Cost-Benefit Evaluation of Soft and Hard Approaches for Lake Erie Shoreline Protection

Final Report

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ABSTRACT

Ohio has approximately 312 miles of shoreline along the southern coast of Lake Erie and around the adjacent islands. Shore erosion is a common hazard along the Ohio side of the Lake Erie coast, resulting in damage and economic loss for both public and private lands, utilities, and infrastructure. Currently, shorelines in Ohio are mainly protected by using hard approaches that are constructed with steel, concrete, rock or wood. However, in some cases, hardening the shoreline can accelerate erosion and, once an unsuccessful hard application is put in place, it is very difficult to restore the shore to its natural condition. The use of a hard shoreline also has adverse impacts on the environment and can destroy the shore ecosystem. Recently, soft shoreline solutions that can provide a sustainable shore environment have gradually attracted the interest of professionals in coastal engineering. However, most public and local professionals are not familiar with the emerging soft techniques, and there is a lack of research-based evidence showing the long-term benefit of soft shorelines, which has limited the use and promotion of green solutions.

In this regard, this project was conducted to demonstrate the benefits of soft shorelines versus hard shorelines in terms of cost. The advantages and disadvantages of three soft solutions (i.e., vegetated sand dunes, beach nourishment and living shorelines) and five hard solutions (i.e., seawalls, breakwaters, groins, bulkheads and revetments) are reviewed. Two specific objectives are addressed in the study: 1) a comparison of benefits and costs for various soft and hard shoreline protection techniques based on the collected cost data for the initial construction cost, maintenance cost, damage cost, environmental degradation cost, and life-cycle cost of each approach; and 2) a comparison of benefits and costs for various soft and hard shoreline protection techniques based on a comprehensive survey of local professionals in Ohio. The survey results include numeric ratings and responses to predefined questions. A synthesis based on these two objectives provides a quantitative understanding of long-term costs and benefits of various techniques for Lake Erie shoreline protection.

The key findings resulting from this project are:

1) The benefit and cost analysis based on the collected cost data clearly demonstrated, given that the life-cycle cost is the major consideration in the selection, soft shoreline protection approaches are in general superior to hard approaches. For example, the 25-yr life-cycle cost estimations of vegetated sand dunes, beach nourishment and living shorelines under

rare storm impacts are approximately $6,553, $10,446 and $3,803 per linear foot, respectively, which are significantly less than the 25-yr life-cycle cost of most hard solutions ($35,288 per linear foot for breakwaters, $17,741 per linear foot for sheet pile seawalls, $18,383 per linear foot for concrete bulkheads, $11,872 per linear foot for rock revetments and $22,775 per linear foot for impermeable revetments).

2) The comprehensive survey study based on numeric ratings shows the advantages of using soft shoreline approaches versus hard approaches in terms of cost savings and environmental/ecological protection. For example, the mean values of numeric ratings on the initial construction cost for the hard solutions are all greater than 5, while the mean ratings for the soft solutions are all less than 5, with a larger value indicating a higher cost. Similarly, the mean ratings on the environmental degradation cost for the hard solutions are all greater than 4, while the mean ratings for the soft solutions are all less than 3, showing the benefits of using soft solutions.

It should be noted that the conclusions based on the survey are nearly identical to those based on the cost data analysis. As indicated by the survey responses, the final decision should also be based on other factors such as wave energy level, site geology, space and infrastructure to be protected. This project provides preliminary research evidence to support decision making for local stakeholders in the selection of a shoreline protection approach.

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1. INTRODUCTION

1.1 Background

Lake Erie has approximately 312 miles of shoreline in Ohio (including islands). Shore erosion is a common hazard along the Ohio Lake Erie coast, causing considerable damage and economic loss to both public and private land, utilities, and infrastructure. Although hundreds of structures such as revetments and breakwaters have been built along Lake Erie coast, no permanent or universal approach has been established to protect the shoreline from erosion. Some commonly used shoreline protection techniques may even lead to increased erosion, structural damage and the destruction of shoreline ecosystems.

Shoreline protection approaches include hard approaches and soft approaches. Hard approaches, including but not limited to seawalls, breakwaters, groins, bulkheads and revetments, are more familiar to professionals and the public. Hard shorelines are generally constructed using steel, concrete, rock or wood to provide an artificial barrier at the waterfront to protect the shoreline from damage caused by wave energy. However, it is known that hard shorelines have irreversible adverse impacts on the nearshore environment and ecosystem. The use of impervious artificial materials can increase carbon emission and disrupt ecological cycles such as the movement of larval fish. Hard shoreline approaches have also been frequently observed to accelerate shoreline erosion. Once hard shorelines are installed, it is difficult to restore the shoreline to its natural condition.

Soft shorelines, on the contrary, are nature-based stabilization approaches that can offer many benefits over typical hard stabilization structures. Soft approaches include but are not limited to beach nourishment, vegetated sand dunes, living shorelines, erosion control matting, etc. There are many advantages for soft approaches: 1) ***coastal engineering benefits*** include the absorption of storm surges and flood waters, the reduction of wave energy impacts at areas seaward of the shoreline, and the trapping of sand to aid in rebuilding eroded shorelines or to maintain the current shoreline; 2) ***environment benefits*** include the filtration of nutrients and other pollutants from the water, creation of a carbon sink (thereby helping to mitigate climate change), and the maintenance of natural shoreline dynamics and sand movement; 3) ecological benefits include providing or enhancing important shoreline habitat; and 4) economic benefits include the maintenance of beach and intertidal areas that offer public access opportunities for wading, fishing, and walking, as well as a reduction in costs for stabilization from bulkheads, rip rap, and other hard structural approaches. Admittedly, soft shorelines have limitations such that they are not suitable for areas where much of the shoreline is already hardened or for high-energy environments. In addition, soft shorelines are more difficult to design and install than traditional hard structural approaches. Moreover, limited information is available on the effectiveness of living shorelines for different types of shorelines, energy regimes, and storm conditions.

In this regard, this Lake Erie Protection Fund project aims to promote soft shoreline protection techniques in Ohio Lake Erie by synthesizing the advantages and disadvantages of soft and hard shorelines, conducting a life-cycle benefit and cost analysis for various soft and hard approaches, comparing the total long-term costs for several commonly used hard approaches and several emerging soft approaches, providing research-based evidence of the benefits of soft shorelines, and enhancing public awareness of soft shorelines to sustain Lake Erie. This project is expected to contribute to the goals outlined in the Lake Erie Protection & Restoration Plan 2016 as well as to benefit Lake Erie stakeholders by providing a better understanding of the long-term performance and longevity of various shoreline protection approaches.

1.2 Study Objectives

This project explores a cost-benefit evaluation of soft and hard approaches for Lake Erie shoreline protection in Ohio. Specifically, two objectives are addressed in the study: 1) a comparison of benefits and costs for various soft and hard shoreline protection techniques based on the collected cost data for the initial construction cost, maintenance cost, damage cost, environmental degradation cost, and life-cycle cost of each approach; and 2) a comparison of benefits and costs for various soft and hard shoreline protection techniques based on a comprehensive survey of local professionals in Ohio. The survey results include numeric ratings and responses to predefined questions. A synthesis based on these two objectives provides a quantitative understanding of the long-term costs and benefits of various shoreline protection techniques for Lake Erie shoreline protection.

1.3 Scope of Study

A review of shoreline protection techniques was performed, and Chapter 2 presents a summary of the advantages and disadvantages for three soft shoreline protection approaches and five hard shoreline protection approaches. Following the literature review, the research team conducted a comprehensive review of the literature as well as an examination of historical projects and the information found on the websites of various agencies. Based on the collected cost data for the various approaches, a life-cycle cost comparison between soft and hard approaches was performed, and the results and findings of this analysis are documented in Chapter 3. In Chapter 4, the design of the survey forms, a summary of the approach for conducting the survey and collecting the responses, and the synthesized survey results are provided. Chapter 5 summarizes the findings and conclusions of this study and provides recommendations for future research.

2. LITERATURE REVIEW

Ohio has 312 miles of shoreline on the southern edge of Lake Erie, and 33% of the shoreline in Ohio has erosion issues to a certain degree [1]. At the national level, coastal erosion is also a growing concern: it has been reported that nearly 14% of the U.S. shoreline is covered in some type of artificial material [2]. However, some of the current methods used to prevent erosion can exacerbate the problem. Each method or solution used to prevent erosion works for a given purpose or situation, and implementation of a solution in the wrong circumstances can limit its effectiveness sometimes even accelerate erosion.

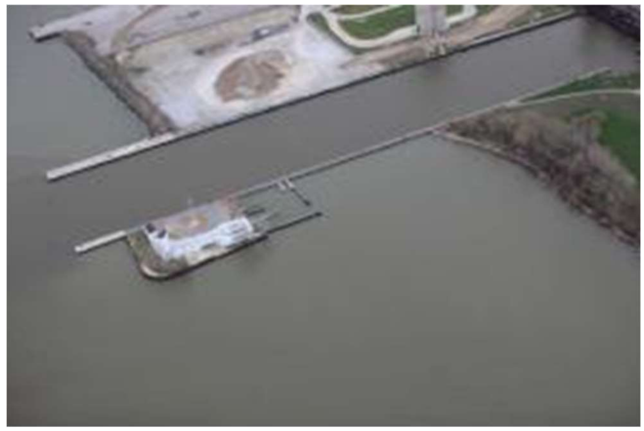
The various shoreline protection solutions can be categorized into two broad types: *hard solutions* and *soft solutions*. The major hard solutions — which involve the construction of a solid structure — include but are not limited to jetties, groins, breakwaters, seawalls, revetments, and bulkheads. On the contrary, soft solutions to alleviate erosion are realized without the use of any permanent artificial structures. Examples of soft solutions are nature-based shoreline, beach nourishment and vegetated dunes. Hard solutions have been widely used in the past. However, some of these solutions may have led to increased erosion, structural damage and destruction of shoreline ecosystems. In recent years, a push has been made for soft solutions because they are viewed as more environmentally friendly. These soft solutions also have specific applications where they work best. In this chapter, five commonly used hard solutions in Ohio (groins and jetties, breakwaters, seawalls, bulkheads and revetments) and three soft solutions under consideration (nature-based shorelines, beach nourishment and vegetated dunes) are reviewed.

2.1 Hard Solutions

2.1.1 Groins and Jetties

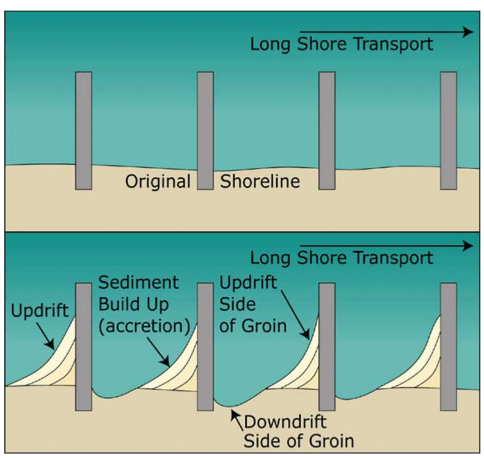
Groins and jetties are structures constructed perpendicular to the shoreline to trap sediments and prevent them from moving down the shoreline, as shown in Figure 2-1. Groins are usually constructed using boulders but can also be made of concrete and timber [3]. Jetties are groins that are used at the mouth of channels or harbor entrances to keep the waterway open for navigation [3]. Groins and jetties can stop the transportation of sediment along the coastline, but they have a considerable impact on the transportation of sediment through longshore currents. As shown in Figure 2-2, groins and jetties generally cause the alteration of the shoreline by accretion in one area and erosion at another [4]. To counter these negative effects in downdrift areas, some groins are designed with notches or lower profiles in order to allow sediments to pass through them [5], as shown in Figure 2-3. The beach is still able to build out to the first notch, and then sediment will continue to move down the shoreline through the notch or over the groin. This design is still relatively new.

(a) Groin at Plum Island, New York.



(b) Jetty around the Cuyahoga River, Cleveland.

Figure 2-1: Photos of a groin and jetty (Army Corp of Engineers Oblique imagery https://greatlakes.erdc.dren.mil).



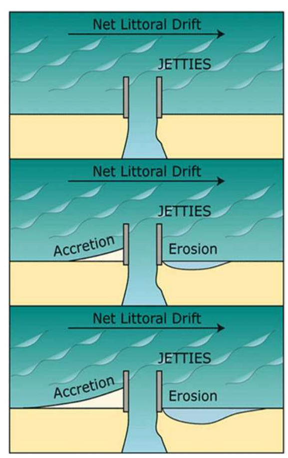
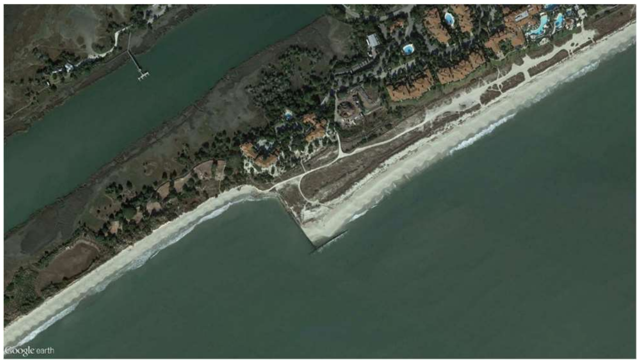


Figure 2-2: Alterations in the shoreline due to the installation of groins and jetties (maps.unomaha.edu/maher/geol1010/lecture14/shorelines2.html).



(a) Accelerated erosion downdrift due to a groin blocking sand in longshore current, Sea Island, Georgia.

(b) A groin field of 16 bags filled with sand, South Beach of Bald Head Island in North Carolina.

Figure 2-3: Erosion caused by groins and jetties (Photo: Olsen Associates Inc. https://www.coastalreview.org/2013/08/bald-heads-battle-with-the-sea/).

Advantages of using groins and jetties

- Groins are very effective at trapping sediment and, as a result, they build out the beach, which protects the shoreline from erosion updrift of the groin.
- Building up the width of the beach is beneficial for recreational use.
- Jetties keep channels from being closed due to longshore currents. Without the use of jetties, the mouth of a channel would need to be dredged more frequently.
- Unlike other structures, groins do not cut off the land areas from the water, so they allow animals to travel freely between the two.

Drawbacks of using groins and jetties

- Groins and jetties only protect the beach on one side, while the downdrift side receives no sediment and, in turn, begins to erode (see Figure 2-1a and Figure 2-3).
- Groins and jetties will not stop flooding from storm surges.
- Because of the increased erosion on the downdrift side of the groin, when one structure is built, a domino effect occurs. This necessitates the construction of additional groins along a stretch of beach (as shown in Figure 2-3b). Multiple groins along a shoreline are referred to as a *groin field* [3].

A letter from Western Carolina University to lawmakers, signed by 24 professors from various universities, stated that the use of groins should remain illegal. In this letter, the professors point out how groins accelerate erosion downdrift of the structure and how the structures can funnel currents during storm events, resulting in scouring and a loss of sediment [4]. Many states (including North Carolina) have outlawed use of hard solutions such as groins, jetties, or any hard structure whose purpose is to trap sediment due to these negative consequences.

2.1.2 Breakwaters

Breakwaters are structures constructed parallel to the shoreline to protect the shoreline from wave-induced erosion by blocking or dissipating wave energy. Breakwaters can be connected to the shoreline (attached) or situated at a location away from the shoreline (detached), as shown in Figures 2-4 and 2-5 [2]. Breakwalls are often used to form the outside walls of a harbor where boats dock. Due to the way that breakwaters dissipate energy from waves, they are good at providing refuge for boats, even those anchored in open water, as shown in Figure 2-6.

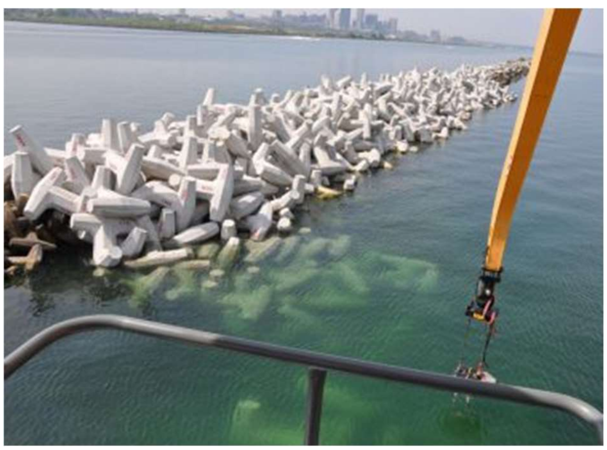


Figure 2-4: Detached breakwater from the repair of the East Breakwater around Cleveland Harbor (http://www.dredgingtoday.com/2016/12/05/usace-to-celebrate-completion-of-cleveland-east-breakwater/).

Figure 2-5: Attached breakwater at Miami Beach, Florida (https://www.geocaching.com/geocache/GC5B53M_miami-beach-breakwaters?guid=681845c5-c312-4878-9eeb-8077bf5e0494).

Breakwaters can be used in areas with various water depths, wave conditions, and shoreline geometries [6]. A properly designed breakwater will collect sediment, forming a *salient*, as shown in Figure 2-7. Once the system reaches equilibrium, sediment will continue to pass behind the breakwater, but at a reduced rate [7]. The failure of a rock breakwater is gradual and will occur over time; thus, it is necessary to monitor the condition of the breakwater by conducting inspections on an annual basis [6]. Monitoring methods include visual inspection at the surface, subsurface inspection by divers, photographic surveys, crane and ball surveys, seismic analysis, side-scan sonar investigation, and laser scanning. The amount of total movement along the breakwater is calculated to determine if maintenance is required [8]. Construction and maintenance are typically expensive due to the required equipment and the amount of material needed for construction or rehabilitation [9].

Figure 2-6: Breakwaters being used to form Crescent City Harbor in California (https://commons.wikimedia.org/wiki/File:Crescent_City_California_harbor_aerial_view.jpg).

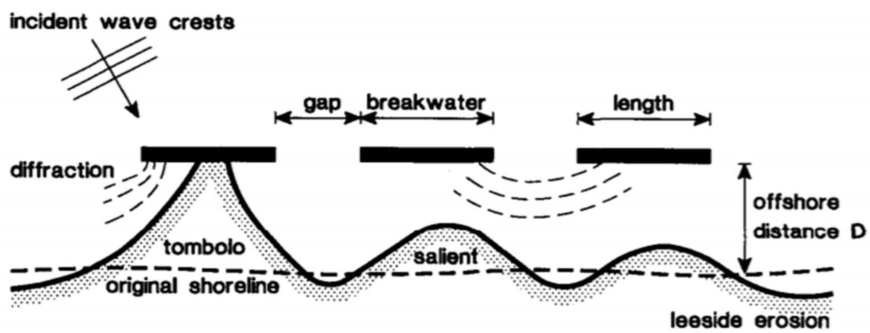


Figure 2-7: Schematic of a detached breakwater with tombolo/salient formation [7].

Advantages of breakwaters

- Breakwaters are effective at protecting a shoreline from high energy waves [7].
- Detached breakwaters are good at protecting harbors or creating harbors for boats so they will have a calm place to dock.
- Detached breakwaters collect sediments behind them, creating a beach for recreational activity.
- Breakwaters are not prone to being flanked.

Drawbacks of breakwaters

- Breakwaters may not stop flooding or storm surges [7].
- Breakwaters will slow or stop the flow of sediment, resulting in downdrift erosion.
- If breakwater(s) do not have the right spacing, offset, and length, then sediment will collect until it reaches the breakwater. This area of sand or sediment, referred to as a *tombolo*, can be seen in Figure 2-7 [7].
- Attached breakwaters cut off access to the water from upland areas, both for humans and animals.

2.1.3 Seawalls

Seawalls are structures constructed parallel to the shoreline and are typically built of either concrete (smooth or rough), precast concrete, boulders, blocks or a combination of materials (Figures 2-8 and 2-9). Seawalls are vertical or nearly vertical structure that reflect waves and wave energy away from the coast to prevent erosion [10]. With this vertical face, seawalls provide boats with direct access to the shoreline for docking [9].

Seawalls are designed to be taller than wave height to keep storm surges and storm waves from topping the structure. They come in many different designs, from smooth surfaces (Figure 2-8) to rough irregular ones (Figure 2-9). Smooth surfaces reflect the wave energy directly away while irregular ones can absorb some of the wave energy and disperse the rest in various directions [10]. Due to the reflection of waves, any hard structure placed on a shoreline landward of the beach can increase the erosion of a beach. This is due to three factors: passive erosion, active erosion, and placement loss.

Passive erosion is the process where a shoreline slowly erodes from waves or sea level rise. Because of the presence of a fixed structure, the beach is slowly squeezed out [11]. *Active erosion* occurs when storm surges and waves flow over the beach and reflect off the seawall. When waves reflect off a seawall or any structure, they can erode the beach by moving sand offshore [11]. Lastly, *placement loss* is simply the loss of land area due to the placement and construction of an erosion control structure [11].

