Marsh Futures

Use of scientific survey tools to assess local salt marsh vulnerability and chart best management practices and interventions

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Marsh Futures: use of scientific survey tools to assess local salt marsh vulnerability and chart best management practices and interventions.

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Executive Summary

Marsh Futures is a tool to provide local site planning support and guidance for investments in salt marsh protection and enhancement. In the Delaware Estuary and vicinity, coastal wetlands are being lost and degraded at an alarming rate (more than an acre per day in the Delaware Estuary). More than 90% of our wetland tracts are eroding significantly, and coastal wetland loss is especially acute in areas dominated by micro-tidal salt marshes. The rate of wetland losses is expected to increase with the increasing rate of sea level rise. This presents enormous challenges to coastal communities and resource managers since coastal wetlands are a hallmark habitat type in the region, responsible for coastal flood protection, fish and wildlife production, and the maintenance of water quality.

Fortunately, monitoring programs such as the Mid-Atlantic Coastal Wetland Assessment (MACWA) are shedding new light on the processes that are contributing to salt marsh decline. Interest in preserving natural coastal infrastructure is also very high because of the lessons learned from Hurricane Sandy, which revealed that coastal flood damages were not as severe in areas that still had protective coastal wetlands. As a result, many new protection and enhancement tactics that are emerging that promise to help offset wetland losses, such as living shorelines and sediment applications; e.g., the Delaware Estuary Living Shorelines Initiative. State and federal agencies are increasingly investing in coastal resilience programs and projects.

Since funding and capacity to (re)build coastal infrastructure is unlikely to ever match the scale of the loss and transformation that is underway, it is vital that investments in habitats such as salt marshes are successful and well matched to local site conditions. Landscape-scale, remote sensing-based tools are being developed to guide regional decision-making and identify potentially suitable locations for various protection and enhancement activities. These tools, such as the Coastal Resilience Planning Tool being developed by The Nature Conservancy and Rutgers University in New Jersey, will fill an important role by assessing the broader needs and opportunities for counties, watersheds and local communities, and in many cases these desktop tools can identify project options for specific parcels. The Marsh Futures tool is being developed to confirm these options and obtain on-the-ground data needed for specific tactic selection and project design. Subtle differences in local site conditions (e.g. elevations, biota) can greatly affect the choice of tactic, sequence of interventions, and project design. Marsh Futures is most applicable in cases where extensive salt marsh tracts and shorelines exist, but where the main drivers of vulnerability and decline (horizontal versus vertical processes), and therefore intervention methods, are unclear.

This study represents the first steps in developing and testing the Marsh Futures approach. Historical aerial imagery was used to assess shoreline erosion rates (horizontal processes). Measured surface elevations were combined with field-collected data on vegetation condition and growth forms to identify vulnerability to drowning, or too much time underwater, (vertical processes), parameterized by estuary-wide salt marsh condition data from MACWA. Various rapid vegetation metrics were tested, and the most informative were retained for further use in the method. Vulnerability maps were then created for the platforms of the study marshes that integrated elevation and vegetation data into a weighted index. Shoreline change maps and these platform vulnerability maps were then used to generate maps...
of recommended interventions and projects to guide local decision-making. Use of the MACWA data was instrumental, helping to discern anomalies in key vegetation metrics at the study sites within the broader context of numerous other Delaware Estuary salt marshes.

The Marsh Futures vulnerability maps indicated that a large portion of the salt marshes near Fortescue are not keeping pace with rising sea levels and would benefit most by sediment addition, augmented by sediment containment. Living shorelines would be an enhancement at Fortescue, but the most urgent need is to stabilize and raise the elevation of the low-sitting interior areas which are “vertically challenged”. In contrast, the greatest vulnerability at the studied salt marsh along the Maurice River was deemed to be edge erosion, and hence it was considered to be more “horizontally challenged”. The studied parcel of Maurice marsh had ample elevation and was likely benefitting from natural processes that create higher levee areas. A variety of types of living shorelines were recommended for that site. The third study marsh which was along Money Island Road, was found to be most disturbed and vulnerable because of hydrological alterations, and various erosion control and stabilization tactics were recommended for that site. Maps of these recommended best management practices (BMPs) are provided for the three study sites.

These results suggest that the Marsh Futures approach can be a useful interim step between landscape level planning and local site project design, providing a basis for tactical decisions that would best address the top vulnerabilities and local ecological needs. Since this was a modest research and development effort with only 1-2 field days per site, more work is needed to refine the Marsh Futures approach. For example, it is possible that the rapid field surveys could be refined to increase efficiency, which would either allow more area to be surveyed per day, or additional data could be collected to better support actual project design needs (e.g. shoreline slope, substrate type, geotechnical integrity, hydroperiod, bivalve populations, etc). The costs associated with a priori Marsh Futures analyses are expected to be modest, in comparison to other types of enhancement projects, and these could be captured as part of baseline monitoring or site characterization.

Introduction

Importance of Salt Marshes

Natural lands that are situated along estuarine coasts generally provide more benefits to people than any other habitat serving as natural buffers at the nexus between land and sea. Seaward-derived stressors are lessened for the land, and landward-derived stressors are lessoned for the sea. These coastal habitats include beaches, emergent marshes, shellfish reefs, submerged beds of aquatic vegetation, and forested swamps. Of these, tidal wetlands are the most productive habitat in the system, performing many vital services, especially in the wetland-rich Delaware Estuary. Tidal wetlands are critical to: protect inland areas from tidal and storm damage; provide water storage; protect against flooding; provide important habitat for a wide variety of wildlife, including waterfowl; filter contaminants and help sustain water quality; capture and sequester carbon; provide spawning and nursery habitat for commercial fisheries; support active and passive recreation; and provide aesthetic value.
Many of the benefits conveyed by coastal marshes were witnessed during and after Hurricane Sandy, which caused tremendous damage to both built and natural infrastructure in the upper mid-Atlantic region in late October, 2012. For example, developments that were situated landward of coastal marshes appeared to suffer less damage than developments that were directly exposed to open water. Thousands of tons of marine debris and pollutants collected in these marshes, sparing other vital habitats and developments from the associated impacts. Although these protective benefits have yet to be quantitatively substantiated with scientific analyses, it is generally accepted that coastal wetlands convey resilience to coastal communities and economies.

**Status and Trends of the Delaware Estuary’s Salt Marshes**

Unfortunately, coastal wetlands continue to be degraded and lost in the Delaware Estuary and vicinity at an alarming rate, approximately one acre per day between 1996-2006 (PDE 2012). These losses are expected to increase and accelerate with climate change and sea-level rise (Kreeger et al. 2010). As tidal ranges and the estuary’s water volume increase in response to rising seas and other systemic alterations, the extent of tidal inundation along coastal areas will also increase. This will result in successional shifts in habitat types as tidal wetlands encroach into non-tidal wetlands and forests. However, this natural migration, or transgression, is impeded in many areas by anthropogenic interference such as development and attempts to secure fixed coastlines. Erosion is increasing along seaward margins of unprotected tidal wetlands, being apparent at >90% of rapidly assessed shoreline points. Taken together, the seaward loss and restricted landward gain leads to substantial net loss of coastal wetland acreage.

A conservative analysis of projected future acreage changes (PDE, 2010) indicated that approximately two-thirds of the current tidal wetland acres in the Delaware Estuary will be lost at the seaward edge by 2100, which will be partially offset by a landward gain of approximately one-third of the current acreage (about 140,000 acres in 2006). The net loss to open water was predicted to be more than 40,000 acres (PDE, 2010). Since this report was released, new, higher, projections for sea level rise suggest that this earlier marsh change analysis underestimated the likely loss of coastal wetlands in this system. Emerging literature suggests that many types of salt marshes, especially those with micro-tidal inundation conditions such as Barnegat Bay, cannot keep pace with rates of sea level rise greater than 6-8 millimeters per year. This may represent a tipping point for marshes prior to mid-century (Fig. 1).
Figure 1. Projected future changes in sea level at different carbon emission scenarios (envelopes), with notes on expected rates of sea level rise in the Delaware Estuary and consequences for micro-tidal salt marshes.

Approaches to Stem Losses of Salt Marshes in the Delaware Estuary
Due to the current and accelerating loss of coastal wetlands, proactive restoration and management tactics that facilitate horizontal, landward migration or vertical accretion of tidal wetlands are expected to become increasingly important to sustain these critical coastal habitats. Since resources to stave off wetland losses are limited, it will also be important to develop and apply strategic planning tools to ensure that investments target places of greatest importance and are well matched to local site conditions to strengthen success.

There are a diverse array of tactics for the protection, enhancement, restoration, and creation of tidal wetlands. These include some well-tested methods, as well as some innovative methods that require additional research and testing to assess their long-term costs and benefits. Regarding the proven methods, numerous textbooks are now available that review the suitability, methods and outcomes from efforts to protect, restore or create wetlands, including tidal marshes, e.g.:

Unfortunately, most of the established texts on wetland protection and restoration do not cover several new and emerging tactics that are focused mainly on tidal wetland enhancement, such as living shorelines and thin-layer sediment spraying. Indeed, there are as yet few published studies that describe these types of approaches and assess their outcomes. For this reason, these tactics are briefly described below.

For the purposes of this study, we do not refer to any of the potential tactics as “restorations” per se. To “restore” suggests that a goal is to rebuild or replace to a historic condition. Considering the dynamic coastline of the Delaware Estuary and vicinity, and changes in key physical drivers (sea level, precipitation, temperature, salinity) targeting historic conditions would not result in long term sustainability in many places. Instead, our goal is to protect and enhance tidal wetlands in ways that maximize net sustainable healthy acreage in the future and promote marsh resiliency. In many cases, these enhancements may need to be repeated periodically, in the same way that dunes and beaches need to be replenished.

For the purposes of this study, tidal marsh enhancements are grouped as follows:

1. **Wetlands Avoidance via Impact Minimization**
   These efforts seek to sustain tidal wetlands in areas where they currently exist by reducing stressors that contribute to wetland degradation and loss. This tactic includes a diverse array of management and protection measures, such as pollutant minimization, sediment supply maintenance/balance, and access restriction. Dredging and boat wakes can be stressors if they alter sediment supply or exacerbate current and wave energies. Colonization by invasive species can act as an important stressor. Another emerging factor that may represent a stressor is increased nutrient enrichment, which might impair a marsh’s ability to build belowground biomass and keep pace with sea level rise. This tactic also includes the enforcement of wetland protection policies to ensure that they are not developed or altered.

