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C. Scott Hardaway Jr.
Virginia Institute of Marine Science

Donna A. Milligan
Virginia Institute of Marine Science

Christine A. Wilcox
Virginia Institute of Marine Science

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Summary Report

C. Scott Hardaway, Jr.
Donna A. Milligan
Christine A. Wilcox

Shoreline Studies Program
Virginia Institute of Marine Science
William & Mary

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1 Introduction

The goal of this project is to monitor effectiveness of nature-based resiliency projects such as those that use living shoreline management strategies. Living shoreline strategies can effectively control shoreline erosion while providing water quality benefits and maintaining natural habitat and coastal processes. These ecosystem-based management systems have been the preferred alternative for stabilizing tidal shorelines in the Commonwealth of Virginia since 2011. However, a recent 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 who may not be convinced about the long-term effectiveness of the systems for shore protection, their maintenance, and the main reason they are being constructed. Research has been performed on the effectiveness of created marsh habitats, but studies on the long-term effectiveness of the structures for shore protection in Chesapeake Bay from a design and construction perspective are relatively few.

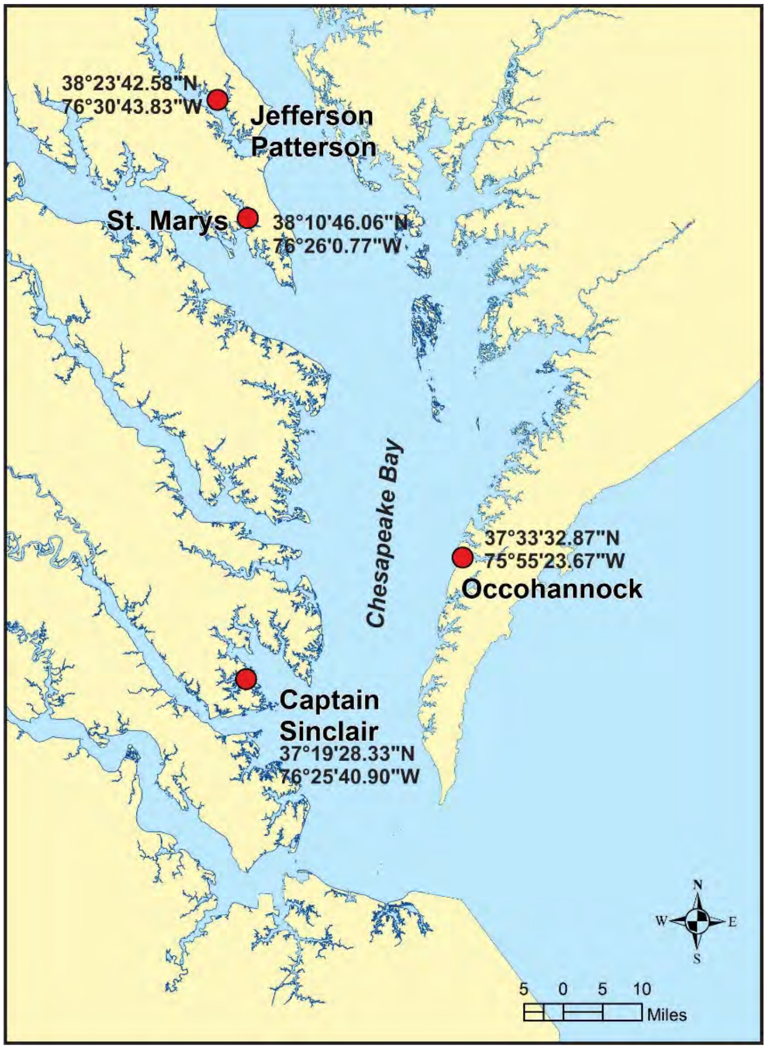

Figure 1-1. Location of the four sites within the Chesapeake Bay estuarine system.

The Coastal Zone Management program, through NOAA grants, has funded several projects in the past that have reviewed design considerations and monitored 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*., 2009) and were in part the basis for the "Living Shoreline Design Guidelines for Shore Protection in Virginia's Estuarine Environments" and the contractor training classes (Hardaway *et al*., 2017). The present project built upon and expanded monitoring at living shoreline systems for determining 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 marshes in Chesapeake Bay, the project sought to determine 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 at four sill sites in Chesapeake Bay (Figure 1-1). Using elevation surveys of each site and the U.S. Army Corps of Engineers climate change adaptation sea-level rise scenarios, the system response to these changes in water level through time was determined at two relatively new sill sites in Virginia that are less than five years old (Occohannock on the Bay and Captain Sinclair's Recreational Area) and two sill sites in Maryland, that are more than 10 years old (Jefferson Patterson Park and Museum and St. Mary's City). Typically, shore protection structures are built in front of eroding banks that input sediment to Chesapeake Bay and provide limited subtidal habitat. Systems that are constructed in front of eroding upland banks have a ”backstop” up which these created intertidal habitats may not be able to migrate as sea level rises. This affects their long-term performance. The collected data was used to project impacts of sea level rise through time on structures, upland banks, marshes, and beaches to determine adaptive management strategies for these sites.

This project is the first part of a three-year project that uses site-specific shore protection and habitat effectiveness for both medium and high energy sites as well as low and high upland banks to develop guidelines for managers, contractors, and homeowners to adapt existing and future living shoreline projects to sea level rise. 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.

2 Coastal Resiliency

Coastal resiliency of shoreline protection measures is often couched in terms of habitat impacts, diversity and what type of environment replaced another when a shore protection strategy was installed. Stone revetments are considered less impactful to the environment than bulkheads, and living shorelines typically provide better habitat opportunities than revetments. However, shoreline erosion control must be designed with site specific parameters and at a certain level of protection so that they are robust enough to withstand physical factors at the site. The question now is, should the design also include a given scenario of sea level rise, and, if so, what level of SLR should be considered? The USACE has developed sea-level rise scenarios (Figure 2-1). In 2050, at the intermediate rate for SLR, 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.

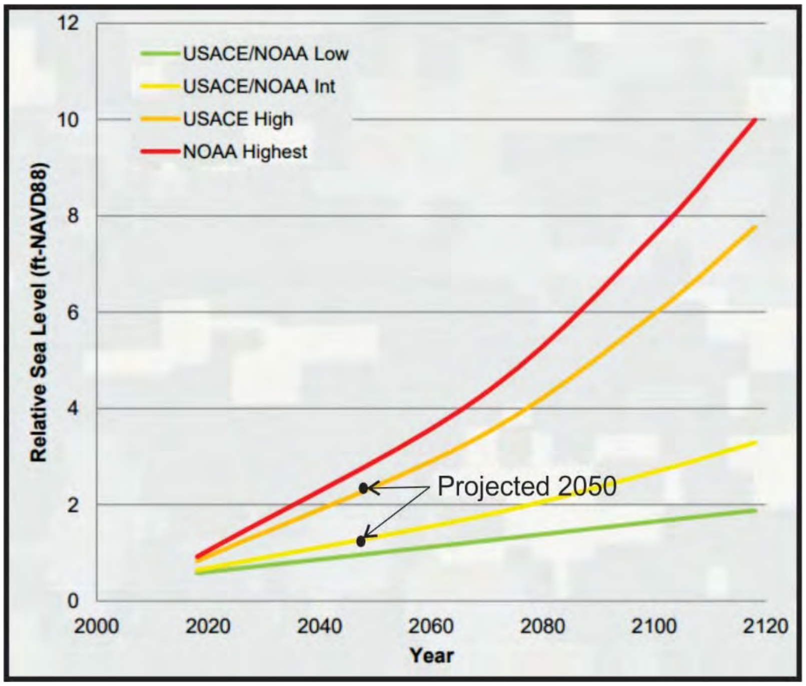

Figure 2-1. Sea-level rise predictions from the U.S. Army Corps of Engineers (2014).

Few researchers have looked at the “long” term maturity of sill systems and what that means to habitat function and, 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 and Mitchell (2013), and Bosch et al. (2006). Bilkovic and Mitchell (2017) stress the habitat component as essential along with shore protection. Accordingly, living shoreline designs should maintain or enhance sedimentation and accretion which promotes increased ecosystem function longevity with sea-level rise.

The Corps of Engineers has developed an adaptive management philosophy regarding future estimates of sea level rise (SLR) (USACE, 2014). Three SLR curves are presented (Figure 2-1). 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 incorporates new assessments and actions throughout the project life based on thresholds and triggers. An option for some bank sites, rather than adding rock and sand to the sill system initially to accommodate some level of SLR or provide a plan for future adaptation, is to include bank grading in the initial design and construction.

Therefore, the most cost effective adoption of this philosophy of Coastal Resiliency is to protect low banks where bank grading costs are less and more gradual bank grades, such as a 4:1 slope rather than the minimal 2:1 slope. More gradual bank grades will allow the wetland component to migrate laterally landward more effectively. For ungraded high banks, the projects are in more of a "Coastal Squeeze" situation. Here, addressing the vertical growth component is the only option. That is unless the existing sill system is moved further offshore to gain a lateral gradient. This would be difficult to permit and costly to build. The question then becomes, when is the addition of rock to the sill structure most timely? Or should it be done initially at present day cost?

According to the USACE, 2014, increased water levels will produce an increase in depth-limit wave height. 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. These statements pertain to much larger rock structures in more exposed wave energy settings. However, the basic premise is the same even at lesser wind wave climate.

Recent research on salt marsh complexes along the Gulf and East Coast indicate that they may in fact be able to keep up with SLR under the right circumstances (Kirwan et al., 2016). According to Kirwan et al. (2016), a 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 predicts 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 of a living shoreline project 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.

3 Methods

In this first year, the research project examined four medium energy shorelines (fetch 1-5 miles) along which rock sills have been built to create marsh 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 was done to determine the condition of the upland bank which will 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 nearshore. Where applicable, changes in submerged aquatic vegetation (SAV) will be 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. These sites were chosen for several reasons including site conditions, duration of the site, and existing data available. All of these sites have previous surveys that can be compared to the results of this project's surveys to determine existing conditions of the site and delineate habitats and how they have evolved. The sites include: 1) select sections of the gapped sill at St. Mary's City, Maryland that was constructed in 2002, high bank; 2) selected sections of Phase 4 at Jefferson Patterson Park & Museum in Maryland that was constructed in 1999, high bank; 3) Captain Sinclair Recreation Area, the Middle Peninsula Chesapeake Bay Public Access Authority's property in Gloucester, Virginia where sills were constructed in 2016, low bank, marsh; and 4) Occohannock on the Bay Camp and Retreat Center on the Eastern Shore of Virginia where sills were constructed in 2013, with both high and low bank

By selecting both high and low bank systems, the impact of sea-level rise can be assessed using the aforementioned U.S. Army Corps of Engineers' climate change adaptation sea-level rise scenarios. The site surveys were analyzed in GIS, and two sea level rise scenarios, a one and two-foot rise by 2050, were assessed for their impact on the structure's design.

4 Sites and Results

4.1 Captain Sinclair

Captain Sinclair Landing Recreational Area (CSRA) is located near the mouth of the Severn River in Gloucester County, VA (Figure 4-1-1). In 2013, almost 100 acres of property was gifted to the Middle Peninsula Chesapeake Bay Public Access Authority (MPCBPAA). The Middle Peninsula Planning District Commission (MPPDC) partnered to the Public Access Authority to develop a management framework for the property. The MPPDC also partnered with the Shoreline Studies Program at VIMS and received a NFWF Small Watershed grant in order to accomplish the Shoreline Management Plan for the property as well develop a living shoreline demonstration site and educational outreach program.

Figure 4-1-1. Location of the living shoreline at Captain Sinclair's Recreational Area.

CSRA is set within the low lying landscape that surrounds the Mobjack Bay. The tidal shoreline is eroding marsh dominated by *Spartina patens* and black needle rush (Figure 4-1-2). Significant shore recession has occurred in front of the main house which has erosion rates of about 0.6 ft/yr. The tide range is 2.5 feet at the mouth of the Severn River. The project was designed to address shoreline erosion along the project coast. There is a fetch to the west of about 2.5 miles and the southwest of 1.8 miles, low medium energy exposure. The upper elevation of sand fill was set at +3.0 ft MLW and extends on a 10:1 slope to about mean tide level at the back of the proposed stone sills. Once established the project will provide an erosion-control marsh fringe. A new pier recently was built along the shoreline.

Figure 4-1-2. Conditions at Captain Sinclair before the project. Photo: Shoreline Studies Program, 1 April 2015.

The sills at CSRA were installed in the winter of 2016. The project consists of 4 rock sill segments and 3 gaps or bays (Figure 4-1-3). The sills are 42 ft, 55 ft, 106 ft, and 77 ft in length, respectively. Bay A is 15 ft wide and allows for the old pier while Bay B is 25 ft wide and allows for the new pier as well as a beach for kayaks and canoes. Bay C is 10 ft wide. The openings allow for habitat diversity and more ingress and egress for marine fauna. The rock structures are low because the existing eroding marsh is low (Figure 4-1-4). The sand fill intersects the sill structures at the “standard” mean tide level and grades up to a +3 across the marsh scarp. The entire system had to stay relatively close to shore to avoid the nearshore SAV beds.

The site was planted in the spring of 2016, and due to subgrade adjustment, the *S. patens* planting was concentrated on the nearfield washover (Figure 4-1-5A). After one year the planging were very much intact (Figure 4-1-5B), and by 2018 had grown into a full width system (Figure 4-1-5C). The rock sill provides a hard substrate for oyster growth along the lower tide zone (Figure 4-1-5D).

Site surveys show the main change is in backshore elevation (Figures 4-1-6 and 4-1-7). The backshore berm has increased in height and apparently not at the expense of the lower beach face. It appears that elevation changes are due mostly to vertical growth of the high marsh, *S. patens*, along the entire length of the project. An increase of almost one foot at profile 250. This bodes well for future adaptation to SLR.

