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Cover Photo taken along St. Mary's City on 24 August 2008

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1 INTRODUCTION

1.1 Statement of Problem

Living shorelines represent a shoreline management option that combines various erosion control methodologies and/or structures while at the same time restoring or preserving natural shoreline vegetation communities. A common living shoreline design in Chesapeake Bay includes a low offshore rock sill to absorb wave energy with an emergent wetland landward of the sill to enhance erosion control, provide critical habitat, and improve water quality condition. This study is part of a larger, ongoing project to (1) evaluate erosion control effectiveness and the sustainability of offshore sill and fringing marsh design and structure, (2) evaluate ecological services (e.g., habitat value, water quality remediation) provided by the various components of the living shoreline design, and (3) develop design criteria that may enhance services provided by living shoreline designs in low and moderate energy environments.

This project measures the performance of sills in Chesapeake Bay in support of developing design guidance. In particular, it assesses how the windows (or gaps/vents) in some sills affect their value for shore protection and water quality. The approach utilizes both field data collection (e.g., site assessment and survey, water quality data collection) and hydrodynamic modeling methodology. Two sites, varying in construction design and age, were assessed at St. Mary's City, Maryland on the St. Mary's River (Figure 1-1). Site 1 is part of a larger project and has about 1,000 feet of shoreline with a gapped sill that was built in 2002 (Figure 1-2). Site 2, a 1,000 feet non-gapped sill, was built in 1998 and is adjacent to Site 1 (Figure 1-2). Previous data exists for Site 1, which includes the implemented construction plan and the as-built survey. Both sites were surveyed to provide the present dimensions of the sill systems. Modeling methodology was used to assess residence time and age of water that flushes through sill structures and associated fringing wetland along part of Site 1. Also analyzed was the impact of several different window configurations and dimensions on beach shape and shore protection as well as the site substrate and vegetation characteristics, surface water and groundwater quality, and nekton.

1.2 Background on sill systems

The use of rock for shore protection structures began in earnest around the Bay in the 1970s with rock revetments increasingly replacing the traditional wood bulkheads. Rock was obviously more durable, and if designed and constructed properly, could provide a greater period of service than wood. This hardening of the coast, wood or stone, became extensive and was even used in small creeks where erosion was more perception than real. Nevertheless, during the 1980s, creating fringe marshes became a viable alternative shore erosion control method in the small, fetch-limited creeks and rivers. By increasing marsh width with the addition of sand more protection was provided from waves during storms (Garbisch and Garbisch, 1994). However, the sand needed to be stabilized because waves would transport the substrate away; short stone groins were employed for the task. This method worked but generally only on shorelines with less than about 0.5 miles of fetch.

Enter the sill, a continuous line of rock placed offshore with sand fill and marsh grass plantings. The rock protected and constrained the sand fill and allowed the marsh to grow and could maintain its integrity during storm wave attack. The Maryland non-structural program under the Maryland Department of Natural Resources in the mid and late 1980s provided match funding for landowners to build marsh systems for shore erosion control. These included sand fill with groins and sill systems. The design of these systems was based on previously installed sills. This allowed the designs to evolve more from a programmatic rather than engineered basis.

In order to evaluate the effectiveness of these installations, a recent study by Bosch *et al. (*2006) surveyed and assessed 80 man-made wetlands in the State of Maryland. Of these, 43 sites had sills and 15 of these had gaps or vents of some type. The sites were ranked according to four elements including 1) vegetation 2) wildlife 3) erosion and 4) was the overall marsh ranking. Elements of a successful marsh with sill are embodied in Figure 1-3; this site had most of the eight factors deemed essential to a successful project according to Bosch *et al.* (2006):

- sunny
- proper filling
- 50/50 split between high and low marsh
- protected shoreline
- staggered or dog-legged vents in sill
- independently stabilized cliff
- proper grading (10:1) and sill placement to allow for flushing
- proper maintenance: 1) marsh is kept clear of debris; 2) no use of chemical lawn treatments; 3) marsh is kept free of unwanted alien invaders

It should be noted that the open water exposed between the marsh and the sill could require additional encroachment into the nearshore. That is an issue with permitting agencies in both Virginia and Maryland when it comes to replacing one habitat (nearshore bottom) with another (rock). Maryland's Department of Natural Resources has created a website on Living Shorelines and lists their applicable regulations and permitting process (http://shorelines.dnr.state.md.us/default.asp#).

Maryland developed design guidelines for marsh creation which outlines various ways to construct marsh fringes for shore erosion control (Luscher and Hollingsworth, 2006). Figure 1-4 shows the general dimension of a typical sill system and state guidelines for installation. It is unclear as to how high the sand fill goes up onto the base of the eroding bank but at a 10:1 it would be about 3 feet above MLW. In Maryland, if you keep the system within 35 feet of MHW, the permitting process is simpler. Adding sand fill elevation and a 10:1 slope would push the structure farther offshore; this allows more shore protection but adds to permitting review.

In Virginia, the use of sills has been more limited due to lack of a funding program and fewer recommendations by consultants and state advisors. This is gradually changing, and the use of stone to hold existing marshes is more wide spread. Durhing *et al.* (2006) documented examples of marsh toe revetments and some sills around fetch-limited Virginia coasts. All of the 36 sites studied had a protective rock structure; three sites were planted with marsh grasses, and the remainder were natural. All had tidal marshes in good condition providing satisfactory shore protection. The inclusion of openings in future sites was a recommendation.

Although generally effective at erosion control and marsh fringe creation, the sill was still seen as a line of rock, a hardening of the shore. Windows or gaps in the sill (as shown in Figure 1-2) were encouraged to allow more free flow of marine fauna to utilize the created marsh fringe, particularly turtles and fish. However, when the sill is opened to allow marine fauna ingress and egress, the local wave climate also comes in as well. The result was twofold: 1) during storms, the waves could impact the upland bank which the sill was designed to protect, and 2) the waves would create a “beach” berm around the perimeter of the opening thereby closing the marsh fringe off and reducing access to the adjacent marsh. In fact, sill openings will create small pocket beaches which are important estuarine habitat themselves. These factors have been addressed by numerous creative opening designs including varying the opening or gap, offset on side to the other, turning the sills offshore to create small spurs, using cobble instead of sand in adjacent to the openings, and others.

1.3 St. Mary’s City Sill Systems

The main purpose of the St. Mary’s Shoreline Project is shoreline erosion control which was achieved with a combination of the stone sill and marsh fringe. The 1998 sill system, Site 2, was basically a continuous sill about 1,700 feet long with three low sections or weirs, supposedly for improved flushing. This project was surveyed as part of this study but pre- and post-construction surveys were unavailable. The shoreline that exists between the two different sill projects has a low, marshy backshore and narrow gravelly beach about 600 feet long. This reach received an additional amount of sand as part of the 2002 project.

The 2002 installation, Site 1 (Figure 1-2), became the primary focus of this study because it had a variety of window types included for demonstration purposes. The window or vent objective, according to the Maryland Department of Natural Resources, was to design different window types to reduce the “berming” of the sand fill thereby allowing more flushing between the opening and the rest of the sill. This would, in theory, provide better access (for marine fauna) and increase water quality when compared to the created fringe marsh behind continuous sections of the system. For construction of Site 1, sand fill was placed at about +2.9 feet MLLW (tidal epoch 1983-2001) against the base of the bank and graded down on about a 8:1 slope to the back of the sill at just below mid-tide level, +0.4 feet MLLW (Figure 1-5) along 2,050 feet of shoreline. Figure 1-6 shows how these elements were constructed at the northern end of Site 1 at Window 8. Using photos taken from the pier at Window 3 through time, Figure 1-7 depicts the initial installation, after planting, during a high water event, and how the sill looked in 2007. 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).

A series of window or gap types were built into the project, an idea proposed by the Maryland Department of Natural Resources and St. Mary’s Soil Conservation District. Originally, these breaks were created to let turtles utilize the marsh, but the idea has since expanded to ingress and egress of fish and all other manner of marine life. In addition, water quality and flushing was theorized to be impacted by the gaps in the sills. However, building windows into a sill system can cost more money since stopping and starting the sill is precise work. The windows also allow the wave energy to impact the backshore and bank during storms.

Overall, the 2002 sill installation has performed well as a shore protection system, enduring Hurricane Isabel and Tropical Storm Ernesto with minimal base of bank scarping. The sill system installed in 1998 had similar dimensions but only had several low sections, weirs, not true openings. Only the 2007 survey is available for this section of shore, and no water quality assessment was done there. The 1998 sill also has provided a high degree of base of bank protection. Although the water levels were well up on the upland bank during these storms, only modest wave action impacted it due to relatively short fetch distances and sheltering from the main storm winds (Figure 1-5).

2 PHYSICAL ASSESSMENT

2.1 Site Setting

St. Mary’s City is located on the St. Mary’s River in St. Mary’s County, Maryland. The tide range at Lewisetta, the closet tide gauge, is 1.2 feet and the tide range at St. Mary’s City is 1.5 feet. The twelve highest water levels from post-construction to the present are shown in Table 2-1. Shore erosion in Chesapeake Bay is driven by the local wind/wave climate. Wave energies are a function of wind speed, fetch and nearshore water depths. Shore erosion on a daily basis is minimal; generally, erosion occurs during periods of elevated water levels and their associated high winds that generate erosional wind driven waves. This particularly true during the infrequent northeasters and hurricanes.

The project site lies along a curvilinear portion of the coast where fetch exposures vary slightly along the length of the project. The main fetch exposure from about mid-site are to the west, northwest, and north of 5,000 feet, 4,500 feet, and 8,000 feet, respectively. Of these site fetch exposures, the west, northwest and north wind frequencies are 10.2%, 15.0% and 22.6% (Table 2-2). This indicates a strong northerly wind/wave component is impacting the site. Through time, the eroded bank sediments differentially segregate with the finer silts and clays being carried offshore, fine to medium sands tend to occur across the nearshore and the coarser sands and gravels accumulating as beach deposits.

The project coast has high upland banks that had a narrow, gravelly beach before construction. The erosion of the base of the bank caused intermittent slumping of the bank face making it generally unstable. A few large slumps historically have occurred, and erosion of the slumped material was proceeding. The bank face is relatively stable except where slumping continues. Historic shore change is shown in Figure 2-1. Shore recession along the 2002 project shore averaged about 1 foot per year between 1848 and 1994. A short wood bulkhead behind Sill 5 was the only structure present before construction of either sill system.

Table 2-1. List of maximum water levels above mean lower low water and associated storm event at Lewisetta, Virginia tide guage since April 1974 (NOAA website, 2007).

Date	Elevation (feet MLW)	Comment
1-Sep-2006	5.65	Tropical Storm Ernesto
19-Sep-2003	5.47	Hurricane Isabelle
5-Feb-1998	3.84	Twin Northeasters
1-Nov-1991	3.73	Halloween Storm
31-Oct-1991	3.66	Halloween Storm
7-Sep-1996	3.59	Hurricane Fran
16-Sep-1999	3.51	Hurricane Floyd
8-Oct-2006	3.49	Tropical Storm
22-Sep-1994	3.39	Northeaster
19-Mar-1983	3.36	Northeaster
15-Jun-2007	3.36	Northeaster
28-Jan-1998	3.35	Twin Northeasters

Table 2-2. Summary wind conditions at Patuxent Naval Air Station between 1945-2001.

Wind Speed (mph)	Wind Direction								Total
	South	South west	West	North west	North	North east	East	South east	
0-5	11,395* 2.35+	8,307 1.71	9,220 1.9	11,478 2.36	56,320 11.6	7,855 1.62	6,860 1.41	7,304 1.5	118,739 24.45
5-10	31,447 6.48	2,7630 5.69	23,146 4.77	27,013 5.56	28,224 5.81	23,741 4.89	17,188 3.54	24,033 4.95	202,427 41.68
10-20	18,356 3.78	2,5752 5.3	15,740 3.24	25,714 5.29	21,409 4.41	13,594 2.8	7,291 1.5	15,221 3.13	143,079 29.46
20-30	1,166 0.24	2,145 0.44	1,528 0.31	7,751 1.6	3,654 0.75	1,666 0.34	395 0.08	1,183 0.24	19,488 4.01
30-40	34 0.01	46 0.01	75 0.31	1,013 0.21	298 0.06	73 0.02	44 0.01	65 0.01	1,649 0.34
40-60	2 0	2 0	2 0	82 0.02	26 0.01	5 0	7 0	12 0	140 0.03
Total	62,401 12.85	63,883 13.15	49,711 10.24	73,055 15.04	109,932 22.64	46,934 9.66	31,786 6.55	47,821 9.85	485,649 100

*Number of Occurrences +Percent

2.2 Survey

A shoreline and nearshore survey was performed at the sill site in May 2007. A Trimble 4700 Real-Time Kinematic Global Positioning System (RTK-GPS) was used to set site control and acquire shore data. The 4700 receiver utilizes dual-frequency, real-time technology to obtain centimeter accuracy in surveying applications. In addition, a Trimble 5600 Robotic Total Station will be used to acquire data in the nearshore. Generally, the surveys included the following elements:

1. Dimensions of the sill;
2. Mean High Water (MHW) and Mean Lower Low Water (MLLW); survey extends to approximately the -2 feet MLW contour; and
3. Base of bank, where appropriate and possible. In addition, the condition of the base of bank were assessed in terms of stability/wave scarping since both sites were impacted by Hurricane Isabel in September 2003 and Tropical Storm Ernesto in September 2006.

Surveys also were taken by St. Mary's Soil Conservation District before (February 2001) and after (March 2002) sill installation. The post-installation survey concentrated on the dimensions of the sill and sand fill. It did not extend into the nearshore. These data were input to Terramodel (Trimble Navigation Limited, 2008) and converted to the coordinate system of the 2007 survey. Control fo r the 2007 survey was in UTM, Zone18 north, NAD83, meters and NAVD88, Geoid99, meters. The elevations were converted to international feet MLLW (tidal epoch 1983-2001) by adding 0.83 feet to points. By overlaying the three surveys, changes in the marsh substrate that was installed as part of the sill system design and construction could be ascertained particularly in the window sections.

2.3 Sill Project Assessment

The evolution of the St. Mary's City sill system installed in 2002 is reflected in profile data. These data, in particular, show the changes that have occurred at the windows or gaps. Nine sill segments and nine windows or gaps in six different configurations were built in the 2002 project (Figure 2-2). The various window configurations were created to test different ways to minimize berm formation as well as provide better shore protection. Originally, these breaks were created to let turtles utilize the marsh, but the idea has since expanded to fish and all other manner of marine life. As the sill systems evolve, the sand fill created a berm in the small pocket beach which blocks open flow and fish ingress/egress into the created marsh fringe on one or both sides of the opening. A concern was that berm blockage would not only minimize flow through the window but, in so doing, increase water temperature in summer as well as trap fish.

The windows created at St. Mary's are labeled as Types I, IIA, IIB, III and V and are shown in Figures 2-3 through Figure 2-10. The Type II window series addresses a balanced or onshore wave approach. This usually results in a berm forming on both flanks of the window beach against the sill as has occurred at windows 2 and 3 (Figures 2-4 and 2-5). However, Type IIB, which was built in windows 1 and 7 has a cobble and gravel pavement to protect the upland base of bank as well as create a reflective beach face that does not berm as easily as sand fill and thus allows for a much reduced berm feature (Figures 2-3 and 2-8).

Window 4, which is Type I, was designed as shown to shelter the window from a dominant wind field coming from the right of the window (Figure 2-6). In general, a berm will form on the windward side at the flex point but will not form as big on the lee side of the window which makes for better opening there.

The Type III window, which was built in window 8, has an offshore submerged breakwater and cobble backshore for wave reduction and minimized berm formation within the window opening (Figure 2-9). The sentinel stones mark the end of the submerged breakwater. Finally, the Type V, window 9, is relatively wide with a stone revetment against the base of bank for protection and to induce wave reflection (Figure 2-10).

The result of our surveys shows that there are varying areas of erosion, accretion and stability along the project length. Figure 2-11 shows the change along the backshore between post-installation and 2007. Because sand was placed along the shore, many areas show minor erosion which is typical of fill adjustment following a project. However, many areas have remained the same or accreted due in part to the plantings and continued growth of grass behind the sills and trapping of bank slough.

Figure 2-12 shows the change in the nearshore between pre-installation (2001) and 2007. Pre-installation was used because the post-installation (2002) data did not extend beyond the base of the sill. Most of the nearshore areas (the area riverward of the sill) was mainly accretionary. Only one small area of erosion occurred. This was the only area that had a lower elevation than pre-installation. The additional sand has accreted in the nearshore with positive change in elevation due to the onshore movement of sand not losses from the project. In the nearshore, no windows lost all of the fill that was placed in the course of the project (Figure 2-12).

Window 1: This opening has a cobble and gravel pavement along the central portion of the embayment which has minimized “berming”. A minor decrease in elevation has occurred as the cobble adjusted to the impinging wave climate, but no evidence of bank scarping exists in the lee of the window. Grasses did not grow in the intertidal zone behind the window opening due to impinging wave action, but the very backshore is vegetated with some *Spartina patens* and a few salt bush. A wrack line is visible at about +2.7 feet MLLW, evidence of higher water levels and wave action.

Window 2: “Berming” occurs on both flanks of the embayment as does a decrease in backshore elevation and consequent scarping of the base of the bank. This has not threatened the integrity of the bank slope to date. No intertidal grasses (*Spartina alterniflora*) are growing and only sparse patches of *S. patens* occur behind the window. *Spartina alterniflora* growth on the berms indicate that the area is intertidal at least at the upper end of the tidal cycle. The *S. patens* comes down close to the sill along the berm crest on the upriver side of the bay beach, indicating the net direction of wave approach from the north.

Window 3: This window was designed to accommodate the existing pier and is relatively wide. Berming, decreased backshore elevation, and base of bank scarping occurs although this had not threatened the integrity of the bank slope. *Spartina alterniflora* exists along the bay beach opposite the opening while and only remnant patches of *S. patens* exist in the backshore. On the down river berm, the *S. patens* grows out along the berm crest and a narrow band of *Spartina alterniflora* exists below that indicating upper tidal flow there.

Window 4: As with these types of offset windows, the berming occurs on both flanks, but a slightly high and wider one forms on the updrift side. The mid bay area is mostly void of grasses due to wave runup. Very slight base of bank scarping exists, but no bank face failure has occurred. The downriver berm is low and fully occupied with *Spartina alterniflora*.

Window 5: This window was created so that an adjacent boat ramp would continue to have access to the river. A berm on the downriver side of the embayment has mostly *Spartina alterniflora* across it. A beach exists around the perimeter with no grasses in the intertidal zone, but *S. patens* occupies the backshore in front of the existing bulkhead. A slight base of bank scarp is visible on the other half of the bay but no bank failure.

Window 6: This window was created to provide a corridor for the pier. No grasses grow in the midbay area due to wave runup and consequently, slight berming occurs on both sides and a base of bank scarp and minor bank failure.

Window 7: Along this window, cobble was placed in the backshore and gravel in the intertidal zone. This pushes MLW out toward the window and little berming occurs. Grasses now grow adjacent to the window opening, but *Spartina alterniflora* occurs as a fringe on each side indicating tidal flow across the low connection. A few sparse patches of *S. patens* grow in the backshore as well as salt bush, indicating a relatively stable area. No base of bank scarping is seen and the bank face is stable.

Window 8: This window has a unique design with cobble within the bay beach zone and a low offshore breakwater. The cobble was placed below MLW. This causes the window bay to be relatively long and linear. Salt bush and *S. patens* occupy the backshore region while *S. patens* has grown out on low cobble berms that may have been a result of construction rather than berming by wave action. The base of bank and bank face are stable.

Window 9: A stone revetment was placed against the base of bank along this window. The bay is relatively deep with little or no berming as evidenced by a full *Spartina alterniflora* fringe on the flanks of the embayment. This appears to allow significant tidal flow into the adjacent sill and fringe.

The site survey and ground photos show the variability in the marsh fringe landscape along the length of the project. No clear patterns of topographic loss or gain emerge along the marsh fringe backshore region. The areas around the windows tend to deflate as they berm up and possibly lose some material offshore. Relatively long stretches of deflation are visible along

Sill 2 and Sill 8 with smaller deflated areas about mid-sill at Sill 4 and 5 (Figure 2-11). Otherwise, no change has occurred along most of the project length.

3 WATER QUALITY MODELING

The Unstructured, Tidal, Residual Intertidal, and Mudflat model (UnTRIM) was used to assess residence time and age of water (a measure of spatial variation of retention time) of water that flushes through sill structures idealized from the sill window designs at St. Mary's City. UnTRIM is a general three-dimensional model capable of simulating both 2-dimensional (vertically averaged) and 3-dimensional hydrodynamics and transport processes. Its orthogonal, unstructured grid allows for a better fit regarding study site boundaries and grid refinements to meet the needs of resolving spatial resolution in numerical modeling tasks. A robust wet-dry algorithm is implemented in the model that is capable of inundation simulation.

