

White Paper: Nature-Based Solutions for Coastal Highway Resilience



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16. Abstract This white paper serves as input to an upcoming round of regional peer exchanges on nature-based solutions, and constitutes an incremental step toward developing an implementation guide for using nature-based solutions to improve the resilience of coastal highways to extreme events and sea level rise. Nature-based solutions include a spectrum of natural and nature-based features that serve as alternatives to, or ecological enhancements of, traditional shoreline stabilization and infrastructure protection techniques. In this case, the ability of nature-based solutions to mitigate storm surge flooding, wave-related damage, erosion, shoreline retreat, and the potential impacts of sea level rise is of interest. While nature-based solutions have been used extensively across a diverse array of coastal settings, they are not commonly deployed within the transportation sector. In some cases, understanding of the engineering tools and methods for designing nature-based solutions to achieve a specific outcome is lacking. This white paper addresses these issues by providing examples of nature-based solutions and highlighting the best available science that describes their performance as solutions for coastal highways' resilience. The implementation guide will be informed by the peer exchanges and will address the issues outlined here for the use of nature-based solutions.					
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1 Introduction and Overview

Natural systems play an important role in protecting built infrastructure along the coast. Healthy beaches, dunes, wetlands and other natural coastal ecosystems reduce the extreme forces of coastal storms. Thus, nature itself is a ‘model’ for coastal engineering resilience.

This white paper briefly describes the current state of practice regarding the use of nature-based coastal solutions in general and with specific emphasis on their use along coastal highways. It provides an overview of available tools for design, implementation challenges, and knowledge gaps.

This white paper is an initial attempt to frame the conversation about using nature-based solutions to improve coastal highway resilience. It was developed as part of an FHWA research effort and will be used to focus the discussion at a series of upcoming peer exchanges around the country on this topic. An implementation guide for nature-based solutions for coastal highways will then be developed.

1.1 Introduction to Nature-Based Solutions to Coastal Highway Protection

Many terms describe similar fundamental concepts:

- *Nature-based solutions*
- *Coastal green infrastructure*
- *Nature-based infrastructure*
- *Living shorelines*
- *Natural and nature-based features*
- *Engineering With Nature (EWN)*
- *Building with Nature (BwN)*
- *Working with Nature (WwN)*

(Bridges et al., 2014; NOAA, 2015; RAE, 2015; Borsje et al., 2017).

Nature-based solutions are approaches to problems (in this case, to coastal highway flood damage and/or disruption) which mimic characteristics of natural features, including habitats, but are created by human design, engineering, and construction. A wide variety of terminology describes similar approaches, some of which are listed at left. The common thread connecting these approaches is the desire to protect or improve the built environment while maximizing the habitat value associated with the natural system.

Because they address a specific ecological or ecosystem function, nature-based solutions are site-specific and scenario-specific applications that require a cross-section of expertise drawing on the fields of coastal ecology, coastal geology, coastal oceanography, and coastal engineering.

1.2 Conventional Engineering Approaches to Coastal Highway Protection

Conventional coastal highway protection includes walls, seawalls, bulkheads, and revetments. Unfortunately, the function of many of our shorelines has been significantly altered because of the interaction of these protection strategies with natural processes. The results include reductions in sediment transport and the loss of intertidal habitats of wetlands and beaches among others (Douglass and Pickel, 1999).

1.3 Hybrid Approaches to Coastal Highway Protection

Modern coastal engineering solutions to coastal highway protection often combine nature-based components with engineered structures. Examples of these so-called “hybrid approaches” include:

- Pocket beaches with headland breakwaters to stabilize the shoreline, and
- Marshes protected by rock or timber sills or breakwaters to attenuate wave energy.

In this white paper, “coastal highways” is a general term that refers to roads and bridges found in coastal settings (defined as coastal areas where hazards like storm surge, waves, and erosion can cause damage).

In some cases, like seawalls buried below sand dunes or beaches, engineered structures are used in combination with nature-based features for the express purpose of storm damage reduction. Under normal conditions, the structure serves no purpose and may not be seen. But in storm conditions, the structure serves to reduce erosion, limit flooding, or attenuate wave energy.

1.4 General Cost Information

The costs of nature-based solutions can be categorized in terms of a shoreline’s exposure to wave energy (VIMS, 2005). Non-structural methods, including bank regrading and planting vegetation, used for low-wave-energy shorelines (i.e., fetch < 1 mile) may cost \$100 to \$200 per linear foot. Hybrid projects that combine natural features with a structure, used in medium energy environments (i.e., fetch 1 to 4 miles), may range in cost from \$100 to \$500 or more per linear foot. Along high energy shorelines (i.e., fetch > 2 miles), structural solutions like bulkheads, revetments, or large breakwaters, may cost \$600 to \$1,200 or more per linear foot. While these general rules of thumb are informative, costs can vary substantially based on setting, method of construction, site accessibility, availability of experienced contractors, and the nature of the permitting requirements. A better understanding of the costs of nature-based solutions in transportation settings is needed.

2 The Role of Nature Based Solutions in Coastal Highway Resilience

2.1 National Extent of Coastal Highway and Bridge Vulnerability

Current literature does not provide an estimate of the total national potential for using nature-based solutions for coastal highway resilience. Today, over 14 percent of the U.S. coastline has been armored, with that amount being as high as 75 percent in some coastal counties (Gittman et al., 2015). Along armored shorelines, an estimated 60,000 U.S. highway miles and 1,000 bridges are vulnerable to coastal storm hazards with present sea levels (FWHA 2008; Webb and Matthews 2014). Some of these roads and bridges already benefit from additional protection or resilience afforded by natural systems and some fraction of the rest are potential candidates for nature-based solutions. However, determining the extent of coastal roadway miles that are candidates for nature-based solutions would require development of an acceptable methodology. At this time, this is a knowledge gap.

2.2 Primary Coastal Hazards and Resources

The primary coastal hazards of interest for nature-based solutions are storm surge, waves, sea level rise, and erosion. These processes are described more fully in HEC-25 (2nd ed.) and HEC-25: Volume 2. Waves are a primary force in many coastal engineering designs. Sea level rise will progressively make some coastal highways more vulnerable to damage (e.g., more exposed to wave action) and disruption (e.g., regular flooding during high tide).

FHWA and other federal agencies have numerous existing resources that summarize the relevant coastal science. Three publications of particular note are:

- [FHWA's Hydraulic Engineering Circular \(HEC\) 25 Volume 2 Highways in the Coastal Environment: Assessing Extreme Events](#): FHWA guidance on estimating relative sea level rise in Section 2.3.1 (FHWA, 2014)
- [NOAA NOS CO-OPS Technical Report 83: Global and Regional Sea Level Rise Scenarios for the United States](#): Relative sea level rise, with probabilities, at all U.S. locations, for scenarios encompassing all the scientifically plausible ranges (Sweet et al., 2017)
- [USGCRP \(2017\) Climate Science Special Report: Fourth National Climate Assessment, Volume I](#): Most recent overall climate science summary assessment which includes the sea level rise scenarios of Sweet et al. (2017)

3 Examples and Lessons Learned from Nature-Based Solutions in the Coastal Environment

3.1 Examples of Successful Projects

3.1.1 Pocket Beach – Yorktown, VA

Along Water Street in Yorktown, VA (37.2370°N 76.5068°W), clean sand fill and rock breakwaters were used to establish a series of pocket beaches—beaches stabilized by artificial or natural headlands. The project provides protection to approximately 0.3 miles of coastal highway along the York River and also serves as a recreational amenity for the Yorktown waterfront. This shoreline is exposed to an average fetch of 10 miles across the mouth of the York River and experiences wave energy from across Chesapeake Bay with a maximum fetch totaling 30 miles. Examples of the shorelines before and many years after construction are shown in Figure 1.

The County of York was the project's primary sponsor and the project was completed as part of an historic waterfront revitalization in conjunction with the Virginia Board on Conservation of Public Beaches. The Virginia DOT participated in the project formulation and provided funding proportional to the extent of the state maintained highway mileage which was previously exposed at the east (right in Figure 1) end of the project.