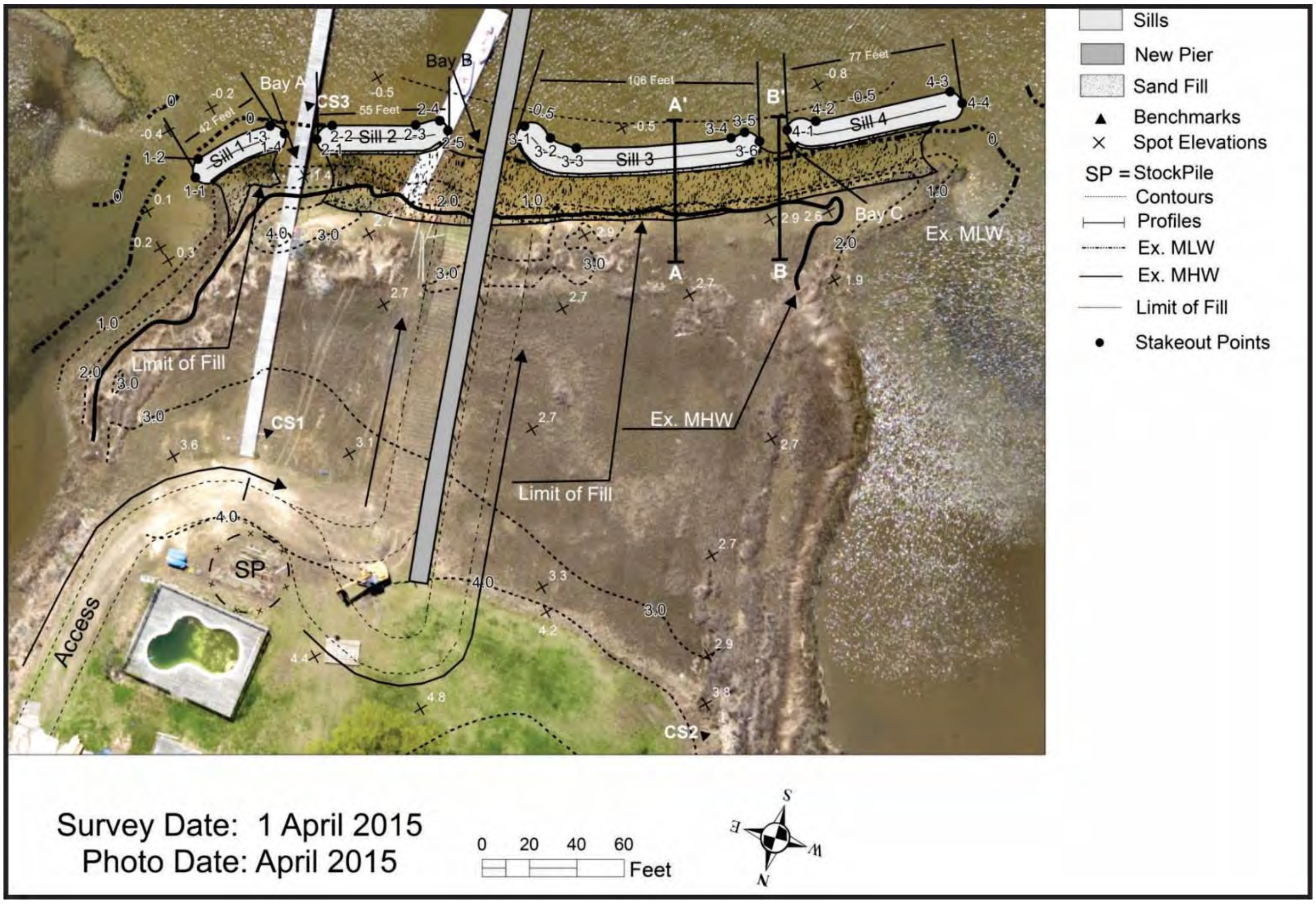

Figure 4-1-3. Living shoreline project design at Captain Sinclair by Shoreline Studies Program, VIMS.

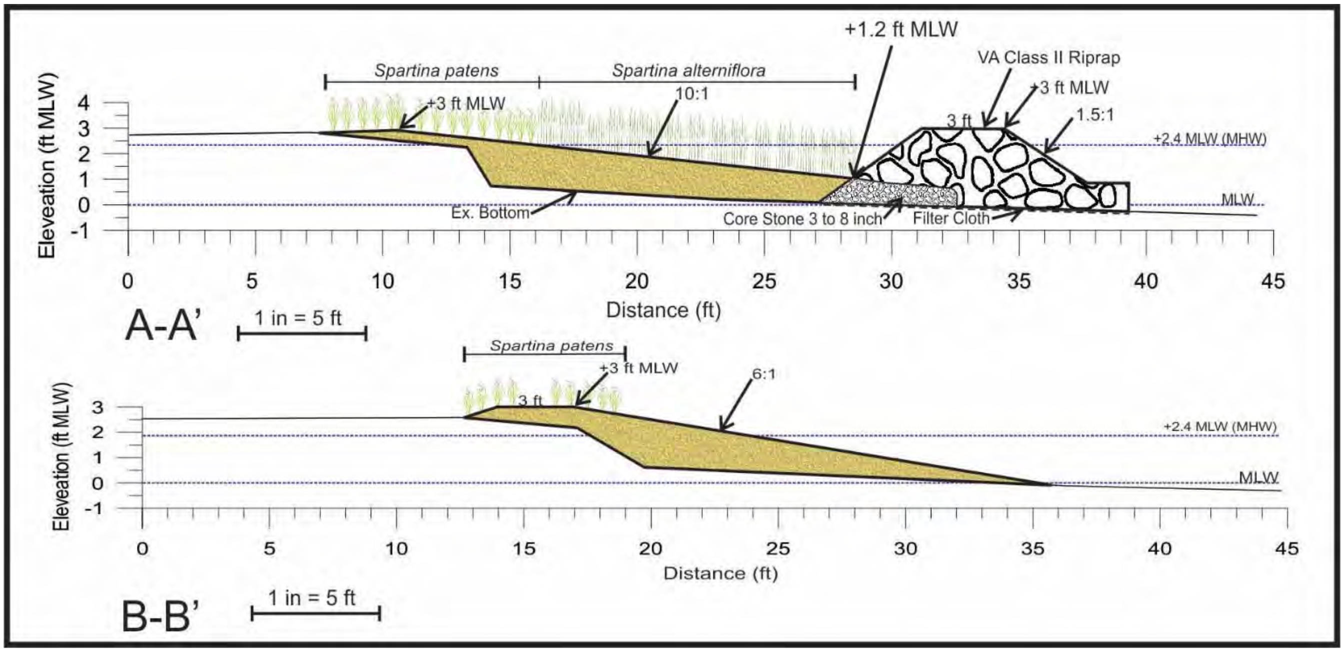

Figure 4-1-4. Typical cross-sections for the Captain Sinclair living shoreline project by Shoreline Studies Program, VIMS.

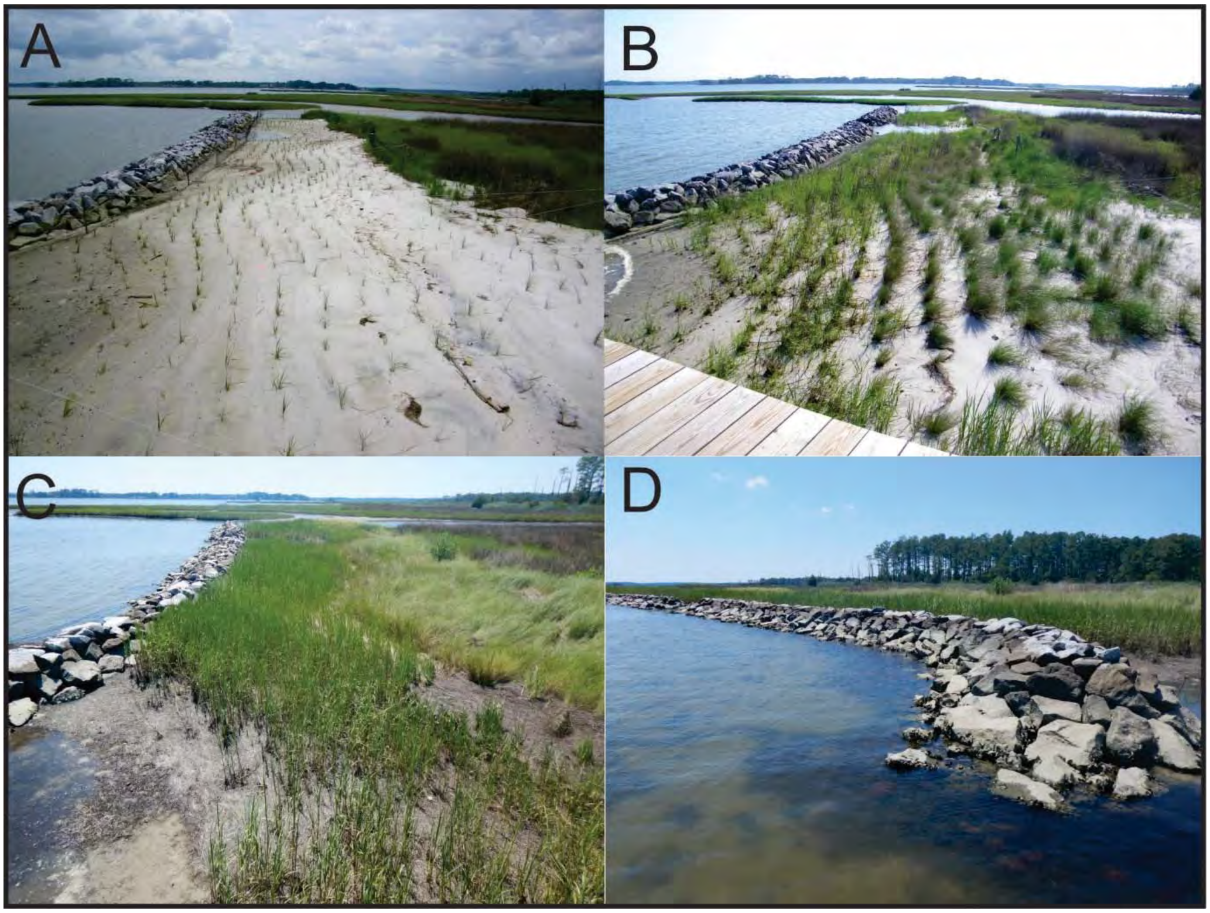

Figure 4-1-5. Photos of Captain Sinclair A) Just planted, 2 June 2016; B) One year post planting, 10 May 2017; C) Two years post-planting, 10 July 2018; D) Oysters line the rock sill shown at low water, 10 July 2018. Photo credit: Shoreline Studies Program.

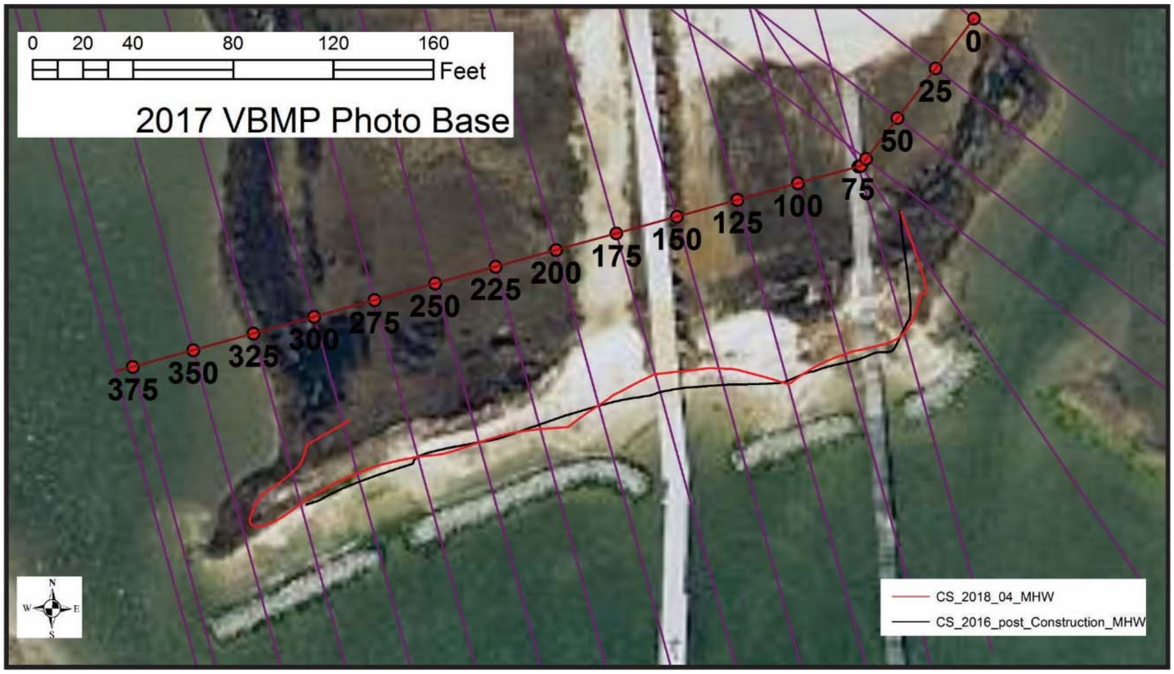

Figure 4-1-6. Basemap for Captain Sinclair showing the profile baseline and the position of mean high water in 2016 and in 2018.

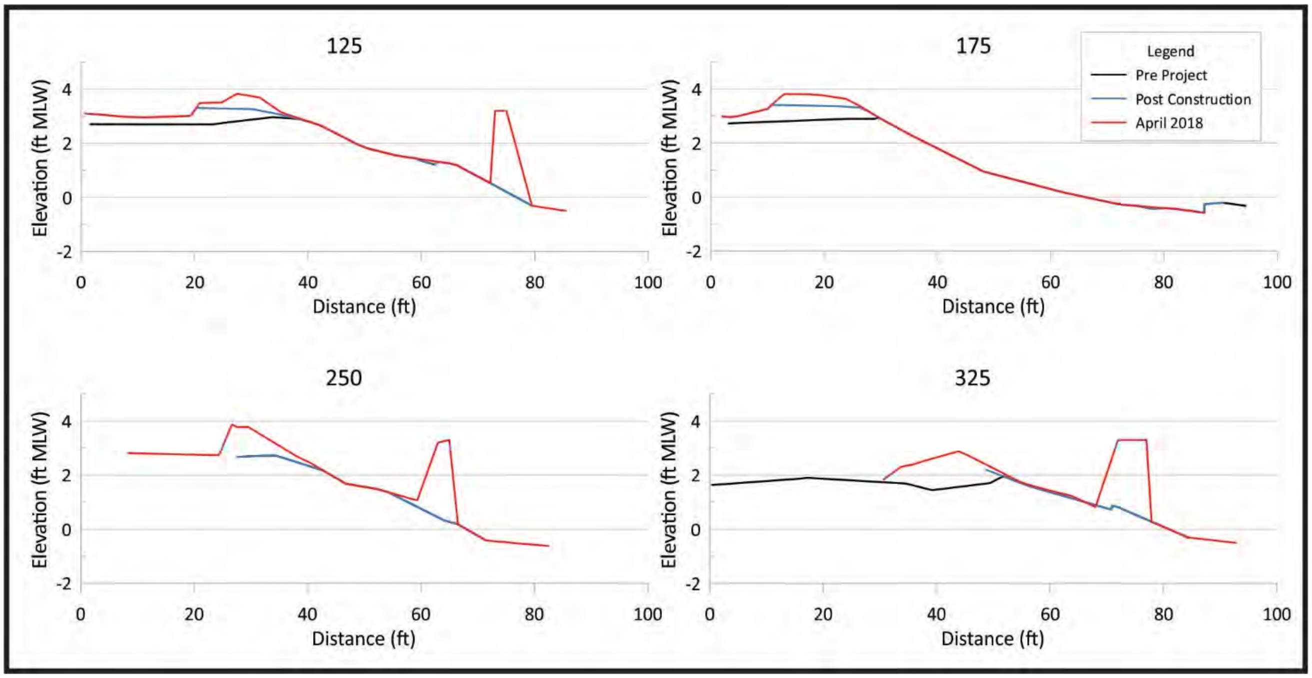

Figure 4-1-7. Cross-sections of survey data for Captain Sinclair.

4.2 Occohannock on the Bay

Occohannock on the Bay, also known as Camp Occohannock, is located near the mouth of Occohannock Creek in Accomac County, Va (Figure 4-2-1). The project shoreline faces south-southwest and is relatively sheltered except for long fetch out the mouth of Occohannock Creek into Chesapeake Bay. The historic erosion rate was about 0.3 ft/yr. The final project shoreline had 3 subreaches, from south to north 1) about 200 feet of low eroding upland bank along the lateral access road, 2) about 100 feet of eroding marsh fringe with an existing small tidal creek and 3) a low eroding bank that increases in elevation from +3 feet to +10 ft MLW in front of the camp office. The "Living Shoreline" project at Camp Occohannock consists of three distinct treatments for each segment (Figure 4-2-2).

Figure 4-2-1. Location of Occohannock on the Bay.

