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# Design and Monitoring of a Small Living Shoreline Scaled for Private Properties on Exposed, Rapidly-Eroding Coasts

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*ABSTRACT*

*Living shoreline projects in exposed sites are unusual unless sponsored by a government agency or a foundation with adequate resources; these tend toward larger scale for obvious economic reasons. Small projects, on the scale of individual private lots, are almost exclusively built at sites with reduced exposure. This paper describes the design and post construction monitoring of a residential property scale living shoreline project on a rapidly eroding, exposed shoreline. The final design was modelled on the award-winning (and much larger) Project Greenshores Phase II built in 2007 in nearby Pensacola Bay, FL. The novel feature for both projects is a constructed salt marsh behind a unique broad-crested, offshore submerged breakwater/oyster reef for wave protection. The project site is on the north-eastern side of Mobile Bay, AL, with a maximum fetch of 129 km. Pre-construction shoreline retreat has averaged -80 cm/year since 1997. The project was constructed in the spring and summer of 2014 and is halfway through a 3-year post construction monitoring program. This paper will describe the site analysis, design process, and the owner's self-imposed adaptive management plan - an equally unique feature for a small-scale project. Results of the monitoring effort and its impact on implementation of the AMP are presented. To date, the design has been successful at eliminating erosion without the usual deleterious effects to adjacent properties associated with traditional shore protection schemes.*

***Keywords:*** *living shoreline, erosion, shore protection, reef breakwater, oyster reef, salt-marsh.*

## 1. INTRODUCTION

Because of both actual and perceived negative impacts, the traditional shoreline protection options for small projects – bulkheads (seawalls), revetments, and groins - have fallen out of favour with regulatory agencies in coastal states and are becoming increasingly harder to permit. A relatively new alternative is a popular, if loosely defined, concept that combines shore protection with at least some habitat restoration. A living shoreline is a "management practice that provides erosion control benefits; protects, restores, or enhances natural shoreline habitat; and maintains coastal processes through the strategic placement of plants, stone, sand fill, and other structural organic materials" (NOAA 2013a). At sites already experiencing significant erosion, vegetation alone has a limited chance of long-term survival unless protected by some sort of wave attenuation feature. Typical layouts use offshore emergent or low crested stone breakwaters in front of replanted subaquatic, intertidal, and/or upland vegetation. Living shoreline projects at exposed, high-energy sites require robust breakwaters and are usually sponsored by a government agency or a foundation with adequate resources to build a larger project. Small living shoreline projects, on the scale of individual residential lots, have been exclusively built at sites with reduced exposure.

The project described in this paper is located on private property southeast of Point Clear on the eastern shore of Mobile Bay, AL (Figure 1) with a maximum fetch of 29 km. Mean tidal range is only 0.4 m, but the region is susceptible to extreme hurricane-induced surges; even a thunderstorm can generate surges exceeding the tidal range. In addition, the property is located near the peak erosional hot spot for this stretch of the bay. Pre-construction shoreline retreat at the site has averaged -80 cm/year since 1997. The client's goals for the shore project were as follows:

- Prevent or significantly reduce erosion of the upland property
- Avoid or minimize interruption of normal LST and negative impacts to neighboring properties.
- Maintain or enhance recreational and swimming access and aesthetic functions of the shoreline

