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July 2021

Executive Summary

The focus of this study was to research the resiliency of rock/sand/plant living shoreline protection systems. These systems have been used in Chesapeake Bay for 40 years to reduce erosion, protect infrastructure, and create habitat that is disappearing from the shoreline as sea level rises. The goal was to determine how they have been affected by storm surge and associated wind-driven waves, sea-level rise. This data informed adaptive management strategies to create site-specific morphologically-resilient projects.

The objectives of this 3-year project is monitoring the effectiveness of nature-based resilience projects over time such as those that use hybrid living shoreline management strategies on medium to high wave energy shorelines. To create effective shore protection on these higher energy shorelines, structures are needed in addition to sand and plants to maintain ecosystems along the shoreline. In particular, rock sills and headland breakwaters are used in Chesapeake Bay to maintain continuous coastal profile and a more natural land-water interface.

Breakwaters and sills system provide stable beach and marsh substrates, respectively and are designed to reduce wave action by attenuation, refraction, and diffraction before it reaches the upland region. A sill has a lower crest, is closer to shore, and usually, is more continuous than larger breakwater units. The sills are installed with sand fill to create a substrate for establishing a marsh fringe. They are typically suitable for areas with smaller fetches.

Thirteen (13) shoreline projects were surveyed over a three-year period to assess changes in the sand substrate that was installed to create beaches and/or marshes as part of the shore protection system. These seven breakwater and 6 sill projects range in age from the Aquia Landing breakwater system (1987) to the Werowocomoco sill system (2016). Consequently, the impacts of the rate of sea-level rise increases with age of each site. These shore protection systems were built fronting both high and low eroding upland banks which provide different impediments and/or opportunities for adaptation to sea-level rise.

From a coastal resiliency perspective, the marshes behind sills at high banks are generally limited in landward migration and accrete vertically in response to sea-level rise, and the marshes fronting low banks can transition landward over time. The same is generally true for breakwater systems as these systems were designed for the 25-year and 50-year storms. In terms of shore protection, they all have met or exceeded the expectation that they would prevent erosion of the upland or marsh. Some adjustments to the coastal profiles have occurred, but they were not unexpected. If the systems have to be adapted to sea-level rise in the future, the addition of rock and sand to the site can maintain the elevations needed for successful shore protection.

Project maintenance over time rarely extends for the more than few years but is an important component, especially regarding maintaining marsh grasses behind sills. Three sill sites have had significant invasions of *Phargmites australis* which, when left unchecked, eventually overcomes and displaces the high marsh.

For existing sites, the process of determining how to adaptively manage living shorelines

for morphologic resiliency should occur over the life of the system. Ongoing maintenance of the site informs this process. However, for new projects, the question becomes when is the addition of rock and sand to the living shoreline most timely? Should it be done when it is needed or should the system be overdesigned for present conditions. This would increase the cost of the system but may save money over the long-term.

The anticipatory strategy includes designing crest elevations to reduce impacts of future or grading property for marsh migration. However, this is a risk because of the uncertainty in the future. They may not be needed in the future or they may cost more now than adaptive strategies in the future. Reactive strategies wait to react until the project is in dire jeopardy generally due to short-term storm events. At that time, it may be more difficult to act due to lack of preparation. In addition, costs may be more expensive by waiting until action is needed immediately. The plan should consist of strategies such as adding rock, sand, and plants to the system to enhance adaptability. Another option is to raise the level of protection significantly at time of construction. This provides increased protection from sea-level rise, but it also increases project costs.

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Introduction

Natural features are created through the action of physical, biological, geologic, and chemical processes operating in nature, and include marshes, beaches, dunes and oyster reefs. Nature-based features are created by human design, engineering, and construction to mimic nature. A living shoreline is an example of a nature-based feature because they maintain continuity of the natural land-water interface and reduce erosion while providing habitat value and enhancing coastal resilience (NOAA, 2015).

These ecosystem-based management systems have been the preferred alternative for stabilizing tidal shorelines in the Commonwealth of Virginia since 2011. However, an analysis has shown that between 2011 and 2016 only 24% of the permits granted for shore protection were considered living shorelines (ASMFC, 2016). These types of systems may be relatively new to many landowners and some managers may not be convinced about the long-term effectiveness of the systems for shore protection and their maintenance as well as the benefits of the ecosystem services they provide. Research has been performed on the ecosystems of created beaches and marsh habitats, but studies on the long-term effectiveness of these systems for shore protection in Chesapeake Bay from a design and construction perspective are relatively few even though human shoreline use (e.g., development, shoreline hardening, boating activity) can dominate physical processes to alter the marsh response to sea level rise (Mitchell, 2018).

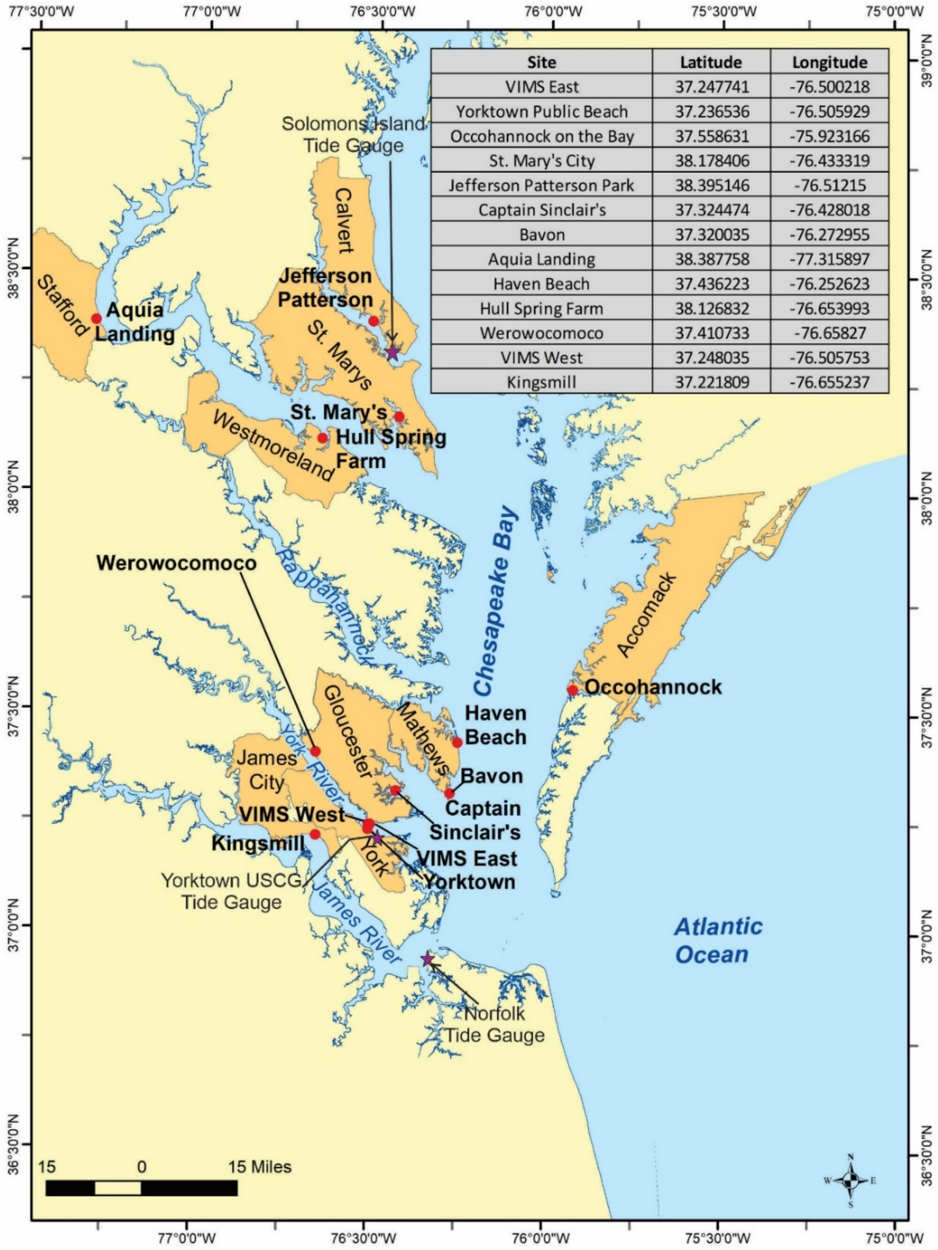
The Coastal Zone Management program, through NOAA grants, has funded several projects that have reviewed design considerations and monitored sill systems for effectiveness. These studies presented data regarding the construction and performance of three living shoreline projects that were built between 1999 and 2003 in Maryland (Hardaway *et al*., 2007 & 2009) and were in part the basis for the “Living Shoreline Design Guidelines for Shore Protection in Virginia’s Estuarine Environments” and the marine professional training classes (Hardaway *et al*., 2021). In addition, extensive research has been done on the design and performance of breakwater systems around Chesapeake Bay (Hardaway & Gunn, 1991; 2010; 2011). Breakwater and beach systems are appropriate for medium to high energy shorelines along Chesapeake Bay and its tributaries.

The goal of this 3-year project is monitoring effectiveness over time of nature-based resilience projects such as those that use hybrid living shoreline management strategies on medium to high wave energy shorelines. To create effective shore protection on these higher energy shorelines, structures are needed in addition to sand and plants to maintain ecosystems along the shoreline. In particular, rock sills and headland breakwaters are used in Chesapeake Bay to maintain continuous coastal profile and a more natural land-water interface.

The present project sought to build upon the research performed in years 1 and 2 of this project (Hardaway et al., 2018 & 2019) by expanding monitoring protocols at sills and headland breakwater systems to determine effectiveness of shore protection and habitat creation and stability through time using a detailed site assessment and survey. In addition, referencing the latest research results of migration and accretion of beaches and marshes in Chesapeake Bay, the project determined what elements make these successful over the short and longer terms.

A second goal of the present project was to determine the coastal habitat response of created wetlands and beaches at living shorelines in the face of sea-level rise. Using a detailed elevation survey of each site and climate change adaptation sea-level rise scenarios, the system was modeled to understand how it may respond to changes in water level through time and its morphologic resilience. The collected data was used to project impacts of sea level rise through time on the structures, the upland banks, and created marshes and beaches to determine adaptive management strategies for these sites.

Over the course of three years, this project used site-specific shore protection and habitat effectiveness for both medium and high energy sites as well as low and high upland banks to develop information for managers, contractors, and homeowners to adapt existing and future living shoreline projects to sea level rise (Figure 1-1). Living shorelines can reduce sediment input as well as provide both subtidal, intertidal, and pore space habitats for diverse estuarine fauna and their predators. Determining how resilient these systems will be in the face of climate change requires understanding how these systems functioned in the past.



Site	Latitude	Longitude
VIMS East	37.247741	-76.500218
Yorktown Public Beach	37.236536	-76.505929
Occohannock on the Bay	37.558631	-75.923166
St. Mary's City	38.178406	-76.433319
Jefferson Patterson Park	38.395146	-76.51215
Captain Sinclair's	37.324474	-76.428018
Bavon	37.320035	-76.272955
Aquia Landing	38.387758	-77.315897
Haven Beach	37.436223	-76.252623
Hull Spring Farm	38.126832	-76.653993
Werowocomoco	37.410733	-76.65827
VIMS West	37.248035	-76.505753
Kingsmill	37.221809	-76.655237

Figure 1-1. Location of sill and breakwater sites used in this study within the Chesapeake Bay estuarine system.

2 Coastal Resiliency

Coastal resilience means creating the ability for a community to "bounce back" after hazardous events such as hurricanes, coastal storms, and flooding – rather than simply reacting to impacts. This capability can prevent a short-term hazard event from turning into a long-term community-wide disaster. From a shore protection perspective, bulkheads and stone revetments are as effective as living shorelines and have less maintenance issues. However, they may provide less coastal resiliency because they can be impacted and overtopped, particularly when events exceed design dimensions. The more continuous coastal profile created by living shorelines, on the other hand, provide ample opportunities to mitigate wave energy during storms. Due to their ability to stabilize the shoreline with minimal impact to the ecology, living shorelines are considered a method to increase coastal community resilience to sea level rise (e.g., Sutton-Grier, Wowk, & Bamford, 2015; Van Slobbe et al., 2013).

Typically, coastal resiliency of shoreline protection measures is often couched in terms of habitat impacts, diversity, and what existing ecosystem was replaced before the measure was installed. In terms of habitat, stone revetments are better than bulkheads, and living shorelines are better than revetments. However, when utilizing living components to mitigate hazardous events, measures to provide shoreline erosion control must be robust enough for the particular energy conditions at the site and designed for a certain level of protection and given scenario of sea-level rise.

2.1 Sea-Level Rise

What rate of sea-level rise should be considered when planning for morphologic resilience? In previous reports, the USACE (2014) scenarios were used to project that in 2050, at the intermediate rate for sea-level rise, sea level will be about 1.1 feet above present levels and at the high rate, sea level with 2.1 feet above present levels. More recent sea-level rise projections developed by VIMS generally agree with these rates (Figure 2-1). Although sea-level projections vary from place to place along the Bay shoreline due to local differences in the processes that control sea-level rise, such as land subsidence, the projections are relatively similar in the Bay. Linear projections of sea-level rise indicate the lowest amount of change, but most scientists feel that these may not be valid due to the measured acceleration of sea-level rise. Better indicators of change are the quadratic trend and quadratic high trend projections (Figure 2-1) which show that by 2050 the intermediate increase in water level would be 1.7 ft and the high would be 2.3 ft. These projections are based on 1992 mean sea level.

All the project sites have been impacted, to some degree, by ongoing sea-level rise. Using the existing rate of sea-level rise, as determined at the NOAA tide gauges in the Bay, the amount of water level change since the installation of the project can be determined. The amount of sea level rise since each sites installation from oldest to youngest are shown in Table 1. Few researchers have looked at the “long” term maturity of headland breakwater and sill systems and what that means to habitat function, but more importantly, for shore protection. Numerous recent studies have looked at relatively new projects, less than 10 years old, including Burke et al. (2005), Bilkovic & Mitchell (2013), and Bosch et al. (2006). In living shoreline systems, the habitat component is integral to shore protection. Accordingly, living shoreline designs need to maintain or enhance sedimentation and accretion to promote increased ecosystem function longevity with sea-level rise (Bilkovic & Mitchell, 2017). Though this makes sense, putting this into practice is difficult without robust maintenance programs to address issues like sea-level rise and invasive plant species. These maintenance issues are often overlooked and end up not being addressed.

2.2 Adaptive Management

The Corps of Engineers developed an adaptive management philosophy regarding future estimates of sea-level rise (USACE, 2014). Implementation strategies range from a conservative anticipatory approach, which constructs a resilient project at the beginning of the project life cycle, to a reactive approach, which consists of doing nothing until the impacts are experienced. Between the two extremes is an adaptive management strategy, which provides a process for dealing with uncertainties and allows the incorporation of ongoing monitoring to determine approaches based on the current available techniques and research which could be significantly different from when the system was originally installed.

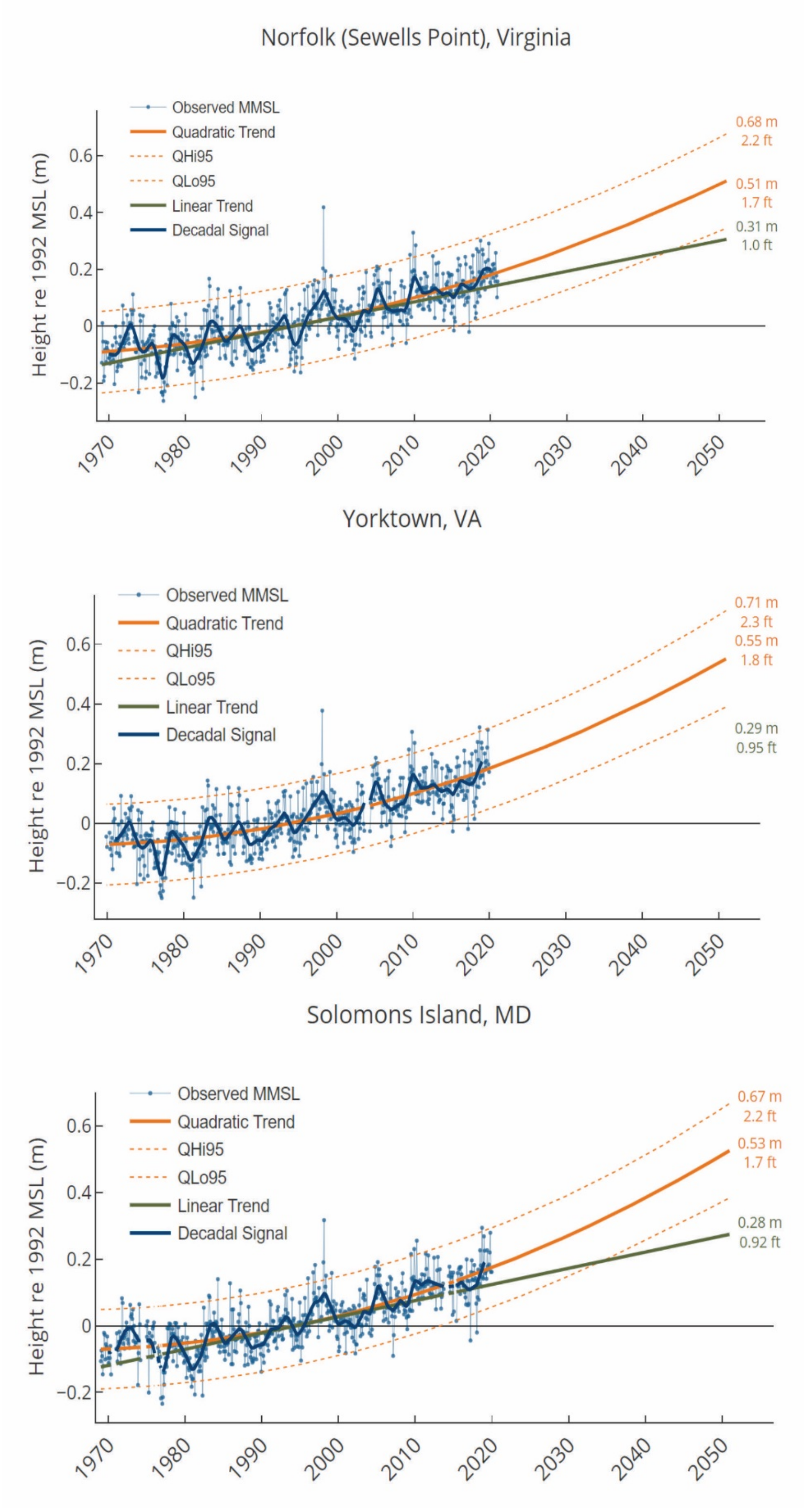


Figure 2-1. Sea-level rise projections based on NOAA tide gauge data. From https://www.vims.edu/bayinfo/bay_slrc/index.php

Adaptive management incorporates new assessments and actions throughout the project life based on thresholds and tipping points. Identifying these critical thresholds and triggers for the project will determine the adaptive options and timing. A critical threshold can identify a water surface elevation at which the structural condition or system performance changes. This can include when a system is overtopped or drainage is impacted. The tipping point generally occurs after the threshold is reached; it is when the stability and/or performance of the systems starts to rapidly decline and impacts increase dramatically (USACE, 2014).

2.3 Capacity for Resilience

The capacity of a shoreline for resilience is related to many factors. These include geomorphology, topography, sediment availability, habitat type, and retreat space. Assessing the existing coastal profile and constructing systems that maintain the connections between land and water ecosystems enhances resilience. Living shorelines allow for more natural shoreline migration through sediment trapping and accretion.

Recent research on salt marsh complexes along the Gulf and East Coasts indicate that they may in fact be able to keep up with sea-level rise under the right circumstances (Kirwan et al., 2016). According to Kirwan et al. (2016), their meta-analysis of marsh elevation change indicates that marshes are generally building at rates similar to or exceeding historical sea-level rise, and the process-base models predict survival under a wide range of future sea level scenarios. They argue that marsh vulnerability tends to be overstated because assessment methods often fail to consider biophysical feedback processes known to accelerate soil building with sea-level rise, and the potential for marshes to migrate landward. Whether the small marsh fringes created as part living shoreline projects can keep up vertically is uncertain but protecting the bay edge from eroding is essential to their long-term stability. Landward migration will depend on upland bank height and grading potential.

Tidal marsh response to sea-level rise has, and will continue to, vary by marsh form, geologic setting, location in the estuary, and surrounding land use decisions (Mitchell, 2018). The fate of tidal marshes can be tied to the elevation of marshes relative to the tides, marshes' frequency of inundation, the salinity of flooding waters, the biomass of marsh platforms, land subsidence, marsh substrate, and the settling of suspended sediment into the marshes.

Schuerch et al. (2018) found that the resilience of global wetlands is primarily driven by the availability of accommodation space, which is strongly influenced by the building of anthropogenic infrastructure in the coastal zone and such infrastructure is expected to change over the twenty-first century. They suggest that rather than being an inevitable consequence of global sea-level rise, large-scale loss of coastal wetlands might be avoidable if sufficient additional accommodation space can be created through careful nature-based adaptation solutions to coastal management (Schuerch et al., 2018).

Marshes are more vulnerable to sea-level rise when more of their vegetation occurs lower in the tide range. Marshes with more space and fewer barriers have greater capacity to survive sea-level rise. Poor water quality from excess nitrogen destabilizes coastal marshes by preventing root development in marsh-forming plants. Sediment-starved marshes lack the local substrate accretion needed to facilitate migration.

Table 1. List of breakwater and sill sites studied and the projected amount of sea-level rise that has occurred at the site since installation.

Site	Installation Date	Project Type	SLR since Installation (inches)	Reference Site
Jefferson Patterson Park and Museum	1999	Sill	2.90	Solomon's Island
Aquia Landing	1987	Breakwaters	4.76	Washington, DC
Yorktown	1995, First Phase	Breakwaters	5.20	Yorktown CGS
Kingsmill	1996	Breakwaters	4.75	Sewells Point
St. Mary's City	2002	Sill	4.18	Lewisetta
Haven Beach	2005	Breakwaters	3.20	Yorktown CGS
Hull Springs Farm	2008	Sill	2.86	Lewisetta
VIMS East	2010	Breakwaters	2.20	Yorktown CGS
VIMS West	2010	Breakwaters	2.20	Yorktown CGS
Occohannock on the Bay	2013	Sill	1.20	Kiptopeke
Bavon Beach	2016	Breakwaters	1.0	Yorktown CGS
Captain Sinclair's Recreational Area	2016	Sill	1.0	Yorktown CGS
Werowocomoco	2016	Sill	1.0	Yorktown CGS

Reference stations (from https://tidesandcurrents.noaa.gov)
Sewells Point, 1927-2020: 4.73 mm/yr +/- 0.22 mm/yr (0.19 in/yr)
Yorktown Coast Guard Station, 1950-2020: 4.9 mm/yr +/- 0.34 mm/yr (0.20 in/yr)
Kiptopeke, 1951-2020: 3.81 mm/yr +/- 0.3 mm/yr (0.15 in/yr)
Lewisetta, 1970-2020: 5.7 mm/yr +/- 0.59 mm/yr (0.22 in/yr)
Washington, DC, 1924-2020: 3.43 mm/yr +/- 0.28 mm/yr (0.14 in/yr)
Solomon's Island, 1937-2020: 3.93 mm/yr +/- 0.23 mm/yr (0.15 in/yr)

3 Storms

3.1 Hurricane Isabel

Short-term increased water levels (storm surge) are events that impact shore protection sites and must be taken into consideration for long-term coastal resiliency. Hurricane Isabel was the most significant storm in terms of water level since 1933. The 1933 hurricane had a 1-minute wind speed of 84 mph at Cape Henry and the tide reached 9.3 feet above MLLW and is the second highest tide of record (weather.gov, 2021). Hurricane Isabel impacted Chesapeake Bay on September 18, 2003 with record high storm surge and winds, and virtually all Chesapeake Bay shorelines were impacted. Those shorelines with open fetch exposures to the north, northeast, east, southeast, and south were especially affected due to the rotation of Isabel's winds from north to south during her passage. The wind/waves generated were significant. The fastest 1-minute wind speed was from the northeast at 54 mph with gusts to 75 mph in Norfolk. The highest tide at Sewells Point was 7.9 feet above MLLW, which was a 5 ft surge (weather.gov, 2021). An offshore buoy located just off VIMS in -25 ft of water in the York River measured wave heights of over 6 feet with 5.5 second wave periods. The entire water column was moving upriver.

The Chesapeake Bay Breakwater Database Project has 57 sites (Figure 3-1). Although more Bay breakwater systems exist, the sites in the database were chosen because they were designed with regard to their site setting, impinging wave climate, and desired level of protection, *i.e.* the 25-year, 50-- year or 100-year storm (refer to the Federal Emergency Management Agency (FEMA) Flood Insurance Study reports for each locality for those storm surge levels and frequencies). Many projects are older than 10 years, and many were impacted by Hurricane Isabel. These sites were used for research to determine design parameters. In addition, Aquia Landing, Kingsmill, Van Dyke, and Yorktown were selected for detailed analysis of Isabel's impacts since the four sites were surveyed immediately prior to the storm (Hardaway et al., 2006). This provided an opportunity to physically determine shore changes that result from a major storm event that equaled the 1933 Hurricane in storm surge level. The hurricane of 1933 is the unofficial 100-year event that FEMA had originally used for a reference datum in Chesapeake Bay.

These four sites were mapped using a real-time kinematic global positioning system before and after the storm. The data were analyzed for changes in sand levels in the beach and nearshore, as well as for any upland or backshore impacts from the storm. To better understand these changes, low-level vertical aerial photography, taken before and after the storm, were geo-rectified and the shorelines digitized. At all sites, the breakwaters performed, well allowing little overall change to beach systems. Since these sites were designed for 25- and 50-year storms, all were "overtopped" with the combination of surge and wave runup. The beach/upland interface at the two high bank sites (Kingsmill and Van Dyke) incurred varying degrees of bank scarping, but no bank failure while the two low backshore sites (Aquia Landing and Yorktown) saw sand washed over into adjacent roadways. Beach planforms adjusted bayward under storm conditions but returned to pre-storm position.

Many shorelines around the Bay without shore protection were eroded 10 to 30 feet landward due to storm surge and waves. Shore reaches with properly designed and constructed headland breakwater systems incurred varying degrees of damage from none to several feet of cut at the adjacent base of the upland banks. Additional research concurs with these results. After Hurricane Florence (2018), living shorelines, on average, experienced significantly less erosion compared to unprotected control segments (Polk et al., 2021).

3.2 Post-Isabel

Although Isabel was arguably the worst storm to hit southeast Virginia since 1933, numerous lesser but still significant storms have occurred since. Some notables include:

Sept. 1, 2006: Hurricane Ernesto; +6.5 MLLW storm surge with mostly easterly winds sustained at 40 knots, gusting to 60 knots. 6 to 8 ft waves. The storm mostly impacted the Eastern Shore and the Middle Peninsula and Northern Neck.

November 11-14, 2009: NorIda; Northeast storm that merged with Hurricane Ida setting in for several days with peak surge of +7 ft MLLW on the 12th and 6 consecutive +5ft high water events.

August 27, 2011: Hurricane Irene; Storm surge +6.2 MLLW with northeast to northwest winds 40 knots gusting to 55 knots.

Super Storm Sandy on October 29, 2012 had only minor effects on most of Virginia. Tangier Island was affected with erosion and flooding, but overall, flooding was the main impact of the storm on Coastal Virginia.

March 2013 Powerful northeaster from March 1 and dissipated March 21, 2013. Impacted coastal Virginia March 6, 2013.

Recent Hurricanes including Mathew in 2016 and Dorian in 2019 have come close to the Virginia coast but with minor storm surges and relatively low winds.

October 30-31, 2017 North American storm complex. Tropical storm-force wind gusts affected much of the Mid-Atlantic, and rainfall totals of 3–5 inches (7.6–12.7 cm) were recorded in interior areas. Wind gusts of 40–60 mph (64–97 km/h) were reported along the coast. Remnant of tropical storm Phillippe.

March 1-3, 2018 northeaster, challenged storm surge records set by other significant storms, such as Hurricane Sandy. It was unofficially named Winter Storm Riley. Although the most severe damage was caused by flooding as well as snow, unusually high tides and storm surges along the coast, wind and downed trees caused massive inland power outage. Wind gusts of 71 miles per hour were reported at Washington Dulles International Airport and 62 miles per hour at Ronald Reagan Washington National Airport. Another similar storm took place just a few days later, March 6-8, 2018. This storm produced high water levels (high tides between 1.5 ft-2.2 ft above MHW) at Yorktown for the entire duration of the storm.

3.3 Summary

NOAA's Mid-Atlantic Regional Integrated Sciences and Assessments (MARISA) is helping Mid-Atlantic communities become more resilient to a changing climate. Their climate studies have produced interesting results regarding the increase in storm events in recent decades. Though the Mid-Atlantic and Northeast regions have historically experienced a lower frequency of tropical storms and hurricanes compared to other regions of the United States, these regions received 6% of such storms annually over the continental U.S. between 1990 to 2017. In the Mid-Atlantic region, the 2004 Hurricane Season brought the most tropical cyclones. Between 2000 and 2020, the Mid-Atlantic saw nearly twice as many hurricanes as the preceding two decades, 1980–2000 (Marisa, 2021).

In general, this correlates to the increases in summer seasonal precipitation the region experienced from 2006-2017 compared to historical averages (1976-2005). The higher percentage of increases in summer precipitation occurred in the eastern half of the Chesapeake Bay Watershed. Also, much of the eastern portion of the watershed has seen double the number of days with extreme precipitation over 3 inches between 2006-2017 when compared to historical averages (Marisa, 2021). Southeastern Chesapeake Bay has seen notable decreases in winter and spring total precipitation.

Since the 1980s, North Atlantic hurricanes, which includes the Atlantic north of the equator, the Gulf of Mexico, and the Caribbean, have increased in intensity, frequency, and duration. The strongest hurricanes, categories 4 and 5, have also increased in frequency. This increase in wind speed of storms has consequences for the shorelines they impact. Modeling of storm winds showed that a 10% potential increase in wind speed can lead to a 20% increase in the significant wave heights generated by these winds (Takagi et al., 2011)

Figure 3-1. Location of breakwater sites that are part of the Shoreline Studies Program's Breakwater Database.

4 Rock Shore Protection Structure Parameters

Living shorelines take many forms in Chesapeake Bay. The focus of this study was to research how resilient rock/sand/plant living shoreline protection systems are. These systems have been used in Chesapeake Bay for 40 years to reduce erosion, protect infrastructure, and create habitat that is disappearing from the shoreline as sea level rises. The goal has been to determine how they have been affected by sea-level rise and how they can be more resilient.

Breakwaters and sills are "free-standing" structures designed to reduce wave action by attenuation, refraction, and diffraction before it reaches the upland region. A sill (Figure 4-1) has a lower crest, is closer to shore, and usually, is more continuous than larger breakwater units. They are installed with sand fill to create a substrate for establishing a marsh fringe. They are typically suitable for lower fetch areas.

Attached or headland breakwaters require beach fill in order to acquire long-term shoreline erosion control (Figure 4-1) since they typically are constructed in areas that are subject to more energetic conditions. Headland breakwaters can be used to accentuate existing shore features. The dimensions of a breakwater system are dependent on the desired degree of protection and potential impacts on littoral processes. Because sills are used in lower energy areas and breakwaters are used in higher fetch areas, sometimes a combination structure is needed. Brills are free-standing rock structures that are larger than sills but are smaller than breakwaters (Figure 4-1). Depending on where they are located, they could have a beach backshore or a marsh fringe. They tend to be shorter than sills and have larger gaps. They typically are not as high as breakwaters or have as wide a backshore.

Understanding the relationships between design parameter for these structures is important when adapting structures for coastal resiliency. If rocks are added to structures, the length-to-gap ratio could change which can impact effectiveness of the system. In addition, as sea-level rises, more water will be in the system, possibly changing the bay indentation-to-gap ratio. The relationship between headland breakwater system parameters was investigated by Hardaway *et al.* (1991) and Hardaway and Gunn (1991) for breakwater embayments around Chesapeake Bay (Figure 3-1). These parameters include breakwater crest length, (Lb), gap between breakwaters (Gb), backshore beach width (Bm) and embayment indentation (Mb), as shown in Figure 4-2. The mid-bay backshore beach width and backshore elevation are important design parameters because they determine the size of the minimum protective beach zone in the headland breakwater system. This beach dimension often drives the bayward encroachment that is required for a particular shore protection design. Stable relationships for Mb and Gb are not valid for transitional bay/breakwater segments that interface the main headland breakwater system with adjacent shores. Numerous variations can occur depending on design goals and impinging wave climate.

Hardaway and Gunn (2000) found that for 14 breakwater sites around the Bay, the Mb vs. Gb ratio varies in range and average for bimodal and unidirectional wind/wave settings. Further research refined these design parameters and developed relationships for Lb:Gb and Mb:Gb for both unidirectional sites and bimodal wave climates (Hardaway & Gunn, 2011) (Table 4-1). Sites with unidirectional wave climates generally are impacted from one direction.

Sites with a bimodal wave climate are impacted by waves that can come from more than one direction, particularly during storms.

