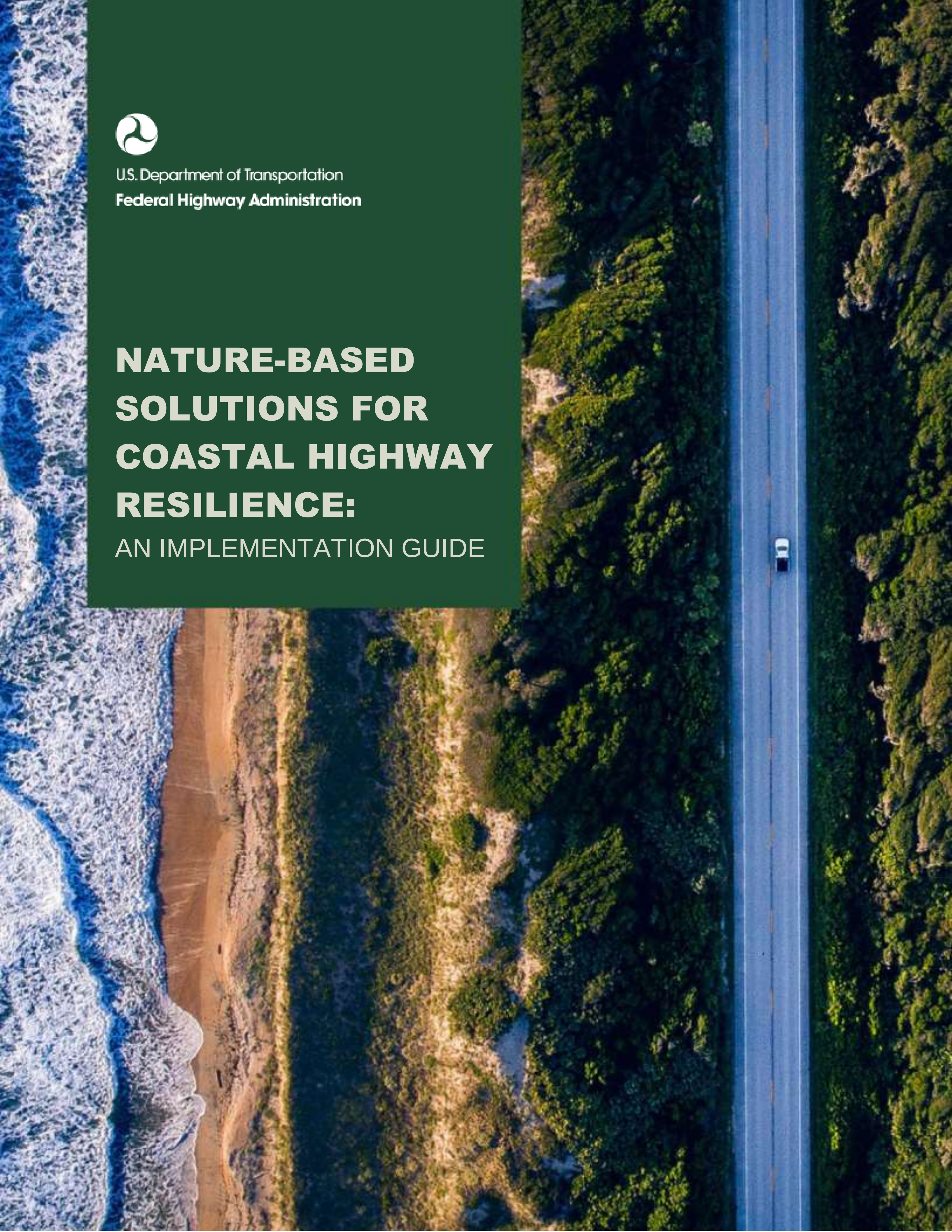
U.S. Department of Transportation
Federal Highway Administration

NATURE-BASED SOLUTIONS FOR COASTAL HIGHWAY RESILIENCE:

AN IMPLEMENTATION GUIDE



This project was carried out in support of 23 U.S.C. § 503(b)(3)(B)(viii), which directs the Department of Transportation "to carry out research and development activities … to study the vulnerabilities of the transportation system to … extreme events and methods to reduce those vulnerabilities."

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Technical Report Documentation Page

1. Report No. FHWA-HEP-19-042	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Nature-Based Solutions for Coastal Highway Resilience: An Implementation Guide		5. Report Date August 2019
7. Author(s) Bret Webb (SCE), Brenda Dix (ICF), Scott Douglass (SCE), Susan Asam (ICF), Charlotte Cherry (ICF), Beau Buhring (SCE)		6. Performing Organization Code 8. Performing Organization Report No.
9. Performing Organization Name(s) and Address(es) ICF 1725 Eye Street, NW, Suite 1000 Washington, DC 20006	South Coast Engineers (SCE) P.O. Box 72 Fairhope, AL 36533	10. Work Unit No. (TRAIS) 11. Contract or Grant No. DTFH6117F00098
12. Sponsoring Agency Name(s) and Address(es) Tina Hodges, Rebecca Lupes, Eric Brown, Rob Hyman, Rob Kafalenos, Heather Holsinger Federal Highway Administration 1200 New Jersey Avenue, SE Washington, DC 20590		13. Type of Report and Period Covered 14. Sponsoring Agency Code
15. Supplementary Notes This report and related materials are available online on FHWA's resilience website.		

16. Abstract

This Implementation Guide is designed to help transportation practitioners understand how and where nature-based and hybrid solutions can be used to improve the resilience of coastal roads and bridges. Upfront, it summarizes the potential flood-reduction benefits and co-benefits of these strategies. From there, the guide follows the steps in the project delivery process, providing guidance on how to consider nature-based solutions in the planning process, how to conduct a site assessment to determine whether nature-based solutions are appropriate, key engineering and ecological design considerations, permitting approaches, construction considerations, and monitoring and maintenance strategies. The guide also includes appendices with site characterization tools, decision support for selecting nature-based solutions, suggested performance metrics, and links to additional tools and resources.

17. Key Words Nature-based solutions, natural solutions, green infrastructure, living shorelines, sea level rise, storm surge, wave, erosion, highway, resilience, vulnerability, beach, marsh, breakwater, revetment, oyster reef, ecology, coastal processes, coastal restoration, mangrove, maritime forest, reef, dune, engineering	18. Distribution Statement

19. Security Classif. (of this report) Unclassified	18. Security Classif. (of this page) Unclassified	20. No. of Pages 229	22. Price

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LIST OF SYMBOLS

B_I	Initial beach width
B_m	Present beach width
$\cot(\theta)$	Side slope of the structure
D	Stone dimensions
E_{be}	Background erosion
E_t	Erosion over time
G_b	Breakwater gap
H	Design wave height
h_b	Water depth
L_b	Length of breakwater crest
M_b	Maximum bay indentations
T	Storm return period
V	Dune volume above the stillwater level
W_b	Width of beach
X_b	Distance offshore

LIST OF ACRONYMS

AASHTO	American Association of State Highway and Transportation Officials
BACI	Before-After-Control-Impact
BLM	Bureau of Land Management
BMP	Best Management Practices
BwN	Building with Nature
CatEx	Categorical Exclusion
CEQ	Council on Environmental Quality
CWA	Clean Water Act
CZMA	Coastal Zone Management Act
CZMP	Coastal Zone Management Plan
DEQ	Department of Environmental Quality
DNREC	Delaware Department of Natural Resources and Environmental Control
DOT	Department of Transportation
EA	Environmental Assessment
EFH	Essential Fish Habitat
EIS	Environmental Impact Statement
EO	Executive Order
ESA	Endangered Species Act
EWN	Engineering With Nature®
FAST Act	Fixing America's Surface Transportation Act
FEMA	Federal Emergency Management Agency
FFRMS	Federal Flood Risk Management Standard
FHWA	Federal Highway Administration
GIS	Geographic Information System
GMSLR	Global Mean Sea Level Rise
ILF	In-Lieu Fee
LiDAR	Light Detection and Ranging
LRSTP	Long-Range Statewide Transportation Plan
MHHW	Mean Higher High Water
MHW	Mean High Water
MLLW	Mean Lower Low Water
MLW	Mean Low Water
MMPA	Marine Mammal Protection Act
MPO	Metropolitan Planning Organization
MSA	Magnuson-Stevens Act
MSE	Mechanically Stabilized Earth
MSL	Mean Sea Level
MTP	Metropolitan Transportation Plan
NACCS	North Atlantic Comprehensive Coastal Study
NBS	Nature-Based Solutions
NEP	National Estuary Program

LIST OF ACRONYMS

NEPA	National Environmental Policy Act
NERRS	National Estuarine Research Reserve System
NGO	Nongovernmental Organization
NHPA	National Historic Preservation Act
NMFS	National Marine Fisheries Service
NNBF	Natural and Nature-Based Features
NOAA	National Oceanic and Atmospheric Administration
NPS	National Park Service
ppt	Parts per Thousand
PRM	Permittee-Responsible Mitigation
PSU	Partial Salinity Unit
REF	Regional Ecosystem Framework
RFI	Request for Information
RFP	Request for Proposal
RFQ	Request for Quotation
RFT	Request for Tender
RIBITS	Regulatory In-Lieu Fee and Bank Information Tracking System
ROD	Record of Decision
RSLR	Relative Sea Level Rise
SAGE	Systems Approach to Geomorphic Engineering
SAV	Submerged Aquatic Vegetation
SHPO	State Historic Preservation Office
SMART	Specific, Measurable, Achievable, Relevant, and Time Bound
TMDL	Total Maximum Daily Load
USACE	U.S. Army Corps of Engineers
USCG	U.S. Coast Guard
USDA FS	U.S. Department of Agriculture Forest Service
USDOT	U.S. Department of Transportation
USEPA	U.S. Environmental Protection Agency
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey
UV	Ultraviolet
VIMS	Virginia Institute of Marine Science
WwN	Working with Nature

Nature-Based Solutions for Coastal Highway Resilience: An Implementation Guide

EXECUTIVE SUMMARY

Nature-Based Solutions

Nature-based solutions use natural materials and processes to reduce erosion, wave damage, and flood risks, serving as alternatives to, or ecological enhancements of, traditional shoreline stabilization and infrastructure protection techniques. Examples include conservation, restoration, or construction of beaches, dunes, marsh, mangroves, maritime forests, and reefs.

Overview

Nature-based solutions can serve as a first line of defense and improve the resilience of coastal highways. FHWA developed *Nature-Based Solutions for Coastal Highway Resilience: An Implementation Guide* to help transportation professionals understand when, where, and which nature-based solutions may work for them. The guide follows the project implementation process from planning all the way through construction and maintenance.

How Can Nature-Based Solutions Help Me?

Nature-based solutions provide risk-reduction benefits to coastal highways by reducing coastal flooding, wave heights, and erosion. These reductions are the result of both physical and biophysical processes, underscoring the importance of the ecological components of a nature-based solution. Vegetative features like tidal marshes, mangroves, and maritime forests can reduce coastal flooding and effectively dissipate wave energy that contributes to wave-induced flooding, erosion, and infrastructure damage. Reefs dissipate wave energy and force waves to break further from shore, leading to reductions in wave runup and overtopping, wave energy, and erosion. Beaches and dunes dissipate wave energy and reduce coastal flooding and are known to effectively minimize damage to the built environment during extreme events.

What Other Benefits do they Offer?

Nature-based solutions offer habitat, water quality, and recreational benefits. The natural aquatic edge or shoreline, provision of substrate, and/or use of structures like marsh sills or breakwaters provide habitat for juvenile finfish and shellfish as well as foraging opportunities for birds and mammals. Water quality improvements result from reductions in available nitrogen, phosphorous, and total suspended solids. The habitat and water quality benefits combine to produce beneficial opportunities for recreational fishing, kayaking, paddle boarding, and bird watching.

How Much do they Cost?

Nature-based solutions are often equal to or less than the initial cost of traditional shoreline armoring, such as rock revetments, and have lower replacement costs following extreme events. However, nature-based solutions may require a level of routine maintenance that traditional shoreline protection does not. Unlike traditional engineering approaches that require replacement or retrofit, nature-based solutions can naturally adapt to sea level rise over time when conditions are suitable. Funding for nature-based solutions is available within the transportation sector, as part of coastal restoration grant efforts, and through hazard mitigation programs.

How to Develop Nature-Based Solutions

Planning

Incorporating nature-based solutions into transportation planning enables systematic consideration across a planning area or state and allows for identification of opportunities at an early stage. Transportation planners can facilitate coordination and collaboration with key stakeholders to mobilize larger projects, which increases the project benefits and can reduce costs. Potential partners include state coastal zone management programs, natural resource agencies, national estuarine research reserves, U.S. Army Corps of Engineers District Offices, and non-profit organizations. Coordination includes early engagement with the public as well as appropriate regulatory professionals. Transportation agencies can leverage *Eco-Logical*, an ecosystem-based approach to transportation planning developed by FHWA and stakeholders, to pre-identify locations where nature-based solutions may be appropriate given existing natural resources and ecological priorities.