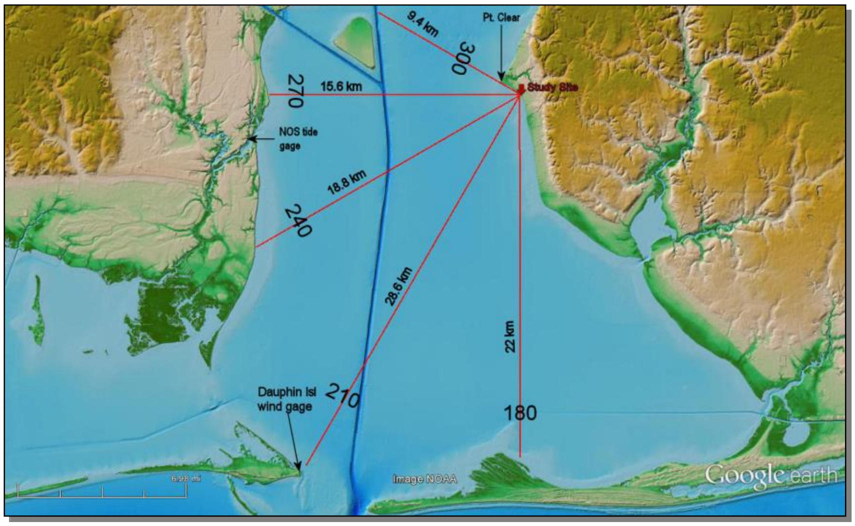


Figure 1. Project Site and Location

The approach selected by the client to achieve these goals was a living shoreline combined with adaptive management practices. The design used in this project is based on concepts developed and implemented by the author that have proven successful under more energetic environmental conditions - the highly successful, award-winning (and much larger) Project Greenshores in nearby Pensacola Bay, FL. The significant and novel feature for both projects is a broad-crested, submerged breakwater/oyster reef. Phase I was completed in 2002 and survived a direct hit by Hurricane Ivan without damage; Phase II was built in 2007 (McGehee 2008).

## 2. SITE ANALYSIS

The mid-term (scale of years to decades) shore processes at this site are dominated by wind-driven waves. Long-shore transport (LST) i.e., movement of sand parallel to the shoreline, is controlled by the cumulative effect of normal, seasonal winds. The typical annual pattern of dominant winds on the northern Gulf coast is bi-modal – somewhat east of southerly in the summer season and somewhat west of northerly in the winter season, so LST stress on the eastern shore is generally northward in the summer months and southward in the winter months. The shoreline south of the study site is aligned roughly north-south and is protected from southeasterly winds but exposed to winds from the south through the west northwest. The shoreline bends to roughly northwest-southeast at the project site and is sheltered from the northwest but exposed to winds from the southeast through the west northwest.

Wind waves offshore of the project site were hindcast using methods of Bretschneider, including shoaling and reduction in wave height caused by bottom friction according to Miche (IKM Engineering 2013). Setup due to wind stress on the bay was calculated for the various wind conditions, using the additional coefficient of 0.5 for enclosed basins. LST potential was estimated from the hindcast wave statistics by way of the CERC formula, as modified by Kamphuis and Readshaw (Smith et al. 2009). Calculated average net LST potential is on the order of several hundred $m^3$/yr to the north at the southern end of the study site. It decreases in magnitude going north until it is essentially negligible near the project site. Continuing northward, LST potential reverses direction to south easterly transport and increases to a few hundred $m^3$/yr near Point Clear.

All of the unprotected shorelines in the general vicinity are retreating, but the most severe erosion observed in the study area, about 60-90 cm/yr, is just south of the project (Figure 2). The obvious question that arises from the LST calculation is this: if net LST comes from both directions toward this site (a LST node), why is it eroding at the fastest rate instead of accreting? Three other factors need addressing to explain the erosion:

First, the LST formulas provide the sediment transport *potential.* This is the maximum amount of sediment that would be transported given an unlimited supply of sediment updrift. At this site, there is effectively no nearshore sediment available south and north of the study area to feed the LST in between due to the extensive groin fields and bulkheading of the shoreline. That is why the central portion does not accumulate sediment in the long term, but that does not explain the significant shoreline retreat.


Figure 2. Project site on aerial photo from 11/02/2013 with historical shorelines from 1997, 2008, 7 2010

The second factor is cross-shore transport (CST), i.e., movement of sand perpendicular to the shoreline. Offshore-directed CST is episodic and occurs almost exclusively during higher wave events; it is insignificant below some energy threshold. Storms produce larger, steeper waves that pull sand from the shoreline offshore to create bars (sometimes called “storm bars”). On an open ocean coastline, swell waves – lower waves with longer periods – occur after and between storms. Swell transports the sediments on the bar shoreward, so in the long-term (and with a constant sea level), cross shore transport is in equilibrium. Mobile Bay often experiences high enough winds and the site has sufficient fetch to produce highly erosive, steep, short-period waves. However, there is insufficient fetch to generate the long-period swell that moves the bars shoreward. Thus, the shoreline retreats with each high wave event and does not fully recover in between. Quantitatively, comparison of the eroded upland volumes with measured offshore profiles taken during the site analysis phase showed that all of the sediment volume lost from the upland shoreline between 1997 and 2013 can be accounted for in the underwater bars within 61 m (200 ft) of the shoreline.