The design parameters shown in Table 4-1 were calculated in Hardaway & Gunn (2011) or were determined for the breakwater sites used in this study. Haven Beach essentially only has one breakwater, so these parameters cannot be determined. A 1:1 relationship means that breakwater length is the same as the gap or that the bay indentation is the same length as the gap. A relationship of 1:2.0 means that gap is double the breakwater length or that the gap is double the bay indentation. Generally, sites with a unidirectional wave climate can have larger gaps than sites with a bimodal wave climate. This is because sand in the embayment generally does not move from side to side as the wave climate shifts. For the Chesapeake Bay estuarine system, the overall average Mb:Gb is 1:1:65 and the overall Lb:Gb is 1:1.4.

Figure 4-1. Top shows a sill with planted marsh at Captain Sinclair's Recreational Area, Gloucester, VA; Middle shows a brill at Westmoreland State Park; and Bottom shows headland breakwaters and beach fill at Yorktown, VA. Photo credit: Shoreline Studies Program, VIMS.

Determining the resiliency of a shore protection system requires an understanding of where they should be situated (Figure 4-3). Fetch can be used as a proxy for the hydrodynamic forces impacting a site. Generally, the higher the wave energy, the higher and wider the structure. Sills can be used along low and medium energy shorelines. Brills can be located along medium and high energy shorelines. The backshore can be either a marsh or a beach depending where the project sits. Breakwaters are versatile and can be sized for medium, high, and very high energy sites. The parameters outlined in Figure 4-3 are guidelines only and all sites need to be designed by experienced coastal professionals.

Table 4-1. Breakwater design ratios for bay indentation to gap and breakwater length to gap calculated for this project and published in Hardaway and Gunn (2011).

Site	Mb:Gb	Lb:Gb	Wave Climate	Range	Average
Aquia Landing	1:2.5	1:1.5	**Mb:Gb**		
Bavon Beach	1.2	1.2	Unidirectional site	1:1.6 to 1:2.5	1:1.9
Kingsmill	1:1.2	1:1.2	Bimodal	1:1.0 to 1:1.7	1:1.4
VIMS East	1:1.2	1:1	**Lb:Gb**		
VIMS West	1:1	1:1	Unidirectional site	1:1.5 to 1:2.0	1:1.8
Yorktown	1:1.9	1:1.8	Bimodal	1:1.0 to 1:1.5	1:1.2

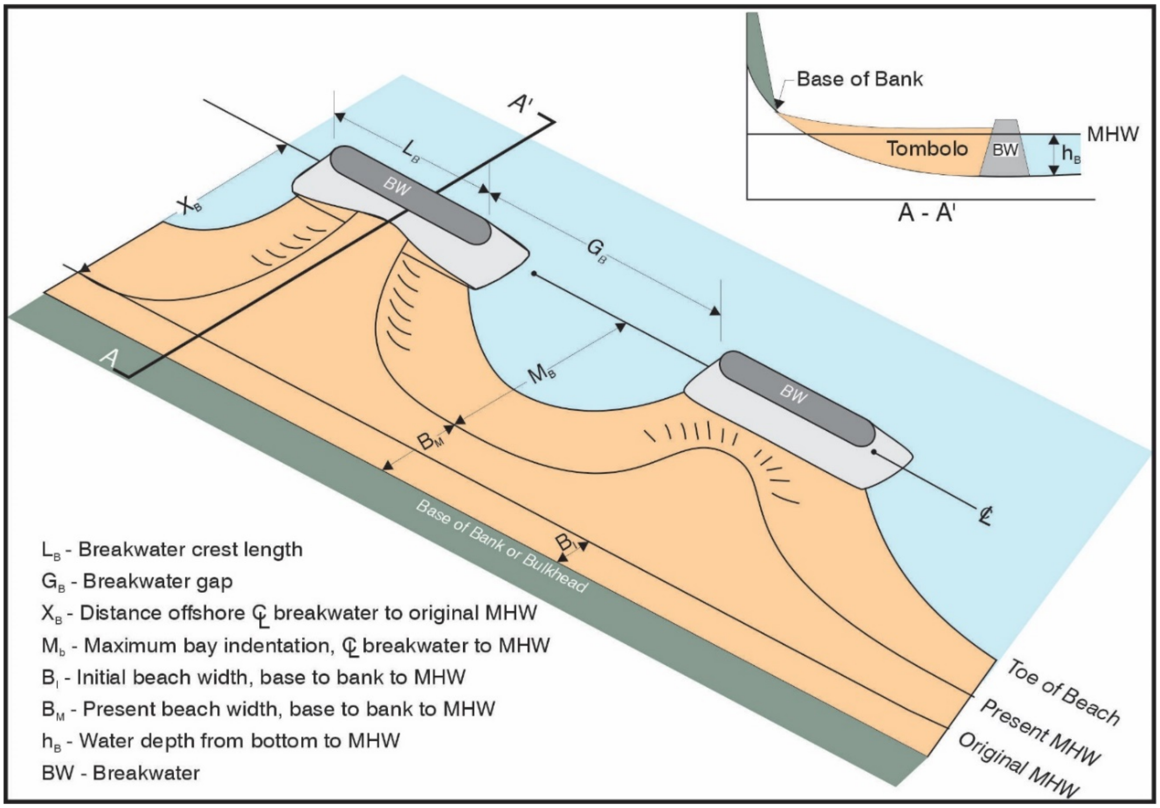


Figure 4-2. Definition of parameters that can be determined at breakwater sites and that can be used in the design process. From Hardaway and Byrne (1999).

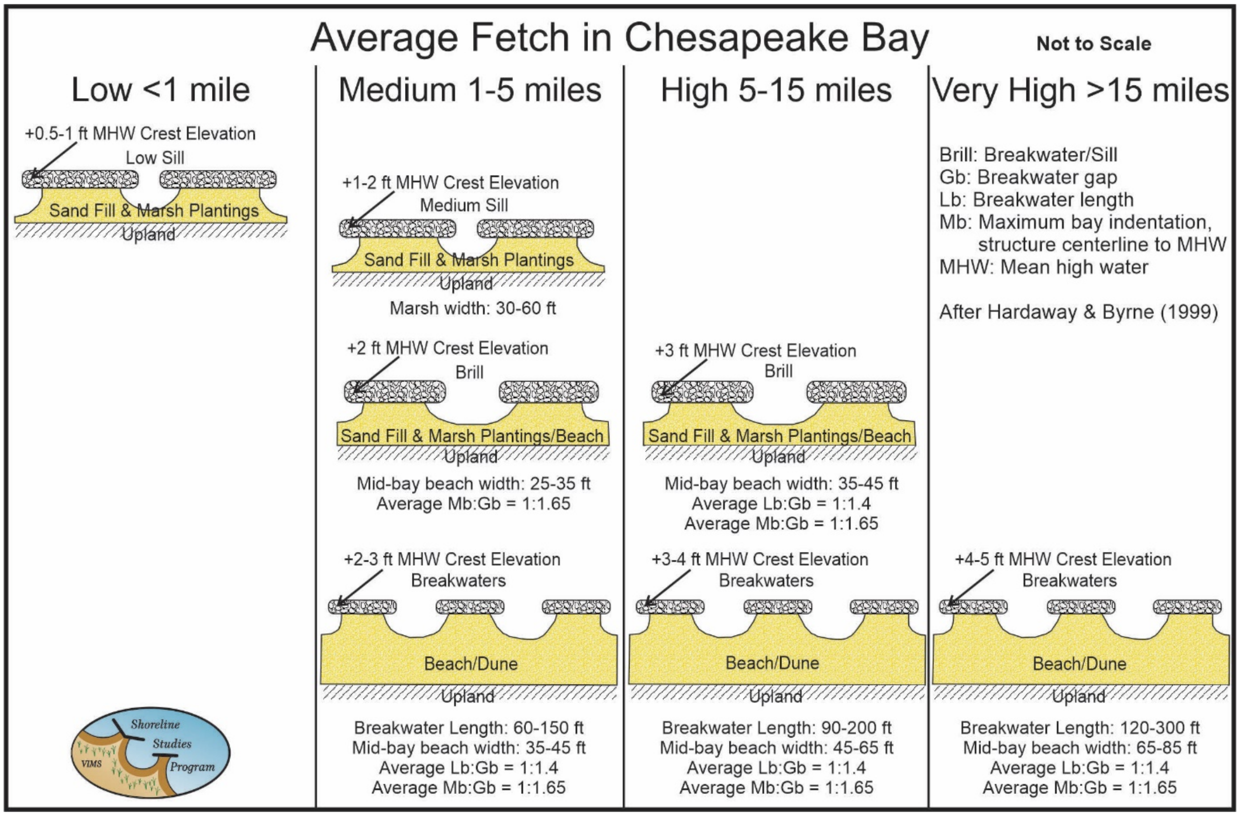


Figure 4-3. Conceptual shore protection strategies for hybrid living shoreline systems with rock, sand, and plants. Average fetch is used to determine site suitability. The parameters outlined shown are guidelines only, and all sites need to be designed by experienced coastal professionals. After Hardaway and Byrne (1999).

5 Methods

In this third year, the research project examined low, medium, high, and very high energy shorelines (fetch <1 mile, 1-5 miles, 5-15 miles, and >15 miles, respectively) where sills and breakwater systems have been built to create marshes and beach habitat. By selecting sites that were recently installed as well as those that have been in place longer, both the short and longer-term shore protection effectiveness and changes in habitats were determined. A detailed site-specific assessment and survey determined the condition of the upland bank and backshore barriers, which affect storm run-up and migration of the marsh and the width and elevations of the marsh which will provide wave attenuation.

The site assessment includes type and condition of habitats, including the marsh, upland bank, riparian buffer, and in the nearshore. Where applicable, changes in submerged aquatic vegetation (SAV) was determined from existing data available from the VIMS, SAV research group. SAV is important habitat for many shallow water species.

Using Real-Time Kinematic GPS and Robotic Total Station technology, four sites were surveyed for elevation and areal extent of habitat where possible (Table 5-1). These sites were chosen for several reasons including site conditions, duration of the site, and existing data available. The sites (with installation dates) include: 1.) VIMS West shoreline (2010) 2.) Haven Beach (2005) 3.) Werowocomoco (2016) and 4.) Hull Springs Farm (2008). By selecting private and public properties, both high and low bank systems, the impact of sea-level rise can be assessed using the climate change adaptation sea-level rise scenarios. The site surveys were analyzed in Trimble Business Center and GIS, and a 2 ft sea-level rise scenario was assessed to show how much change could occur by 2050. The elevations of existing habitats and the shore planforms were assessed to determine the potential impacts as sea level rises

Static GPS data was collected for benchmarks at each site. Static data was processed by the National Geodetic Survey’s Online Positioning User System (OPUS). Horizontal datum for the survey data is universal transverse Mercator (UTM), zone 18 north, international feet. The vertical datum was collected at North American Vertical Datum 88 (NAVD88) and converted to a local tidal datum, mean low water (MLW), using data derived from NOAA’s VDATUM software. Because many of these sites have been looked at before by Shoreline Studies Program personnel, ground photography taken over time also was used to show changes at the sites.

Table 5-1. Survey dates for the selected breakwater and sill sites.

Site	Survey Date	Site	Survey Date
Vims West	9 Feb 2010	Haven Beach	2002
	30 Jun 2020		14&28 Oct 2020
Werowocomoco	31 Mar 2015	Hull Springs Farm	19 Nov 2020
	7 Jun 2016		
	25 Oct 2020		

6 Virginia Institute of Marine Science-West, Gloucester County

6.1 Site Background

The Virginia Institute of Marine Science (VIMS) is located at Gloucester Point, Virginia (Figure 6-1). VIMS was established in 1940 as the Virginia Fisheries Laboratory. The west coast of Gloucester Point has been an accretionary spit feature for many years. Like the VIMS East shoreline, the sand beach/dune system was a product of sedimentary processes along the York River (Hardaway et al., 2019). The high eroding upland banks upriver of Gloucester Point had, for many years, provided sand to the littoral system that helped build the point feature and occurred in the nearshore (Figure 6-2). As these banks were developed and subsequently hardened with bulkhead, revetments and later small breakwaters; the sand source and sediment transport pathways were greatly reduced.

The transformation of Gloucester Point began in 1960 when the boat basin and entrance channel were dredged out from the existing tidal marsh and two small jetties were installed to secure the channel inlet (Figure 6-3). A long wood groin was installed on the shoreline sometime before 1978 along with a small groin just upriver of the boat basin entrance channel. The effect of these can be seen in 1978 aerial imagery (Figure 6-4). Sometime between 1978 and 1994, sand had accreted against the long wood groin, and sand was bypassing around the groin. Three short gabion basket breakwaters also were put in the embayed coast between the long groin and the channel entrance, the downriver reach. However, because sand was bypassing the wood groin, these small structures were completely covered in sand.

Since 1937, the upriver shoreline has been eroding while the downriver shoreline accreted. By 2002, the effects of upriver, updrift shoreline hardening and breakwaters resulted in a reduced beach near the upriver boundary of VIMS, but shore advance on the downriver reach (Figure 6-5). The VIMS west shoreline is impacted by a high energy regime. The shoreline faces west, and the fetch from the northwesterly direction is about 25 miles. During post-northeast storms, wind waves travel the length of the York River to impact this site. Tide range is 2.3 ft.

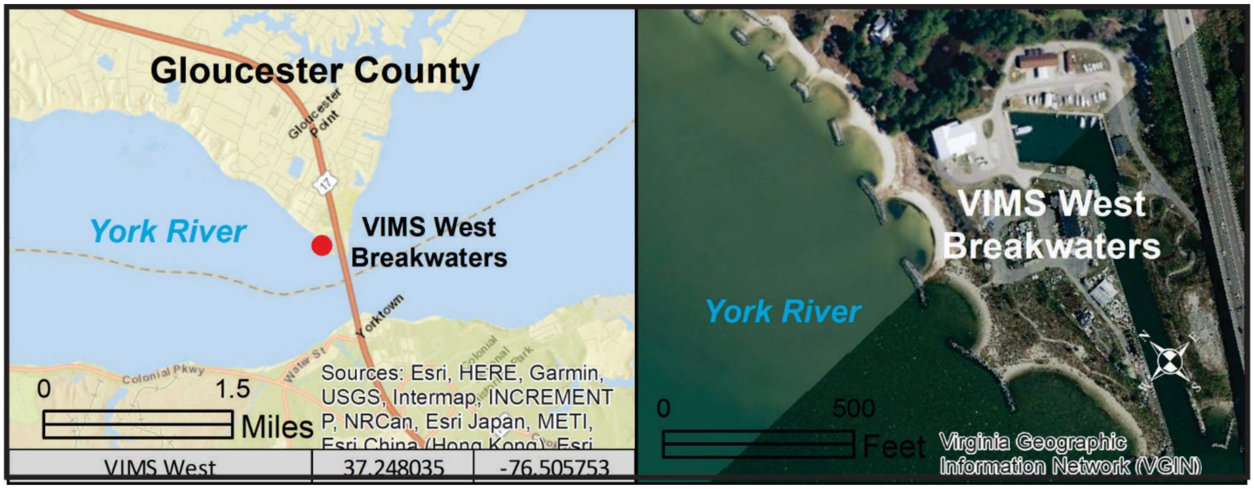


Figure 6-1. Location of VIMS West living shoreline breakwater shore protection system.

A conceptual Shoreline Management Plan for the VIMS shoreline was developed in 2002 and modified in 2008; it consisted of three subaerially attached breakwaters and a channel jetty spur for the west coast (Figure 6-6 and 6-7). Significant damage occurred to the VIMS shoreline in September 2003 with the passage of Hurricane Isabel. The ferry pier and wave gauge were destroyed and flooding of the boat basin occurred. Subsequent storms, including Hurricane Ernesto, caused additional damage leading VIMS to implement the Shoreline Management Plan. Under a design/build contract, the structures were constructed in 2010.

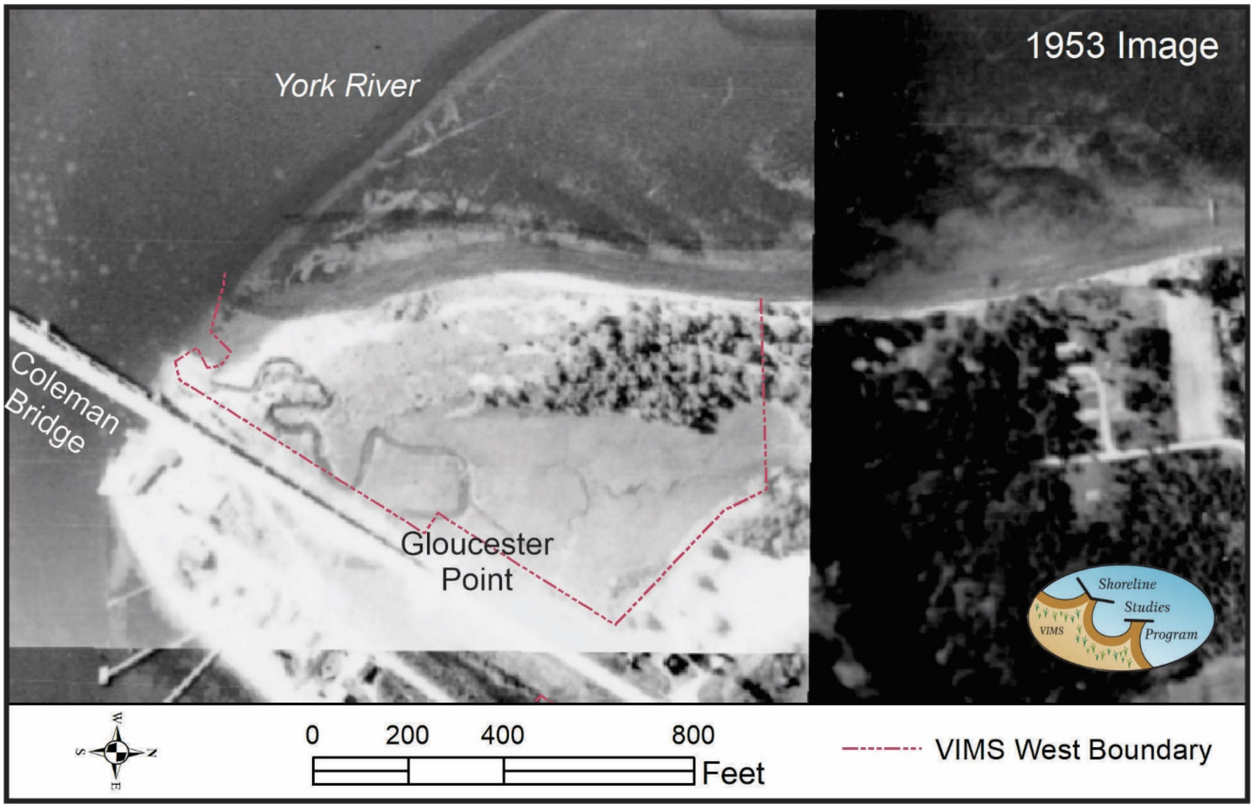


Figure 6-2. VIMS West shoreline in 1953 showing the present-day boundary of the VIMS West campus. In subsequent years, the tidal marsh was dredged to become the marine institute's boat basin (from Shoreline Studies Program shore change database).

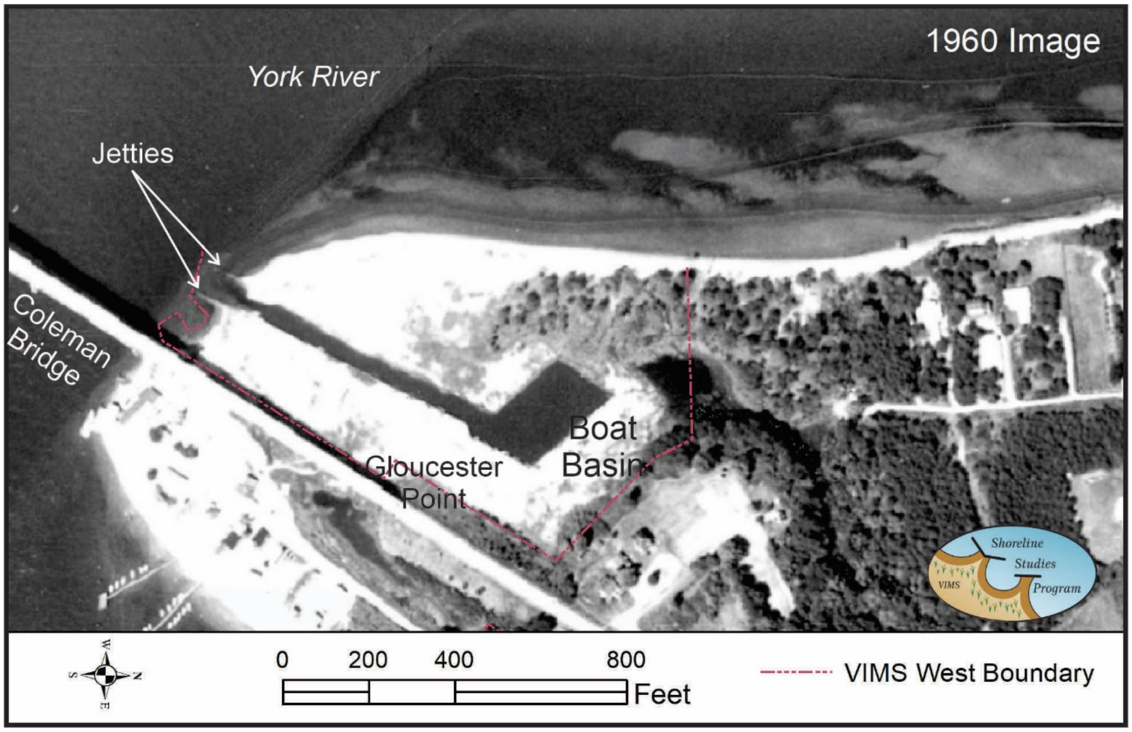


Figure 6-3. VIMS West shoreline in 1960 showing the present-day boundary of the VIMS West campus and the construction of the marine institute's boat basin (from Shoreline Studies Program shore change database).

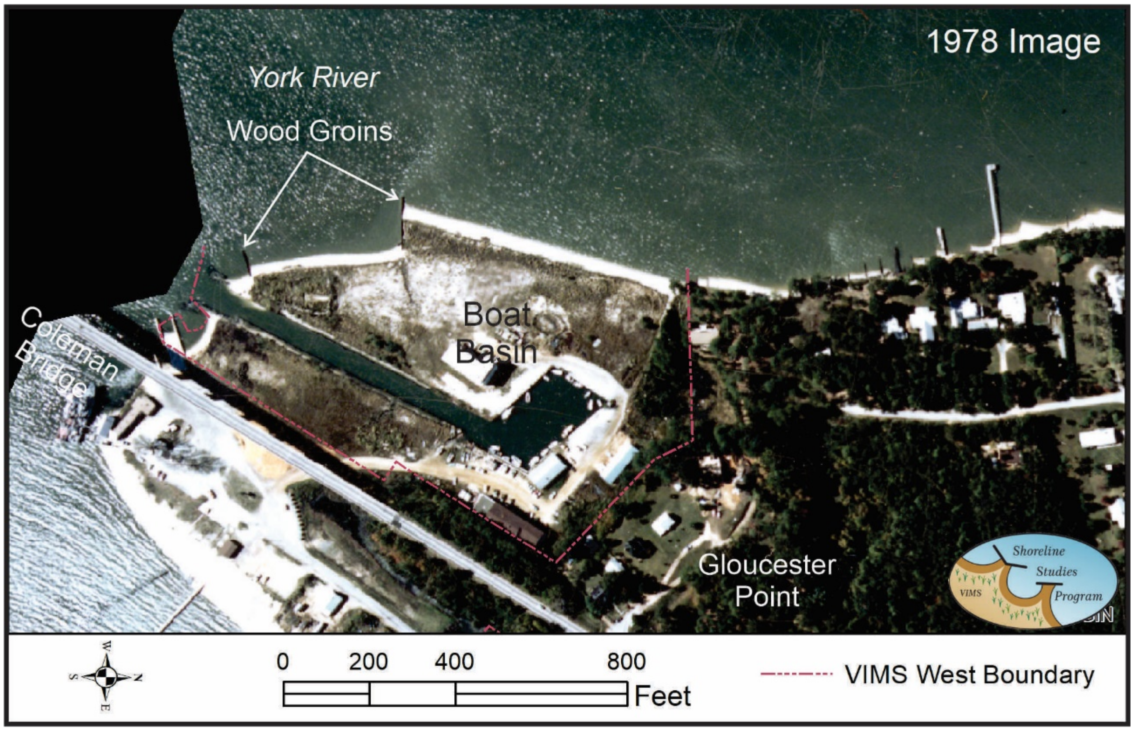


Figure 6-4. VIMS West shoreline in 1978 showing the present-day boundary of the VIMS West campus and the impact of two wood groins constructed along the shoreline (from Shoreline Studies Program shore change database).

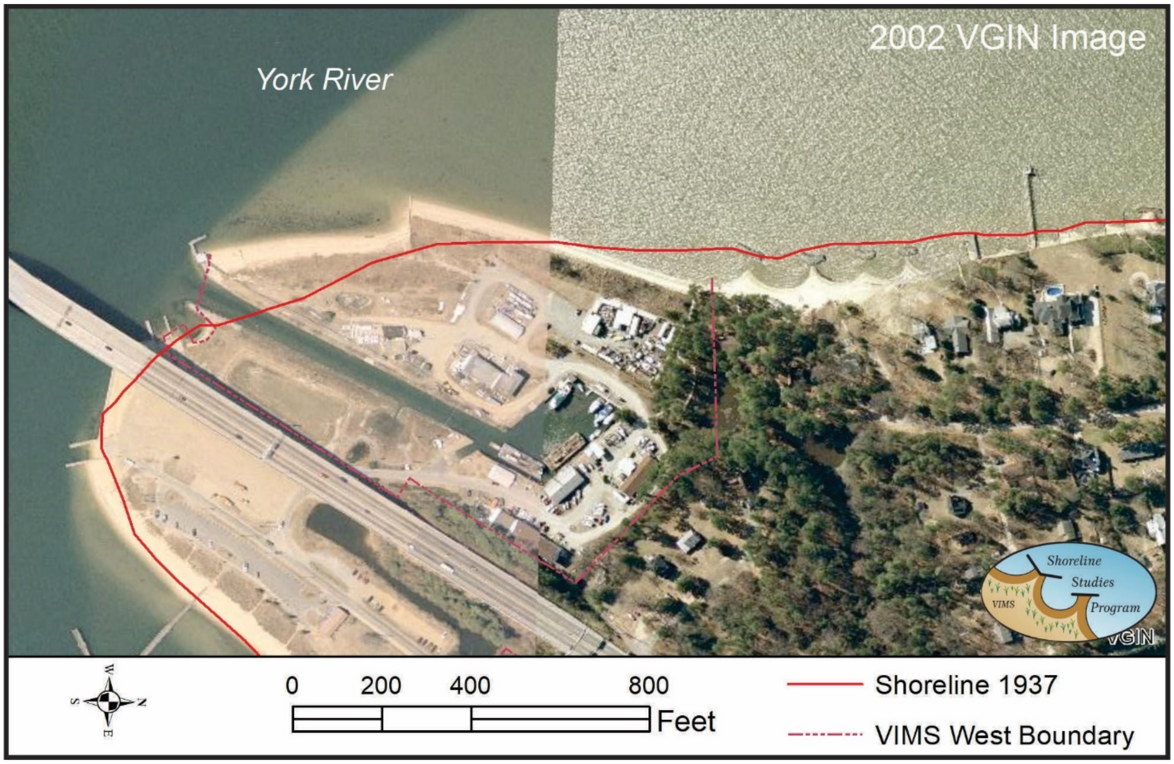


Figure 6-5. VIMS West shoreline in 2002 showing the present-day boundary of the VIMS West campus and the 1937 digitized shoreline (from Shoreline Studies Program shore change database). Over the years, many buildings were constructed around the VIMS boat basin and were impacted by storms.

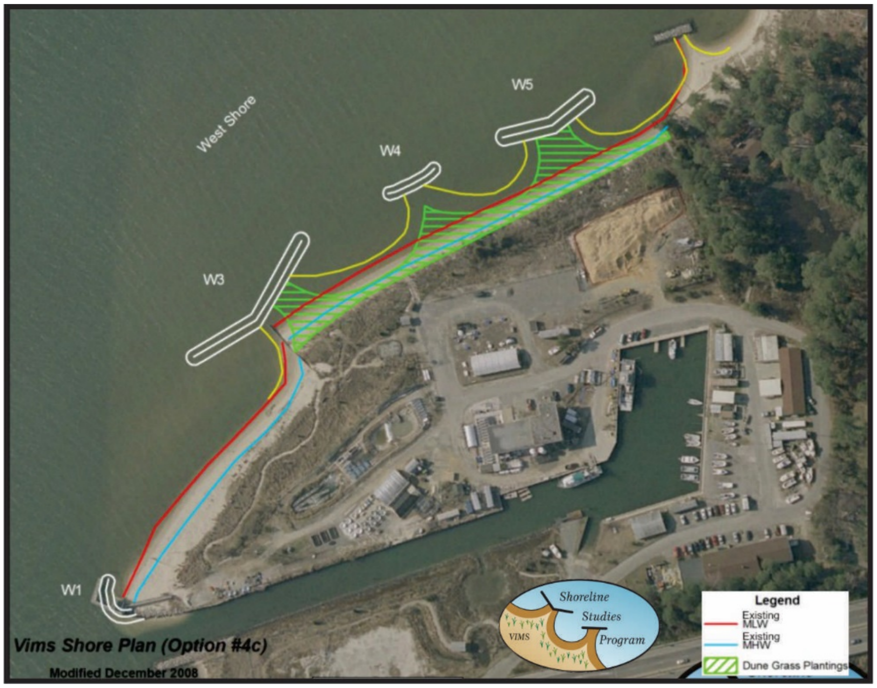


Figure 6-6. Shoreline Management Plan created by Shoreline Studies Program for the VIMS West shoreline in 2002 and modified in 2008.

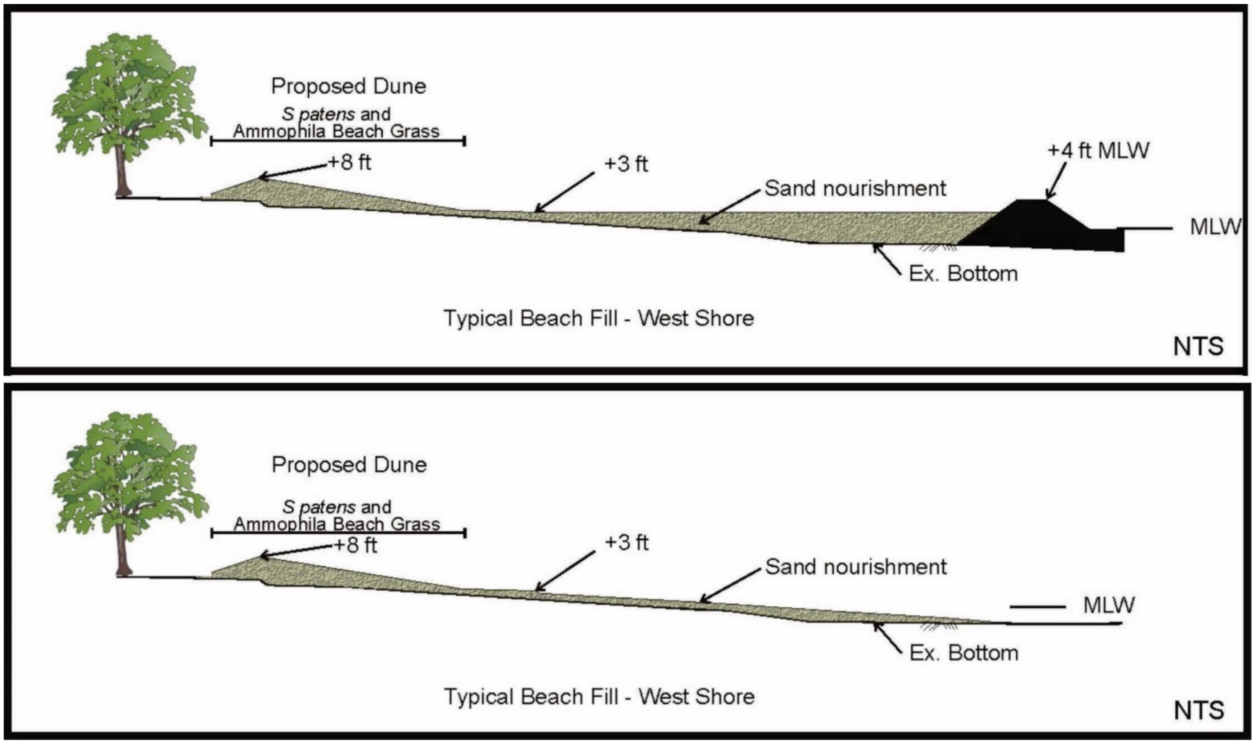


Figure 6-7. Typical cross-sections of the VIMS West Shoreline Management Plan developed by Shoreline Studies Program.

6.2 Site Performance

Prior to construction, the VIMS West shoreline was sandy with a low marsh upland (Figure 6-8). Though the shoreline near the point was stable, the upriver section was eroding. After several large storms impacted the VIMS shoreline, funding was received to construct living shorelines on both sides of the VIMS campus. The VIMS West breakwaters and beach fill were placed in September 2010 (Figure 6-9 and 6-10). Beach grasses were planted the following spring (Figure 6-11).

Storms impacted VIMS West after the project was installed, particularly in 2012 (Hurricane Sandy) and in 2013 (March Extratropical Cyclone). As shown in Figure 6-12, water levels completely overtopped the structures at VIMS West. As a result, the subaerial attachment at breakwaters 2 and 3 became narrow. However, maintenance planting and natural marsh vegetation colonized the attachment (Figure 6-13). Over the next six years, natural low marsh vegetation increased behind breakwaters 2 and 3, increasing the width of the attachment (Figure 6-14). In addition, the gabion breakwaters that were uncovered are functioning as semi-detached breakwaters. The channel jetty spur supports that embayment, Bay A.