Figure 2-8: Precast smooth concrete seawall pieces. The curve in the seawall directs waves and spray seaward to limit damage upland, but this type reflects almost all of the energy seaward without dissipating any energy. (http://www.precastconcreteconstruction.com/140/wave-wall-units-for-shetland-by-moore-concrete/sea-walls-1)

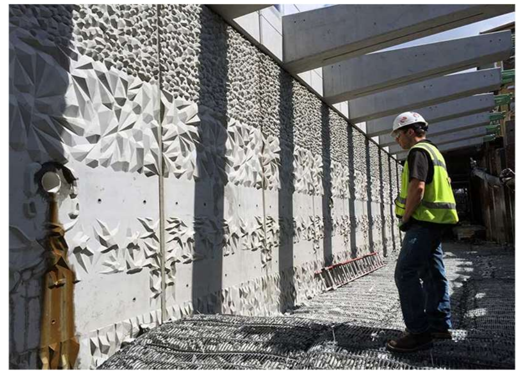


Figure 2-9: A rough concrete seawall at Central Waterfront of Seattle. The rough surface scatters the waves as they hit, dissipating the energy.

(http://www.haddad-drugan.com/seawall-strata/)

Advantages of seawalls

- Seawalls provide a platform where people can stand while fishing [12].
- Seawalls are effective at stopping erosion and protecting infrastructure along the coastline [10].
- Seawalls are helpful in preventing flooding [10].

Drawbacks of seawalls

- Seawalls built behind a beach can increase the rate at which the beach erodes [11].
- Seawalls can increase erosion in areas downdrift of the structure.
- Seawalls are prone to scouring at the toe due to erosion in the area in front of the seawall [11].
- Seawalls prevent humans and animals from accessing to the water from areas upland.
- Seawalls can be flanked by waves, which can increase erosion on both ends of the structure.

2.1.4 Bulkheads

Bulkheads are completely vertical structures that are placed parallel to the shoreline, and they are usually constructed from sheet piles, concrete, or timber, as shown in Figures 2-10 and 2-11. Construction of a metal bulkhead requires pile driving machinery, while timber bulkheads are cheaper to construct and easier to repair [9].The main purpose of a bulkhead is to hold back and stabilize the land [13]. In this sense, bulkheads are essentially retaining walls that are built along the shoreline. Bulkheads are primarily used in bays, ports, or harbors to hold back upland fill or concrete from eroding into the water in areas with low-energy waves, since they lack the necessary strength or durability; to hold back land along shorelines with constant pounding by high-energy waves, a seawall is more appropriate. Just like seawalls, bulkheads provide a platform for shore fishing and allow boats to have direct access to the shoreline [9].

It is necessary to use backfill behind the bulkhead and install drainage to help prevent the bulkhead from failing [14]. The installation of a bulkhead can increase erosion on the beach itself. Figure 2-12 shows the process by which hard structures installed in upland areas can increase the erosion on a beach. Also shown in Figure 2-10, the beach has been flattened, which is a sign of erosion, and the navy wall is beginning to be undermined in locations, in a process known as *toe scour*. All vertical shoreline structures are prone to toe scour [9].

Advantages of bulkheads

- Bulkheads hold back the land, preventing mass wasting into the water.
- Bulkheads provide a platform for fishing and boat docking.
- Bulkheads can be used in areas with low-to-moderate wave energy.
- They protect moderately well against flooding, but this is not their primary design.

Drawbacks of bulkheads

- Bulkheads are not designed to handle storm surges [13].
- If a bulkhead is constructed behind a beach, beach erosion will be accelerated during storm events.
- Bulkheads cut off access by humans and animals to the water from upland areas.

- Bulkheads can result in the loss of ecosystems due to increased beach erosion as well as loss of continuity between terrestrial and aquatic environments.
- Bulkheads can be flanked by erosion on both sides.

Figure 2-10: Timber navy wall bulkheads hold back a dune from mass wasting onto the beach.

Figure 2-11: Steel sheet pile drop wall bulkheads on the edge of a property to maintain the land at an elevation higher than the waterline.

(http://www.shorelinebulkheading.com/bulkheading.html)

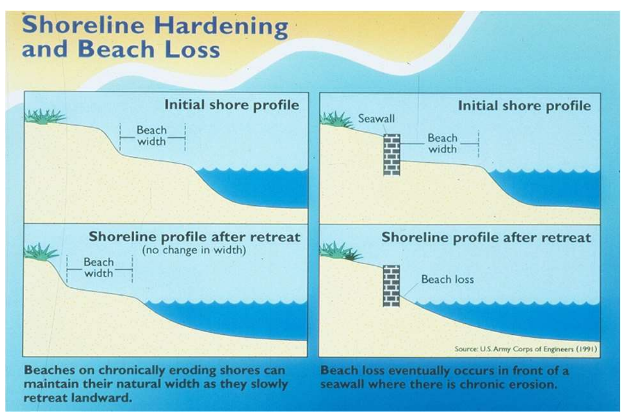


Figure 2-12: Diagram showing how hard structures increase erosion on a beach while protecting areas upland from mass wasting (http://www.nichols.edu/departments/physicalworld/beachman.htm).

2.1.5 Revetments

Revetments are similar to seawalls and are appropriate for locations with lower-energy waves. They are placed parallel to the shoreline and are typically made up of boulders or stone, concrete, or asphalt, as shown in Figure 2-13 [15]. Revetments have a sloping profile that allow wave energy to dissipate as it runs up onto the structure. Typically, these structures have a filter layer that supports armor rocks on top, and this layer is permeable. This permeability enables them to dissipate more wave energy into the structure, rather than reflecting it all away [16].

Figure 2-13: Revetments have shallow slopes and are permeable. This allows them to dissipate energy rather than reflect it (http://www.rpcltd.co.uk/contracts/revetment.html#prettyPhoto).

Because they dissipate wave energy, revetments are less prone to accelerated beach erosion in areas where a beach is located between the structure and the shoreline. They are also less prone to *flanking*, which results when reflected wave energy wraps around the ends of a structure, eroding the areas around them. Due to the gradual slope of the structure, revetments tend to take up a larger area as compared to a vertical seawall [14], resulting in a high amount of placement loss compared to other hard structures [9]. From initial short-term costs to long-term maintenance, the cost of a revetment is considered to be moderate. A rock revetment rarely fails all at once, and this can lead to lower repair and maintenance costs over the service life of the structure [9].

Some types of revetments (those built of rock or concrete) can be hazardous to walk on. Other alternative design options for a revetment consist of using downed trees on the banks to protect the shoreline. To bring more aesthetic appeal to a concrete or rock revetment, it may be possible to plant trees, shrubs, or grass in the gaps between the structures (Figure 2-13) to obtain a more natural look for the shoreline [14].

Advantages of revetments

- The toe of a revetment is armored to prevent scour [15].
- The permeability of a revetment helps prevent uplift forces.
- The low profile of the structure does not limit the view of the coast.
- Revetments can be used at the base of other structures (like seawalls or bulkheads) to prevent toe scour.
- Revetments can be used in locations with low-energy waves.

Drawbacks of revetments

- Revetments can stop or limit the flow of sediments through longshore currents.
- Revetments are not appropriate for locations with moderate or high wave energy.
- Revetments do not allow beach access.
- A revetment cannot protect the area behind it against storm surges or flooding.
- Revetments can be flanked by erosion on both sides.
- A revetment increases erosion in areas between the waterline and the revetment (see Figure 2-14).

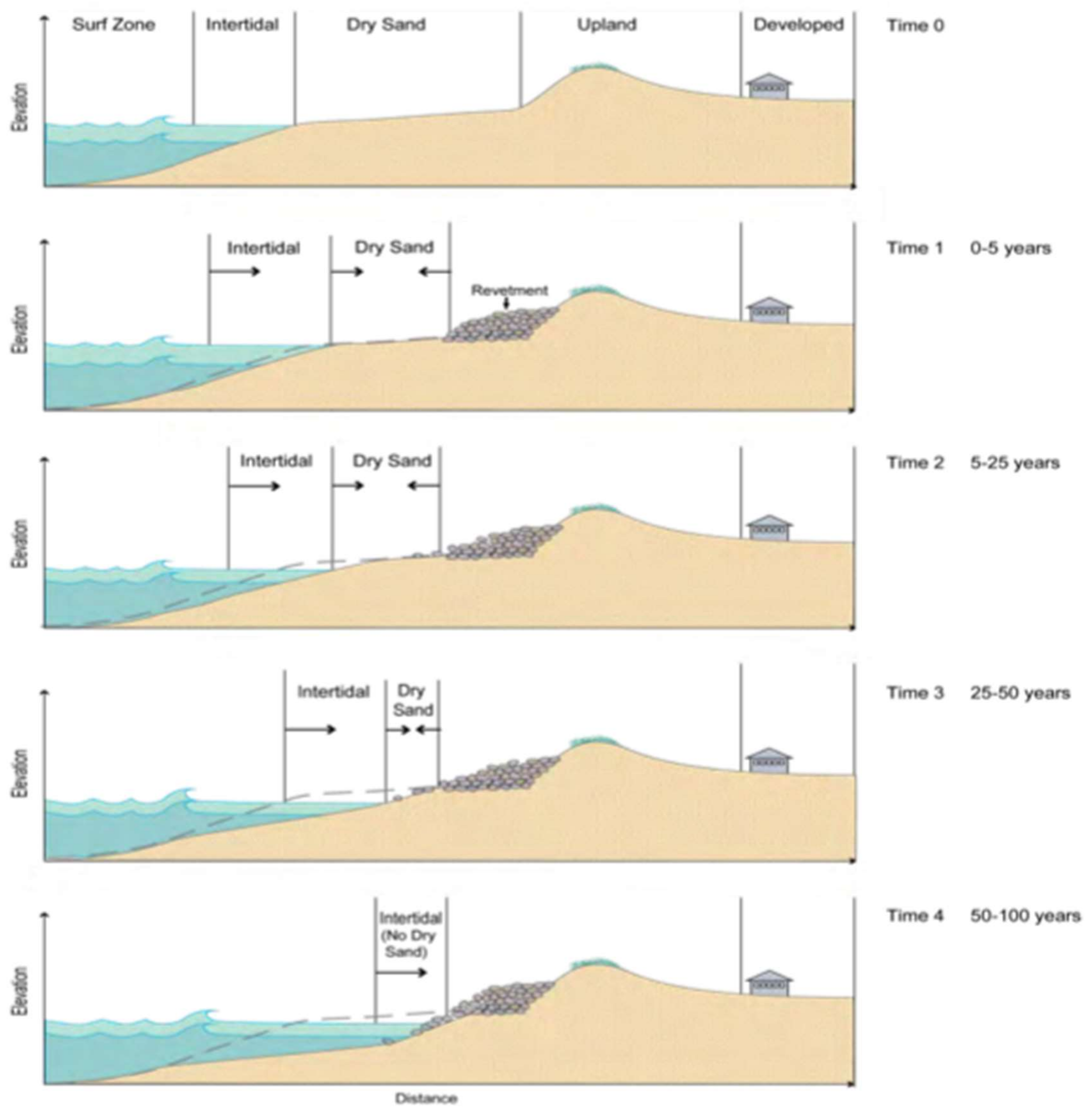


Figure 2-14: Effects of a revetment on existing beach profile between the waterline and revetment (http://martinsbeach.blogspot.com/2013/03/seawall-threatens-martins-beach.html).

2.2 Soft Solutions

2.2.1 Nature-Based Shorelines

Methods for nature-based shorelines include vegetation, edging, and sills, as shown in Figure 2-15 [17]. One technique is to plant vegetation along the edge of the shoreline, as the roots of the vegetation can hold soil in place. Edging is the process of using a silt fence, snow fence, or geotextile fabric along the waterline to increase soil strength, thereby helping to prevent erosion. Another method is to install a sill, where a light rock armoring with gaps is used to stabilize the shoreline. All of these approaches maintain the continuity between the aquatic and terrestrial environments. Sometimes, a fully green, natural solution is not suitable for a location of a certain site, so a hybrid solution that combines natural features and armoring is proposed, as shown in Figure 2-15. These hybrid solutions help to stabilize the shoreline without completely losing the continuity between habitats.

Natural shorelines promote biodiversity and provide habitats for fish and other animals, while helping to clean and filter runoff before it reaches a waterway [18]. These shorelines can also provide natural way to control geese, as demonstrated in a project in the Shoreline Park in Sandusky, Ohio. By installing tall marsh grasses at the shoreline, the designers of this project were able to deter the Canada geese by taking advantage of the birds' fear of predators in high vegetation. The project also involved installation of floating wetlands that clean nitrogen from the water, which may help to prevent algal blooms.

Nature-based shorelines also increase the aesthetic appeal of the shoreline, which can attract more visitors for recreational use. Over time, vegetation grows taller with a stronger root base, which better stabilizes the shoreline. In addition, living shorelines accrete sediment that is trapped in the vegetation, which in turn provides area for more vegetation to expand and further stabilizes the shoreline [19].

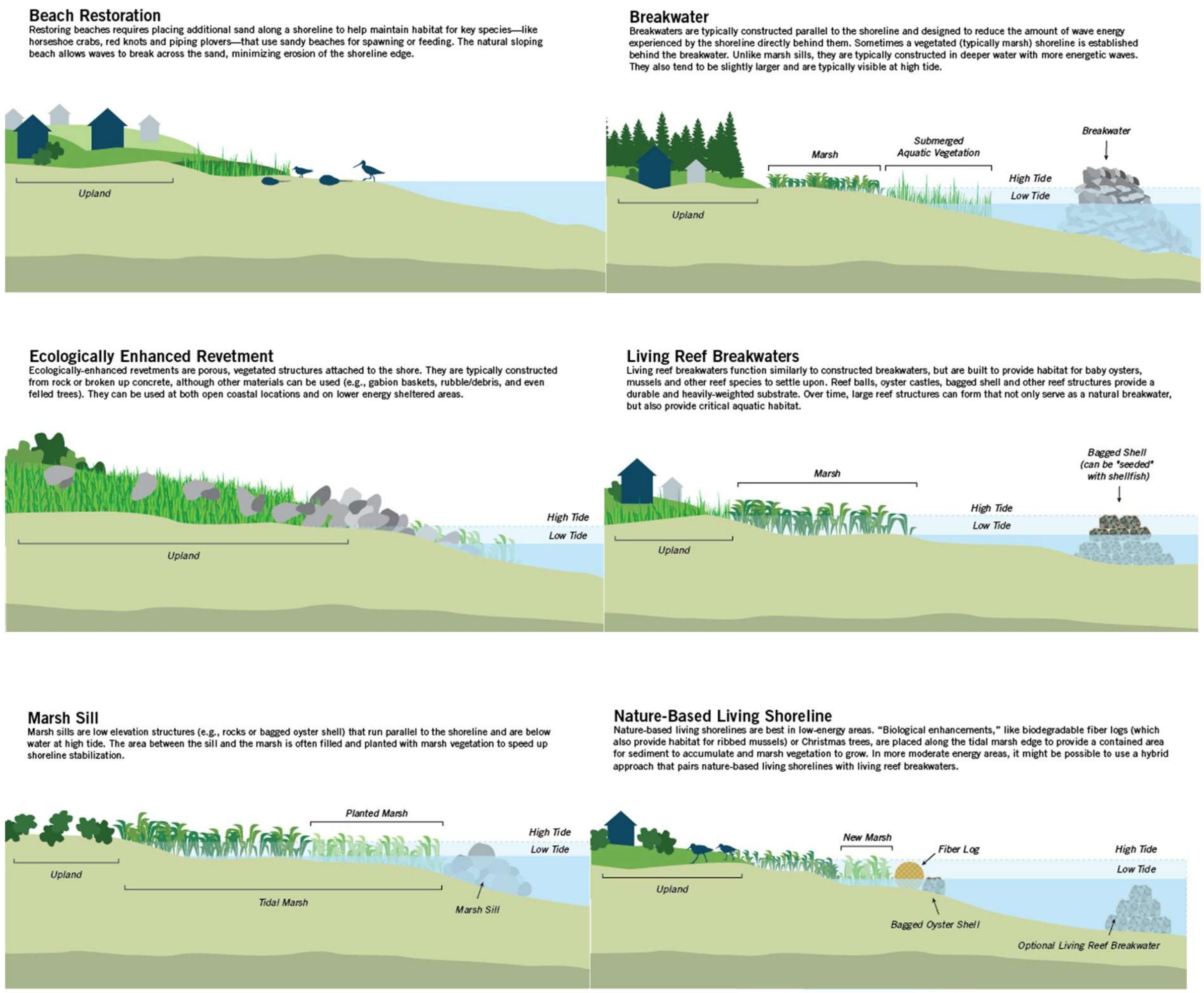


Figure 2-15: Six approaches for a nature-based shoreline (http://coastalresilience.org/project/restoration-explorer/).

Advantages of nature-based shorelines

- Nature-based shorelines can restore habitats for fish and wildlife [17].
- Nature-based shorelines maintain continuity between terrestrial and aquatic environments.
- These shorelines can improve access to the waterfront for recreational activities [17].
- Nature-based shorelines can improve water quality by providing water filtration, and they can also provide carbon sequestration [20].
- Nature-based shorelines can enable beneficial use of dredge materials [20].
- This type of shoreline is good at protecting from frequent low-intensity events [21].

- Nature-based shorelines can limit erosion, leading to sediment accretion and reduced water turbidity [21].

Disadvantages of nature-based shoreline

- The installation of nature-based shorelines is a new technique, which may limit its use [17].
- Nature-based shorelines are used for low energy environments. This type of shoreline does not protect from flooding and is not effective in high-energy environments. Living shorelines are prone to damage from severe storms [19]. Rapid water level rise and heavy waves will damage or even kill all vegetation [17].
- Edging and sills have no effect in preventing coastal flooding due to rising sea levels [21].
- Sediment accretion at edging and sill locations can cause increased erosion in downdrift areas [21].

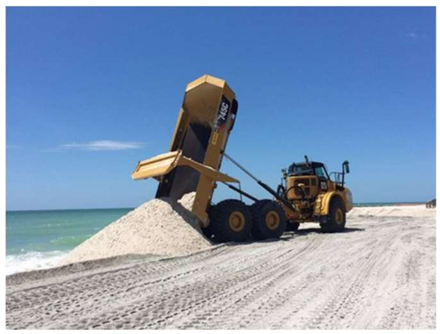
2.2.2 Beach Nourishment

Beach nourishment is the process of adding sands to a beach in order to offset the effects of erosion. By dumping or pumping sand onto a beach, the beach is widened (Figure 2-16). However, this approach is a temporary fix and does not stop erosion; it only buys time while the beach continues to wash away [22]. Beach nourishment is therefore an ongoing process that requires more sand to be added every few years. To help predict the frequency of sand replenishment for a project, a profile of the beach should be obtained at regular intervals – ideally, before and after the project. This method is generally used for larger-scale public projects in order to protect recreational beaches [23].

In beach renourishment, the location where the sand is placed is very important. The sand does not need to be placed directly on the beach just within the littoral zone (Figure 2-17). Sediment is typically placed on the beach and on a dune, building them seaward, and wave action helps to level the sand on the beach face, giving it a more natural appearance. If space is available, a dune should be created and vegetated as part of a beach nourishment project. During the construction process, the beach area and nearby waters become unusable due to increased turbidity in the water, which can also be harmful to marine life [24]. The length of time that a beach nourishment project will last can vary, as it depends on the weather and the wave conditions at a given location. A large storm can deplete a beach nourishment project in a single event. For this reason, when using beach nourishment, a cost-benefit and risk analysis should be conducted to ensure that the project is worth the cost and effort and to determine the risk that a storm will erode the new sand shortly after it is placed [23].

(a)

(b)



(c)

Figure 2-16: Beach nourishment can supply sand via many different mechanisms, including (a) spraying of dredged materials (http://www.climatetechwiki.org/content/beach-nourishment), (b) pumping of dredged materials onto the beach (http://mycepd.com/beach-nourishment.cfm), or (c) trucking in quarried materials (http://www.wtsp.com/news/local/sarasotacounty/longboat-key-beach-nourishment-project-sand-from-immokalee/124872960).

Advantages of beach nourishment

- Beach nourishment increases the sediment downdrift, preventing further erosion at other locations [21].
- It improves access to waterfront for recreational users and maintains continuity between terrestrial and aquatic environments.
- It allows possible beneficial use of dredged material.
- It can provide increased ecological value [21].

Disadvantages of beach nourishment

- Beaches require periodic sand renourishment [21].
- Newly placed sands can be eroded quickly by extreme storm surges and waves [21].
- Due to poor estimation and storm events, most projects require renourishment before their estimated due date.
- Beach renourishment does not prevent flooding [21].

