BOLD
THINKERS
DRIVING
REAL-WORLD
IMPACT

Case Study: Cost-Effectiveness of Reducing Coastal Erosion through Living Shorelines in the Hurricane Sandy Coastal Resilience Program

Contract # 5359

PREPARED FOR:

National Fish and Wildlife Foundation
1133 Fifteenth Street, N.W., Suite 1000
Washington, DC 20005

U.S. Department of the Interior
1849 C Street, NW
Washington, DC 20240

SUBMITTED BY:

Abt Associates
6130 Executive Blvd.
Rockville, MD 20852

IN PARTNERSHIP WITH:
Virginia Institute of Marine Science,
Center for Coastal Resources Management
Crucial Economics Group, LLC

FINAL
2019

Case Study: Cost-Effectiveness of Reducing Coastal Erosion through Living Shorelines in the Hurricane Sandy Coastal Resilience Program

Prepared by Abt Associates, September 2019

Summary

Purpose

This case study forms part of a larger 2019 evaluation of the Hurricane Sandy Coastal Resilience Program (Hurricane Sandy Program) of the U.S. Department of the Interior (DOI) and the National Fish and Wildlife Foundation (NFWF). It provides an in-depth analysis of the program's living shorelines, with a particular emphasis on understanding their cost-effectiveness as compared to a traditional gray infrastructure approach (i.e., a stone revetment) to reduce coastal erosion.

Scope

We examined 17 projects, encompassing 29 project sites, in the Hurricane Sandy Program portfolio to reduce coastal erosion through the creation of living shorelines. Eleven of these 17 projects, encompassing 22 project sites, were selected for an in-depth cost-effectiveness analysis.

Findings

Key findings identified using archival materials, a survey and interviews of project leads, and peer-reviewed literature include:

- The Hurricane Sandy program created nearly 53,000 linear feet of living shorelines, protecting the coastlines behind these shorelines and avoiding coastal erosion on up to 440 acres of land; these projects will help sustain wildlife and human use of these areas over the next few decades.[a]
- To protect existing coastlines, living shoreline projects restored habitat; these projects restored approximately 40 acres of marshes, beaches, oyster reefs, and submerged aquatic vegetation (SAV). [a]
- For erosion protection, living shorelines were typically more cost-effective than stone revetments, and their cost-effectiveness improved when considering additional benefits of the habitat restored.
- Living shorelines are providing more ecological benefits through habitat restoration than stone revetments, bulkheads, or other gray systems.

Conclusion

Hurricane Sandy Program investments in living shorelines appear to be a cost-effective and ecologically sound approach for reducing coastal erosion and improving resilience. Living shorelines were more cost-effective than a comparable gray infrastructure approach (i.e., a stone revetment) at reducing coastal erosion at project sites, assuming the two approaches perform similarly over time. The cost-effectiveness of living shorelines was even higher when we included the amount of habitat restored in our calculations. While data were not available to provide a robust assessment of on-the-ground performance of specific projects, anecdotal observations suggest that erosion has been reduced and habitat is recovering in project areas. These observations are preliminary, however, and more years of recovery and monitoring data are needed to better understand long-term ecological and socioeconomic impacts of living shorelines.

a. This number includes all living shoreline projects (both active and completed), meaning this number may be subject to change from adjustments to in progress projects.

1. Introduction

This case study of living shorelines forms part of a larger 2019 evaluation of the DOI and NFWF Hurricane Sandy Coastal Resiliency Program (Hurricane Sandy Program). Between 2013 and 2016, the Hurricane Sandy Program, administered through DOI and NFWF, invested over $302 million to support 160 projects designed to improve the resilience of ecosystems and communities to coastal storms and sea level rise.[1] The program supported a wide array of activities, including aquatic connectivity restoration, marsh restoration, beach and dune restoration, living shoreline creation, community resilience planning, and coastal resilience science to inform decision-making. Each of these activities has a distinct impact on ecosystem and community resilience.

DOI and NFWF drafted the following five questions to serve as the focus of the evaluation:

1. To what extent did projects **implement activities** as intended? What factors facilitated or hindered project success?
2. What **key outcomes** were realized for habitat, fish and wildlife, and human communities?
3. Is there evidence that investments in green infrastructure are **cost-effective** compared to gray infrastructure?
4. Did investments in tools and knowledge related to resilience **improve decision-making**?
5. What **information is needed** to better understand the long-term impacts of investments in resilience?

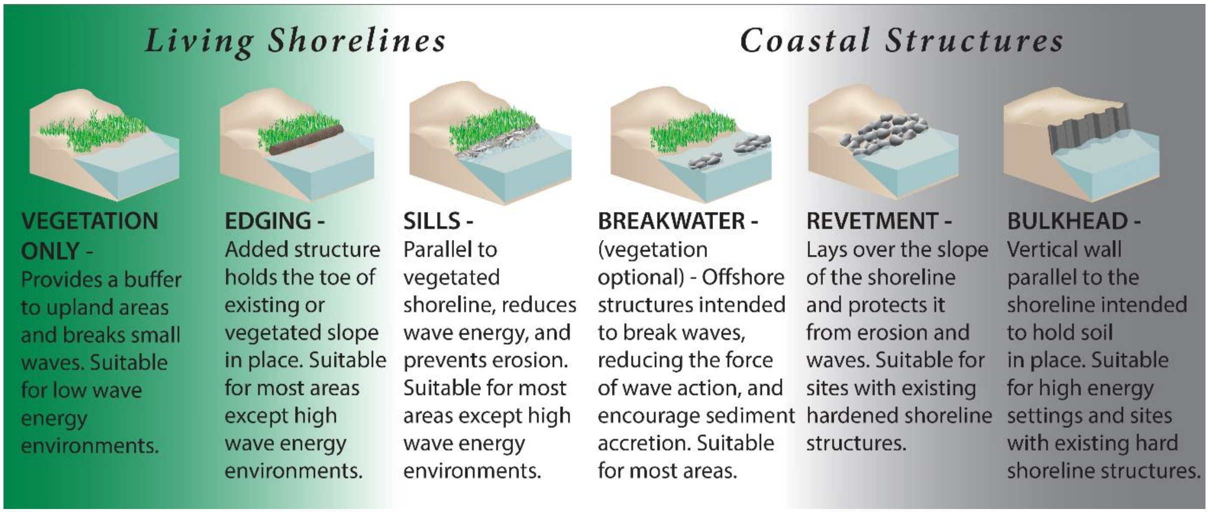
The evaluation includes six case studies, each providing a deeper level of analysis on a subset of the projects.

1.1 Purpose

This case study provides a cost-effectiveness analysis of living shorelines, and focuses on evaluation questions #1, #2, #3, and #5. More specifically, we compare the cost-effectiveness of living shorelines to an equivalent "gray infrastructure" reference project (i.e., a stone revetment) that is assumed to provide the same amount of protection from erosion (Box 1). Living shorelines are stabilized using soft (e.g., vegetation and sand) elements alone or in combination with hard structures such as oyster reefs, rock sills, or anchored large wood. Living shorelines can both protect and stabilize the shoreline; and restore or enhance aquatic, wetland, and beach habitats. In addition, living shoreline and other natural infrastructure projects increase stability over time, whereas hard infrastructure (e.g., stone revetment and bulkhead) deteriorates over time.

[1] The evaluation covers these 160 projects. In some cases DOI and NFWF reinvested unspent funds in new, additional projects after the December 2016 cutoff date. These new projects are not included in the evaluation.

Box 1. Shoreline stabilization techniques, where objects on the left side of this continuum represent green, living shoreline techniques; and projects on the right represent gray, harder shorelines stabilization techniques.



Source: Figure 1 in NOAA (2015).

1.2 Scope

The case study examined 17 projects, encompassing 29 project sites, in the Hurricane Sandy Program portfolio that implemented living shorelines to reduce coastal erosion. Eleven of these projects, encompassing 22 project sites, were selected for the in-depth, cost-effectiveness analysis. These projects were selected because the costs of the living shoreline activity could be disaggregated from total project costs (see Appendix A for a full list of relevant projects, including those selected for this cost-effectiveness analysis). Many projects that incorporated living shoreline construction also included other types of resilience interventions (e.g., marsh or beach/dune restoration). In this case study, we focus solely on the living shoreline-related aspects of these projects; however, we provide an analysis of the potential synergies of different resilience activities in the main evaluation report.

1.3 Organization

The remainder of this document is organized as follows:

- Section 2 provides an overview of the methods and information sources used for this case study
- Section 3 provides a detailed overview of the living shoreline projects included in the Hurricane Sandy Program
- Section 4 discusses key case study findings, organized by evaluation question and topic
- Section 5 provides a brief conclusion.