Net change in shoreline position is dramatic pre-post project (Figure 6-15). In some areas, the position of MLW is shifted over 100 ft riverward. The center of the embayments had the least change between pre and post construction. All profiles showed a large volume of sand placed except Profile 5 (Figure 6-16). Since construction, generally, the upriver section of shoreline is accreting (north of BW3), embayments B and C are stable, but embayment A is still equilibrating to its equilibrium position (Figure 6-17). The gabion breakwaters have become uncovered and are influencing the shoreline in embayment A as well.

The vegetation is an important component of the shore protections system by providing substrate stability. Both the high and low marsh at the site are very lush (Figure 6-18). The beaches in the embayments are relatively steep, and some shrubs have colonized in the backshore where beach grasses were planted. However, generally, the beach grasses are sparser than the high and low marsh grasses (Figure 6-19).

SAV occurs in the embayments. Prior to the installation of the breakwaters, historical SAV records show that the underwater grasses come and go at the site. Yearly records indicate a lack of SAV at the site between 1971 and 1990. After that, patches occurred at the site until 2002 when the nearshore was covered with SAV along the entire site. However, that coverage declined until no SAV existed in 2007. With the construction of the breakwaters in 2010, the opportunity existed for SAV to colonize the shallow embayments between the structures, and presently, a large amount of SAV occurs at the site (Figure 6-14).

Figure 6-8. The VIMS West coast was a low eroding shoreline with wood groins for shore protection prior to installation of the breakwaters. Photo credit: Shoreline Studies Program, VIMS

Figure 6-9. VIMS West shoreline during construction of the living shoreline in 2010. Photo credit: Shoreline Studies Program, VIMS.

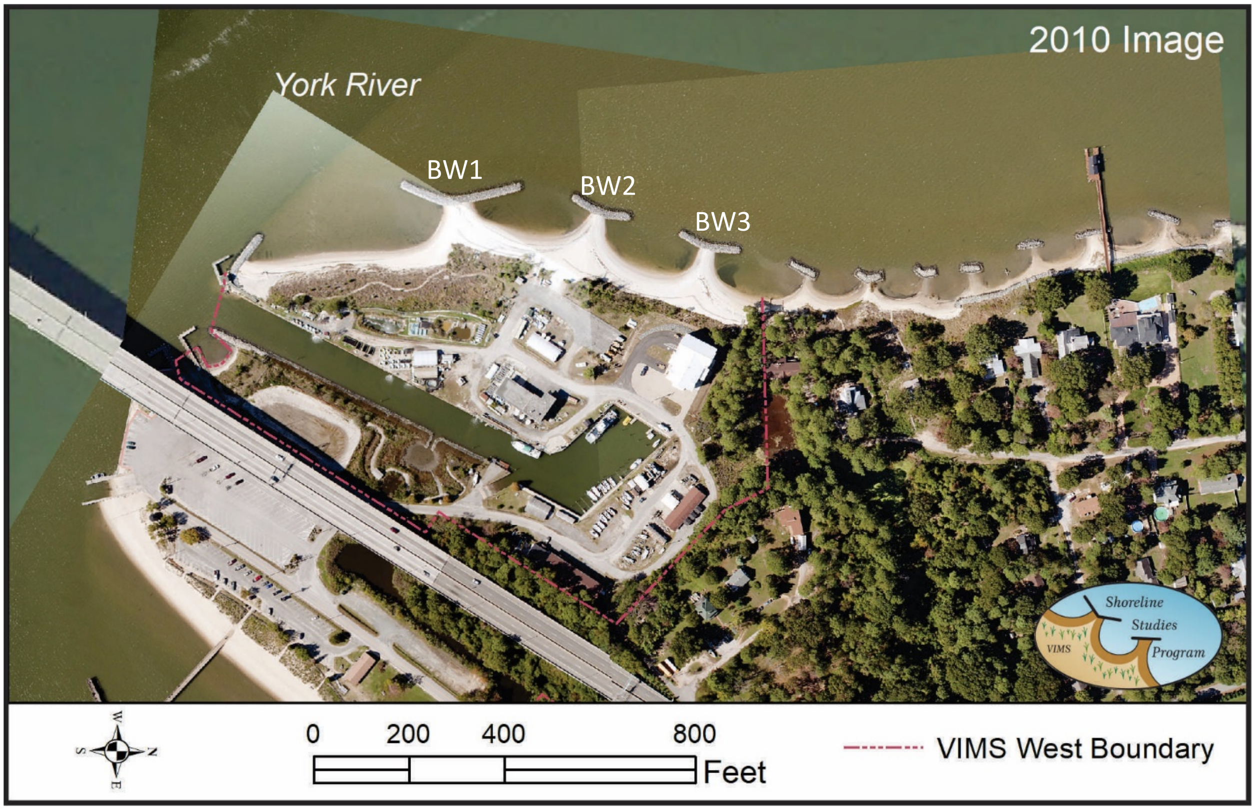


Figure 6-10. VIMS West aerial photo taken October 17, 2010 showing the newly constructed breakwaters and beach fill.

Figure 6-11. Planting of beach grasses took place the spring after construction. Photo credit: Shoreline Studies Program, VIMS

Figure 6-12. Photos taken at VIMS West during the passage of the March 2013 Northeast storm. Water levels are high enough to overtop the structures, but by the next day, tide levels had dropped. Photo credit: Shoreline Studies Program, VIMS

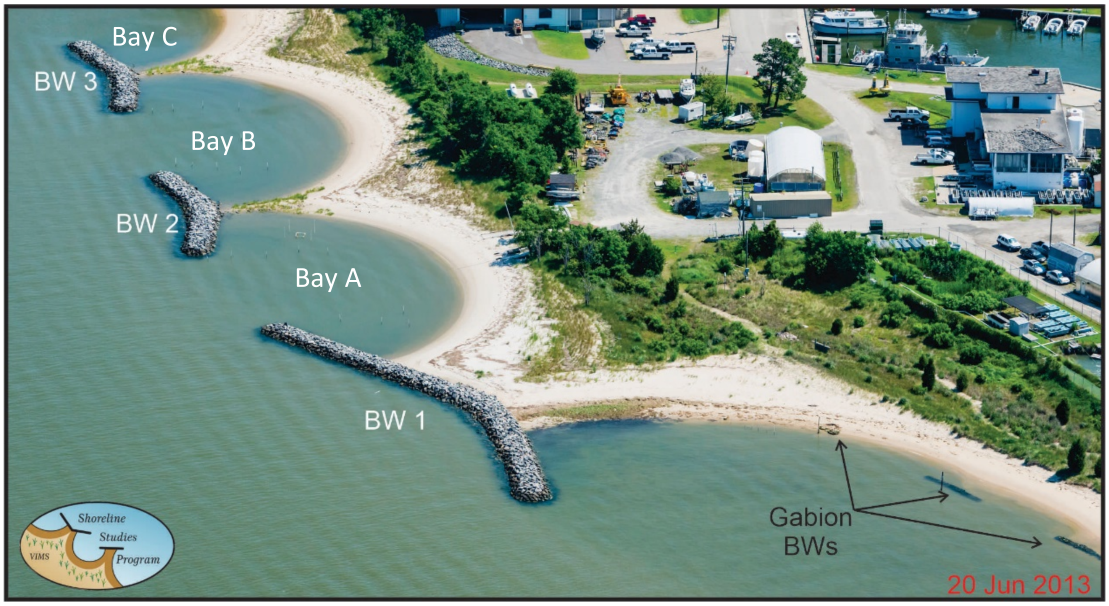


Figure 6-13. Aerial photo taken in June 2013 showing VIMS West 2.5 years after construction.

Figure 6-14. Aerial photo taken in September 2019 showing VIMS West nearly 9 years after construction.

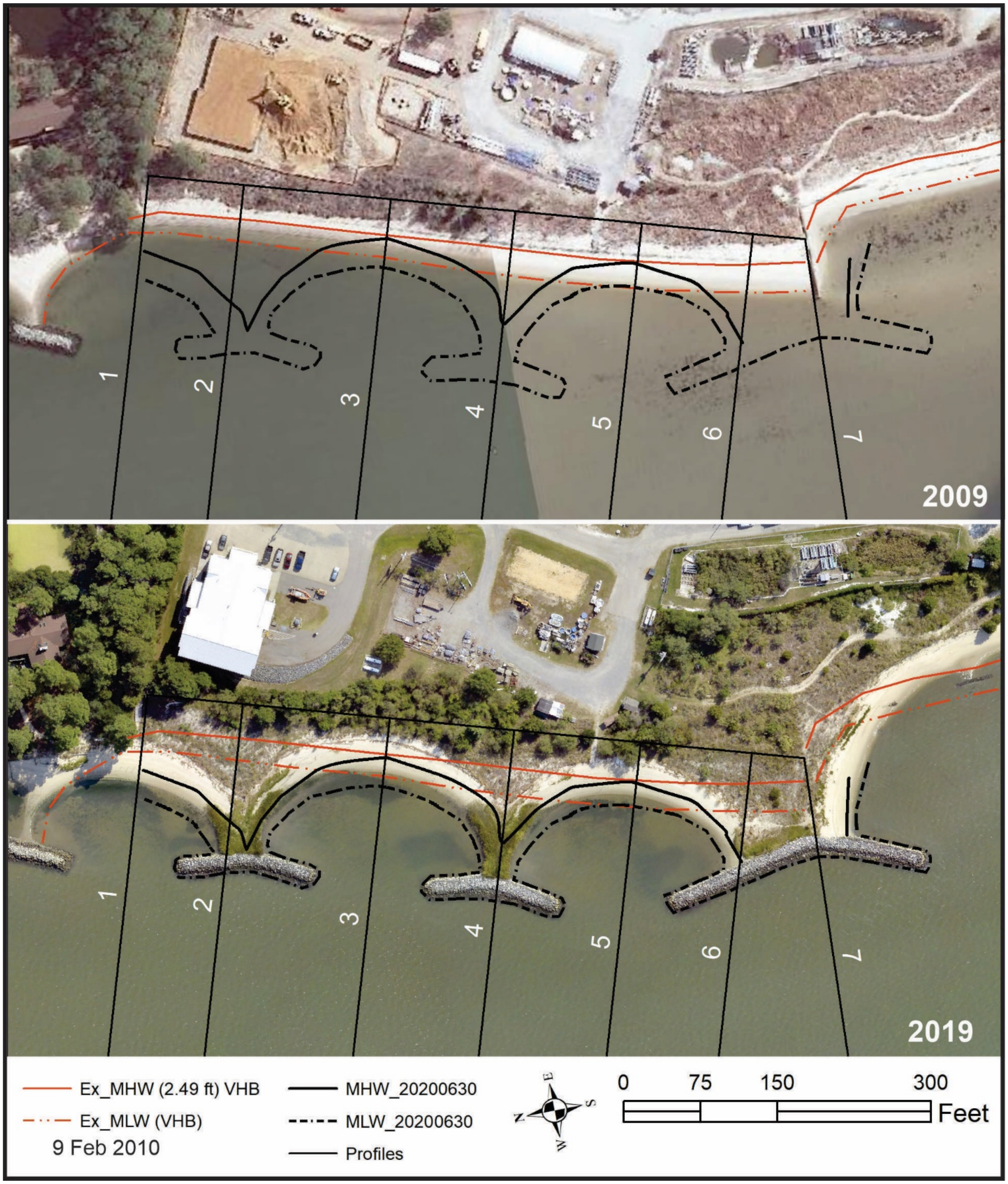


Figure 6-15. Survey data analysis at VIMS West showing the position of MHW and MLW before construction in February 2010 (VHB survey) and in June 2020, about 9.5 years after construction. Top photo base is 2009 VGIN image, bottom image is SSP's September 2019 image.

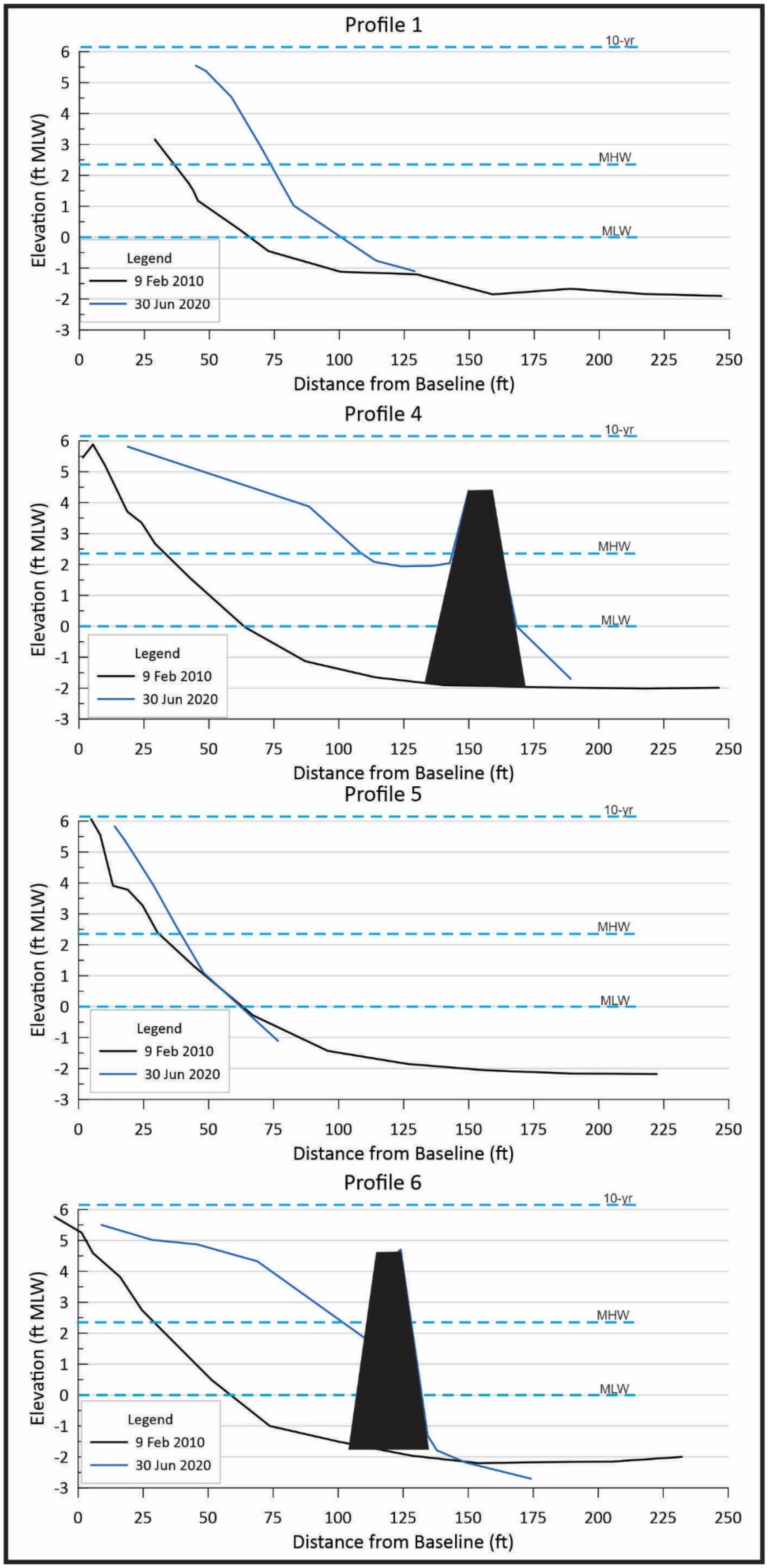


Figure 6-16. Profile data taken in February 2010 (pre-construction, VHB survey) and in June 2020 by SSP.

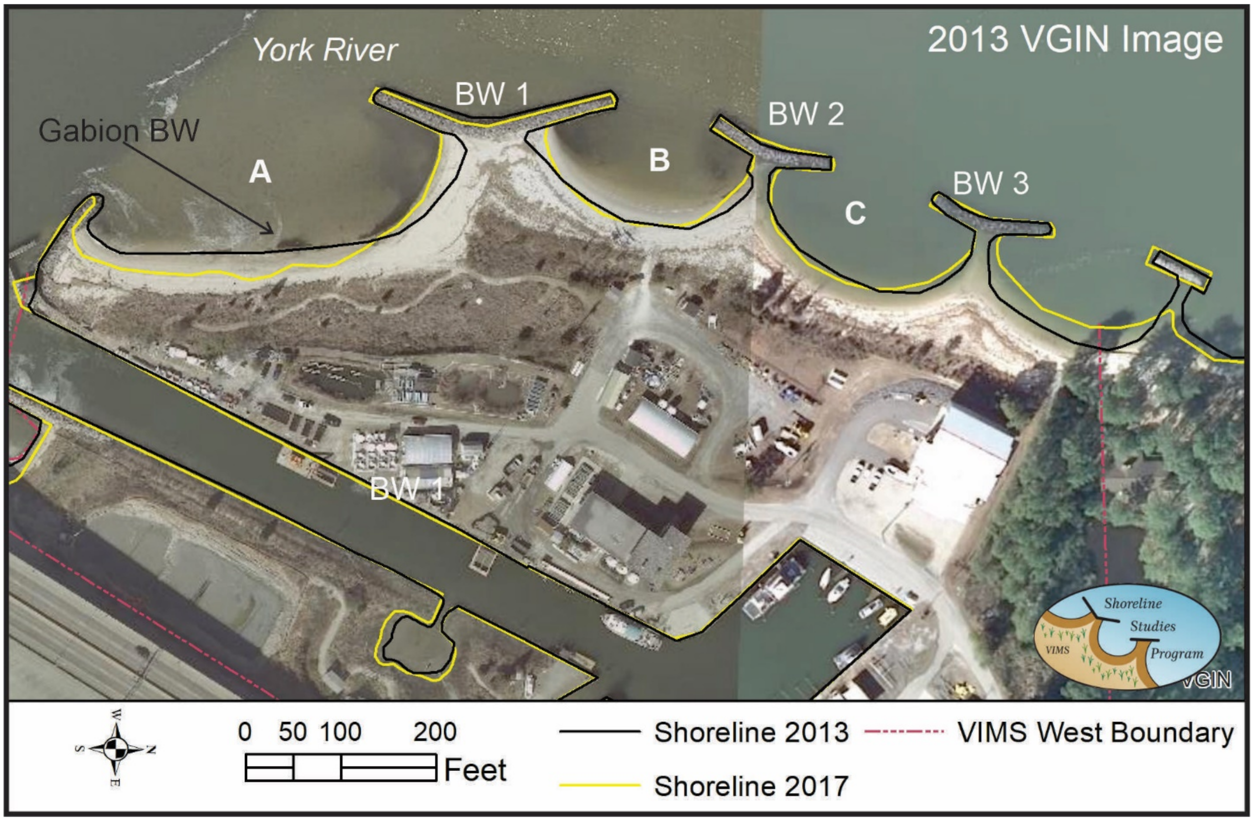


Figure 6-17. A 2013 VGIN photo showing the 2013 and 2017 digitized shorelines.

Figure 6-18. State of VIMS West in June 2020 about 9.5 years after construction. The structures are stable and the high and low marsh grasses are lush. SAV has colonized in the embayments. Photo credit: Shoreline Studies Program, VIMS.

Figure 6-19. Backshore vegetation is sparser at VIMS West although some shrubs have colonized the area after 9.5 years. Photo credit: Shoreline Studies Program, VIMS.

7 Werowocomoco National Park, Gloucester County

7.1 Site Background

Werowocomoco is located on the York River in Gloucester County, Virginia (Figure 7-1). Historical documents identified Werowocomoco as the headquarters of Powhatan, the Algonquian political and spiritual leader when the English founded Jamestown in 1607. For many years, the exact location of the site was unknown; however, in 2003, archeological digs at the site on the York River between Leigh and Bland Creeks confirmed the location. The site has been occupied by Native Americans since 8,000 before the common era (BCE) and is one of the most important Native American sites in the nation.

In 2016, the 264-acre Werowocomoco site came under the protection of the National Park Service. Presently, the site is part of the Captain John Smith Chesapeake National Historic Trail. The property has almost two miles of open water tidal shoreline (Figure 7-2) along Leigh Creek, the York River, and Bland Creek (Milligan et al., 2016). Shoreline erosion, historically, is greater along the more open reaches of the York River, but the marshes on either end of the site are also eroding quickly. The calculated rates of change between 1937 and 2017 indicate that the middle section of the property along the York River had very low rates of change (<-1 ft/yr) while the ends are eroding at low (-1 to -2 ft/yr) and medium (-2 to -5 ft/yr) rates of change (Figure 7-3). The shoreline has fetches of 2.4 miles to the west, 3.5 miles to the west-northwest, and 2.8 miles to the southwest which results in a medium energy wave climate (Milligan et al., 2016). Tide range is 2.8 ft. The estimated water level associated with a 10-year storm return frequency is 6.8 ft MLW (FEMA, 2014).

Werowocomoco sits within the natural embayment of Purtan Bay. The upland in the vicinity of the shoreline is relatively high and ranges from 12-27 feet MLW (Milligan et al., 2016). The marshes on either side of the upland at the entrances to the creeks are much lower, between 2 to 7 feet MLW. The nearshore is very shallow with the six-foot MLW contour about 3,500 feet offshore, and extensive tidal flats exist along the shoreline and into the creeks (Milligan et al., 2016).

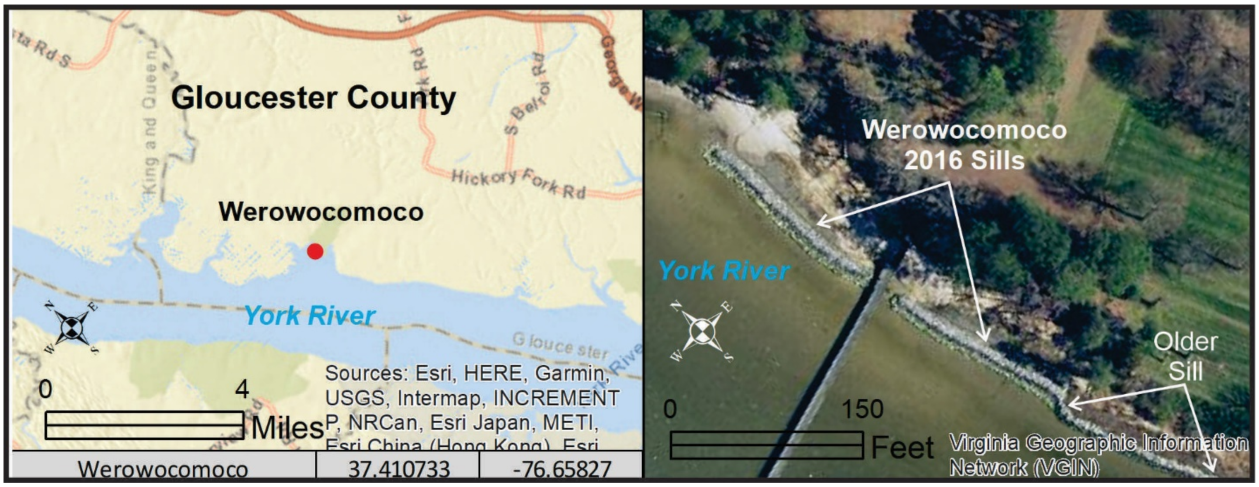


Figure 7-1. Location of Werowocomoco living shoreline sill shore protection system.

Several sections of the York River shoreline are protected with a high sill in front of the house and a revetment along the York River shoreline closer to Bland Creek. However, the section of shoreline near the pier was eroding into the bank (Figure 7-4). Great concern existed for the loss of high value archaeology associated with Powhatan and the Native American occupation of the site due to continued erosion of the bank in unprotected areas. This resulted in the construction of a stone gapped sill living shoreline system (Figure 7-1).

In 2014, VIMS received a grant from the National Fish and Wildlife Foundation to design, permit, and build the structures (#45177) and develop an overall shoreline management plan for the entire tidal shoreline. Additional funding from the Virginia Department of Conservation and Recreation's Water Quality Improvement Fund (WQIF-2016-03) was received to support the construction project (Milligan et al., 2016). The project was built in March to May 2016, and planted with marsh grasses in May to June 2016.

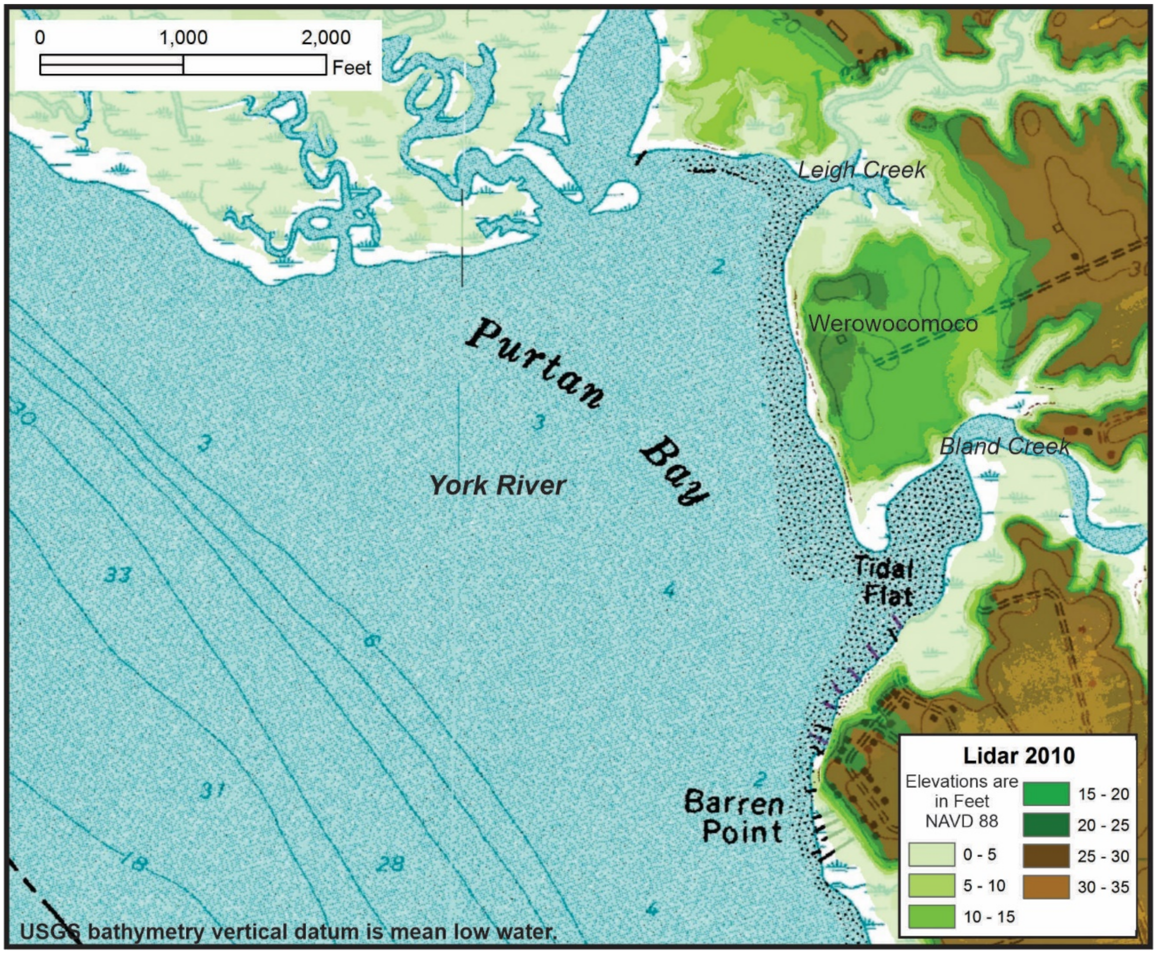


Figure 7-2. Lidar elevation data and bathymetric data in the vicinity of Werowocomoco. From Milligan et al., 2016.

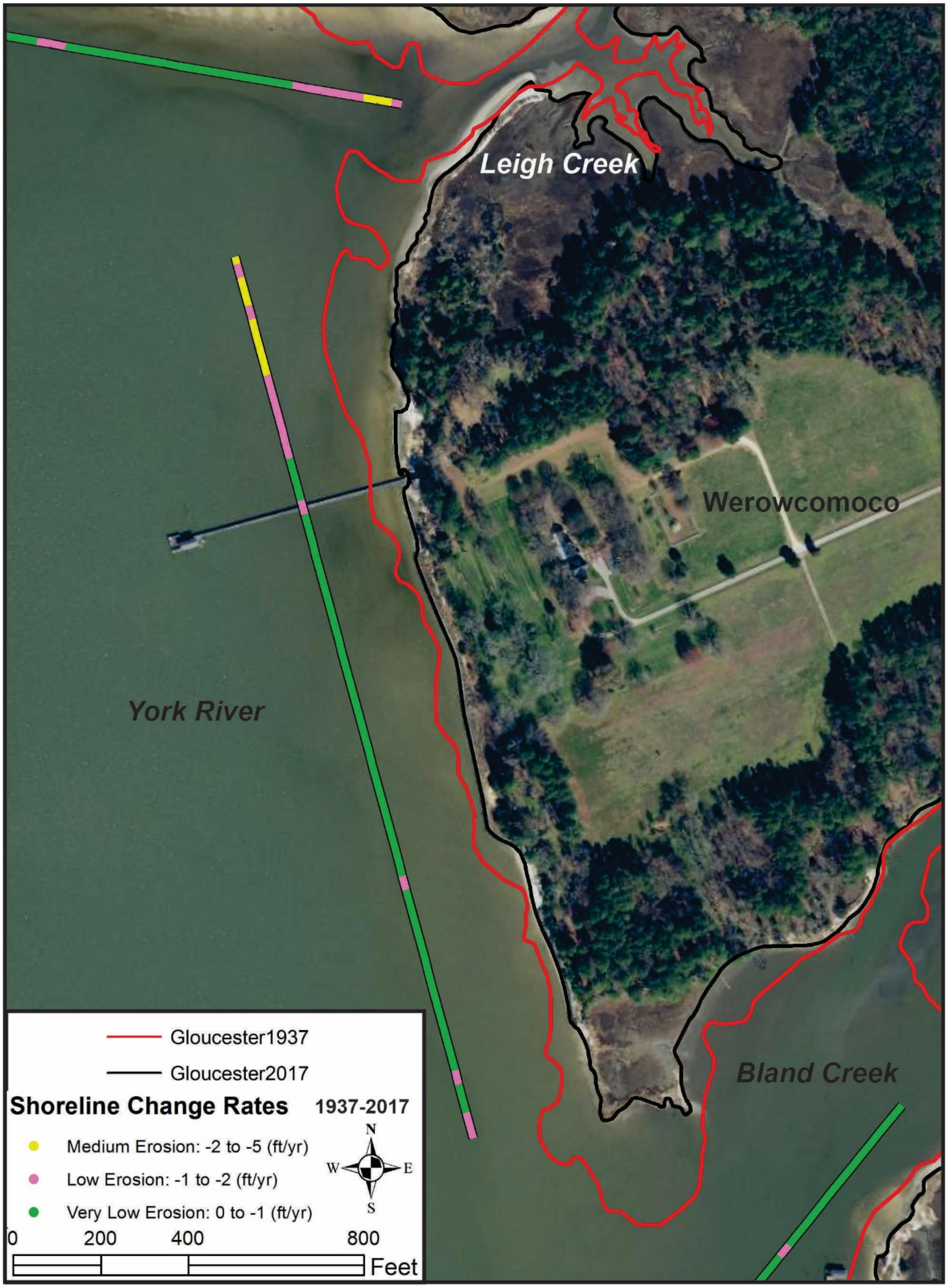


Figure 7-3. Shorelines digitized on the 1937 and 2017 aerial photos and the calculated rate of change along Werowocomoco's York River shoreline. From Shoreline Studies Program's shoreline change database.

Figure 7-4. Werowocomoco shoreline and eroding upland bank in 2012. Very little of what used to be an extensive marsh fronting the upland bank remained, and the bank was being directly impacted by high water levels during storms. Photo credit: Shoreline Studies Program, VIMS.

7.2 Site Performance

The Werowocomoco Living Shoreline project created/restored estuarine intertidal and riparian habitat, provided sustainable coastal hazards protection to a vulnerable historic resource, and provided the structure to mitigate the effects of sea level rise as well as sediment reduction to Chesapeake Bay. Two stone, gapped sills (152 and 170 ft long) with one window (25 ft wide) were constructed along 330 feet of shoreline (Figure 7-5). The southern sill (Sill 1) was attached to an existing higher, continuous sill. The upper elevation of sand fill was set at +5.0 ft MLW to interface with the eroding bank, and extended on a 12:1 slope to about mean tide level at the back of the stone sills (Figure 7-6).

After installation, the placed sand was allowed to adjust for about 2 weeks. Soon after, approximately 15,000 square feet of *Spartina alterniflora* (low marsh) and *Spartina patens* (high marsh) were planted in May/June 2016 to create marsh habitat (Milligan et al., 2016). The grasses were planted on a 2 ft grid, and Osmocote fertilizer was put in the hole at time of planting (Figure 7-7). Generally, the grasses were planted from mid-tide to the base of the bank, and goose exclusion fencing was placed at the site to protect the marsh grass plugs from geese.