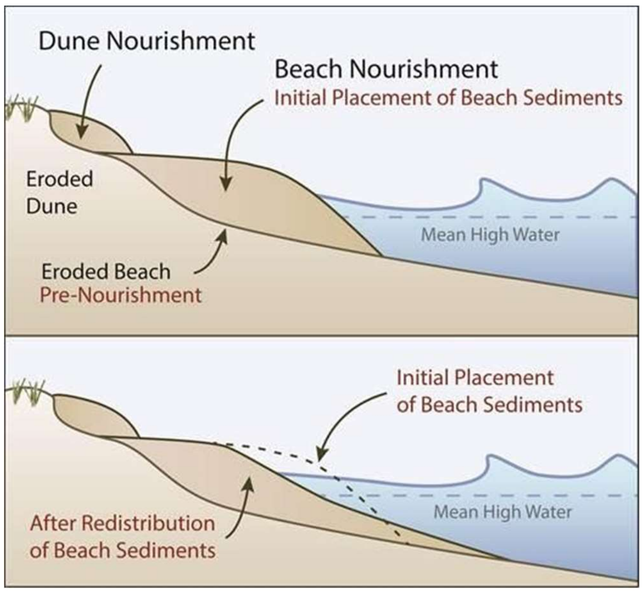


Figure 2-17: Typical sand placement in a beach nourishment projects (http://climateactiontool.org/content/restore-natural-coastal-buffers-beach-and-dune-nourishment-and-restoration).

2.2.3 Vegetated Dunes

Dunes are natural barriers that can protect upland features from high waves and storm surges (Figure 2-18). Dunes form when wind blows sand landward. The sands hit the dune, and some of the sand becomes trapped in vegetation on the dune [25]. Thus, the vegetation on a dune plays a key role in its formation as well as in the accretion of sand. When creating a new dune, one technique involves installing snow fences in order to catch sands until vegetation becomes established, as shown in Figure 2-19 [23]. However, a snow fence should not be installed in a location where the fence will interfere with vegetation growth [26]. To protect vegetation, it is common for elevated boardwalks to be installed over a dune to prevent people and vehicles from coming into contact with the dune, which kills vegetation and increases erosion [26]. A vegetative dune can be installed in a location where beach nourishment is used. However, not all beach nourishment projects involve the creation and vegetation of a dune, due to space constraints and costs.

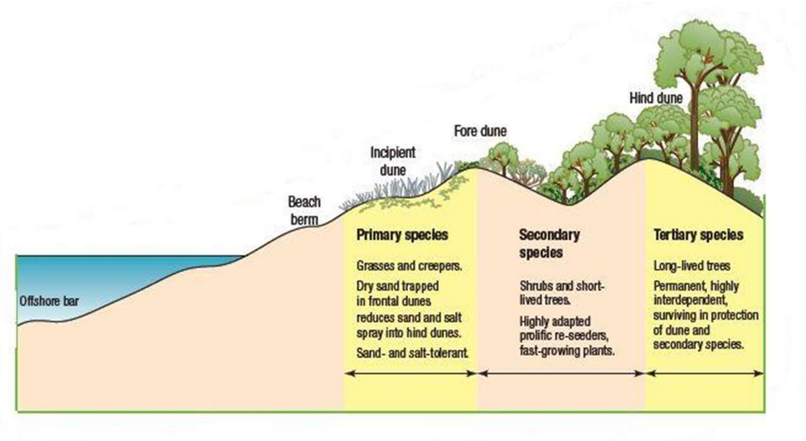


Figure 2-18: Species distribution for a vegetated dune
(http://hamishnewbysgeographyblog.blogspot.com/2011/03/unit-78-stuarts-point-questions.html)

Advantages of vegetated dunes

- Vegetated dunes have all the benefits of beach nourishment.
- Vegetated dunes can provide protection against storm surges [21].
- A vegetated dune is more efficient at stopping erosion and protecting infrastructure than a berm [21].

Drawbacks of vegetated dunes

- This technique requires a level site, which limits the places where a dune can be placed [21].
- Vegetated dunes can limit the view of waterfront, affecting the aesthetics of the beach.
- Artificial dunes may not perform as well as natural dunes in storm conditions [21].
- It is possible that a vegetated dune will divert high-velocity wave flow, which might result in erosion of the sides of the dune as well as adjacent areas [21].
- Human activity on the dunes will kill vegetation, limiting the effectiveness of the dune in preventing erosion.

Figure 2-19: Snow fencing is an effective way to begin formation of a dune; however the fence should not interfere with the growth of vegetation (http://netcomanage.com/sand-drift-fencing-using-snow-fence/; http://www.dunedoctors.com/).

2.3 Summary

In this chapter, a review of three soft shoreline protection approaches (.e., vegetated dunes, beach nourishment and living shorelines) and five hard shoreline protection approaches (i.e., groins, breakwaters, seawalls, bulkheads and revetments) are documented. The advantages and disadvantages of each approach are also synthesized. It should be noted that although there are several other types of shoreline protection techniques that are not included in this literature review, we only focus on the several representative approaches as documented in this chapter.

3. COST ANALYSIS

3.1 Data Collection and Itemization

In order to compare the long-term costs and benefits of various soft and hard shoreline protection approaches, a comprehensive review of the literature and historical projects was conducted. The literature search included published journal and conference papers, research reports, online articles, theses and dissertations. In addition, the research team also performed a thorough online search on the state of the practice for shoreline protections from a number of agencies, including but not limited to Ohio Sea Grant, Wisconsin Sea Grant, Mississippi-Alabama Sea Grant, US Army Corps of Engineers, National Oceanic and Atmospheric Administration, Hudson River Estuary Research Reserve, Governors' South Atlantic Alliance, National Park Service, European Climate Adaption Platform, and various government websites related to coastal management. Based on the data collected, four cost categories for each shoreline protection approach are itemized in this study: (1) initial construction cost, (2) maintenance cost, (3) damage cost and (4) environmental degradation cost.

The *initial construction cost* mainly refers to the cost in terms of the material and labor involved in the construction phase, without accounting for costs for design and permitting (if any, including the time waiting for a permit). It is considered to be a one-time payment for any shoreline solution technique. It is noted that the initial cost data does not include the costs for design, permitting, and demolition. For most hard shoreline approaches, the design fee, time cost to receive a permit, labor fee and equipment fee can cost much more than the implementation of soft solutions. As such, the initial construction costs for hard solutions in the cost analysis of this study are considered to underestimate the full costs of implementation.

The *damage cost* refers to the cost associated with the removal of damaged structures after a major failure due to a storm event. It is known that for soft shorelines, vegetation and sand dunes can be significantly damaged during a strong storm and thus, damage costs can occur with some frequency in the long-term cost analysis. On the other hand, although hard shorelines can perform better during a strong storm, a portion of the shoreline can be subject to failure during the design life. Considering the materials, labor, equipment and permitting expenses for repairs, the cost due to damage for hard approaches can also be massive.

The *maintenance cost* mainly refers to the cost associated with monitoring, inspection, re-vegetation, dredging and repair of normal wear and minor structural damage. In this study, most of the collected cost data for maintenance is lumped into an annual maintenance cost that covers all maintenance activities.

The *environmental degradation cost* mainly results from the 1) depletion of resources such as water (e.g., use of impermeable structures) and soils (e.g., soil erosion in front of the structure), 2) destruction of ecosystems, 3) loss of habitat, 4) extinction of wildlife, 5) pollution, and 6) carbon emission. While environmental degradation is not a factor that is obvious to the public during the selection phase of shoreline protection approaches, it can be devastating over the course of a number of years. The cost due to environmental degradation has been rarely reported or quantified in previous research on shoreline management, mainly due to the difficulties in quantifying the negative environmental impacts. In fact, the cost of environmental degradation is hard to quantify. Since it is site-specific, it can involve multiple variables, and there may be a lack of quantitative data. In this study, for the sake of simplicity, the costs reported by the U.K. Environment Agency and Scottish Natural Heritage (as published in Hudson et al. [31]) are adopted as objective indices for the cost of environmental degradation.

3.2 Rationale in Cost Analysis and Comparison

In order to rationally calculate the cost for each shoreline protection approach, the long-term cost is determined using the cost data collected from the literature, which are considered as objective evidence. The following criteria are used in the cost analysis:

1) The total cost for 25-year service for each shoreline protection approach is considered;
2) All the raw cost data published in various periods are converted to US dollars in 2018;
3) The inflation rate is 4% for projecting the published cost data in a given year to 2018;
4) The unit cost per linear foot for each approach is calculated;
5) The frequency of a strong storm that may cause severe damage to soft approaches is presumed to be five years;
6) For any cost where a range of values is reported, the average value is used; and
7) In the cost comparison, an underestimation of costs is used for hard approaches, while an overestimation is used for soft approaches.

Using these predefined criteria, this study aims to demonstrate the advantages and benefits of soft shoreline approaches by conducting a comparison of long-term costs. The raw cost data for various soft and hard approaches as well as the costs in terms of 2018 US dollars are summarized in Tables 3-1 to 3-8. The sources of the corresponding raw cost data are also provided. Table 3-9 summarizes the costs for various soft and hard approaches. Detailed cost calculations are documented in the subsequent section.

3.3 Cost Data Calculation and Summary

3.3.1 Vegetated Dunes

Based on the cost data collected in Table 3-1, the cost in 2018 for a vegetated dune is estimated as follows (all cost values are US dollars per linear foot):

(1) Initial construction cost = \$3.94 + \$438.22 + \$10.40 = \$452.56

(2) 25-yr maintenance cost = \$243.33/yr × 25 yr = \$6,083.25

(3) Damage cost

Considering an extreme scenario were dunes are damaged by storms every five years:

(\$5.62 + \$2.81 + \$54.56) × 5 = \$314.95

Re-construction cost (to rebuild dunes at the end of 5 yr, 10 yr, 15 yr, 20 yr and 25 yr):

\$452.56 × 5 = \$2,262.80

Thus, the total damage cost is estimated to be \$314.95 + \$2,262.80 = \$2,577.75

(4) Environmental degradation cost = \$17.40/ft

According to the currency exchange rate as of April 2018, £1.0 = \$1.40. Thus, £1.00/m (in 2000) = £1.00 × $(1 + 4\%)^{18}$/m (in 2018) = £2.03/m (in 2018) = \$0.87/ft (in 2018)

Therefore, the environmental cost reported by Scottish Natural Heritage (as of 2000) is converted to \$3.48–\$17.40/ft. It is noted that the upper bound value is used in the cost benefit analysis.

For areas that experience frequent storms, the total 25-yr cost = (1) + (2) + (3) + (4) = \$452.56 + \$6,083.25 + \$2,577.75 + \$17.40 = \$9,130.96 per linear foot

For rare storm areas (where damage costs are less likely), total 25-yr cost = (1) + (2) + (4) = $452.56 + $6,083.25 + $17.40 = <u>$6,553.21 per linear foot</u>

Table 3-1: Itemized cost data for vegetated dunes

Item	Raw cost data	Reference	Year reported	2018 US dollars
(1) Initial construction cost	$1.30 – $3.50/ft for vegetation	Mississipi-Alabama Sea Grant [27]	2015	$1.46 – $3.94/ft
	$3 – $10/cubic yard for sand; 20 cubic yard sand/ft	Trembanis and Pilkey [28]	1998	$131.47 – $438.22/ft
	$9.25/ft for fence installation	City of Norfolk, Va. [29]	2015	$10.40/ft
(2) Maintenance cost	$200/ft annually; maintenance frequency 1–5 years	State of Massachusetts [30]	2013	$243.33/ft
(3) Damage cost	$5.00/ft for fence removal	City of Norfolk, Va. [29]	2015	$5.62/ft
	$2.50 each for post removal	City of Norfolk, Va.	2015	$2.81/ft
	$48.50/ft lump sum for debris removal	City of Norfolk, Va. [29]	2015	$54.56/ft
(4) Environmental degradation cost	£4 – £20/m by Scottish Natural Heritage	Hudson et al. [31]	2000	$3.48 –17.40/ft

<u>3.3.2 Beach nourishment</u>

Based on the cost data collected in Table 3-2, the cost in 2018 for beach nourishment is estimated as follows (all cost values are in US dollars per linear foot):

(1) Initial construction cost

Two sources of cost data are compared herein. The cost bounds reported by Trembanis and Pilkey [28] (as of 1998) are converted to $262.93/ft –$2,191.12/ft (the US dollar value in 2018), with an average value of ($262.93 + $2,191.12)/2 = $1,227.03.

The cost bounds reported by Hudson et al. (as of 2000) [31] is converted to $40.52–$1,620.65/ft (US dollar value in 2018), with an average value of ($40.52 + $1,620.65)/2 = $830.59.

The differences in the cost data may be a result of the specific equipment and site conditions. The larger average value ($1,227.03) is used as the initial construction cost for beach nourishment.

Table 3-2: Itemized cost data for beach nourishment

Item	Raw cost data	Reference	Year reported	2018 US dollars
(1) Initial construction cost	$120–$1,000/ft	Trembanis and Pilkey [28]	1998	$262.93–$2,191.12/ft
	$20–$800/ft	Hudson et al. [31]	2000	$40.52–$1,620.65/ft
(2) Maintenance cost	$200/ft annually, Maintenance frequency of 5–10 years	State of Massachusetts [30]	2013	$243.33/ft
(3) Damage cost*	$120–$1,000/ft	Trembanis and Pilkey [28]	1998	$262.93–$2,191.12/ft
	$20–$800/ft	Hudson et al. [31]	2000	$40.52–$1,620.65/ft
(4) Environ-mental degradation cost	£350–£6,450/m by Environmental Agency	Hudson et al. [31]	2007	$231.00–$4,257.00/ft
	£50–£2,000/m by Scottish Natural Heritage	Hudson et al. [31]	2000	$43.50–$1,740/ft

*The damage cost for beach nourishment is set to be the same as the initial construction, with a very conservative assumption that the entire beach requires re-nourishment after a major storm.

(2) 25-yr maintenance cost = $243.33/yr × 25 yr = $6,083.25

(3) Damage cost

Damage cost for beach nourishment is set to be the same as the initial construction, with a very conservative assumption that the entire beach requires re-nourishment after a major storm. The cost analysis considers an extreme scenario where the dunes are damaged by storms every five years:

$$\$1,227.03/\text{yr} \times 5\ \text{yr} = \underline{\$6,135.15}$$

(4) Environmental cost

According to the currency exchange rate in April 2018, £1.0 = $1.40. Thus, £1.00/m (in 2000) = £1.00 × $(1 + 4\%)^{18}$/m (in 2018) = £2.03/m (in 2018) = $0.87/ft (in 2018). Therefore, the environmental cost estimated by Scottish Natural Heritage (as of 2000) is converted to

\$43.50–\$1,740. The average environmental costs estimated by Scottish Natural Heritage = (\$43.50 + \$1,740)/2 = \$891.75.

In addition, £1.00/m (in 2007) = £1.00 × $(1 + 4\%)^{11}$/m (in 2018) = £1.54/m (in 2018) = \$0.66/ft (in 2018). Therefore, the environmental cost estimate by the Environmental Agency in the U.K. (as of 2007) is converted to \$231–\$4,257. The average environmental cost by the Environmental Agency = (\$231 + \$4,257)/2 = \$2,244.00

For areas with frequent storms, the total 25-yr cost = (1) + (2) + (3) + (4) =
\$1,227.03 + \$6,083.25 + \$6,135.15 + (\$891.75 + \$2,244) = \$16,581.18 per linear foot

For areas where storms are rare (and damage is unlikely), total 25-yr cost = (1) + (2) + (4) =
\$1,227.03 + \$6,083.25 + (\$891.75 + \$2,244) = \$10,446.03 per linear foot

3.3.3 Nature-based living shorelines

Based on the cost data collected in Table 3-3, the cost in 2018 for nature-based living shorelines approach is estimated as follows (all cost values are US \$ per linear foot):

(1) Initial construction cost = \$1,081.60

(2) 25-yr maintenance cost = \$108.16/yr × 25 yr = \$2,704.00

(3) Damage cost

Considering an extreme scenario where dunes are damaged by storms every five years:

(\$3.94/yr + \$112.49/yr + \$54.56/yr) × 5 yr = \$170.99

Reconstruction cost (to rebuild dunes at the end of 5 yr, 10 yr, 15 yr, 20 yr and 25 yr):

\$1081.60/yr × 5 yr = \$5,408.00

Therefore, the damage cost is estimated to be \$170.99 + \$5,408.00 = \$5,578.99

(4) Environmental cost = \$17.40/ft

According to the currency exchange rate in April, 2018, £1.0 = \$1.40. Thus, £1.00/m (in 2000) = £1.00 × $(1+4\%)^{18}$/m (in 2018) = £2.03/m (in 2018) = \$0.87/ft (in 2018). Therefore, the environmental cost estimated by Scottish Natural Heritage (as of 2000) [31] is converted to

$3.48–$17.40/ft. The upper bound of the cost from Scottish Natural Heritage is selected for the cost benefit analysis = $17.40.

For areas with frequent storms, the total 25-yr cost = (1) + (2) + (3) + (4) = $1,081.60 + $2,704.00 + $5,578.99 + $17.40 = $9,381.99 per linear foot

For areas where storms are rare (and damage is unlikely), total 25-yr cost = (1) + (2) + (4) = $1,081.60 + $2,704.00 + $17.40 = $3,803 per linear foot

Table 3-3: Itemized cost data for nature-based living shorelines

Item	Raw cost data	Reference	Year reported	2018 US dollars
(1) Initial construction cost	$65/ft – $100/ft for wooden sills	Mississippi-Alabama Sea Grant [27]	2015	$73.12 – $112.49/ft
	$361/ft for living shoreline	Governors' South Atlantic Alliance [32]	2016	$390.46/ft
	$1,000/ft for living shoreline	National Park Service [33]	2016	$1,081.60/ft
(2) Maintenance cost	$100/ft annually	National Park Service [33]	2016	$108.16/ft
	Maintenance frequency 1 to 3 years	State of Massachusetts [30]	2013	
(3) Damage cost	$1.30/ft – $3.50/ft for vegetation	Mississippi-Alabama Sea Grant [27]	2015	$1.46 – $3.94/ft
	$65/ft – $100/ft for wooden sills	Mississippi-Alabama Sea Grant [27]	2015	$73.12 – $112.49/ft
	$ 4,850 lump sum for debris removal/100ft	The City of Norfolk [29]	2015	$54.56/ft
(4) Environ-mental degradation cost	£4/m – £20/m by Scottish Natural Heritage	Hudson et al. [31]	2000	$3.48 – $17.40/ft

3.3.4 Groins

Unlike all other shoreline protection approaches involved in this study, groins are structures that are perpendicular to the shoreline. The specific cost of groins depends on the length of groins and the number of groins per unit length of shoreline. based on the cost data collected in Table 3-4, the cost in 2018 is estimated as follows (all cost values are US $ per linear foot perpendicular to the shoreline):

(1) Initial construction cost

($5,474.28 + $6,842.85)/2 + $109.55 = $6,268.12 **for concrete and steel groins**

$1,642.28 + $109.55 = $1,751.83 **for rock and stone groins**

(2) 25-yr maintenance cost

The annual maintenance cost is reported to be 10-15% of initial construction cost. The lower bound 10% is selected. Thus, the 25-yr maintenance cost for concrete and steel groins = 10% × $6,268.12/yr × 25 yr = $15,670.30; the 25-yr maintenance cost for rock and stone groins = 10% × $1,751.83/yr × 25 yr = $4,379.58

(3) Damage cost

For concrete and steel groins, the cost to remove concrete is averaged to be ($684.28 + $2,052.85)/2 = $1,368.57. For repairs, 10% of initial construction cost = 10% × $6,158.57 = $615.86. The damage cost is estimated to be $1,368.57 + $615.86 = $1,984.43.

For rock and stone groins, the cost to rock is $684.28. For repairs, 10% of initial construction cost = 10% × $1,751.83 = $175.18. The damage cost is estimated to be $684.28 + $175.18 = $859.46

(4) Environmental cost

According to the currency exchange rate in April, 2018, £1.0 = $1.40. Thus, £1.00 (in 2000) = £1.00 × $(1+4\%)^{18}$ (in 2018) = £2.03 (in 2018) = $ 2.84 (in 2018). Therefore, the environmental cost from Scottish Natural Heritage (as of 2000) is converted to $28,400 – $284,000 per structure. The average environmental cost is estimated to be ($28,400 + $284,000)/2 = $156,200 per structure.