2. Methods Overview

This case study integrates information from the following information sources:

- Archival materials from Hurricane Sandy Program project files (e.g., proposals, interim and final reports)
- A survey of project leads via a web-based instrument

- Interviews and emails with 12 project leads (i.e., grant recipients) who led living shoreline projects
- Interviews with NFWF and DOI staff
- Quantitative information provided by project leads in their reports (e.g., linear feet of living shorelines constructed, acres of habitat restored)
- Literature or data searches addressing specific contextual issues (e.g., restoration recovery trajectories, erosion rates, stone revetment costs).

Using this information, we conducted two types of cost-effectiveness analyses. In the first analysis, we compared the cost per unit area protected (i.e., erosion prevented) of each living shoreline to a comparable “gray infrastructure” project (i.e., stone revetment) that was scaled to fit the site’s wave energy conditions. In the second analysis, we compared costs of each project per area of land protected and area of habitat restored to the comparable stone revetment project. We estimated total project costs (in present value over a 30-year life span) by summing planning, design, construction, and maintenance costs. Our analyses captured differences in maintenance costs between green and gray projects, but we assumed that erosion control effectiveness was comparable, based on available evidence. We also compared the implementation cost per foot of shoreline length among projects for additional insights. See Appendix A for project details that fed into these analyses, and the evaluation report (Abt Associates, 2019) for a more detailed description of evaluation methods.

3. Overview of Projects

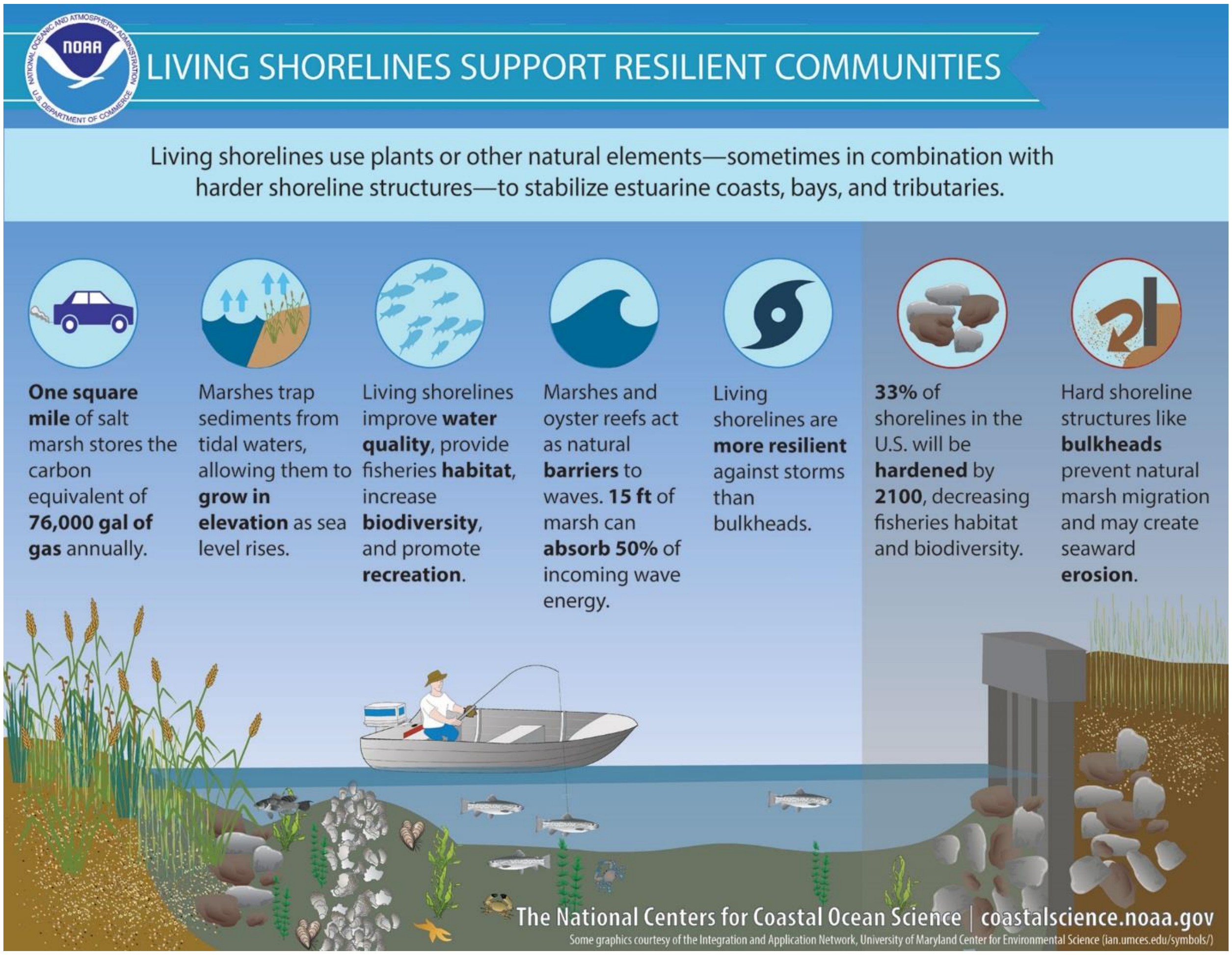
Coastal erosion is a critical threat to coastal communities and ecosystems along the Atlantic Coast. While coastal erosion is a natural process, it can lead to the degradation or loss of valuable coastal resources. Stabilizing shorelines can help make coastal areas more resilient to intense storms and sea level rise, which are likely to increase in the future. The creation of living shorelines is an increasingly popular approach to reducing coastal erosion, in large part due to the potential ecological benefits that can be provided through the habitat protected and created through their construction, particularly in contrast to comparable gray infrastructure approaches (Figure 1). NFWF and DOI supported the construction of living shorelines as an environmentally sound approach for protecting important coastal resources in areas affected by Hurricane Sandy.

Overall, the Hurricane Sandy Program invested more than $37.6 million in living shorelines in 17 projects (Table A.1), 11 of which also included other resilience activities; the total funding provided by the program for all of the activities in the 17 projects was $68.2 million.[2] Living shorelines were implemented in five states: Maryland, New Jersey, New York, Rhode Island, and Virginia (Figure 2; Table A.1).

Living shorelines varied in design and in the type of ecosystems being restored and protected, due to differing site attributes and project objectives. Most living shorelines used a combination of soft and hard natural materials (e.g., hybrid projects), but some living shorelines used only soft materials. We categorized the living shorelines as hybrid-major, hybrid-minor, or oyster-natural (see Box 2).

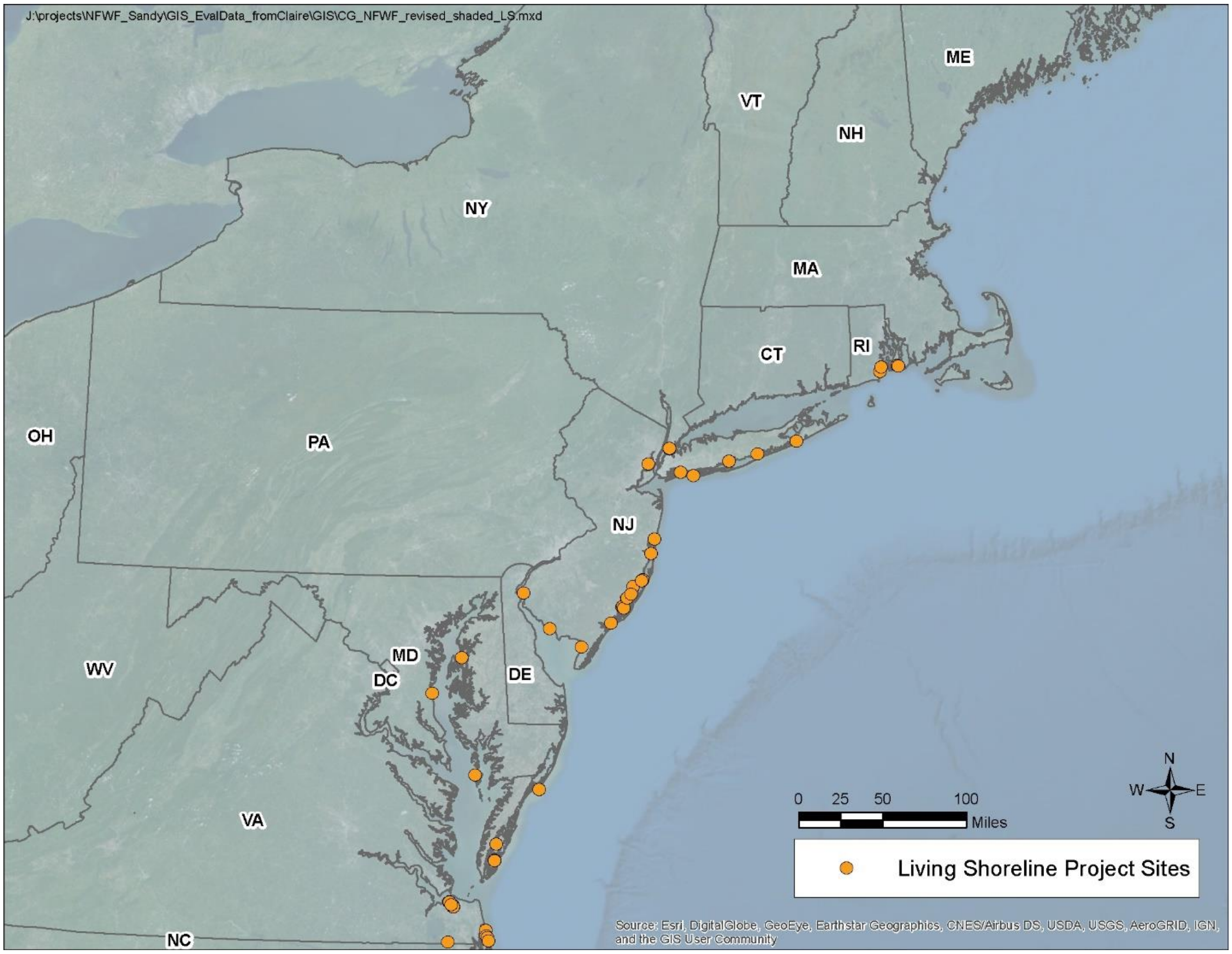
[2] Table A.1 presents the amount of project funding specifically allocated to living shoreline activities. For 6 projects, this is the full project funding amount; and for 11 projects, this is a subset of the total project funding. The allocation was based on available project documentation.