Site Assessment

Selecting an appropriate nature-based solution involves site characterization and resilience characterization. This guide describes the characterization process so the practitioner can determine what type of solution will best fit project needs. Site characterization is the process of developing an understanding of historical and present site conditions. This process allows you to answer the simple question, What does nature support at this location? When thinking about nature-based solutions, it is best to let nature be your guide. The types of site characterization parameters addressed in the guide include:

System Parameters	Hydrodynamic Parameters
1. Shoreline Type 2. Infrastructure 3. Erosion Rate 4. Sea Level Rise 5. Tide Range	1. Wind Waves 2. Boat Wakes 3. Currents 4. Ice 5. Storm Surge
Terrestrial Parameters	**Ecological Parameters**
1. Upland Slope 2. Shoreline Slope 3. Width 4. Nearshore Slope 5. Water Depth 6. Soil Strength	1. Water Quality 2. Soil Type 3. Sunlight 4. Salinity
Additional Parameters	
1. Permits 2. End Effects 3. Constructability	4. Species 5. Debris 6. Monitoring

Resilience characterization involves identifying coastal highway vulnerabilities to determine resilience needs. Resilience needs may include flood reduction, wave attenuation, erosion reduction, shoreline stabilization, etc. Nature-based solutions can play an important role in enhancing resilience to events, including long-term sea level rise, ranging from minor and frequent to extreme and infrequent. The guide provides potential nature-based solutions to address the following vulnerabilities:

Highway Hydraulics	Coastal Roadways
1. Sea Level Rise 2. Increased Flooding from Sea Level Rise 3. Storm Surge 4. Sedimentation	1. Sea Level Rise 2. Increased Flooding from Sea Level Rise 3. Storm Surge 4. Wave Action 5. Erosion 6. Shoreline Retreat
Coastal Bridges	**Coastal Tunnels**
1. Sea Level Rise 2. Storm Surge 3. Wave Action 4. Erosion	1. Sea Level Rise 2. Storm Surge 3. Wave Action

Design Considerations

Successful nature-based solutions benefit from a wide variety of technical expertise applied throughout the entire implementation process. This guide contains helpful information regarding engineering and ecological design considerations for common nature-based materials and techniques. The guide refers to established methods and techniques for project design. It also provides important lessons learned regarding structure design, selection of materials, addressing ecological needs, and accommodating coastal processes. The guide illustrates the protective benefits of nature-based solutions through examples, which serve as a framework for performing similar analyses on a case-by-case basis. Six design examples demonstrate the wide variety of nature-based solutions, each created for a site-specific application that addresses the relevant vulnerabilities while accommodating the regional setting.

Photo credit: Bret Webb

Permitting

Nature-based solutions require Federal, State, and perhaps even local/municipal review for compliance and permitting. Nationwide, regional, and individual permits exist at the Federal level, each having their own set of requirements when permitting a nature-based solution. Working in consultation with district mitigation leads, nature-based solutions can be used to meet compensatory mitigation requirements.

Permitting & Regulations

Most nature-based solutions are subject to Section 404 of the Clean Water Act of 1972; Sections 9 and 10 of the Rivers & Harbors Act of 1899; the National Environmental Policy Act; the Endangered Species Act; and potentially others. The two primary issues that often apply to projects in coastal states or territories include coastal zone management and impacts to public (state-owned) lands.

Construction

Performance-based contracts allow innovation in construction techniques and can be a good option for including maintenance. For land-based construction, soft soils may require a timber mat or lighter equipment. Water-based construction may need to be timed for high tide in shallow areas. You may need to avoid nesting season for sensitive species or time vegetation planting or oyster placement for seasonal growth windows. “Pardon our Mess” signs during construction and interpretive signs explaining project benefits aid public support.

Monitoring, Maintenance, & Adaptive Management

Monitoring a project’s performance provides an opportunity to measure and assess impacts. There are three key monitoring plan components: identify project goals; identify relevant performance metrics; and select appropriate measurement methods. Maintenance requirements vary by project type and setting. Once established, routine maintenance costs for nature-based solutions should be minimal but are unlikely to be zero. Transportation professionals can use the monitoring results as part of an adaptive management strategy to help ensure project success and longevity as site conditions, or transportation needs, evolve.

Selecting Nature-Based Solutions

The decision to use a purely nature-based approach, a fully structural approach, or a hybrid solution to mitigate coastal hazards depends on (1) the type of nature-based solution that your site will support (e.g., Is it a beach or a marsh?), and (2) the infrastructure vulnerabilities or risks you seek to mitigate through project implementation. To help understand the options available for a given site, the following table presents common coastal hazards (column 1), relevant transportation asset types (column 2), and representative examples of possible management strategies (nature-based, structural, and hybrid)

Issue	Application	Natural & Nature-Based	Structural	Hybrid (possible examples)
Nuisance Flooding	Roads Causeways Drainage	Dunes Berm	Elevate Bulkhead Seawall Flood Barrier	Dunes + Bulkhead/Seawall/Barrier Berm + Bulkhead/Seawall/Barrier
Storm Flooding	Roads Causeways Bridges Tunnels Drainage	Beach Dunes Maritime Forest Marsh Mangroves	Elevate Bulkhead Seawall Flood Barrier	Beach + Dunes + Seawall/Barrier Marsh/Mangrove + Seawall/Barrier
Wave Runup & Overtopping	Roads Causeways Tunnels	Dunes Marsh Mangroves Reefs	Elevate Revetment Flood Barrier Breakwaters Sill	Dunes + Seawall/Barrier Marsh/Mangrove + Revetment Marsh/Mangrove + Sill Marsh/Mangrove + Reef/Breakwater
Wave Forces	Bridges Revetments	Marsh Mangroves Reefs	Elevate Breakwaters	Beach + Dunes + Reef/Breakwater Marsh/Mangrove + Reef/Breakwater
Erosion	Roads Causeways Bridges	Dunes Marsh Mangroves Reefs	Revetment Armoring Sill	Dunes + Vegetation Marsh/Mangrove + Sill Marsh/Mangrove + Revetment
Shoreline Retreat	Roads Bridges	Beach Marsh Mangrove Reefs	Bulkhead Seawall Revetment Breakwaters	Beach + Reef/Breakwater Marsh/Mangrove + Reef/Breakwater Beach + Revetment/Wall Marsh/Mangrove + Revetment/Wall

For More Information

Visit Nature Based Resilience for Coastal Highways project website for the following resources:

- Implementation Guidebook
- White Paper
- Peer-Exchange Report
- Pilot Reports
- Resources from other agencies

1. INTRODUCTION

Nature-Based Solutions
Nature-based solutions use natural materials and processes to reduce erosion, wave damage, and flood risks, serving as alternatives to, or ecological enhancements of, traditional shoreline stabilization and infrastructure protection techniques. Nature-based solutions include both natural and nature-based features, which US Army Corps of Engineers authorizing legislation (WIIN Act 2016, Section 1184) defines as follows:

- Natural features: created through the action of physical, geological, biological, and chemical processes over time.
- Nature-based features: created by human design, engineering, and construction to provide risk reduction in coastal areas by acting in concert with natural processes.

1.1 Purpose and Scope

This guide describes how transportation professionals can implement nature-based solutions that enhance the resilience of coastal highways under conditions ranging from typical to extreme weather events and sea level rise. Here the term *coastal highway* describes the roads, bridges, and other infrastructure that make up transportation systems exposed to, or occasionally exposed to, tides, storm surge, waves, and sea level rise. Briefly, the term *nature-based solution* describes a natural or nature-based (i.e., engineered) approach that reduces coastal hazards and damage as an alternative to, or in combination with, traditional engineered solutions.

The purpose of this guide is to provide information to transportation professionals that will enable them to consider nature-based solutions for protecting coastal highways as part of a broader portfolio, or system, of resilience measures. There are many reasons why transportation agencies should consider implementing nature-based solutions:

- When appropriately designed, a nature-based solution enhances resilience to flooding, wave action, and erosion while simultaneously facilitating natural ecosystem function, with benefits such as improved water quality, habitat, and fisheries.
- Nature-based solutions are often equal to or less than the initial cost of traditional shoreline armoring.
- One significant advantage of nature-based solutions is that some can naturally adapt to sea level rise, whereas traditional structural features require replacement or retrofit to achieve similar goals.
- The traveling public generally perceives nature-based solutions as more aesthetically pleasing, and they value the tourism and recreation benefits.

The scope of this guide is intentionally broad. The document aims to provide transportation professionals with relevant, timely, and science-based information regarding the complete project implementation process for nature-based solutions. Where possible, the guide summarizes existing design guidance with the caveat that the design of nature-based solutions requires a complete understanding of the site-specific issues that often drive the design, types of materials, and construction methods. Transportation professionals will benefit from a more fundamental understanding of programmatic implementation issues related to nature-based solutions, particularly considering the lack of coastal ecological and/or coastal engineering design expertise in the broader transportation community at this time. To that end, this guide recommends that transportation professionals engage the services of local practitioners with the requisite expertise in the design of nature-based solutions (Section 5.1).

1.2 What Are Nature-Based Solutions?

Related Terminology

- Coastal green infrastructure
- Natural infrastructure
- Living shoreline
- Natural and nature-based features (NNBF)
- Engineering With Nature® (EWN)
- Building with Nature (BwN)
- Working with Nature (WwN)

Nature-based solutions use natural materials and processes to reduce erosion, wave damage, and flood risks. Nature-based solutions often serve as alternatives to, or ecological enhancements of, traditional shoreline stabilization and infrastructure protection techniques. In this guide, the term *nature-based solution* is inclusive of both natural and nature-based features. Natural features are created through the action of physical, geological, biological, and chemical processes over time; nature-based features are created by human design, engineering, and construction to provide risk reduction in coastal areas (WIIN Act 2016, Section 1184). A wide variety of terminology describes nature-based solutions, some of which are listed in the text box at left. The common thread connecting these approaches is the desire to protect or improve the built environment while maximizing the ecological function of the natural system. Because they address a specific ecological or ecosystem function, nature-based solutions are often site-specific and scenario-specific, and their design requires a cross-section of expertise drawing on the fields of coastal ecology, coastal geology, coastal oceanography, and coastal engineering.

This guide addresses the following examples of nature-based solutions: tidal marshes, mangroves, maritime forests, reefs, beaches, and dunes. In this case, the nature-based solutions considered can mitigate storm surge flooding, wave-related damage, erosion, shoreline retreat, and the potential impacts of sea level rise, which pose threats to coastal infrastructure. A nature-based solution may consist entirely of natural elements (e.g., vegetation, beach, dune) or some combination of natural elements, constructed natural elements, and traditional coastal structures (e.g., sill, breakwater, revetment, seawall). A nature-based solution that combines natural and constructed elements is called a *hybrid approach*. Table 1-1 includes brief definitions and examples for each of these measures.

Along a continuous spectrum from mild to steep slopes, small to large waves, and sheltered shorelines (e.g., estuaries, bays, sounds) to open coast environments, nature-based solutions increasingly rely on some sort of coastal structure or armoring (Figure 1-1). For example, in that figure, as exposure to large waves or the level of desired risk reduction increases, a more substantial coastal structure and/or armoring are likely. The progression of structural armoring might include a small structure close to the shoreline (e.g., a sill); a more substantial structure located some distance from the shore (e.g., a breakwater); or a continuous rock revetment or seawall in some cases. In some parts of the United States, particularly in the Pacific Northwest, the use of dynamic revetments requires an important caveat. While incorporating many of the engineering features of a traditional revetment, a dynamic revetment mimics the behavior of a cobble beach while offering the protective benefits of a revetment (see the Oregon Department of Transportation (DOT) case study in Section 5.7 for more information).

Table 1-1. Full array of coastal risk-reduction measures

Terminology	Brief Description and Examples
Policy Measures	Policy measures, also called *non-structural measures*, are instituted at the programmatic level through public policy, management practices, and/or regulatory requirements. *Examples: acquisition/buyout, relocation, land use, zoning changes*
Natural Features	Natural features are created through physical, biological, geological, and chemical processes, over time, by nature. *Examples: marshes, mangroves, maritime forests, reefs, beaches, dunes*
Nature-Based Features	Nature-based features are created by human design, engineering, and construction to mimic nature and include natural features. *Examples: constructed marshes, mangrove restoration, constructed reefs, nourished beaches, restored/constructed dunes*
Structural Features	Structural features are engineered structures implemented for the purpose of coastal risk reduction by decreasing flooding, wave action, and/or erosion. *Examples: sills, breakwaters, bulkheads, revetments, seawalls*
Hybrid Approaches	Hybrid approaches incorporate a combination of natural or nature-based measures and structural measures. Many nature-based solutions, including living shorelines, use hybrid approaches. *Examples: marsh and sill, mangrove and reef breakwater, beach and breakwater*

When exposure to large waves or the required level of risk reduction decreases, an appropriate nature-based solution may require little to no structure, instead focusing more on natural features or engineered and constructed nature-based features. The example provided in Figure 1-1 includes, but is not exclusive to, beach nourishment with and without vegetated dunes; edging, which is a form of low shoreline bank stabilization typically used in conjunction with newly placed sediment and planted vegetation; and shoreline and/or upland stands of vegetation.