1. Along Reach 1 the original revetment was replaced with a 185-foot-high sill Section BB and ZZ (Figure 4-2-3) to protect the actively eroding upland and access path. Sand fill intersected the sill at +1.0 ft MLW and graded to a +4 ft at the low upland bank.
2. Reach 2 begins with Sill #1 then a gap (Bay B) for the tidal creek, Section CC. Sand fill went to edge of low eroding marsh scarp. Beyond Bay A, Sill #2 continues along the remaining marsh shore transitioning to the low upland banks, Section DD.
3. Reach 3 begins at Bay C which is 40 feet wide between Sill 2 and Sill 3 and is the present location of the kayak and canoe access beach. The added sand fill provides a protective beach for the adjacent low upland bank. Sill 3 continues for 220 feet and protects the adjacent actively eroding upland bank. The upland bank increases from +5 ft MLW to +12 ft MLW along the length of Sill 3 and bank grading is proposed as shown (Section EE). Sand fill was taken to +5 MLW against the graded bank. It should be noted that the Sill 3 sand nourishment covered approximately 5,980 sq.ft of existing low marsh was not wide or robust enough for adequate shore protection. The project created 6,900 sq.ft of intertidal marsh and 9,120 sq.ft of high marsh.

Figure 4-2-2. Camp Occohannock living shoreline plan.

The project was built in 2013. Reach 1 is shown in Figure 4-2-4A pre-construction in 2013, and after 5 years Figure 4-2-4B. Full marsh growth is evident. Small pine trees and salt bush are pioneering the backshore along the low bank (Figure 4-2-4C). Reach 2 shown right after planting and after 5 years (Figure 4-2-5A and 4-2-5B). Blue arrows indicate small tidal creek channel still functioning. Abundant oyster growth on rocks and fish utilization are seen along entire project (Figure 4-2-5C). Reach 3 is seen before construction, after construction and after 5 years in Figures 4-2-6A, B, and C, respectively. The low marsh section has developed “bare” areas where the *S. alterniflora* is absent even with some maintenance planting. A reduction in grade is expected. However, non-vegetated wetlands are still very valuable habitat and the high marsh and shore protection terrace is still very much intact. As this site matures pioneering small pines are becoming abundant and should be thinned to reduce the potential for shading the erosion resistant high marsh “turf”.

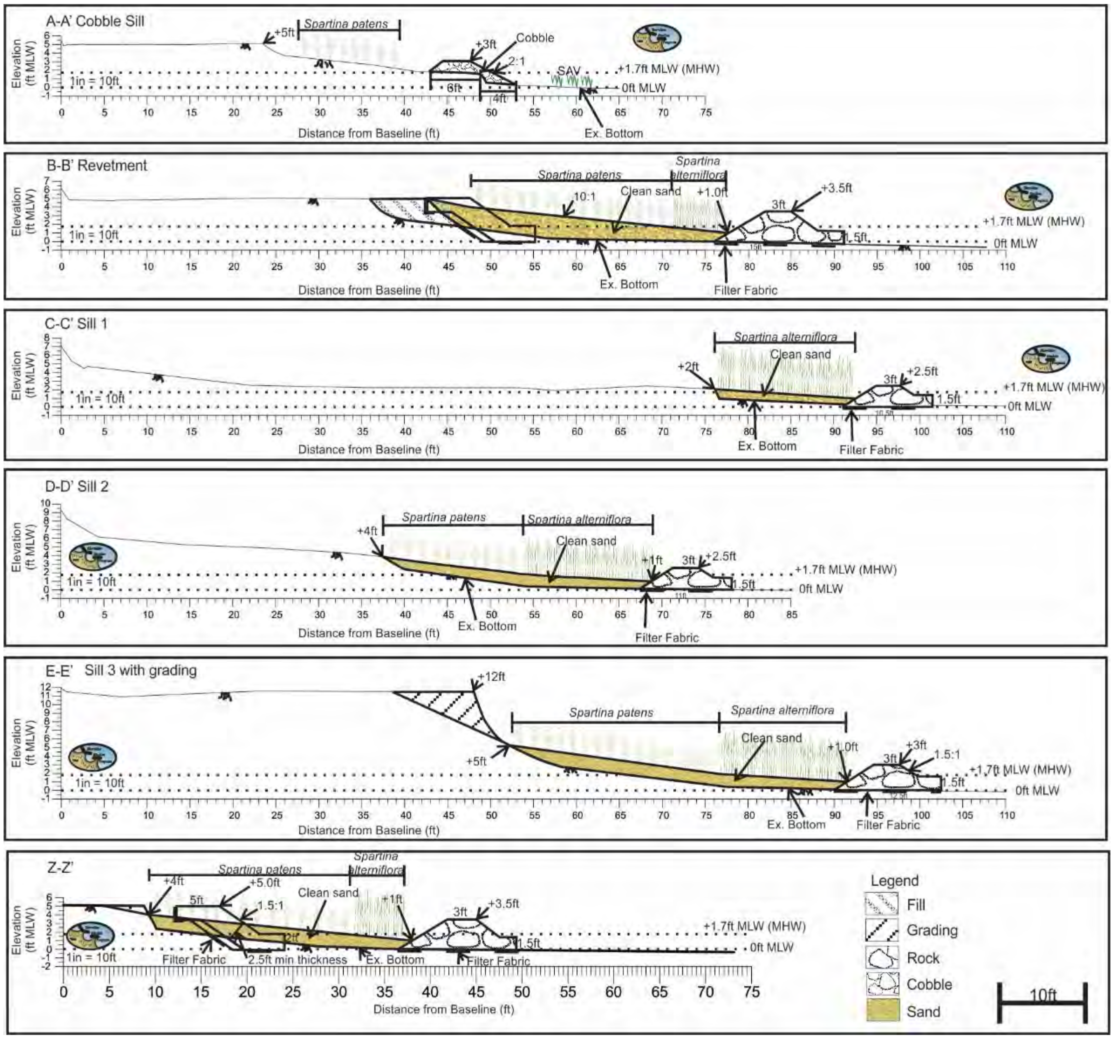

Figure 4-2-3. Typical cross-sections for Camp Occohannock living shoreline.

Survey data shows Reach 1 sill (ZZ) with elevated substrate from the sand fill in sections P587 (Figure 4-2-7 and Figure 4-2-8). The upland bank edge was graded slightly to the back of the sand fill. Reach 2, Sill 1 shows the mouth of the tidal creek has shifted and deepened slightly (P503). The tidal creek flat behind sill # 3, P440 has remained relatively stable transitioning to the sand fill going north, P 394. Reach 3 sections P151 and P79 show the graded bank and wide stable sand fill.

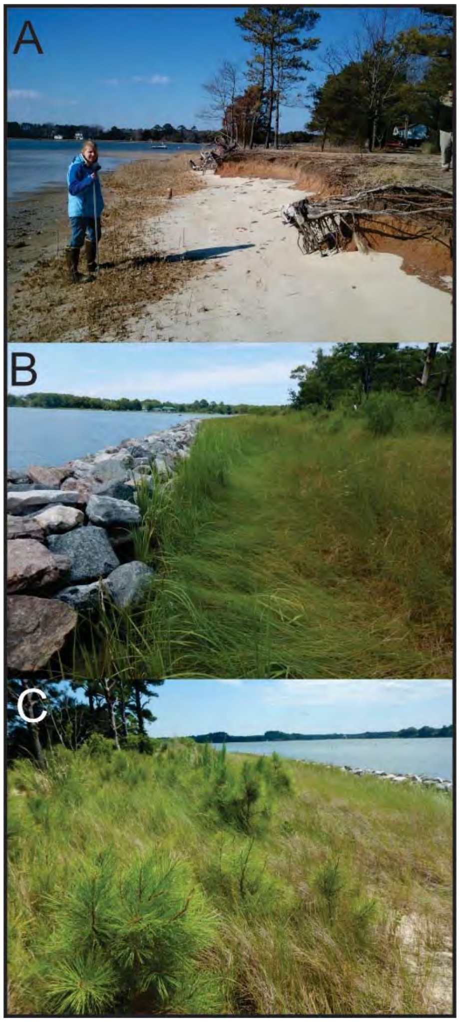

Figure 4-2-4. Photos of reach 1 at Occohannock on the Bay A) before installation (April 2013), B) after 5 years (July 2018), C) after 5 years, the backshore is being colonized by trees.

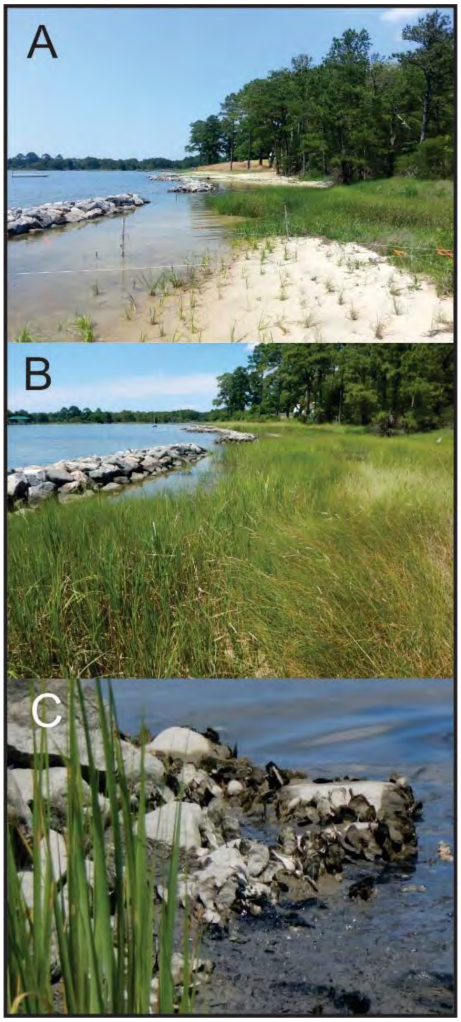

Figure 4-2-5. Photos of reach 2 at Occohannock on the Bay A) after planting (May 2013), B) after 5 years (July 2018), C) after 5 years there is abundant oyster growth around the end and outsides of the rock sills.

Figure 4-2-6. Photos of reach 3 at Occohannock on the Bay A), before construction (March 2013), B) after planting (May 2013), C) after 5 years.

Figure 4-2-7. Location of cross-sectional profiles at Occohannock and the 2018 surveyed position of mean high water.

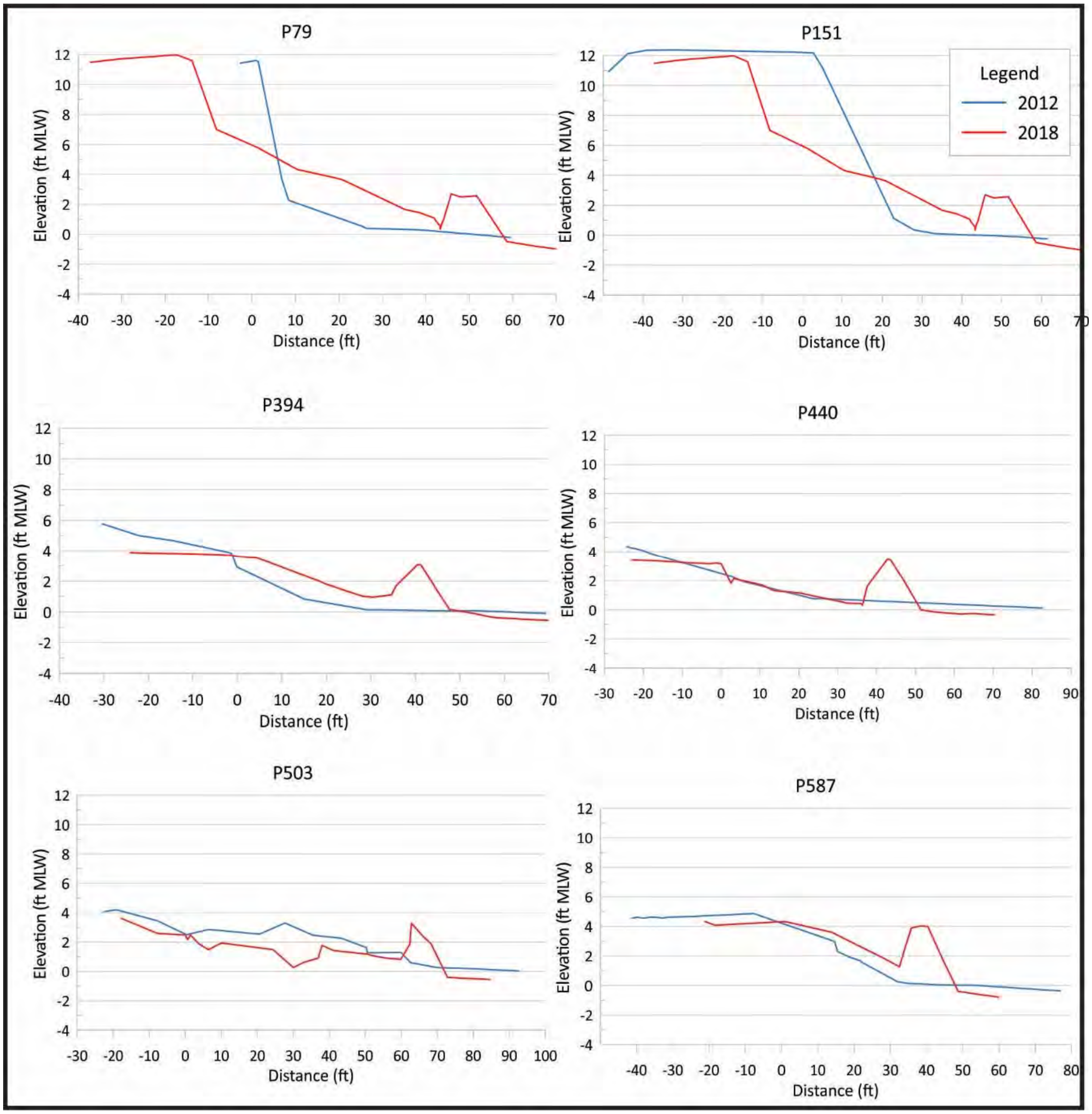

Figure 4-2-8. Cross-sectional profiles at Occohannock taken before the living shoreline project was installed and in 2018.

4.3 St. Mary's City

St. Mary's City is located on the St. Mary's River in St. Mary's County, Maryland (Figure 4-3-1). The project site lies along a curvilinear portion of the coast where fetch varies slightly along the length of the project. The site has very high upland banks and had a narrow, gravelly beach before construction. Erosion was occurring at the base of the bank causing intermittent slumping. Shore recession averaged about 1 ft/yr between 1848 and 1994. No shore protection structures were present before construction of the sill system. The fetches from about mid-site are to the west, northwest and north of 0.9, 0.9, and 0.6 miles, respectively. The tidal range St. Mary's City is 1.5 ft. SLR since 2002 for the Lewisetta Gauge has been 0.27 feet.

The gapped sill at St. Mary's City was built in 2002 and has about 1,000 ft of shoreline (Figure 4-3-2). The main purpose of the St. Mary's Shoreline Project was shoreline erosion control which was achieved with a combination of the stone sill and marsh fringe. Sand fill was placed at about +2.9 feet MLLW (tidal epoch 1983-2001) against the base of the bank and graded on an 8:1 slope to the back of the sill just below mean tide level, +0.4 feet MLLW. The sill height was set at +2.4 feet MLLW, about a foot above MHW, typical of many sill systems installed in Maryland (Bosch *et al.*, 2006). As discussed in Hardaway *et al.* (2007), the project was designed as a demonstration of various types of sill openings.

