# Cost and Effectiveness Analysis of Select New Jersey Living Shoreline Projects

*Prepared for:*

The Nature Conservancy (TNC)

*Prepared by:*

Laura Kerr, DanaRose Brown
and Jon K. Miller, PhD

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# Executive Summary

The costs and the effectiveness of five recently constructed living shoreline projects in New Jersey were evaluated. The projects selected are representative of the diversity of the project types found in New Jersey. They range in size from large to small, from simple to complex, and from relatively inexpensive to costly. At several sites, cost information was also obtained for nearby conventional gray shoreline treatments. This allowed for a qualitative comparison between green and gray alternatives. The cost information for each project was provided by organizations involved in their funding, design, and construction. The level of detail provided varied significantly. All provided costs were compiled and grouped into categories for analysis and comparison. It should be noted that not all of the cost estimates included enough detail for a complete cost breakdown, therefore the results need to be interpreted cautiously.

The total cost for the five living shoreline projects in the study ranged from $88 per linear foot to $2,018 per linear foot. The five conventional alternatives ranged in cost from $462 per linear foot to $3,448 per linear foot. In general, the smallest, least complex project of each type was the least expensive, and the largest, most complex project was the most expensive. Overall, design and permitting costs, maintenance and adaptive management costs and monitoring costs were higher for the living shoreline projects than for conventional projects; however, construction costs for the living shoreline projects were generally lower. Some of the living shorelines projects were constructed either partially or wholly with volunteer labor which helped reduce costs.

In terms of the distribution of the costs associated with each project type, significant differences were found. For the living shoreline projects, materials and labor made up a wide range (34.5% to 91.8%) of the total project costs. For the conventional projects, materials and labor consistently made up the largest proportion (88.9% to 98.6%) of the total cost. The split between materials and labor was different as well; construction costs were more evenly split between materials and labor for the living shoreline projects, while they were more heavily weighted towards material costs for the conventional projects. Design and permitting, monitoring, maintenance, and adaptive management costs, all made up a greater proportion of the cost of the living shoreline projects. This is driven in part by the relative inexperience with living shoreline projects within the state that often increases the permitting and monitoring costs, and in part by the way in which maintenance and adaptive management is viewed/interpreted. For living shoreline projects, maintenance and adaptive management is often considered up front, as a part of the initial planning process and the collected cost information reflects that; whereas for conventional projects, maintenance and adaptive management are often considered separate projects entirely and therefore these costs are not contained in the information provided. For some of the living shoreline projects, the non-construction costs were found to be more than double the construction costs.

The long-term costs of all the projects were estimated using a framework developed as a part of the Hudson River Sustainable Shorelines Project (HRSSP). The framework was chosen because of its adaptability, including the ability to modify and add new cost categories. The framework requires a set of assumptions related to interest and discount rates, sea level rise, damage potential, and maintenance including replacement. One of the main conclusions from the long-term cost analysis was that the costs of the living shoreline projects are more evenly distributed through time, while the costs for the conventional shoreline stabilization approaches are more concentrated. The major costs associated with all of the conventional structures were associated with initial construction costs and replacement costs, while the living shoreline projects were more influenced by maintenance, monitoring, adaptive management, and damage costs.

The effectiveness of the living shoreline projects was evaluated by analyzing and comparing pre- and post-construction shoreline changes and comparing them to a nearby control site. Overall, three of the five living shoreline projects (Berkeley Island, Gandys Beach, and Matts Landing) were found to be clearly effective at stabilizing the shoreline in their respective project areas, and in some cases even promote shoreline advancement (Gandys Beach and Matts Landing). The results of the shoreline stability analysis at the other two sites are less obvious due to the lack of high-quality historical imagery prior to project installation. These two sites exhibited the lowest pre-construction rates of shoreline change and standard deviations of 40 to 65% of their annual rate of shoreline change post-construction.

A second measure of effectiveness was evaluated for the three living shoreline projects that contain feature wave dissipation structures (Gardner's Basin, Gandys Beach, and Berkeley Island). For these projects, waves were measured offshore and inshore of the wave dissipation elements, and wave attenuation was calculated. All three projects were found to be effectively attenuating waves. At Gardner's Basin, the majority of wave heights were reduced by 50% or more, while wave heights at Berkeley Island were reduced between 25% and 75%. At Gandys Beach, the wave attenuation was more variable, due to the complexity of the hydrodynamic conditions at the site; however, attenuation of between 0% and 50% was most common.

The effectiveness of the gray alternatives was not evaluated as a part of this study because comparing the results to the living shoreline projects could result in misleading conclusions. While bulkheads and revetments are generally very effective at maintaining the shoreline (particularly when newly constructed), the length of the study precludes consideration of some of the other long-term, effects which need to be considered if their effectiveness is to be directly compared to living shoreline projects.

Overall, some of the key takeaways from the analysis of the cost and effectiveness data for the five living shoreline and five conventional shoreline stabilization projects were:

1. Costs for both living shoreline and conventional shoreline stabilization projects were found to vary widely; however, the living shoreline project costs were generally lower.
2. The distribution of costs for living shoreline and conventional shoreline projects were found to be different, with design and permitting, monitoring, maintenance, and adaptive management costs making up a larger proportion of the living shoreline project costs.
3. The long-term cost of living shoreline projects was determined to be more evenly spread over time, while the costs of conventional projects were concentrated at discrete times representing initial construction and replacement.
4. Three of the five living shoreline projects were found to be effective in reducing erosion compared to a nearby control.
5. All three living shoreline projects containing wave-attenuating structures effectively attenuated waves although the degree of attenuation was found to vary.

# Contents

# Project Overview

Coastal communities have conventionally responded to coastal hazards like erosion, flooding, and sea level rise with gray infrastructure such as bulkheads and seawalls. However, these "hard" structures often cause unintended adverse impacts, as wave energy is reflected into the surrounding environment, and the interface between land and water is obstructed, resulting in damage to aquatic and terrestrial habitats. As awareness of the value of marshes and other coastal habitats grows among New Jersey's coastal communities, there is increasing demand for "living shorelines" and other risk mitigation approaches that provide protection from coastal hazards while also preserving coastal habitats. Amid this increasing demand, state regulatory authorities have moved to enable the first generation of "living shoreline" projects with the passage of the "Living Shorelines General Permit" (N.J.A.C. 7:7-6.24) in 2013. This has led to a proliferation of projects in various phases ranging from initial conception to constructed, and in some cases, even monitored.

In the process of working with communities and shepherding these projects through the design process, a number of impediments have been identified which cause people to choose conventional gray shore protection over living shoreline projects in spite of the clear ecological benefits. Two of the most commonly cited are 1) uncertainty related to the costs and 2) uncertainty related to the effectiveness of living shoreline projects. The goal of the current project is to reduce some of this uncertainty by examining the costs and effectiveness of several projects recently constructed in New Jersey. Projects were selected in consultation with The Nature Conservancy (TNC) and were chosen to highlight the diversity of living shoreline projects in the state. The five projects selected were:

1. Berkeley Island County Park segmented sill in Berkeley Township, NJ,
2. Strathmere Boat Ramp terraced slope in Strathmere, NJ,
3. Gardner's Basin sill in Atlantic City, NJ,
4. Gandys Beach Oyster Castle breakwater in Downe Township, NJ, and
5. Matts Landing coir roll edge protection in Heislerville, NJ.

A site location map is provided as Figure 1. The sites are distributed throughout southern New Jersey, and are situated in diverse environments, ranging from extremely low energy to moderately high energy. While the goal of each project was to stabilize the shoreline, typically consisting of a marsh edge, the approach differed from site to site. Two of the projects (Matts Landing and Strathmere) directly addressed the edge, while three of the projects attempted to reduce the energy reaching the shoreline through the construction of an offshore breakwater or sill (Berkeley Island, Gardner's Basin, and Gandys Beach). Materials used in the construction of the projects ranged from coir rolls, to rock, to augmented concrete.

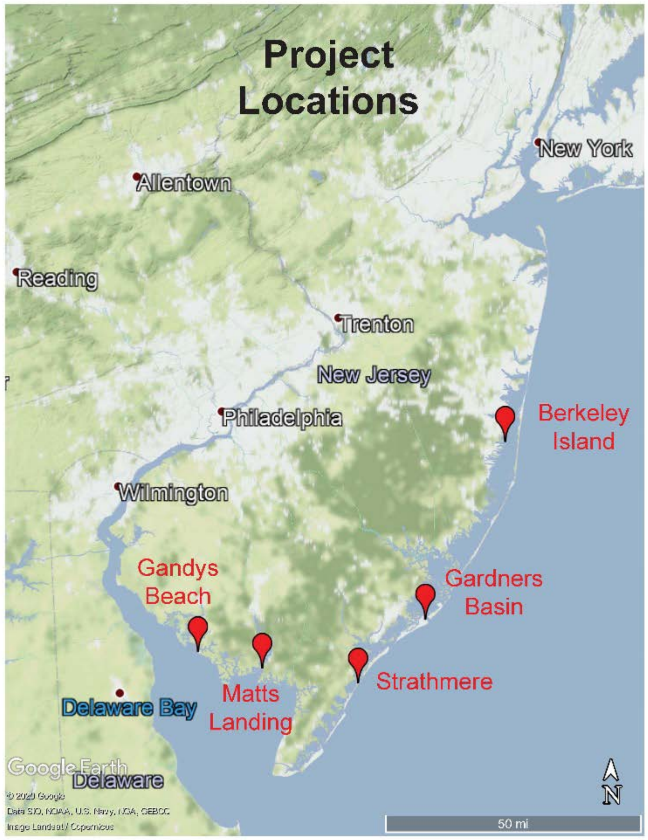


*Figure 1: Project location map.*

# Methodology

The main objectives of the study were to evaluate the costs and the effectiveness of each of the five projects. Due to the inability of a single metric to adequately capture the performance across the range of project types selected, the costs and the effectiveness were considered separately. The methodologies for the independent cost and effectiveness analyses are described below.

## Cost Analysis

The cost analysis consists of two separate parts. The first part is a compilation of the actual costs involved in the design, permitting, construction, and management of each project. Cost information for each of the projects was solicited from a variety of sources including project funders, project engineers, and the New Jersey Department of Environmental Protection (NJDEP). Cost information was obtained for each project; however, the type of information and the level of detail provided varied from project to project. In some cases, actual costs were provided in extreme detail, in others, only a high-level breakdown of estimated costs was provided. To supplement the analysis and enable a comparison between the costs of living shoreline projects and conventional gray shoreline stabilization projects, cost information was also solicited for nearby, recently constructed conventional, gray shoreline stabilization projects. The information obtained for each project was broken down and categorized into the following groupings:

- Mobilization
- Materials

- Labor
- Design and Permitting
- Maintenance
- Adaptive Management
- Monitoring

Tables containing the cost information for each project are provided in the body of the report, in as much detail as possible. This is done to provide guidance for planning future projects; however, the reader is cautioned that costs for similar items can vary widely from project to project. As an example, some cost estimates do not separate out labor and materials, while others do. A cost for "living shoreline plantings" may refer to just the plants, or the plantings and the labor to plant them. Throughout the document, a consistent color scheme (Mobilization - yellow, Materials – light green, Labor – orange, Design and Permitting - blue, Maintenance - gray, Adaptive Management - violet, Monitoring - dark green) is used for the various cost categories.

The second part of the cost analysis is an adaptation of the long-term cost framework developed by Rella and Miller (2014) for the Hudson River Sustainable Shorelines Project (HRSSP). The framework was developed to compare the costs of ten different shoreline stabilization approaches at three sites within the Hudson River Estuary under two sea level rise scenarios. The ten stabilization approaches considered consisted of a mix of conventional, gray methods and ecologically enhanced, green approaches. The framework was conceived with the objective of making it adaptable such that updated or new information could easily be integrated. A brief description of the HRSSP framework and the updates incorporated into the current analysis is provided below. Information on interpreting the long-term cost analysis tables is provided in Appendix A.

### Description of HRSSP Cost Analysis Framework

The HRSSP cost analysis framework evaluated the long-term costs of ten different shoreline stabilization options at three sites, under two sea level rise scenarios. For simplicity, costs were broken into four main categories: Initial Cost (IC), Maintenance and Repair Cost (MC), Damage Cost (DC), and Replacement Cost (RC). IC were developed by considering each individual site and either developing a "reconnaissance level" cost estimate based on material and labor, or by direct application of a bulk cost (i.e. $X/linear foot). All of the other costs were formulated as a percentage of the IC using the best available information and engineering judgement. Maintenance and Repair Costs (MC) were described as the costs associated with inspecting and performing basic maintenance on the project. Damage Costs (DC) were described as the costs to repair a project after a storm event. DC fall outside of the scope of typical MC and were calculated as the DC associated with a single occurrence of an event multiplied by the most likely number of occurrences of that event over a specified period. The final cost category considered was Replacement Cost (RC). RC was only applied to the specific approaches that would likely need to be replaced during the period considered in the analysis. In the HRSSP report, sea level rise was taken into consideration through an assumed increase in the frequency of damaging storms and a corresponding increase in the amount of DC incurred over time. All costs presented in the HRSSP report used a present value approach with 2012 as the base year. Discounting and inflation were applied using the methodology and data contained in *Construction Cost Estimating Guide for Civil Works* (USACE, 2008) and *Economic Guidance Memorandum, 12-01, Federal Interest Rates for Corps of Engineers Projects for Fiscal Year 2012* (USACE 2012). Based on the information in those documents, a discount rate of 4.0% and inflation rate of 1.7% were utilized.

## Cost Analysis Updates

The approach taken in the present work is to utilize the HRSSP cost analysis framework described above, but to update it and make it more locally relevant by using the cost information obtained for the five projects selected for this study. Each of the updates that were incorporated into the framework are described below.

### *Time Frame Adjustment*

The original HRSSP methodology used a 70-yr period for consistency with other planning efforts taking place in NY State at the time. This necessitated using uneven intervals in the analysis with Period 1 and Period 2 being 25 years, and Period 3 being 20 years. In the present analysis, a 60-year period was selected so that three consistent 20-year intervals (Period 1 - 2020-2040; Period 2 - 2040-2060; Period 3 - 2060-2080) could be defined.

### *Discount Rate Adjustment*

The discount rate was updated to reflect the most recent federal guidance contained in *Economic Guidance Memorandum (EGM), 18-01, Federal Interest Rates for Corps of Engineers Projects for Fiscal Year 2020* (USACE, 2020a). In accordance with the information provided in the document, the discount rate was adjusted from 4.0% to 2.8%.

### *Inflation Rate Adjustment*

The inflation rate was updated to be consistent with the most recent guidance contained in the US Army Corps of Engineers planning document, *Civil Works Direct Program Development Policy Guidance (USACE, 2020b)*. In accordance with the information provided in the document, the inflation rate was adjusted from 1.7% to 2.9%.

### *Sea Level Rise Adjustment*

The sea level rise and storm encounter scenarios used in the original HRSSP report were updated to reflect more recent, local information. In the original HRSSP report, the probability of specific water levels being exceeded (corresponding to storm induced flooding) were based on water level data from The Battery, NY. The present study uses information from the Atlantic City tide gauge maintained by NOAA (https://tidesandcurrents.noaa.gov/est/stickdiagram.shtml?stnid=8534720). A curve fit is used to obtain the water levels for the 25-yr and 40-yr return period storms. The annual exceedance probability (AEP), return period ($T_r$), and corresponding water level (in meters above Mean Sea Level - MSL) at Atlantic City are shown in Table 1.

The water levels for the 10, 25, 40, and 50-yr storms were then adjusted for future seal level rise using the moderate emissions scenario from (Kopp et al., 2019). The expected sea level rise (from present day) at the midpoint of each analysis period are shown in Table 2.

Table 3 combines the information in the previous two tables, and details the resulting modified return periods and expected number of storm encounters for each of the design storms during each of the analysis periods.

*Table 1: Annual water level exceedance probabilities (AEP) as determined by NOAA for Atlantic City, NJ.*

| Atlantic City Annual Exceedence Probability | | |
|---|---|---|
| **AEP** | **Tr** | **m MSL** |
| 1 | 100 | 2.29 |
| 2 | 50 | 2.157 |
| 2.5 | 40 | 2.11 |
| 4 | 25 | 2.01 |
| 10 | 10 | 1.83 |
| 50 | 2 | 1.55 |
| 99 | 1 | 1.31 |

*Table 2: Sea level rise (SLR) estimates under a moderate emissions scenario according to Kopp et al., 2019.*

| Expected Sea Level Rise | | |
|---|---|---|
| **Period** | **Mid Point** | **Expected SLR (m)** |
| P1 (2020-2040) | 2030 | 0.089 |
| P2 (2040-2060) | 2050 | 0.315 |
| P3 (2060-2080) | 2070 | 0.541 |

*Table 3: Expected frequency of 10, 25, 40 and 50-year return periods (Tr) under a moderate sea-level rise scenario.*

| Modified Encounter Probabilities | | | | | | |
|---|---|---|---|---|---|---|
| **Current Tr** | **P1 (2020-2040)** | | **P2 (2040-2060)** | | **P3 (2060-2080)** | |
| | **Modified Tr** | **# Storms** | **Modified Tr** | **# Storms** | **Modified Tr** | **# Storms** |
| 10 | 6.71 | 2.98 | 3.10 | 6.45 | 0.76 | 26.44 |
| 25 | 16.37 | 1.22 | 5.50 | 3.64 | 1.85 | 10.83 |
| 40 | 26.07 | 0.77 | 8.76 | 2.28 | 2.94 | 6.80 |
| 50 | 32.52 | 0.61 | 10.92 | 1.83 | 3.67 | 5.45 |

### *Additional Costs*

Based on recent experience in New Jersey, several new categories of costs were identified and included in the analysis. The first relates to design and permitting. Some of the early New Jersey living shoreline projects experienced significant delays in permitting which increased the overall costs. Although recent experience suggests this has improved since the adoption of N.J.A.C. 7:7-6.24 (commonly known as the living shorelines general permit), the costs associated with engineering design and permitting continue to be an impediment for many small projects. The costs associated with design and permitting are incorporated into the long-term cost analysis by including them as a separate one-time cost incurred at the start of the project.

A new category of damage costs related to ice was also added. This category was added based on recent experience where ice has caused significant damage to several New Jersey projects. Because relatively little information on the likelihood of ice damage exists, ice damage costs were treated differently than wave/surge damage costs. For all projects susceptible to ice damage, it was assumed that two icing events would occur during the first period (2020-2040), one would occur during the second period (2040-2060) and none would occur during the third period (2060-2080). The incidence of ice damage was assumed to decrease over time due to global warming. Since little information is available on the costs related to ice damage, an engineering estimate was used based on the assumed potential impacts to each type of project from ice. This is consistent with the approach taken in the HRSSP analysis to assign damage costs to wave/surge damage.

Finally, a new cost category was added which includes monitoring and adaptive management (MA). The decision was made to add this category as it is becoming increasingly obvious that monitoring and adaptive management are critical to the success of living shoreline projects. MA costs are included in the long-term cost analysis as a one-time cost incurred during the first period. While it could be argued that monitoring needs to be continued beyond that, the reality is that most projects are only monitored very early on. For the purposes of the cost analysis, any modification to a project occurring during the second or third analysis period are assumed to be either Maintenance Costs (MC) or Damage Costs (DC) and not adaptive management.

#### *Local Costs Adjustment*

All costs were updated to reflect the most recent costs contained in the information provided for each project. In cases where more up-to-date local information was not available, the default values used in the HRSSP report were utilized. For the new cost categories, engineering estimates were used if specific project data was not available (same approach as HRSSP).

## Effectiveness

Each of the selected project sites is situated in a diverse environment; however, all share the common objective of reducing shoreline/edge erosion. Several of the projects attempt to do this by lining the edge with an erosion resistant material (coir roll and/or stone). The others attempt to reduce the incident energy (typically wave) before it reaches the shoreline. The effectiveness of the projects was evaluated by measuring how well they 1) stabilize the edge and 2) reduce wave energy.

A two-year field campaign spanning fall 2018 to spring 2020 focused on monitoring the effectiveness of each site is detailed below. The field campaign included at least biannual surveying of the shoreline and water level/wave attenuation data collection (at the sill and breakwater sites). Data collection campaigns were performed on the following schedule: fall/winter 2018 (F/W 2018), spring/summer 2019 (S/S 2019), fall/winter 2019 (F/W 2019) and spring/summer 2020 (S/S 2020).

### Shoreline Stability

One of the most common engineering objectives of living shoreline projects is to reduce erosion along exposed shorelines, while at the same time preserving or creating habitat. The effectiveness of a particular project can be determined by comparing the shoreline change rate at the location of interest and a nearby control site, to the historical shoreline changes. Comparing post-construction changes to historical changes provides information as to whether conditions are improving, while comparing to an adjacent site puts this information into context with changes occurring in the system as a whole. In other words, if things have improved, is it due to the project, or a change in the conditions experienced throughout the larger system. Surveys intended to capture both the temporal and spatial context are commonly referred to as following the BACI (**B**efore, **A**fter, **C**ontrol, **I**mpact) approach (Yepsen et al., 2016).

Shoreline stability has been evaluated over the duration of this project using a combination of RTK GPS (real-time kinematic global positioning system) surveying and UAV (unmanned aerial vehicle; or drone) imagery. Shorelines, vegetation lines, and/or the extent of any vertical scarps at some project sites were tracked using RTK GPS and used to supplement the UAV imagery collected at all sites. Images captured by the UAV were post-processed using a technique called Structure from Motion (SfM) to derive orthomosaic images and surface elevations from which Digital Elevation Models (DEMs) were constructed. This technique is considered complementary to the RTK GPS technique as there are some limitations related to dealing with dense vegetation in the imagery. The RTK GPS (applicable only at Berkeley Island and Matts Landing) and UAV surveys collected during the study are detailed in Table 4. All surveys were performed at low tide to capture the greatest amount of exposed intertidal area.

*Table 4: Unmanned aerial vehicle survey dates for the five project sites. Real-time kinematic global positioning system (RTK GPS) data were collected simultaneously at some locations.*

| Study Area | F/W 2018 | S/S 2019 | F/W 2019 | S/S 2020 |
|---|---|---|---|---|
| **Berkeley Island*** | 7/31/2018 | 6/24/2019 | 11/15/2019 | 5/5/2020 |
| **Gardner's Basin** | 10/4/2018 | 5/14/2019 | 11/13/2019 | 5/7/2020 |
| **Strathmere** | 10/4/2018 | 5/14/2019 | 11/13/2019 | 5/7/2020 |
| **Gandys Beach** | 10/19/2018 | 4/30/2019 | 12/20/2019 | 4/6/2020 |
| **Matts Landing**** | 10/19/2018 | 6/27/2019 | 12/19/2019 | 4/7/2020 |
| *RTK GPS of wet/dry shoreline additionally collected | | | | |
| **RTK GPS of top and bottom of scarp additionally collected | | | | |

### *Historical Imagery Analysis*

To better understand the effectiveness of the living shoreline projects, it is necessary to consider them in the context of the historical changes that occurred before the installation of the project. Information on the historical changes at each site was obtained by analyzing Google Earth images. Prior to using each image, a quality control check was performed. Poor quality images, or images where the shoreline was not clearly visible, were not included in the analysis and only "good" images were analyzed. It should be noted that even the better-quality images need to be interpreted cautiously, because imagery taken at different times of the year or different stages of the tide will often be misleading. The results presented in the report are based on the subset of images that are considered most representative.

At each site, baselines were established for both the project and control sites. These baselines were situated such that, despite fluctuations, the shoreline would rarely, if ever, intersect the baseline. Perpendicular transects were defined at regularly-spaced intervals along these baselines. For each acceptable image, the distance between the baseline and the shoreline was measured and recorded at each transect. Specific information on each baseline, transect spacing, and shoreline identification are given in the results section for each project site.

### *Drone Imagery Analysis*

The high-quality high-resolution orthomosaics produced from the UAV imagery collected at low tide were analyzed using a similar approach as detailed for the historical imagery. The same project and control baselines were used, and in most cases the same transects and methodology for choosing the shoreline were used. At sites where additional RTK GPS data were available, it was used to aid in the determination of the shoreline at that site.

### *Combined Shoreline Stability Analysis*

For all sites, the pre-construction shoreline stability analysis is based entirely on the results obtained from the analysis of historical Google Earth imagery. For two of the most recently constructed projects (Strathmere and Gardner's Basin), the post-construction trends are based solely on the analysis of UAV imagery collected as part of this study. For the other three projects (Berkeley Island, Gandys Beach, and

Matts Landing) the post-construction" analysis includes a combination of historical imagery collected after the project's installation and the UAV images collected as part of this project.

To summarize the changes over time, a linear least-squares regression was used to find the pre- and post-installation rates of shoreline change at each transect. These values were averaged across the site to determine the average shoreline change rate for both the project site and the control site. Standard deviations were also calculated to provide an estimate of the longshore variability of the shoreline changes.

### Wave Attenuation

Three of the selected projects (Berkeley Island, Gandys Beach, and Gardner's Basin) include offshore structures intended to reduce wave energy at the shoreline. At these sites, wave attenuation was selected as a second measure of effectiveness. Sills and breakwaters function by attenuating wave energy prior to it reaching some landward feature such as a beach or marsh edge. For each of the sites containing a sill or breakwater (Gardner's Basin, Berkeley Island, Gandys Beach), waves were measured both offshore and inshore of the wave attenuation structure. Ocean Sensor Systems Wavelogger IIIs (waveloggers) were used to measure total water level at a sampling frequency high enough to extract the wave climate in post-processing. A typical wave sampling transect is shown in Figure 2. As illustrated in the figure, it was common for there to be no water at the inshore wavelogger during periods of low tide. During these periods, inshore waves could not be measured, and wave attenuation statistics could not be calculated. The actual duration of each data collection period was based on the expected dominant contributor to wave energy at each site. Table 5 summarizes the deployment and retrieval dates for wave data collection at each of the sites throughout the study period.

*Figure 2: The effectiveness of a sill or breakwater can be evaluated by measuring the waves both in-front-of (offshore) and behind (inshore) the sill or breakwater to calculate effectiveness at attenuating waves under various conditions. Above shows two Wavelogger IIIs deployed at Berkeley Island, NJ, for such purpose in January 2019. The waveloggers are mounted to posts, which are pounded into the ground.*

*Table 5: Wave attenuation data collection dates. Two datasets were collected at Berkeley Island during the spring/summer of 2019; they are differentiated in name as A and B.*

| Study Area | F/W 2018 | S/S 2019 | F/W 2019 | S/S 2020 |
|---|---|---|---|---|
| Berkeley Island | 3/28/19 - 4/1/19 | A: 1/16/19 - 1/23/19<br>B: 6/13/19 - 6/16/19 | 10/30/19 - 11/4/19 | 3/19/20 - 4/1/20 |
| Gardner's Basin | 10/8/18 - 10/10-18 | 4/15/19 - 4/15/19 | 10/29/19 - 11/04/19 | 5/7/20 - 5/15/20 |
| Gandys Beach | 10/22/18 - 10/30/18 | 4/29/19 - 5/14/19 | 10/3/19 - 10/9/19 | 4/6/20 - 4/14/20 |

During each instrument deployment, the waveloggers sampled at a minimum of 10 Hz for 59 minutes every hour. The near-continuous water-level time-series at each location were divided into synchronous 18-minute bursts starting at minute 1:30, 21:30, and 40:30 during post-processing. These bursts were processed to remove the tidal signal. A 60-second moving average was used on each burst to approximate the mean water surface, which was then subtracted from the readings. The moving average filter shortens each burst to 17 minutes. Once the mean water level was removed, a zero upcrossing approach was used to identify individual wave events. Wave statistics were calculated for each burst including both significant wave height (average of the highest 1/3rd of the measurements) and maximum wave height.

Wave attenuation can be reported in several ways. In this analysis, attenuation is presented as percent reduction, which is defined as:

$$R = \frac{H_o - H_i}{H_o} x100$$

where $H_o$ and $H_i$ are the wave heights offshore and inshore of the structure, respectively. Waves measuring less than 1 cm were not included in the analysis as they are near the sensitivity limit of the instruments. At Berkeley Island and Gandys Beach, the percent reduction calculation was based on the significant wave height for each sampling period. At Gardner's Basin, the maximum wave height during each sampling period was used instead, because the majority of the wave energy is related to boat wakes. Boat wakes are episodic events, which would not be accurately represented by an average wave height statistic such as significant wave height.

# Berkeley Island County Park

## Site Description

Berkeley Island is located in Berkeley Township along the western shore of Barnegat Bay in Ocean County. Originally an island, the landmass that is currently home to the John C. Bartlett, Jr. County Park was connected to the mainland at some point between 1956 and 1963 (Miller et al, 2014). In the early 2010's Ocean County began to develop plans to restore several eroding shorelines within the park. Of immediate concern was the southern facing shoreline, which by 2010 had eroded to the extent that it was threatening the main parking lot. Rather than simply constructing a bulkhead or placing riprap along the shoreline, the county collaborated with the NJDEP and Stevens to develop one of the first large scale living shoreline projects in a moderate-high energy environment in the state. Stevens developed a conceptual design for a stone sill structure with several gaps using their engineering guidelines (Miller et al., 2014). The county then worked with their consulting engineer (T&M Associates) to refine and ultimately build the project. During the design phase, the consulting engineer identified extremely unstable subsurface conditions during its geotechnical investigation. The creative solution proposed and ultimately constructed by the design engineer was to introduce a low-crested wooden bulkhead spine. The spine runs through the middle of the original stone sill and ensures that if the rocks settle over time, the structure will still dissipate enough energy to prevent the interior shoreline from eroding. Several of the gaps were also modified during construction based on observed erosion. A site location map and project photos are presented in Figures 3 and 4; additional site photos can be found in Appendix C.