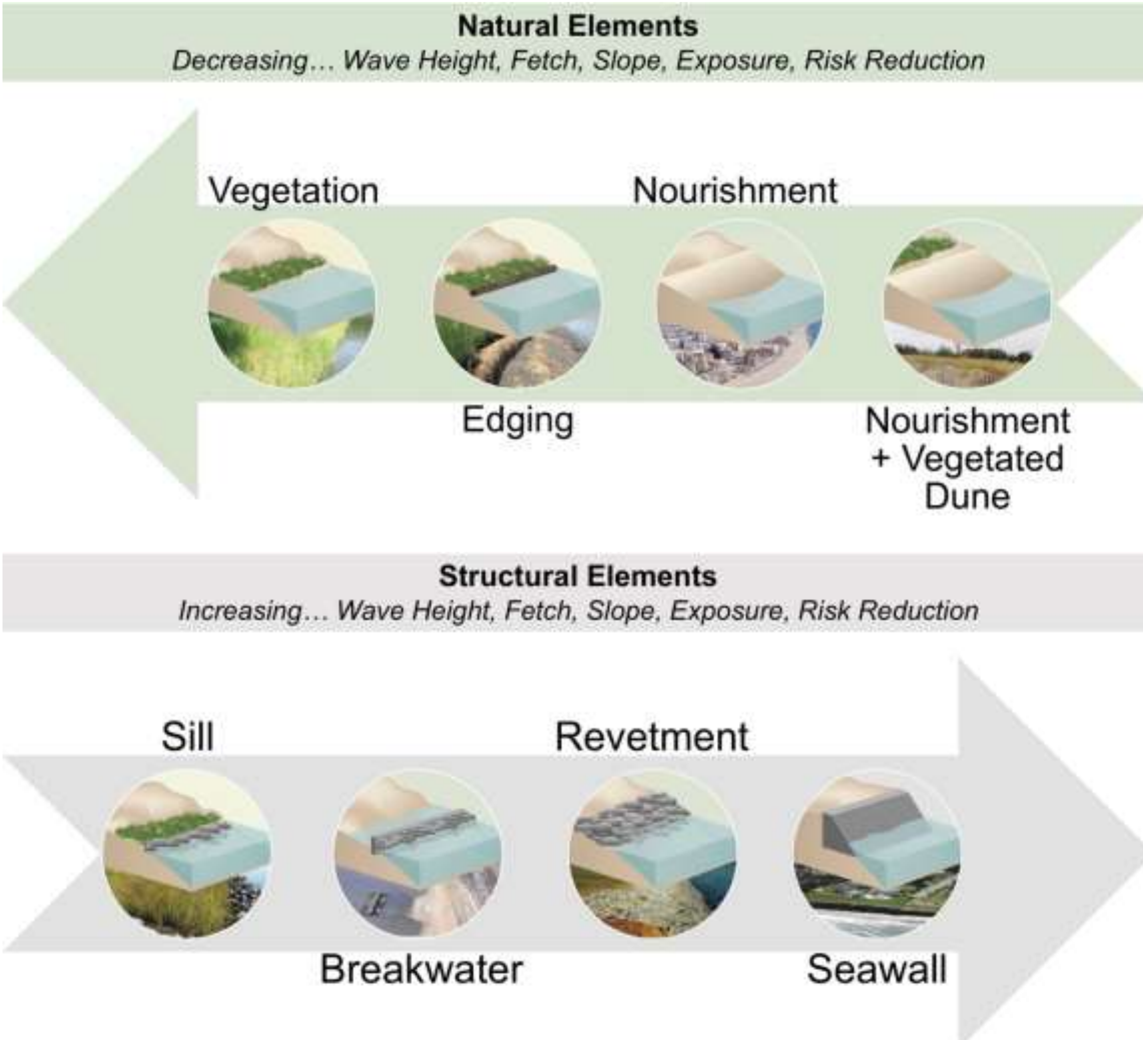


Figure 1-1. Nature-based solutions consist of varying degrees of natural, nature-based, and structural elements depending on the setting, exposure to wave action, and resilience needs (adapted with modifications from SAGE 2017).

The purpose of a coastal structure in a hybrid nature-based solution is to protect or enhance the natural features and/or provide additional risk reduction for adjacent infrastructure. Functionally, the coastal structure achieves these outcomes by manipulating the wave conditions (i.e., wave height and direction) at the site, by directly stabilizing sediments, or through a combination of both actions. The combination of natural and structural elements in a hybrid nature-based solution provide benefits that traditional armoring does not achieve on its own. Specifically, the combination of features used in hybrid nature-based solutions are effective at attenuating wave energy and provide superior habitat value and ecosystem services (Gittman et al. 2016b).

The decision to use a purely nature-based approach, a fully structural approach, or a hybrid solution depends on the following:

- Resilience needs or desired risk reduction
- Ecological and geological setting
- Exposure to large waves

- Project objectives
- Project cost
- Desired reliability
- Local policy and/or regulations

1.3 Linkages to Other Federal Efforts

This guide was developed to be complementary but not redundant to existing guides and sources of information. The U.S. Department of Transportation (USDOT) provides technical guidance and recommendations to transportation professionals charged with the planning, design, and operation of highways. In addition to this implementation guide, the USDOT Federal Highway Administration (FHWA) offers relevant coastal highway information in their Hydraulic Engineering Circulars HEC-25 2nd ed. (FHWA 2008), HEC-25 Volume 2 (FHWA 2014), and also HEC-25 3rd ed. (FHWA 2019a). Other Federal agencies are also including nature-based solutions as part of their systems approach to addressing flood risks and hazards along the coast (Table 1-2).

Additionally, there are international efforts aimed at the implementation of nature-based solutions. For example, the World Bank (2017) provides an international perspective on the principles of implementing nature-based flood protection.

1.4 Other Related FHWA Efforts

This implementation guide is part of the USDOT FHWA effort to develop information for transportation professionals that illustrates how nature-based solutions can protect coastal highways from flood and flood-related risks while also providing environmental benefits. Prior to developing this guide, FHWA partnered with State departments of transportation (DOTs) and others on five pilot projects to assess the potential for nature-based solutions to improve the resilience of coastal roads and bridges (FHWA 2019b). The findings from these pilot projects are used to illustrate key concepts throughout this guide. FHWA also published a white paper that describes the potential use of nature-based solutions for coastal highway resilience (FHWA 2018e); conducted four regional peer exchanges to solicit input from experts, end users, and key stakeholders on nature-based solutions; and later published a report that synthesizes the major findings and outcomes of those meetings (FHWA 2018b).

1.5 Audience

The audience for this implementation guide includes transportation planners, engineering practitioners, operations and maintenance professionals, environmental permitting staff, partnering agencies, and specialized consultants assisting transportation agencies with their work.

INTRODUCTION

Table 1-2: Federal agency nature-based solutions efforts

Agency	Nature-Based Solutions Efforts
Federal Emergency Management Agency (FEMA)	FEMA describes the benefits of using bioengineering stabilization methods, such as nature-based solutions, as long-term solutions to reduce risk from natural hazards in FEMA (2019). FEMA also supports flood risk-reduction practices as part of their Hazard Mitigation Assistance grant programs (FEMA 2018).
U.S. Army Corps of Engineers (USACE)	As part of their North Atlantic Comprehensive Coastal Study (USACE 2015). USACE developed the report, *Use of Natural and Nature-Based Features (NNBF) for Coastal Resilience* (Bridges et al. 2014). This report provides an integrative framework that classifies NNBF approaches, characterizes vulnerability, develops performance metrics, places monitoring and adaptive management within a systems perspective, and addresses important policy issues. Through their Engineering With Nature® initiative and international collaboration, USACE is developing international guidelines for NNBF to support engineering functions that achieve sustainability and resilience within coastal systems (EWN 2019).
National Oceanic and Atmospheric Administration (NOAA)	NOAA serves as the program administrator for the National Coastal Zone Management Program (CZMP). CZMP is a voluntary partnership between the Federal Government and U.S. coastal and Great Lakes States and territories (see Appendix D, Table 10-11, for a list of State CZMP agencies). CZMP aims at protecting, restoring, and responsibly developing our Nation's coastal areas and resources. NOAA encourages the use of nature-based solutions to provide, maintain, or improve habitat or ecosystem function and enhance coastal resilience (NOAA 2015).
USACE and NOAA	USACE and NOAA developed a community of practice, the Systems Approach to Geomorphic Engineering (SAGE) group, to help broaden participation in the implementation of nature-based solutions (SAGE 2017). The SAGE group consists of Federal, State, and local agencies; nongovernmental organizations (NGOs); academic institutions; engineering practitioners; and private companies.

1.6 Organization of this Guide

Following this introduction, we provide factsheets on nature-based solutions that give an overview of techniques; a short case study of where each was used; notes on their benefits, challenges, and costs; and some regional considerations. Section 2, which follows the factsheets, provides readers with a summary of the benefits (flood reduction, ecological benefits, long-term performance, and other co-benefits) and typical costs of nature-based solutions. The remaining sections of the guide are intentionally organized to closely mimic the project delivery process. A brief description of each section follows.

- Section 3 describes how transportation professionals might incorporate nature-based solutions into their planning process, key stakeholders to engage, and potential sources of funding for project implementation.
- Section 4 focuses on the process for selecting an appropriate nature-based solution that addresses local coastal highway concerns.

- Section 5 describes engineering and ecological considerations for the design of nature-based solutions, and presents a few selected case studies from around the U.S.
- Section 6 describes common regulatory permitting requirements for nature-based solutions, as well as information about National Environmental Policy Act (NEPA) compliance, and compensatory mitigation opportunities.
- Section 7 provides information specific to the construction phases of a nature-based solution.
- Section 8 address monitoring, maintenance, and adaptive management for nature-based solutions.

The appendices of this guide provide site characterization tools and resources, decision trees for selecting nature-based solutions, suggested performance metrics, and lists of other tools and resources for nature-based solutions.

TECHNCIAL FACTSHEETS

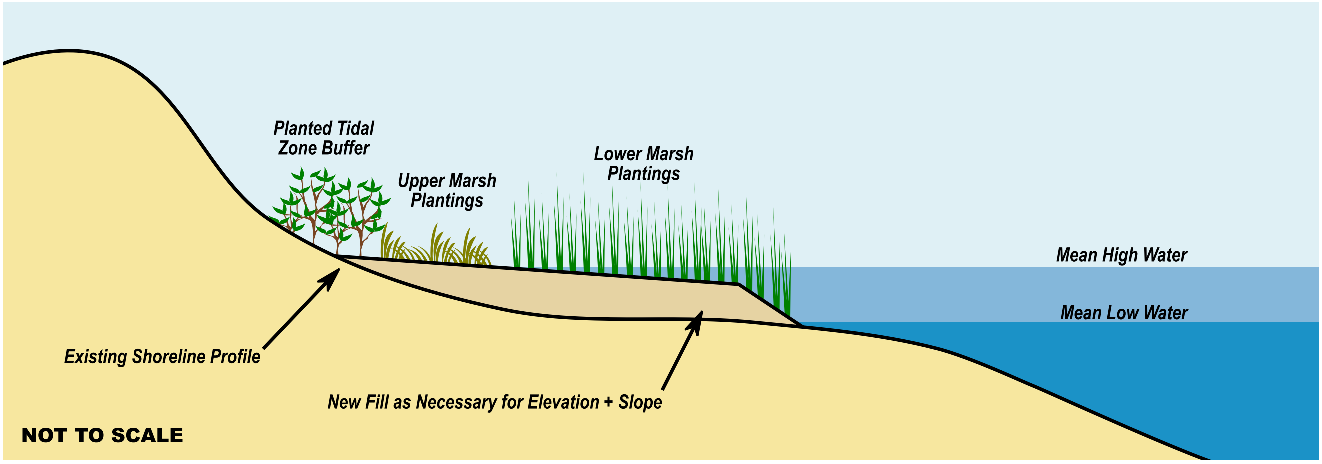
These technical factsheets for select nature-based solutions can be helpful to practitioners considering implementing one of these strategies. The factsheets cover the following solutions:

- Marsh Vegetation
- Marsh Breakwater
- Marsh Sill
- Beach Nourishment
- Pocket Beach
- Dune Restoration

MARSH (VEGETATION)

The construction of a marsh, including fill and plantings but without structural elements, in the intertidal zone of a shoreline.

Design Schematics



Overview of Technique

Materials

Native marsh plants appropriate for the site conditions (e.g., tide range, salinity, wave energy) along with sediment, if necessary, to build a platform of gradual slope at an appropriate elevation for the marsh to sustain itself.

Habitat Components

Salt marsh habitat

Durability and Maintenance

Maintenance is most important early in the life of a marsh. Waterfowl can damage young plants, and lost plants must be replaced quickly to ensure the health of the entire marsh. After the early stages, invasive species and runoff issues can affect long-term success. Frequent removal of debris and large items in the wrack line will reduce plant breakage.

Design Life

Because of changes that are difficult to predict, such as sediment supply and ability to keep pace with sea level rise, it is difficult to predict the design life of a marsh. There are many examples of constructed marshes in Maryland and Virginia that are thriving 30+ years after construction. If marsh slope and elevation maintain appropriate values, marshes should be resilient with considerable longevity.

Ecological Services Provided

Marshes provide a number of ecological benefits. They can filter water, including runoff, and they increase the uptake of nutrients, filtration, denitrification, and sediment retention. The root systems of marsh vegetation help stabilize the soil they inhabit, reducing erosion. The marsh platform and plant stems attenuate wave energy, further reducing erosion risk.

Case Study

“The Teaching Marsh at the Virginia Institute of Marine Science (VIMS) in Gloucester Point, VA is a one-acre site restored to marshland for both practical and educational purposes. The marsh is designed and maintained by VIMS wetlands experts to naturally remove contaminants from Coleman Bridge stormwater runoff, improving water quality in the York River. The Teaching Marsh also provides a demonstration area for regulated wetland plant species identified in the Tidal Wetlands Act of 1972." http://ccrm.vims.edu/wetlands/teaching_marsh/


Photo courtesy of VIMS

Project Proponent	Virginia Institute of Marine Science (VIMS)
Status	Completed (1999)
Permitting Insights	Establish open and direct communication with local, State & Federal regulatory authorities, rather than assume permit requirements or exemptions will apply to government public education and wetland restoration project.
Construction Notes	Excess fill excavated to the appropriate marsh elevation and used to create berms between salt/fresh marshes and walkways. 12,000 plants of various species.
Maintenance Issues	Some species died out and were replaced with saltmarsh cordgrass.
Final Cost	$25,000
Challenges	Failure of some species may be because of salinity incompatibility.

MARSH (VEGETATION)

The construction of a marsh, including fill and plantings but without structural elements, in the intertidal zone of a shoreline.


Photo courtesy of Beau Buhring


Photo courtesy of Bret Webb

Implementation Notes

Summary of Benefits

Marshes provide a variety of ecological benefits, generally improving water quality and reducing erosion risk while providing habitat for a variety of species.

Challenges

The flood risk reduction and wave attenuation benefits of marshes depend heavily on the water level. Marshes best attenuate waves when the water surface elevation is below the tops of the plantings.

Initial Cost

Upfront costs include the procurement of sediment and plantings for the marsh area, as well as any preventative measures such as bird exclusionary fencing. Upland stormwater BMPs and pruning of shade trees may also factor into initial cost.

O&M Cost

Maintenance costs will likely include the removal of dead plants and debris from the marsh and the planting of new plants, especially early in the life of the marsh.