The site was surveyed before construction (31 Mar 2014), after construction (7 Jun 2016), and on 26 Oct 2020, more than 4 years after installation (Figure 7-8). The mean high water (MHW) line advanced riverward due to the placement of sand for the project. Most areas behind the sill have maintained the sand. The riverward advances on the Sill 2 are due to placement of additional sand after the as-built survey. The sand placed in front of the revetment at the pier has shifted. Of note, the shoreline north of Sill 2 is continuing to erode. Additional structures are needed to protect this section of shoreline (Figure 7-9).

Figure 7-10 shows the cross-sections of the shoreline. Profile 150 shows that very little change has occurred since installation. At profile 200, which occurs between the structures, some of the sand fill has been eroded in front of the small, existing rock revetment. Sand was dumped over the bank on both sides of the pier so that the machinery could access the shoreline. This was done in lieu of grading to protect the existing archeology. Both profiles 200 and 250 show that sand was placed farther up the bank to facilitate access. Some additional sand was placed at profile 350 after the as-built survey occurred.

Since installation, this living shoreline project is functioning as expected. The eroding shoreline now has a wide high and low marsh behind the sills (Figure 7-11 and Figure 7-12) except for in the small embayment at the pier, which is beach. A well-established, lush marsh occurs from the back of the sill to the base of the bank. The sand was placed on a 12:1 slope which is slightly gentler than many other sills in Chesapeake Bay. This increased the width possible for the marsh, which in turn provides more wave reduction during storms and reduces wave impact on the upland bank. This southwest facing shoreline provides an extremely suitable area for marsh growth.

The site was only planted to mid-tide but now has filled in completely behind sill. Additionally, *S. patens* was planted up the slope of the upland bank where the sand was placed to provide access to the shoreline (Figure 7-13). It has done well growing up the slope. The survey also revealed that the approximate line between where *S. alterniflora* and *S. patens* were growing was at about 3.1 ft MLW in 2020 (Figure 7-14). This biologic benchmark is about the same as it was before the project was built, 3.2 ft MLW on the adjacent marsh shoreline.

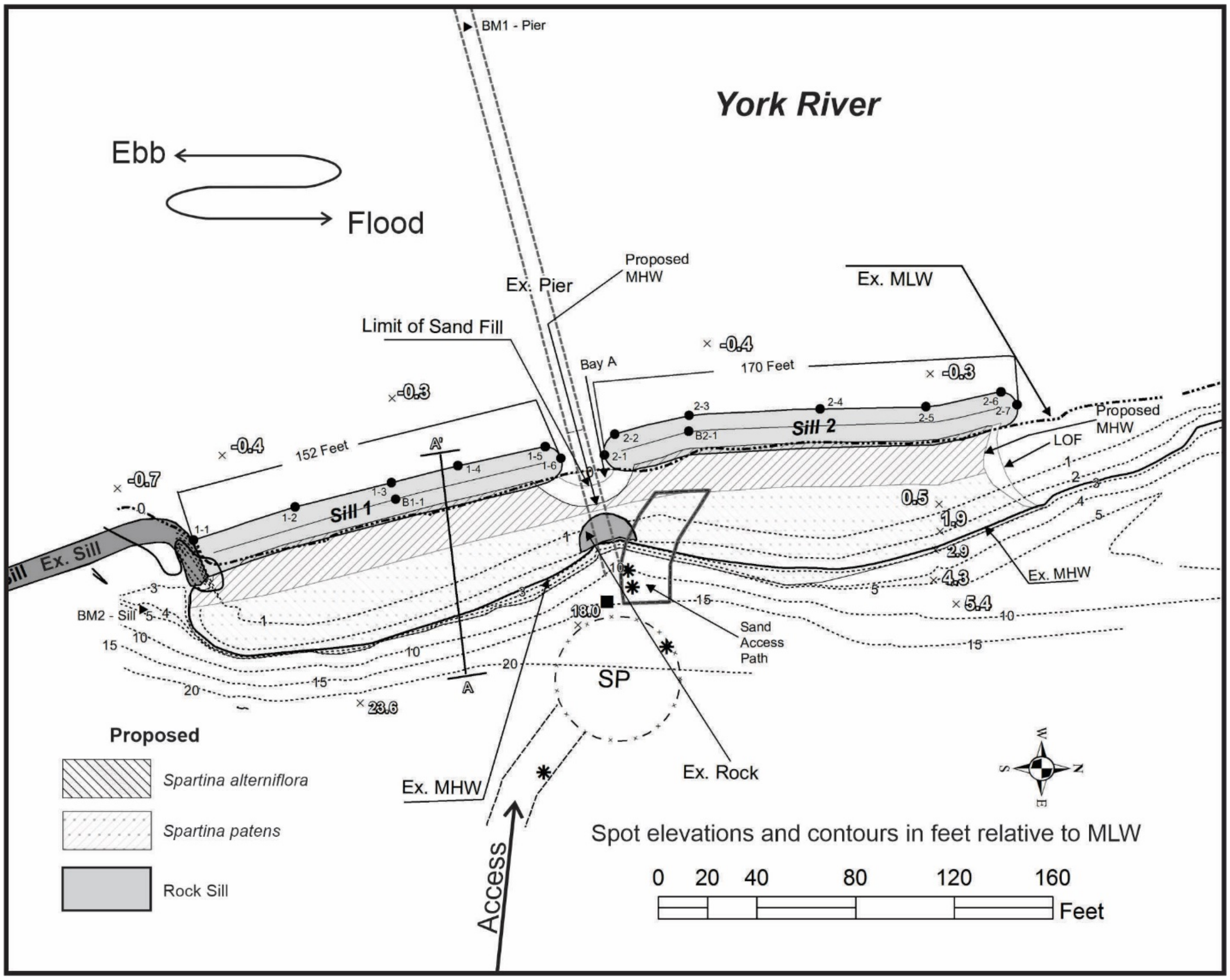


Figure 7-5. Planform of existing and proposed conditions at Werowocomoco living shoreline project.

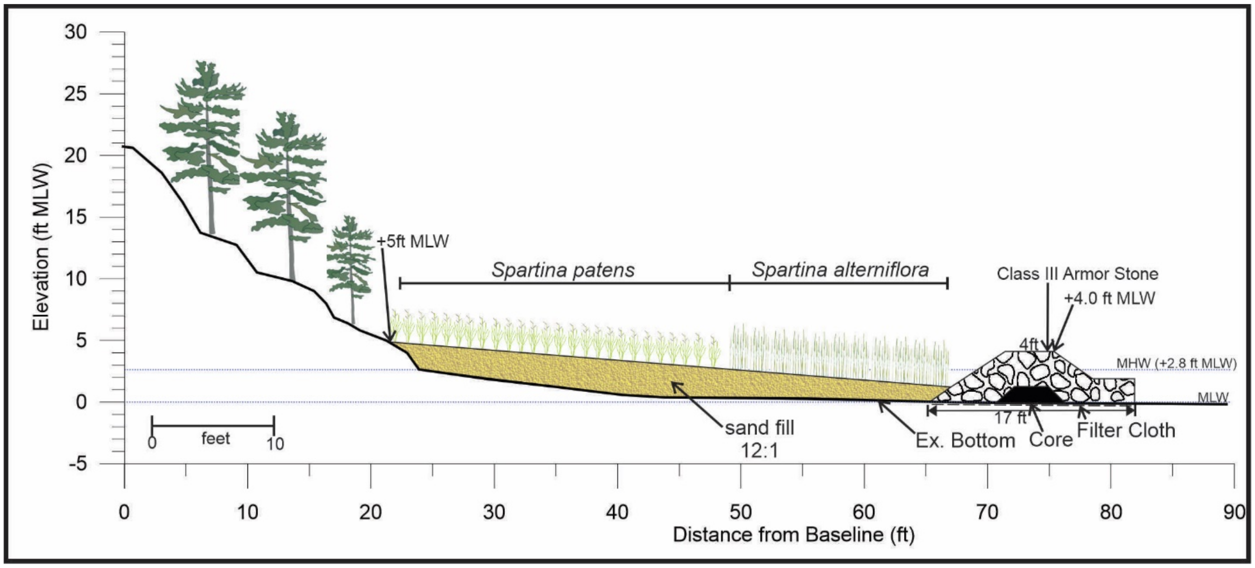


Figure 7-6. Typical cross-section of the sill and sand fill at Werowocomoco living shoreline project.

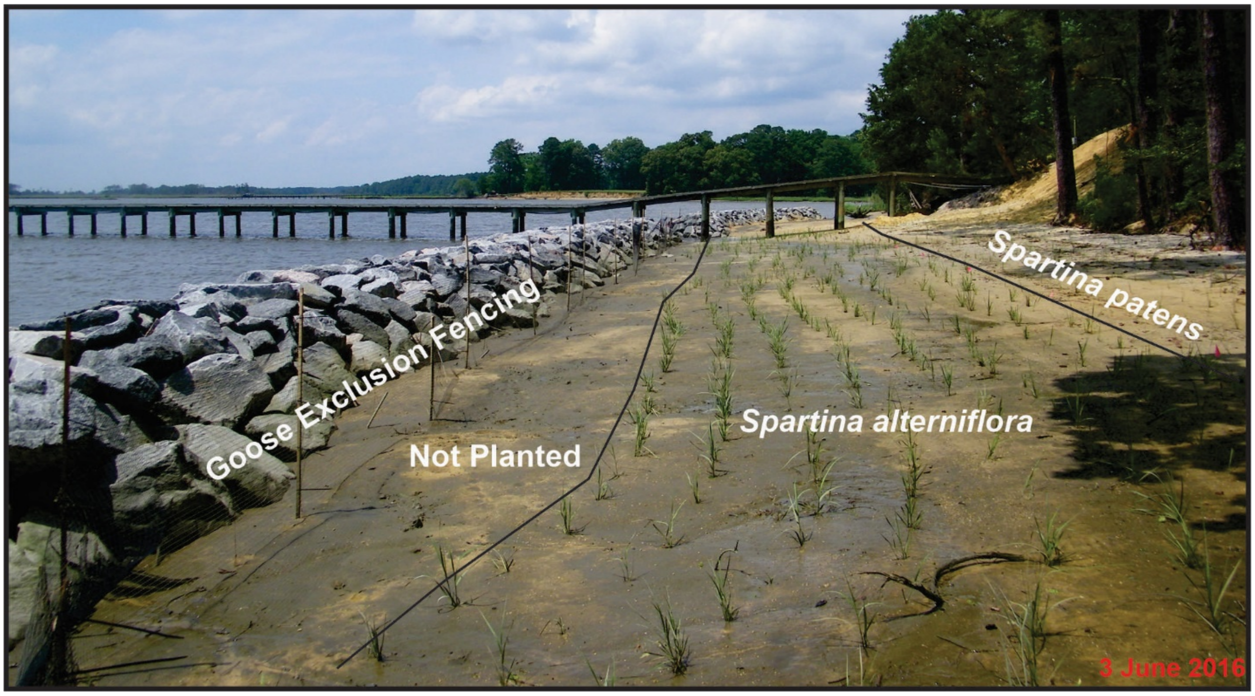


Figure 7-7. Planting zones of low and high marsh grasses. The sand equilibrated for about two weeks after it was placed. Photo credit: Shoreline Studies Program, VIMS.

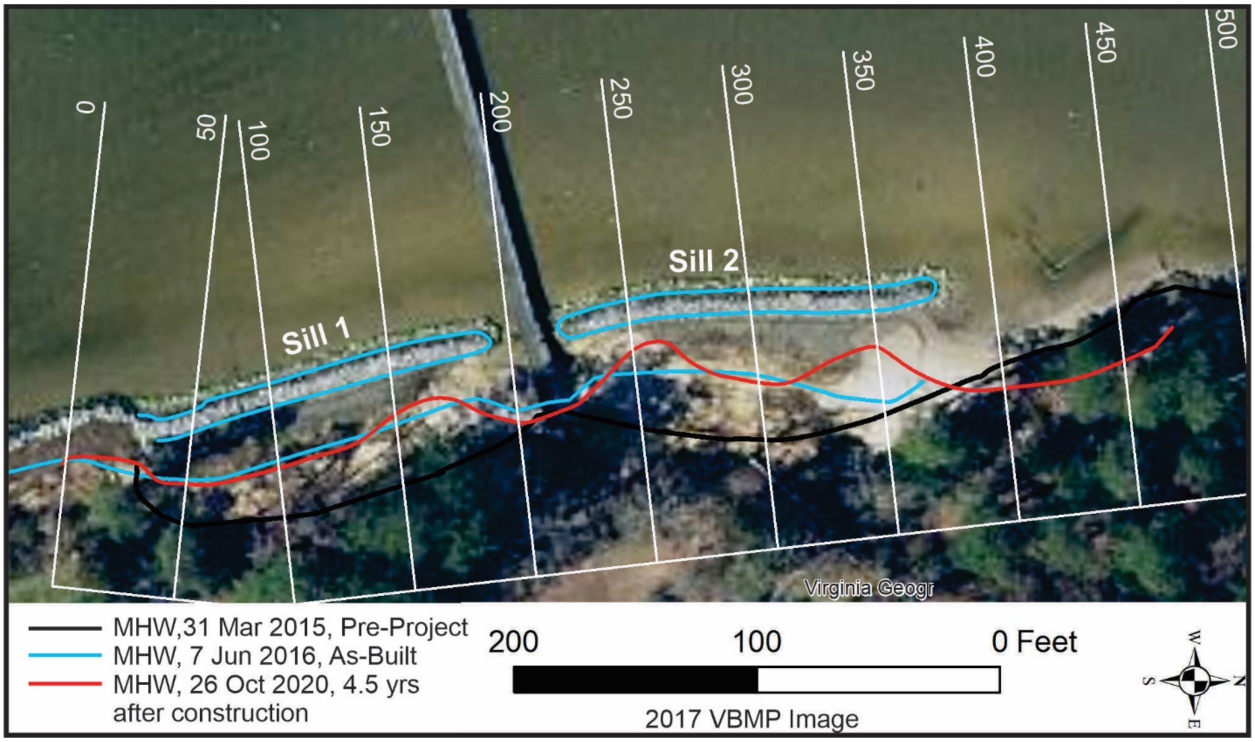


Figure 7-8. The survey baseline and profiles at Werowocomoco. Also shown is the surveyed mean high water line at each of the survey dates.

Figure 7-9. Eroding shoreline north of Sill 2. An additional structure is needed to protect the bank along this section of shoreline. Photo credit: Shoreline Studies Program, VIMS.

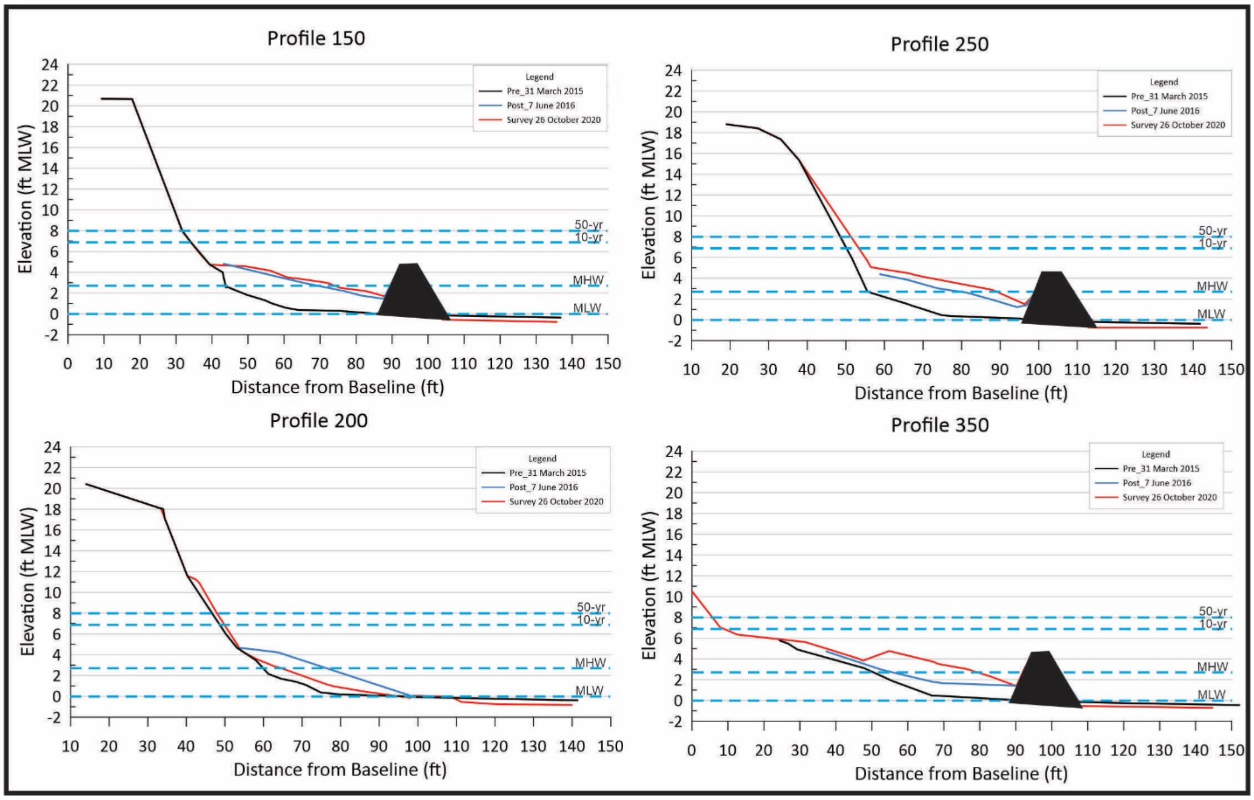


Figure 7-10. Profiles at Werowocomoco living shoreline pre-project, as-built and about 4.5 years later.

Figure 7-11. Pre-project shoreline showing an eroding bank with fallen trees (top); and Sill 2 about 4.5 years after construction showing a lush marsh (bottom). Photo credit: Shoreline Studies Program, VIMS.

Figure 7-12. Pre-project shoreline showing an eroding bank with fallen trees (top); During construction of Sill 1 (middle); and Sill 1 about 4.5 years after construction showing a lush marsh (bottom). Photo credit: Shoreline Studies Program, VIMS.

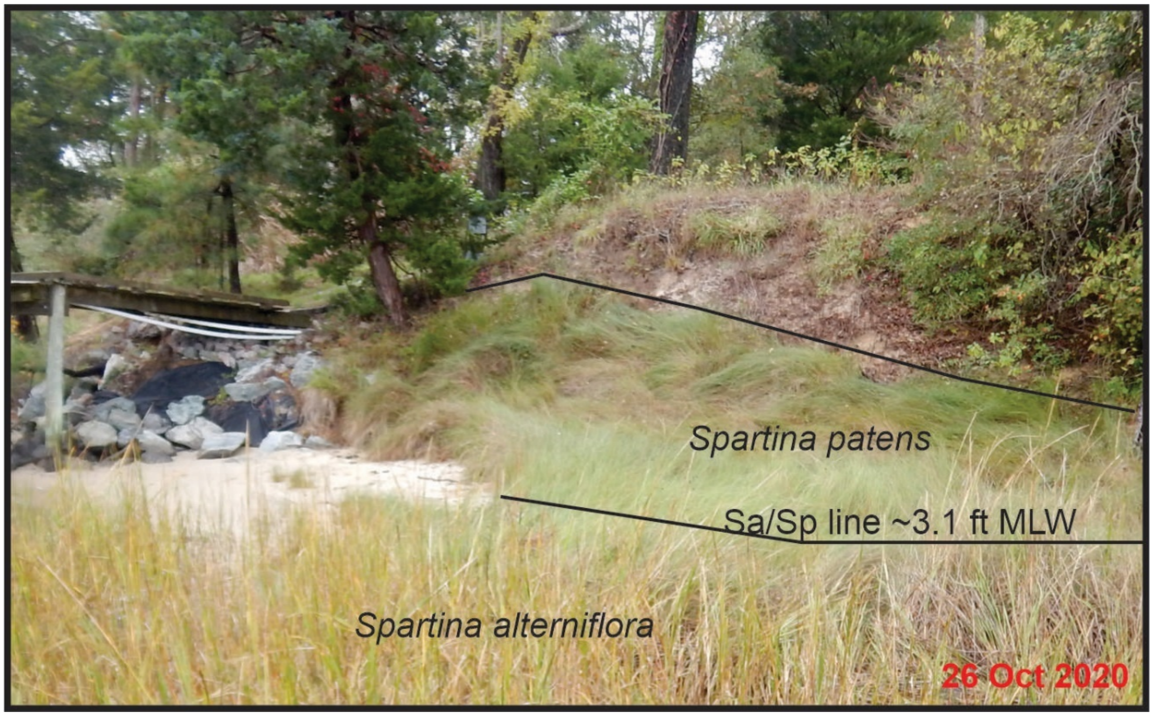


Figure 7-13. Marsh behind Sill 1 about 4.5 years after construction. The S. alterniflora/S. patens biologic benchmark is similar to what it was pre-project. Photo credit: Shoreline Studies Program, VIMS.

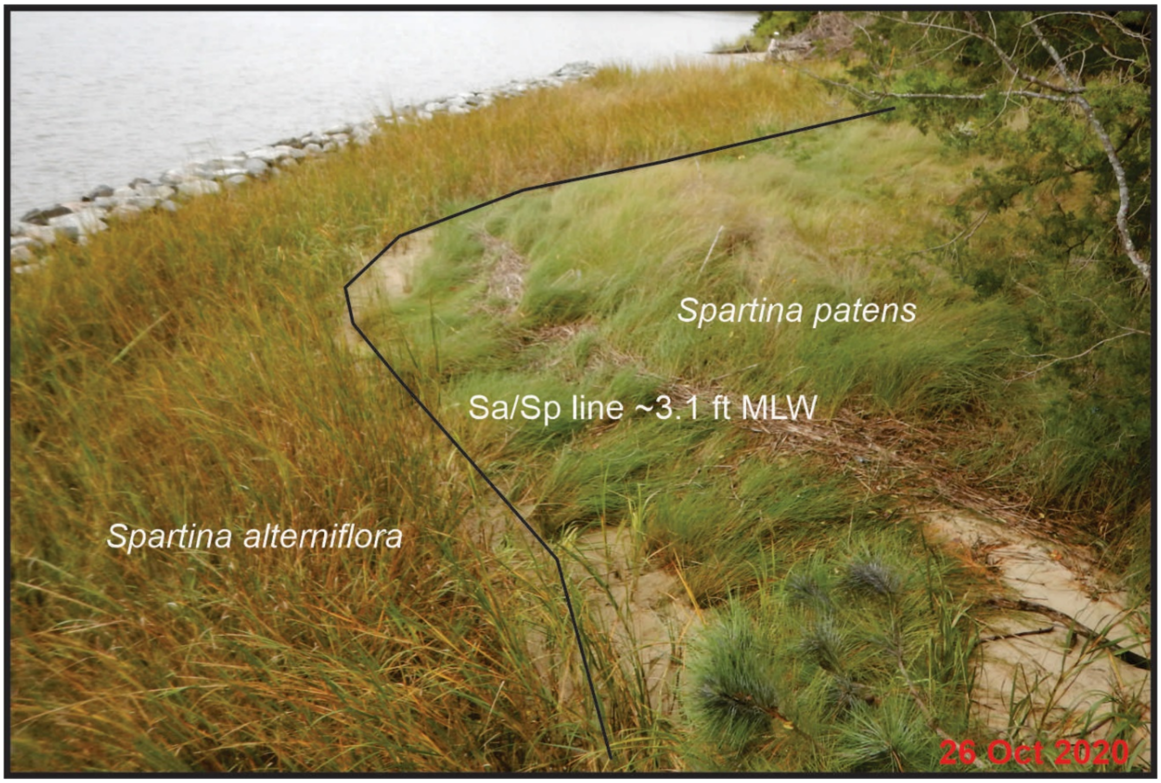


Figure 7-14. Marsh behind Sill 1 about 4.5 years after construction. The S. alterniflora/S. patens biologic benchmark is similar to what it was pre-project. Photo credit: Shoreline Studies Program, VIMS

8 Haven Beach, Mathews County

8.1 Site Background

Haven Beach is located in Mathews County, Virginia (Figure 8-1). It is part of a low barrier beach/dune feature that is migrating (receding) westward rapidly. In 1953, the present location of the beach was well inland, and Rigby Island was still attached to the mainland although the location of attachment was very narrow (Figure 8-2). By 1994, Rigby Island had detached and was rapidly deteriorating (Figure 8-3). In 2017, Rigby Island had broken into two sections, and the small, southern, Rigby Island remnant was just barely above the water level in 2017 (Figure 8-4). Long-term shoreline change analysis between 1937 and 2017 showed that the Chesapeake Bay shoreline at Haven Beach was eroding at a high rate, between -5 to -10 ft/yr (Figure 8-4). However, the shoreline behind Rigby Island was protected and had mostly very low erosion rates (less than -1 ft/yr). By July 2020, the Rigby Island remnant has completely eroded, and this shoreline has become exposed to a higher wave climate over time. More recent, shorter-term erosion has likely increased along this section of shoreline that was previously protected as indicated by the several sections of shoreline that have a low erosion rate (-1 to -2 ft/yr).

Haven Beach historically has been used by residents and visitors for recreation and Bay access. In 1985, State Route 643 ended at the shore where a small sandy parking area existed behind a timber bulkhead. The fairly continuous beach along Haven Beach had several concrete well curb groins (Figure 8-5). In an attempt to alleviate erosion at this site, five experimental breakwaters were installed in 1985, but these ultimately failed. Today, none of these original shore protection structures exist as the shoreline has continued to migrate landward.

In 2005, the county installed one large breakwater (280 ft long, 30 ft wide) and one small breakwater (100 ft long, 21 ft wide) with 4,000 cy of beach fill behind the structures to stop erosion and protect the marsh habitat in the backshore (Figure 8-6). The overall cost of the project was $540,000 and included construction of a parking lot (Hamilton, 2016). Though two full-sized breakwaters were designed by Vanasse, Hangen, and Brustlin, Inc. (VHB) for the site, limited funding reduced the length of the second breakwater that could be installed. This smaller length reduced the effectiveness of the overall system. At this time, most of the shoreline north and south of the breakwaters consisted of an old peat surface that intersected the beach at about mean tide level. Above the peat, wash-over sand occurred over the marsh; it was sparsely populated with upper marsh and dune grasses. Sand fencing was installed along the entire public beach length for this project.

Haven Beach faces east on Chesapeake Bay and is impacted by a high energy wave climate. The shoreline has experienced a high rate of erosion at -5 to -10 ft/yr along the unprotected shorelines of Chesapeake Bay. Tide range is 1.3 ft. No SAV occurs in the nearshore of Haven Beach. Sediment transport is to the south along this section of Chesapeake Bay. Sediment sampling taken in 2010 at the site indicates that toe is coarse with 60% gravel (Table 8-1). The beach and backshore median grain size is medium to coarse sand, and the nearshore is mostly fine sand with 30% mud due to the presence of the eroding peat scarps.

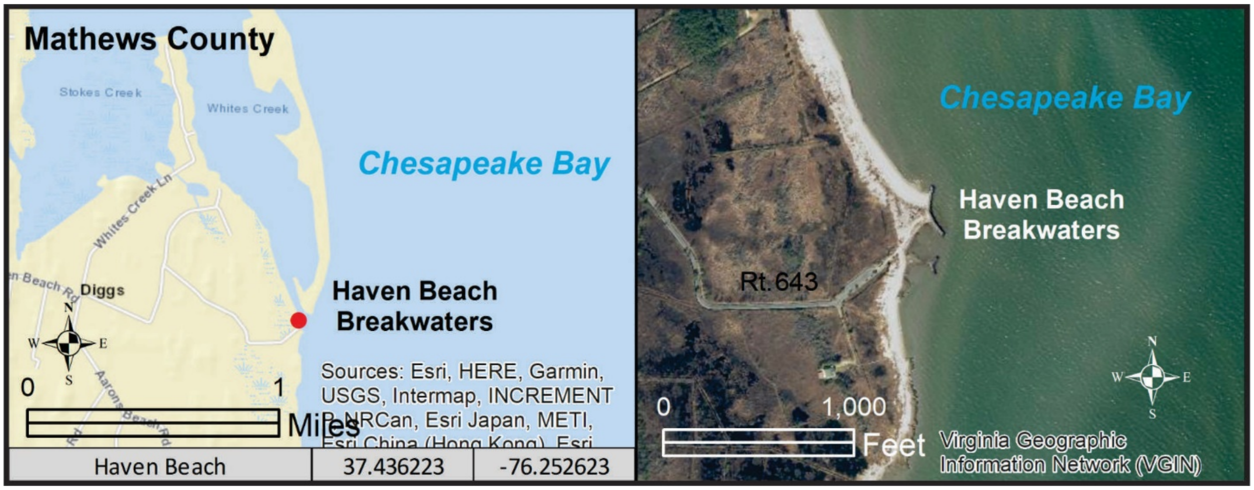


Figure 8-1. Location of Haven Beach living shoreline breakwater shore protection system.

Table 8-1. Sediment analysis for samples taken at specific beach features along a cross-shore profile at Haven Beach in 2010 by Shoreline Studies Program personnel. The percent gravel, sand, and mud are shown as well as the mean, median, and standard deviation of the grain size.

sample	Description	Total Sample Statistics					
#		%Gravel	%Sand	% Mud	mean (mm)	median (mm)	stdde (mm)
1	Edge of Vegetation	0.0	99.9	0.1	0.70	0.68	0.32
2	Upper Berm	0.2	99.6	0.2	0.48	0.37	0.45
3	Lower Berm	0.0	99.6	0.4	0.36	0.31	0.33
4	Mid-Beach	0.0	99.0	1.0	0.29	0.28	0.09
5	Toe	60.2	39.5	0.3	7.17	8.63	5.09
6	Nearshore	0.1	68.6	31.3	0.27	0.22	0.42

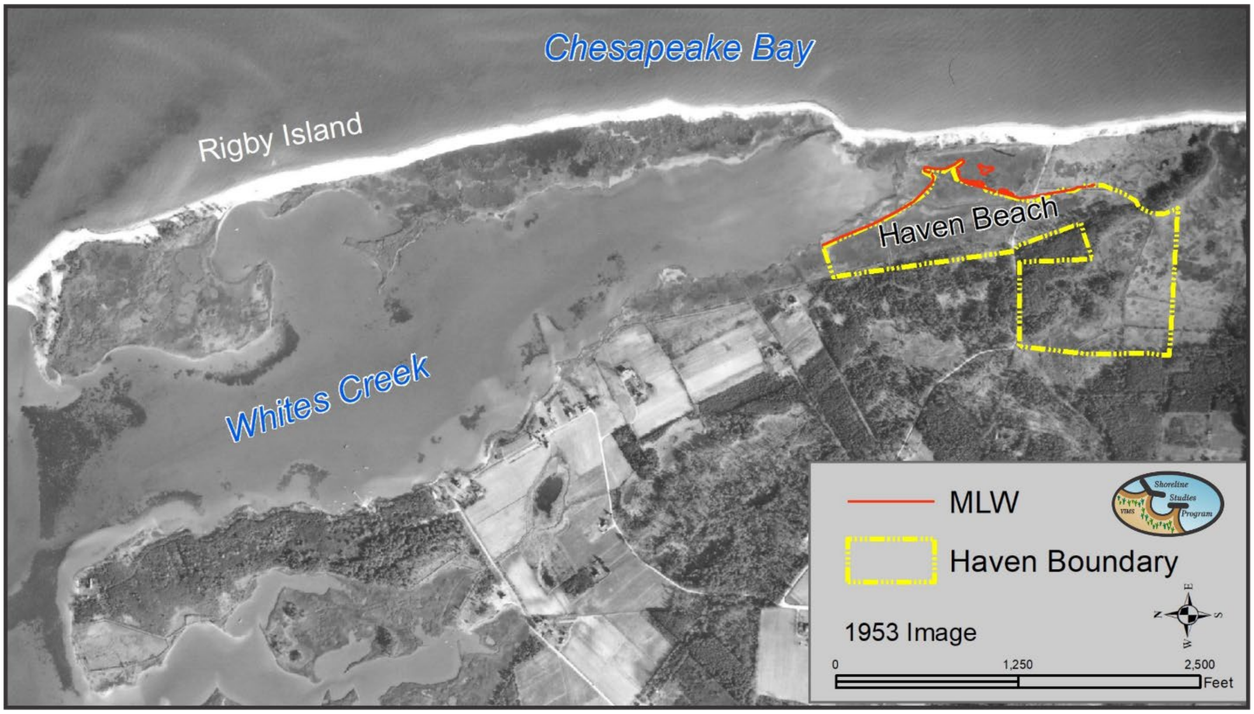


Figure 8-2. Haven Beach boundary as shown on a 1953 aerial imagery. The present beach was well inland in 1953. The whole shore system has migrated landward due to erosion. From SSP Shoreline Change Database.