## Cost Analysis

The costs for the Berkeley Island project were not made available; however, T&M Associates provided the costs for a similar structure built at Iowa Court in Little Egg Harbor Township. T&M was the design engineer for both projects, and the design for the Iowa Court project was nearly identical to that used at Berkeley Island. Therefore, it is expected that the costs for the Iowa Court project can be considered representative of the type of structure constructed at Berkeley Island. The costs for the Iowa Court project are provided in Table 6, and represent costs billed by the contractor. Minor adjustments were made to remove costs clearly associated with repairing the roadway, which was also part of the Iowa Court contract. On the surface it appears as though materials represent the bulk of the cost; however, labor is likely included in several of the lump sum cost items. As the project is recently constructed, no information is available regarding maintenance or adaptive management. In comparison to many of the other projects, monitoring represents a significant cost component, as both pre- and post-construction monitoring are included in the total project cost.

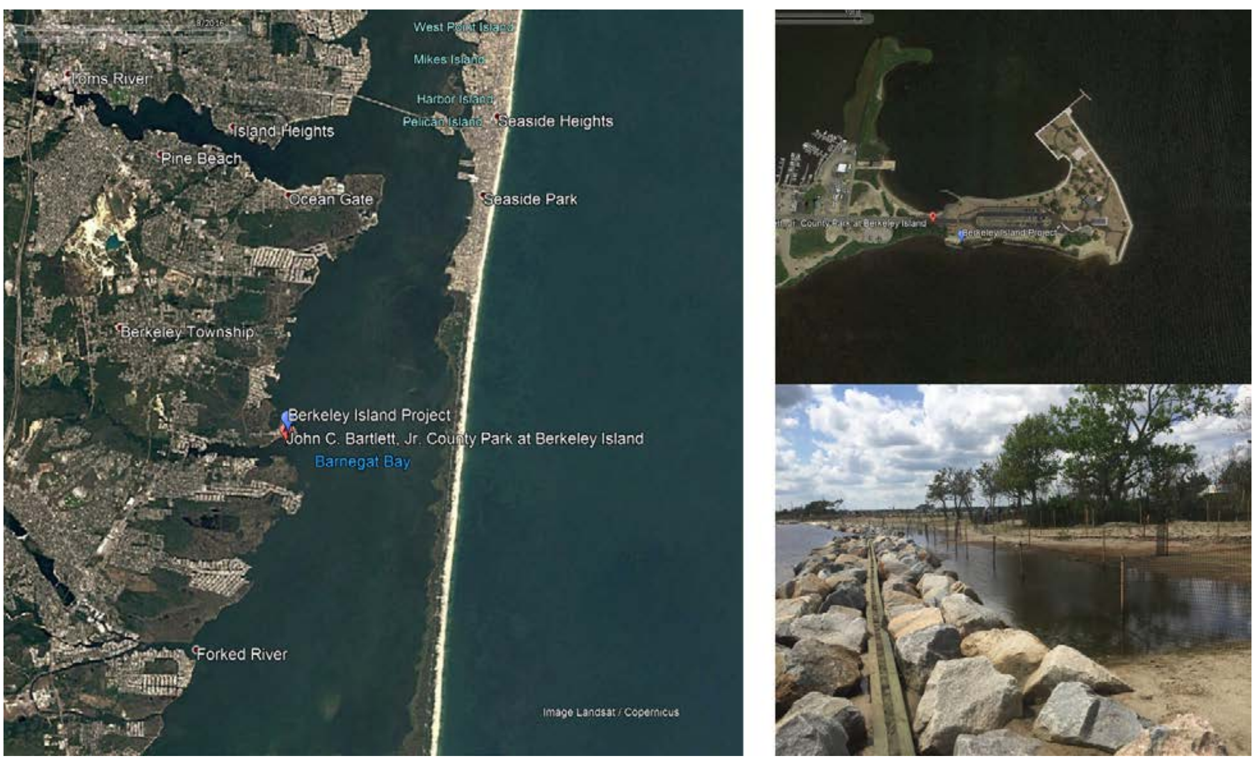


*Figure 3: Site map and project photo of the Berkeley Island living shoreline site.*

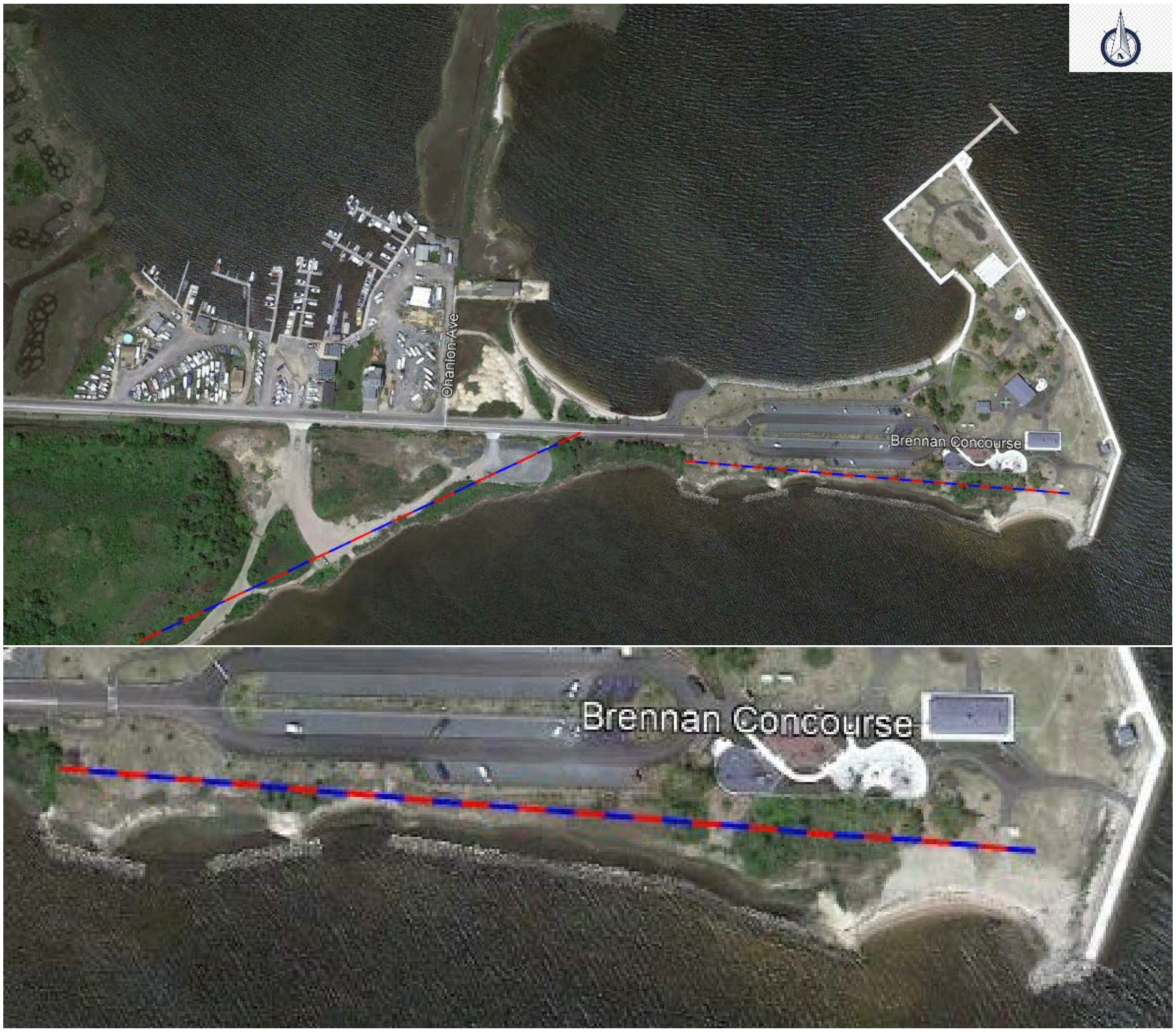


*Figure 4: Google Earth Image (May 2019) showing Berkeley Island County Park, Berkeley Township, NJ, at two scales. The red and blue lines on the left in the top image are the baseline for the control area of the shoreline stability analysis. The red and blue line, landward of the breakwater/sill structures, is the baseline for the project area used in the shoreline stability analysis.*

*Table 6: Berkeley Island living shoreline project costs. LS – Lump Sum.*

| Berkeley (Iowa Court) (~500 ft) | | |
|---|---|---|
| ***Installation Costs*** | **Unit Cost** | **Unit** |
| Mobilization | $ 66,690 | LS |
| Site Work | $ 16,690 | LS |
| Soil Erosion and Sediment Control | $ 27,669 | LS |
| Rip-Rap | $ 41,206 | LS |
| Capstone | $ 110,754 | LS |
| Timber Sheet (20' long) | $ 375,760 | LS |
| Timber Pile | $ 22,500 | LS |
| RipRap Scour | $ 10,000 | LS |
| Beach Sand | $ 109,600 | LS |
| Spartina Alterniflora | $ 32,250 | LS |
| Spartina Patens | $ 10,850 | LS |
| Demodb and Site Rest | $ 6,669 | LS |
| ***Miscellaneous Costs*** | | |
| Post Const As-Built Survey | $ 9,969 | LS |
| Pre-construction Monitoring | $ 46,752 | LS |
| Post-Construction Monitoring (5 yrs) | $ 81,200 | LS |
| ***Maintenance/Adaptive Management Costs*** | | |
| Additional Stone | $ 38,186 | LS |
| Goose protection | $ 2,500 | LS |

## Long-term Cost Estimate

The long-term cost estimate for the Berkeley Island/Iowa Court project is given below in Table 7. Of the five living shoreline projects evaluated in this study, Berkeley Island was the most expensive overall, and the most expensive per linear foot due to the complexity of the project. As the project contains elements of both a conventional rock sill as well as a wooden bulkhead, the long-term cost analysis reflects that. Damage costs are assumed to be associated with replacing or moving rock and vegetation during storms with a longer than 40-yr return period. Due to the bulkhead core and rock exterior, the Berkeley island project is not expected to experience significant ice damage and annual maintenance is anticipated to be minimal. A key factor increasing the long-term cost of the Berkeley Island project is deterioration of the wooden bulkhead, which is expected to need replacement at some point during the 60-year period considered.

*Table 7: Long-term cost estimate for the Berkeley Island living shoreline project. Ext – Extended.*

| Long-term Cost Estimate - Berkeley Island (Iowa Court) Living Shoreline | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | P1 (2020-2040) | | P2 (2040-2060) | | P3 (2060-2080) | | Total (2020-2080) | |
| **Category** | **Storm $T_r$** | **% IC** | **# Events** | ***Cost** | **# Events** | ***Cost** | **# Events** | ***Cost** | **Ext Cost** | **% Final** |
| **Initial Cost (IC)** | NA | NA | NA | NA | NA | NA | NA | NA | $ 830,638 | 25.5% |
| **Damage Cost (DC)** | 50 | 0% | 0.62 | $ - | 1.83 | $ - | 5.45 | $ - | $ - | 0.0% |
| **Damage Cost (DC)** | 40 | 10% | 0.77 | $ 64,660 | 2.28 | $ 198,127 | 6.80 | $ 607,815 | $ 870,603 | 26.8% |
| **Damage Cost (DC)** | 25 | 0% | 1.22 | $ - | 3.64 | $ - | 10.81 | $ - | $ - | 0.0% |
| **Damage Cost (DC)** | 10 | 0% | 2.98 | $ - | 6.45 | $ - | 26.32 | $ - | $ - | 0.0% |
| **Damage Cost Ice** | NA | 0% | 2.00 | $ - | 1.00 | $ - | 0.00 | $ - | $ - | 0.0% |
| **Replacement Cost (RC)** | NA | 100% | 0.00 | $ - | 1.00 | $ 867,797 | 0.00 | $ - | $ 867,797 | 26.7% |
| **Maintenance Costs (MC)** | NA | 5% | 1.00 | $ 42,142 | 1.00 | $ 43,390 | 1.00 | $ 44,674 | $ 130,206 | 4.0% |
| **Mon & Adapt Man (MA)** | NA | 14.7% | 1.00 | $ 123,898 | 0.00 | $ - | 0.00 | $ - | $ 123,898 | 3.8% |
| | | HRSSP | | | **Post-Construction Costs (DCs+RC+MC+MA)** | | | | $ 2,364,139 | 72.7% |
| | | Assumed | | | **Design and Permiting Costs** | | | | $ 56,721 | 1.7% |
| | | | | | | | | **Total Cost** | $ 3,251,498 | 100.0% |

*Costs are calculated as the IC x %IC x #Events with inflation and discounting applied mid period

## Effectiveness

### Shoreline Stability

Transects perpendicular to the pre-defined baseline (shown in Figure 4) used in the Berkeley Island shoreline stability analysis were spaced at 25-foot intervals. The shoreline feature selected for analysis at this location was the wet/dry line, where available, and, otherwise, the vegetated edge. The vegetated edge is particularly relevant/useful in areas of marsh erosion and scarp formation. The shoreline identified as the control area is located to the east of the project area. Figure 5 and Figure 6 show the pre- and post-installation shoreline positions at each transect relative to the project and control baselines. Figure 5 illustrates that before installation of the living shoreline project, changes throughout the area were relatively homogenous with the exception of the eastern tip of the area; in this location, there is a hardened edge where no change is observed. Figure 6 shows that that there is an initial adjustment of the shoreline to the project in the project area (May 2018 to June 2019), after which the shoreline stabilizes. This commonly occurs during/immediately after the construction of nearshore structures, as the sediment adjusts to the presence of the structures. In the case of segmented breakwaters, it is typical for the shoreline to accrete behind the structure and retreat to a stable position behind the gaps, as shown in Figure 4.

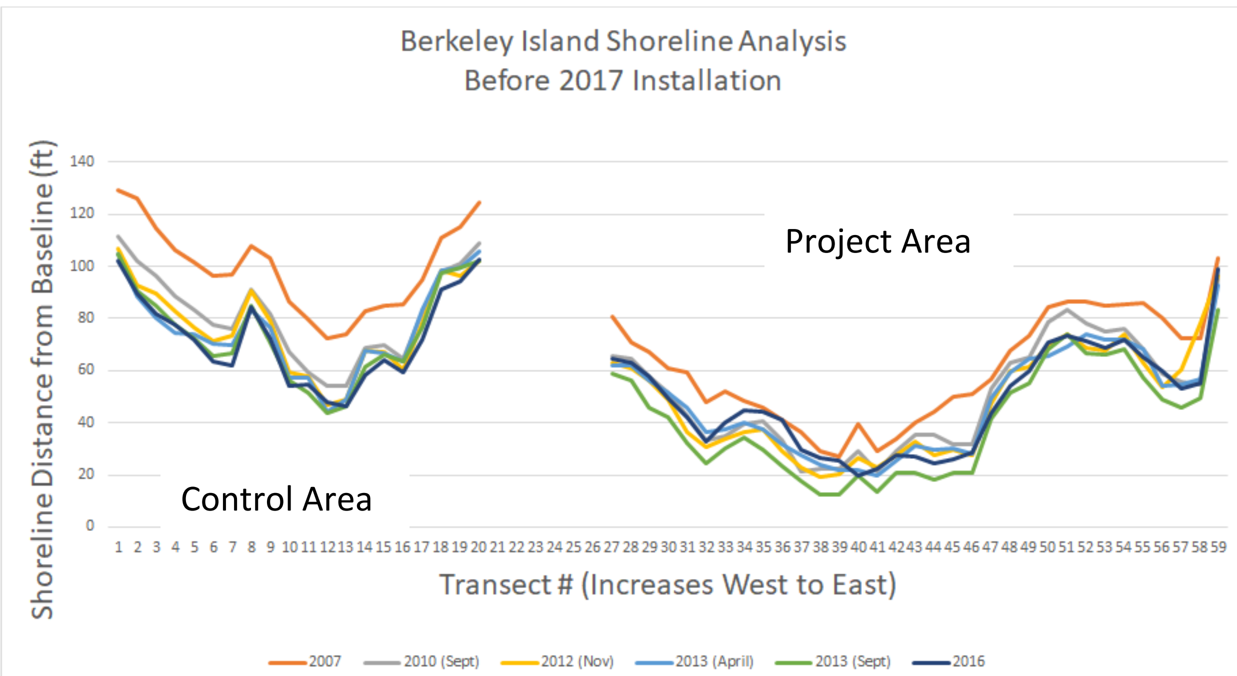


*Figure 5: Pre-installation shoreline stability analysis for Berkeley Island County Park living shoreline. Analysis is based on historical imagery provided in Google Earth. Historical Imagery is shown as a solid line; drone surveys are shown as dashed lines.*

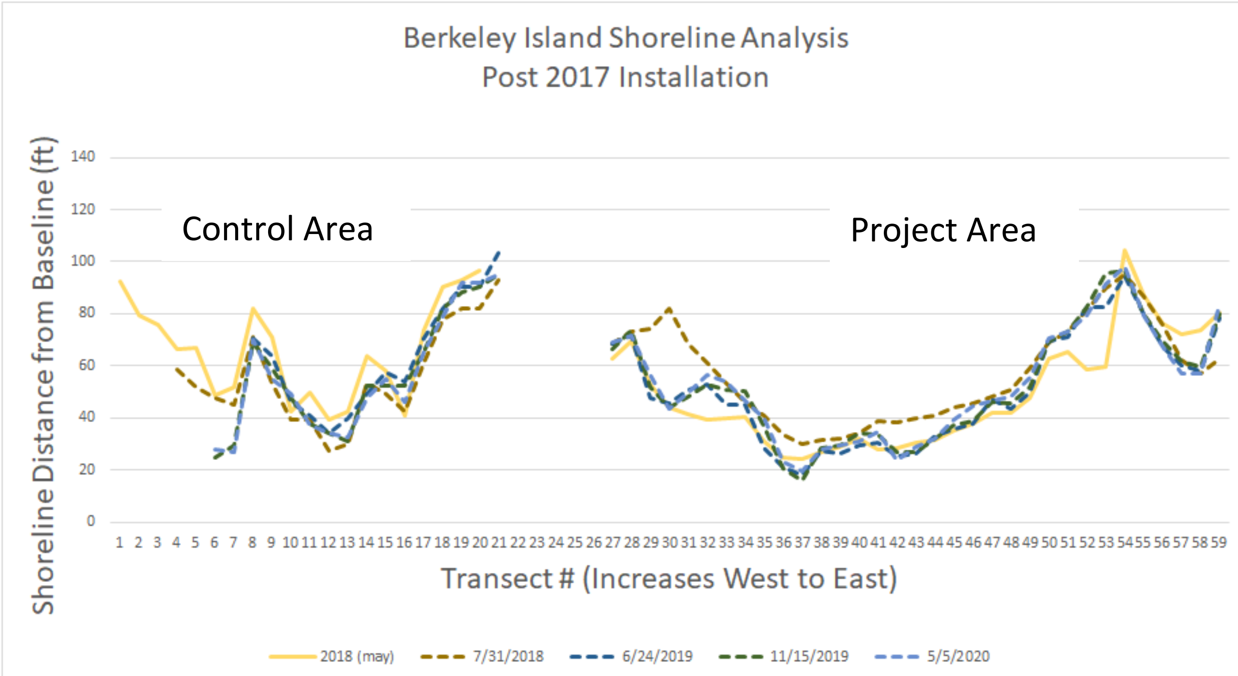


*Figure 6: Post-installation shoreline stability analysis for Berkeley Island living shoreline. Analysis is based on imagery collected by the UAV as part of this study. Historical Imagery is shown as a solid line; drone surveys are shown as dashed lines.*

Shoreline change rates at the site are summarized in Table 8. The average rate of shoreline change in the project area was found to be -1.7 ft/year (erosion) prior to the project installation and 0.0 ft/year (stable) after installation. This contrasts with the control site where the average rate of change was measured at -3.1 ft/year (erosion) before project installation and -5.8 ft/year (erosion) after. These numbers indicate that the project is having a positive impact on the shoreline, effectively stabilizing it during an otherwise erosive period. The standard deviation of the shoreline change rates was also calculated and is presented in Table 8. The larger values after project construction are thought to be related to the adjustment process as the shoreline strives to find a new equilibrium to a non-uniform structure.

*Table 8: Summary of the Berkeley Island shoreline stability analysis for the project and control areas both before and after the installation of the project in 2017. Negative rates of change represent net erosion of the shoreline. Standard deviation is a measure of uniformity with low values indicating the changes are uniform across the site and large values indicating a high degree of variability.*

| Berkeley Island - Installation 2017 | | | | |
|---|---|---|---|---|
| (ft/yr) | Living Shoreline | | Control Site | |
| | Before 2017 | After 2017 | Before 2017 | After 2017 |
| Average Rate of Change | -1.7 | 0.0 | -3.1 | -5.8 |
| Standard Deviation | 0.7 | 4.7 | 0.7 | 10.0 |

Overall, it appears as though the living shoreline project at Berkeley Island has been successful in stabilizing the shoreline in the project area, essentially stopping the retreat of that shoreline inshore of the structure while the unprotected area (i.e., the control area) continues to retreat. The variability seen in the rate of change post-installation in both the control and project areas is likely an adjustment of the shoreline in response to the structure. At least in the short term, it is expected that the control area will continue to erode, and the project shoreline will remain stabilized. In order to more fully understand how the project will maintain its functionality given projected rises in sea level and increased storminess, continued monitoring is required

## Wave Attenuation

Water level measurements for calculating wave attenuation were collected offshore and inshore of the sill at Berkeley Island County Park over five data collection periods as detailed in Table 5. An example of the results for one of the five deployments is shown below in Figure 7. The complete results for all deployments appear in Appendix B. During the F/W 2019 deployment shown in Figure 7, 43.4% of the wave heights (significant) recorded offshore of the breakwater exceeded 5 cm, and 23.63% of the waves exceeded 10 cm. This deployment includes a significant wave event on October 31 - November 1 that clearly illustrates the wave attenuation capability of the structure. The average percent reduction during the F/W 2019 deployment was 42.7% overall and 51.4% when the offshore wave heights exceeded 5 cm.

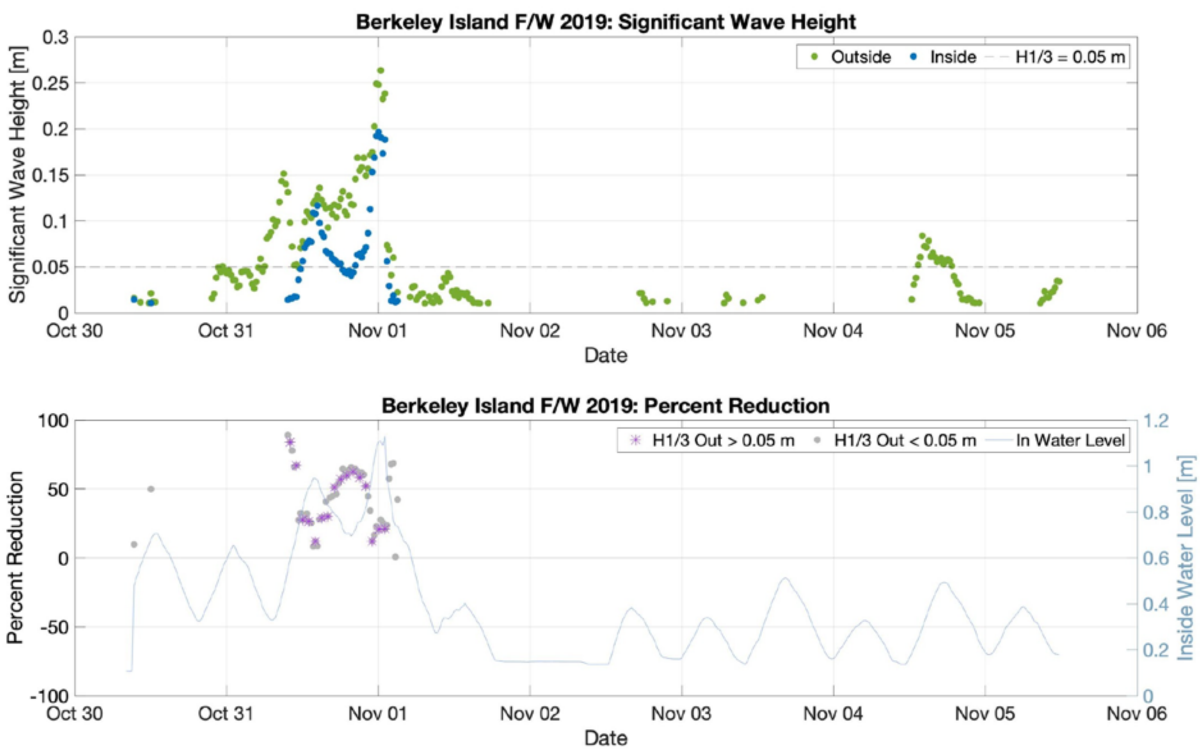


*Figure 7: Significant wave heights, percent reduction and inshore water level for Berkeley Island during the fall/winter 2019 monitoring period. All percent reduction values are shown in gray, and purple stars were added to highlight periods when offshore significant wave heights exceeded 5 cm.*

When considering data collected during all five Berkeley Island deployments, on average 42.5% of the offshore wave heights exceeded 5 cm and 16.2% exceeded 10 cm. The distribution of the percent reduction values during all five of the deployments is summarized in the histogram shown in Figure 8. All waves were positively attenuated at Berkeley Island during all deployments. The average percent reduction measured during the study was 48.8%, with over half of the values falling between 25% and 75%. The distribution of the percent reduction values during only the larger wave events (offshore significant wave heights greater than 5 cm) is additionally shown. The average percent reduction for just these larger wave events was 52.1%.

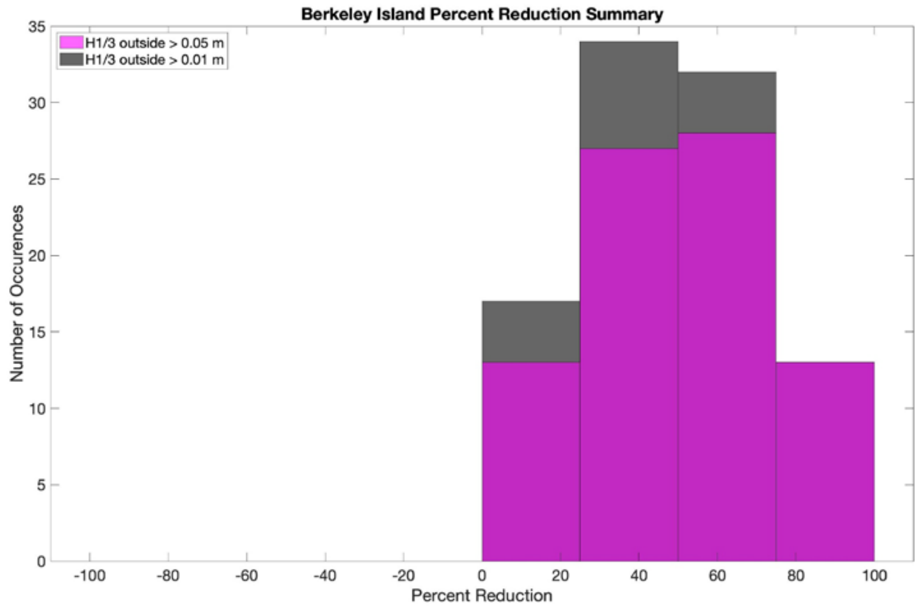


*Figure 8: Histogram describing the distribution of percent reduction values at Berkeley Island during all deployments for offshore significant wave heights greater than 1 cm (gray) and greater than 5 cm (purple).*

# Gardner's

## Site Description

Gardner's Basin is located on the waterfront in the northwestern corner of Atlantic City. Located just off of Absecon Inlet, the basin itself is home to the Atlantic City Aquarium, and a variety of recreational and commercial businesses. Among these are a number of recreational boating and commercial fishing businesses. The majority of the shoreline within Gardner's Basin is bulklheaded to support these interests. In 2016, Atlantic City collaborated with the NJ DEP to construct a living shoreline project to reduce flooding and protect the shoreline along one of the last remaining non-bulkheaded shorelines within Gardner's Basin. The project, which was funded by the town with a grant from the National Fish and Wildlife Foundation (NFWF) administered by the New Jersey Department of Environmental Protection (NJDEP), resulted in the construction of a low crested sill, planted marsh, and berm. The sill design at the site is unique in that it incorporates a gap and sloping beach section to preserve access for horseshoe crabs, which were found in abundance during site visits. A site location map and project photos are presented in Figures 9 and 10; additional site photos can be found in Appendix C.