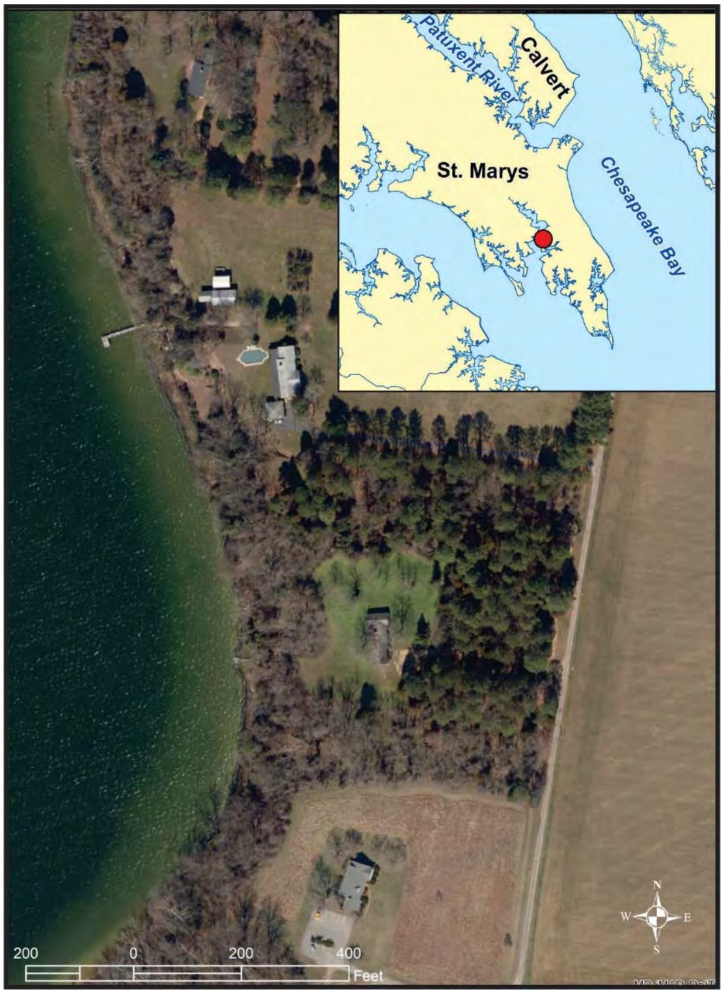

Figure 4-3-1. Location of St. Mary's sills.

The Shoreline Studies Program monitored the project in 2007 and 2009 (Hardaway et al., 2007 and 2009). Results indicated a general steeping of the marsh terrace with bank slumping and the slight reduction of sand grade behind the sills and slight accretion on the river side (Figure 4-3-3). The base of bank sand intersection increased about 0.5 ft from a +3.0 to a +3.5 ft MLW. The sill sand intersection decreased about 0.5 ft from a +1.0 to a +0.5 ft MLW with the resulting slope going from about a 10:1 to a 6:1 but still stable.

This project is a follow up of those efforts. The 2018 survey extended from Sill 1 to Sill 6 along the project shore. It has been almost 10 years since the last assessment of the project, and one glaring change has been the significant invasion of *Phragmites australis* (Phragmites) which made surveying very difficult. This invasive grass is a very common intruder into marsh sill systems due in part to lack of maintenance, but also due to elevations favoring the grass which prefer to be above mean high water. Small patches of Phragmites were seen during the 2007 survey, but not enough to interfere with the survey as it did in 2018.

Access to the site is easiest down the hill to Sill #1. A series of photos show how that section of the project has evolved over time Figures 4-3-4A to 4-3-4D. Two years after construction, the low marsh is relatively intact. Tree limbs along the base of the bank had been cut back during construction

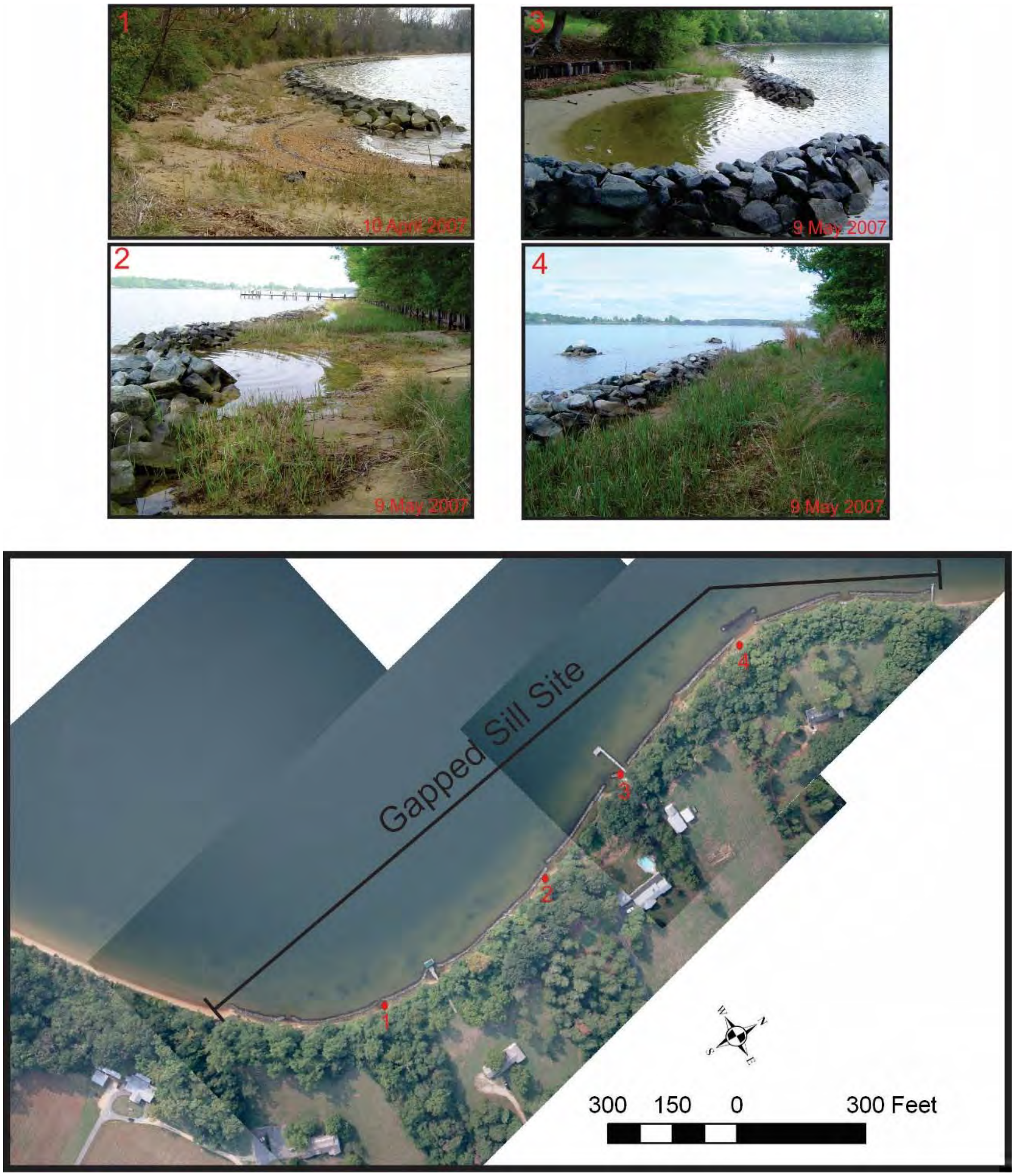

Figure 4-3-2. A photo mosaic of the St. Mary's City, Maryland shoreline on August 24, 2007 indicating the four sites of gapped fill projects and ground photographs of each site.

and began to grow back over time often shading the marsh. Elevation changes allowed salt bush and Phragmites to become established (Figure 4-3-4D).

An element to the original project was experimenting with different type of sill (windows) openings in order to reduce sand attached maintain "flushing" behind the sill (Hardaway et al., 2007). In Window #1 the stable cobble substrate allowed low marsh to become established (Figure 4-3-5A and Figure 4-3-5B).

The evolution of the site vegetation over time can be seen in along Sill #7 looking north toward Window #8 with the offshore breakwater defined by two sentinel stones (Figure 4-3-6A). In 2007, the high and low marsh fringe is intact with a few salt bushes coming in and modest tree limb cover. By 2018 the low marsh in the foreground is very robust, but Phragmites has overcome both species farther along shore and significant limb growth occurs such that the shading inhibits any vegetation growth under that canopy.

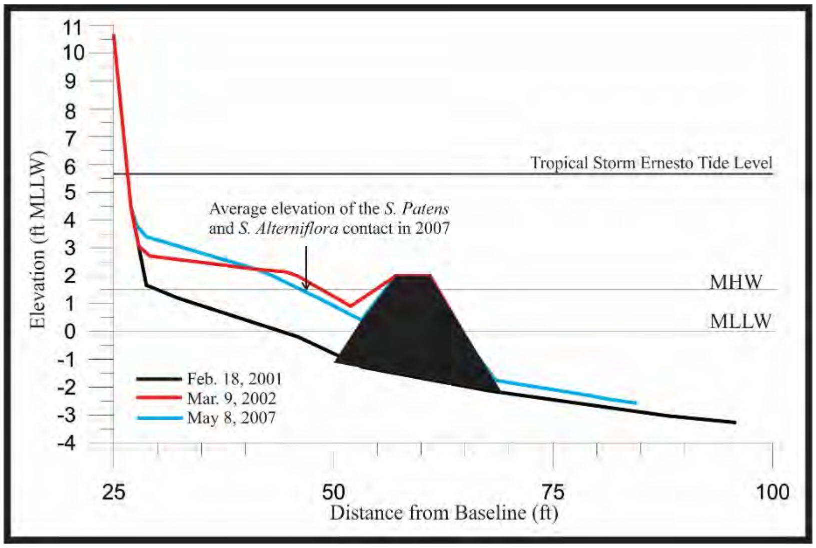

Figure 4-3-3. Typical St. Mary's City sill profile from survey data.

More evidence of vegetation change is seen from the same point but looking south, the same survey pier can be seen. In 2007, (Figure 4-3-7A), 5 years after construction, the marsh fringe is robust with both species intact, an occasional salt bush and a few slightly overhanging limbs. By 2018, (Figure 4-3-7B), Phragmites has completely taken over this section of marsh with heavy overhanging trees.

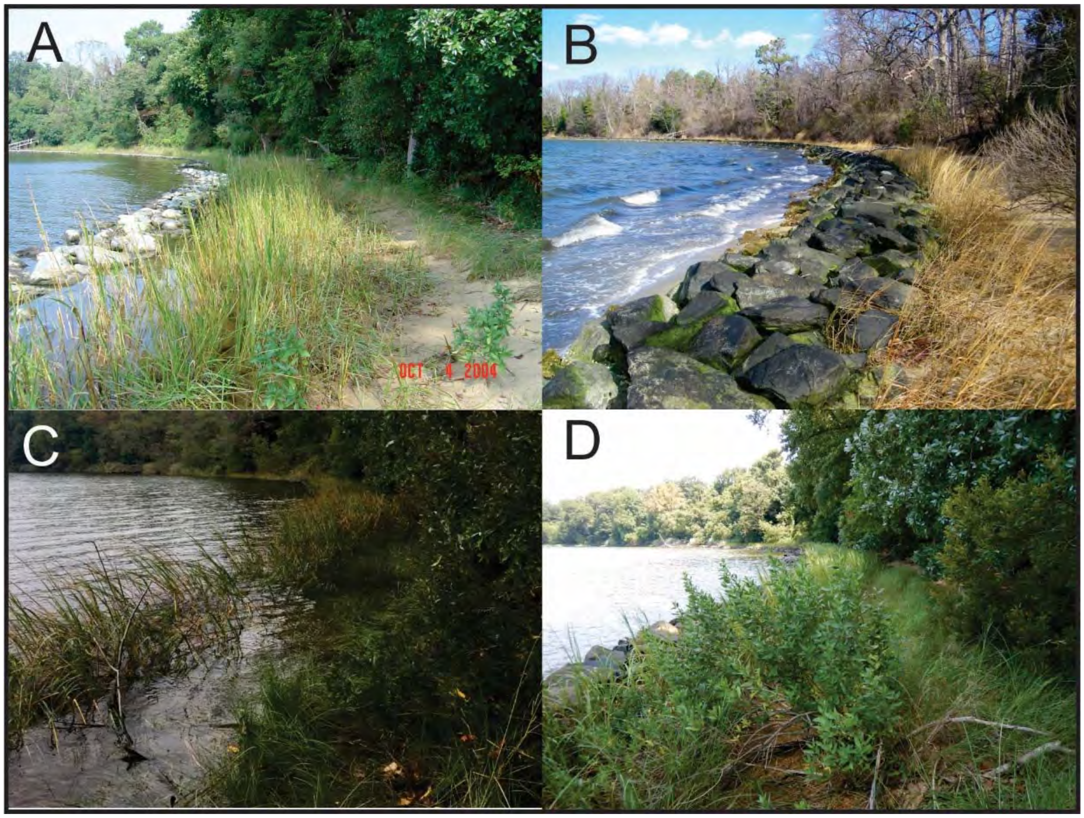

Figure 4-3-4. Photos of St. Mary's A) two years after construction (4 Oct 2004), B) 11 years after construction (1 Feb 2013), C) 15 years after construction (13 Oct 2017), D) 16 years after construction (15 Aug 2018).

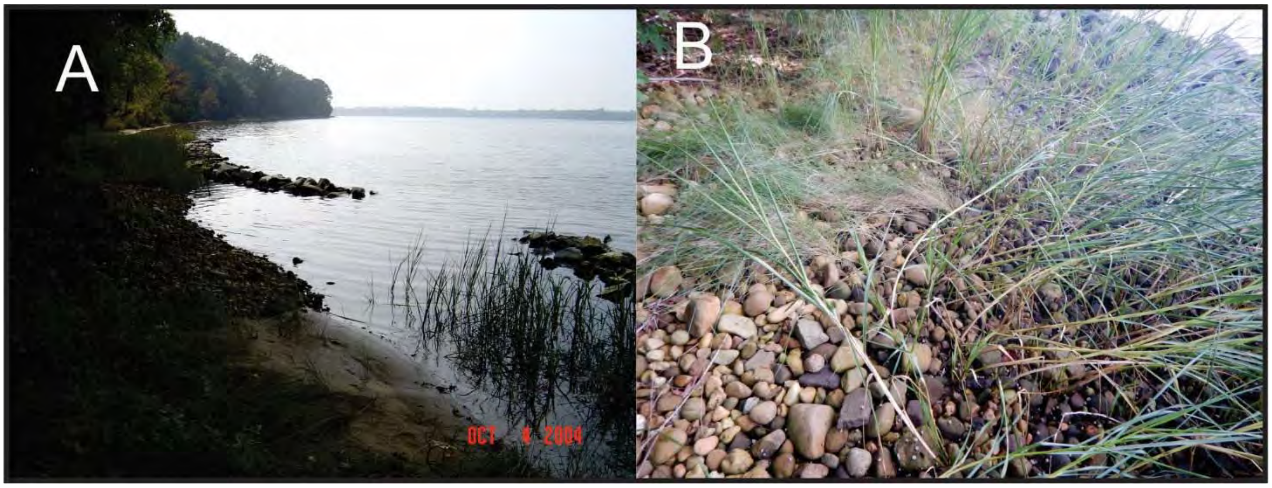

Figure 4-3-5. Gap at St. Mary's A) two years after construction, B) 16 years after construction (15 Aug 2018).

