modeled sediment transport patterns proximal to North Inlet at the same timestep during flood tide, shown with white arrows, during storm conditions (left panel) and typical daily conditions (right panel).

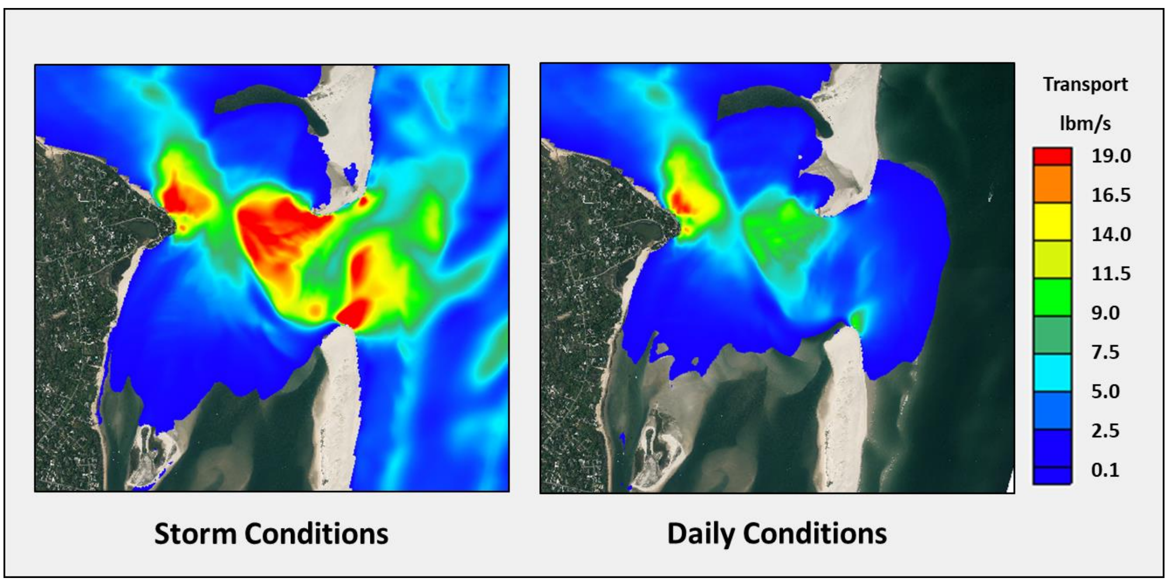


Figure 5.26 Modeled sediment transport magnitude proximate to North Inlet at the same timestep during flood tide, during storm conditions (left panel) and typical daily conditions (right panel).

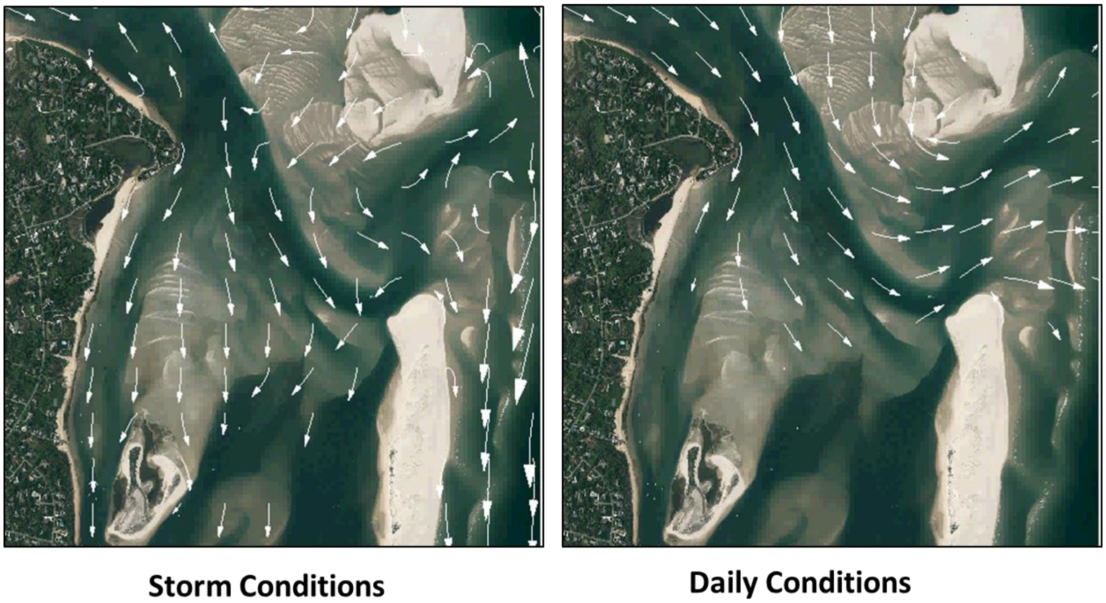


Figure 5.27 Modeled sediment transport patterns proximate to North Inlet at the same timestep during ebb tide, shown with white arrows, during storm conditions (left panel) and typical daily conditions (right panel).

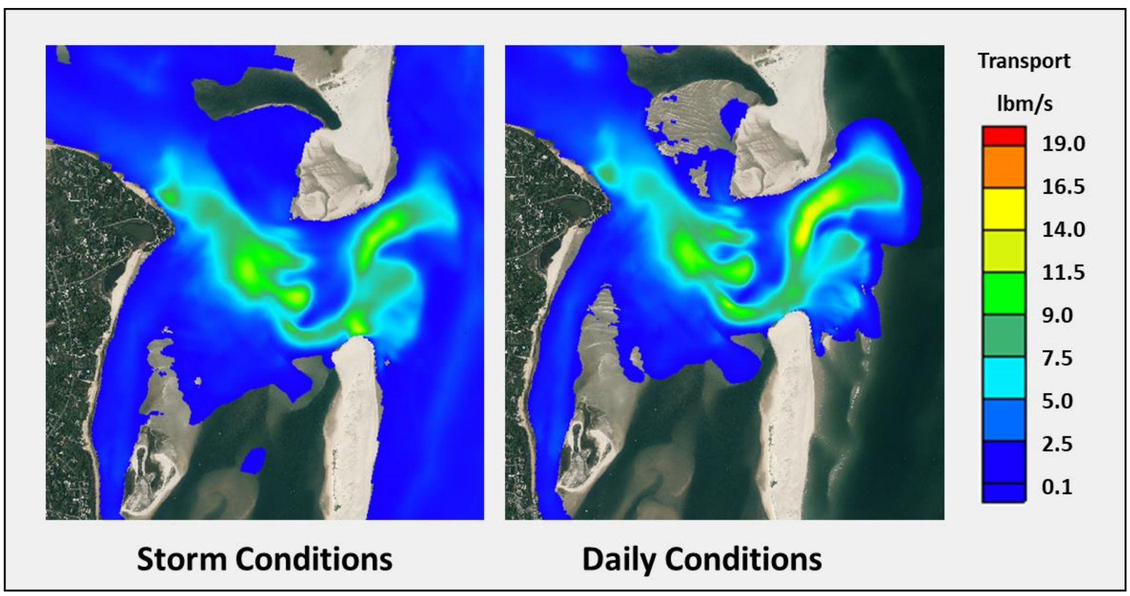


Figure 5.28 Modeled sediment transport magnitude proximate to North Inlet at the same timestep during ebb tide, during storm conditions (left panel) and typical daily conditions (right panel).

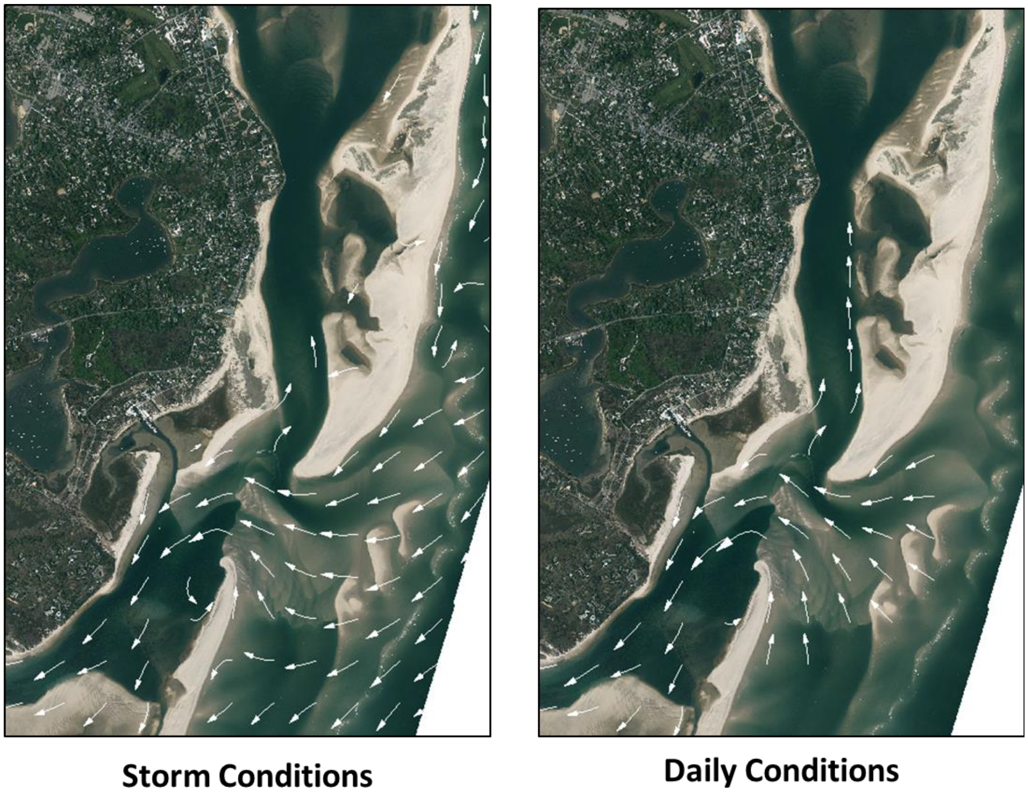


Figure 5.29 Modeled sediment transport patterns proximal to South and Fools Inlets at the same timestep during flood tide, shown with white arrows, during storm conditions (left panel) and typical daily conditions (right panel).

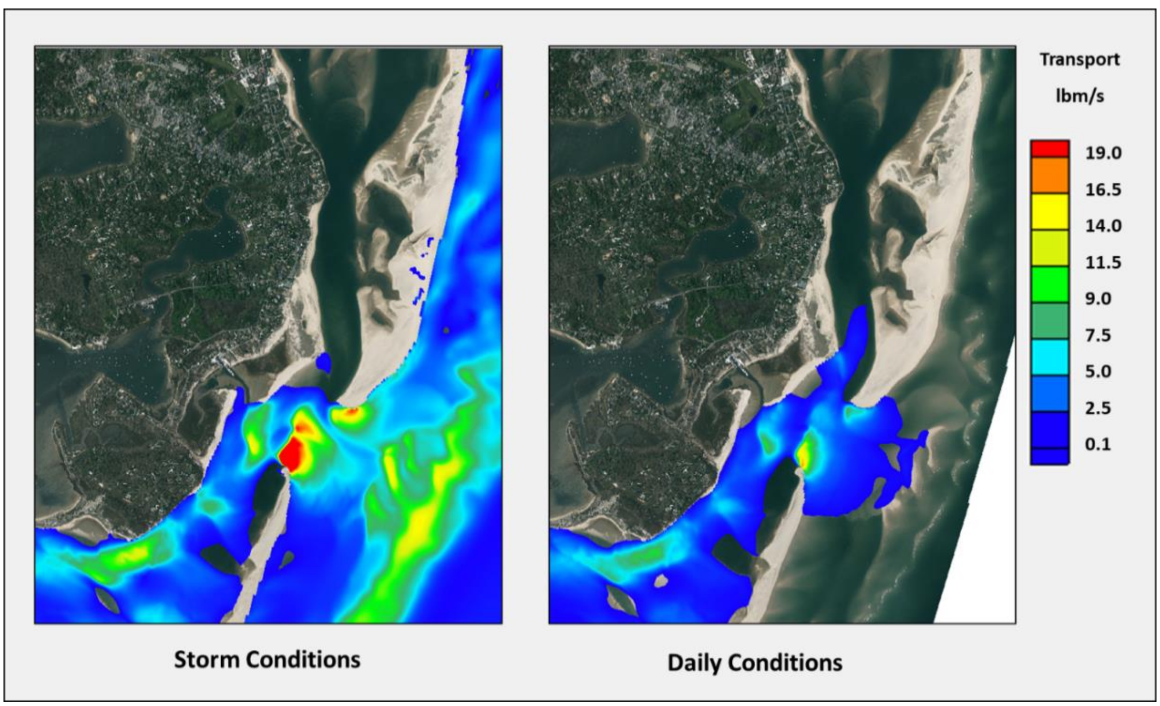


Figure 5.30 Modeled sediment transport magnitude proximate to South and Fools Inlets at the same timestep during flood tide, during storm conditions (left panel) and typical daily conditions (right panel).

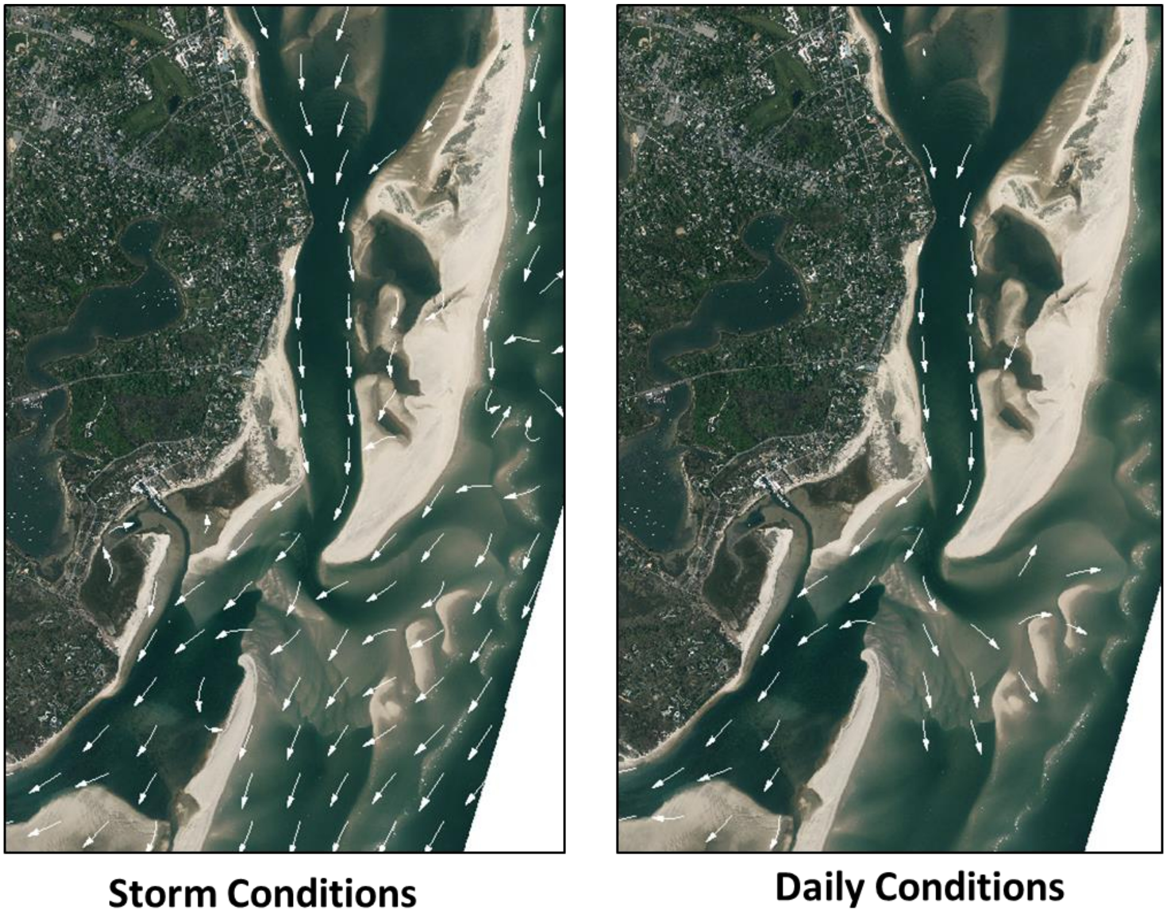


Figure 5.31 Modeled sediment transport patterns proximal to South and Fools Inlets at the same timestep during ebb tide, shown with white arrows, during storm conditions (left panel) and typical daily conditions (right panel).

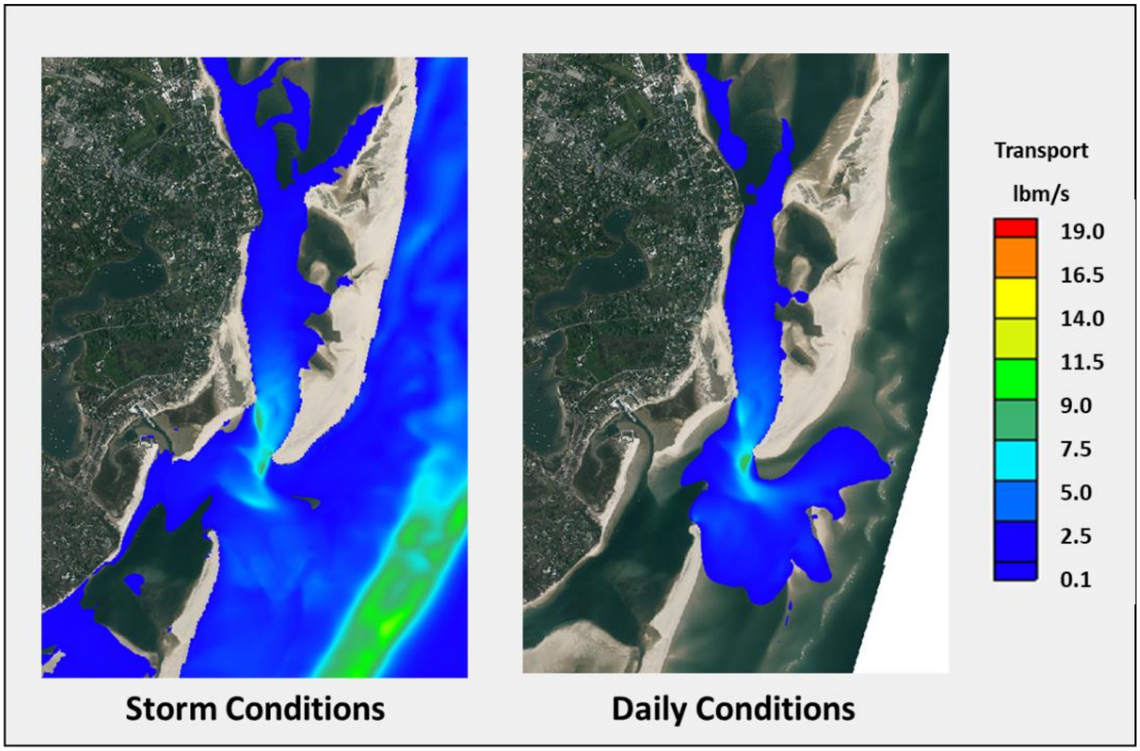


Figure 5.32 Modeled sediment transport magnitude proximate to South and Fools Inlets at the same timestep during ebb tide, during storm conditions (left panel) and typical daily conditions (right panel).

6.0 INLET/CHANNEL MIGRATION AND EVOLUTION ANALYSIS

Using the numerical morphological models developed to represent different recent configurations of Nauset Beach and the Chatham Harbor inlets (2006, 2007, and 2018) as well as a thorough literature review (Borrelli et al. 2016; Friedrichs et al. 1993; Giese 1978; Giese 1988; Giese et al. 2009), marine and terrestrial patterns were evaluated and historical rates of spit growth and inlet migration were incorporated to project the location of inlets and the surrounding shoals in approximately 30 years. The majority of historical studies produced largely 2-dimensional data sets of barrier position and inlet migration and location. The more morphological modeling analyses provided sediment transport and wave-induced transport patters that helped inform the forecast of shoal development and inlet evolution.

6.1 Past and Present Morphological Patterns

There are three predominant and recognizable patterns seen in the cyclical cycle of inlet evolution along Chatham's open ocean coastline. First, the barrier remnants south of a migrating inlet form into a "boomerang" shape where the upper half arcs landward, migrates westward, and ultimately welds onto the mainland. Second, the southern half of a barrier remnant elongates in a southerly direction as it migrates westward before also welding onto the mainland. The third pattern seen through historical analysis is a southerly elongation of the barrier beach north of a migrating inlet. It is noted in Giese et al. 2009 that this migration south does not occur until the remnant barrier to its south undergoes significant erosion and westward migration (Giese et al. 2009).

These patterns can be seen after the 1846 breach in Figure 6.1 and Figure 6.2, when the northern half of the remnants south of the new inlet arced towards Aunt Lydia's Cove and joined a spit already attached to Minister's Point. Additionally, the southern elongation of the southern half of those remnants is visible in the 1886 panel (Figure 6.2). Lastly, Figure 6.2 illustrates the southern migration of the barrier beach north of the migrating inlet, when the end of Nauset Beach migrated from offshore Minister's Point to offshore Aunt Lydia's Cove in approximately 30 years.

The patterns can be seen again following the 1987 breach that occurred at Chatham Light: the northern half of the remnants rotated landward in a boomerang shape that welded onto the mainland at Little Beach while the southern half elongated in a southern direction and eventually attached to Monomoy, as shown in the 2006 panel (Figure 6.3).

Continuing this pattern, following the 2007 breach the northern half of North Beach Island has been experiencing rollover, as shown in Figure 5.21 and discussed in Section 5.4. This has blocked the backside channel along the barrier at Chatham Harbor and largely reduced tidal flow, as discussed in Section 5.2. This sets up a potential boomerang shape towards Tern Island as was seen in the late 1800s. Additionally, North Beach Island has elongated rapidly in a southern direction from its position when North Inlet breached in 2007, as seen in Figure 6.4 and Figure 6.5. This material is likely coming from the middle of North Beach Island where erosion has been observed from 2007 to 2018, as shown in Figure 5.22 of Section 5.4.

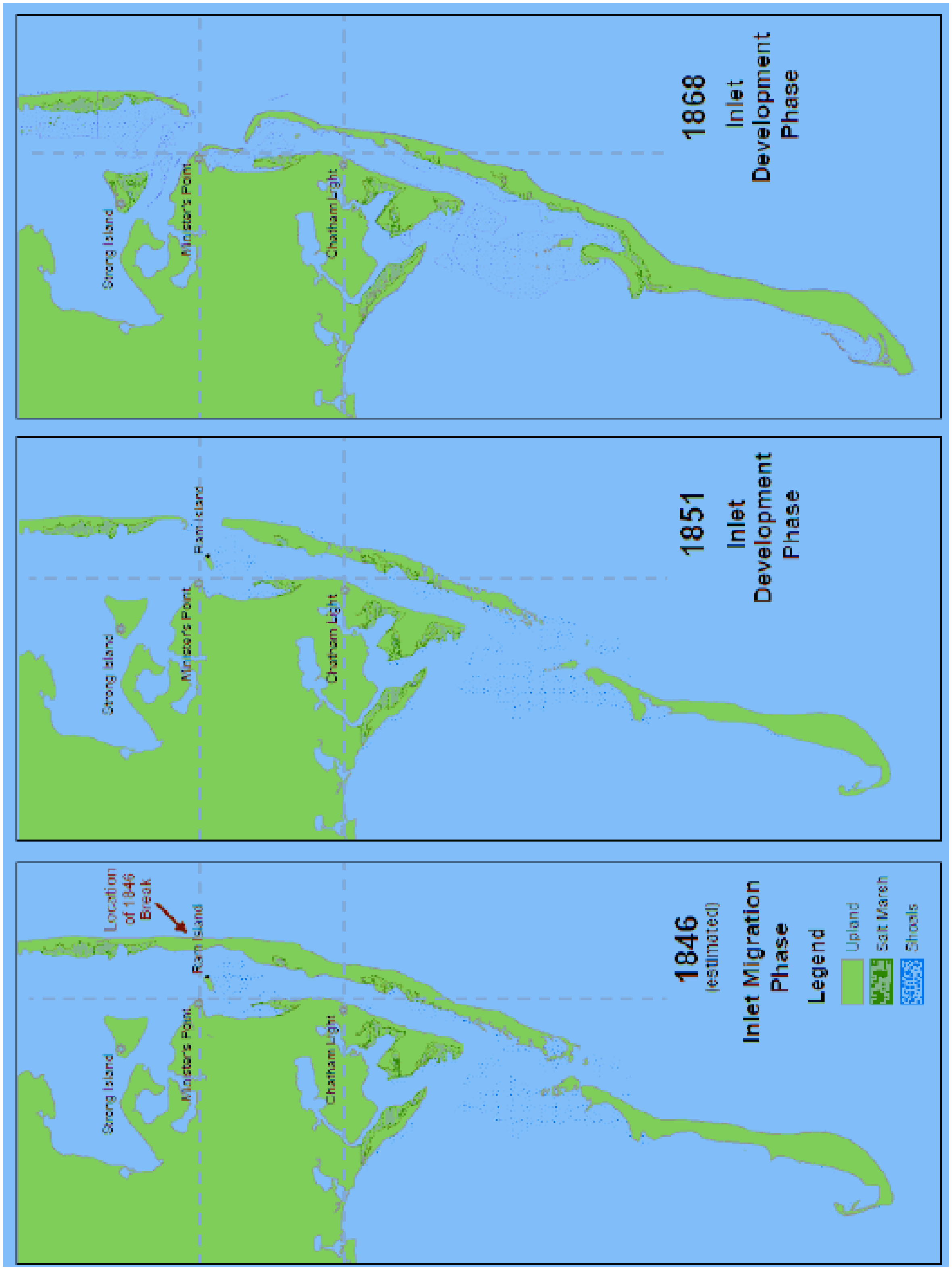


Figure 6.1 Chatham barrier inlet configuration in 1846, 1851, and 1868 during the development of the 1846 inlet that breached offshore of Minister's Point. The southern remnants form a 'boomerang' arcuate shape as they migrate westward, visible in the 1868 panel. From Giese et al. 2009.