3.1 Retention Time Simulation

Sills combine elements of rock revetments and offshore breakwaters. Rock sills generally have a “free standing” trapezoidal cross-section similar to breakwaters. Sills can be used in higher wave energy regimens to establish intertidal marsh grasses. Two typical types of sill windows are used in the St. Mary’s River of the Chesapeake Bay, which is illustrated in Figure 3-1. Water floods into the fringe marsh through the sill windows during the flood tide and flows out of the marsh during the ebb tide. In the model, the amount of time the marsh is submerged depends on the type and size of windows and the gaps between windows. The design of windows and gaps between windows can affect the value for shore protection and water quality. One important dynamic indicator of water quality is the water residence time. Residence time is often defined as time as the remainder of the lifetime of a water particle in a waterbody (Takeoka, 1984; Shen and Haas, 2004). For a coastal embayment where the influence of tide is the dominant force, the flushing time is often used to quantify the transport property of a well mixed system. Therefore, the tidal prism method often used can be written as (Dyer

$$T_f = \frac{VT}{(1-b)P}$$

1973):

Where T is tidal period, P is tidal prism that is the volume between high and low tide, and b is the return ratio that is the fraction (0.0 – 1.0) of ebb water returning to embayment during the flood.

Unlike coastal embayments, a fringe marsh is submerged (wet) during the flood tide and becomes dry during the ebb tide. Therefore, it is more important to know how long it will take for the fringe marsh to be submerged and the retention time or how long the marsh will be wet.

To understand the influences of sill window type and gaps between windows to the wetting processes, a numerical model was used as a tool to simulate the wetting and drying processes of fringe marsh. The fringe marsh along the St. Mary’s River was used as a prototype and both an ideal model domain to represent the shoreline and sill structure and a model domain with survey geometry to conduct model simulations were generated. Using the ideal modeling area, the design of sill window type and gaps can be better assessed.

3.2 Model Grid and Setup

A prototype fringe marsh has a dimension of 600 feet by 20 feet. The sill has a trapezoidal shape with a width of 12 feet. The offshore region extends to 68 feet. The grid resolution is 1.0 feet. Based on the sill windows structure, two types of winds, type A and B, were used to generate the model grid. Three types of model grids were generated utilizing sill window types one, two, and three. The distance between windows is about 55m. Model grids are shown in Figure 3-2. The dimension of windows placed in the model grids were based on the design window type and dimension, which are shown in Figure 3-3.

The model grid was based on the survey data taken by Shoreline Studies Program personnel in May 2007. Coarse model grids were placed in the offshore region and fine model grids were placed in the nearshore and marsh area. The grid resolution in the marsh area is about 1 to 5 feet. A model grid is shown in Figure 3-4

No long-term tidal observation stations occur near the shoreline of the St. Mary's River. The tidal range used for the model open boundary condition is obtained from the Chesapeake Bay large domain model (Shen *et al.*, 2006). The dominant tide in the region is M_2 tide with an amplitude of 0.21 m, followed by S_2, K_1, and O_1 with amplitude about 0.03m. The model was forced by M_2 tide with a mean tidal range of 0.5 m.

3.3 Model Results

Figure 3-5 shows the sequence of the submerging processes of the fringe marsh with one sill window. The flood starts at Hour 0.5. The entire marsh area is covered by the water at Hour 3.3, approximately 2.8 hours. The water remains on the marsh for about 3.2 hours before all the water empties indicating that the water retention time is about 3.2 hours. Figure 3-6 shows the sequence of the submerging processes with two sill windows. It takes about 2.8 hours to submerge the entire marsh area with two sill windows. The water remains on the marsh for 3.2 hours before all the water empties. The time required for the marsh to be submerged does not increase very much by adding one sill window on the left side because the wetting processes on the right side of the marsh is mainly controlled by the middle window. Figure 3-7 shows the sequence of the submerging processes of the fringe marsh with three sill windows. With three windows, the marsh will be covered by the water for 1.3 hours, which is about 2 hours shorter than the marsh with one sill window. Water retention time is about 5 hours, 2 hours longer than the case with one sill window. Table 3-1 summarizes the model results. The difference in the number of windows is mainly in the time required for the marsh to be covered by the water. Once the marsh is submerged, the flushing process is mainly controlled by the tide. Water in the marsh area will be completely empted as tide retreats.

The width of a sill window is commonly set as 7 feet to 11 feet. A model test was conducted with one sill windows as shown in Figure 3-3. However, the width was set as 7 feet instead of 11 feet as shown in Figure 3-3. The model result is shown in Figure 3-8. The influence of the width of sill window is not significant. Both submerging time and retention time are the same as the sill window with the width of 11 feet.

Along rock sills, water seepage occurs along the sill. To test the influence of seepage, some water was allowed to seep through the sill for a model test. Figure 3-9 shows the marsh with one window with even seepage along the sill. The time required for the marsh to be submerged is about 1.2 hours, which is similar to the time required for the marsh to be submerged with three sill windows. The water retention time is about 4.7 hours. Seepage is an important factor controlling water quality of the marsh. Note that rate of seepage can affect the time for the marsh to be submerged.

Figure 3-10 shows the wetting-dry processes of a section of the marsh of St. Mary River. Approximately 1.3 hours after the flooding, the marsh is covered by the water. The retention time is about 5.6 hours.

Table 3-1. Variation of retention time.

	1 window	2 windows	3 windows	1 window with seepage
Hours required for marsh submersion	2.8	2.8	1.3	1.3
Retention time (hours)	3.2	3.2	4.7	4.7

4 ECOLOGICAL SERVICES

Field studies were conducted to determine water quality and fish use of fringing marshes located behind selected established sill structures in the St. Mary's River.

4.1 Materials and Methods

Sill Structures Design

The study was conducted on the St. Mary's River near St. Mary City, Maryland. The selected sill structures, constructed in 2002, are part of a larger St. Mary's City shore protection plan that utilized a variety of sill and gap/window designs (Figure 4-1). In our sampling design, the study sills were classified as "open" and "blocked" in order to reflect the ability of nekton to freely access (open) the fringing marsh shoreward of the sill through designed window features. Blocking access to the fringe marsh was accomplished by deploying two tightly meshed nets on either end of the sill structure that terminated on a supra-tidal point on the immediately adjacent shoreline. Study sills were constructed of 300-900 lbs. (136-408 kg) rock with a top and base width of approximately 3 feet (0.9 m) and 12 feet (3.7 m), respectively. Linear extent of the open sill was 212 feet (64.6 m) and the blocked sill was 130 feet (39.6 m). Design specifications called for low marsh (*Spartina alterniflora*) being established from 0.5 to 2.5 feet (0.15-0.76 m) above mean low water (MLW) and high marsh (*S. patens*) being established 2.5 to 3 feet (0.76-0.91 m) above MLW. Vegetation was planted at 1.5 feet (0.46 m) centers for a distance on the order of 20 feet (6.1 m) behind the sill structure. The study site had a west to northwest exposure to the St. Mary's River.

Emergent Vegetation Survey

Non-destructive vegetation sampling was conducted on a one-time basis to characterize intertidal emergent wetland vegetation shoreward of the studies sill structures. Vegetation sampling occurred on August 15, 2007 in order to coincide with near or peak standing biomass. Three transects, on the order of 10-13 feet (3-4 m) in length and running perpendicular from the base of the sill structure to or near the high marsh/upland edge were randomly sampled at each sill site. Each transect consisted of three 1 m^2 plots incorporating the low marsh, intermediate marsh and high marsh regions; plots were placed immediately to one another in a "conveyor belt" manner. Basal percent cover for each species was determined through visual inspection of the m^2 plot. Given the sparse coverage of vegetation in some regions, an additional cover class, bare substrate, was assigned to larger unvegetated portions of the m^2 plot. Stem density, by species of concern, was determined within a 0.25 m^2 subregion of the m^2 plot. Maximum height was determined as the mean of the three tallest individuals of each species.

Substrate Survey

Physical and hydrophysical sediment properties were determined at the site to define sediment structure and water transmission characteristics. Grain size and percent organic matter were determined on composite samples of surficial (upper 2 cm) sediment collected from the vegetated marsh region behind each sill site. Grain size mass ratios were determined on homogenized samples by wet sieving and pipet analysis (Folk, 1980). The Wentworth grain scale was used to separate sediment into gravel, sand, silt and clay size fractions. Percent organic matter was determined by percent weight loss following combustion of oven-dried sediments at 930 °F (500 °C) (Dean, 1974). Saturated horizontal hydraulic conductivity (K_h) of fringing marsh substratum was determined from replicate measurements (N=3) of four wells using the Bouwer slug test method (Bouwer, 1989). Hydraulic conductivity is the ease with which water moves through pore spaces and depends on the permeability of the material and it's saturation. Saturated hydraulic conductivity describes water movement through saturated material.

Surface Water Quality Studies

Surface water quality studies were conducted to document spatial and temporal variations in key parameters, including temperature and dissolved oxygen, which provide insight as to nekton habitat suitability of the fringing marsh located behind sill structures. YSI multi-parameter water quality sondes (models: 6600 V2, 6600 and 6000) were used to continuously (15 minute intervals) measure water quality over selected tidal cycles in May (5/15-16/07), June (6/13-14/07) and August (8/13-15/07) 2007. Multi-parameter sondes were pre and post calibrated as per the YSI instrument manual. Sondes were deployed at varying distances behind the open (distances from down river or southwest sill window approximated 8, 53, 106, 159 and 204 feet) and blocked (distances from down river or southwest sill window approximated 46 and 92 feet) sills and at a single offshore location (100 feet seaward of the open sill); water quality sonde locations are depicted in Figure 4-2.

Groundwater Studies

Shallow monitoring wells were established at two locations along the open sill structure to measure interstitial water temperature, salinity and water table fluctuations over selected tidal cycles. At each location, wells were installed perpendicular to the sill structure with one well located in the low marsh and the other near the upland edge in the high marsh region. Wells were hand-augered (3.2 inch or 8.25 cm) and penetrated approximately 3.3 feet (1 m) into the unconfined aquifer. Wells were constructed of 1.3 inch PVC casing with 2 feet of well screening (0.01 inch slot width). Well screens were sand packed with native material and the surface 20 cm was sealed with bentonite to eliminate vertical infiltration next to annular well space. Well tops and adjacent ground level was surveyed to a reference benchmark. Water levels, temperature and salinity were measured periodically with both hand-held meters (YSI Model 85 Multi-Parameter Instrument and Solinst Model 101 level meter) and continuously deployed Solinist Model 3001 level loggers. Seepage meters were used to directly measure the discharge of water across the sediment-water interface at random locations within the low marsh behind the sill structure. Seepage meters were constructed of nalgene and transparent plexiglass, and followed the basic design of Lee (1977). Seepage meters enclosed 0.07 m^2 of sediment with a head-space of approximately 1 cm. Discharge rates were calculated by volume changes within collection bladders over time per unit area. Seepage meter collection bladders were pre-wetted with 100 ml of ambient water prior to deployment to minimize anomalous short-term influx (Shaw and Prepas, 1989). The contribution of freshwater to total discharge was calculated based on a mass balance between salinity in the upland groundwater (assuming 0 ppt), initial water column salinity, and volume and salinity changes over time within the seepage meter (Gallagher *et al.,* 1996). Seepage meters were generally deployed on a falling tide and measurements were terminated prior to exposure.

Passive Nekton Collection

In order to investigate nekton access and activity to emergent fringing marshes behind sill structures, commercially available minnow traps were used to passively collect nekton at various shoreline locations at the study site. Fish had access to the fringing marshes through three pathways, these are: (1) sill window features, (2) through macro-pores in the sill structure, and (3) when tidal overtopping of the sill structure occurs. Figures 4-3 and 4-4 are presented to exhibit basic rock sill structure and representative macro-pore or space between individual rocks. Passive sampling traps were deployed immediately seaward of the sill structure (offshore), within windows between sill structures (sill window), and within fringing emergent wetlands immediately shoreward of blocked (blocked) and open (open) sill structures (Figure 4-2). Two tightly meshed blocking nets with weighed bottoms were deployed on either end of the "blocked" sill structure and terminated within the supra-tidal region. In order to ensure adequate sealing, sand bags were placed on the block nets where they contacted the sill structure and the intertidal substrate. These nets effectively blocked nekton access to the fringing marsh via the sill window features. With exception of the offshore sampling sites, all sampling sites were intertidal and generally exposed at low tide.

Cylindrical minnow traps were constructed of galvanized steel mesh (0.64 cm^2), measured 17 inch (42 cm) in length and 9 inch (22 cm) wide at their largest diameter, and had two funnel-shaped throats with 1 to 1.2 inches (2.5-3.0 cm) diameter entry-hole openings. Traps were fished with bait bags consisting of almost 2 ounces (50 g) of dry dog food. Blocked and open fringe marsh traps were placed on the bottom substrate during low-tide conditions and were fished the subsequent flood and ebb tide. In an attempt to standardize fishing times for traps, offshore and window traps were deployed when water levels were sufficient to allow fishing of marsh-associated traps. With exception of selected visual inspections during the flooding tide, traps were left undisturbed and collected at a time prior to exposure of entry holes by the receding tide. Soak time, based on marsh surface and tide elevation data, was the total time that the mid point of the trap opening was submerged between deployment and retrieval of traps. Kneib and Craig (2001) have demonstrated that trap escape rates were highest immediately following immersion but approached a constant value after 0.5 hours. Fish were identified and total length of each individual was measured to the nearest millimeter. All fish were released back in the immediate vicinity where caught following a specific tidal study.

4.2 Results

Site Substrate and Vegetation Characterization

Based on USDA soil textural classifications, surficial sediments behind the blocked and open sill structures were categorized as sand and gravely sand, respectively (Table 4-1). Hydraulic conductivity estimates indicated a moderately high ability to transmit water. Measured mean K_h ranged from 2.82 10^{-3} to 3.33 10^{-3} and were consistent with reported values for relatively clean fine sands (1.16 10^{-3} to 5.78 10^{-3} cm·sec^{-1}; Bouwer, 1978) (Table 4-2).

Table 4-1. Percent grain size and organic matter (%OM) of marsh surficial sediments.

Site	Gravel	Sand			Silt	Clay	%OM
		Coarse	Medium	Fine			
Blocked sill	51.2	34.1	12.7	2.0	0.0	0.0	0.7
Open sill	21.1	25.6	40.6	11.5	12.0	0.0	1.3

Table 4-2. Saturated horizontal hydraulic conductivity (K_h) at open sill well sites.

Well ID	Average cm·sec^{-1}	Std Dev cm·sec^{-1}	N
High marsh/ upland edge 1	3.33×10^{-3}	0.34×10^{-3}	3
High marsh/ Upland edge 2	3.31×10^{-3}	0.42×10^{-3}	3
Low marsh/ Sill edge 1	2.87×10^{-3}	0.21×10^{-3}	3
Low marsh/ Sill edge 2	2.82×10^{-3}	0.27×10^{-3}	3

Vegetation patterns behind sill structures can broadly be characterized as *Spartina alterniflora* dominated low marsh transitioning into the irregularly flooded high marsh dominated by *S. patens*. Percent cover, stem density and maximum height data by distance landward of sill structures are presented in Tables 4-3 and 4-4. Pooling open and blocked sill data, percent total vegetation cover ranged from 6-20% in the low marsh region (distance = 1 m behind sill), 1-26% in the transition zone and 5-50% in the high marsh region (distance = 3 m behind sill). Individual plot stem densities were highly variable and reflect various mixing patterns among dominant plant species due to slight variations in elevation. Total stem density (*S. alterniflora* and *S. patens* combined) ranged from 36-135 per m^2 within 3.3 feet (1 m) of the sill structure, 4-904 per m^2 at the 6.6 feet (2 m) distance and 13-656 per m^2 at 10 feet (3 m). *S. alterniflora* dominated percent cover and stem density counts in 5 of 6 plots located 3.3 feet (1 m) from the sill structure, 4 of 6 plots at the 6.6 feet (2 m) distance and 0 of 6 plots at the 10 foot (3 m) distance. A Mann-Whitney signed rank test was used to identify if significant differences in marsh percent vegetation cover and stem density occurred between the two sites. No significant differences in percent vegetation cover was observed between the open and blocked sill sites within the low marsh (p=.487), transition (p=.658) and high marsh regions (p=.105;

Figure 4-5). In addition, no significant differences in total stem density was observed between the open and blocked sill sites within the low marsh, transition and high marsh regions (p=.513 for all tests).

Table 4-3. Vegetation cover classification and stem density for selected transects at the open sill site.

Transect	Distance (m)	Cover Classification	% Cover	Stem Density m^{-2}	Max. Height (m)
1	1	*S. alternilflora*	10	36	1.14
		S. patens			
		Substrate	90		
	2	*S. alternilflora*	1	4	0.46
		S. patens			
		Substrate	99		
	3	*S. alternilflora*			
		S. patens	5	13	0.76
		Substrate	95		
2	1	*S. alternilflora*	15	52	1.22
		S. patens			
		Substrate	85		
	2	*S. alternilflora*	15	68	1.55
		S. patens			
		Substrate	85		
	3	*S. alternilflora*	5	16	0.91
		S. patens	20	640	
		Substrate	75		
3	1	*S. alternilflora*	1	6	
		S. patens	5	129	0.74
		Substrate	94		
	2	*S. alternilflora*	1	4	
		S. patens	25	900	0.81
		Substrate	74		
	3	*S. alternilflora*			
		S. patens	25	103	1.00
		Substrate	75		

Table 4- 4. Vegetation cover classification and stem density for selected transects at the blocked sill site.

Transect	Distance (m)	Cover Class	%	Stem Density m^{-2}	Max. Height m
1	1	*S. alternilflora*	20	76	1.40
		S. patens			
		Substrate	80		
	2	*S. alternilflora*	1	16	0.40
		S. patens			
		Substrate	99		
	3	*S. alternilflora*			
		S. patens	40	380	0.75
		Substrate	60		
2	1	*S. alternilflora*	10	60	1.52
		S. patens			
		Substrate	90		
	2	*S. alternilflora*			
		S. patens	5	24	1.40
		Substrate	95		
	3	*S. alternilflora*			
		S. patens	25	188	1.24
		Substrate	75		
3	1	*S. alternilflora*	10	84	1.02
		S. patens			
		Substrate	90		
	2	*S. alternilflora*	10	37	0.69
		S. patens	1	2	
		Substrate	89		
	3	*S. alternilflora*			
		S. patens	50	360	0.99
		Substrate	50		

Surface Water Quality Studies

Studies occurred under a wide variety of tidal conditions, which resulted in study extremes where flooding water elevations were inadequate to inundate the low marsh region (end of May sampling) to conditions that resulted in overtopping of the sill structures (selected June and August samplings) (Figure 4-6). Water temperatures generally fluctuated with the diel (24 hr) cycle, reaching a minima in the morning hours; water temperature measurements by sampling station are presented in Figures 4-7 to 4-9. Mean (sampling depth varied from 2 to 47 inches (5 to 120 cm)) water temperatures offshore the sill structures for May, June and August sampling were 19.4°C (range: 17.5-21.9°C), 24.4°C (range: 23.2-25.9°C) and 28.2°C (range: 27.2-29.8°C), respectively. Water quality data gaps did occur due to issues arising from instrument deployment in such a shallow environment. During the initial sampling periods, YSI sondes were deployed horizontally to obtain maximum data prior to air exposure during ebbing and low tide conditions. This deployment configuration resulted in some erroneous readings due to sensor interference with air bubbles and therefore subsequent (August) sampling utilized vertically deployed sondes. Mean differences between offshore waters and waters behind the sill structure ranged from 0.2 and 0.6°C with maximum observed differences between individual readings varying from 1.9 to 5.8°C during the May sampling (Figure 4-7); positive values denote higher temperatures behind sill structures. Mean temperature differences between offshore waters and waters landward of the sill structure ranged from -0.3 to -0.7°C(maximum individual measurement differences: 0.2 to 0.5°C) for the June sampling and -0.6 to 0.1°C (maximum individual measurement differences: 2.0 to 2.5°C) for the August sampling (Figures 4-8 and 4-9). It should be noted that a frontal system moved through the study area during the June sampling that resulted in a depression of mean daily air temperatures on the order of 5°C for June 14-15, 2007.

As with water temperature, dissolved oxygen concentrations fluctuated with the diel cycle, reaching minimum levels in the early morning and maximum levels in the afternoon (Figures 4-10 to 4-12). Mean surface (sampling depth varied from 2 to 47 inches (5 to 120 cm)) water dissolved oxygen concentrations offshore the sill structures for May, June and August sampling were 10.35 $mg \cdot L^{-1}$ (range: 9.14-11.68 $mg \cdot L^{-1}$), 7.80 $mg \cdot L^{-1}$ (range: 4.40-9.86 $mg \cdot L^{-1}$) and 6.04 $mg \cdot L^{-1}$ (range: 3.52-8.19 $mg \cdot L^{-1}$), respectively. Mean differences between the offshore readings and readings behind the sill structure ranged from -2.21 to - 0.98 $mg \cdot L^{-1}$ with maximum observed differences between individual readings varying from -4.66 to -2.43 $mg \cdot L^{-1}$ during the May sampling (negative values denote lower dissolved oxygen concentrations behind sill structures). Mean dissolved oxygen concentration differences between offshore waters and waters landward of the sill structure ranged from -1.70 to -1.00 $mg \cdot L^{-1}$ (maximum individual measurement differences: -8.14 to -6.49 $mg \cdot L^{-1}$) for the June sampling and -0.60 to 0.22 $mg \cdot L^{-1}$ (maximum individual measurement differences: -5.17 to -2.37 $mg \cdot L^{-1}$) for the August sampling.