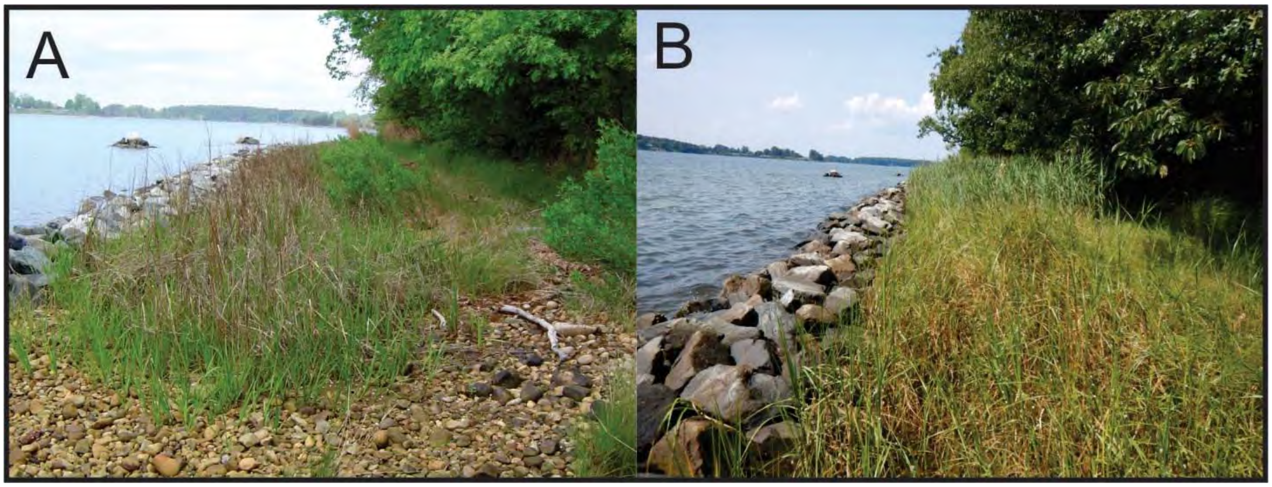

Figure 4-3-6. Gap and sill at St. Mary's A) five years after construction (9 May 2007), B) 16 years after construction (15 Aug 2018).

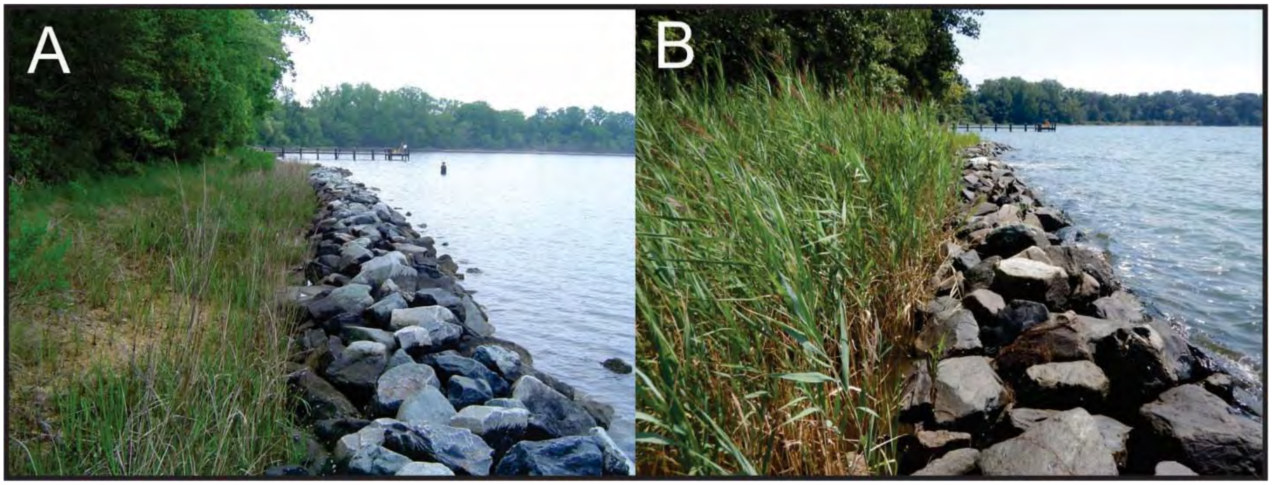

Figure 4-3-7. Sill at St. Mary's A) five years after construction (9 May 2007), B) 16 years after construction (15 Aug 2018). Phragmites has colonized behind the structures.

This was not the case everywhere especially in front of the one segment of existing bulkhead where on low marsh was planted in 2002, and by 2007 had become well established (Figure 4-3-8A). The fringe remained robust in 2018 with a few overhanging limbs but no Phragmites (Figure 4-3-8B). Phragmites does not tolerate regular tidal flooding in brackish water. Black needle rush is another species that has colonized St. Mary's shoreline (Figure 4-3-9A); it is often found with the intertidal snail (*Littorina littorina*). It occupies the zone where high and low marsh transition.

From a faunal habitat perspective, the St. Mary's City project had shown significant fish and crab usage (Hardaway et al., 2007). Qualitatively, this does appear to continue (Figure 4-3-9B). The vegetative communities may have changed slightly, but fish function appears to continue. The one stable element in the sill system is the rock sill itself. Even if it becomes submerged with SLR it will remain a fish haven.

Although Phragmites has compromised some of the marsh fringe, it is a very tough plant and once rooted in is difficult to eradicate and will serve well for shore protection, but it does not create a diverse habitat perspective. Phragmites is a mono-cultural species meaning no other plant will be able to share the same square footage unlike the planted species, *S. patens* and *S. alterniflora* which will co-exist with other wetlands plants.

The survey showed that there were gradient adjustments between construction and the 2008 survey, but since then the net change across the stable vegetated backshore has very been little with some areas of reduction usually between +1 ft and +2 ft. This is the high water swash zone, where grasses are under the most stress from wave impact. Changes are in the order of 0.1 to 0.3 ft. Little new sediment enters the system either from the upland banks because they are very stable or from offshore due to the rock sill barrier.

Along Sill #1, there were slight decreases in the lower limit of *S. alterniflora* and in the nearshore (1622). Sill #2 (P1955), the backshore remained stable while behind Sill #3 (P2052) there was a slight increase, +0.3 ft from the back of the sill to about +2.5 ft at the edge of the heavy backshore vegetation. Further up at Sill #6 (P3142) shows no change across the backshore. We estimate almost 10

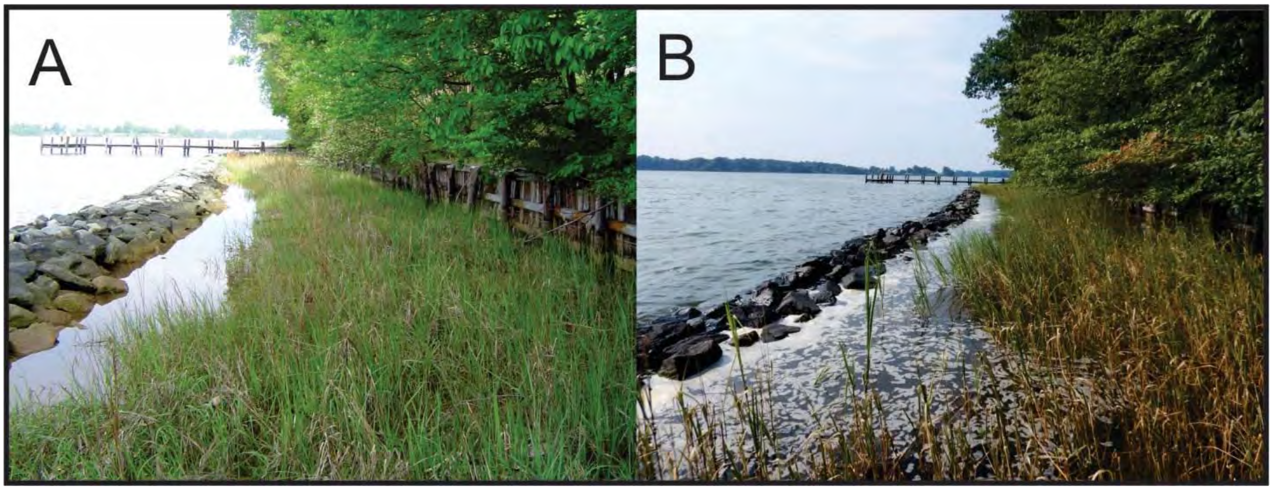

Figure 4-3-8. Sill backed by bulkhead at St. Mary's A) five years after construction (9 May 2007), B) 16 years after construction (15 Aug 2018). No change in the plants occurred.

to 15% of the surveyed shoreline had Phragmites. The overhanging tree limbs just about the entire shoreline and negatively impacts the high marsh growth.

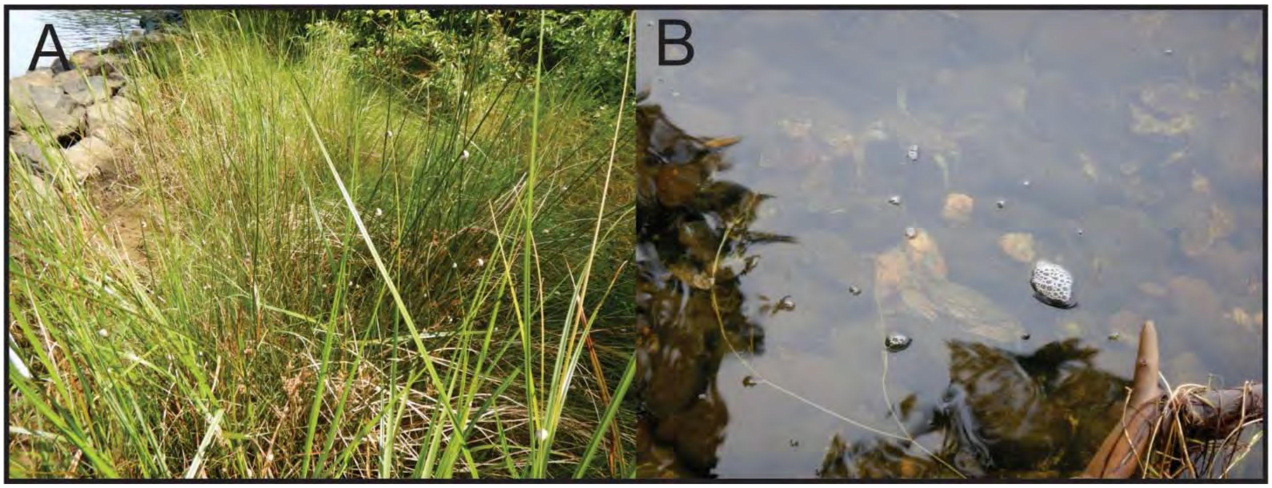

Figure 4-3-9. Sill at St. Mary's (15 Aug 2018) A) Needlerush has colonized some sections, B) blue crabs are prevalent along the shore.

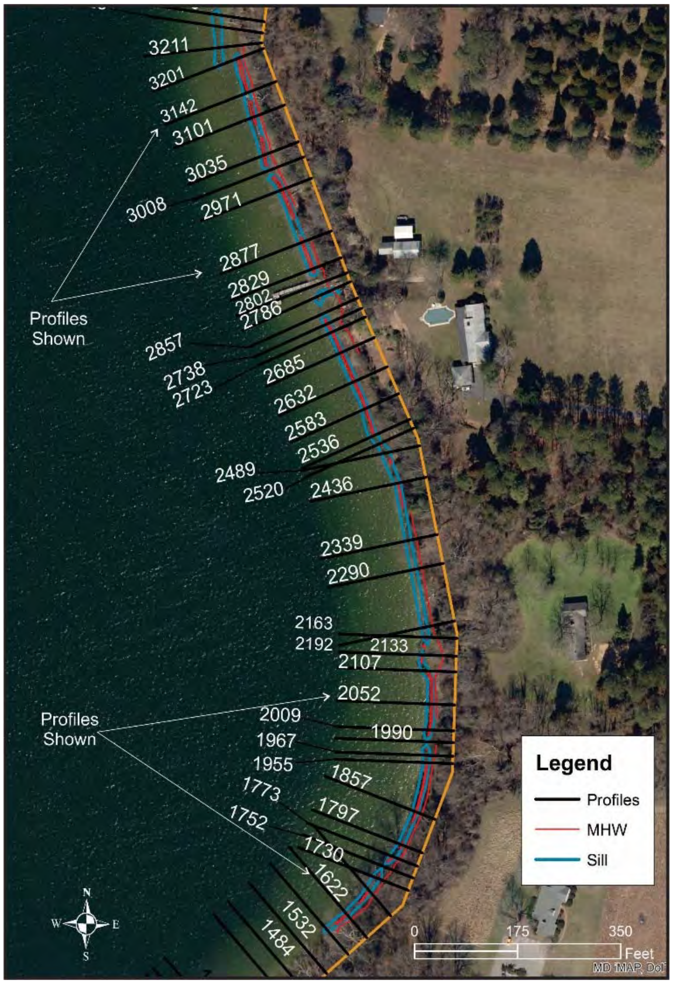

Figure 4-3-10. Cross-sectional profile baseline. Also shown are the outline of the sill structures (blue) and the 2018 mapped mean high water line.

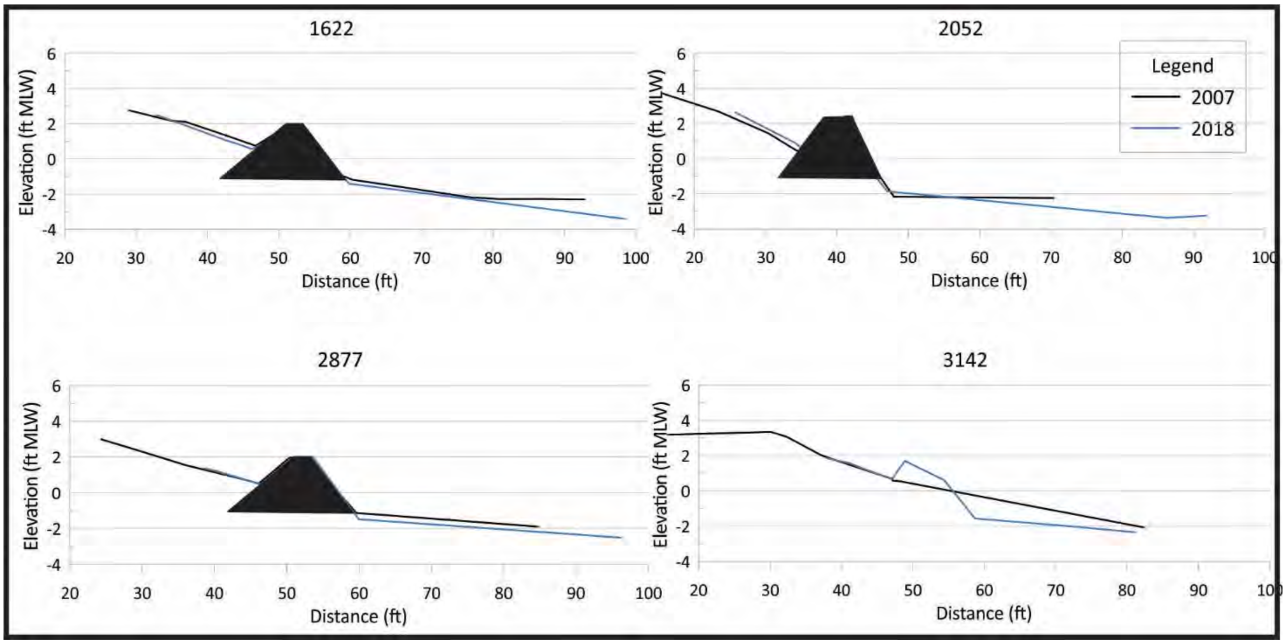

Figure 4-3-11. Selected cross-sectional profiles showing the shoreline in 2007, 5 years after construction and in 2018.

4.4 Jefferson Patterson Park & Museum

Jefferson Patterson Park & Museum (JPPM) is located on the north shore of the Patuxent River beginning at Petersons Point and extending over 2 miles upriver (Figure 4-4-1). Their shoreline is protected by several projects built in phases since 1986. Because of availability of pre-, and post construction surveys, the Hardaway et al. (2007) study concentrated on Phase 4 which was built in 1999 (Figure 4-4-2). Due to excessive Phragmites growth and dense bank growth north and south, the present study concentrated on Sill 4 going north to BW4 and south to Sill 3-2 where Phragmites had not invaded.