Figure 1. Conceptual representation of the benefits of using living shorelines to stabilize coastlines.



Source: NOAA, 2019.

Figure 2. Location of living shorelines restoration activities.[a]



a. Since some projects conducted restoration activities in multiple sites (see Appendix A), the number of sites (dots) exceeds 17 (the total number of living shorelines).

Box 2. Categories of living shorelines.

Hybrid-major if project used large rock sills or off-shore wave attenuation structures, such as breakwaters (14 of 29 sites).

Hybrid-minor if project used relatively small rock sills or structures to stabilize sites (7 of 29 sites).

Oyster-natural if project used oyster castles, oyster reefs, or soft materials such as coir logs to stabilize shorelines (8 of 29 sites).

Living shorelines were designed to protect coastal communities, including roads and public use facilities near the coast as well as marshes and beaches that further protect coastal communities from storm surge and waves. To protect coastlines, many of these projects also restored habitat within the footprint of the constructed breakwater. For example, projects revegetated marshes, re-nourished beaches, and created oyster reefs to improve wildlife habitat behind the breakwater of the living shoreline. These habitats serve to increase surface roughness, further reducing wave action and reducing erosion; they also support fish and wildlife in the area (see the Project Outcomes section for a more detailed discussion of the community and ecological benefits from land protection and habitat restoration).

The size of the living shorelines varied substantially among projects. The 11 living shorelines included in the cost-effectiveness analysis ranged from 35 to over 20,000 linear feet, with an average length of just over 2,000 linear feet (Table A.2). The costs of design, construction, and maintenance of the living shorelines also varied from approximately $5,000 to over $8 million, with an average cost of approximately $880,000 (Table A.2).

4. Findings

Topic: Project Implementation (PI)

Finding PI.1: Approximately half of the living shorelines successfully completed their proposed activities at the time of the evaluation.

Archival and web-based materials show that 8 of the 17 projects included in this case study were completed[3] at the time of the evaluation, with 9 active projects. Of the eight completed, three projects were completed in 2016, one in 2017, three in 2018, and one in 2019.

Finding PI.2: A combination of factors delayed most projects, including seasonal limitations on restoration work, the need for additional data collection or design work, and difficulties with contracting or procurement.

A combination of issues resulted in nearly every project in the living shorelines portfolio experiencing significant delays compared to proposed completion estimates. The data available through official contract amendments submitted to NFWF and DOI show that 14 of the 17 projects requested extensions for completing their work, with many projects requesting multiple contract extensions. These projects were delayed on average by a year and a half (548 days). Each project nearly always cited a combination of factors that contributed to project delays (see Box 3).

[3] While our evaluation generally provides findings elicited through the review of archival materials received through December 2018, project status information reflects information gathered through April 2019 (updated project status information was obtained through a supplementary web search in March 2019 and an updated spreadsheet provided by NFWF).

Box 3. Factors that contributed to the delay of living shorelines restoration activities.

Seasonal limitations

Nine project leads noted that the weather- and seasonal-dependent nature of living shoreline construction and restoration activities, particularly dredging and vegetation planting, contributed to delays. Weather events and growing seasons can limit the time available to perform restoration, and work was sometimes delayed for months by waiting for appropriate working conditions to return. In addition, construction is often restricted to specific times of the year to avoid harming wildlife (e.g., during migration or breeding seasons).

Additional data collection or design work

Eight project leads noted that they needed to gather additional data or adjust their project designs given onsite conditions, which caused unexpected project delays. For example, one project lead noted that the complexity of drainage in a site required hiring an external contractor to provide analysis and recommendations, resulting in a delay in designing and installing the proper water control structure.

Contracting or procurement

Six project leads reported difficulties in contracting or procurement that led to delays, some of which were due to securing agreements with contractors or engineering firms. At other times, it was difficult for project leads to ensure that contractors had completed all required work before seasonal construction limitations kicked in.

Finding PI.3: Completed living shorelines have generally achieved their design objectives.

Archival materials suggest that completed living shorelines generally met their construction goals. For example, archival materials provided detailed information about realized project objectives for six of the eight completed projects. Five of the six projects reported either reaching or exceeding project design goals in terms of acres of habitat restored, linear feet of living shoreline constructed or protected, or oysters recruited. Only one project constructed a living shoreline that was smaller than proposed (by 920 linear feet) due to conflicting activities occurring at one site preventing activities, and degradation of their installed structures due to faulty manufacturing at another site.

Project reports and project lead interviews, however, suggested that at least some adaptive management should be expected and built into project timelines and project budgets. For example, four projects noted the need to replant some marsh vegetation due to mortality from wildlife grazing, sediment compaction, hypersaline waters, or other causes. In addition, two projects noted the need to redesign and reinstall living shorelines after the first attempt failed because of inadequate fill in high wave-energy environments.

Topic: Project Outcomes (PO)

4.1 Human Community Outcomes

Finding PO.1: Nearly 53,000 linear feet of living shorelines will protect the shoreline and avoid erosion on up to 440 acres of land that people can use or benefit from, including marshes, roads, residential areas, beaches, and public facilities, helping sustain human use of these areas over the next few decades.

Living shorelines protect natural habitat and infrastructure by reducing or avoiding coastal erosion. Project lead-reported data show that the living shorelines included in this case study will protect nearly 53,000 linear feet of shoreline. Based on coastal erosion rates provided by project leads or federal and state data, we estimate these projects protect or reduce coastal erosion from approximately 300 to 440 acres of land over the 30-year project lifespan (Table 1; estimates of area protected depend on assumed erosion rates). Living shorelines that protect marshes both reduce waves and storm surge for communities living near the shore and provide habitat for commercially important fish. These living shorelines also protect:

Table 1. Area estimated to be protected by land type.

Land use type protected	Area to be protected after 30 years (acres)[a, b]	
	Low	**High**
Marsh	240.9	344.1
Road	39.3	72.4
Residential	5.5	8.4
Beach	5.1	14.2
Public use facilities	0.8	1.0
Total	**291.6**	**440.1**

a. Low and high estimates of area to be protected depend on assumed erosion rates.
b. This number includes all living shoreline projects (both active and completed), meaning this number may be subject to change as projects close and provide final numbers.

- Critical roads, including those used as emergency evacuation routes or for beach access (Box 4)
- Residential areas
- Beaches for human use, including for recreation and for hosting community and cultural events
- Public use facilities, such as visitor centers, educational kiosks, and boat launches in national wildlife refuges.