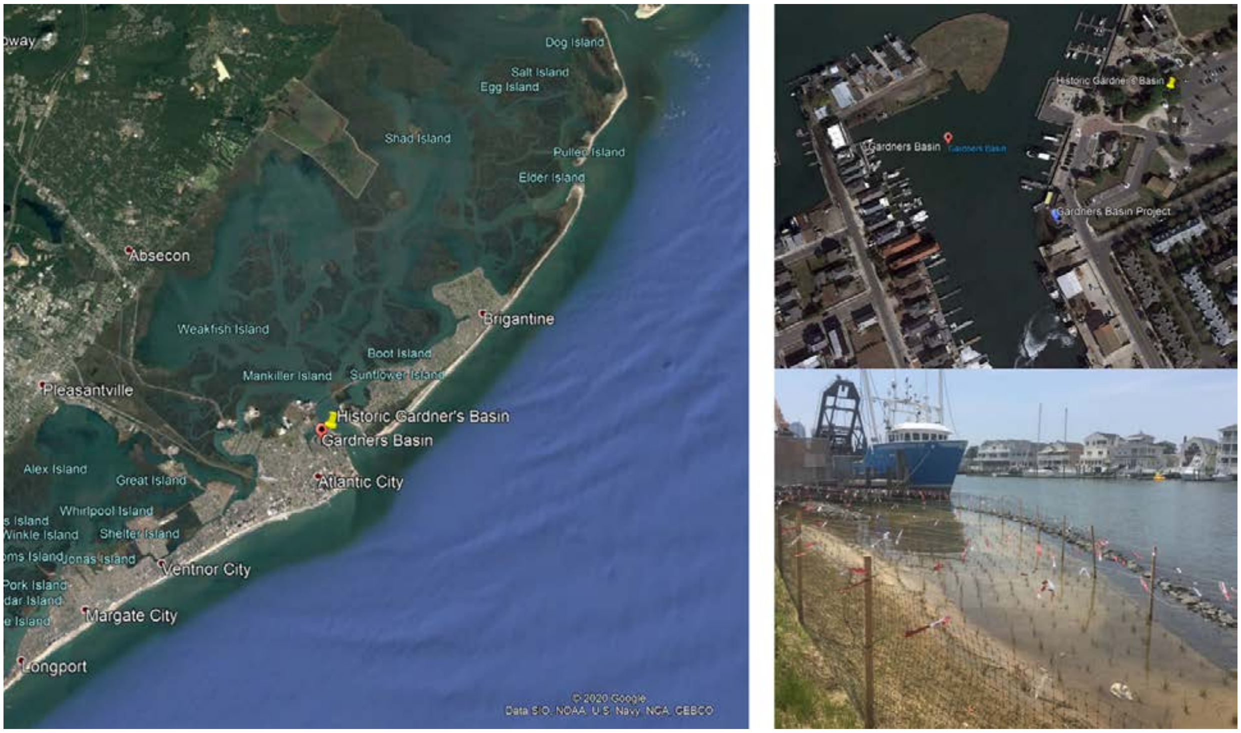


*Figure 9: Site map and project photo of the Gardner's Basin living shoreline site.*

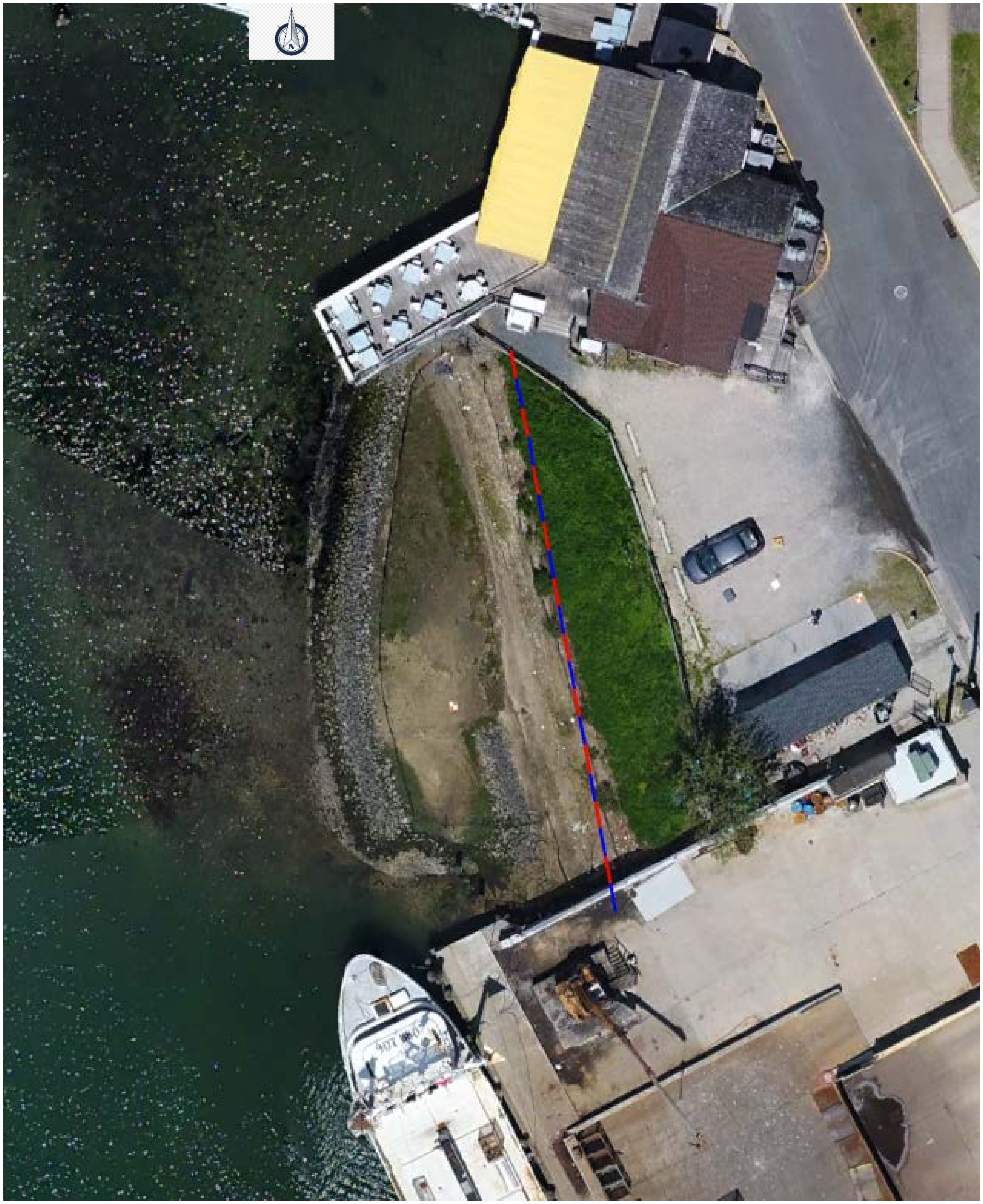

*Figure 10: Orthomosaic from Imagery collected on May 7, 2020, showing Gardner's Basin, Atlantic City, NJ. The red and blue line located landward of the sill is the baseline for this project site that was used in the shoreline stability analysis. There is no suitable control area for this project site as the surrounding region is bulkheaded and developed.*

## Cost Analysis

Cost data for the Gardner's Basin living shoreline project was taken from a budget prepared by the project engineer, Arthur W. Ponzio and Company Associates. The budget included a basic breakdown of costs related to the construction of the project. The total construction cost was estimated at $135,000 and was split between the municipality and the NJDEP. Separate estimates were provided for design, permitting, surveying, and construction management. Those costs were estimated at $39,000. All of the costs are summarized below in Table 9. No information was provided on maintenance and adaptive management costs.

*Table 9: Gardner's Basin living shoreline project costs. LS – Lump Sum.*

| Gardners Basin (~100 LF) | | |
|---|---|---|
| ***Installation Costs*** | **Unit Cost** | **Unit** |
| Mobilization | $ 15,000 | LS |
| Embankment Work | $ 45,000 | LS |
| Geosynthetic Mat | $ 75,000 | LS |
| ***Miscellaneous Costs*** | | |
| Surveying | $ 10,000 | LS |
| Design and Permitting | $ 29,000 | LS |

Cost information in the form of contractor bids was also obtained for a 1,000 linear foot conventional bulkhead/revetment shoreline stabilization project for a second property within Gardner's Basin. For comparison purposes, that information was compiled and the average bid price for each item was calculated. The results are given in Table 10.

*Table 10: Gardner's Basin bulkhead/revetment project costs. LS – Lump Sum.*

| Gardners Basin Gray (~1083 LF) | | |
|---|---|---|
| ***Installation Costs*** | **Unit Cost** | **Unit** |
| General Work | $ 330,320 | LS |
| Site Clearing | $ 139,885 | LS |
| Steel Sheetpile (35') | $ 2,391,597 | LS |
| Rehandle Stone A | $ 90,899 | LS |
| Rehandle Stone B | $ 35,283 | LS |
| New Stone A | $ 121,785 | LS |
| New Stone B | $ 45,208 | LS |
| Seal | $ 79,238 | LS |
| Splashpad | $ 228,092 | LS |
| Soil | $ 335,685 | LS |
| ***Miscellaneous Costs*** | | |
| Survey | $ 30,775 | LS |
| Monitoring | $ 24,615 | LS |

## Long-term Cost Estimate

The long-term cost estimate for the Gardner's Basin living shoreline project is given below in Table 11. Consistent with the HRSSP analysis, the major damage cost is assumed to be associated with replacing or rehandling rock during storms with a 40-yr or greater return period. Due to the potential for ice to form in the basin and for the ice to displace some of the rocks and vegetation, 10% of the IC were assumed to repair ice damage. The damage cost associated with ice formation is consistent with that used for the 40-yr storm, as the impacts are expected to be similar. Consistent with the assumptions used in the HRSSP analysis for sills, MCs of 10% of the IC were included for each period. This covers the cost of general site maintenance including trash removal and limited replanting of vegetation and rehandling of rock. While MA costs were not provided, a nominal amount of 5% of the IC was assumed. Design and permitting costs were taken from the engineer's cost estimate and makeup approximately 8% of the long-term cost.

*Table 11: Long-term cost estimate for the Gardner's Basin living shoreline project. Ext – Extended.*

| Long-term Cost Estimate - Gardners Living Shoreline | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | P1 (2020-2040) | | P2 (2040-2060) | | P3 (2060-2080) | | Total (2020-2080) | |
| Category | Storm $T_r$ | % IC | # Events | *Cost | # Events | *Cost | # Events | *Cost | Ext Cost | % Final |
| Initial Cost (IC) | NA | NA | NA | NA | NA | NA | NA | NA | $ 135,000 | 28.9% |
| Damage Cost (DC) | 50 | 0% | 0.62 | $ - | 1.83 | $ - | 5.45 | $ - | $ - | 0.0% |
| Damage Cost (DC) | 40 | 10% | 0.77 | $ 10,509 | 2.28 | $ 32,201 | 6.80 | $ 98,786 | $ 141,495 | 30.3% |
| Damage Cost (DC) | 25 | 0% | 1.22 | $ - | 3.64 | $ - | 10.81 | $ - | $ - | 0.0% |
| Damage Cost (DC) | 10 | 0% | 2.98 | $ - | 6.45 | $ - | 26.32 | $ - | $ - | 0.0% |
| Damage Cost Ice | NA | 10% | 2.00 | $ 27,397 | 1.00 | $ 14,104 | 0.00 | $ - | $ 41,501 | 8.9% |
| Replacement Cost (RC) | NA | 0% | 0.00 | $ - | 0.00 | $ - | 0.00 | $ - | $ - | 0.0% |
| Maintenance Costs (MC) | NA | 10% | 1.00 | $ 13,698 | 1.00 | $ 14,104 | 1.00 | $ 14,521 | $ 42,324 | 9.1% |
| Mon & Adapt Man (MA) | NA | 5% | 1.00 | $ 6,849 | 0.00 | $ - | 0.00 | $ - | $ 6,849 | 1.5% |
| | | HRSSP | | | Post-Construction Costs (DCs+RC+MC+MA) | | | | $ 292,569 | 62.7% |
| | | Assumed | | | Design and Permiting Costs | | | | $ 39,000 | 8.4% |
| | | | | | | | | Total Cost | $ 466,569 | 100.0% |

*Costs are calculated as the IC x %IC x #Events with inflation and discounting applied mid period

The long-term cost estimate for a nearby conventional shoreline stabilization project consisting of a bulkhead and a revetment is provided in Table 12. The project was by far the most expensive of all the projects reviewed, but also the longest. Few details on the structure other than the cost estimate were provided. For the purposes of assigning costs, it was assumed that a revetment fronting a bulkhead would protect the shoreline, and thus the structure would be very resilient. Damage costs of 5% of the IC, potentially associated with scour and overtopping, were assumed during a 50-yr storm. MCs of 5% of the IC were assumed during each period related to stone movement and general degradation of the materials. MA costs as well as design and permitting costs were taken directly from the cost estimates provided. The biggest post-construction cost is associated with the replacement of the steel bulkhead, which is assumed to occur in Period 3.

*Table 12: Long-term cost estimate for a nearby conventional shoreline stabilization project within Gardner's Basin consisting of a bulkhead and a revetment. Ext – Extended.*

| Long-term Cost Estimate - Gardners Bulkhead/Revetment | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | P1 (2020-2040) | | P2 (2040-2060) | | P3 (2060-2080) | | Total (2020-2080) | |
| Category | Storm $T_r$ | % IC | # Events | *Cost | # Events | *Cost | # Events | *Cost | Ext Cost | % Final |
| Initial Cost (IC) | NA | NA | NA | NA | NA | NA | NA | NA | $ 3,797,991 | 32.1% |
| Damage Cost (DC) | 50 | 5% | 0.62 | $ 118,506 | 1.83 | $ 363,360 | 5.45 | $ 1,113,179 | $ 1,595,045 | 13.5% |
| Damage Cost (DC) | 40 | 0% | 0.77 | $ - | 2.28 | $ - | 6.80 | $ - | $ - | 0.0% |
| Damage Cost (DC) | 25 | 0% | 1.22 | $ - | 3.64 | $ - | 10.81 | $ - | $ - | 0.0% |
| Damage Cost (DC) | 10 | 0% | 2.98 | $ - | 6.45 | $ - | 26.32 | $ - | $ - | 0.0% |
| Damage Cost Ice | NA | 0% | 2.00 | $ - | 1.00 | $ - | 0.00 | $ - | $ - | 0.0% |
| Replacement Cost (RC) | NA | 100% | 0.00 | $ - | 0.00 | $ - | 1.00 | $ 4,085,368 | $ 4,085,368 | 34.5% |
| Maintenance Costs (MC) | NA | 5% | 1.00 | $ 192,690 | 1.00 | $ 198,395 | 1.00 | $ 204,268 | $ 595,353 | 5.0% |
| Mon & Adapt Man (MA) | NA | 0.7% | 1.00 | $ 25,050 | 0.00 | $ - | 0.00 | $ - | $ 25,050 | 0.2% |
| | | HRSSP | | | Post-Construction Costs (DCs+RC+MC+MA) | | | | $ 8,000,070 | 67.6% |
| | | Assumed | | | Design and Permiting Costs | | | | $ 30,775 | 0.3% |
| | | | | | | | | Total Cost | $11,828,836 | 100.0% |

*Costs are calculated as the IC x %IC x #Events with inflation and discounting applied mid period

## Effectiveness

### Shoreline Stability

Transects perpendicular to the pre-defined baseline (shown in Figure 10) used in the Gardner's Basin shoreline stability analysis were spaced at 5-foot intervals. The shoreline of interest at this location was chosen as the wet/dry line. There is no suitable control for this project as the entire area is bulkheaded or otherwise armored, therefore, the shoreline stability analysis was only performed for the project area. Figure 11 and Figure 12 show the pre- and post-installation shoreline positions at each transect relative to the project baseline. The variability seen in the historical analysis is likely a reflection of the generally poor quality of the aerial imagery of the site and the resulting difficulty in delineating the wet/dry line. The stability displayed by the post-construction shoreline is more indicative of what would be expected at such a low-energy site.

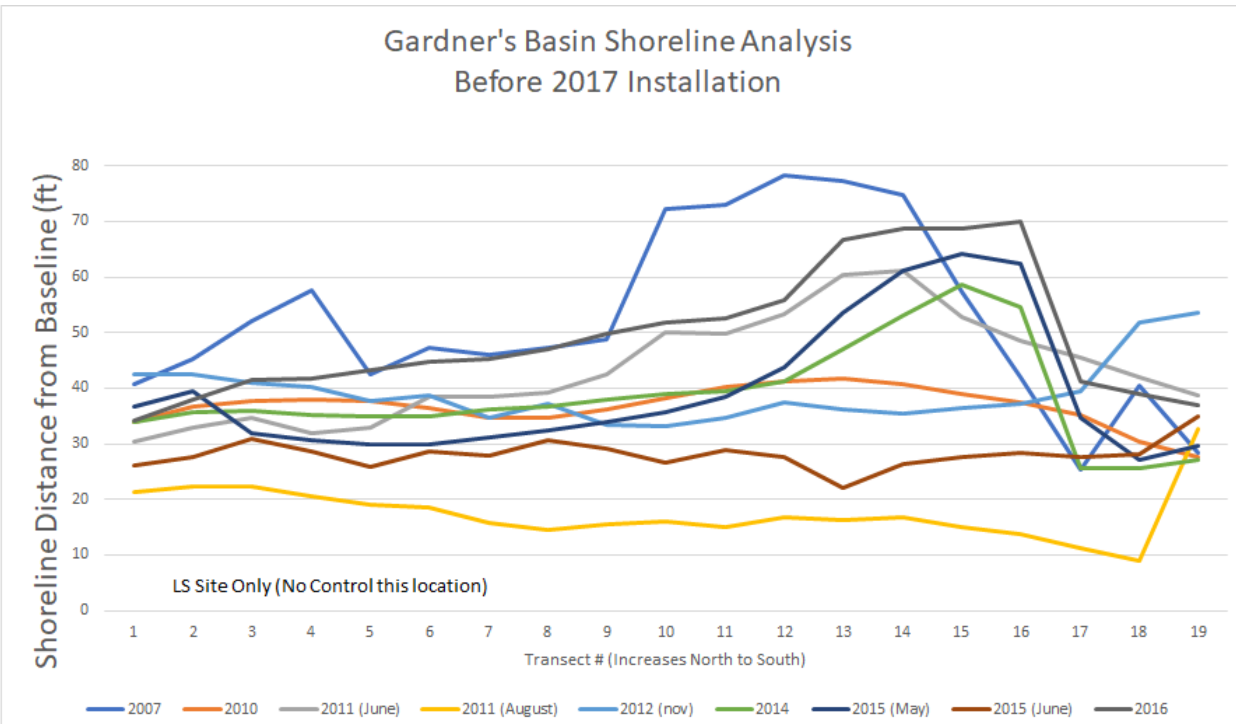


*Figure 11: Pre-installation shoreline stability analysis for Gardner's Basin living shoreline. Analysis is based on historical imagery provided in Google Earth.*

A summary of the measured shoreline changes is presented in Table 13. At Gardner's Basin, it was found that the average rate of shoreline change in the project area was -0.7 ft/year (erosion) prior to installation and -0.9 ft/year (erosion) after installation with a pre-installation range of -2.6 (erosion) to -2.3 ft/year (erosion) pre-installation and a post-installation range of -3.3 (erosion) to 0.8 ft/year (accretion). The standard deviation, which measures the uniformity of the shoreline fluctuations, did not change, remaining constant at 1.3 ft/year.

The shoreline analysis suggests that the living shoreline project at Gardner's Basin has only had a de minimis effect on the shoreline. Without a control against which to compare the results, it is difficult to determine if the project was successful in mitigating erosion. This project has successfully achieved other goals; however, such as increasing the visual appeal of the area and creating a habitat more conducive to natural biota. Continued regular monitoring of this site is necessary to determine if the project succeeded in stabilizing the shoreline.

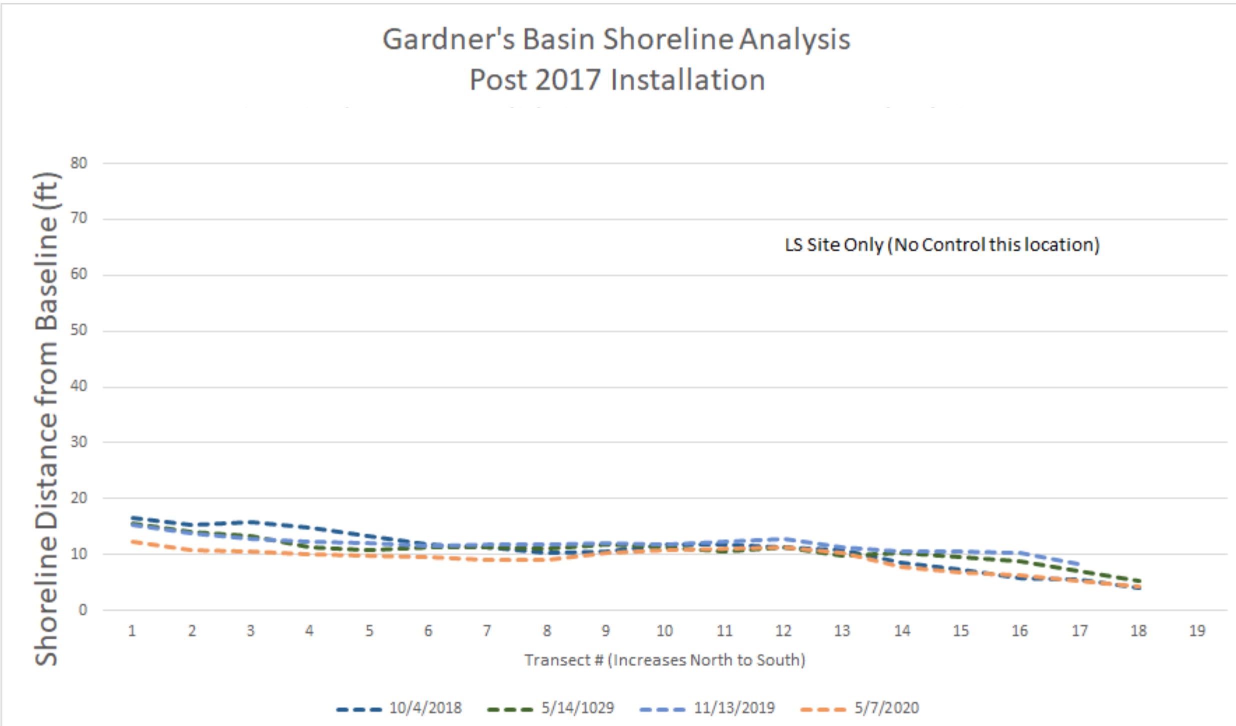


*Figure 12: Post-installation shoreline stability analysis for Gardner's Basin living shoreline. Analysis is based on imagery collected by the UAV as part of this study.*

*Table 13: Summary of the Gardner's Basin project area shoreline stability analysis both before and after the installation of the project in 2017. Negative rates of change represent net erosion of the vegetated shoreline. Standard deviation is a measure of uniformity with low values indicating the changes are uniform across the site and large values indicating a high degree of variability.*

| Gardner's Basin - Installation 2017 | | |
|---|---|---|
| (ft/yr) | Living Shoreline | |
| | Before 2017 | After 2017 |
| Average Rate of Chage | -0.7 | -0.9 |
| Standard Deviation | 1.3 | 1.3 |

## Wave Attenuation

Water level measurements for calculating wave attenuation were collected offshore and inshore of the sill at Gardner's Basin over the four deployment periods detailed in Table 5. Due to the limited fetch within Gardner's Basin, the majority of the waves are created by boat wakes. Because boat wakes are intermittent, average wave statistics such as significant wave height do not represent the wave climate well. Therefore, maximum wave heights, and percent reduction based on maximum wave heights were used instead of significant wave heights for all analyses related to Gardner's Basin. An example of the results for one of the four deployments is shown in Figure 13. The complete results appear in Appendix B.

During the F/W 2019 deployment at Gardner's Basin, only 16.3% of the recorded maximum wave heights exceeded 5 cm and only 9.6% of the maximum wave heights exceeded 10 cm. This number is extremely low when considering these values represent maximums and not averages and illustrates the lack of wave energy at the site. During the F/W 2019 deployment, there were several intermittent events during which wave attenuation could be measured. Unfortunately, during some of the larger wave events, the water level inshore of the structure was too low to reliably measure waves. This is true for approximately half of the large waves measured offshore of the structure on October 31.

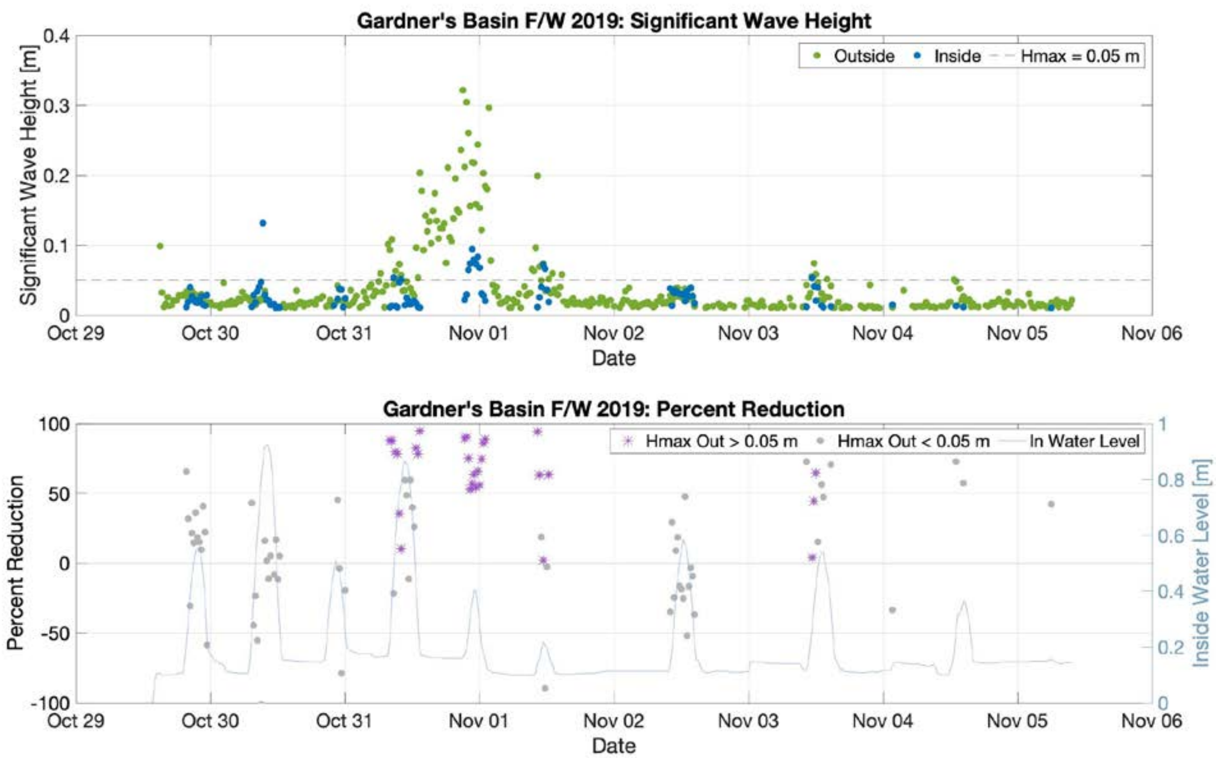


*Figure 13: Maximum wave heights, percent reduction and inshore water level for Gardner's Basin during the fall/winter 2019 monitoring period. All percent reduction values are shown in gray, and purple stars were added to highlight periods when offshore maximum wave heights exceeded 5 cm.*

Over the four deployments at Gardner's Basin, on average only 11.5% of the maximum wave heights exceeded 5 cm, and only 5.2% exceeded 10 cm. This represents a small proportion of the total number of potential waves. The distribution of the percent reduction values for all the deployments at Gardner's Basin is summarized in the histogram shown in Figure 14. On average, the sill at Gardner's Basin reduced the incident waves by 20.7%. Cases where negative percent reduction values were calculated correspond to periods when the waves measured inshore of the sill were larger than those measured offshore of the sill. Kerr, et al. (2020), discusses a number of possible physical explanations; however, at Gardner's Basin all of these instances occur when the offshore waves were smaller than 5 cm. This is close to the measurement and noise threshold of the instrument. If only the waves larger than 5 cm are considered (purple in Figure 14), the negative percent reduction values are eliminated, the average percent reduction increases to 65.9%, and the vast majority exceed 50%. All leading to the conclusion that the sill is effectively attenuating waves.