The first three breakwaters and sand beach fill were constructed in September 1994 and the rest were added over the next 10 years as the success of the initial project became clear. The original breakwaters, 7,500 cubic yards of beach fill, and planted *Spartina alterniflora* and *Spartina patens* cost \$260,000 for protection of 1,350 feet of shoreline for an average cost of \$193 per linear foot (Milligan et al., 1996). The project was designed for a 50-year storm but its level of performance currently exceeds the 100-year storm. It was subjected to the 100-year storm event in Hurricane

Isabel (2003) and the system experienced sand losses and local scour but maintained its overall integrity with no damage to the breakwater units themselves. The beach required only the placement of 3,500 cubic yards of sand to be brought back to its pre-storm condition (Milligan et al., 2005).

The project has performed well by providing protection to the road, and the infrastructure behind the road, while also providing a sandy beach for tourists and locals for over two decades. The beach and vegetation provide intertidal habitat and shore bird habitat. Aside from flooding of Water Street during storms, which has been mitigated by a raised stone wall running parallel to the sidewalk, the road and sidewalks have not sustained damage from coastal storms (Milligan et al., 1996).



Figure 1. Pocket beaches along Water Street in Yorktown, VA (top panel, 1994; bottom panel, 2016).

3.1.2 Marsh with Breakwaters – Holts Landing, DE

An eroding sandy shoreline at Holts Landing State Park, along Indian River Bay in Delaware (38.5917°N 75.1279°W) was stabilized using a constructed saltwater marsh and offshore segmented breakwaters. Although this project does not protect a highway, it is a good example of a successful, engineered, hybrid marsh creation project and could be an appropriate nature-based strategy along some coastal highways. The erosion was threatening a small boat (kayak) launch and small recreational beach.

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In 2005, the State of Delaware, Division of Parks and Recreation, Department of Natural Resources and Environmental Control (DNREC) built the offshore breakwaters in lieu of a bulkhead with the goal of creating wetland habitat while stabilizing the shoreline. The project protects approximately 1,000 feet of intertidal shoreline located 4 miles southwest of the Indian River Inlet. The offshore segmented breakwaters also attenuate wave energy when wind blows along the fetches, which vary from 2 miles to 4 miles. Pre- and post-construction photos are shown in Figure 2.



Figure 2. A series of offshore segmented breakwaters are used to attenuate wave energy to protect a constructed saltmarsh at Holts Landing, DE (top panel, 1992; bottom panel, 2017).

Today over a half-acre of productive wetland lies in the lee of the breakwaters with a significant amount of wetland/open water edge. It is considered capable of providing 50-year storm protection with significant function remaining in less frequent storms. This durability is due to the general nature of rock breakwater resilience and the reduced wave loads in extremely high storm surges. Maintenance and repair cost information is not known for this project.

This project has performed exceptionally well in successfully stabilizing the shoreline, protecting the kayak launch and small sandy beach, and creating productive wetland habitat for over a decade.

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3.1.3 Other Examples – Coastal Highways

Other examples of nature-based solutions which have successfully solved coastal highway problems are listed in Table 1. Some additional information for each of those examples is also provided in the text below. Coordinates for these examples are provided in the table so the reader can use software like Google Earth or Google Maps to develop a better understanding of the project and surrounding area. Using Google Earth’s timeline tool allows the user to see the project performance over time.

Table 1. Other examples of nature-based solutions protecting coastal highways.

Location	Coordinates	Asset	Strategy
Cape Lookout State Park, OR	45.363°N, 123.971°W	Campground	Cobble Berm and Artificial Dune
Holly Beach, LA	29.767°N, 93.514°W	Louisiana 82	Beach Nourishment with Breakwaters
Pensacola, FL	30.417°N, 87.196°W	Bayfront Pkwy, US 98	Marsh Creation with Breakwaters
Delray Beach, FL	26.458°N, 80.059°W	Florida A1A	Beach Nourishment
Buxton, NC	35.270°N, 75.519°W	North Carolina 12	Constructed Dune and Road Relocation
Gloucester Point, VA	37.246°N, 76.503°W	Greate Road	Beach Nourishment
Presque Isle State Park, PA	42.132°N 80.146°W	Peninsula Drive	Beach Nourishment with Breakwaters
Great Egg Harbor Bay, NJ	39.300° N, 74.592°W	New Jersey 52	Marsh Restoration

- A cobble beach berm and artificial dune were constructed to serve as natural protective features in response to damage to the **Cape Lookout State Park** campground and facilities in Tillamook, Oregon. The project was constructed in 2000 at a cost of \$125,000. The cobble berm, acting like a dynamic revetment, requires regular maintenance but has performed well (ODOT, 2017).
- The **Holly Beach, LA** project protects a long stretch of coast parallel highway and is built on several generations of failed State DOT revetments constructed to protect the road from shoreline recession (erosion) and the subsequent loss of adjacent wetlands. Between 1991 and 1995 the Louisiana Department of Natural Resources partnered with the State DOT to construct 85 breakwaters. A large nourishment of sand was added in 2003 along 5.3 miles of shoreline (CPRA, 2011). In the 27 years preceding construction of the breakwaters (1963-1990), an average of \$600,000 per year was spent on repairs and protection of the roadway and embankment (LADNR, 1997). Costs for breakwater and shoreline stabilization efforts between 1991 and 1995 were not found, but a 1997 feasibility study describes an effort to enhance the

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breakwaters and beach, by nourishment, at an estimated cost of nearly \$24 million (*ibid*). For reference, the estimated cost of a Galveston-type seawall was \$84 million.

- In **Pensacola, FL**, “**Project GreenShores**,” a constructed marsh with breakwaters designed to create habitat, provides some protection to the nearly 0.5-mile section of coastal parallel highway embankment. It is highly visible from a major urban coastal highway and bridge thus enhancing the aesthetics of the area. The habitat restoration project has been funded by more than \$2.5 million in grants from various agencies, but started with an initial grant of \$150,000 given by Gulf Power to the Florida Department of Environmental Protection.
- The **Delray Beach, FL** beach nourishment is notable because it has performed exceptionally well for over 40 years (initially built in 1973 and renourished five times). It survived several major hurricanes and the level of protection is somewhere beyond the 25-year storm. Although the beach nourishment project was funded by the municipality as a community amenity, it relieved the State DOT from the need to protect the state highway by replacing a failed interlocking block revetment/seawall, built by the DOT in 1970, which is buried by the beach nourishment. The annualized nourishment program costs \$980,000 (CP&E, 1991) with a resulting 10.4 benefit to cost ratio, according to a 1996 publication by Beachler and Mann (1996).
- In **Buxton, NC** the State DOT has intentionally built portions of the coastal highway behind large, constructed sand dunes to protect it from damage in hurricane overwash events. This project was part of a larger effort to replace or repair roads damaged during Hurricanes Bonnie and Dennis. The 3,500 feet of roadway relocation cost was \$450,000, or just less than \$129 per linear foot of roadway (WRAL, 2018).
- The beach nourishment protecting a public parking lot and Greate Road in **Gloucester Point, VA** from storms and shoreline recession is stabilized by structures at both ends of the project.
- The **Presque Isle, PA** hybrid project on Lake Erie uses sand with 55 offshore segmented breakwaters constructed to protect a road from recession (erosion) along 6 miles of lake-front shoreline. The cost of construction was less than \$30 million and the fully inflated 50-year project cost, including beach nourishment, is estimated at \$150 million (Pilkey, 2012). The annualized project cost is less than \$95 per linear foot of shoreline per year.
- The **Great Egg Harbor Bay, NJ** project is a marsh shoreline stabilization project which was part of improvements to the primary access road to Ocean City. The state environmental protection agency requested that New Jersey DOT install shoreline protection wherever existing tidal channels were being realigned or where marsh shorelines would be exposed to boat wakes for the first time as a result of the larger improvements. More information about this project is found in Traylor (2017).

3.2 Lessons Learned from Prior Projects

The primary lesson learned from prior projects is that man-made marshes and beaches can protect coastal highways. It is likely that the same is true for other habitats like reefs, mangroves, and forests near highways (but this document does not identify any specific known cases). Some of these nature-based solutions have worked for decades at providing both infrastructure protection and habitat value more typical of the natural shoreline than of a seawall or bulkhead.