2. **Wetland Enhancement via Hydrological Repair**
   These restoration tactics typically seek to remove or reduce the negative impacts of specific hydrological stressors, such as by restoring tidal flushing to areas that have been separated from tidal connectivity, or plugging excessive ditches that may be contributing to marsh erosion. The natural hydrology (tidal flushing) of tidal marshes has been heavily managed and manipulated for diverse reasons, such as to decrease drainage/flushing for salt hay farming, increase fish access via ditch creation to control mosquitoes, and to reduce tidal flooding. These manipulations include a variety of levees, dikes, roads, tide gate restrictions, and ditching. As a consequence, many marshes have not received their estuarine
or riverine sediment subsidy, or are otherwise over or under flushed by typical tidal ranges and frequencies.

3. Wetland Enhancement via Elevation Repair
These tactics boost elevations of low-sitting marshes to match the optimal plant needs, and can lead to increased production while also prolonging the amount of time until drowning. This approach therefore seeks to maximize the “elevation capital” of the marsh (resilience to drowning). The foundation of emergent marshes is the productive vascular plants that contribute to peat formation and accumulation. The productivity of these plants varies widely depending on their elevation within the tidal prism, and every dominant species of wetland plant has an optimal growth range, typically between the mean sea level and mean higher high water level. Compromised marshes that are not keeping pace with sea level rise (or that have been starved of external sediment supplies) typically are dominated by plant communities that are sitting at suboptimal (low) elevations within their growth range.

4. Wetland Enhancement via Shoreline Stabilization
Living shorelines are an example of erosion control tactics that seek to stem the landward retreat of tidal marshes while also enhancing the resilience and ecological health along the seaward edge. Since more than 90% of natural tidal wetland shorelines in the Delaware Estuary are net eroding, living shorelines should not be misconstrued as natural shoreline restorations. They are engineered structures that work to enhance the natural ecological features such as plants and shellfish that impart the greatest resilience and resist erosive forces. There is a diverse array of living shoreline methods, ranging from biological-based designs suitable mainly for low energy locations to complex hybrid designs that are needed in high energy areas.

Tidal wetlands are valued and managed for many different reasons (see above). Therefore, it is vital that the purpose and goals of any wetland protection or enhancement project be identified and defined before selecting tactics, as the different tactics focus on specific goals. For example, stances on invasive species control (e.g. *Phragmites* eradication) may differ depending on whether a project’s goal is to enhance a marsh’s fish and wildlife habitat value (eradicate) versus to protect a coastal community from flooding (stabilize). Another important consideration in tactic selection is the local site conditions; every location has unique physical, chemical and biological parameters that affect the viability of different tactics.

An exhaustive review of all types of tidal wetland protection and enhancement tactics is beyond the scope of this report. Below is a brief summary of some of the types of enhancement tactics that are currently being considered or implemented in the Delaware Estuary and vicinity.
Example Tactics to Stem Losses of Salt Marshes in the Delaware Estuary

Bio-Based Design Options

**Riparian Vegetation Management**

The goal of this tactic is to increase vegetation at the upland-wetland interface, both in abundance and diversity, for the purpose of stabilizing a bank that slopes to a shoreline. This includes trimming overhanging tree branches to increase sunlight, selectively choosing desirable plants for natural regeneration, or planting. Vegetated buffers can be used to intercept storm water runoff and control invasive species that degrade or destabilize habitat. Most tidal shorelines are suitable for some type of riparian vegetation management or enhancement activity along their landward margins.

**Beach Nourishment and Dune Restoration**

Beach nourishment is the addition of sand to a beach or dune to raise elevation or increase width, to enhancing its ability to buffer the upland from wave action. Beach restoration to support spawning horseshoe crabs and associated shorebirds is also a current focus due to the need to repair critical habitats that were severely damaged by Hurricane Sandy. Dune restoration is the process of reshaping and stabilizing a dune with appropriate plants, typically after a beach nourishment event (e.g., Fig. 2). Common plant species for Chesapeake Bay beaches and dunes include *Ammophila breviligulata*, *Panicum amarum*, and *Spartina patens*.

These actions are best suited for gently sloping, sandy beach shorelines with low erosion. Beach and bank erosion may still occur during storms. Periodic replenishment is usually needed to maintain the desired beach profile. This method may not provide sufficient protection where no beach currently exists or where tidal currents and wave action remove sand frequently and rapidly without reciprocal depositional phases.

**Tidal Marsh Nourishment and Enhancement**

Tidal marsh enhancement includes adding sediment and/or new marsh plants to low elevation, barren or sparsely vegetated marsh areas (e.g., Fig. 3). Sand or mud fill (e.g., ‘beneficial use’ of dredge material) can be added to a marsh surface to raise the elevation of low-sitting areas so that dominant vegetation is situated in its optimal growth range within the local tidal prism. Existing marshes that appear to be
drowning in their interior areas, evidenced by widening open water and sparse, leggy plants, are examples of likely candidates for sediment application to build elevation.

When paired with suitable containment strategies to stabilize newly added sediments, this tactic can also be used to widen a marsh to add more protection. Replacing marsh vegetation washed out during storm events and a reduction in mowing of wetland vegetation can also enhance the stabilizing and habitat features of a tidal marsh.

To date, thin-layer sediment projects have been identified opportunistically based on the proximity of maintenance dredging in the vicinity of tidal wetlands. In some areas, thin-layer projects represent a less expensive beneficial reuse of dredged materials than landfill disposal. However, it is important to first estimate the impact on the targeted wetland by sediment additions because of the very narrow range of elevations that govern plant productivity and marsh health. Some wetlands may also be vulnerable to compaction. Too much sediment addition could also smother fauna and flora. Containment of sprayed material during dewatering may be another challenge depending on subtle differences in slope and hydrology. Since much of the sedimentation in navigation channels likely is derived from eroding wetlands, thin-layer spraying and reuse of dredged material represents a promising and potentially cost-effective tactic, but few projects and studies have been completed in our area and future projects are therefore advised to carefully design and monitor the projects.

**Tidal Marsh Creation**

Tidal marsh creation can sometimes be applied where a natural marsh does not exist by planting non-vegetated intertidal areas with appropriate species on the existing substrate, thereby converting the area to a tidal marsh. Because of the complex interactive factors needed for effective stabilization, this method normally requires either grading (see next section) the riparian area landward or filling channelward into the low intertidal or subtidal area to engineer a broader, more gently sloping intertidal zone. Appropriate plant species are dependent on local salinity and depth and duration of tidal flooding (hydroperiod). Two common tidal marsh grasses used for this purpose are *Spartina alterniflora* and *S. patens*.

The most suitable shorelines for tidal marsh creation have wide, gradual slopes from the upland bank to the subtidal waters, and abundant sunlight. Extensive tree removal in the riparian buffer to create
suitable growing conditions for a tidal marsh should be avoided, especially if the forested bank is relatively stable (Smith, 2006). Salt marsh plants have limited tolerance for wave action; therefore, the wave climate, frequency and amplitude, must also be considered (Perry, et al., 2001). Several types of new commercial products have been developed to help stabilize the plants and encourage rooting, but most of these tactics have not been tested locally as yet. Since new marshes are difficult and costly to create, an increased net gain can usually be realized by stemming the loss of existing wetlands through enhancement.

**Bank Grading**

Bank grading physically alters the slope of a shoreline segment in order to ease steep shorelines and reconnect ecological systems. Immediately after re-grading, vegetation that will form dense and deep root mats should be planted. The upper reach of vegetation creates a buffer for upland runoff and groundwater seepage, and in the lower portion, provides stabilization in the wave strike zone. Bank grading can also be combined with planted tidal marshes and beach nourishment.

Low eroding banks with only partial or no vegetative cover are particularly suited for bank grading. Confining layers in the bank material and the transition to adjacent shorelines may dictate the extent of possible grading. Surface and groundwater management measures may be needed. In urban areas, past land use, fill, and potential contaminants may need to be considered.

**Fiber Logs**

Recycled coconut fiber logs are also known as coir logs or biologs. These biodegradable logs come in a variety of sizes and grades for different applications. In tidal marsh applications, they must be aggressively staked into place to prevent them from being lifted and moved by tidal currents and wave action. In soft substrates, they may need to be placed on fiber mats to prevent sinking. Fiber logs are particularly useful to create low energy areas protected from waves where suspended sediments can precipitate. Fiber logs should be installed in early spring to maximize growth-time availability.

PDE has worked with the Rutgers University Haskins Shellfish Laboratory since 2007 to develop, test and implement bio-based living shorelines that are comprised of fiber logs, paired with a variety of other natural materials (PDE, 2011). These research and development efforts have been a key element of the

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*Figure 4. Coconut fiber logs, called ‘coir logs,’ are used in the PDE/HSRL living shoreline tactic. Credit: PDE.*
Delaware Estuary Living Shoreline Initiative (DELSI), and the fiber log approach has also been coined the “DELSI Method,” although the program now is testing a variety of other tactics. This success of the fiber log approach depends on many site-specific physical and biological features, such as elevation, energy, slope, salinity, and sediment availability. A key variable is targeting the appropriate final elevation to facilitate rapid production and rooting of the plants so their roots and rhizomes help to stabilize the integrity of the fiber logs before the logs decay. Sites with low sediment availability (i.e., low suspended sediments in the water column) may require too much time to naturally trap sediments and may need to be backfilled so that planting can commence.

Fiber logs decay generally in five years or less. The quality of the logs (standard versus premium) is important, and only the highest quality logs (highest packing density) are recommended for tidal conditions. The placement of the logs is also crucial to alleviate excessive rocking or buffeting; for example, they should never be placed directly parallel and against an undercut bank. Even when premium logs are installed in correct arrangements, decay can still occur and so logs should be inspected regularly. An adaptive management contingency fund should be maintained in case some logs need to be replaced prior to site maturation. Armoring the front of fiber logs with bags of oyster or clam shell, as demonstrated by the PDE/Rutgers DELSI tactic, can greatly increase log survival, while also potentially attracting shellfish settlement that provide long-term armoring.

The placement of “donut- or horseshoe-shaped” configurations of fiber logs upon the vegetated marsh platform has also been suggested as a potential way to encourage high marsh redevelopment and enhance species richness. Although untested, this idea by the DELSI research team might help to address sinking marshes where high marsh has converted to low marsh, and where low marsh has converted to open water. These high marsh creation cells would likely only work in areas where suspended sediment concentrations are high.

“Hybrid” Design Options

Marsh Toe Revetment

Marsh toe revetments are low profile structures typically constructed with quarry stone, and placed to stabilize the eroding edge of an existing tidal marsh (e.g., Fig. 5). Like fiber logs, they are designed to help break, or buffet, waves to prevent erosion, while allowing sediments to settle out of the water in the calmer areas behind the treatments.