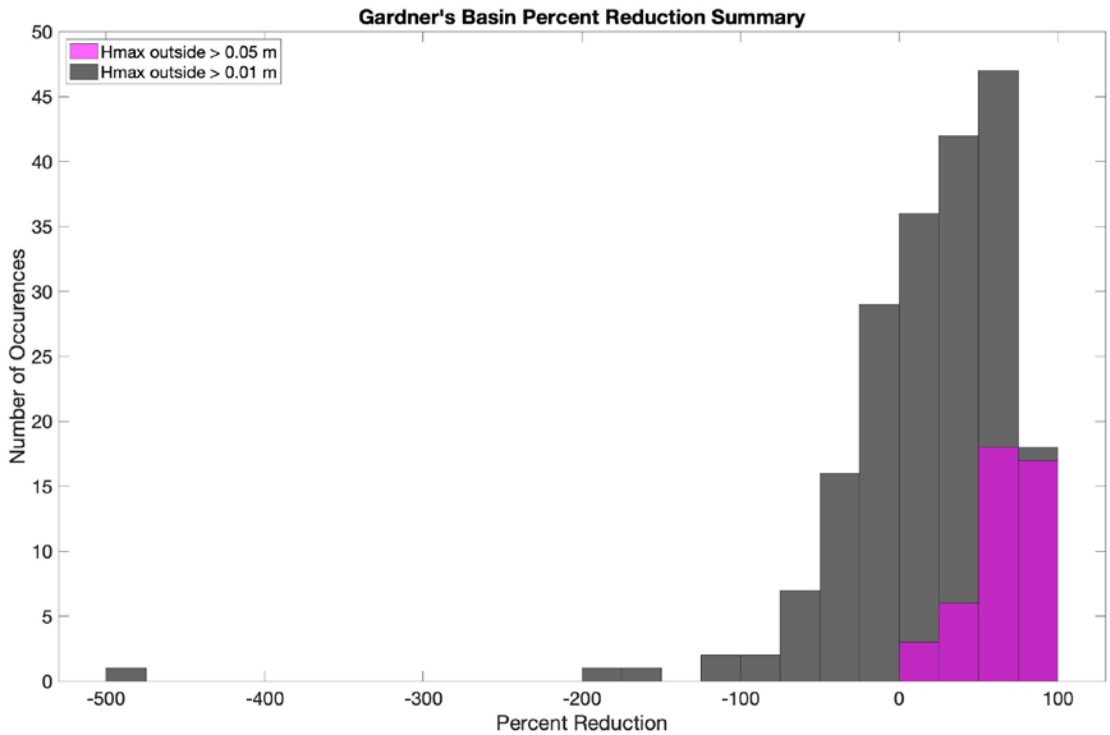


*Figure 14: Histogram describing the distribution of percent reduction values at Gardner's Basin during all deployments for offshore maximum wave heights greater than 1 cm (gray) and greater than 5 cm (purple).*

# Strathmere

## Site Description

In 2014, Upper Township collaborated with the NJDEP to design and build a living shoreline project along Bayview Drive in the community of Strathmere (Figure 15 and Figure 16). The project was a multi-faceted project, which also included the reconstruction of a bulkhead and boat ramp. The living shoreline component of the project was intended to address the persistent erosion of the marsh immediately southwest of the boat ramp and to potentially reduce flooding on Bayview Drive. An analysis of the site conditions performed by Stevens identified ice, boat wakes and upland drainage as potential reasons for the observed erosion and recommended the construction of a submerged sill to address the problem. Ultimately, a hybrid terraced structure consisting of a lower marsh with a stone toe and an upper marsh with a coir roll toe was constructed. Unfortunately, due to heavy icing during the first winter after construction, the coir roll and many of the upper marsh plantings were removed. As of the writing of this report, the project has not been repaired. A site location map and project photos are presented in Figures 15 and 16; additional site photos can be found in Appendix C.


*Figure 15: Site map and project photo of the Strathmere living shoreline site.*

*Figure 16: Orthomosaic created from UAV imagery collected on May 7, 2020, showing Strathmere, Upper Township, NJ. The red and blue lines to the left of the image is the baseline for the control area of the shoreline stability analysis. The two red and blue lines, landward of the sill and landward of the vegetated shoreline, to the right of the image are the baselines for the project area used in the shoreline stability analysis.*

## Cost Analysis

The Strathmere living shoreline project was part of a larger project, which included the reconstruction of a boat ramp along with several bulkheads. The town's municipal engineer provided cost information for the larger project. The costs were divided between the living shoreline and bulkhead components and are summarized below in Table 14 and Table 15. For items such as mobilization that relate to both parts of the project, the costs were apportioned according to the relative costs of the bulkhead and living shoreline components. Compared to the other cost estimates that were reviewed, the level of detail for Strathmere was fairly coarse.

*Table 14: Strathmere living shoreline project costs. LS – Lump Sum.*

| Strathmere LS (100 LF) | | | |
|---|---|---|---|
| ***Installation Costs*** | **Unit Cost** | | **Unit** |
| Living Shorelines Plantings | $ | 38,967 | LS |
| ***Miscellaneous Costs*** | | | |
| Mobilization | $ | 27,500 | LS |
| Permitting | $ | 20,000 | LS |
| Engineering Design | $ | 6,811 | LS |

*Table 15: Strathmere bulkhead project costs. LS – Lump Sum.*

| Strathmere BH (201 LF) | | | |
|---|---|---|---|
| ***Installation Costs*** | **Unit Cost** | | **Unit** |
| Bulkhead Installation | $ | 82,611 | LS |
| ***Miscellaneous Costs*** | | | |
| Mobilization | $ | 27,500 | LS |
| Permitting | $ | 20,000 | LS |
| Engineering Design | $ | 6,811 | LS |

## Long-term Cost Estimate

The long-term cost estimate for the Strathmere living shoreline project is shown below in Table 16. Damage costs of 5% of the IC were assumed to occur during a 10-yr storm and 10% of the IC during a 25-yr storm. During these smaller storms, it is considered more likely that the energy will be focused on the lower stone toe and upper coir roll toe of the terraced structure. Some damage is expected due to scour and overtopping during these events. During larger storms, it is assumed that the project is sufficiently submerged to avoid significant damage. Ice damage costs are estimated at 25% of the ICs. This is the estimated cost associated with replacing the coir roll and some of the vegetation. Design and permitting costs for the living shoreline component of the project were derived by scaling the total design cost by the relative construction costs. Damage costs (10-yr, 25-yr, and ice) represent nearly half of the estimated long-term costs associated with the Strathmere project. The susceptibility of the coir roll to erosion is the predominant reason. Any project repair should consider replacing the original coir roll toe with a stone toe to reduce future costs.

*Table 16: Long-term cost estimate for the Strathmere living shoreline project. Ext – Extended.*

| Long-term Cost Estimate - Strathmere Living Shoreline | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | P1 (2020-2040) | | P2 (2040-2060) | | P3 (2060-2080) | | Total (2020-2080) | |
| Category | Storm $T_r$ | % IC | # Events | *Cost | # Events | *Cost | # Events | *Cost | Ext Cost | % Final |
| Initial Cost (IC) | NA | NA | NA | NA | NA | NA | NA | NA | $ 40,727 | 16.3% |
| Damage Cost (DC) | 50 | 0% | 0.62 | $ - | 1.83 | $ - | 5.45 | $ - | $ - | 0.0% |
| Damage Cost (DC) | 40 | 0% | 0.77 | $ - | 2.28 | $ - | 6.80 | $ - | $ - | 0.0% |
| Damage Cost (DC) | 25 | 10% | 1.22 | $ 5,049 | 3.64 | $ 15,472 | 10.81 | $ 47,361 | $ 67,882 | 27.1% |
| Damage Cost (DC) | 10 | 5% | 2.98 | $ 6,159 | 6.45 | $ 13,725 | 26.32 | $ 57,643 | $ 77,527 | 31.0% |
| Damage Cost Ice | NA | 25.0% | 2.00 | $ 20,663 | 1.00 | $ 10,637 | 0.00 | $ - | $ 31,300 | 12.5% |
| Replacement Cost (RC) | NA | 0.0% | 0.00 | $ - | 0.00 | $ - | 0.00 | $ - | $ - | 0.0% |
| Maintenance Costs (MC) | NA | 10.0% | 1.00 | $ 4,133 | 1.00 | $ 4,255 | 1.00 | $ 4,381 | $ 12,768 | 5.1% |
| Mon & Adapt Man (MA) | NA | 0.0% | 0.00 | $ - | 0.00 | $ - | 0.00 | $ - | $ - | 0.0% |
| | | HRSSP | | | Post-Construction Costs (DCs+RC+MC+MA) | | | | $ 207,699 | 83.0% |
| | | Assumed | | | Design and Permiting Costs | | | | $ 1,716 | 0.7% |
| | | | | | | | | Total Cost | $ 250,142 | 100.0% |

*Costs are calculated as the IC x %IC x #Events with inflation and discounting applied mid period

The long-term cost estimate for the bulkhead portion of the Strathmere project is given below in Table 17. All costs were treated consistently with the bulkhead analyses in Rella and Miller (2014). Damages were assumed due to scour and overtopping during the 25-yr and 50-yr storms. MCs of 5% of the ICs were assumed during each period and it is assumed that the bulkhead will need to be replaced once during the 60-year study period. Ice damage and MA, costs that were not considered in the HRSSP report, are assumed minimal. Based on these assumptions, the long-term costs associated with a conventional bulkhead shoreline stabilization project would be expected to be split relatively evenly amongst initial construction, small and large repairs, and the eventual replacement of the bulkhead.

*Table 17: Long-term cost estimate for the Strathmere bulkhead project. Ext – Extended.*

| Long-term Cost Estimate - Strathmere Bulkhead | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | P1 (2020-2040) | | P2 (2040-2060) | | P3 (2060-2080) | | Total (2020-2080) | |
| Category | Storm $T_r$ | % IC | # Events | *Cost | # Events | *Cost | # Events | *Cost | Ext Cost | % Final |
| Initial Cost (IC) | NA | NA | NA | NA | NA | NA | NA | NA | $ 87,836 | 22.8% |
| Damage Cost (DC) | 50 | 10% | 0.62 | $ 5,481 | 1.83 | $ 16,807 | 5.45 | $ 51,489 | $ 73,777 | 19.2% |
| Damage Cost (DC) | 40 | 0% | 0.77 | $ - | 2.28 | $ - | 6.80 | $ - | $ - | 0.0% |
| Damage Cost (DC) | 25 | 5% | 1.22 | $ 5,445 | 3.64 | $ 16,685 | 10.81 | $ 51,071 | $ 73,201 | 19.0% |
| Damage Cost (DC) | 10 | 0.0% | 2.98 | $ - | 6.45 | $ - | 26.32 | $ - | $ - | 0.0% |
| Damage Cost Ice | NA | 0.0% | 2.00 | $ - | 1.00 | $ - | 0.00 | $ - | $ - | 0.0% |
| Replacement Cost (RC) | NA | 100.0% | 0.00 | $ - | 1.00 | $ 91,765 | 0.00 | $ - | $ 91,765 | 23.9% |
| Maintenance Costs (MC) | NA | 5.0% | 1.00 | $ 4,456 | 1.00 | $ 4,588 | 1.00 | $ 4,724 | $ 13,769 | 3.6% |
| Mon & Adapt Man (MA) | NA | 0.0% | 0.00 | $ - | 0.00 | $ - | 0.00 | $ - | $ - | 0.0% |
| | | HRSSP | | | Post-Construction Costs (DCs+RC+MC+MA) | | | | $ 291,810 | 75.8% |
| | | Assumed | | | Design and Permiting Costs | | | | $ 5,091 | 1.3% |
| | | | | | | | | Total Cost | $ 384,737 | 100.0% |

*Costs are calculated as the IC x %IC x #Events with inflation and discounting applied mid period

## Effectiveness

### Shoreline Stability

Transects perpendicular to the pre-defined baseline used in the Strathmere shoreline stability analysis were spaced at 5-foot intervals. The shoreline feature analyzed at this site was the vegetated edge. As illustrated in Figure 16 the control area for this site was located to the South of the project site. Due to the orientation of the site, two distinct baselines were used within the project area. The first project baseline was established running approximately northwest to southeast in the “Stone Toe” area to the south of the boat ramp. A second project baseline oriented approximately North-South was placed on the "Beach" area as shown in Figure 16.

Figure 17 and Figure 18 show the pre- and post-installation shoreline positions at each transect relative to the project baselines. The pre-construction shorelines in the control and stone toe areas display a significant amount of variability. While this may be real, there is also a possibility that at least some of the variability is related to the challenges associated with interpreting some of the older historical images from Google Earth. The data in Figure 17 shows that both the northern edge of the control area and the southern end of the stone-toe area eroded significantly before the living shoreline was installed. The UAV imagery collected at low tide indicates that since the installation of the project, both the beach and control areas appear to be relatively stable. Unfortunately, no traceable features (vegetated shoreline or wet/dry line) could be identified in the drone images in the "Stone Toe '' section, therefore no data is presented for this area.

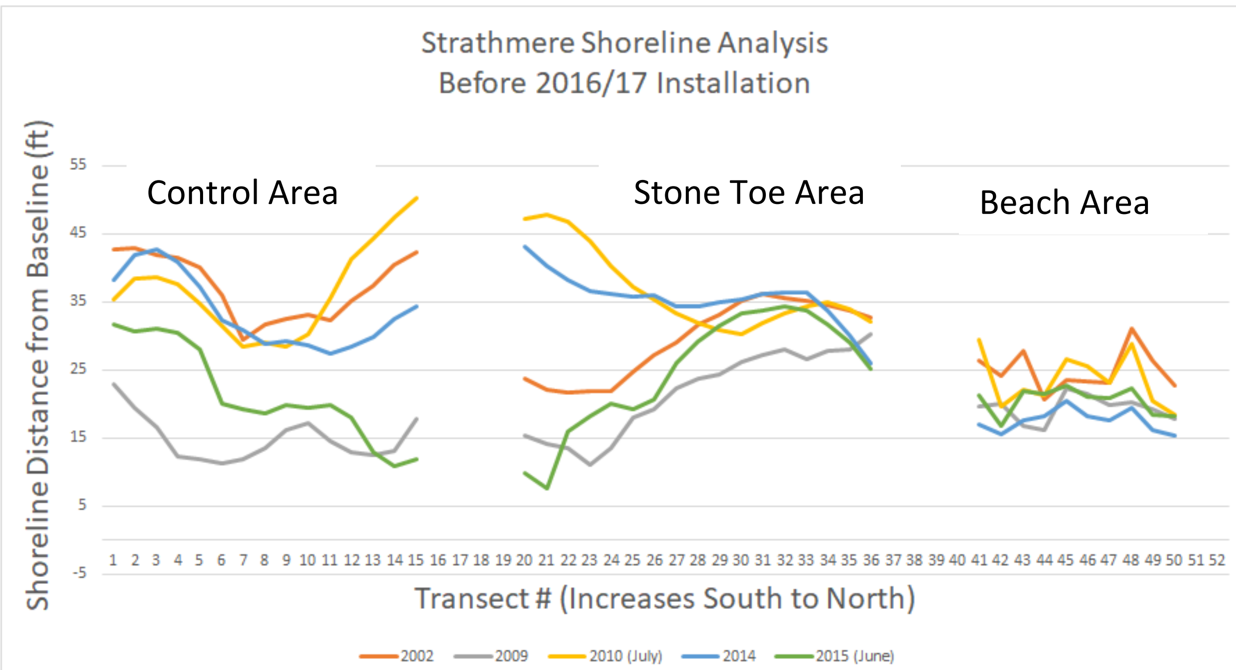


*Figure 17: Pre-installation shoreline stability analysis for Strathmere living shoreline. Analysis is based on historical imagery provided in Google Earth.*

A summary of the shoreline analysis for the Strathmere site is presented in Table 18. It was found that the average rate of shoreline change in the area of the beach decreased from -0.4 ft/year (erosion) prior to installation of the project to -0.3 ft/year (erosion) after installation. A similar result was obtained at the control site, where the average rate of change was measured at -0.6 ft/year (erosion) before the 2016/17 installation of the project and -0.3 in the years since its installation. These are insignificant changes, within the measurement error, and overall suggest a stable shoreline both before and after the project's installation. The rate of change in the area of the stone toe prior to its installation was measured to be 0.1 ft/year. The standard deviation values presented in Table 18 suggest that while there is some longshore variability, overall, the shoreline change rates are in the +/- 1ft/yr range at both the control and project sites both prior to and after installation.

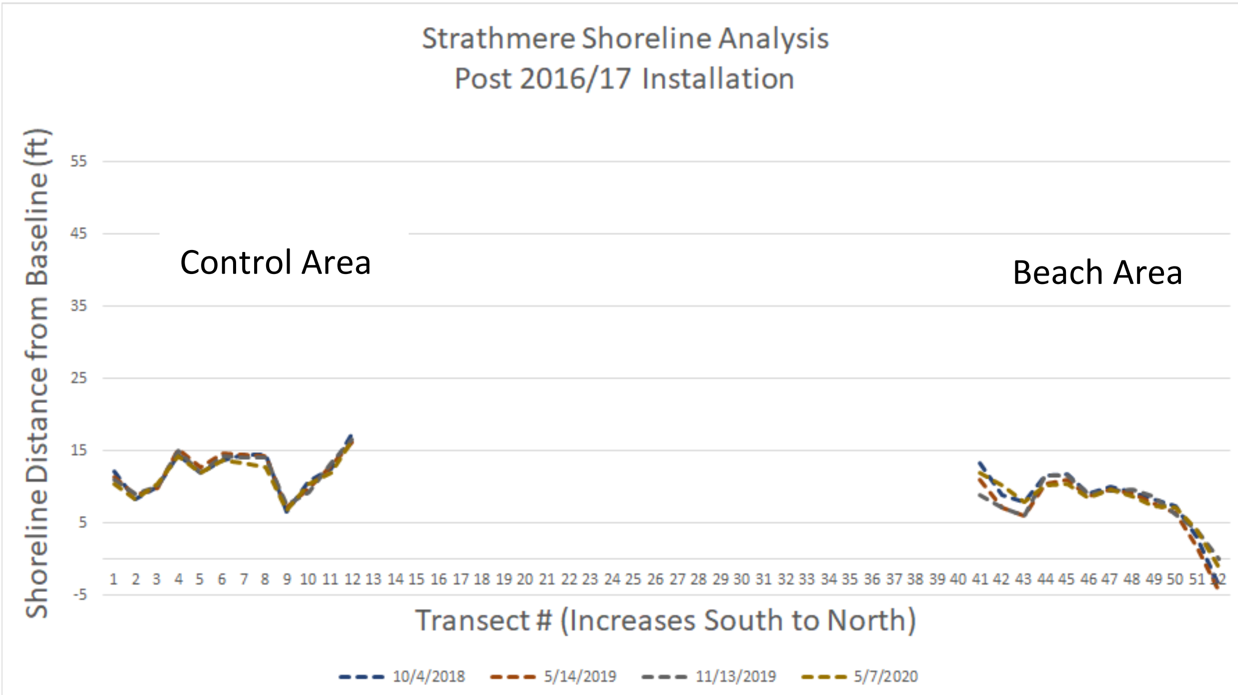


*Figure 18: Post-installation shoreline stability analysis for Strathmere living shoreline. Analysis is based on imagery collected by the UAV as part of this study.*

*Table 18: Summary of the Strathmere shoreline stability analysis for the project and control areas both before and after the installation of the project in 2016/17. Negative rates of change represent net erosion of the vegetated shoreline. Standard deviation is a measure of uniformity with low values indicating the changes are uniform across the site and large values indicating a high degree of variability.*

| Strathmere - Installation 2016/2017 | | | | | | |
|---|---|---|---|---|---|---|
| (ft/yr) | Living Shoreline Site | | | | Control Site | |
| | Stone Toe | | Beach | | | |
| | Before 2016 | After 2016 | Before 2016 | After 2016 | Before 2016 | After 2016 |
| Average Rate of Change | 0.1 | N/A | -0.4 | -0.3 | -0.6 | -0.3 |
| Standard Deviation | 0.3 | N/A | 0.2 | 0.5 | 0.4 | 0.5 |

In summary, the shoreline stability analysis indicates a stable shoreline, with a slight decrease in the overall erosional rate for both the control and beach areas. This small site-wide decrease suggests that the erosive conditions have stayed the same or decreased in the time since the project's installation. While the shoreline has not experienced an increase in erosion, shortly after the project's installation significant damage was caused by winter icing. The ice removed the coir logs and damaged much of the newly planted vegetation. As of the writing of this report, no repair or adaptive management has been performed. While no measurements were made post-installation in the area of the stone toe, it appears to be holding the wet/dry shoreline in place, despite a lack of vegetation. Continued monitoring will allow for a better understanding of the long-term success of this project.

## Gandys Beach

### Site Description

The Gandys Beach Oyster Castle breakwater living shoreline project was part of a US Fish and Wildlife Service (USFWS) funded effort to stabilize two sections of shoreline on TNC's Gandys Beach Preserve in Downe Township, Cumberland County. TNC, the Partnership for the Delaware Estuary (PDE) and the Rutgers Haskin Shellfish Research Laboratory (RHSRL) carried out the project. In total, 37 shell bag reefs and 27 Oyster Castle breakwaters were constructed at the site between July 2014 and December 2017. Although the entire project stretches across 2750 ft of shoreline and includes six groups of Oyster Castle breakwaters, the effectiveness analysis focused on a single set of breakwaters located 500 ft south of the foot of Bayview Rd. This particular breakwater set consists of four individual structures each approximately 30 ft in length oriented in a north-south direction. However, the cost analysis, including the long-term cost estimate, covers the entire project. A site location map and project photos are presented in Figure 19 and 20; additional site photos can be found in Appendix C.

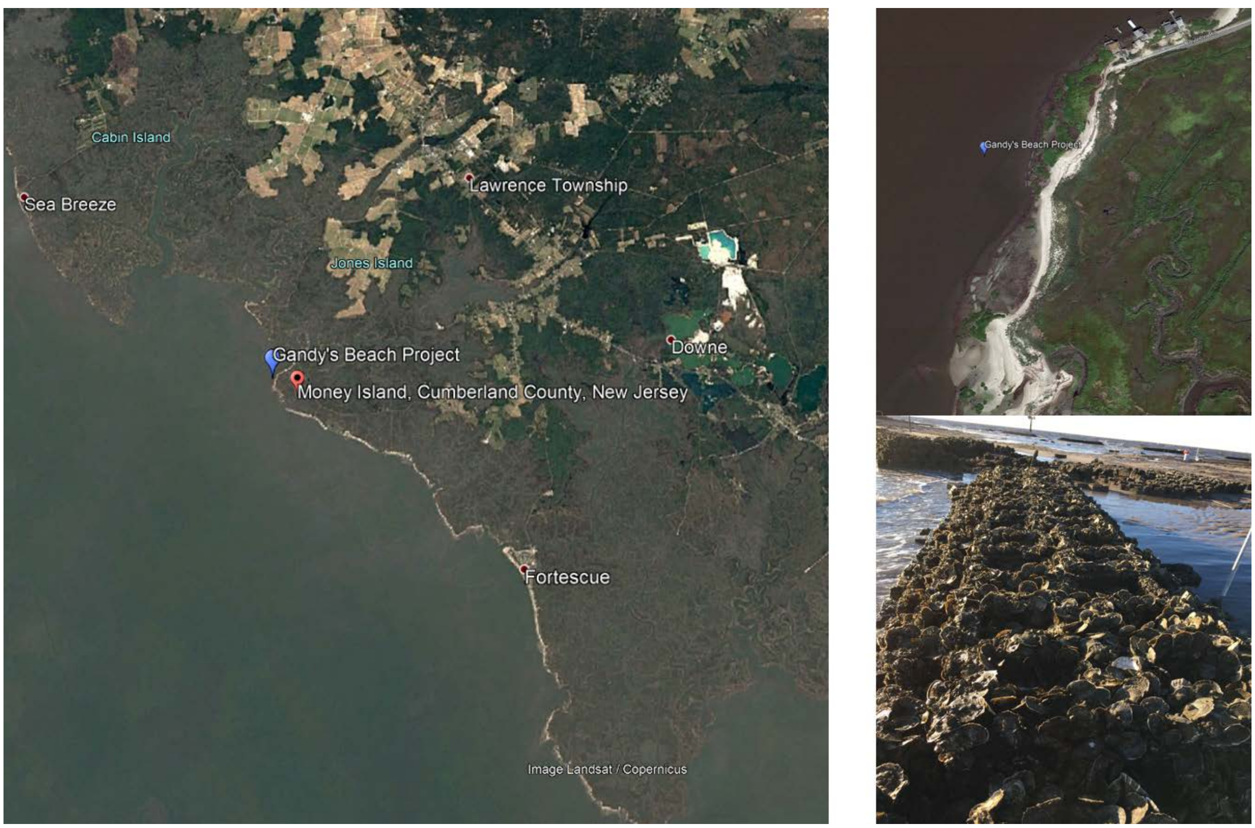


*Figure 19: Site map and project photo of the Gandys Beach living shoreline project site.*

*Figure 20: Orthomosaic created from UAV imagery collected on April 6, 2020, showing the Gandys Beach, Downe Township, NJ. The red and blue lines to the North (top) are the baseline for the control area of the shoreline stability analysis. The red and blue line, landward of the Oyster Castle structures at the bottom of the image is the baseline for the project area used in the shoreline stability analysis.*

## Cost Analysis

Cost information for the Gandys Beach project was provided by TNC and was comprehensive compared to the other sites. The costs, which include information on maintenance, adaptive management, and monitoring, are summarized in Table 19. While the evaluation of effectiveness focuses on a single set of Oyster Castle breakwaters, the cost information provided includes the entire project. Due to the innovative nature of the project, costs for items such as design, monitoring, and adaptive management were significantly higher for the Gandys Beach project than for most of the other projects. These costs make up more than half of the total project cost for the Gandys Beach project; however, they should not be considered typical of future Oyster Castle breakwater living shoreline projects.

*Table 19: Gandys Beach living shoreline project costs. LS – Lump Sum.*

| Gandys Beach (2750 LF) | | |
|---|---|---|
| ***Installation Costs*** | **Unit Cost** | **Unit** |
| Barge | $ 26,100 | LS |
| Coir Mats | $ 1,655 | LS |
| Oyster Castles | $ 93,385 | LS |
| Miscellaneous Costs | $ 1,177 | LS |
| Construction | $ 188,216 | LS |
| TNC Labor | $ 64,491 | LS |
| ***Maintenance/Adaptive Management Costs*** | **Unit Cost** | **Unit** |
| Maintenance post construction | $ 8,000 | LS |
| Monitoring (2014-2022) | $ 443,063 | LS |
| Adaptive Management Design | $ 9,000 | LS |
| Adaptive Management Implementation | $ 65,516 | LS |
| ***Miscellaneous Costs*** | | |
| Design | $ 74,910 | LS |
| Planning/Project Management | $ 32,745 | LS |
| Construction Permit | $ 409 | LS |

Cost information in the form of contractor bid estimates were also obtained for a nearby project, which included bulkhead construction. Those estimates were analyzed and the costs specific to the bulkhead construction were isolated. Three different alternatives - wood, steel sheet pile, and composite sheet pile - were included in each bid. The average of the bid estimates was assumed representative of the cost of bulkhead construction in the area. These costs make up the costs for the Gandys gray alternatives, which are summarized in Table 20.

*Table 20: Gandys Beach bulkhead project costs. LS – Lump Sum.*

| Gandys Gray (~1083 LF) | | |
|---|---|---|
| ***Installation Costs*** | **Unit Cost** | **Unit** |
| Clearing | $ 57,571 | LS |
| Bulkhead (Wood) | $ 445,895 | LS |
| Scour Protect | $ 49,071 | LS |
| Bulkhead (Composite) | $ 491,902 | LS |
| Bulkhead (Steel) | $ 426,056 | LS |

## Long-term Cost Estimate

The long-term cost estimate for the Gandys Beach living shoreline project is given below in Table 21. The damage mechanisms for an Oyster Castle sill are assumed to be similar to those of a rock sill. During a 40-

yr storm, it is assumed that some of the structural units will need to be replaced. A nominally higher percentage of the IC (12% vs 10%) is assigned to repairing damage to an Oyster Castle sill as restacking the units after organisms have begun to colonize the structure is expected to be difficult. Ice damage costs are estimated at 15% of the IC of the structure based on experience with Oyster Castles in New Jersey. Although there is some anecdotal evidence that the situation has improved lately, many of the older Oyster Castle were brittle, and did not stand up well to New Jersey's harsh winters.

MCs and MA costs were taken directly from the information provided. It should be noted that the Gandys Beach project was one of the first projects of its type and scale in the state, and as such, extensive monitoring was required. As a result, the monitoring costs play a disproportionate role in escalating the long-term costs compared to what should be expected for a "normal" Oyster Castle project. The same can be said for the design and permitting costs, which were increased by the innovative nature of the project. The net result is that the long-term costs are disproportionately comprised of post-construction costs.