Groundwater Studies

Ranges of values of temperature and salinity for shallow groundwater (*i.e.* interstitial water) within the shoreline region are presented in Table 4-5. Shallow groundwater or interstitial water in the high marsh/upland edge exhibited cooler temperatures, on the order of 3-5 °C, than flooding offshore surface waters. While less pronounced, interstitial waters in the low marsh/sill region were also cooler than flooding offshore waters by 0-2 °C. Groundwater salinities were relatively fresh (range: 0.0 to 2.5 ppt) in the high marsh/upland edge and increased downgradient (0.1 to 8.4 ppt) to the low marsh/sill region. Driven by elevated upland head pressures, water comprised of various mixtures of fresh groundwater and high salinity waters of surface water origin was discharged across the sediment-water interface within the intertidal fringing wetland region. Total and freshwater discharge rates are presented in Table 4-6. The discharge of groundwater at the study site was of significant magnitude to impact physical water quality behind the sill structure. Observations made along the landward and seaward side of the sill during near mid falling tide conditions exemplify this for salinity where values were depressed on the landward side of the sill (Figure 4-13). Given diel temperature fluctuations and the timing of the measurements (early afternoon), one would not expect to see a dramatic cooling impact by groundwater discharge.

Table 4-5. Measurement ranges of temperature and salinity within monitoring wells and offshore waters.

Sampling Period/Location	Temperature °C	Salinity ppt
May		
High marsh/Upland edge	16.7-17.4	0.1
Low marsh/sill	18.8-20.7	0.1-0.2
Offshore surface water	17.5-21.9	8.9-9.4
June		
High marsh/Upland edge	19.1-20.2	0.1
Low marsh/sill	22.3-23.4	0.8-1.3
Offshore surface water	23.2-25.9	11.3-11.8
August		
High marsh/Upland edge	23.4-25.7	0.0-2.5
Low marsh/sill	25.5-29.5	1.1-8.4
Offshore surface water	27.2-29.8	14.7-15.1

Table 4-6. Summary statistics for seepage discharge by sampling period. Average values are presented with standard deviation and sample number shown parenthetically.

Sampling Period	Total Discharge $L \cdot m^{-2} \cdot hr^{-1}$	Freshwater Discharge $L \cdot m^{-2} \cdot hr^{-1}$	% Freshwater Contribution
May	4.39 (5.03, 5)	0.79 (1.03, 5)	17.4 (7.0, 5)
June	3.04 (1.18, 16)	0.23 (0.27, 16)	7.0 (8.2, 16)
August	3.28 (2.19, 10)	0.20 (0.17, 10)	10.3 (13.1, 10)
Pooled Data	3.34 (2.40, 31)	2.40 (0.48, 31)	9.7 (10.3, 31)

Nekton Collection Studies

Passive trap nekton collection studies were conducted in concert with surface water quality studies. Ten fish species were represented in the total of 2904 fish captured in the passive traps (Table 4-7). *Fundulus heteroclitus* was the most commonly captured species at all sampling areas (Table 4-7) and represented 97 percent of the total number of individuals caught (N=2818). *F. heteroclitus* was followed by the common marsh resident minnows *Cyprinodon variegates* and *F. majalis*, where each accounted for one percent of the total fish caught. Recognizing the variation in number of total traps set in each sampling area, 95 percent of the three common marsh minnows were captured within the fringing marsh region behind the sill structures, 5 percent were captured within sill window regions and less that one percent caught in the immediate seaward side of the sill structures. Of note, fish commonly associated with hard rock and oyster reef structures (e.g., *Gobiesox strumosus, Chasmodes bosquianus* and *Gobiosoma bosci*) were only captured within the cobbled sill window and in the region immediately seaward of the sill structure.

Overall summary statistics of pooled total fish and marsh minnows caught by sampling location are presented in Table 4-8. Marsh minnow catches from individual traps ranged from 0-106 at the open sill site, 0-92 at the blocked sill site, 0-44 in sill windows and 0-3 fish shoreward of the sill structure. Average number and CPUE of total fish and marsh minnows for the open and blocked sill sites were similar and on the order of 3 and 40 fold greater than measured in the sill windows and offshore locations, respectively. Trap soak times were dependent on tidal and weather conditions and varied from 4.75-11.50 at the open sill site, 3.25-11.50 at the blocked sill site, 5.50-12.08 at the sill windows and 5.15-12.08 hours at sampling locations shoreward of the sill structure. As depicted in Figure 4-6, tidal conditions were highly variable and resulted in both lack of fringe marsh inundation by flood waters to overtopping of sill structures and presence of water within the low marsh region during low slack tide conditions. Traps were visually inspected on all day-time and most night-time deployments to verify presence of fish prior to any overtopping of sill structures by flooding waters.

Statistical comparisons, focusing on common marsh resident minnows, were made between sampling stations using the nonparametric Kruskal-Wallis single factor analysis of variance with tied ranks. Data were analyzed using total number of marsh minnows caught per trap and a catch per unit effort (CPUE) index that was calculated as the number of individual caught divided by the trap soak time (Tables 4-9 and 4-10). Results of analysis of variance on pooled data indicated differences between sampling stations for both total number of marsh minnows caught (Hc=34.78, p<0.001) and CPUE (Hc=41.78, p<0.001). To identify which sampling locations varied significantly, Tukey-type multiple comparisons (=0.05) with unequal sample sizes were utilized. Test results were similar for both total count and CPUE values and indicate no significant differences between the open and blocked marsh sampling locations, significant differences between marsh and sill window and offshore locations, and significant differences between the sill window and offshore locations.

During the June and August samplings, 5 seine (3 mm mesh) hauls were taken offshore the sill structure and the immediately adjacent unvegetated beach in order to provide preliminary information as to fish presence in the adjacent offshore locations. The seine area, 30-50 m2, was delineated by measured lines which were deployed perpendicular to the shoreline prior to sampling and seine hauls were towards the shore. A line connecting the wings assured a consistent 5 m width throughout the seining process. Summary statistics of for nekton collected with seine nets are presented in Table 4-11.

Table 4-7. Summary statistics for all fish species collected in passive traps by sampling location. Count represents the total number of traps set at each location as was used to generate average and standard deviation values.

	Sampling Location			
Fish Species	Open Sill	Blocked Sill	Sill Window	Offshore
F. heteroclitus (Mummichog)	∑ = 1402 Avg = 31.2 Stdev = 24.8 Count = 45	∑ = 1245 Avg = 27.7 Stdev = 8.6 Count = 45	∑ = 154 Avg = 8.6 Stdev = 13.0 Count = 18	∑ = 17 Avg = 0.5 Stdev = 0.9 Count = 36
Cyprinodon variegatus (Sheephead minnow)	∑ = 27 Avg = 0.6 Stdev = 1.4 Count = 45	∑ = 7 Avg = 0.2 Stdev = 0.6 Count = 45	∑ = 1 Count = 18	∑ = 0 Count = 36
Fundulus majalis (Striped killifish)	∑ = 14 Avg = 0.3 Stdev = 0.8 Count = 45	∑ = 20 Avg = 0.4 Stdev = 1.4 Count = 45	∑ = 0 Count = 18	∑ = 0 Count = 36
Gobiosoma bosci (Naked goby)	∑ = 0 Count = 45	∑ = 0 Count = 45	∑ = 1 Count = 18	∑ = 2 Avg = 0.1 Stdev = 0.2 Count = 36
Leiostomos xanthurus (Spot)	∑ = 0 Count = 45	∑ = 1 Count = 45	∑ = 0 Count = 18	∑ = 1 Count = 36
Gobiesox strumosus (Skilletfish)	∑ = 0 Count = 45	∑ = 0 Count = 45	∑ = 1 Count = 18	∑ = 0 Count = 36
Menidia menidia (Silversides)	∑ = 1 Count = 45	∑ = 0 Count = 45	∑ = 1 Count = 18	∑ = 4 Avg = 0.1 Stdev = 0.4 Count = 36
Syngnathus sp (Pipefish sp)	∑ = 0 Count = 45	∑ = 0 Count = 45	∑ = 0 Count = 18	∑ = 2 Avg = 0.1 Stdev = 0.2 Count = 36
Anguilla rostrata (American eel)	∑ = 2 Avg = 0.1 Stdev = 0.2 Count = 45	∑ = 0 Count = 45	∑ = 0 Count = 18	∑ = 0 Count = 36
Chasmodes bosquianus (Striped blenny)	∑ = 0 Count = 45	∑ = 0 Count = 45	∑ = 0 Count = 18	∑ = 1 Count = 36

Table 4-8 . Overall average number of fish caught per trap, CPUE and trap soak time by sampling locations. Standard deviation and trap count are shown parenthetically.

	Total Fish		Marsh Minnows		
Location	Fish (fish· trap^{-1})	CPUE (fish·hr^{-1})	Fish (fish·trap^{-1})	CPUE (fish· hr^{-1})	Trap Soak Time (hr)
Open Sill	32.2 (25.4, 45)	4.6 (4.3, 45)	32.1 (25.4, 45)	4.6 (4.3, 45)	7.7 (2.4, 45)
Blocked Sill	28.2 (26.8, 45)	4.6 (5.3, 45)	28.2 (26.9, 45)	4.6 (5.3, 45)	7.2 (2.9, 45)
Sill Window	10.0 (12.9, 18)	1.2 (1.6, 18)	9.8 (12.8, 18)	1.2 (1.6, 18)	7.8 (2.6, 18)
Offshore	0.7 (1.1, 36)	0.1 (0.2, 36)	0.4 (0.9, 36)	0.1 (0.1, 36)	7.7 (2.6, 36)

Table 4- 9. Overall average number of marsh minnows per trap by sampling locations. Standard deviation and trap count are shown parenthetically.

Sampling Period	Open Sill	Blocked Sill	Sill Window	Offshore
5/15/2007 Day	13.0 (16.5, 5)	2.6 (4.3, 5)	13.0 (15.6, 2)	0.8 (1.5, 4)
5/15-16/2007 Night	7.8 (7.0, 5)	7.2 (3.7, 5)	0.5 (0.7, 2)	0.0 (0.0, 4)
6/13-14/2007 Night	30.4 (18.1, 5)	13.4 (7.3, 5)	22.5 (7.8, 2)	1.0 (0.8, 4)
6/14/2007 Day	21.2 (11.2, 5)	18.4 (11.1, 5)	24.0 (28.3, 2)	0.3 (0.5, 4)
6/14/2007 Night	26.4 (14.4, 5)	11.6 (11.5, 5)	11.0 (7.1, 2)	0.5 (1.0, 4)
8/13/2007 Day	61.6 (9.4, 5)	72.6 (23.1, 5)	1.0 (1.4, 2)	1.3 (1.5, 4)
8/13-14/2007 Night	38.0 (25.2, 5)	28.8 (15.7, 5)	0.0 (0.0, 2)	0.0 (0.0, 4)
8/14/2007 Day	23.0 (5.1, 5)	56.2 (20.4, 5)	12.0 (15.6, 2)	0.3 (0.5, 4)
8/14-15/2007 Night	67.2 (34.3, 5)	43.0 (23.9, 5)	4.5 (6.4, 2)	0.0 (0.0, 4)
Entire Study Pooled	32.1 (25.4, 45)	28.2 (26.9, 45)	9.8 (12.8, 18)	0.4 (0.9, 36)

Table 4-10. Overall average number of marsh minnows CPUE by sampling locations. Standard deviation and trap count are shown parenthetically.

Sampling Period	Open Sill	Blocked Sill	Sill Window	Offshore
5/15/2007 Day	2.4 (3.0, 5)	0.6 (1.0, 5)	2.4 (2.8, 2)	0.1 (0.3, 4)
5/15-16/2007 Night	1.6 (1.4, 5)	2.2 (1.1, 5)	0.1 (0.1, 2)	0.0 (0.0, 4)
6/13-14/2007 Night	2.7 (1.6, 5)	1.2 (0.6, 5)	1.9 (0.7, 2)	0.1 (0.1, 4)
6/14/2007 Day	2.3 (1.2, 5)	2.0 (1.2, 5)	2.6 (3.0, 2)	0.0 (0.1, 4)
6/14/2007 Night	2.3 (1.3, 5)	1.0 (1.0, 5)	0.9 (0.6, 2)	0.0 (0.1, 4)
8/13/2007 Day	13.0 (2.0, 5)	16.1 (5.1, 5)	0.2 (0.2, 2)	0.2 (0.3, 4)
8/13-14/2007 Night	5.6 (3.7, 5)	4.6 (2.5, 5)	0.0 (0.0, 2)	0.0 (0.0, 4)
8/14/2007 Day	3.1 (0.7, 5)	8.0 (2.9, 5)	2.1 (2.7, 2)	0.0 (0.1, 4)
8/14-15/2007 Night	8.4 (4.3, 5)	5.7 (3.2, 5)	0.6 (0.8, 2)	0.0 (0.0, 4)
Entire Study Pooled	4.6 (4.3, 45)	4.6 (5.3, 45)	1.2 (1.6, 18)	0.1 (0.1, 36)

Table 4-11. Summary statistics for all fish and crab species collected in seines. Total sums are provided with mean and standard deviation presented parenthetically. N=5 for calculation of mean and standard deviation values.

Fish Species	Beach	Sill
Menidia menidia (Silversides)	∑ = 329 (65.8, 82.9)	∑ = 73 (14.6, 20.1)
Leiostomos xanthurus (Spot)	∑ = 9 (1.8, 3.0)	∑ = 23 (4.6, 7.7
Gobiesox strumosus (Skilletfish)	∑ = 8 (1.6, 2.2)	∑ = 1 (0.2, 0.4)
Morone Americana (White perch)	∑ = 2 (0.4, 0.5)	∑ = 0 (-,-)
Syngnathus sp (Pipefish sp)	∑ = 5 (1.0, 1.4)	∑ = 7 (1.4, 1.5)
Gobiosoma bosci (Naked goby)	∑ = 1 (0.2, 0.4)	∑ = 6 (1.2, 1.8)
Trinectes maculates (Hog Choker)	∑ = 1 (0.2, 0.4)	∑ = 2 (0.4, 0.9)
Strongylura marina (Needlefish)	∑ = 1 (0.2, 0.4)	∑ = 0 (-,-)
Callinectes sapidus (Blue crab)	å = 47 (9.4, 6.6)	å = 72 (14.4, 13.3)

4.3 Discussion

Constructed in 2002, surficial soil of the young fringing marsh at both sill sites was characterized by coarser sandy/gravel sized sediment (>95%) with low organic matter content (~1%). The substrate was conducive to ground water transport that was documented at the site. Both high and low marsh vegetation was establishing behind both sill structures; however the low marsh was not as well developed. Percent coverage of *S. alterniflora* within the low marsh was on the order of 10% (as compared to 30% for *S. patens* in the high marsh) and stem density (average 52.3 stems·m^{-2}, std dev 28.4, N=6) was below typical reported for values (~200-300 stems·m^{-2}) in natural marshes (Craft *et al.*, 2003). Marsh development at this site may be compromised to some degree by the level of fresh groundwater discharge at the site. Review of literature suggests that optimal salinity for growth of *S. alterniflora* is between 10-20 ppt. While surface water salinities were characteristic of mesohaline conditions during the late spring and summer, the relative constant root exposure to low salinity interstitial water may have a negative impact. Conversely, other studies have shown elevated growth rates of *S. alterniflora* in freshwater as opposed to higher salinity regimes (Crain *et al.*, 2004). With respect to other ecological attributes, the coarsely textured soils and associated high hydraulic conductivities may enhance organic matter decomposition rates resulting in a slower development and accumulation of soil organic matter. Initial planting density for *S. alterniflora* and *S. patens* is on the order of 1-2 sprigs on 45 cm (18”) centers resulting in an initial stem density on the order of 11-22 stems·m^{-2}. Given observed stem densities and percent coverges, the restored marsh appears to be fairly well established. Craft *et al.* (2003) report that full development (e.g., above ground biomass, stem density) of vegetation communities in restored marsh systems may take on the order of 5 to 15 years. As of 2007, the marsh at the study site has experienced 6 growing seasons.

Temperature is one of the most important controlling factors governing nekton distribution and behavior. Several of the fundulids, including *F. heteroclitus*, have adapted to exposures of extreme temperatures (up to 95°F) and as a result can utilize shallow water habitats that frequently experience temperature extremes. Water temperatures at the study site generally fluctuated with the diel cycle, reaching minima in the morning hours. Due to the lower volume of water behind sill structures, temperature variations were somewhat more pronounced as compared to the offshore region. The maximum observed temperature within the marsh region during the study period was 89°F with maximum elevated differences between surface waters behind sill structures and offshore on the order of 36-43°F. The duration of temperatures exceeding 86°Fbehind the sill structure ranged between 45 minutes and 2.5 hours. While approaching threshold temperature limits for some species, the threshold for the target species *F. heteroclitus* of 95°F was not exceeded. In addition, the discharge of groundwater would be expected to have a moderating effect with respect to both warm and cold temperature extremes.

Diel variations in dissolved oxygen concentration of shallow water landward of sill structures were observed at the study site; concentrations varied from super-saturated conditions (>100% of air saturation) to 13.3 % air saturation. This is phenomenon is often observed in temperate unstratified shallow habitats where nighttime respiration temporarily deplete water oxygen levels which are subsequently replenished by photosynthesis during day-time conditions. While commercially important fish (e.g., spot, croaker) and blue crab have been observed to avoid hypoxic areas (DO concentrations of $\leq$ 2 mg·L^{-1}; Eby and Crowder, 2002), *F. heteroclitus* have been collected in abundance in regions with demonstrated low oxygen conditions. Fundulids have been observed to alter respiratory behavior when exposed to progressive hypoxia; behaviorial responses include aquatic surface respiration (e.g., vetilating gills within the top 0.4 inches of water), increased ventilation rates and air breathing (Love and Rees, 2002; Smith and Able, 2003).

The U.S.EPA has developed both continuous (exposures > 24 hrs) and cyclic and/or episodic (exposures < 24 hrs) ambient aquatic life water quality criteria for dissolved oxygen in order to protect coastal and estuarine animals in the Virginian Province (Cape Cod, MA to Cape Hatteras, NC)(U.S.EPA, 2000). For juvenile and adult survival, the dissolved oxygen criteria for persistent exposure is 2.3 mg·L^{-1} and is time dependent for cyclic (includes tidal and diel influenced cycles where DO concentrations fluctuate above and below the continuous limit) and episodic exposures; see equation 1 (ex.: 1 hr duration = 1.10, 2 hr duration = 1.35..…24 hr duration = 2.30 mg·L^{-1}). Dissolved oxygen concentrations below 2.30 mg·L^{-1} were not observed during the May 2007 sampling period. During the June and August sampling periods, dissolved oxygen concentrations below 2.30 mg·L^{-1} were measured at a number of locations on the landward side of the sill structure, however given the short time durations of low dissolved oxygen events (range: 0.25 to 1.25 hrs), water criteria were not exceeded. It should be noted that studies were conducted over a very narrow time frame and one cannot exclude the potential for extremely low dissolved oxygen events driven by local respiration or by offshore waters flooding the intertidal marsh habitat at this site (note: dissolved oxygen levels below 4 mg·L^{-1} were measured in offshore waters during the August sampling).

$$DO = 0.370 \times \ln(t) + 1.095$$

where:
DO = Allowable dissolved oxygen concentration
t = exposure duration in hours

With respect to nekton habitat use, the focus of this study was directed on common marsh minnows with the mummichog, *Fundulus heteroclitus*, serving as the principal target species. *F. heteroclitus* serves as an excellent sentinel species for examining the success of marsh restoration and assessing overall habitat value of sill-marsh shoreline protection designs due to a wide variety reasons that include: (1) being a year-round resident of tidal creeks and wetlands, (2) being a predominantly shoreline-associated species with a limited home range on the order of 30-40 m (Lotrich, 1975), (3) being able to endure extreme changes in temperature (2 to 35 °C; Abraham 1985), salinity (0-120 ppt; Abraham, 1985), and dissolved oxygen, (4) being an omnivorous mid-level consumer feeding on polycheates, crustacean, insect larvae, eggs, carrion and plant material (Radtke and Dean, 1979; Scott and Scott, 1988) and subsequently serving as a forage species for piscivorous fish, larger crustaceans and wading birds (Frederick and Loftus, 1993), and (5) having a broad geographic range along the coast of North America (Adams *et al.*, 2006). Given the dependency of specific common minnows on marshes for food and nesting habitat, and their importance in energy relay to higher trophic levels, demonstrated access and utilization of sill-marsh structures by this fish group would infer benefit to all estuarine and coastal life.

Recognizing the drawbacks of passive sampling traps, which can include species selectivity, low and variable catches, and integration of nekton density over an unspecified area (Rozas and Minello, 1997), minnow traps do provide an estimate of movement and/or activity rate (Knieb and Craig, 2001) and are selective towards fundulids (Layman and Smith, 2001), common marsh resident minnows and the target fish group for this study. The common marsh minnows clearly had access to and utilized the marsh habitat landward of the offshore sill structures. Access to fringing marshes behind the sill appears to occur through three pathways and include (1) the sill window features, (2) through macro-pores in the sill structure and (3) when tidal water overtopping of the sill structure occurs. Given no major differences between fringing marshes located behind the open and blocked sill sites, it was assumed that both marshes had the same capacity to attract marsh minnows. Results were similar for both total marsh minnow count and CPUE measurements and indicate no significant differences between the open and blocked marsh sampling stations. There were significant differences between marsh locations and sill window and offshore locations, and significant differences between the sill window and offshore locations.