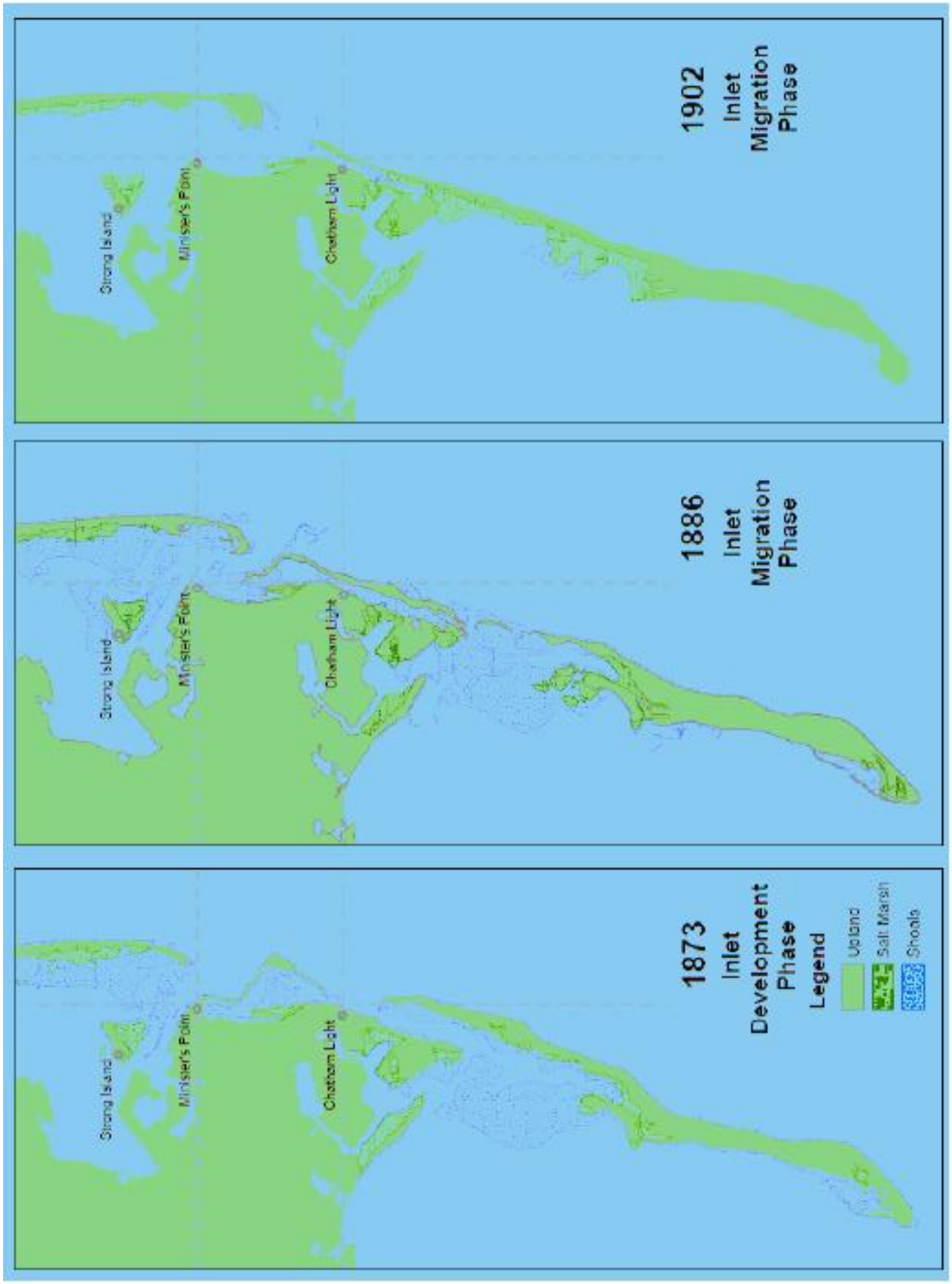


Figure 6.2 Chatham barrier inlet configuration in 1873, 1886, and 1902 during the inlet development phase of the 1846 inlet that breached offshore of Minister's Point. The southern remnants form a 'boomerang' arcuate shape as they migrate westward, visible in the 1873 panel and also elongate in a southerly direction, visible in the 1886 panel. From Giese et al. 2009.

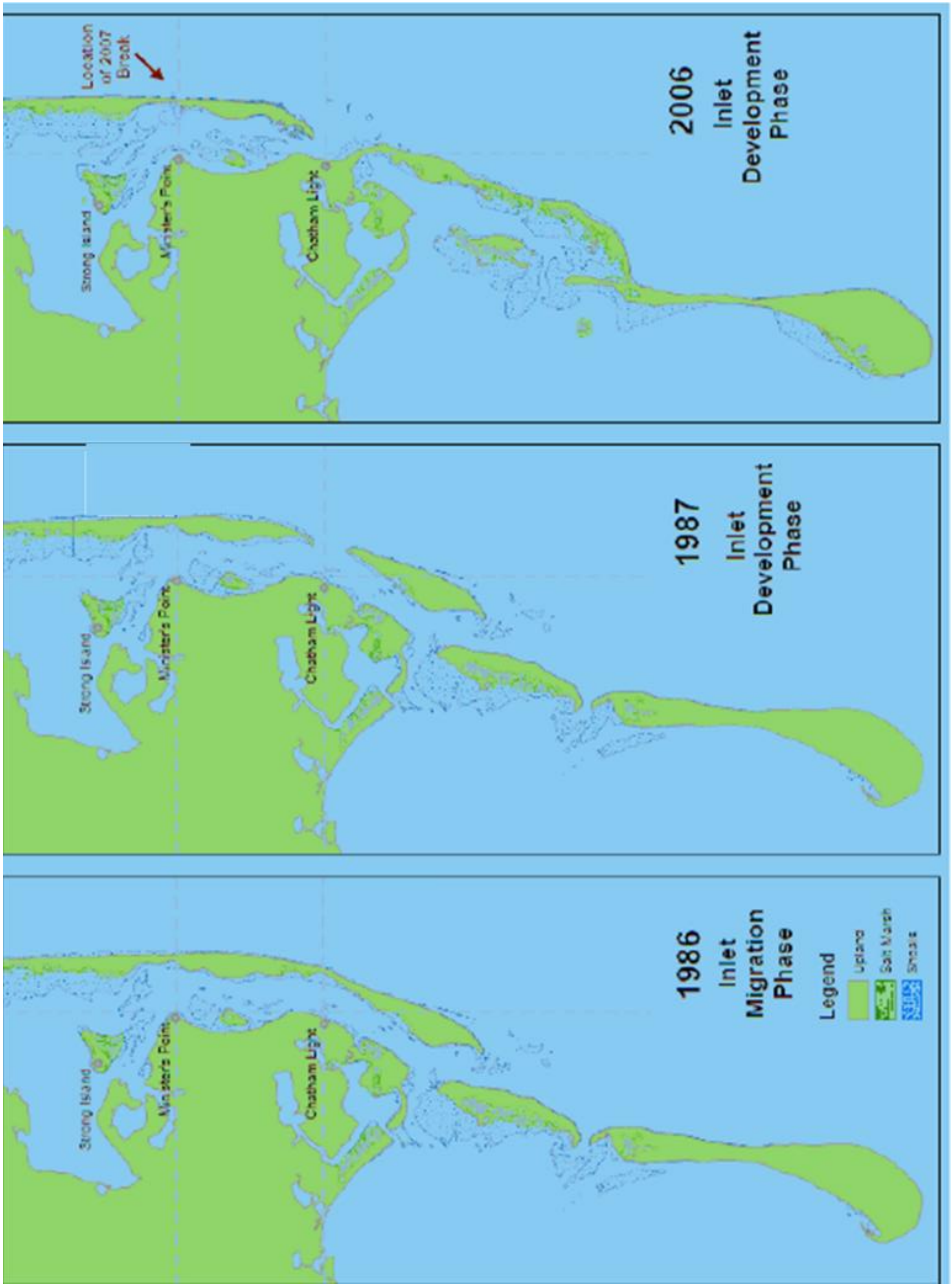


Figure 6.3 Chatham barrier inlet configuration in 1986, 1987, and 2006 showing how the southern remnants following the 1987 breach welded to the mainland visible in the 2006 panel and South Inlet was created at Watch Hill, visible in the 2006 panel. From Giese et al. 2009.

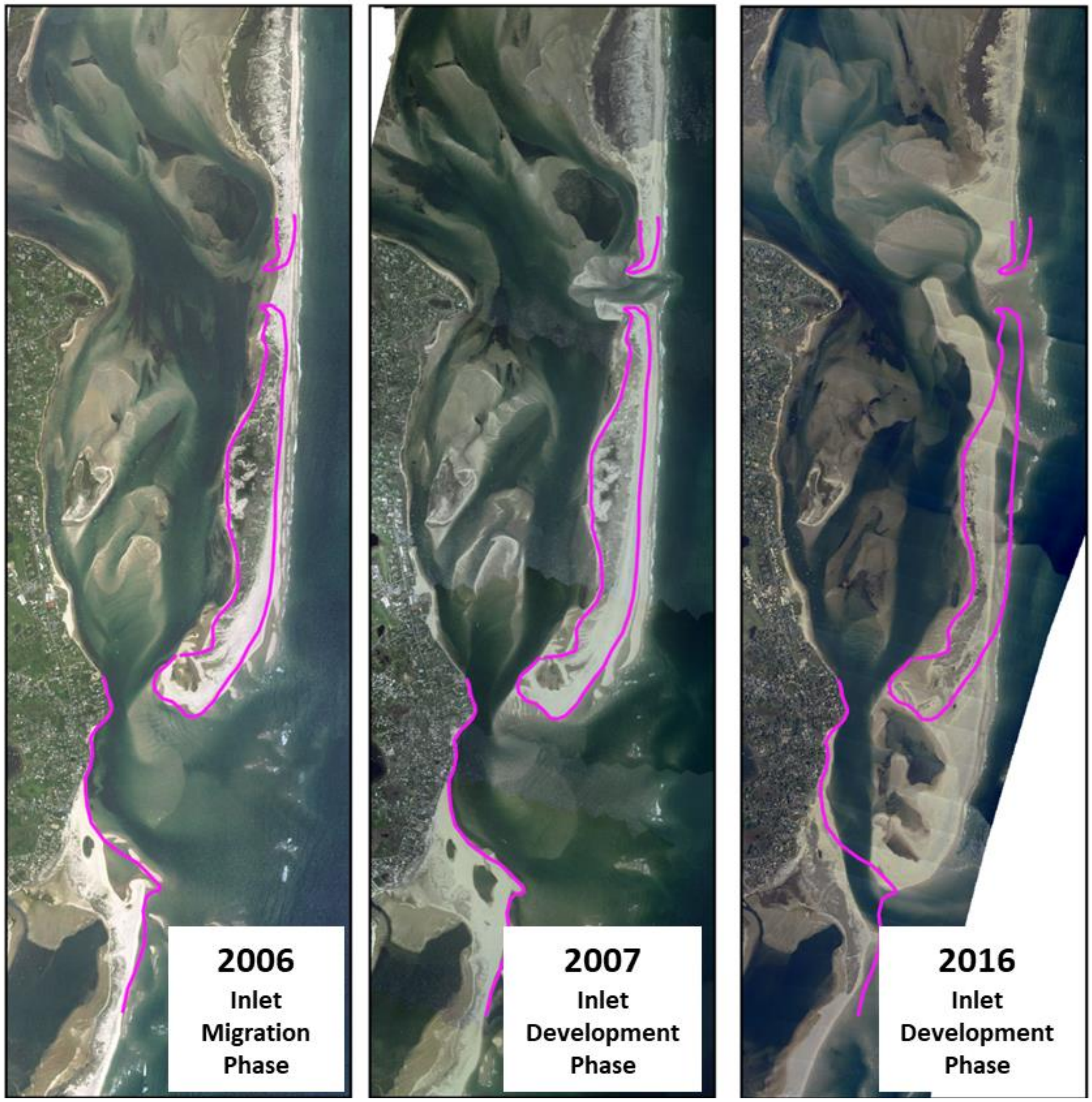


Figure 6.4 Aerial photos from the Town of Chatham showing the 2007 breach and inlet evolution to 2016. The magenta line traces the high-water line at the initiation of the 2007 breach and shows the narrowing, southern elongation, and westward migration of North Beach Island.

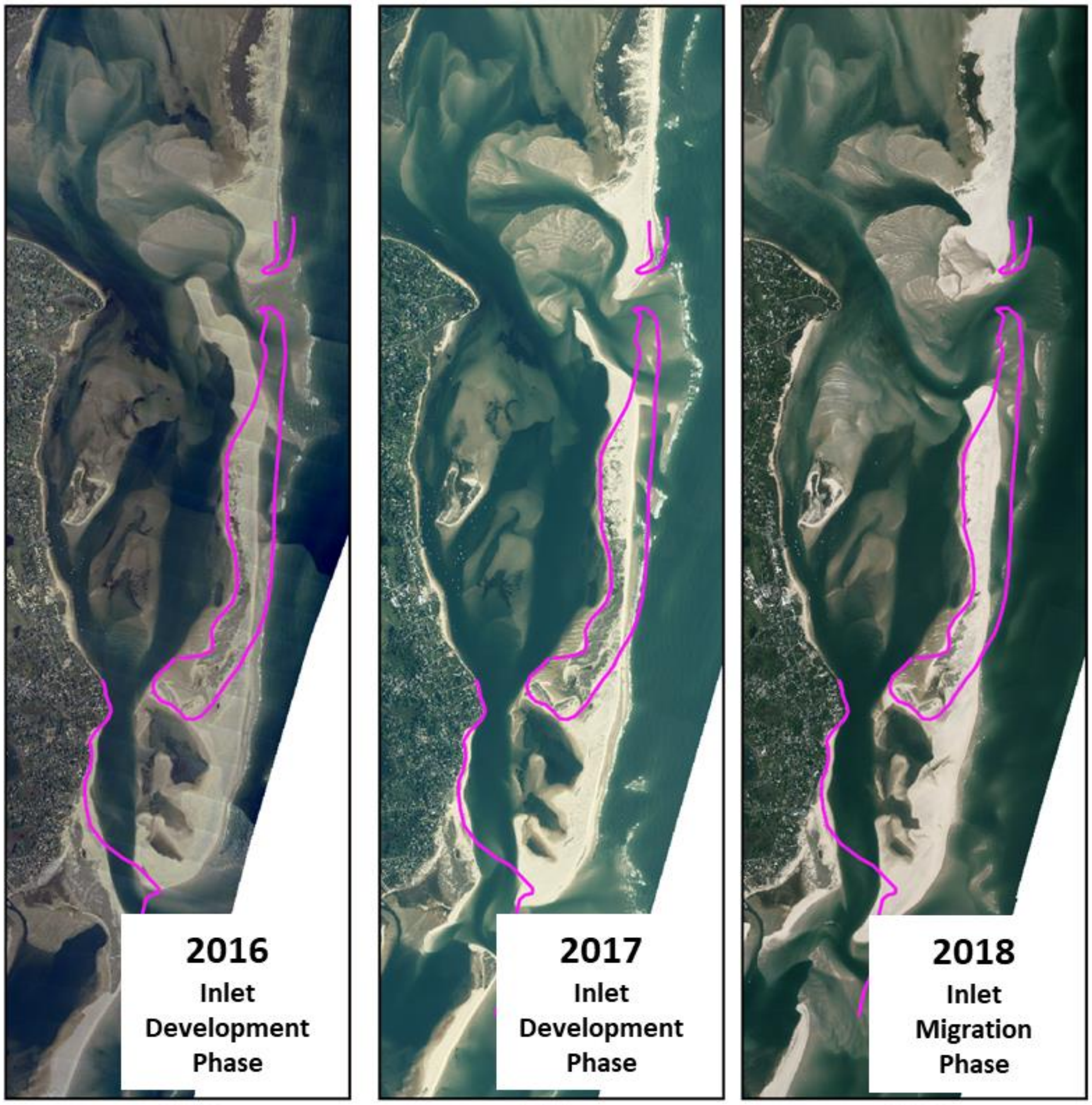


Figure 6.5 Aerial photos from the Town of Chatham showing the 2017 breach evolution to 2018. The magenta line traces the high-water line at the initiation of the 2007 breach and shows the narrowing, southern elongation, and westward migration of North Beach Island.

As discussed previously and shown in Figure 2.3, these historical patterns have occurred in an approximate 150-year cycle.

The present inlet configuration is similar to historical documentation of the inlets in the late 1860s to early 1870s timeframe, shown in Figure 6.1 and Figure 6.2, respectively. The 1846 inlet breached in approximately the same location as current North Inlet (Figure 6.1), creating a two-inlet system that would have had conditions similar to those experienced in Chatham from 2007 to 2017. The main difference between these time periods is the location of South Inlet: in the mid-1800s South Beach extended along the entirety of the mainland and South Inlet was located south of Morris Island; in the 2007-2017 timeframe, the remnants of the 1987 breach had welded to the mainland near Little Beach, creating South Inlet at Watch Hill (Figure 6.3). The barrier remnants south of North

Inlet (North Beach Island) have shown narrowing, westward migration, and southern elongation as discussed in Section 5.1 and shown in Figure 6.4 and Figure 6.5.

It is expected that North Beach Island will continue to migrate landward, particularly since the north and south inlet(s) have begun to “decouple” from each other resulting in reduced tidal flow through Chatham Harbor, as discussed by Giese and Legare (2019) and confirmed in the 2018 hydrodynamic model results presented in Section 5.0. The reduced flow in Chatham Harbor will allow for increased shoaling and creation of the historical ‘boomerang’ arcuate shape as North Beach Island continues to roll over. Historic charts also show complex shoal systems that form at the migrating inlets as well as on the oceanside of the barrier remnants. Once this increased shoaling and landward migration has occurred, it is expected that North Beach will migrate south, as was seen in the 1870’s. Therefore, the forecasted 2045 configuration takes into account all of these patterns in an attempt to predict a future inlet configuration for the 25-years-after-present timeframe.

In the south: North Beach Island is rolling over in the northern part and narrowing/eroding in the southern part. This erosion is being moved in a southerly direction due to predominant longshore transport direction in this area and accreting onto the southern tip of North Beach Island. Simultaneously, flow though South Chatham Harbor has decreased to approximately 30% of the 2007 volume South Inlet has become almost completely unidirectional, allowing accelerated accretion at the southern extent of North Beach Island

6.2 Future 2045 Configuration

The inlet configuration and bathymetry forecasted for 2045, shown in Figure 6.6, was determined using the quantitative analysis of coastal change and sediment transport processes as well as historical documented morphology and rates of spit elongation. For a 25-year-long planning window, this should be a valid forecast assumption since the forces driving the evolution of the inlet system are not expected to change wildly within that relatively short time period. Uncertainty due to changing storm frequency and intensity, along with highly accelerated rates of sea level rise would be potentially more important for time periods longer than the 25-year forecast. Other variables such as sediment supply, human induced changes such as dredging, and other natural and anthropogenic phenomena potentially could influence the actual evolution and location of the inlet in 2045 but are difficult to quantify and predict.

The 2045 forecast includes a boomerang shape that connects to current-day Tern Island and southern elongation of the North and South Beach remnants. The deep area at Watch Hill is shallower than 2018; this is the relic channel from the pre-2007 one-inlet configuration that will slowly shoal as tidal flows through this area continue to decrease. The oceanside of the boomerang remnant has large shoals and therefore shallower water depths than the present configuration. The channel connecting North Inlet to Pleasant Bay is slightly shallower than what is seen in 2018, as flows are expected to continue to reduce as North Island begins its southern migration.

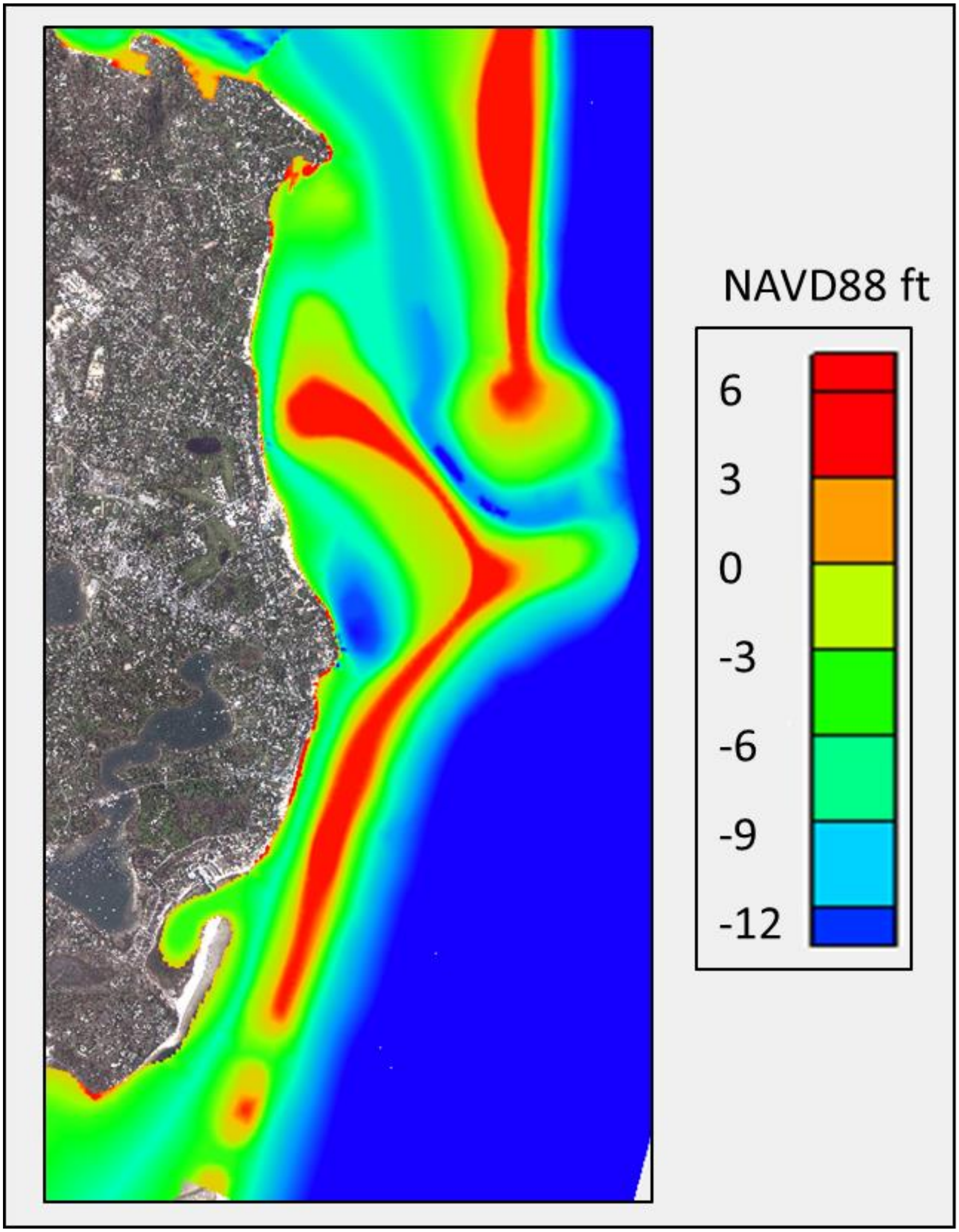


Figure 6.6 Projected 2045 inlet configuration and bathymetry, produced in coordination with the Center for Coastal Studies.

6.3 Model Setup

The same hydrodynamic and wave model setups discussed in Section 4.1 and Section 4.6, respectively, were used after updating each model grid with the 2045 projected bathymetry. The 2045 model was run for the same 200 hour period used for calibration of the 2018 model, however, in the 2045 model the tidal boundary conditions were adjusted for expected sea level rise using the "mid" sea level rise scenario of 6 mm/yr developed in the 2016 Pleasant Bay Alliance report discussed in Section 2.3. The 2018 measured tides for the offshore Atlantic Ocean and Nantucket Sound were shifted by +0.5 ft, which is the equivalent to 162 mm, calculated by multiplying the difference in years between 2045 and 2018 (27 years) by 6 mm/year. The adjusted boundary condition tides are shown in

Figure 6.7. Storm waves were applied to the 2045 model to evaluate changes during typical northeast storm conditions, as was modeled also for 2007 and 2018 inlet configurations.

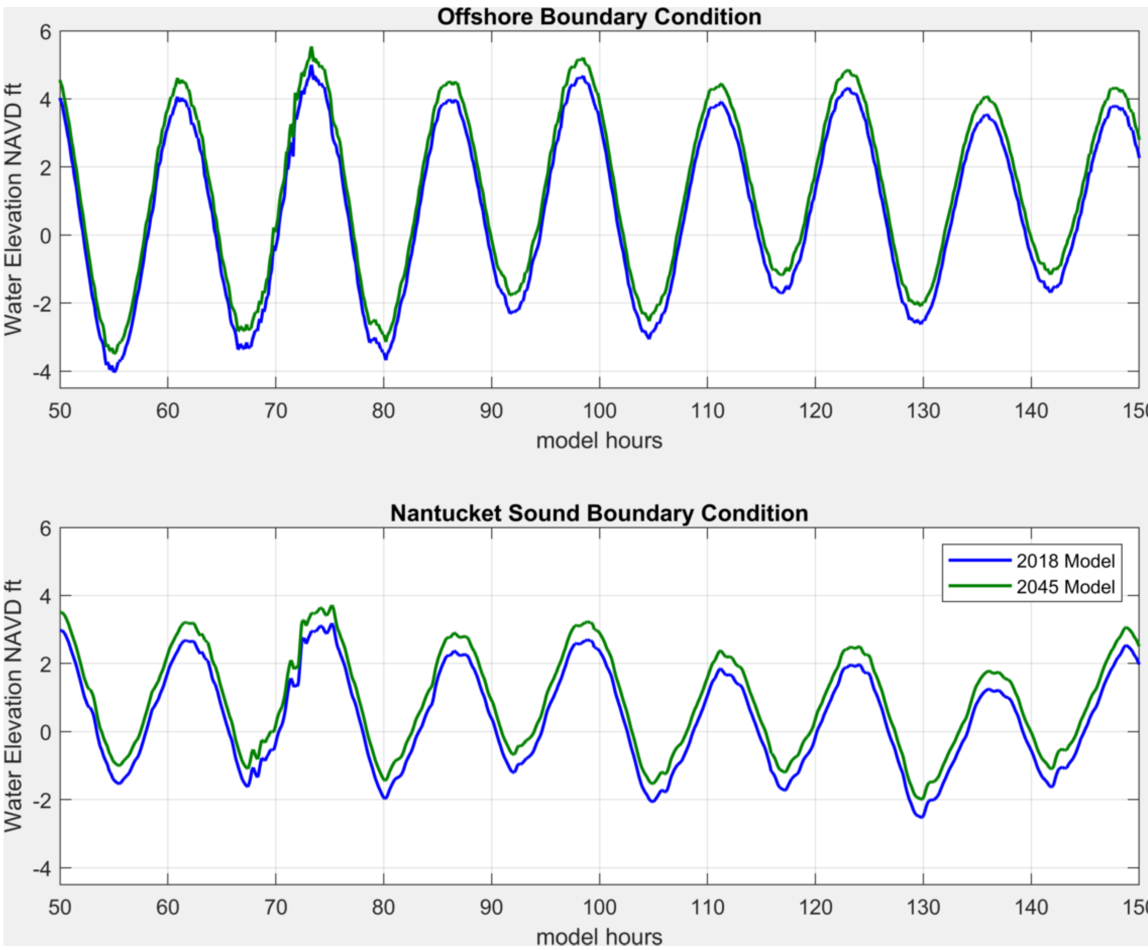


Figure 6.7 Boundary conditions used for the 2018 and the 2045 models.

6.4 Results for 2045 Model

A direct comparison of 2007, 2018 and 2045 hydrodynamic conditions in Pleasant Bay was done by running the 2045 model grid using the same tidal boundary condition used in the 2007 and 2018 models, but shifted by +162 mm for sea level rise for the 2045 conditions. Similar to the previous comparison of 2007 and 2018 model results made in

Section 5, by driving each model with the same offshore tide, biases in the measured data that occur because of time period differences are eliminated.

6.4.1 Tide Data Analysis

Modeled water elevations from 2045 were compared to 2018 for overall changes in elevation reduction and phasing. Figure 6.8 shows the modeled water elevations in 2045 for the same sample period and locations as Figure 3.6. A similar pattern from 2018 can be seen in 2045 where the tide range decreases with increased distance from an inlet, and Meetinghouse Pond has the smallest tide range of the inner locations. The majority of this decrease in range occurs as the low tide elevation increases at inner bay locations. There is also a similar time lag to 2018, although slightly smaller at 3.4 hours between low tides at Meetinghouse Pond and Offshore.

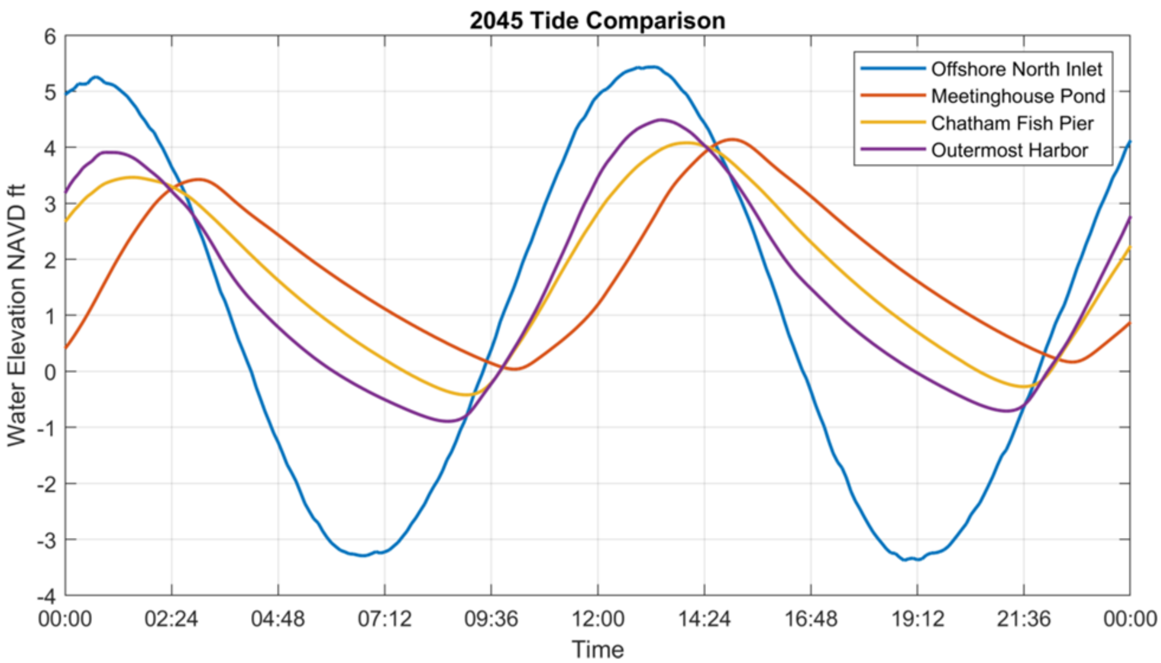


Figure 6.8 Plot showing two modeled tide cycles for the offshore boundary and three inner Bay stations in 2045. This is the same time period and locations used in Figure 3.6.