*Table 21: Long-term cost estimate for the Gandys Beach living shoreline project. Ext – Extended.*

| Long-term Cost Estimate - Gandys Living Shoreline | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | P1 (2020-2040) | | P2 (2040-2060) | | P3 (2060-2080) | | Total (2020-2080) | |
| **Category** | **Storm $T_r$** | **% IC** | **# Events** | ***Cost** | **# Events** | ***Cost** | **# Events** | ***Cost** | **Ext Cost** | **% Final** |
| **Initial Cost (IC)** | NA | NA | NA | NA | NA | NA | NA | NA | **$ 373,847** | **20.3%** |
| **Damage Cost (DC)** | 50 | 0% | 0.62 | $ - | 1.83 | $ - | 5.45 | $ - | **$ -** | **0.0%** |
| **Damage Cost (DC)** | 40 | 12% | 0.77 | $ 34,922 | 2.28 | $ 107,006 | 6.80 | $ 328,273 | **$ 470,201** | **25.5%** |
| **Damage Cost (DC)** | 25 | 0% | 1.22 | $ - | 3.64 | $ - | 10.81 | $ - | **$ -** | **0.0%** |
| **Damage Cost (DC)** | 10 | 0% | 2.98 | $ - | 6.45 | $ - | 26.32 | $ - | **$ -** | **0.0%** |
| **Damage Cost Ice** | NA | 15% | 2.00 | $ 113,802 | 1.00 | $ 58,586 | 0.00 | $ - | **$ 172,388** | **9.4%** |
| **Replacement Cost (RC)** | NA | 0% | 0.00 | $ - | 0.00 | $ - | 0.00 | $ - | **$ -** | **0.0%** |
| **Maintenance Costs (MC)** | NA | 2.1% | 1.00 | $ 7,966 | 1.00 | $ 8,202 | 1.00 | $ 8,445 | **$ 24,613** | **1.3%** |
| **Mon & Adapt Man (MA)** | NA | 138.4% | 1.00 | $ 525,007 | 0.00 | $ - | 0.00 | $ - | **$ 525,007** | **28.5%** |
| | | HRSSP | | | **Post-Construction Costs (DCs+RC+MC+MA)** | | | | **$ 1,359,471** | **73.8%** |
| | | Assumed | | | **Design and Permiting Costs** | | | | **$ 108,064** | **5.9%** |
| | | | | | | | | **Total Cost** | **$ 1,841,382** | **100.0%** |

*Costs are calculated as the IC x %IC x #Events with inflation and discounting applied mid period

Long-term cost estimates for the three nearby bulkhead alternatives are given below in Table 22, Table 23, and Table 24. All costs were treated consistently with the bulkhead analyses in the HRSSP report. Damages were assumed due to scour and overtopping during the 25-yr and 50-yr storms. Ice damage and MA costs, which were not considered in the HRSSP report, are assumed minimal for all three alternatives. Differences among the long-term costs for the three bulkhead alternatives were driven by differences in the IC and MC associated with the different materials. ICs were based on the provided bid prices. Consistent with the HRSSP report, MCs were assumed to be significantly higher for the wood alternative (20% of the IC vs only 5% for steel/composite) due to the more rapid degradation of the material. The wood bulkhead would also likely need to be replaced sooner (nominally after 30 years); however, since the analysis only covers 60 years, only one replacement occurs within the analysis period. This is the same as might be expected for steel and composite structures, which typically have longer lifespans. A consideration which does not show up in the analysis is that after 60 years, the wooden bulkhead would likely be in a state of disrepair and need replacement once again, while the steel and composite structures would have significant serviceable life left.

*Table 22: Long-term cost estimate for the Gandys Beach wood bulkhead project. Ext – Extended, ?? - Unknown.*

| Long-term Cost Estimate - Gandys Wood Bulkhead | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | P1 (2020-2040) | | P2 (2040-2060) | | P3 (2060-2080) | | Total (2020-2080) | |
| Category | Storm $T_r$ | % IC | # Events | *Cost | # Events | *Cost | # Events | *Cost | Ext Cost | % Final |
| Initial Cost (IC) | NA | NA | NA | NA | NA | NA | NA | NA | $ 552,538 | 20.9% |
| Damage Cost (DC) | 50 | 10% | 0.62 | $ 34,481 | 1.83 | $ 105,725 | 5.45 | $ 323,894 | $ 464,100 | 17.5% |
| Damage Cost (DC) | 40 | 0% | 0.77 | $ - | 2.28 | $ - | 6.80 | $ - | $ - | 0.0% |
| Damage Cost (DC) | 25 | 5% | 1.22 | $ 34,249 | 3.64 | $ 104,956 | 10.81 | $ 321,268 | $ 460,473 | 17.4% |
| Damage Cost (DC) | 10 | 0.0% | 2.98 | $ - | 6.45 | $ - | 26.32 | $ - | $ - | 0.0% |
| Damage Cost Ice | NA | 0.0% | 2.00 | $ - | 1.00 | $ - | 0.00 | $ - | $ - | 0.0% |
| Replacement Cost (RC) | NA | 100.0% | 0.00 | $ - | 1.00 | $ 577,256 | 0.00 | $ - | $ 577,256 | 21.8% |
| Maintenance Costs (MC) | NA | 20.0% | 1.00 | $ 112,131 | 1.00 | $ 115,451 | 1.00 | $ 118,869 | $ 346,452 | 13.1% |
| Mon & Adapt Man (MA) | NA | 0.0% | 0.00 | $ - | 0.00 | $ - | 0.00 | $ - | $ - | 0.0% |
| | | HRSSP | | | Post-Construction Costs (DCs+RC+MC+MA) | | | | $ 2,095,491 | 79.1% |
| | | Assumed | | | Design and Permiting Costs | | | | ?? | - |
| | | | | | | | | Total Cost | $ 2,648,029 | 100.0% |

*Costs are calculated as the IC x %IC x #Events with inflation and discounting applied mid period

*Table 23: Long-term cost estimate for the Gandys Beach steel bulkhead project. Ext – Extended. ?? - Unknown*

| Long-term Cost Estimate - Gandys Steel Bulkhead | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | P1 (2020-2040) | | P2 (2040-2060) | | P3 (2060-2080) | | Total (2020-2080) | |
| Category | Storm $T_r$ | % IC | # Events | *Cost | # Events | *Cost | # Events | *Cost | Ext Cost | % Final |
| Initial Cost (IC) | NA | NA | NA | NA | NA | NA | NA | NA | $ 590,270 | 23.1% |
| Damage Cost (DC) | 50 | 10% | 0.62 | $ 36,835 | 1.83 | $ 112,944 | 5.45 | $ 346,013 | $ 495,792 | 19.4% |
| Damage Cost (DC) | 40 | 0% | 0.77 | $ - | 2.28 | $ - | 6.80 | $ - | $ - | 0.0% |
| Damage Cost (DC) | 25 | 5% | 1.22 | $ 36,588 | 3.64 | $ 112,123 | 10.81 | $ 343,207 | $ 491,918 | 19.3% |
| Damage Cost (DC) | 10 | 0.0% | 2.98 | $ - | 6.45 | $ - | 26.32 | $ - | $ - | 0.0% |
| Damage Cost Ice | NA | 0.0% | 2.00 | $ - | 1.00 | $ - | 0.00 | $ - | $ - | 0.0% |
| Replacement Cost (RC) | NA | 100.0% | 0.00 | $ - | 1.00 | $ 616,676 | 0.00 | $ - | $ 616,676 | 24.2% |
| Maintenance Costs (MC) | NA | 5.0% | 1.00 | $ 29,947 | 1.00 | $ 30,834 | 1.00 | $ 31,747 | $ 92,528 | 3.6% |
| Mon & Adapt Man (MA) | NA | 0.0% | 0.00 | $ - | 0.00 | $ - | 0.00 | $ - | $ - | 0.0% |
| | | HRSSP | | | Post-Construction Costs (DCs+RC+MC+MA) | | | | $ 1,961,006 | 76.9% |
| | | Assumed | | | Design and Permiting Costs | | | | ?? | - |
| | | | | | | | | Total Cost | $ 2,551,276 | 100.0% |

*Table 24: Long-term cost estimate for the Gandys Beach composite bulkhead project. Ext – Extended. ?? - Unknown*

| Long-term Cost Estimate - Gandys Composite Bulkhead | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | P1 (2020-2040) | | P2 (2040-2060) | | P3 (2060-2080) | | Total (2020-2080) | |
| Category | Storm $T_r$ | % IC | # Events | *Cost | # Events | *Cost | # Events | *Cost | Ext Cost | % Final |
| Initial Cost (IC) | NA | NA | NA | NA | NA | NA | NA | NA | $ 656,116 | 23.0% |
| Damage Cost (DC) | 50 | 10% | 0.62 | $ 40,944 | 1.83 | $ 125,544 | 5.45 | $ 384,611 | $ 551,099 | 19.3% |
| Damage Cost (DC) | 40 | 0% | 0.77 | $ - | 2.28 | $ - | 6.80 | $ - | $ - | 0.0% |
| Damage Cost (DC) | 25 | 5% | 1.22 | $ 40,669 | 3.64 | $ 124,630 | 10.81 | $ 381,493 | $ 546,792 | 19.1% |
| Damage Cost (DC) | 10 | 0.0% | 2.98 | $ - | 6.45 | $ - | 26.32 | $ - | $ - | 0.0% |
| Damage Cost Ice | NA | 0.0% | 2.00 | $ - | 1.00 | $ - | 0.00 | $ - | $ - | 0.0% |
| Replacement Cost (RC) | NA | 100.0% | 0.00 | $ - | 0.00 | $ - | 1.00 | $ 705,761 | $ 705,761 | 24.7% |
| Maintenance Costs (MC) | NA | 5.0% | 1.00 | $ 33,288 | 1.00 | $ 34,273 | 1.00 | $ 35,288 | $ 102,849 | 3.6% |
| Mon & Adapt Man (MA) | NA | 0.0% | 0.00 | $ - | 0.00 | $ - | 0.00 | $ - | $ - | 0.0% |
| | | HRSSP | | | Post-Construction Costs (DCs+RC+MC+MA) | | | | $ 2,200,054 | 77.0% |
| | | Assumed | | | Design and Permiting Costs | | | | ?? | - |
| | | | | | | | | Total Cost | $ 2,856,170 | 100.0% |

*Costs are calculated as the IC x %IC x #Events with inflation and discounting applied mid period

## Effectiveness

### Shoreline Stability

Transects perpendicular to the pre-defined baseline used in the Gandys Beach shoreline stability analysis were spaced at 5-foot intervals. The shoreline feature for this analysis was the most shoreward vegetated edge. As illustrated in Figure 20 the control area for this site was located to the North of the project site.

Figure 21 and Figure 22 show the pre- and post-installation shoreline positions at each transect relative to the project baselines. The pre-installation analysis is based strictly on historical imagery from Google Earth. Care was taken to select only images collected at lower stages of tide but there is still uncertainty in identifying the vegetated edge due to the extreme tidal variation at Gandys Beach. Keeping this uncertainty in mind, there does appear to be a consistent erosive trend throughout the project and control areas prior to the Oyster Castle breakwater installation in 2015. Post-installation, erosion was found to continue in the control area, most significantly just after installation at the southern end, but more recently at the northern end of the control area as well. In the project area, after an initial adjustment of the shoreline landwards in the area of the gaps between the breakwaters, the vegetated shoreline seems to have recovered and maintained its position.

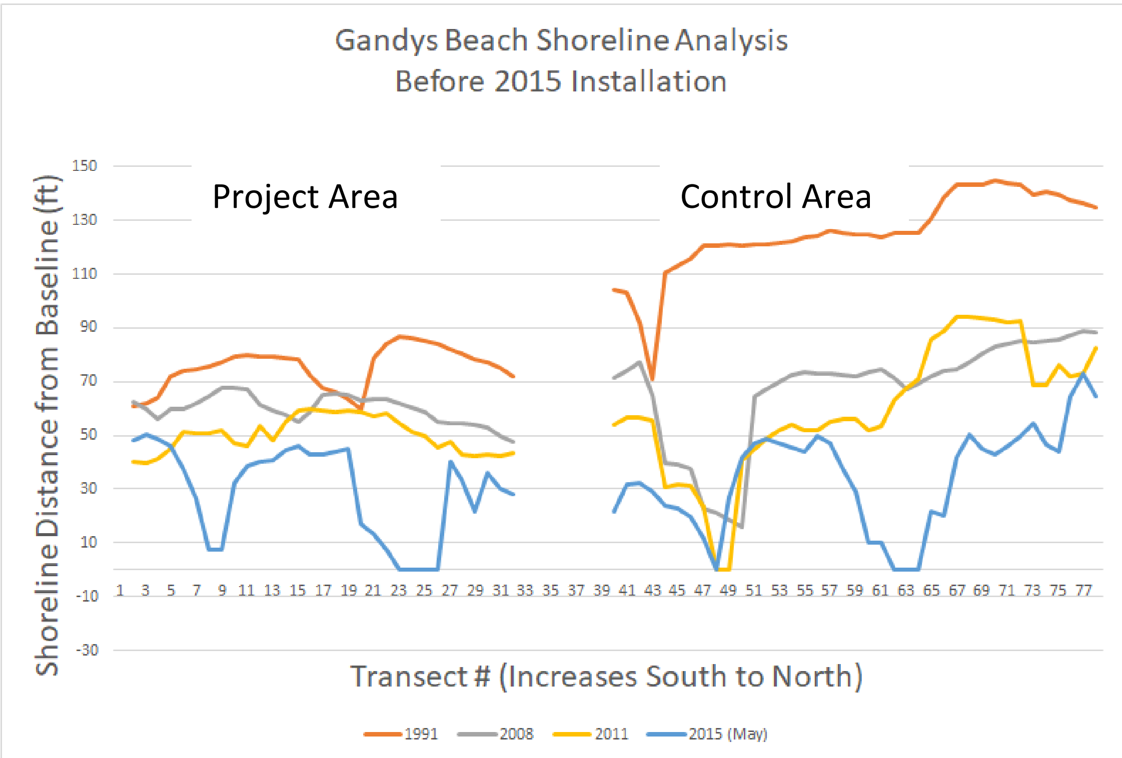


*Figure 21: Pre-installation shoreline stability analysis for Gandys Beach living shoreline. Analysis is based on historical imagery provided in Google Earth.*

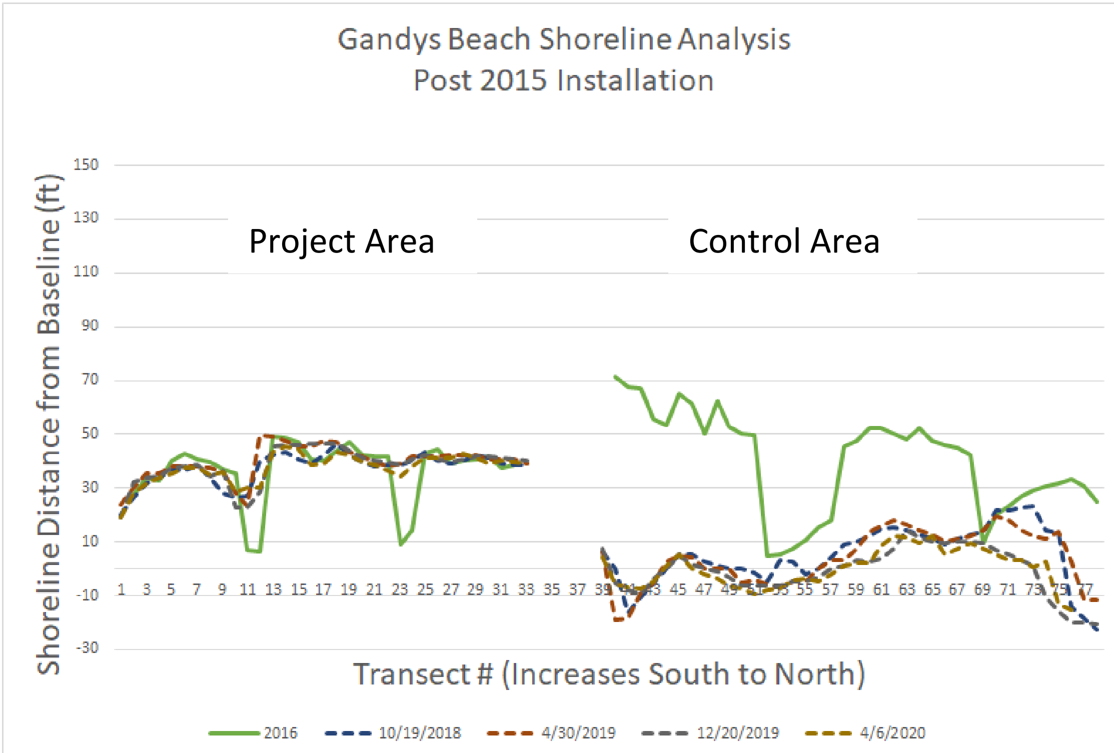


*Figure 22: Post-installation shoreline stability analysis for Gandys Beach living shoreline. Analysis is based on imagery collected by both historical imagery provided in Google Earth and the UAV imagery collected as part of this study. Historical Imagery is shown as a solid line; drone surveys are shown as dashed lines.*

A summary of the shoreline change rates at Gandys Beach is presented in Table 25. The data indicate that the average rate of shoreline change in the area of the project decreased from slightly erosional (-1.5 ft/year) to stable (0.0 ft/year) after the project was installed. This contrasts with the control site where the average rate of change was measured to be moderately erosional (-3.5 ft/year) before the project's installation and highly erosional (-9.7 ft/year) since. Referring to Figure 22, it can be seen that the trend at the control site is largely being driven by a singular erosion event between 2016 and 2018, and that since 2018, the control site has stabilized as well. The standard deviation calculations reflect increased longshore variability after project construction in both the project and control areas, with the standard deviation value rising from 0.5 to 2.2 and 0.7 to 5.0 ft/year respectively in each region. As described above, a significant amount of the increased variability in the project area is related to the initial vegetation response behind the gaps, which has since recovered and stabilized.

*Table 25: Summary of the Gandys Beach shoreline stability analysis for the project and control areas both before and after the installation of the project in 2015. Negative rates of change represent net erosion of the vegetated shoreline. Standard deviation is a measure of uniformity with low values indicating the changes are uniform across the site and large values indicating a high degree of variability.*

| Gandys Beach - Installation 2015 | | | | |
|---|---|---|---|---|
| (ft/yr) | Living Shoreline Site | | Control Site | |
| | Before Install | After Install | Before Install | After Install |
| Average Rate of Chage | -1.5 | 0.5 | -3.5 | -9.7 |
| Standard Deviation | 0.5 | 2.2 | 0.7 | 5.0 |

In summary, the section of the Gandys Beach Oyster Castle installation monitored in this study appears to have stabilized the shoreline edge in the project area. There is significant variability in the measurements, but it is believed they capture the initial rapid adjustment of the shoreline in response to the installation of the structure. As discussed, detecting shorelines in Google Earth is difficult at a site such as Gandys Beach due to the seasonal and tidal effects. The UAV results are believed to be more reliable and show less variability. The stability of the project area is particularly impressive when compared to the increased erosion at the control site. To better understand the long-term effects of the Oyster Castle breakwaters on this system, continued monitoring of this area is recommended.

### Wave Attenuation

Water level measurements for calculating wave attenuation were collected offshore and inshore of the Oyster Castle breakwater at Gandys Beach over four deployment periods as detailed in Table 5. Percent reduction values at Gandy's beach were based on significant wave heights calculated for the offshore and inshore gauges. A typical example of the results for one of the four deployments is shown below in Figure 23. The complete results appear in Appendix B.

During the selected fall/winter 2018 monitoring period, 81.8% of the recorded wave heights exceeded 5 cm and 59.5% exceeded 10 cm. Over all the deployments, on average, 56.9% of wave heights exceeded 5 cm, while 33.6% exceeded 10 cm. Compared to the other two sites where wave attenuation was measured (Gardner's Basin and Berkeley Island), Gandys Beach is significantly more energetic. Wave attenuation during the selected deployment varied widely, which is typical for this site (Kerr et al., 2020). The average reduction during the deployment was -7.5%, and the average reduction when the offshore wave heights were larger than 5 cm was -12.8%. Negative reduction values correspond to periods when the waves inshore of the breakwater are larger than those measured offshore of the breakwater. Some of the physical reasons why this may occur, particularly during periods of low wave energy, are discussed in Kerr et al. (2020). It has been found that most of these observations occur when the waves offshore of the structure are small, and since the offshore wave height appears in the denominator of the percent reduction formula, this amplifies their importance. For example, if an inside wave is 5 cm, and an outside wave is 10 cm, the percent reduction is 50%; however, if the same inside wave is measured with an outside wave of only 2.5 cm, the percent reduction is -100%. A few small waves can skew the average results; therefore, it is more instructive to consider the distribution of percent reduction values.

The range in percent reduction at Gandys Beach is displayed in the histograms shown in Figure 24. The full distribution depicted in gray shows a wide range including many negative values. The modified distribution shown in purple, only includes the larger waves (offshore waves greater than 5 cm) and indicates that for these waves proportionally more dissipation occurs. The average reduction over all deployments at the site was -15.8% and the average reduction when the outside wave heights exceed 5 cm was 5.2%.

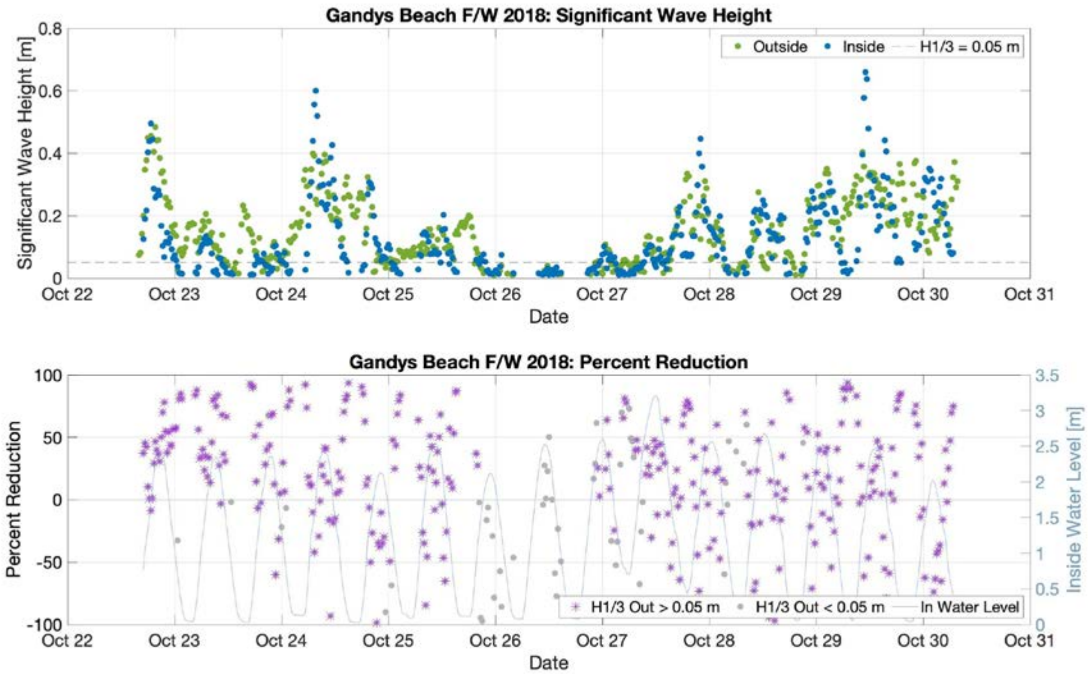


*Figure 23: Significant wave heights, percent reduction and inshore water level for Gandys Beach during the fall/winter 2018 monitoring period. All percent reduction values are shown in gray, and purple stars were added to highlight periods when offshore significant wave heights exceeded 5 cm.*

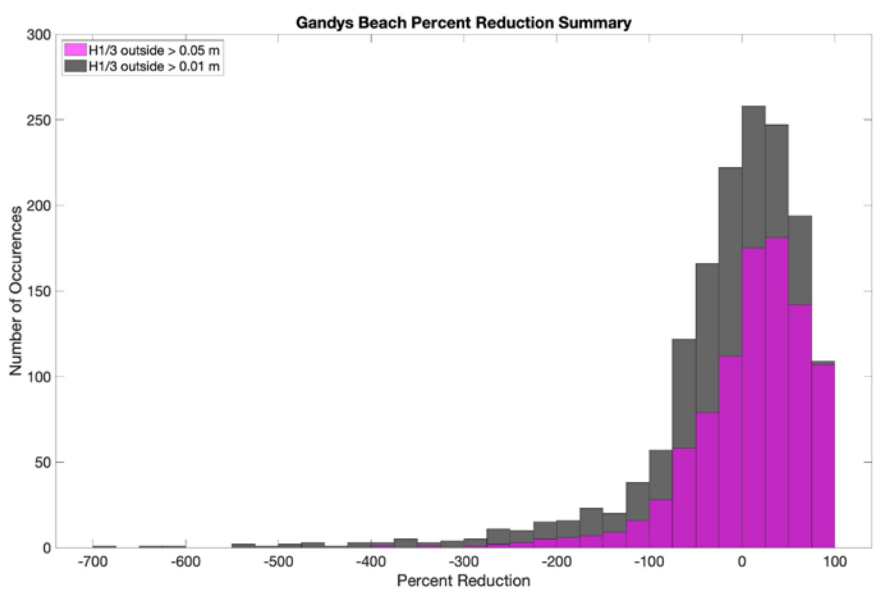


*Figure 24: Histogram describing the distribution of percent reduction values at Gandys Beach during all deployments for offshore maximum wave heights greater than 1 cm (gray) and greater than 5 cm (purple).*

# Matts Landing

## Site Description

The Matts Landing living shoreline project along the Maurice River in Cumberland County was one of the first living shoreline projects in the state of New Jersey. The project was constructed in 2010 by PDE as part of Phase 3 of testing of the DELSI Tactic. The DELSI Tactic was used by PDE and the RHSRL in 2008 as a way to stabilize shorelines, trap sediment, and restore critical marsh habitat. The DELSI Tactic involves utilizing natural materials and working with the natural contours of a site. The Matts Landing project was constructed along the eastern bank of the Maurice River, just north of Matts Landing marina. The primary materials used in the construction of the project were a series of coir rolls and loose and bagged shell. The project was constructed to achieve two goals: 1) to stabilize an eroding section of the shoreline and 2) to restore a more natural shoreline along a previously stabilized riprap shoreline. A site location map and project photos are presented in Figures 25 and 26; additional site photos can be found in Appendix C. Although the project has survived and thrived since its construction, PDE has taken an active role in monitoring and maintaining the project.


*Figure 25: Site map and project photo of the Matts Landing site.*

*Figure 26: Orthomosaic created from UAV imagery collected on April 7, 2020, showing Matts Landing, Heislerville, NJ. The red and blue line is the baseline for both the control and project area of the shoreline stability analysis. The living shoreline project is along the southern edge of this strip of shoreline, and the control is immediately to the North.*

## Cost Analysis

Costs for the Matts Landing living shoreline project were provided by the Partnership for the Delaware Estuary. The costs provided covered a number of living shoreline configurations, and included both maintenance and adaptive management components. The detail provided included several options for the layout of the coir roll. For the purposes of determining a project cost, the average value of the alternatives provided was utilized. No labor costs were included as a significant amount of volunteer labor was used in the construction of the project. The costs are summarized in Table 26.

*Table 26: Matts Landing living shoreline project costs. LS – Lump Sum.*

| Matts Landing (~81 LF) | | |
|---|---|---|
| ***Installation Costs*** | **Unit Cost** | **Unit** |
| Cusp 1 Deck 1 (no planting) | $ 1,884 | LS |
| Second Deck (no planting) | $ 1,548 | LS |
| Cusp 2 Deck 1 (no planting) | $ 1,780 | LS |
| 2 Cusp 1 Deck (no planting) | $ 3,884 | LS |
| 2 Cusp; 2nd Deck on Cusp 1 (no planting) | $ 5,431 | LS |
| Cusp 1 Deck 1 (with planting) | $ 3,926 | LS |
| Second Deck (with planting) | $ 1,548 | LS |
| Cusp 2 Deck 1 (with planting) | $ 2,388 | LS |
| 2 Cusp 1 Deck (with planting) | $ 6,314 | LS |
| 2 Cusp; 2nd Deck on Cusp 1 (with planting) | $ 7,861 | LS |
| Average of Alternatives | $ 3,656 | LS |
| ***Maintenance/Adaptive Management Costs*** | | |
| Maintenance - Shellbags | $ 1,200 | LS |
| Adaptive Management (Shellbags + Coir) | $ 2,290 | LS |

## Long-term Cost Estimate

The long-term cost estimate for the Matts Landing living shoreline project is given below in Table 27. Damage estimates were based on engineering judgement and the documented performance of the project in prior storms. During large storms, it is expected that the project will be submerged and damage will be minimal. During smaller storms, it is assumed that some limited scour may occur around the coir logs and that some vegetation may be removed, requiring repair, consistent with documented maintenance activities at the site. Although ice has been known to damage coir rolls, the Matts Landing project has fared well thus far. Consequently, the damage cost associated with ice has been reduced from the value used elsewhere for coir rolls (Strathmere). MCs and monitoring and adaptive management costs were taken directly from the information provided.