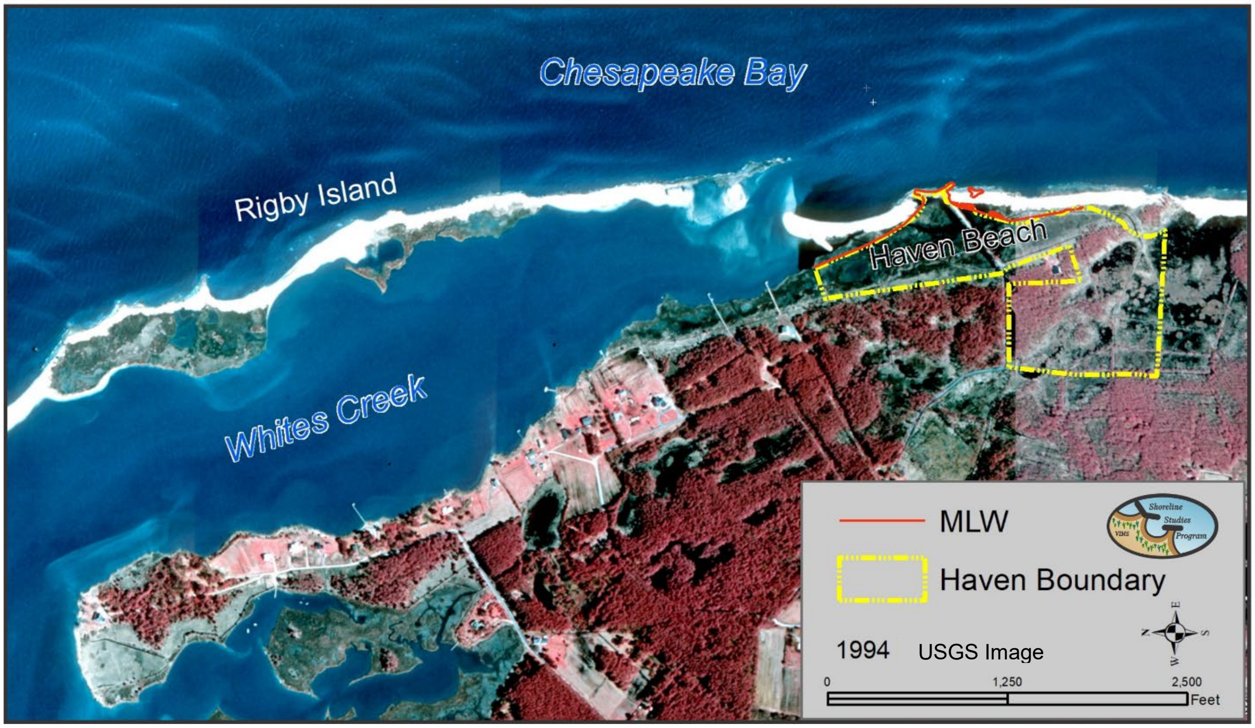


Figure 8-3. Haven Beach boundary in 1994. The whole system is still migrating landward with the present beach shoreline still inland. From SSP Shoreline Change Database.

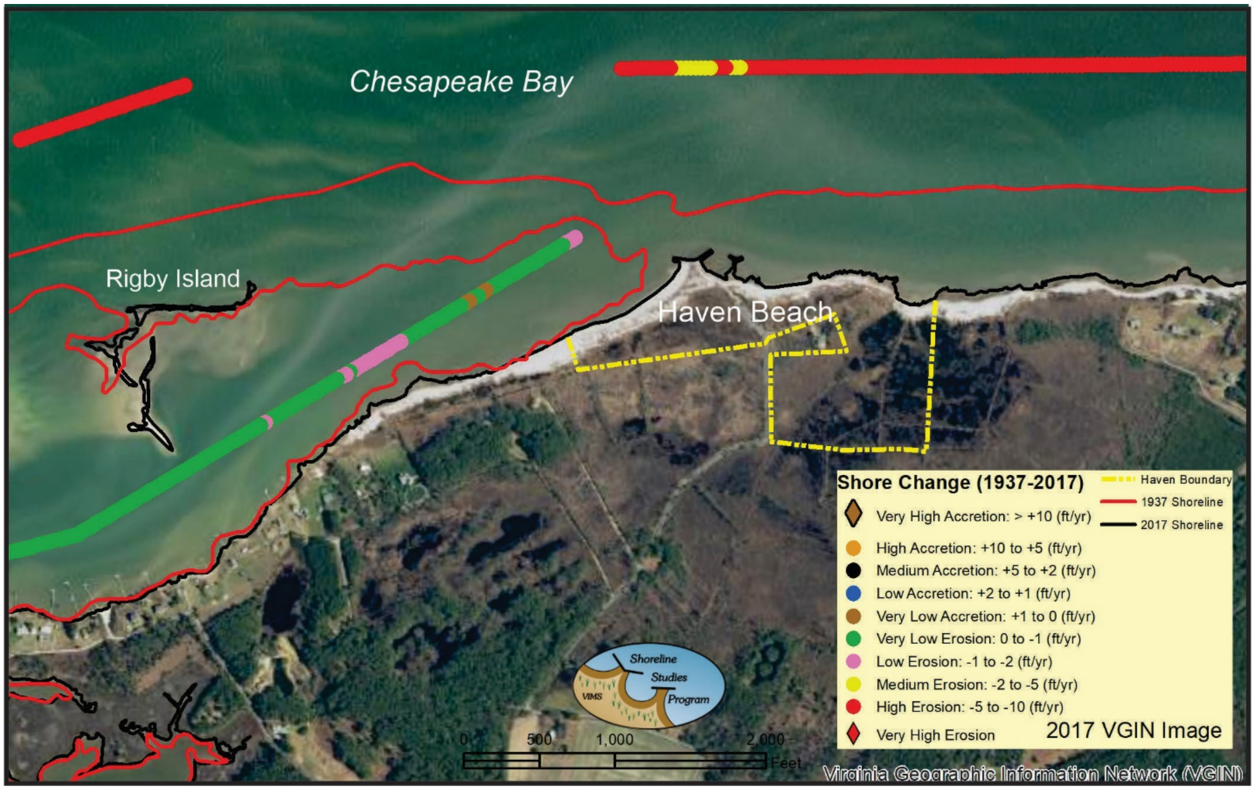


Figure 8-4. Haven Beach boundary in 2017. Also shown is the position of the 1937 and the 2017 digitized shorelines. The end point rate of shoreline change between 1937-2017 is shown. Overall, Haven Beach is experiencing a high rate of erosion. From the SSP Shoreline Change Database.

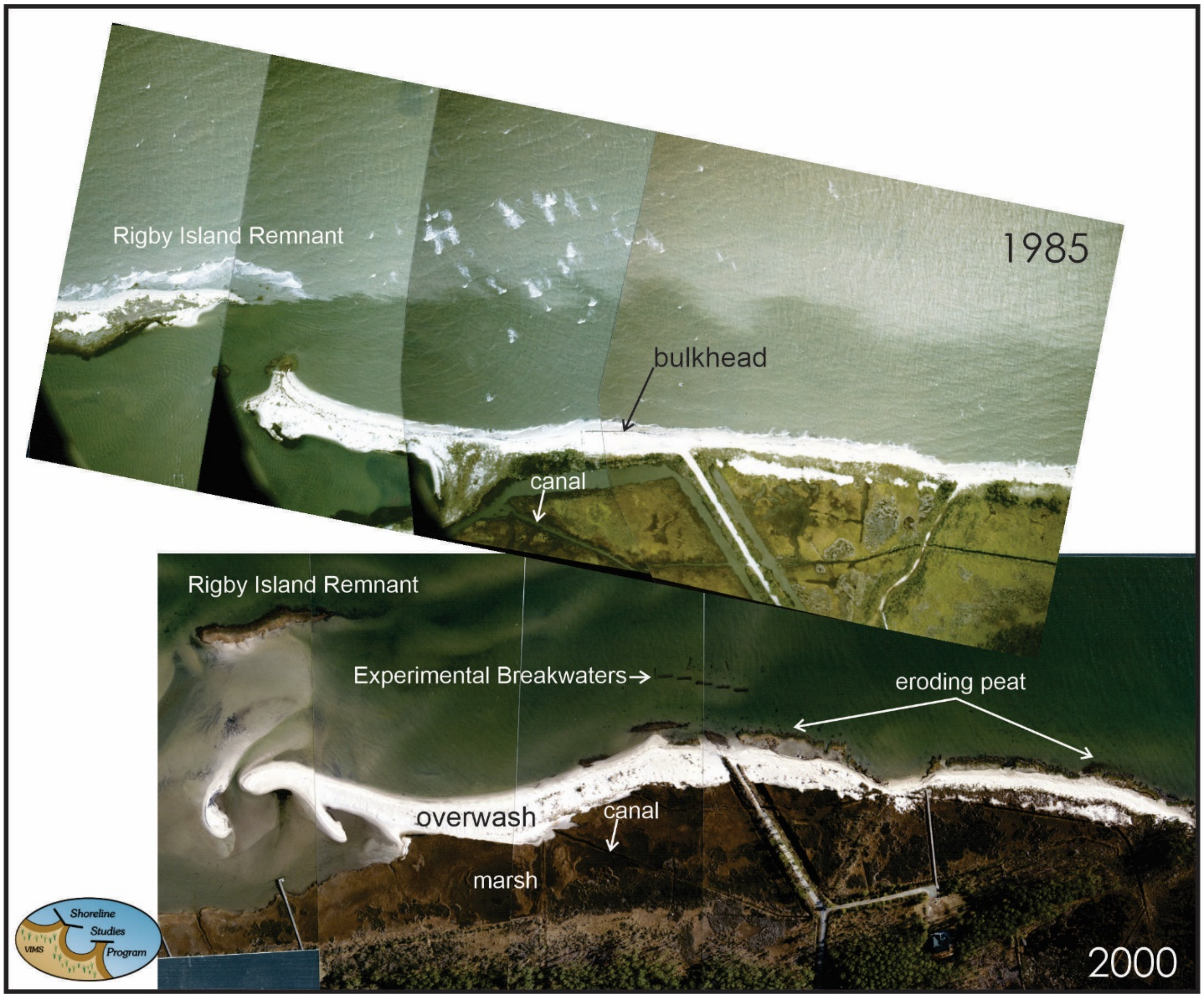


Figure 8-5. Aerial photos taken in 1985 and 2000. Previous shore protection structures such as the timber bulkhead in 1985 and the experimental breakwaters shown in 2000 failed.

Figure 8-6. Photos at Haven Beach submitted with the Virginia Marine Resource Commission permit application #20022188. Top shows the view looking north along the site and bottom shows the view looking south. Exposed peat and wider peat terraces occur along the site. Above these, a beach and dune/washover occur.

Figure 8-7. Haven Beach in 2005 just after the construction of the shore protection system. Sand fill was placed behind the structures and sand fencing was installed to help maintain the sand in the system. Photo credit: Shoreline Studies Program, VIMS.

8.2 Site Performance

Drone imagery taken 30 July 2020 shows the system as it occurs today (Figure 8-8). The top image shows a long view of the site from the south. Peat outcrops occur along the shoreline south of the breakwaters. Near the southern boundary of the site, a small sand embayment occurs between two peat headlands. In some areas, the peat forms a wide terrace south of the breakwater that has supported the regrowth of smooth cordgrass. Sandy beaches front washover dunes and vegetated and non-vegetated wetlands. The middle photo shows a closer view of the breakwaters that were installed in 2005. The tombolo behind the large breakwater is heavily vegetated, but no sand occurs behind the small breakwater.

Due to the southerly movement of sand along this section of shore, sand accumulated updrift of the large breakwater over time, and the northern section of Haven Beach became a sandy beach/dune complex vegetated by dune grasses (Figure 8-8, bottom). This beach/dune fronts the marsh and provides protection during storms. Though the large breakwater is functioning well as shore protection, the smaller breakwater has not been able to withstand the storms that have impacted the site. Most of the sand was lost from behind during a storm in 2015 (Hamilton, 2016).

The site was surveyed in October 2020 (Figure 8-9). Survey data cross-sections show the development of the site over time. On the northern section of the site, a high, wide dune has grown over time. Survey 5+48 (Figure 8-10) shows that the crest elevation of the dunes is nearly +10 ft MLW and provides protection for the lower marsh behind it. The breakwaters were designed at +6 ft MLW as shown by cross-section 8+89 (Figure 8-10). Survey data taken in 2002 for another SSP project shows that prior to the project, the shoreline was low with very little protection for the marsh behind the beach. Though the as-built survey could not be obtained, it is likely that the tombolo has accreted and become higher behind the structure. With the high breakwater structure and the very wide tombolo, waves are mitigated during storms reducing impacts to the marsh behind.

Profile 11+65 shows the change between the pre-installation profile and that taken in 2020 at the small breakwater (Figure 8-11). The breakwater is slightly narrower with a lower crest elevation (+5 ft MLW). All of the sand that was placed during construction has eroded from behind the smaller breakwater. The entire beach/dune system has moved landward. Though most of the loss occurred during a storm event, averaging out the change at MHW between 2002 and 2020 behind the small breakwater, the rate is -6 ft/yr which is in line with the calculated long-term rate of change at the site (-7 ft/yr). Although the system has moved landward, overall the beach/dune is higher than it was prior to the installation of the breakwaters. The 2002 profile does not extend landward to intersect with the 2020 survey, however, the shoreline behind the breakwater now has a small dune with a crest elevation of about +7 ft MLW.

Just south of the breakwaters at profile 14+14, the impact is similar though the rate of landward migration has slowed. The position of the shoreline at MHW and MLW has migrated landward about 20 ft between 2002 and 2020 resulting in a rate of change at about -1 ft/yr. This is a significant reduction in erosion from the calculated long-term rate for the Chesapeake Bay shoreline in this area (-7 ft/yr). This is likely due to the erosion of the beach fill from behind the small breakwater as the sand was transported south. This sand also led to the development of a higher beach/dune system than it was prior to the shore protection project (Figure 8-11). The maximum beach/dune height in 2002 was about +5 ft MLW, but in 2020 it was +8 ft MLW. This provides additional protection for the marsh behind the beach during storms.

At profile 19+16, no pre-project profile exists (Figure 8-12). The effect of the shore protection project is lessened at this distance from the breakwaters, though the maximum elevation of the beach/dune is slightly higher than the pre-project profiles north of here. Those elevations were just over +5 ft MLW as shown on profiles 8+89, 11+65, and 14+14. However, presently at profile 9+16, the maximum elevation of the beach/dune is at about +6.5 ft MLW. Also, a 30 ft wide peat terrace occurs along this profile. It has a flatter slope than the surrounding sand and occurs between about +2 ft MLW and mid-tide. This peat outcrop creates a headland that sets the northern extent of the small sand embayment shown in Figure 8-8 (top) at the southern boundary of the site.

Ground photos show the state of the beach in October 2020. Figure 8-13 shows the northern section of the shoreline. A wide beach and high dune vegetated with dune grasses exists. However, *Phragmites australis* is infiltrating the site. It occurs in the marsh behind the beach/dune system on the northern end of the project. Though erosion is not affecting the marsh behind the system, sea-level rise is. The trees behind the marsh are dying as sea level rises creating a ghost forest. Figure 8-14 shows the tombolo behind the large breakwater and how heavily vegetated it is. Beach and dune grasses effectively hold the sand and provide a buffer for wind transport. Figure 8-15 displays the peat terrace and beach/dune south of the breakwaters. The marsh is closer to the shoreline along this reach, so the *Phragmites* is closer to the beach. The beach/dune is lower in elevation than in the areas farther north. Much of the marsh behind this project has been infiltrated by *Phragmites* (Figure 8-16).

Overall, this breakwater project has functioned well. The large breakwater has remained attached, and the tombolo is higher than immediately post-project and has become well-vegetated. This well-positioned structure has allowed sand to accrete updrift creating a high, wide protection beach/dune. This northern section of shoreline has a complicated morphologic history due to the loss of Rigby Island (Figure 8-17). This loss has provided sand to the system through erosion, but it also has allowed more impact from waves. The rate of landward migration has slowed and even stopped north of the structure. With continued sand transport south along this section of shoreline, it is likely that sediment will continue to accrete north of the breakwater. South of the breakwaters, shore loss continues to occur. The rates are lower closer to the structures, but farther south of the structures, the rate of change continues to be at the high long-term average.

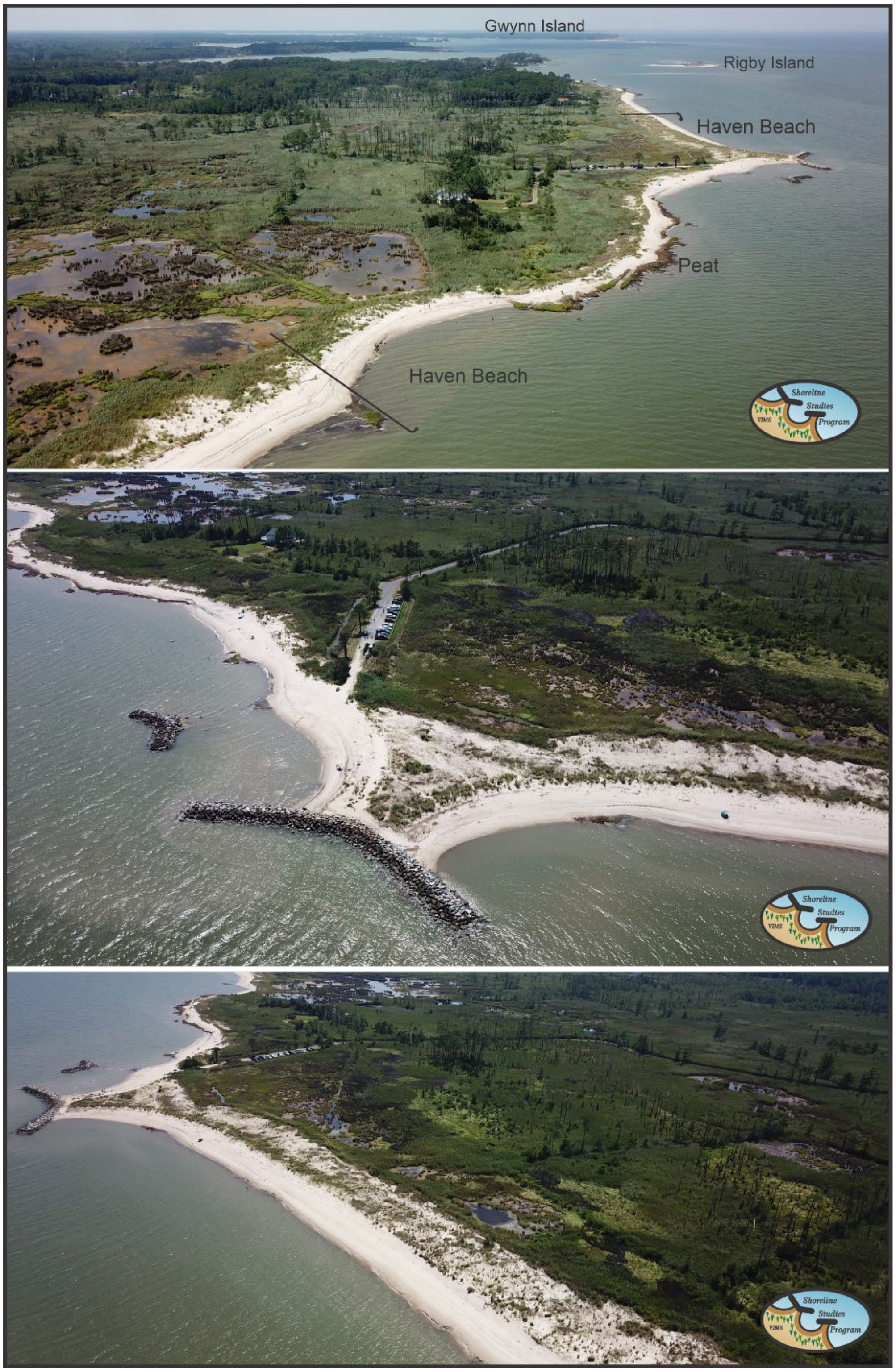


Figure 8-8. Drone imagery taken in July 2020 showing the evolution of Haven Beach. Top: the boundaries Haven Beach are shown. South of the breakwaters, erosion is still occurring and peat is exposed. Middle: The tombolo behind the large breakwater is well-formed with beach and dune vegetation while no sand occurs behind the small breakwater. Top: North of the breakwater, a large beach/dune system has grown since installation of the structures.

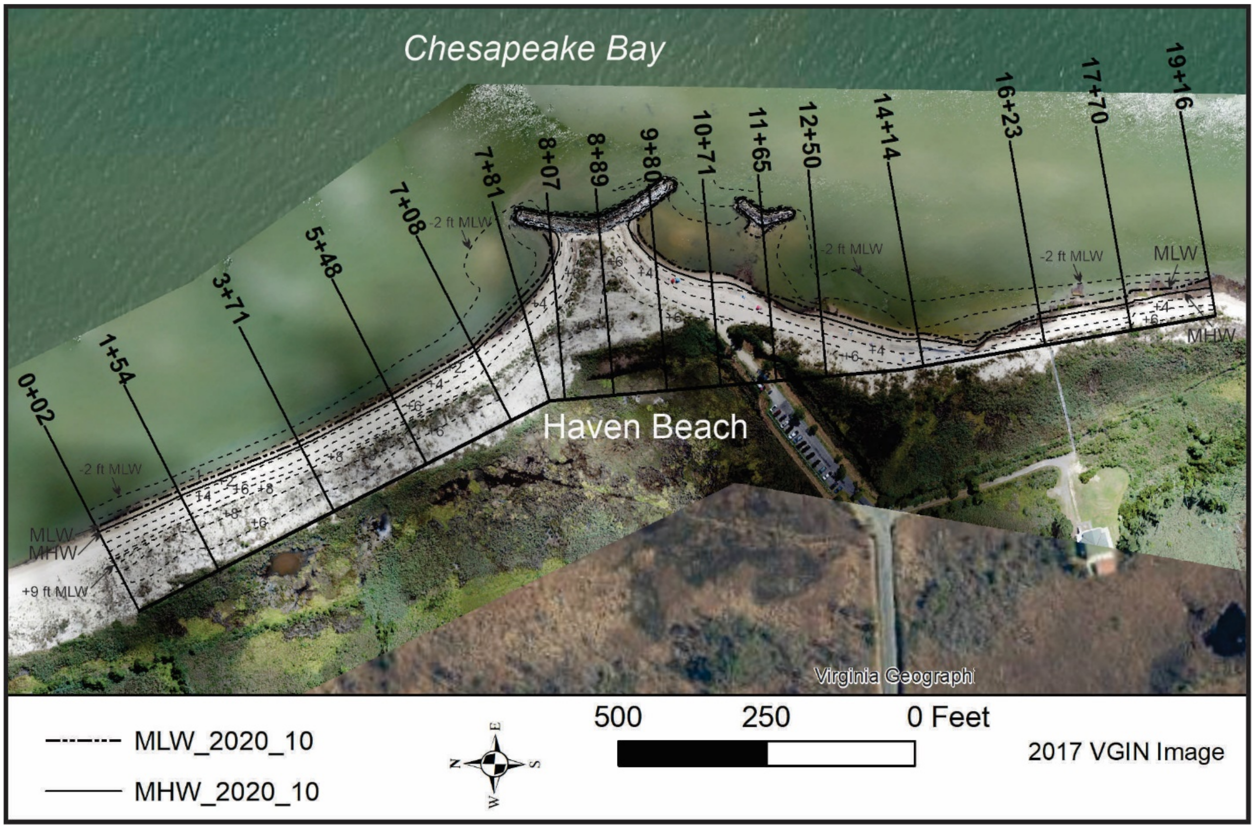


Figure 8-9. Survey contours from the October 2020 survey. Also shown are the positions of the cross-shore profiles.

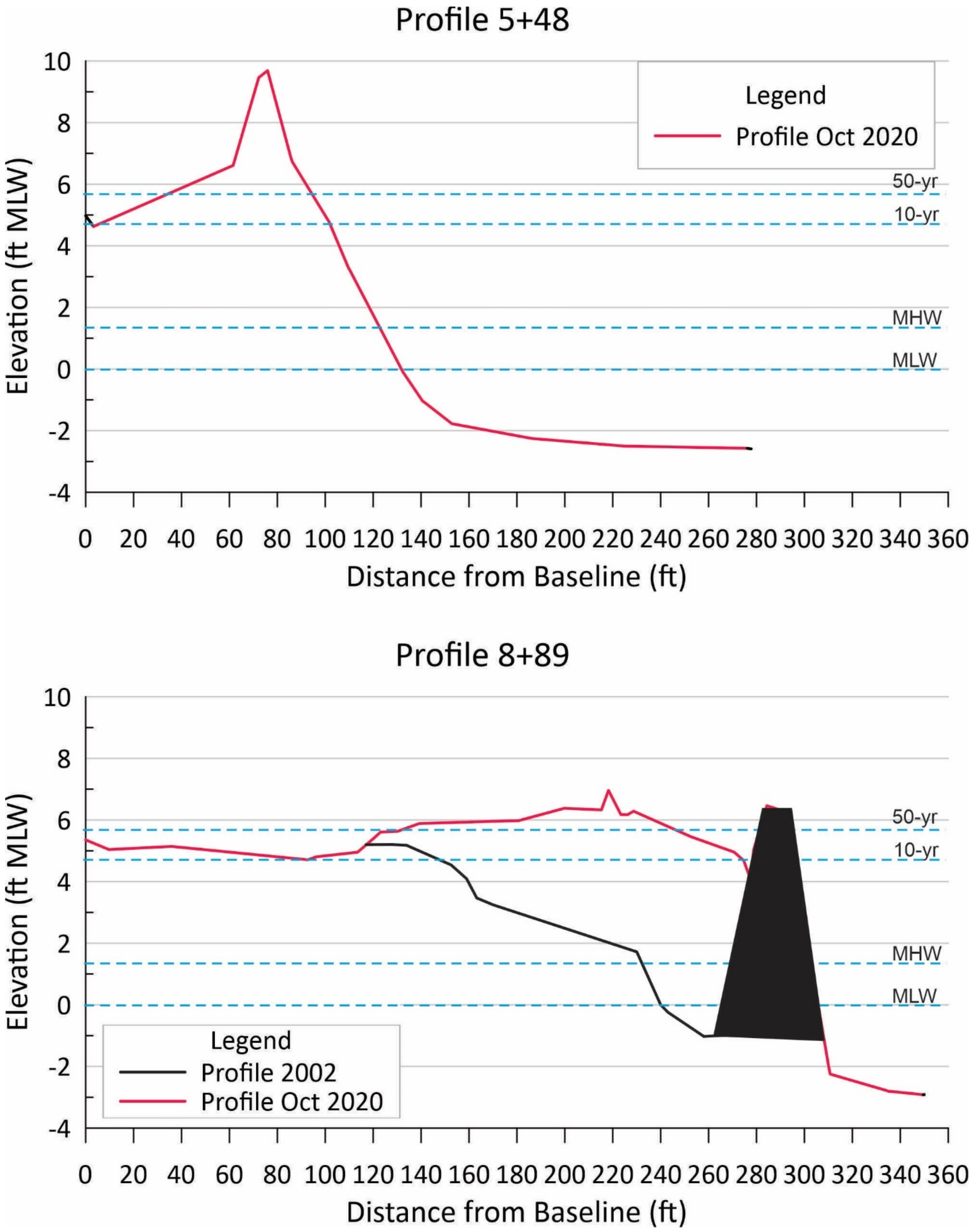
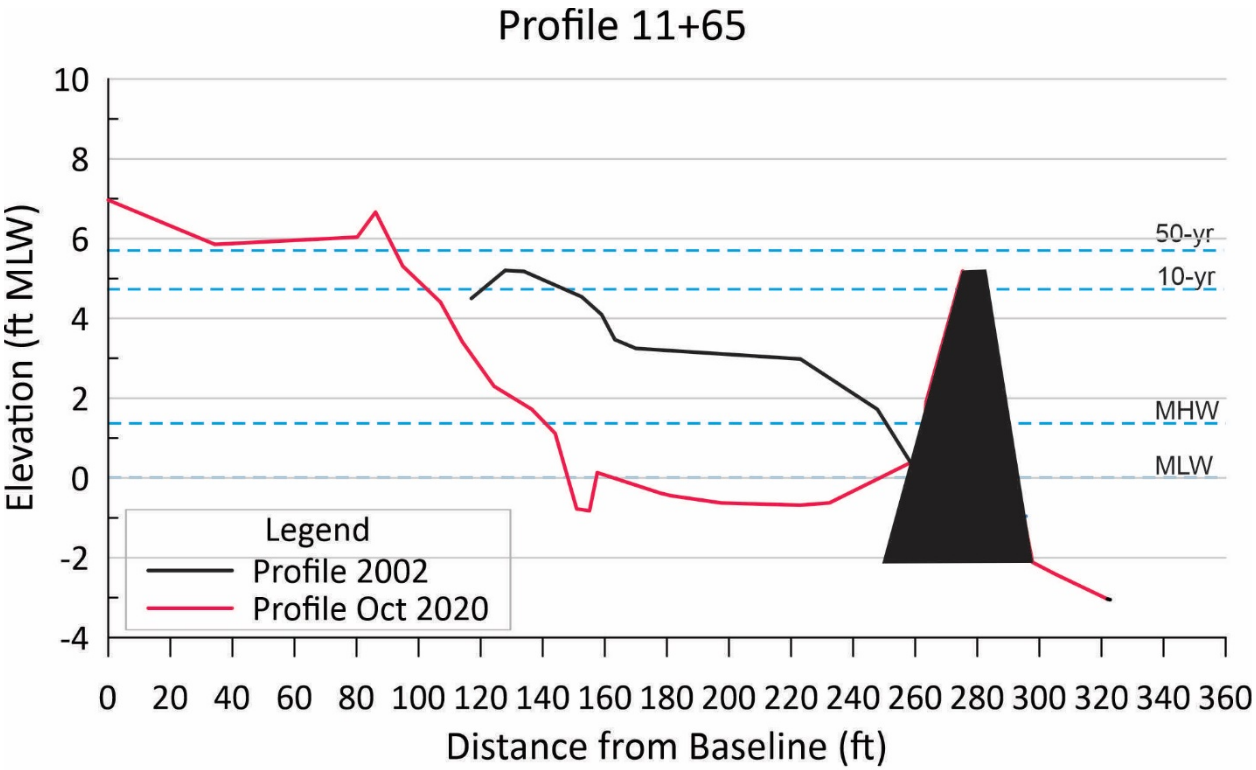


Figure 8-10. Cross-shore profiles at Haven Beach. Top: profile 5+48 shows the high wide dune that exists north of the large breakwater. Bottom: profile 8+89 crosses the large breakwater and shows the change between 2002 and 2020.



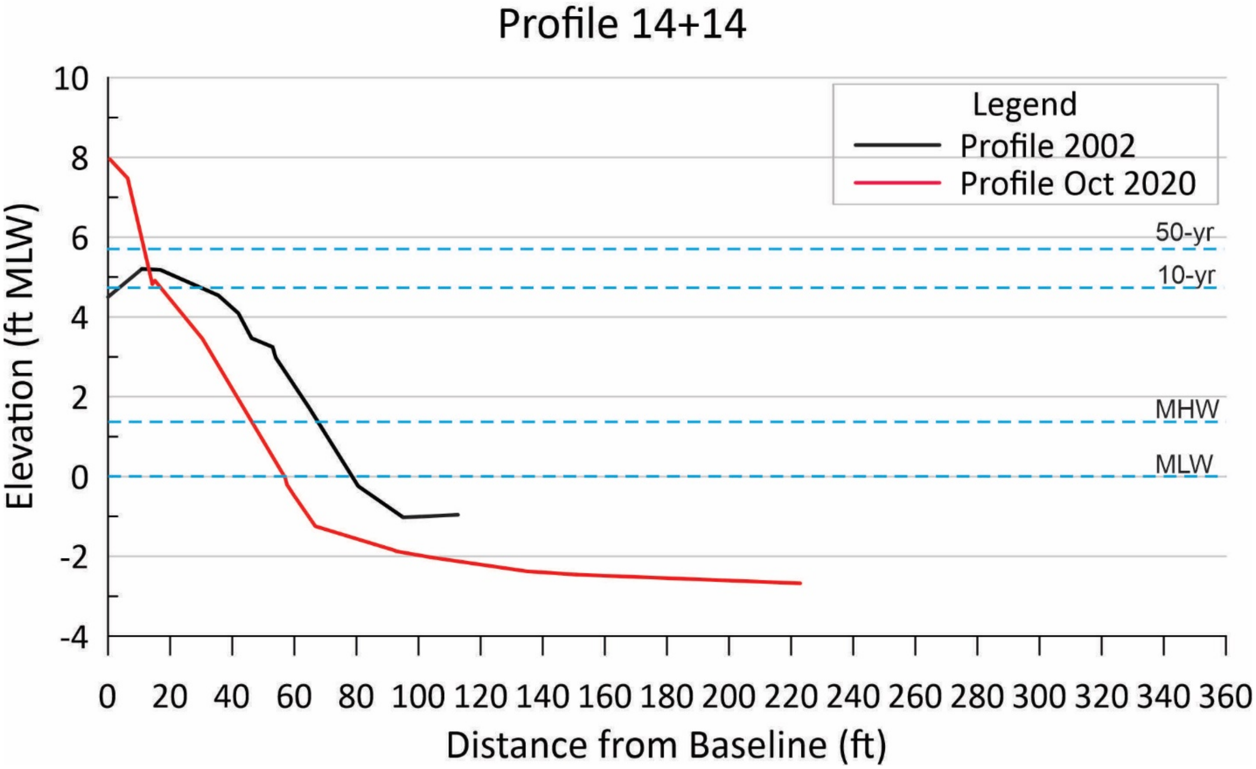


Figure 8-11. Cross-shore profiles at Haven Beach. Top: profile 11+65 crosses the small breakwater and shows the loss of the sand fill and landward migration of the shoreline after construction of the project. Bottom: profile 14+14 is just south of the small breakwater shows the change between 2002 and 2020.