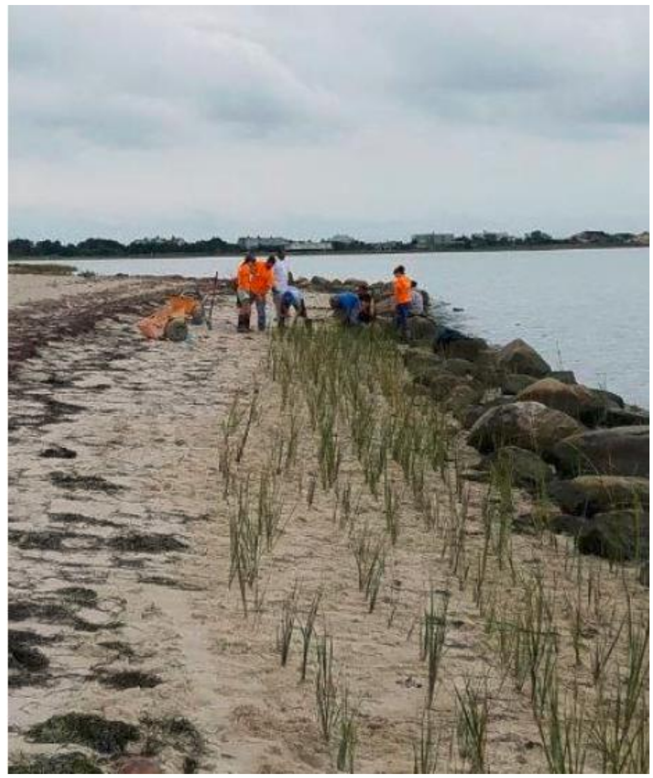
Box 4. A living shoreline under construction in the Town of North Beach, Maryland. Project prevents further erosion, protects the surrounding community and an emergency vehicle route.

4.2 Habitat, Fish, and Wildlife Outcomes

Finding PO.2: Living shorelines restored nearly 40 acres of habitat, including marshes, beaches, oyster reefs, and SAV.

These projects also restore or create habitat behind the living shoreline to further protect natural habitat and infrastructure (Box 5). Project lead-reported data show that the portfolio of living shoreline restoration projects included in this case study have restored or created nearly 40 acres of wildlife habitat, including approximately 22 acres of marshes, 11 acres of beaches, 5 acres of oyster reefs, and 2 acres of SAV (Table 2). It is important to note that these acres of habitat are only those directly behind the footprint of the protection provided by the breakwater of each living shoreline. In most cases, project leads integrated living shoreline activities into a larger project with multiple components, including large areas of marsh or beach restoration. However, these larger restoration efforts outside of the footprint of the living shorelines are included and assessed in other case studies (e.g., marsh restoration or beach and dune case studies), and thus are not included here.

Box 5. Living shoreline restoration at Shinnecock Reservation in Southampton, New York. Project reduces reduce erosion, increases habitat, and strengthens shoreline resiliency.



While on average each living shoreline project only directly protects and restores a modest amount of habitat, these habitats can play an important role in providing foraging, resting, and reproductive habitats for key bird, fish, and other wildlife in the region. For example, the salt marsh sparrow, red knot, alewife, and river herring all depend on salt marsh habitat for foraging and reproduction (Audubon, 2014; ASMFC, 2019; Cornell Lab of Ornithology, 2019). Beach habitat can support endangered species, including the regionally threatened piping plover and red knot (Audubon, 2014; USFWS, 2019; see the salt marsh and beach/dune case studies for more details about habitat-related benefits to wildlife). Oyster reefs and SAV improve water quality and provide critical

Table 2. Summary of area of habitat restored

Habitat type restored	Area restored (acres)[a, b]
Marsh	21.5
Beach	10.7
Oyster reef	5.3
SAV	1.7
Total	**39.2**

a. We assumed that these areas persist for the anticipated 30-year project life.
b. This number includes all living shoreline projects (both active and completed), meaning this number may be subject to change from adjustments to in progress projects.

habitat for a wide variety of forage fish, invertebrates, and shellfish, further supporting the larger fish and birds that feed on organisms that depend on reefs. While full realization of these benefits is expected to accrue over time, six projects reported initial improvements in oyster reef recruitment and anecdotal observations of increases in bird and fish numbers at restored sites.

4.3 Trajectories of Outcome Achievement

Finding PO.3: Early observations at living shoreline project sites are consistent with expected timelines of recovery after restoration, but project information about habitat recovery was limited.

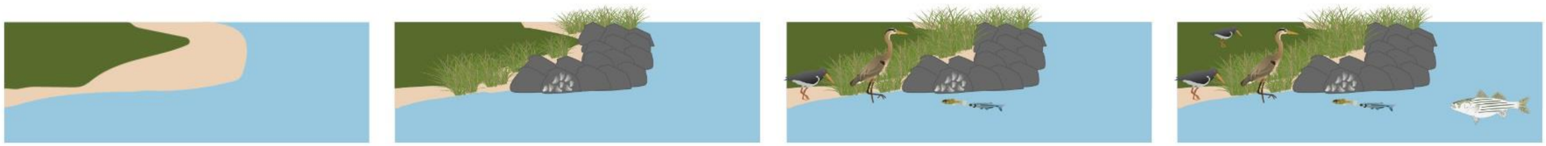
The ecological benefits of most living shorelines funded through the Hurricane Sandy Program will take time to materialize after restoration activities are completed. To better understand and convey the potential timing of the achievement of key outcomes, the Abt Associates evaluation team developed conceptual timelines of recovery after restoration using information from key peer-reviewed articles in combination with professional judgment from our team's subject matter experts (Figure 3).

More specifically, while some ecological components of living shorelines may begin to recover immediately following restoration actions (e.g., shoreline stabilization, recruitment of invertebrates such as oysters, seagrass recruitment), they may require more than 10 years to reach maximum function (Piazza et al., 2005; Davis et al., 2006; Scyphers et al., 2011; Manis, 2013; Bilkovic and Mitchell, 2017). While relatively few studies examine the long-term recovery of living shorelines, those with data for restored areas older than 10 years indicate that recovery continues for many years. For example, wildlife populations associated with living shorelines continue to increase after 10 years, and vegetation – particularly marsh vegetation – may take 10–30 years to match reference site conditions (Moreno-Mateos et al., 2012; Bilkovic and Mitchell, 2017; Lee et al., 2018).

Erosion control, often the primary reason for implementing a living shoreline project, begins immediately following restoration actions and continues to improve throughout the life of the project. The initial breakwater provides immediate protection, which provides opportunities for oysters and other filter-feeding species to become established; seagrass, if present, may also begin to establish in areas immediately behind and adjacent to the breakwater (Piazza et al., 2005; Scyphers et al., 2011; Manis, 2013; Patrick et al., 2014; Sharma et al., 2016). As marsh vegetation, seagrasses, and oyster reefs mature, the elevation and surface roughness of the area increases, providing increased erosion control protection (Bilkovic and Mitchell, 2017; Lee et al., 2018).

Initial observations of living shoreline recovery in Hurricane Sandy Program projects are consistent with the likely short-term outcomes described above. For example, six projects (completed between 2016 and 2018, plus one active project to be completed in 2019) reported use of restored habitat by wildlife, which primarily consisted of oyster reef recruitment, survival, or growth following restoration, with occasional fish and bird use of the habitat noted.
Four projects reported observations indicating improved erosion control, including shoreline stabilization and reduced wave energy. One project observed mixed improvements in vegetation; however, most projects were focused on assessing the success of installed oyster reefs, and examining the response of vegetation was not a high priority at this early stage.

Figure 3. Site recovery following living shoreline restoration activities over time.[a]



Realization timeframe[b]	Year 0 (pre-project)	Short-term (1–2 years) outcomes 2018–2022	Mid-term (3–7 years) outcomes 2020–2027	Long-term (10+ years) outcomes 2027+
Vegetation	Native vegetation may be sparse or missing; invasive species frequently dominate marshes.	Vegetation planted during restoration begins to establish; seagrass recruitment begins.	Marsh vegetative productivity approaches reference conditions; continued seagrass recruitment.	Vegetation comparable to reference marshes and seagrass beds achieved between 15 and 30 years after restoration.
Habitat/wildlife use	Area provides minimal support to key wildlife species.	Depending on restoration action(s), early recruitment of filter-feeding species begins (e.g., oysters, mussels, barnacles); seagrass habitat begins to establish; mudflats or beaches stabilize.	Native biota increase in restored areas, including macroinvertebrates, fish, and birds; seagrass continues to recolonize adjacent areas; continued stabilization of mudflats and beaches.	Ongoing population increases for all biota as habitat conditions improve and stabilize.
Erosion control	Unrestored habitat is prone to erosion.	Shoreline stabilization begins immediately following living shorelines structure installation through reduced wave energy, and increased sediment stability and accretion.	Reduced wave energy, sediment accretion, and vegetation growth help stabilize shorelines.	Shoreline elevation is stabilized or increases, supported by reduced wave energy, established vegetation, and surface roughness.

a. Marsh recovery timelines, which are relevant to living shoreline installations, are covered in detail in the marsh restoration case study. Habitat and wildlife use here is focused on the habitat provided by the breakwater or restored seagrass areas.

b. Assuming projects completed between 2017 and 2020.