6.4.2 Bathymetric Change

In the 2045 configuration, the size of Chatham Harbor has become greatly reduced as the barrier remnants migrate westward and the interior of the barrier system has shallowed relative to 2018 and 2007. There is a single, narrow connection to the northern and southern extents of the system proximal to Chatham Fish Pier. The distinct S-shaped channel connecting North Inlet to Pleasant Bay remains but has smoothed in shape and shoaled slightly. The deepest portion of the channel remains just south of the tip of North Beach. There are complex shoals on the oceanside of the barrier that have developed as part of the rollover and western migration process. North Beach has elongated in a southerly direction, together with the southern tip of North Beach Island. The elongation of North Beach overlaps the west-migrating North Beach Island at the north inlet, providing near continuous protection for the mainland from exposure to open ocean waves.

6.4.3 Tidal Currents

The bathymetric and morphologic changes projected for 2045 can be correlated to changes in the hydrodynamics. Modeled water elevations were compared for 2007, 2018, and 2045 to evaluate changes. Meetinghouse Pond, Chatham Fish Pier, and Watch Hill water elevations were compared for all three models, shown in Figure 6.9, Figure 6.10, and Figure 6.11, respectively. Outermost Harbor and Stage Harbor were compared for 2018 and 2045 only, as they were not included in the 2007 model, and are shown in Figure 6.12 and Figure 6.13. The changes in tide range between all five locations are summarized in Table 6.1. Each of the five locations indicate a continuing decrease in tide range for 2045 relative to past or present conditions. This reduction, similarly to those seen from 2007 to 2018, is primarily due to increasing low water elevations. As the barrier remnants elongate, it increases the channel length between inlets, simultaneously decreasing flushing efficiency within the system.

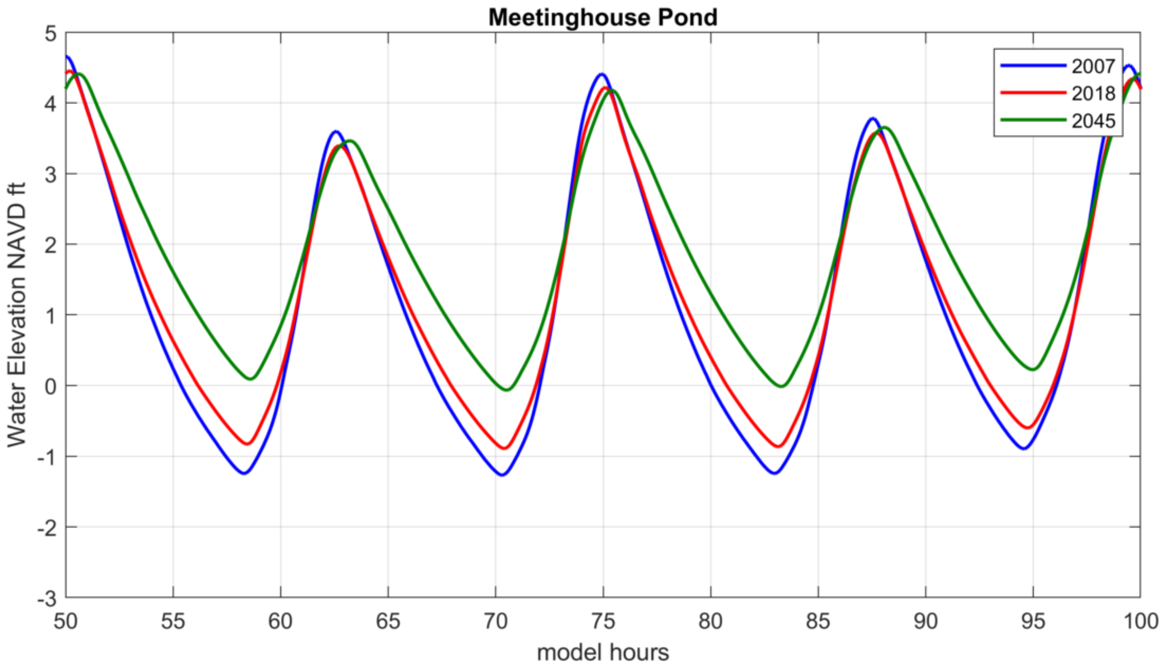


Figure 6.9 Modeled water elevation (NAVD88 ft) at Meetinghouse Pond for the 2007 (blue), 2018 (red), and 2045 (green).

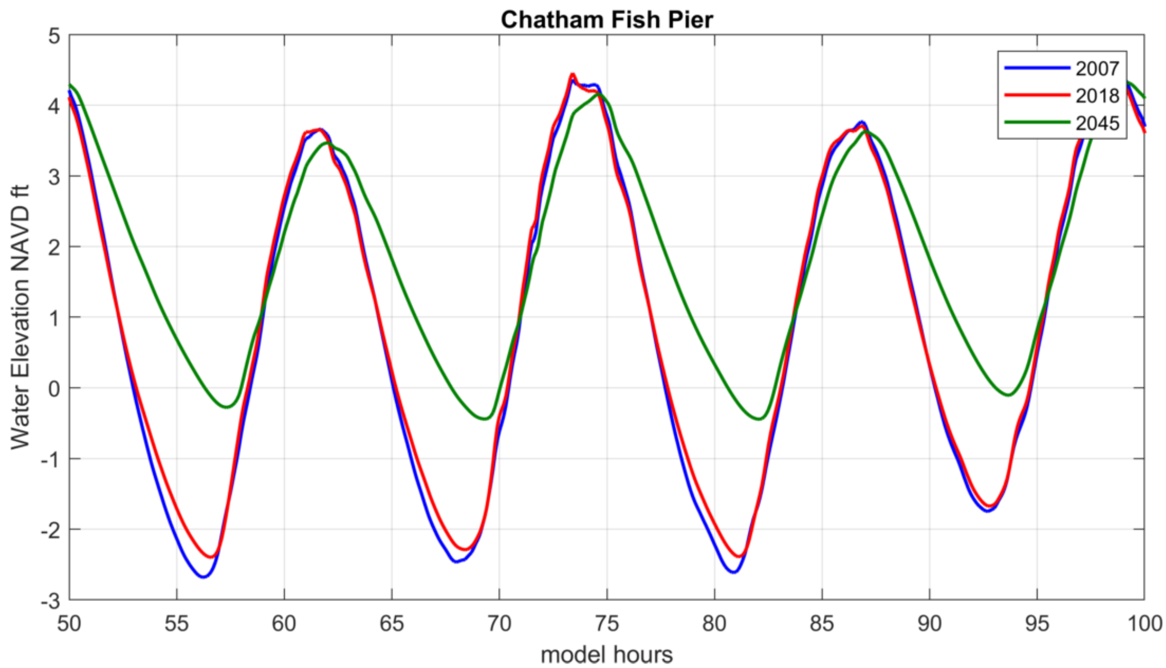


Figure 6.10 Modeled water elevation (NAVD88 ft) at Chatham Fish Pier for the 2007 (blue), 2018 (red), and 2045 (green).

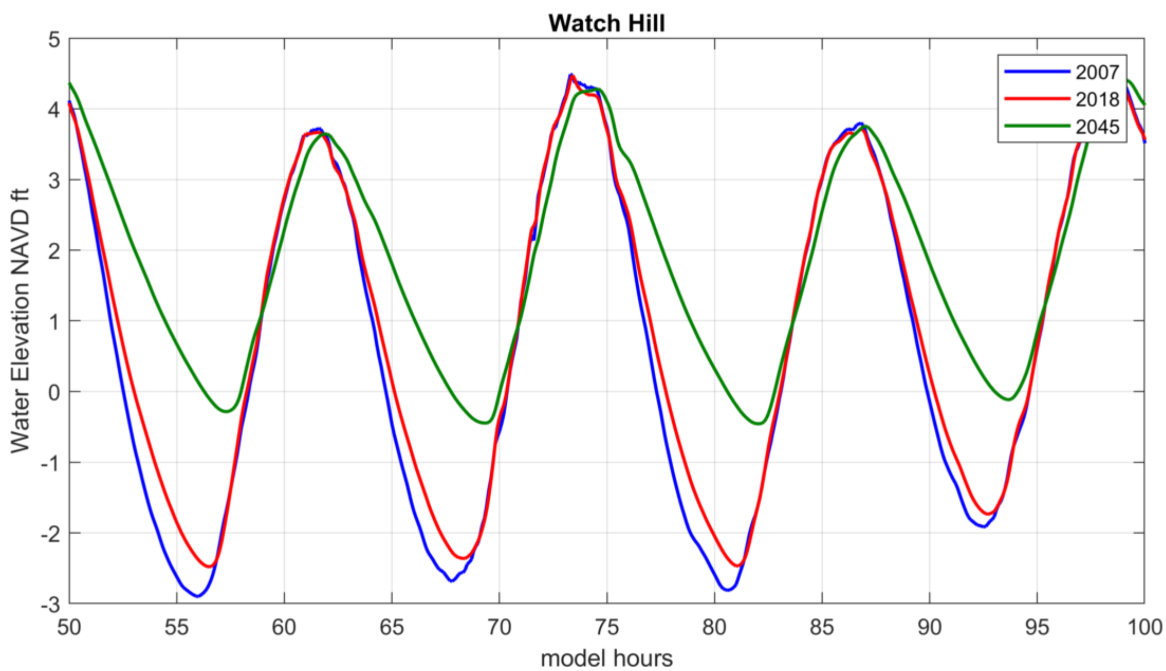


Figure 6.11 Modeled water elevation (NAVD88 ft) at Watch Hill for the 2007 (blue), 2018 (red), and 2045 (green).

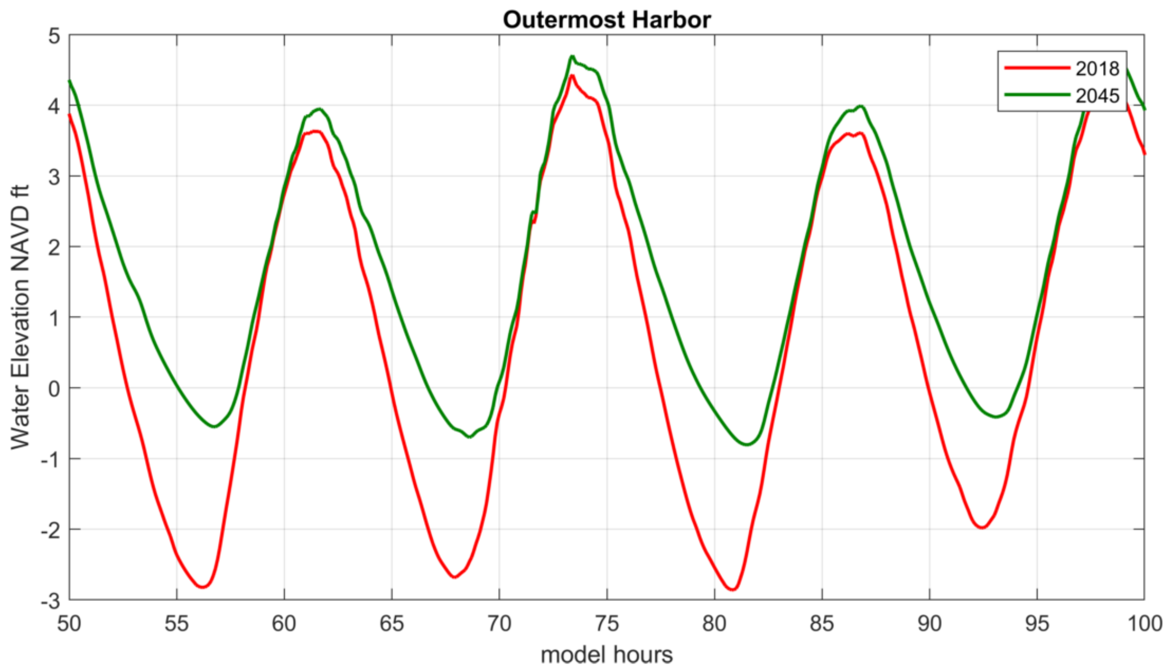


Figure 6.12 Modeled water elevation (NAVD88 ft) at Outermost Harbor for 2018 (red) and 2045 (green).

Table 6.1 Modeled tide ranges during the 200-hour calibration period for 2007, 2018, and 2045, in NAVD88 ft.

Model Year	Meeting-house Pond	Fish Pier	Watch Hill	Outermost Harbor	Stage Harbor Nantucket Boundary	Offshore Boundary
2007	4.9	5.9	6.1	N/A	N/A	6.9
2018	4.4	5.7	5.8	6.0	4.0	6.9
2045	3.6	3.9	4.1	4.3	4.0	6.9

Figure 6.13 and Figure 6.14 show contour maps of modeled depth averaged velocities at the point of maximum ebb and flood currents, respectively, for 2007, 2018, and 2045 inlet configurations. Each of the plots represent the same model time step. In the northern part of the system, the area where max flood and ebb currents above 4 ft/sec occur has increased. Flood and ebb tidal currents remain high in the vicinity of North Inlet in 2045, with slighter higher and a greater extent of flood currents, as shown in Figure 6.14. There is restricted flow along the west side of Chatham Harbor at the Fish Pier through a narrow channel. In the southern section of the 2045 configuration, there are high ebb flows through the area south of Watch Hill, proximal to Little Beach. This is due to secondary flow coming exiting Pleasant Bay that does not exit the system through North Inlet. It is restricted in the southern part of the system and the speed remains high.

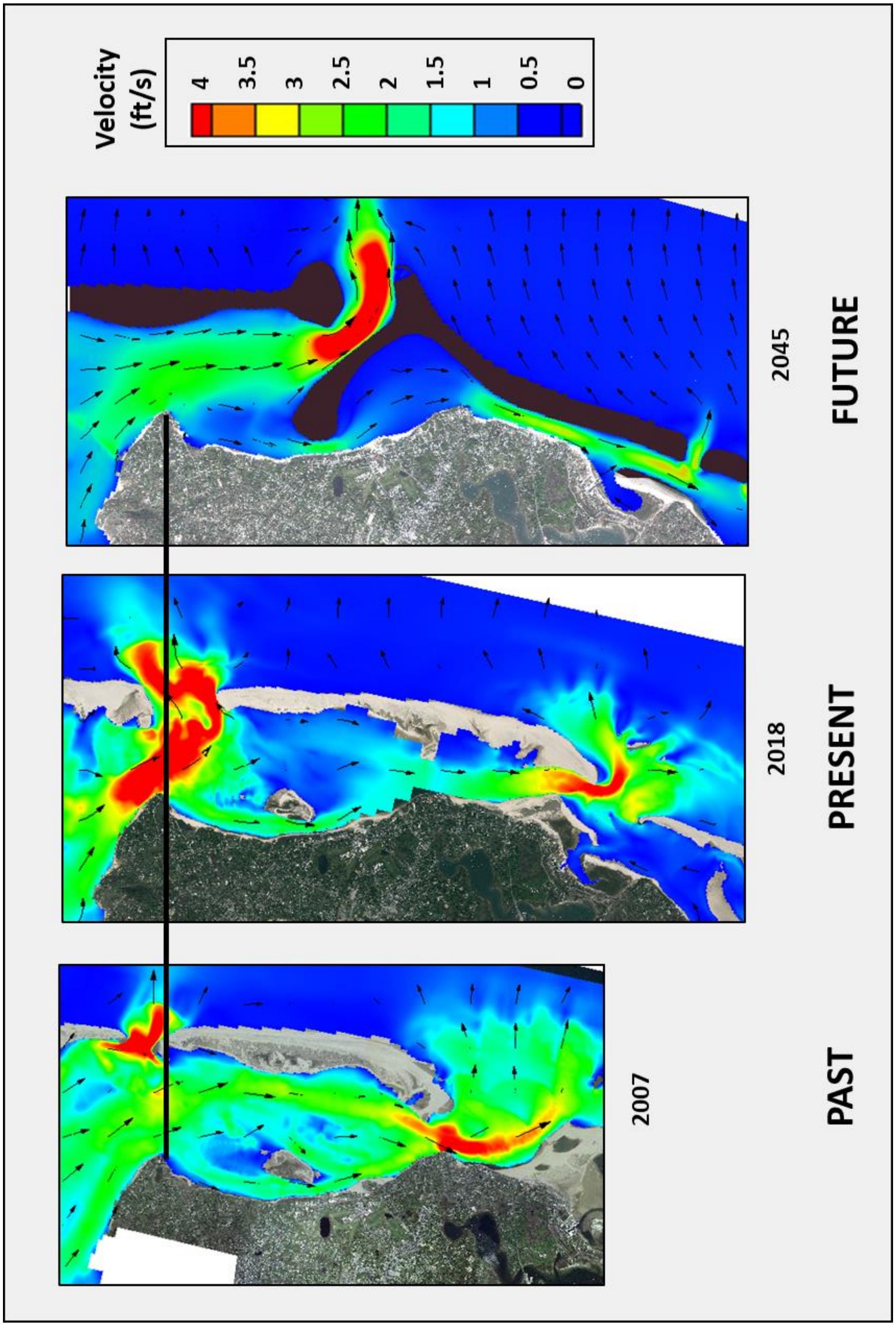


Figure 6.13 Contour plots of depth-averaged maximum ebb currents from 2007, 2018, and 2045 at the same timestep.

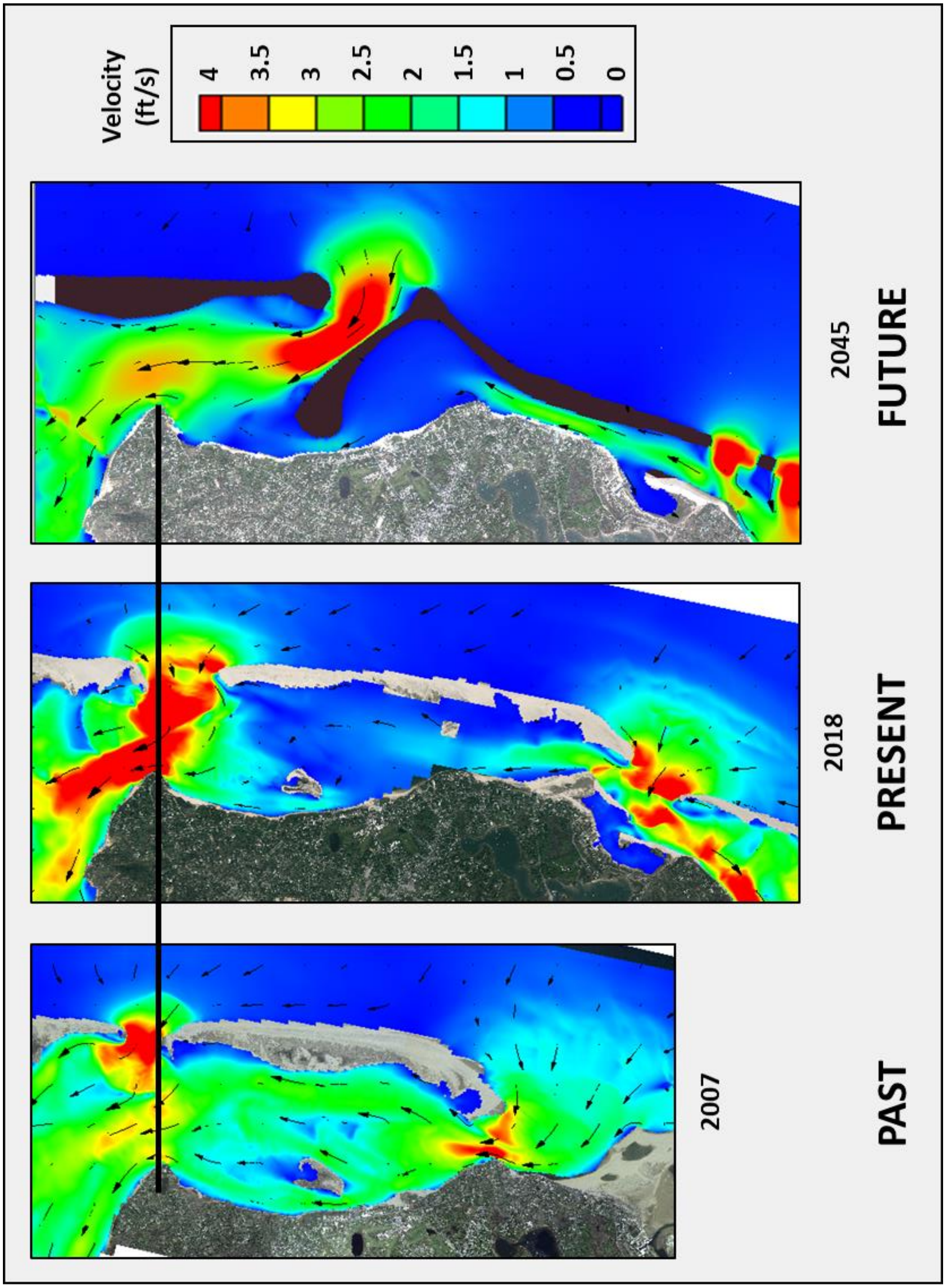


Figure 6.14 Contour plots of depth-averaged maximum flood currents from 2007, 2018, and 2045 at the same timestep.

The same six reference locations discussed in Section 5.0 are shown on the 2045 configuration in Figure 6.15. They were evaluated to better quantify tidal current changes throughout the system. Tidal current plots were plotted with an initiation of motion threshold of 0.6 m/s, based on Van Rijn 1993 and shown in Figure 5.9. Tidal current plots for each model year are shown by location in Figure 6.16 through Figure 6.21. Table 6.2 summarizes changes in average flood and ebb speeds and durations in 2045 as compared to 2007 and 2018.

Based on the expected morphological changes, reference location 5 (Chatham Southeast) will be at approximately the deepest portion of the North Inlet/Pleasant Bay Channel and will therefore experience the highest tidal currents in the system in 2045. The 2045 channel will continue north and reference location 6 will be slightly east of it; currents are expected to increase from 2018 and return to approximate 2007 magnitudes. Reference locations 1 and 2 (Minister's Point and North Chatham Channel, respectively) will be slightly southwest of the channel and tidal currents are expected to be reduced from 2018.

Minister's Point will return to magnitudes experienced in 2007 and North Chatham Channel will experience lower magnitudes than experienced in either 2007 or 2018 as the system shallows and North Beach elongates south, providing additional protection from open ocean exposure. South of the North Inlet/Pleasant Bay channel, currents at reference location 3 (Chatham Fish Pier) will remain similar to those experienced in both 2007 and 2018 while reference location 4 (Watch Hill) will continue its pattern of decreasing current magnitudes as barrier remnants further restrict flow through the channel fronting it.

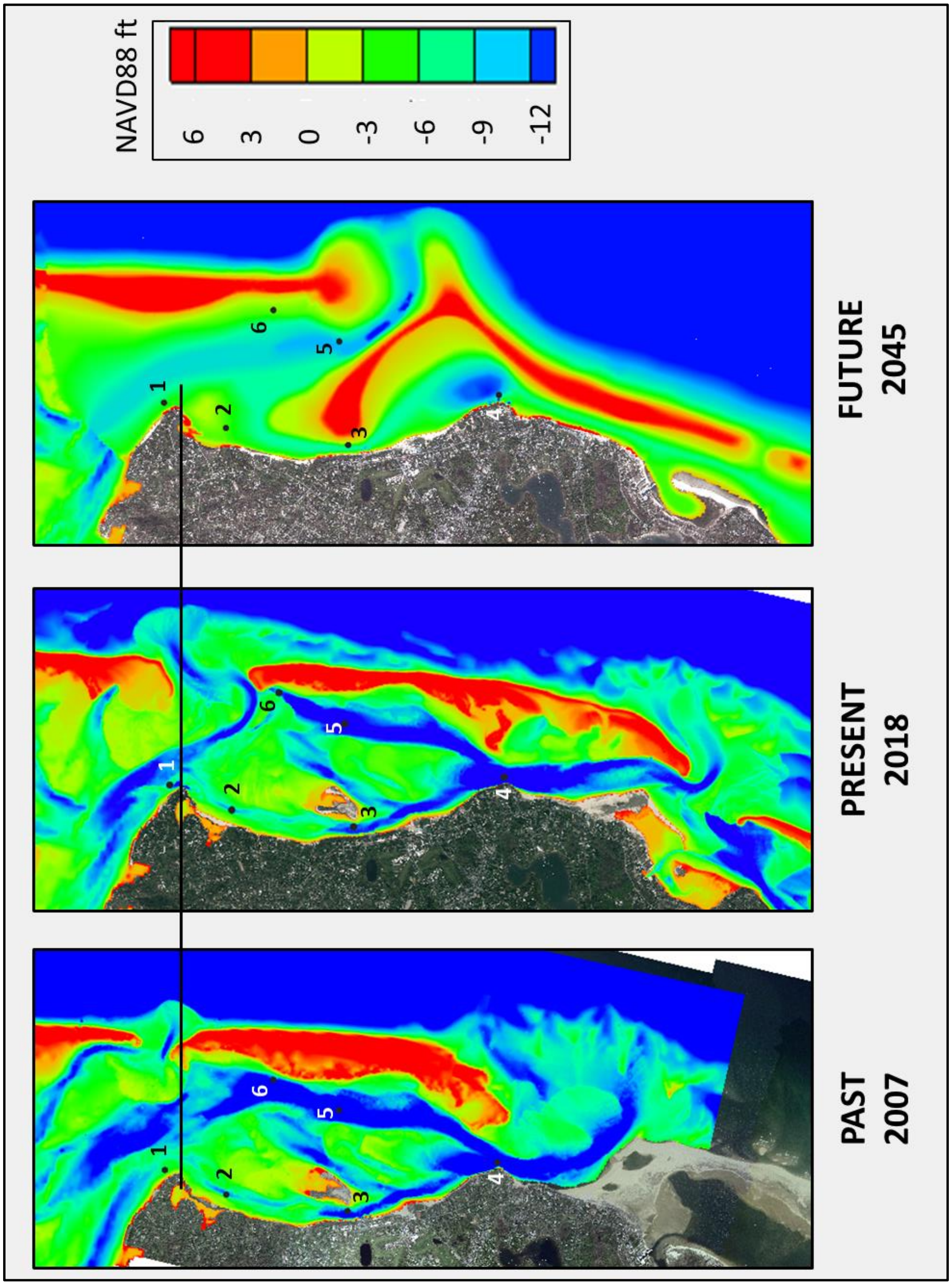


Figure 6.15 LiDAR data showing water depth from 0 to -12 ft NAVD88. 2007 inlet configuration on left, 2018 inlet configuration center, 2045 configuration on right and scale on far right. The same six reference locations for comparing water elevation and current speeds are shown on each configuration: 1 Minister's Point; 2 North Chatham Channel; 3 Chatham Fish Pier; 4 Watch Hill; 5 Chatham Southeast; 6 Chatham Northeast

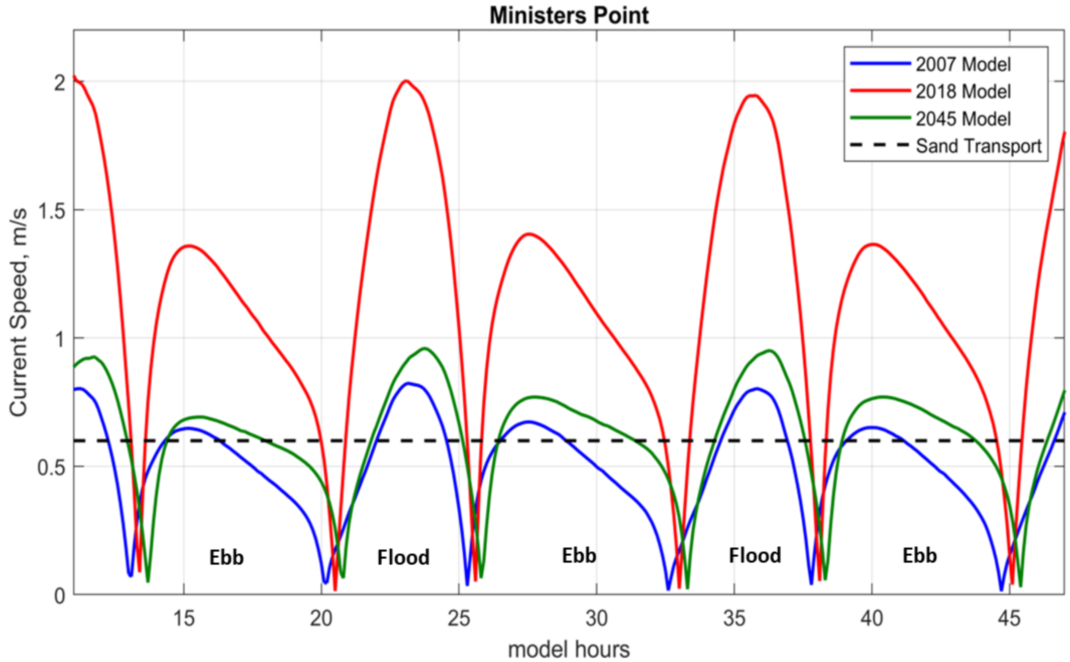


Figure 6.16 Modeled current speed using October 2018 offshore and Nantucket tides at Minister's Point (Location 1) from the 2007 model (blue) and 2018 model (red). Tides were adjusted for sea level rise for the 2045 model (green). Horizontal dotted lines indicate approximate initiation of motion.