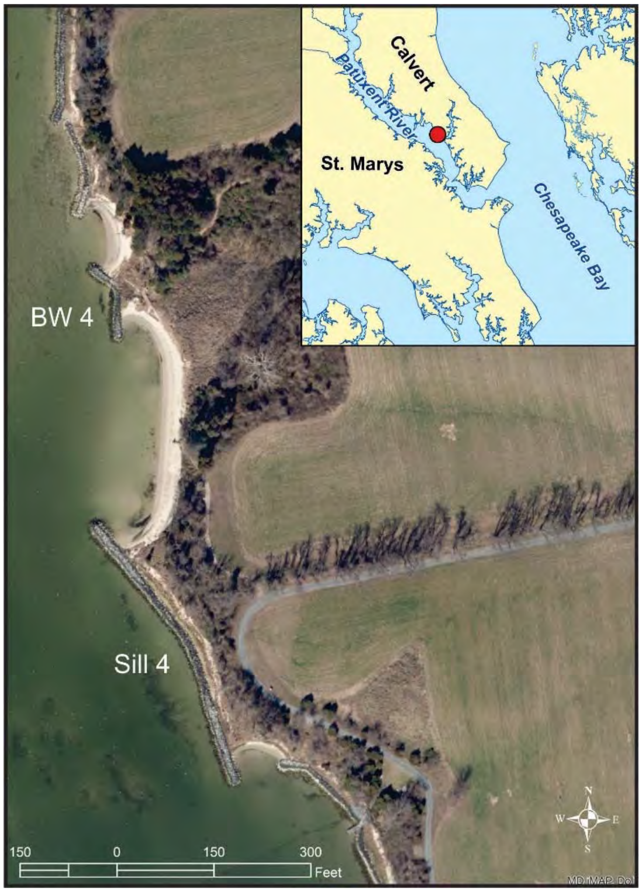

Figure 4-4-1. Location of living shoreline at Jefferson Patterson Park & Museum.

Overall, this shoreline has historic erosion rates of about 1 ft/yr. The shoreline has as an intermittently eroding bank that averages about +25 feet MLW with several low drainages. The middle drainage occurs within the Phase 4's limits. A small line of stone which acted as a very low sill existed at the site, but it did not offer long-term shore protection for the failing upland banks. One of the main reasons for the project was to protect valuable archaeological resources contained in the banks. Another feature was the paleontological resources along the base of the bank, an indurated highly fossiliferous marl.

This site has fetches to the northwest, west, southwest, south, and south-southeast of 1.3 miles, 2.5 miles, 1.9 miles, 1.3 miles, and 4.0 miles, respectively. The tide range is 1.2 ft. Storm surge frequencies at Solomon's Island according to Boon *et al.* (1978) are 4.0 ft, 4.7 ft, 5.4 ft, and 6.1 ft above MLW for the 10, 25, 50 and 100-yr storms. Hurricane Isabel had an estimated maximum storm surge of just over +4.5 ft MLW placing it arguably in the 25-year return range for this particular site.

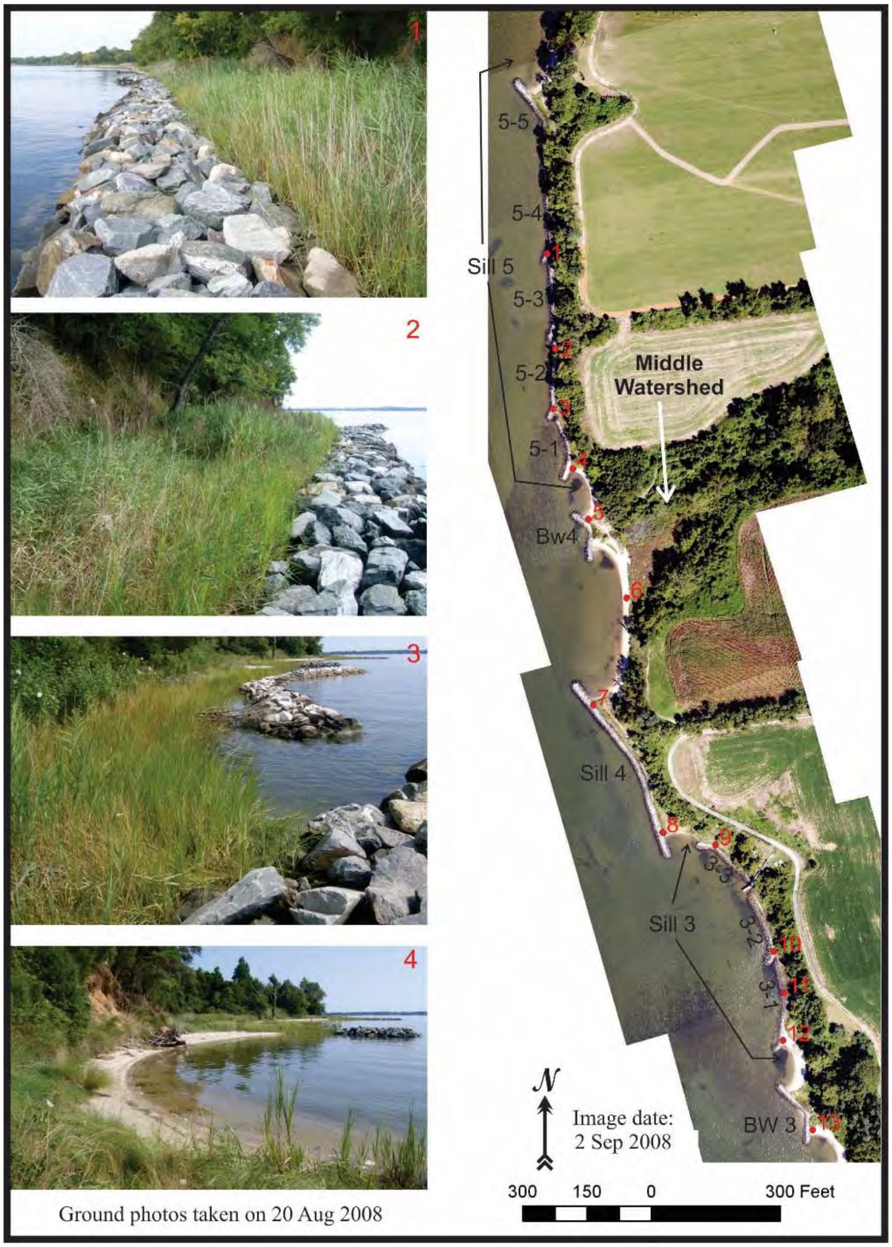

Figure 4-4-2. A photo mosaic of Jefferson Patterson Park & Museum shoreline on August 20, 2008 depicting the location of sills and breakwaters and indicating the locations of the ground photographs.

The overall design philosophy was to address subtle headlands with breakwaters or large sills and utilize gapped sills along the adjacent shorelines. The transition between different structures types is accomplished with spurs and side pocket beaches. The gaps or windows between sill segments address the dominant northwest winds and waves with a short spur on the south side of each window "turning" into the wind.

The typical sill (Figure 4-4-3A) was designed to address the 25-year event. Since the bank could not be graded due to archaeological concerns, the sand fill was brought up to +6 ft MLW at the base of the bank then graded down on about 3.5:1 to +4 ft MLW. From there, the fill followed about a 10:1 slope to about MTL (0.6 ft MLW) intersecting the back of the sill structure. The typical sill crest was set at +2.0 ft MLW. This provided about 50 ft of sand and sill from the intersection of the sand fill with the base of the bank to the outside edge of this stone sill. Other structural units were used to address headlands, structural transitions to pocket beaches and windows.

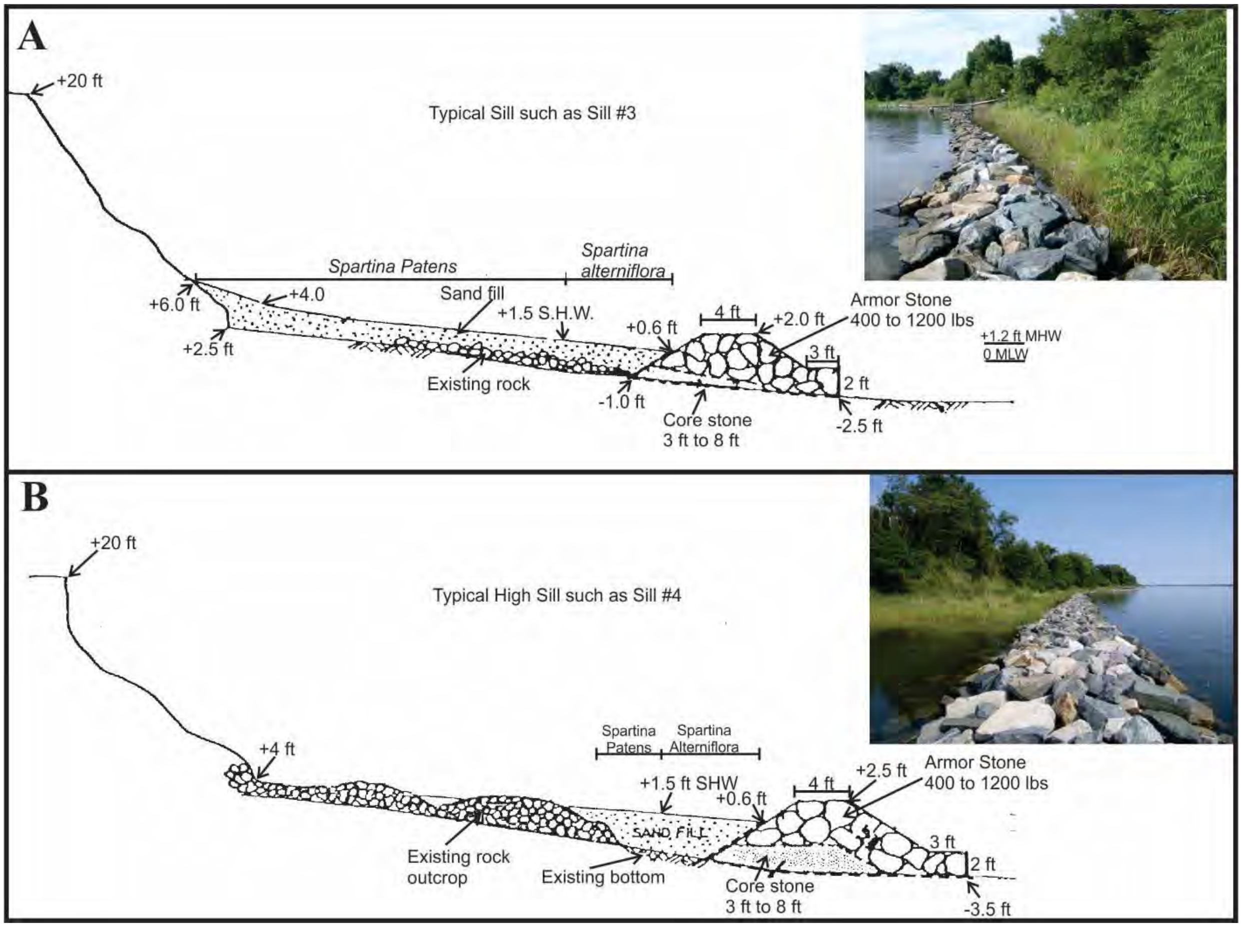

Figure 4-4-3. Design cross-sections of structures built at Jefferson Patterson Park & Museum in Phase 4 showing A) a typical sill such as Sill #3 (shown in the photo) and B) a typical high sill such as Sill #4 (shown in photo).

Breakwater #3 was placed in front of a subtle headland with a pocket beach that transitions both up and down river into gapped sills including sill #3. A larger and broader headland was addressed with sill #4, a high, continuous sill bounded by spurs (Figure 4-4-3B). The headland was the result of a basal, indurated fossil layer that was more erosion resistant than adjacent conditions. Beyond the middle watershed the remaining shore was addressed with breakwater #4 and sill #5.

Sill #4 is shown in 2008 and 2018 (Figure 4-4-4A and Figure 4-4-4B). In 2008, 9 years after construction, the lower limit of low marsh had receded due to gradient decrease behind the lower central weir section of the sill and tree limbs were shading the backshore/base of bank area. Ten years later and 19 years old, Sill #4 still has robust low marsh along the central weir section and behind the elevated sill as seen in the foreground of Figure 4-4-4B. However evident along with very dense tree growth across the back shore that inhibits grass growth (Figure 4-4-4C) but does not really impact the overall shore protection capability.

Looking downriver toward from the end of Sill #4 toward Sill #3-3, wetland growth was good in 2008 that became very shaded by 2018 (Figure 4-4-5A and 4-4-5B). Also, extensive patches of Phragmites can been seen in the distance alongshore. Moving upriver from Sill 5-1, Phragmites was

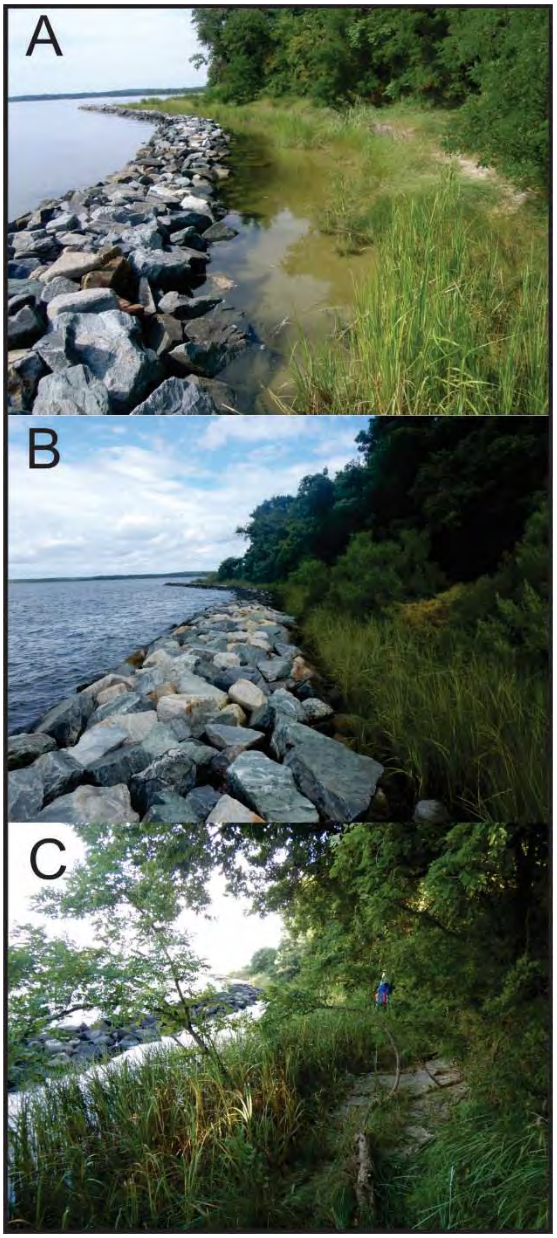

Figure 4-4-4. Photos of Sill #4 at Jefferson Patterson on 20 Aug 2018 A) along the low weir section, B) higher section of sill, C) along the backshore.

present in 2008 and continues in 2018 (Figure 4-4-6A and Figure 4-4-6B) indicating a relatively stable condition regarding maintaining elevation relative to daily tidal incursion.

The embayment between BW4 and Sill 5-1 still has a narrow beach and an adjacent eroding bank (Figure 4-4-7A and Figure 4-4-7 B). The sand attachment at the end of Sill 5-1 and the tombolo on BW4 are still Phragmites free.