For a 100-ft long groin, the environmental cost is $156,200/100 ft = $1,562/ft

For **concrete and steel groins**, total 25-yr cost = (1) + (2) + (3) + (4) = \$6,268.12 + \$15,670.30 + \$1,984.43 + \$1,562 = <u>\$25,210.98 per linear foot perpendicular to the shoreline.</u>

Considering a 100-ft long groin and 2 to 3 groins per 100 ft along the shoreline (as recommended by an agency adviser from Ohio Department of Natural Resources), the cost per linear foot along to the shoreline (C_1) can be converted from the cost per linear foot perpendicular to the shoreline (C_2):

$$C_1 = \frac{C_2 \times 100ft \times 2}{100ft} \tag{3-1}$$

Thus, for concrete and steel groins the total 25-yr cost = (1) + (2) + (3) + (4) = \$12,536.24 + \$31,340.60 + \$3,968.86 + \$3,124 = <u>\$50,969.70 per linear foot parallel to the shoreline.</u>

For **rock and stone groins**, total 25-yr cost = (1) + (2) + (3) + (4) = \$1,751.83 + \$4,379.58 + \$859.46+ \$1,562 = <u>\$8,552.87 per linear foot perpendicular to the shoreline</u>. **Using Eq. (3-1), for rock and stone groins, the total 25-yr cost = (1) + (2) + (3) + (4) = \$3,503.66 + \$8,759.16 + \$1,718.92 + \$3,124 = <u>\$17,105.74 per linear foot parallel to the shoreline</u>.**

Table 3-4: Itemized cost data for groins

Item	Raw cost data	Reference	Year reported	2018 US dollars
(1) Initial construction cost	$2,750/ft for construction	Town of North Topsail Beach, N.C. [34]	2009	$3,914.11/ft
	$3,000 – $4,000/ft for timber pile groin	N.C. Terminal Groin Study [35]	2010	$4,105.71 – $5,474.28/ft
	$1,200 – $6,500/ft for rock			$1,642.28 – $8,895.70/ft
	$4,000 – $5,000/ft for concrete & steel			$5,474.28 – $6,842.85/ft
	$3 – $10/cubic yard for sand Assuming 5 cubic yard sand/ft	Trembanis and Pilkey [28]	1998	$32.87–$109.55/ft
(2) Mainte-nance cost	10% – 15% of initial construction cost annually	N.C. Terminal Groin Study [35]	2010	
	Design life: 10 – 25 years for wooden groins; 1–5 years for gabion groins	European Climate Adaption Platform [36]	2015	
(3) Damage cost	$250/ft for timber removal	N.C. Terminal Groin Study [35]	2010	$342.14/ft
	$500/ft for steel removal			$684.28/ft
	$750/ft for concrete sheet removal			$1,026.43/ft
	$500 – $1,500/ft for rocks and concrete removal			$684.28 – $2,052.85/ft
	10% of initial construction cost	Rella and Miller [37]	2012	
(4) Environ-mental degradation cost	£10,000 –£100,000 per structure by Scottish Natural Heritage	Hudson et al. [31]	2000	$28,400 – $284,000 per structure

3.3.5 Breakwaters

Based on the cost data collected in Table 3-5, the present costs in 2018 dollars for a breakwater approach is estimated as follows (all cost values are US $ per linear foot):

(1) Initial construction cost = $17,305.60 + $131.47 = $17,437.07

(2) 25-yr maintenance cost = $540.80/yr × 25 yr = $13,520

(3) Damage cost = 10% × $17,305.60 = $1,730.56

(4) Environmental cost

According to the currency exchange rate as of April 2018, £1.0 = $1.40. Therefore, £1.00/m (in 2000) = £1.00 × $(1 + 4\%)^{18}$/m (in 2018) = £2.03/m (in 2018) = $0.87/ft (in 2018). Therefore, the environmental cost from Scottish Natural Heritage (as of 2000), when converted to US dollars, is $348 – $870. The average environmental cost from Scottish Natural Heritage = ($348 + $870)/2 = $609

In addition, £1.00/m (in 2007) = £1.00 × $(1+4\%)^{11}$/m (in 2018) = £1.54/m (in 2018) = $0.66/ft (in 2018). Therefore, the environmental cost from Environmental Agency (as of 2007) is converted to $1,145.10 – $2,838. The average environmental cost from Environmental Agency = ($1,145.10 + $2,838)/2 = $1,991.55

Total 25-yr cost = (1) + (2) + (3) + (4) = $17,437.07 + $13,520 + $1,730.56 + ($609 + $1,991.55) = $35,288.18 per linear foot

Table 3-5: Itemized cost data for breakwaters

Item	Raw cost data	Reference	Year reported	2018 US dollar
(1) Initial construction cost	$16,000/ft	National Park Service [33]	2016	$17,305.60/ft
	$3 – $10/cubic yard for sand; 20 cubic yard sand/ft	Trembanis and Pilkey [28]	1998	$131.47 – $438.22/ft
(2) Maintenance cost	Over $500/ft annually	National Park Service [33]	2016	Over $540.80/ft
	Design life 30 – 50 years	European Climate Adaption Platform [36]	2015	
(3) Damage cost	10% of initial construction cost	Rella and Miller [37]	2012	$1,730.56/ft
(4) Environmental degradation cost	£1,735 – £4,300/m by Environmental Agency	Hudson et al. [31]	2007	$1,145.10 – $2,838/ft
	£400 – £1,000/m by Scottish Natural Heritage	Hudson et al. [31]	2000	$348 – $870/ft

3.3.6 Seawalls

Based on the cost data collected in Table 3-6, the present cost in 2018 for **sheet pile seawalls** is estimated as follows (all cost values are US $ per linear foot):

(1) Initial construction cost = <u>$6,000</u>

(2) 25-yr maintenance cost = $243.33/yr × 25 yr = <u>$6,083.25</u>

Although the annual maintenance fee for seawalls is reported to be greater than $500/ft (Cunniff and Schwartz 2015), the smaller annual maintenance cost of $200/ft annually (State of Massachusetts 2013) is used in the maintenance cost calculation.

(3) Damage cost = 10% × $6,000 = <u>$600</u>

Table 3-6: Itemized cost data for seawalls

Item	Raw cost data	Reference	Year reported	2018 US dollar
(1) Initial construction cost	$5,000 – $10,000/ft	Cunniff and Schwartz [21]	2015	$5,624.32 – $11,248.64/ft
	$6,000/ft for sheet pile wall construction	County of Monterey, Ca. [38]	2018	$6,000/ft
(2) Mainte-nance cost	$200/ft annually; Design life of 20 – 25 years	Mass.gov [30]	2013	$243.33/ft
	>$500/ft annually	Cunniff and Schwartz [21]	2015	>$562.43/ft
(3) Damage cost	10% of initial construction cost	Rella and Miller [37]	2012	$562.24 – $1,124.86/ft
(4) Environ-mental degradation cost	£700 – £5,400/m by Environmental Agency	Hudson et al. [31]	2007	$462 – $3,564/ft
	£2,000 – £5,000/m by Scottish Natural Heritage	Hudson et al. [31]	2000	$1,740 – $4,350/ft

(4) Environmental cost

According to the currency exchange rate as of April, 2018, £1.0 = \$1.40. Thus, £1.00/m (in 2000) = £1.00×(1+4%)^{18}/m (in 2018) = £2.03/m (in 2018) = \$0.87/ft (in 2018). Therefore, the environmental cost from Scottish Natural Heritage (as of 2000) is converted to \$1,740 – \$4,350. The average environmental cost by Scottish Natural Heritage = (\$1,740 + \$4,350)/2 = \$3,045

In addition, £1.00/m (in 2007) = £1.00 × (1+4%)^{11}/m (in 2018) = £1.54/m (in 2018) = \$0.66/ft (in 2018). Therefore, the environmental cost from Environmental Agency (as of 2007) is converted to \$462 – \$3,564. The average environmental cost by Environmental Agency = (\$462 + \$3,564)/2 = \$2,013

Total 25-yr cost = (1) + (2) + (3) + (4) = \$6,000 + \$6,083.25 + \$600 + (\$3,045 + \$2,013) = \$17,741.25 per linear foot.

3.3.7 Bulkheads

Based on the cost data collected in Table 3-7, the cost in 2018 for implementing the bulkhead approach is estimated as follows (all cost values are US \$ per linear foot):

(1) Initial construction cost

Vinyl bulkheads = \$741.98

Wood bulkheads = \$705.20

Concrete bulkheads = (\$2,249.73 + \$5,624.32)/2 = \$3,937.03

(2) 25-yr maintenance cost

For vinyl bulkheads and wood bulkheads: \$112.49/yr × 25 yr = \$2,812.25

For concrete bulkheads: (\$112.49/yr + \$562.43/yr)/2 × 25 yr = \$8,436.50

(3) Damage cost

For vinyl bulkheads and wood bulkheads, considering one occasion of replacement = (\$540.80 + \$1,081.60)/2 = \$811.20, the damage cost = \$811.20

Considering one occasion of replacement = ($540.80 + $1,081.60)/2 = $811.20, and concrete removal = $140.61. Thus, the damage cost = $811.20 + $140.61 = $951.80 for concrete bulkheads.

(4) Environmental cost

According to the currency exchange rate as of April 2018, £1.00 = $1.40. Thus, £1.00/m (in 2000) = £1.00 × $(1 + 4\%)^{18}$/m (in 2018) = £2.03/m (in 2018) = $0.87/ft (in 2018). Therefore, the environmental cost from Scottish Natural Heritage (as of 2000) is converted to $1,740 – $4,350. The average environmental cost from Scottish Natural Heritage = ($1,740 + $4,350)/2 = $3,045

In addition, £1.00/m (in 2007) = £1.00 × $(1+4\%)^{11}$/m (in 2018) = £1.54/m (in 2018) = $0.66/ft (in 2018). Therefore, the environmental cost from Environmental Agency (as of 2007) is converted to $462 – $3,564. The average environmental cost from Environmental Agency = ($462 + $3,564)/2 = $2,013

For vinyl bulkheads, total 25-yr cost = (1) + (2) + (3) + (4) = $741.98 + $2,812.25 + $811.20 + ($3,045 + $2,013) = $9,423.43 per linear foot

For wood bulkheads, total 25-yr cost = (1) + (2) + (3) + (4) = $705.20 + $2,812.25 + $811.20 + ($3,045 + $2,013) = $9,386.65 per linear foot

For concrete bulkheads, total 25-yr cost = (1) + (2) + (3) + (4) = $3,937.03 + $8,436.5 + $951.81+ ($3,045 + $2,013) = $18,383.34 per linear foot

Table 3-7: Itemized cost data for bulkheads

Item	Raw cost data	Reference	Year reported	2018 US dollar
(1) Initial construction cost	$686/ft for vinyl w/toe protection	Governors' South Atlantic Alliance [32]	2016	$741.98/ft
	$652/ft for wooden w/toe protection	Governors' South Atlantic Alliance [32]	2016	$705.20/ft
	$2,000 – $5,000/ft for concrete w/toe protection	Cunniff and Schwartz [21]	2015	$2,249.73 – $5,624.32
(2) Maintenance cost	$1.30 – $3.50/ft for additional vegetation	Mississippi-Alabama Sea Grant [27]	2015	$1.46 – $3.94/ft
	$100 – $400/ft for repair	Governors' South Atlantic Alliance [32]	2016	$108.16 – $432.64/ft
	$100 – $500 annually	Cunniff and Schwartz [21]	2015	$112.49 – $562.43
	Design life 15 – 20 year	Shoreline Stabilization Guidelines [39]		
(3) Damage cost	$55/ft for wood removal	Green Shorelines [40]	2015	$61.87/ft
	$80/ft for riprap removal	Green Shorelines [40]	2015	$89.99/ft
	$125/ft for concrete removal	Green Shorelines [40]	2015	$140.61/ft
	$500 – $1,000 for replacement	Governors' South Atlantic Alliance [32]	2016	$540.80 – $1,081.60/ft
(4) Environmental degradation cost	£700 – £5,400/m by Environmental Agency	Hudson et al. [31]	2007	$462 – $3,564/ft
	£2,000 – £5,000/m by Scottish Natural Heritage	Hudson et al. [31]	2000	$1,740 – $4,350/ft

3.3.8 Revetments

For riprap revetments, based on the cost data collected in Table 3-8, the cost in 2018 is estimated as follows (all cost values are US $ per linear foot):

(1) Initial construction cost = ($134.98 + $202.48)/2 = $168.73

(2) 25-yr maintenance cost = $112.49/yr × 25 yr = $2,812.25

(3) Damage cost

As indicated by Rella and Miller [37], the damage cost is considered to be 10% of the initial construction cost. Thus, the damage cost is estimated to be 10% × $168.73 = $16.87

(4) Environmental cost

The highest cost for timber revetments is used here to estimate the cost for riprap revetments. According to the currency exchange rate as of April 2018, £1.00 = $1.40. Thus, £1.00/m (in 2000) = £1.00 × $(1 + 4\%)^{18}$/m (in 2018) = £2.03/m (in 2018) = $0.87/ft (in 2018). Therefore, the environmental cost from Scottish Natural Heritage (as of 2000) is converted to $9.60 – $240.06/ft. The upper bound of environmental cost by Scottish Natural Heritage = $240.06.

For riprap revetments, total 25-yr cost = (1) + (2) + (3) + (4) = $168.73 + $2,812.25 + $16.87 + $240.06 = $3,237.91 per linear foot

For rock revetments, based on the cost data collected in Table 3-8, the cost in 2018 is estimated as follows (all cost values are US $ per linear foot):

(1) Initial construction cost = ($475.90 + 507.27)/2 = $491.59

(2) 25-yr maintenance cost = ($112.49/yr + $562.43/yr)/2 × 25 yr = $8,436.50

(3) Damage cost

As indicated by Rella and Miller (2012), the damage cost can be 10% of the initial construction cost. Thus, the damage cost is estimated to be 10% × $491.59 = $49.16

(4) Environmental cost

According to the currency exchange rate as of April 2018, £1.00 = \$1.40. Thus, £1.00/m (in 2000) = £1.00 × (1 + 4%)^{18}/m (in 2018) = £2.03/m (in 2018) = \$0.87/ft (in 2018). Therefore, the environmental cost from Scottish Natural Heritage (as of 2000) is converted to \$87 – \$2,610. The average environmental cost from Scottish Natural Heritage = (\$870 + \$2,610)/2 = <u>\$1,740.</u>

In addition, £1.00/m (in 2007) = £1.00 × (1 + 4%)^{11}/m (in 2018) = £1.54/m (in 2018) = \$0.66/ft (in 2018). Therefore, the environmental cost from Environmental Agency (as of 2007) is converted to \$429 – \$1,881. The average environmental cost from Environmental Agency = (\$429 + \$1,881)/2 = <u>\$1,155.</u>

For rock revetments, total 25-yr cost = (1) + (2) + (3) + (4) = \$491.59 + \$8,436.50 + \$49.16 + (\$1,740 + \$1,155) = <u>\$11,872.25 per linear foot</u>

For impermeable revetments, based on the cost data collected, the cost in 2018 is estimated as follows (all cost values are US \$ per linear foot):

(1) Initial construction cost = (\$5,624.32 + \$11,248.64)/2 = <u>\$8,436.48</u>

(2) 25-yr maintenance cost = (\$112.49/yr + \$562.43/yr)/2 × 25 yr = <u>\$8,436.50</u>

(3) Damage cost = 10% × \$8,436.48 = <u>\$843.65</u>

(4) Environmental cost

According to the currency exchange rate as of April 2018, £1.00 = \$1.40. Thus, £1.00/m (in 2000) = £1.00 × (1 + 4%)^{18}/m (in 2018) = £2.03/m (in 2018) = \$0.87/ft (in 2018). Therefore, the environmental cost from Scottish Natural Heritage (as of 2000) is converted to \$1,740 – \$4,350. The average environmental cost from Scottish Natural Heritage = (\$1,740 + \$4,350)/2 = <u>\$3,045.</u>

In addition, £1.00/m (in 2007) = £1.00 × (1 + 4%)^{11}/m (in 2018) = £1.54/m (in 2018) = \$0.66/ft (in 2018). Therefore, the environmental cost from Environmental Agency (as of 2007) is converted to \$462 – \$3,564. The average environmental cost from Environmental Agency = (\$462 + \$3,564)/2 = <u>\$2,013.</u>

For impermeable revetments, total 25-yr cost = (1) + (2) + (3) + (4) = \$8,436.48 + \$8,436.50 + \$843.65 + (\$3,045 + \$2,013) = <u>\$22,774.63 per linear foot.</u>

Table 3-8: Itemized cost data for revetments

Item	Raw cost data	Reference	Year reported	2018 US dollars
(1) Initial construction cost	$120 – $180/ft for riprap	Mississippi-Alabama Sea Grant [27]	2015	$134.98 – $202.48/ft
	$440 – $469/ft for granite	Governors' South Atlantic Alliance [32]	2016	$475.90 – $507.27/ft
	$5,000 – $10,000/ft for impermeable revetments	Cunniff and Schwartz [21]	2015	$5,624.32 – $11,248.64/ft
(2) Mainte-nance cost	$100 – $250/ft for repair	Governors' South Atlantic Alliance [32]	2016	$108.16 – $270.40/ft
	$100 – $500/ft annually	Cunniff and Schwartz [21]	2015	$112.49 – $562.43/ft
	Design life: 10 – 20 years for toe protection, 20 – 25 years for full height	State of Massachusetts [30]	2013	
(3) Damage cost	10% of initial construction cost	Rella and Miller [37]	2012	
(4) Environ-mental degradation cost	For timber revetments: £20 – £500/m Scottish Natural Heritage	Hudson et al. [31]	2000	$9.60 – $240.06/ft
	For rock revetments: £1,000 – £3,000/m by Scottish Natural Heritage	Hudson et al. [31]	2000	$870 – $2,610/ft by Scottish Natural Heritage
	For rock revetments: £650 – £2,850/m by Environment Agency	Hudson et al. [31]	2007	$429 – $1,881/ft by Environment Agency
	For impermeable revetments: £2,000 – £5,000/m by Scottish Natural Heritage	Hudson et al. [31]	2000	$1,740 – $4,350/ft by Scottish Natural Heritage
	For impermeable revetments: £700 – £5,400/m by Environment Agency	Hudson et al. [31]	2007	$462 – $3,564/ft by Environment Agency

Table 3-9: Summary of cost data for various shoreline protection approaches
(all amounts are in US dollars per linear foot)

Approach		#1 - Initial Construction	#2 - Maintenance	#3 - Damage Cost	#4A - Scottish Natural Heritage	#4B - Environmental Agency
1a	Vegetated dunes in frequent storm areas	452.56	6,083.25	2,577.75	0.00	17.40
1b	Vegetated dunes in rare storm areas	452.56	6,083.25	0.00	0.00	17.40
2a	Beach nourishment in frequent storm areas	1,227.03	6,083.25	6,135.15	891.75	2,244.00
2b	Beach nourishment in rare storm areas	1,227.03	6,083.25	0.00	891.75	2,244.00
3a	Nature-based living shorelines in frequent storm areas	1,081.60	2,704.00	5,578.99	0.00	17.40
3b	Nature-based living shorelines in rare storm areas	1,081.60	2,704.00	0.00	0.00	17.40
4a	Groins: rock and stone	3,503.66	8,759.00	1,718.92	0.00	3,124.00
4b	Groins: concrete and steel	12,536.24	31,340.60	3,968.86	0.00	3,124.00
5	Breakwaters	17,437.07	13,520.00	1,730.56	609.00	1,991.55
6	Seawalls: sheet pile	6,000.00	6,083.25	600.00	3,045.00	2,013.00
7a	Bulkheads: vinyl	741.98	2,812.25	811.20	3,045.00	2,013.00
7b	Bulkheads: wood	705.20	2,812.25	811.20	3,045.00	2,013.00
7c	Bulkheads: concrete	3,937.03	8,436.50	951.81	3,045.00	2,013.00
8a	Revetments: riprap	168.73	2,812.25	16.87	240.00	0.00
8b	Revetments: rock	491.59	8,436.50	49.16	1,740.00	1,155.00
8c	Revetments: impermeable	8,436.48	8,436.50	843.65	3,045.00	2,013.00

3.4 Cost Comparison between Soft Approaches and Hard Approaches

Table 3-9 summarizes the calculated cost items for the three soft approaches (Nos. 1 to 3) and five hard approaches (Nos. 4 to 8). As can be noticed from this table, some approaches have subcategories to consider different materials or storm conditions. Thus, a total of sixteen (16) different scenarios are considered. The estimated four cost categories are: 1) initial construction cost, 2) maintenance cost, 3) damage cost, and 4) environmental degradation cost. As mentioned previously, the effect of environmental degradation is rarely reported or quantified in the literature on shoreline management. As such, the environmental degradation cost is indexed using the cost information published by Environmental Agency and Scottish Natural Heritage. Figures 3-1 to 3-7 visualize the cost data in Table 3-9. Some details about the cost comparison are provided in the following paragraphs.

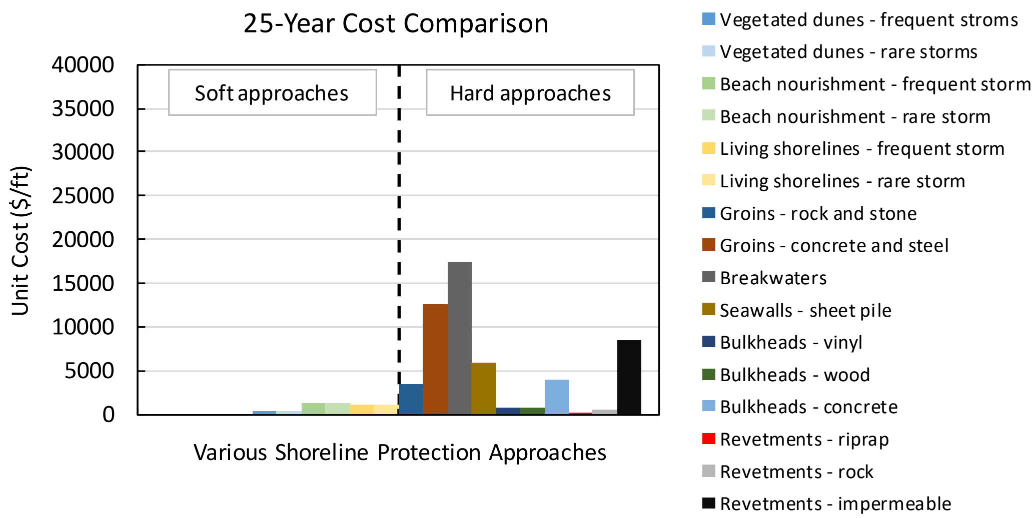


Figure 3-1: Initial construction cost: soft approaches vs. hard approaches.