A common theme reiterated in many nature-based projects is the importance of monitoring so as to plan for adaptive management. Monitoring allows the project performance to be assessed over time. If and when a problem is identified, it can be addressed through adaptive management which usually takes the form of some type of project modification or repair.

Describing project challenges, and their solutions, is an important component of improving the overall success and reliability of nature-based solutions. Some other relevant lessons learned are briefly presented here across four general themes: structure design, selection of materials, addressing ecological needs, and accommodating coastal processes.

3.2.1 Inappropriate Structure Design

In a hybrid approach, some form of structure is used to attenuate waves and/or stabilize shorelines when nature-based methods are used in medium-to-high energy wave environments (e.g., fetch greater than 1 mile, as per Hardaway and Byrne, 1999). Examples of such structures include traditional rock breakwaters or sills, timber structures, or complex habitat-type devices. The size, characteristics, and location of the structure must be designed to meet the project objectives. Common mistakes include:

- Under- or over-designing structures for their intended application;
- Using non-traditional structures (e.g., alternatives to rock breakwaters) whose performance is not well understood;
- Placing structures in locations that may actually exacerbate shoreline erosion; and
- Unintended or anticipated adverse effects.

Most marsh erosion occurs under non-storm conditions, with about 1 percent occurring during extreme events (Leonardi et al., 2016). Therefore, a structure designed to protect a coastal marsh (and behind that, a coastal roadway) should address the water level and wave conditions that occur the majority of the time, not necessarily those associated with extreme events that occur infrequently.

Understanding how effective a structure is in reducing wave heights is critical for achieving an appropriate design. Use of non-traditional structures, including proprietary devices and systems focused on habitat benefits, which lack performance data and design equations has led to poor project performance, in terms of shoreline stabilization, in some cases.

Finally, anticipating the potential consequences that a structure has on the ecosystem is key to ensuring positive outcomes. For example, structures that overly restrict tidal circulation, impair

the movement of finfish and shellfish, redirect wave energy to adjacent shorelines, or exacerbate storm flooding behind them should be avoided.

3.2.2 Inappropriate Selection of Materials

Inappropriate selection and use of materials also translates to poor project performance. Examples include:

- Using inappropriate vegetation;
- Using inappropriate fill material for marsh, beach, or dune establishment;
- Placing vegetation at inappropriate tidal elevations; and
- Using loose or under-sized materials that may shift under typical wave conditions.

Marsh restoration and bank restoration projects should always use native, local vegetation planted at the appropriate elevation. While most natural marshes are underlain with extremely fine soils (due to many years of detritus), constructed marshes can thrive in sands, which are much more resistant to currents and waves, since nutrients arrive via the water column.

The use of loose substrate (e.g., oyster shell), coir fiber logs, and woody debris has not performed well when exposed to wave action. For example, loose oyster shell substrate tends to degrade over time due to scatter and abrasion. Abrasion from wave action can potentially limit the successful attachment and growth of juvenile oysters and other shellfish. Coir fiber logs may fail due to abrasion of the encapsulating netting against the stakes and strapping used to secure them to the ground. Also, loose woody debris becomes buoyant when submerged and is easily transported by waves.

3.2.3 Failure to Address Ecological Needs

Since nature-based solutions mimic the natural ecological and physical functions of a shoreline, habitat, or marine system, site-specific design for intended outcomes and desired co-benefits is critical. Some relevant examples of strategies that can result in failure to address ecological needs are:

- The selection and use of inadequate fill material for shorelines and marshes leading to poor ecological function and reduced physical performance;
- The improper selection and use of vegetation, particularly with respect to ecological setting and elevation;
- The overuse and improper placement of structures in hybrid approaches limiting tidal connectivity of the marsh;
- Designing an artificial reef without the appropriate tidal or wave exposure to support the target species; and

The timing of vegetation plantings, particularly marsh plants, should be scheduled based on the local growing seasons... which may not coincide with a particular phase of the project schedule.

- Improper timing of construction relative to growing or spawning seasons of the target habitats. For example, constructing an oyster reef one month too late may delay recruitment by an entire year.

3.2.4 Failure to Accommodate Coastal Processes

Failing to address the site-specific physical coastal processes is another potential downfall. Understanding the water levels and waves—their frequencies and magnitudes—at a site is imperative for developing an appropriate nature-based solution. Such understanding includes the local geomorphology, sediment transport processes, sediment characteristics and future sea level (or sea level rise projections).

Structures that substantially reduce or block longshore sand transport produce negative impacts on adjacent shorelines. Long, artificial offshore reefs may also block or greatly inhibit the cross-shore movement of sand.

Another important consideration is ensuring that materials used for shoreline stabilization match those of the native shoreline as closely as possible. For instance, using sands that are too small or too large can lead to poor performance of beach nourishment projects.

3.3 Examples of Potential Projects and Concepts

Recently, FHWA facilitated a number of engineering adaptation assessments and pilot projects that focus on transportation resilience in the coastal environment. A number of these projects considered potential nature-based strategies but they have not yet been constructed. Some specific examples drawn from FHWA literature are summarized in Table 2. Additional examples can be found here:

https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/green_infrastructure/examples.cfm.

Table 2. Examples of proposed nature-based projects and concepts in FHWA pilot projects.

Location	Asset	Stressor(s)	Strategy	Document
Brookhaven, NY	Two-lane road	Flooding, waves, erosion	Constructed marsh with protection	FHWA (2016b)
Phippsburg, ME	Two-lane road	Erosion	Bank regrading and vegetation	Pilot Project Report ¹
Portsmouth, NH	Two-lane causeway	Erosion	Constructed marsh	Pilot Project Report ¹
New Jersey	Two-lane causeway	Flooding	Marsh enhancement	Pilot Project Report ¹
Delaware	Two-lane road	Flooding, erosion	Living shoreline	Pilot Project Report ¹

¹ https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/green_infrastructure/

Location	Asset	Stressor(s)	Strategy	Document
Florida	Four-lane divided highway	Storm surge, waves, erosion, sea level rise	Buried protection	FHWA (2016a)
Mississippi	Simply supported bridge	Storm surge, waves, currents	Vegetated berm	Pilot Project Report ¹
Oregon	Coastal highway	Bluff erosion	Dynamic revetment	Pilot Project Report ¹
California	Interstate highway	Flooding, sea level rise	Living levee	Bonham-Carter et al. (2014)

4 Performance and Reliability of Nature-Based Solutions

4.1 Nature-Based and Hybrid Solution Performance

This white paper and the subsequent implementation guide seek to better describe the performance and capabilities of nature-based solutions within the context of coastal highways. The effectiveness of some nature-based solutions has already been described (e.g., Bridges et al., 2014) but their characteristics are sensitive to location, setting, and exposure. Improved understanding of nature-based solutions is very much an area of active research. Some of this pertinent research is briefly summarized below in an attempt to frame the general characteristics of saltwater marshes, mangroves, maritime forests, reefs, beaches, dunes, as well as their potential sensitivity to sea level rise.

4.1.1 Saltwater Marshes

Saltwater marshes provide many benefits during storm and non-storm conditions. Marsh vegetation is effective at dissipating wave energy, reducing water velocity, reducing flood depths in the marsh, and minimizing net sediment loss. However, the capacity of marsh vegetation to provide these benefits changes with the water level.

When water levels are below the tops of marsh plants, the vegetation is effective at reducing wave heights, and therefore wave energy. The reduction in wave height is non-linear and happens quickly as waves interact with vegetation on the edge of the marsh. The rate of wave height decay diminishes with distance into the marsh. A study by Anderson et al. (2013) shows that wave height decay in real marsh vegetation (*S. alterniflora*) is predicted well by an exponential decay function. Wave height reductions of 60 percent to over 80 percent are reported in their laboratory study of an approximately 30-foot span of marsh grass. In most cases, a majority of the wave height decay occurs within the first 10 feet of the marsh edge. The results

When marshes are completely submerged, and water levels are above the tops of the marsh plants, they enhance flood depth reduction but are less effective at attenuating waves. The reduction in flood depth is strongly tied to reductions in wave height, wave setup, and water velocity through the marsh.