The third factor is sea-level rise. Under rising sea levels, all shorelines retreat landward; it is the dominant influence on the scale of decades to centuries. The Bruun rule is a simple model for quantifying the eventual response of a shoreline to sea-level rise. Using the 3 mm/yr rate of sea level rise at Mobile between 1966 and 2012 (NOAA 2013b), the predicted shoreline retreat over the 16 years covered in the historical shoreline analysis is about 2.1 m (7 ft).

## 3. DESIGN

The design condition is a wind of 20 m/s with a direction band of 220º to 250º True (*T*). Winds greater than this threshold occurred just 0.03% of the time, an average of less than 3 hours per year, between 1997 and 2008 (NDBC 2013). For this wind speed, the wave hindcast/transformation analysis produced the maximum incident wave condition of 0.8 m wave height, $H_D$, with a period, $T_D$, of 4.1 sec. Inside the 1 m contour, the incident direction band of the design wave was from 215º to 240º True (*T*), and the wavelength, $L_D$, was about 13 m. The wind setup for these conditions is 35 cm. The design water level is the occurrence of the design conditions at mean high tide for a total water level of 75 cm MLLW. The design water depth, $h_D$, for a structure with a toe about 50 m offshore, is 1.2 m. The maximum wave height in that water depth (for braking index, $\gamma$ = 0.6) is 0.7 m, so the design wave is conservative for structural response considerations. Figure 3 is the profile of the design used to meet the client's goals under these design conditions. Figure 4 is an aerial photograph of the project taken 01/30/2015, 6 months after completion. Profile lines described in the Monitoring section are also shown. Elements of the design are discussed in the following sections.

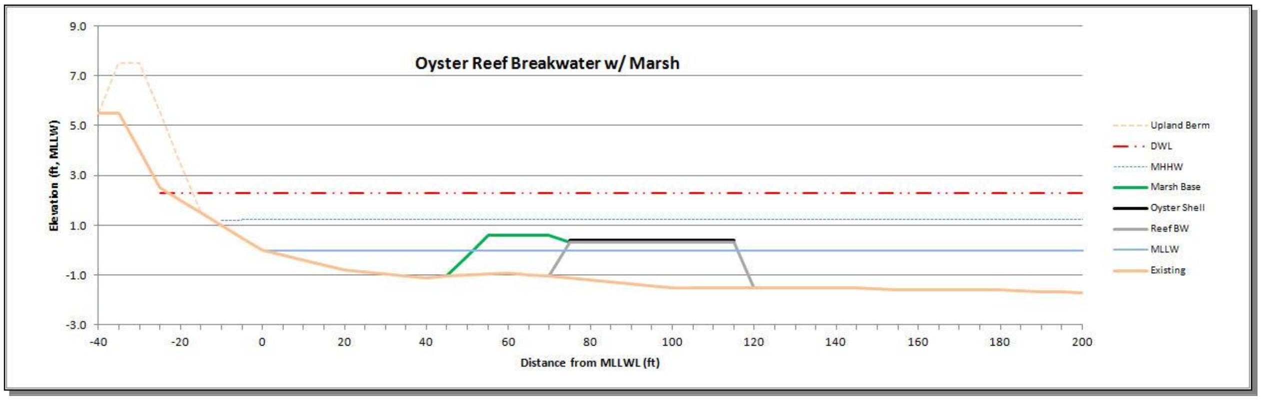


Figure 3. Project design profile


Figure 4. Project post construction, 1/30/2015, with survey profiles 5S through 5N

## 3.1. Submerged Reef Breakwater

Living shorelines in general, and submerged reef breakwaters specifically, are relatively new engineering approaches with little data and guidance for design. Typical living shorelines utilize either shore-connected or detached breakwaters with narrow-crested trapezoidal cross-section designs refined over the previous century. These function well in protecting harbors from incident wave energy, but there are two major drawbacks to this choice for protecting sandy shorelines, depending upon the crest height of the breakwater.