Sources: **Vegetation:** Warren et al., 2002; Craft et al., 2003; Moreno-Mateos et al., 2012; Patrick et al., 2014; Sharma et al., 2016; Ebbets et al., 2019. **Habitat/wildlife use:** Piazza et al., 2005; Davis et al., 2006; Scyphers et al., 2011; Manis, 2013; Bilkovic and Mitchell, 2017; Hollweg et al., In review. **Erosion control:** Piazza et al., 2005; Scyphers et al., 2011; Manis, 2013; Bilkovic and Mitchell, 2017; Lee et al., 2018; professional judgment.

Topic: Cost-Effectiveness (CE)

This section highlights key findings of our analysis comparing the cost-effectiveness of a living shoreline to that of a comparable stone revetment. We made three important analytical assumptions that are critical to understanding and interpreting the results presented below. First, because the projects analyzed had been completed within two years of the evaluation, we had limited information to assess project performance in terms of erosion control. The literature also provided little information about living shoreline performance, particularly over the long-term. We thus assumed that projects that were fully implemented were successful at achieving their land protection and restoration goals; the same assumption was made for comparable stone revetments. Put simply, we assumed that both the living shoreline and stone revetment ceased all erosional loss at the site for 30 years, and this represented the amount of land protected by the project. Second, we bracketed our analysis using both "high" and "low" local erosion rates to estimate the annual amount of land protected (i.e., we calculated the amount of land that would have been lost if the project had not been implemented and assumed that all of this land would be successfully protected by the project). Third, we assumed that the comparable stone revetment projects were focused only on protecting existing land and thus did not restore habitat.

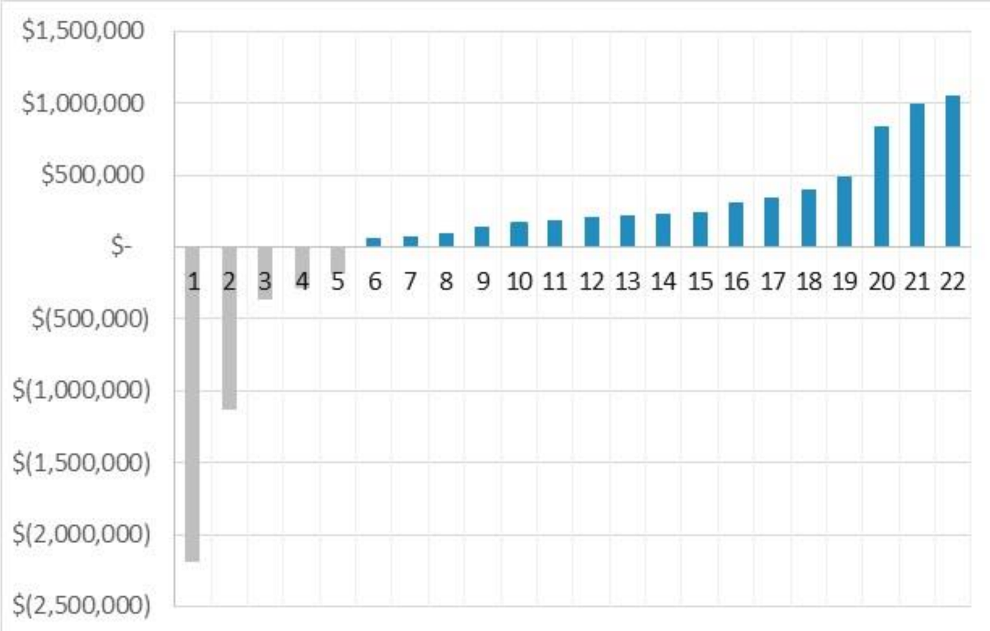
Finding CE.1: Living shorelines provided more ecological benefits than stone revetments.

As noted in Finding PO.1 above, the portfolio of living shoreline projects restored or created approximately 40 acres of wildlife habitat in addition to shoreline habitat being protected by the projects. While we assume both stone revetment and living shoreline projects protect existing shoreline habitat equally well, these restoration-related benefits are only secured through living shorelines.

Finding CE.2: Living shorelines were typically more cost-effective than stone revetments for erosion protection.

In almost all cases, living shoreline costs per area protected were lower than that of the comparable stone revetment. The average difference in costs per acre protected across all 22 project sites was approximately $84,800 for an assumed low erosion rate (Table A.2). The difference between stone revetment and living shoreline costs over 30 years (the assumed project lifetime) ranged from approximately a negative $2.2 million (i.e., the stone revetment was less expensive) to a positive $1.1 million (the living shoreline was less expensive; Figure 4; Table A.2). Negative values, which indicate that the living shoreline was less cost-effective than the stone revetment, were seen at only 5 of the 22 sites, all of which are located in low-energy environments with smaller waves (Figure 4; Table A.2). Cost-effectiveness results were similar when simply comparing implementation costs (construction plus planning) instead of using present value, suggesting that the assumptions we used to create the present value of costs, such as applying a discount rate, do not substantially affect our findings.

Figure 4. Differences in living shoreline costs per area protected versus comparable stone revetment costs.[a]

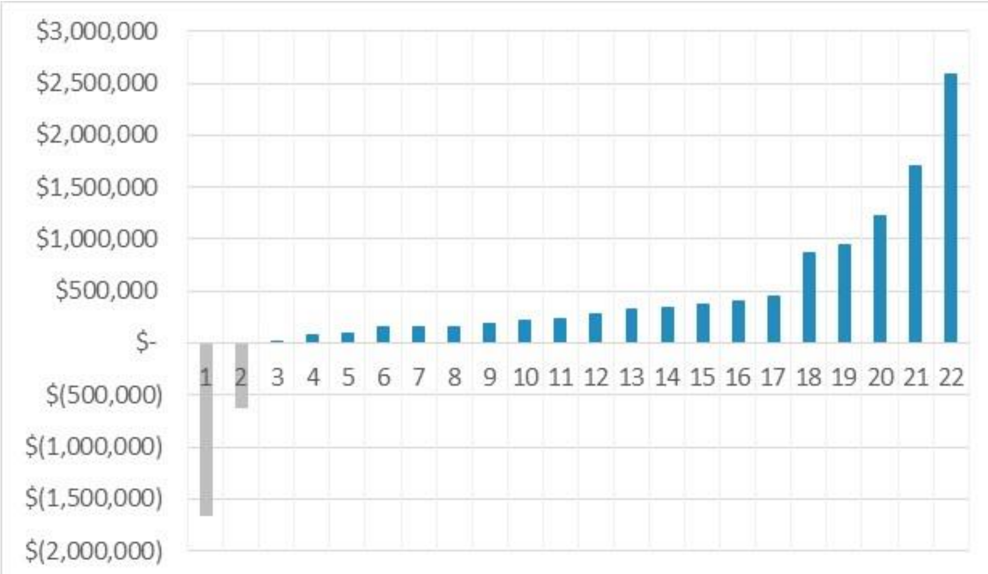


a. Values are sorted from low to high cost differences. Gray = living shoreline more costly; blue = living shoreline less costly. See Table A.2 for full project information (project identification numbers are not included here for visual simplicity).

Finding CE.3: When the additional benefits of habitat created were considered, living shorelines were substantially more cost-effective than gray approaches.

The cost-effectiveness of living shorelines increased markedly with including area restored in our assessment of cost-effectiveness (Table A.2). Including the amount of habitat restored into our measurement of cost-effectiveness for living shorelines reduced the estimated costs per unit of land area benefiting by approximately 30–40% (Table A.2). In addition, using this modified benefit metric, the cost-effectiveness of living shorelines compared to stone revetments increased by roughly 5- to 8-fold (Table A.2), and only two living shoreline sites had lower cost-effectiveness than comparable stone revetment projects (Figure 5, Table A.2). Living shorelines with the highest cost-effectiveness compared to equivalent stone revetments were those that added the most habitat (i.e., marsh, oyster reefs, or SAV).