The most suitable sites for this treatment have existing tidal marshes with eroding edges. Gaps should be used to facilitate tidal exchange, especially if the

structure height exceeds mean high water, or if the target shoreline requires a long continuous structure. Gaps, sometimes referred to as “windows”, also facilitate the free passage of fish and other motile fauna. Wave height and shoreline length will need to be examined before installation.

**Marsh Sill**

Marsh sills are low stone structures installed in shallow subtidal, nearshore areas adjacent to marshes and below the low tide line. In comparison to a marsh toe revetment which usually abuts or is directly in front of the vegetated marsh, a marsh sill is typically installed at a greater distance seaward from the vegetated marsh along a gradual slope. One goal of the sill is to encourage sediment trapping, and in cases where this does not occur naturally, sills can be backfilled with clean sand. The goal is a gently sloping elevation of sediment landward of the sill, which might extend high enough in the intertidal zone to support planted tidal marsh vegetation. Like marsh toe revetments, the height and configuration of the sill can be adjusted to minimize interruption of tidal exchange, and in some cases, encourage vigorous growth of submerged aquatic vegetation that impart added resilience and ecosystem services. Being subtidal, sills are not designed to attenuate waves but might help to encourage larger waves to break near the sill, especially at low tide.

Marshes with broad, shallow mudflats or eroding banks without a tidal marsh present are candidate sites for marsh sills, particularly if marshes exist in the general vicinity or were present on the site historically. However, the physical alterations needed to create sills should not require major disturbance to desirable existing shoreline habitats, such as shellfish beds or submerged aquatic vegetation. If bank grading is appropriate to create target slopes, then the bank material can possibly be used to backfill a marsh sill if it is mostly coarse-grained sand. Sand fill can also be imported from an upland source. In low energy areas, other types of finer sediments might be trapped or added if vegetated quickly to stabilize the substrate.

Low intertidal and shallow subtidal reefs of calcareous organisms, such as oysters or tube-building worms (*Sabellaria*) can function similar to sill structures, providing more natural opportunities for the encouragement of sill functions (e.g., Fig. 6). Due to warming from climate change, winter kill of intertidal organisms such as these is becoming less frequent, and permanent intertidal oyster reefs now exist in many areas of the Delaware Estuary. Wherever possible and permissible by state regulatory agencies, shellfish reefs should be encouraged.

**Marsh with Groins**

Groins are short stone structures placed perpendicular to the shoreline to support a planted marsh, often on sand fill, similar to marsh sills, which are placed parallel to the

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*Figure 6. Oyster reefs are beginning to become established in low intertidal habitats of many coastal tributaries of the Delaware Estuary, providing natural wave attenuation services while also promoting water quality and fish and wildlife habitat. Credit: PDE, April, 2014.*
shoreline. This method is suitable for lower energy shorelines where erosion of the unprotected marsh edge is expected to be minimal and where longshore currents are a contributing factor to erosion. In contrast, sills are often more suitable than groins in cases where direct wave action and boat wakes need to be reduced, and the potential effects on sediment transport and down drift need to be considered before selecting a groin approach. Additionally, groins may be used in tandem with sills or fiber logs when direct incoming energy is the primary erosive source, but longshore currents may provide a scouring effect water-ward of installed materials.

**Nearshore or Offshore Breakwater System**

A breakwater system is a series of freestanding structures strategically positioned in low intertidal or shallow subtidal areas to dampen incoming erosive waves and currents. Breakwaters are similar to sills, but they extend above the mean low water line and often high into the intertidal zone because one of the main goals is typically wave attenuation (e.g., Fig. 7). Breakwaters can also help to stabilize sediments and encourage natural sedimentation, similar to sills. Often, the elevations are raised enough to allow vascular plants or other aquatic vegetation to be planted in the quiescent areas landward of the structures. Some tactics encourage the creation of a stable beach profile with embayments.

Even though they tend to be larger and more costly projects, breakwater systems can be paired with other living shoreline approaches in areas where erosive energy is elevated due to high energy currents and larger waves associated with wide fetch. Breakwaters should be segmented to encourage free movements of aquatic organisms. Depending on the width of the windows, the resulting living shoreline habitats landward of the breakwater can form a habitat mosaic that includes sand beaches, marshes, submerged aquatic vegetation, and calcareous reefs. Non-vegetated beach areas can be encouraged by breakwater systems, providing habitat for terrestrial and aquatic wildlife, including shorebirds, turtles, terrapins, and the northeastern beach tiger beetle. Oysters, mussels, algae, and other reef-dwelling organisms may colonize shallow water areas.

Suitable sites for offshore breakwater systems are medium and high-energy shorelines where sand beaches, banks, marshes, and bluffs show a historic trend for rapid landward retreat. Like groins, offshore breakwater systems can interrupt longshore sediment transport, and careful engineering is required. Beach nourishment and vegetative stabilization typically occur in tandem, rather than waiting for natural accretion of sand, to minimize downdrift sediment starvation.

**Figure 7.** Low intertidal oyster habitat breakwater, installed as part of a hybrid living shoreline adjacent to the DuPont Nature Center at Mispillion River, Delaware. This project is designed to encourage the expansion of an existing low intertidal oyster reef and associated water quality benefits. Credit: PDE, July 2014.
Hybrid Living Shorelines and Other Considerations

This brief inventory includes methods for erosion protection and habitat enhancement collectively referred to as “living shoreline” approaches for stabilizing and building resilience along vulnerable tidal shorelines. Choosing the least intrusive, yet effective, method is the main objective. Nonstructural methods that emphasize the use of dense riparian and wetland vegetation paired in some places with calcareous shellfish and submerged vegetation, can be applied to many low energy shorelines that have minimal wave action or boat wakes. In higher energy areas, bio-based approaches can be combined with more aggressive, traditional approaches into hybrid designs, such as a marsh sill or oyster breakwater paired with bank grading or planted marsh.

Hybrid types of living shorelines consist of mixtures of tactics that are tailored to the unique physical and biological conditions of a site. Often, hybrid designs target ecologically harmonious, synergistic communities of organisms, such as nearshore oyster reefs to attenuate wave energy paired with bio-based tactics to strengthen the integrity of the beach or marsh edge (e.g., Fig. 8). A mosaic of healthy coastal habitat types may be more resilient than single habitats because of mutualistic or synergistic benefits. Properly designed, hybrid projects can minimize disruption to tidal exchange while also enhancing sediment capture.

Figure 8. Conceptual design for a hybrid living shoreline that consists of a low intertidal oyster breakwater paired with mid-intertidal coir log enhancements along the vegetated marsh edge. Credit: PDE, February, 2014.
Figure 9. The amount of hard and soft materials used in living shoreline projects depends on the level of energy and goals for a project location. The photo on the left depicts a biolog cell designed for a lower energy site and having only oyster shell bags for armoring of the front log; whereas, the photo on the right depicts a biolog cell designed for a moderate energy location and having oyster shell bags and oyster castles deployed inside and in front for additional stabilization. Credit: PDE, July and September, 2014.

A goal of all living shoreline projects is to enhance natural resiliency properties of ecological communities, while also minimizing the use of traditional “hard” tactics such as seawalls and rip rap. The relative proportions of soft and hard treatments are dependent on the local energy regime, with a greater acceptance for harder materials in moderate to high energy locations (e.g., Fig. 9).

Some methods were not included in this summary of living shoreline design options as they are not widely practiced and their effectiveness is currently being investigated. The planting of loose oyster shell has been shown to be exceptionally successful in rebuilding natural oyster beds in deeper offshore areas, but in dynamic shallow water systems it is not clear if uncontained oyster shell is sufficiently resistant to wave action and tidal currents. The placement of oyster shell adjacent to existing or planted marshes to support native oyster restoration efforts is most likely suitable even with limited erosion protection benefits.

Pre-cast concrete or other commercially prepared structures in various shapes have also been deployed in intertidal and subtidal areas to provide wave dissipation as well as habitat for shellfish and other reef dwellers. In the upper Mid-Atlantic region that includes the Delaware Estuary, oysters will eventually be able to colonize a wider array of intertidal habitats (like in Virginia and other coastal southern states), which, dependent on permitting restriction, will allow practitioners to pursue more diverse shell-based living shoreline tactics.

“Living walls” for steep bank stabilization is another method commonly applied to upland slopes, but only recently installed on tidal shorelines in Virginia. This engineered system of support structures with planted vegetation is intended to provide stabilization without extensive land disturbance and bank grading.

Depending on the level of protection that is needed, nonstructural and hybrid methods may not always be easier, less costly, or require less maintenance than rock revetments and bulkheads. Professional design and engineering assistance will often be necessary to ensure success. Local knowledge or
predictions of tide range, elevation profiles, local sediment budgets, predominant wind direction, and wave height will help to design successful projects. The amount of sand fill needed for sills, groins, and breakwater systems needs to be accurately calculated to prevent adverse downdrift effects. Similar, the placement of fine sediments in beneficial reuse projects associated with dredging needs to be carefully calculated to match the elevation goals of the recipient wetland. In areas where concentrations of suspended sediments are high in the water, passive trapping of fine sediments could in turn benefit navigation interests by reducing maintenance dredging costs.

Wider acceptance of the living shoreline approach with its inherent limitations could help shift the current trend for shoreline armoring, particularly in very low energy settings. The guiding principles presented here can assist with the selection of suitable tactics, but all projects must be tailored to local conditions and designed to address specific goals. Importantly, projects are science-based and monitored where possible to assess ecological benefits and drawbacks while also achieving stabilization or enhancement goals. Since there have been few projects implemented in the Delaware Estuary and vicinity, quantitative analysis will facilitate the sharing of any lessons learned so that future projects can be strengthened.

In summary, there are many different concepts that define a living shorelines approach. Living shorelines is a concept based on an understanding and appreciation of the dynamic and inherent ecological value that our natural shorelines provide. Living shoreline projects apply these natural principles in the design and construction of shorelines to enhance habitat and maintain shoreline processes. Living shorelines should not be misconstrued as natural restorations as they are designed, engineered structures that will need to be maintained. However, as discussed above, many types of natural shorelines such as tidal wetlands are no longer self-sustaining without reinvestment. Decisions concerning living shorelines and other best management practices (BMPs) will largely be governed by management goals, the perceived relative values of different types of coastal habitats, and their maintenance cost:benefit ratios.