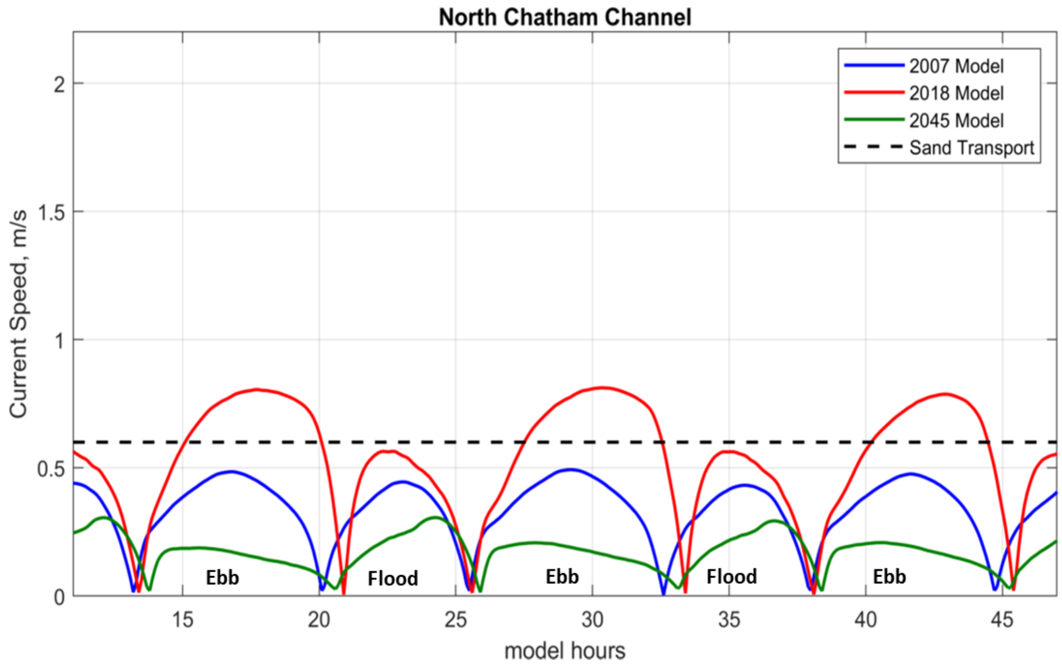


Figure 6.17 Modeled current speed using October 2018 offshore and Nantucket tides at North Chatham Channel (Location 2) from the 2007 model (blue) and 2018 model (red). Tides were adjusted for sea level rise for the 2045 model (green). Horizontal dotted lines indicate approximate initiation of motion.

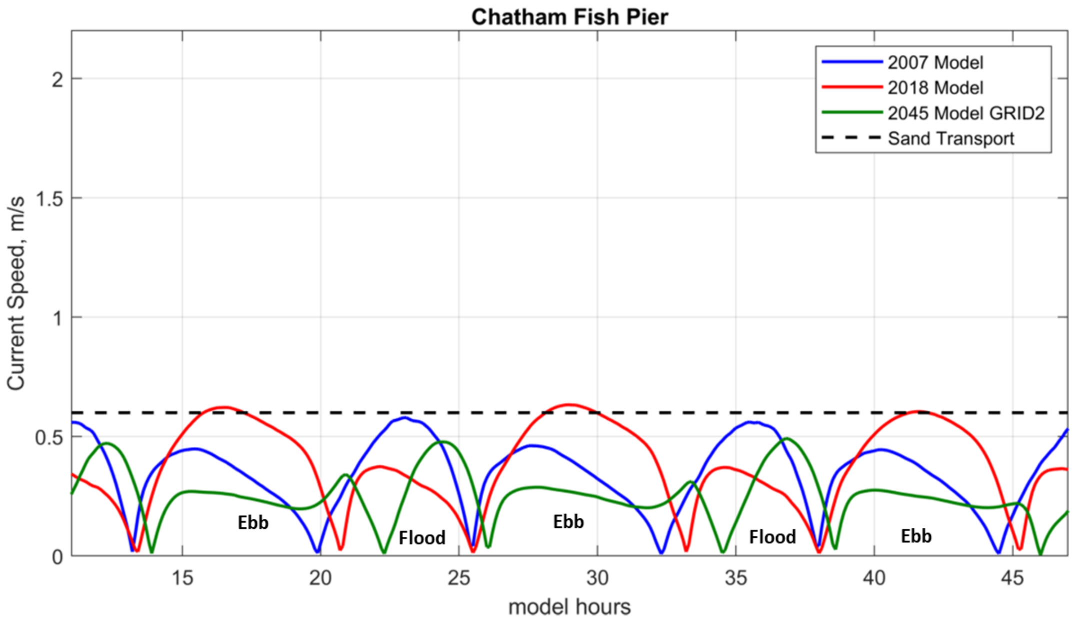


Figure 6.18 Modeled current speed using October 2018 offshore and Nantucket tides at Chatham Fish Pier (Location 3) from the 2007 model (blue) and 2018 model (red). Tides were adjusted for sea level rise for the 2045 model (green). Horizontal dotted lines indicate approximate initiation of motion.

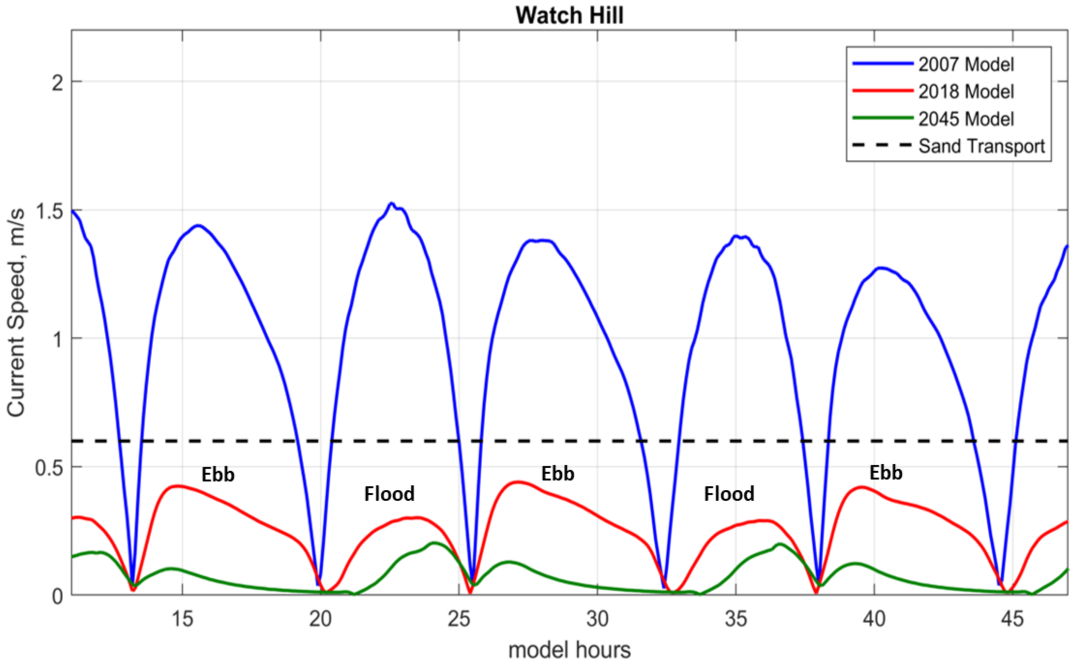


Figure 6.19 Modeled current speed using October 2018 offshore and Nantucket tides at Watch Hill (Location 4) from the 2007 model (blue) and 2018 model (red). Tides were adjusted for sea level rise for the 2045 model (green). Horizontal dotted lines indicate approximate initiation of motion.

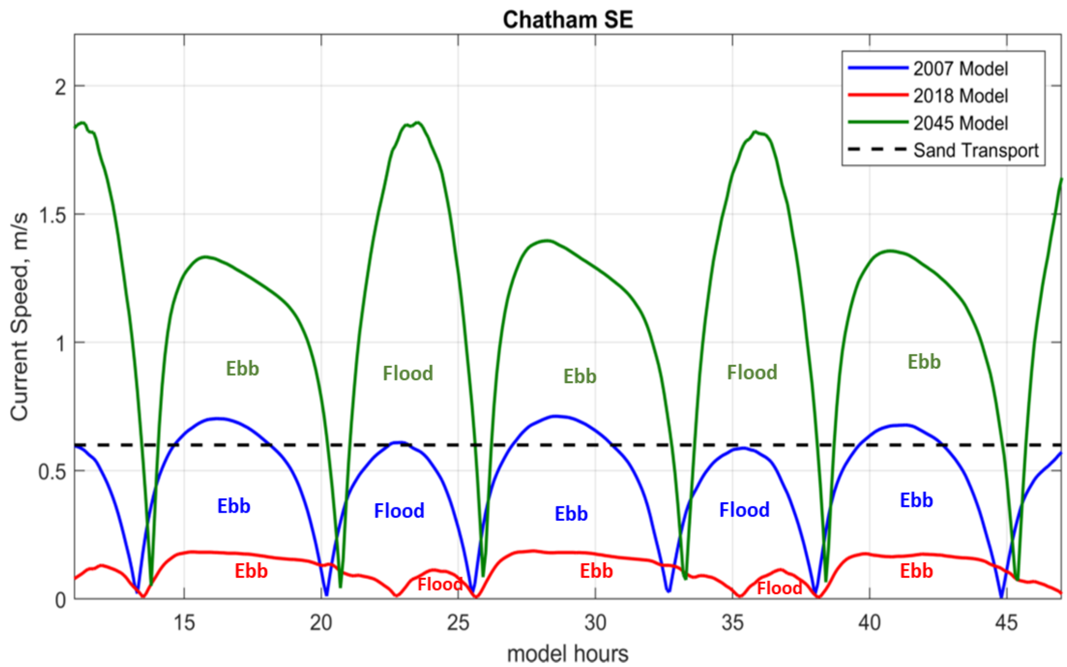


Figure 6.20 Modeled current speed using October 2018 offshore and Nantucket tides at Chatham Southeast (Location 5) from the 2007 model (blue) and 2018 model (red). Tides were adjusted for sea level rise for the 2045 model (green). Horizontal dotted lines indicate approximate initiation of motion.

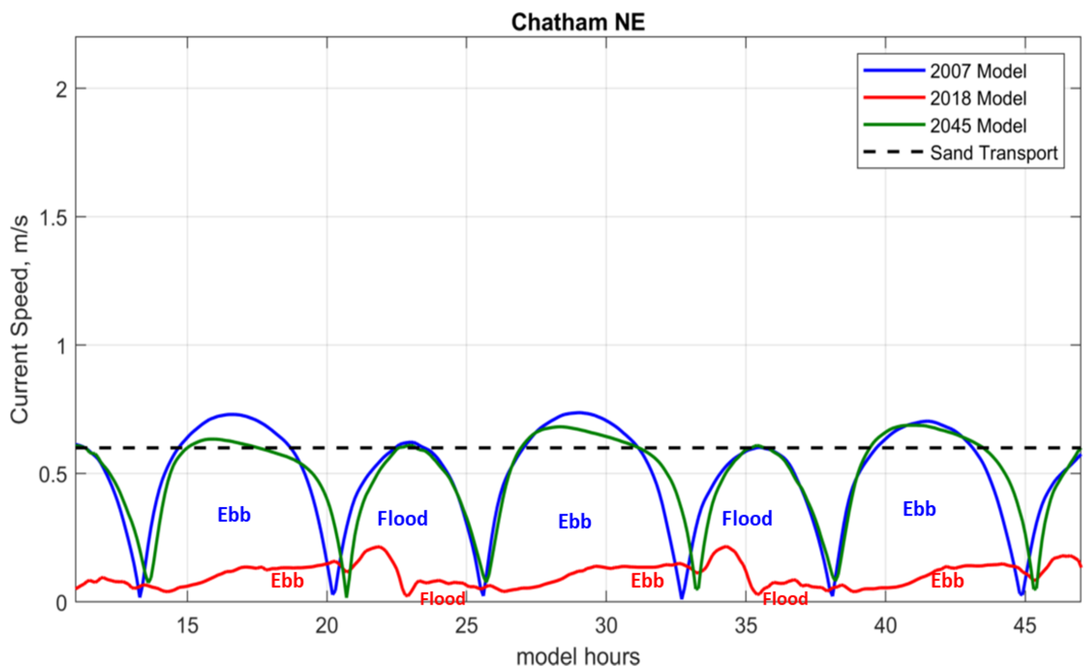


Figure 6.21 Modeled current speed using October 2018 offshore and Nantucket tides at Chatham Northeast (Location 6) from the 2007 model (blue) and 2018 model (red). Tides were adjusted for sea level rise for the 2045 model (green). Horizontal dotted lines indicate approximate initiation of motion.

Table 6.2 Computed Percent differences between average flood and ebb tide current speeds between 2045 and 2018 and between 2045 and 2007.

	% Diff 2045 to 2018		**% Diff 2045 to 2007**	
	Mean Max Speed		**Mean Max Speed**	
	Ebb	**Flood**	**Ebb**	**Flood**
1 Minister's Point	-40	-50	+20	+15
2 North Chatham Channel	-75	-30	-60	-1
3 Chatham Fish Pier	-50	+25	-35	-9
4 Watch Hill	-40	-20	-80	-80
5 Chatham SE	+700	+1,700	+100	+200
6 Chatham NE	+200	+460	-10	-20

6.4.4 Storm Patterns: Wave Heights

The 2045 model was run using the same northeast storm conditions as was for the 2007 and 2018 models.

Figure 5.7 and Figure 5.24, which presented modeled wave heights at high and low tide respectively for 2007 and 2018 inlet configurations, were updated to include the 2045 results at the same timestep (Figure 6.22 and Figure 6.23). Similarly to 2007 and 2018, the results from the 2045 simulation show that waves to not propagate as far into the estuary during low tide as they do during high tide.

From 2007 to 2018 there was a southern shift in the “window” of high wave heights that reached the mainland based on inlet configuration. In 2007, these windows were at North Inlet (north of reference location 1) and near Watch Hill (reference location 4); in 2018, these areas were at Minister’s Point/North Chatham Channel (reference locations 1 and 2) and Little Beach (south of reference location 4). In 2045, the windows of wave exposure continue to migrate south as North Beach and North Beach Island elongate in a southerly direction. The highest wave heights in 2045 can be seen to occur at reference location 5, formerly Chatham Southeast. The mainland of this area is protected from direct exposure through this energy window because the North Beach Island remnant has formed into a boomerang shape and migrated landward. This portion of the barrier beach continues to attenuate most of the wave energy but is overtopped at high tide, allowing some waves (with a height of approximately 1 to 2 feet) reach the mainland. This is less than or equal to wave energy experienced at Minister’s Point/North Chatham Channel (reference locations 1 and 2) and Watch Hill (reference location 4) in 2018 or 2007. As the barrier island migrates landward in 2045, some wave energy is overtopping it but is greatly attenuates once it reaches the mainland. The southern elongation of North Beach and North Beach Island by 2045 also will serve to protect large areas of the mainland.

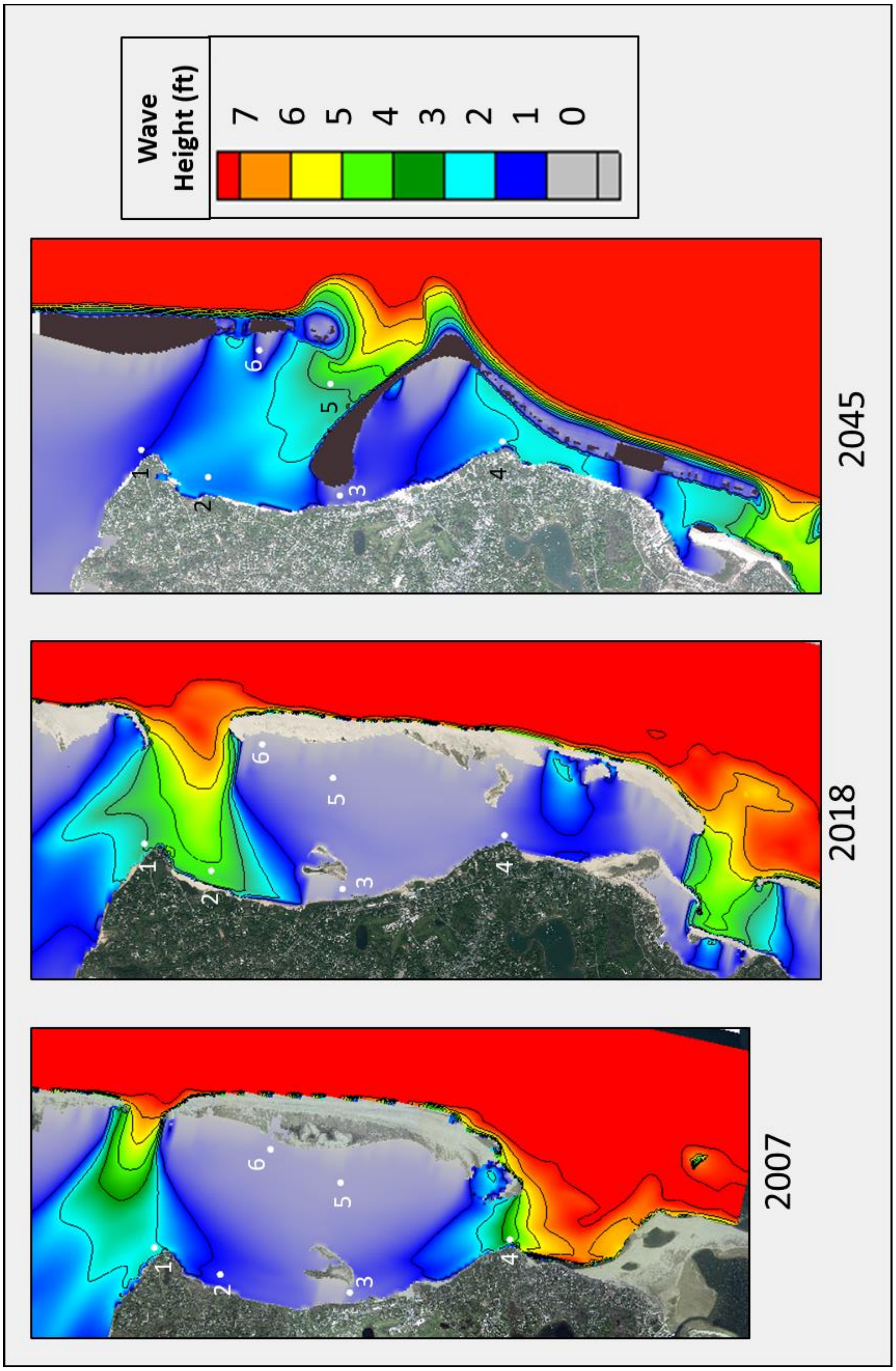


Figure 6.22 Modeled wave heights at high tide using the same time step during October for offshore and Nantucket sound tides in 2007, 2018, and 2045. The same 6 reference locations are shown 1 – Minister's Point; 2 – Chatham Channel North; 3 – Chatham Fish Pier; 4 – Watch Hill; 5 – Chatham Southeast; 6 – Chatham Northeast

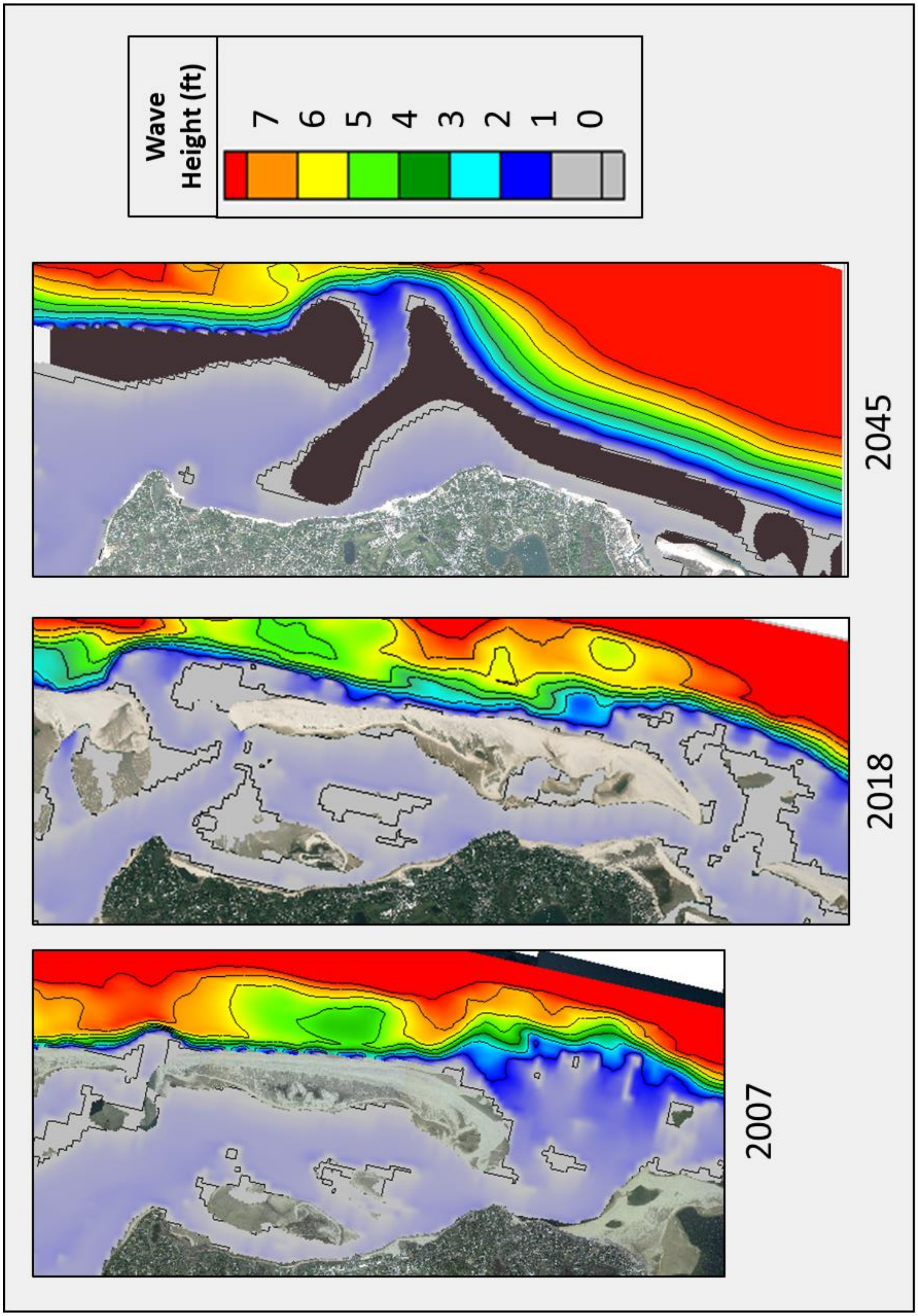


Figure 6.23 Modeled wave heights at low tide using the same time step during October for offshore and Nantucket sound tides in 2007, 2018, and 2045.

7.0 FUTURE PLANNING FOR COASTAL RESILIENCY

Based on knowledge of historical and anticipated future cyclical patterns associated with the Nauset barrier beach system, it is anticipated that ongoing management of the Chatham mainland shoreline will require a range of mitigation efforts to provide enhanced coastal resiliency depending on expected morphological changes. The migration of the barrier beach, shoals, and tidal channels will create “hot spots” of both coastal erosion and flooding concerns depending on exposure to open ocean wave conditions and tidal current patterns. Recently, formation of both the North Inlet and Fools Cut have altered the coastal processes dynamics, leading to increased coastal erosion in the vicinity of Ministers Point, the North Chatham shoreline, and increase storm surge risk to the Little Beach area. In addition, morphological changes to the shoal systems have led to increased concerns regarding safe navigation through the inlets for search and rescue operations of the U.S. Coast Guard and Harbormaster, for the commercial fishing fleet and recreational boaters, as well as rapid infilling of the Outermost Marine channel vital to the functioning of this private marina. As the barrier beach and estuarine system continue to evolve over the next two-to-three decades, some areas that presently are relatively quiescent likely will experience more storm wave energy, as well as potentially increased nearshore tidal currents that can scour deeper channels along the mainland shoreline while also creating shoals in other channel locations impacting navigation. Based on the predicted morphological changes described in Section 6, an assessment of coastal resiliency needs and mitigation actions was developed for the Chatham mainland shoreline.

The future shoreline management strategy focused on the areas likely to experience the most dramatic adverse impacts from the ongoing morphological changes in the short-term. As the inlet formation and barrier beach evolution process is similar to the previous cycle that was initiated with the 1846 breach across from Ministers Point, shifting of shoals and channels likewise are anticipated to be similar to these past trends. In addition, formation of tidal inlets reduces the natural alongshore sediment transport along the open coast shoreline. This loss in sediment supply to the downdrift beaches (in this case, beaches south of the inlets) leads to long-term erosion and loss of barrier beach elevation. Eventually, these sediment-starved features will become overtopped by storms and begin to migrate landwards. The influence of these rapidly migrating barrier beach features controls both wave energy and tidal flow along the shoreline. Therefore, depending on the location along the Chatham mainland shoreline, the influence of future geomorphology changes on coastal management will vary. To address this, an understanding of how different areas of the shoreline would be affected by the barrier beach system evolution is critical to future planning efforts.

7.1 Assessment Areas

Utilizing the information developed in Section 6, the coast was divided into five (5) management segments, depending on both the type of shoreline that presently exists and the anticipated future conditions in 2045. The extents of each study area are summarized in Figure 7.1 and are described in more detail below.