Figure 5. Differences in living shoreline costs per area protected and restored versus comparable stone revetment costs.[a]

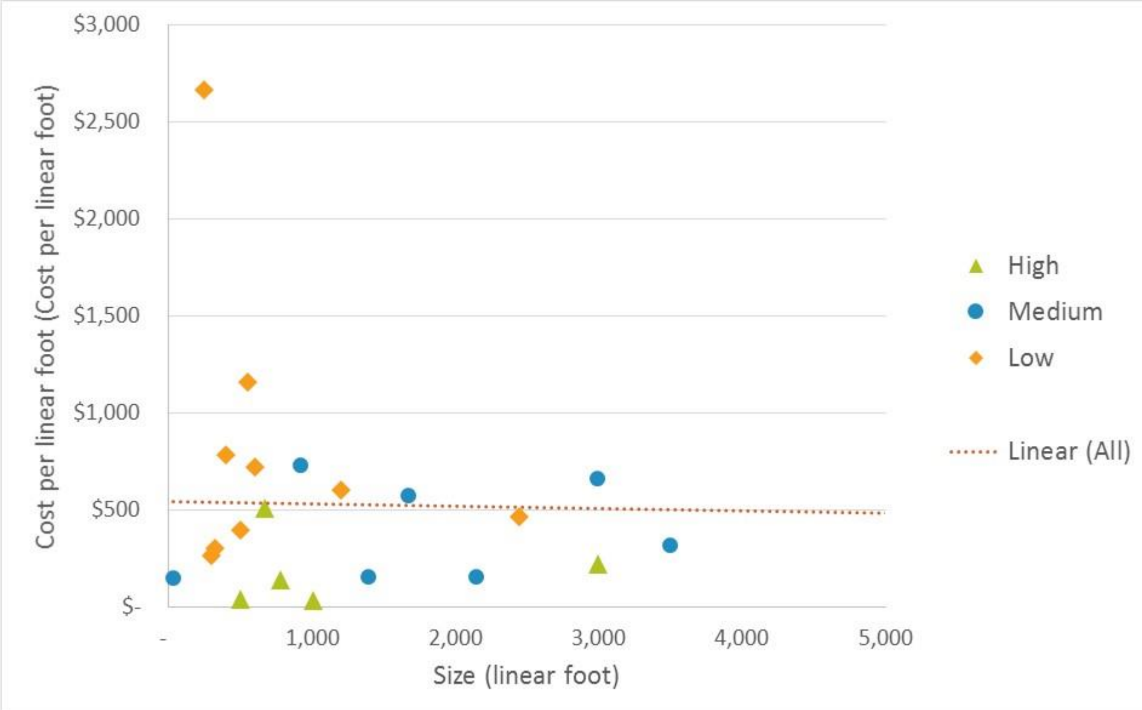


a. Values are sorted from low to high. Gray = more-costly living shorelines; blue = less-costly living shorelines. See Table A.2 for full project information (project identification numbers are not included here for visual simplicity).

Finding CE.4: There were no substantial economies of scale in creating living shorelines.

We found only weak evidence of economies of scale with project size (Figure 6), and the small negative relationship between unit cost and size was not statistically significant. When hybrid-major projects (i.e., those that used a large amount of rocks) were isolated (see triangles in Figure 6), the regression slope became slightly more negative, indicating a greater reduction of unit costs with size; however, the relationship was still not statistically significant. An outlier far to the right (i.e., data from Fog Point, which restored 20,950 linear feet of shoreline) was omitted from the graph to improve readability; although we included the outlier in the regression analyses, our findings were not affected by its inclusion.

Figure 6. Economies of scale in living shoreline projects. Project costs for each foot of living shoreline do not decrease significantly with project size.



Topic: Information Gaps (IG)

Finding IG.1: More time is needed to assess how well living shorelines prevent erosion and improve resilience.

The evaluation team was not able to fully assess the on-the-ground performance of living shorelines projects because they were either not finished or had only recently been completed at the time of this evaluation. The ability of living shorelines to reduce coastal erosion will not be fully realized until restored habitat is allowed to mature, and our understanding of their effectiveness will be limited until they are tested by weather events. As noted above, we assumed in our cost-effectiveness analyses that living shorelines would be equally effective at preventing erosion as stone revetments, bulkheads, or other gray systems, as long as they have been designed to fit the energy conditions at a site. This critical assumption needs to be tested with site-based data in the future.

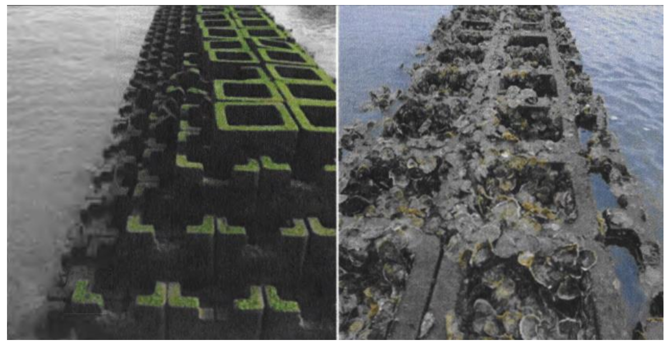
We also lacked information to test a common assumption associated with living shorelines – that they will be more resilient to sea level rise and changing weather patterns than comparable gray infrastructure projects, and may require less maintenance. This is assumed to be true because natural ecosystems, such as marshes, have the ability to respond to environmental forces. For example, marsh accretion rates have been observed to match rates of sea level rise under some conditions, and oyster reefs have some capacity to adapt to changing wave or water conditions. This is in contrast to gray infrastructure, which can be built to withstand future sea level increases, but cannot adapt if forces exceed design conditions.

To address these gaps, long-term monitoring of erosion, sediment accretion, vegetation dynamics, and maintenance costs will be needed to assess whether living shorelines successfully promote resilience and offer cost savings compared to gray infrastructure approaches. Long-term monitoring at living shorelines sites (described in Finding IG.4) will capture the ecological data needed to test our effectiveness and resilience assumptions.

Finding IG.2: Very few habitat benefits provided by living shorelines were directly measured by projects.

Living shorelines support more acreage of natural ecosystems than stone revetment, bulkhead, or other gray systems, but project monitoring is not typically focused on assessing how well those ecosystems support wildlife and human uses. Instead, project monitoring is typically focused on ensuring that project design goals have been met (e.g., linear feet of shoreline constructed, the establishment of oyster populations; Box 6). However, to fully understand the benefits provided by living shorelines (and to allow a more accurate and complete cost-effectiveness analysis), more information is needed about how these projects affect meaningful ecological and social endpoints (e.g., foraging use, nesting success, recreational use).

Box 6. Oyster recruitment and growth on an oyster castle breakwater in June 2016 and November 2017 at Gandy's Beach, New Jersey.



Finding IG.3: Project costs need to be consistently and carefully tracked, and documented.

Our team had difficulty securing estimates of key aspects of project costs, which are critical to the cost-effectiveness analysis. For example, it was often not clear whether total project costs included project design, volunteer labor hours, or cost-sharing arrangements. While our team filled these gaps through either soliciting information directly from project leads or by leveraging information from the peer-reviewed literature, future analyses would benefit from consistent data gathering and reporting on living shoreline project costs. Furthermore, ongoing rehabilitation and maintenance costs will be key to understanding the full long-term costs of living shorelines, and should be carefully tracked and documented.

Finding IG.4: Some of the information gaps described above may be addressed through a new long-term monitoring initiative run through NFWF and DOI.

Recognizing the need for long-term, systematic data collection to assess restoration success, NFWF and DOI are supporting additional, future long-term monitoring for 10 of the 17 living shoreline projects through 2024 (Table A.1).

To identify the most appropriate metrics for these projects to measure over the long-term, NFWF and DOI leveraged work done by an internal DOI metrics expert group, which developed a suite of standardized performance metrics for different types of Hurricane Sandy resilience projects (DOI, 2015). Projects selected for long-term monitoring had to propose a specific subset of these metrics for their projects. Most of the projects including in long-term monitoring are assessing the ecological effectiveness of their restoration actions by measuring changes in the health of living shorelines (e.g., oysters coverage and population), water quality benefits (e.g., water temperature and salinity), and shoreline stability (e.g., structure resilience to waves, shoreline position and topography). All of the ecological metrics included are consistent with those identified in the DOI (2015) report, but have been adapted in some cases to meet project-specific needs. While these data will provide important information about marsh resilience over time, fewer than four projects plan to monitor wave energy and erosion rates; these key data gaps will likely remain for most projects.

In addition to these ecologically focused metrics, NFWF and DOI are also supporting long-term monitoring to understand the impacts of living shorelines on human well-being, primarily through the benefits gained by reducing impacts on human health, infrastructure, including transportation and critical facilities, and economic resilience from storm surge, waves or inundation. As with the ecological monitoring described above, the socioeconomic metrics being monitored were previously identified as potential standardized performance metrics for Hurricane Sandy Program resilience projects (Abt Associates, 2015).