**Determining Best Management Practices and Interventions**

The focus of this study is on coastal wetland preservation and enhancement, specifically tidal salt marshes of the Delaware Estuary and vicinity. Although there are many BMPs and tactics that can help sustain a salt marsh (see above), once a particular marsh is prioritized for retention it is vital that the appropriate tactic be selected based on local, prevalent conditions contributing to vulnerability. Remote sensing data and models can provide an important context and provide some recommendations, but invariably local site conditions need to be examined to “fine tune” strategic plans and tactic selection.

**Key questions:**

1. Is the marsh of interest (MOI) healthy or unhealthy? Degradation of marsh condition often precedes loss, and is therefore an indicator of vulnerability.
2. If compromised, what are the vital signs that indicate the type of vulnerability? Is it eroding at the edge (horizontal vulnerability), not keeping pace with SLR on the platform (vertical vulnerability), or is it suffering from interior breakup due to ecological problems related to pollutants and other stressors (condition vulnerability)?
3. What tactics can address the top site-specific issues, and are they feasible at the location? (e.g., thin layer pipe length near dredging sources, etc).
4. How urgent are the interventions needed, and is there any recommended sequence of steps that would strengthen outcomes or decrease risks?

The “Marsh Futures” Approach

The goal of Marsh Futures approach is to provide science-based guidance to coastal communities and environmental managers regarding the future of important coastal wetlands. In cases where wetland losses are expected, the second goal is to recommend when and how best to intervene.

Watershed to Local Context

The Marsh Futures approach is designed to fill a vital on-the-ground verification step in strategic decision making regarding where and how to invest in natural coastal infrastructure (Fig. 10). At the regional or watershed scale (Tier 1 in Fig. 10), broad habitat investment priorities can be set to guide funding and capacity for environmental projects, such as addressed via the PDE-led Regional Restoration Initiative (RRI; PDE 2010). The RRI uses a natural capital approach to identifying critical habitats and areas in the Delaware Estuary in need of focused protection and enhancement attention, such as coastal wetlands, shellfish communities, urban waterfronts, and headwater streams. The RRI is one example of watershed-based prioritization, and other approaches have also shown to be useful at setting broad priorities, such as the Delaware River Basin Conservation Priorities effort led by The Nature Conservancy of New Jersey, and the Delaware River Watershed Initiative being supported by the William Penn Foundation. Since Hurricane Sandy, many regional priorities have become refocused on natural infrastructure that best imparts coastal resilience.

Once regional priorities are set, remote sensing tools and modeling approaches can be utilized to develop guidance on the potential suitability of various BMPs and enhancement tactics for sustaining and enhancing high priority habitats at the landscape scale (Tier 2 in Fig. 10). New satellites, LIDAR data, monitoring networks, and models exist that can help to pinpoint the most vulnerable natural habitats and the most viable places to direct tactics. Coordination and information sharing among various public and private sectors can identify opportunities and places to apply some tactics, such as matching dredging schedules with beneficial sediment reuse needs. An example of a coordinated effort to use desktop applications and partner coordination is the Coastal Resilience Tool currently being developed for New Jersey by a team of researchers led by The Nature Conservancy. This tool has already been used successfully in
other parts of the United States to model temporal vulnerability of coastal habitats and to pair tactics with prevailing physical conditions, thereby stoking ideas for new project development in areas of high interest.

Marsh Futures is designed as an on-the-ground assessment method for verifying outputs from desktop guidance from remote sensing studies and models. Shown as Tier 3 in Figure 10, Marsh Futures examines actual local site conditions which can differ in subtle but important ways from Tier 2 outputs. These data then provide information for conceptual suggestions regarding tactics and implementation scenarios. For example, very small differences in marsh elevation (2-5 cm) can translate into large differences in vulnerability, but LIDAR data typically resolve elevations only within a range of 30 cm.

**Marsh Futures Steps**

**Selection of Marshes of Interest**
Marsh Futures begins by indentifying salt marsh tracts that are deemed by local communities or managers as being important for sustaining, referred to here as Marshes of Interest (MOIs) or Areas of Interest (AOIs). It is generally accepted that marsh loss will be extensive, funds to stem the losses will be limited, and therefore, “strategic retreat”, or landward habitat conversion, will be the only option for many areas. Marsh Futures addresses actions that can be taken in those areas where there is broad agreement for the importance and preservation of the tract based on input from coastal communities and/or coastal resource managers. Therefore, for this study, local communities and resource agencies were engaged to identify example areas of broad consensus and interest in particular salt marsh parcels.

The community engagement process used for selection of the MOIs is not discussed in this report, but is covered in the Sustainable Infrastructure Plan for the South Jersey Bayshore. The actual MOIs that were chosen were near Fortescue, Money Island, and Bivalve, New Jersey (see methods).

**Remote Sensing Data and GIS Tools**
Available data on past, current, and projected conditions related to the study tract are gathered and analyzed to develop a first order understanding of the main physical conditions and drivers that characterize the MOIs (e.g. elevation, wind/wave energy, past land use, erosion/drowning trajectories). Where coastal wetland assessments have been completed or data exist in the vicinity (e.g. as part of the Mid-Atlantic Coastal Wetland Assessment program), those data are also consulted to enrich the understanding of conditions at the MOIs or their vicinities. Of special interest are historical change analyses such as shoreline retreat rates. The most current available LIDAR elevation data for the MOIs are also examined. Access and analysis of these existing data can be facilitated in areas where complimentary analyses exist, such as via the new Coastal Resilience Tool, NJ Flood Mapper, etc. Data on levees, past management or land use practices, nutrient loadings, etc. help provide added context and understanding of prevailing stressors in the vicinity of the MOIs.

**Scientific Surveys of Physical and Biological Conditions**
Field reconnaissance within the MOIs is then used to gather additional data on local conditions. Elevations are mapped using Real-Time Kinetic GPS equipment, providing <2 cm horizontal accuracy and
3 cm vertical accuracy. The general biological condition of the dominant vegetation is characterized in representative subsections of each MOI, focusing on evidence of stress such as indicated by abnormal or sparse growth forms that may indicate high vulnerability to drowning (e.g., Fig. 11). Finally, the firmness of the substrate is characterized as evidence for vulnerability. The substrate and vegetation metrics are then used as weighted measures to adjust elevation maps and produce vulnerability maps.

Maps of Best Management Practices and Tactics
Best scientific judgment is then used to interpret the MOI vulnerability maps and additional observations of local conditions (e.g., erosion types, obscure marsh features) in the context of all available BMPs and enhancement tactics (see inventory above). In cases where a MOI has experienced a high rate of erosion, tactics that stem edge erosion may be more warranted to stem horizontal retreat. In cases where a MOI has low elevation, tactics that encourage natural sedimentation, or that deliver sediments, may be more warranted to encourage vertical growth. Additional field observations on substrate type, firmness, and slope help to guide which specific tactic is needed. Where appropriate, guidance is also provided regarding the urgency and recommended sequence of any interventions. These Marsh Futures products can therefore serve as parcel-sized “master plans” to guide local decision-making and investments, where needed.
Figure 11. Cartoon showing typical growth forms of the dominant salt marsh plant species, *Spartina alterniflora*, subject to different inundation stress. Healthy plants are typically short and dense in the high marsh (A) or moderately-tall and dense in the low marsh (B). Plants vulnerable to drowning are often very tall and often sparse in the low marsh (C).
Methods

This was a methods development and testing study where the methodological steps were based on outcomes from the previous activity. Therefore, some results are included within this methods section where they assist in understanding the basis and sequence of activities, decisions and outcomes that occurred.

Description of the Marshes of Interest (MOIs)

Three study areas were selected which contain salt marsh habitats of high interest to local communities due their role infrastructure and flood protection (Fig. 12). These were specific salt marsh tracts at Fortescue, Maurice River mouth, and Money Island.

![Figure 12. Locations of three study areas in the New Jersey Bayshore that contain salt marshes identified as important by local communities: Maurice River, Fortescue and Money Island.](image)

Within each of the three study areas, local communities were presented with various tracts of marsh for scientific focus as Marshes of Interest (MOIs) for in depth analysis and testing of the Marsh Futures approach. Candidate MOI tracts were identified as areas where the technical crew would have access. For example, in the Fortescue study area three tracts were identified, as shown in Figure 13. Due to the constraints of this project budget, only one of the three MOI tracts was able to be included. The site identified in Figure 13 as “F West of Road” was chosen as the MOI because of easy access. Of additional
interest, PDE had earlier developed a conceptual plan and budget for a potential living shoreline near Fortescue, which would have been situated in the “F East of Road” tract (see PDE 2012).

Similarly, in the vicinity of Money Island, New Jersey, three candidate study areas were presented to local communities for discussion as possible detailed analysis locations. The MOI chosen was the “Money Island Road” location shown in Figure 14. This road represents the only access to the town, which supports a vibrant commercial fishing community and associated docks. Flooding is common along this road, and the local community recognizes the important buffering role that the abutting marshes provide.

Numerous candidate MOIs were identified in the vicinity of Bivalve, New Jersey, an area that has seen some of the most dramatic changes in coastal landscapes and marsh loss. Two of the candidate MOIs are portrayed in Figure 15. The tract identified as “Maurice River NW Reach” was chosen due to dramatic changes as evidenced by historic aerial photography, and it was of a size that was similar to the chosen MOIs in the other two study areas (Fortescue and Money Island).
Existing Data Review
LiDAR data used to compare to RTK collected data was sourced from the South New Jersey County LiDAR Project completed by Dewberry, Inc. and facilitated by the USGS. The 1-meter DEM files were used to display elevation. The 1-meter Digital Elevation Model (DEM) files were also used to create 6-inch contours. Maps of the DEMs and contours were created for the wider areas of interest before the specific areas of interest were narrowed down.

Wetland assessment stations that are part of the Mid-Atlantic Coastal Wetland Assessment network exist in the vicinity of these study areas, and pertinent physical and biological data were consulted to understand general stressors and vulnerability in the Bayshore salt marshes (Kreeger and Padeletti, 2013). In addition, rapid assessment data from a wetland study that was recently completed on the tidal wetlands of the Maurice River watershed was consulted (Kreeger et al., 2012). Finally, a report card on wetland health and function in the Dividing Creek watershed (PDE 2014) was examined to provide additional context for nearby Fortescue marshes.

Based on the 2012 State of the Delaware Estuary report and additional data on shoreline erosion rates (e.g., Moody 2013), these tidal marshes in the vicinity of these MOIs have been experiencing some of the greatest rates of shoreline retreat in the Delaware Bay system. Marsh acreage losses have been markedly greater in the New Jersey Bayshore compared to the Delaware Bayshore (PDE 2012).