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show a dependence of wave height decay on plant density (i.e., number of stems per unit area) and plant height relative to the water depth. The study also shows that marsh vegetation reduces velocity by more than 80 percent over the 30-foot span of marsh grass. As with wave height attenuation, velocity reduction is most pronounced when the plant height is large relative to the water depth. The substantial reductions in velocity translate to positive benefits in terms of reducing erosion and sediment loss from the marsh surface.

Marshes reduce storm surge by reducing wave heights, which affect the water level over the marsh, and by slowing the flow of water as it travels across the marsh. No published equations



Figure 3. A coastal saltmarsh at mid-tide level. Photo courtesy: Bret Webb.

describe the reduction in flood depth through a marsh, but the literature supports overall reductions up to 40 percent. A recent field study by Paquier et al. (2017) found water level attenuation rates on the order of 60 centimeters per kilometer of marsh (3 feet per mile). Water level attenuation rates observed in that study fall within the range of values (4 to 70 centimeters per kilometer) reported (in Paquier et al., 2017) by seven other independent studies conducted in the Netherlands, Louisiana, Florida, and Massachusetts.

The existence and health of saltwater marshes is regulated by a variety of factors including sediment type and supply, elevation, nutrient levels, and wave climate. A study by Roland and Douglass (2005) quantifies the wave tolerance of *S. alterniflora* in southern Alabama and that guidance has been used in the design of several successful marsh creation projects. The presence of marsh vegetation is shown as a function of wave height and frequency of occurrence in Figure 4. Roland and Douglass (2005) determined that the upper limit for non-eroding salt marsh is a median significant wave height of 0.1 meter (0.33 feet) and a corresponding 80th percentile significant wave height of 0.2 meter (0.66 feet). In other words, marsh vegetation is stable when significant wave heights are less than 0.2 meter (0.66 feet) 80 percent of the time and less than 0.3 meter (1 foot) 95 percent of the time. Their finding is generally consistent with an old “rule of thumb” that marsh grasses exist where maximum storm wave heights are less than a foot. These values serve as practical engineering guidance on the wave tolerance of typical marsh vegetation to incident waves. When incident wave heights are greater than these limits, some type of structure is used to reduce wave heights below these critical thresholds. The gray area between the two regions in Figure 4 reflects locations with eroding and marginal marsh vegetation.

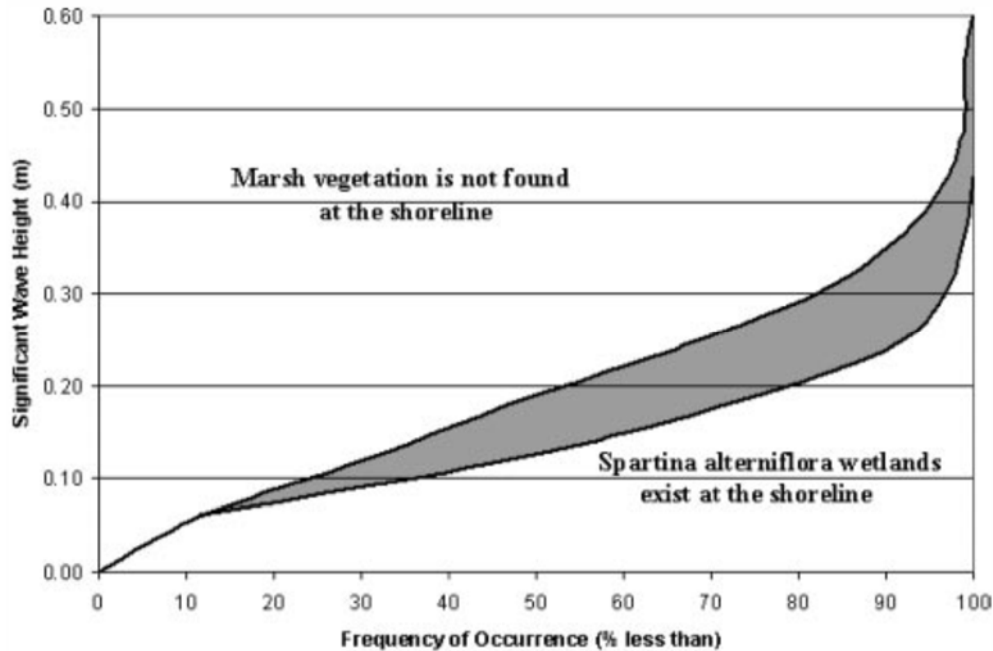


Figure 4. Wave tolerance of *Spartina alterniflora* as a function of significant wave height and frequency of occurrence (from Roland and Douglass, 2005).

4.1.2 Mangroves

Mangroves and mangrove forests provide mitigation benefits similar to those of saltwater marshes. Their complex root structure and canopies are known to reduce wave heights, wave run-up, and storm surge. They are also capable of reducing tsunami run-up. As with marsh vegetation, the benefits of mangroves change as water levels increase. When water levels are within the root structure, mangroves are effective at reducing wave action and wave run-up, but as water levels increase, mangroves are more effective at reducing storm surge than they are wave action.

As with marshes, wave height decay through mangroves is represented by an exponential decay function (Blankespoor et al., 2017). The rates of wave height decay are variable, depending on the density of the mangrove forest. Decay rates range from 20 percent to over 50 percent per 100 meter (~330 feet) of mangrove forest (Hashim and Catherine, 2013; Mazda et al., 1997; Zhang et al., 2012). Published studies show that wave height attenuation through mangroves is 2 to 7.5 times more effective than in cases without mangroves (Hashim and Catherine, 2013; Quartel et al., 2007). Young mangroves are somewhat ineffective at reducing wave heights as compared to established mangroves (Mazda et al., 1997).

Mangroves are also effective at reducing storm surge and surge-like features such as tsunami runup. Studies by Krauss et al. (2009) and Zhang et al. (2012) report surge decay rates between 9 and 50 centimeters per kilometer (0.5 ft to 2.6 feet per mile) depending on the density of mangroves. The study by Zhang et al. (2012) also demonstrated that much of the reduction in surge height occurs rapidly through the initial width of mangroves (15 to 30 percent reduction), with much smaller reductions (< 5 percent) progressing further into the mangroves. Ismail et al.

(2012) note the ability of mangroves to quickly reduce tsunami runup by 36 percent over the first 100 meters (~330 feet), and up to 50 percent over a 200 meter (~660 feet) section of mangroves.

4.1.3 Maritime Forests

The term “maritime forest” as used here refers to an upland coastal forest of trees and shrubs, not mangroves or marshes. No widely accepted tools predict the wave or surge attenuation in maritime forests, but there are some values that describe their potential capabilities. A numerical study by Mei et al. (2014) shows wave height reductions of up to 40 percent when the forest width is at least equal to the wavelength, but no substantial reductions as the size of the forest grows larger relative to the wavelength. A numerical study by Das et al. (2010) suggests that reductions in storm surge and flow velocity could be as high as 22 percent and 49 percent, respectively, over a 300-meter-wide (~980 feet) vegetation belt.

4.1.4 Reefs

Reefs represent another nature-based feature that possess some capacity to reduce wave energy. With respect to recent nature-based restoration practices, most attention is given to oyster reefs in particular, though coral reefs function similarly. Reefs attenuate waves through transmission, breaking, and energy dissipation due to friction. Some natural coral reefs may attenuate up to 97 percent of wave energy, with 86 percent of the energy dissipation occurring on the reef crest alone (Ferrario et al., 2014). Because of their ability to reduce wave heights, reefs also have the ability to modify sediment erosion and deposition patterns. Reefs do not contribute substantially to reductions in storm surge, but they can contribute to changes in the mean water level due to wave breaking (Servold et al., 2015).