Survey results indicate a relatively stable substrate over time due in part to very significant Phragmites invasion (Figure 4-4-8 and Figure 4-4-9). It is estimated that from the upriver end of Sill #5 down to BW 3 that Phragmites has overtaken about 30% -40% of the backshore terrace above high water. Shading from limbs compounds high marsh grass growth as well. The reduced surveyed area showed accretion behind BW 4 (P1039) and erosion at the upriver end of Sill # 4 (P1486). The central weir section of Sill #4 (P1615) got a little deeper at high tide as MHW expanded landward. The MHW position remained fairly stable in the three surveyed embayments supporting the original design template.

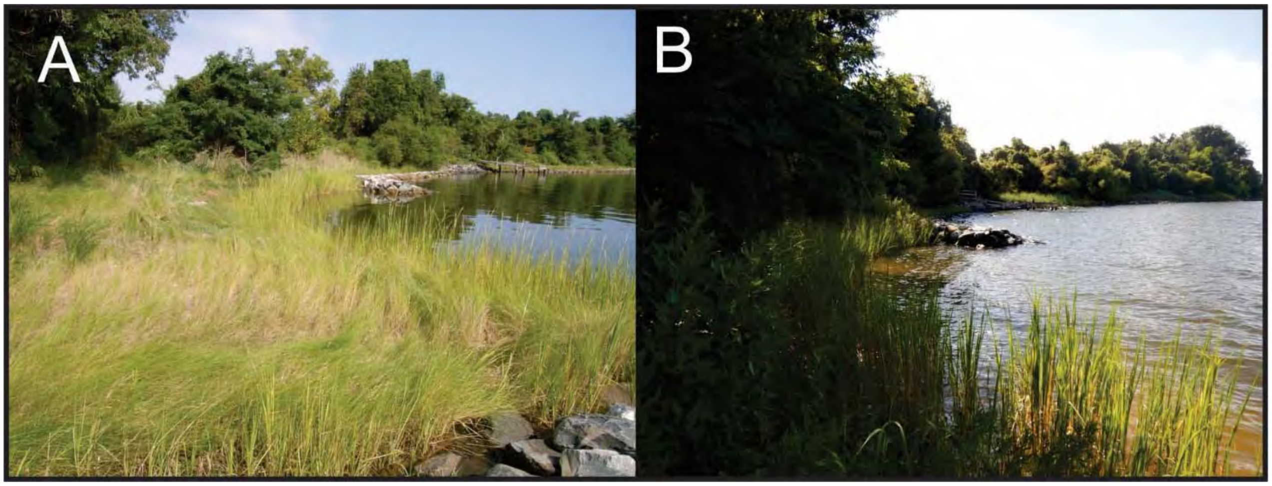

Figure 4-4-5. Photos at Jefferson Patterson looking from sill #4 downriver toward sill #3-3 in A) 2008 and B) 2018 where extensive Phragmites is visible.

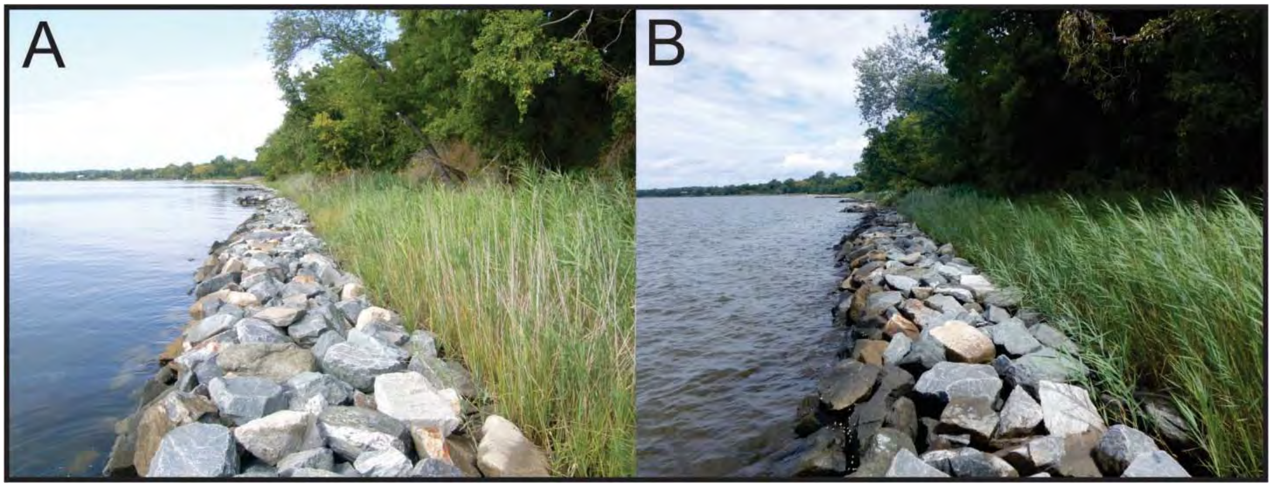

Figure 4-4-6. Photos at Jefferson Patterson looking from sill #5-1 and beyond in A) 2008 and B) 2018 where extensive Phragmites is visible.

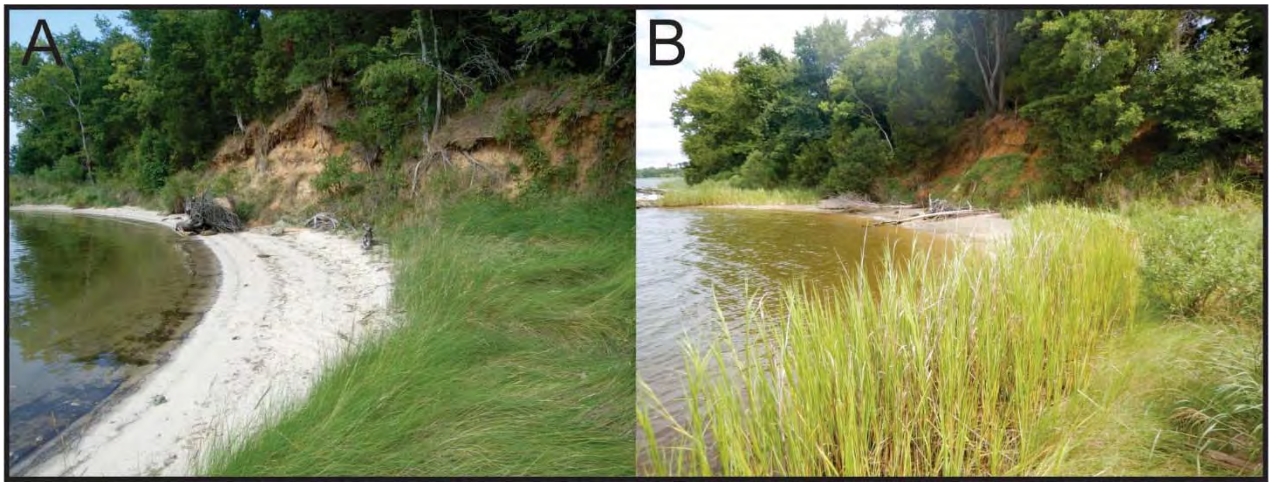

Figure 4-4-7. Photos at Jefferson Patterson of the embayment between BW4 and Sill 5-1 in A) 2008 and B) 2018 where Phragmites is visible.

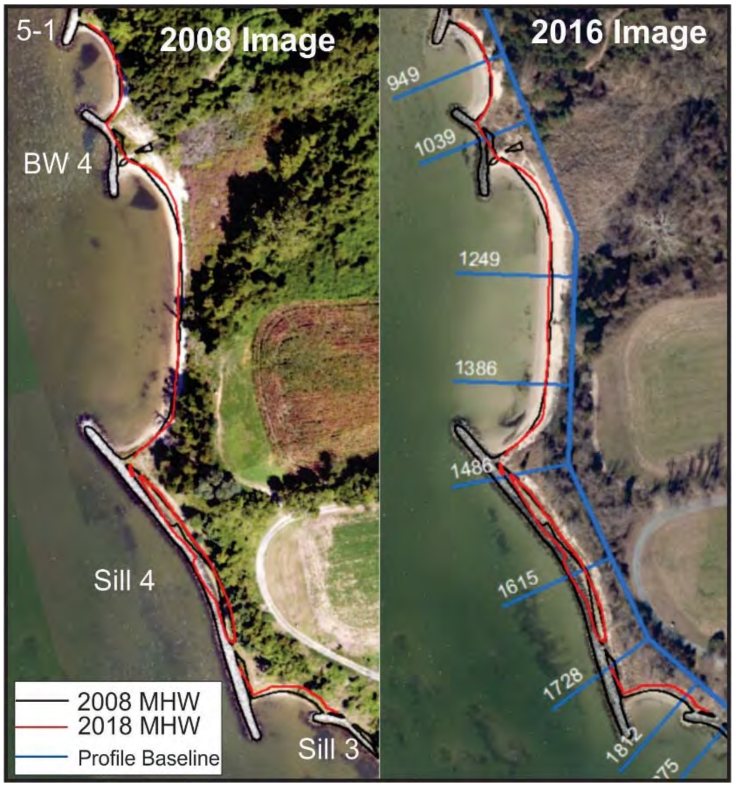

Figure 4-4-8. Aerial photos taken in 2008 and 2016 showing the cross-sectional profile locations and the surveyed position of mean high water in 2008 and 2018.

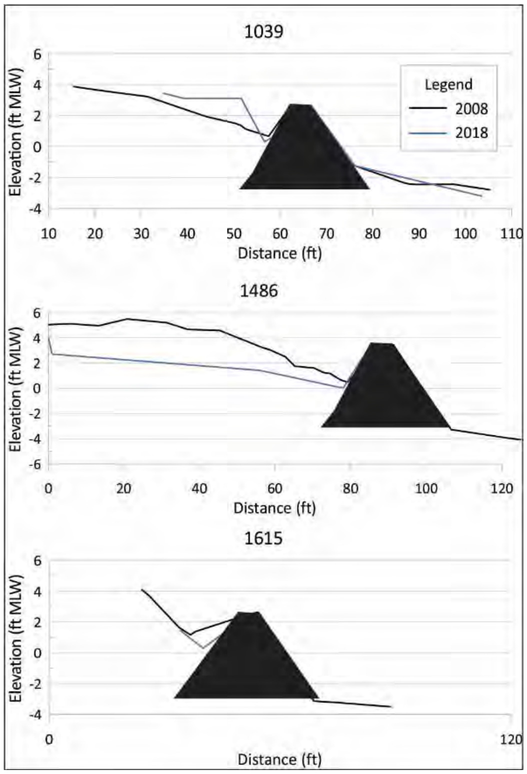

Figure 4-4-9. Cross-sectional profiles at Jefferson Patterson.

5 Adaptive Management

In order to adapt to SLR at these sites, it may be necessary to add rock and/or sand to each project. The plantings become almost secondary in that some filling of existing marsh substrate maybe required to re-set the system. Each site was modeled on the intermediate position of sea level as described by the USACE (2014) of 1-foot rise by 2050. The results can be depicted on the design cross-section to examine the needs of the system. Assumptions of the model include: the 1-foot rise in sea level; the system transitions linearly with no invasive plant species; and the mean tide range does not change. Present day is show in black, the +1 ft rise by 2050 scenario is shown in red, and the +2 ft by 2050 is shown in blue.

5.1 Captain Sinclair

Based on the model at Captain Sinclair, the lower limit of *S. alterniflora* will be about 8 feet landward of the sill (5-1-1) because mid-tide, which is the lower limit of S. alterniflora, extends farther inland. The *S. patens* along the back berm will be replaced by *S. alterniflora*. The sill will become submerged at MHW thereby slightly reducing its wave attenuation capability but also becoming more of reef type structure. Adding rock to the sill is not an option because this low bank shore will be flooded. If this system is able to migrate vertically and horizontally either naturally or with the addition of sand, by 2050, it will have preserved about 0.14 acres of marsh habitat.

Beyond 2050 (or increased rate of SLR), the marsh system will begin to drown. At an increase of 2 ft in sea level, the system will become almost subtidal and the wide marsh behind the sills will be impacted. The rock sill will become a fully submerged reef which will still reduce wave energy impacting the shoreline, but it will not provide effective shore protection. Once the system is subtidal, SAV might move into the old marsh substrate.

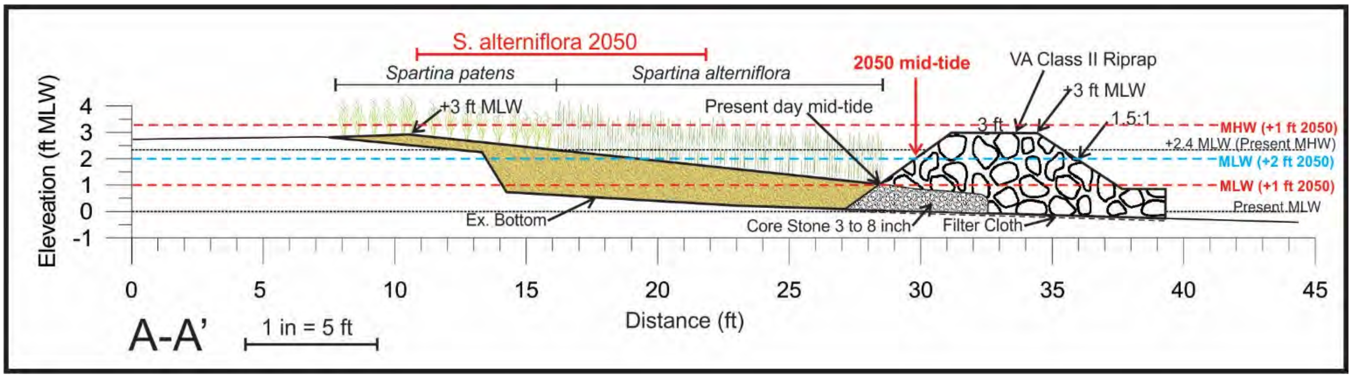

Figure 5-1-1. Sea-level rise scenarios modeled at Captain Sinclair and depicted on a typical cross-section.

5.2 Occohannock on the Bay

By 2050 with a 1 projected one-foot rise in sea level, impacts will have different impacts to the various Camp shorelines. In Reach 1, the sill should still be functioning to attenuate waves because it is still exposed at high water. However, the low marsh fringe will recede 8 to 10 feet (Figure 5-2-1). The high marsh and salt bush will occupy a narrower corridor. One more foot of SLR will submerge the sill at high water and drown much of the high marsh leaving only a narrow section of low marsh and broader subtidal terrace. The upland will be just above MHW so the access path might become a high marsh terrace. More wave energy will impact the site, and an increase in rock height maybe warranted.

A 1 foot SLR along Reach 2 will submerge the low rock sill at high water (Section C; see Figure 4-2-2) and cause the lower limit of low marsh to retreat landward. The low marsh along Section DD will also retreat landward leaving non-vegetated intertidal and subtidal flat. The high marsh and remaining low marsh fringe may move landward if the trees are removed. A 2 foot SLR will mostly submerge the rock sill except for very crest which would appear at low water.

The upland bank along Reach 3 under the 1 SLR will still be protected by the marsh fringe even though MHW and the low marsh will move landward 5 to 7 feet and the rock sill will be almost submerged at high water (Figure 5-2-2). Much of the lower marsh area today will become intertidal non-vegetated wetlands, and only a small area of *S. alterniflora* will exist because of the steeper elevation between the low marsh and the bank. A 2 foot SLR may warrant the addition of rock to the sill which will be one foot underwater at high tide because the marsh fringe and base of upland bank may also become compromised because of increase in wind wave impacts during even modest storm events.