If the breakwater is an emergent structure that is rarely overtopped, it completely interrupts LST behind it. Sediment that settles in the lee of the breakwater forms a dry beach bulge in the shoreline that reaches either partially (a salient) or completely (a tombolo) to the back side of the breakwater. In either case, all LST is captured and the "starvation" of the sediment to the downdrift beach results in a localized erosional hot spot - the so called "groin effect" (Department of the Army 1992); see the lower right portion of Figure 2 for an example near the project due to a groin. If the crest is low or submerged so that it is routinely overtopped, the overtopping waves produce a set-up of the mean water level in the lee of the structure. Under higher wave conditions, the return flow of the elevated water can produce significant gyres in the lee to each side of the structure that result in erosion to the adjacent shorelines (Stauble et al. 2003; Pilarczyk 2003).

By contrast, a submerged, broad-crested breakwater reduces wave energy by friction and dissipation, like a natural reef, rather than by reflecting the incident wave energy. However, because it is broad crested, the transmission coefficient is not a constant – it is a function of frequency. Steep, higher frequency waves that cause nearshore and backshore erosion due to offshore-directed CST are highly attenuated by friction during the breaking process. Low-steepness, longer period waves that tend to move sediment shoreward are less attenuated. It is, in effect, a low-pass filter for wave energy, not a wave barrier. For example, the reef is completely transparent to tides (and their associated currents), which facilitates natural flushing and promotes water quality. Making the reef broad-crested solves the setup drawback as well. Since the setup takes place on the reef, and not behind it, the return flow is directed toward the sides of the reef that are stable under these currents, not near the highly erodible sand in the nearshore.

Finally, the reef breakwater can reduce or even eliminate the groin effect. Since it is routinely overtopped, even under mild wave conditions, some wave energy is still transmitted shoreward, especially under storm conditions with associated surges. Thus, LST can continue in the lee of the structure, though at a reduced rate. As much as half of the total LST on a shoreline takes place in the swash zone by waves that are too small to break further offshore or have already broken and reformed. Since the potential transport rate is much greater than the actual rate at this site, even a much reduced LST rate can bypass the quantities that normally move downdrift.

The main quantitative performance criterion of the breakwater is to reduce the incident wave, $H_i$, to a transmitted wave, $H_t$, which will allow the emergent salt marsh to thrive. Douglass and Stout (2004) established a maximum wave climate for non-eroding marsh shorelines along Mobile Bay based on the wave height, $H_x$, exceeding an x percent occurrence: $H_{50} < 0.15$ m and $H_{80} < 0.25$ m. The marsh will be newly planted, so a more restrictive criterion was selected for reducing the transmitted design wave height, $H_{t,D} < 0.25$ m. There is limited engineering guidance on three-dimensional design of submerged porous structures; in this case, property boundaries controlled the plan dimensions. Desire for a recreational, swimming beach established dimensions for the inner edge, and navigational access to an existing boat dock established the outer edge, while regulations mandated a 3 m (10 ft) side setback from the owner's riparian boundary. The breakwater was placed essentially within these constraints.

As is true for other aspects of reef breakwater design, there is little guidance on stone size for stability. The classic Hudson formula was derived for emergent breakwaters with relatively steep slopes. Using a horizontal slope in the formula forces the stone size to 0. Stability under the design wave is predicted for randomly placed angular stone ($\rho$= 2,400kg/m$^3$ or 150 lb/ft$^3$) with a median weight, $w_{50}$, of 5 kg (11 lb) and median diameter, $D_{50}$, of about 15.2 cm (6 in)[1] if placed on a 1:20 slope, so it should be a conservative choice for a horizontal surface. The material is limestone, though clean, graded, crushed concrete would have also worked. The outer face of the structure is anticipated to respond to waves above the design condition dynamically by readjusting to a more stable, s-shaped profile.