Transportation and Other Benefits

Issue	Description
Flooding Reduction	Low, some reductions to flooding caused by reducing wave action
Wave Attenuation	Medium, marsh platform and plant stems break waves
Erosion Reduction	Medium, root systems hold soil in place
Multi-Benefits	High, creates/restores habitat, educational opportunity
Locale	Various, adaptable to site
Elevation + Slope	Low/Medium + Low/Medium, most valuable in the intertidal zone
Width	High, the area of marsh created is an important metric of success

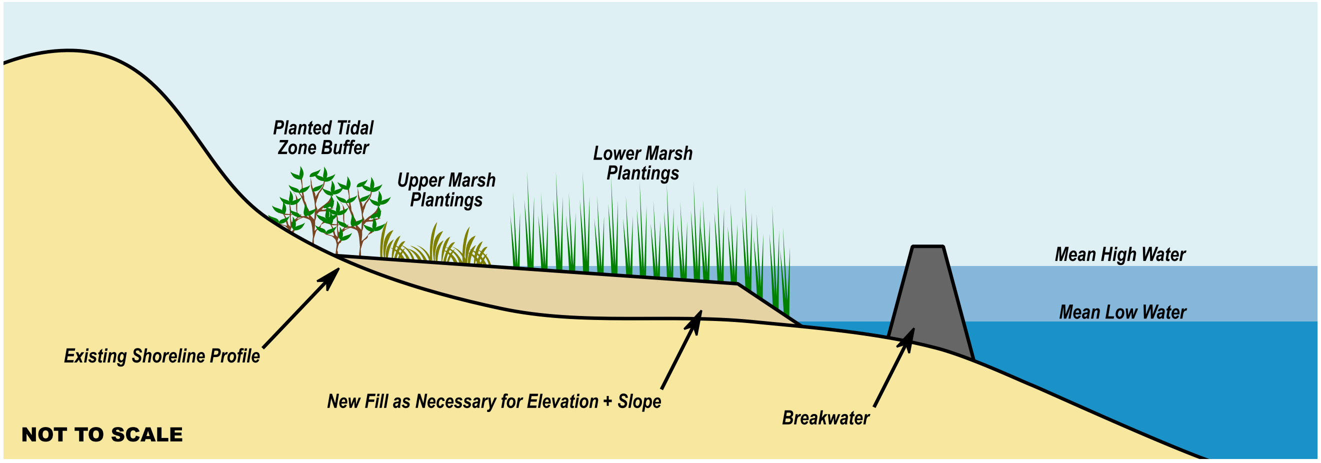
Regional Factors

Issue	Description
Gulf of Mexico	Intertidal marsh slope, elevation, selection of appropriate plant species are keys to success. Some marshes vulnerable to high rates of RSLR.
Southeast	Intertidal marsh slope, elevation, and selection of appropriate plant species are keys to success.
Mid-Atlantic	Intertidal marsh slope, elevation, and selection of appropriate plant species are keys to success. Marshes vulnerable to high rates of RSLR.
Northeast	Large tidal fluctuations may preclude intertidal marshes in some areas. Ice formation may damage plants.
Great Lakes	Large lake-level fluctuations may preclude intertidal marshes. Ice formation may damage plants.
Pacific Northwest	Large tidal fluctuations may preclude intertidal marshes in some areas. Ice formation may damage plants.
Pacific Southwest	Select appropriate species based on salinity and marsh elevation.
Hawaii & Pacific Islands	Mangroves more common than intertidal marshes.

MARSH (BREAKWATER)

The construction of a marsh, including fill and plantings, in the intertidal zone of a shoreline, including segmented breakwaters to reduce incident wave energy.

Design Schematics



Overview of Technique

Materials

Native marsh plants appropriate for the site conditions (e.g., tide range, salinity, wave energy) along with sediment, if necessary, to build a platform of gradual slope at an appropriate elevation for the marsh to sustain itself. Shore parallel breakwaters are usually made of stone, formed concrete units, or bagged shell material.

Habitat Components

Intertidal salt marsh habitat, potentially with oyster habitat on the structural elements.

Durability and Maintenance

Maintenance is most important early in the life of a marsh. Waterfowl can damage young plants, and lost plants must be replaced quickly to ensure the health of the entire marsh. After the early stages, invasive species and runoff issues can affect long-term success. Frequent removal of debris and large items in the wrack line will reduce plant breakage.

Design Life

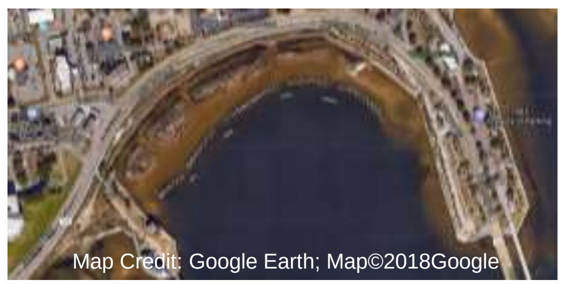
Because of changes that are difficult to predict, such as sediment supply and ability to keep pace with sea level rise, it is difficult to predict the design life of a marsh. There are many examples of constructed marshes in Maryland and Virginia that are thriving 30+ years after construction. If marsh slope and elevation maintain appropriate values, marshes should be resilient with considerable longevity.

Ecological Services Provided

Marshes provide a number of ecological benefits. They can filter water, including runoff, and they increase the uptake of nutrients, filtration, denitrification, and sediment retention. The root systems of marsh vegetation help stabilize the soil they inhabit, reducing erosion. The marsh platform and plant stems attenuate wave energy, further reducing erosion risk.

Case Study

Project GreenShores (Pensacola, FL) is a marsh creation project protected by several types of oyster reef breakwaters. Site 1 used traditional emergent breakwaters, while Site 2 used broad-crested submerged reefs. The project protects a one mile segment of Bayfront Parkway from wave impacts and erosion.



Map Credit: Google Earth; Map©2018Google

Project Proponent	Florida Department of Environmental Protection
Status	Completed (2008)
Permitting Insights	Not available
Construction Notes	Phased construction at two sites. Site 1 breakwaters were built from > 20,000 tons of limestone, recycled concrete, and concrete blocks. Marsh islands constructed using 35,000 cubic yards of sand and 41,000 *Spartina alterniflora* plants. Site 2 used 25,000 cubic yards of recycled concrete, 16,000 cubic yards of sand, and 30,000 plants. Site 2's breakwaters were built to be submerged.
Maintenance Issues	The submerged breakwaters at Site 2 have not effectively attenuated wave energy, leading to erosion of the marsh islands and loss of plants at that site.
Final Cost	$6,000,000
Challenges	Not available

MARSH (BREAKWATER)

The construction of a marsh, including fill and plantings, in the intertidal zone of a shoreline, including segmented breakwaters to reduce incident wave energy.


Photo courtesy of Beau Buhring


Photo courtesy of Sam St. John

Implementation Notes

Summary of Benefits

Marshes provide a variety of ecological benefits, generally improving water quality and reducing erosion risk while providing habitat for a variety of species. The marsh is stabilized with offshore breakwaters that attenuate wave energy.

Challenges

The flood risk reduction and wave attenuation benefits of marshes depend heavily on the water level. Marshes best attenuate waves when the water surface elevation is below the tops of the plantings.

Initial Cost

Upfront costs will focus on the procurement of sediment and plantings for the marsh area, as well as the toe protection material and any preventative measures such as bird exclusionary fencing. Likely initial cost of $150–340 per linear foot of marsh protected by breakwaters.

O&M Cost

Maintenance costs will likely include the removal of dead plants and debris from the marsh and the planting of new plants, especially early in the life of the marsh.

Transportation and Other Benefits

Issue	Description
Flooding Reduction	Low, some reductions to flooding caused by reduced wave action
Wave Attenuation	Medium, breakwater, marsh platform and plant stems break waves
Erosion Reduction	Medium, root systems hold soil in place
Multi-Benefits	High, creates/restores habitat, educational opportunity
Locale	Various, adaptable to site
Elevation + Slope	Low/Medium + Low/Medium, most valuable in the intertidal zone
Width	High, the area of marsh created is an important metric of success

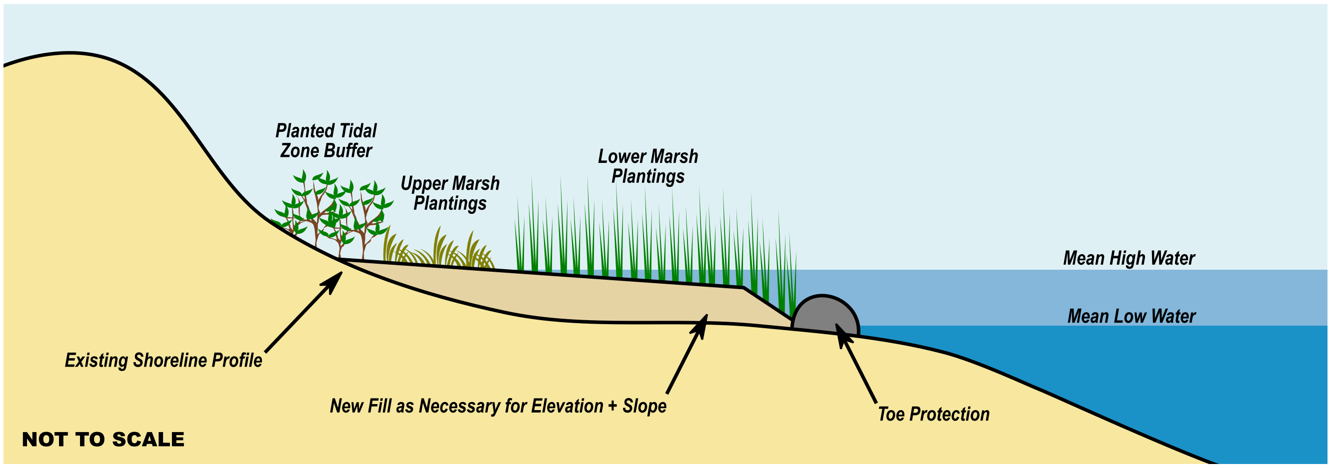
Regional Factors

Issue	Description
Gulf of Mexico	Intertidal marsh slope, elevation, and selection of appropriate plant species are keys to success. Some marshes are vulnerable to high rates of RSLR.
Southeast	Intertidal marsh slope, elevation, and selection of appropriate plant species are keys to success.
Mid-Atlantic	Intertidal marsh slope, elevation, and selection of appropriate plant species are keys to success. Marshes are vulnerable to high rates of RSLR.
Northeast	Large tidal fluctuations may preclude intertidal marshes in some areas. Ice formation may damage plants.
Great Lakes	Large lake-level fluctuations may preclude intertidal marshes. Ice formation may damage plants.
Pacific Northwest	Large tidal fluctuations may preclude intertidal marshes in some areas. Ice formation may damage plants.
Pacific Southwest	Select appropriate species based on salinity and marsh elevation.
Hawaii & Pacific Islands	Intertidal marshes not widespread.

MARSH (SILL)

The construction of a marsh, including fill and plantings, fronted by toe protection in the intertidal zone of a shoreline.

Design Schematics



Overview of Technique

Materials

Native marsh plants appropriate for the site conditions (e.g., tide range, salinity, wave energy) along with sediment, if necessary, to build a platform of gradual slope at an appropriate elevation for the marsh to sustain itself. Toe protection is provided around the edge of the marsh, usually in the form of a rock revetment. Other materials have been used for toe protection as well.

Habitat Components

Salt marsh habitat, potentially with oyster habitat on the structural elements.

Durability and Maintenance

Maintenance is most important early in the life of a marsh. Waterfowl can damage young plants, and lost plants must be replaced quickly to ensure the health of the entire marsh. After the early stages, invasive species and runoff issues can affect long-term success. Sill maintenance is typically very low.

Design Life

Stone sills have an indefinite design life and do not require replacement. Timber sills will require complete replacement after 20 to 30 years because of degradation. Coir logs and similar edging materials used as toe protection will naturally biodegrade over the span of a few years, during which time the restored marsh should have stabilized.

Ecological Services Provided

Marshes provide a number of ecological benefits. They can filter water, including runoff, and they increase the uptake of nutrients, filtration, denitrification, and sediment retention. The root systems of marsh vegetation help stabilize the soil they inhabit, reducing erosion. The marsh platform and plant stems attenuate wave energy, further reducing erosion risk.

Case Study

Restoration of low and high marsh along North Mill Pond, in Portsmouth, NH, with about half of the area consisting of new marsh creation, and the other half of the area consisting of restoration of degraded low and high marsh through sediment addition. The purpose of this project was to re-establish the natural, intertidal marsh shoreline.

Photo courtesy of David Burdick

Project Proponent	City of Portsmouth, Stantec (wetlands consultant), University of New Hampshire (assisted plan development)
Status	Completed (May 2016)
Permitting Insights	NH Dept. of Environmental Services and USACE permits for drainage outfall into pond. Affected 600 square feet of coastal wetland; salt marsh restoration used as mitigation.
Construction Notes	Imported fill to create marsh platform, planted 3,055 square feet of high marsh area. Created microtopography and interior drainage channels. 12-inch diameter coir logs staked at seaward edge of marsh to stabilize toe. Large boulders used to break up winter ice sheets.
Maintenance Issues	Survival of low marsh plants is good; survival of high marsh salt hay is fair to poor. Survived 2016–2017 winter well.
Final Cost	$60,000
Challenges	Construction did not have a provision for within plot drainage; many plants were washed out by runoff gullies during the first year.

MARSH (SILL)

The construction of a marsh, including fill and plantings, fronted by toe protection in the intertidal zone of a shoreline.

Photo courtesy of VIMS

Photo courtesy of Bret Webb

Implementation Notes

Summary of Benefits

Marshes provide a variety of ecological benefits, generally improving water quality and reducing erosion risk while providing habitat for a variety of species. The marsh is stabilized with toe protection in the form of a sill.

Challenges

The flood risk-reduction and wave attenuation benefits of marshes depend heavily on the water level. Marshes best attenuate waves when the water surface elevation is below the tops of the plantings, and what flood reduction benefits they have are maximized at higher water levels.

Initial Cost

Upfront costs will focus on the procurement of sediment and plantings for the marsh area, as well as the toe protection material and any preventative measures such as bird exclusionary fencing. Likely initial cost of $150–340 per linear foot of marsh with sill.

O&M Cost

Maintenance costs will likely include the removal of dead plants and debris from the marsh and the planting of new plants, especially early in the life of the marsh.