Open sill marsh   Blocked sill marsh > Sill window > Offshore of sill

The similarity between the open and blocked sill total marsh minnow count and CPUE as determined from passive traps (fish count: 32.1 versus 28.2 fish· trap^{-1}; CPUE: 4.6 vs. 4.6 fish·

hr^{-1}), suggests that transit through the macro-pores in the sill structure to assess the fringing marsh region is a viable pathway. While on several occasions the sill structure was overtopped during sampling periods, visual observation of traps prior to overtopping confirmed fish presence at both the blocked and open sill sites. Another interesting finding was the near absence of marsh minnows in the offshore traps which rested on the seaward side of the sill structure (fish count: 0.4 fish· $trap^{-1}$; CPUE: 0.1 fish· hr^{-1}. This, when coupled to the lack of marsh minnows caught in the offshore seine nets, suggests that the marsh minnows may reside within the filled pore spaces of the sill structure during low water and move with rising waters into the intertidal marsh regions. Aggregating within the sill structure during low water conditions may serve as a behavioral adaption to minimize predation risk. The larger rock, 300-900 lbs., used to construct the study site sills may provide for enhanced access through pore spaces and enhanced refugia as compared to smaller rock with associated smaller interstitial spaces.

5 SUMMARY

The 2002 project has evolved over the past five years to a be a viable system for shore protection and habitat creation. Variations in landscape due to slight increases and decreases in elevation only serve to diversify site vegetation communities. The site has been impacted by several high water events that significantly exceeded the design elevations. This has caused only minor bank scarping, mostly within some of the window areas with no evidence of bank failure.

Window 9, Type 5, with revetment, appears to be the best in terms of maintaining tidal flow across and adjacent to the opening and providing for protection of the bank in the midbay region. The inclusion of cobble and gravel enhanced shore protection and allowed much less berming around the bay perimeter than those windows with the standard sand fill requirement.

The flushing model for these types of systems showed that more windows allow for better flushing if there is no interchange through the sills. The seepage model run allows for significant exchange between the river and silled marsh. The reality is that water moves through the rock void and that the porosity of the rock is as important, if not more important, than the window opening. Oversized stone may even be preferred to create larger pore spaces.

The ecological services provided by a stone sill system is significant, especially from a fisheries perspective. Access to the fringe marsh behind the sill occurs through three pathways: 1) the sill windows, 2) macro-pores in the sill, and 3) overtopping by tidal waters. At St. Mary’s, the porosity of the sill does not really impact water flow or fish movement. In fact, results indicate that marsh minnows reside within the filled pore spaces of the St. Mary’s sill during low water and move with rising water into the intertidal marsh region. Aggregating within the sill structure during low water conditions may serve as a behavioral adaptation to minimize predation risk. Having some part of the sill below MLW may be an important design component for sills. The idealized “good marsh” from Bosch *et al.* (2006) embodies this as well.

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Figure 1-1. Location of St. Mary's City within the Chesapeake Bay estuarine system.

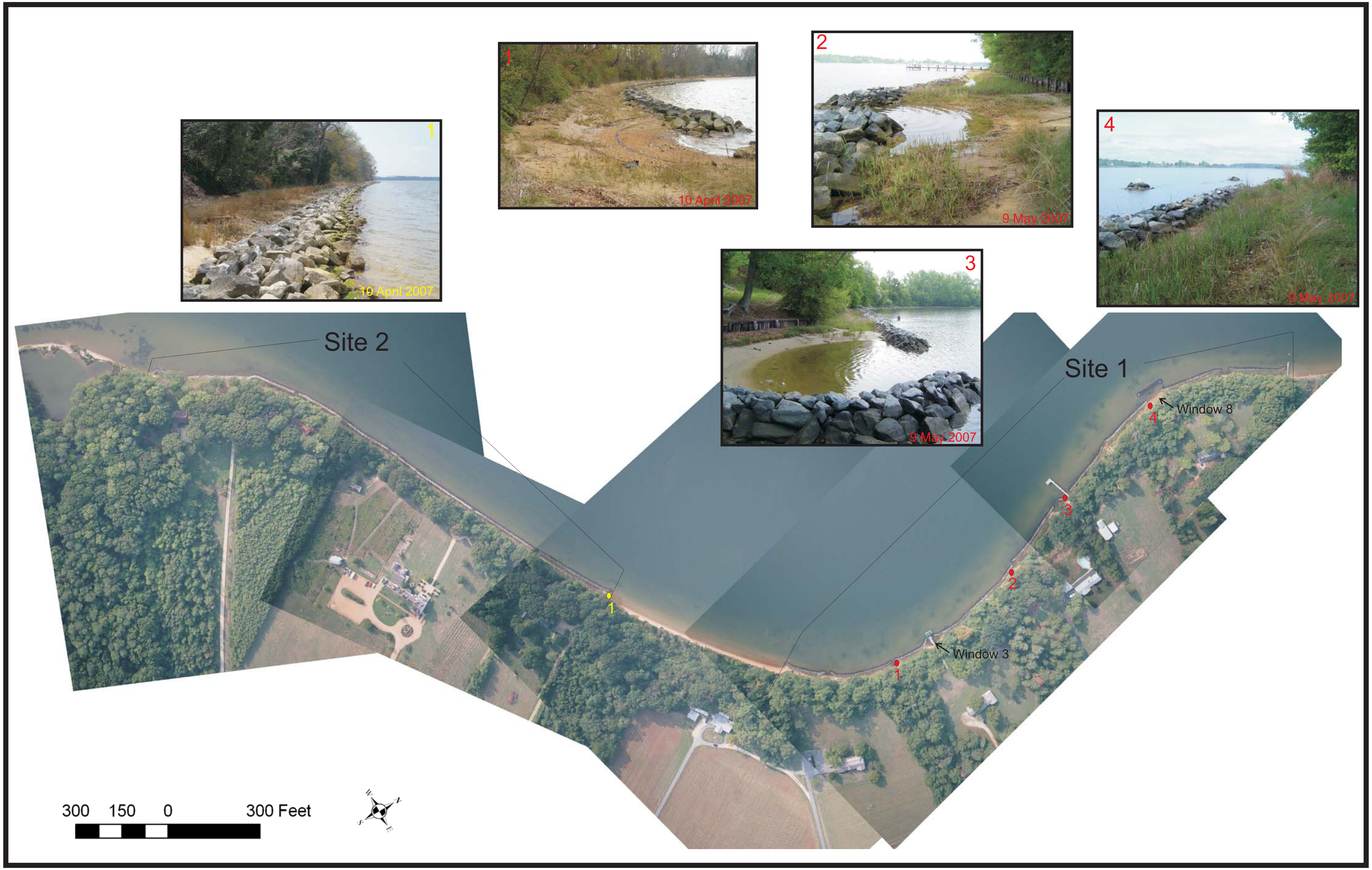


Figure 1-2. Photo mosaic of St. Mary's City's shoreline showing Sill Site 1 and Sill Site 2 and ground photos taken along the site. (Photo mosaic date 24 Aug 2007).

Figure 1-3. The Poster Child for Successful Marsh Projects. Photos taken at a community marsh in Anne Arundel County.This site received the highest overall marsh ranking and embodies many of the factors deemed essential to a successful project (from Bosch *et al*., 2006).

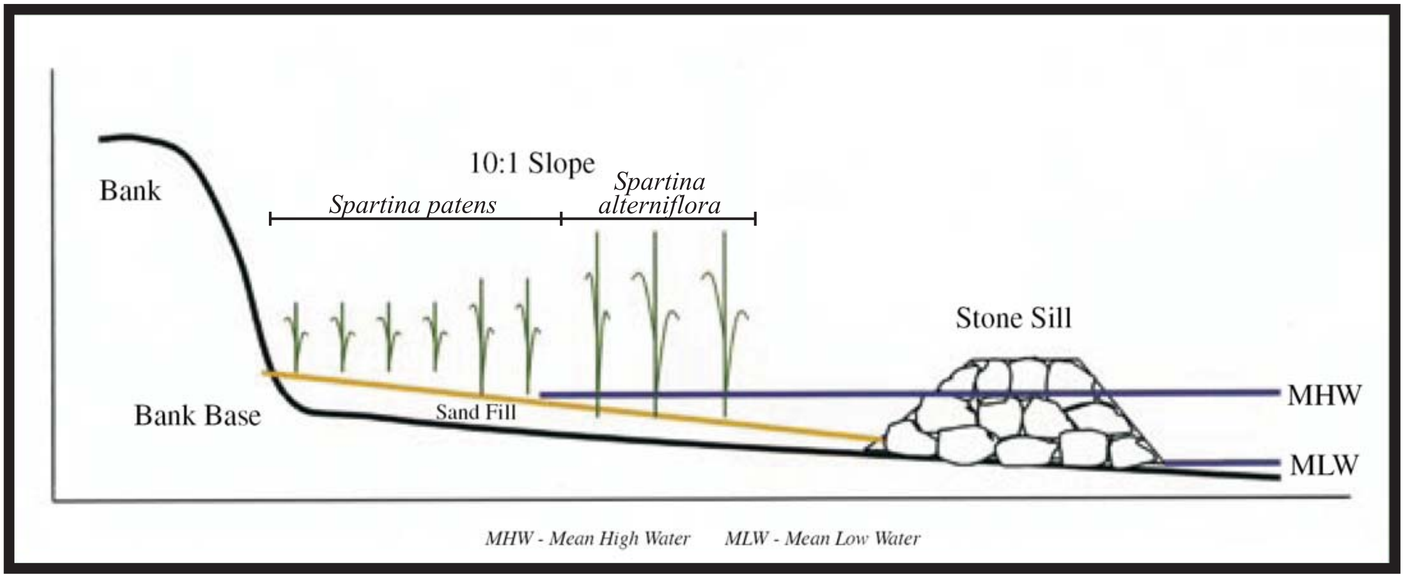


Figure 1-4. Profile of a typical marsh edge stabilization project used to prevent wetland edge loss (from Luscher and Hollingsworth, 2005).

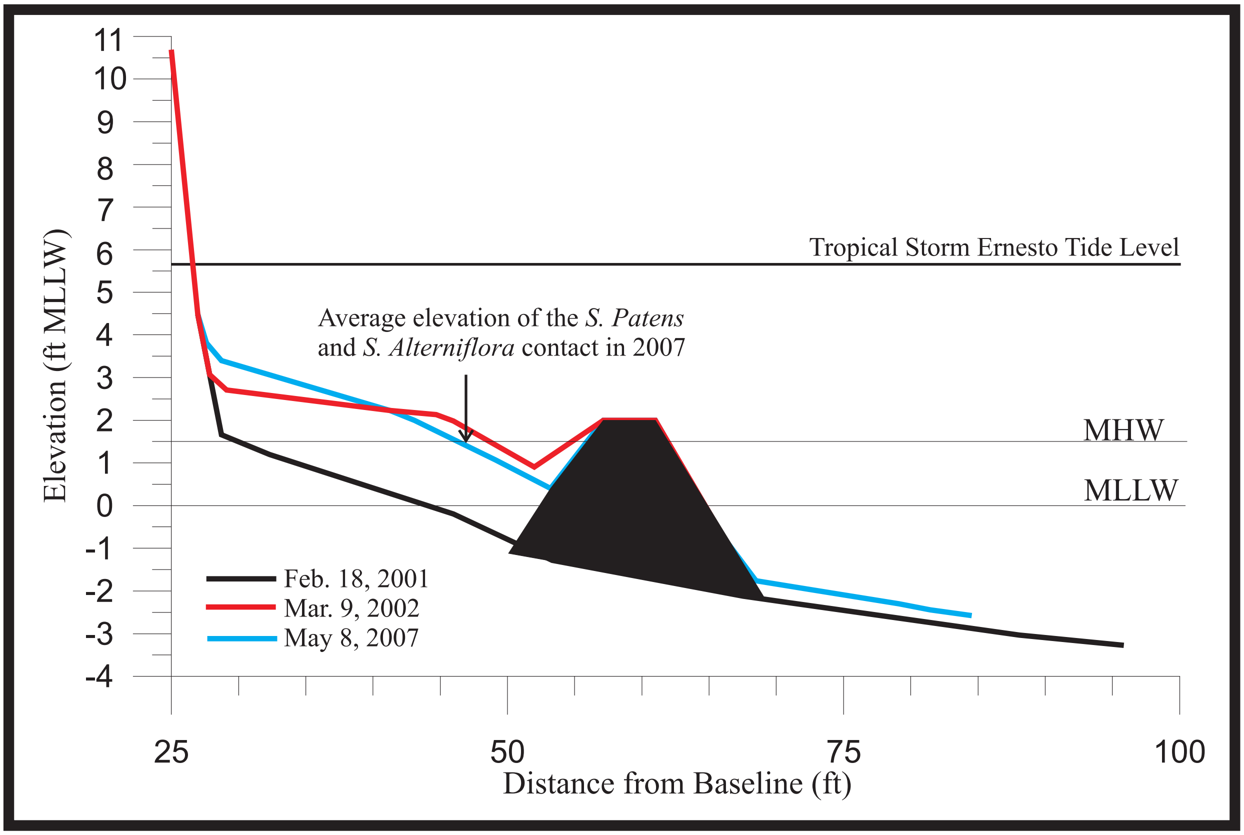


Figure 1-5. Typical St. Mary's City sill profile from survey data.

Figure 1-6 . Photos of Window 8 showing the elements of the sill project. These photos were taken before the marsh grass was planted.

Looking south from the pier at Window 3. Post Installation.

Looking south from the pier at Window 3. *Spartina patens* have been planted along the sand fill/planting terrace.

Looking south from the pier at Window 3. During a high water event with northwest winds. The water covers the sill, and the waves are attenuated by the grasses.

Looking south from the pier at Window 3. Five years after installation.

Looking north from the pier at Window 3. Post Installation.

Looking north from the pier at Window 3. *Spartina patens* have been planted along the sand fill/planting terrace.

Looking north from the pier at Window 3. During a high water event. The water covers the sill and is impacting the upper marsh. Note wrack line.

Looking north from the pier at Window 3. Five years after installation.

Figure 1-7. Photos taken through time looking north and south from the pier at Window 3.

Photo Date: August 24, 2007

Figure 2-1. Historic shore change between 1853 and 1993 along the St. Mary's City shoreline.

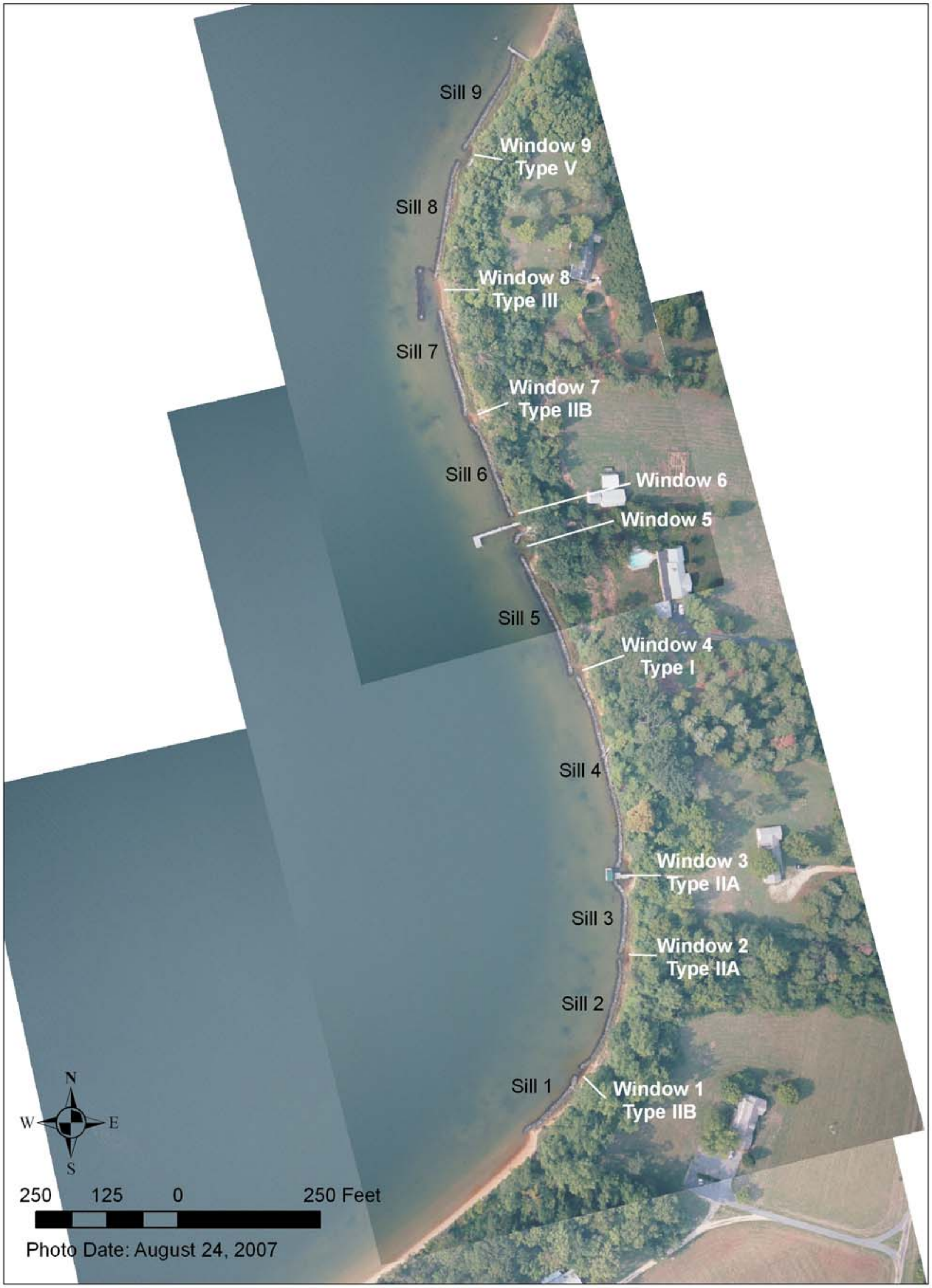


Figure 2-2. Location map of the nine sill segments and nine sill windows along Site 1 at St. Mary's City. Window type is noted.

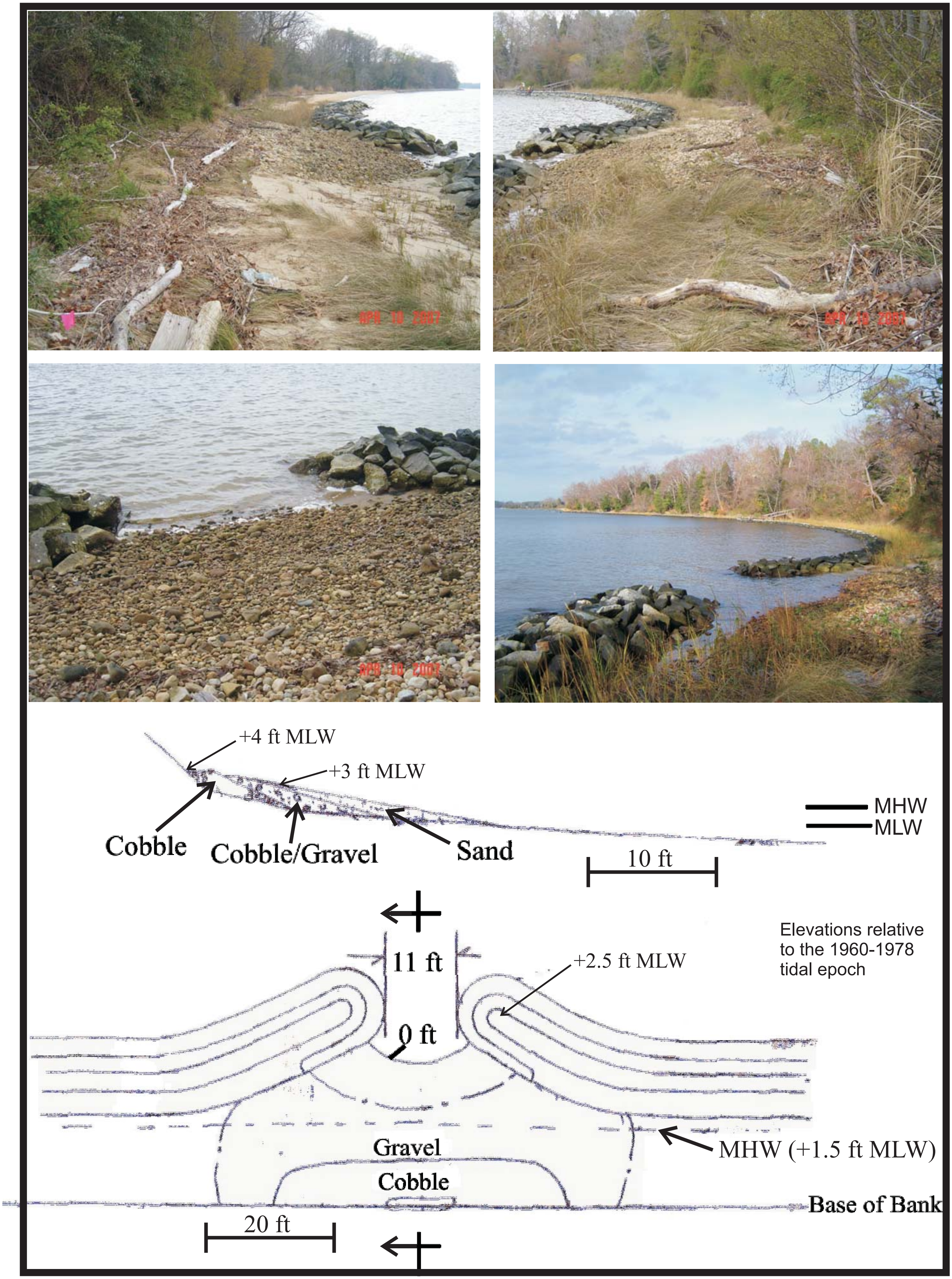


Figure 2-3. Photos showing Window 1 in 2007. Window 1 is a Type IIB window or vent along Site 1 that has a cobble and gravel backshore as shown in the planform and cross-sectional design.