Figure 3-1 shows the comparison of initial construction costs in the 16 scenarios for the various shoreline protection approaches. The left side of Figure 3-1 summarizes the cost information for the three soft solutions (vegetated dunes, beach nourishment and living shorelines), while the right side shows the cost information for the five hard solutions (groins, breakwaters, seawalls, bulkheads and revetments). It is clearly shown in Figure 3-1 that the initial construction cost required by soft shoreline protection approaches is significantly lower than for most hard approaches including groins, breakwaters, sheet pile seawalls, concrete bulkheads and impermeable revetments. On the other hand, some hard approaches using cheaper materials—such as vinyl bulkheads, wood bulkheads, riprap revetments and rock revetments—show a comparable cost to the soft approaches. In this study, the benefit of using soft solutions in terms of the initial construction cost is explicitly shown.

Next, Figure 3-2 shows a comparison of the maintenance costs for the 16 scenarios for shoreline protection. In this comparison, the maintenance cost for soft solutions is shown to be comparable to those of most hard solutions (e.g., sheet pile seawalls, bulkheads and revetments). However, groins and breakwaters have a higher maintenance cost than the soft approaches. This observation in Figure 3-2 makes intuitive sense, since most groins and breakwaters are installed at shorelines subjected to high wave energy impacts, frequent inspection and maintenance may be needed. Generally, this study shows that the maintenance costs of soft approaches are slightly lower than those for hard solutions.

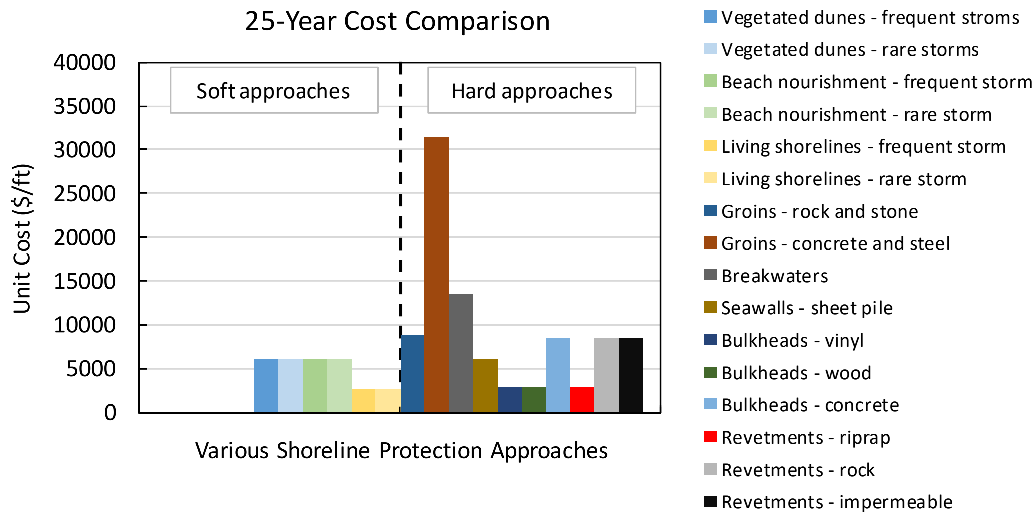


Figure 3-2: Maintenance cost: soft approaches vs. hard approaches.

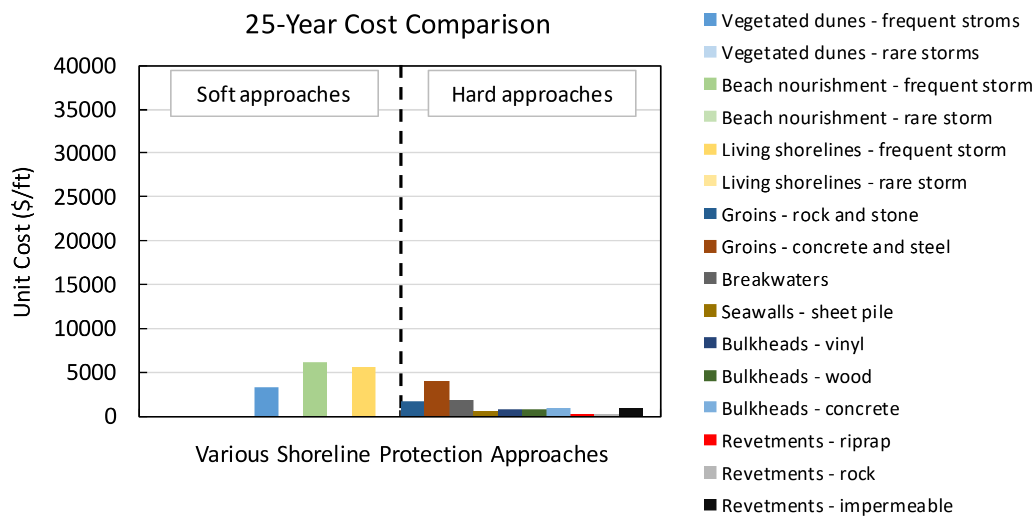


Figure 3-3: Damage cost: soft approaches vs. hard approaches.

Figure 3-3 shows a comparison of the damage cost for the 16 scenarios for shoreline protection. As expected, the damage cost for using soft approaches in locations with frequent storms is higher than that for all hard approaches. However, for soft approaches used along shorelines subjected to infrequent or rare storm events, the damage cost can be minimal, as shown in Figure 3-3.

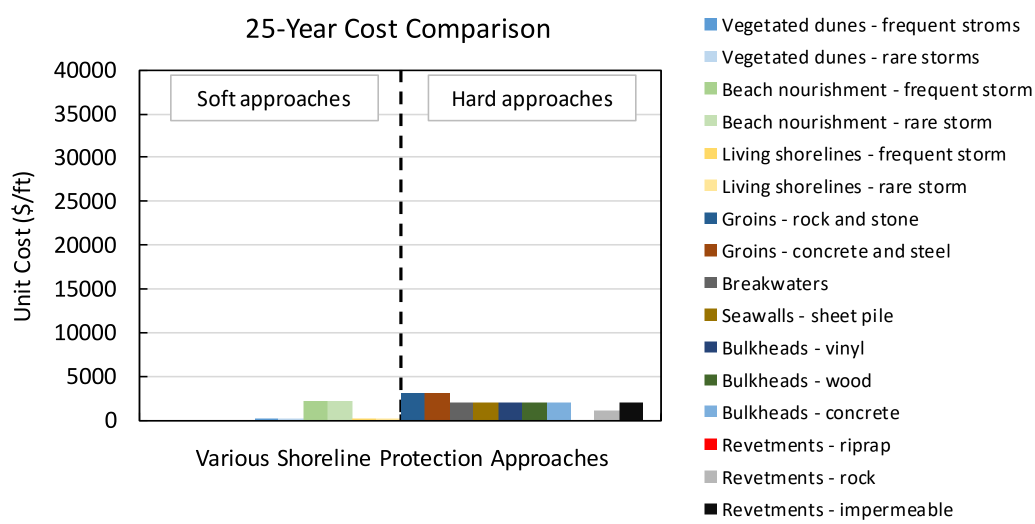


Figure 3-4: Environmental Agency cost comparison: soft approaches vs. hard approaches.

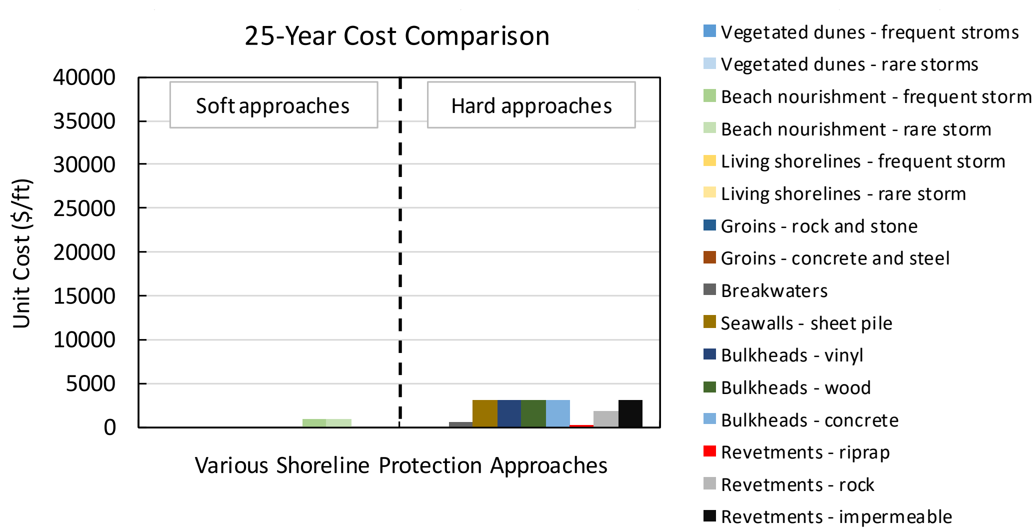


Figure 3-5: Scottish Natural Heritage cost comparison: soft approaches vs. hard approaches.

As mentioned previously, there has been a lack of quantitative cost data in the literature on the environmental degradation caused by artificial shoreline protection structures. In this regard, the cost data published by Environmental Agency and Scottish Natural Heritage are adopted as objective indices in this study. Further comprehensive economic loss evaluation and long-term observations are still needed. Figures 3-4 and 3-5, which are based on the data published in Hudson et al. [31], show a comparison of environmental costs for 16 shoreline protection scenarios. It is clearly shown that the cost of environmental degradation caused by hard approaches is significantly higher than that for soft approaches. In addition, of the three soft solutions, it is shown in Figures 3-4 and 3-5 that the cost of environmental degradation for beach nourishment is higher than that for vegetated dunes and living shorelines, which both have a negligible environmental degradation cost. In beach nourishment, the beach area and nearby waters become unusable due to increased turbidity in the water during the construction process, and this turbidity can also be harmful to aquatic life [24], resulting in some negative impacts to the environment and ecological systems. The observations in Figures 3-4 and 3-5 are consistent with general observations on the environment impact resulting from the use of various shoreline protection structures.

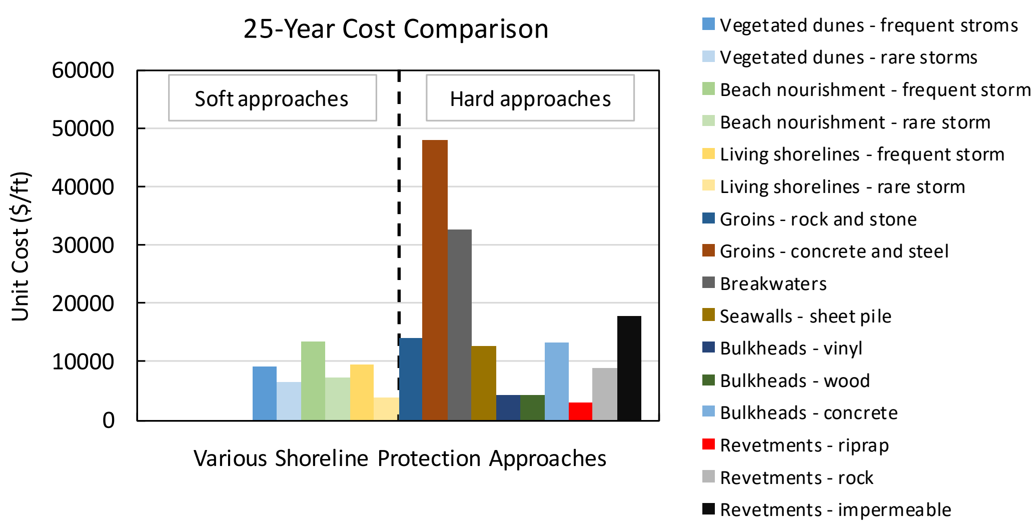


Figure 3-6: Total 25-yr cost when excluding environmental degradation cost: soft approaches vs. hard approaches (summation of initial construction cost, 25-yr maintenance cost and damage cost).

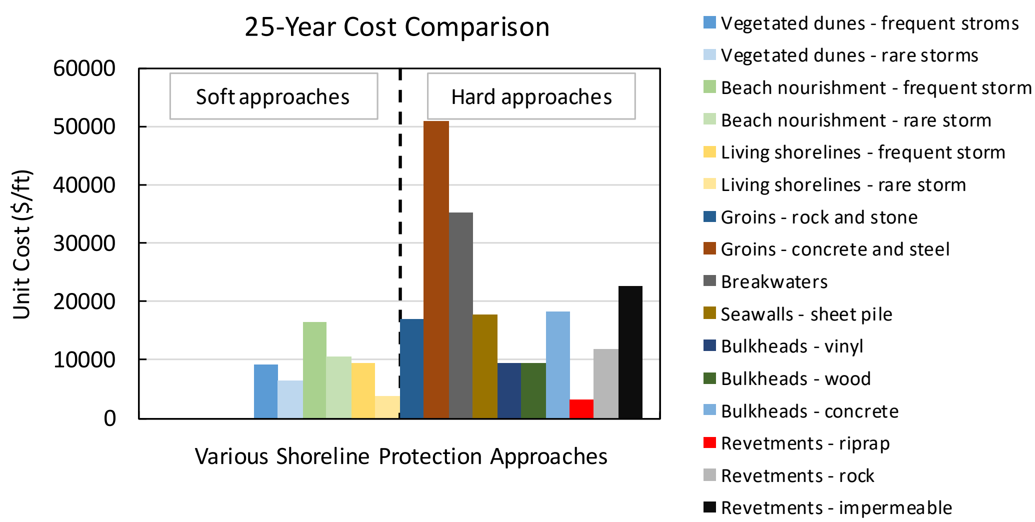


Figure 3-7: Total 25-yr cost comparison when including environmental degradation cost: soft approaches vs. hard approaches (summation of initial construction cost, 25-yr maintenance cost, damage cost and environmental degradation cost).

Finally, a total 25-year life-cycle cost for each approach was computed based on the data in Table 3-9, and the results and comparison are shown in Figures 3-6 and 3-7. Figure 3-6 shows the total cost for all 16 scenarios, which is a summation of the initial construction cost, 25-year maintenance cost and damage cost (the environmental degradation cost is not included). Several observations are made:

1) The life-cycle costs for soft solutions are comparable to several of the hard solutions including rock and stone groins, sheet pile seawalls, concrete bulkheads and rock revetments. If cost is the dominant factor in the design decision-making process, it is advisable to select soft solutions for shoreline protection, given that factors such as low wave energy condition, site geology, and space can be satisfied.
2) The life-cycle costs for soft solutions are significantly lower than several of the hard solutions including concrete and steel groins, breakwaters and impermeable revetments. Similarly, if cost is the dominant factor in the design decision-making process, it is rational to select soft solutions for shoreline protection, given that factors such as low wave energy condition, site geology and space can be satisfied.
3) The life-cycle costs of soft solutions are slightly higher than several hard solutions including vinyl bulkheads, wood bulkheads and riprap revetments. Although in a given scenario, the soft approaches cost more, it is still advantageous to choose soft solutions

over hard solutions, considering that bulkheads and revetments have disadvantages such as adverse environmental and ecological impacts, unsightliness, and the potential to cause injury to residents and tourists who visit.

Similarly, Figure 3-7 shows the total cost for all 16 scenarios, including the environmental degradation cost. Identical observations and conclusions to those in Figure 3-6 are obtained for the comparison shown in Figure 3-7. If cost is the dominant factor in the design decision-making process, it can be seen from Figure 3-7 that the life-cycle costs for soft approaches are either comparable to or lower than most hard solutions, except for riprap revetments. This result indicates that soft solutions are more cost-effective than hard solutions. As such, in terms of cost, this study demonstrates the benefits and advantages of selecting soft shoreline protections.

3.5 Summary of Cost Analysis

A comprehensive literature review was conducted, and the collected cost data for three soft shoreline protection approaches (vegetated dunes, beach nourishment and living shorelines) and five hard shoreline protection approaches (groins, breakwaters, seawalls, bulkheads and revetments) are collected. The cost data published in previous years were converted to US dollars in 2018. Comparisons of initial construction cost, maintenance cost, damage cost and 25-yr life-cycle cost were conducted. The results of the cost analysis explicitly show that soft solutions are superior to hard approaches in terms of cost. Considering environmental and ecological factors, soft shoreline protection approaches are recommended, given that factors such as low wave energy condition, site geology and space requirements can be satisfied.

It should be noted that several other important factors, such as recreational value; effects on nearby private property; and the impacts of wave energy, on-site geology and space, etc., are not included in this cost analysis. It is noted that an ongoing research project funded by Ohio Sea Grant is studying the economic benefit of a beach on the local economy. These other factors can be readily implemented in the cost comparison framework employed in this study.

4. SURVEY OF LOCAL PROFESSIONALS IN OHIO

4.1 Survey Data Collection

To further investigate the benefit and cost of various soft and hard shoreline protection techniques, a comprehensive survey of local professionals in Ohio was conducted. Based on the discussions and input from our Agency Adviser, Debi Beck at the Ohio Department of Natural Resources (ODNR), the research team prepared a comprehensive survey form, which covers the three soft shoreline protection approaches (vegetated dunes, beach nourishment and living shorelines) and five hard shoreline protection approaches (groins, breakwaters, seawalls, bulkheads and revetments) as described in Chapters 2 and 3. Some other potential uses of shoreline protection approaches such as slope cutting were also indicated in the survey form. The surveyees were also encouraged to indicate other types of shoreline protection approaches and provide a rating for the approaches on the survey form. The rating sheet from the survey form is shown in Figure 4-1.

In the headings of the survey form (Figure 4-1) are spaces for surveyees to provide their company/agency names, contact names, and contact information. Four cost items are included in the survey form: initial construction cost, maintenance cost, damage cost and environmental degradation cost. These four cost items are consistent with Tables 3-1 to 3-8 in Chapter 3. In addition, a column for "maintenance frequency" is also included in the survey form. Considering the difficulty in obtaining actual cost data for a specific site, numeric ratings were adopted in the survey. Numeric values from 1 to 10 are prepared for each candidate shoreline protection technique in the survey form, with a larger value indicating a higher cost. At the bottom of the survey form, a list of survey questions was also prepared, to obtain the engineering judgments from the surveyees regarding the preferred choice of a shoreline protection approach. As shown in Figure 4-1, the three questions are:

1. *Do you recommend soft solutions? If yes what types?*
2. *Is there any monitoring difference between soft and hard solutions?*
3. *Do you know cost information for any solutions?*

ODNR provided the research team with a detailed list of local stakeholders, including but not limited to 167 state/local shoreline jurisdictions, 36 coastal practitioners/design engineers, and 162 general contractors/consultants. Using this list, the research team performed comprehensive survey activities by emailing the survey to each person on the list. During this phase, an education intern

Company Name:																				Contact Name:																				Contact Information:										
Solution Type	Construction Cost										Maintenance Cost										Maintenance Frequency										Damage Cost										Environmental Degradation Cost									
Groin/Jetties	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10
Breakwaters	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10
Seawalls	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10
Bulkheads	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10
Reventments	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10
Beach Nourishment	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10
Vegetated Dunes	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10
Living shorelines	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10
Slope Cutting	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10
Other Nature based:	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10
	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10

Note: a larger value corresponds to a higher cost

1. Do you recommend soft solutions? If yes what types?
2. Is there any monitoring difference between soft and hard solutions?
3. Do you know cost information for any solutions?

Figure 4-1: Survey rating sheet.

at ODNR who reached out to the PI for information regarding this project also completed a survey form. The respondents filled the survey form on their own, and the returned survey forms were formatted by the research team for consistent markers, as shown in **Appendix A**. The responses received for this survey are summarized in Table 4-1.

As shown in Table 4-1, most survey forms that were sent out by the research team did not receive a response or were returned as "wrong email." Some surveyees responded to the research team that their backgrounds made them unqualified to complete the survey. As a result, a total of fourteen (14) valid survey forms were obtained, including eleven state/local shoreline jurisdictions, one coastal practitioner, one general consultant and one education intern. These 14 completed survey forms provide numeric ratings for each shoreline protection approach, and most of these surveyees responded to the three questions attached at the bottom of the form.

The backgrounds of these 14 surveyess cover a variety of agencies and firms at local and national level, including ODNR, National Oceanic and Atmospheric Administration (NOAA), US Army Corps of Engineers (USACE), Erie Metroparks, Cleveland Metroparks, City of Lakewood, Black Swamp Conservancy, Coldwater Consulting and AECOM.

Table 4-1: Summary of survey response

	State/local shoreline jurisdictions	Coastal practitioners/ design engineers	General contractors/ consultants	Education intern
Responded	11	1	1	1
No response	124	34	137	0
Wrong email	15	0	18	0
Unqualified	17	1	6	0
Total	**167**	**36**	**162**	**1**

4.2 Survey Results

As indicated in the survey rating sheet (Figure 4-1), the survey results consists of numeric ratings on each shoreline prediction structures and answers to the three questions. The summary and discussions of these two survey results are provided in the following two sections.