*Table 27: Long-term cost estimate for the Matts Landing living shoreline project. Ext – Extended.*

| Long-term Cost Estimate - Matts Landing Living Shoreline | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | P1 (2020-2040) | | P2 (2040-2060) | | P3 (2060-2080) | | Total (2020-2080) | |
| **Category** | **Storm $T_r$** | **% IC** | **# Events** | ***Cost** | **# Events** | ***Cost** | **# Events** | ***Cost** | **Ext Cost** | **% Final** |
| **Initial Cost (IC)** | NA | NA | NA | NA | NA | NA | NA | NA | **$ 3,656** | **14.0%** |
| **Damage Cost (DC)** | 50 | 0% | 0.62 | $ - | 1.83 | $ - | 5.45 | $ - | **$ -** | **0.0%** |
| **Damage Cost (DC)** | 40 | 0% | 0.77 | $ - | 2.28 | $ - | 6.80 | $ - | **$ -** | **0.0%** |
| **Damage Cost (DC)** | 25 | 10% | 1.22 | $ 453 | 3.64 | $ 1,389 | 10.81 | $ 4,251 | **$ 6,094** | **23.3%** |
| **Damage Cost (DC)** | 10 | 5% | 2.98 | $ 553 | 6.45 | $ 1,232 | 26.32 | $ 5,175 | **$ 6,959** | **26.6%** |
| **Damage Cost Ice** | NA | 15% | 2.00 | $ 1,113 | 1.00 | $ 573 | 0.00 | $ - | **$ 1,686** | **6.5%** |
| **Replacement Cost (RC)** | NA | 0% | 0.00 | $ - | 0.00 | $ - | 0.00 | $ - | **$ -** | **0.0%** |
| **Maintenance Costs (MC)** | NA | 32.8% | 1.00 | $ 1,218 | 1.00 | $ 1,254 | 1.00 | $ 1,291 | **$ 3,762** | **14.4%** |
| **Mon & Adapt Man (MA)** | NA | 62.6% | 1.00 | $ 2,322 | 0.00 | $ - | 0.00 | $ - | **$ 2,322** | **8.9%** |
| | | HRSSP | | | **Post-Construction Costs (DCs+RC+MC+MA)** | | | | **$ 22,459** | **86.0%** |
| | | Assumed | | | **Design and Permiting Costs** | | | | **??** | **-** |
| | | | | | | | | **Total Cost** | **$ 26,115** | **100.0%** |

*Costs are calculated as the IC x %IC x #Events with inflation and discounting applied mid period

## Effectiveness

### Shoreline Stability

Transects perpendicular to the pre-defined baseline used in the Matts Landing shoreline stability analysis were spaced at 4-foot intervals. The shoreline feature chosen for Matts Landing was the most shoreward vegetated edge. As illustrated in Figure 26 the control area for this site was located to the north of the project site.

Figure 27 and Figure 28 show the pre- and post-installation shoreline positions at each transect relative to the project baseline. The pre-installation plot shows the shoreline accreting between 2002 and 2009; however, this is a questionable result based off the only two clear historical images of the site from Google Earth. As described previously, identifying shorelines within Google Earth can be difficult even with the best of images, and with only two data points, little confidence can be placed in this "trend". Post-installation, an accretion of the shoreline is initially seen followed by a relative stabilization of the shoreline with small fluctuations from year to year. These fluctuations also occur at the control site.

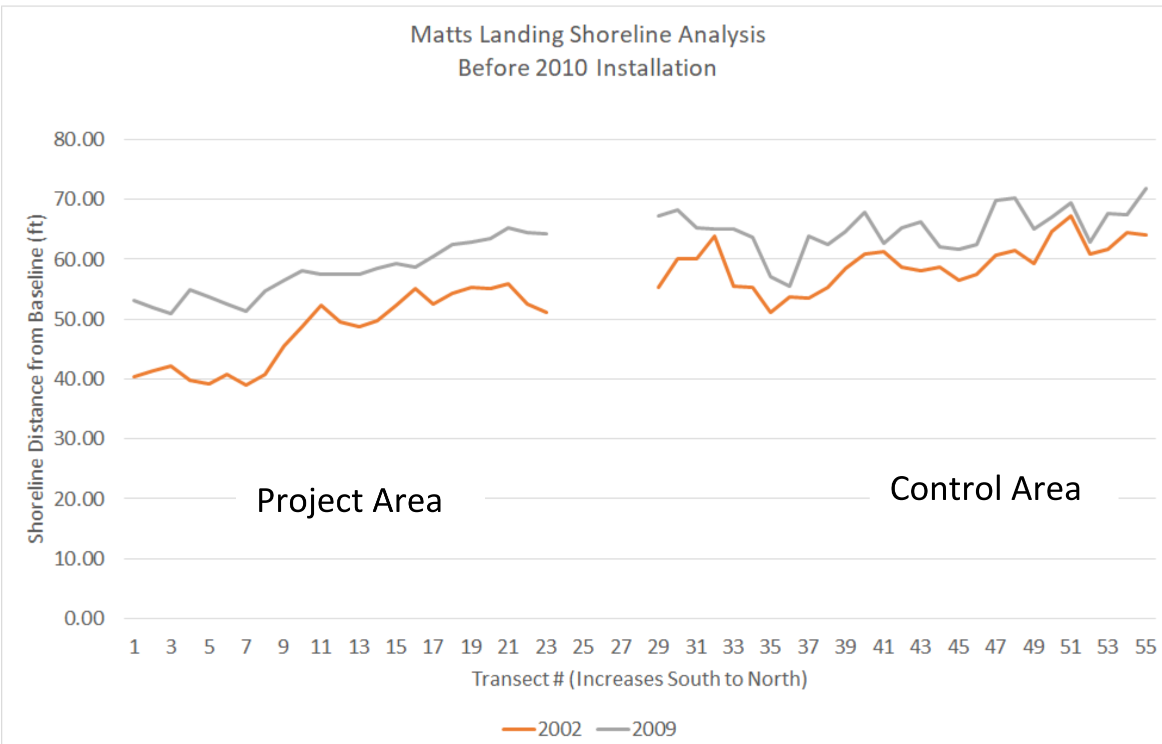


*Figure 27: Pre-installation shoreline stability analysis for Matts Landing living shoreline. Analysis is based on historical imagery provided in Google Earth.*

Table 28 summarizes the results of the shoreline analysis at Matts Landing. The average rate of shoreline change in the area of the project decreased from 1.4 ft/year (accretion) prior to installation to 1.1 ft/year (accretion) thereafter. This contrasts with the control site where the average rate of change was measured to be 0.8 ft/year (accretion) before the 2010 installation, but -0.6 ft/yr (erosion) in the years since. The fact that the standard deviation values are relatively low reflects the fact that the shoreline changes are fairly uniform across both the project and control sites. The post-construction increase in standard deviation values within the project area is largely being driven by the southern few transects, which exhibit more variability. As discussed above, the pre-installation values are not considered reliable because they are based on a limited amount of relatively low-quality data. Comparing the post-installation control and project shorelines suggests that, overall, the project has stabilized the shoreline within the project area.

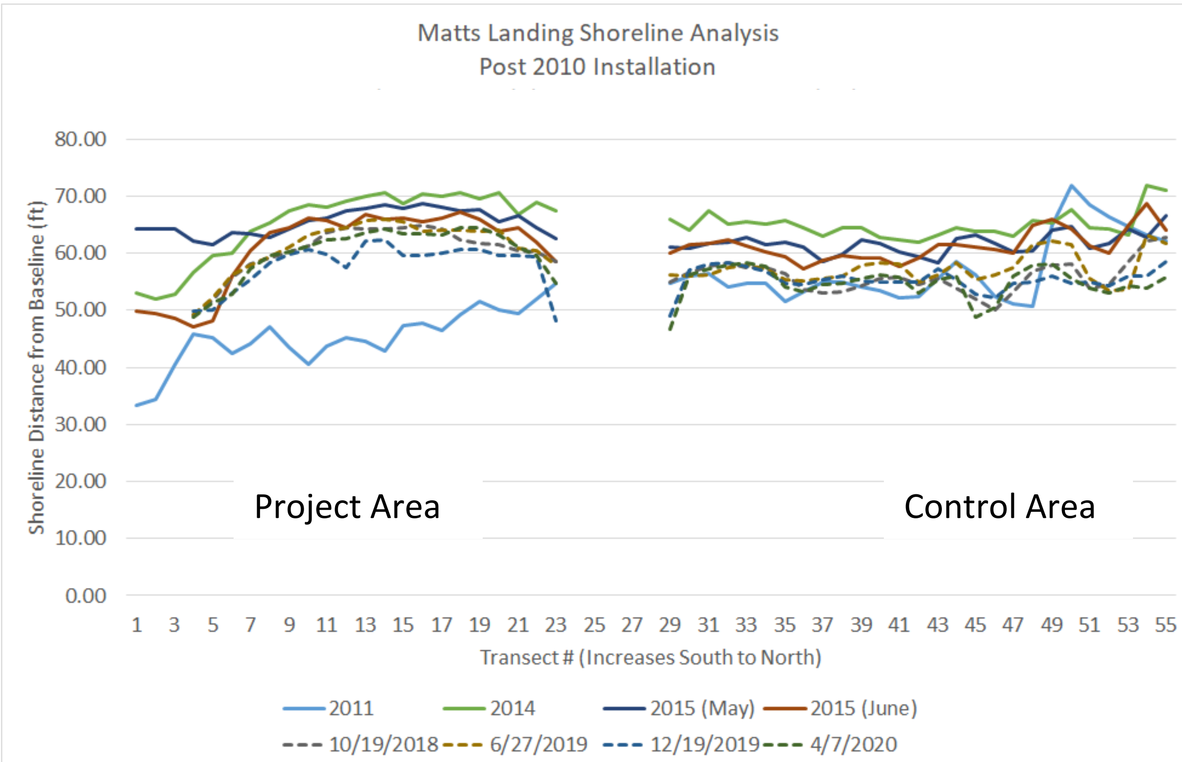


*Figure 28: Post-installation shoreline stability analysis for Matts Landing living shoreline. Analysis is based on both historical images provided in Google Earth and imagery collected by the UAV as part of this study. Historical Imagery is shown as a solid line; drone surveys are shown as dashed lines.*

*Table 28: Summary of the Matts Landing shoreline stability analysis for the project and control area both before and after the initial installation of the project in 2010. Negative rates of change represent net erosion of the vegetated shoreline. Standard deviation is a measure of uniformity with low values indicating the changes are uniform across the site and large values indicating a high degree of variability.*

| Matts Landing - Initial Installation 2010 | | | | |
|---|---|---|---|---|
| (ft/yr) | Living Shoreline Site | | Control Site | |
| | Before 2010 | After 2010 | Before 2010 | After 2010 |
| Average Rate of Change | 1.4 | 1.1 | 0.8 | -0.6 |
| Standard Deviation | 0.4 | 1.5 | 0.4 | 0.5 |

As a supplement to our analysis, we can look at the results obtained by the PDE for the years 2010 to 2016. PDE has been surveying (via RTK GPS) the vegetation line in and around Matts Landing on an approximately yearly basis since 2010. Vegetation lines from the surveys at both the marsh treatment and control areas are shown in Figure 29. The total amount of shoreline change between each survey and the total amount over the entire study period were calculated. The results are presented in Table 29, and show an average shoreline change rate for 2010 to 2016 of 1.7 ft/year (accretion) in the project area ("treatment") and -0.4 ft/year (erosion) in the control area. These results closely match the results of our analysis for the period from 2010 through 2020, further documenting the effectiveness of the living shoreline at Matts Landing.

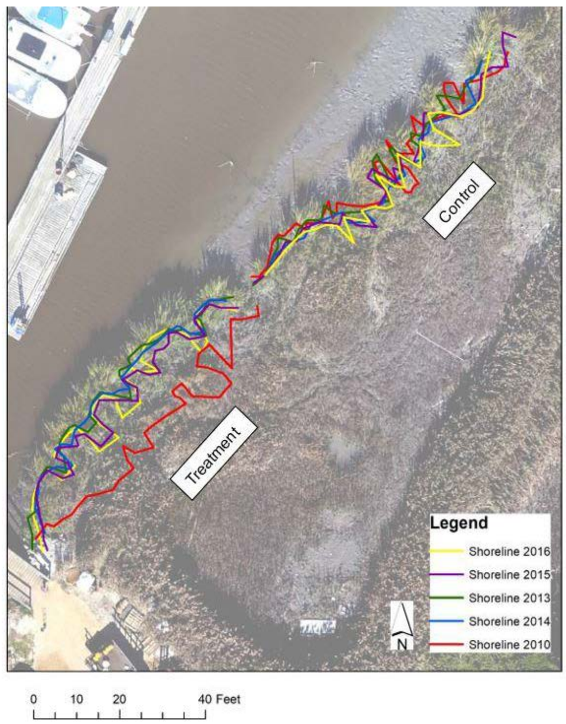


*Figure 29: Image shows historical shoreline data collected by PDE at the Matts Landing treatment and control sites. Background imagery is the October 19, 2018 Stevens orthomosaic*

*Table 29: Table showing change in shoreline position, standard deviation, and percent erosion over the entire period of PDE's historical surveying (2010 to 2016) and incrementally between (near) annual surveys.*

| | ft. | | ft. | ft. | ft. | ft. |
|---|---|---|---|---|---|---|
| | **2010 to 2016** | | **2010 to 2013** | **2013 to 2014** | **2014 to 2015** | **2015 to 2016** |
| Treatment Avg | 9.9 | Treatment | 11.3 | 0.1 | -1.8 | 0.4 |
| Treatment STD | 5.2 | Treatment | 4.4 | 1.5 | 1.7 | 2.1 |
| Percent Erosional | 3% | Treatment | 0% | 55% | 97% | 37% |
| Control Avg | -2.2 | Control | -0.3 | -1.3 | 0.1 | -0.8 |
| Control STD | 3.1 | Control | 2.3 | 1.7 | 1.7 | 1.8 |
| Percent Erosional | 83% | Control | 62% | 78% | 46% | 75% |

## Summary of Results

### Cost Analysis

The tables below (Tables 30 – 36) summarize the provided project costs. The first set of tables (Table 30 and Table 31) summarizes the categorized costs for the green and gray projects considered. As costs vary widely from project to project, and the level of detail in the information provided was inconsistent, it is more useful to consider ranges in costs, rather than specific projects. The total cost for the five living shoreline alternatives in the study ranged from $88 per linear foot to $2,018 per linear foot. The five conventional alternatives ranged in cost from $462 per linear foot to $3,448 per linear foot. In general, the smallest, least complex project in each set (Matts Landing living shoreline and Strathmere bulkhead) was the least expensive, and the largest, most complex project (Berkeley Island/Iowa Court and Gardner's bulkhead/revetment) was the most expensive. Overall, design and permitting costs, maintenance and adaptive management costs and monitoring costs were higher for the living shoreline projects. This can at least partially be attributed to the continued lack of experience with living shoreline techniques within the state, which frequently extends the design and permitting timeline, and leads to increased monitoring requirements. The Gandys Beach project is a prime example where the extreme monitoring costs are driven by the desire to understand and document the results of an innovative project. In contrast, maintenance, adaptive management, and monitoring costs were generally not included for any of the conventional projects. These costs are generally not considered as part of the upfront costs of conventional projects, but rather separate projects with separate costs incurred down the line. If only the initial construction costs are considered, the range in cost for the living shoreline and conventional projects drops to $45 per linear foot to $1,661 per linear foot and $437 per linear foot to $3,507 per linear foot, respectively.

*Table 30: Summary of living shoreline project costs.*

| **Estimated Costs** | **Gandy's** | **Strathmere LS** | **Matts** | **Berkley/Iowa** | **Gardners** |
|---|---|---|---|---|---|
| **Project Length (ft)** | **2,750** | **100** | **81** | **500** | **100** |
| Mobilization | $ 26,100 | $ 1,760 | Unknown | $ 66,690 | $ 15,000 |
| Materials | $ 95,040 | Unknown | $ 3,656 | $ 712,920 | $ 75,000 |
| Labor | $ 252,707 | Unknown | Unknown | $ 51,028 | $ 45,000 |
| Material+Labor | $ 347,747 | $ 38,967 | $ 3,656 | $ 763,948 | $ 120,000 |
| Total Construction | $ 373,847 | $ 40,727 | $ 3,656 | $ 830,638 | $ 135,000 |
| Design and Permitting | $ 108,064 | $ 1,716 | Unknown | $ 56,721 | $ 39,000 |
| Maintenance | $ 8,000 | Unknown | $ 1,200 | Unkonown | Unknown |
| Adaptive Management | $ 74,516 | Unknown | $ 2,290 | $ 40,686 | Unknown |
| Monitoring | $ 443,063 | Unknown | Unknown | $ 81,200 | Unknown |
| Total (inc monitor) | $ 1,007,489 | $ 42,443 | $ 7,146 | $ 1,009,244 | $ 174,000 |
| Cost/LF (inc monitor) | $ 366 | $ 424 | $ 88 | $ 2,018 | $ 1,740 |
| Total (exc monitor) | $ 564,427 | $ 42,443 | $ 7,146 | $ 928,044 | $ 174,000 |
| Cost/LF (exc monitor) | $ 205 | $ 424 | $ 88 | $ 1,856 | $ 1,740 |
| Cost (Const only) | $ 373,847 | $ 40,727 | $ 3,656 | $ 830,638 | $ 135,000 |
| Cost/LF (Const only) | $ 136 | $ 407 | $ 45 | $ 1,661 | $ 1,350 |

*Table 31: Summary of conventional gray shoreline stabilization costs.*

| Estimated Costs | Gandy's Wood | Gandy's Steel | Gandy's Comp | Strathmere BH | Gardners Gray |
|---|---|---|---|---|---|
| **Project Length (ft)** | **394** | **394** | **394** | **201** | **1,083** |
| Mobilization | Unknown | Unknown | Unknown | $ 5,225 | Unknown |
| Materials | Unknown | Unknown | Unknown | Unkown | $ 2,973,512 |
| Labor | $ 57,571 | $ 57,571 | $ 57,571 | Unknown | $ 596,386 |
| Material+Labor | $ 494,967 | $ 532,699 | $ 598,545 | $ 82,611 | $ 3,797,991 |
| Total Construction | $ 552,538 | $ 590,270 | $ 656,116 | $ 87,836 | $ 3,797,991 |
| Design and Permitting | Unknown | Unknown | Unknown | $ 5,094 | $ 30,775 |
| Maintenance | Unknown | Unknown | Unknown | Unknown | Unknown |
| Adaptive Management | Unknown | Unknown | Unknown | Unknown | Unknown |
| Monitoring | Unknown | Unknown | Unknown | Unknown | $ 24,615 |
| Total (inc monitor) | $ 552,538 | $ 590,270 | $ 656,116 | $ 92,930 | $ 3,853,381 |
| Cost/LF (inc monitor) | $ 1,402 | $ 1,498 | $ 1,665 | $ 462 | $ 3,558 |
| Total (exc monitor) | $ 552,538 | $ 590,270 | $ 656,116 | $ 92,930 | $ 3,828,766 |
| Cost/LF (exc monitor) | $ 1,402 | $ 1,498 | $ 1,665 | $ 462 | $ 3,535 |
| Cost (Const only) | $ 552,538 | $ 590,270 | $ 656,116 | $ 87,836 | $ 3,797,991 |
| Cost/LF (Const only) | $ 1,402 | $ 1,498 | $ 1,665 | $ 437 | $ 3,507 |

The second set of tables (Table 32 and Table 33) provides a breakdown of the categorized costs as a percentage of the total costs for the living shoreline and conventional alternatives. For the living shoreline projects, materials and labor made up a wide range (34.5% to 91.8%) of the total project costs. For the conventional projects, materials and labor consistently made up the largest proportion (88.9% to 98.6%) of the total cost. For the living shoreline projects, materials and labor make up between 34.5% and 91.8%, while the range for the conventional projects was much higher and much narrower (88.9% to 98.6%). Part of this disparity is due to the nature of the projects, and part is due to the greater level of detail provided for the living shoreline projects. In particular, design and permitting, maintenance and adaptive management, and monitoring costs were more available for the living shoreline projects. Design and permitting costs ranged from 4.0% to 22.4% for the living shoreline projects and from 0.8% to 5.5% for the conventional projects. Typically, it would be expected that design and permitting cost for conventional projects would run in excess of 10% of the construction cost. Maintenance and adaptive management costs for the living shoreline projects ranged from 0.8% to 32.0% of the total costs, while none of the conventional projects reported maintenance and adaptive management costs. Although not appearing directly in the cost information provided, these costs were estimated using a part of the long-term cost analysis. Monitoring costs were significantly higher for the living shoreline projects, ranging from 8.1% to 44.0%, while the monitoring cost for the only conventional project to report such information was less than 1%. As discussed above, as living shoreline projects become more common this cost is likely to decrease as the burden to prove their success is reduced to match that of conventional projects.

*Table 32: Living shoreline project component costs as a percentage of total project cost.*

| Percentage of Total Cost - Green | | | | | |
|---|---|---|---|---|---|
| | **Gandy's** | **Strathmere LS** | **Matts** | **Berkley/Iowa** | **Gardners** |
| Mobilization | 2.59% | 4.15% | NA | 6.61% | 8.62% |
| Materials | 9.43% | NA | 51.16% | 70.64% | 43.10% |
| Labor | 25.08% | NA | NA | 5.06% | 25.86% |
| Material+Labor | 34.52% | 91.81% | 51.16% | 75.70% | 68.97% |
| Total Construction | 37.11% | 95.96% | 51.16% | 82.30% | 77.59% |
| Design and Permitting | 10.73% | 4.04% | NA | 5.62% | 22.41% |
| Maintenance | 0.79% | NA | 16.79% | NA | NA |
| Adaptive Management | 7.40% | NA | 32.04% | 4.03% | NA |
| Monitoring | 43.98% | NA | NA | 8.05% | NA |
| **Total (incl monitor)** | **100.00%** | **100.00%** | **100.0%** | **100.0%** | **100.00%** |

*Table 33: Conventional gray shoreline stabilization project component costs as a percentage of total project cost.*

| Percentage of Total Cost - Gray | | | | | |
|---|---|---|---|---|---|
| | **Gandy's Wood** | **Gandy's Steel** | **Gandy's Comp** | **Strathmere BH** | **Gardners Gray** |
| Mobilization | NA | NA | NA | 5.62% | NA |
| Materials | NA | NA | NA | NA | 77.17% |
| Labor | 10.42% | 9.75% | 8.77% | NA | 15.48% |
| Material+Labor | 89.58% | 90.25% | 91.23% | 88.90% | 98.56% |
| Total Construction | 100.00% | 100.00% | 100.00% | 94.52% | 98.56% |
| Design and Permitting | NA | NA | NA | 5.48% | 0.80% |
| Maintenance | NA | NA | NA | NA | NA |
| Adaptive Management | NA | NA | NA | NA | NA |
| Monitoring | NA | NA | NA | NA | 0.64% |
| **Total (incl monitor)** | **100.00%** | **100.00%** | **100.00%** | **100.00%** | **100.00%** |

The final set of tables (Table 34 and Table 35) provides a breakdown of the categorized costs as a percentage of the construction costs. Analyzing the information this way evens the playing field, as a similar level of detail related to construction costs was provided for all projects. For the living shoreline projects, material and labor costs were more varied, while for the conventional projects material and labor costs typically made up in excess of 90% of the total project cost. Design and permitting, monitoring, maintenance, and adaptive management costs, all made up a greater proportion of the cost of the living shoreline projects. This is driven in part by the relative inexperience with living shoreline projects within the state that often increases the permitting and monitoring costs, and in part by the way in which maintenance and adaptive management is viewed/interpreted. For living shoreline projects, maintenance and adaptive management is often considered up front, as a part of the initial planning process and the collected cost information reflects that; whereas for conventional projects, maintenance and adaptive management are often considered separate projects entirely and therefore these costs are not contained in the information provided. For some of the living shoreline projects, the non-construction costs were found to be more than double the construction costs.

*Table 34: Living shoreline project component costs as a percentage of construction cost.*

| Percentage of Construction Cost - Green | | | | | |
|---|---|---|---|---|---|
| | **Gandy's** | **Strathmere LS** | **Matts** | **Berkley/Iowa** | **Gardners** |
| Mobilization | 6.98% | 4.32% | NA | 8.03% | 11.11% |
| Materials | 25.42% | NA | 100.00% | 85.83% | 55.56% |
| Labor | 67.60% | NA | NA | 6.14% | 33.33% |
| Material+Labor | 93.02% | 95.68% | 100.00% | 91.97% | 88.89% |
| Total Construction | 100.00% | 100.00% | 100.00% | 100.00% | 100.00% |
| Design and Permitting | 28.91% | 4.21% | NA | 6.83% | 28.89% |
| Maintenance | 2.14% | NA | 32.82% | NA | NA |
| Adaptive Management | 19.93% | NA | 62.63% | 4.90% | NA |
| Monitoring | 118.51% | NA | NA | 9.78% | NA |
| **Total (incl monitor)** | **269.49%** | **104.21%** | **195.45%** | **121.50%** | **128.89%** |

*Table 35: Conventional gray shoreline stabilization project component costs as a percentage of construction cost.*

| Percentage of Construction Cost - Gray | | | | | |
|---|---|---|---|---|---|
| | **Gandy's Wood** | **Gandy's Steel** | **Gandy's Comp** | **Strathmere BH** | **Gardners Gray** |
| Mobilization | NA | NA | NA | 5.95% | NA |
| Materials | NA | NA | NA | NA | 78.29% |
| Labor | 10.42% | 9.75% | 8.77% | NA | 15.70% |
| Material+Labor | 89.58% | 90.25% | 91.23% | 94.05% | 100.00% |
| Total Construction | 100.00% | 100.00% | 100.00% | 100.00% | 100.00% |
| Design and Permitting | NA | NA | NA | 5.80% | 0.81% |
| Maintenance | NA | NA | NA | NA | NA |
| Adaptive Management | NA | NA | NA | NA | NA |
| Monitoring | NA | NA | NA | NA | 0.65% |
| **Total (incl monitor)** | **100.00%** | **100.00%** | **100.00%** | **105.80%** | **101.46%** |

The major conclusions from the cost analysis relate to the overall costs and the distribution of costs, which are fundamentally different for living shoreline versus conventional shoreline projects. Although the types of projects considered and the associated costs varied widely across both living shoreline and conventional projects, overall, the living shoreline projects cost less per linear foot than the conventional projects, even when maintenance, monitoring and adaptive management are included. If only construction costs are considered, the gap between the lower-cost living shoreline and higher-cost conventional projects grows.

## Long-term Cost Estimate

The HRSSP long-term cost analysis framework was updated and applied to each of the projects. The framework was chosen because of its adaptability, including the ability to modify and add new cost categories. Table 36 provides a summary of the 60-yr costs using a set of assumptions related to interest and discount rates, sea level rise, damage potential, and maintenance including replacement. While the assumptions used are defensible, the results are sensitive to these assumptions; therefore, the 60-yr costs should be interpreted with caution. The more useful information is contained in the main body of the report (Table 7, Table 11, Table 16, Table 21, Table 27) as these tables illustrate how the assumptions affect the final cost. One takeaway of the analysis, however, is that the long-term costs of living shoreline projects are more evenly spread out over time, while the costs for conventional shoreline stabilization approaches are concentrated at the beginning and replacement phases of the structure lifecycle. Major costs of the conventional gray shoreline stabilization alternatives are associated with the initial construction and ultimate replacement of the structure; whereas the living shoreline projects tend to need more consistent monitoring and maintenance, but typically do not require complete replacement.

*Table 36: Comparison of estimated long-term project costs.*

| Project | Estimated 60-yr Cost | Post-Construction Cost Percentage |
|---|---|---|
| **Living Shorelines Projects** | | |
| Berkeley Island | $ 3,251,497.67 | 86% |
| Gardners Basin | $ 466,569.10 | 63% |
| Strathmere | $ 250,142.02 | 83% |
| Gandys Beach | $ 1,841,382.33 | 74% |
| Matts Landing | $ 26,114.82 | 86% |
| **Traditional Projects** | | |
| Garners -Bulkhead | $ 11,828,835.51 | 68% |
| Strathmere - Bulkhead | $ 384,737.34 | 76% |
| Gandys - Wood | $ 2,648,028.63 | 79% |
| Gandys - Steel | $ 2,551,275.63 | 77% |
| Gandys - Composite | $ 2,856,170.06 | 77% |

## Effectiveness

### Shoreline Stability

Table 37 summarizes the key results of the shoreline stability analysis performed for this study. Overall, three of the five living shoreline projects (Berkeley Island, Gandys Beach, and Matts Landing) were found to have a positive effect on shoreline stability. Furthermore, the vegetation at Gandys Beach and Matts Landing has advanced since installation of the living shoreline. The results of the shoreline stability analysis at Gardner's Basin and Strathmere were less clear, but it is believed that this could be a shortcoming related to the lack of high-quality historical imagery for the pre-installation analysis. Those two sites exhibited the lowest pre-installation rates of shoreline change and the highest amount of variability (standard deviations of 40 to 65% of their annual rate of shoreline change post-installation). Continued monitoring of these sites in particular would be needed to strengthen any conclusions related to shoreline stability. It is recommended that monitoring continue at all five sites in order to better understand the conditions under which each project is most effective.

*Table 37: Summary of the results of the shoreline stability analysis for the five living shoreline project sites and the corresponding control areas. Negative shoreline change represents erosion of the shoreline as identified in the historical images or orthomosaics produced from the drone imagery; this may be either the wet/dry line, vegetation, or a combination of both.*

| Study Area | Shoreline Identifier | Annual Rate of Shoreline Change (ft/yr) | | | |
|---|---|---|---|---|---|
| | | Living Shoreline | | Control Site | |
| | | Before Install | After Install | Before Install | After Install |
| **Berkeley Island** | wet/dry (2nd veg) | -1.7 | 0.0 | -3.1 | -5.8 |
| **Gardner's Basin** | vegetation | -0.7 | -0.9 | n/a | n/a |
| **Strathmere "Beach"** | wet/dry line | -0.4 | -0.3 | -0.6 | -0.3 |
| **Gandys Beach** | vegetation | -1.5 | 0.5 | -3.5 | -9.7 |
| **Matts Landing** | vegetation | 1.4 | 1.1 | 0.8 | -0.6 |

### Wave Attenuation

Overall, the three breakwater or sill projects were found to be effective at attenuating waves. Table 38 summarizes the percentage of offshore wave heights exceeding 5 cm and 10 cm that occurred at each site. Gandys Beach was by far the most energetic of the sites studied. Only a very small number of sporadic wave events associated with the movement of boats within Gardner's Basin measured above even the lower threshold. Table 39 summarizes the average amount of attenuation that was achieved at each site during each deployment for all waves exceeding 1 cm as well as a subset of larger waves, those where the offshore wave height exceeding 5 cm. At Gardner's Basin and Berkeley Island, over 50% attenuation was achieved on average during larger wave events. The low values at Gandys Beach are influenced by a number of periods during which the wave attenuation is negative, reflecting times when the wave height measured inshore of the breakwater exceeds that measured offshore. These instances are relatively rare, and, overall, the waves are most commonly attenuated between 0 and 50 percent at Gandys Beach.