Reefs may be intertidal (submerged only at high tide) or subtidal (completely submerged). In either case, the wave transmission characteristics of natural reefs are similar to those of submerged and emergent breakwaters (Allen and Webb, 2011; Webb and Allen, 2015). There are established methods for estimating the wave attenuating capabilities of such structures through calculation of their transmission coefficients: examples include d’Angremond et al. (1996) and van der Meer et al. (2005). However, some artificial oyster reef restoration projects rely on the use of habitat structures that may not always provide the same wave attenuating capabilities as natural reefs or breakwaters because of geometric characteristic differences including the width of the structures (Servold et al., 2015; Webb and Allen, 2015). When used as a form of shoreline stabilization, oyster reef restoration has had mixed success correlated with wave energy and exposure (La Peyre et al., 2014 and 2015; Meyer et al., 1997). It shows most promise in low-wave-energy environments (Piazza et al., 2005).

4.1.5 Beaches

The role of beaches in protecting upland infrastructure is well established in the literature. Beaches serve two critical purposes during a storm event. Initially, they act as a volume of erodible material when storm water levels are at or below the beach berm elevation. As the beach berm is submerged during a storm, the beach serves to dissipate wave energy through friction and breaking. Therefore, wider beaches, beaches with higher berm elevations, and

beaches with larger volumes, provide more protection to upland infrastructure. Depending on the geological setting, beaches may be composed of fine and coarse sand grains or cobbles, with the latter typically occurring along the U.S. pacific coast.

Distance from the coast is a significant predictor of infrastructure damage (Hatzikyriakou et al., 2016; Walling et al., 2015). A study by Dean (2000) demonstrates that widening a beach, through nourishment, yields storm damage reductions comparable to those of moving infrastructure landward by a similar amount. A number of post-Sandy assessments demonstrate this concept,



Figure 5. Beach renourishment following a major hurricane. Photo courtesy: Bret Webb.

with structures behind wider beaches sustaining less damage than those behind narrow beaches or beaches with lower berm elevations (Barone et al., 2014; Griffith et al., 2014).

In addition to beach nourishment along open coasts, smaller forms of beach stabilization are appropriate along sheltered shorelines. These are often called “pocket beaches” because of the indentations that develop in-between the structures. Pocket beaches are a type of hybrid nature-based solution where some rock or other appropriate materials are used to create

permanent “headlands” that control the position of the shoreline. The position of the shoreline in between artificial headlands is fairly well predicted using established engineering tools which suggest it will reach an “equilibrium” with the directional wave climate at the site. Hsu et al. (2010) suggest that a parabolic shoreline planform shape will develop between two headlands, “Bodge’s one-third rule” suggests that the depth of that shoreline embayment between two headlands will be about one-third the gap width between the headlands (Bodge, 2003), and Hardaway and Gunn (2002, 2010) suggest different shoreline geometric characteristics which have also proven to work well (see Figure 1).

The methods described above are commonly applied to sandy beaches. The design and performance of cobble beaches and berms, and their use as dynamic revetments, is also available (e.g., ODOT, 2005; Berry and Ruggiero, 2013).

4.1.6 Dunes

Sand dunes provide protective benefits during storm events by eliminating or reducing storm surge flooding and wave action behind them. Post-Sandy assessments demonstrate that the presence of dunes contributed substantially to reductions in storm damage (Tomiczek et al., 2017) and flooding (Walling et al., 2014). Dunes also function as a reservoir of sand affecting storm processes by blocking wave energy until the dune is overwashed and then sometimes burying roads under sand, and reducing damage, in larger storms.

Two important characteristics of dunes are their volume above storm water levels and the elevation of their crest. Hallermeier and Rhodes (1988) provide an equation relating dune erosion

to storm return period which can be used in the design of dunes. Though the equation is known to contain considerable uncertainty, it was developed for and is still used by FEMA to determine the limit of wave action on coastal flood maps. Dune erosion during a major storm can remove all the wave protection afforded by a small dune. This tool was developed to define how large a



Figure 6. These large sand dunes are eroding due to shoreline retreat. Photo courtesy: Bret Webb.

dune has to be to survive an extreme storm and is sometimes referred to as the “540 Rule” by those familiar with coastal flood mapping regulations. If the dune has a width/thickness of a cross-sectional area of less than 540 square feet (or 540 cubic feet per foot of shoreline) above the expected 100-year return period storm water level, FEMA assumes it will be completely removed during that level storm for flood mapping and wave penetration estimates. Smaller, more frequent, storms have correspondingly smaller numerical volumes.

No engineering tools specifically account for the positive effects of vegetation on dune performance. However, in all published studies dune vegetation was found to substantially decrease dune erosion and retreat rates (Figlus et al., 2014), and was effective at reducing wave runup, overtopping, and overwashing (Gralher et al., 2012; Kim et al., 2016; Kobayashi et al., 2013; Silva et al., 2016).

4.1.7 Combinations of Nature-Based Features

The preceding sections describe the general characteristics of individual features and their ability to reduce wave heights, water levels, flooding, velocity, and/or erosion, but only in isolation. Recent studies show that appropriate combinations of nature-based solutions often yield benefits beyond those achieved individually. For example, a study by Manis et al. (2015) found that combining a restored oyster bed with marsh vegetation had a greater impact on reducing wave energy than either approach by itself. Similarly, a study by Guannel et al. (2016) shows that more protective services are achieved by combining corals, sea grasses, and mangroves than any individual habitat or any combination of two habitats.

4.1.8 Hybrid Solutions

Nature-based features possess some inherent capacity to reduce storm hazards through reductions in wave height, flood depths and extent, and erosion. In many cases, however, these natural systems are most effective at mitigating these hazards under low to moderate intensity events. Combining nature-based approaches with traditional gray infrastructure may address some of these shortcomings while simultaneously enhancing the resilience of both the infrastructure and the ecosystem.

Potentially beneficial combinations of nature-based solutions and gray infrastructure already exist or have been suggested in the literature. For example:

- A relic stone seawall buried under a sand dune in New Jersey substantially reduced storm damage during Hurricane Sandy (Irish et al., 2013; Smallegan et al., 2016).
- A sheetpile wall and buried revetment protect a coastal highway in Florida without disrupting the adjacent shoreline and dunes (FHWA, 2016a).
- A living shoreline, consisting of a constructed saltwater marsh, may protect a coastal roadway from embankment erosion now, and later be combined with a sheetpile wall or barrier along the edge of pavement to prevent frequent flooding (FHWA, 2016b).

Bulkheads, revetments, and seawalls are commonly used to protect upland infrastructure, including coastal roads and bridges. While there may be legitimate and appropriate opportunities to combine them with a nature-based feature, it is important to acknowledge their long-term impacts as well. For example, if a particular marsh is incapable of maintaining its elevation as sea levels rise, it will attempt to migrate to higher elevations. Installing a bulkhead, revetment, or seawall behind such a marsh will prevent it from migrating and it will drown in place. Accounting for the potential incompatibilities between nature-based features and gray infrastructure will ultimately determine their co-benefits over time.

4.2 Sensitivity to Sea Level Rise

Marshes and other coastal vegetation are sensitive to relative sea level rise (RSLR), as are reefs and beaches.

- **Marshes:** Some studies suggest that marshes could possibly keep pace with RSLR rates as high as 1.2 centimeters/year - but only under optimal conditions (Morris et al., 2002). This rate is more than 3 times the current rate of global sea level rise, more than the projected RSLR rates through the end of this century at most U.S. locations under the NOAA Intermediate-Low scenario but equivalent to the projected RSLR rates by mid-century at most U.S. locations under the NOAA Intermediate scenario (Sweet et al., 2017). The optimal conditions depend on the current elevation of the marsh, the supply of inorganic sediment to the marsh, and the ability of the marsh to migrate to higher elevations over time. Development, including roads, behind marshes can restrict the ability of marshes to migrate (Titus, 2009; Titus et al., 2009).
- **Coral and oyster reefs:** The change in reef exposure due to sea level rise may be particularly damaging to some oyster reefs (Ridge et al., 2015). However, at least one study suggests that oysters are capable of outpacing sea level rise (Rodriguez et al., 2014). Other potential consequences of climate change include ocean acidification and changes in average ocean temperature. The long-term sustainability of coral reef systems is sensitive to both of these effects (Hoegh-Guldberg et al., 2007).
- **Beaches:** Beaches have some natural capacity, dependent upon sand supply, to keep pace with historic values of sea level rise, but a study by Houston (2016)

demonstrates that traditional forms of beach nourishment are most effective at combating shoreline retreat due to rising sea levels.