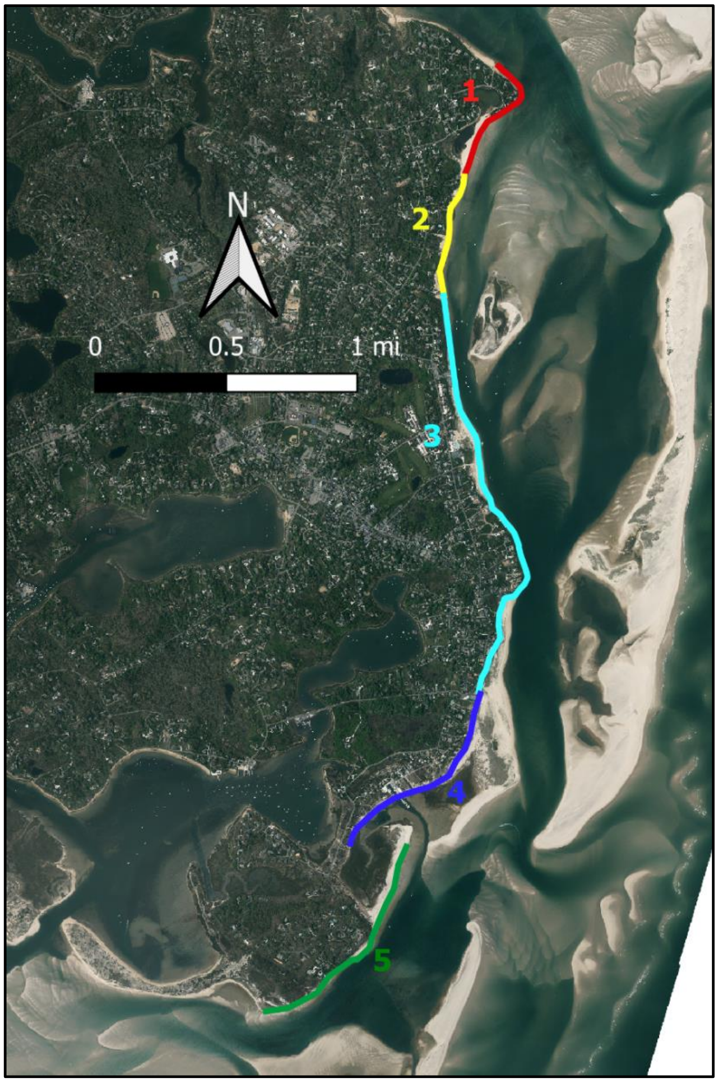


Figure 7.1 Assessment areas along the Chatham shoreline delineated based upon current shoreline management concerns to evaluate current and future engineered alternatives. 1 – Minister's Point to Linnell Ln Beach; 2 – Linnell Ln Beach to Thayer Ln; 3 – Thayer Ln to Chatham Lighthouse; 4 –Little Beach/Outermost Harbor; 5 – Quitnessett Barrier Beach to Morris Island

7.1.1 Assessment Area 1: Minister's Point to Linnell Lane Beach

2007 to Present:

Assessment Area 1 is presently located directly east of North Inlet that originally formed in 2007. Over the past 12 years, this inlet has become the dominant pathway for tidal exchange for the Pleasant Bay/Chatham Harbor estuary. Specifically, nearly all tidal prism into and out of Pleasant Bay is directed through North Inlet. When North Inlet first developed, the hydraulic connection to Pleasant Bay consisted of two main channels that carried flow; however, the evolution of sand shoals around North Inlet and rollover of North Beach has blocked the north channel, subsequently funneling flow into a single channel that has migrated westward, increasing current speeds and proximity of high flows to private property on Minister's Point. Widening of North Inlet has also increased wave propagation and wave heights during storms throughout this study area as compared to past conditions. Modeled typical nor'easter conditions suggest that sediment transport reverses still-water conditions and moves in a net southerly direction along Linnell Lane Beach. Minister's Point is armored with a continuous revetment, as shown in Figure 7.2, however, revetment undermining as a result of tidal current scour, as well as potential future failures of the revetments fronting the effected properties, remains a concern due to increased energy in the system. South of Minister's Point, Linnell Lane Beach experienced significant overwash and recession during the winter storms of 2018. This overwash lowered the beach elevation, caused infilling of the salt marsh landward of the beach, and closed the tidal inlet near the south end of the beach. Once closed, water 'ponded' in the salt marsh area and even reestablishment of a tidal connection to the estuary adjacent to the Minister's Point revetment has not created favorable conditions for the salt marsh. At this time, the main portion of historical salt marsh landward of Linnell Lane Beach has been converted to a tidal pond with minor tidal exchange through the new shallow tidal channel adjacent to the revetment. Figure 7.2 illustrates the overwashed beach at low tide.

Present to 2045:
The estuarine flow into Pleasant Bay is not expected to change substantially over the next 20-to-30 years; therefore, the channel connecting North Inlet to Pleasant Bay is expected to remain active, although it may change position. This change in position generally will coincide with an overall decrease in energy throughout Assessment Area 1 as North Inlet migrates southward. North Beach will elongate in a southerly direction, increasing storm wave protection to Assessment Area 1, and altering the stable position of the channel "thalweg" (deepest portion of the channel) away from Minister's Point. It is expected that current speeds will decrease in the area of the failing revetments; however, this process may take several years. Following historical trends from the time period following the 1846 breach, it is anticipated that the "S-curve" that forces strong currents against Minister's Point will eventually fill in, as the inlet migrates to the south. In addition, there is evidence of a more hydraulically efficient channel forming across the flood shoal from the May 2019 aerial photograph (Figure 7.3). Although it is unlikely this secondary channel will become the primary conduit for tidal flow, it represents the natural system seeking the most efficient conduit for tidal exchange. This ongoing process will eventually lead to straightening of the channel as North Beach continues to migrate south, reducing erosion pressures on the Minister's Point shoreline.

Presently, on incoming tides, the area of Minister's Point and Linnell Lane Beach are exposed to open ocean waves associated with nor'easters. As the inlet system evolves to the expected 2045 morphology described in Section 6, wave exposure will be dramatically reduced over time in Assessment Area 1. As North Inlet migrates to the south, the reduction in wave exposure will also lower the wave setup component of storm surge, decreasing to amount of waves overtopping the barrier beach.

Figure 7.2 Area Number 1: Linnell Lane Beach facing north, showing the low-lying overwash area. Image illustrates the continuous revetment at Minister's Point, as well as the eroded beach face and exposed marsh peat layer from historical salt marsh that had recently been located on the landward side of the barrier beach.

Figure 7.3 Aerial photography from May 7, 2019 suggests that a new secondary channel may be developing at North Inlet

7.1.2 Assessment Area 2: Linnell Lane Beach to Thayer Lane

2007 to Present

Assessment Area 2 extends from the southern limit of Linnell Lane Beach to Thayer Lane, north of Chatham Fish Pier, and opposite the Tern Island Flats (the extensive large shoals north of Tern Island shown in Figure 7.4). This area is located south of the present North Inlet location, but due to wind and wave propagation during typical nor'easter conditions, this area experiences some limited increased wave energy and southerly sediment transport along the mainland during storms. This increase in wave energy along this region since the natural widening of North Inlet since 2007, as well as the dominance of the south-directed ebb current along much of this shoreline, has created a net north-to-south littoral drift along this shoreline. The influx of sand along this shoreline is evident by the accretion across some of the fringing salt marsh areas. Additional wave energy also has led to erosion of salt marsh peat, where both marsh erosion and increased sand accretion is visible in Figure 7.5.

Figure 7.4 Assessment Area 2: Cow Yard Public Access, facing east at low tide, Tern Island flats visible in the distance directly offshore.

Present to 2045

Southerly migration of North Inlet will expose Assessment area 2 to open ocean wave conditions for a period prior to growth and southern elongation of North Beach, serving as a barrier to storm wave conditions. In general, the exposure to storm wave energy will increase over the next 5-to-15 years; however, there is not expected to be a significant increase in tidal currents. Storm wave energy likely will make long-term sustainability of the fringing salt marsh along this shoreline difficult. This exposure to higher energy wave conditions will dissipate as North Beach continues to elongate southward.

Figure 7.5 Area Number 2: Cow Yard Public Access, facing south, Tern Island and Chatham Fish Pier visible in the distance. Image shows wave ripples and outcropping marsh with accreting sand landward (west) during low tide.

7.1.3 Assessment Area 3: Thayer Lane to Chatham Lighthouse

<u>1987 to Present</u>

Assessment Area 3 is currently protected by North Beach Island and is not proximal to any of the barrier beach inlets. During the present cycle of barrier island inlet formation, this area was the primary region impacted by the initial breach in 1987, directly east of Chatham Lighthouse. Once the initial breach widened to form 'New Inlet', the strong tidal currents inhibited and/or prevented migration of natural littoral sediments along the beach. Instead, much of the wave-driven sand traveling along the Nauset Beach face deposited either in the flood or ebb shoals. The flood shoal, which forms during the flooding portion of the tide, established the series of shoals within Chatham Harbor that extend north from the inlet (Figure 7.6). In addition, a shallow 'swash platform' extended from the southern end of North Beach. During storm conditions, waves propagating into the southern portion of Chatham Harbor impacted properties immediately south of the lighthouse to Watch Hill. As the inlet system continued to evolve, the mainland beach width increased between Chatham Lighthouse and Andrew Harding's Lane Beach, and by the mid-2000s this beach generally protected these areas from the damaging forces of storm wave conditions. However, the series of shoals that formed inside the inlet subsequent to the 1987 breach caused a narrowing of the main channel along Watch Hill that connected the Atlantic Ocean to the Chatham Harbor/Pleasant Bay estuary. Strong tidal currents caused substantial scouring in the area immediately east of the Watch Hill bluff and the shoreline in this area was armored in response to these conditions, visible in Figure 7.7. However, the scouring progressed to the point that portions of the revetment began to fail due to undermining, requiring modifictions to the design and repairs along a few of the properties. This Assessment Area contains the Chatham Fish Pier (shown in Figure 7.5) and associated moorings for the commercial fishing fleet. Due to the historical shifting of the inlet and shoals since the 1987 breach, ongoing dredging efforts have been necessary to maintain access to the Fish Pier, as well as ensure adequate depth within the mooring basin. The channel providing access in the vicinity of the Fish Pier was authorized as a Federal Navigation Project in 1994.

Present to 2045

Because of existing armoring as well as the protection provided by Tern Island and North Beach Island, Assessment Area 3 is not expected to experience significant shoreline management needs in the future, however, maintaining access to Chatham Fish Pier is a historical concern that will continue into the future. Over the next 20-to-30 years, it is anticipated that North Beach Island will continue to erode, as the natural north-to-south littoral sediment supply is interrupted by North Inlet. Over this time period, overwash and landward migration of North Beach Island is expected. Similar to the barrier beach evolution cycle that began with the 1846 breach, it is anticipated that the present cycle will include a relatively rapid rollover, deterioration, and landward migration of the most northerly portion of North Beach Island. Regardless of the specific details related to this morphologic change to the system, it appears that the shoreline along Assessment Area 3 will remain protected from open ocean wave energy through 2045, and tidal currents along the shoreline likely will remain relatively quiescent. However, the revetments in the vicinity of Watch Hill should continue to be monitored for signs of settlement or failure due to the deep nearshore depths at the base of the revetments resulting from the previous bottom scouring.

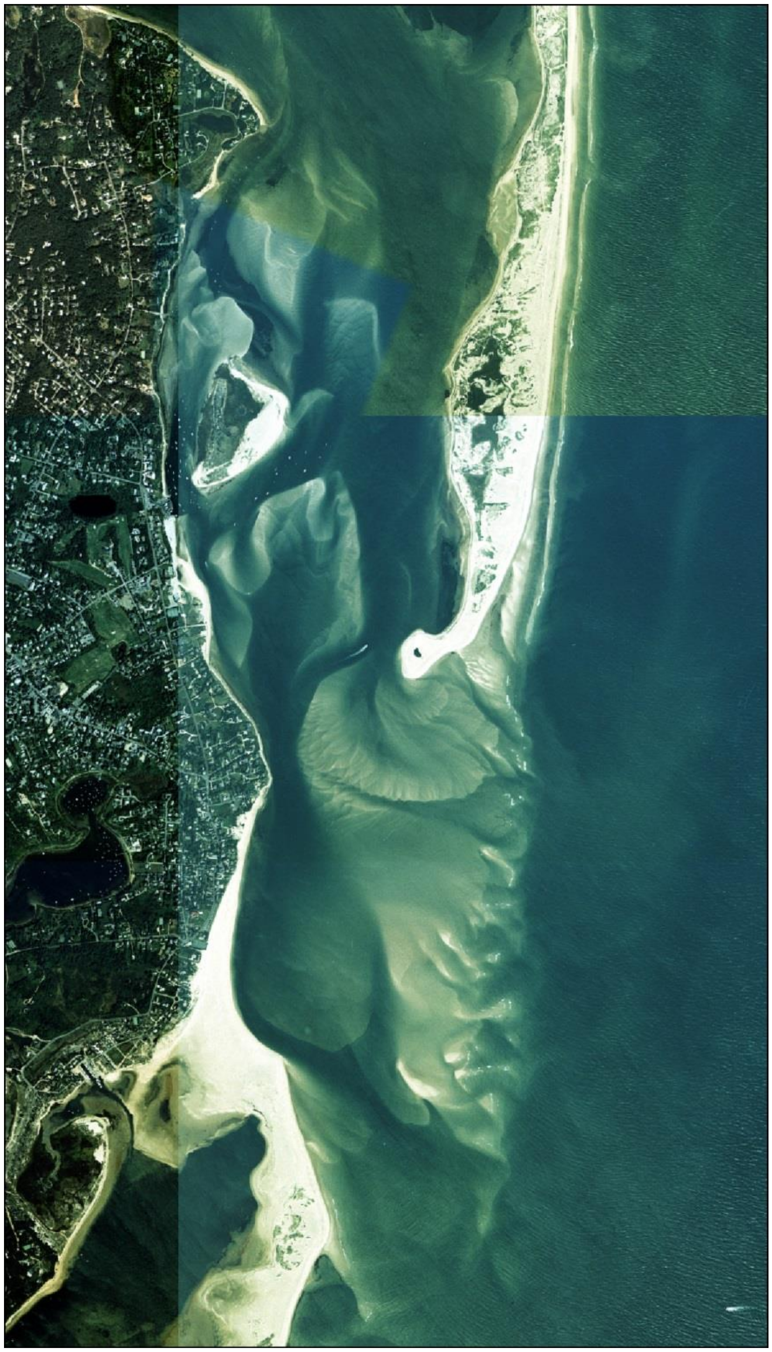


Figure 7.6 Aerial photograph from September/October 1994 illustrating changes in the inlet geomorphology (source: MassGIS).

Figure 7.7 Assessment Area 3: Looking north from Chatham Lighthouse towards Andrew Harding Beach and Watch Hill. Shoreline armoring is visible in the form of a revetment along the Watch Hill shoreline. Recent beach accretion south of Watch Hill has provided a protective buffer from storm wave energy. In this area, several revetments are now fronted by a wide natural beach system (e.g. at Chatham Lighthouse).

Figure 7.8 Assessment Area 3: Chatham Fish Pier with fleet boats moored; view facing east/northeast.

7.1.4 Assessment Area 4: Little Beach/Outermost Harbor

2007 to Present:

Prior to the breach and inlet development of Fools Inlet, Assessment Area 4 was fronted by South Beach, which extended beyond the southern end of Morris Island and provided natural protection to the coastline, as shown in Figure 7.9. Following Fools Inlet development in 2017, Assessment Area 4 became exposed to the direct influence of nor'easters from the open Atlantic Ocean, including the effects of wave set-up added to the storm tide levels. During early 2018, significant nor'easters in January and again in March created substantial storm tides that exceeded the 10-year return period elevation and nearly reached the 50-year return period level, as shown in Figure 7.10. Extensive coastal flooding within Assessment Area 4 occurred during these storm events, where inundation occurred in all areas shown in Figure 7.11 that are shaded red, orange, and yellow. Observations subsequent to the storms indicated that flow pathways of coastal storm waters scoured portions of the beach and dune system, as well as upland areas where anthropogenic features funneled flow.

Due to storm conditions experienced in 2018, some emergency measures were implemented to mitigate flooding including a temporary sand bag wall, and an artificial dune was constructed fronting the Condo Association at the eastern end of Starfish Lane, shown in Figure 7.12 As depicted in Figure 7.13, the elevation in this area is very low with limited natural protection, and while this temporary wall and dune provide some protection from coastal flooding from the east, the various flooding pathways (including the launching ramp at Outermost Marina) likely will make efforts of this limited extent ineffective in larger storm events. Since the development of Fools Inlet, flooding during the 2018 winter storms extended inland to Morris Island Road (Figure 7.14). When this road is impassable during flood events, the majority of Assessment Area 4 has no emergency egress and it is not possible to access areas further south on Morris Island.

Since formation of Fools Inlet, the extensive barrier beach, dune, and salt marsh system adjacent to Little Beach have been dramatically altered as a result of both tidal and wave-induced sediment transport associated with the new inlet. Due to the tidal offset between the Atlantic Ocean and Nantucket Sound, tidal flow through Fools Inlet is primarily uni-directional, where flow generally is directed towards Nantucket Sound. Therefore, sediment transport pathways also are directed along the shoreline towards Nantucket Sound in this region. The observed barrier beach and shoal migration since 2017 has led to extensive infilling of the Outermost Harbor channel which provides access to a private marina and small public mooring area (Figure 7.15).

Present to 2045:

As South Inlet and Fools Inlet continue to evolve, it is expected that remnants of the barrier beach system that presently provides limited shore protection for Little Beach will continue to degrade. The overall pattern of barrier beach migration is anticipated to follow the previous pattern initiated in 1846, where South Inlet is expected to infill and the barrier beach system will eventually become contiguous south of North Inlet, as shown in Figure 7.16 from the 1888 navigation chart. It should be noted that the 1888 chart does not provide elevations for this rapidly evolving and migrating barrier beach spit that formed between the late 1860s and 1880s; however, similar to the rapidly accreting spit on the south end of North Beach Island, it is anticipated that the elevation of the barrier beach system fronting the Little Beach area will be relatively low and provide limited protection during storm conditions. To this end, the barrier beach system that was projected to form by 2045 is anticipated to have small inlets that maintain a hydraulic connection with the Atlantic Ocean. Therefore, the flooding conditions related to storm surge from the open Atlantic Ocean are expected to continue over the next 20-to-30 years. In addition, maintaining the inlet to Outermost Harbor Marine, which also serves as the hydraulic connection to the adjacent salt marshes, likely will prove challenging over the next 10 years, as the interior barrier beach continues to provide sediment to shoal this channel.

Figure 7.9 Inlet configuration proximal to Assessment Area 4 prior to (2007, left panel) and after (2018, right panel) Fools Inlet development.

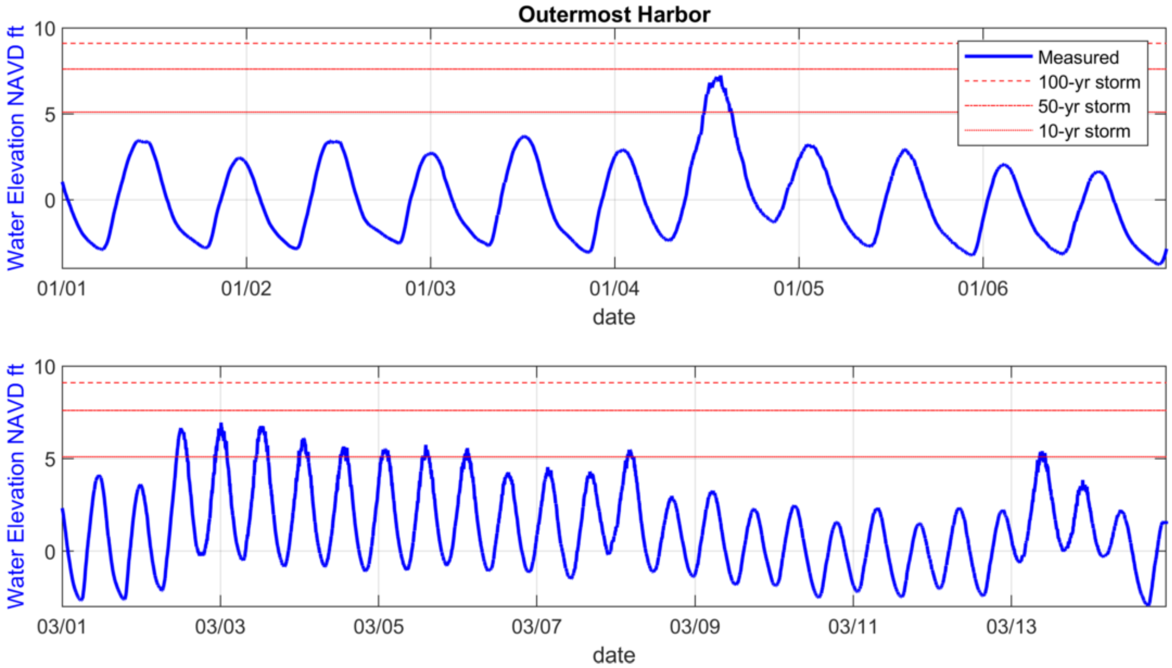


Figure 7.10 Observed tide elevations at Outermost Harbor for nor'easters in January 2018 (top) and March 2018 (bottom), where measurements are compared to FEMA 10-year, 50-year, and 100-year predicted water levels.

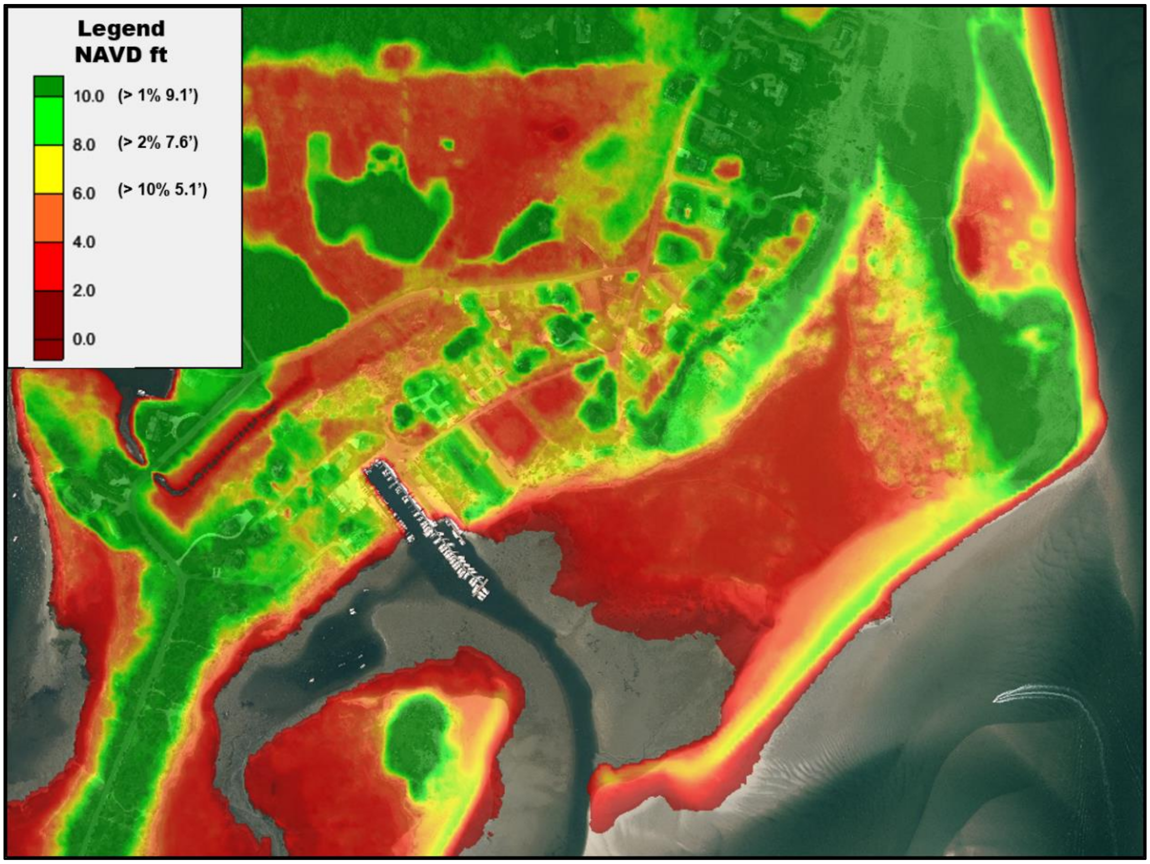


Figure 7.11 Land elevations of the Little Beach area, where all areas not shown in green are below the 50-year return period flood elevation.

Figure 7.12 Area Number 4: Little Beach with an engineered temporary sand bag levee and dune to help alleviate flooding

Figure 7.13 Assessment Area 4: Little Beach, low elevation marsh seaward of sandbag/dune levee temporary fix, view facing east.

Figure 7.14 Assessment Area 4: A temporary sandbag levee, shown in magenta, has been placed proximal to Outermost Harbor, shown in green, however, the low elevation in this Study Area allows flooding to occur inland onto Morris Island Road, shown in red, which provides emergency egress to this area as well as areas further south.

Figure 7.15 Assessment Area 4: Outermost Harbor navigation channel which also serves as the tidal channel to private marina, public mooring area and adjacent salt marsh.

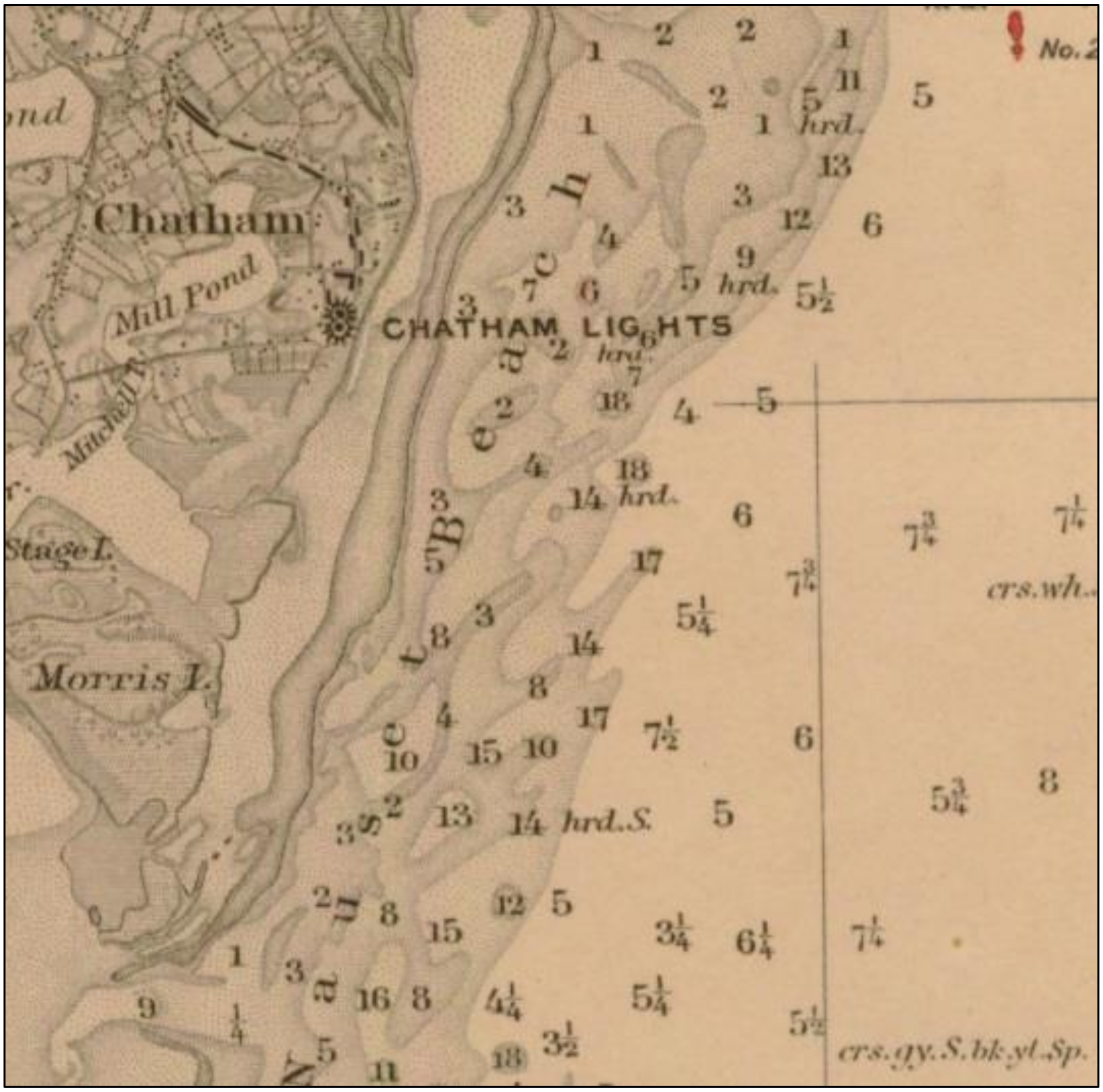


Figure 7.16 Portion of the 1888 U.S. Coast and Geodetic Survey navigation chart indicating the generally contiguous barrier beach fronting the Little Beach area approximately 40 years after the 1846 breach.