*Table 38: Summary of the distribution of offshore wave heights ($H_{1/3}$ at Gandys Beach and Berkeley Island and $H_{max}$ at Gardner's Basin).*

| | % Wave Heights > 5 cm | % Wave Heights > 10 cm |
|---|---|---|
| **Gardner's Basin** | 11.4 | 5.2 |
| **Gandys Beach** | 56.9 | 33.6 |
| **Berkeley Island** | 42.5 | 16.2 |

*Table 39: Summary of wave attenuation values for all sill and breakwater sites ($H_{1/3}$ at Gandys Beach and Berkeley Island and $H_{max}$ at Gardner's Basin).*

| | Avg % Reduction (Wave Heights > 1 cm) | Avg % Reduction (Wave Heights > 5 cm) |
|---|---|---|
| **Gardner's Basin** | 20.7 | 65.9 |
| **Gandys Beach** | -15.8 | 5.2 |
| **Berkeley Island** | 48.8 | 52.1 |

Overall, some of the key takeaways from the analysis of the cost and effectiveness data for the five living shoreline and five conventional shoreline stabilization projects were:

1. Costs for both living shoreline and conventional shoreline stabilization projects were found to vary widely; however, the living shoreline project costs were generally lower.
2. The distribution of costs for living shoreline and conventional shoreline projects were found to be different with design and permitting, monitoring, maintenance, and adaptive management costs making up a larger proportion of the living shoreline project costs.
3. The long-term cost of living shoreline projects was determined to be more evenly spread over time, while the costs of conventional projects were concentrated at discrete times representing initial construction and replacement.
4. Three of the five living shoreline projects were found to be effective in reducing erosion compared to a nearby control.
5. All three living shoreline projects containing wave-attenuating structures effectively attenuated waves although the degree of attenuation was found to vary.

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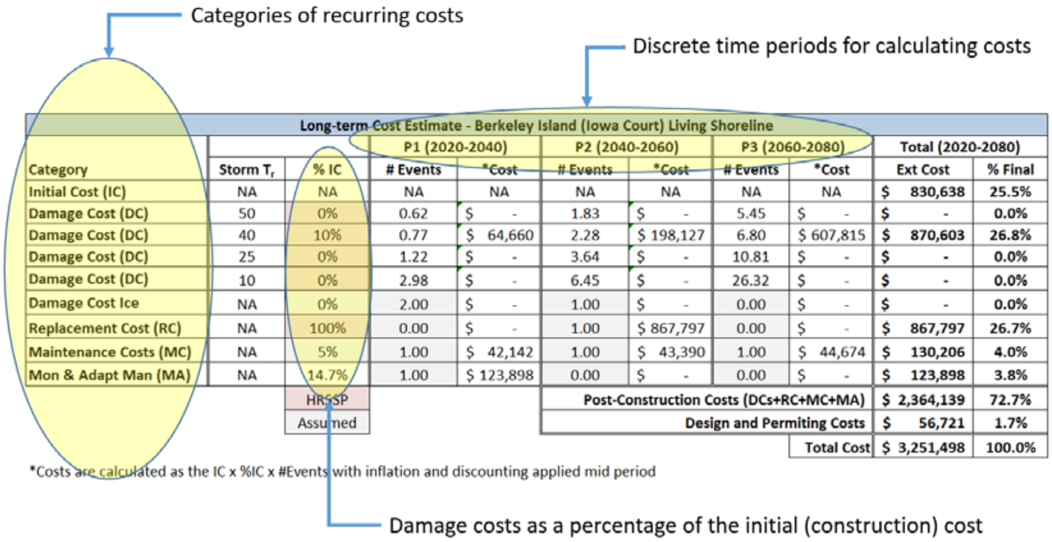
# APPENDIX A

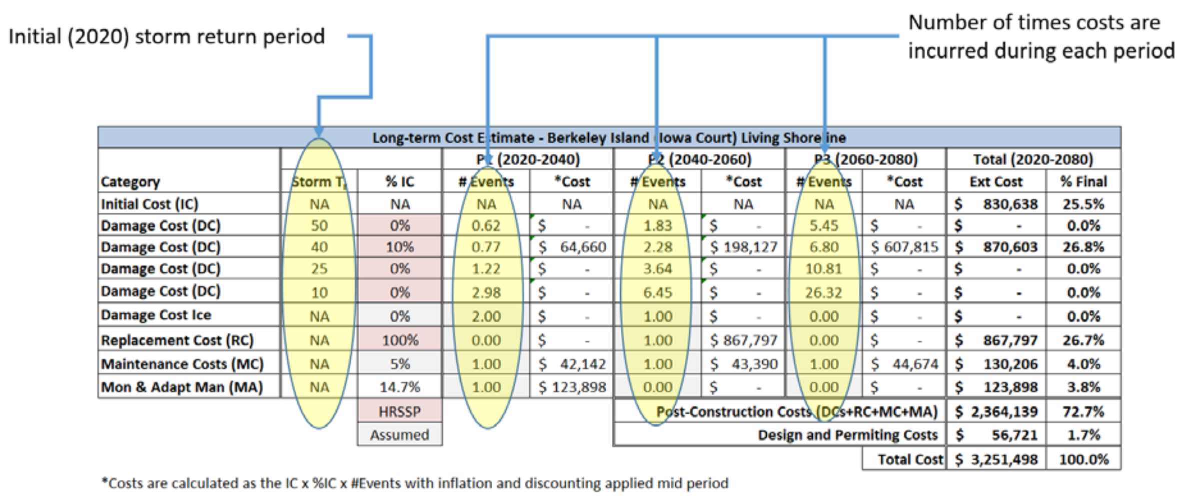
## Interpreting the Long-term Cost Analysis Tables




| Long-term Cost Estimate - Berkeley Island (Iowa Court) Living Shoreline | | | P1 (2020-2040) | | P2 (2040-2060) | | P3 (2060-2080) | | Total (2020-2080) | |
|---|---|---|---|---|---|---|---|---|---|---|
| Category | Storm $T_r$ | % IC | # Events | *Cost | # Events | *Cost | # Events | *Cost | Ext Cost | % Final |
| Initial Cost (IC) | NA | NA | NA | NA | NA | NA | NA | NA | $ 830,638 | 25.5% |
| Damage Cost (DC) | 50 | 0% | 0.62 | $ - | 1.83 | $ - | 5.45 | $ - | $ - | 0.0% |
| Damage Cost (DC) | 40 | 10% | 0.77 | $ 64,660 | 2.28 | $ 198,127 | 6.80 | $ 607,815 | $ 870,603 | 26.8% |
| Damage Cost (DC) | 25 | 0% | 1.22 | $ - | 3.64 | $ - | 10.81 | $ - | $ - | 0.0% |
| Damage Cost (DC) | 10 | 0% | 2.98 | $ - | 6.45 | $ - | 26.32 | $ - | $ - | 0.0% |
| Damage Cost Ice | NA | 0% | 2.00 | $ - | 1.00 | $ - | 0.00 | $ - | $ - | 0.0% |
| Replacement Cost (RC) | NA | 100% | 0.00 | $ - | 1.00 | $ 867,797 | 0.00 | $ - | $ 867,797 | 26.7% |
| Maintenance Costs (MC) | NA | 5% | 1.00 | $ 42,142 | 1.00 | $ 43,390 | 1.00 | $ 44,674 | $ 130,206 | 4.0% |
| Mon & Adapt Man (MA) | NA | 14.7% | 1.00 | $ 123,898 | 0.00 | $ - | 0.00 | $ - | $ 123,898 | 3.8% |
| | | HRSSP | | | Post-Construction Costs (DCs+RC+MC+MA) | | | | $ 2,364,139 | 72.7% |
| | | Assumed | | | Design and Permiting Costs | | | | $ 56,721 | 1.7% |
| | | | | | | | | Total Cost | $ 3,251,498 | 100.0% |

*Costs are calculated as the IC x %IC x #Events with inflation and discounting applied mid period

*Figure 30: Basic layout of cost of long-term cost analysis tables. Each row in the body of the table corresponds to a different type of cost, which is estimated as a percentage of the initial cost (IC). Columns illustrate the cost break down as a function of time, i.e., how much expense can be expected during each period.*





| Long-term Cost Estimate - Berkeley Island (Iowa Court) Living Shoreline | | | P1 (2020-2040) | | P2 (2040-2060) | | P3 (2060-2080) | | Total (2020-2080) | |
|---|---|---|---|---|---|---|---|---|---|---|
| Category | Storm $T_r$ | % IC | # Events | *Cost | # Events | *Cost | # Events | *Cost | Ext Cost | % Final |
| Initial Cost (IC) | NA | NA | NA | NA | NA | NA | NA | NA | $ 830,638 | 25.5% |
| Damage Cost (DC) | 50 | 0% | 0.62 | $ - | 1.83 | $ - | 5.45 | $ - | $ - | 0.0% |
| Damage Cost (DC) | 40 | 10% | 0.77 | $ 64,660 | 2.28 | $ 198,127 | 6.80 | $ 607,815 | $ 870,603 | 26.8% |
| Damage Cost (DC) | 25 | 0% | 1.22 | $ - | 3.64 | $ - | 10.81 | $ - | $ - | 0.0% |
| Damage Cost (DC) | 10 | 0% | 2.98 | $ - | 6.45 | $ - | 26.32 | $ - | $ - | 0.0% |
| Damage Cost Ice | NA | 0% | 2.00 | $ - | 1.00 | $ - | 0.00 | $ - | $ - | 0.0% |
| Replacement Cost (RC) | NA | 100% | 0.00 | $ - | 1.00 | $ 867,797 | 0.00 | $ - | $ 867,797 | 26.7% |
| Maintenance Costs (MC) | NA | 5% | 1.00 | $ 42,142 | 1.00 | $ 43,390 | 1.00 | $ 44,674 | $ 130,206 | 4.0% |
| Mon & Adapt Man (MA) | NA | 14.7% | 1.00 | $ 123,898 | 0.00 | $ - | 0.00 | $ - | $ 123,898 | 3.8% |
| | | HRSSP | | | Post-Construction Costs (DCs+RC+MC+MA) | | | | $ 2,364,139 | 72.7% |
| | | Assumed | | | Design and Permiting Costs | | | | $ 56,721 | 1.7% |
| | | | | | | | | Total Cost | $ 3,251,498 | 100.0% |

*Costs are calculated as the IC x %IC x #Events with inflation and discounting applied mid period


*Figure 31: The recurrence of storm damage costs is a function of the frequency of the storm event. The first highlighted column is the present-day description of the storm. The subsequent highlighted columns describe the number of times a storm of the given magnitude is expected to occur in each period. The number of expected occurrences increases with time due to sea level rise. For the damage categories that are not related to storm frequency based on water level exceedances (RC, MC, MA, and ice), the number of events simply describes the number of times the cost is incurred during each period.*

Costs incurred in each category during each period

| Long-term Cost Estimate - Berkeley Island (Iowa Court) Living Shoreline | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | P1 (2020-2040) | | P2 (2040-2060) | | P3 (2060-2080) | | Total (2020-2080) | |
| Category | Storm $T_r$ | % IC | # Events | *Cost | # Events | *Cost | # Events | *Cost | Ext Cost | % Final |
| Initial Cost (IC) | NA | NA | NA | NA | NA | NA | NA | NA | $ 830,638 | 25.5% |
| Damage Cost (DC) | 50 | 0% | 0.62 | $ - | 1.83 | $ - | 5.45 | $ - | $ - | 0.0% |
| Damage Cost (DC) | 40 | 10% | 0.77 | $ 64,660 | 2.28 | $ 198,127 | 6.80 | $ 607,815 | $ 870,603 | 26.8% |
| Damage Cost (DC) | 25 | 0% | 1.22 | $ - | 3.64 | $ - | 10.81 | $ - | $ - | 0.0% |
| Damage Cost (DC) | 10 | 0% | 2.98 | $ - | 6.45 | $ - | 26.32 | $ - | $ - | 0.0% |
| Damage Cost Ice | NA | 0% | 2.00 | $ - | 1.00 | $ - | 0.00 | $ - | $ - | 0.0% |
| Replacement Cost (RC) | NA | 100% | 0.00 | $ - | 1.00 | $ 867,797 | 0.00 | $ - | $ 867,797 | 26.7% |
| Maintenance Costs (MC) | NA | 5% | 1.00 | $ 42,142 | 1.00 | $ 43,390 | 1.00 | $ 44,674 | $ 130,206 | 4.0% |
| Mon & Adapt Man (MA) | NA | 14.7% | 1.00 | $ 123,898 | 0.00 | $ - | 0.00 | $ - | $ 123,898 | 3.8% |
| | | HRSSP | | | Post-Construction Costs (DCs+RC+MC+MA) | | | | $ 2,364,139 | 72.7% |
| | | Assumed | | | Design and Permiting Costs | | | | $ 56,721 | 1.7% |
| | | | | | | | | Total Cost | $ 3,251,498 | 100.0% |

*Costs are calculated as the IC x %IC x #Events with inflation and discounting applied mid period

Total costs incurred in each category over project life

*Figure 32: The costs incurred in each category during each period are the number of events times the cost per occurrence, which is calculated as a percentage of the IC. Adjustments are made for inflation and discounting. The total long-term cost for each category of expense is obtained by summing the costs in each category over the three periods.*

Proportion of the total long-term cost

| Long-term Cost Estimate - Berkeley Island (Iowa Court) Living Shoreline | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | P1 (2020-2040) | | P2 (2040-2060) | | P3 (2060-2080) | | Total (2020-2080) | |
| Category | Storm $T_r$ | % IC | # Events | *Cost | # Events | *Cost | # Events | *Cost | Ext Cost | % Final |
| Initial Cost (IC) | NA | NA | NA | NA | NA | NA | NA | NA | $ 830,638 | 25.5% |
| Damage Cost (DC) | 50 | 0% | 0.62 | $ - | 1.83 | $ - | 5.45 | $ - | $ - | 0.0% |
| Damage Cost (DC) | 40 | 10% | 0.77 | $ 64,660 | 2.28 | $ 198,127 | 6.80 | $ 607,815 | $ 870,603 | 26.8% |
| Damage Cost (DC) | 25 | 0% | 1.22 | $ - | 3.64 | $ - | 10.81 | $ - | $ - | 0.0% |
| Damage Cost (DC) | 10 | 0% | 2.98 | $ - | 6.45 | $ - | 26.32 | $ - | $ - | 0.0% |
| Damage Cost Ice | NA | 0% | 2.00 | $ - | 1.00 | $ - | 0.00 | $ - | $ - | 0.0% |
| Replacement Cost (RC) | NA | 100% | 0.00 | $ - | 1.00 | $ 867,797 | 0.00 | $ - | $ 867,797 | 26.7% |
| Maintenance Costs (MC) | NA | 5% | 1.00 | $ 42,142 | 1.00 | $ 43,390 | 1.00 | $ 44,674 | $ 130,206 | 4.0% |
| Mon & Adapt Man (MA) | NA | 14.7% | 1.00 | $ 123,898 | 0.00 | $ - | 0.00 | $ - | $ 123,898 | 3.8% |
| | | HRSSP | | | Post-Construction Costs (DCs+RC+MC+MA) | | | | $ 2,364,139 | 72.7% |
| | | Assumed | | | Design and Permiting Costs | | | | $ 56,721 | 1.7% |
| | | | | | | | | Total Cost | $ 3,251,498 | 100.0% |

*Costs are calculated as the IC x %IC x #Events with inflation and discounting applied mid period

Total post construction costs (does not include IC)

Design and permitting costs

Total long-term cost

*Figure 33: The total post-construction costs are the sum of the DC, RC, MC, MA, and ice damage costs. Design and permitting costs are considered separately. The total long-term cost is the sum of all of the project costs. The last column shows how the total long-term costs are distributed amongst the various categories.*

# APPENDIX B

## Wave Attenuation Summary Plots

Each figure contains two plots. The upper plot shows the wave measurements ($H_{1/3}$ – significant wave height, or $H_{max}$ – maximum wave height) made offshore (green dots) and inshore (blue dots) of the wave attenuation structures. For reference, a line indicating a wave height of 5 cm is also shown. Only wave heights in excess of 1 cm are shown in the plots. The lower plot shows percent reduction; percent reduction values when the offshore waves are larger than 5 cm are shown with a purple star, while values for smaller waves are shown with a grey dot. The water level measured inshore of the structure is shown for reference.

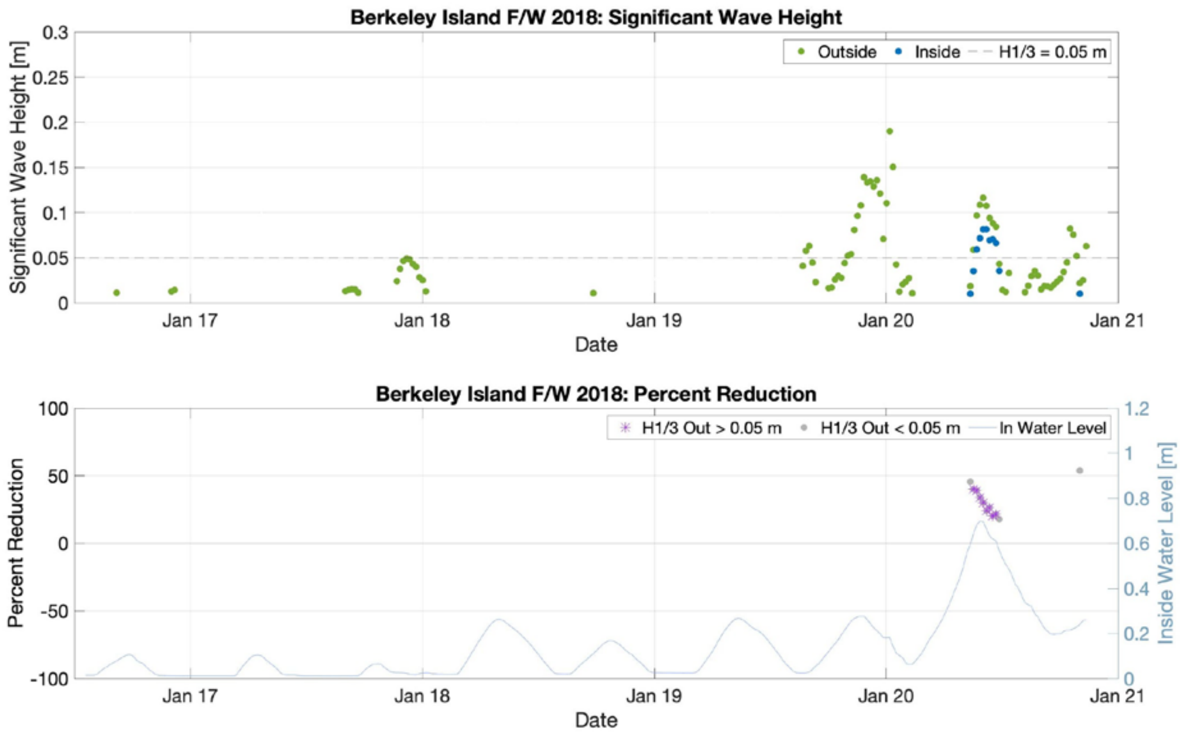



*Figure 34: Significant wave height and percent reduction for Berkeley Island fall/winter 2018 deployment.*

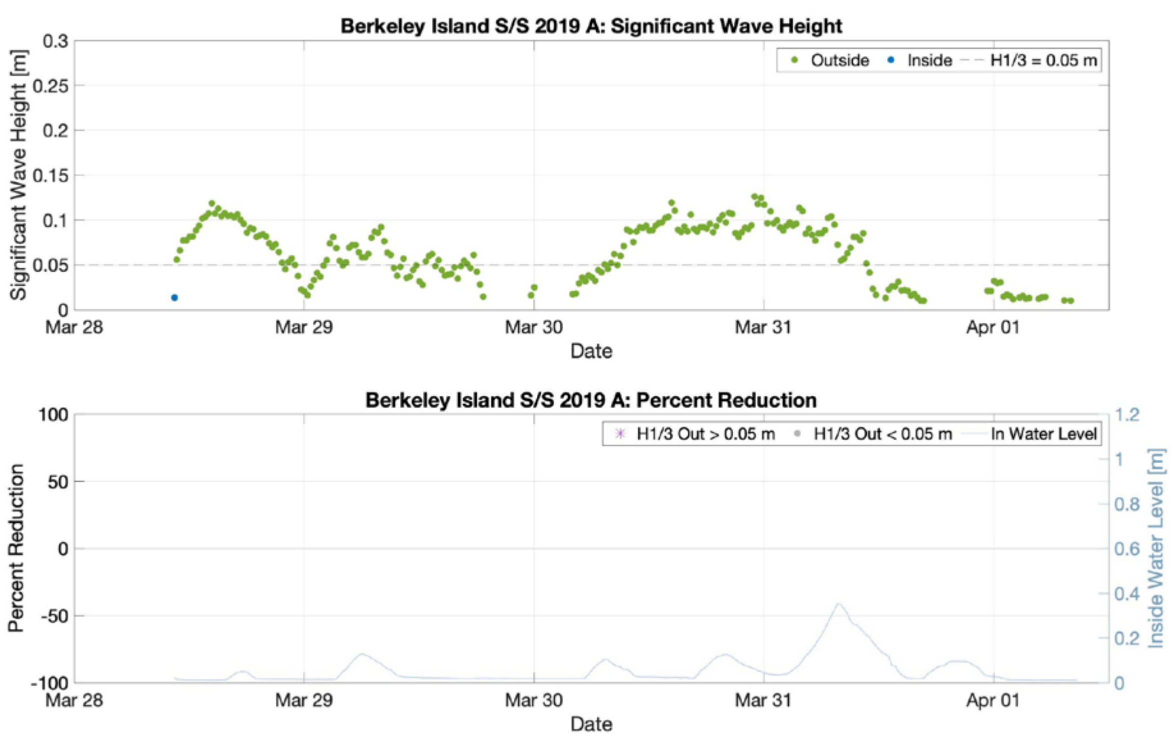



*Figure 35: Significant wave height and percent reduction for Berkeley Island spring/summer 2019 A deployment.*

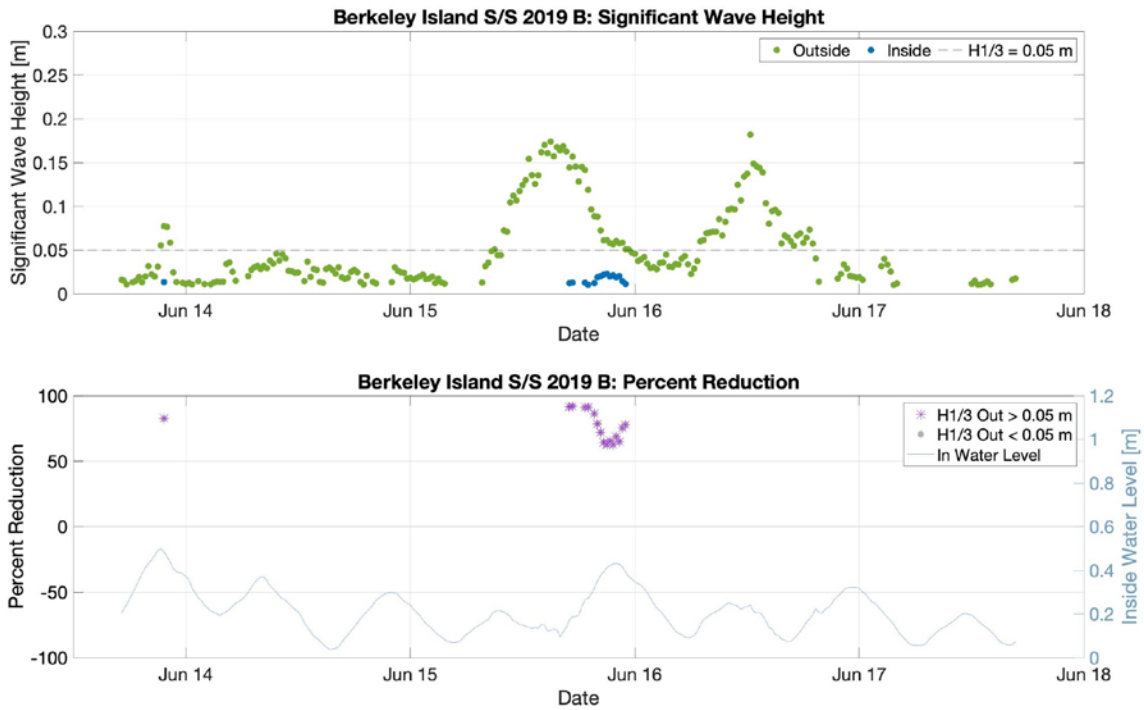



*Figure 36: Significant wave height and percent reduction for Berkeley Island spring/summer 2019 B deployment.*

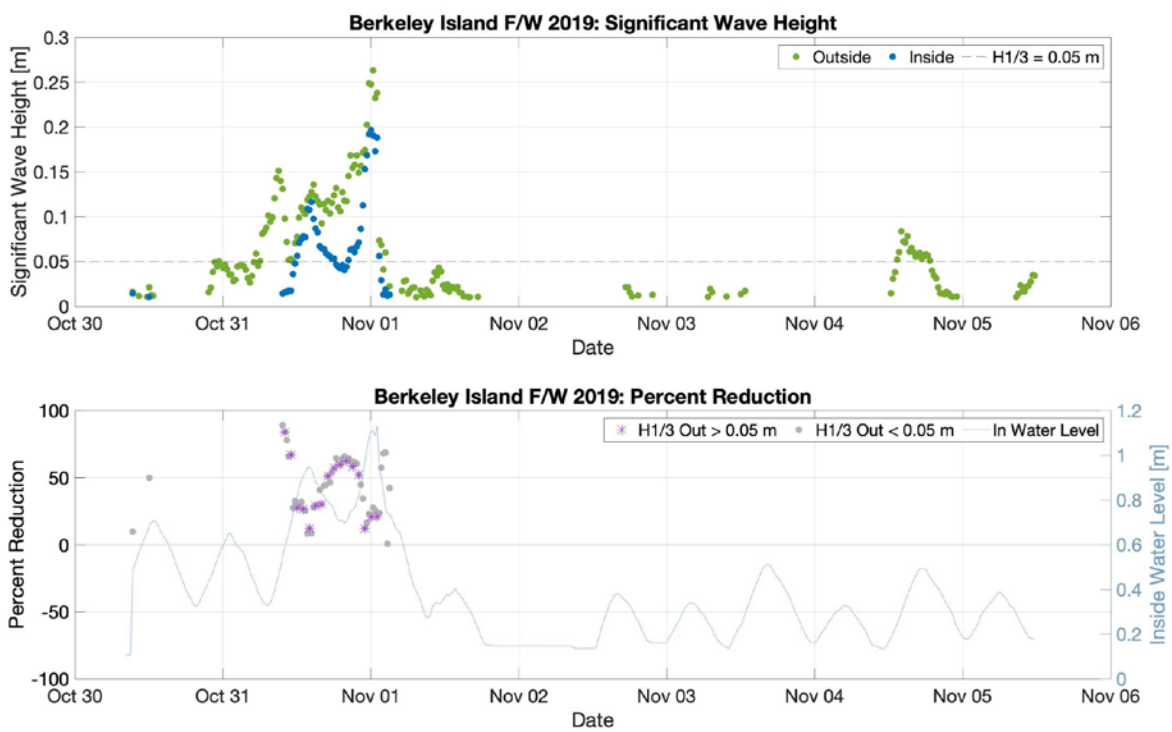



*Figure 37: Significant wave height and percent reduction for Berkeley Island fall/winter 2019 deployment.*