Natural systems can adapt to sea level rise better than gray infrastructure in some circumstances. Marshes increase in elevation or migrate in response to sea level rise and changes in salinity. Oyster reefs respond to sea level rise by increasing their elevation to maintain their exposure relative to tide range.

In addition to sea level rise, changes in sedimentation processes may hinder the ability of marshes and beaches to adapt to sea level rise. Specifically, Stevenson et al. (1998) suggest that reduced sediment input may be more damaging to marsh health than sea level rise alone. Reduced sediment input to the coast, particularly within estuaries, also represents a threat to the long-term position of shorelines.

5 Key Knowledge Gaps and Implementation Hurdles

Using a nature-based solution rather than hard infrastructure requires a shift in typical engineering design practice and philosophy. Typical engineering practice seeks to control environmental variability and account for uncertainty through conservatism in design. To allow for ecological succession and dynamic natural processes, the engineer and project sponsor have to be comfortable with a range of effectiveness and the dynamic nature of nature-based solutions. They must also recognize the need for long-term maintenance. The choice of whether to implement a nature-based solution ultimately depends upon several factors: an engineer's confidence in its design; their ability to anticipate and explain its performance over time; an economic justification in terms of risk reduction over the life of the project; and whether the project complies with regulatory requirements.

5.1 Transportation-Specific Implementation Hurdles

Transportation-specific implementation hurdles exist in both policy and process concerning the use of nature-based solutions. But there are also potential opportunities. One hurdle is the timing of considering nature-based solutions. Once a roadway is in place, the flood response activities are usually conducted by maintenance personnel with an interest in immediate solutions to restore access so they are less likely to consider nature-based solutions. Likewise, if nature-based solutions are only considered in the NEPA process, it will likely be too late for serious consideration.

Consideration of nature-based solutions to coastal highway resilience should ideally occur in the ongoing long range transportation planning process. Trying to interject nature-based solutions during the NEPA process has significant limitations. Push back from both the State DOT and the federal resource agencies is likely at the NEPA stage due to pressure to streamline NEPA and facilitate quick project delivery. This is not resistance to better solutions, just acknowledgement that early consideration is more likely to result in a positive outcome. There is considerable pressure to move project delivery forward quickly, and many State DOTs (Maryland and North Carolina as examples) have developed a process to integrate nature-

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based solutions into long range planning and project development. There are many opportunities for nature-based solutions when the conversation begins early and includes broad participation by decision making agencies and affected stakeholders.

The FHWA Eco-Logical approach helps State DOTs create broad partnerships that can facilitate increased consideration of nature-based solutions in the long range planning process. Developing an understanding of how and when to begin considering nature-based solutions can help State DOTs implement more projects. Additionally, under the Transportation Research Board Second Strategic Highway Research Program (SHRP2), there was research to develop an Integrated Ecological Framework (see <https://fhwaapps.fhwa.dot.gov/planworks/Application/Show/10>). The concept is based on cooperation between resource agencies and transportation agencies at the regional level to create coordinated planning documents that identify critical interests and environmental priorities for consideration before transportation additions or improvements are made. Caltrans is a strong example of a DOT committed to a regional eco-system approach. Another example is Delaware DOTs Watershed Resources Registry, which can be used to pre-identify potential sites that could be candidates for nature-based solutions. Once identified, a nature-based enhancement at that site may potentially be used to satisfy or offset mitigation requirements due to impacts at another (i.e., advance mitigation, mitigation banking, eco-crediting). For example, creation of a coastal saltwater marsh along a shore parallel highway could be counted as mitigation for wetland impacts somewhere else. Many states are currently set up to consider this type of opportunity. As another example, North Carolina has a partnership under the Ecosystem Enhancement Program (EEP) between the State DOT and the environmental agency.

Generally speaking, a substantial policy hurdle is related to a long-standing belief that State DOTs are “... not in the beach business,” or “... not in the marsh business,” etc. However, State DOTs are in the business of maintaining their coastal highways and nature-based solutions should be considered as part of that long-term commitment. At the very least, nature-based solutions should be evaluated in addition to, or as alternatives to, traditional shoreline armoring in order to evaluate and compare their first costs, long-term maintenance costs, and benefits or impacts to the environment.

One of the specific hurdles to transportation agencies include right-of-way issues to develop adequate room for some nature-based solutions and the need to partner with other agencies with responsibility for coastal resources. Transportation agencies often focus on “their” right-of-way for obvious reasons and yet robust nature-based solutions could be more effective by looking at a larger footprint. For example, an eroding marsh adjacent to a road might be a candidate for a nature-based solution in coordination with the owner of the marsh prior to the shoreline recession reaching the road right-of-way. In most states, the coastal waters below the mean high tide line are held in trust for the people and managed by one of the state’s resource agencies. In some specific coastal areas, the Coastal Barrier Resources Act severely restricts federal funds for infrastructure but has an exemption for maintenance of existing roads. That exemption is usually interpreted to be restricted to the right-of-way. In the many places where

natural systems already exist within the right-of-way, their conservation, through maintenance or restoration, can further serve to protect coastal highways.

Wherever possible, State DOTs should consider partnering with municipalities or the private sector when their nature-based solutions may directly benefit those near it. In this way, project costs can be shared or at least reduced among beneficiaries.

5.2 Transportation-Related Knowledge Gaps

There are some transportation-related knowledge gaps related to using nature-based solutions to enhance the resilience of coastal highways. As indicated in Section 2.1, the extent to which nature-based solutions can be used to protect vulnerable coastal highways is currently unknown. A suitable methodology for addressing this knowledge gap is needed in order to answer this question, but is not available at this time. Considerations of the physical/ecological setting, exposure to wave energy, land ownership, and regulatory constraints complicate the issue. One gap that can be filled is the absence of examples where nature-based solutions have been used to address a transportation-related need. This white paper has identified a few successful projects, but better documentation and tracking of nature-based solutions is needed.

5.3 Key Technical Knowledge Gaps

The most obvious technical gap is that the performance or resilience of many of the nature-based features described in this white paper are not described in an engineering context. The implementation guide will provide the engineering context and include guidance for the uncertainty inherent in dealing with nature. The behavior of these natural features is highly variable and site-specific (Saleh and Weinstein, 2016). Engineering design can address some of the issues, however, some large technical gaps cannot be addressed by the implementation guide. These include reconciling the natural variability in wave or surge reduction values, overcoming the lack of prototype (real world) conditions, and the lack of field measurements during storms. Therefore, it may be more appropriate to view nature-based solutions as resilience enhancements as opposed to resilience providers. As described in studies following Hurricane Sandy, combinations with traditional engineering approaches may yield the greatest benefits over time.

Another key technical gap is the relationship between the benefits of nature-based solutions and time. First, there is very little information describing the ability of nature-based features to reduce storm hazards as a function of storm duration. Second, the long-term reliability and performance of nature-based solutions are, like all coastal infrastructure, subject to the effects of sea level rise. The degree to which these natural systems will continue to provide equivalent benefits in terms of hazard mitigation are dependent upon the magnitude of future rates of sea level rise. These are technical gaps that cannot be addressed in the implementation guide.

The use of non-traditional materials in nature-based solutions represents another technical gap. This mostly applies to the use of habitat structures in place of more traditional rock breakwaters, including proprietary products that do not have published performance data. Many of these breakwater alternatives are relatively small compared to the incident wavelengths and, therefore, do not provide much wave attenuation (Webb and Allen, 2015). Wavelength is the distance between wave crests and it has long been recognized in the ocean and coastal engineering community that small diameter structures, like pilings, have little effect on wave energy propagation because their size is small compared with wavelength. While filling this technical gap is beyond the scope of the implementation guide, there are methods that can be substituted and used to provide realistic, if not conservative, results.

In some cases, non-traditional breakwater alternatives are chosen for their superior habitat benefits or because properly sized rock is difficult, or expensive, to obtain. A recent study by Gittman et al. (2016) found that the biodiversity and abundance observed on riprap and rock breakwaters were similar to those of natural shorelines, but this can be a site-specific result (Bilkovic and Mitchell, 2017).