5. Conclusion

Hurricane Sandy Program investments in living shorelines generally seem to be a cost-effective and ecologically sound approach for reducing coastal erosion and improving resilience. Our analysis shows that living shorelines were more cost-effective than a comparable gray infrastructure approach (i.e., a stone revetment) at reducing coastal erosion at project sites, assuming the two approaches provide the same level of erosion reduction over time. The cost-effectiveness of living shorelines was even higher when we included the amount of habitat restored in our calculations. While data were not available to provide a robust assessment of on-the-ground performance of specific projects, anecdotal observations suggest that erosion has been reduced and habitat is recovering in project areas, which helps protect coastal communities from storm surge and waves. These observations are preliminary, however, and many more years of recovery and monitoring data are needed to more fully understand the long-term ecological and socioeconomic impacts of living shorelines. More specifically, additional information is needed about (1) coastal erosion rate changes at project sites; (2) the nature and rate of recovery of habitats restored in a living shoreline; (3) project costs, particularly those related to maintenance and repair; and (4) whether living shorelines adapt to local conditions over time as expected. Recognizing the need for long-term, systematic data collection to assess restoration success, NFWF and DOI are supporting additional, future long-term monitoring for 10 of the 17 living shoreline projects through 2024 using standardized ecological and socioeconomic metrics.

6. References

Abt Associates. 2015. Developing Socioeconomic Metrics to Measure DOI Hurricane Sandy Project and Program Outcomes. Abt Associates, Bethesda, MD. Available: https://www.doi.gov/sites/doi.gov/files/uploads/Socio_Economic_Metrics_Final_Report_11DEC2015_0.pdf. Accessed 7/12/2019.

Abt Associates. 2019. Evaluation of Hurricane Sandy Coastal Resilience Program. Abt Associates, Rockville, MD.

ASMFC. 2019. Shad & River Herring. Available: http://www.asmfc.org/species/shad-river-herring. Accessed 5/15/2019.

ASMFC. Undated. Alewife (*Alosa pseudoharengus*) Life History and Habitat Needs. Fact Sheet. Atlantic States Marine Fisheries Commission. Available: http://nemo.uconn.edu/tools/fotc/fact_sheets/alewifeHabitatFactsheet.pdf. Accessed 4/5/2019.

Audubon. 2014. Red Knot. Available: https://www.audubon.org/field-guide/bird/red-knot. Accessed 5/9/2019.

Bilkovic, D.M. and M.M. Mitchell. 2017. Designing living shoreline salt marsh ecosystems to promote coastal resilience. Chapter 15 in *Living Shorelines: The Science and Management of Nature-Based Coastal Protection,* D.M. Bilkovic, M. Mitchell, M. La Peyre, and J. Toft (eds.). CRC Press, Taylor & Francis Group. pp. 293–316.

Cornell Lab of Ornithology. 2019. All about Birds Guide. Available: https://www.allaboutbirds.org/guide/. Accessed 5/9/2019.

Craft, C., P. Megonigal, S. Broome, J. Stevenson, R. Freese, J. Cornell, L. Zheng, and J. Sacco. 2003. The pace of ecosystem development of constructed *Spartina alterniflora* marshes. *Ecological Applications* 13(5):1417–1432.

Davis, J.L.D., R.L. Takacs, and R. Schnabel. 2006. Evaluating ecological impacts of living shorelines and shoreline habitat elements: An example from the Upper Western Chesapeake Bay. *Proceedings of the 2006 Living Shoreline Summit, Management, Policy, Science, and Engineering of Nonstructural Erosion Control in the Chesapeake Bay*. Available: https://www.vims.edu/cbnerr/_docs/ctp_docs/ls_docs/06_LS_Full_Proceed.pdf#page=71. Accessed 5/28/2019.

DOI. 2015. Recommendations for Assessing the Effects of the DOI Hurricane Sandy Mitigation and Resilience Program on Ecological System and Infrastructure Resilience in the Northeast Coastal Region. U.S. Department of the Interior. Available: https://www.doi.gov/sites/doi.gov/files/migrated/news/upload/Hurricane-Sandy-project-metrics-report.pdf. Accessed 7/12/2019.

Ebbets, A.L., D.R. Lane, P. Dixon, T.A. Hollweg, M.T. Huisenga, and J. Gurevitch. 2019. Using meta-analysis to develop evidence-based recovery trajectories of vegetation and soils in restored wetlands in the northern Gulf of Mexico. *Estuaries and Coasts* 1–19.

Hollweg, T.A., M.C. Christman, J. Lipton, B.P. Wallace, M.T. Huisenga, D.R. Lane, and K.G. Benson. Meta-analysis of nekton recovery following marsh restoration in the northern Gulf of Mexico. (In review.)

Lee, T.S., J.D. Toft, J.R. Cordell, M.N. Dethier, J.W. Adams, and R.P. Kelly. 2018. Quantifying the effectiveness of shoreline armoring removal on coastal biota of Puget Sound. *PeerJ* 6(4275). doi: 10.7717/peerj.4275.

Manis, J. 2013. Assessing the Effectiveness of Living Shoreline Restoration and Quantifying Wave Attenuation in Mosquito Lagoon, Florida. University of Central Florida, Master's Thesis. Available: https://stars.library.ucf.edu/cgi/viewcontent.cgi?referer=https://www.google.com/&httpsredir=1&article=3814&context=etd. Accessed 5/28/2019.

Moreno-Mateos, D., M.E. Power, F.A. Comín, and R. Yockteng. 2012. Structural and functional loss in restored wetland ecosystems. *PLoS Biology* 10(1):e1001247.

NOAA. 2015. Guidance for Considering the Use of Living Shorelines. Available: https://www.habitatblueprint.noaa.gov/wp-content/uploads/2018/01/NOAA-Guidance-for-Considering-the-Use-of-Living-Shorelines_2015.pdf. Accessed 7/14/2019.

NOAA. 2019. Living Shorelines. National Oceanic and Atmospheric Administration. Available: https://www.habitatblueprint.noaa.gov/living-shorelines/. Accessed 5/28/2019.

Patrick, C., D.E. Weller, X. LI, and M. Ryder. 2014. Effects of shoreline alteration and other stressors on submerged aquatic vegetation in subestuaries of Chesapeake Bay and the Mid-Atlantic Coastal Bays. *Estuaries and Coasts* 37:1516–1531.

Piazza, B.P., P.D. Banks, and M.K. La Peyre. 2005. The potential for created oyster shell reefs as a 700 sustainable shoreline protection strategy in Louisiana. *Restoration Ecology* 13:499–506.

Scyphers, S.B., S.P. Powers, K.L. Heck Jr., and D. Byron. 2011. Oyster reefs as natural breakwaters mitigate shoreline loss and facilitate fisheries. *PLoS ONE* 6(8).

Sharma, S., J. Goff, R.M. Moody, A. McDonald, D. Byron, K.L. Heck Jr., S.P. Powers, C. Ferraro, and J. Cebrian. 2016. Effects of shoreline dynamics on saltmarsh vegetation. PLOS ONE 11(7): e0159814. Available: https://doi.org/10.1371/journal.pone.0159814. Accessed 5/28/2019.

USFWS. 2019. Piping Plover Fact Sheet. U.S. Fish and Wildlife Service. Available: https://www.fws.gov/Midwest/endangered/pipingplover/pipingpl.html. Accessed 5/23/2019.

Warren, R.S., P.E. Fell, R. Rozsa, A.H. Brawley, A.C. Orsted, E.T. Olson, V. Swamy, and W.A. Niering. 2002. Salt marsh restoration in Connecticut: 20 years of science and management. *Restoration Ecology* 10(3):497–513.

Appendix A. Project Summaries

Table A.1. Living shoreline restoration projects supported through the Hurricane Sandy Program. This table presents the amount of project funding specifically allocated to living shoreline activities. For 6 projects, this is the full project funding amount; and for 11 projects, this is a subset of the total project funding. The allocation was based on available project documentation. Projects included in the cost-effectiveness analysis are listed first. All dollars rounded to the nearest hundred.