7.1.5 Assessment Area 5: Quitnesset Barrier Beach to Morris Island

2007 to Present:

Similar to Assessment Area 4, prior to the inlet development of Fools Inlet in 2017, Assessment Area 5 was fronted by South Beach, which provided natural protection to the coastline, as shown in Figure 7.8. Following Fools Inlet development, Assessment Area 5 also is presently exposed to increased wave heights and impacts during storms. The Monomoy National Wildlife Refuge Visitors Center is located on Morris Island, where recent storms have continued to cause coastal bank erosion, as shown in Figure 7.17. As described above, coastal flooding causes the single access road to Morris Island to become inundated; impacting emergency egress to Morris Island.

Due to the tidal offset between the Atlantic Ocean and Nantucket Sound, tidal flow through Fools Inlet is primarily uni-directional, where flow generally is directed towards Nantucket Sound. Therefore, sediment transport pathways also are directed along the shoreline towards Nantucket Sound in this region. Due to the southerly migration of the fronting barrier beach system, an increase in local storm surge has led to overtopping and landward recession of the Quitnesset Beach system. Increased tidal currents, as well as wave-induced currents during storm conditions, likely contributing to nearshore erosion; however, impacts of this process is not evident at this time.

Present to 2045:

As South Inlet and Fools Inlet continue to evolve, it is expected that the remnants of the barrier beach system that presently provides limited shore protection for Morris Island and Quitnessett Beach will continue to degrade. As described above, the overall pattern of barrier beach migration is anticipated to follow the previous pattern that was initiated in 1846, where the South Inlet is expected to infill and the barrier beach system will eventually become contiguous south of North Inlet, as shown in Figure 7.16 from the 1888 navigation chart. It should be noted that the 1888 chart does not provide elevations for this rapidly evolving and migrating barrier beach spit that formed between the late 1860s and 1880s; however, similar to the rapidly accreting spit on the south end of North Beach Island, it is anticipated that the elevation of the barrier beach system fronting the Morris Island area will be relatively low and provide very limited protection during storm conditions. As described in Section 6, the barrier beach system that was projected to form by 2045 is anticipated to have small inlets that maintain a hydraulic connection with the Atlantic Ocean. Therefore, the flooding conditions related to storm surge from the open Atlantic Ocean are expected to continue over the next 20-to-30 years and Quitnessett Beach likely will continue to be overtopped on an episodic basis. The south-directed tidal flow also will continue to erode the Morris Island shoreline until the eventual formation of a contiguous barrier beach that prevents tidal exchange directly to the Atlantic Ocean. The revetment constructed after the 1987 breach on Morris Island will continue to provide some protection to the shoreline as it becomes more exposed to open ocean wave energy.

Figure 7.17 Assessment Area 5: Monomoy National Wildlife Refuge, view facing south, where recent coastal erosion of the natural coastal bank has occurred. Note the revetment further south.

7.2 Present to 2045: Coastal Management Evaluation

Once the present and anticipated future conditions over the next 20-to-30 years were evaluated utilizing the coastal processes modeling tools, coastal erosion and flooding implications for each Assessment Area were developed to help assess sustainable management approaches for the east-facing coastline of Chatham. Due to the rapidly evolving series of tidal inlets, barrier beaches, shoals, and channels, it was anticipated that management strategies would be 'temporary' to the extent possible, understanding that proactive shore protection measures may only be needed for a short period before erosional and/or flooding pressures are naturally reduced by the inlet/barrier beach migration. Rather than attempting to prioritize specific Assessment Areas based upon specific shore protection risk criteria, it was determined that the overall approach would focus on measures needed to maintain the sustainability of the shorefront infrastructure through the current barrier beach re-formation cycle. In this manner, the recommended strategies provide an adaptive management approach to address the temporary impacts associated with the ongoing inlet migration process. As indicated in the Center for Coastal Studies Report (2018), in the case of the Chatham Harbor/Pleasant Bay estuarine system, the overall inlet and barrier beach morphology dominate local coastal processes and are more critical to near-term coastal resiliency than concerns related to relative regional sea-level rise.

Based on information regarding existing coastal hazards, an understanding of both coastal erosion and flooding for each Assessment Area provided information regarding existing shore protection needs. As the system evolves over the next 20-to-30 years, there will be significant regional changes in barrier beach morphology that will require an adaptive approach to coastal management strategies. Many of these morphology changes are relatively predictable from the perspective of areas likely to be impacted by both changes in nearshore tidal currents and storm waves propagating through inlets facing the open Atlantic Ocean. While the predictions of inlet morphology provide a generally accurate guide to expected coastal management needs, it should be understood *a priori* that precise prediction of barrier beach position in a specific timeframe may be unrealistic. However, the overall progression of barrier beach and inlet can be expected to follow the modeled predictions, in close agreement with historical patterns of the barrier beach evolution process.

Section 6 provides a summary of the overall morphologic changes that will occur by 2045. It is understood that these changes occur on a continuum, where the morphology will shift both episodically, as a result of storms, and gradually as typical daily waves and tidal currents continue to shape the shoreline. The southerly migration of North Inlet, accompanied by the landward migration and related southerly elongation of North Beach Island, will create a series of coastal management challenges over the next three decades. As North Inlet moves to the south, Chatham mainland shoreline regions that have not been exposed to open ocean wave conditions will be impacted as the inlet opens a 'window' to the Atlantic Ocean. Due to the rapidly evolving system, it is anticipated that many of the adverse impacts related to coastal erosion and flooding will be relatively short-lived (next 5 to 15 years) for most areas of the shoreline. As described in Section 5, North Inlet provides nearly all of the tidal exchange to Pleasant Bay. As the system continues to evolve, South Inlet will become redundant, allowing re-formation of a continuous low-lying barrier island/shoal feature offshore. Due to the limited littoral sediment supply to the area south of North Inlet, the long-term shore protection provided by this southerly barrier beach feature will likely decrease.

Based on the anticipated inlet/barrier beach evolution over the next 20-to-30 years, potential shore protection risks for the five Assessment Areas were developed, as shown in Table 7.1. The following categories were utilized to define the relative risk level relative to potential shore protection needs:

- *Severe* (Red) – The shoreline stretch is subject to either substantial coastal erosion pressure (from waves and/or tidal currents) or storm tide levels that create frequent flooding of the infrastructure inland of the shoreline.
- *Moderate to Severe* (Orange) - The shoreline stretch is subject to either significant coastal erosion pressure (from waves and/or tidal currents) or storm tide levels that create occasional flooding of low-lying features inland of the shoreline. Due to migration of both North and South Inlets, these shoreline areas may be subjected to rapidly changing conditions from present to 2045.
- *Moderate* (Yellow) - The shoreline stretch is subject to either modest coastal erosion pressure (from waves and/or tidal currents, typically only during storm conditions) or storm tide levels that create infrequent flooding of low-lying areas inland of the shoreline. In general, moderate conditions are typified by shoreline areas that are primarily impacted only during storm conditions, where average daily conditions do not cause shore protection concerns.
- *Minimal* (Green) - The shoreline stretch is subject to relatively quiescent conditions associated with waves and/or tidal currents. In general, storm-induced flooding is less of a concern due to elevation of infrastructure within this region.

Table 7.1. Prioritization by Study Area for current and future shoreline management concerns.

Assessment Area	**Location**	**Present**	**Future to 2045**
1	Minister's Point to Linnell Lane Beach	Severe	Moderate
2	Linnell Lane Beach to Thayer Lane	Moderate	Moderate to Severe
3	Thayer Lane to Chatham Lighthouse	Minimal	Minimal
4	Little Beach/Outermost Harbor	Severe	Severe
5	Quitnesset Barrier Beach to Morris Island	Moderate	Moderate to Severe

Areas were evaluated with respect to how energy conditions will change as the inlets migrate towards the projected 2045 condition. It is expected that Assessment Areas 1 and 2 eventually will have increased protection as North Beach elongates southward. In the long-term both of these areas are expected to have improved shore protection provided by North Beach; however, in the near-term Assessment Area 1 is experiencing significant erosion/scour as a result of tidal currents directly against the Minister's Point shoreline. As the inlet migrates south, tidal currents will moderate in this area and open ocean wave exposure will lessen within Assessment Area 1. However, this will expose the shoreline in Assessment Area 2 to open ocean wave conditions. This exposure likely will initially cause severe erosion pressures, but will moderate by 2040.

In the vicinity of Thayer Lane, where the shoreline is fronted by Tern Island, it is not anticipated that open ocean waves, increased tidal flooding, or strong tidal currents will be a significant issue as the barrier beach system evolves. Specifically, the general hydraulic split of the Chatham Harbor/Pleasant Bay estuarine system that has occurred since North Inlet began dominating tidal exchange with Pleasant Bay has lowered tidal currents along this stretch of shoreline, and this trend is expected to continue through 2045. The remnants of North Beach Island's north end eventually are expected to weld on to Tern Island, as described in Section 6. This morphologic change will hydraulically restrict tidal exchange within the harbor area south of Tern Island. Following the 2007 formation of North Inlet, tide range within Chatham Harbor and Pleasant Bay increased; however, analysis of long-term data by Provincetown Center for Coastal Studies (Geise, et al, 2019) indicates that the tide range is beginning to decrease. For the area from Tern Island south, it is anticipated that the tide range will decrease by 2045, as this area shoals and the hydraulic connection to Nantucket Sound becomes more prevalent.

As a result of the anticipated landward migration of North Beach Island towards the mainland Chatham shoreline, the shoreline within Assessment Area 3 likely will remain protected from the direct influence of open ocean storm waves. This ongoing barrier beach protection, combined with the reduced tide range along this shoreline, will generally provide conditions similar to the present through 2040. Large expanses of this shoreline were armored following the 1987 breach, generally expanding on historical armoring that became uncovered as the shoreline rapidly eroded following inlet formation. This historical armoring was a remnant of shore protection structures placed in response to erosion occurring during the previous inlet cycle that impacted this shoreline approximately a century ago. Coastal erosion should not be a significant concern in Assessment Area 3 through 2040, however, some of the revetments are likely not stable due to deep nearshore depths at the toe of the revetments which could lead to failure of the armoring under extreme storm conditions. A more pressing issue is continued shoaling of local navigation channels leading into Aunt Lydia's Cove over the next 10-to-30 years, which will make continued access to and operation of the commercial fishing fleet at the Chatham Fish Pier challenging. However, specific issues related to navigation concerns are beyond the scope of the present assessment.

South of Chatham Lighthouse, the Little Beach neighborhood extends along Morris Island Road south of Bridge Street. This region, depicted as Assessment Area 4, consists of generally low-lying properties that were initially developed since the 1930s and 1940s (Figure 7.18) when a hydraulic connection existed between Stage Harbor and Chatham Harbor. As shown in the figure, many of the dwellings shown on the map are depicted in marsh areas that were subsequently filled when this tidal connection was filled and this area developed. Figure 7.19 also illustrates the overall susceptibility of this region to coastal flooding, where much of the area landward of the fronting beach is below the 1% annual chance flood elevation predicted by FEMA. As shown, this is the only developed area along the east-facing coast of Chatham where a majority of it is flooded during a significant storm event.

Figure 7.18 illustrates that the Nauset Beach system had accreted to the point where the mainland shoreline within Assessment Area 3 was protected by the late-1940s. Prior to that time period, the previous incarnation of North Beach Island had provided some limited protection to this area during the late 1800s (Figure 7.20). Due to the lack of sediment supply to North Beach Island, this feature tends to migrate landward through storm overwash processes, as shown in the right panel of Figure 7.20 for 1917. For storm waves to consistently cause overwash that leads to the observed rapid migration of the barrier towards the mainland between 1893 and 1917, the remnants of North Beach Island would be at a low elevation that would not effectively mitigate the impacts of coastal storm surge against the mainland coast. It is anticipated that it will be several decades before Nauset Beach again provides substantial protection for the Little Beach area. For the time period between the present and 2040, it is anticipated that the barrier beach fronting this area will continue to degrade and open Atlantic Ocean storm surge flooding will continue to occur.

The migration of North Beach Island material towards the mainland shoreline will continue to shoal nearshore channels in the Little Beach area, including those at Outermost Harbor Marine and the adjacent salt marsh systems. This large volume of sediment will also provide some wave attenuation during storms. As seen in the earliest available aerial photograph for the region (December 1938 shown in Figure 7.21), significant beach accretion has historically been caused by the remnants of North Beach Island welding onshore within Assessment Areas 3, 4, and 5. A similar trend is expected in the future; however, this process likely will still be in progress by 2045.

Assessment Area 5 represents both Morris Island and the attached barrier beach and marsh to the north (Quitnesset Beach). Similar to Assessment Area 4, this area has historically been subjected to an increased wave and storm surge climate as North Beach Island/South Beach degrades. It is anticipated that a similar process will occur between present and 2045. Since much of the developed shoreline along Morris Island is fronted by revetments and is constructed at a relatively high elevation, the primary concerns for this region through 2045 are related to coastal erosion. At present, tidal currents through Fools Inlet are nearly uni-directional, where flow is nearly always from the Atlantic Ocean towards Nantucket Sound. During storm conditions, the combination of wave action and increased tidal currents can drive a significant volume of sediment along this shoreline, potentially leading to erosion of the shoreline. Over the next several years, the migration of North Beach Island likely will decrease this current-induced erosion concern. However, the lack of beach elevation of the remnant North Beach Island will not mitigate the impacts of coastal storm surge against the Morris Island coast. Therefore, it is anticipated that over the next 20-to-30 years Assessment Area 5 will remain a moderate to severe coastal management concern.

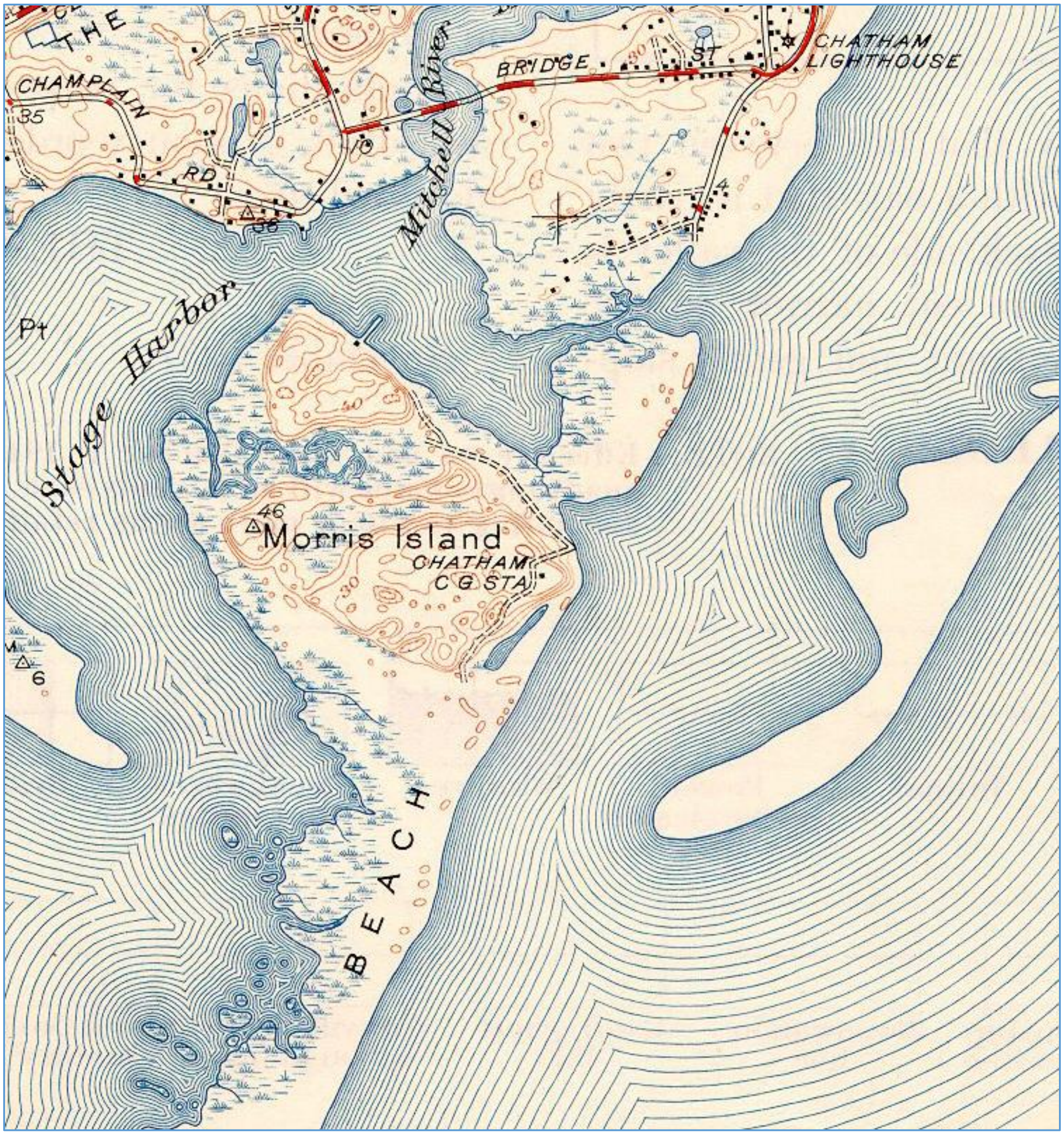


Figure 7.18 A portion of the 1948 U.S. Geological Survey map illustrating the offshore position of Nauset Beach protecting the Little Beach and Morris Island shoreline from open ocean waves. This time period pre-dates construction of the Morris Island dike, and shows a hydraulic connection between Stage Harbor and Chatham Harbor. The initial stages of low-lying development are shown within the marsh area in the Little Beach area.

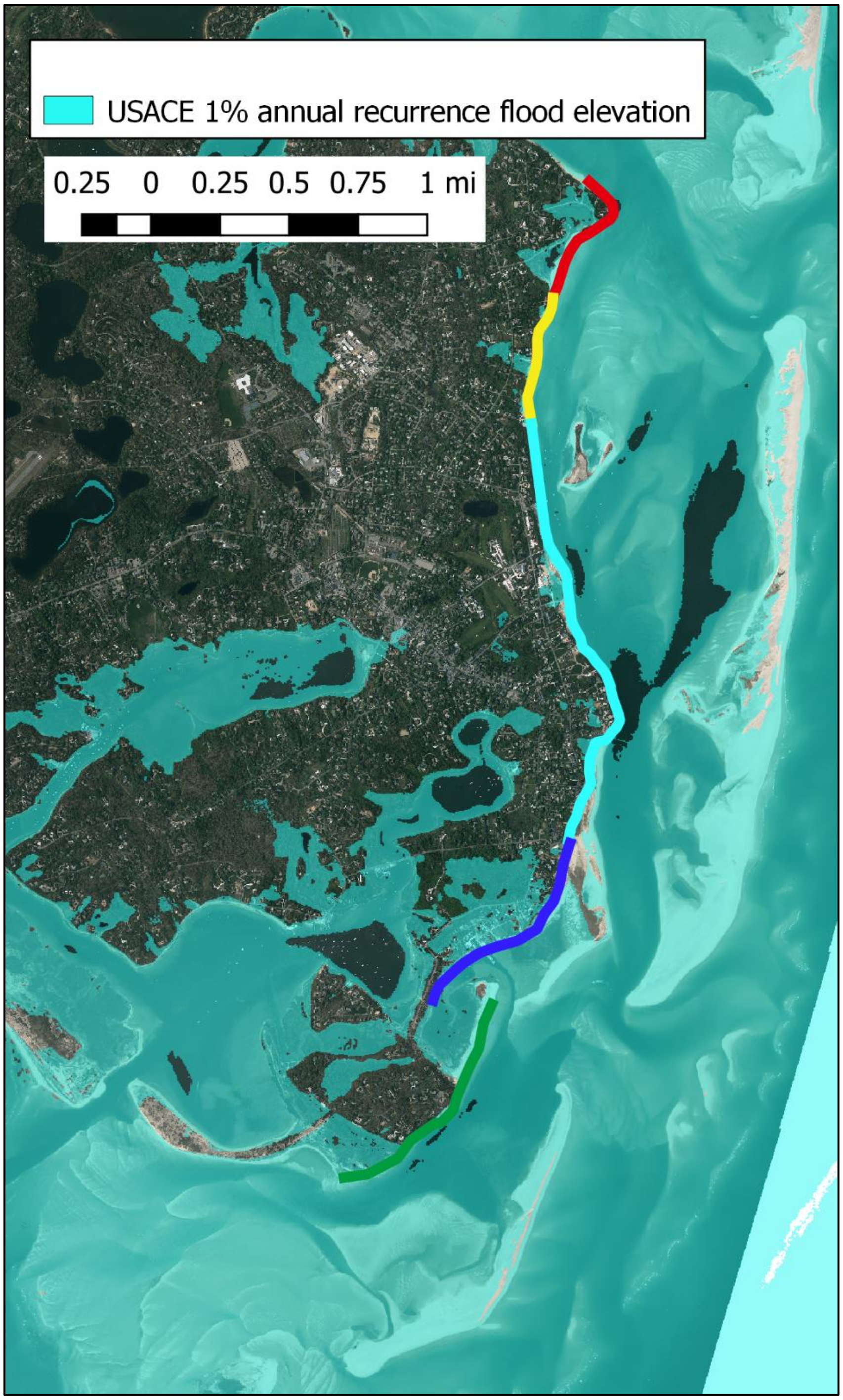


Figure 7.19 Areas along the Chatham coastline that are below the USACE 1% annual recurrence flood elevation (9.1 feet NAVD88).

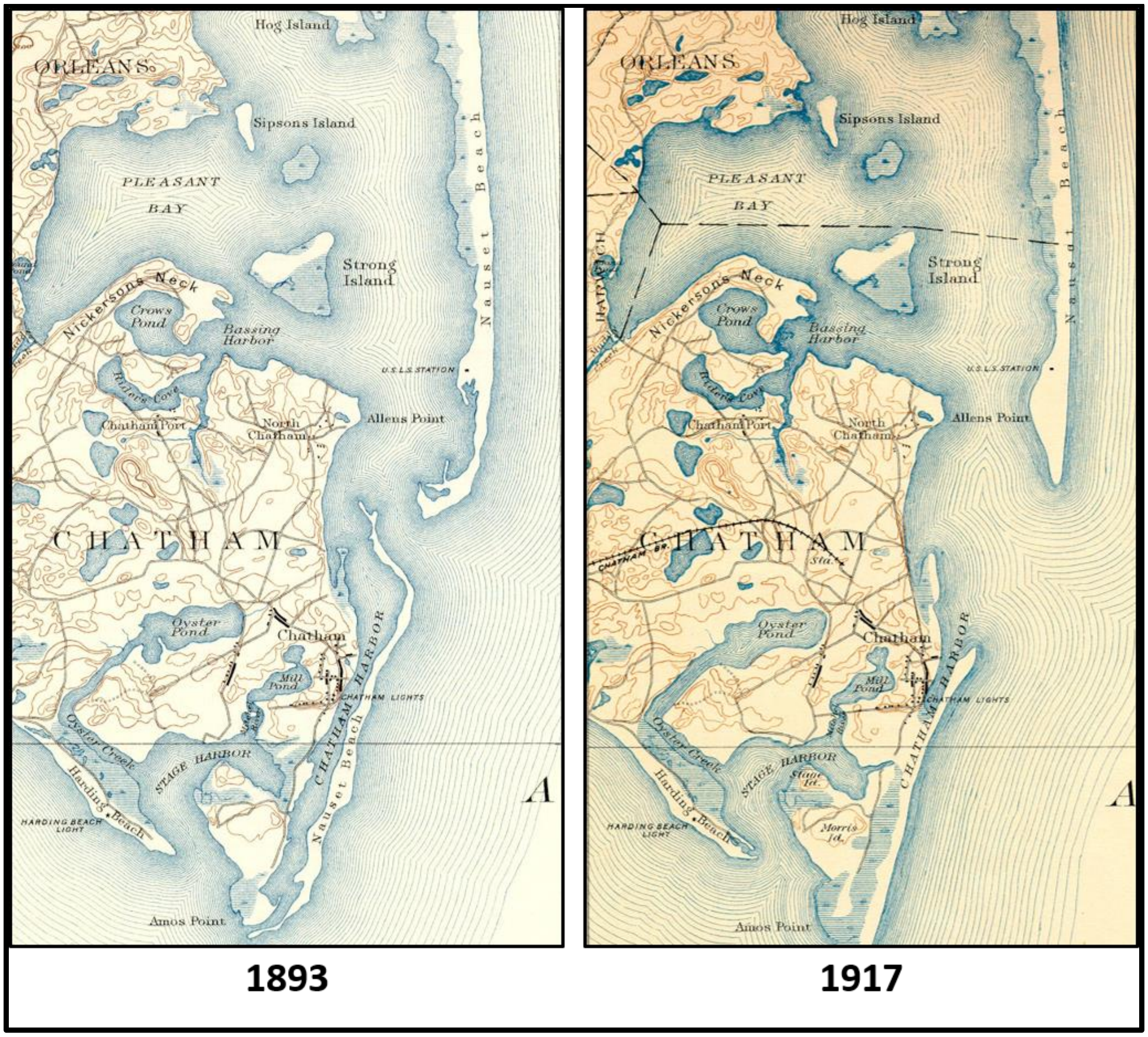


Figure 7.20 A comparison of the 1893 and 1917 U.S. Geological Survey maps showing the remnants of North Beach Island (labeled Nauset Beach on the left panel) migrating landward over the 24-year period.

Figure 7.21 The December 1938 aerial photograph indicating the relatively wide beach along the east-facing Chatham shoreline south of Chatham Lighthouse. This beach accretion represents the long-term influence of sediment associated with North Beach Island migrating onshore.

7.3 Assessment Area-Specific Management Strategies

The cyclical geological evolution of the east-facing shoreline of Chatham presents significant management challenges for both near-term and long-term shore protection strategies to protect existing infrastructure. While future sea-level rise is a concern, the rapidly migrating geomorphology of the Nauset Beach system dominates both local coastal erosion and flooding issues. In general, evaluation of coastal erosion and flooding alternatives requires an exhaustive analysis to mitigate concerns in the most environmentally appropriate manner. However, the rapid migratory nature of the barrier beach system combined with associated coastal erosion and flooding impacts make the number of effective alternatives limited. While it is understood that the alternatives are limited, the overall goal is to ensure the long-term viability of the east-facing Chatham shoreline is performed in an environmentally responsible manner to sustain and preserve important wetland resources. With this in mind, 'hard engineering' structures were considered sparingly in areas that require long-term protection (i.e. at least three decades).

7.3.1 Assessment Area 1

Due to the ongoing severe scour that has occurred along the Minister's Point revetments, as well as the erosion and storm overwash at Linnell Lane Beach, Assessment Area 1 represents one of the most significantly impacted shorelines relative to the existing inlet/barrier beach morphology. Similar to the Watch Hill area further to the south that experienced scour along the revetment face after the 1987 breach, nearshore tidal currents have increased dramatically along the Minister's Point shoreline since formation and subsequent widening of the 2007 breach (North Inlet). By 2040, it is anticipated that both open ocean wave exposure and the nearshore tidal currents within this area will moderate significantly, decreasing shore protection concerns gradually over the next 20-to-30 years. However, at present, shore protection of dwellings on Minster's Point is a critical concern.