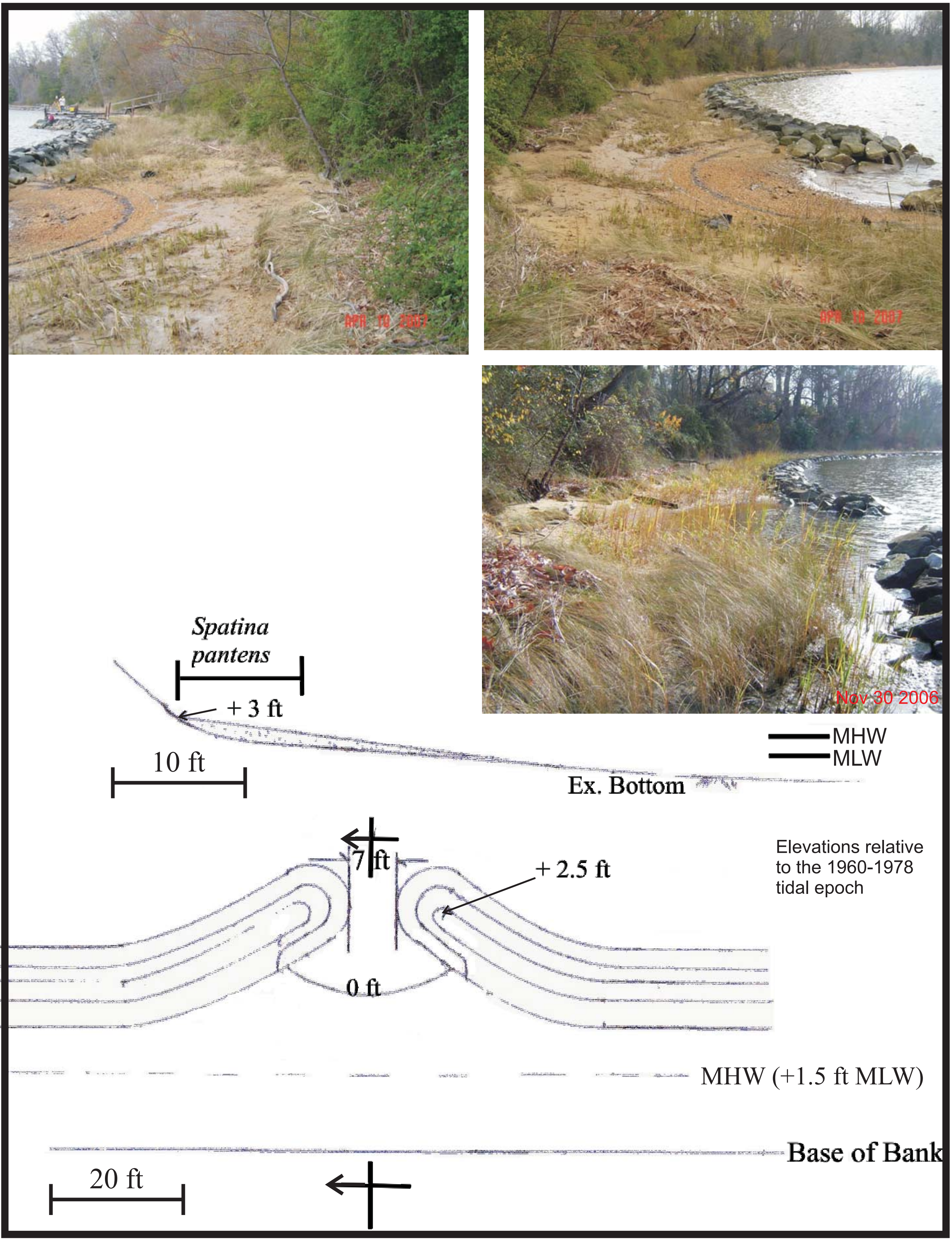
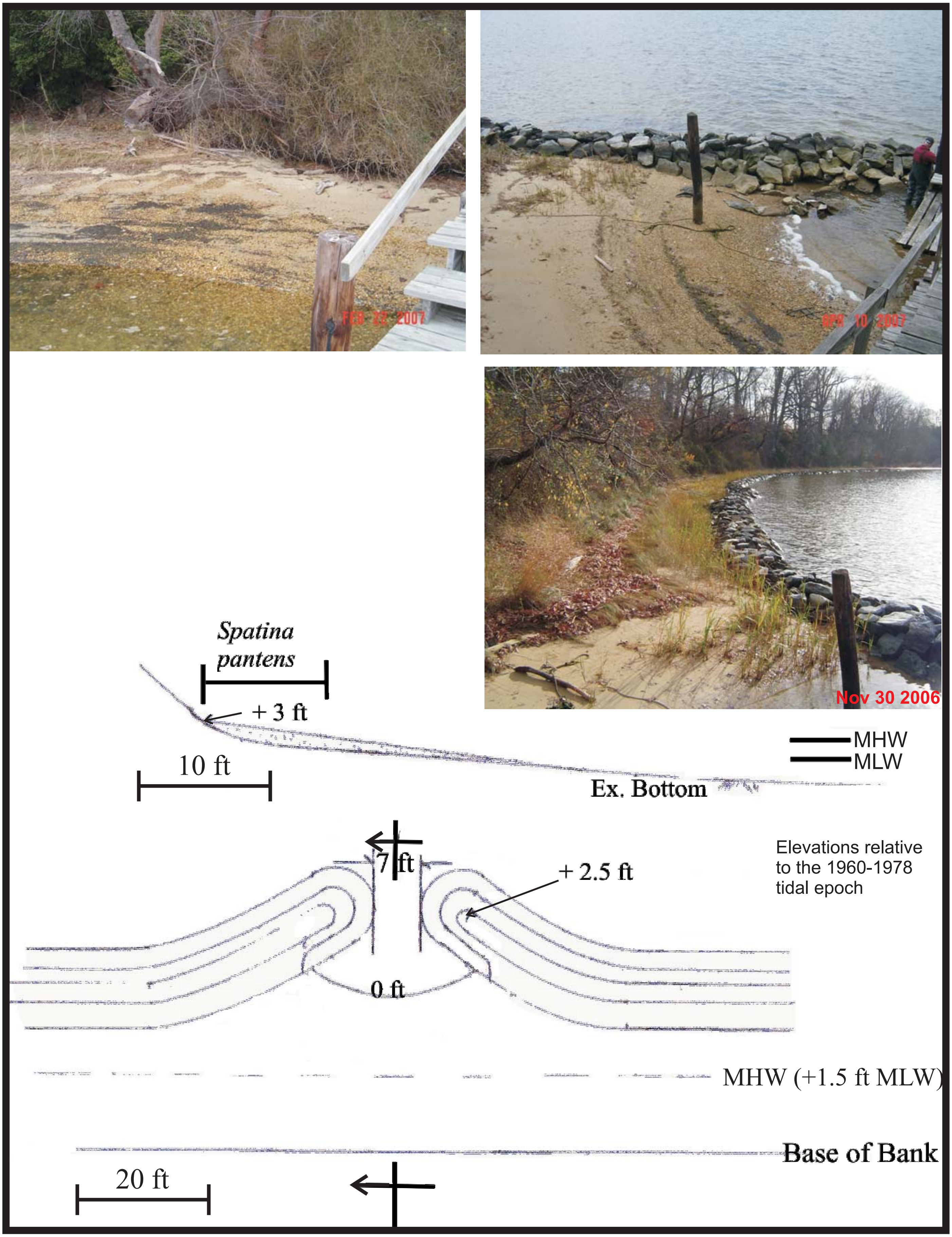
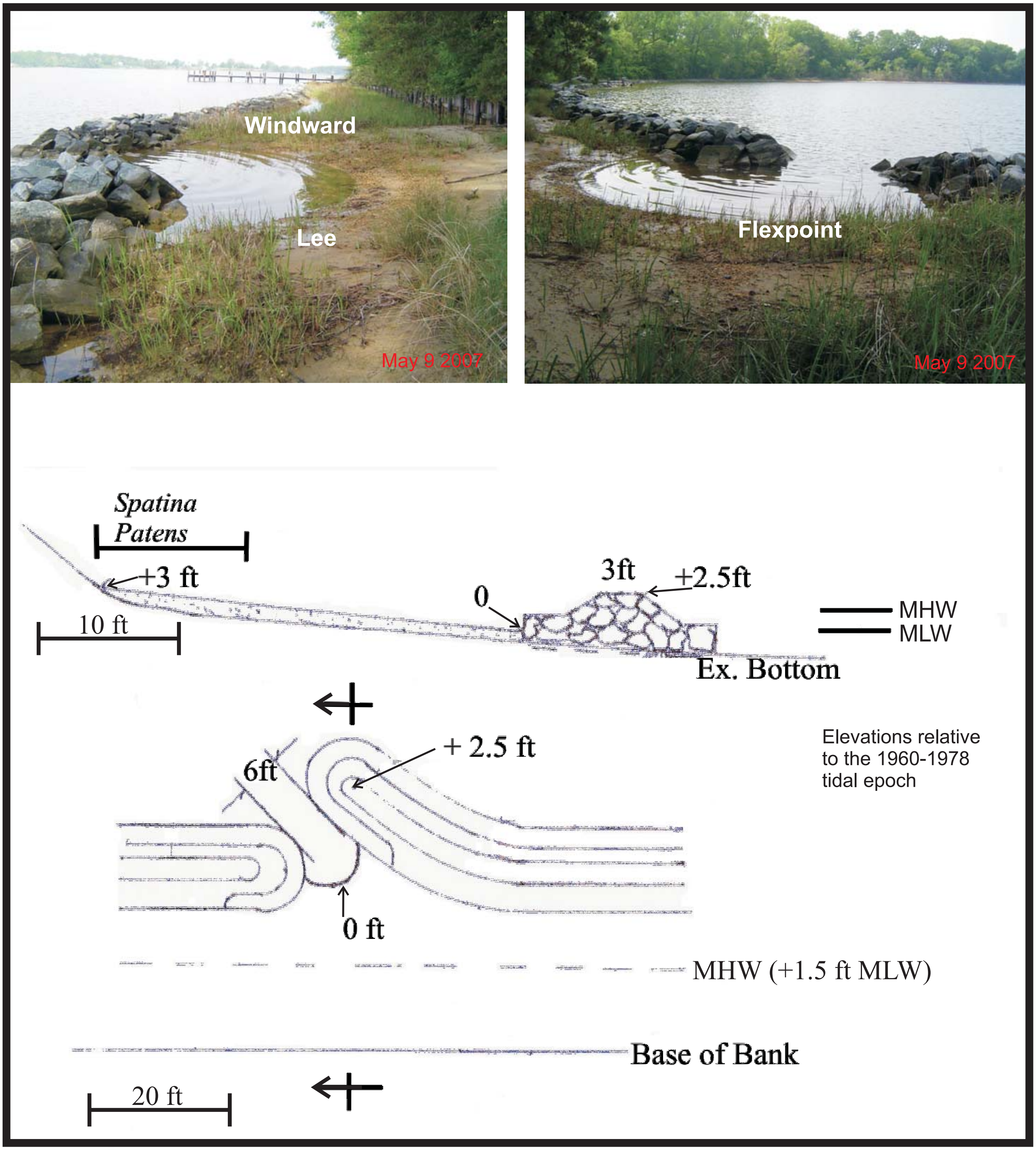


Figure 2-4. Photos showing Window 2 in 2006 and 2007. Window 2 is a Type IIA window or vent along Site 1 as shown in the planform and cross-sectional design.



Elevations relative to the 1960-1978 tidal epoch

Figure 2-5. Photos showing Window 3 in 2006 and 2007. Window 3 is a Type IIA window or vent along Site 1 as shown in the planform and cross-sectional design.



Elevations relative to the 1960-1978 tidal epoch

Figure 2-6. Photos showing Window 4 in 2007. Window 4 is a Type I window or vent along Site 1 as shown in the planform and cross-sectional design.

Figure 2-7. Photos showing Window 5 in 2007. Window 5 was created to have access an existing boat ramp. No design planform exists for this window.

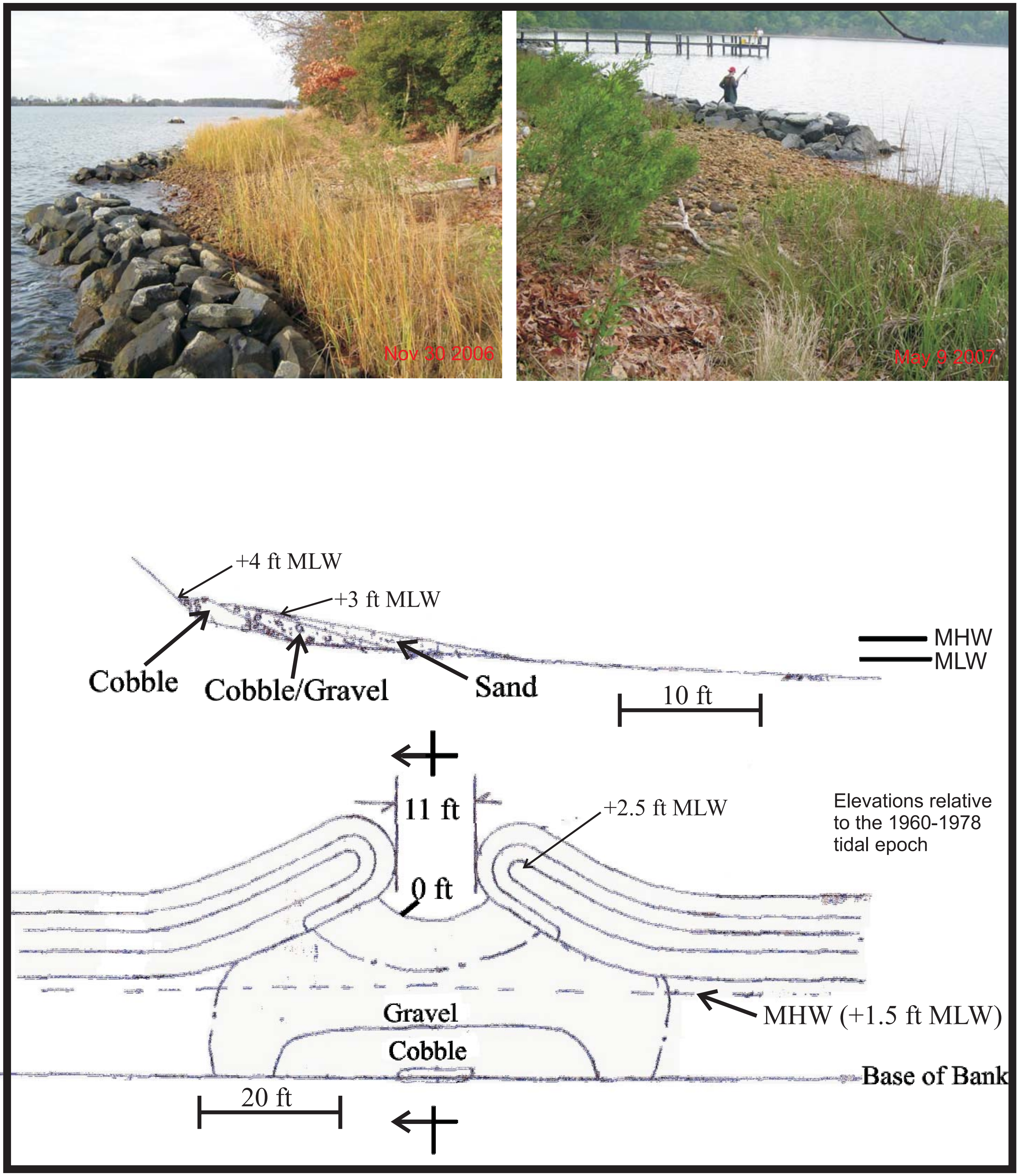


Figure 2-8. Photos showing Window 7 in 2006 and 2007. Window 7 is a Type IIB window or vent along Site 1 with a gravel and cobble backshore as shown in the planform and cross-sectional design.

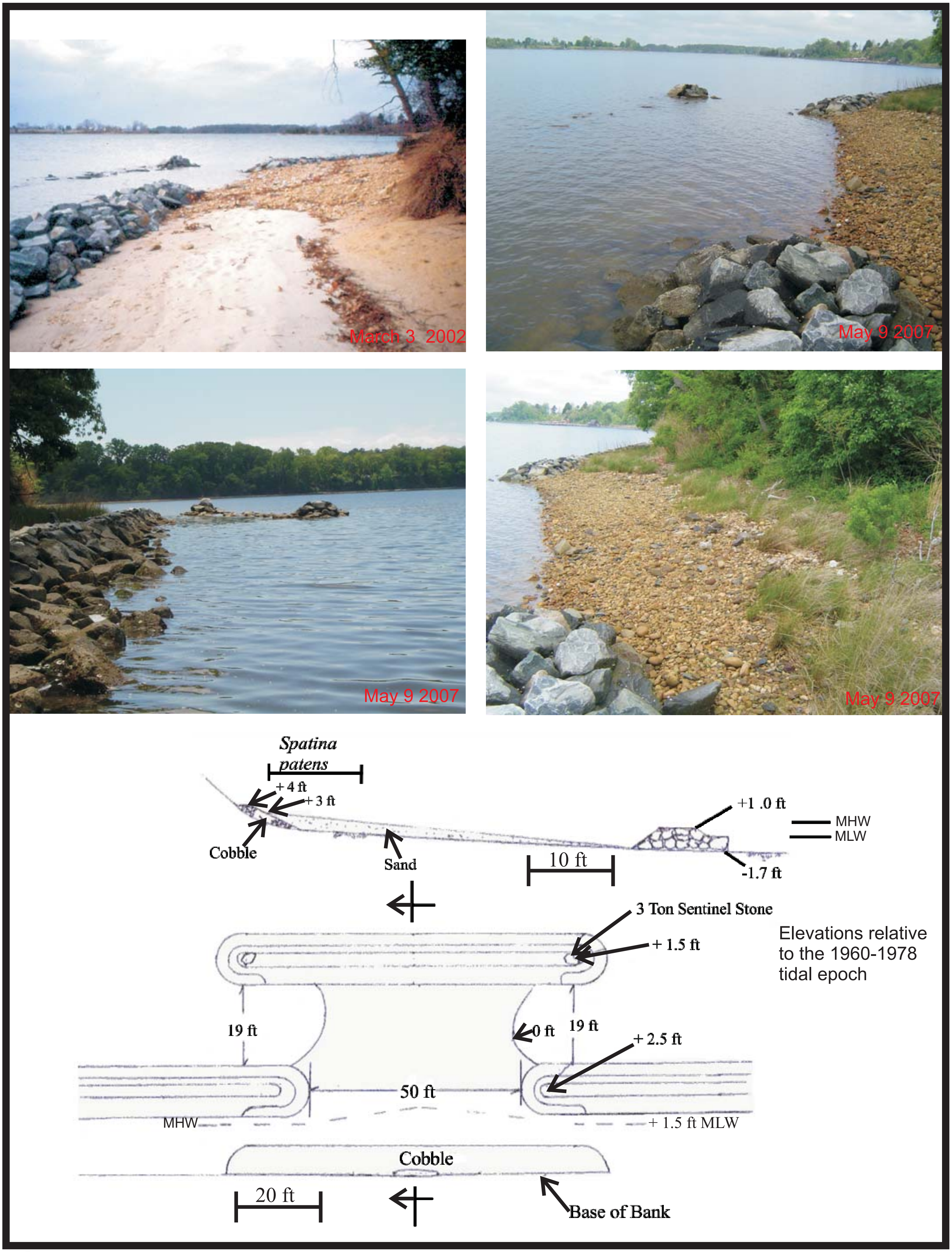
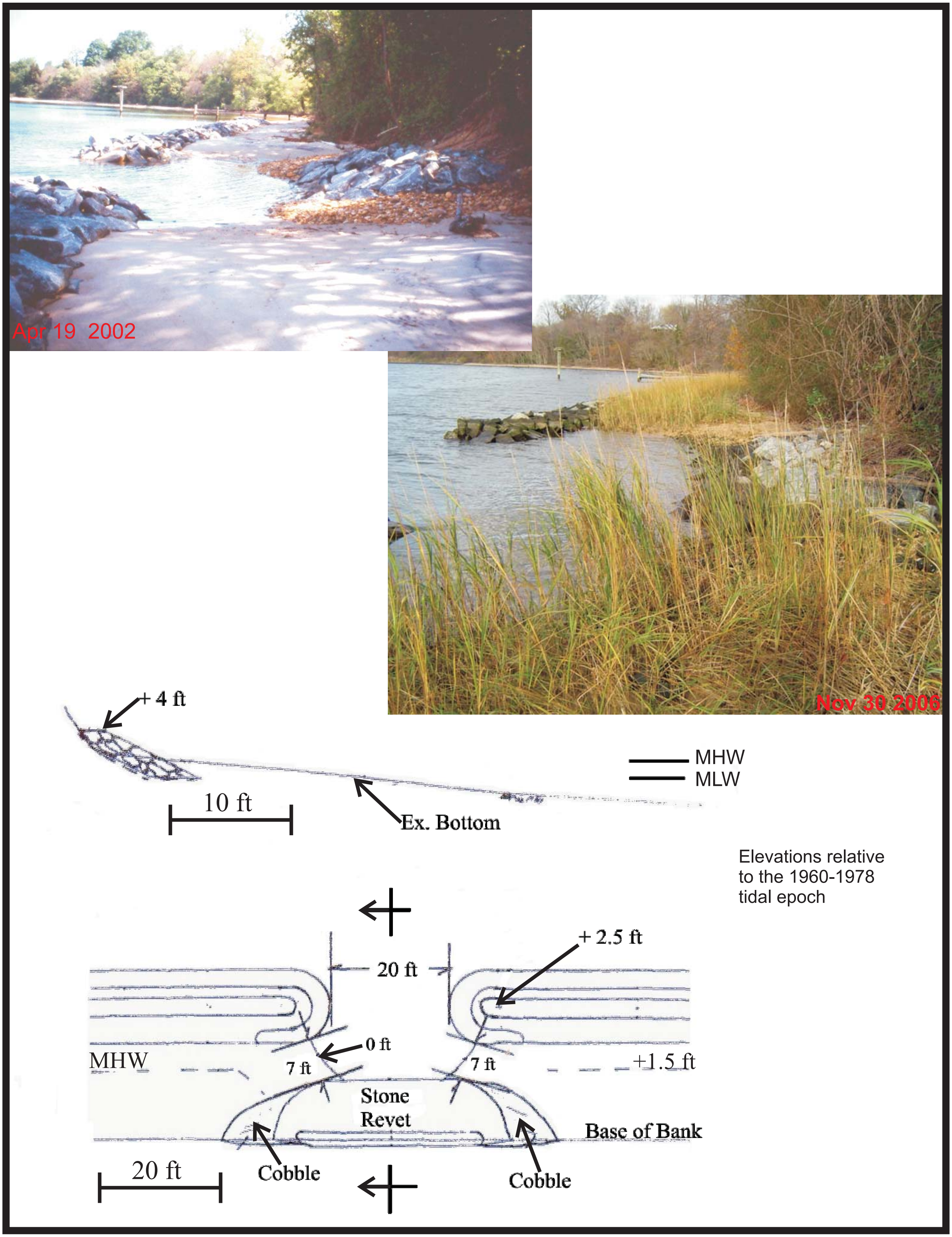