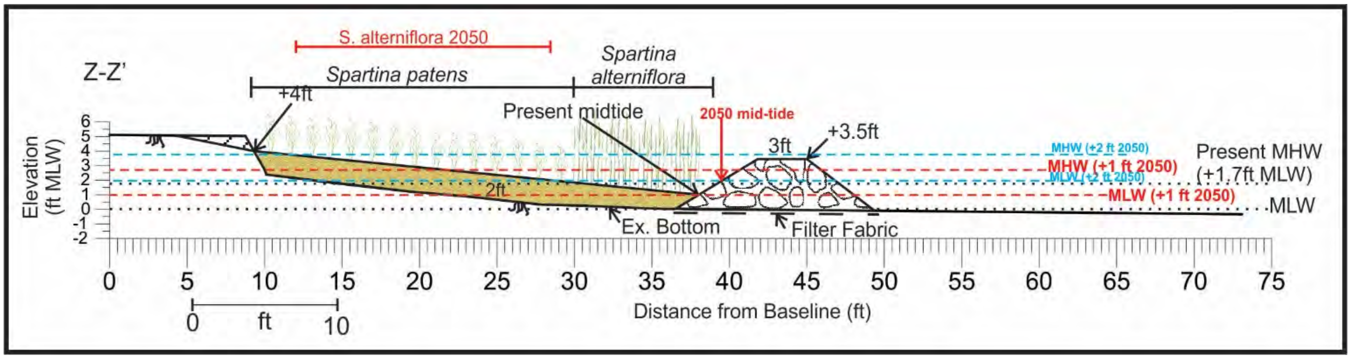

Figure 5-2-1. Sea-level rise scenarios modeled at Occohannock, Reach 1, and depicted on a typical cross-section.

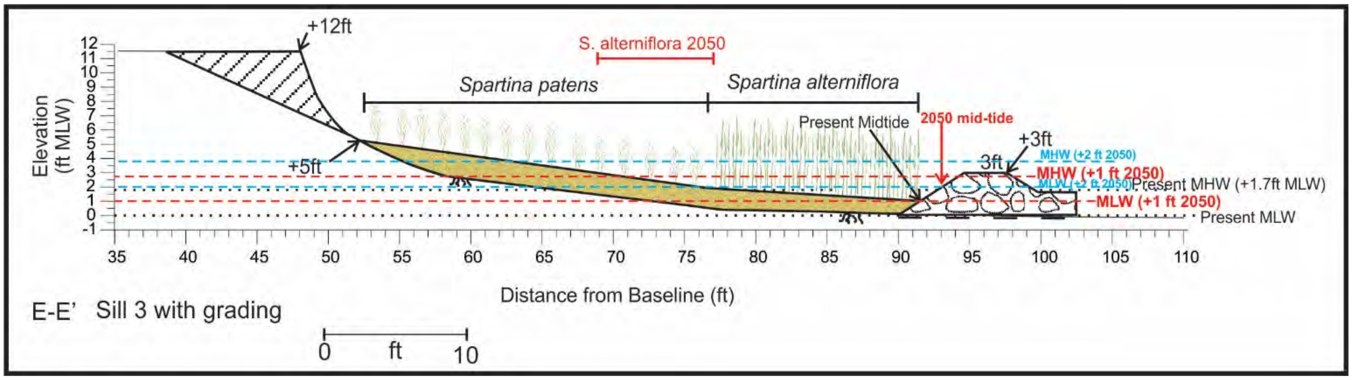

Figure 5-2-2. Sea-level rise scenarios modeled at Occohannock, Reach 3, and depicted on a typical cross-section.

5.3 St. Mary's City

Mean sea level has risen about 0.2 ft since the project was installed. On the original design, the total sea level rise modeled by 2050 includes the 1-foot projected sea level in addition to the 0.2 ft that has already occurred. This means that the 2050 MHW will be +3.2 ft above the position of MLW in 2002. This moves the lower limit of *S. alterniflora* landward over 10 feet which amounts to significant "coastal squeeze". The rock sill is submerged at MHW and the base of the bank will also be flooded (Figure 5-3-1). The existing vegetation will change and the Phragmites may disappear as it is submerged twice a day. high marsh and wave attenuation of the sill will be reduced. The intertidal and subtidal area will expand behind the sill. A 2-foot rise will submerge the whole system at low water.

Presently, the system is working to provide shore protection to the high bank coast along this relatively low fetch shoreline. However, this site maybe a candidate for SLR modifications in the future due in part to ease of accessibility by water which will allow barges to bring in material and to be used in construction. One scenario would be to add proportionate rock and sand to the system and replant after cutting back the overhanging limbs (Figure 5-3-2). The existing marsh fringe would be completely covered, and the project would start all over again at a higher elevation. Before this could be implemented, it would be important to dig out all the Phragmites and commit to a maintenance plan.

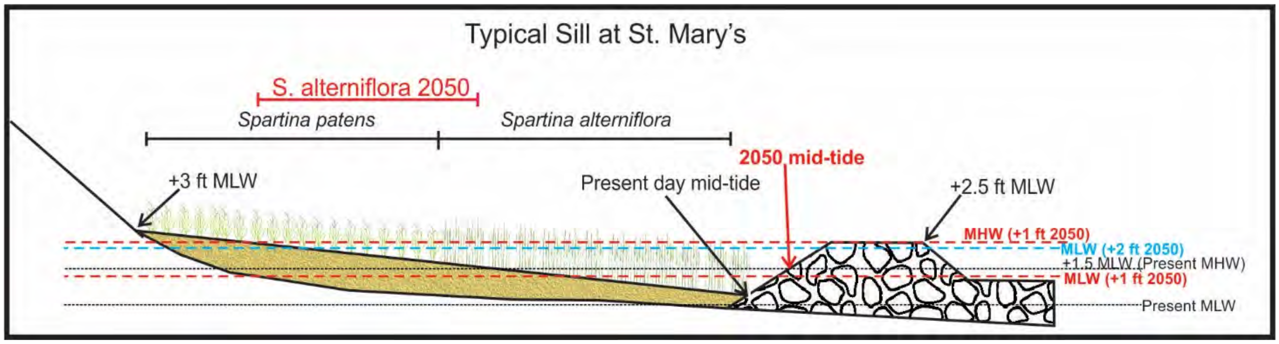

Figure 5-3-1. Sea-level rise scenarios modeled at St. Mary's and depicted on a typical cross-section.

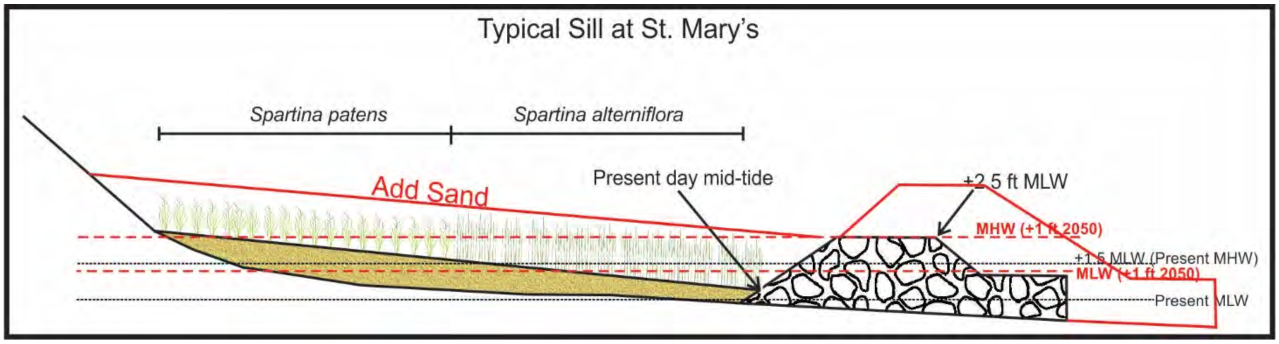

Figure 5-3-2. Sea-level rise scenarios modeled at Occohannock. Also shown is the adaptive management strategy coastal resiliency of the living shoreline. Rock and sand could be added to the system to "reset" it thereby protecting the base of the bank.

5.4 Jefferson Patterson Park & Museum

With a one-foot rise in sea level, *S. alterniflora* would migrate upgrade leaving a wider non-vegetated intertidal zone. The sill would be submerged at high water (Figure 5-4-1) The extensive Phragmites already covers much of the sill system and would persist even with a 2-foot rise in sea level. This system would be a good candidate site for just adding rock to the sill to protect the base of bank from wave attack (Figure 5-4-2). Adding sand could be done too but at additional costs. Again these options are viable because of barge access for construction.

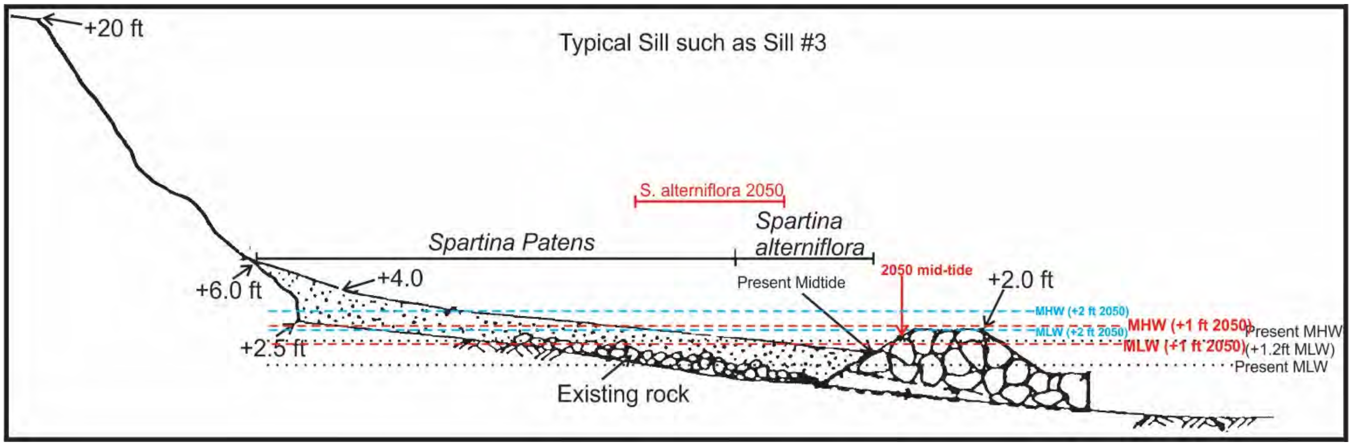

Figure 5-4-1. Sea-level rise scenarios modeled at Jefferson Patterson and depicted on a typical cross-section.

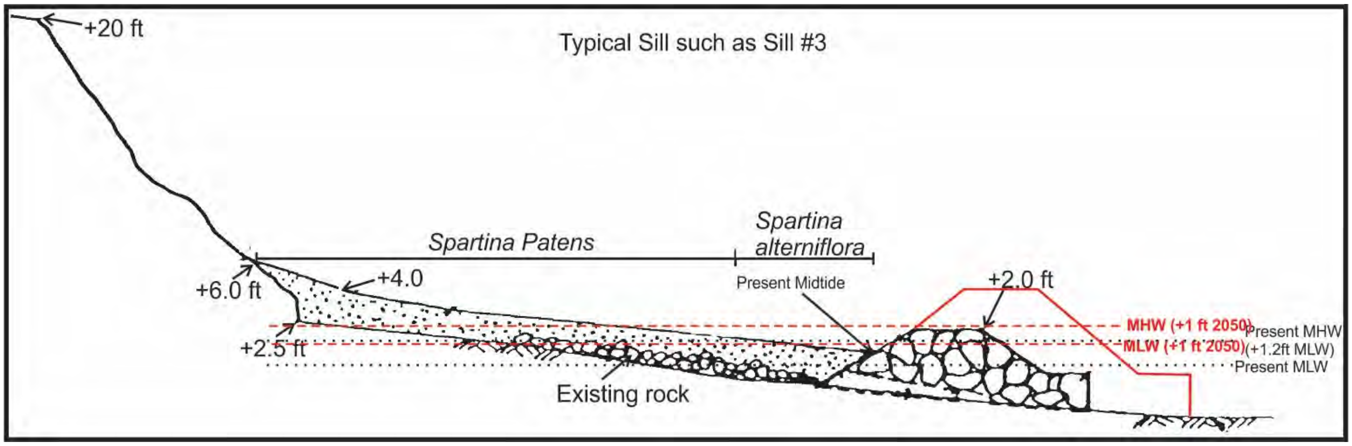

Figure 5-4-2. Sea-level rise scenarios modeled at Jefferson Patterson. Also shown is the adaptive management strategy coastal resiliency of the living shoreline. Rock could be added to the sill to protect the base of the bank.

6 Summary

Hundreds of sill sites occur around Chesapeake Bay in a variety of settings, installed at different times over the past 30 years. The four sites in this report are just a sample in terms of site setting and age. The basic application of rock sand and plants has taken on significant modifications in design and construction but basics of creating a stable marsh for shore protection remains. Fetch exposure drives design especially as it relates to shore protection, the primary reason for sill system installations. These sites are functioning quite well for their intended purpose, shore protection with enhanced coastal habitats. Invasive species will always be problem.

Captain Sinclair, after two years, has a continuous robust dual species marsh fringe with an increased vegetated backshore berm. No maintenance is needed at this point. For this low marsh system, adding rock to the raise the elevation of the structure is not an option because the upland will flood. The addition of sand when needed in the future could give the marsh the ability to migrate vertically.

Occohannock, after 5 years has a continuous and robust dual species marsh fringe. Landward adjustments to the lower limit of *S. alterniflora* behind Sill #3 are not unexpected; it adds diversity to the habitat and does not affect its shore protection capability. Maintenance in terms of thinning the young pine saplings should occur.

St. Mary's City, after 16 years, has a continuous robust vegetated backshore region. Though most the upper backshore is shaded by overhanging limbs, no discernible base of bank erosion occurs. Much of the low marsh remains, but the high marsh in compromised by shading and Phragmites. The increase in Phragmites coverage is unfortunate from a diverse habitat perspective but is probably good for shore protection.

Jefferson Patterson, after 19 years, has a continuous vegetated backshore behind the sills and breakwaters with extensive and intermittent dense patches Phragmites. From the original two grass species design, the high marsh is impacted the most due to overhanging limbs and Phragmites. The small pocket beaches are generally stable with some ongoing bank erosion that has minor impacts to the adjacent bank faces.

Phragmites austrailus is an invasive grass which can tolerate salinities less the 15 ppt (Lissner and Schierup 1997). This is the salinity range of both St. Mary's and Jefferson Patterson. However, during the fall, salinities in the mid-bay including the St. Mary's river are higher up to 20% which might slightly inhibit Phragmites growth there.

At each site, prior to the installation of the living shoreline projects, shoreline erosion occurred because of the lack of a stable natural marsh or beach feature to buffer the impinging wave climate. Due to their fetch exposures just adding sand and planting that subgrade is not sustainable. Therefore, the rock sill is required to provide shore protection. An adaptive management strategy for these systems is an increase in sill height to deal with the reality of sea level rise.

With increasing sea level rise and the ongoing desire to provide shore protection with these types of system, it is important to look back on what has been done and how has it functioned. Systems may not provide the habitat diversity when invasive species colonize the project, but the system's ability to provide shore protection is not compromised. Even with mono-cultural species, these living shorelines are arguably better habitat than the traditional bulkhead or revetment. These living shorelines will continue to provide habitat and shore protection long into the future.

These lower fetch environments are only part of the story. Research is underway to review the effectiveness of breakwaters in high energy environments in terms of their ability to maintain a level of protection in the face of sea-level rise. The modeling for adaptive management will continue to be refined based on additional knowledge.

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