In most living shoreline designs, the marsh or subaquatic vegetation is the intended "living" component – the breakwater is merely functional. This reef's second major role is to serve as a significant additional submerged habitat – in fact, the largest portion of the living shoreline created. A single, thin layer of oyster shell, either fossilized or air dried and quarantined for at least 3 months, was placed on the top surface of the reef to provide substrate for oyster spat colonization. Data on natural oyster reef growth rates in the bay are limited, but it is likely that a thriving reef could grow vertically with SLR, providing long-term resilience to the project. No foundation was designed, but allowance for 10.2 cm (4 in) of settlement was made during construction by advance placement of this much additional stone.

## 3.2. Marsh

The marsh primarily serves as a highly functional habitat with a secondary aesthetic role of blocking the view of the exposed reef from the shore when water levels are below the crest elevation. It also provides some additional wave attenuation effects, but due to lack of published guidance, this will not be considered in the performance of the project. Previous experience in similar conditions has verified that the sand base for the marsh should be near mid tide elevation, or 0.6 ft MLLW[2]. Placing the outer edge of the marsh directly behind the reef makes it a perched beach, which enhances its stability. By keeping the inner edge of the marsh within the -0.3 m (1 f)t contour, a protected water swimming area was achieved with a maximum depth of 0.7 m (2.2 ft)at high tide, a depth considered safe for small children. Emergent marsh sprigs, including *Spartina alterniflora* (smooth cordgrass), *Scirpus validus* (soft-stem bulrush), and *Juncus romerianus* (black needlerush) were manually installed on 60 cm

[1] This is the same size and material used at the Project Greenshores Phase II submerged reef, which has shown no degradation in 8 years.
[2] This is consistent with the marsh elevation used in Project Greenshores Phase I and II, which have proven highly viable and stable for 13 years.

centers. The marsh accumulates sediment and grows upward, so it may be able to maintain its elevation under rising sea levels.

### 3.3. Upland Berm

The upland berm provides vegetated upland habitat and reduces additional backshore during energetic conditions. As it erodes, it will provide easily replaced feeder material for the littoral zone. The face and crest was planted with native vegetation including *Spartina patens* (marsh hay), *Panicum amarum* (bitter panicgrass), *Ammophila breviligulata* (American beachgrass), and *Scirpus robustus* (salt marsh bulrush) on 60 cm centers.

### Adaptive Management Plan

Localized negative impacts on adjacent unprotected shorelines are practically assured for traditional shore protection options such as bulkheads, revetments, and groins at this site and frequently lead to disputes or legal actions between neighbours. Because of both the variability in the seasonal and annual wave climate and the limited prior data available on reef breakwater performance, it is conceivable that this project will as well. The client agreed to proactively include a mitigating response in this instance and included it in the permit application. However, it is important to distinguish impacts related to the project from either the pre-existing and ongoing regional shoreline retreat or from temporary, small scale waterline undulations that occur routinely on unprotected shorelines and that are often self-correcting. Negative impacts related to the project could occur to the downdrift shoreline only if the project significantly captures the net LST that would have transited the property. As described earlier, while the long term downdrift shoreline is to the north, the direction may reverse from year to year, so the impact could be felt on either side of the project. This effect will be recognizable if the following two symptoms occur in synchrony:

1. Localized shoreline retreat on one side of the project that is significantly greater than the existing 0.6-0.9 m/yr (2-3 ft/yr).
2. Accumulation of an equivalent volume of sediment on the upstream side and/or behind the project.

If these symptoms persist, the accumulated sediment above the MHWL will be mechanically transported (bypassed) at the client's expense to the affected shoreline and deposited where it can re-enter the littoral zone. A small skid loader could move several years' worth of captured LST in a day. This option would not be nearly as practical if there were groins, a revetment, or a bulkhead blocking access to the sediment near the waterline.