Another technical gap is estimating the costs of construction and especially the cost of long-term maintenance of nature-based solutions. The published literature presents conflicting information regarding whether the maintenance costs of nature-based solutions are more or less than those of traditional approaches. Some publications describe material/method costs and are generally consistent across different regions. Construction costs, however, are known to be more difficult to predict. Cost information for nature-based solutions is a gap that will be addressed in the implementation guide.

5.4 Quantifying Ecosystem Services

Ecosystem services represent the direct and indirect contributions of ecosystems to human well-being. These services may be in the form of commerce, food, water quality improvements, carbon sequestration, nitrogen cycling, and storm damage reduction to name a few. Quantifying the total ecosystem services of nature-based solutions is an emerging area of study and research. It can be used in justifying the costs and benefits of nature-based solutions as well. There is a growing body of literature related to quantifying ecosystem services (Barbier et al., 2008 and 2011; Barbier 2015), but few unified studies that draw on wide sets of data and characteristics. Also, there is a lack of information concerning the role of ecosystem services and how they might best be leveraged as part of transportation planning or impact mitigation. The general ecological benefits of nature-based solutions will, however, be described in the subsequent implementation guide.

5.5 Selecting Appropriate Nature-Based Techniques

According to Saleh and Weinstein (2016), “...there is no ‘one size fits all’ solution to address site-specific conditions,” when it comes to the selection of an appropriate nature-based solution or technique. The selection of an appropriate nature-based solution will be a function of the ecological and geomorphological setting, the critical coastal processes affecting the site, and the desired resilience enhancement that it must provide. Typically, the most appropriate nature-based technique for any site simply mimics the natural setting. Replacing, restoring, or enhancing the existing or historic shoreline function is typically the most appropriate strategy but one that may require some other technique, like a structure to attenuate wave energy, to address the factors that have contributed to its degradation over time.

The selection of the most appropriate nature-based solution is at the nexus of coastal engineering and coastal ecology. The most successful projects typically include the expertise of coastal engineers, coastal scientists, and coastal ecologists with knowledge of the site-specific processes and habitat characteristics. An implementation guide, the anticipated FHWA product detailing the use of nature-based solutions for coastal highways, will provide some specific recommendations on how to select an appropriate approach for a given set of conditions.

There is also a need for guidance on how to appropriately track the health and effectiveness of the nature-based solution over time. This information should feed into a long-term adaptive management plan with triggers for action.

5.6 Lack of Engineering Design Tools

The implementation guide will include engineering tools that can be used in the planning, analysis, and design of nature-based solutions for coastal highways. In this way, the implementation guide fills an existing knowledge gap related to the use of nature-based solutions for coastal highway resilience. In some cases, a few tools already exist including the known wave tolerance of marsh vegetation, and the relationship between dune erosion and storm return period. Methods are established for the design of pocket beaches, and for predicting the wave transmission past a reef. However, equivalent methods for describing the performance of other natural features are lacking. No unified values describe attenuation or decay rates of wave height or surge through marsh vegetation, mangroves, or other common types of vegetation. More quantitative national and/or regional guidance, which is specific to wave tolerance of commonly-used approaches (e.g., coir logs, oyster shells in bags, etc.), is needed and would be a valuable addition to the FHWA implementation guide.

The engineering tools listed above do have some weaknesses. For example, the wave tolerance threshold described by Roland and Douglass (2005) is specific to *S. alterniflora* and may or may not be transferable to other marsh species or other latitudes due to differences in vegetative productivity relative to growing season length. No similar threshold was found for mangroves or any other type of vegetation (with the exception of seagrass, which is not considered here). Furthermore, the dune erosion model suggested by Hallermeier and Rhodes (1988) is known to have considerable uncertainty in the results and does not describe the performance of a

vegetated dune. Wherever needed, the uncertainty associated with these methods (marsh tolerance and dune erosion), and those described in the preceding paragraph (wave and surge decay), will be highlighted even though they still provide useful information to the design engineer.

5.7 Regulatory Considerations

All construction projects along the coast require regulatory permits. Federal regulations are usually addressed in a joint state-federal coastal permit application which varies from state to state and usually incorporates a check on any required local government permits.

*The joint state-federal coastal permit process is typically administered by the US Army Corps of Engineers in coordination with the lead state agency delegated with regulatory permit responsibility. It usually incorporates **all** the federal agency reviews; US Fish and Wildlife Service, National Oceanic and Atmospheric Administration, Environmental Protection Agency, US Coast Guard, etc.; and **all** the state agency reviews; the permit agency, the natural resource agency, the State Historic Preservation Office, the public health agency, etc.; with regulations and responsibility for coastal resources. A pre-application meeting with these agencies, early in the planning process, is highly recommended for transportation agencies considering projects that include coastal, nature-based solutions.*

Regulatory support for some nature-based solutions, like living shorelines, varies around the U.S. While the permit process represents an implementation hurdle because of regulations which seem to favor gray infrastructure (NRC 2007), efforts in many states have changed that over the past decade. The State of Maryland passed the Living Shorelines Protection Act in 2008, which requires the use of nonstructural shoreline stabilization methods in tidal wetlands. Recently, the U.S. Army Corps of Engineers created Nationwide Permit 54 to streamline the process of permitting a living shoreline. This permit limits activities to only those projects having a substantial biological component (i.e., marsh, wetland, reef) and minimal use of structure. The permit limits the size of a project to within 30 feet of the mean low water line and no more than 500 feet in length along the bank. Some states adopted the permit as written, some with modifications, and some rejected it. Some states, like Alabama and Mississippi, have regional general permits for living shorelines that provide greater project flexibility through consultation with regulatory agencies. However, some states prohibit activities on state-owned water bottoms, including the use of fill to establish a marsh, or the use of a structure to protect a shoreline. In many cases the delineation of private and public lands is a tidal datum, like mean high water. In summary, regulations vary from state to state as do costs associated with the different types of permits regulating a project.

6 Glossary

ABUTMENT: A structure sustaining one end of a bridge span and at the same time supporting the embankment which carries the roadway.

ADAPTATION: Adjustment in natural or human systems in anticipation of or response to a changing environment in a way that effectively uses beneficial opportunities or reduces negative effects.

ATTENUATE: To lessen the height or amplitude of a wave, wave-like feature, or velocity.

BAY: 1) A body of water almost completely surrounded by land but open to some tidal flow communications with the sea. 2) A recess in the shore or an inlet of a sea between two capes or headlands.

BAYOU: A body of water, usually part of an estuary, resembling either a slow moving river or a marshy lake.

BEACH: The zone of unconsolidated material, typically sand, that extends landward from closure depths where sand is moved by waves to the place where there is marked change in material or physiographic form, or to the line of permanent vegetation (usually the effective limit of storm waves).

BEACH NOURISHMENT: The direct placement of large amounts of good quality sand on the beach to widen the beach.

BERM: A nearly horizontal part of the beach or backshore formed by the deposit of material by wave action.

BREAKING: Reduction in wave energy and height. In the surf zone breaking is due to limited water depth.

BREAKWATER: A structure protecting a shore area, harbor, anchorage, or basin from waves.

BRIDGE SPAN: The structure that rests between the supports of a bridge which conveys the roadway.

BULKHEAD: A structure or partition to retain or prevent sliding of the land. A secondary purpose is to protect the upland against erosion from wave action.

COASTAL HIGHWAYS: A general term that refers to roads and bridges found in coastal settings.

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COIR FIBER LOGS: Tube-shaped erosion-control devices filled with straw, flax, rice, coconut fiber material, or composted material.

CROSS-SHORE: Perpendicular to the shoreline.

DEPTH-LIMITED WAVE HEIGHT: A wave height that is limited by the local depth of water.

DIKE: An earthen embankment that blocks an area on a reservoir or lake rim that is lower than the top of the dam. Also called a levee.

DUNE: A ridge or mound of loose, wind-blown material, usually sand.

ECOSYSTEM SERVICES: The direct and indirect contributions of ecosystems to human well-being.

EMBANKMENT: A volume of earthen material that is placed and compacted for the purpose of raising the grade of a roadway (or railway) above the level of the existing surrounding ground surface.