Figure 2-9. Photos showing Window 8 post construction in 2002 and in 2007. Window 8 is a Type III window or vent along Site 1 with a cobble backshore and an offshore low breakwater as shown in the planform and cross-sectional design.



Elevations relative to the 1960-1978 tidal epoch

Figure 2-10. Photos showing Window 9 post construction in 2002 and in 2006. Window 9 is a Type V window or vent along Site 1 with a stone revetment along the backshore shown in the planform and cross-sectional design.

Profile Number	Backshore Volume Change	Profile Number	Backshore Volume Change
	2002-2007		2002-2007
	(cy/ft)		(cy/ft)
1622	0.00	2685	0.10
1677	-0.02	2723	0.64
1730	-0.34	2738	-0.23
1752	0.06	2757	-0.50
1773	0.49	2802	-0.16
1797	0.05	2829	0.00
1857	-0.05	2877	-0.01
1955	-0.18	2971	0.12
1967	-0.11	3008	0.36
1990	-0.86	3035	0.00
2009	-0.04	3101	0.04
2052	-0.10	3201	0.23
2107	0.00	3211	-0.34
2133	-0.12	3228	-0.10
2163	0.00	3302	-0.19
2192	0.22	3364	-0.32
2339	0.06	3427	0.38
2436	0.01	3438	0.08
2489	-0.14	3452	-0.04
2520	0.07	3513	0.09
2536	0.33	3569	0.14
2632	0.11	3616	-0.17

Note: Changes <0.1± are considered no change.

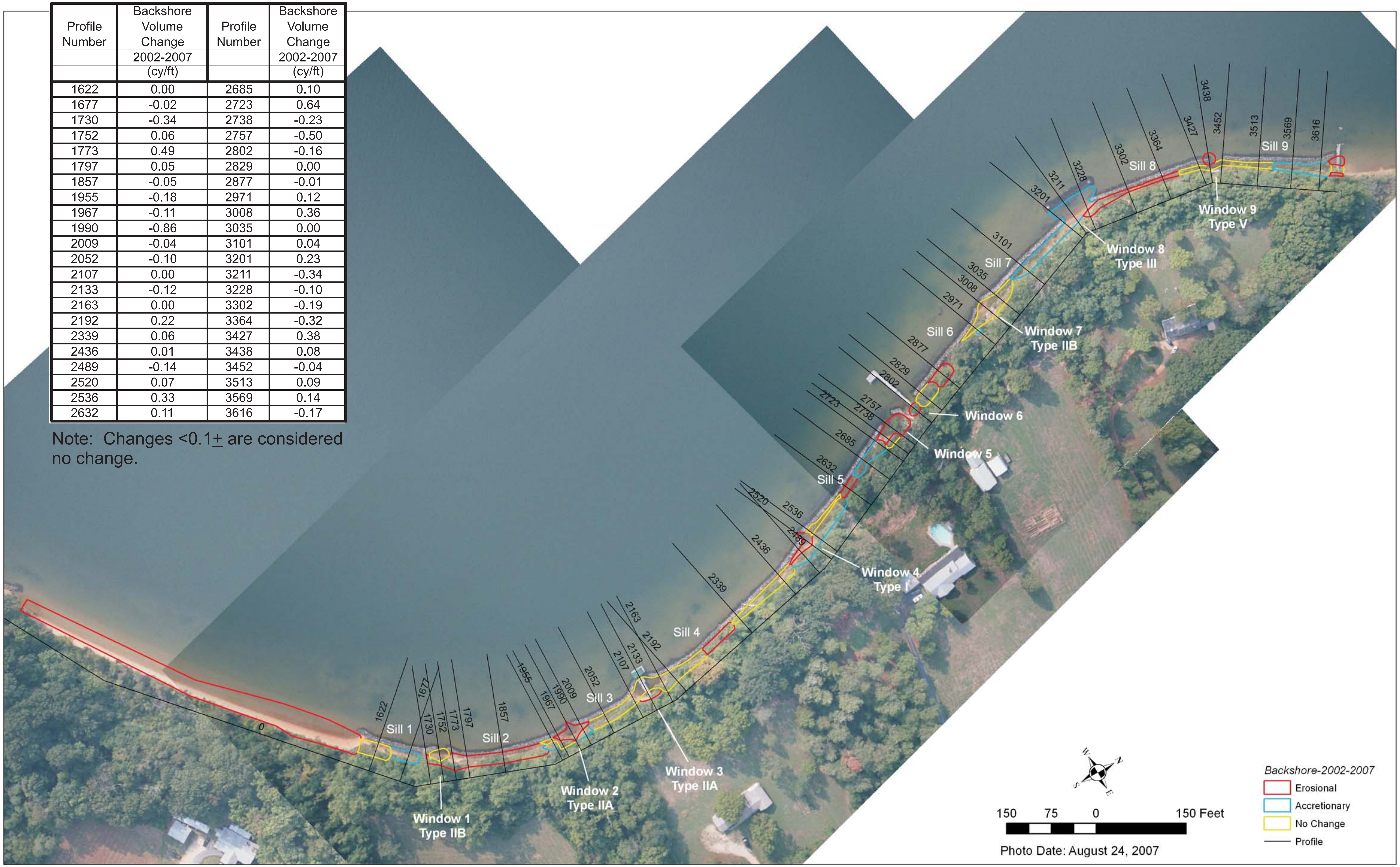


Photo Date: August 24, 2007

Figure 2-11. Map showing the change along the backshore planting terrace between 2002 and 2007 based on profile data. Also shown are profile lines and volume change in cy/ft associated with each profile.

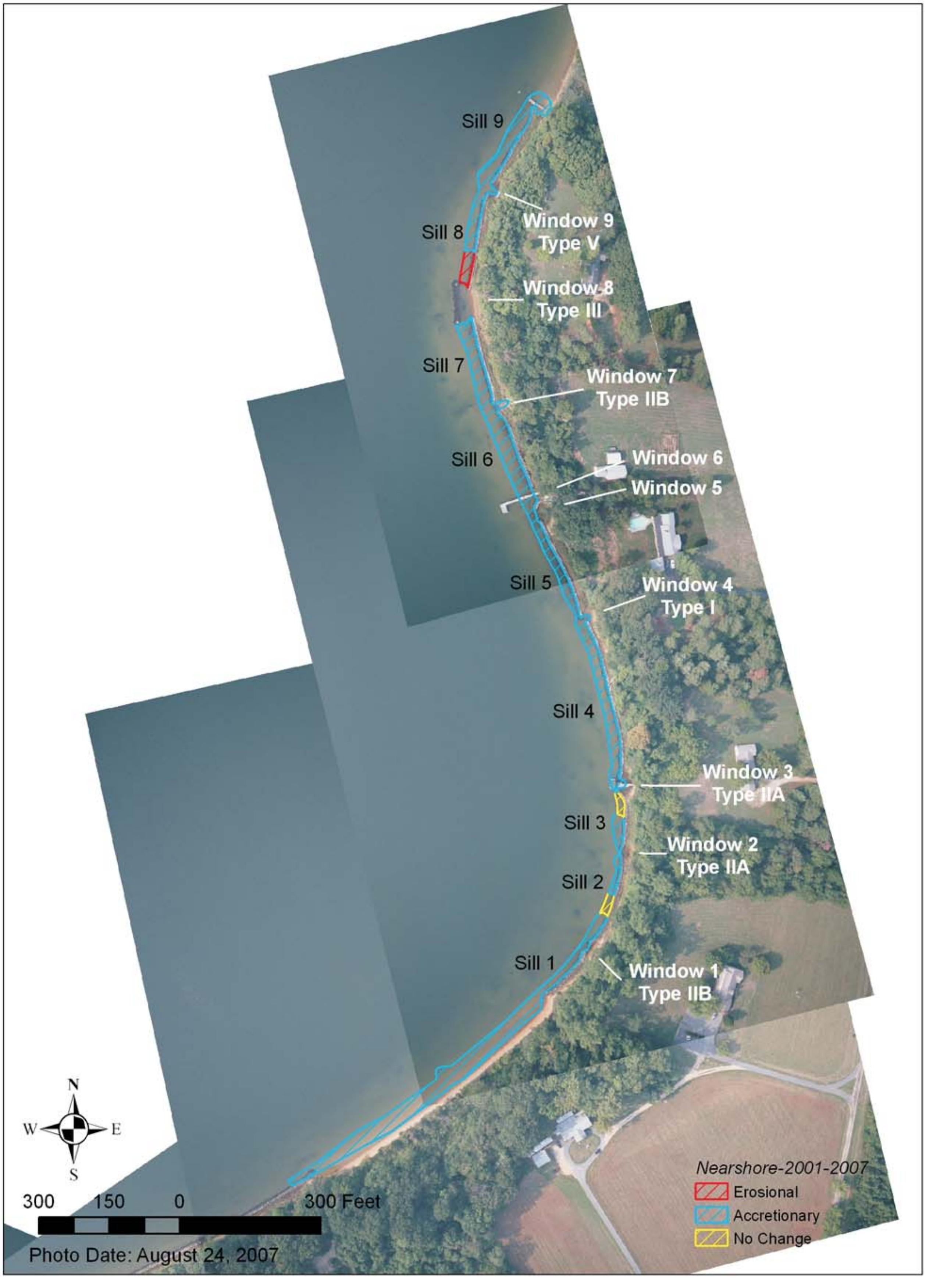


Figure 2-12. Map depicting changes in the nearshore between preinstallation (2001) and recently (2007).

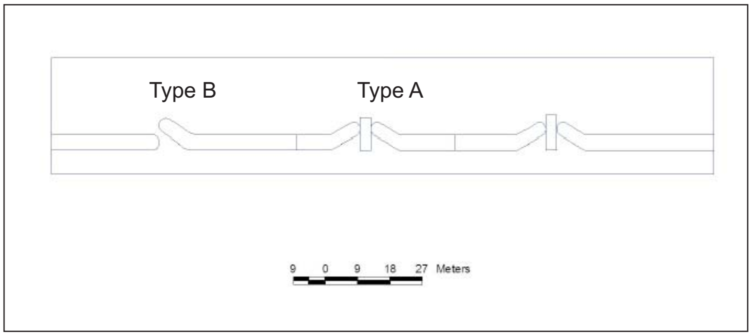


Figure 3-1. A diagram of sill types.

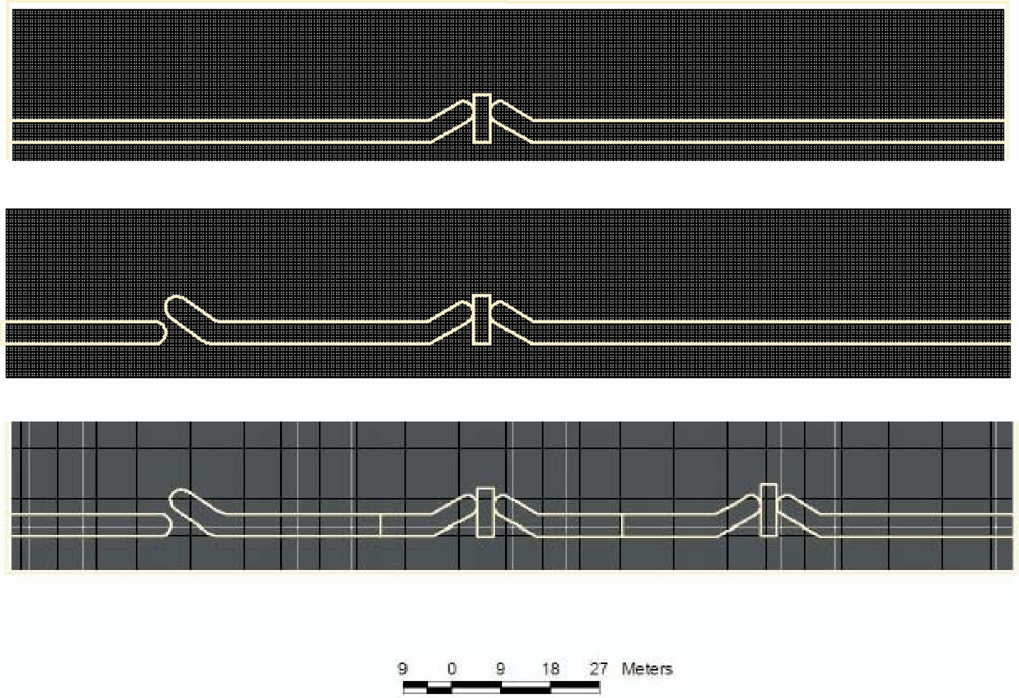


Figure 3-2. An illustration of the model grids.

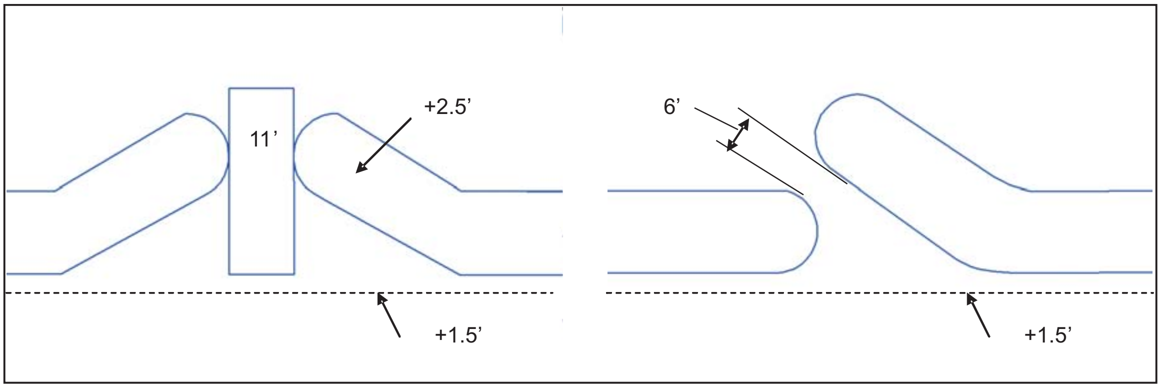


Figure 3-3. Configuration of sill windows.

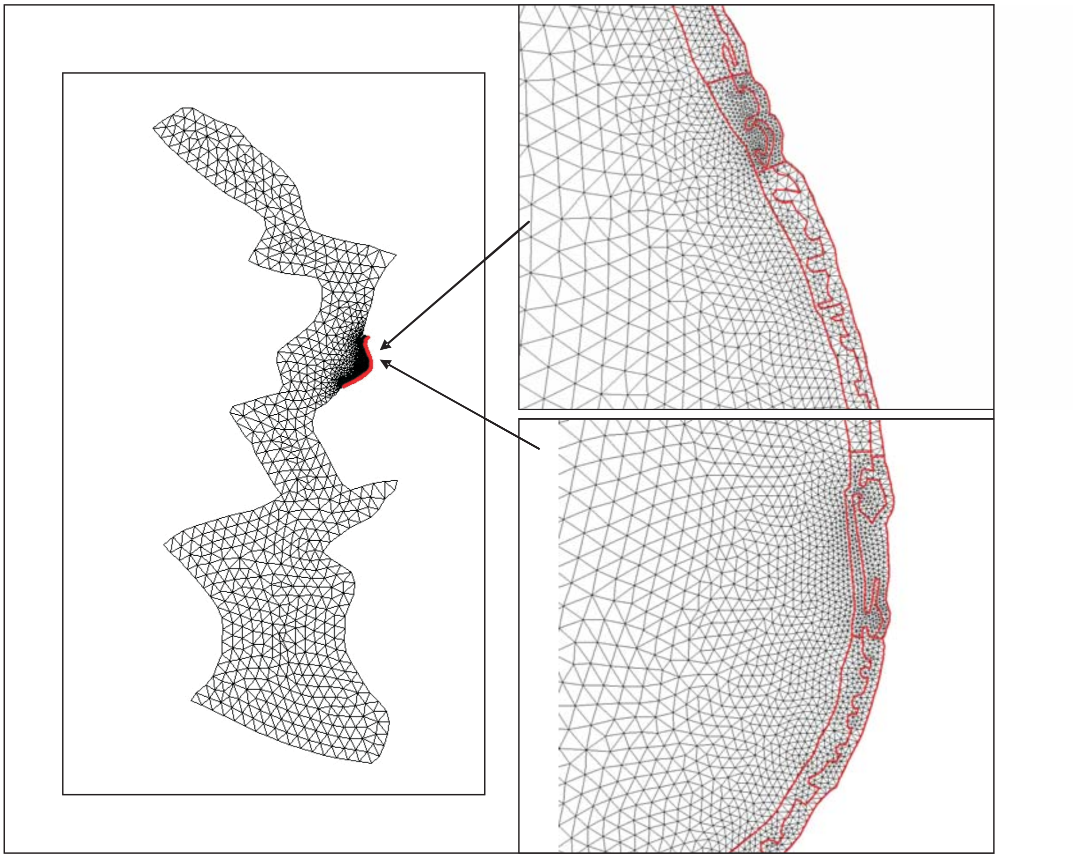


Figure 3-4. Model grid of St. Mary River.