4.2.1 Numeric ratings on cost for soft and hard solutions

The numeric ratings on the four cost items (initial construction cost, maintenance cost, damage cost and environmental degradation cost) for various hard and soft solutions rated by local professions are shown in Figures 4-2 to 4-6. In each figure, the mean ratings by the fourteen respondents are shown as red boxes, and the minimum and maximum ratings are also depicted using upper and lower bar lines (–) in the figures.

Figure 4-2 shows the numeric ratings on the initial construction cost for various hard (jetty/groins, breakwaters, seawalls, bulkheads and revetments) and soft shoreline protection approaches (beach nourishment, vegetated dunes and living shorelines). By comparing the mean ratings (red boxes), it is shown that the initial construction costs for hard solutions are generally higher than those for soft solutions. Only one soft solution, beach nourishment, shows initial construction costs that are comparable to those of hard solutions. Although a different cost indicator is used in the cost rating study (a numeric rating scale from 1 to 10 versus the actual dollar amount), the survey results for the initial construction cost comparison for the various approaches is consistent with the previously presented initial construction cost comparison that uses real dollar amounts (in reference to Figure 3-1) presented in Chapter 3. Both Figure 3-1 and Figure 4-2 show that the initial construction costs for a soft solution are lower than that for a hard solution.

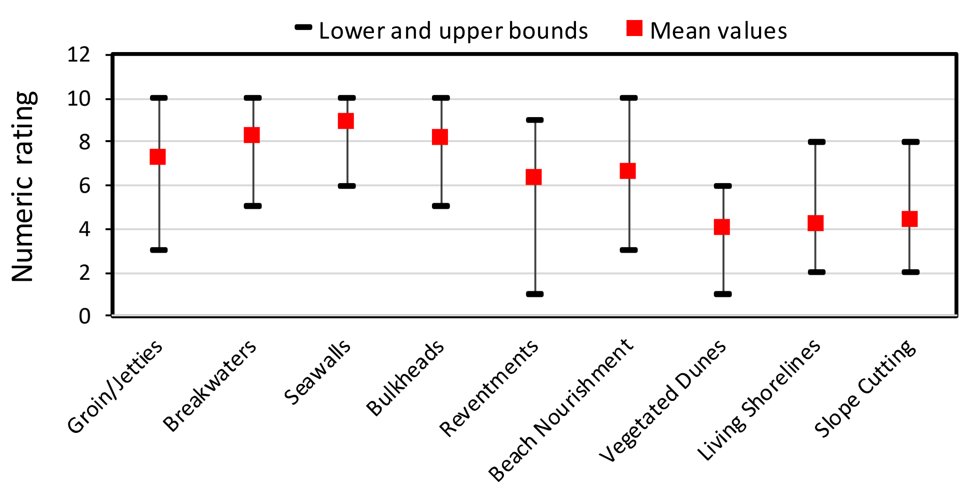


Figure 4-2: Numeric ratings from the survey regarding initial construction costs for various hard and soft shoreline protection approaches (Note: a larger number indicates a higher cost).

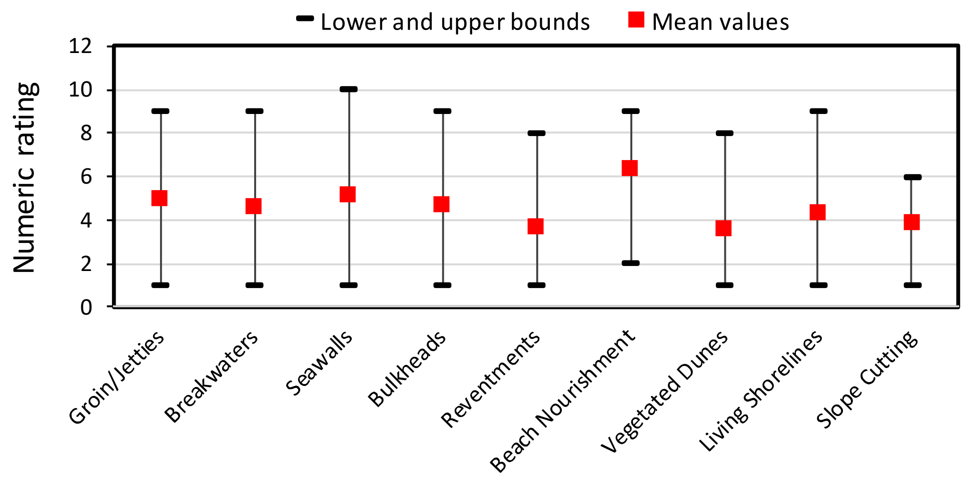


Figure 4-3: Numeric ratings from the survey regarding maintenance costs for various hard and soft shoreline protection approaches (Note: a larger number indicates a higher cost).

Similarly, Figure 4-3 shows the numeric ratings on the maintenance construction costs for various hard (jetty/groins, breakwaters, seawalls, bulkheads and revetments) and soft shoreline protection approaches (beach nourishment, vegetated dunes and living shorelines). Compared to hard solutions, most soft solutions requires a slightly lower maintenance costs except for beach nourishment. Beach nourishment requires slightly higher maintenance costs, as indicated by the ratings provided by professionals. This observation obtained from the survey is similar to the results of the cost data comparison (in reference to Figure 3-2 in Chapter 3): Figure 3-2 shows that the maintenance costs for soft solutions are comparable with the costs for most of the hard solutions, except that groins and breakwaters have higher maintenance costs. Combining the findings from both cost data analysis and the survey, it is concluded that considering the maintenance savings, it is advisable to adopt soft shoreline protection approaches, given a proper cost evaluation for beach nourishment.

Figure 4-3 shows the numeric ratings on the maintenance frequency for various hard (jetty/groins, breakwaters, seawalls, bulkheads and revetments) and soft shoreline protection approaches (beach nourishment, vegetated dunes and living shorelines). As expected, soft shoreline structures require more frequent maintenance.

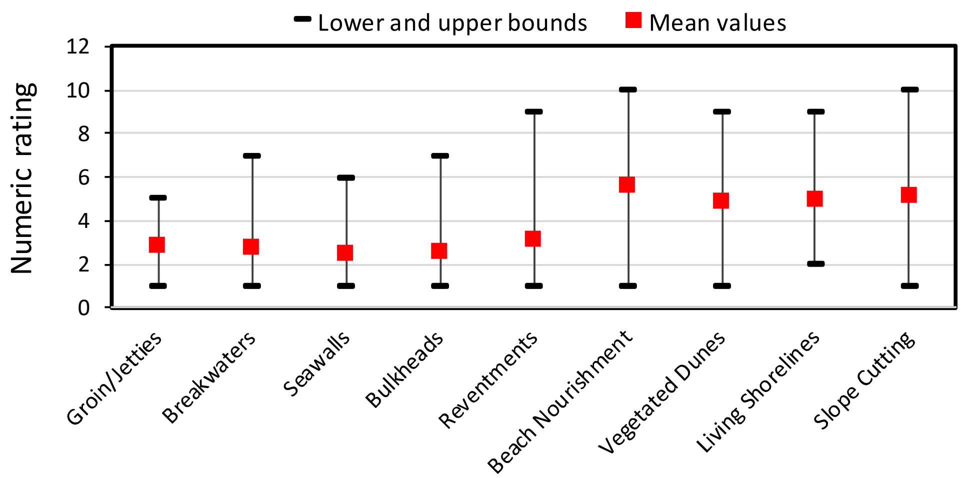


Figure 4-4: Numeric ratings from the survey regarding maintenance frequency for various hard and soft shoreline protection approaches (Note: a larger number indicates a higher frequency).

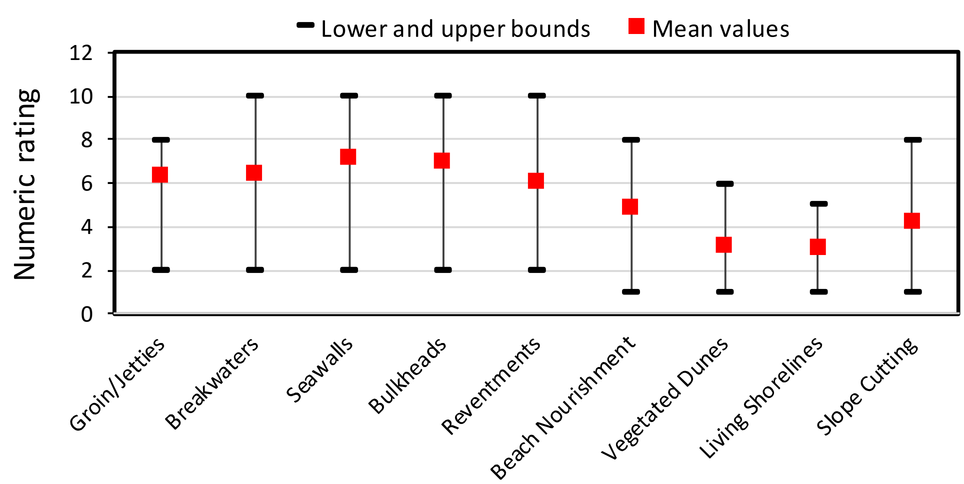


Figure 4-5: Numeric ratings from the survey regarding damage cost for various hard and soft shoreline protection approaches (Note: a larger number indicates a higher cost).

Next, the numeric ratings in Figure 4-5 show that the associated damage cost due to storms for soft shoreline protection approaches (beach nourishment, vegetated dunes and living shorelines) is less than that for hard solutions (jetty/groins, breakwaters, seawalls, bulkheads and revetments). This observation is somewhat different from the result of the cost data comparison in Figure 3-3. Nevertheless, the survey results for damage cost further indicate the benefit of using soft shoreline solutions.

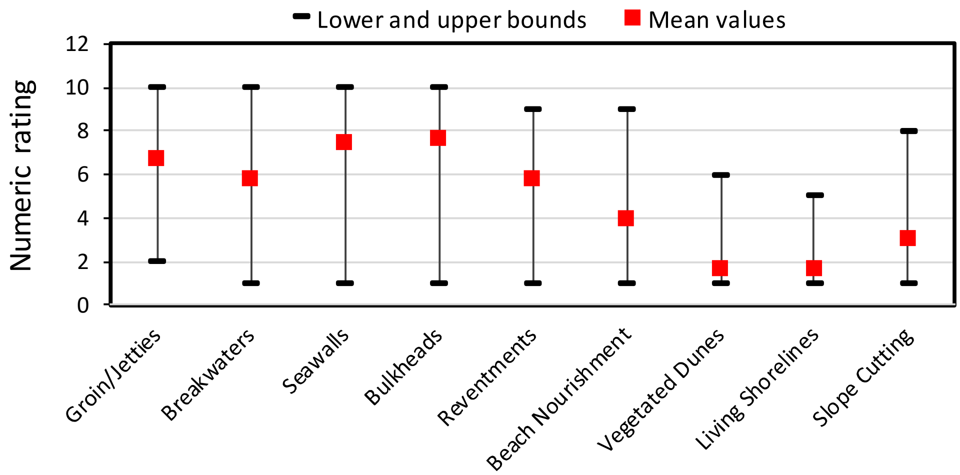


Figure 4-6: Numeric ratings from the survey regarding environmental degradation costs for various hard and soft shoreline protection approaches (Note: a larger number indicates a higher cost)

Last, a comparison of environmental degradation costs for various hard and soft shoreline protection approaches by local professionals is presented in Figure 4-6. It is demonstrated that the soft approaches (beach nourishment, vegetated dunes and living shorelines) can lead to significantly lower environmental degradation costs, as compared to hard approaches (jetty/groins, breakwaters, seawalls, bulkheads and revetments). In addition, vegetated dunes and living shorelines can further reduce the environmental degradation, as compared to beach nourishment and slope cutting. It should be noted that the observations made by the surveyed professionals regarding the environmental degradation cost are identical to the observations previously presented in Figures 3-4 and 3-5 in Chapter 3. It is concluded that if other factors such as geology, wave energy and available space at the project site can be satisfied, it is more rational to choose soft solutions to protect environmental and ecological systems as well as the shorelines.

Considering that in the literature, the environmental degradation cost is rarely reported due to the difficulty in quantifying it, the survey results as presented in Figure 4-6 provide state-of-the-practice evidence on the environmental and ecological benefits of selecting a soft technique for shoreline protection.

4.2.2 Responses to survey questions

The remaining portions of the survey obtained responses from surveyees regarding the three questions that were included on the survey rating sheet (as shown in Figure 4-1). Answers to the three questions that were provided by various local professionals are summarized in Tables 4-2, 4-3 and 4-4.

Table 4-2 summarizes the answers to Question #1: "Do you recommend soft solutions? If yes, what types?" Most surveyees answered positively with a "Yes" except for two professionals at the same agency, who responded "No" and "Generally not." On the same two forms, these two professionals further indicated that they only have implemented hard solutions in their city, which might be the reason for their negative responses. This finding highlights the importance of further research and efforts to promote soft shoreline approaches in order to educate local professionals and enhance public awareness of the benefit of implementing green soft shorelines.

In Table 4-2, professionals also noted several favorable soft shoreline solutions, including but not limited to "incorporating vegetation and trees and beaches into designs," "beach nourishment," "living shorelines," "wetland restoration," "dune restoration," "slope cutting," "use of coir mats into large envelopes and bags filled with locally compatible beach sand," and green-gray infrastructure. These professionals also expressed their engineering opinion about the limitations of soft solutions: "soft solutions have limitations in high energy systems," and "should be applied with care especially when the project goal is long term protection of shoreline infrastructure (i.e. buildings, roads, municipal facilities)."

Table 4-3 summarizes the answers to Question #2: "Is there any monitoring difference between soft and hard solutions?" Most answers confirm that hard solutions require annual monitoring, while most agencies/companies have limited experience in monitoring soft shorelines. One survey respondent suggested that "monitoring of soft solutions should incorporate ecological monitoring of habitat to watch for invasive species and presence of important species." One professional implied that soft solutions do not work well with Lake Erie erosion protection, as compared to hard solutions. This indicate that future research is needed to address these problems; such efforts could include 1) multiple factor analysis to determine if a soft solution can be applied at a specific location, 2) standardized design and workmanship for soft shoreline construction, and 3) beneficial use of dredged materials by chemical and mechanical improvement.

Table 4-2: Responses from various agencies/companies to Question #1

1. Do you recommend soft solutions? If yes what types?
"Yes. We try to encourage property owners to incorporate vegetation and trees and beaches into designs."
"Yes. In almost all instances, soft solutions are less costly, more environmentally friendly and require less maintenance. Depends on the topography, land use, geological characteristics and soils. Beach nourishment would be an acceptable solution on shorelines where land use is predominately recreational. Vegetated dunes would suffice in areas where longshore current, prevailing winds and a continual source of sand would potentially be available. Acceptable sites would be parks, nature areas or vacant/unused shoreline. Living shoreline can take on many forms from live stakes to a mix of vegetative cover types. Beneficial in backwater areas, lagoons and residential sites."
"Yes. Living shorelines, wetland restoration, dune restoration, and slope cutting."
"Yes, wherever possible. Slope regrading, nourishment, dune plantings, slope vegetation, drainage improvements."
"Yes, but siting at the right locations for the right purposes is important. Soft solutions have limitations in high energy systems for long term shoreline protection, and should be applied with care especially when the project goal is long term protection of shoreline infrastructure (i.e. buildings, roads, municipal facilities). Off shore breakwaters, low sills, locked logs, plantings, are all great ways to manage shoreline erosion and promote ecologic function, when the risks of failure are not too great. For instance along parkland, natural areas, or otherwise minimally developed land."
"No."
"Yes."
"Yes, soft solutions are favorable ecologically, but may not hold up well to high wave energy. Soft solutions are not advisable when valuable infrastructure needs protected that is in very close proximity to the water. Living shoreline, nature based, slope grading"
"Yes. Fabrication of coir (a natural fiber extracted from the husk of coconut) mats into large envelopes and bags which are then filled with locally compatible beach sand and constructed into terraces extending up the face of the coastal bank. These soft materials absorb wave and surf impacts, help encourage sand to build up or accrete naturally and fosters reduced wave reflection. http://www.marejournal.com/single-post/2016/10/24/Hard-vs-Soft-Solutions-for-Coastal-Erosion"
"Yes. Vegetated dunes, green-gray infrastructure."
"Generally not."

Table 4-3: Responses from various agencies/companies to Question #2

2. Is there any monitoring difference between soft and hard solutions?
“Groins and breakwaters require yearly sand volume monitoring. No experience with nature-based shoreline monitoring.”
“Yes, hard solutions can require specific monitoring standards, often requiring personnel with specific disciplines of training and education. Soft solutions such as vegetation and living shoreline.”
“Yes, monitoring of soft solutions should incorporate ecological monitoring of habitat to watch for invasive species and presence of important species.”
“Generally, hard structures (if well designed and built) require fewer inspections during the year but all structures require some level of annual monitoring.”
“Monitoring of soft solutions can include assessment of habitat usage. Typically hard structures do not provide these habitat benefits.”
“Soft solutions do not work well with Lake Erie erosive forces are more for creeks and rivers. Hard solutions work well with Lake Erie and last longer and have less maintenance costs.”
“Yes.”
“No ecological monitoring differences.”
“N/A.”
“Yes, manmade structures tend to be more monitored more because they reflect wave energy and this causes more damage to their structure.”

Finally, Table 4-4 summarizes the answers to Question #3: “Do you know cost information for any solutions?” Most respondents answered, “No.” Some professionals provided statements regarding the variability and difficulty in estimating the actual cost in dollars for most shoreline protection structures, such as “costs are highly variable depending on the site, bluff height, bathymetry length, etc.” “In general, hard solutions such as steel, vinyl or concrete seawall and bulkheads can run anywhere from $200.00- $1,000 per linear foot.” “I do not. The soft solutions I have worked on have varied drastically in price based on project goals and surrounding land use.” “Not specifically. Typically hear it secondhand from property owners and consultants.” “It’s highly variable and dependent on site conditions.” To this end, the use of numeric ratings on the cost item provides a reasonable index in the benefit and cost analysis of soft and hard shoreline solutions.

Table 4-4: Responses from various agencies/companies to Question #3

3. Do you know cost information for any solutions?
"Costs are highly variable depending on the site, bluff height, bathymetry length, etc." "In general, hard solutions such as steel, vinyl or concrete seawall and bulkheads can run anywhere from $200.00- $1,000 per linear foot." "I do not. The soft solutions I have worked on have varied drastically in price based on project goals and surrounding land use." "Not specifically. Typically hear it secondhand from property owners and consultants." "It's highly variable and dependent on site conditions." "Revetment is about $1,300 per foot." "No." "No." "No." "No." "We only have done hard solutions at the City of Lakewood."

4.3 Summary

A comprehensive survey of local professionals in Ohio was conducted, and the resulting survey data was summarized and used for a comparison of soft and hard shoreline solutions. The numeric ratings by various local professionals further confirm the advantages of using soft shoreline approaches versus using hard approaches, in terms of cost savings and environmental/ecological protection. The results of this survey also indicate that when deciding between the use of soft approaches and hard approaches, there is a need to consider factors such as on-site geology, wave energy, infrastructures to be protected, among other factors.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The benefit and cost analysis for three soft shoreline solutions (i.e., vegetated dunes, beach nourishment and living shoreline) and five hard shoreline solutions (i.e., groins, breakwaters, seawalls, bulkheads and revetments) were conducted in this project. The two major research tasks completed in this project are: 1) the comparison of benefit and cost using cost data collected from the literature, and 2) the comparison of benefit and cost using the numeric rating data collected from a comprehensive survey of local professionals in Ohio. The following conclusions are drawn:

1) The benefit and cost analysis based on the *collected cost data* clearly demonstrate—given that life-cycle costs are the major consideration in the selection process—that soft shoreline protection approaches are superior to hard approaches.

   1-A) In this cost comparison, the benefit of using soft solutions in terms of the initial construction cost is explicitly shown. The initial construction costs required for soft shoreline protection approaches are significantly less than those required for most hard approaches, including groins, breakwaters, sheet pile seawalls, concrete bulkheads and impermeable revetments. On the other hand, some hard approaches using less expensive materials (such as vinyl bulkheads, wood bulkheads, riprap revetments and rock revetments) show costs that are comparable to those of soft approaches.

   1-B) The cost comparison based on the collected cost data shows that the maintenance costs for soft approaches are slightly less than those for hard solutions. In this comparison, the maintenance costs for soft solutions are shown to be comparable to those for most of the hard solutions (e.g., sheet pile seawalls, bulkheads and revetments). However, groins and breakwaters have higher maintenance costs than those for soft approaches.

   1-C) As expected, the damage costs for soft approaches under frequent storm conditions are higher than the damage costs for all hard approaches. However, for soft approaches used along shorelines subjected to infrequent or rare storms, the damage costs are minimal.