As depicted in Figure 7.22, a private revetment fronts the series of dwellings that sit on top of the glacial deposit forming Minister's Point. As the series of flood shoals associated with North Inlet continue to force the channel entering Pleasant Bay to the west and the existing revetments prevent natural migration of the channel in this direction, the system dynamics force the strong tidal currents to scour a deeper channel against the shoreline. Historically (i.e. during the previous cycle of inlet formation and barrier spit growth initiated in 1846), Minister's Point and the adjacent shoreline were allowed to erode, which provided sufficient sediment to eventually form a low-lying barrier spit just offshore of Minister's Point Figure 7.23). At present, it does not appear that sufficient nearshore sediment is available to mitigate for the observed scour hole that has been forming along the Minister's Point revetments. Therefore, proactive measures may be required to maintain the shore protection in this area for the near-term, at least until the current-induced scour moderates over the next several years. Shore protection options along the presently armored shoreline could either consist of potential measures to re-direct currents away from the base of the revetment (e.g. shore-attached groins or an offshore structure to guide tidal currents) or direct improvements to scour protection for the existing revetments. As design details of the existing revetments are unknown, the evaluation provided information regarding the alternative concepts as described in Table 7.2 and Table 7.3. Overall, it is anticipated that if modifications to the existing revetments can be developed that withstand the ongoing toe scour, this likely would be the most straight-forward mechanism to address the ongoing issues at Minister's Point in the short-term.

Figure 7.22 The limits of Assessjment Area 1 showing the private revetment fronting Minister's Pointg, as well as the beach nourishment projecta t Scatteree Landing.

South of Minister's Point, Linnell Lane Beach has experienced significant changes since the widening of North Inlet in 2017. The low-lying barrier beach that had originally formed under relatively quiescent conditions (when Nauset Beach provided protection for this shoreline) experiences open ocean wave energy during storms, leading to barrier beach overwash and landward migration. One methodology for limiting the amount of overwash is to increase the elevation and overall volume of the barrier beach. An example transect is shown in Figure 7.24, along with a conceptual template for a nourishment design (Figure 7.25) that could withstand the conditions experienced at the site. Based on the length of beach requiring protection, it is anticipated that initial nourishment construction would require between 30,000 and 35,000 cubic yards of sand. Longevity of the nourishment would be dependent upon the relative position of North Inlet over the next 20-to-30 years. One added complication to a more robust nourishment program at Linnell Lane Beach is the need to maintain and/or improve tidal exchange to the salt marsh/pond system fronted by the barrier beach. The beach nourishment concept at Linnell Lane Beach is summarized in Table 7.4.

Table 7.2. Pros, cons, and challenges of stabilizing the revetment toe at Minister's Point in Assessment Area 1.

Pros	Cons
• Direct protection of dwellings on Minister's Point	• Potential increased scour due to tidal currents • Cost
Challenges • Potential regulatory concerns regarding seaward encroachment on resource areas, etc. • Requires accurate design considerations to ensure proper function without unintended impacts	

Table 7.3. Pros, cons, and challenges of offshore structures to re-direct currents at Minister's Point in Assessment Area 1.

Pros	Cons
• Reduce/eliminate scour along Minister's Point	• Potential increased scour at other locations • Cost
Challenges • Likely significant regulatory concerns regarding encroachment on resource areas, potential impacts on other resources by re-directing currents, etc.	

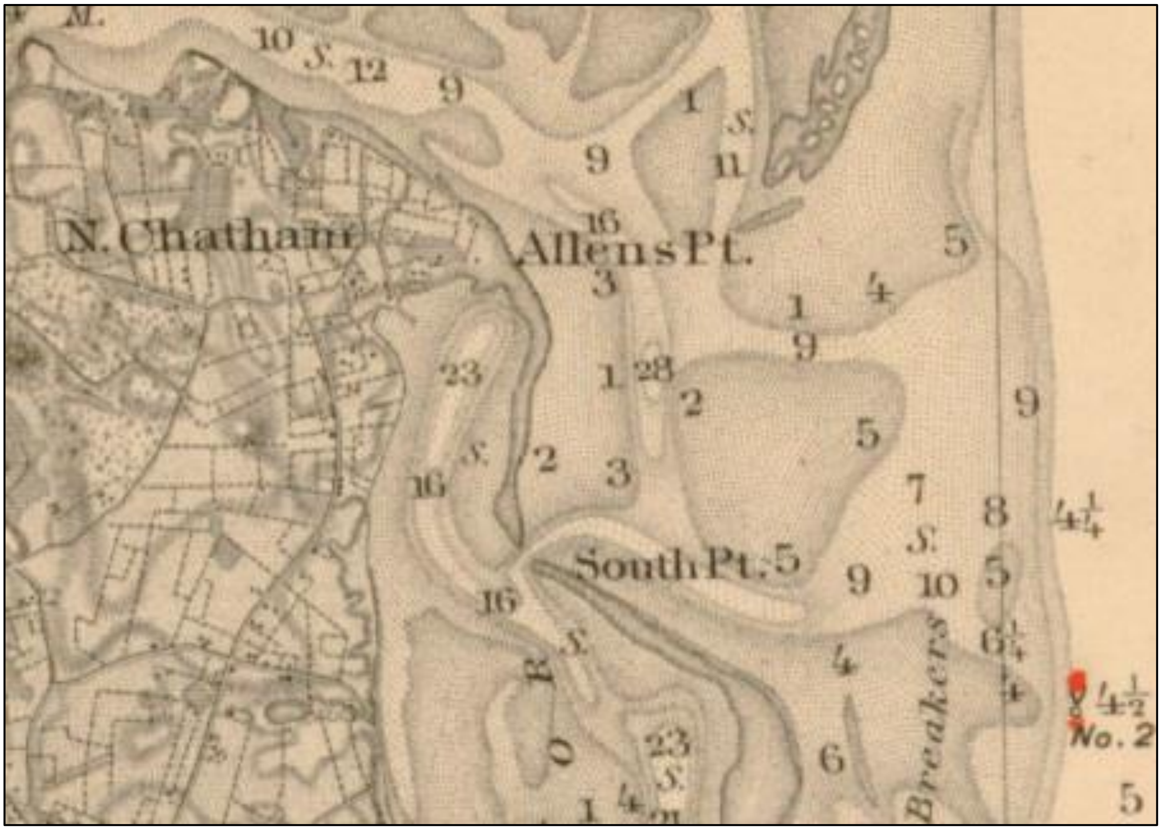


Figure 7.23 A portion of the 1879 nautical chart showing the barrier beach area that accreted seaward of Minister's Point (referred to as Allens Point on the chart).

Figure 7.24 Transect position along Linnell Lane Beach utilized to define existing cross-section and the potential beach nourishment template.

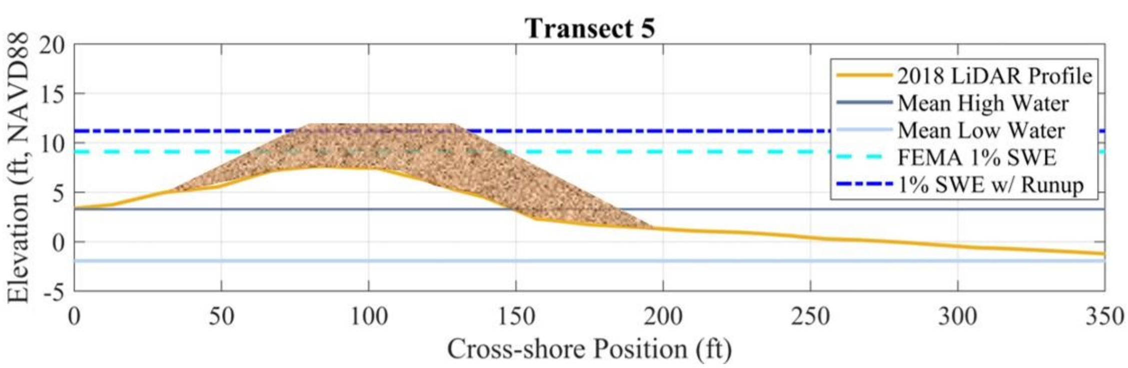


Figure 7.25 Conceptual beach nourishment template for Transect 5 (shown in Figure 7.24) indicating a proposed berm elevation approximately one foot above the 1% Still Water Elevation (SWE) with runup.

Table 7.4. Pros, cons, and challenges of Linnell Lane Beach Nourishment in Assessment Area 1.

Pros	Cons
• Prevent storm-induced overwash into salt marsh and Linnell Lane area • Provide sediment supply to downdrift beaches • Provides protection to private infrastructure landward of beach/marsh system	• Increased sediment supply will make maintaining inlet to the salt marsh difficult (may require a culvert) • Maintenance costs until North Inlet migrates further south
Challenges • Need to maintain and/or improve salt marsh/tidal flushing. • Need to avoid endangered species habitat	

7.3.2 Assessment Area 2

The shoreline south of Linnell Lane Beach extending to the vicinity of Thayer Lane is presently exposed to limited storm wave action entering through North Inlet; however, it is anticipated that southerly migration of the inlet will expose Assessment Area 2 to more severe wave conditions over the next 10+ years. Similar to the post-1987 breach concerns, whether “hard” shoreline armoring will be necessary as this area becomes more exposed is not clear. One major difference for Assessment Area 2 is the anticipated rapid rate of southerly inlet migration over the next 20-to-30 years. This rapid migration will limit the amount of time properties along this shoreline stretch are exposed to more energetic storm wave and surge conditions.

Historically, stone revetments have been one of the primary forms of shore protection in Chatham Harbor. Stone revetments can provide increased wave dissipation, reduced wave overtopping, and increased storm protection. This storm protection is not permanent because revetments can cause accelerated lowering of the fronting beach over time, which will eventually destabilize these structures and negatively impact wetland resources. 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. While revetments cause adverse downdrift impacts and may not be the best solution in areas of higher shoreline erosion rates, these structure do provide a “sense of security” for the upland property owners. As shown in Figure 7.26, there are on limited shore protection structures within Assessment Area 2, as this area historically is a relatively quiescent area of the Harbor.

Figure 7.26 The limits of Assessment Area 2 showing the private coastal engineering structures in the vicinity of the Cowyard and fronting a private home.

For Assessment Area 2, the expected alterations to the shoreline over the next 20-to-30 years likely will not require a significant level of “hard” armoring of the shoreline, due to the limited period of exposure. Instead, it is anticipated that “softer” shore protection measures including proactive nourishment, potentially with limited temporary structural enhancements, will provide necessary shore protection without adverse impacts associated with coastal armoring structures alone. Specifically, two conceptual shore protection concepts were developed for the Assessment Area 2 shoreline: Tern Island Flats nourishment, and combined beach nourishment and groins along the Assessment Area 2 shoreline.

The Tern Island Flats nourishment would require construction of a wave attenuating sand berm along the length of the flats, running in a generally north-south ditrection, as shown in Figure 7.27. An initial conceptual evaluation was performed for a berm with a length of approximately 2,700 feet, a crest width of 150 feet, and a crest elevation of 6 feet NAVD. The total approximate nourishment volume required for a berm of this size is 150,000 cubic yards. Figure 7.28 illustratess the effect of the berm on nearshore storm waves compared to existing conditions. The overall concept of the flats nourishment is to protect the shoreline in Assessment Area 2. An added potential benefit is that it provides an area to place dredged material from navigation projects, a process similar to the natural westward migration of North Beach Island. A summary of the Tern Island Flats nourishment is presented in Table 7.5.

More direct protection for upland properties along Assessment Area 2 can be achieved through nourishment and wooden groin placement along the existing beach system. Conceptually, this is shown in Figure 7.29. Since fringing salt marsh exists within Assessment Area 2, protection of this resource area would need to be considered as part of the design process. Based on the recent widening of North Inlet in 2017 and the increased wave exposure along the Assessment Area 2 shoreline, significant alongshore north-to-south sediment transport has been observed. This increase in sediment transport and in many cases, beach width, has begun to naturally impact the existing salt marsh resources. As North Inlet continues to migrate south, the fringing salt marsh will be exposed to even higher sediment transport rates and increased storm wave energy, further degrading and/or destroying the existing salt marsh resource along the Assessment Area 2 shoreline. As the inlet migrates south, it is anticipated that nourishment and groin construction could be performed from north-to-south on and as needed basis. General parameters for the beach nourishment and groins are shown for selected transects along Assessment Area 2, as illustrated in Figure 7.30 and Figure 7.31. Any wood groins constructed could be readily removed when no longer needed, where Figure 7.32 shows a typical wooden groin structure. A summary of the Assessment Area 2 nourishment and temporary groin placement is presented in Table 7.6.

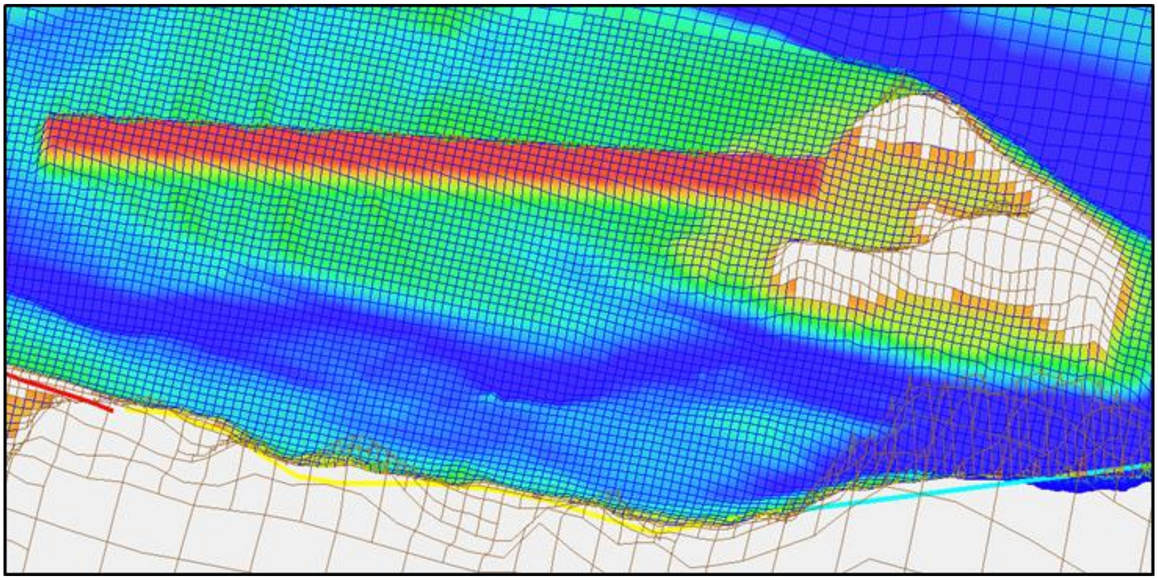


Figure 7.27 Birds-eye view of the Tern Island Flats berm shown as it is represented in the model grid, where red represents areas above water level and blue represents the channels. Tern Island is shown in white at the right of the figure.

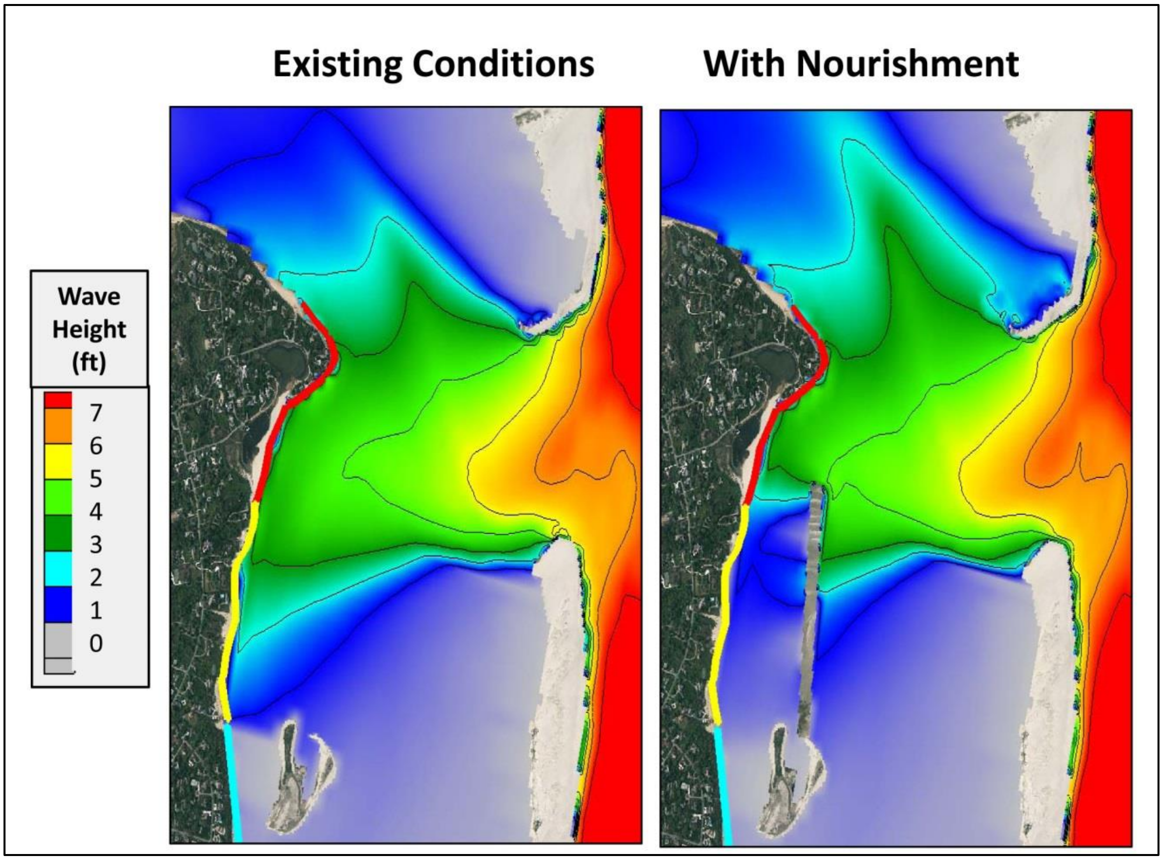


Figure 7.28 Comparison of storm waves conditions as they exist today and as they would be modified by the construction of the Tern Island Flats nourishment.

Figure 7.29 General conceptual placement of wooden groins approximately every 300 feet along the Assessment Area 2 shoreline along with beach nourishment placement.

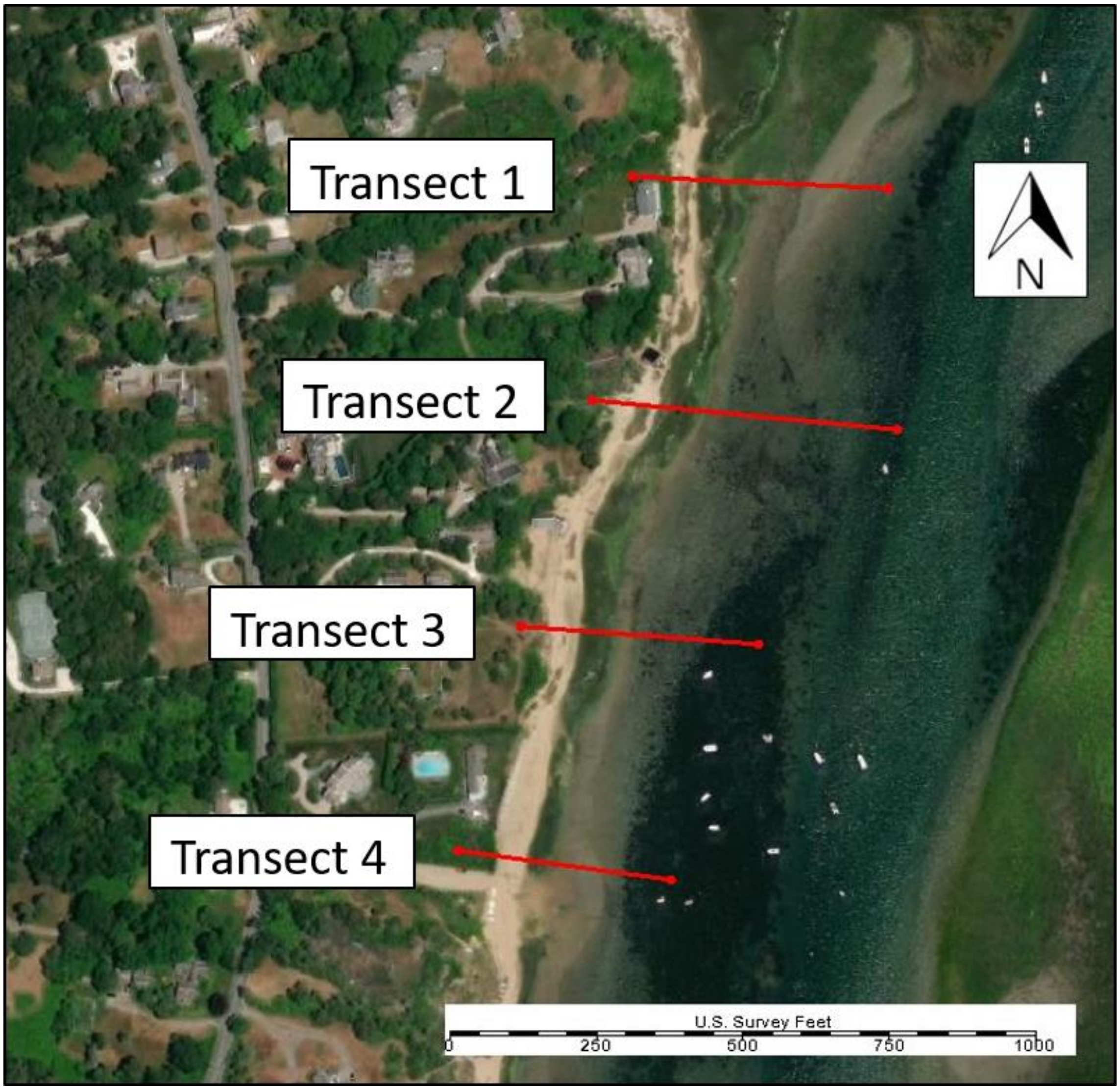


Figure 7.30 Location of beach profiles evaluated to determine potential limits of beach nourishment and temporary groin placement.

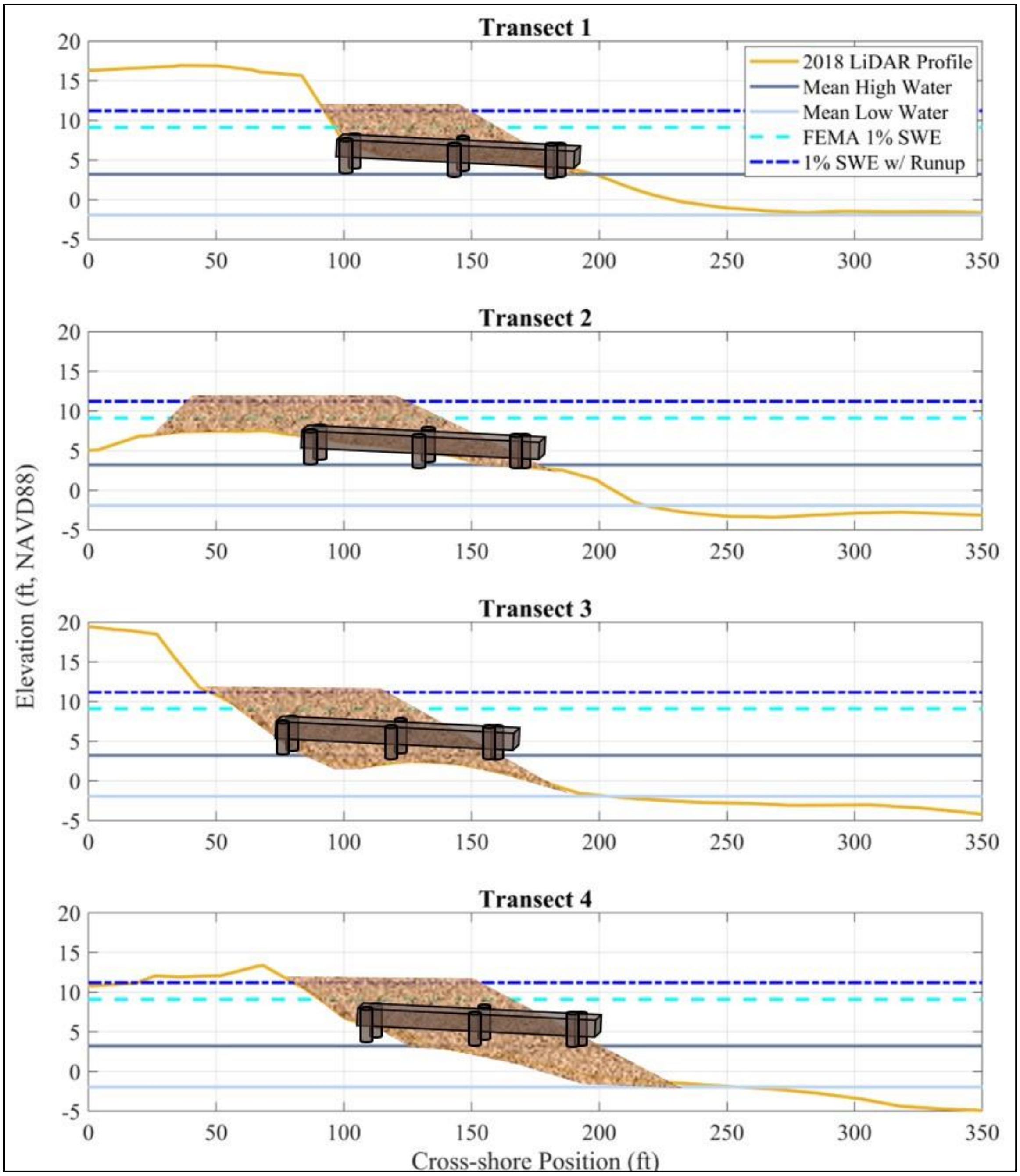


Figure 7.31 Profiles for each of the transects shown in Figure 7.30, where nourishment placemen and groin construction generally are landward of the existing mean high water line.

Figure 7.32 Example temporay wood groin.

Table 7.5. Pros, cons, and challenges of Tern Island Flats Nourishment in Assessment Area 2.	
Pros • Reduce storm wave energy along shoreline until North Inlet migrates further south • Provide sediment supply to nearshore area	**Cons** • Cost (including maintenance) • Will not provide complete protection of the shoreline during severe storm events
Challenges • Impacts to nearshore resource areas (fisheries concerns) • Impacts to endangered species habitat on Tern Island (although could be a net benefit) • May accelerate infilling of navigation channels and mooring areas west of berm	

Table 7.6. Pros, cons, and challenges of Temporary Groins and Nourishment in Assessment Area 2.

Pros	Cons
• Direct protection to upland properties • Provide sediment supply to downdrift shorelines (if designed properly) • Temporary – groins can be removed when no longer needed	• Will not provide complete protection of the shoreline during severe storm events • Potential impacts to nearshore salt marsh resources

Challenges
- Impacts to downdrift shorelines if groin cells are not kept filled
- Private property issues that can make a contiguous management approach problematic
- The groin cell must be kept filled to comply with permit requirements
- Regular monitoring will be required

7.3.3 Assessment Area 3

The shoreline between Thayer Lane and Chatham Lighthouse experienced significant erosion immediately following development of the 1987 breach that formed South Inlet. This a shoreline that has had more historical development than other regions of the Chatham east-facing coast. As such, Assessment Area 3 has had numerous coastal engineering structures constructed in the past, with many enhancements resulting from erosion pressures following the 1987 breach. Existing coastal engineering structures along the shoreline are shown in Figure 7.33.