Transportation and Other Benefits

Issue	Description
Flooding Reduction	Low, some reductions to flooding caused by reducing wave action
Wave Attenuation	Medium, marsh platform and plant stems break waves
Erosion Reduction	Medium, root systems hold soil in place
Multi-Benefits	High, creates/restores habitat, educational opportunity
Locale	Various, adaptable to site
Elevation + Slope	Low/Medium + Low/Medium, most valuable in the intertidal zone
Width	High, the area of marsh created is an important metric of success

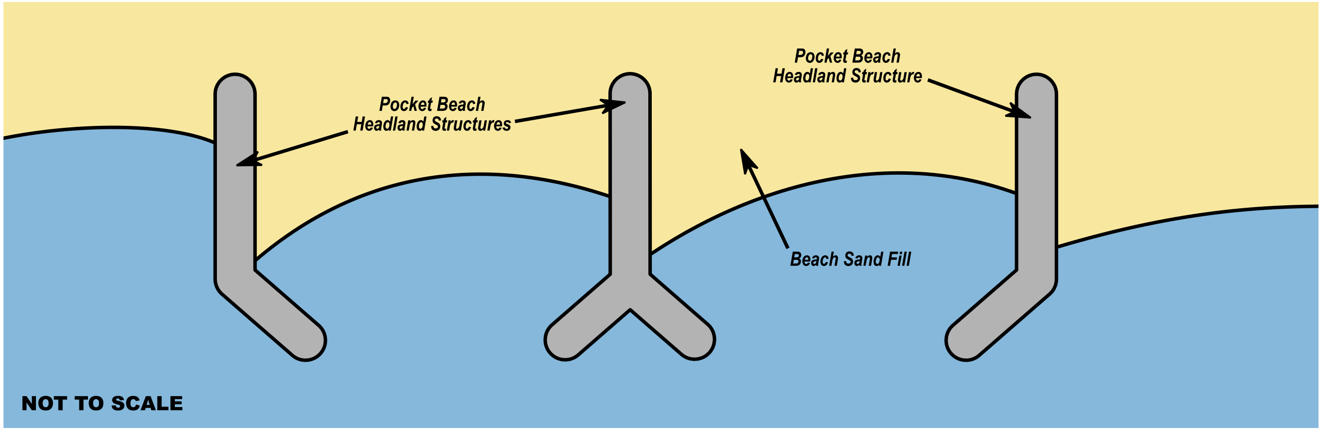
Regional Facts

Issue	Description
Gulf of Mexico	Small tide range easily accommodates sill design. Timber structures have a limited life.
Southeast	Vertical sills occasionally used to minimize impacts to benthic resources. Marsh sills may incorporate oyster shell in some way.
Mid-Atlantic	Long record of successful stone sills. Designs range from continuous to segmented.
Northeast	Large tidal fluctuations may increase sill size and cost. Impact of ice formation on sill materials is a concern.
Great Lakes	Large lake-level fluctuations may increase size and cost. Low water levels undermine foundations. Impact of ice formation on sill materials is a concern.
Pacific Northwest	Large tidal fluctuations may increase sill size and cost. Impact of ice formation on sill materials is a concern.
Pacific Southwest	Sills may need to accommodate large tide ranges and long fetches.
Hawaii & Pacific Islands	Likely not applicable to these areas.

POCKET BEACH

Beach nourishment coupled with the installation of headland breakwater structures to slow the movement of sand out of the project area.

Design Schematics



Overview of Technique

Materials

Sand is sourced from an offshore borrow area, an upland sand pit, or a coastal dredging project. The grain size distribution of the fill sand is an important consideration and should closely match that of the native beach sand. Headland structures can be built from a variety of materials; however, rock is most common, especially for high-energy environments. Timber is a useful, lower cost option for low wave energy locales.

Habitat Components

As with beach nourishment, pocket beaches can provide habitat for foraging shorebirds and nesting sea turtles.

Durability and Maintenance

The proper application of headland structures should dramatically improve the stability and longevity of the beach fill. Some pocket beaches create enclosed, isolated littoral cells where little, if any, sand is lost to longshore sand transport. Correct sizing of the armor stone for the native wave environment is crucial to the stability of the structures and the beach as a whole. The use of standard riprap is typically inadequate.

Design Life

The headland structures should increase the design life of the beach project practically indefinitely. Sea level rise will eventually increase the wave forces the headlands experience, so this should be a consideration in design. Ongoing erosion updrift or downdrift could flank shore-perpendicular structures or affect the incident waves that the structures experience.

Ecological Services Provided

The beach fill itself provides additional beach habitat. The structural elements attenuate waves and improve the stability of the beach, which, in turn, can also attenuate waves during storm events for upland resources.

Case Study

Perdido Bay, AL, Pocket Beach between two timber and sheet-pile bulkheads. This beach was built on the property of a single homeowner to restore a beach on a stretch of shoreline that is heavily armored by individual bulkheads.


Photo courtesy of Scott Douglass

Project Proponent	Homeowner
Status	Completed (2018)
Permitting Insights	Easement for a non-existent county road runs just bayward of the site.
Construction Notes	Neighboring bulkheads were used with permission as the landward anchor points for the headlands (cost to homeowner reduced).
Maintenance Issues	None noted. The beach is an isolated littoral cell. As a small scale, homeowner-level project, this beach needed to be "fire and forget," as there is no guarantee the homeowner will maintain it.
Final Cost	$40,000
Challenges	Ensuring that the beach will be monitored in the future.

POCKET BEACH

Beach nourishment coupled with the installation of headland breakwater structures to slow the movement of sand out of the project area.

Photo courtesy of VIMS

Photo courtesy of Scott Douglass

Implementation Notes

Summary of Benefits

Combined approach of beach nourishment and headland structures stabilizes the beach project significantly.

Challenges

The inclusion of structural elements (especially those that are partly shore-perpendicular) that may trap sand is a hurdle to permitting. The pocket beach must be designed to improve the stability of the beach with minimal impact to adjacent shorelines.

Initial Cost

Upfront costs will focus on the procurement of sand and construction of the headland structures.

O&M Cost

When properly designed and constructed, a combination of structures and beach should be more stable than a typical beach nourishment project.

Right-of-Way Issues

Conversion of submerged lands to emergent dry beach may cause the property interest to revert to the State, which is both a regulatory concern and can be an implementation barrier. Almost every project requires temporary construction easements to work on/over/across private property.

Transportation and Other Benefits

Issue	Description
Flooding Reduction	High, protects upland resources during storms
Wave Attenuation	High, protects upland resources during storms
Erosion Reduction	High, beach fill should be very stable
Multi-Benefits	High, creates/protects habitat, recreational use
Locale	Various, adaptable to site
Elevation + Slope	Various + Various
Width	Moderate to High

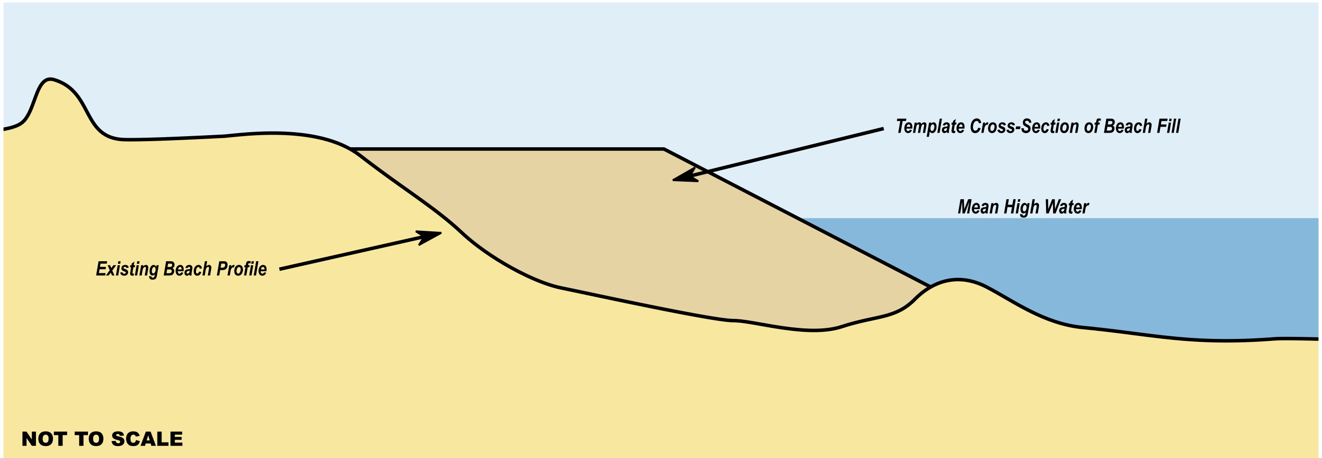
Regional Factors

Issue	Description
Gulf of Mexico	Cultural resource issues (e.g., submerged sites or artifacts of historical significance) may limit activities. Availability of suitable armor stone is poor. Use of limestone requires larger rock for stability.
Southeast	Cultural resource issues may limit activities. Availability of suitable armor stone is poor. Use of limestone requires larger rock for stability.
Mid-Atlantic	Cultural resource issues may limit activities. Use of structures may require mitigation for impacts on benthic resources.
Northeast	High tide ranges and long fetches may increase the cost of structural elements. Regulatory restrictions may limit the use of structures.
Great Lakes	Large lake-level fluctuations and long fetches may increase the cost of structural elements. Extreme low water conditions may undermine foundations.
Pacific Northwest	High tide ranges and long fetches may increase the cost of structural elements.
Pacific Southwest	High tide ranges and long fetches may increase the cost of structural elements.
Hawaii & Pacific Islands	High tide ranges and long fetches may increase the cost of structural elements.

BEACH NOURISHMENT

The placement of large quantities of good-quality sand directly on the beach to restore the beach.

Design Schematics



Overview of Technique

Materials

Sand is sourced from an offshore borrow area, an upland sand pit, or a coastal dredging project (i.e., beneficial use). The grain size distribution of the fill sand is an important consideration and should closely match that of the native beach sand.

Habitat Components

Restored beaches provide habitat to a variety of species, including nesting and feeding habitat for shorebirds and nesting habitat for sea turtles.

Durability and Maintenance

Beach nourishment does not, by itself, resolve the causes of beach erosion, so restored beaches require maintenance through periodic renourishment. The renourishment interval, determined before construction, is a function of the existing erosion rate, beach fill project, and minimum design beach width. The renourishment volume is sacrificial and will erode during storm events and regular conditions.

Design Life

Subject to site-specific characteristics such as grain size distribution and beach slope, increasing the volume, elevation, and width of the beach berm enhances the longevity of the project. The estimated project half-life—the time required for 50 percent of the material to leave the project—is a function of the project length squared. Increasing the length of a project substantially increases the project's half-life. In some cases, structures are used to extend the half-life of a beach nourishment project.

Ecological Services Provided

Wide nourished beaches provide improved wave attenuation during storms for natural resources (dunes and other coastal habitats) and human infrastructure (roadways and structures). Sand may erode from nourished beach projects and migrate to other beach areas, improving the performance of local beaches.

Case Study

The Dauphin Island East End Beach and Barrier Island Restoration Project in coastal Alabama placed 320,000 cubic yards of sand on an eroding beach that protects a maritime forest, freshwater lake, and substantial upland infrastructure.

Photo courtesy of Sam St. John

Project Proponent	Town of Dauphin Island
Status	Completed (March 2016)
Permitting Insights	Extensive, detailed cultural resources survey in an offshore borrow area, interaction of State law and Federal policy with a U.S. Coast Guard facility within the project limits.
Construction Notes	Included rehabilitation of existing, detached, shore-perpendicular rock groins into breakwater headlands.
Maintenance Issues	Ongoing erosion mitigated by rock headland breakwaters; project has endured several tropical storms and hurricanes.
Final Cost	$6.7M
Challenges	Initial project grant funding was inadequate to cover all project costs. The project owner secured additional grant funding to cover the shortfall without compromising project design.

BEACH NOURISHMENT

The placement of large quantities of good-quality sand directly on the beach to restore the beach.

Photo courtesy of Tina Hodges

Implementation Notes

Summary of Benefits

Nourished beaches improve habitats, improve recreational and economic value, improve risk reduction factors, and help maintain the shoreline position.

Challenges

Borrow sand sources can contain historical or cultural resources, such as shipwrecks and other artifacts, which must be avoided. Construction activities can affect these and ecological resources, including habitat. Beach nourishment construction affects nesting activities, and often must occur outside of nesting seasons.

Initial Cost

Upfront costs include the procurement of beach fill material and dredge/equipment mobilization. These costs vary widely but are typically ~ $600–900 per linear foot for small to moderate projects. Dredge mobilization is often a considerable expense for small to moderate projects.

O&M Cost

Renourishment has similar requirements to the initial placement of beach sand. Renourishment volumes are often less than the original volume placed for the nourishment project, but mobilization costs remain unchanged.

Right-of-Way Issues

Conversion of submerged lands to emergent dry beach may cause the property interest to revert to the State, which is both a regulatory concern and can be an implementation barrier. Almost every project requires temporary construction easements to work on/over/across private property.