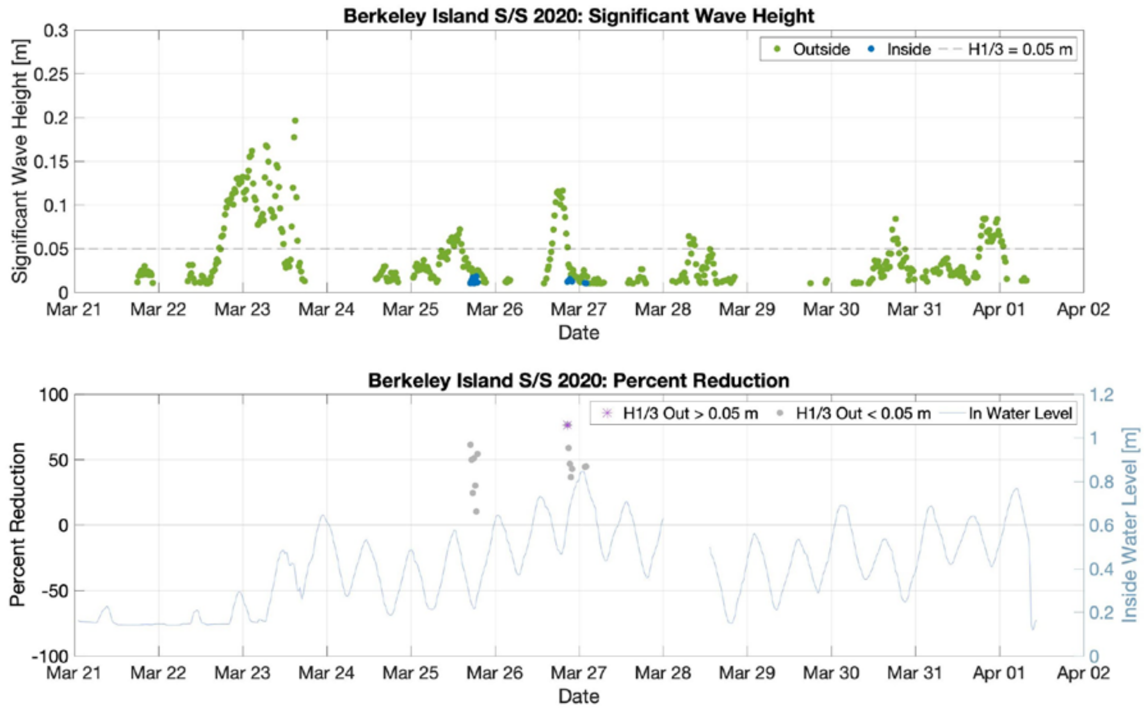



*Figure 38: Significant wave height and percent reduction for Berkeley Island spring/summer 2020 deployment.*

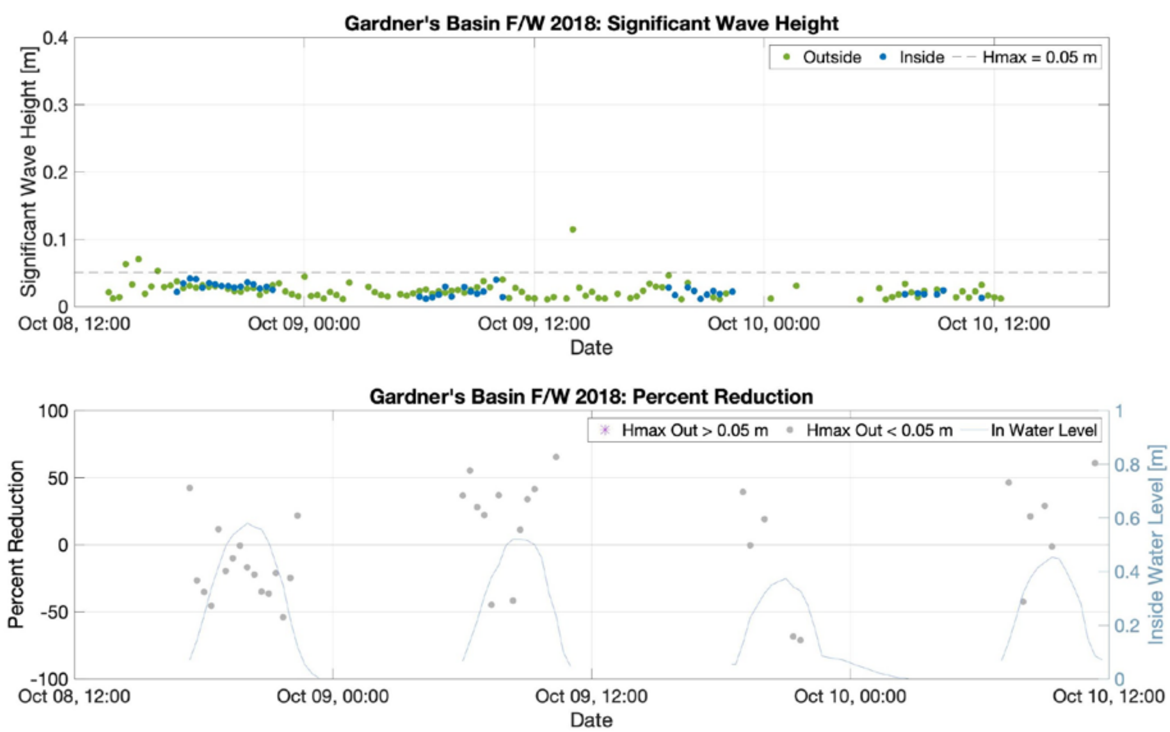



*Figure 39: Significant wave height and percent reduction for Gardner's Basin fall/winter 2018 deployment.*

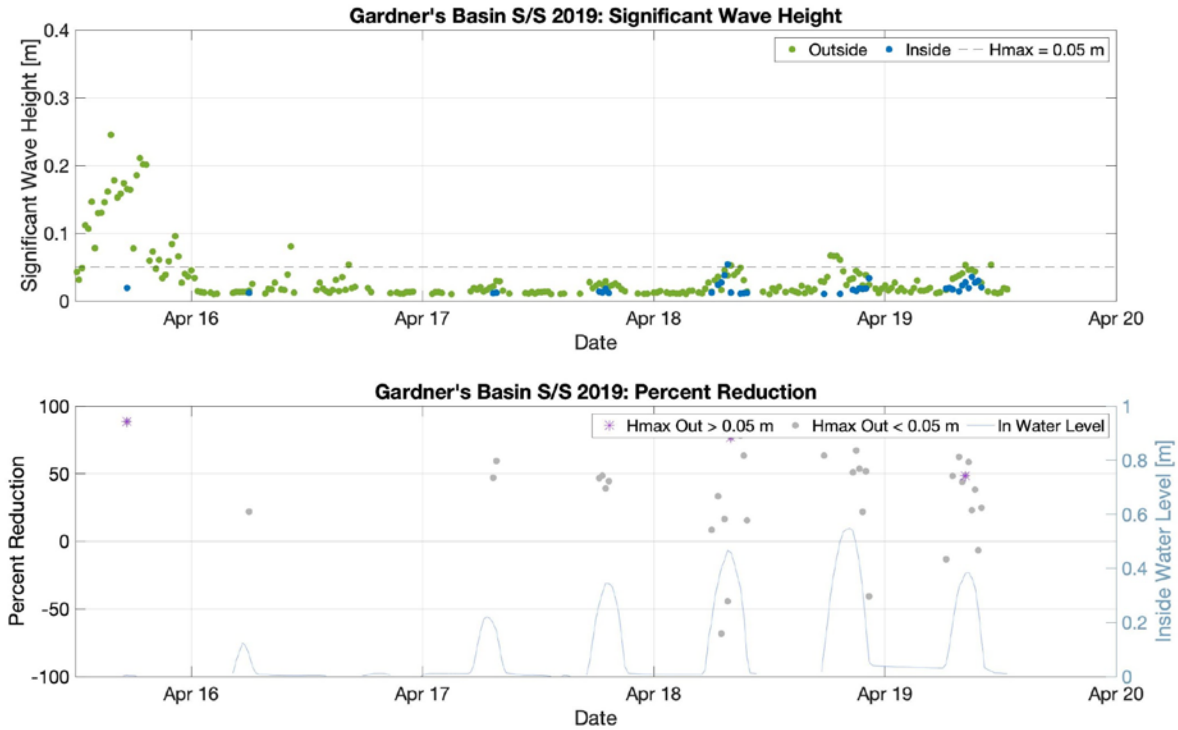



*Figure 40: Significant wave height and percent reduction for Gardner's Basin spring/summer 2019 deployment.*

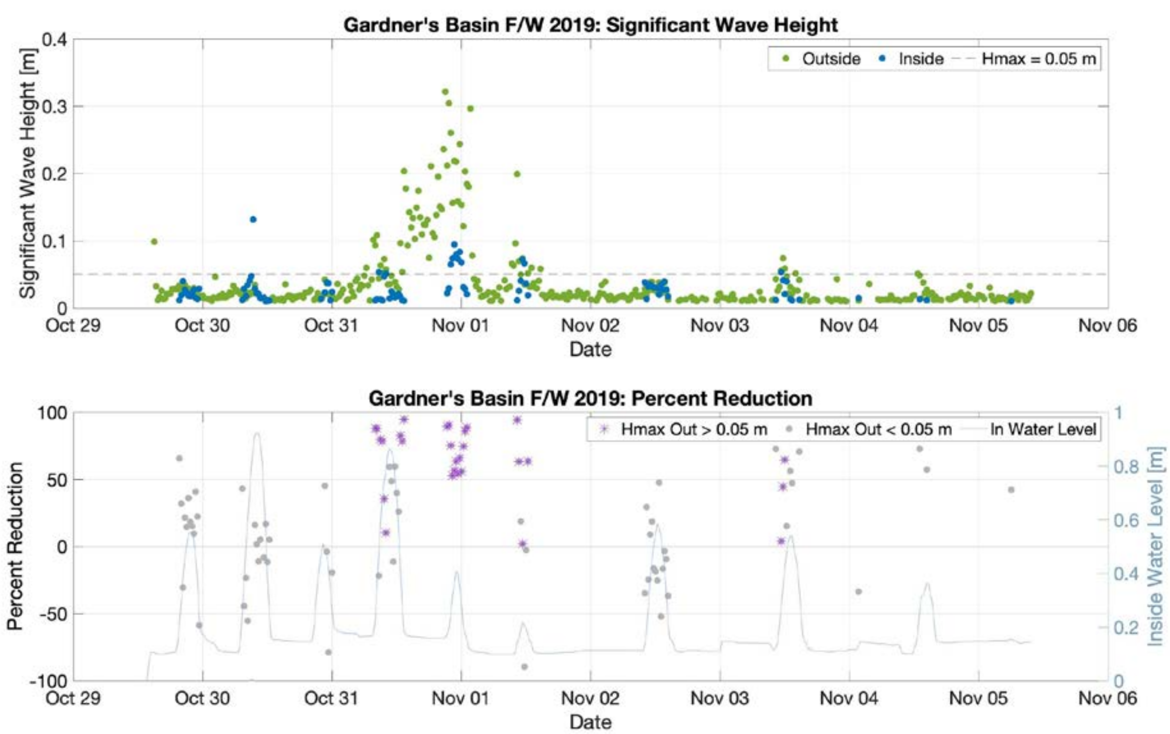



*Figure 41: Significant wave height and percent reduction for Gardner's Basin fall/winter 2019 deployment.*

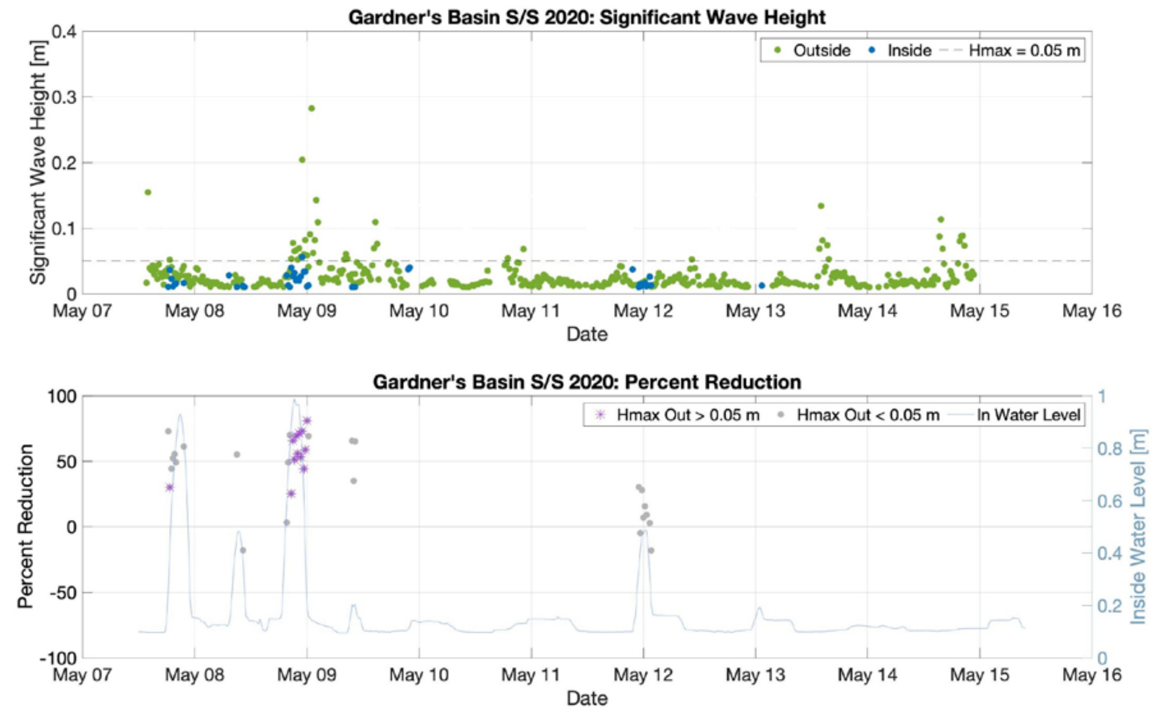



*Figure 42: Significant wave height and percent reduction for Gardner's Basin spring/summer 2020 deployment.*

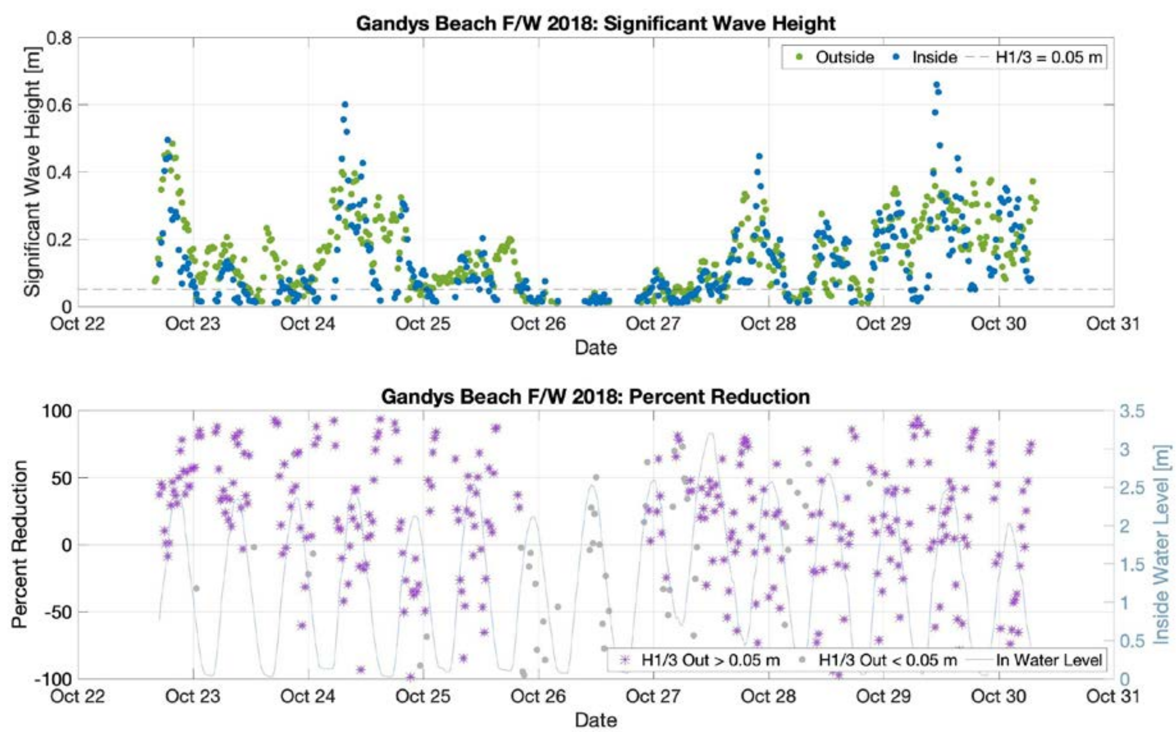



*Figure 43: Significant wave height and percent reduction for Gandys Beach fall/winter 2018 deployment.*

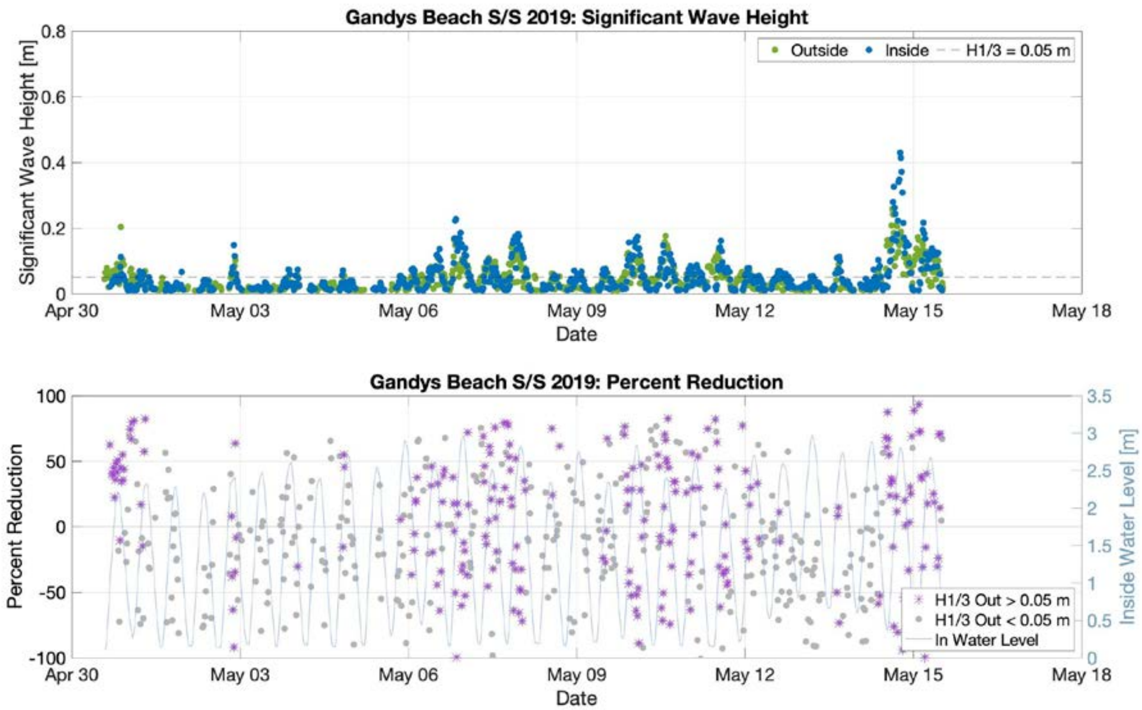



*Figure 44: Significant wave height and percent reduction for Gandys Beach spring/summer 2019 deployment.*

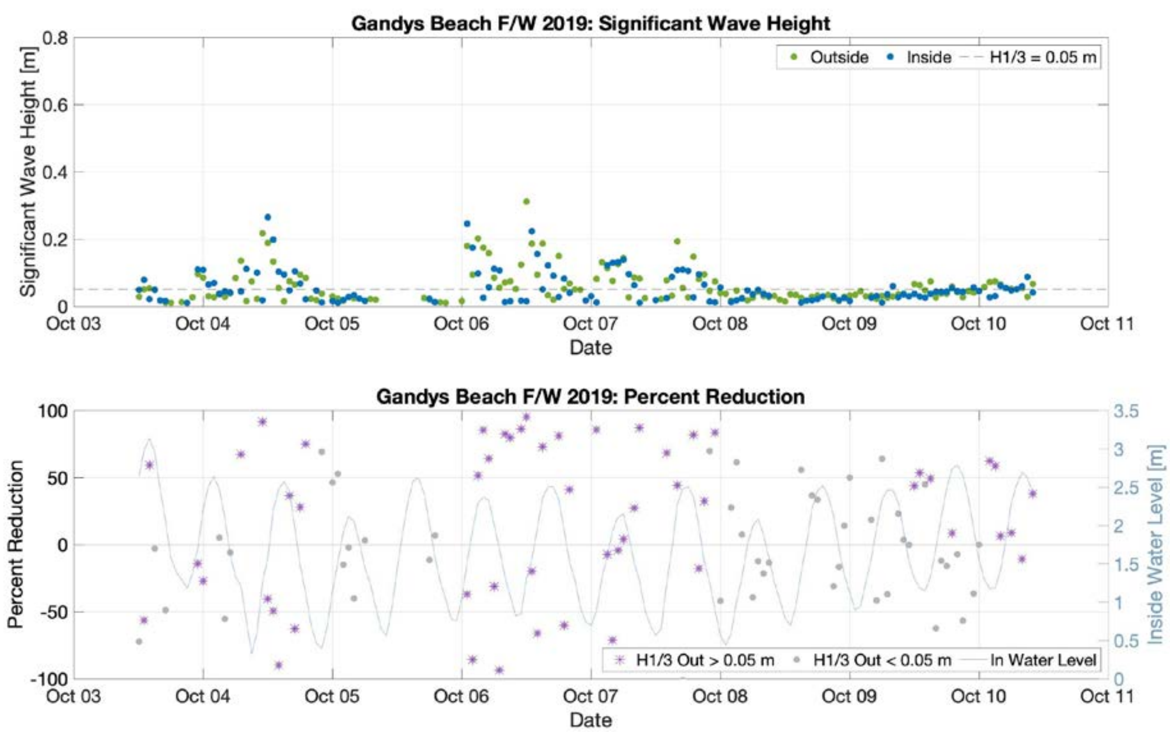



*Figure 45: Significant wave height and percent reduction for Gandys Beach fall/winter 2019 deployment.*

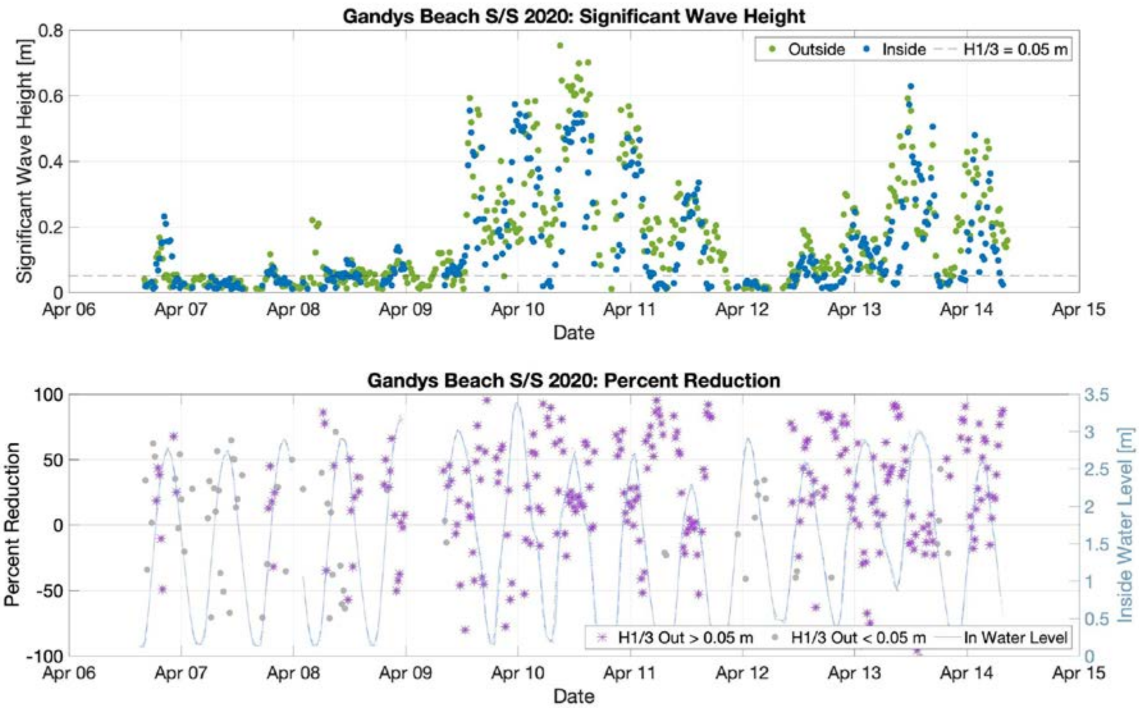



*Figure 46: Significant wave height and percent reduction for Gandys Beach spring/summer 2020 deployment.*

# APPENDIX C

## Field Site Photographs

Berkeley Island Site Photos

Gardner's Basin Site Photos



Matts Landing Site Photos

Gandys Beach Site Photos

Strathmere Site Photos


# Glossary

**Adaptive Management** – Modifications made to the original design of a project within the first one or two years after construction intended to optimize the function of the project. In contrast to maintenance, adaptive management costs are assumed to decrease over time as the project becomes established.

**BACI (Before, After, Control, Impact) Survey Design** – Technique commonly used in the design of environmental surveys where differences between the area of interest and a control area are measured Before and After an Impact

**Bulkhead** – Structures which are intended to retain sediment and are often constructed on coastlines as a way of limiting or controlling upland erosion. Bulkhead structures are most commonly vertical and can be constructed of wood, concrete, steel, vinyl and other materials.

**Breakwater** – Structures that are built within a water body to reduce wave energy and erosion in its lee. Types include rubble mound breakwaters, floating breakwaters, and living breakwaters.

**Coir Roll** – Coastal bio-erosion control element consisting of coir (coconut husk fibers) bound together by a mesh and formed into cylinders 12 to 20 inches in diameter. The rolls are typically secured to an eroding bank as a means of providing either temporary or permanent protection.

**Damage Costs (DC)** - Cost category used in the long-term cost estimate that represents the costs to repair a project after a storm event. Damage Costs fall outside of the scope of typical Maintenance and Repair Costs.

**Digital Elevation Model (DEM)** – A geospatial three dimensional model of a surface.

**Discount Rate** - Rate of return used to discount future cash flows back to their present value. The discount rate used in the analysis is consistent with the federal guidance contained in Economic Guidance Memorandum (EGM), 18-01, Federal Interest Rates for Corps of Engineers Projects for FiscalYear 2020 (USACE, 2020a).

**Inflation Rate** - Rate at which the value of a currency is falling and consequently the general level of prices for goods and services is rising. The inflation rate used in the analysis is consistent with the guidance contained in the US Army Corps of Engineers planning document, Civil Works Direct Program Development Policy Guidance (USACE, 2020b).

**Initial Cost (IC)** – Cost category used in the long-term cost estimate that represents the initial cost of constructing a project.

**Living Shoreline Project** – The term “living shoreline” has many different definitions. Here the term is used to describe a suite of shoreline stabilization approaches designed with consideration of the ecology of the setting in mind.

**Maintenance and Repair Costs (MC)** - Cost category used in the long-term cost estimate that represents the costs associated with inspecting and performing basic maintenance on the project.

**Maximum Wave Height ($H_{max}$)** – The maximum individual wave height recorded during a wave sampling event.

**Mobilization** – Costs related to getting equipment, materials, and sometimes people to a site prior to the start of construction.

**Monitoring and Adaptive Management Costs (MA)** – Cost category used in the long-term cost estimate that represents the costs associated with monitoring the project and providing any necessary adaptive management.

**Oyster Castle** – Interlocking concrete blocks, made with a special concrete mix designed to encourage the settlement and growth of oysters.

**Percent Reduction (R)** – A parameter for assessing wave attenuation. Percent Reduction is defined as the difference between the wave height measure offshore ($H_o$) and inshore ($H_i$) of wave attenuation structures as a percentage of the offshore wave height.

**Real Time Kinematic Global Positioning System (RTK GPS)** – A satellite based geopositioning system capable of defining locations in real-time with an accuracy on the order of several centimeters.

**Return Period ($T_r$)** – In statistical terms, return period is defined as one over the annual exceedance probability. In lay terms, return period is commonly used to refer to the expected time period between the occurrence of relatively rare events.

**Replacement Costs (RC)** - Cost category used in the long-term cost estimate that represents the costs associated with the replacement of a structure which has deteriorated to the point at which repair is no longer cost-effective.

**Revetment** – Sloping structures often used along the banks of eroding shorelines to absorb energy and prevent further erosion. Revetments are most commonly constructed out of rock, however a variety of other materials including concrete, rubble, and woody debris can also be used.

**Sea Level Rise (SLR)** – Rate at which water levels along the coast are rising as a result of natural and man-made processes. impacts. Specifically, the report utilizes the moderate emissions sea level rise scenarios contained in (Kopp et al., 2019).

**Significant Wave Height ($H_s$)** – Wave height parameter commonly used to represent wave conditions defined as the average of the highest one-third of wave observations in any record.

**Sill** - Low-profile, shore parallel mounds placed offshore with the purpose of retaining sediment and elevating the nearshore profile. Sills can be constructed of natural (stone, soil, etc) or synthetic (geotextile rolls) materials and are typically used as part of a perched beach system.

**Structure from Motion (SfM)** – Technique based on stereo imaging that allows three-dimensional information to be extracted from a series of two-dimensional photographs taken from varying angles containing common points.

**Conventional Gray Shoreline** – The terms “conventional” and “gray” are commonly used to describe shoreline stabilization approaches that do not incorporate ecological considerations in the design.

**Unmanned Aerial Vehicle (UAV)** – Commonly referred to as drones, UAV’s are unmanned vehicles controlled by an operator that can be used as a platform for a variety of sensors.

**Wave Attenuation (Dissipation)** – Reduction in wave energy often associated with an encounter with a natural or built feature such as a marsh sill.