Project identification number	Project title	Project state	Project lead organization	Award amount	Reported matching funds
				Values represent living shoreline activities only[c]	
NFWF-41931	Developing self-sustaining oyster population in Jamaica Bay, New York	NY	New York City Department of Environmental Protection	$900,000	$337,500
NFWF-42019	Restoring Bronx River shoreline at Starlight Park, New York	NY	New York City Department of Parks and Recreation	$3,960,000	$792,000
NFWF-42551[a]	Green infrastructure in Accomack and Northampton counties, Virginia	VA	The Nature Conservancy	$133,900	$27,100
NFWF-43308[a]	Developing a green infrastructure plan and network for the Lafayette River Watershed, Virginia	VA	City of Norfolk	$3,914,400	$217,100
NFWF-43849[a]	Developing coastal resiliency regional models, Virginia	VA	Wildlife Foundation of Virginia	$860,400	$82,600
NFWF-43939	Restoring Newark Bay's wetlands, New Jersey	NJ	City of Newark	$780,000	$7,500
NFWF-44068	Restoring over one hundred wetland acres in Great Egg Harbor Bay, New Jersey	NJ	City of Ocean City	$2,630,000	$1,276,800
NFWF-44109[b]	Replenishing Little Egg Harbor's marshes and wetlands, New Jersey	NJ	Little Egg Harbor Township	$2,130,000	$76,800
NFWF-44167[a, b]	Protecting North Beach's salt marsh and emergency route, Maryland	MD	Town of North Beach	$278,900	$62,600
NFWF-44225[a, b]	Improving Shinnecock Reservation's shoreline habitats, New York	NY	Shinnecock Indian Nation	$1,975,300	$165,400
USFWS-1[a, b]	Salt marsh restoration and enhancement at Seatuck, Wertheim and Lido Beach National Wildlife Refuges, Long Island, New York	NY	U.S. Fish and Wildlife Service	$594,300	$76,700
USFWS-31[a, b]	Fog Point living shoreline restoration, Martin National Wildlife Refuge	MD	U.S. Fish and Wildlife Service	$9,000,000	$1,083,500
USFWS-37[b]	Restoring coastal marshes in New Jersey National Wildlife Refuges	NJ	U.S. Fish and Wildlife Service	$7,500,000	$1,500,000

Project identification number	Project title	Project state	Project lead organization	Award amount	Reported matching funds
				Values represent living shoreline activities only[c]	
USFWS-57[a, b]	Hail Cove living shoreline restoration, Eastern Neck National Wildlife Refuge	MD	U.S. Fish and Wildlife Service	$1,550,000	$16,000
USFWS-65[a, b]	Protecting property and helping coastal wildlife: Enhancing salt marsh and estuarine function and resiliency for key habitats on impacted wildlife refuges from Rhode Island to southern Maine	Multi: RI, MA, ME	U.S. Fish and Wildlife Service	$166,700	$10,000
USFWS-76[a, b]	Living shoreline-oyster reef restoration and construction at Chincoteague National Wildlife Refuge, Virginia	VA	U.S. Fish and Wildlife Service	$553,400	$0
USFWS-77[a, b]	Gandy's Beach Shoreline Protection Project, Downe Township, Cumberland County, New Jersey	NJ	The Nature Conservancy; U.S. Fish and Wildlife Service	$720,000	$0

a. Denotes a project included in the cost-effectiveness analysis for the case study.

b. Denotes a project for which long-term monitoring funding has been secured through NFWF and DOI.

c. Costs in the table do not represent the full cost of the project and may not reflect the total match.

Table A.2. Living shoreline restoration projects and project sites included in the cost-effectiveness analysis.

Project identification	Project site	Energy environment	Living shoreline (LS)							Stone revetment			LS cost difference (Revetment – LS)	
			Type	Length (linear feet)	Acres protected	Acres restored	Total cost	$/acre protected[a]	$/acre protected + restored[a]	Acres protected	Total cost[a]	$/acre protected[a]	$/acre protected[a]	$/acre protected + restored[a]
NFWF-42551	1. Man and Boy Marsh	High	Oyster-natural	1,008	5.9	0.0	$39,864	$6,732	$6,692	5.9	$1,436,816	$242,638	$235,906	$235,945
	2. Little Tom's Cove (Chincoteague)	High	Oyster-natural	504	3.2	0.1	$24,562	$7,700	$7,537	3.2	$718,408	$225,212	$217,512	$217,675
	3. Short Prong Marsh	High	Oyster-natural	780	5.5	0.1	$126,769	$23,204	$22,713	5.5	$1,111,822	$203,510	$180,306	$180,797
NFWF-43308	1. Beach Ave, Norfolk	Low	Hybrid-major	1,202	0.8	0.8	$863,358	$1,042,925	$527,137	0.8	$713,894	$862,374	($180,551)	$335,237
	2. Hermitage Museum West Side, Norfolk	Medium	Hybrid-major	923	0.6	2.6	$797,591	$1,254,715	$248,032	0.6	$931,923	$1,466,037	$211,322	$1,218,004
	3. Knitting Mill, Norfolk	Low	Hybrid-major	550	0.4	0.1	$755,864	$1,995,481	$1,485,617	0.4	$326,657	$862,374	($1,133,107)	($623,243)
	4. North Shore, Norfolk	Medium	Hybrid-major	1,681	1.2	1.0	$1,136,983	$982,093	$517,348	1.2	$1,697,250	$1,466,037	$483,943	$948,689
	5. Villa Circle, Norfolk	Low	Hybrid-major	2,450	1.7	1.6	$1,353,833	$802,353	$418,195	1.7	$1,455,108	$862,374	$60,021	$444,180
NFWF-43849	1. False Cape	Low	Hybrid-major	600	0.5	0.2	$512,554	$932,617	$642,407	0.5	$356,353	$648,402	($284,215)	$5,995
	2. Back Bay Visitor Center	Low	Hybrid-major	400	0.4	0.4	$373,530	$1,019,484	$499,063	0.4	$237,569	$648,402	($371,082)	$149,338
	3. Horn Point	Low	Hybrid-major	500	0.5	0.0	$233,972	$510,868	$489,685	0.5	$296,961	$648,402	$137,534	$158,717
NFWF-44167	1. North Beach	High	Hybrid-major	670	2.3	0.6	$405,708	$175,847	$139,555	2.3	$955,026	$413,940	$238,093	$274,385
NFWF-44225	1. Shinnecock Reservation	Medium-high	Hybrid-minor	3,250	0.7	0.2	$2,542,761	$3,442,507	$2,738,166	0.7	$3,281,418	$4,442,535	$1,000,028	$1,704,369

			Living shoreline (LS)							Stone revetment			LS cost difference (Revetment – LS)	
Project identification	**Project site**	**Energy environment**	**Type**	**Length (linear feet)**	**Acres protected**	**Acres restored**	**Total cost**	**$/acre protected[a]**	**$/acre protected + restored[a]**	**Acres protected**	**Total cost[a]**	**$/acre protected[a]**	**$/acre protected[a]**	**$/acre protected + restored[a]**
USFWS-1	1. Lido Beach	Low	Hybrid-major	250	0.3	0.1	$791,104	$2,702,783	$2,163,788	0.3	$148,480	$507,279	($2,195,504)	($1,656,509)
	2. Seatuck NWR	Medium-high	Oyster-natural	35	0.1	0.1	$5,939	$68,253	$37,137	0.1	$35,338	$406,104	$337,851	$368,968
USFWS-31	1. Fog Point, Martin NWR	High	Hybrid-major	20,950	216.4	18.4	$10,096,671	$46,652	$43,000	216.4	$29,862,388	$137,980	$91,328	$94,980
USFWS-57	1. Hail Cove; Eastern Neck NWR	Medium	Hybrid-major	3,500	7.2	1.2	$1,306,628	$180,688	$155,163	7.2	$3,533,835	$488,679	$307,991	$333,516
USFWS-65	1. John H Chafee NWR	Low	Hybrid-minor	325	0.1	4.4	$115,232	$1,560,057	$25,757	0.1	$193,025	$2,613,256	$1,053,198	$2,587,499
	2. Sedge Island rock apron	Low	Hybrid-major	300	0.2	-	$94,747	$458,576	$458,576	0.2	$178,177	$862,374	$403,798	$403,798
USFWS-76	1. Assateague Bay	Medium	Oyster-natural	2,150	11.2	-	$390,741	$34,952	$34,952	11.2	$2,170,784	$194,177	$159,225	$159,225
	2. Tom's Cove	Medium	Oyster-natural	1,400	16.8	2.5	$254,436	$15,175	$13,178	16.8	$1,413,534	$84,303	$69,129	$71,125
USFWS-77	1. Gandy's Beach	High	Hybrid-minor	3,080	4.2	0.5	$814,156	$191,908	$173,402	4.2	$4,390,270	$1,034,849	$842,941	$861,448
Total				**46,508**	**280.2**	**34.9**	**$23,037,002**	**$17,455,571**	**$10,847,100**	**280.2**	**$55,445,035**	**$19,321,239**	**$1,865,668**	**$8,474,139**
Average				**2,022**	**12.7**	**1.6**	**$1,047,136**	**$793,435**	**$493,050**	**12.7**	**$2,520,229**	**$878,238**	**$84,803**	**$385,188**

a. All cost-effectiveness values are for the low-erosion scenario, in present value dollars, and discounted at 3%. Only includes the 22 project sites included in the cost-effectiveness analysis.