Field Surveys of Local Conditions in MOIs
To determine appropriate marsh enhancement techniques, information regarding the marsh platform elevation and topography, vegetation health and marsh edge retreat rates were required. Data concerning marsh platform elevation and topography was collected using Trimble R6 Real-Time Kinematic GPS (RTK) and analyzed using the Geospatial Analyst Tool extension in ArcGIS 10.2 to assess vulnerability due to elevation within the local tidal prism. The RTK unit uses a global navigation satellite system (GNSS) to measure latitudinal/longitudinal and vertical (elevation) position with an accuracy of 8mm (+1ppm RMS) and 15mm (+1ppm RMS) respectively. The additional error attached to each
measurement reflects the distance of the unit from the base station; for every 1km of distance and addition 1mm of potential error measurement is added. The average accuracy for these AOIs, including error adjustments, is within 16mm horizontally and 30mm vertically.

In addition to horizontal and vertical positioning, data concerning the vegetation type present at each point was also collected. These data were used to assess the changing vegetative communities and their elevations across the marsh platform. Within the different vegetative marsh communities, measurements of vegetative health were collected based on plant height, density, canopy cover, and substrate, and were used to adjust vulnerability due to elevation to reflect emergent vegetative conditions. Historical marsh edge retreat rates between 1970 and 2012 were measured within each MOI using digital aerial photography that was acquired from the state of New Jersey (njwebmap.state.nj) and analyzed using Digital Shoreline Analysis System (DSAS) Tool.

**Test of Point Density for RTK**

To determine the number of points needed to accurately model the marsh surface, a pilot study was conducted at the Money Island, NJ, AOI, whose topographic surface was considered highly complex, containing multiple inter-marsh creeks and sloping surfaces as well as hummock and hollow topography, thus representing the most complex surface of the AOIs. To conduct this analysis, 798 points were collected in the 1ha AOI. This was the maximum number of points that were able to be collected in a single day from mid ebb tide to mid flood tide. These points on the tidal cycle allowed access in and out of the AOI safely. A clustered collection technique was employed in which a high density of points was collected in the complex (hummock/hollow) and transition (sloping area along creek edges) areas, and a lower density was collected in the more topographically uniform high marsh areas.
The full set of 798 points was considered the high point density data set. A half point density data set was created by removing every other point in the high point density set (effectively doubling the distance between points in each set; n=399 points), and a quarter point density data set was created by removing every other point from the mid-point density set (n=200 points). Empirical Bayesian Kriging (Geostatistical Analyst Extension, ArcGIS 10.2.1) was employed to create an interpolated surface elevation models of the study area using the entire data set (high), half point density, and one-quarter point density. Model cross validation comparison between high and half point densities revealed minimal elevation prediction error differences between the models, while half and quarter point density model comparison exhibited greater discrepancies (Fig. 16). Additionally, Nearest Neighbor Analysis revealed high and half point density models retained clustered point densities (p < 0.5) necessary to predict complex topographic changes, while the quarter point model exhibited a random distribution (p > 0.5). No increase in elevation spatial resolution above 400 points (half point density) was detected, and it was concluded that collecting more than ~400 points per ha of complex salt marsh would not provide any additional information. Since 800 points were able to be collected in 1 ha of complex marsh habitat in one day, we would, at the minimum in complex habitat, be able to collect data in 2 ha per day. In more uniform habitats however, a larger acreage may be able to be surveyed per day.

Figure 16. Results of model comparison between point density data sets containing all points and half points (a), and half points and quarter points (b)
RTK Elevation Surveys
Marsh elevation and topographic surveys were conducted in each MOI by walking transects that extended from the largest water body's edge, across the platform, into the high marsh (Fig. 17). Point density was collected in a clustered manner. A high density of points were collected in areas of greater elevation heterogeneity (e.g., slopes along the marsh edge and inter-marsh creek networks, and hummock/hollow topography), and a lower density of points were collected in areas of high topographic uniformity (e.g., the high marsh platform). The assessed point density threshold, as defined in the point density test above, was met in the Maurice River (408 points; 0.96ha) and Money Island (418 Points; 1.35ha.) The ratio of points per hectare was lower in Fortescue (807 points; 4.22ha) due to the large expanse of uniform high marsh that comprised the majority of that MOI.

Elevation mapping and Marsh Type Delineation
The RTK point survey data were used to create a surface elevation model of each MOI (Empirical Bayesian Kriging, ArcGIS 10.2), which was then exported as elevation polygon layers to create fine-scale topographic maps. Since dominant vegetation species (and growth forms) were also recorded at every RTK survey point, these data for vegetation type were then paired with the elevation maps to generate separate layers for the main two marsh categories: high marsh and low marsh. Low marsh vegetation was characterized as tall-form *Saprtina*

*Figure 17. RTK survey point locations for each MOI.*
alterniflora, whereas the high marsh zone was delineated wherever vegetation was dominated by short-form *Spartina alterniflora*, *Spartina patens*, *Distichlis spicata*, and/or *Salicornia* spp.

Elevations for high and low marshes exhibited no evidence that they were not normally distributed (p > 0.5, Shapiro-Wilk Test) and were separated into quartiles. Subsequently, high and low marshes were each divided into three sub-categories to reflect their relative position within the local tidal prism: Low (< first quartile), Mid (first quartile ≤ x ≤ third quartile), and High (> third quartile). Therefore, the lowest 25% of points within the low marsh was assigned a marsh type as “Low Marsh Low Elevation”, the middle 50% of points was delineated as “Low Marsh Mid Elevation”, and the highest 25% of elevation points within the low marsh zone was delineated as “Low Marsh High Elevation”. This approach was repeated for the high marsh zone, thus creating six marsh types (a.k.a., zones) based on the RTK-generated data for true elevation paired with vegetation type data: Low Marsh Low (LML), Low Marsh Mid (LMM), Low Marsh High (LMH), High Marsh Low (HML), High Marsh Mid (HMM), and High Marsh High (HMH).

![Figure 18](image.png)

**Figure 18.** Base map of marsh types within the Fortescue study tract, based on elevation contours and dominant vegetation.
In the point file for each MOI, an attribute column was then created to reflect “marsh type”, which was populated with the above categories. The elevation polygon layer was categorized as a marsh type polygon layer based on the population of marsh type points it contained. In a small proportion of cases, these generated layers of marsh types overlapped in their true elevations (e.g., low marsh high versus and high marsh low). These polygons were manually restructured to contain the correct marsh type points. Each marsh type polygon was then assigned a marsh type score based on type and position in the tidal spectrum: LML=1; LMM=2; LMH=3; HML=4; HMM=5; HMH=6. Hence, lower scores represent marsh areas that typically sit lower in the tidal prism than marsh areas with higher score. Mapping results from these analyses are shown in

**Figure 19.** Base map of marsh types within the Money Island study tract, based on elevation contours and dominant vegetation.

**Figure 20.** Base map of marsh types within the Maurice River study tract, based on elevation contours and dominant vegetation.
Location of Biological Assessment Plots

Working from these base maps of the six different marsh types (elevation-vegetation zones; Figs 18-20), three replicate plots were then situated within each of marsh type per MOI (i.e., 18 plots per MOI). These plots were established to conduct rapid biological assessments. The locations of the replicate plots within each marsh type were spread across each MOI to avoid spatial autocorrelation concerning vegetative health and substrate.

Rapid Biological Surveys

Rapid measures of marsh condition were examined as representative plot locations within each MOI. These measures were selected from a diverse array of metrics used in MACWA rapid and fixed station monitoring, focusing on those that have yielded the most informative data on marsh condition and vulnerability. Data for five metrics were collected, although we expected that not all would be used in the final analysis because of potential redundancy. For example, plant canopy robustness was examined using several different measures, as noted below. Since this was a methods development study, we collected more information than was actually needed, and so future studies are expected to be less onerous, and require less field
Vegetative health was assessed for each of the rapid assessment plots, which consisted of eighteen 1m² plots per MOI (Fig. 21). At each assessment plot, four indicator measures of vegetative health were assessed: blade height, canopy cover, bearing capacity and horizontal view obstruction (Fig. 22). These measures were chosen because a) they can be rapidly collected, and b) they reflect different features of the vegetative conditions. Blade height reflects the vertical height of the canopy, which can be correlated with inundation and nitrogen enrichment as salt marsh plants typically grow taller in lower marsh areas that may be more vulnerable. The horizontal vegetation obstruction index, on the other hand, reflects the horizontal density and fullness of the plants. Canopy cover, as measured by light attenuation, is another measure of fullness, integrating the density and width of plant stems and blades. Whereas these three measures examine aboveground vegetation robustness, bearing capacity is a rapid measure of belowground biomass because softer substrates tend to have lower amounts of live and dead roots and rhizomes (peat).

Twenty five measures of blade height were taken in each plot from the most water-ward corner of the plot towards the middle of the plot. This method followed the established MACWA standard operating procedure (SOP) for assessing mean blade height within permanent vegetation plots (see Quality Assurance Project Plan for Site-Specific Intensive Monitoring for the Mid-Atlantic Coastal Wetland Assessment).

Canopy cover was measured using a light meter. A measurement is taken in each corner and the center of the plot above the vegetation and at the sediment surface below the plant canopy. The final score is evaluated as 1-(mean value at marsh surface/mean value above vegetation). This method followed the established standard operating procedure (SOP) for assessing canopy cover using light attenuation, as used defined in the Regional Applied Research Effort study by PDE and EPA (see Quality Assurance Project Plan; available on request).

Figure 22. Example of field data collection for vegetation health metrics: (a) blade height, (b) canopy cover, (c) bearing capacity and (d) horizontal obstruction.
Soil bearing capacity is a measure of the softness of the sediment surface. Bearing capacity is measured using a slide hammer technique in which a marked post is placed onto the marsh surface and a slide hammer is placed on top. The initial depth of the post is noted as well as the vertical distance traveled (depth) after 5 successive blows of the slide hammer. The final score is the difference between the initial depth and the final depth. This method followed the established MACWA standard operating procedure (SOP) for assessing bearing capacity as part of the Mid-Atlantic Tidal Wetland Rapid Assessment Method (see Quality Assurance Project Plan for Site-Specific Intensive Monitoring for the Mid-Atlantic Coastal Wetland Assessment; http://delawareestuary.org/node/199).

Horizontal Vegetation Obstruction was measured by counting the number of alternating red and white striped bars visible on a 1m wooden board, from a distance of 3m through the standing vegetation in the plot. The bar counts are repeated at different elevations above the marsh surface (0.25, 0.50, 0.75, 1.0 m), and the count is then totaled. This method followed the established MACWA standard operating procedure (SOP) for assessing canopy obstruction as part of the Mid-Atlantic Tidal Wetland Rapid Assessment Method (see Quality Assurance Project Plan for Site-Specific Intensive Monitoring for the Mid-Atlantic Coastal Wetland Assessment; http://delawareestuary.org/node/199).