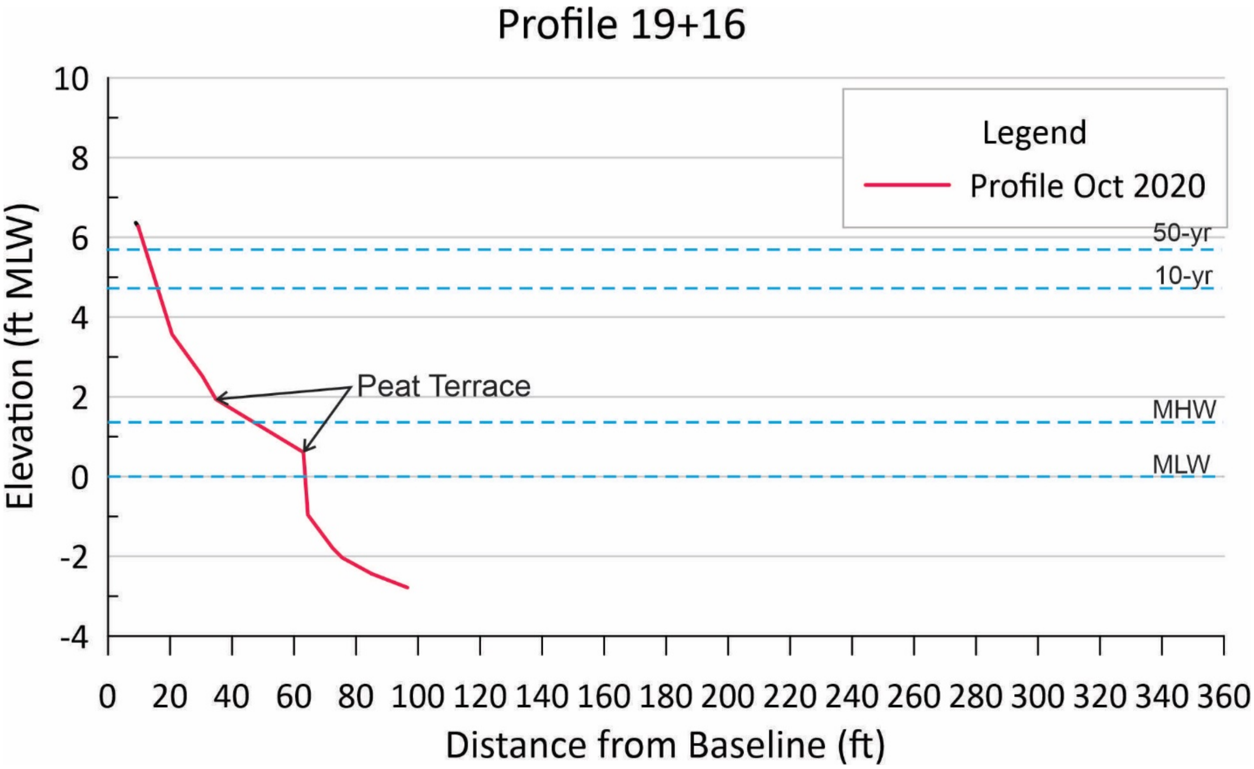


Figure 8-12. Cross-shore profile 19+16 at Haven Beach south of the breakwaters shows the wide peat terrace that occurs.

Figure 8-13. Ground photos showing the shoreline (top) and dune (bottom) north of the large breakwater. Photo credit: Shoreline Studies Program, VIMS.

Figure 8-14. Ground photos showing the tombolo behind the large breakwater. Photo credit: Shoreline Studies Program, VIMS

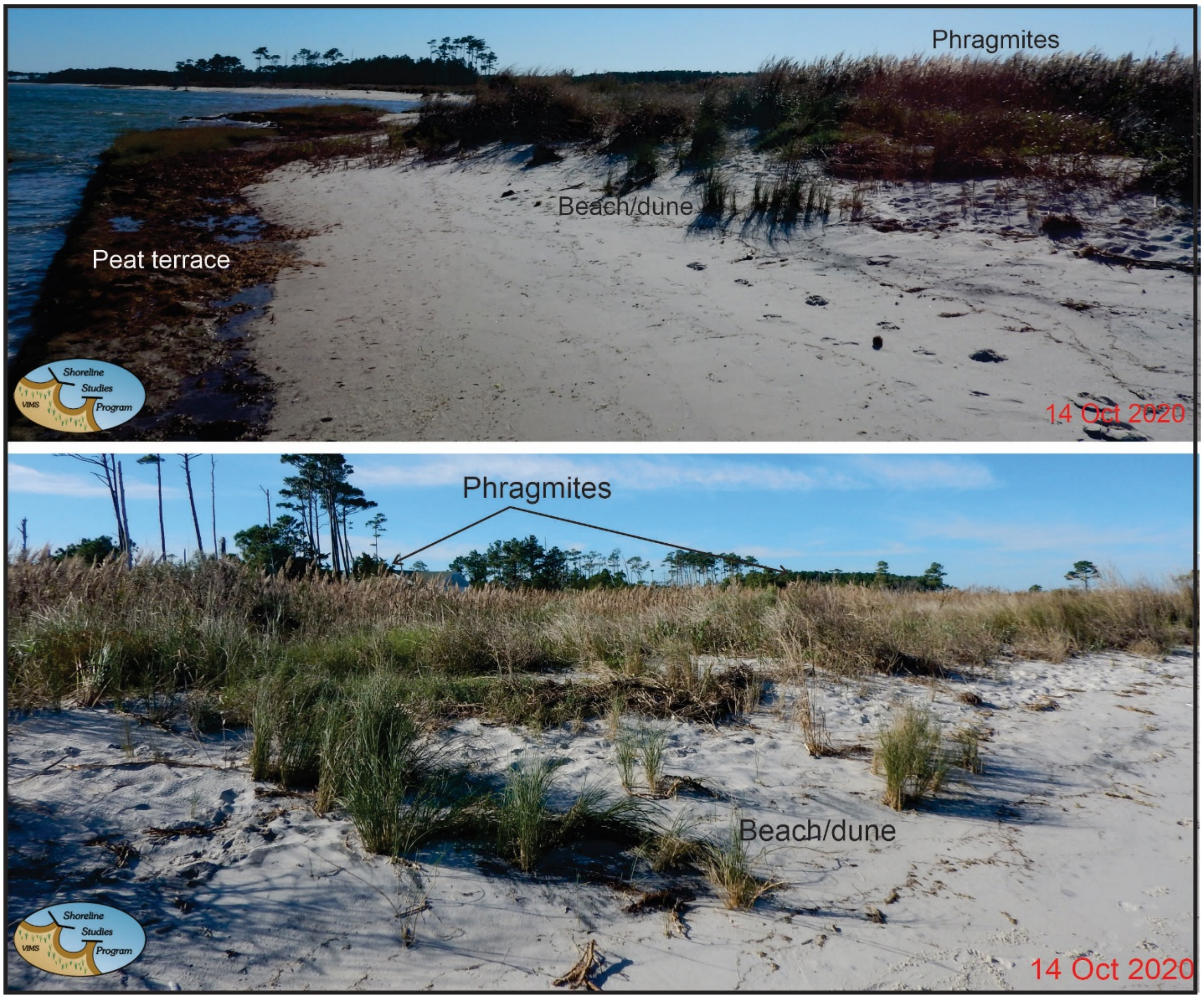


Figure 8-15. Ground photos showing the reach of shoreline south of the breakwaters. Top shows the peat terrace and the low beach/dune behind it. The bottom photo shows the low beach/dune with the Phragmites immediately adjacent in the marsh. Photo credit: Shoreline Studies Program, VIMS.

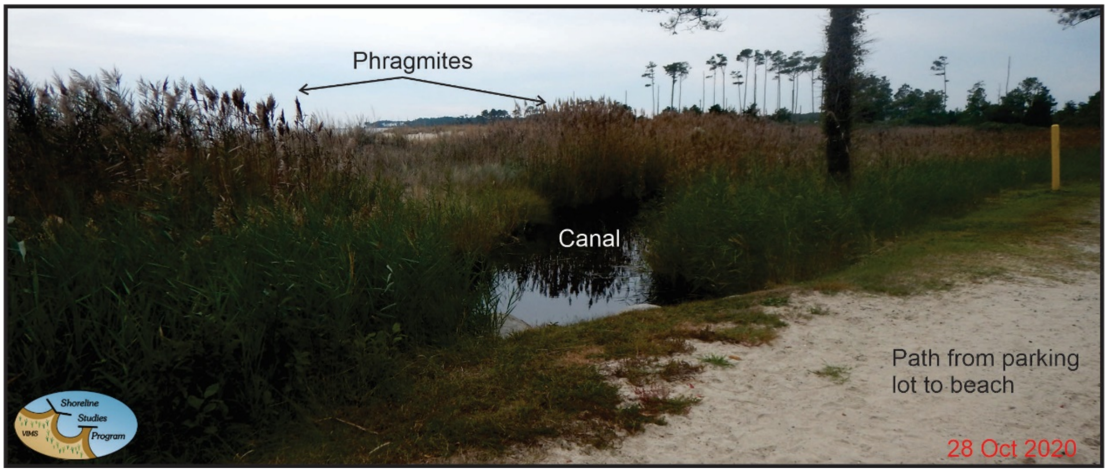


Figure 8-16. The marsh behind the beach has a great deal of *Phragmites australis* growing. Photo credit: Shoreline Studies Program, VIMS.

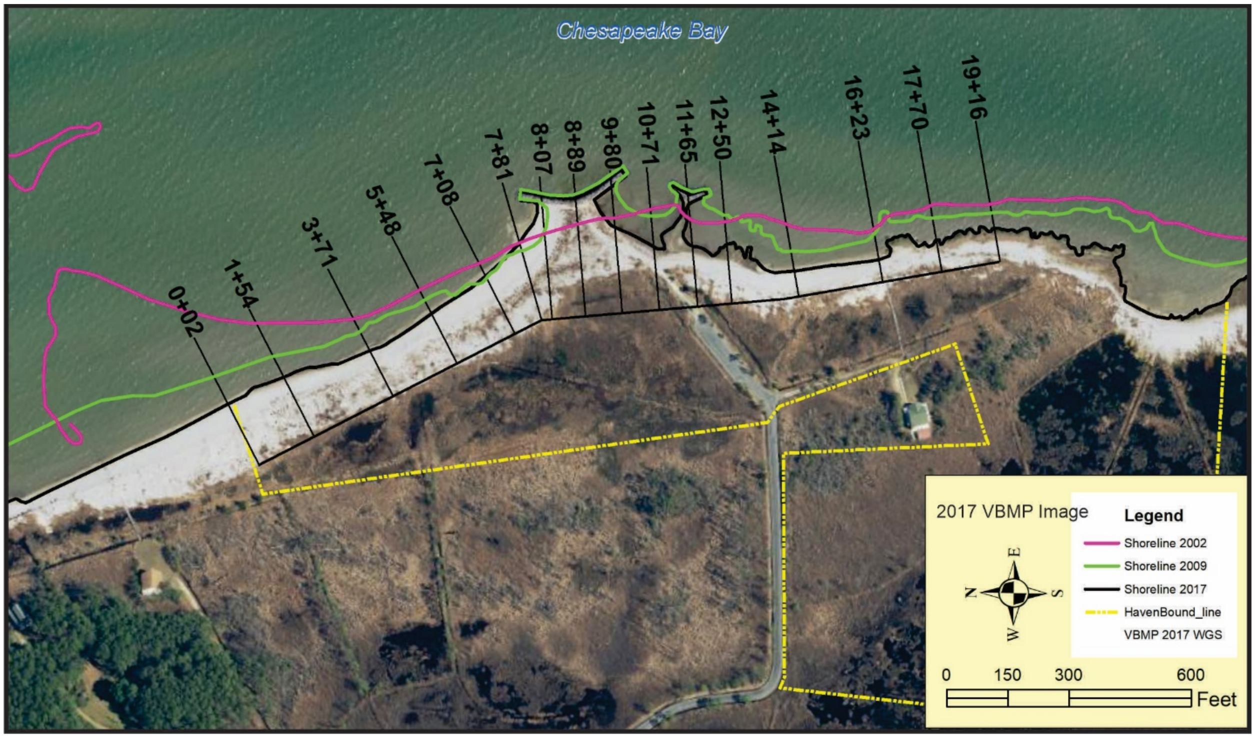


Figure 8-17. Recent digitized shorelines, 2002, 2009, and 2017, from the Shoreline Studies Programs' shoreline change database. In 2002, the morphology of the northern section of the site was affected by the Rigby Island remnant which has complicated the change along this shoreline.

9 Hull Springs Farm, Westmoreland County

9.1 Site Background

Hull Springs Farm in located in Westmoreland County, Virginia and belongs to Longword University (Figure 9-1). It is located at the confluence of Glebe Creek and Aimes Creek, both tributaries to the Lower Machodoc Creek. Lower Machodoc feeds into the Potomac River. It occurs on a peninsula and is surrounded by water on three sides. The long-term rate of change between 1937 and 2017 is very low (<-1 ft/yr) along the eastern side of the peninsula and shows accretion due to the sill construction on the western end (Figure 9-2). In 1937 and 1969, a sand spit occurred at the mouth of Glebe Creek (Figure 9-3). This created a low fetch environment (about 0.5 miles) for Hull Springs Farm. Once the spit eroded, as shown by the 1994 shoreline, the fetch increased to 1.5 miles as the farm faces northeast directly out the mouth of Glebe Creek.

In 2006, the shoreline had an undercut high bank with an eroding base of bank and narrow fringe marsh adjacent to the farmhouse and 400-year-old historic oak tree (Figure 9-4). The bank decreases in elevation to the north and becomes a low bank with old concrete bulkhead (Figure 9-5). The end of the bulkhead is being flanked. This shoreline was part of the Lower Machodoc Shoreline Management Plan (Figure 9-6) created by Longwood University and the Northern Neck Planning Commission to provide guidance to homeowners on where living shorelines could be constructed. According to that document, the site qualified for an H-2 recommendation, marsh fringe with sill.

A conceptual design was created by Shoreline Studies Program (Figure 9-7) and typical cross-sections were drawn by Bayshore Design for the permit application (Figure 9-8 and 9-9). Two low sills were designed to protect the upland bank and create a marsh. The sill was designed to be higher and narrower on the ends at 2 ft wide and +2 ft MLW as shown by typical cross-sections AA and DD. In front of the existing concrete bulkhead, the sill is lower and wider (+1 ft MLW and 5 ft wide) as shown on section BB. The tide range at the site is 1.8 ft so the ends of the sill extend above MHW, but the middle of the sill is intertidal (Figure 9-8). Cobble was placed in the gaps to prevent sand salient formation as shown on typical section CC. The cobble extended from +3 ft MLW to 13 ft riverward of MLW (Figure 9-9).

Due to Tropical Storm Ernesto in 2006, the base of bank was significantly impacted, and the nature of the long-term erosion was dramatically revealed. The wave-cut bank scarp from the storm was 6 ft high and eroded 1 to 2 ft in some areas (Hardaway et al., 2017). It was evident that the proposed sill was not sufficient for immediate protection of the base of bank since continued erosion would threaten the old oak tree on top of the bank. The design was modified to include a stone revetment in the vicinity of, and adjacent to, the old oak to ensure that the historic tree on top of the bank was not impacted by bank erosion during storms (Figure 9-9).

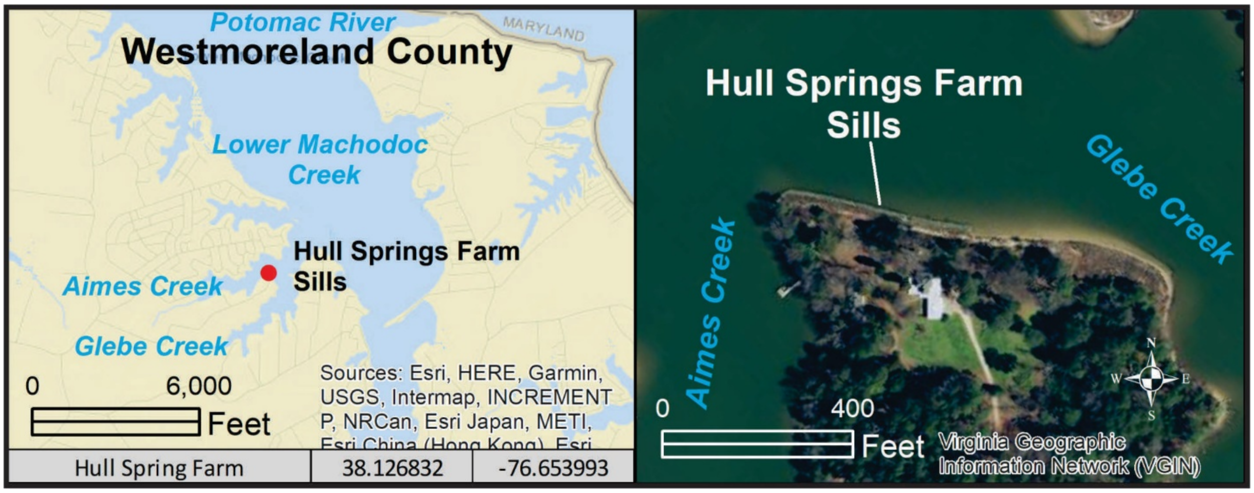


Figure 9-1. Location of Haven Beach living shoreline breakwater shore protection system.

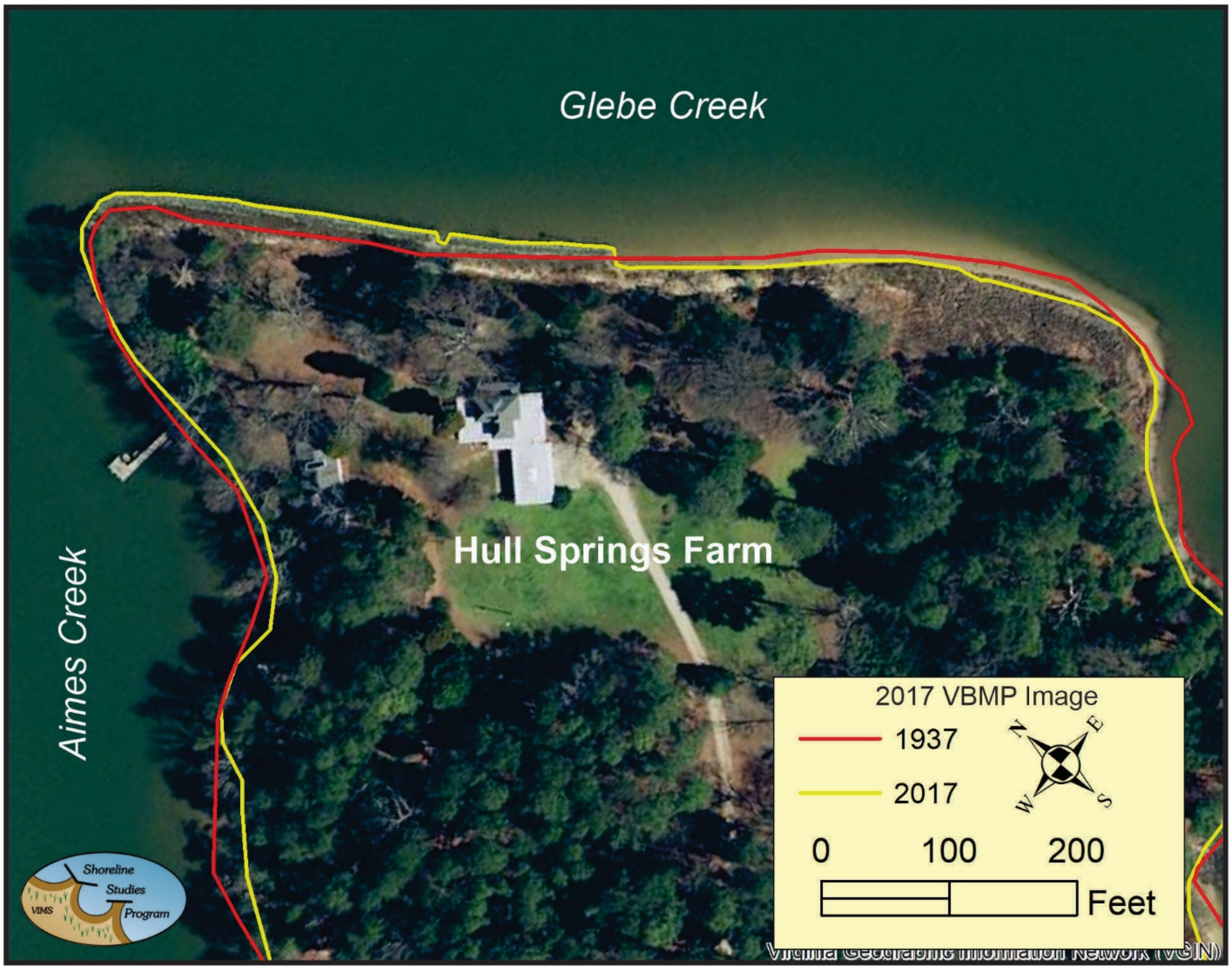


Figure 9-2. Shore change between 1937 and 2017 at Hull Springs Farm. Digitized shorelines from the SSP shoreline change database.

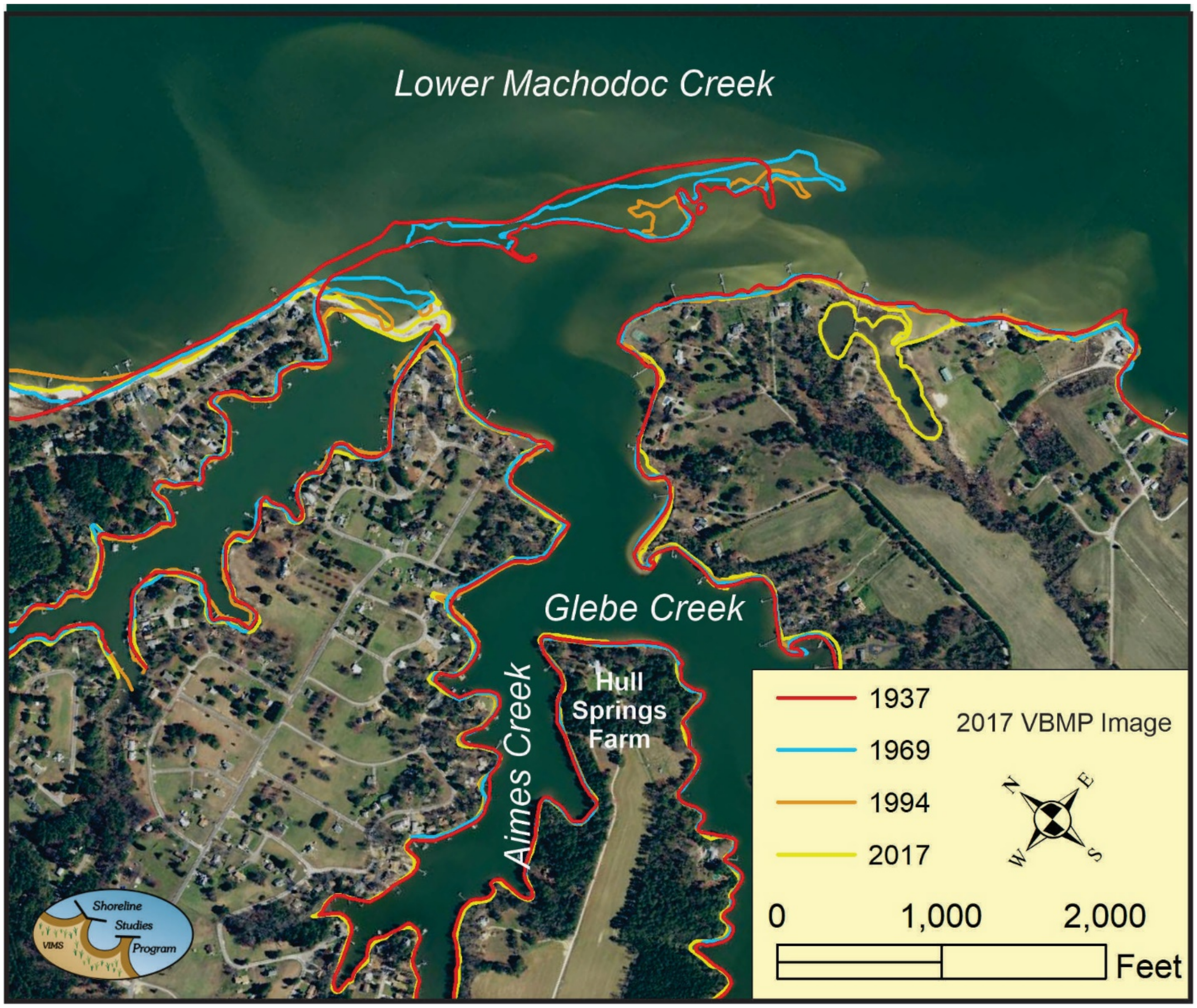


Figure 9-3. Digitized shorelines in 1937, 1969, 1994, and 2017 along the Lower Machodoc Creek and tributaries. The sand spit that occurred across the mouth of Glebe Creek in 1937 and 1969 had eroded away by 1994 increasing the fetch at Hull Springs Farm. Digitized shorelines from the SSP shoreline change database.

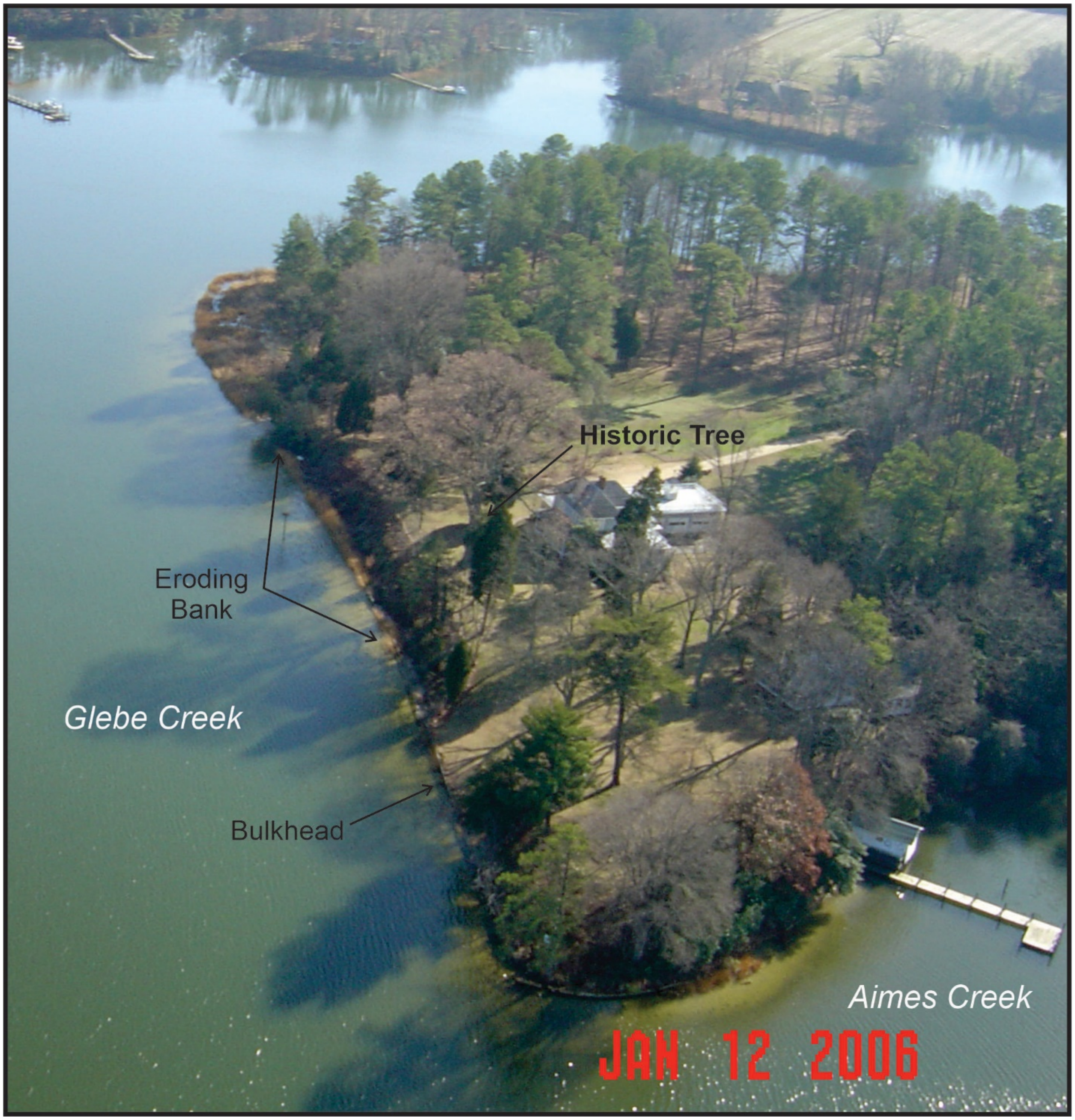


Figure 9-4. Aerial photo of the peninsula that Hull Springs Farm sits on. The shoreline has a high eroding bank and a failing bulkhead. The historic tree was a key part of the project design. Photo credit: Shoreline Studies Program, VIMS.

Figure 9-4. Ground photos of the Hull Springs Farm shoreline. Top: the western section of shoreline has a failing bulkhead; Bottom: Post Ernesto: the center section of the peninsula has an eroding base of bank and a fringe marsh. Photo credit: Shoreline Studies Program, VIMS.

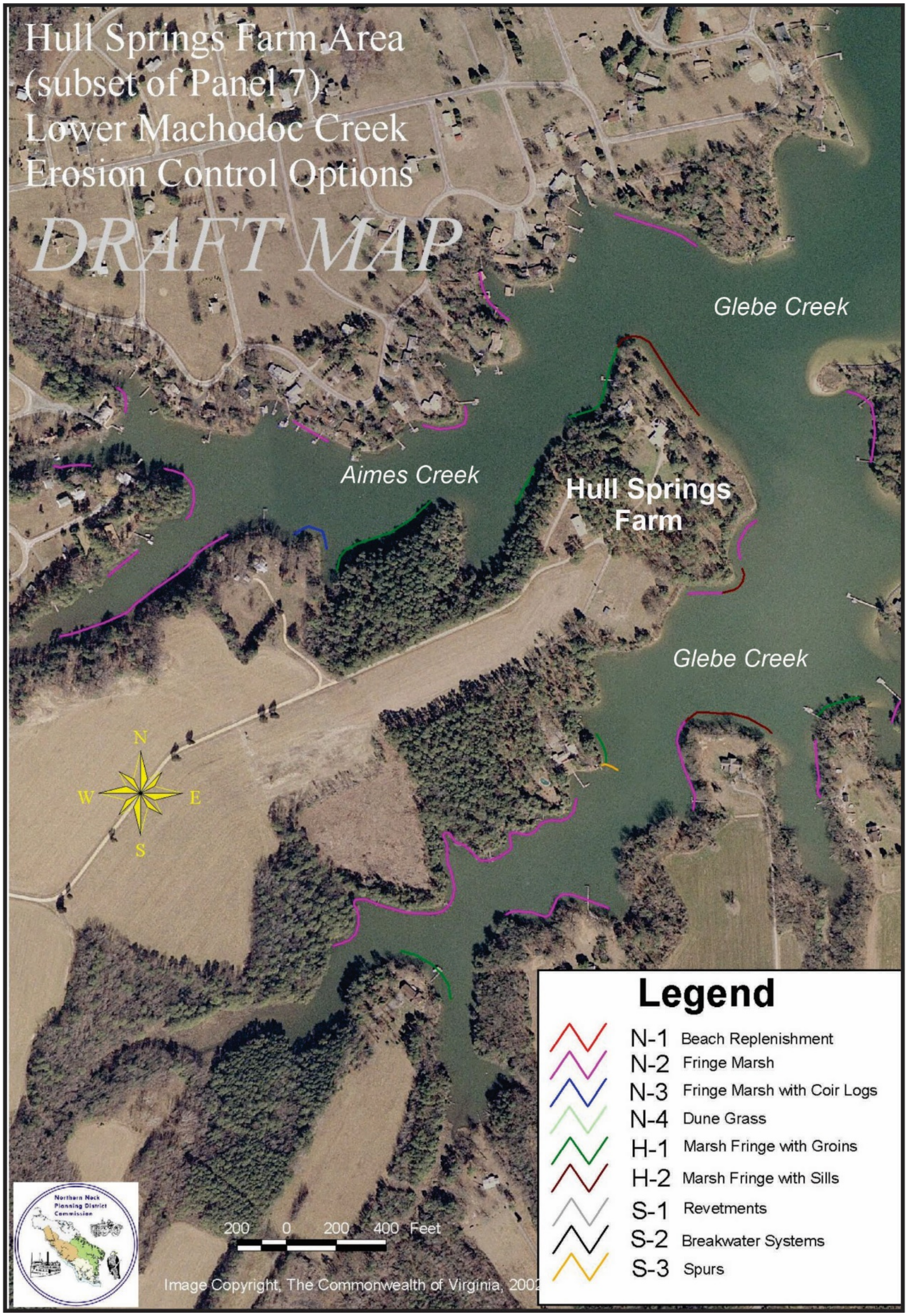


Figure 9-6. Lower Machodoc Creek Living Shoreline Management Plan created by the Northern Neck Planning District Commission.