ENGINEERING WITH NATURE: The intentional alignment of natural and engineering processes to efficiently and sustainably deliver economic, environmental and social benefits through collaborative processes.

EROSION: The wearing away of land by the action of natural forces. On a beach, the carrying away of beach material by wave action, tidal currents, littoral currents, or by deflation.

ESTUARY: 1) The region near a river mouth in which the fresh water of the river mixes with the salt water of the sea and which receives both fluvial and littoral sediment influx. 2) The part of a river that is affected by tides.

EXTREME EVENT: Significant, longer return period, storm events. Consequences of extreme events can include safety concerns, damage, destruction, and/or economic loss.

FETCH: The distance or area in which wind blows across the water forming waves.

FLOODWALL: A long, narrow concrete, or masonry embankment usually built to protect land from flooding.

GABION MATTRESS: A wire basket filled with rocks or concrete used to stabilize embankments.

GEOMORPHOLOGY: 1) That branch of physical geography which deals with the form of the Earth, the general configuration of its surface, the distribution of the land, water, etc. 2) The investigation of the history of geologic changes through the interpretation of topographic forms.

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GRAY INFRASTRUCTURE: A term used in contrast to "green infrastructure," referring to traditional, engineered structures made of such materials as concrete and steel.

GREEN INFRASTRUCTURE: Natural and nature-based solutions used to increase resilience and provide habitat.

GROUNDWATER: Water in the zone of saturation where all openings in rocks and soil are filled, the upper surface of which forms the water table; water within the earth that supplies wells and springs.

HEADLAND: a narrow piece of land that projects from a coastline out into a sea.

HEADLAND BREAKWATER: A breakwater constructed to function as a headland by retaining an adjacent sandy pocket beach.

HYBRID APPROACH: An integrated approach to shoreline stabilization that combines nature-based solutions with structures and possibly policy measures.

INUNDATION MAP: A map that shows the extent and elevation of flooding in coastal or riverine settings.

INTERTIDAL: Refers to a feature that is covered by water during high tide and uncovered during low tide.

LEVEE: An earthen embankment that blocks an area on a reservoir or lake rim that is lower than the top of the dam. Also called a dike.

LIVING SHORELINES: A method of shoreline stabilization that uses appropriate combinations of natural materials, and possibly some structure, to complement the natural ecological and geological setting and shoreline function.

LONGSHORE SAND TRANSPORT: The movement of beach material in the littoral zone by waves and currents. Includes movement parallel (longshore drift) and sometimes also perpendicular (cross-shore transport) to the shore.

MANGROVE: Any of a group of tropical maritime trees or shrubs that live in the coastal intertidal zone.

MARITIME FOREST: A coastal wooded area, usually found on higher ground than dune areas within range of salt spray.

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MARSH: 1) A tract of soft, wet land, usually vegetated by reeds, grasses and occasionally small shrubs. 2) Soft, wet area periodically or continuously flooded to a shallow depth, usually characterized by a particular subclass of grasses, cattails and other low plants.

MEAN WATER LEVEL: The elevation of the water surface if all wave and wind action were to cease. Also called stillwater level.

NATURAL AND NATURE-BASED FEATURES: Features that define natural coastal landscapes and are either naturally occurring or have been engineered to mimic natural conditions. See nature-based solutions.

NATURE-BASED INFRASTRUCTURE: See green infrastructure.

NATURE-BASED SOLUTIONS: Approaches to problems (in this case, coastal highway problems) which mimic characteristics of natural features, including habitats, but are created by human design, engineering, and construction.

NUISANCE FLOODING: Minor, recurrent flooding that occurs at high tide or during minor storms.

OCEAN ACIDIFICATION: A reduction in the pH of the ocean over an extended period of time, caused primarily by uptake of carbon dioxide (CO₂) from the atmosphere.

OVERTOPPING: Passing of water over the top of a structure (e.g., seawall, roadway) usually as a result of wave run-up and/or coastal storm surge. Riverine flow can contribute to overtopping.

OVERWASHING: Sustained movement of water, and possibly sediment, over the top of a barrier island or roadway as a result of coastal storm surge and wave action.

POCKET BEACH: A beach, usually small and curved, in a coastal embayment between two headland littoral barriers.

REEF: Offshore consolidated rock. Often refers to coral fringing reefs in tropical waters, but may also include shellfish reefs such as oyster.

RELATIVE SEA LEVEL RISE: Sea level change at a coastal location relative to the land. This includes both the global sea level rise component and the vertical land movement (VLM) component. This is the sea level change measured by long-term tide gages.

RISK: Chance or probability of failure due to all possible environmental inputs and all possible mechanisms. The concept of flood risk typically captures both the probability of the flood event and the consequences of the flood event. May also refer to the likelihood of an event.

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RESILIENCE: The ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions.

REVTMENT: A layer or layers of stone, concrete, etc., to protect an embankment, or shore structure, against erosion by wave action or currents.

SCOUR: Removal of underwater material by waves and currents, especially at the base or toe of a structure.

SCREEN: An emergent wall of segmented or otherwise permeable boards or planks (usually timber) that serves to attenuate waves.

SEA LEVEL RISE: The long-term trend in mean sea level not accounting for the effects of land movement.

SEAWALL: A structure, often concrete or stone, built along a portion of a coast to prevent erosion and other damage by wave action. Often it retains earth against its shoreward face. A seawall is typically more massive and capable of resisting greater wave forces than a bulkhead.

SHEETPILE: Interlocking boards or planks of steel, vinyl, concrete, wood, or other materials that are driven into the ground to form a wall.

SHORELINE: The intersection of a specified plane of water with the shore or beach (e.g., the high water shoreline would be the intersection of the plane of mean high water with the shore or beach). The line delineating the shoreline on National Ocean Service nautical charts and surveys approximates the mean high water line.

SHORELINE RETREAT: Landward movement of the shoreline. A net landward movement of the shoreline over a specified time.

SILL: A coast-parallel, low profile structure built with the objective of reducing the wave action on the shoreline by forcing wave breaking over the sill.

STORM SURGE: A rise in average (typically over several minutes) water level above the normal astronomical tide level due to the action of a storm. Storm surge results from wind stress, atmospheric pressure reduction, and wave setup.

SUBSIDENCE: A gradual settling or sudden sinking of the Earth's surface due to the removal or movement of subsurface earth material.

SUBTIDAL: Refers to a feature that is always submerged, even at low tide.

TIDAL CIRCULATION: The movement of water into, through and out of a water body caused by the action of tides.

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TIDAL WETLAND: A coastal wetland with a water level controlled primarily by the tide.

TRANSMISSION: The movement of a wave through some porous obstruction, which usually causes some attenuation of the wave.

TSUNAMI: A long-period wave, or series of waves, caused by an underwater disturbance such as a volcanic eruption or earthquake. Commonly miscalled "tidal wave."

TSUNAMI RUNUP: The large amount of water that a tsunami pushes onshore.

UPLIFT: Upward movement of the Earth's surface relative to a geodetic datum. Results in increased elevation.

VERTICAL LAND MOVEMENT: A general term for processes affecting the elevation at a given location. See also uplift and subsidence.

VULNERABILITY: The extent to which a transportation asset is susceptible to sustaining damage from hazards (including climatic). Vulnerability is a function of exposure, sensitivity, and adaptive capacity.

WAVE: A ridge, deformation, or undulation of the surface of a liquid.

WAVELENGTH: The horizontal distance between similar points on two successive waves measured perpendicular to the crest.

WAVE ENERGY: A general term referring to the incident wave environment. A measure of the energy in a sea state that is proportional to the square of the wave height.

WAVE HEIGHT: The vertical distance between a crest and the preceding trough.

WAVE RUNUP: The upper level reached by a wave on a beach or coastal structure, relative to the still water level.

WEIR-FLOW DAMAGE: Damage, including pavement undermining, of the downstream side of roadways due to coastal storm surge waters flowing across roadway embankment like it is a weir.

WETLANDS: Lands whose saturation with water is the dominant factor determining the nature of soil development and the types of plant and animal communities that live in the soil and on its surface (e.g., coastal marsh wetlands).

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