**Assessment of Biological and Substrate Data**

The goal of the biological assessments was to adjust the marsh type scores with vulnerability weightings that reflect areas where poor vegetative health was observable. It is common to observe different vegetation health in areas that have the same elevation and species cover. For example, an area that is characterized by tall, “leggy” and sparse vegetation is deemed to be less resilient than an area with the same species assemblage that has dense and consistent vegetative cover. To identify anomalous growth forms and substrate conditions that can be indicative of high vulnerability and low resilience, we consulted the 4-year database on plant growth ranges and robustness measures that has been collected as part of MACWA (see above). For example, 313 random coastal wetland points have been

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**Figure 23.** Distribution of data for bearing capacity, as recorded at representative salt marsh locations throughout the Delaware Estuary, 2010-2014 (from MACWA rapid assessment surveys). The left and right vertical dashed lines delineate the lower and upper break points used to detect anomalous values. For bearing capacity, higher values to the right were deemed indicative of poor conditions (softer substrates).
rapidly assessed, many within salt marshes in the vicinity of this study’s MOIs. Repeated measures datasets now also exist for some of them as well, such as blade heights within permanent study plots at MACWA long-term monitoring stations. For each of our four vegetation condition measures (blade height, horizontal obstruction, canopy density, bearing capacity), we examine all salt marsh data collected from the Delaware Estuary (MACWA data from Barnegat Bay marshes were not included). For each metric, we examined the distribution of data and identified thresholds that appeared to be most indicative of the break point between “poor,” “fair” or “good” vegetative health. For the purposes of this study, these thresholds were generally delineated as differences that exceeded one standard deviation from the MACWA mean (poor versus good), with the middle of the distribution around the mean being regarded as fair (e.g., Fig. 23).

These break points within the overall MACWA dataset for comparable salt marshes of the Delaware Estuary were then contrasted with the distribution of data collected in this study within each of the three MOIs. In cases where the vegetation metric scored within the “poor” range, the marsh type score (see above) for that point was assigned a negative weight for that metric. If there was no evidence that vegetation condition was poor (i.e., it was fair or good, and did not exceed the suboptimal break point), then the weighting was null and it was assigned a value of zero in the dataset for that metric.

In our analysis of the MACWA data distributions and MOI values for each of the four tested metrics, one metric was deemed to not be as useful as the other three in this weighting approach. Data distribution patterns for the horizontal vegetation obstruction index were not as normally distributed (modal), and the tails of the distribution contained many extreme outliers. A comparative analysis of spatial patterns associated with good, fair and poor conditions as evidenced by the horizontal obstruction index was also inconsistent with patterns evidenced with other measures. We concluded that this metric may be useful as an indicator of general marsh condition (for purposes of MACWA that examine diverse stressor-response relationships), but may not be as useful as the other metrics tested here as an indicator of vulnerability to marsh drowning. Furthermore, canopy cover was considered to be a similar, integrative measure of vegetation canopy robustness, and so the deletion of the potentially redundant horizontal vegetation obstruction from the analyses will enhance the field assessment efficiency and reduce costs for future applications of the Marsh Futures approach.

For the three rapid biological measures that were retained as weightings for marsh type scores, the actual break points for the analysis are summarized in Table 1.

<table>
<thead>
<tr>
<th>Metric</th>
<th>Mean</th>
<th>SD</th>
<th>Mean +SD</th>
<th>Adjusted Threshold</th>
<th>Score Adjustment Value</th>
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<td>Blade Height</td>
<td>81.67</td>
<td>34.71</td>
<td>116.37</td>
<td>110.00</td>
<td>-0.5</td>
</tr>
<tr>
<td>Canopy Cover</td>
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<td>21.05</td>
<td>53.85</td>
<td>53.85</td>
<td>-0.5</td>
</tr>
<tr>
<td>Bearing Capacity</td>
<td>4.22</td>
<td>2.58</td>
<td>6.80</td>
<td>6.00</td>
<td>-1.0</td>
</tr>
</tbody>
</table>
Blade Height (cm). Vegetation growing low within its optimum growth elevation range will grow taller as it attempts to keep pace with rising tides. A mean value was calculated from the height of 25 random blades measured within each plot. The statistical threshold of 116.4 cm was adjusted to 110 cm based on best scientific judgment of actual growth conditions associated with visibly impaired marsh plots. Plots with mean blade heights surpassing 110cm were given a score of -0.5.

Canopy Cover (klum). Canopy cover was calculated as one minus the ratio of the mean light at the marsh surface divided by the mean ambient light above the vegetation canopy. Higher canopy cover is therefore indicative of greater light attenuation by the canopy, resulting in less light penetrating to the substrate surface. Therefore, in dense vegetation, canopy cover scores will be higher. Plots having with a canopy cover below 53.85 kLum received a score of -0.5.

Bearing Capacity (cm). High penetration of the substrate by successive blows from the slide hammer is indicative of non-compacted, “soupy” soils, whereas lower bearing capacity values indicates more densely packed, healthy below ground biomass. The threshold was adjusted based on familiarity with these MOIs, and observations that bearing capacities collected in high marsh environments tend to contain generally firmer substrates. Bearing capacity scores equal or greater than 6 cm were considered more vulnerable and received a score of -1. This metric was assigned a higher weighting relative to the two plant metrics because bearing capacity is associated with belowground biomass, whereas blade height and canopy cover are two measures of aboveground biomass.

Analyses for each plot (n=18/MOI; 3/marsh type/MOI) therefore yielded three weighting scores, one for each metric: blade height (0 or -0.5), canopy cover (0 or -0.5) and bearing capacity (0 or -1). The resulting range of total weightings for the three metrics would 0, -0.5, -1.0, -1.5 or -2.0. The actual metric values that would correspond to negative scoring are specified in Table 1.

The geospatial results of this biological metrics analyses are summarized in Figures 23a, 24a and 25a for Fortescue, Money Island and Maurice River MOIs, respectively. In these figures, actual weightings per metric are summarized in the circles which are positioned where each of the 18 assessments plots were situated per MOI. For reference, the colored polygons in the background correspond to the base maps of marsh elevation type shown earlier in Figures 18-20.

Platform Vulnerability Determination

After each plot was assigned a combined elevation adjustment weighting for the three metric s (range: 0 to -2), that weighting was then used to adjust the marsh type score (range: 1 to 6) for all RTK points that fell within the same polygon where the plot was situated, yielding a final “vulnerability score” for that polygon. Although the biological assessment plots were selected to be representative of prevailing conditions across the MOI, some polygons did not contain a bioassessment plot. Any marsh type polygon that did not contain a bioassessment plot did not have its score adjusted. Although some marsh type polygons may appear to contain more than one plot in the maps below (24a-26a), this is an artifact of the inter-marsh polygon borders not being displayed. Many of what appear to be large, singular polygons of a marsh type, are actually multiple adjacent polygons. After the marsh type scores per polygon were adjusted with the plot weightings, the resulting polygon maps are referred to as Platform
Vulnerability Maps. These maps are shown in Figures 24b, 25b and 26b, adjacent to the base maps (24a-26a) of marsh type and metrics results, for comparison. Areas where the color shift deepened on the vulnerability maps compared to the base maps represent places where the pace of change is likely to be quicker and where interventions are recommended, such as measures to avert drowning in the lower low marsh elevations or measures to preserve high marsh in the lower high marsh areas.
Figure 24a (top) and 24b (bottom). Bioassessment scores per plot (shown as circles) shown on the map of marsh elevation type (top, A) and corresponding marsh vulnerability map (bottom, B) for the Fortescue Marsh of Interest. For the plot circles in A, the background shading (white to gray) shows the relative degree to which the bioassessment metrics lowered the marsh type score. White plots did not have their score affected by metrics. As the shade grows darker, metrics decreased the marsh type score to a greater degree.
Figure 25a (top) and 25b (bottom). Bioassessment scores per plot (shown as circles) shown on the map of marsh elevation type (top, A) and corresponding marsh vulnerability map (bottom, B) for the Money Island Marsh of Interest. For the plot circles in A, the background shading (white to gray) shows the relative degree to which the bioassessment metrics lowered the marsh type score. White plots did not have their score affected by metrics. As the shade grows darker, metrics decreased the marsh type score to a greater degree.
Figure 26a (top) and 26b (bottom). Bioassessment scores per plot (shown as circles) shown on the map of marsh elevation type (top, A) and corresponding marsh vulnerability map (bottom, B) for the Maurice Marsh of Interest. For the plot circles in A, the background shading (white to gray) shows the relative degree to which the bioassessment metrics lowered the marsh type score. White plots did not have their score affected by metrics. As the shade grows darker, metrics decreased the marsh type score to a greater degree.
Edge Vulnerability
To assess edge vulnerability, shoreline position change between 1970 and 2012 was calculated for each MOI by measuring the change in distance between the shorelines. Perpendicular transects from the 1970 shoreline to the 2012 shoreline were created using the Digital Shoreline Analysis System (DSAS), developed by the U.S. Geological Survey to be used as an extension to ArcGIS Desktop. The shoreline vector files were digitized in ArcGIS Desktop using historical aerial photographs supplied by the New Jersey Geographical Information Network, maintained by the New Jersey Office of Information Technology, Office of GIS. More information on the aerial photographs can be found here: https://njgin.state.nj.us/NJ_NJGINExplorer/jviewer.jsp?pg=about_njgin.

In addition to shorelines digitized for each area, a baseline file was created. The baseline serves as a starting point for generating a series of perpendicular transects for which quantitative, replicate retreat rates can be calculated. The baseline file was a buffered distance from the 2012 shoreline, as recommended by the DSAS User Guide and Instructions. The buffer line varied for each area of interest, depending on the distance from the 1970 shoreline to the 2012 shoreline. The baseline file needed to be farther away from the current

Figure 27. Digitized shorelines, measurement transects, and erosion rates compared among transects along shorelines adjacent to the Fortescue (top), Money Island (middle) and Maurice (bottom) MOIs.
Figure 28. Deviation of LiDAR elevation measurements from RTK data.

shoreline than the 1970 shoreline in order for the transect to encompass shoreline from all years. Once these transects were created, the DSAS software was used to calculate the shoreline retreat rate (meters per year), using the End Point Rate analysis tool. Those rates were used to symbolize the shoreline retreat of the three MOIs, and the actual transects are shown in Figure 27 with color coding per transect that reflects the relative rate of retreat. The same retreat rate color scale was used for all three MOIs to enable visual comparison of the relative degree of mean shoreline erosion that has occurred during this 42 year period.