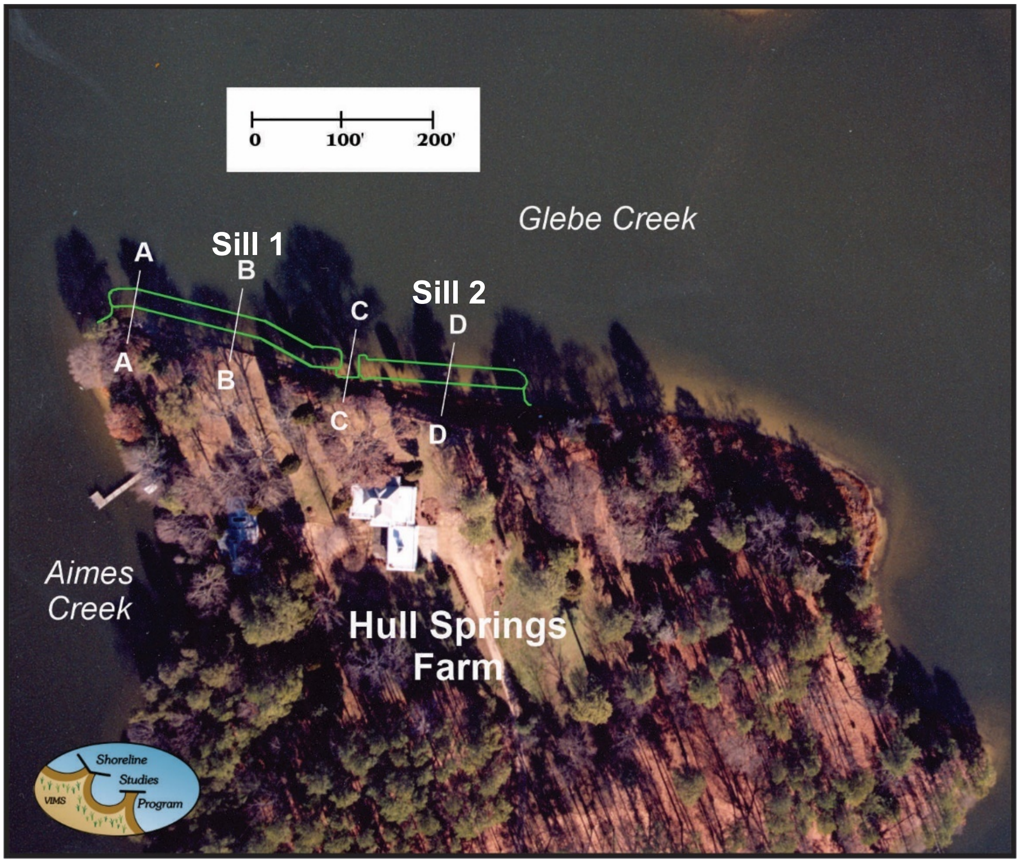


Figure 9-7. Conceptual plan for Hull Springs Farm shown in green and the location of the typical cross-sections used in the permit drawings.

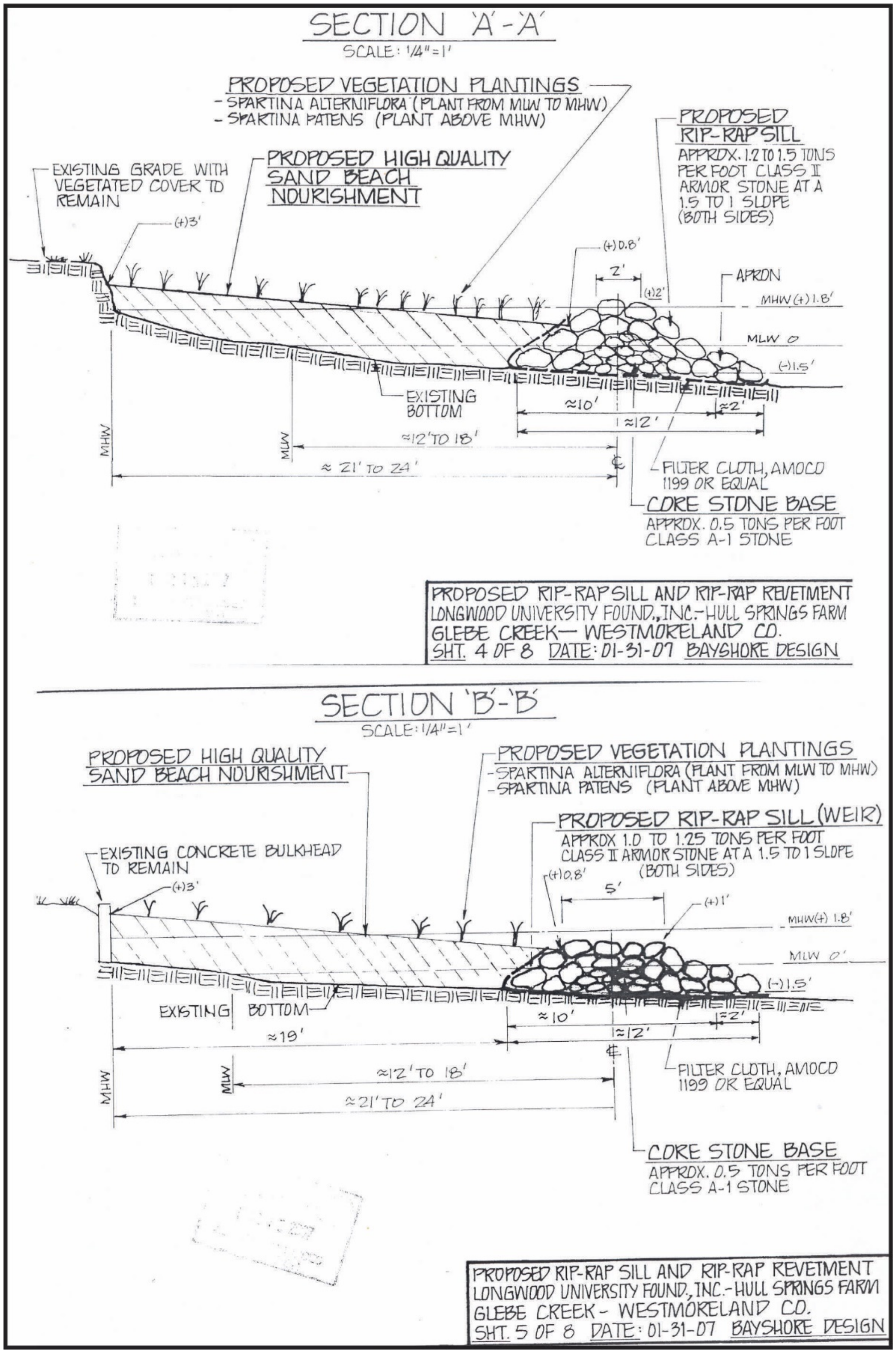


Figure 9-8. Typical cross-sections AA and BB for the living shoreline project at Hull Springs Farm. AA is the westernmost section. BB shows the sill along with the existing concrete bulkhead. Cross-sections courtesy of Bayshore Design.

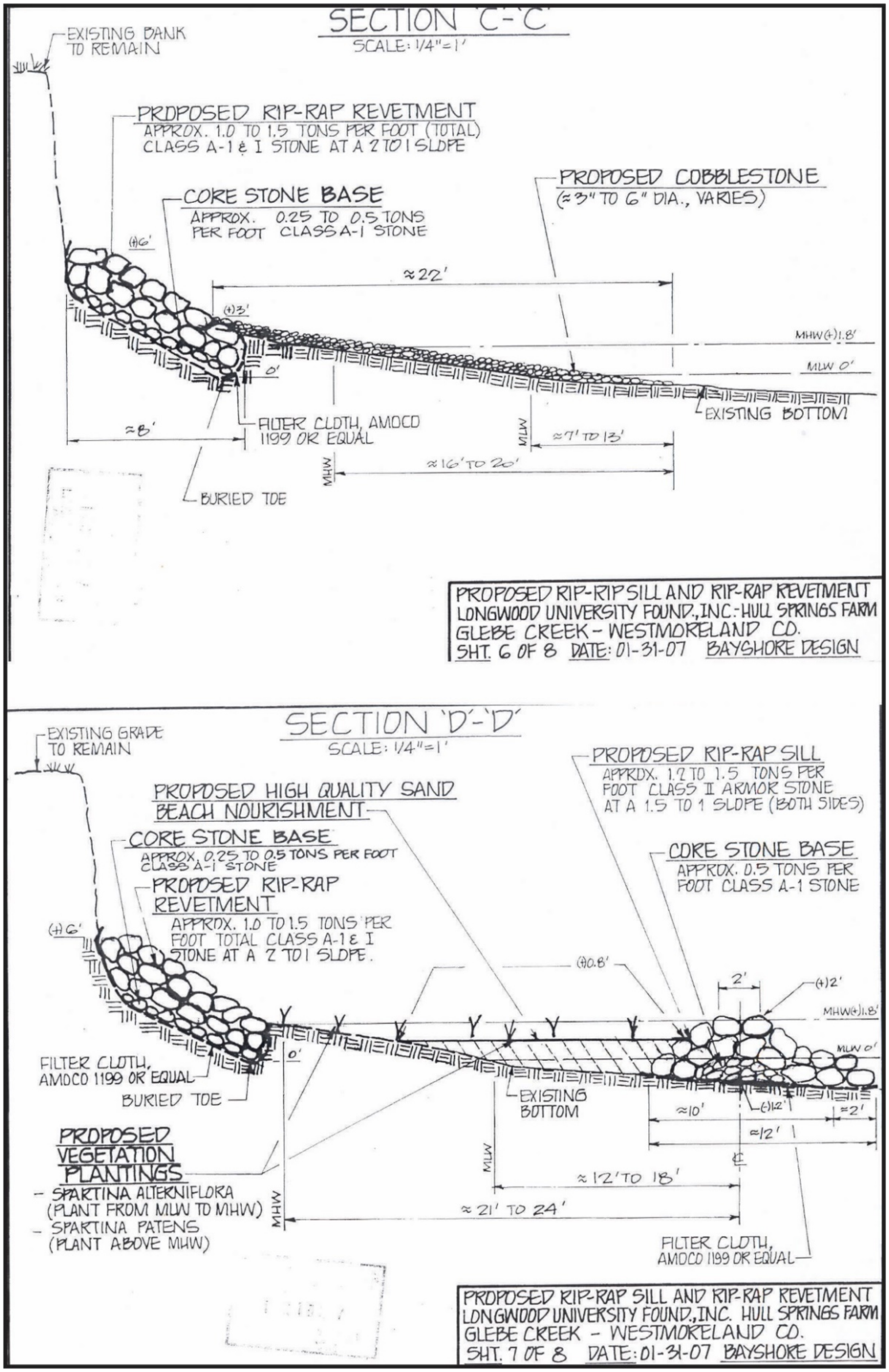


Figure 9-9. Typical cross-sections for the Hull Springs Farm Living Shoreline project. CC shows the cobble gap, and DD shows the revetment at the base of bank as well as the sill. Cross-sections courtesy of Bayshore Design.

9.2 Site Performance

The Hull Springs Farm sill was built in late summer 2008 along about 300 ft of shoreline. It was built as designed with the sill built in front (waterside) of the revetment (Figure 9-10). The existing concrete bulkhead remained, and sand was filled to almost the top. The trees on the bank were limbed but not cut down. Low marsh (*Spartina alterniflora*) and high marsh (*Spartina patens*) grasses were planted on a 1.5 ft x1.5 ft spacing after the sand had a chance to equilibrate for several tidal cycles.

After about six months, the low marsh was growing well, but the high marsh was not as lush (Figure 9-11). The site was performing as designed six years after installation in 2015 (Figure 9-12). The low marsh behind sill 2 was lush. The bank had slumped covering the revetment, but it also was vegetated which provides additional protection. This historic tree, which was estimated to have started growing in 1595 CE, was well protected from erosion. The high marsh did not grow as well as the low marsh (Figure 9-13). Though scrub/shrub were starting to grow at the higher elevations, the *Spartina patens* that were planted were relatively sparse. This is likely due to overhanging trees that were beginning to shade the high marsh. At this point in time, no *Phragmites* occurred at the site.

The shoreline was surveyed on 19 November 2020 (Figure 9-14). No previous data could be located. The cross-sections are shown, and the revetment is highlighted in teal on the map. Generally, the position of MHW is closer to the base of the upland bank and MLW is on the sill structures. Figures 9-15 and 9-16 show the cross-sections of the profile data. Profiles 98 and 181 cross Sill 1. The bank height ranges from 11-13 ft MLW. The sill was built to design with a crest elevation of about +1.8 ft MLW (Figure 9-15). Profile 259 crosses the shore through the cobble gap (Figure 9-16). The base of the revetment is at about +2 ft MLW. The bank is at about +16 ft MLW behind Sill 2.

Twelve years after installation, the sill structure remains intact (Figure 9-17). In addition, the low marsh has nearly 100% coverage behind sill 1. The upper limit of *S. alterniflora* was measured at about +1.5 ft MLW. Two other marsh species have colonized into the site, black needle rush (*Juncus roemerianus*) and three-square bulrush (*Schoenoplectus pungens*). The upper limit of black needle rush was measured at +1.6 ft MLW. Tide range is 1.8 ft MLW. The high marsh has more vegetation than in previous years behind sill 1, but bare spots occur. The scrub/shrub has grown into the backshore in this area. The cobble gap is vegetation free and allows access to the water (Figure 9-18). However, with time, the invasion of *Phragmites* along parts of Sill 1 and Sill 2 forced the Longwood University to initiate an eradication program which killed much of the healthy marsh grass too (Figure 9-19). The backshore is bare in areas as the native vegetation tries to recolonize those areas. Still, most of the marsh away from this area is intact.

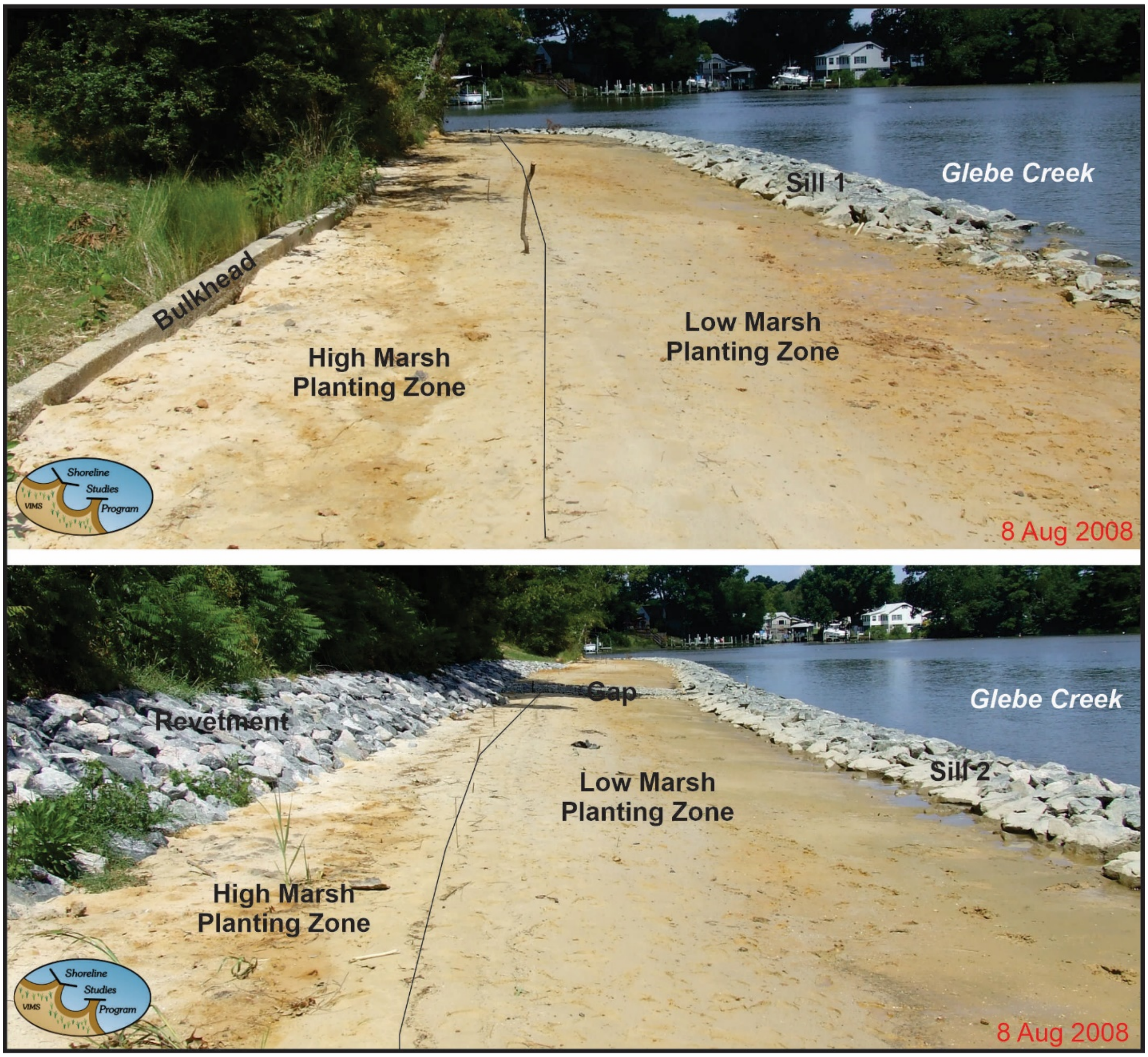


Figure 9-10. Post construction ground photos showing the low and high marsh planting zones. The marsh was planted soon after.

Figure 9-11. Hull Springs Farm living shoreline after about 1 year. The elements were constructed as designed, and the low marsh has filled in well. Photo credit: Shoreline Studies Program, VIMS.

Figure 9-12. Hull Springs Farm about 6 years after construction. Top: Sill 2 has lush low marsh behind the structure, but the high marsh is not as vegetated. Bottom: The bank has slumped over the revetment. The sediment is vegetated which adds additional stability to the bank to protect the historic tree. Photo credit: Shoreline Studies Program, VIMS.

Figure 9-13. Hull Springs Farm about 6 years after construction. Top: The backshore where the upper marsh should be does not have as much grass vegetation as the low marsh. Bottom: The low marsh is doing well behind sill 1. Photo credit: Shoreline Studies Program, VIMS.

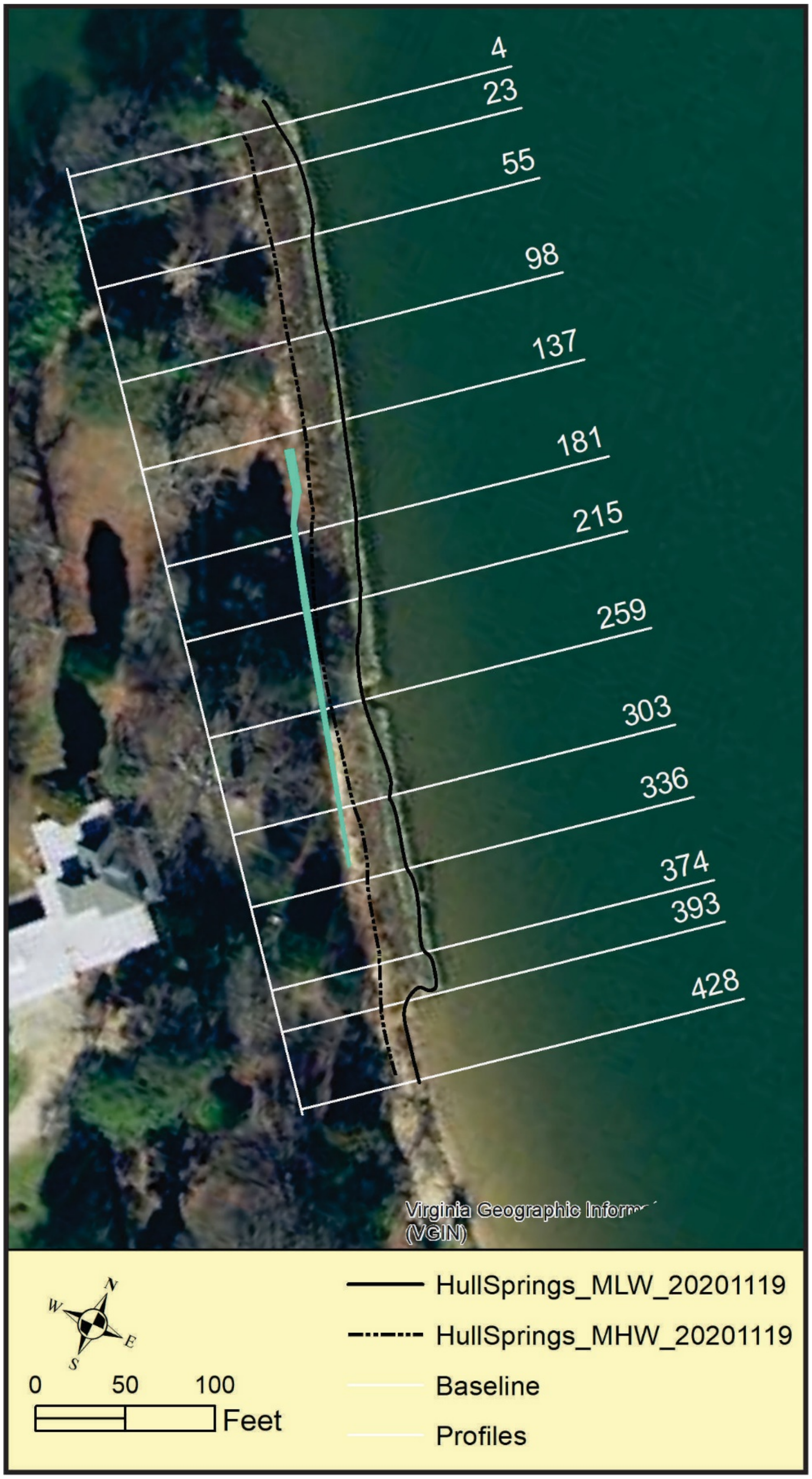
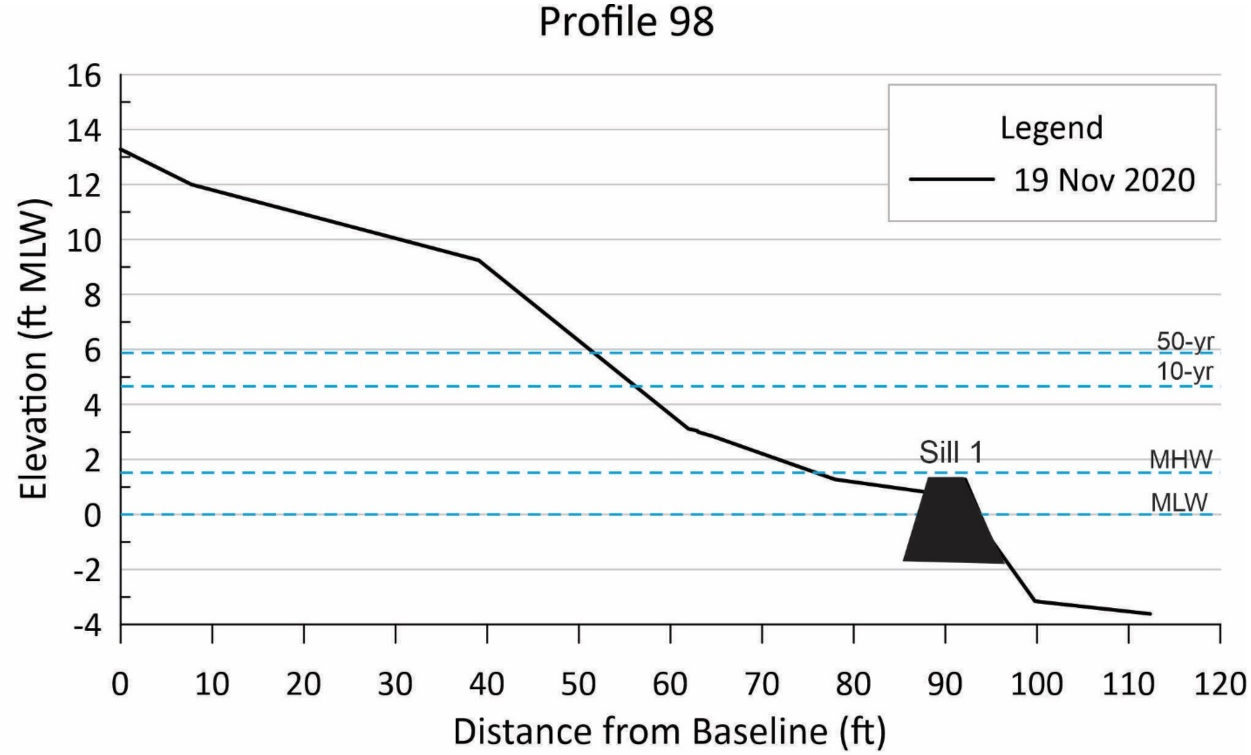


Figure 9-14. The position of MHW and MLW from the 2020 survey. Also shown are the profile cross-section locations. The location of the revetment is highlighted in green.



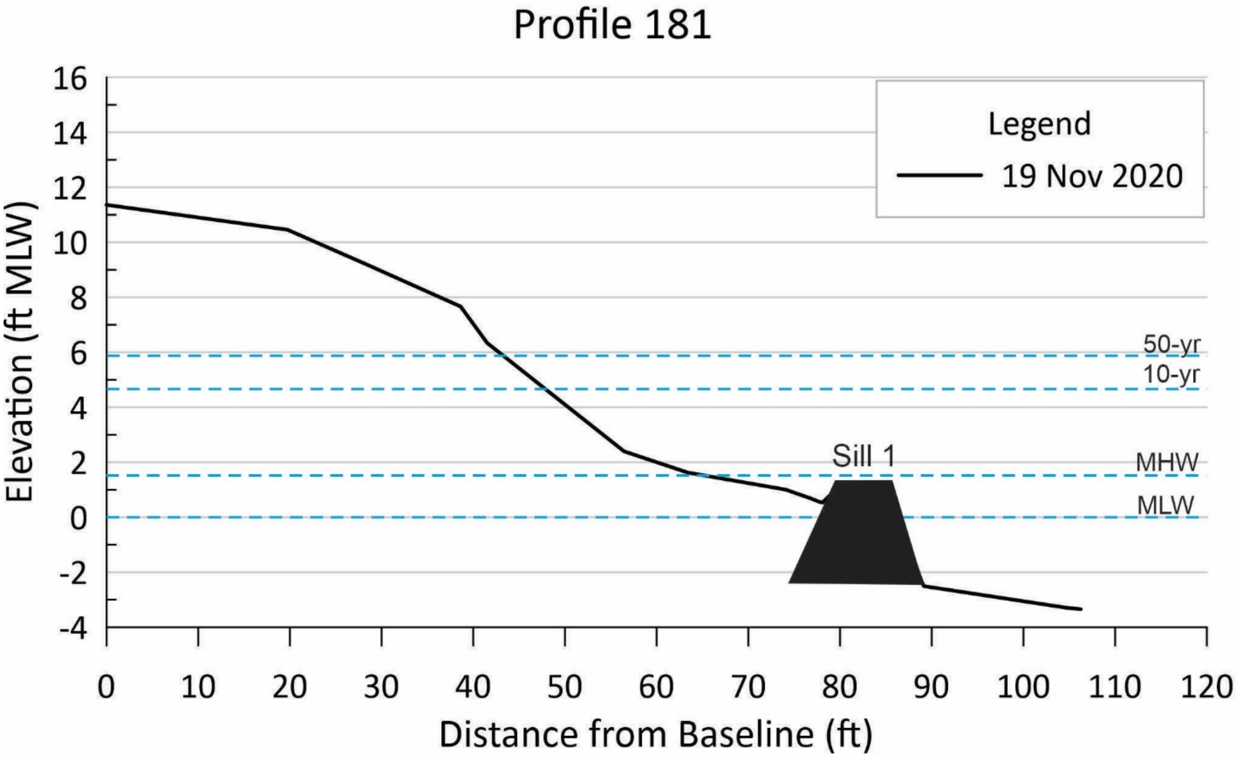
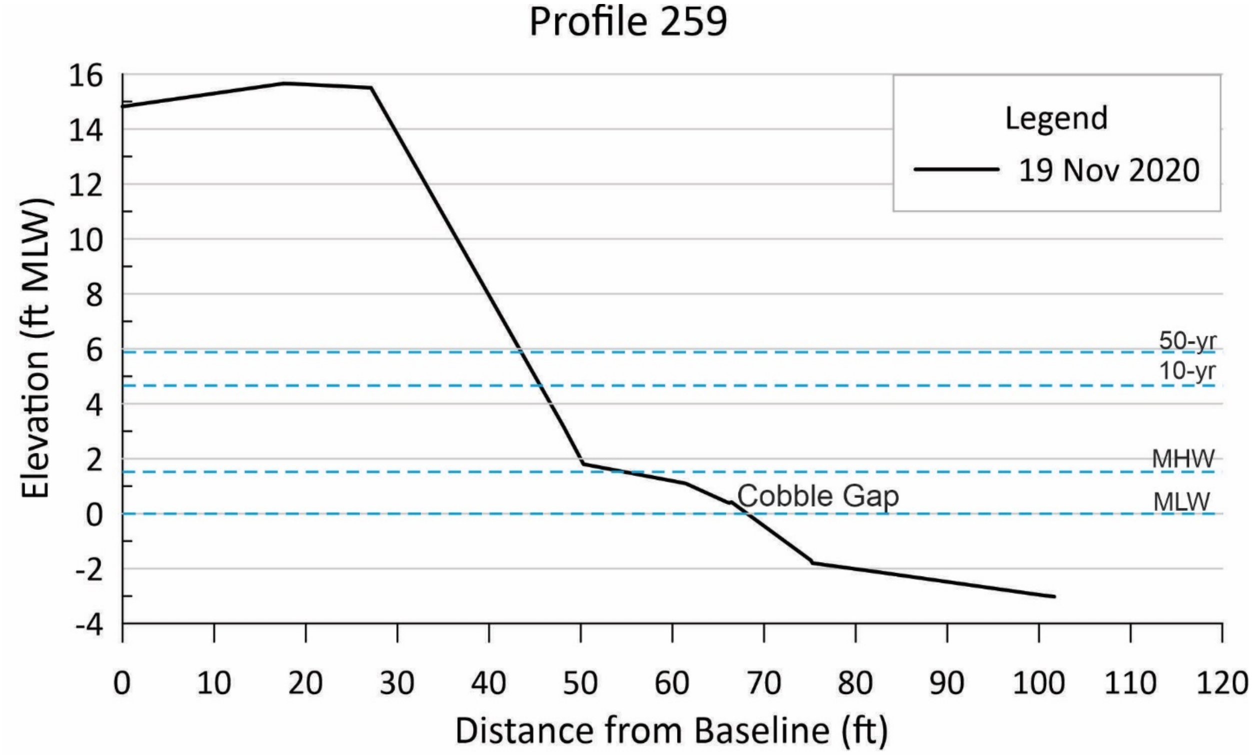


Figure 9-15. Profile cross-sections from Hull Springs Farm taken on 19 November 2020. Profiles 98 and 181 cross Sill 1.



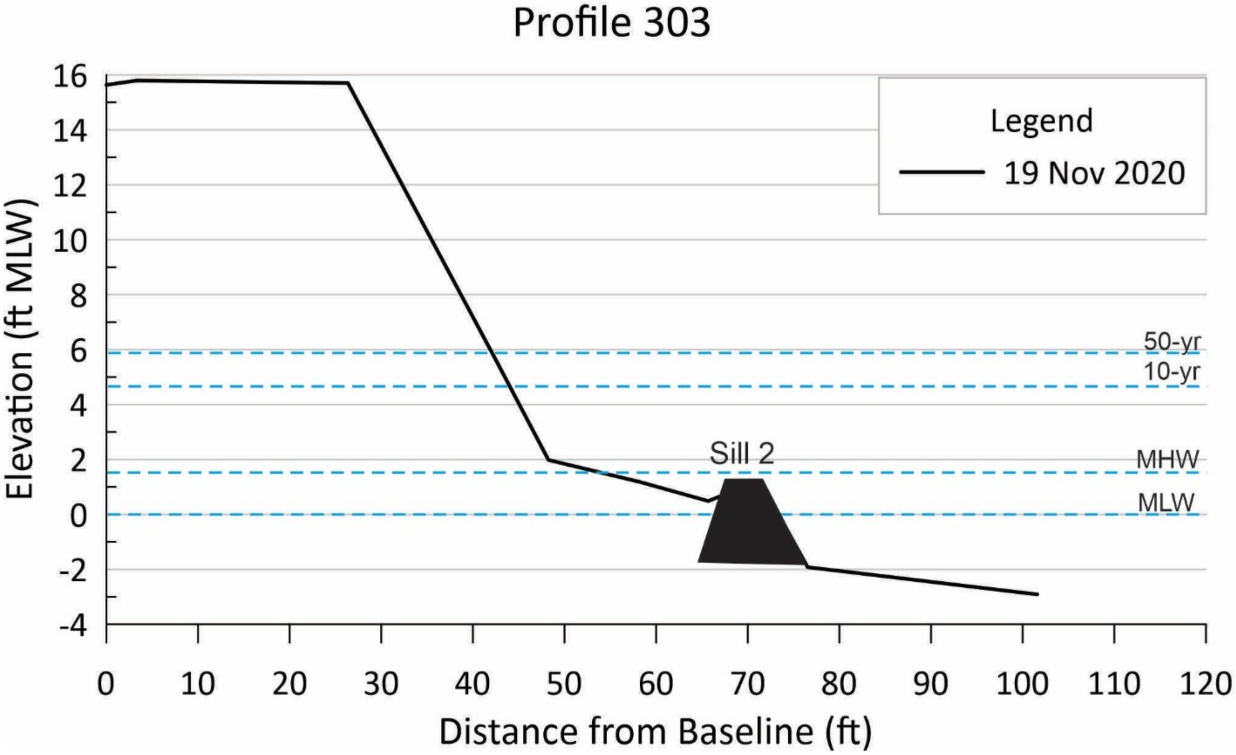


Figure 9-16. Profile cross-sections from Hull Springs Farm taken on 19 November 2020. Profile 259 crosses the cobble gap between Sills 1 and 2 and Profile 303 crosses Sill 2.