   1-D) Using the cost data published by British Environmental Agency and Scottish Natural Heritage that were adopted as objective indices in this study, it is clearly shown that the cost of environmental degradation caused by hard approaches is significantly higher than the environmental degradation costs for soft approaches. In addition, among the three soft solutions, the cost of environmental degradation for beach nourishment is higher than that for vegetated dunes or living shorelines, which both have negligible environmental degradation costs.

1-E) The total costs for soft solutions are generally more advantageous than those for hard solutions: a) the life-cycle costs for soft solutions are comparable with several hard solutions (including rock and stone groins, sheet pile seawalls, concrete bulkheads and rock revetments); b) the life-cycle costs for soft solutions are significantly less than those for several hard solutions (including concrete and steel groins, breakwaters and impermeable revetments); and c) the life-cycle costs for soft solutions are slightly more expensive than the life-cycle costs for several hard solutions (including vinyl bulkheads, wood bulkheads and riprap revetments).

2) The comprehensive benefit and cost analysis based on numeric ratings from the survey shows the advantages of using soft shoreline approaches verses hard approaches, in terms of cost savings and environmental/ecological protection.

2-A) The initial construction costs for hard solutions are generally higher than those for soft solutions. Only one soft solution (beach nourishment) shows comparable initial construction costs to those for hard solutions.

2-B) Compared to hard solutions, most soft solutions require slightly lower maintenance costs. Beach nourishment has a slightly higher maintenance cost, as indicated by the ratings from professionals in Ohio.

2-C) The damage costs due to storms for soft shoreline protection approaches (beach nourishment, vegetated dunes and living shorelines) is lower than those for hard solutions (jetties/groins, breakwaters, seawalls, bulkheads and revetments). This observation is somewhat different from the result of the cost comparison using data from literature.

2-D) Soft approaches can lead to significantly lower environmental degradation loss, as compared to hard approaches. In addition, vegetated dunes and living shorelines can further reduce the environmental degradation loss as compared to beach nourishment and slope cutting.

3) The conclusions based on the survey are, for the most part, identical to those for the cost analysis based on data obtained from the literature. It is expected that the benefit of using soft solutions will be further magnified if the costs due to environmental degradation can be quantified and subsequently included in the benefit and cost analysis.

4) The responses to the three questions in the survey show the importance of further research and promotion of soft shoreline approaches, to educate local professionals about these approaches and to enhance public awareness of the benefits of implementing nature-based soft shorelines. Most of the survey respondents support the use of soft solutions, although some professionals also expressed their engineering opinion about the limitations of these solutions.

5) If cost is the dominant factor in the design making, it is advisable to select soft solutions for shoreline protection, given that other requirements (such as low wave energy condition, site geology and space) are satisfied.

5.2 Recommendations for future research

1) In this study, the cost benefit analysis of using soft approaches and hard approaches is based on cost information and focuses on only three soft methods and five hard methods; thus, it is a preliminary study. Future research would include a more comprehensive analysis of other soft and hard shoreline protection approaches (e.g., slope cutting) and would need to consider other factors, such as the on-site geology, wave energy, and the infrastructure to protect.

2) The survey responses indicate that most professionals are not familiar with the use of soft solutions. More effort is needed to promote these green soft shorelines, to develop design standard or guidelines for their implementation, and to conduct demonstration projects, such as the existing Shoreline Park in Sandusky, Ohio. Fortunately, the Ohio Coastal Training Program has partnered with the Erie Conservation District to conduct training of site contractors related to urban storm water solutions and on-site sediment and erosion control, which could be further expanded to cover training of local contractors regarding soft shoreline approaches. As a good first step, the education intern at the Ohio Department of Natural Resources has started to conceptualize materials relating to the subject of nature-based alternatives to shoreline management for homeowners in the summer of 2018. More research-based evidence can aid these training programs and be used to enhance promotional materials on soft shorelines.

3) As indicated by some professionals in their survey forms, soft solutions may not work well at all sites, especially when considering locations with erosive forces as strong as those of Lake Erie. It is expected that soft shorelines such as beaches and sand dunes are prone to be eroded subject to the strong waves of Lake Erie and the strength of the prevailing winds. In addition to exploring the aforementioned site-specific factors, it is also advisable to adopt the use of dredged materials from Lake Erie for shoreline erosion control. With the passage of Ohio Senate Bill 1 (of the 131st General Assembly), dredged materials may no longer be dumped in the open waters of Lake Erie after July 1, 2020. The potential beneficial uses of dredged materials include applications for shoreline erosion control. However, the dredged materials are highly moist and soft, and thus they would need to be dewatered in a timely manner and strengthened using a chemical or mechanical improvement method. Future studies, such as those that focus on the best management practices for stabilizing dredged materials in Ohio, are recommended.

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APPENDIX A

SURVEY RATING SHEETS RETURNED BY SURVEYEES

Solution Type	Construction Cost										Maintenance Cost										Maintenance Frequency										Damage Cost										Environmental Degradation Cost									
Groin/Jetties	1	2	3	4	5	6	**7**	8	9	10	**1**	2	3	4	5	6	7	8	9	10	**1**	2	3	4	5	6	7	8	9	10	1	2	**3**	4	5	6	7	8	9	10	1	2	3	4	5	**6**	7	8	9	10
Breakwaters	1	2	3	4	5	6	7	8	**9**	10	**1**	2	3	4	5	6	7	8	9	10	**1**	2	3	4	5	6	7	8	9	10	1	2	**3**	4	5	6	7	8	9	10	1	2	3	4	5	6	7	**8**	9	10
Seawalls	1	2	3	4	5	6	7	8	**9**	10	**1**	2	3	4	5	6	7	8	9	10	**1**	2	3	4	5	6	7	8	9	10	1	2	**3**	4	5	6	7	8	9	10	1	2	3	4	5	6	7	**8**	9	10
Bulkheads	1	2	3	4	5	6	7	8	**9**	10	1	**2**	3	4	5	6	7	8	9	10	**1**	2	3	4	5	6	7	8	9	10	1	2	**3**	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	**9**	10
Reventments	1	2	3	4	5	6	7	**8**	9	10	**1**	2	3	4	5	6	7	8	9	10	**1**	2	3	4	5	6	7	8	9	10	1	2	**3**	4	5	6	7	8	9	10	1	2	3	4	5	**6**	7	8	9	10
Beach Nourishment	1	2	3	4	5	6	**7**	8	9	10	1	2	3	**4**	5	6	7	8	9	10	1	2	3	**4**	5	6	7	8	9	10	1	2	3	4	5	**6**	7	8	9	10	1	**2**	3	4	5	6	7	8	9	10
Vegetated Dunes	1	**2**	3	4	5	6	7	8	9	10	1	2	**3**	4	5	6	7	8	9	10	1	**2**	3	4	5	6	7	8	9	10	1	**2**	3	4	5	6	7	8	9	10	1	**2**	3	4	5	6	7	8	9	10
Living shorelines	1	2	3	4	**5**	6	7	8	9	10	1	2	3	4	**5**	6	7	8	9	10	1	2	3	4	5	6	7	**8**	9	10	1	2	3	4	**5**	6	7	8	9	10	1	**2**	3	4	5	6	7	8	9	10
Slope Cutting	1	2	**3**	4	5	6	7	8	9	10	1	2	3	4	5	**6**	7	8	9	10	1	2	3	4	5	**6**	7	8	9	10	1	2	**3**	4	5	6	7	8	9	10	1	**2**	3	4	5	6	7	8	9	10
Other Nature based:	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10
	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10

Solution Type	Construction Cost										Maintenance Cost										Maintenance Frequency										Damage Cost										Environmental Degradation Cost									
Groin/Jetties	1	2	3	4	5	6	7	8	**9**	10	1	2	3	4	5	6	**7**	8	9	10	1	2	3	4	**5**	6	7	8	9	10	1	2	3	4	5	6	7	**8**	9	10	1	2	3	4	5	6	7	8	9	**10**
Breakwaters	1	2	3	4	5	6	7	8	**9**	10	1	2	3	4	5	6	**7**	8	9	10	1	2	3	4	**5**	6	7	8	9	10	1	2	3	4	5	6	7	**8**	9	10	1	2	3	4	5	6	7	8	9	**10**
Seawalls	1	2	3	4	5	6	7	8	9	**10**	1	2	3	4	5	6	7	**8**	9	10	1	2	3	4	5	**6**	7	8	9	10	1	2	3	4	5	6	7	8	**9**	10	1	2	3	4	5	6	7	8	9	**10**
Bulkheads	1	2	3	4	5	6	7	8	9	**10**	1	2	3	4	5	6	7	**8**	9	10	1	2	3	4	5	6	**7**	8	9	10	1	2	3	4	5	6	7	8	**9**	10	1	2	3	4	5	6	7	8	9	**10**
Revetments	1	2	3	4	5	6	**7**	8	9	10	1	2	3	4	5	**6**	7	8	9	10	1	2	3	4	5	6	**7**	8	9	10	1	2	3	4	5	6	**7**	8	9	10	1	2	3	4	5	6	7	8	**9**	10
Beach Nourishment	1	2	3	4	5	**6**	7	8	9	10	1	2	3	4	**5**	6	7	8	9	10	1	2	3	4	5	6	**7**	8	9	10	1	2	3	4	5	**6**	7	8	9	10	1	2	3	4	5	**6**	7	8	9	10
Vegetated Dunes	1	2	3	4	**5**	6	7	8	9	10	1	2	3	**4**	5	6	7	8	9	10	1	2	**3**	4	5	6	7	8	9	10	1	2	**3**	4	5	6	7	8	9	10	**1**	2	3	4	5	6	7	8	9	10
Living shorelines	1	2	3	**4**	5	6	7	8	9	10	1	2	**3**	4	5	6	7	8	9	10	1	2	**3**	4	5	6	7	8	9	10	1	2	**3**	4	5	6	7	8	9	10	**1**	2	3	4	5	6	7	8	9	10
Slope Cutting	1	2	3	4	5	6	**7**	8	9	10	1	2	3	4	5	**6**	7	8	9	10	1	2	3	4	5	6	**7**	8	9	10	1	2	3	4	5	6	**7**	8	9	10	1	2	3	4	5	**6**	7	8	9	10
Other Nature based:	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10
	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10

Solution Type	Construction Cost	Maintenance Cost	Maintenance Frequency	Damage Cost	Environmental Degradation Cost
Groin/Jetties	1 2 3 4 5 6 **7** 8 9 10	1 2 3 4 5 6 **7** 8 9 10	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 **7** 8 9 10	1 2 3 4 5 6 **7** 8 9 10
Breakwaters	1 2 3 4 5 6 **7** 8 9 10	1 2 3 4 5 6 **7** 8 9 10	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 **7** 8 9 10	1 2 3 4 5 6 **7** 8 9 10
Seawalls	1 2 3 4 5 6 **7** 8 9 10	1 2 3 4 5 6 **7** 8 9 10	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 **7** 8 9 10	1 2 3 4 5 6 **7** 8 9 10
Bulkheads	1 2 3 4 5 6 **7** 8 9 10	1 2 3 4 5 6 **7** 8 9 10	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 **7** 8 9 10	1 2 3 4 5 6 **7** 8 9 10
Reventments	1 2 3 4 5 6 **7** 8 9 10	1 2 3 4 5 6 **7** 8 9 10	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 **7** 8 9 10	1 2 3 4 5 6 **7** 8 9 10
Beach Nourishment	1 2 3 4 5 **6** 7 8 9 10	1 2 3 4 5 **6** 7 8 9 10	1 2 3 4 5 **6** 7 8 9 10	1 2 3 4 5 **6** 7 8 9 10	1 2 3 4 5 **6** 7 8 9 10
Vegetated Dunes	1 2 3 4 5 **6** 7 8 9 10	1 2 3 4 5 **6** 7 8 9 10	1 2 3 4 5 **6** 7 8 9 10	1 2 3 4 5 **6** 7 8 9 10	1 2 3 4 5 **6** 7 8 9 10
Living shorelines	1 2 3 **4** 5 6 7 8 9 10	1 2 3 **4** 5 6 7 8 9 10	1 2 3 **4** 5 6 7 8 9 10	1 2 3 **4** 5 6 7 8 9 10	1 2 3 **4** 5 6 7 8 9 10
Slope Cutting	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10
Other Nature based:	1 2 3 **4** 5 6 7 8 9 10	1 2 3 **4** 5 6 7 8 9 10	1 2 3 **4** 5 6 7 8 9 10	1 2 3 **4** 5 6 7 8 9 10	1 2 3 **4** 5 6 7 8 9 10
	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10

Solution Type	Construction Cost	Maintenance Cost	Maintenance Frequency	Damage Cost	Environmental Degradation Cost
Groin/Jetties	1 2 **3** 4 5 6 7 8 9 10	1 2 3 4 5 **6** 7 8 9 10	1 2 3 4 **5** 6 7 8 9 10	1 2 3 4 5 6 7 **8** 9 10	1 2 3 4 5 6 **7** 8 9 10
Breakwaters	1 2 3 4 **5** 6 7 8 9 10	1 2 3 4 5 6 **7** 8 9 10	1 2 3 4 5 6 **7** 8 9 10	1 2 3 4 5 6 **7** 8 9 10	1 2 3 4 5 **6** 7 8 9 10
Seawalls	1 2 3 4 5 6 7 8 9 **10**	1 2 3 4 5 6 7 8 9 **10**	**1** 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 **10**	1 2 3 4 5 6 7 8 9 **10**
Bulkheads	1 2 3 4 5 6 7 8 **9** 10	1 2 3 4 5 6 7 **8** 9 10	1 **2** 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 **9** 10	1 2 3 4 5 6 7 8 **9** 10
Reventments	**1** 2 3 4 5 6 7 8 9 10	1 2 **3** 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 **9** 10	1 2 3 4 5 **6** 7 8 9 10	1 2 3 4 **5** 6 7 8 9 10
Beach Nourishment	1 2 3 **4** 5 6 7 8 9 10	1 2 3 4 5 **6** 7 8 9 10	1 2 3 4 5 6 7 8 9 **10**	1 **2** 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 **8** 9 10
Vegetated Dunes	1 2 3 4 5 **6** 7 8 9 10	**1** 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 **8** 9 10	1 2 **3** 4 5 6 7 8 9 10	**1** 2 3 4 5 6 7 8 9 10
Living shorelines	1 **2** 3 4 5 6 7 8 9 10	1 **2** 3 4 5 6 7 8 9 10	1 2 3 **4** 5 6 7 8 9 10	**1** 2 3 4 5 6 7 8 9 10	1 **2** 3 4 5 6 7 8 9 10
Slope Cutting	1 2 3 4 5 6 7 **8** 9 10	1 2 3 **4** 5 6 7 8 9 10	1 2 3 4 5 **6** 7 8 9 10	1 2 3 **4** 5 6 7 8 9 10	1 2 3 **4** 5 6 7 8 9 10
Other Nature based:	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10
Wetland restoration	1 2 3 4 5 6 **7** 8 9 10	1 2 3 4 **5** 6 7 8 9 10	1 2 **3** 4 5 6 7 8 9 10	1 2 3 4 **5** 6 7 8 9 10	1 2 **3** 4 5 6 7 8 9 10
	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10

Solution Type	Construction Cost	Maintenance Cost	Maintenance Frequency	Damage Cost	Environmental Degradation Cost
Groin/Jetties	1 2 3 4 5 6 7 8 **9** 10	1 2 3 4 **5** 6 7 8 9 10	1 **2** 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 **8** 9 10	1 2 3 4 5 6 **7** 8 9 10
Breakwaters	1 2 3 4 5 6 7 8 **9** 10	1 2 3 4 **5** 6 7 8 9 10	1 **2** 3 4 5 6 7 8 9 10	1 2 3 4 5 6 **7** 8 9 10	1 2 3 4 5 6 **7** 8 9 10
Seawalls	1 2 3 4 5 6 **7** 8 9 10	1 **2** 3 4 5 6 7 8 9 10	1 **2** 3 4 5 6 7 8 9 10	1 2 3 4 5 6 **7** 8 9 10	1 2 3 4 5 6 7 8 **9** 10
Bulkheads	1 2 3 4 5 6 7 **8** 9 10	1 **2** 3 4 5 6 7 8 9 10	1 **2** 3 4 5 6 7 8 9 10	1 2 3 4 5 6 **7** 8 9 10	1 2 3 4 5 6 7 8 9 **10**
Reventments	1 2 3 4 **5** 6 7 8 9 10	1 2 **3** 4 5 6 7 8 9 10	1 **2** 3 4 5 6 7 8 9 10	1 2 3 4 5 6 **7** 8 9 10	1 2 3 4 **5** 6 7 8 9 10
Beach Nourishment	1 2 3 4 **5** 6 7 8 9 10	1 2 3 4 5 6 **7** 8 9 10	1 2 3 4 5 **6** 7 8 9 10	1 2 3 4 5 **6** 7 8 9 10	1 2 **3** 4 5 6 7 8 9 10
Vegetated Dunes	1 2 **3** 4 5 6 7 8 9 10	1 2 3 4 5 **6** 7 8 9 10	1 2 3 4 5 **6** 7 8 9 10	1 2 3 4 5 **6** 7 8 9 10	**1** 2 3 4 5 6 7 8 9 10
Living shorelines	1 **2** 3 4 5 6 7 8 9 10	1 2 3 4 5 **6** 7 8 9 10	1 2 3 **4** 5 6 7 8 9 10	1 2 3 **4** 5 6 7 8 9 10	**1** 2 3 4 5 6 7 8 9 10
Slope Cutting	1 **2** 3 4 5 6 7 8 9 10	1 2 3 4 5 **6** 7 8 9 10	1 2 **3** 4 5 6 7 8 9 10	1 2 3 **4** 5 6 7 8 9 10	1 **2** 3 4 5 6 7 8 9 10
Other Nature based:	**1** 2 3 4 5 6 7 8 9 10	1 2 3 4 5 **6** 7 8 9 10	1 2 3 4 **5** 6 7 8 9 10	1 2 3 **4** 5 6 7 8 9 10	**1** 2 3 4 5 6 7 8 9 10
	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10

Solution Type	Construction Cost	Maintenance Cost	Maintenance Frequency	Damage Cost	Environmental Degradation Cost
Groin/Jetties	1 2 3 4 5 6 7 8 9 **10**	1 2 3 4 5 6 7 8 **9** 10	1 **2** 3 4 5 6 7 8 9 10	1 2 3 4 5 **6** 7 8 9 10	1 2 3 4 5 6 7 8 **9** 10
Breakwaters	1 2 3 4 5 6 7 8 9 **10**	1 2 3 4 5 6 7 8 **9** 10	1 **2** 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 **10**	1 2 3 4 5 6 7 **8** 9 10
Seawalls	1 2 3 4 5 6 7 8 9 **10**	1 2 3 4 5 6 7 8 **9** 10	1 **2** 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 **9** 10	1 2 3 4 5 6 **7** 8 9 10
Bulkheads	1 2 3 4 5 6 7 8 **9** 10	1 2 3 4 5 6 7 8 **9** 10	1 **2** 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 **9** 10	1 2 3 4 5 6 **7** 8 9 10
Reventments	1 2 3 4 5 6 7 **8** 9 10	1 2 3 4 5 6 7 **8** 9 10	1 2 3 **4** 5 6 7 8 9 10	1 2 3 4 5 6 7 **8** 9 10	1 2 3 4 5 **6** 7 8 9 10
Beach Nourishment	1 2 3 4 5 6 7 **8** 9 10	1 2 3 4 5 6 7 **8** 9 10	1 2 3 4 5 **6** 7 8 9 10	1 2 3 4 **5** 6 7 8 9 10	1 **2** 3 4 5 6 7 8 9 10
Vegetated Dunes	1 2 3 **4** 5 6 7 8 9 10	1 2 **3** 4 5 6 7 8 9 10	1 2 3 4 5 6 **7** 8 9 10	1 **2** 3 4 5 6 7 8 9 10	**1** 2 3 4 5 6 7 8 9 10
Living shorelines	1 2 3 4 5 6 **7** 8 9 10	1 2 3 **4** 5 6 7 8 9 10	1 2 3 4 5 6 **7** 8 9 10	1 **2** 3 4 5 6 7 8 9 10	1 **2** 3 4 5 6 7 8 9 10
Slope Cutting	1 2 3 **4** 5 6 7 8 9 10	1 2 3 **4** 5 6 7 8 9 10	1 2 3 4 5 **6** 7 8 9 10	**1** 2 3 4 5 6 7 8 9 10	**1** 2 3 4 5 6 7 8 9 10
Other Nature based:	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10
Offshore Breakwater	1 2 3 4 5 6 7 **8** 9 10	1 2 3 4 5 6 **7** 8 9 10	1 2 **3** 4 5 6 7 8 9 10	1 2 3 4 **5** 6 7 8 9 10	1 2 **3** 4 5 6 7 8 9 10
Low Sill	1 2 3 4 5 **6** 7 8 9 10	1 2 3 4 **5** 6 7 8 9 10	1 2 3 **4** 5 6 7 8 9 10	1 2 **3** 4 5 6 7 8 9 10	1 **2** 3 4 5 6 7 8 9 10
Bioengineering (Locked Logs), Plantings	1 2 **3** 4 5 6 7 8 9 10	1 2 **3** 4 5 6 7 8 9 10	1 2 3 4 5 **6** 7 8 9 10	1 **2** 3 4 5 6 7 8 9 10	**1** 2 3 4 5 6 7 8 9 10
Native Shrub Plantings, live stakes	**1** 2 3 4 5 6 7 8 9 10	**1** 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 **9** 10	**1** 2 3 4 5 6 7 8 9 10	**1** 2 3 4 5 6 7 8 9 10
Green Breakwaters	1 2 3 4 5 6 7 8 9 **10**	1 2 3 4 5 6 7 8 **9** 10	1 **2** 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 **10**	1 2 3 4 5 6 **7** 8 9 10
	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10