**Construction of Best Management Practice Maps**

The technical team has experience with many of the types of salt marsh enhancements that are inventoried in the Introduction. Outcomes from both the platform and edge vulnerability analyses were therefore interpreted in the context of potential interventions that best match the needs of the different MOIs. Best scientific judgment was then exercised to consider the types of interventions that are recommended, the sequence if multiple tactics are suggested, and urgency.

**Results**

**Comparison of Available LIDAR and RTK Sourced Data**

When evaluating tidal wetland vulnerability, elevation within the local tidal spectrum is important (Fig. 11). At intertidal sites such as salt marshes, fine-scale measures of elevation provide critical information regarding inundation time which affects local vegetation production. It is therefore important to understand the optimal growth range of dominant plants for an area, and then to examine site specific aboveground biomass tidal positioning relative to that regional optimal growth range (Morris, 2002).

Although LiDAR data is very useful in determining elevation for large expanses of terrain, its use for wetland elevation assessment is limited. Elevation calculations derived from LiDAR are determined by tracking the time it takes emitted light from a sensor to reflect back to its source from a target surface such as bare ground. When vegetation is present, the canopy can cause reflection, even during “leaf off” times when the vegetation is senesced. Litter, dead vegetation and wrack may remain on the surface and also contribute to inaccurate LIDAR measurements.
Additionally, standing water on the surface of the marsh may absorb the emitted light, resulting in null elevation values. The highest resolution LiDAR elevation contours available for our MOIs were 6”, significantly lower resolution than the 3cm accuracy of the RTK GPS.

Since existent LiDAR datasets could reduce field survey time, available LiDAR data was compared to RTK sourced data at the Money Island MOI. Elevation point data collected with the RTK GPS was overlaid on a LiDAR sourced digital elevation model and map algebra was used to calculate the deviation of the LiDAR measurement from the RTK measurement at each point (Fig. 28). Results showed that 82% of the LiDAR elevations deviated by more than 5cm from the RTK elevation measurements. Elevations that were within 5cm accuracy tended to be located on the topographically less complex high marsh platform, while measurements along the sloping edges of the low marsh and inter-marsh creeks almost uniformly deviated by more than 10cm. An error range of 5-10 cm for LIDAR was considered unacceptable for local site project planning due to the sensitivity of marshes to small changes in elevation, and hence on-the-ground RTK elevation surveys are recommended for Marsh Futures until more advanced technologies are available.

**Biological and Substrate Surveys**

For the three rapid assessment metrics that were retained in marsh vulnerability scoring, average values are shown in Figure 29 for each marsh elevation zone within each of the three MOIs. Blade heights were not significantly different among marshes, although there was variability within marshes. Generally, blade heights were greater in the low marsh than the high marsh (Fig. 28, top). Fortescue exhibited the sharpest increase in blade height moving from high marsh low to low marsh high. Blade height across marsh type at the Maurice MOI had the lowest variance.

Canopy cover was significantly lower at Money Island
than at Maurice and Fortescue, which were not significantly different from each other. Within-march variation was also lower at Maurice and Fortescue than at Money Island.

As with blade height, bearing capacity did not differ among marshes but did differ within marshes. Money Island had significantly greater bearing capacity (was less firm) in Low Marsh Low areas, and Fortescue followed a similar, but not as prominent, trend.

**Platform Vulnerability Maps**

Vulnerability scores reflected the combination of surveyed elevations and biological/substrate scores. Marsh areas with deteriorating conditions were identified by contrasting datasets per MOI with 4-year datasets for general Delaware Estuary salt marshes (from MACWA). Anomalies that elicited negative biological weightings were generally considered to be the most deteriorated, exceeding one standard deviation from the mean, per metric (see methods). A mix of low and high scores is to be expected for a healthy salt marsh having both low and high marsh zones, and for Marsh Futures we further delineated 3 sub-zones within each category of low and high marsh. However, in many cases the weighted elevation zones shifted lower relative to their true elevation, and it is these polygons that were regarded as having greatest vulnerability to future change as reflected by the current anomalous conditions.

Although the lowest zones were deemed most vulnerable to immediate drowning and are denoted by red colorations in maps, it should be noted that many high marsh areas appear to be transitioning to low marsh but were not flagged as highest vulnerability. Polygons denoted by green colorations are currently high marsh and therefore at lower risk temporally, but they might be designated as places to continue to monitor and protect. In many cases, protection and enhancement measures might be directed at stemming this high marsh to low marsh conversion due to the value of high marsh refuges for certain nesting birds, etc. In such cases, these Marsh Futures vulnerability maps can be equally useful at selecting sites to target for interventions (e.g. sediment applications, island logging) to stem the high to low conversions. Finally, a description of vulnerability mapping outcomes follows for each MOI.

**Fortescue**

Assessment of the Fortescue MOI indicated that multiple interior areas of the marsh platform are sitting low in the tidal spectrum. Vegetation in these areas is exhibiting signs of deteriorating health which has the potential to result in interior marsh die-off. Platform vulnerability was concentrated along the western shoreline, the north western corner and in the central portion of the MOI where there is a convergence of intra-marsh creeks. Each of these areas exhibited high bearing capacity, indicating that the substrate is less firm in these areas. Additionally, blade heights surpassed the indicator threshold along the western shore and in the central portion indicating that these areas are experiencing subsidence or a high degree of inundation. These vegetation characteristics resulted in increased vulnerability within these areas. Additionally, the high marsh between the western shoreline and the lower elevation central area had a reduced vulnerability score, possibly due to proximity to highly vulnerable areas.
Maurice River
The vegetation along northeast marsh edge adjacent to the creek, is exhibiting signs of drowning most likely due to erosion from creek widening even though the energy along this area is likely to be lower than along the river edge. The central, high marsh platform area of the MOI did not display any signs of vulnerability, with a possible exception in the central northwest area. Bearing capacity in this plot scored as vulnerable, and it is located in a small patch of tall-form *Spartina alterniflora*. This is an area with a small drainage creek and an area to watch in the future for signs of deterioration. The most vulnerable plots were located along the large creek in the northern portion of the MOI, and along the Maurice River shoreline in the southern portion of the study area, which had high bearing capacity and very tall grasses.

Money Island
The assessment of the Money Island MOI indicated that although the marsh platform and associated vegetation appeared healthy and stable, vegetation and elevation profiles along the multiple creek edges exhibited signs of vulnerability. Creek edge elevation profiles were extremely low in the local tidal prism and vegetation health indicators indicated that the low positioned vegetation was in poor health. The deteriorating edge conditions are indicative of creek widening, the lateral expansion of the channel. As vegetation dies and the associated root complexes are no longer able to stabilize the sediment, sediment sloughs off the edge and is washed away with ebb tide. Areas of vulnerability were concentrated along the creek edges on both sides of the MOI. The “Y” shaped creek on the eastern side of the road scored high for bearing capacity and blade height, and low for canopy cover. A similar scoring pattern occurred on the western side of the MOI along the drainage creek next to the road. These scores, along with the low elevation measurements in these areas, indicate a high level of vulnerability and potentially areas of creek widening. Minimal areas of concern were located on the marsh platform, with the exception of high bearing capacity scores in the central eastern portion of the MOI, potentially indicating water retention or subsidence in this area. Money Island Road represents a barrier to normal hydrological flows and so it is not surprising that our bioassessments revealed anomalous outcomes in this MOI, which straddled this system alteration.

Edge Vulnerability Maps
Shoreline retreat rates between 1970 and 2012 varied widely among the three MOIs. For comparison, the same unit of scale and legend was used to portray the results, which are shown in Figure 30. Edge erosion at Fortescue during this 42-year timer series was found to be low (~0 -0.5 m/yr), compared to the other two MOIs. The only shoreline segment at Fortescue that may warrant some intervention was at the southwest point of the study area where shoreline retreat rates were higher (~0.5 – 1 m/yr).
In contrast, shoreline change at the Maurice River study marsh was comparatively severe between 1970-2012 (~1.0 - 3.5 m/yr). Most salt marshes of the Delaware Estuary that are eroding quickly have edge retreat rates of about one meter per year, but at this Maurice site, some areas were eroding at up to 3.5 meters per year (more than 11 feet). The point of the MOI that has these highest erosion rates is in the northwest along the river edge.

Our study area in the Money Island MOI was not situated directly along a shoreline, but the nearest shoreline segment was also examined for comparison. Here, rates of shoreline retreat due to erosion were the lowest of the three MOIs, perhaps because of historic and current marina activity at the site. Hard infrastructure (rip rap, bulkheads) exist along the western edge of the studied shoreline, and a pier once extended in front of the assessed shoreline. Indeed, the time series of aerial photographs of this shoreline suggested that erosion might have occurred more quickly in the 1970s than in the 1980’s-1990’s, and more recently changes have been inconclusive. Severe flooding occurred in this area during Hurricane Sandy, and the main vulnerability may be associated with altered hydrology that constrains flows during storms.

Available BMPs and Interventions
Best Management Practices (BMPs) have evolved from more traditional, “hard” techniques such as bulkheads and revetments, to more “soft”, or

**Figure 30.** Shoreline vulnerability maps for the Fortescue, Money Island and Maurice MOIs.
simulated natural techniques such as living shorelines and thin-layer sediment placement (see Introduction and Fig. 30). Hard techniques tend to separate the sub-tidal and supra-tidal zones which are vital areas of interaction for important biogeochemical processes such as nutrient cycling and for food web interaction.

In contrast, soft methods attempt to stabilize and enhance the natural ecological properties to achieve resilience. These soft enhanced marshes can still function as “fish factories”, providing shelter and protection for juvenile fish, and as storm surge sponges, absorbing the large volumes of water sent landward during high intensity storms. Traditional hardened structures do not absorb energy; rather, they reflect it, resulting in benthic scouring in front of them, and a transition of energy and water, up and behind them. Infrastructure positioned behind such structures was found to have sustained more damage during hurricanes Irene and Sandy than that situated behind more natural, “soft”, techniques.

Examples of various BMPs and other interventions were reviewed in the Introduction. The intent of the Marsh Futures approach is to develop guidance for the subset of protection and enhancement measures that can be applied to specific parcels of salt marsh. Management of sediment budgets, water quality, and alleviation of other stressors at the watershed scale are beyond the scope of the local site plans recommended here; however, where field reconnaissance reveals the presence of more broadly applicable stressor-response relationships, Marsh Futures datasets can strengthen our general understanding of degradation processes (i.e. bolster MACWA) and be a factor in other management decisions. The focus here is on those projects and tactics that can be used at the local scale, such as thin-layer sediment application, living shorelines, green revetments and hydrology repairs.