## 4. MONITORING

Permits for the project were received in February of 2014, and construction commenced the following May. In June, the Alabama Department of Conservation and Natural Resources issued a unique requirement to conduct semiannual monitoring for three years following project completion. Eleven profiles extending up to 61 m (200 ft) offshore and photographic documentation are required each spring and fall. Three profiles cover the north, center, and south bounds of the project, and four pairs of profiles are spaced 7.6 m, 15.2 m, 30 m, and 75 m north and south of the project bounds. Figure 4 shows the location of the profiles, numbered consecutively from the center of the project (profile 0) outward to the south and north (profiles 1S - 5S & 1N - 5N, respectively). Each profile was measured using wading survey methods and local instantaneous water levels as a datum. Elevations were adjusted to MLLW using measured water levels at the time of each profile from nearby National Ocean Service tide gages (Figure 1). To date, surveys have been made on October 8, 2014; May 2, 2015; and September 19, 2015. Additional site visits were photo documented in July of 2013; in June, July, August and December of 2014; and in August, September, and October of 2015.

Figure 5 provides sample profiles from the first three surveys. The most obvious change is the expected growth of the salient directly behind the breakwater at profile 0. However, the trend of shoreline advancement was consistent (except for localized undulations due to debris in the swash zone) along the entire study area, as evidenced by the average of all the profiles. It is even seen at profiles 5S and 5N, well outside any possible impacts from the project over this time period. The implication is that the period since the monitoring program began has been unusually mild in terms of erosive wave conditions.