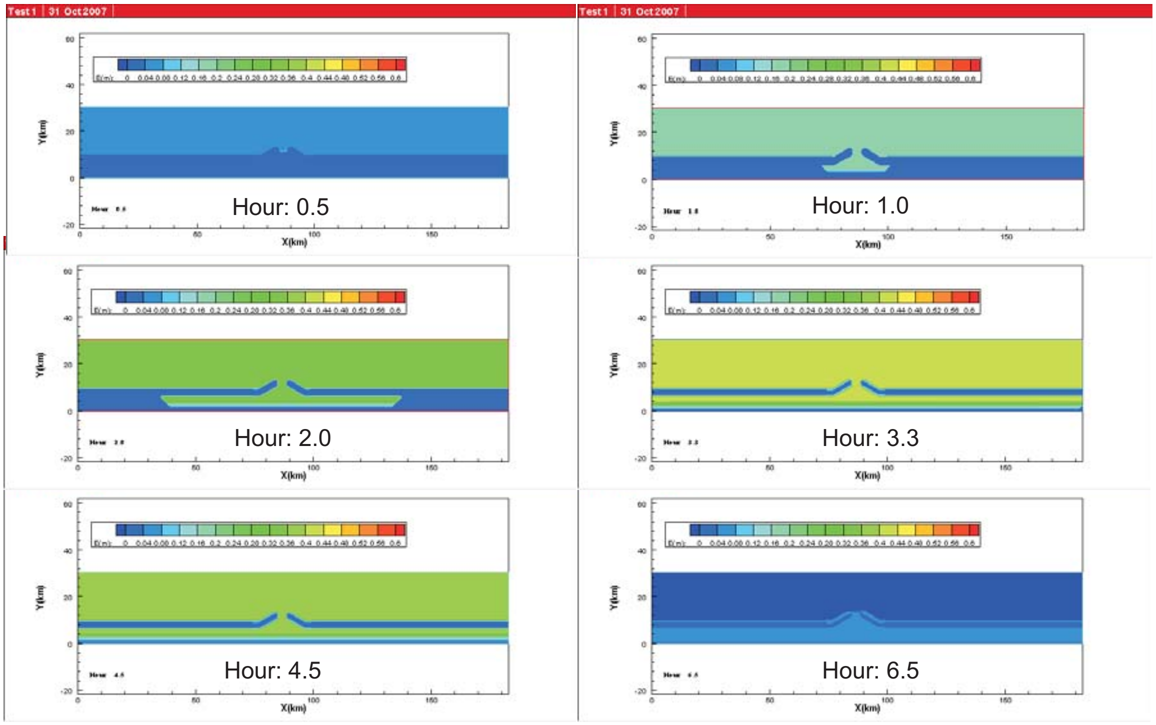


Figure 3-5. Sequence of submerging processes (1 window).

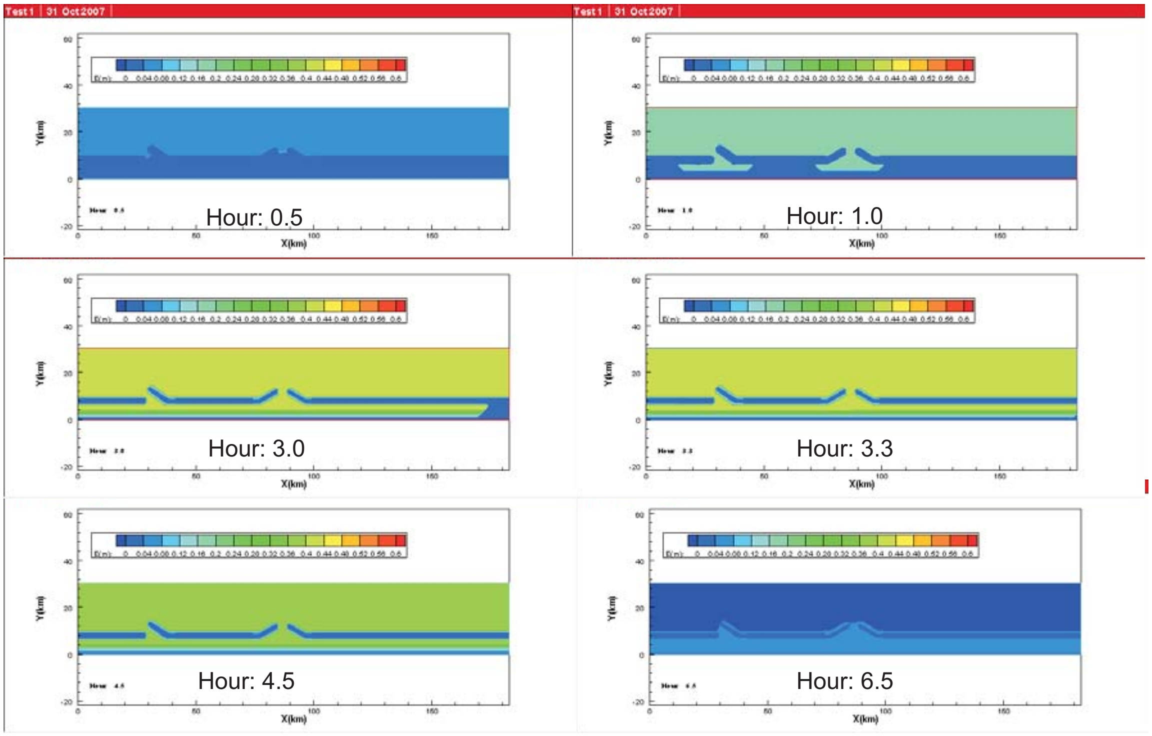


Figure 3-6. Sequence of submerging processes (2 windows).

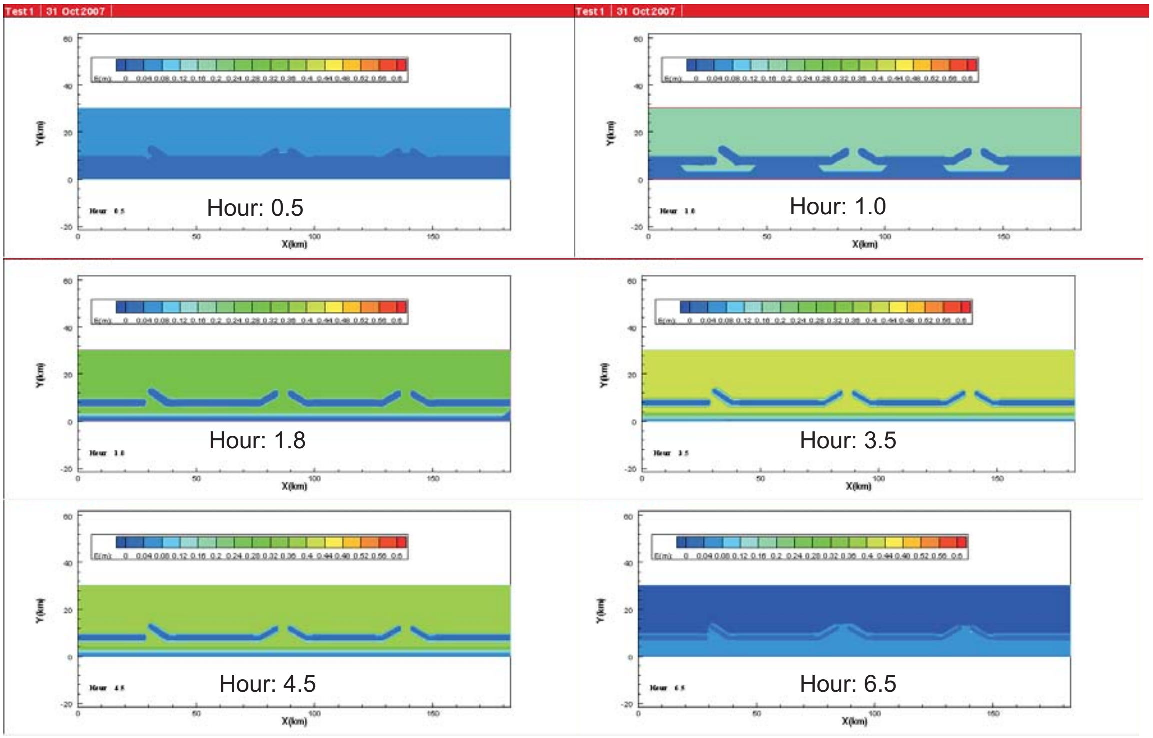


Figure 3-7. Sequence of submerging processes (3 windows).

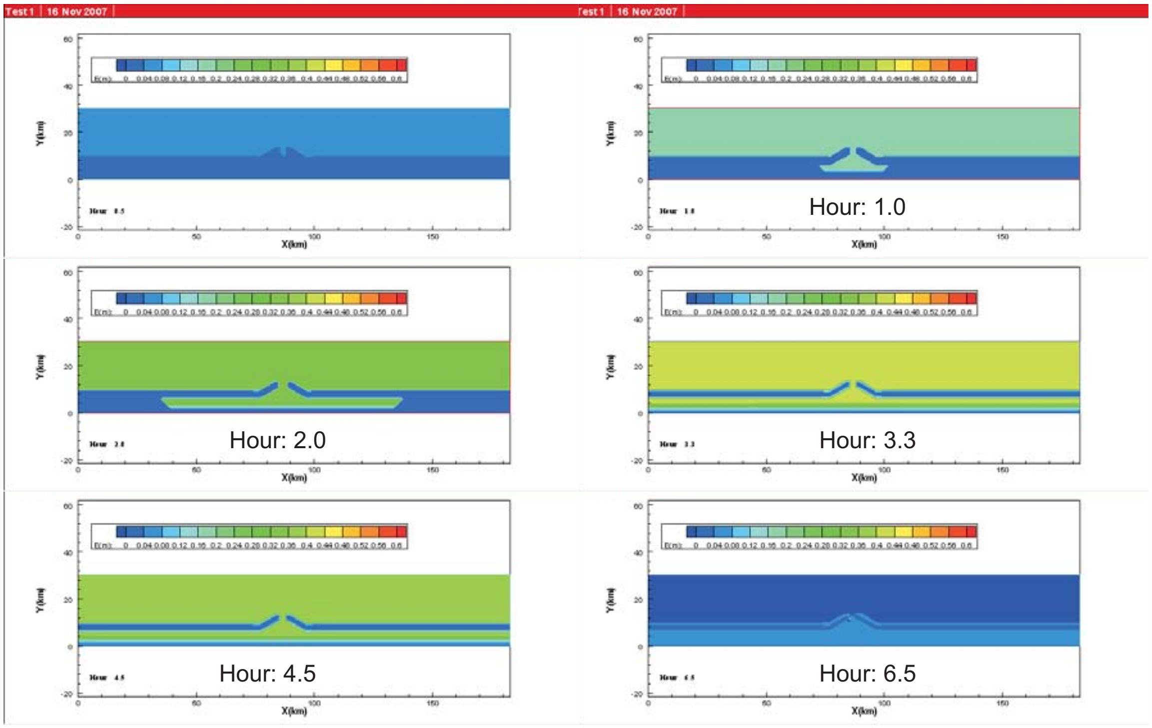


Figure 3-8. Sequence of submerging processes (reduced window width).

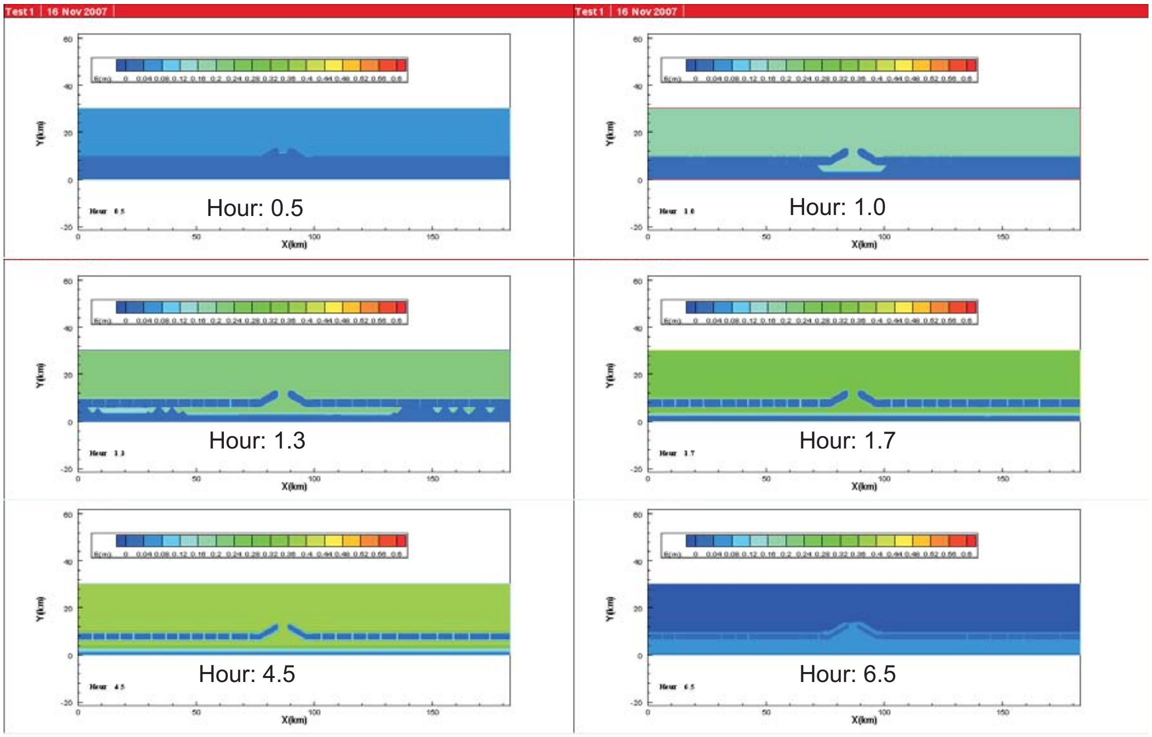


Figure 3-9. Sequence of submerging processes with seepage.

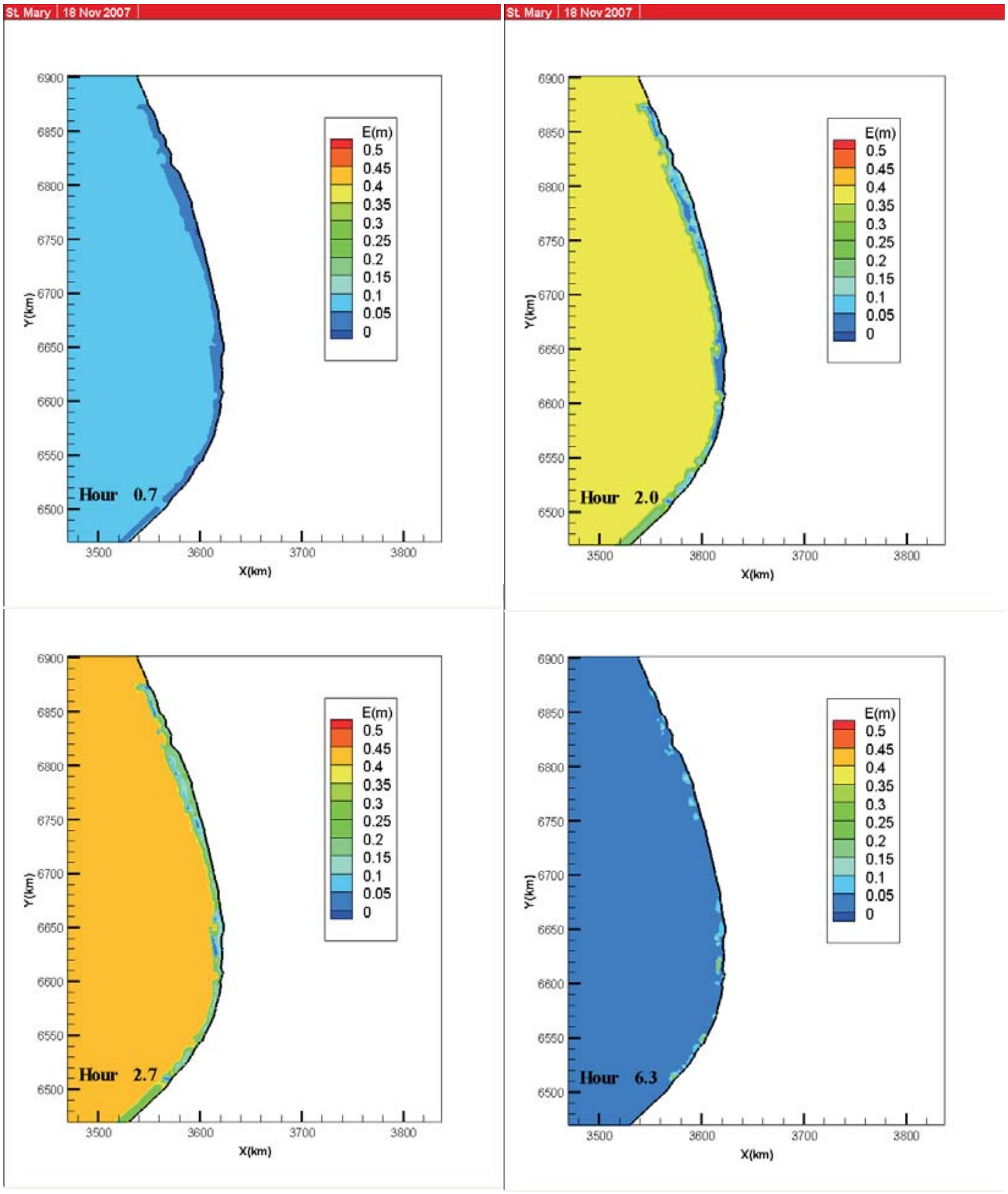


Figure 3-10. Sequence of submerging processes of St. Mary's River.

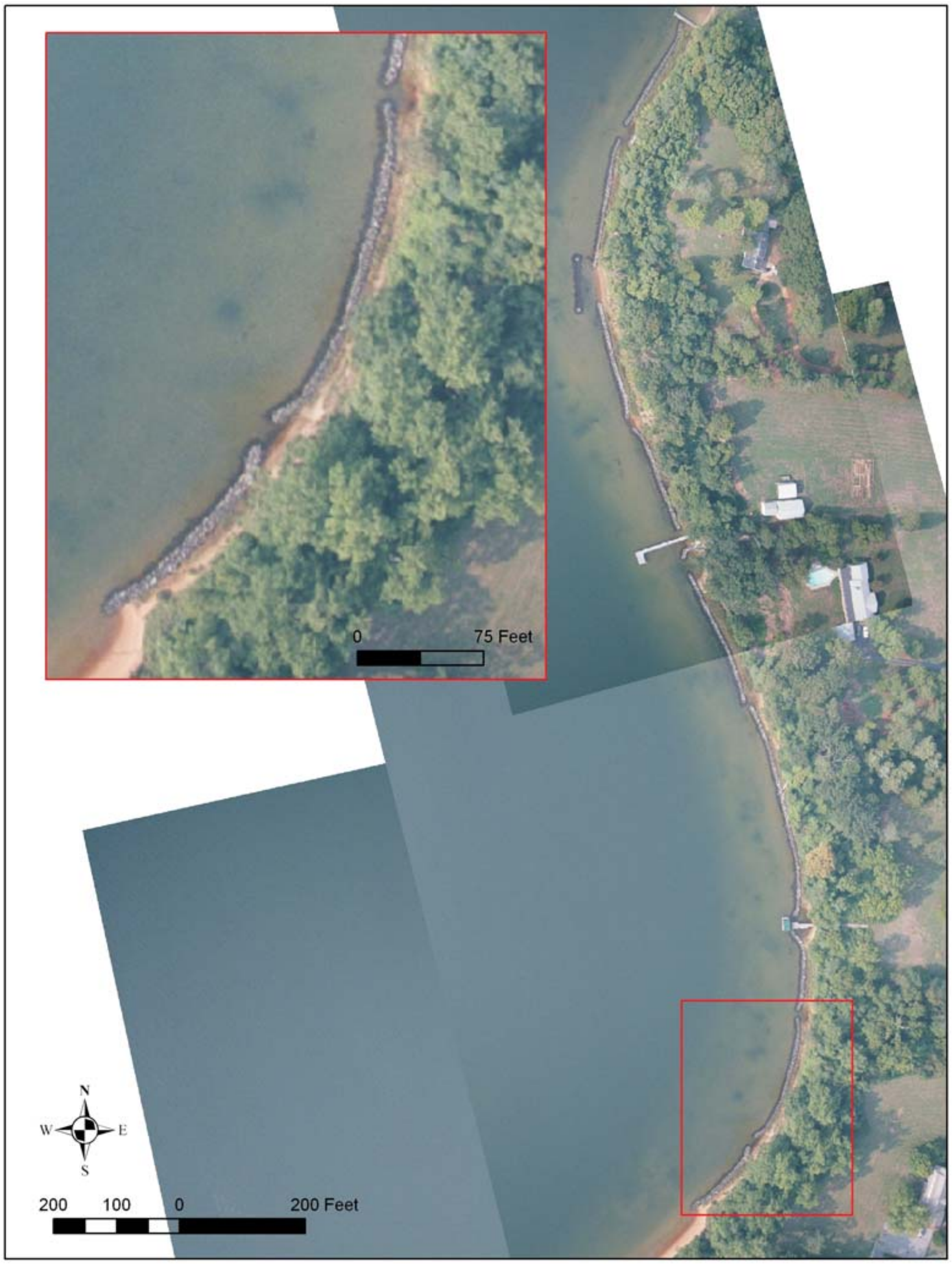


Figure 4-1. Aerial photograph of study and adjacent shoreline area. Study sills are highlighted in photograph insert.

Figure 4-2. Sampling locations of water quality sondes and fish traps. Numbers represent distance in feet from southwest sill window.

Figure 4-3. Basic sill structure with fish traps and water quality sonde in the foreground and blocking net in the background.