“Marsh Futures” Maps of Recommended BMPs and Interventions

Fortescue

Thin-layer enhancement is suggested for the interior of the marsh platform, augmented with an intertidal or shallow subtidal living shoreline at the southwestern point (Fig. 31). Additional bio-based living shorelines may be installed along the lateral stretches if funding is available as a lower priority need. The sequence of interventions will be important for the Fortescue MOI, as follows:

1. **High Marsh Containment**: Baffling constructed of natural materials (coir/hay) is installed in strategic areas slightly down-slope of the polygons selected for thin layer enhancement. The materials are placed in configurations that break the larger area into multiple subareas in order to ensure that sediment spread over the marsh surface does not wash out or concentrate (to avoid smothering biota too). Hydrologic or GIS assessments are recommended to ensure that creek networks are appropriate for drainage. This Marsh Futures dataset can be used to calculate sediment volumes needed, and could serve as baseline elevation data for monitoring.

2. **Thin-Layer Platform Enhancement**: Enhancing the elevation of the surface of the marsh platform will place the vegetation in the proper growth range within the local tidal spectrum and will result in a more resilient vegetated surface and root system, able to trap sediment and keep pace with sea-level rise. Fine sediment dredge material is sprayed in low-lying areas at thicknesses determined by additional high resolution surveying and correction for compaction,
subsidence rates and position in tidal prism. Detailed plans should consider the need for containment and appropriate drainage networks. Terraced benches could be created to enhance both low and high marsh areas if suitable coir log containment structures are installed before sediment application. This Marsh Futures dataset can be used to calculate sediment volumes needed, and could serve as baseline elevation data for monitoring.

3. **Intertidal/Subtidal Hybrid Living Shoreline**: Currently, the southwest point of the MOI is characterized by an unvegetated intertidal slope leading to a tall, steep gradient to upland vegetation (from earlier dredge spoil). A living shoreline at this location will slow erosion rates and trap sediment along the intertidal mudflat, allowing for a more natural intertidal marsh leading to the upland area. Additional surveying and assessment of intertidal and subtidal slope and substrate conditions are needed to determine exact placement and height of wave attenuation materials; however, existing data from this Marsh Futures study delineate the target elevations for key vegetation.

4. **Intertidal Bio-based Living Shoreline**: Minimal erosion was detected along the foreshore straightaways of the MOI, but if funding is available, as a secondary measure, preventative fortification of the marsh edge can be accomplished using the coir log bio-based tactic. Cusps of interlocking logs will be installed in the intertidal zone to trap sediment and promote grass growth and ribbed mussel habitat.

![Figure 31. Marsh Futures Project Maps for the Fortescue study marsh.](image)
Maurice River

Large scale wave attenuation devices in both the sub-tidal and intertidal portions of the Bay-ward side of the MOI is recommended, as soon as possible, if intervention proceeds at this location (Fig. 32). In addition, bio-based living shorelines are recommended along the entire east-facing marsh edge, with intertidal groins placed near the creek mouth.

1. **Sub-tidal Sills and Breakwaters**: As the primary driver of erosion at this MOI is the large scale incoming wave energy due to exposure to the entire fetch of the Bay, subtidal sills/breakwaters are recommended to dampen the energy moving up river and act as a first line of defense against high magnitude storm surges. The feasibility and exact placement of materials would be contingent on geotechnical, hydrologic and bathymetric surveys.

2. **Intertidal/Subtidal Hybrid Living Shorelines**: A secondary line of defense is recommended, consisting of hybrid living shorelines comprised of oyster castle breakwaters. These would provide additional energy attenuation of wind driven waves behind the subtidal, offshore sills/breakwaters. A final line of coir fiber logs along the intertidal vegetated marsh edge would help to trap sediment for grass production and mussel recruitment, leading to enhanced marsh strength and resistance to erosion along the Bay-ward edge.

3. **Intertidal Bio-based Living Shorelines**: Along the creek edge, bio-based living shorelines would help to stem creek widening and promote a healthy, vegetative edge. Cusps of interlocking logs would be installed in the intertidal zone to trap sediment that is being removed from the marsh.

![Maurice River BaySIPP AOI n=408 points](image)

**Figure 32.** Marsh Futures Project Maps for the Maurice study marsh.
by creek drainage, and promote grass growth and ribbed mussel habitat.

4. *Intertidal Groins*: Intertidal groins of oyster castles would be placed along these bio-based installations at the Bay-ward end. This would help to intercept and decrease incoming wave energy before making contact with the soft armor coir logs.

Money Island

Low energy, bio-based living shorelines are recommended to initially stabilize and trap eroding sediment, especially in the lowest areas along and near the road (Fig. 33). Over time, these would provide a stable environment for enhanced vegetative growth, possibly decreasing erosion along the road. In addition, high marsh sediment retention pods would be an extra measure of resilience if installed on the marsh platform to enhance high/low marsh habitat complexity.

1. *Intertidal Bio-based Living Shorelines*: Along the creek edges, bio-based living shorelines would help to stem creek widening and promote a healthy, vegetative edge. Cusps of interlocking logs installed in the intertidal zone would trap sediment that is being removed from the marsh by creek drainage, and promote grass growth and ribbed mussel habitat.

2. *High Marsh Sediment Retention Pods*: Habitat complexity is a sign of healthy, resilient marshes. Although the marsh platform is exhibiting stable conditions, the uniform nature of the low elevation and vegetation community may leave it more vulnerable to subsidence and

![Figure 33. Marsh Futures Project Maps for the Money Island study marsh.](image-url)
deterioration. By installing sediment retention pods (coir circles used to raise the interior elevation of the pod), a greater complexity of elevation profiles can be developed on the marsh platform, providing better wildlife habitat and helping to break up sheet flow during high flood stages. This increased complexity would enhance resiliency, especially during storm surges and other extreme weather events.

**Discussion and Conclusions**

The Marsh Futures approach was found to be useful for providing discrete guidance for strategic local planning. For example, the methodology was able to detect subtle differences in elevation and local biological conditions within and among the studied marsh tracts that yielded significant differences in recommended marsh enhancement projects and coastal resilience tactics. At Fortescue where shoreline erosion has not been very severe, large interior sections of the studied marsh are highly vulnerable to drowning and may be on the verge of collapse. Here, the recommended tactics are designed to restore the elevation via either direct sediment application or tactics that can trap and retain sediment naturally. Direct delivery via thin-layer spraying of dredged fine sediments is recommended as it would likely expedite a sustainable marsh platform elevation. In order to maximize the likelihood of success, precise calculation of sediment volumes, geospatial placement, and retention factors are required. The MOI at Fortescue may secondarily benefit from a living shoreline along the “point” where erosion has been greater than elsewhere at the site.

In contrast, the Maurice MOI is acutely jeopardized by shoreline erosion, which was greater than 3 meters per year in some locations. The marsh platform had the most “elevation capital” of the three MOIs, representing a natural levee that was probably built up by storm-driven sediments that had their source from nearby erosion. This vertical expansion at the expense of horizontal attrition suggests that acreage loss is greatest in the Maurice MOI, and this marsh tract will likely disappear entirely within the next 10 years. This conclusion is consistent with aerial imagery that shows large losses of adjacent marshes over time. Hence, any interventions at this MOI must be very soon, robust, and focused on stemming the retreat of the vegetated edge and shoreline. Recommended interventions include a suite of different sill and living shoreline installations along the entire shoreline. Even if fully implemented, success may depend on other stabilization efforts in the vicinity due to the consistent large scale energy and exposure to periodic extreme storm events at this location.

The Money Island MOI exhibited vastly different stressors from the Fortescue and Maurice sites, primarily built infrastructure. The Money Island Road has served as a barrier to water flow across the marsh platform, and as a result, a concentrated network of widening tidal creeks has developed. The creeks constrict and redirect water flows, likely contributing to enhanced water logging, marsh pooling and erosion along the creek edges. Much of the marsh vegetation, particularly on the east side of the road, exhibits signs of drowning and poor health. Interventions are recommended that would stabilize erosion along the creeks and enhance the structural complexity by restoring some high marsh islands, which serve to break up sheet flow during storm surges. Ultimately, hydrological reconnections may be
warranted to allow water to flow more freely under the road (culverts, causeway). The adjacent shoreline along Nantuxent Creek had not exhibited significant erosion over the 1970-2012 period, potentially due to the influence of past and current marina infrastructure at the site. However, more recent aerial imagery suggests that some attention may be warranted as high water flows and storm surges appear to be impacting the area.

Due to the level of rigor needed to suitably map elevations on-the-ground, the Marsh Futures approach is most applicable for areas that range between 0.5 and 20 hectares. Some economy of scale would likely reduce costs in assessments of larger tracts. For larger areas or very small budgets, it may still be useful to obtain a smaller or less dense set of measurements to support project decision-making, designs and to enhance success. A stratified probabilistic approach could be adapted from the Marsh Futures approach in cases where detailed guidance is needed for very large tracts (100’s of hectares per site).

Biotic and substrate surveys across the marsh platform were useful in identifying areas of low vegetative health that were generally associated with areas of lower elevation. Future field surveys should aim to maximize marsh type plots and conduct reduction analysis to identify the number of plots needed per hectare. The dataset being amassed via the Mid-Atlantic Coastal Wetland Assessment (MACWA) program was essential to performing this Marsh Futures study as it provided critical data concerning dominant plants that helped us identify anomalous conditions among the three smaller MOIs. Importantly, our bioassessment methods matched those used in MACWA, allowing us to examine MACWA data distributions for plant community metrics to identify the key break points for the weighted measures approach used to identify vulnerable areas. Use of the Marsh Futures approach will therefore be easier and outcomes more robust in areas where representative data from MACWA exist. There are additional metrics and datasets in MACWA and other assessment studies that could potentially be incorporated into future Marsh Futures applications, strengthening outcomes and providing more detailed site characterization needed for more robust project designs.

Salt marshes are in rapid decline and will be under increasing pressures in the future. Strategic retreat is most likely to be the only viable option in many, if not most, locations due to the high intervention cost for such large expanses of marsh. But, in areas where salt marshes are considered essential to protecting coastal communities or supporting vital ecologies, the Marsh Futures approach can serve as a useful local site planning tool to provide refuge managers, townships, and other interested groups with recommended next steps based on concrete on-the-ground assessments.
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