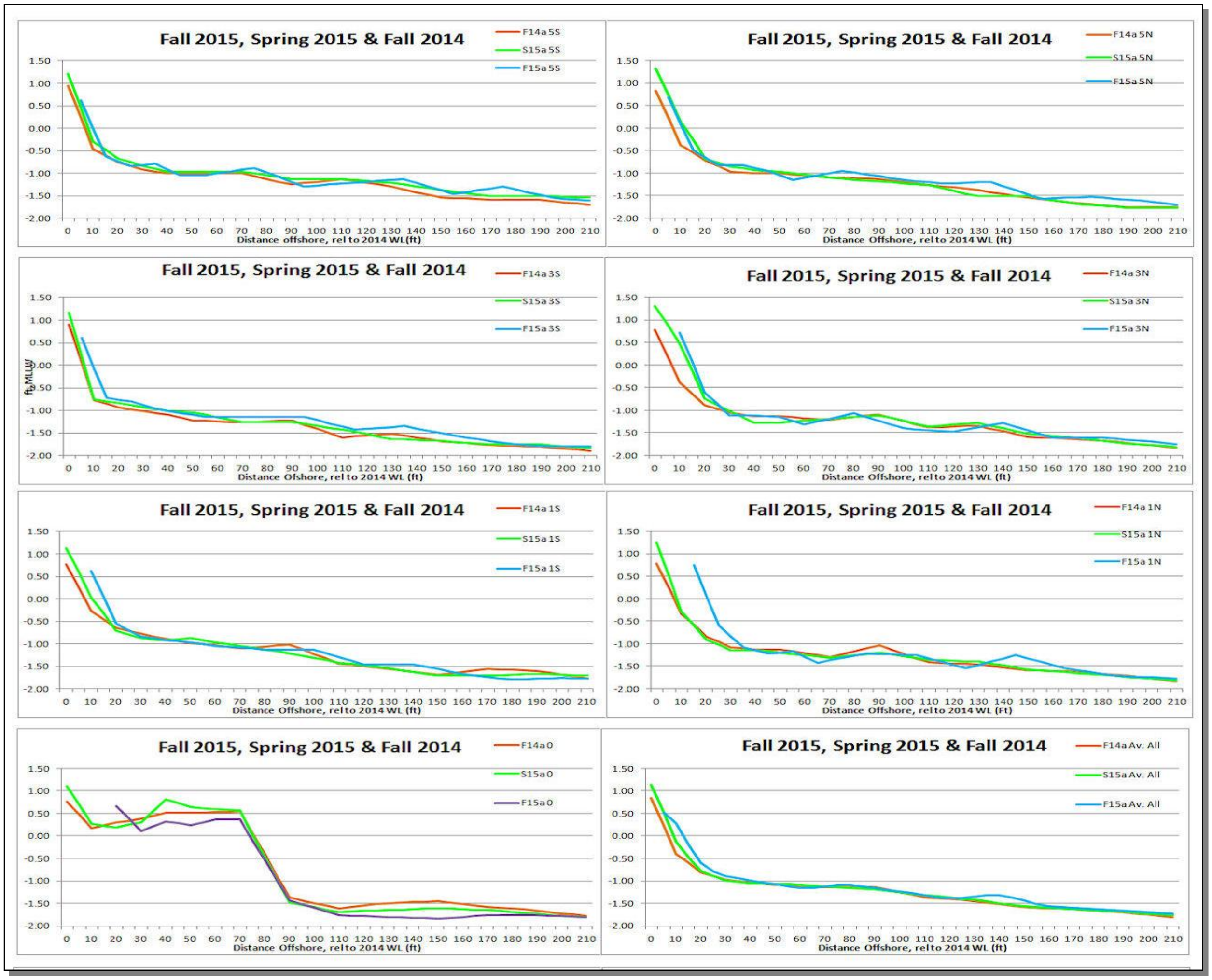


Figure 5. Measured underwater profiles from fall 2014, spring, 2015, and fall 2015.

Figure 6 is a sequence of ground-level photos of the project and nearby shorelines. Figure 6(a) was taken one week after construction of the offshore portion but before the berm was vegetated. A minor salient has already begun to form. Figure 6(b) was taken about one year after construction. The salient has prograded to a tombolo, but neither the photo nor the surveys in Figure 5 reveal observable erosion of the adjacent shorelines. Material for the tombolo could also be coming from the pre-placed sand in front of the berm and/or from deeper water offshore of the breakwater. Implementation of the adaptive management plan was discussed at this time, but it was decided to wait until the following spring to see if higher wave conditions would reduce the tombolo. It is apparent that the emergent marsh is thriving.

A moderate storm occurred on October 25, shortly after the fall 2015 survey, that produced winds from the southeast near the design conditions and water levels exceeding the design water level. Incident waves were not measured but probably did not exceed the design wave because of the reduced fetch to the southeast. No post-storm surveys were conducted, but a site inspection showed that shorelines to the south were noticeably eroded (Figure 6(c)). Figure 6(d), taken two days after the peak of the storm shows remnant waves passing over the reef and through the marsh before impinging, much attenuated, on the shoreline. There were no impacts to the marsh or the backshore, but the tombolo that formed under mild wave conditions had been reduced considerably (Figure 6(e)). Figure 6(f), looking northward from the project site, illustrates how a significant portion of the tombolo was transported northward and deposited on the adjacent foreshore, verifying that LST continues under higher wave conditions. Subsequent surveys will determine if the effect is persistent and quantify volume of sediment transported in the longer term.


Figure 6. Sequence of ground level photos of the completed project and adjacent shorelines.

## 5. CONCLUSIONS

A novel, small-scale living shoreline designed for an exposed, eroding shoreline has been shown to be stable and functional under conditions exceeding the design wind and water levels. The submerged, broad-crested reef breakwater greatly increases the amount of habitat created – the "living" portion – compared to traditional narrow crested sections while, to date, avoiding some of the negative impacts typical of more traditional hard solutions. By eliminating structure near the waterline, it maintains aesthetic and recreational features of a natural beach while allowing for affordable mitigation if the self-imposed adaptive management plan is required. Halfway through a 3-year monitoring plan, the project appears to be functioning as designed.

## 6. ACKNOWLEDGMENTS

Acknowledgement is due to the project owner, Mr. Daniel Reimer, for his progressive outlook and informed involvement in the project and his willingness to abide by the state requested monitoring plan, which made this paper possible. Mr. Taylor Kirschenfeld was responsible for the biological elements of the design and the surveys.

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