Figure 4-4. Example of pore space between individual rocks. Note scale by presence of adult blue crab.

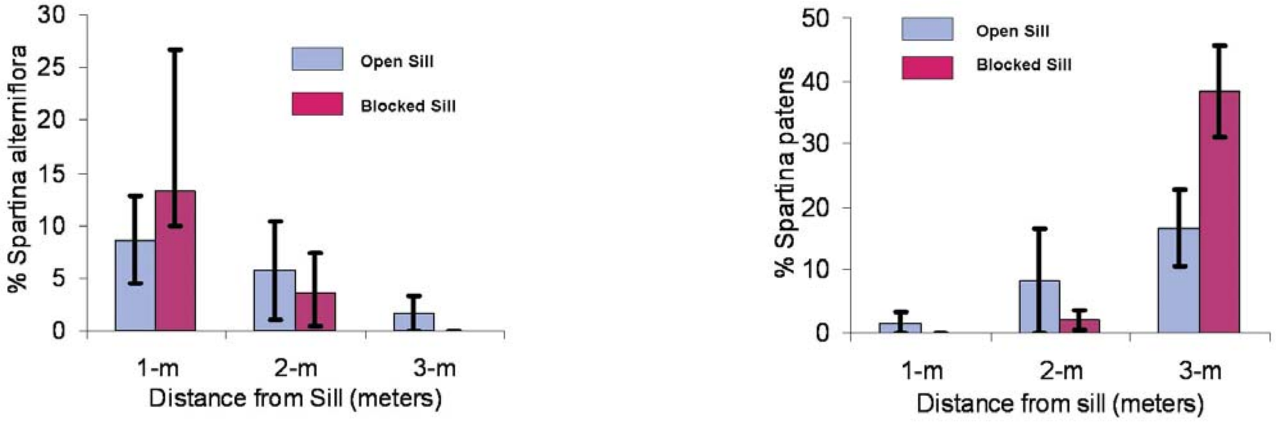


Figure 4-5. Mean ± standard deviation of percent *S. alterniflora* and *S. patens* cover density of study site fringing marsh by distance from landward sill edge.

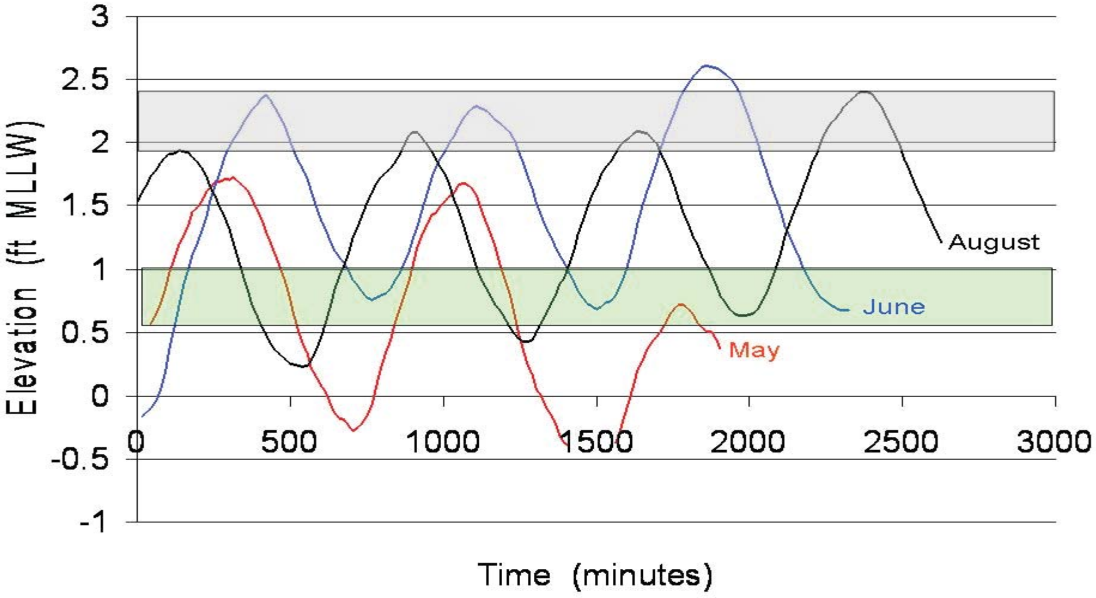


Figure 4-6. Tidal elevations referenced to MLLW for May, June, and August 2007 sampling. Shaded green region represents surface elevation range where the low marsh begins to inundate with flooding waters and the shaded gray region represents elevation range where the sill structure begins to be overtopped with flooding waters.

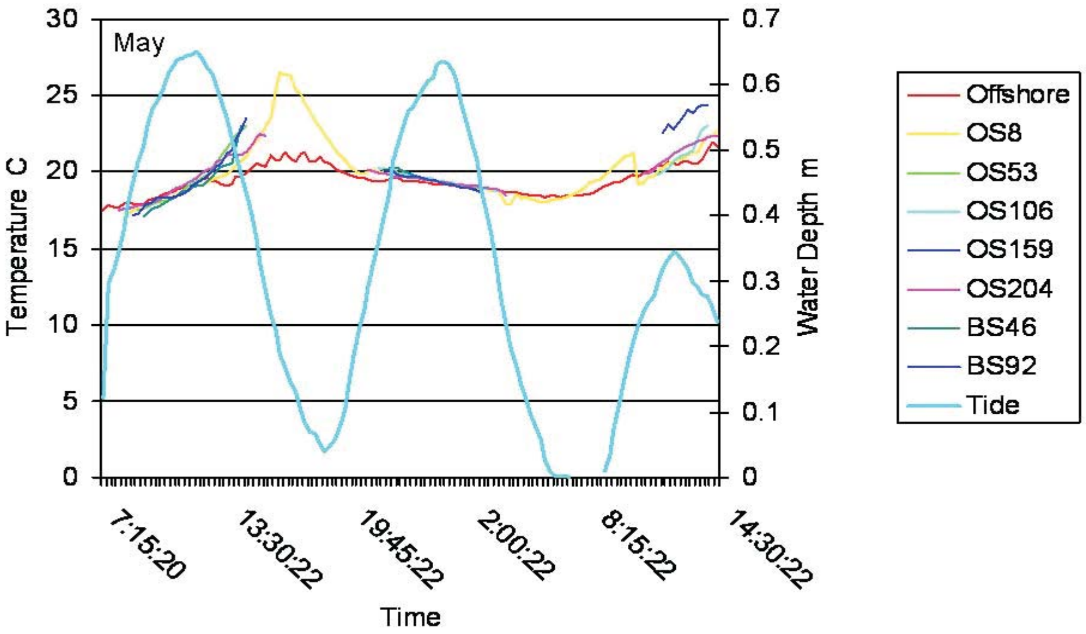


Figure 4-7. Water temperature by site location for the May 15-16, 2007 sample period. Legend nomenclature is as follows: OS denotes open sill site, BS denotes blocked sill site and numeric values represent distance in feet from the nearest southwest sill window. Water depth is a measure of water depth above the sonde sensor and not referenced to a standard vertical datum.

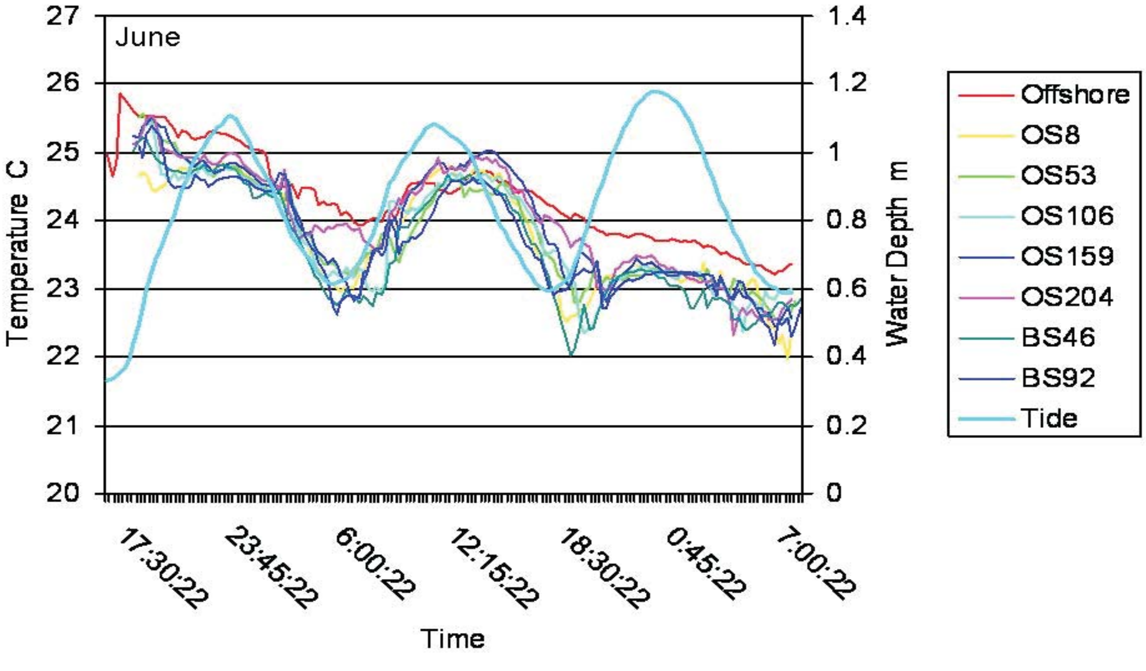


Figure 4-8. Water temperature by site location for the June 13-14, 2007 sample period. See Figure 4-7 for legend nomenclature.

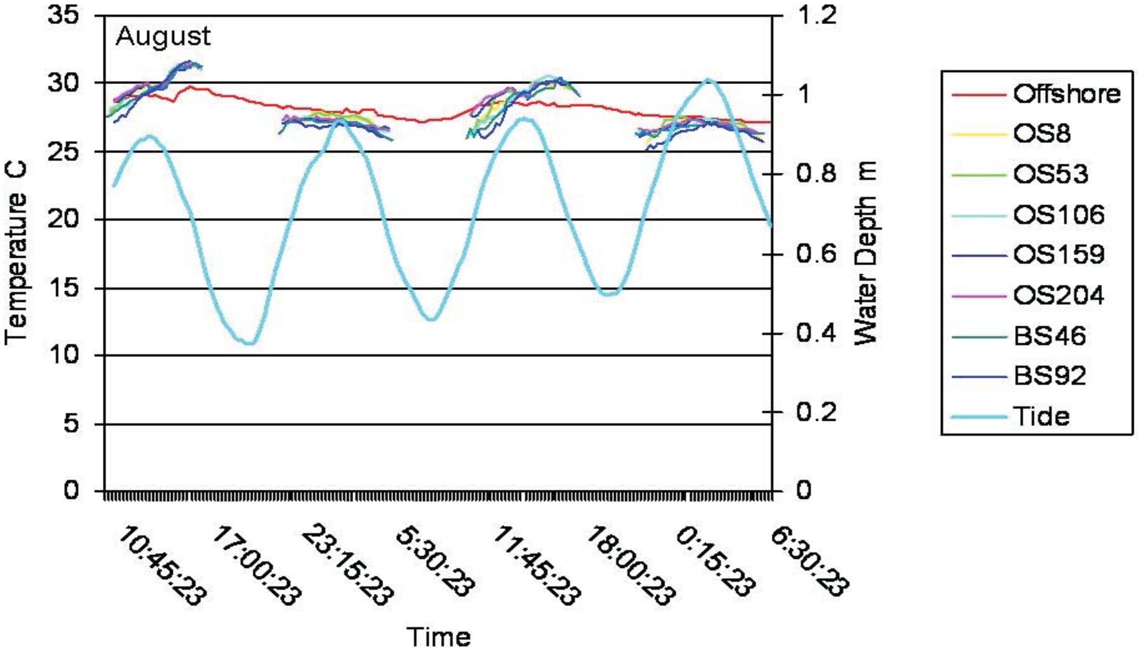


Figure 4-9. Water temperature by site location for the August 13-15, 2007 sample period. See Figure 4-7 for legend nomenclature.

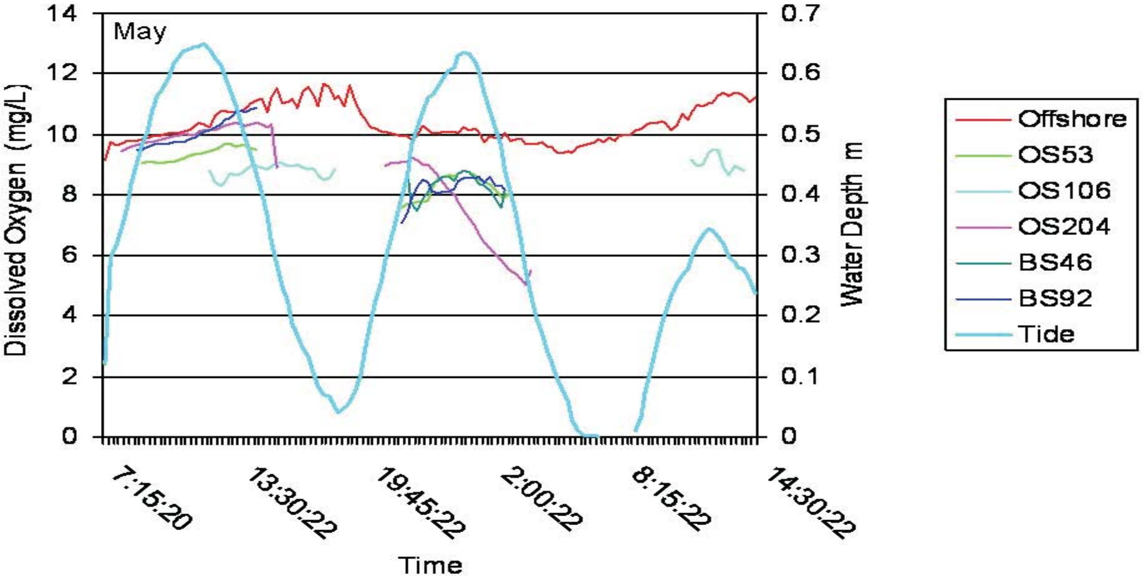


Figure 4-10. Dissolved oxygen concentrations by site location for the May 15-16, 2007 sample period. Legend nomenclature is as follows: OS denotes open sill site, BS denotes blocked sill site and numeric values represent distance in feet from the nearest southwest sill window. Water depth is a measure of water depth above the sonde sensor and not referenced to a standard vertical datum.

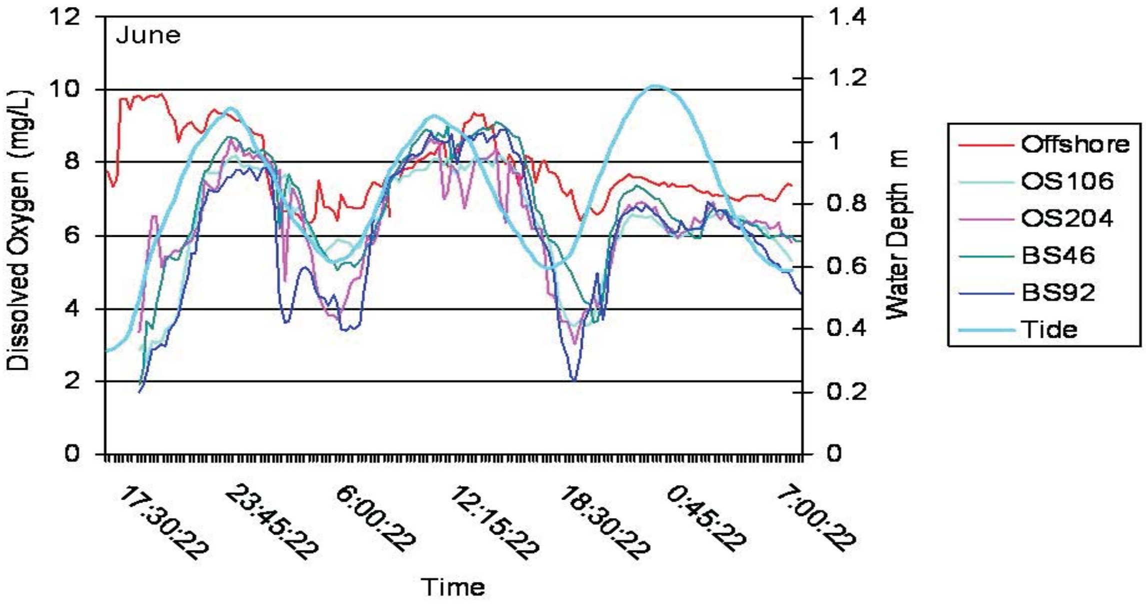


Figure 4-11. Dissolved oxygen concentration by site location for the June 13-14, 2007 sample period. See Figure 4-10 for legend nomenclature.

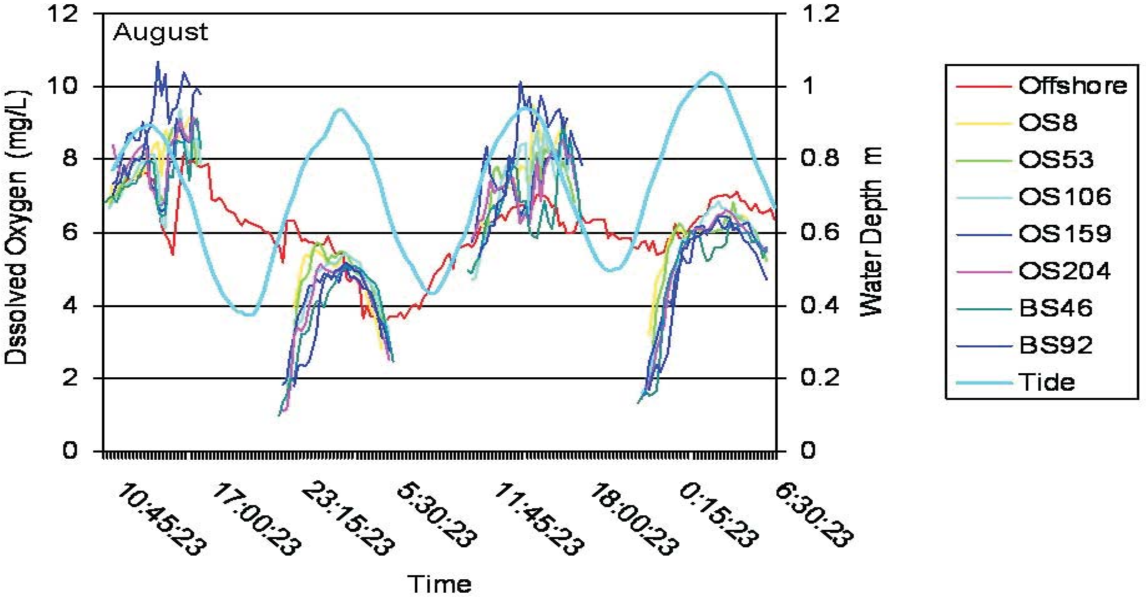


Figure 4-12. Dissolved oxygen concentration by site location for the August 13-15, 2007 sample period. See Figure 4-10 for legend nomenclature.

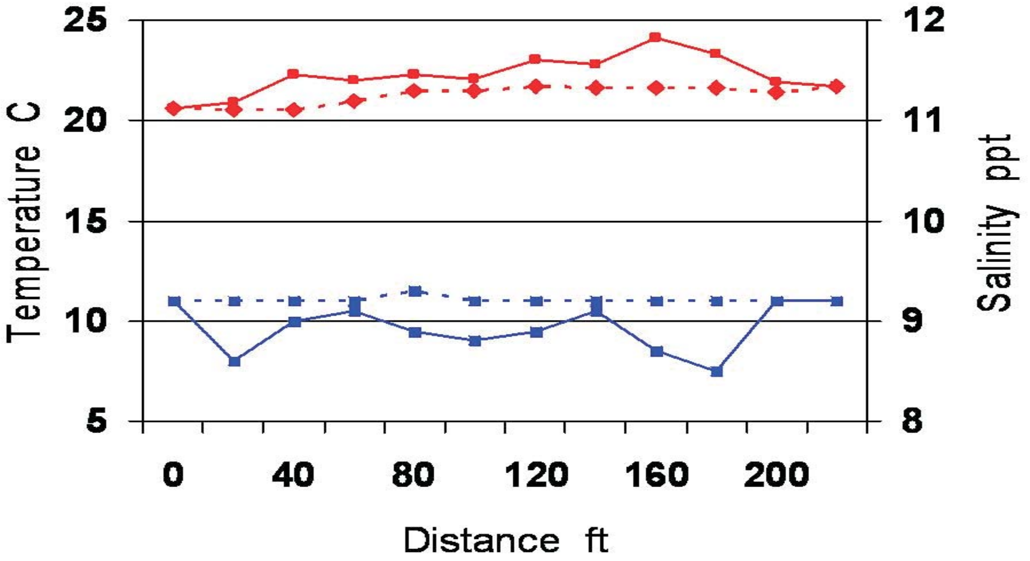


Figure 4-13. Surface water temperature (red) and salinity (blue) taken on the seaward (solid lines) and landward (dashed lines) side of the study site sill structure. Date: 5/15/2007; Time: 13:55 EST approximately two hours past peak high tide.