Transportation and Other Benefits

Issue	Description
Flooding Reduction	High, protects upland resources during storms
Wave Attenuation	High, protects upland resources during storms
Erosion Reduction	Medium, may require renourishment
Multi-Benefits	High, habitat, recreation, tourism, property values, etc.
Locale	Various, adaptable to site, but may require structural elements in some situations
Elevation + Slope	Various + Various
Width	High

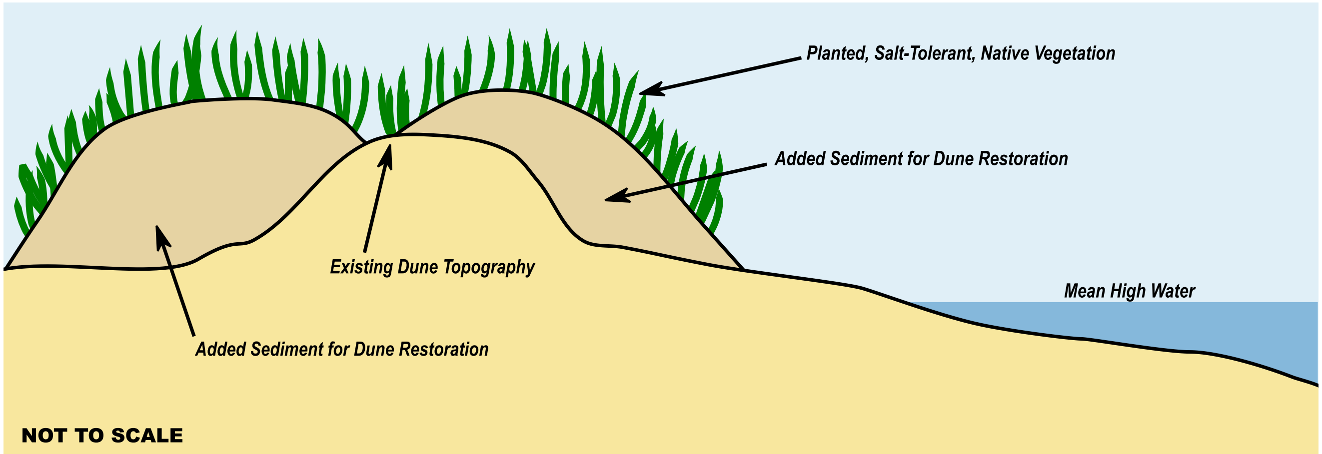
Regional Factors

Issue	Description
Gulf of Mexico	Cultural resources, oil and gas pipelines complicate offshore dredging. Working outside of turtle nesting season. Avoiding impacts on critical/essential habitat.
Southeast	Cultural resources, offshore reefs complicate offshore dredging. Working outside of turtle nesting season. Avoiding impacts to critical/essential habitat.
Mid-Atlantic	Cultural resources may complicate offshore dredging and/or onshore work.
Northeast	Cultural resources may complicate offshore dredging and/or onshore work.
Great Lakes	Regulatory restrictions for fill taken from or used beyond regulatory limit.
Pacific Northwest	Compatibility of borrow source material and mixtures of sand and cobble may complicate the project. Integration of beach with coastal bluffs is challenging.
Pacific Southwest	Avoiding impacts on critical/essential habitat. Integration of beach with coastal bluffs is challenging.
Hawaii & Pacific Islands	Cost and availability of borrow material, critical and endangered species protection, turtle nesting, cultural resource concerns, and offshore reefs result in complex project requirements.

DUNE RESTORATION

The placement of good-quality sand to either rebuild existing dunes or create an artificial dune by building up a mound of sand at the back of the beach.

Design Schematics



Overview of Technique

Materials

Sand is sourced from an offshore borrow area, an upland sand pit, or a coastal dredging project (i.e., beneficial use). The grain size distribution of the fill sand is an important consideration and should closely match that of the native beach sand.

Habitat Components

With incorporated grass plantings, restored or created dunes provide habitat for beach-going animals such as shorebirds.

Durability and Maintenance

Dunes with plantings are more stable and more resilient, so any planted grasses should be replaced if damaged. Dunes may lose sand or be damaged by waves during storm events and may need periodic placement of sand. Provide dune walkovers or designated paths to prevent foot traffic from destroying vegetation.

Design Life

Dunes at the rear of a beach that is dry at high tide will survive the longest. Without a significant beach seaward of the dune, the dune will erode quickly.

Ecological Services Provided

Dunes enhance existing beaches or beach nourishment projects by helping to keep sand on the beach (as opposed to blowing landward). When dunes are damaged by waves during storms, the "lost" material helps to replenish the sandy beach. Dunes act as a wave and flooding barrier during storms for upland resources. Dunes may also protect roads by burying them in sand during overtopping conditions.

Case Study

Relatively high beach and dune erosion (approximately 3 feet per year) prompted Ferry Beach Park Association (FBPA) in Saco, ME to undertake a dune restoration project to help protect roads and homes from flooding and erosion. Given the relatively high erosion rate, it was decided that placing sediment for restoration seaward of the existing dune would be short-lived. A secondary dune ridge landward of the existing dune crest was constructed instead, allowing native vegetation to establish.


Photo courtesy of Peter Slovinsky

Project Proponent	FBPA
Status	Completed (Spring 2009)
Permitting Insights	Permit-by-Rule needed from Maine Department of Environmental Protection
Construction Notes	Included 800-foot-long secondary dune built 1 foot above effective FEMA 100-year base flood elevation. Volunteers planted native American Beach grass.
Maintenance Issues	Sand fencing installed to help trap sand in the constructed dune. Continued shoreline erosion has eaten into the dune since May 2017.
Final Cost	$29,000+ volunteer hours
Challenges	Dump trucks hauling sand when passing through the community. Construction and planting timing restricted during piping plover nesting season.

DUNE RESTORATION

The placement of good-quality sand to either rebuild existing dunes or create an artificial dune by building up a mound of sand at the back of the beach.


Photo courtesy of Beau Buhring


Photo courtesy of Bret Webb

Implementation Notes

Summary of Benefits

Restored and created dunes offer wave and flooding risk reduction during storms, especially when coupled with an existing wide beach or a beach nourishment project. They also provide dry beach habitat.

Challenges

This approach depends on the existence of a wide beach, and similar to beach nourishment, borrow site investigations are needed. Construction will likely be structured around the nesting seasons of shorebirds.

Initial Cost

Upfront costs will focus on the procurement of sand and planting of grasses on the dunes. Low cost compared to, but often coupled with, beach nourishment.

O&M Cost

Varies by site and depends on the width of the adjacent beach, vulnerability to foot traffic, and maintenance of vegetation.

Right-of-Way Issues

Construction of dunes within the right-of-way is possible, but space constraints may reduce dune performance. Sand-filled geotextiles are often used to anchor dunes in narrow easements. The reinforced dune core also provides erosion mitigation during major storm events. Dunes constructed within utility easements will require special provisions for access to fire hydrants, utility boxes, and overhead power transmission lines.

Transportation and Other Benefits

Issue	Description
Flooding Reduction	High, protects upland resources during storms
Wave Attenuation	High, protects upland resources during storms
Erosion Reduction	N/A, often coupled with beach nourishment, may reduce erosion by replenishing beach
Multi-Benefits	Medium, provides habitat for animals, but not suitable for recreation or human use
Locale	Various, adaptable to site
Elevation + Slope	Various + Various
Width	High, wide beach needed for success

Regional Factors

Issue	Description
Gulf of Mexico	Beach-compatible material, vegetation type, dune walkovers
Southeast	Beach-compatible material, vegetation type, dune walkovers
Mid-Atlantic	Beach-compatible material, vegetation type, dune walkovers
Northeast	Beach-compatible material, vegetation type, dune walkovers, interaction with coastal bluffs
Great Lakes	Beach-compatible material, vegetation type, dune walkovers, interaction with coastal bluffs
Pacific Northwest	Beach-compatible material, interaction with cobble beach and sand veneer, interaction with coastal bluffs
Pacific Southwest	Beach-compatible material, vegetation type, dune walkovers, interaction with coastal bluffs
Hawaii & Pacific Islands	Beach-compatible material, vegetation type

2. RISK-REDUCTION PERFORMANCE, ECOLOGICAL BENEFITS, AND MONETARY COSTS

This section plays an important role in the rest of the guide, allowing readers to answer the question, *Why consider nature-based solutions for coastal highway resilience?* Feedback from transportation professionals during the regional peer exchanges (FHWA 2018b) underscored the importance of being able to communicate to stakeholders that nature-based solutions offer some risk-reduction potential, provide multiple benefits, and have reasonable costs. This section aims to provide that information and cites specific studies, reports, and other documents that underpin the characterization of nature-based solutions. This section begins with a summary of risk-reduction benefits relevant to coastal highways, namely the reduction of flooding, wave heights, and erosion. The reader then will learn about habitat, water quality, and the recreational benefits provided by nature-based solutions. The text then introduces the typical costs of nature-based solutions and concludes with a discussion on long-term performance, including the potential impacts of long-term sea level rise on nature-based solutions.

2.1 Risk-Reduction Benefits

Nature-based solutions reduce coastal flooding, wave heights, and erosion (Bridges et al. 2014; Cunniff and Schwartz 2015; Shepard et al. 2011; Spalding et al. 2014; Sutton-Grier et al. 2015, 2018; USACE 2015). Nature-based solutions provide flood-reduction benefits through a variety of physical and biophysical means (Narayan et al. 2016). For example, bottom friction and drag provided by vegetation, reefs, and inundated landscapes are effective at reducing flow velocities and wave heights. These reductions inhibit or lessen the potential for erosion and, in some cases, are effective at promoting sediment deposition (Shepard et al. 2011). Some nature-based solutions can adapt to sea level rise through trapping sediment or migrating inland to higher elevations (Spalding et al. 2014; Beck et al. 2018). The flood-reduction performance of nature-based solutions is sensitive to location, setting, and wave energy exposure.

Wave Attenuation
Coastal habitats reduce wave heights between 35 percent and 71 percent, and often are less expensive than coastal structures that provide similar benefits (Narayan et al. 2016).

The benefits of flood reduction (broadly summarized in Table 2-1) to coastal highway resilience include, but are not limited to the following:

- Decreased road or lane closures during flood events.
- Reduced road pavement damage.
- Reduced damage to bridges.
- Reduced erosion of roadway embankments.
- Decreased vulnerability to shoreline retreat.

Table 2-1. Summary of risk-reduction performance and resilience attributes by strategy (adapted with modifications from USACE 2015)

KEY High: Significant benefit Medium: Some benefit Low: Minimal benefit None: No benefit			**Risk-Reduction Benefit**			**Multiple Benefits[1]**	**Resilience**
			Flooding	**Wave Attenuation**	**Erosion**		**Adaptive Capacity[2]**
RESILIENCE MANAGEMENT STRATEGY	Policy (Non-Structural)	Acquisition	High	High	High	High	High
RESILIENCE MANAGEMENT STRATEGY	Policy (Non-Structural)	Retrofit	High	Low	Low	Low	Low
RESILIENCE MANAGEMENT STRATEGY	Policy (Non-Structural)	Land-Use Mgmt.	Medium	None	None	High	Medium
RESILIENCE MANAGEMENT STRATEGY	Structural	Floodwalls and Levees	High	Low	None	Low	Low
RESILIENCE MANAGEMENT STRATEGY	Structural	Storm Surge Barriers	High	Medium	None	Low	Low
RESILIENCE MANAGEMENT STRATEGY	Structural	Seawalls and Revetments	Low	High	High	Low	Low
RESILIENCE MANAGEMENT STRATEGY	Nature-Based Solutions	Beach Restoration (nourishment, dunes)	High	High	Medium	High	High
RESILIENCE MANAGEMENT STRATEGY	Nature-Based Solutions	Beach and Breakwaters	High	High	High	High	Medium
RESILIENCE MANAGEMENT STRATEGY	Nature-Based Solutions	Living Shorelines	Low	Medium	Medium	High	High
RESILIENCE MANAGEMENT STRATEGY	Nature-Based Solutions	Reefs	Low	Medium	Medium	High	High
RESILIENCE MANAGEMENT STRATEGY	Nature-Based Solutions	Marshes/ Mangroves	Low	Medium	Medium	High	High
RESILIENCE MANAGEMENT STRATEGY	Nature-Based Solutions	Maritime Forests	High	Medium	Medium	High	High

[1] Multiple benefits include socioeconomic contributions to human health and welfare above and beyond flood-reduction benefits, such as recreation, habitat, and water quality improvements.
[2] Measure of a strategy's ability to adjust to changing conditions and forces through natural processes, operation and maintenance, and/or adaptive management.

Saltwater Marshes

Saltwater marshes and similar coastal wetlands provide many direct 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 (FHWA 2018e). The capacity of marsh vegetation to provide these benefits changes with water level, growing season, and age. Manis et al. (2015) shows that some coastal wetland benefits increase over time as the marsh matures.

Marshes Reduce Damage
The annualized benefit of coastal wetlands for storm protection services in the United States alone is $23.2 billion (Costanza et al. 2008). During Hurricane Sandy, coastal wetlands averted $625 million in direct flood damages and nearby communities experienced 20 percent less property damage than those without coastal wetlands (Narayan et al. 2017; Sutton-Grier et al. 2015).

The reduction in wave height is non-linear and occurs quickly as waves interact with vegetation at the edge of the marsh. The rate of wave height decay diminishes with distance into the marsh (e.g., Anderson et al. 2013). Laboratory and field studies both confirm this rapid attenuation, with reductions in wave height on the order of 60 percent to 80 percent over an approximately 30-foot-wide span of emergent marsh grass (in the direction of wave travel) (Anderson et al. 2013), and up to 50 percent reductions in wave energy, which is proportional to the wave height squared, within the first 10 feet of the marsh edge (Knutson et al. 1982). This means that even relatively narrow marshes provide measurable wave attenuation benefits that can lead to reductions in wave-induced flooding, erosion, and/or damage. Coastal marshes are less effective at reducing wave heights during extreme events when water levels are above the height of the grasses, but are still more effective than bare, unvegetated mudflats (Garzon et al. 2019).

Wave height attenuation and velocity reduction are most pronounced when the plant height is large relative to the water depth. The substantial reductions in velocity translate to positive benefits, such as reduced erosion and sediment loss from the marsh surface. Shepard et al. (2011) demonstrate a strong positive correlation between the presence of marsh vegetation and sediment/shoreline stabilization, and note the role that belowground biomass, in the form of roots and rhizomes, plays in enhancing soil shear strength and resistance to erosion.

Tidal marshes can mitigate many forms of storm flooding that affect coastal highways. Marshes are most effective at reducing wave-induced flooding given their ability to attenuate wave heights. Wave-induced flooding affects coastal highways through wave runup on slopes and embankments, wave overtopping, and through wave setup along the shoreline. Because of their ability to reduce wave heights and wave-induced flooding, coastal marshes can be effective nature-based solutions for improving the resilience of flood protection systems, such as levees. As cited in Saleh and Weinstein (2016), van Heerden (2007) notes the mitigative role that coastal marshes played in protecting levee systems during Hurricane Katrina in 2005.