As described previously, the anticipated landward migration of North Beach Island towards the mainland Chatham shoreline will protect the shoreline within Assessment Area 3 from the direct influence of open ocean storm waves. This ongoing barrier beach protection, combined with the reduced tide range along this shoreline, will generally provide conditions similar to the present through 2040. While coastal erosion should not be a major concern in Assessment Area 3 through 2040, continued shoaling of local navigation channels leading into Aunt Lydia's Cove over the next 10-to-30 years will make continued operation of the commercial fishing fleet at the Chatham Fish Pier challenging. Specific issues related to navigation concerns are beyond the scope of the present assessment; however, it should be noted that navigation dredging can serve as a source of needed nourishment material to provide shore protection in other Assessment Areas. Due to the natural protection provided by the barrier beach system, no specific shore and/or flood protection strategies were recommended. As mentioned previously, portions of the existing revetments may be unstable due to previous scour activity and should be monitored for further settlement and/or failure.

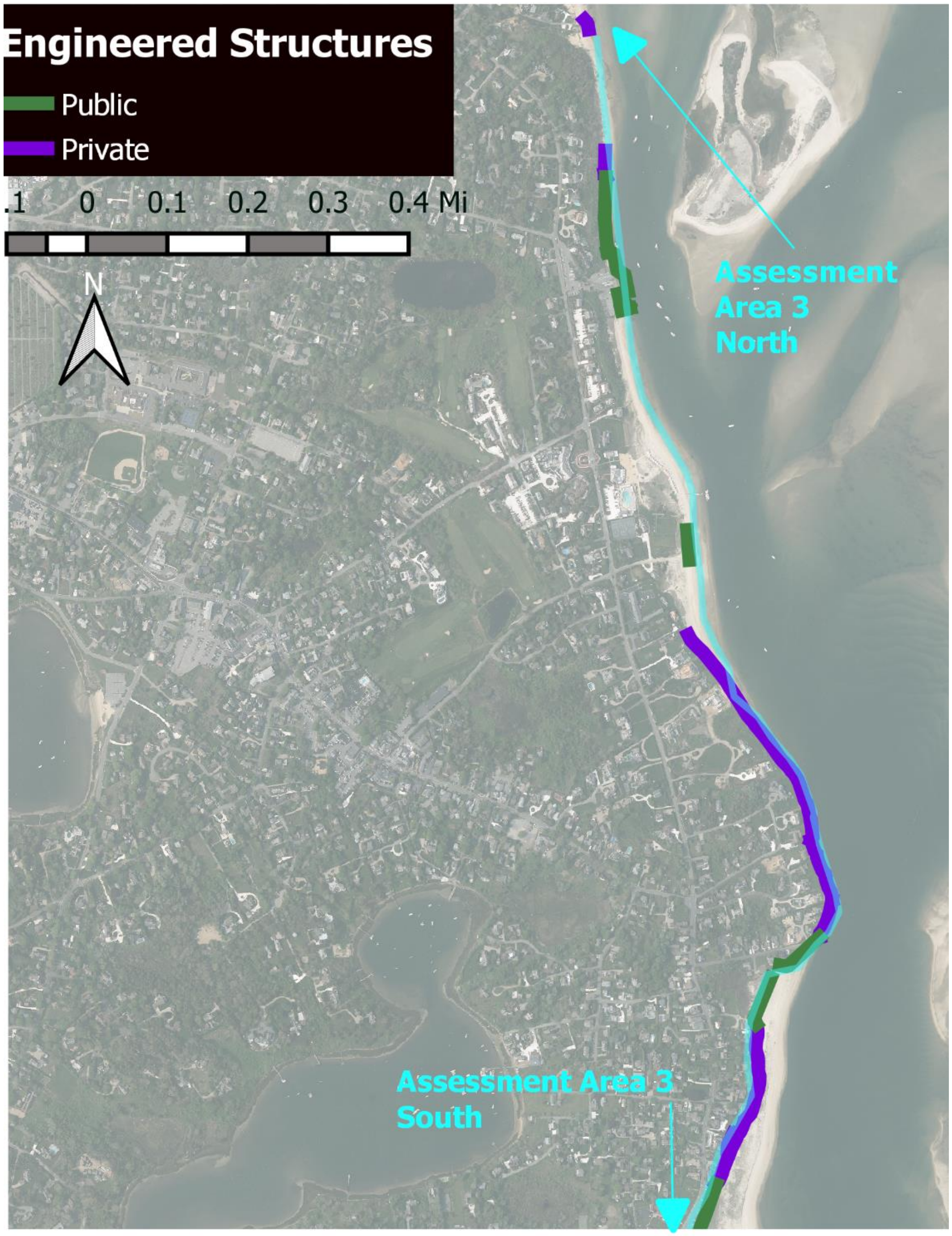


Figure 7.33 Coastal engineering structures along Assessment Area 3.

7.3.4 Assessment Area 4

As shown in Table 7.1, the Assessment Area 4 shoreline is subject to severe erosion and flooding problems under existing conditions, and this situation is expected to persist over the next 20-to-30 years. Figure 7.34 illustrates the existing shore protection structures, where they are primarily limited to area associated with Outermost Harbor Marine. As described previously, the entire area in the vicinity of the marina is significantly below the 100-year flood elevation; therefore, the existing structures do not provide protection, except during minor storm conditions.

The Little Beach neighborhood has been working with the Town of Chatham to develop a Hazard Mitigation Grant application to FEMA. The overall concept for this application is to construct a dune, as well as structural raising of existing structures within the marina, to an elevation of 9 feet NAVD to withstand significant storm conditions. The overall conceptual 'footprint' is illustrated in Figure 7.35, with the outline overlayed on the LiDAR topography in Figure 7.36. As shown, the intent of the project is to connect the higher existing dune features together by increasing the elevation of the existing landforms along the shoreline. This shore protection would form a contiguous higher elevation barrier from flood waters approaching the Little Beach area from the open Atlantic Ocean. However, drainage of water from the area landward of this proposed protection remains a concern.

Another similar conceptual alternative is shown in Figure 7.37. This concept provides similar shoreline protection to the alternative above, but also adds a redundant berm component that serves to separately protect the neighborhood north of Outermost Harbor Marine, as it is understood that protection of the low-lying marina property may be the weakest link in the plan relative to engineering considerations. A summary of the Assessment Area 4 flood barrier concept is presented in Table 7.7.

It should be noted that it is anticipated that substantial volumes of littoral drift and barrier beach overwash is expected to influence Assessment Area 4 over the next 20-to-30 years. This sediment likely will provide some shore protection benefits; however, it may prove challenging to maintain navigation access to Outermost Harbor Marine.

Figure 7.34 Coastal engineering structures along Assessment Area 4.

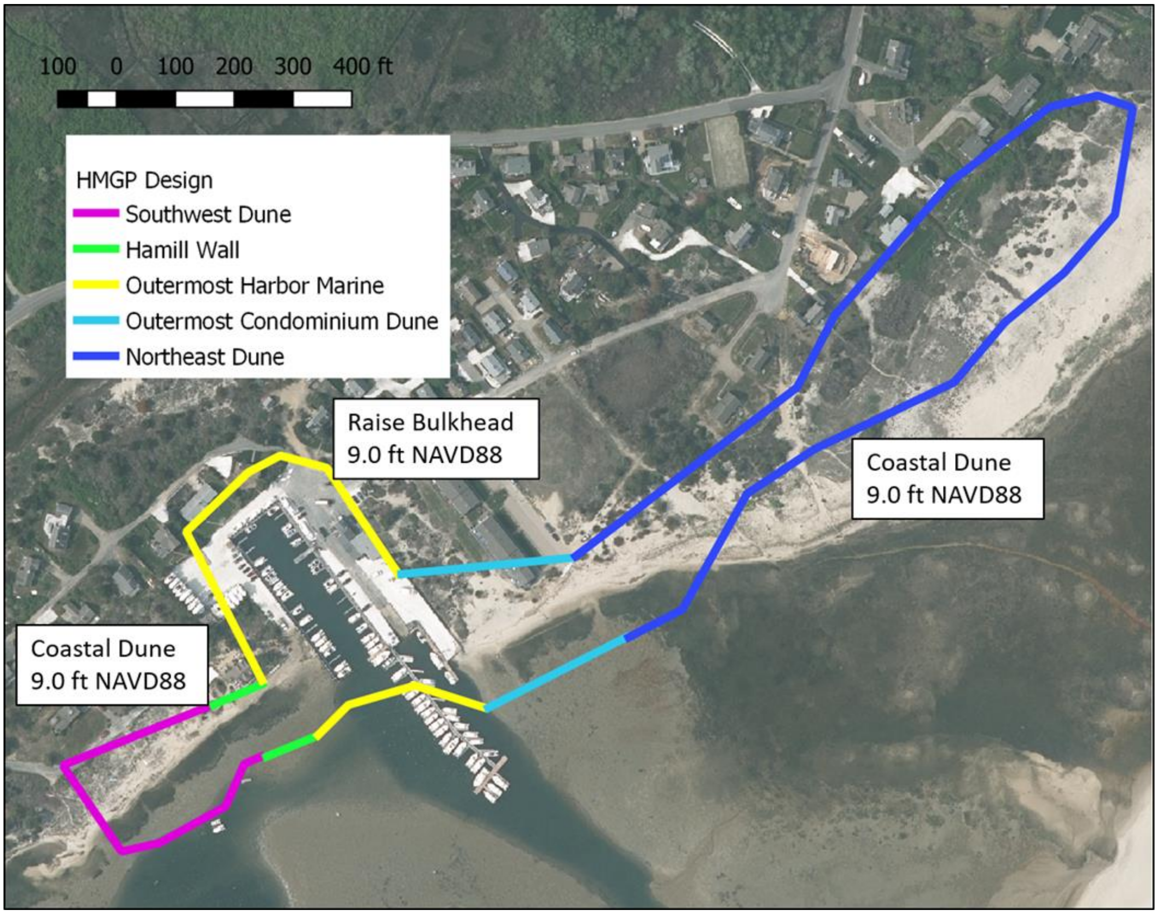


Figure 7.35 The flood barrier overall conceptual plan the Town of Chatham submitted as part of the HMGP (Hazard Mitigation Grant Program) process.

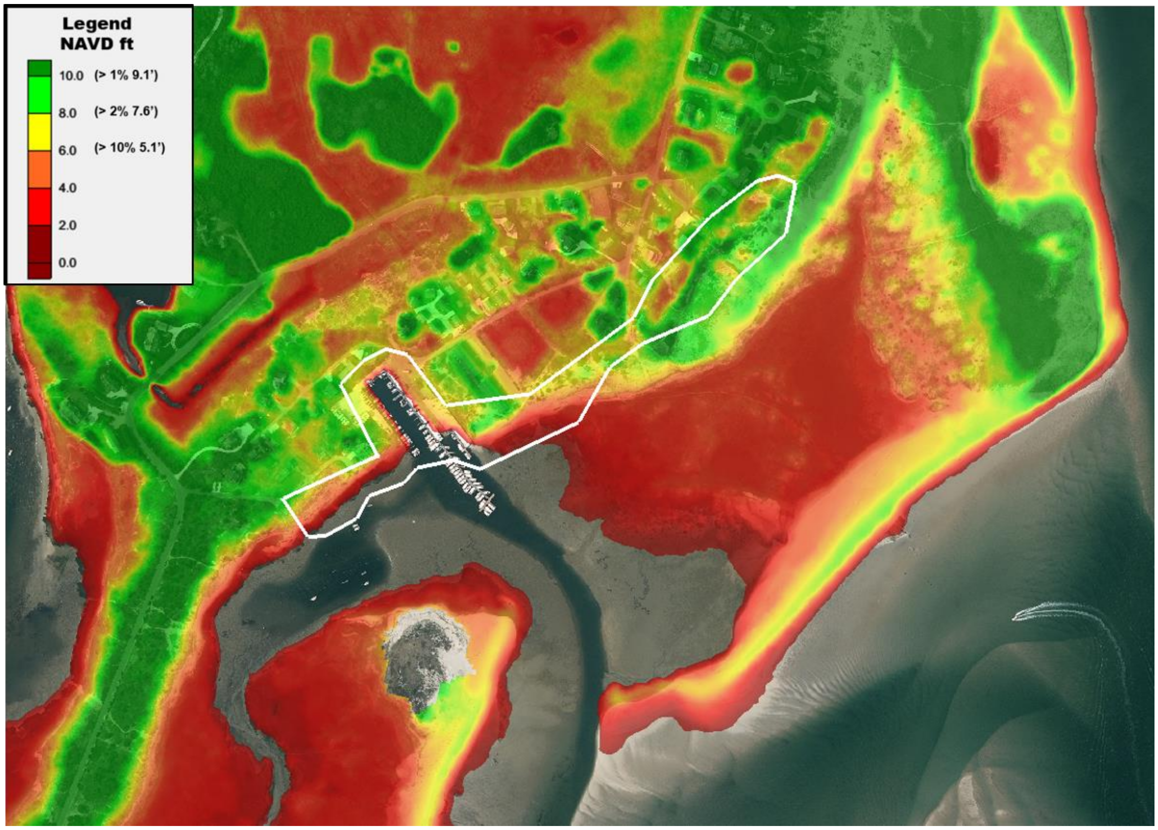


Figure 7.36 Outline of the flood barrier overall conceptual plan overlaied on the existing LiDAR topography. This illustrates the connection to higher elevation features at both the north and south ends of the proposed protection.

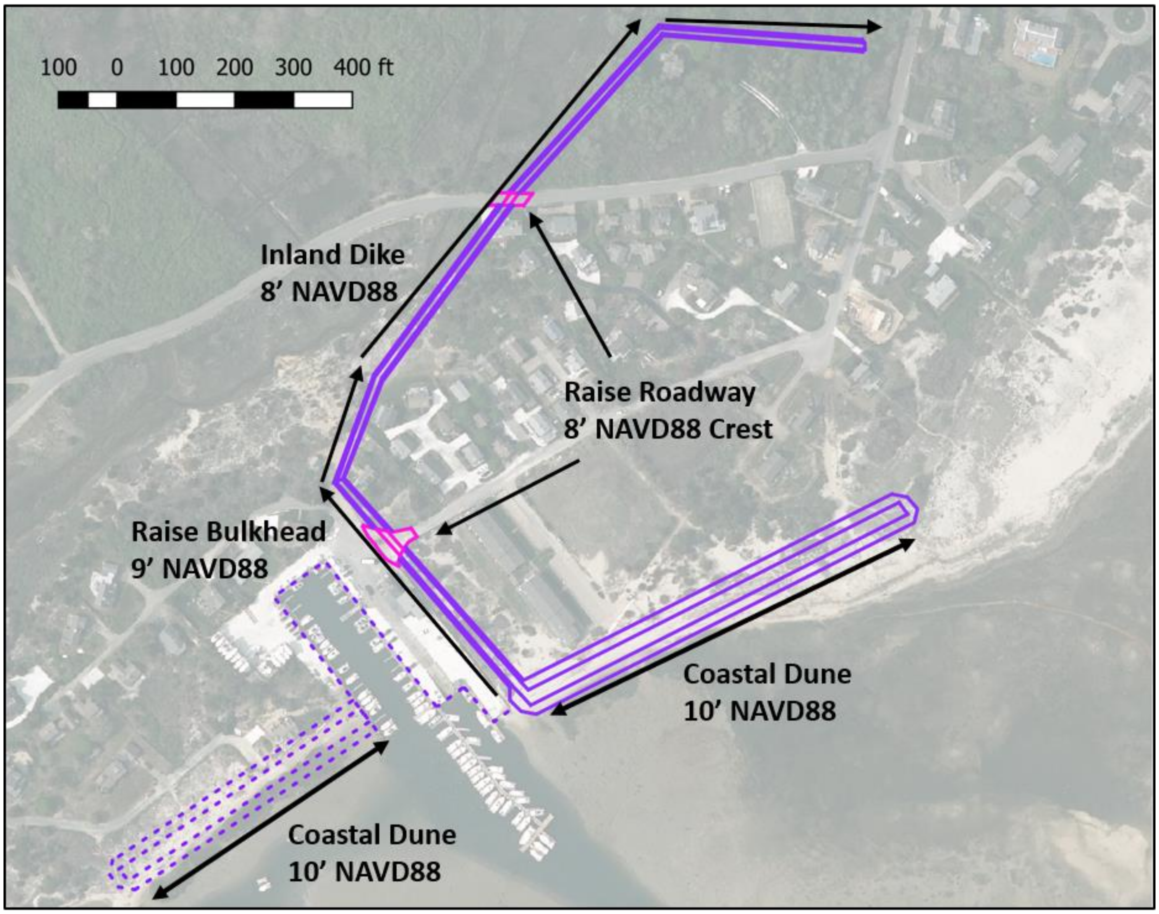


Figure 7.37 An alternative dune/berm/flood wall protection concept, where redundant protection is provided for the area north of Outermost Harbor Marina.

Table 7.7. Pros, cons, and challenges of Flood Barrier (Dune/Berm/Bulkhead) in Assessment Area 4.

Pros	**Cons**
• Direct protection to upland properties • Provide protection for emergency egress route to both Little Beach area and Morris Island	• Will not provide protection of all properties during severe storm events • Does not address likely accretion of beach that will impact Outermost Harbor Marina • If open ocean wave conditions persist in the future, dune likely cannot withstand the forces (retrofit/redesign likely required) • Cost to construct and maintain (frequent inspection)
Challenges • Connection between “soft” dune/berm and “hard: bulkhead at marina may cause a weak link in the design • Drainage landward of protection may be problematic • Private property issues that can make a contiguous management approach problematic	

7.3.5 Assessment Area 5

Over the next 20-to-30 years, Assessment Area 5 will be exposed to some wave activity from the open Atlantic Ocean. In addition, tidal currents running between Fools Inlet and Nantucket Sound will continue to cause shoreline erosion within this area. The specific barrier beach migration patterns are difficult to predict in this area, therefore, the level of protection provided by these migrating shoals and overwashed barrier islands are likewise difficult to predict. With these uncertainties in mind, management over the next 20-to-30 years for Assessment Area 5 should focus on monitoring future inlet formation and shoal migration patterns relative to overall shore protection for this shoreline.

Figure 7.38 shows existing coastal engineering structures, which are limited to private revetments along Morris Island. These structures appear to be in relatively good condition at present, although future sand nourishment along Quitnessett Barrier Beach and/or the revetment on Morris Island could enhance resilience. If wave-induced or tidal current-induced erosion increases along this shoreline, potential adverse impacts along the northern terminus of the revetment may occur. However, it is anticipated that the existing structures likely will provide necessary protection in the near-term. A summary of the Assessment Area 5 maintaining of existing protection is presented in Table 7.8.

Figure 7.38 Coastal engineering structures along Assessment Area 5.

Table 7.8. Pros, cons, and challenges of maintaining or improving existing revetments in Assessment Area 5.

Pros	Cons
• Direct protection to upland properties already fronted by revetments • Improving structural stability with sand nourishment could increase coastal resiliency	• May cause end effects if exposed to increased wave energy • Does not protect Monomoy National Wildlife Refuge property • Cost, if tidal currents cause significant scour

Challenges

- Minor concerns regarding environmental impacts of improved structures

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ATTACHMENT 1

Center for Coastal Studies

Data Collection Methods

Vessel-based Acoustic Surveys

The R/V Marindin was used for all vessel-based work, it is a 1995 Eastern® with a 200 HP Yamaha outboard. It has a retractable bow mount with power hoist to raise and lower the sonar for safe operation and ease of deployment/retrieval. The bow mount eliminates most of the noise from the vessel and engine thus improving the quality of the acoustic data. This vessel combines an adequate beam (2.54 m) that yields stability at low survey speeds, a shallow draft (0.61 m) for safe operation in nearshore waters, and a modified V-hull for optimal transit time. The vessel also has a diver ladder and a davit. The requisite safety equipment onboard includes radar, depth-sounder and GPS and compass for navigation.

A suite of instruments is required to conduct high-resolution, vessel-based acoustic surveys. The Edgetech 6205 is a dual-frequency, phase-measuring sidescan sonar and was used for all surveys. Its operating frequencies are 550 and 1600 kHz for backscatter imagery and 550 kHz for bathymetry. The sidescan sonar range resolution is 1 cm, and the horizontal beamwidth is 0.5 degrees at 550 kHz. The corresponding quantities at 1600 kHz are 0.6 cm and 0.2 deg. The bathymetric range and vertical resolution are both 1 cm. Use of chirp signals and correlation processing has enabled the stated range resolutions. The respective bandwidths at 550 and 1600 kHz are 67 and 145 kHz (Edgetech, 2014). The effective bathymetric swath width is 6-8 times the height of the sonar over the bottom. A Teledyne TSS DMS-05 Motion Reference Unit mounted on the sonar collects data on heave, pitch, and roll, measuring heave to 5 cm and roll and pitch to 0.05° (Teledyne TSS, 2006). A HemisphereGPS® V110 vector sensor is used to measure heading. Two differential GPS receivers spaced 2 m apart yield heading accuracies of <0.10° RMS (HemisphereGPS, 2009). A Trimble® R10 GNSS receiver utilizing Real-Time-Kinematic GPS (RTK-GPS) is used for positioning and tide correction for vessel-based surveys. The R10 was also used to collect shoreline data on the barriers adjacent to the inlets in Chatham Harbor.

CCS subscribes to a proprietary Virtual Reference Station network (KeyNetGPS) that provides virtual base stations via cellphone from southern Maine to Virginia. This allows CCS to collect RTK-GPS without the need to setup a terrestrial base station or post-process the GPS data, thereby reducing mobilization and demobilization costs, streamlining the field effort, and maximizing vessel-based survey time.

CCS undertook a rigorous analysis of this system to quantify the accuracy of this network. Twenty-nine (29) National Geodetic Survey (NGS) and Massachusetts Department of Transportation (MassDOT) survey control points, with published state plane coordinate values relating to the Massachusetts Coordinate System, Mainland Zone (horizontal: NAD83; vertical NAVD88), were occupied. Control points were distributed over a wide geographic area up to 50 km away from CCS.

Multiple observation sessions, or occupations, were conducted at each control point with occupations of 1 second, 90 second, and 900 second. To minimize potential initialization error, the unit was shut down at the end of each session and re-initialized prior to the beginning of the next session. The results of each session (i.e., each 1 s, 90 s, and 900 s occupation) were averaged to obtain final x, y, and z values to further evaluate the accuracy of short-term occupation. Survey results from each station for each respective time period were then compared with published NGS and MassDOT values and the differences (error) used to assess and quantify uncertainty. Significantly, there was little difference between the error obtained for the 1 s, 90 s, and 900 s occupations. The overall uncertainty analysis for these data yielded an average error of 0.008 m in the horizontal (H) and 0.006 m in the vertical (V). A Root Mean Squared Error (RMSE) of 0.0280 m (H) and 0.0247 m (V) and a National Standard for Spatial Data Accuracy (95%) of 0.0484 m (H) and 0.0483 m (V).

Edgetech’s Discover Bathymetric® was used to monitor all incoming data streams and control settings for onboard acoustic instruments to optimize data quality for at-sea conditions. Survey planning was performed using Hypack Survey® for line planning, coverage mapping and helmsman navigation. Both Discover Bathymetric® and Hypack’s Hysweep® were used to collect data with the final raw output in JSF and HSX file formats respectively.

Post-processing of bathymetric data was performed using CARIS HIPS®. Raw HSX files were converted to CARIS HDCS format using vessel configuration files developed from vessel offsets, and device information. RTK-GPS tide corrections were applied in the conversion process. Sound velocity corrections were applied using measurements collected in-situ by an internal sound velocimeter located in the sonar housing and water column profiles obtained from casts performed for each survey using a YSI Castaway® CTD. Patch tests were performed to determine motion and timing offsets (roll, pitch, yaw and latency). Those offsets were recorded in the vessel file and applied when the survey lines were merged. Real-time uncertainty data collected in Discover Bathymetric and stored in JSF format were not supported in CARIS, and therefore not utilized at the time of processing. However, Total Propagated Uncertainty (TPU) was computed using device manufacturer specifications recorded in the vessel file. Select filters were applied to the bathymetric data in order to remove noise in the far-field regions and depth outliers. When necessary, area editors were used to manually remove spurious soundings. Final surfaces were created from the processed sounding data using the CUBE (Combined Uncertainty Bathymetry Estimator) algorithm (Calder, et al., 2006), and were exported to multiple formats including Geotiffs, Bathymetric Attribute Grids (BAGs) and ASCII files.

Tidal data

A Teledyne Sentinel V® (op. freq. 1000 kHz) Acoustic Doppler Current Profiler (ADCP) was deployed on the seafloor off the coast of Chatham to collect water level (tidal) data. The ADCP is attached to a bottom mount which is lowered to the seafloor during deployment. A buoy is attached to the bottom mount and an acoustic release is used to separate the buoy from the bottom mount during retrieval. The buoy floats to the surface attached to a line that is used to retrieve the instrument. The ADCP has both acoustic and pressure sensors. The acoustic sensors primarily collect data on tidal current vectors and the pressure sensors collect data on the water levels, including waves. The ADCP collected water level data from a Keller pressure sensor with an accuracy of +/- 0.1% of FS plus a drift of +/- 0.11%. Data on waves and currents were not used in the model and are not discussed here. Data are downloaded from the ADCP using Teledyne *Velocity*® software.

In order to correct for atmospheric changes and sensor drift over the course of the deployment period the Center maintained a HOBO U20 pressure logger at the Chatham Fish Pier collecting atmospheric readings every 6 minutes throughout the ADCP deployment. Water level data were also obtained as part of another study at six-minute intervals at four locations, Chatham Fish Pier, Meeting House Pond, Outer Most Harbor Marina, and Stage Harbor. There data were used herein as described below. Pressure loggers are affixed to stationary structures, such as pilings on piers, at various locations. The loggers are inserted into a PVC pipe for protection and holes are drilled to allow the free flow of water. The PVC pipe is mounted using two stainless steel hanger bolts. This allows easy access for data download and re-deployment. The top bolt provides a stable platform for elevation surveys using an RTK-GPS, allowing for the creation of a vertical datum offset which is needed to convert sensor depth to a standard elevation datum, in this case NAVD88 (m). A tide staff was established at Meeting House Pond for a periodic visual check of calculated tide levels. The tide staff was surveyed in the same manner as the tidal stations with offsets established to convert local tide staff readings to NAVD88 (m).

Elevation surveys were conducted at each station at fixed location and a minimum of three survey points were collected. A Trimble® R10 GNSS receiver utilizing Real-Time-Kinematic GPS (RTK-GPS) was used for all survey positioning and offset creation. The Center subscribes to a proprietary Virtual Reference Station (VRS) network (KeyNetGPS) that provides virtual base stations via cellphone from Southern Maine to Virginia. This allows the Center to collect RTK-GPS without the need to setup a terrestrial base station or post-process the GPS data, streamlining the field effort.

The HOBO pressure sensor has an operation range of 0-207 kPa approximately 0 - 9m water depth. Factory calibration ranges from 69 to 207 kPa (10 to 30 psia), 0° to 40°C (32° to 104°F) and has a water level typical error: ±0.05% FS, 0.5 cm (0.015 ft) water and maximum error: ±0.1% FS, 1.0 cm water. Pressure response time is <1 second; measurement accuracy also depends on temperature response time. The logger has a battery life of 5 years with 1 minute or greater logging interval and 64K bytes of memory or approximately 21,700 pressure and temperature readings.

Data was offloaded from the Hobo pressure sensors using a HOBO waterproof shuttle and HOBOware® software. Each data set was checked for anomalies and data was corrected if needed. Utilizing the barometric compensation assistant, the atmospheric data was imported and the HOBOware software calculated depth of seawater (sensor depth). This data set was exported to a comma separated file and data gaps and anomalies were removed and then interpolated, and a continuous data set was created. Sensor depth was converted into geodetic datum, NAVD88 (m).

Data from the stations were corrected for the effects of atmospheric pressure using data from adjacent atmospheric pressure recorders. The tidal data presented in this report were corrected relative to NAVD88 (m), by means of precision RTK-GPS surveys. Trends in water level were compared to Boston tide data and to the “surface tracking” feather exported by the Velocity Software. Pressure sensor drift was identified and corrected using Boston and the “surface tracker” as a reference point.