Solution Type	Construction Cost										Maintenance Cost										Maintenance Frequency										Damage Cost										Environmental Degradation Cost									
Groin/Jetties	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10
Breakwaters	1	2	3	4	5	6	7	8	9	**10**	**1**	2	3	4	5	6	7	8	9	10	**1**	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	**7**	8	9	10	**1**	2	3	4	5	6	7	8	9	10
Seawalls	1	2	3	4	5	6	7	8	9	**10**	**1**	2	3	4	5	6	7	8	9	10	**1**	2	3	4	5	6	7	8	9	10	1	2	3	4	**5**	6	7	8	9	10	**1**	2	3	4	5	6	7	8	9	10
Bulkheads	1	2	3	4	**5**	6	7	8	9	10	**1**	2	3	4	5	6	7	8	9	10	**1**	2	3	4	5	6	7	8	9	10	1	2	3	4	**5**	6	7	8	9	10	**1**	2	3	4	5	6	7	8	9	10
Reventments	1	2	**3**	4	5	6	7	8	9	10	1	2	**3**	4	5	6	7	8	9	10	1	**2**	3	4	5	6	7	8	9	10	1	2	**3**	4	5	6	7	8	9	10	**1**	2	3	4	5	6	7	8	9	10
Beach Nourishment	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10
Vegetated Dunes	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10
Living shorelines	1	**2**	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	**9**	10	1	2	3	4	5	6	7	8	**9**	10	1	**2**	3	4	5	6	7	8	9	10	**1**	2	3	4	5	6	7	8	9	10
Slope Cutting	1	2	**3**	4	5	6	7	8	9	10	**1**	2	3	4	5	6	7	8	9	10	1	**2**	3	4	5	6	7	8	9	10	1	2	**3**	4	5	6	7	8	9	10	**1**	2	3	4	5	6	7	8	9	10
Other Nature based:	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10
	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10

Solution Type	Construction Cost										Maintenance Cost										Maintenance Frequency										Damage Cost										Environmental Degradation Cost									
Groin/Jetties	1	2	3	4	5	6	7	8	**9**	10	1	2	3	4	5	6	**7**	8	9	10	1	2	**3**	4	5	6	7	8	9	10	1	2	3	4	5	6	**7**	8	9	10	1	2	3	4	5	6	**7**	8	9	10
Breakwaters	1	2	3	4	5	6	7	8	9	**10**	1	2	3	4	5	6	7	**8**	9	10	1	2	**3**	4	5	6	7	8	9	10	1	2	3	4	5	6	7	**8**	9	10	1	2	3	4	5	6	**7**	8	9	10
Seawalls	1	2	3	4	5	6	7	8	9	**10**	1	2	3	4	5	6	7	**8**	9	10	1	2	**3**	4	5	6	7	8	9	10	1	2	3	4	5	6	7	**8**	9	10	1	2	3	4	5	6	**7**	8	9	10
Bulkheads	1	2	3	4	5	6	7	8	**9**	10	1	2	3	4	5	6	**7**	8	9	10	1	2	3	**4**	5	6	7	8	9	10	1	2	3	4	5	6	**7**	8	9	10	1	2	3	4	5	6	7	8	**9**	10
Reventments	1	2	3	4	5	6	7	**8**	9	10	1	2	3	4	**5**	6	7	8	9	10	1	2	**3**	4	5	6	7	8	9	10	1	2	3	4	5	6	**7**	8	9	10	1	2	3	4	5	6	7	**8**	9	10
Beach Nourishment	1	2	3	4	5	6	7	8	**9**	10	1	2	3	4	5	6	7	8	**9**	10	**1**	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	**8**	9	10	1	2	3	4	5	**6**	7	8	9	10
Vegetated Dunes	1	2	3	4	**5**	6	7	8	9	10	1	2	**3**	4	5	6	7	8	9	10	1	2	3	4	**5**	6	7	8	9	10	1	2	3	**4**	5	6	7	8	9	10	**1**	2	3	4	5	6	7	8	9	10
Living shorelines	1	2	3	4	**5**	6	7	8	9	10	1	2	3	**4**	5	6	7	8	9	10	1	2	3	4	5	6	7	**8**	9	10	1	2	3	4	**5**	6	7	8	9	10	**1**	2	3	4	5	6	7	8	9	10
Slope Cutting	1	2	3	4	**5**	6	7	8	9	10	1	2	**3**	4	5	6	7	8	9	10	1	2	3	4	5	6	7	**8**	9	10	1	2	**3**	4	5	6	7	8	9	10	1	2	**3**	4	5	6	7	8	9	10
Other Nature based:	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10
	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10

Solution Type	Construction Cost										Maintenance Cost										Maintenance Frequency										Damage Cost										Environmental Degradation Cost									
Groin/Jetties	1	2	3	4	**5**	6	7	8	9	10	1	2	3	**4**	5	6	7	8	9	10	1	2	3	4	**5**	6	7	8	9	10	1	2	3	4	5	6	7	**8**	9	10	1	2	3	4	5	6	**7**	8	9	10
Breakwater	1	2	3	4	5	6	7	8	**9**	10	1	2	3	4	**5**	6	7	8	9	10	1	2	3	4	**5**	6	7	8	9	10	1	2	3	4	5	6	7	**8**	9	10	1	2	3	**4**	5	6	7	8	9	10
Seawall	1	2	3	4	5	6	**7**	8	9	10	1	2	3	4	5	**6**	7	8	9	10	1	2	**3**	4	5	6	7	8	9	10	1	2	3	4	5	6	7	**8**	9	10	1	2	3	4	5	6	7	8	**9**	10
Bulkhead	1	2	3	4	5	6	**7**	8	9	10	1	2	3	4	**5**	6	7	8	9	10	1	2	**3**	4	5	6	7	8	9	10	1	2	3	4	5	6	7	**8**	9	10	1	2	3	4	5	6	7	8	**9**	10
Reventment	1	2	3	4	5	6	7	**8**	9	10	1	2	3	4	**5**	6	7	8	9	10	1	2	**3**	4	5	6	7	8	9	10	1	2	3	4	5	6	7	**8**	9	10	1	2	3	4	5	6	**7**	8	9	10
Beach Nourishment	1	2	3	4	5	6	7	8	9	**10**	1	2	3	4	5	6	7	8	**9**	10	1	2	3	4	**5**	6	7	8	9	10	1	2	3	4	5	6	7	**8**	9	10	1	2	3	4	5	6	7	8	**9**	10
Vegetated Dunes	1	2	3	4	**5**	6	7	8	9	10	1	2	**3**	4	5	6	7	8	9	10	1	2	3	**4**	5	6	7	8	9	10	1	2	3	**4**	5	6	7	8	9	10	**1**	2	3	4	5	6	7	8	9	10
Living shoreline	1	2	3	4	5	**6**	7	8	9	10	1	2	**3**	4	5	6	7	8	9	10	1	2	3	**4**	5	6	7	8	9	10	1	2	3	**4**	5	6	7	8	9	10	**1**	2	3	4	5	6	7	8	9	10
Slope Cutting	1	2	3	**4**	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10
Other Nature based:	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10
	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10

Solution Type	Construction Cost										Maintenance Cost										Maintenance Frequency										Damage Cost										Environmental Degradation Cost									
Groin/Jetties	1	2	3	4	**5**	6	7	8	9	10	1	2	**3**	4	5	6	7	8	9	10	**1**	2	3	4	5	6	7	8	9	10	1	2	3	4	**5**	6	7	8	9	10	1	**2**	3	4	5	6	7	8	9	10
Breakwaters	1	2	3	4	**5**	6	7	8	9	10	1	2	**3**	4	5	6	7	8	9	10	**1**	2	3	4	5	6	7	8	9	10	1	2	3	4	**5**	6	7	8	9	10	1	**2**	3	4	5	6	7	8	9	10
Seawalls	1	2	3	4	5	6	7	8	9	**10**	1	2	3	4	**5**	6	7	8	9	10	1	2	**3**	4	5	6	7	8	9	10	1	2	3	4	5	6	7	**8**	9	10	1	2	3	4	5	6	7	8	**9**	10
Bulkheads	1	2	3	4	5	6	**7**	8	9	10	1	2	**3**	4	5	6	7	8	9	10	1	**2**	3	4	5	6	7	8	9	10	1	2	3	4	5	6	**7**	8	9	10	1	2	3	4	5	6	7	8	**9**	10
Reventments	1	2	3	**4**	5	6	7	8	9	10	**1**	2	3	4	5	6	7	8	9	10	**1**	2	3	4	5	6	7	8	9	10	1	2	3	**4**	5	6	7	8	9	10	**1**	2	3	4	5	6	7	8	9	10
Beach Nourishment	1	2	3	4	**5**	6	7	8	9	10	1	2	3	4	**5**	6	7	8	9	10	1	2	3	**4**	5	6	7	8	9	10	**1**	2	3	4	5	6	7	8	9	10	**1**	2	3	4	5	6	7	8	9	10
Vegetated Dunes	1	2	3	**4**	5	6	7	8	9	10	**1**	2	3	4	5	6	7	8	9	10	**1**	2	3	4	5	6	7	8	9	10	**1**	2	3	4	5	6	7	8	9	10	**1**	2	3	4	5	6	7	8	9	10
Living shorelines	1	2	3	4	**5**	6	7	8	9	10	**1**	2	3	4	5	6	7	8	9	10	1	**2**	3	4	5	6	7	8	9	10	1	**2**	3	4	5	6	7	8	9	10	**1**	2	3	4	5	6	7	8	9	10
Slope Cutting	1	**2**	3	4	5	6	7	8	9	10	**1**	2	3	4	5	6	7	8	9	10	**1**	2	3	4	5	6	7	8	9	10	1	**2**	3	4	5	6	7	8	9	10	**1**	2	3	4	5	6	7	8	9	10
Other Nature based:	1	2	3	4	**5**	6	7	8	9	10	**1**	2	3	4	5	6	7	8	9	10	**1**	2	3	4	5	6	7	8	9	10	1	**2**	3	4	5	6	7	8	9	10	**1**	2	3	4	5	6	7	8	9	10
	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10

Solution Type	Construction Cost	Maintenance Cost	Maintenance Frequency	Damage Cost	Environmental Degradation Cost
Groin/Jetties	1 2 3 4 5 6 7 **8** 9 10	1 2 3 4 5 6 **7** 8 9 10	1 2 3 **4** 5 6 7 8 9 10	1 2 3 4 5 6 7 **8** 9 10	1 2 3 4 5 6 7 8 **9** 10
Breakwaters	1 2 3 4 5 6 7 8 **9** 10	1 **2** 3 4 5 6 7 8 9 10	**1** 2 3 4 5 6 7 8 9 10	1 2 3 4 **5** 6 7 8 9 10	1 2 3 4 **5** 6 7 8 9 10
Seawalls	1 2 3 4 5 6 7 8 9 **10**	1 2 3 4 5 **6** 7 8 9 10	1 2 3 **4** 5 6 7 8 9 10	1 2 3 4 5 6 7 8 **9** 10	1 2 3 4 5 6 7 8 9 **10**
Bulkheads	1 2 3 4 5 6 7 8 9 **10**	1 2 3 4 **5** 6 7 8 9 10	1 2 **3** 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 **10**	1 2 3 4 5 6 7 8 9 **10**
Reventments	1 2 3 4 5 6 7 8 **9** 10	1 2 **3** 4 5 6 7 8 9 10	1 2 **3** 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 **10**	1 2 3 4 5 6 7 8 **9** 10
Beach Nourishment	1 2 3 4 5 6 **7** 8 9 10	1 **2** 3 4 5 6 7 8 9 10	1 **2** 3 4 5 6 7 8 9 10	1 2 **3** 4 5 6 7 8 9 10	**1** 2 3 4 5 6 7 8 9 10
Vegetated Dunes	1 2 3 **4** 5 6 7 8 9 10	1 **2** 3 4 5 6 7 8 9 10	1 **2** 3 4 5 6 7 8 9 10	1 **2** 3 4 5 6 7 8 9 10	**1** 2 3 4 5 6 7 8 9 10
Living shorelines	1 2 3 4 5 6 7 **8** 9 10	1 2 3 **4** 5 6 7 8 9 10	1 2 **3** 4 5 6 7 8 9 10	1 2 **3** 4 5 6 7 8 9 10	**1** 2 3 4 5 6 7 8 9 10
Slope Cutting	1 2 3 4 5 **6** 7 8 9 10	**1** 2 3 4 5 6 7 8 9 10	**1** 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 **8** 9 10	1 **2** 3 4 5 6 7 8 9 10
Other Nature based:	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10
	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10

Solution Type	Construction Cost	Maintenance Cost	Maintenance Frequency	Damage Cost	Environmental Degradation Cost
Groin/Jetties	1 2 3 4 5 **6** 7 8 9 10	1 2 3 4 5 **6** 7 8 9 10	1 2 **3** 4 5 6 7 8 9 10	1 2 3 4 5 **6** 7 8 9 10	1 2 3 4 5 6 **7** 8 9 10
Breakwaters	1 2 3 4 5 6 **7** 8 9 10	1 2 3 4 5 **6** 7 8 9 10	1 2 3 4 **5** 6 7 8 9 10	1 2 3 4 5 **6** 7 8 9 10	1 2 3 4 5 6 **7** 8 9 10
Seawalls	1 2 3 4 5 **6** 7 8 9 10	1 2 3 4 5 **6** 7 8 9 10	1 2 **3** 4 5 6 7 8 9 10	1 2 3 4 5 **6** 7 8 9 10	1 2 3 4 5 6 **7** 8 9 10
Bulkheads	1 2 3 4 5 **6** 7 8 9 10	1 2 3 4 5 **6** 7 8 9 10	1 2 **3** 4 5 6 7 8 9 10	1 2 3 4 5 **6** 7 8 9 10	1 2 3 4 5 6 **7** 8 9 10
Reventments	1 2 3 4 5 **6** 7 8 9 10	1 2 3 4 5 **6** 7 8 9 10	1 2 **3** 4 5 6 7 8 9 10	1 2 3 4 5 **6** 7 8 9 10	1 2 3 4 5 6 **7** 8 9 10
Beach Nourishment	1 2 3 4 5 6 7 **8** **9** 10	1 2 3 4 5 6 7 **8** 9 10	1 2 3 4 5 **6** 7 8 9 10	1 **2** 3 4 5 6 7 8 9 10	**1** 2 3 4 5 6 7 8 9 10
Vegetated Dunes	1 2 3 4 **5** **6** **7** 8 9 10	1 **2** 3 4 5 6 7 8 9 10	1 2 3 **4** 5 6 7 8 9 10	1 **2** 3 4 5 6 7 8 9 10	**1** 2 3 4 5 6 7 8 9 10
Living shorelines	1 2 3 **4** **5** **6** 7 8 9 10	1 2 **3** 4 5 6 7 8 9 10	1 **2** 3 4 5 6 7 8 9 10	1 **2** 3 4 5 6 7 8 9 10	**1** 2 3 4 5 6 7 8 9 10
Slope Cutting	1 2 3 4 **5** 6 7 8 9 10	1 2 3 **4** 5 6 7 8 9 10	1 2 3 4 5 **6** 7 8 9 10	1 2 3 **4** **5** 6 7 8 9 10	1 2 **3** 4 5 6 7 8 9 10
Other Nature based:	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10
	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10

Solution Type	Construction Cost	Maintenance Cost	Maintenance Frequency	Damage Cost	Environmental Degradation Cost
Groin/Jetties	1 2 3 4 5 6 7 8 9 **10**	**1** 2 3 4 5 6 7 8 9 10	**1** 2 3 4 5 6 7 8 9 10	1 **2** 3 4 5 6 7 8 9 10	1 2 3 4 **5** 6 7 8 9 10
Breakwaters	1 2 3 4 5 6 7 8 9 **10**	**1** 2 3 4 5 6 7 8 9 10	**1** 2 3 4 5 6 7 8 9 10	1 **2** 3 4 5 6 7 8 9 10	1 2 3 4 **5** 6 7 8 9 10
Seawalls	1 2 3 4 5 6 7 8 9 **10**	**1** 2 3 4 5 6 7 8 9 10	**1** 2 3 4 5 6 7 8 9 10	1 **2** 3 4 5 6 7 8 9 10	1 2 3 4 **5** 6 7 8 9 10
Bulkheads	1 2 3 4 5 6 7 8 **9** 10	**1** 2 3 4 5 6 7 8 9 10	**1** 2 3 4 5 6 7 8 9 10	1 **2** 3 4 5 6 7 8 9 10	1 2 3 4 **5** 6 7 8 9 10
Reventments	1 2 3 4 5 6 7 **8** 9 10	**1** 2 3 4 5 6 7 8 9 10	**1** 2 3 4 5 6 7 8 9 10	1 **2** 3 4 5 6 7 8 9 10	1 2 3 4 **5** 6 7 8 9 10
Beach Nourishment	1 2 **3** 4 5 6 7 8 9 10	1 2 3 4 5 **6** 7 8 9 10	1 2 3 4 5 6 **7** 8 9 10	1 **2** 3 4 5 6 7 8 9 10	**1** 2 3 4 5 6 7 8 9 10
Vegetated Dunes	1 2 **3** 4 5 6 7 8 9 10	1 2 3 4 5 **6** 7 8 9 10	1 2 3 4 5 6 **7** 8 9 10	1 **2** 3 4 5 6 7 8 9 10	**1** 2 3 4 5 6 7 8 9 10
Living shorelines	1 2 **3** 4 5 6 7 8 9 10	1 2 3 4 5 **6** 7 8 9 10	1 2 3 4 5 6 **7** 8 9 10	1 **2** 3 4 5 6 7 8 9 10	**1** 2 3 4 5 6 7 8 9 10
Slope Cutting	1 2 3 **4** 5 6 7 8 9 10	1 2 3 4 **5** 6 7 8 9 10	1 2 3 4 5 6 **7** 8 9 10	1 2 3 4 5 **6** 7 8 9 10	1 2 3 **4** 5 6 7 8 9 10
Other Nature based:	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10
	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10

Solution Type	Construction Cost	Maintenance Cost	Maintenance Frequency	Damage Cost	Environmental Degradation Cost
Groin/Jetties	1 2 3 4 5 6 7 **8** 9 10	1 2 **3** 4 5 6 7 8 9 10	1 2 **3** 4 5 6 7 8 9 10	1 2 3 4 5 6 7 **8** 9 10	1 2 3 4 **5** 6 7 8 9 10
Breakwaters	1 2 3 4 5 6 7 **8** 9 10	1 2 **3** 4 5 6 7 8 9 10	1 2 **3** 4 5 6 7 8 9 10	1 2 3 4 5 6 7 **8** 9 10	1 2 3 4 **5** 6 7 8 9 10
Seawalls	1 2 3 4 5 6 7 8 9 **10**	1 2 **3** 4 5 6 7 8 9 10	1 2 **3** 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 **10**	1 2 3 4 5 **6** 7 8 9 10
Bulkheads	1 2 3 4 5 6 7 8 9 **10**	1 2 **3** 4 5 6 7 8 9 10	1 2 **3** 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 **10**	1 2 3 4 5 **6** 7 8 9 10
Reventments	1 2 3 4 5 6 7 **8** 9 10	**1** 2 3 4 5 6 7 8 9 10	1 2 **3** 4 5 6 7 8 9 10	1 2 3 4 5 6 7 **8** 9 10	1 2 3 4 5 **6** 7 8 9 10
Beach Nourishment	1 2 3 4 5 6 7 **8** 9 10	1 2 3 4 5 6 7 **8** 9 10	1 2 3 4 5 6 7 **8** 9 10	1 2 3 4 5 6 7 **8** 9 10	1 2 3 4 5 6 **7** 8 9 10
Vegetated Dunes	**1** 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 **8** 9 10	1 2 3 4 5 6 7 8 **9** 10	1 2 3 **4** 5 6 7 8 9 10	1 2 3 4 **5** 6 7 8 9 10
Living shorelines	1 **2** 3 4 5 6 7 8 9 10	1 2 3 4 5 6 **7** 8 9 10	1 2 3 4 5 6 7 8 **9** 10	1 2 3 **4** 5 6 7 8 9 10	1 2 3 4 **5** 6 7 8 9 10
Slope Cutting	1 2 3 4 5 **6** 7 8 9 10	1 2 3 4 5 **6** 7 8 9 10	1 2 3 4 5 **6** 7 8 9 10	1 2 3 4 5 6 **7** 8 9 10	1 2 3 4 5 6 7 **8** 9 10
Other Nature based:	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10
	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10