In addition to reducing wave heights, marshes mitigate storm flooding by slowing the flow of water as it travels over the marsh, as mentioned in the preceding paragraph. While marshes can reduce storm surge depths during fast-moving storms, substantial reductions require large expanses of habitat that often do not exist in urban settings (Saleh and Weinstein 2016). For example, achieving a flood depth reduction of 3 feet may require up to 1 mile of coastal marsh (Paquier et al. 2017). Marshes are less effective at mitigating flooding during astronomical tides or increased high tides from sea level rise until, or unless, the marsh has migrated to a higher elevation. This is because the inundation during high tide progresses too slowly for drag or friction to play a significant role.

Mangroves

Mangroves and mangrove forests provide flood-reduction benefits similar to those of saltwater marshes. Their complex root structure and canopies are known to reduce wave heights, wave runup, storm surge, and tsunami runup (FHWA 2018e; Spalding et al. 2014). The magnitude of wave height attenuation depends on the density and size of the mangrove forest. Wave height reductions ranging from 20 percent to more than 50 percent per 100 meters (~330 feet) of mangrove forest are possible (Hashim and Catherine 2013; Mazda et al. 1997; Zhang et al. 2012). Similar 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).

Mangroves Reduce Damage

Barbier (2016) found that the protective benefits of mangroves vary between $750 and $2,300 per acre in reduced storm damages, and they also reduce the potential for loss of life in some cases.

Large stands of mangroves reduce storm surge and surge-like features (e.g., tsunami runup). Studies by Krauss et al. (2009) and Zhang et al. (2012) report surge decay of 0.5 to 2.6 feet per mile depending on the density of mangroves. As much as 30 percent of the surge decay occurs quickly over the edge of the mangrove stand (Zhang et al. 2012). Ismail et al. (2012) show that mangroves reduce tsunami runup by 36 percent within 100 meters (~330 feet) of their edge, and up to 50 percent within twice that distance. This protection significantly reduces storm damages (see text box above) (Barbier 2016).

Maritime Forests

The term *maritime forest* refers to an upland coastal forest of trees and shrubs. 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. A 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 1,000-foot-wide stand of vegetation perpendicular to the coast. Shorelines with established forests can reduce flooded areas by as much as 30 percent when compared to shorelines without forests (Kalakan et al. 2016). The implementation of coastal forests for tsunami runup mitigation also shows positive benefits (Irish et al. 2014), as did their presence during a major tsunami event in Japan (Nateghi et al. 2016).

Preservation Opportunities

Maritime forests play an important role in coastal resilience when displacing or discouraging development in high hazard areas. As a mitigative tool, their implementation may be less desirable as their benefits accrue slowly. Active preservation of maritime forests along transportation corridors is likely a more effective resilience strategy.

Reefs

The annual value of flood risk reduction provided by coral reefs in the United States is more than 18,000 lives and more than $1.8 billion in 2010 U.S. dollars (Storlazzi et al. 2019). Reefs provide positive flood benefits by reducing wave heights, moderating nearshore currents, and subsequently reducing coastal erosion. Reefs attenuate waves through transmission, breaking, and friction (Spalding et al. 2014). Coral reefs reduce wave heights by 70 percent, on average (Narayan et al. 2016). The protective services provided by coral reefs are expected to increase with sea level rise (Beck et al. 2018).

Benefits of Coral Reefs
In the United States alone, coral reef systems avert as much as $94 million annually in damages from extreme events. These protective services are expected to increase with sea level rise (Beck et al. 2018).

Because of their ability to reduce wave heights, reefs also modify patterns of sediment erosion and deposition. However, unhealthy or damaged reef systems can have the opposite effect. In one case, the deterioration of a coral system resulted in enhanced shoreline erosion and damage to coastal infrastructure (Reguero et al. 2018a).

Reefs may be intertidal (submerged only at high tide) or subtidal (completely submerged at all tide levels). In either case, the wave transmission characteristics of natural reefs are like 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 the calculation of their transmission coefficients; examples include d'Angremond et al. (1997) and van der Meer et al. (2005). However, some artificial oyster reef restoration projects rely on the use of habitat structures that do not provide the same wave-attenuating capabilities as natural reefs or breakwaters (Servold et al. 2015; Webb and Allen 2015). The controlling factors are often the structure crest elevation relative to the mean sea level tidal datum, and the size of the structure relative to the incident wavelength.

Reefs do not contribute substantially to reductions in coastal flooding, although they do mitigate some forms of wave-induced flooding, such as wave runup and wave overtopping, by forcing the waves to break on the reef. Prolonged wave breaking increases the time-averaged water level at the shoreline through a process known as wave setup. Shorelines adjacent to natural reef systems respond to wave setup and establish an equilibrium over time.

When used as a form of shoreline stabilization, oyster reef restoration shows some promise in low wave energy environments (Piazza et al. 2005), under environmental conditions that are reflective of their needs (i.e., appropriate levels of salinity and sedimentation). This is likely because oyster reef restoration, to date, has not been performed on a scale large enough to provide major reductions in wave energy. When oyster reef restoration is combined with more traditional forms of coastal engineering protection, such as engineered breakwaters, shoreline stabilization is a realistic goal (Sharma et al. 2016).

Beaches

The greatest flood protection benefit of a beach is wave attenuation (Spalding et al. 2014). The buffering distance it provides in between the shoreline and built infrastructure serves as an indirect benefit, giving waves more space to dissipate their energy. On their own, beaches are not necessarily a form of erosion control: they erode naturally! Beach nourishment and periodic renourishment are used to mitigate shoreline retreat and the reduction of the protective buffer that it provides. The appropriate use of coastal structures, such as breakwaters, groins, and combinations thereof, can substantially extend the life and performance of beach fill projects (NRC 1995).

The distance from the coast is a significant predictor of infrastructure damage (Hatzikyriakou et al. 2016; Walling et al. 2014, 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. Post-storm assessments following Hurricane Sandy demonstrate this concept: structures behind wider beaches sustained less damage than those behind narrow beaches or beaches with lower berm elevations (Barone et al. 2014; Griffith et al. 2014).

Dunes

Sand dunes provide protective benefits during storm events by blocking or reducing storm surge flooding and wave action. Dunes function as sacrificial volumes of sand that minimize storm impacts until the dunes are eroded by waves or overtopped by storm surge. 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 with sand fencing and vegetation trap and stabilize sand, leading to increases in dune volume and dune height over time. Through physical modeling of vegetated dunes in the laboratory, Bryant et al. (2018) show that the combination of belowground and aboveground vegetation biomass reduced the loss of dune volume by a factor of three when compared to an unvegetated dune during a wave overwashing event. Additional literature regarding the positive impacts of vegetation on dune performance are cited and described in Bryant et al. (2017).

Combinations of Nature-Based Features

Nature-based solutions possess some inherent capacity to reduce storm hazards through reductions in wave height, flood depth and extent, and erosion. These natural systems are most effective at mitigating hazards of low to moderate intensity. It also is worth considering combinations of nature-based solutions (depending on the regional setting), which recent studies show often yield benefits beyond those achieved by individual nature-based features. For example, a study by Manis et al. (2015) finds that combining a restored oyster reef with marsh vegetation has a greater impact on reducing wave energy than either approach by itself. Similarly, work 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. In addition, combining beach nourishment with dune construction/restoration typically yields a wider range of benefits than beach nourishment alone (Rogers 2000).

Hybrid Solutions

It may be prudent to consider hybrid solutions when coastal hazards and wave action are characterized by high intensity, or when coastal infrastructure is critical, sensitive, or lacking redundancy. Hybrid approaches, which combine nature-based approaches with traditional engineered coastal infrastructure, may provide higher levels of protection from coastal hazards while simultaneously enhancing the resilience of both the infrastructure and the ecosystem. In these cases, the structural features may improve the reliability and/or performance of the system while also providing the specific hazard-reduction benefits that a nature-based solution, on its own, may not. Examples of hybrid approaches are listed below. Under each example is a brief description of services provided by the natural element, and services performed by the structural element, in order of significance:

When To Go Hybrid
When fetch length *exceeds about 1 mile*, most nature-based solutions will require some structure to attenuate wave energy and/or stabilize shoreline sediments. These structures provide additional infrastructure resilience and those benefits can be substantial.

- **Constructed Marsh With a Stone or Timber Sill**
  - Natural feature: Stabilize sediment, enhance habitat, improve water quality, attenuate the energy of small waves, reduce water velocity.
  - Structural element: Attenuate incident wave energy, stabilize the toe of the slope, enhance sediment deposition, protect or enhance habitat.
- **Marsh/Mangroves With Breakwaters, Reefs, or Habitat Devices**
  - Natural feature: Stabilize sediment, enhance habitat, improve water quality, attenuate the energy of small waves, reduce water velocity.
  - Structural element: Attenuate and/or redirect incident wave energy, stabilize the shoreline, enhance sediment deposition, enhance habitat.
- **Beach Nourishment With Breakwaters and/or Groins**
  - Natural feature: Advance shoreline seaward, reduce flooding, attenuate wave energy, enhance habitat.
  - Structural element: Attenuate and/or redirect incident wave energy, stabilize the shoreline, protect or enhance habitat.
- **Constructed Dunes With Reinforced Cores**
  - Natural feature: Reduce flooding, reduce wave overtopping, trap wind-blown sand, enhance habitat.
  - Structural element: Stabilize dune position, prevent landward erosion following dune removal, reduce flooding, attenuate wave energy.

Some examples of beneficial combinations of nature-based solutions and engineering infrastructure are provided below:

- 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 sheet pile 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 may later be combined with a sheet pile wall or barrier along the edge of the pavement to prevent frequent future flooding (FHWA 2016b).
- The lower portion of a traditional riprap revetment, modified to accommodate a constructed intertidal marsh, submerged aquatic vegetation habitat, and nearshore segmented breakwaters, does not significantly alter the project cost and potentially saves more than $500,000 in compensatory mitigation costs (see Mobile Bay case study in Section 5.7).

2.2 Habitat, Water Quality, and Recreational Benefits

In addition to their flood-reduction benefits, nature-based solutions also provide habitat, water quality, and recreational benefits. Nature-based solutions provide habitat for juvenile finfish and shellfish and foraging opportunities for birds and mammals (Sharma et al. 2016). The habitat benefits are often related to an increase in the aquatic edge (i.e., the length of shoreline in contact with the waterbody) or shoreline, the provision of substrate for the settling and growth of shellfish, and the incorporation of structure that offers protection for juvenile species.

Don’t Forget the Co-Benefits
The co-benefits of nature-based solutions include habitats for commercial and recreational fish species, biodiversity enhancement, improved aesthetics, tourism, recreation, and improved water quality. These co-benefits can have an annual value of up to $100 billion (Sutton-Grier et al. 2018).

Nature-based solutions improve water quality by reducing available nitrogen and phosphorous in coastal waters, by reducing total suspended solids through deposition and trapping of sediments, and through increased light penetration to the seabed (e.g., Forand et al. 2015; Beck et al. 2017; Morris et al. 2018; Onorevole et al. 2018). The water quality benefits, nursery areas, and foraging opportunities offered by nature-based solutions directly enhance habitat for fish (Gittman et al. 2016a). Structural features, by themselves, do not typically provide these benefits (Bilkovic and Mitchell 2013). Sutton-Grier et al. (2018) compare the annual water quality and fish production value of nature-based solutions to that of seawalls and bulkheads, finding that the former is valued at $4,000 to $28,000 per acre per year, while the latter is effectively $0 per acre per year. Barbier et al. (2011) cites specific metrics for the water quality benefits provided by coastal marshes, with an estimated $785 to $15,000 per acre capitalized cost savings over traditional waste treatment systems in the United States (Breaux et al. 1995).

Nature-based solutions also provide positive recreational and aesthetic benefits that traditional infrastructure does not. The habitat and water quality benefits combine to produce beneficial opportunities for recreational fishing, kayaking, paddle boarding, and bird watching. Providing appropriate access to accommodate these activities is often a consideration in the project design phase.

Table 2-2 summarizes the provision of ecosystem services, using relative terminology, to habitat provision, nutrient uptake, food production, biodiversity, recreation, and aesthetic value. Nature-based solutions also can provide other co-benefits that are not listed in Table 2-2, such as improved tourism, education, and research opportunities (Morris et al. 2018). Some nature-based solutions—beaches, dunes, mangroves, marshes, and seagrasses—also sequester carbon (Davis et al. 2015; Morris et al. 2018).

Table 2-2. Ecosystem services provided by structural features and nature-based solutions (adapted with modifications from NRC 2007)

Ecosystem Services		Structural Features			Nature-Based Solutions						
Key Contribution to Ecosystem Services: ● High ◉ Moderate ○ Low – Irrelevant		Bulkheads and Seawalls	Revetments	Breakwaters and Sills	Beaches	Dunes	Marshes and Mangroves	Seagrasses	Reefs	Beach Nourishment	Marsh/Mangrove Restoration
Habitat	Fish	○	◉	●	○	○	●	●	●	◉	●
	Mollusks	◉	◉	◉	●	○	●	●	–	◉	●
	Crustaceans	–	○	○	◉	○	●	●	◉	○	●
	Turtles	–	–	–	●	◉	○	◉	◉	◉	○
	Birds	–	–	–	◉	●	●	○	–	◉	●
Nutrient Uptake and Cycling		○	○	○	◉	○	●	●	○	○	●
Food Production		○	○	○	○	○	●	●	◉	○	●
Biodiversity		○	○	○	◉	●	●	●	●	○	●
Recreation		◉	○	◉	●	●	●	●	●	●	●
Aesthetic Value		–	–	–	●	●	●	●	○	●	●

2.3 Typical Monetary Costs

The typical costs of nature-based solutions vary widely in the literature. Some costs include materials only, while others factor in labor and/or possibly other costs. There is, however, a positive correlation between project cost and exposure to wave energy. In other words, as wave exposure increases, so does the project cost. Project costs and benefits also may depend on the amount of risk reduction allocated to the nature-based solution, and how that may change over time with future sea level rise. A study by Reguero et al. (2018b) analyzes some of these issues through an analysis of cost-effectiveness for nature-based and coastal adaptation techniques along the U.S. Gulf Coast. With the exception of local levees and beach nourishment in some parts of Texas, nature-based approaches provided far more cost-effective mitigation than increasing the elevation of infrastructure. Table 2-3 provides one representative example of average low, median, and high erosion control costs as a function of wave energy exposure. This table was adapted from Luscher and Hollingsworth (2007) with modifications. Average low, median, and high costs were found in the published literature. Under the "Condition" heading, depth refers to the water depth adjacent to the shoreline or bank; fetch refers to the distance along the surface of the adjacent water body over which wind can blow to generate waves; and erosion rate refers to the rate of shoreline retreat rather than vertical elevation change.