Figure 9-17. Ground photos of the site after 12 years showing the low marsh and high marsh areas of the sill. Photo credit: VIMS, Shoreline Studies Program.

Figure 9-18. Ground photo of the site showing the cobble sill gap. Photo credit: VIMS, Shoreline Studies Program.

Figure 9-19. Bare spots behind the sill where *Phragmites* was eradicated and native grasses have not grown back yet. Photo credit: VIMS, Shoreline Studies Program.

10 Adaptive Management for Coastal Resiliency

Adaptive management strategies allow the incorporation of ongoing monitoring to determine the approaches based on the current available techniques and research. Incorporating new assessments and actions throughout the project life will determine adaptive options and the timing of the response. (ref?)

10.1 Coastal Resiliency Assessment

10.1.1 Site-Specific Capacity for Resiliency

Determining a shore protection system's capacity for morphologic resiliency should occur during the design phase for new systems and throughout the life of the project especially for those that are already installed. The US Army Corps of Engineers' adaptive management philosophy allows for the implementation of strategies that range from a conservative anticipatory approach, which constructs a resilient project at the beginning of the project life cycle, to a reactive approach, which consists of doing nothing until the impacts are experienced. The goal is to assess the system for stability and performance under the selected future water levels. Each site requires its own plan for the future and as always, cost is a factor.

For the type of hybrid living shorelines studied in this report, in the simplest terms, resiliency is tied to the elevation of the structure and whether or not the marsh can migrate/accrete. Hardaway et al. (2018 & 2019) found that adding rock and sand to the system is a viable alternative to extend the life of these shore protection projects by increasing the elevations of both the structure and the marsh. To determine how best to address coastal resiliency at a site, these questions could be asked:

- Is the system designed to provide wave protection at increased water levels?
    - Most shoreline protection systems are engineered to address a certain level of protection such as a 25 year or 50-year storm. The structure must be tall enough to address the impinging wave climate, and the sand should slope up and intersect the bank at a predicted storm surge elevation so that under increased water levels, waves attenuate across the marsh/beach and do not break on the upland bank. As sea level rises, the structure and upper limit of sand slope must increase to maintain the design level of protection.
- Are structures designed for the increased water levels that bring a consequent increase in wave energy to the shoreline?
    - Sea-level rise will affect structures due to changes in loading, runup, and overtopping. As sea level rises, structures that encounter depth-limited waves will be exposed to ever-increasing wave heights. With increased wave heights, structures may be under-designed for increased loading (USACE, 2014). Various elements of the design can be affected, including the armor unit size, crest elevation, crest width, side slopes, and toe projection. Higher crest elevation, wider crest-widths, and larger footprints may be needed to keep a project functional as sea level rises.
    - Another concern is that increased water levels will produce an increase in depth-

    limited wave height (USACE, 2014). Because rubble-mound armor unit stability is proportional to the wave height cubed (H^3), a relatively moderate increase in water depth produces a much higher load on armor units. Generally, these design considerations pertain to larger rock structures in more exposed wave energy settings. However, the basic premise is the same even at lesser wind wave climate and, as such, could be a concern for the future stability of structures along the shoreline particularly for those structures that are undersized.

- Will addition of rock and/or sand change the design parameters of the system thereby reducing the system's effectiveness?
    - This is a concern particularly for existing systems because adding a layer of armor rock will not only raise the elevation but also widen and lengthen structures. This could affect the Lb:Gb ratio as the gap between the structures shrinks which should actually be a benefit to the wave diffraction processes at play. Adding sand in the embayments will help maintain the Mb:Gb ratio.
- What is the elevation of the upland immediately adjacent to the system?
    - On low banks, marshes can migrate up the bank, but on high banks, marshes will be squeezed unless the bank is graded.
    - To accommodate some level of sea-level rise or provide a plan for future adaptation, the most cost-effective approach is to protect lower banks where bank grading costs are less. For higher banks, grading the bank to a gentler slope, such as a 4:1 slope rather than the minimal 2:1 slope, would create a platform over which the marsh can migrate laterally landward more effectively. However, in developed areas, this may not be practical due to the distance landward that the bank would have to be graded. Generally, very high banks cannot be easily graded due to the lateral distance needed as well as having to dispose of a great deal of excavated material.
    - For ungraded and graded high banks, the projects are in more of a "coastal squeeze" situation. Though the system could be moved farther offshore to gain a lateral gradient, this would be difficult to permit and costly. The only other option is to address the vertical growth component by adding rock and sand to create a higher system.
- What is the coverage of plants in the marsh?
    - Plant height and density are positively related to the marshes ability to dissipate wave energy (Gedan et al., 2011), which can increase sediment capture (as long as there is sufficient sediment supply) for overall marsh accretion.
    - Determining why bare spots occur in the marsh is required because it will provide the action needed to remedy the situation. If the bare spot is due to shading, trees can be trimmed. If it is due to the low elevation of the marsh substrate which causes flooding, additional sand may be needed to raise the elevation. Overland or spring freshwater flows may be affecting marsh growth and may need to be redirected.
- How wide is the upper marsh?
    - Wider upper marshes provide room for the marsh to migrate. Design parameters such as the distance of the structure offshore and the slope of the sand fill can be adjusted to balance high and low marsh plantings as needed to address coastal resiliency concerns.

- Are nutrients affecting the marsh?
    - Nutrients, possibly from agricultural fields and septic tanks can reduce marsh grass coverage because the nutrients affect root growth. However, *Phragmites* thrives in these conditions and will colonize the system.
    - However, Gedan & Fernández-Pascual (2019) found that marsh migration into some abandoned farmlands produced a larger variety of plant communities. As these fields become more saline, the plant communities are influenced by both the natural marsh communities as well as the cultivation legacy. These patterns suggested that abandoned, saline agricultural fields may develop somewhat differently than natural marsh boundaries, with more shrub dominance and greater resilience to *Phragmites australis* invasion.
- Are sediments readily available?
    - In areas where much of the shoreline is protected, particularly with bulkheads and revetments, the coastal system may lack an adequate sediment supply to allow the marsh to accrete vertically. In such areas, placing sediment (sand) in the existing marsh (and possibly replanting) would increase the overall marsh elevation.

10.1.2 Identifying When Action is Needed

The effectiveness of a shore protection system may decrease over time due to an increase in sea level, a lack of maintenance, and changes in vegetation. The project’s decline in performance may happen slowly over time so that it is not easily recognized, or it may happen quickly during a storm. Understanding the short-term and long-term effects of hazardous events on the living shoreline is crucial to determining when action is needed. Short-term events can result in a reactive approach to resiliency because there is usually little time before the event to address potential impacts.

Longer-term effects due to an increase in sea level must also be considered. Knowing the flood risk for the system If the system was not installed recently, the structural integrity of the structures should be observed. The structures could have been constructed with rock that is not sized correctly to the elevated energy levels impacting the site. This could lead to a failure of the entire system. Typically, most rock structures have adequate rock sizes for the 50-year to 100-year storms (See breakwater database). Additional long-term considerations are tree growth in the upper marsh and upland, loss of marsh grasses or change in vegetation.

Maintenance

Maintenance is critical for the success of a living shoreline project. Keeping the shore protection system at its most effective is the best way to negate impacts from short-term hazardous events. Regularly maintaining the site will provide needed information to determine when the system’s effectiveness needs to be addressed.

The erosion resistant marsh and dune grasses are an important component of the living shoreline. Maintaining these are crucial to the success of the overall system. Routinely replanting vegetation as needed, trimming tree branches to reduce shade on the marsh (depending on the native vegetation’s sunlight requirements), removing debris that can smother grasses, and removing any invasive species, such as *Phragmites australis* are all items that need to be addressed by the property owner.

Phragmites australis

Phragmites australis (common reed) is one of the most widespread invasive species in wetland habitats of North America. It can tolerate a wide range of salinities allowing it to spread to many areas of the Bay. Both juvenile and rhizome-grown plants have low mortality when salinities are less than 15‰ within rooting depth (Lissner & Schierup, 1997). Three-fourths of the rhizome grown plants survived salinities up to 22.5‰, but only about 12% of the juvenile plants survived at such high salinities. No *Phragmites* plants survived at salinities 35‰ and higher (Lissner & Schierup, 1997). Because of *Phragmites'* salt tolerance, it can affect shorelines in the rivers and from about mid-Bay north.

Sciance et al. (2016) found that agricultural land use and shoreline armoring were significant predictors of *Phragmites* occurrence. Invasion by *Phragmites* can negatively impact wetland structure and function by altering dynamics in fish (Jones et al. 2014; Jones and Able 2015), terrapins (Cook et al., 2017), and birds (Prosser et al. 2017). However, the consequences of invasion may not all be negative because *Phragmites* patches are not biological deserts, especially for some animals (Kiviat, 2013; Dibble and Meyerson, 2014). The high growth rate of *Phragmites* may also contribute to sequestration of carbon and nitrogen (Kiviat, 2013) and enable wetlands to keep pace with sea-level rise and minimize resulting wetland loss (Rooth and Stevenson, 2000), which may be especially important in regions where the rate of sea-level rise is high.

The mechanisms behind the rapid expansion of *Phragmites* have been particularly well studied in Chesapeake Bay brackish tidal wetlands, and three key factors appear to promote local expansion (Prosser et al., 2018). First, natural and human-related disturbances create physical spaces where seedlings can become established. Second, multiple genotypes are present because *Phragmites* can only produce seeds by cross-pollination between different genotypes (Kettenring et al. 2011). Third, elevated nitrogen levels promote expansion because seedlings grow faster, and more flowers are produced which results in higher seed production (Kettenring et al., 2015). Meschter (2015) found that *Phragmites* roots are significantly deeper than native marsh grass communities which gives them the ability to utilize deeper nitrogen pools and take up nitrogen from deeper depths. This enhanced rooting structure gives the invasive *Phragmites* the ability to potentially access lower salinity water, as well as tap nutrients unavailable to native marsh plant communities. Research suggests that minimizing nutrient loading into coastal marshes could be an important factor in slowing the spread of common reed into the low marsh zone as global temperature rises (Legault et al., 2018).

Some sites may want to remove the *Phragmites* to allow the native vegetation a chance to recolonize the system. Hazelton et al. (2017) investigated whether management efforts to remove *Phragmites* may act as a disturbance, potentially fostering reinvasion. The research indicated that if passive revegetation is the primary means of restoration, the species that re-establish themselves will likely be similar to those species present in the local subestuary especially *Phragmites*. The prolific and resilient *Phragmites* may require diverse treatments, such as mowing, grazing, and burning, or active revegetation. If spraying *Phragmites* is the only option, research results suggest that herbicide treatment must continue in perpetuity (Hazelton, 2018).

Elsey-Quirk and Leck (2020) found that planting native vegetation to outcompete *Phragmites* seedlings and total removal of *Phragmites* to cut off the seed supply may be necessary for successful longer-term restoration and establishment of native species.

10.2 Determining Strategies for Adaptive Management

All of the thirteen systems studied for this research project have been functioning as designed, no matter if they were recent installations or if they are 30 years old. From a habitat perspective, these systems have both flora and fauna utilizing the shore. Other marsh grasses and upper marsh scrub/shrubs have colonized some of the older sites such as Jefferson Patterson Park & Museum in St. Mary's City, Hull Springs Farm, Occohannock on the Bay, and VIMS West. Some sites have grown overhanging trees that need to be limbed. All the sill sites have shellfish attached to the rock, SAV in the nearshore, and crabs, turtles, and fish utilizing the protected marsh and the rock pore space. The high bank sites, Jefferson Patterson, Kingsmill, Occohannock on the Bay (both low and high sections), St. Mary's City, and Werowocomoco had no discernable bank erosion. Hull Springs Farm and VIMS East have a revetment/bulkhead behind the living shoreline structures, but they did not have bank erosion either.

Some sites do have individual issues that should be addressed. For example, one of the breakwaters at Aquia Landing is sinking due to a soft bottom. It is still holding sand, but as sea level rises, that section of shore may need to be addressed first. At Occohannock on the Bay, the sand in one section behind the sill adjusted to a lower elevation, and marsh grass will not grow in the area. At Haven Beach, the lack of funds during construction resulted in a breakwater that is too short to protect the shoreline and as such has lost all the sand behind it. St. Mary's City, Jefferson Patterson, and Hull Springs Farm have *Phragmites* growing on the site. St. Mary's City and Jefferson Patterson have not addressed the issue, but Hull Springs Farm is actively trying to eradicate it. Over time, all the sites must be examined to determine if any maintenance issues exist that can be rectified to enhance the sites shore protection capacity.

The potential strategies to enhance morphologic resiliency due to a rise in sea level can natural or nature-based measures for hybrid structural systems. Once the expected sea level is projected, the system components need to be looked at individually. For this project, a +2 ft rise in sea level is projected by 2050. A simplistic view is whether the site has a low or high bank landward of the project. Having a low marsh behind a project has fewer opportunities for morphologic resiliency than a higher bank does because the higher tide levels will cover the entire system. Having a higher bank does not allow for migration of the marsh and will "squeeze" and eventually overtop the system. To adapt to sea-level rise at these sites, it may be necessary to add rock and sand to the shoreline as well as re-establishing the marsh.

10.2.1 Low Bank

The sill sites that were examined for this project that have low banks are Captain Sinclair's Recreational Area and Occohannock on the Bay. The low bank breakwater sites were Aquia Landing, Bavon Beach, Haven Beach, VIMS West, and Yorktown.

When a sill system has a low backshore, adding rock to raise the elevation of the structure is not an option because the upland will flood (Figure 10-1). However, as the marsh migrates landward, an intertidal/subtidal shoal will develop landward of the rock structure. This would change the habitat from marsh to benthic bottom which could be inhabited by shellfish and SAV. The shellfish habitat could be enhanced with additional structures such as oyster castles or oyster bags. The rock structure will still provide some wave attenuation. The addition of sand when needed in the future, could give the marsh the ability to migrate vertically.

Breakwater sites that have a low shore can benefit from adding rock and sand to enhance morphologic resiliency (Figure 10-2). As the height of each structure is raised, the front slope extends farther bayward, and the structure gets longer. With a 2-foot increase, the breakwaters could each increase by 9 to 10 feet on each end resulting in an 18 to 20 feet increase in breakwater length. By closing the gap between the structures, the newly elevated beach planform will be further stabilized. The new armor should be at least 2-3 feet higher to accommodate the required rock size (1 to 2-ton armor stone). The shore planform can only adjust vertically with sea-level rise unless the system is moved offshore. Determining the cost of the rock and sand volume to move the breakwaters offshore is needed to find out if it is cost-effective.

Another option for raising breakwaters would be to add a rock/concrete block/rectangle along the crest. As an example, these could be on the order of 3 ft x 3 ft x 8 ft, weighing about 6 tons each. Dimensions placement would vary as needed at each site. These would simply be placed along the top of each unit, and, although expensive to "fabricate" in the quarry it may be cheaper than adding and constructing additional armor layers.

At several breakwater sites, low barriers occur along the back of the beach to protect the access road. In addition to raising the elevation of the barrier to better hold the larger sand volume, the access road will have to be raised as well. Several sites may lose access as sea-level rises, particularly during short-term storm events.

At energetic beach/dune breakwater sites, having excess sand in the system whether from beach fill or from the alongshore transport system, led to development of higher, wider dunes that protect the low marsh backshore. Sea-level rise will affect the marsh due to salt water intrusion which may need to be addressed in the future, but this future marsh loss would not have a direct impact on the breakwater, beach/dune shore protection system.

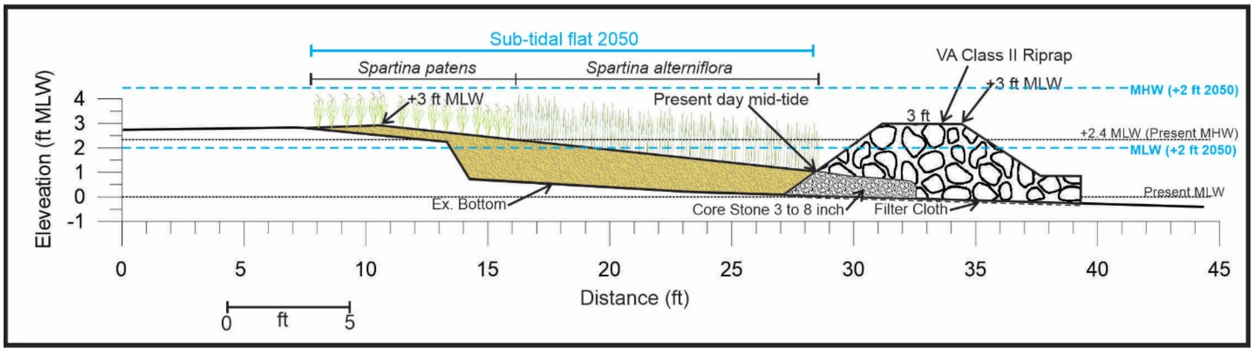


Figure 10-1. A typical low bank sill cross-section (Captain Sinclair Recreational Area) showing the design components as well as the projected sea levels in 2050 (blue). This low system is backed by a wide, low marsh so the marsh will be flooded, but the sill structure would become a nearshore reef. After Hardaway et al. (2018).

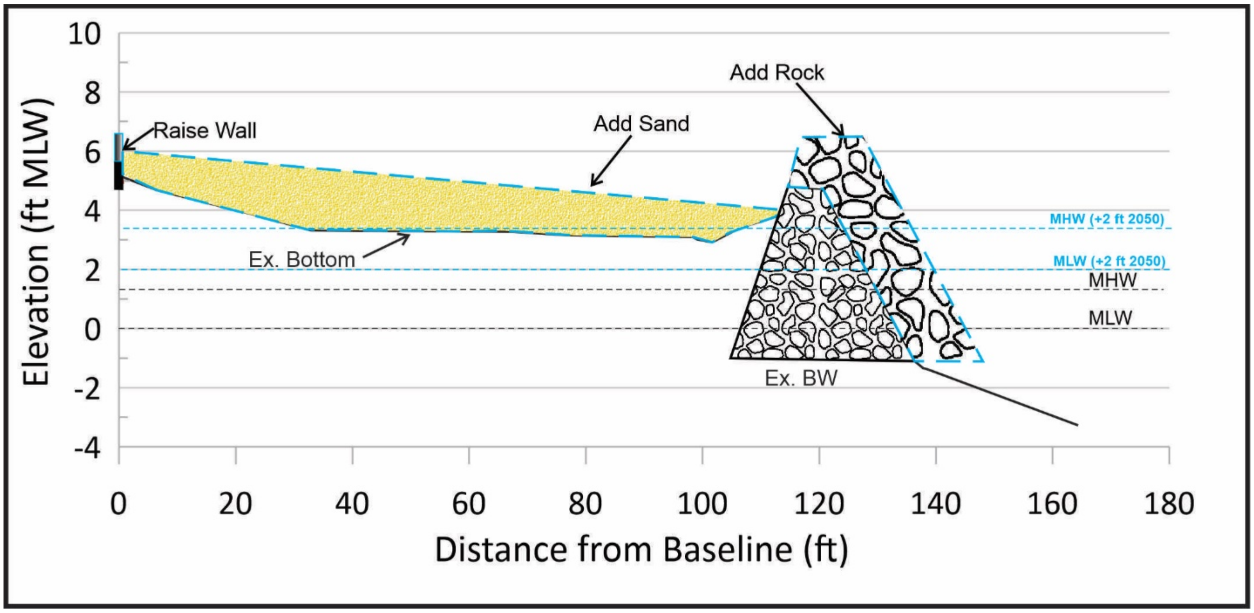


Figure 10-2. A typical cross-section of existing conditions at a low bank breakwater site (Aquia Landing). The system is backed by a low wall that could be raised to contain the added sand to adapt the system to 2050 projected sea levels (blue). Rock could be added to the breakwater structures. After Hardaway et al. (2019).

10.2.2 High Bank

The sills that had high banks included Hull Springs Farm, Jefferson Patterson Park and Museum. St. Mary's City, and Werowocomoco. The high bank breakwater sites were Kingsmill and VIMS East. Under the coastal squeeze scenario, the structures will require an increase in elevation with additional rock and sand as sea level rises because the marsh will not be able to migrate up the bank (Figure 10-3).

Both sills and breakwaters systems built adjacent to high upland banks can be enhanced morphologically with additional rock, sand, and plants as sea level rises. One important consideration is not only the elevation needed to maintain the marsh, but care should also be given to determining where the sand should intersect the bank. This is important to determining what the future level of protection will be. During storms, waves will attenuate over the structure and the gradual marsh slope so that the bank does not erode.

For some mid-sized banks, grading could be an option if infrastructure is not close to the shoreline (Figure 10-4). A 2:1 slope is generally recommended for stability, but if space allows, a 4:1 slope will allow more marsh migration up a gentler slope. However, the amount of material that will need to be disposed is a large consideration.

As with structures adjacent to low banks, when rock is added to structures adjacent to high banks and the height of each structure is raised, the front slope extends farther bayward and the structure gets longer (Figure 10-5). The new armor should be at least 2-3 feet higher to accommodate the required rock size (1 to 2-ton armor stone). This also increases the structure's length reducing the width of the gap between the structures which will help stabilize the beach. When beach fill is added to the bays, ensuring that it meets the Mb:Gb parameter is important. This added sand also increases the beach and backshore width to help accommodate an evolving dune system. At some sites like Kingsmill, the breakwater system has remained relatively stable with extensive vegetative growth across the wide backshore including numerous trees such as cedar, pine, sweet gum, live oak and even cypress. These have the impact of shading out more the low grasses that are providing an erosion resistant turf. The trees will eventually die due to rising sea level, with the possible exception of cypress and should be selectively thinned. The south facing shoreline will provide the necessary sunlight for a robust vegetative buffer.

As with any type of infrastructure, living shorelines need to be maintained and updated over time, so cost is a consideration. Some systems may require only minor morphologic adaptations to be resilient to sea-level rise. Others may require a complete rebuilding of the system on the same as the original project. Other sites may require additional adaptations such as raising adjacent back barriers and roads. It is site-specific and a plan should be developed over the life of the project. Determining the cost of the rock and sand volume to adapt living shorelines to increase sea level is needed to find out if it is cost-effective.

As mentioned in the previous section, another option for raising breakwaters exists. Placing an appropriately-sized rock/concrete block/rectangle along the crest would increase height without enlarging the structure overall. Specific dimensions would vary by site. These would simply be placed along the top of each unit and although expensive to fabricate it could be cheaper than adding and constructing additional armor layers.

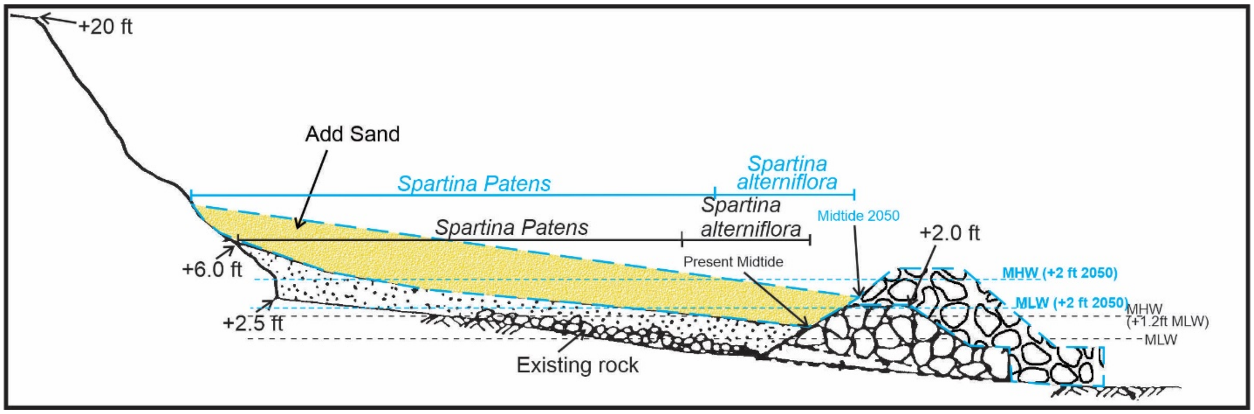


Figure 10-3. A high bank sill system (Jefferson Patterson) typical cross-section showing the design conditions at the site as well as the projected 2050 tide level (blue). Rock and sand can be added to the system to maintain its effectiveness. To not squeeze the system, rock would need to be added to the outside of the structure. After Hardaway et al., (2018).

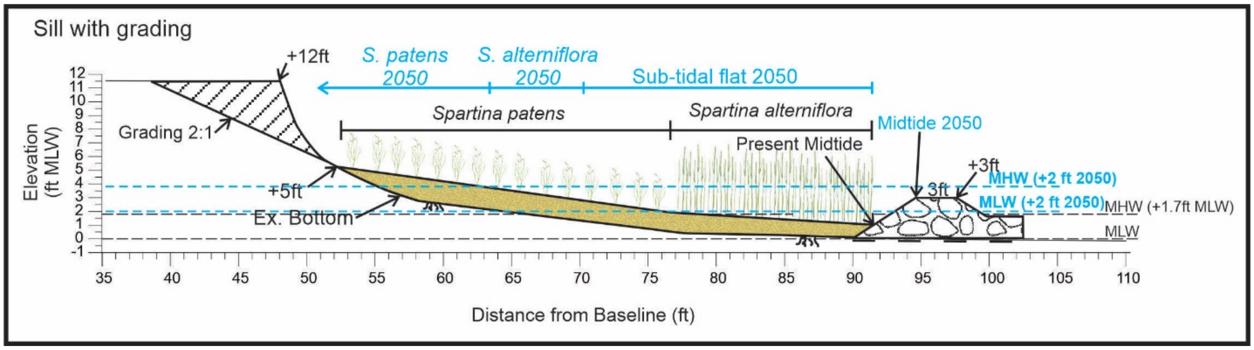


Figure 10-4. A high bank sill system typical design cross-section showing the adaptation to 2050 tide levels (blue). The top of the bank can be graded which will allow the marsh to migrate up the bank. The area behind the structure would become an intertidal and subtidal flat and only top of the structure would be at about mid-tide. Sill system at Occohannock on the Bay in Accomack County, after Hardaway et al. (2018).

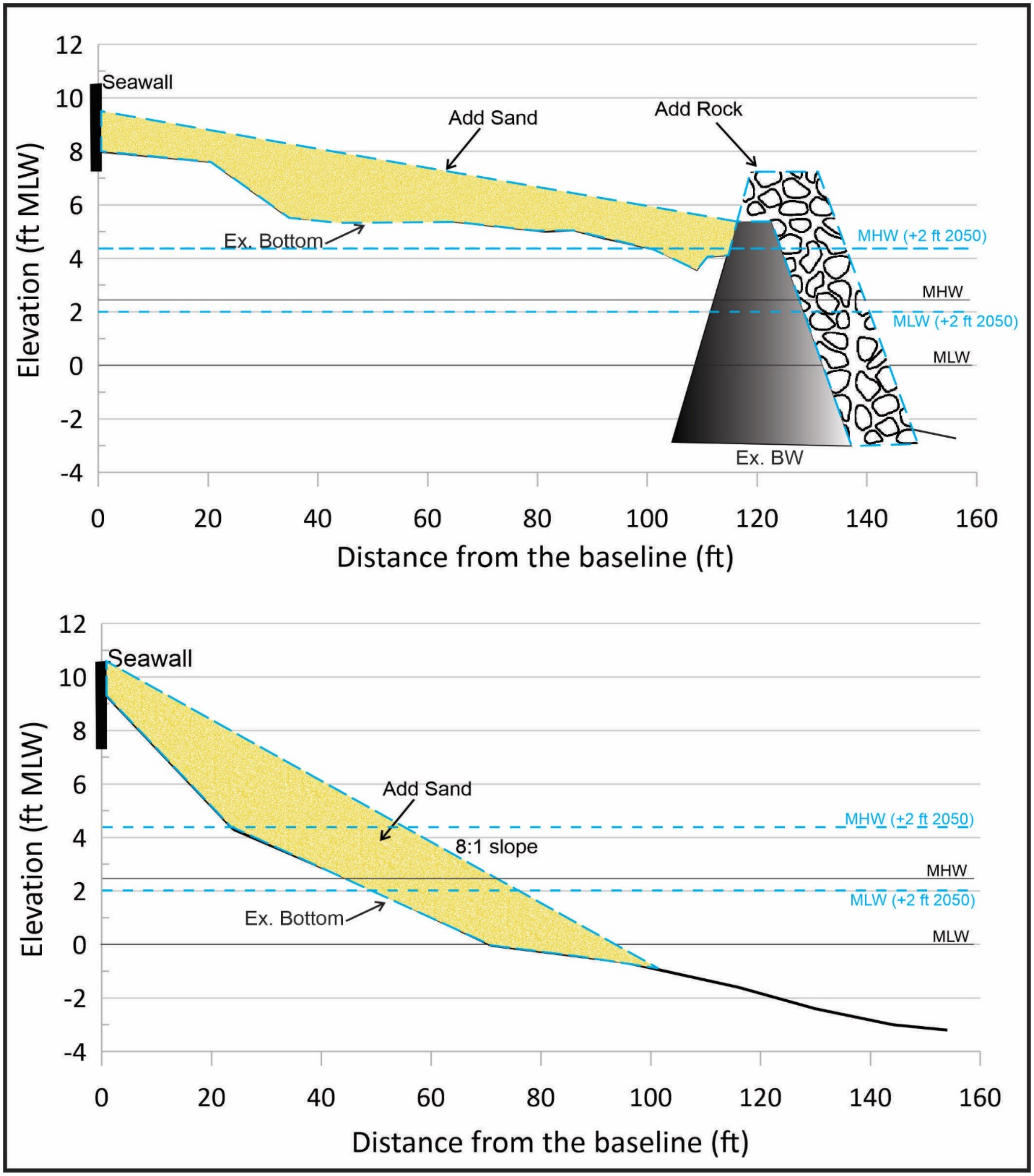


Figure 10-5. Existing conditions at a high bank breakwater site (VIMS East). The land continues to rise behind the seawall and infrastructure exists so the site could not be graded. To raise the elevation of the system to adjust for the projected 2050 tide level (blue) rock can be added to the structures. In addition, sand can be added behind the structures and in the embayments to enhance adaptability. After Hardaway et al., (2019).

11 Summary

Living shorelines are being used increasingly as method of shoreline protection in Chesapeake Bay because they provide shore protection and habitat enhancement along the coast. Understanding how these systems have evolved over time is critical to creating site-specific strategies to adapt for morphologic resilience. As sea-level rises, the sites will be impacted by higher water levels on a daily basis but also during short-term storm events. With more water, wave impacts increase. Determining how to respond to these issues is needed to maintain the effectiveness of the living shorelines because the resilience and protective benefits provided by coastal ecosystems against waves, floods and storm surge is very valuable. Loss of these wetlands through sea level rise could pose a real threat to coastal economies and water quality if they are lost.

Many living shorelines that utilize rock, sand, and plants occur that around Chesapeake Bay in a variety of settings have been installed at different times over the past 30 years. The thirteen sites studied over the course of this three-year project are just a sample in terms of site setting and age. However, by breaking the considerations down to a more simplistic view, general strategies can be developed. Fetch is used as an approximation of the wave energy impacting a site, which in turn drives design. The physical parameters, such as structure elevation and sand fill width, vary due to energy impacting the site and need to be determined for an effective system. Different considerations occur depending on whether the shoreline has a low backshore or a high upland bank. Low banks can provide a route for marsh migration, and understanding their succession trajectories can inform interventions to preserve native biodiversity, ecosystem services, and socio-economic well-being in landscapes affected by sea-level rise and saltwater intrusion. To adapt to rising sea-levels at high banks, the rock and sand have to increase in elevation over time to maintain the protected marsh and beach/dune habitats.

For existing sites, the process of determining how to adaptively manage living shorelines for morphologic resiliency should occur over the life of the system. Ongoing maintenance of the site informs this process. However, for new projects, the question becomes when is the addition of rock and sand to the living shoreline most timely? Should it be done when it is needed or should the system be overdesigned for present-day conditions. This would increase the cost of the system but may save money over the long-term. The anticipatory strategy includes designing crest elevations to reduce impacts of future or grading property for marsh migration. However, this is a risk because of the uncertainty in the future. They may not be needed in the future, or they may cost more now than adaptive strategies in the future.

Reactive strategies wait to react until the project is in dire jeopardy generally due to shorter-term storm events. At that time, it may be more difficult to act due to lack of preparation. In addition, costs may be more expensive by waiting until action is needed immediately. However, using an adaptive management strategy has relatively low possible consequences because, as future changes occur, they can be addressed with a cost-effective, responsive plan (USACE, 2014). The plan should consist of strategies such as adding rock, sand, and plants to the system to enhance adaptability. Another option is to design shore protection using FEMA's 500-year storm event rather than the 50 year or 100 year. This effectively raises the level of protection significantly, but it also will increase project costs.

Based on projections of ongoing sea-level rise, eventually, all the shoreline projects will be flooded and possibly abandoned. In which case, the breakwaters, beaches, and dunes could become an offshore rock reef with submerged shoals along the shoreline. These will provide quiescent areas for juvenile fish, and they may still offer some shore protection as the submerged rock becomes substrate for oysters and associated fish communities.

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