Table 2-3. Summary of conditions and project costs as a function of wave energy (adapted with modifications from Luscher and Hollingsworth 2007)

Condition	Wave Energy								
	Low			Moderate			High		
Shoreline Location	Creek or Cove			Tributary			Estuary, Sound, Bay		
Depth (feet)	< 1			1–4			4–15		
Fetch (miles)	0.5–1.0			1.0–2.0			> 2.0		
Erosion Rate (feet/year)	< 2			2–8			8–20		
Erosion Control Treatment	Bank Regrading, Beach Fill, Vegetation, Edging			Vegetation + Structure, Beach Fill + Structure			Beach + Structures, Shoreline Hardening		
Average Cost ($/linear foot)	Low	Med	High	Low	Med	High	Low	Med	High
	78	182	286	117	360	603	457	711	966

More than 60 reference documents, reports, and publications reviewed for this study contain some cost information regarding shoreline stabilization structures, natural features, and nature-based solutions. Of those, approximately 39 provide useful data and/or are not duplications of information presented in other documents (see Section 10 for citations of the materials used in this analysis). Table 2-4 summarizes the average low, median, and high cost information extracted from these documents. The documents' publication years range from 2000 to 2018, so the cost information is relatively recent. The cost data are reflective of all major regions of the United States, including the Northeast, Mid-Atlantic, Southeast, Gulf of Mexico, Great Lakes, Pacific West, and Pacific Northwest. These cost data generally include materials and installation.

Table 2-4 does not list costs for every structure or technique found in the literature. Examples of other commonly used features include gabions (low/median/high: $120/$135/$150 per linear foot), and geotubes (low/median/high: $50/$125/$200 per linear foot). The review documents also contained the costs of live stakes, root wads, large woody debris, fascines, and policy measures; however, they are not reported here as the sample numbers were typically less than two.

The true cost of nature-based solutions should consider more than capital costs. NRC (2007) recommends evaluating nature-based solutions using seven different metrics:

- Capital costs
- Operating costs, including monitoring and maintenance (Section 8)
- Probability that the actions will reduce/eliminate erosion for *N* years
- Impacts (positive and negative) on adjacent upland properties
- Impacts (positive and negative) on public uses
- Impact on ecosystem services
- Aesthetics

A competent professional with expertise in erosion control projects can assess the first five items on this list. Assessing the impact on environmental benefits is often performed by assigning values to specific functions performed by the system. A method for assigning these values is described in NRC (2005), *Valuing Ecosystem Services*.

Figure 2-1. A constructed, vegetated dune protects this low-elevation barrier island roadway during storm events (photo courtesy of Bret Webb).

Table 2-4. Summary of costs for shoreline hardening, structural features, and nature-based solutions

Costs typically include materials and installation.			Number of Samples (*N*)	Average Costs ($/linear feet)		
				Low	Median	High
RESILIENCE MANAGEMENT STRATEGY	Shoreline Hardening	Bulkheads (unspecified)	12	394	872	1,349
		Vinyl Bulkheads	3	125	163	200
		Vinyl Bulkheads With Toe Protection	4	333	361	389
		Timber Bulkheads	6	208	237	265
		Timber Bulkheads With Toe Protection	5	305	332	360
		Sheet Pile Bulkheads (steel)	5	616	766	916
		Seawall (concrete, masonry)	12	1,481	1,717	1,952
		Other Walls (e.g., cribs, specialty)	6	398	423	448
		Revetments	28	417	569	721
	Structures	Breakwaters (stone)	20	279	388	496
		Groins	2	618	1571	2,525
		Sills	16	301	320	340
		Proprietary Habitat Units	19	391	403	415
	Nature-Based Solutions	Living Shorelines (unspecified)	10	355	491	627
		Marsh + Sill/Breakwater	11	157	246	336
		Beach Nourishment (small to moderate)	17	613	802	992
		Bioengineering Activities	5	126	187	248
		Oyster Reefs	6	203	294	386
		Coir Logs	5	56	66	76
		Vegetation Only	18	68	90	113

2.4 Long-Term Performance

The body of knowledge related to nature-based solutions is less than 40 years. Some of the earliest nature-based solutions were constructed in the early 1980s in the State of Maryland on the Chesapeake Bay and its many tributaries. These “living shorelines” typically consisted of some bank regrading, placement of fill where necessary, the use of appropriate marsh vegetation, and the use of stone sills where appropriate. Initially, estimated project lifespans were equivalent to the 25-year loan terms used to finance and cost-share the living shorelines. In their retrospective of 258 living shoreline projects in Maryland, Subramanian et al. (2006) estimate that these projects have stabilized more than 117,000 feet of intertidal shoreline, prevented nearly 50,000 tons of sediment per year from entering the coastal waters, created more than 2.3 million square feet of tidal wetlands, reduced nitrogen by more than 41,000 pounds per year, and reduced phosphorous by more than 27,000 pounds per year. Many of these early projects are still doing well today, much more than 25 years following their construction.

The long-term performance and success of nature-based solutions is a function of the following, at a minimum:

- Accurate assessment of site conditions
- Selection and use of appropriate materials (vegetation, fill, and structure)
- Appropriate project design
- Preventative and reactive maintenance
- External influences, including the impacts of other nearby projects
- Extreme event frequency and magnitude
- Sea level rise

The practitioner/designer can somewhat control the first four items on this list. To a certain degree, addressing these first four items will minimize the potential negative impacts associated with the last three items. If the project design is sound, and materials do not degrade in the marine environment, the lifespan of a nature-based solution may be indefinite (Faulkner 2010). However, failures in other areas, such as not accounting for the impacts of sea level rise or the lifespan of materials, could significantly shorten this “indefinite” timeframe.

Adaptive Capacity
Natural systems can adapt to sea level rise in some circumstances. For example, marshes can trap sediment and increase in elevation or migrate inland in response to sea level rise. Oyster reefs respond to sea level rise by increasing their elevation to maintain their exposure relative to tide range.

Sea level rise (SLR) will impact the long-term performance of nature-based solutions and the protective benefits they provide. Understanding these impacts is important in both the planning and design phases of project implementation. Sea level position, particularly local rates of relative sea level rise (RSLR), is a controlling factor in many nature-based solutions: It controls shoreline position, as well as the elevation of tidal datums, such as mean low water (MLW), mean sea level (MSL), and mean high water (MHW), that serve as important ecological benchmarks for some species. Practitioners should consider both historical and projected future rates of RSLR in the planning and design of a project.

Historically, global MSL has risen by 7 to 8 inches since 1900, with approximately 3 of those inches occurring since 1993. Future projections of global mean SLR, relative to sea level position in 2000, range from 1.0 to 4.3 feet by 2100. Projections of global mean SLR exceeding 8 feet by 2100 are scientifically plausible, although the probability of such an extreme outcome is currently unknown (USGCRP 2017).

The effects of global mean SLR will be unique along the U.S. coastline because of local and/or regional processes. At any one location, the combination of global mean SLR and other processes is RSLR. In most areas of the United States, rates of RSLR exceed the global average because of land subsidence. The reader is directed to FHWA (2019a) for additional information on selecting and applying future RSLR projections in the planning and design of coastal highways. These same recommendations are useful for the planning and design of nature-based solutions.

Nature-based features possess an inherent ability to adapt to SLR, particularly when they have room to migrate or expand to higher elevations. Mitchell and Bilkovic (2019) refer to a “dynamic design” concept that leads to resilient projects. In their paper, they stress the importance of embracing the dynamic characteristics of these projects in order to allow their adaptive capacity to enhance their resilience. If SLR rates exceed adaptive capacity, inland migration space is not available, and retreat of the infrastructure is not possible, then direct action is necessary. Direct action may come in the form of the following:

- Addition of sediment to meet target elevations for vegetation[1]
- Addition to, or expansion of, reefs to meet tidal exposure requirements (e.g., oyster and coral reefs)
- Addition to, or expansion of, structures to meet wave attenuation goals (e.g., marsh sills, breakwaters)
- Periodic renourishment of beaches and dunes through the direct placement of beach-quality sands

The following sections describe the adaptive features and limitations of several nature-based features, as well as actions that can be taken to improve long-term performance.

Marshes

In tidal marshes, sediment settles out of the water column and onto the surface of the marsh during periods of tidal flooding. Deposition rates are highest in low-elevation marshes that are inundated for long periods of time (Kirwan and Megonigal 2013). The balance of plant root growth and decay directly adds organic matter to the soil profile, raising elevation by sub-surface expansion. Sediment deposition rates, vegetation growth, and organic matter accumulation tend

[1] Beneficial use of dredged sediment and thin layer placement are described in O’Donnell, et al. (2018).

to increase with flooding duration and the rate of SLR (Kirwan et al. 2016).

Adaptation to Sea Level Rise

Some studies suggest that marshes could possibly keep pace with RSLR rates as high as 1.2 centimeters per year, but only under optimal conditions (Morris et al. 2002). This rate is more than three times the current rate of global SLR. Under the NOAA Intermediate-Low scenario, this rate is more than the projected RSLR rates through the end of this century at most U.S. locations. However, it is equivalent to the projected RSLR rates by mid-century at most U.S. locations under the NOAA Intermediate scenario (Sweet et al. 2017).

The rate of SLR that marshes can withstand is highly site-specific and heavily influenced by human impact, ranging from a few millimeters to several centimeters per year (Kirwan and Megonigal 2013). As found in a study of marshes in the Mid-Atlantic region, their survival under higher future rates of SLR depends on optimal hydrology and sediment supply conditions (Reed et al. 2008). Human activities that reduce the ability of marshes to adapt to SLR include activities that restrict sediment supply, such as construction of dams and reservoirs, and activities that contribute to subsidence, such as groundwater withdrawal, artificial drainage of wetlands, and oil and gas extraction. Factors that reduce the likelihood of marshes keeping pace with SLR include smaller tidal ranges and lower sediment supplies. The Gulf of Mexico and the Chesapeake Bay region have lost large areas of wetlands and are characterized by smaller tidal ranges, lower sediment inputs, fast rates of RSLR, and low elevations. The optimal conditions depend on the elevation of the marsh, tidal range, the supply of organic and inorganic sediment to the marsh, and the ability of the marsh to migrate to higher elevations over time (Kirwan and Megonigal 2013; Mitchell et al. 2017). Stevenson et al. (1988) suggest that reduced sediment input is possibly more damaging to marsh health than SLR alone.

Allowing room for marsh migration should be considered during project design. Development behind marshes, including roads, can restrict the ability of marshes to migrate (Titus et al. 2009a, 2009b). Providing a vegetated buffer adjacent to a coastal highway may allow the marsh to migrate landward, and to higher elevations, as it adjusts to changes in local MSL (Kirwan et al. 2016). The use of structural elements in nature-based solutions that would impede the migration of the marsh could interfere with its effectiveness over time. A revetment on an embankment above a marsh would prevent lateral and vertical migration of the marsh over time, causing it to drown in place. Accounting for these types of incompatibilities between nature-based features and engineering infrastructure will ultimately determine the co-benefits produced over time.

Thin layer placement—a method of artificially adding sediment to a marsh to meet target elevations for vegetation—can help marshes adapt to rising levels (Figure 2-2). For example, USACE used dredged material to increase the elevation of marshes in Blackwater Wildlife Refuge by 4 to 6 inches in order allow the marsh to keep pace with SLR (Bridges et al. 2018).

Figure 2-2. Thin layer placement of dredged material (photo courtesy of USACE 2019b).

An FHWA-funded pilot study with USACE (FHWA 2018c) analyzed the potential for thin layer placement to restore areas of marsh surrounding Great Bay Boulevard in Tuckerton, NJ, and reduce flooding of the roadway (Figure 2-3).

Figure 2-3. Flooding of Great Bay Boulevard during high tide (FHWA 2018c).

SLR can increase erosion of the marsh edge because increases in water depth reduce the amount of dissipation that occurs as incoming waves move across tidal flats (Kirwan and Megonigal 2013). Adding structures such as marsh sills and breakwaters can be an adaptive measure to attenuate waves, reducing erosion by reducing the wave energy hitting the marsh edge and also allowing more sediment to settle out of the water column. Raising these structures over time is an additional adaptive measure.

Resilient Marsh Restoration Design

Marsh restoration projects implemented by the U.S. Fish and Wildlife Service as part of the U.S. Department of Interior Hurricane Sandy Resilience Program were designed to ensure future sustainability. Once such project, the Prime Hook National Wildlife Refuge marsh restoration project, will provide benefits to ecosystems and communities for 30 years or more. This project rebuilt about 1 mile of dunes and barrier island beach, restored 4,000 acres of back-barrier tidal marsh, and established more than 20 miles of tidal channels to improve tidal connectivity with Delaware Bay.

Reefs

Reduction in reef exposure—the amount of time the crest is above MHW—because of SLR may be particularly damaging to some oyster reefs (Ridge et al 2015). However, at least one study suggests that oysters are capable of outpacing SLR (Rodriguez et al. 2014). Providing substrate at higher elevations is one potential strategy for combating the impacts of future SLR on reef restoration. For example, increasing the crest elevation of a reef or reef structure will accommodate future SLR. In that manner, an emergent reef or reef structure will convert to an intertidal reef and then possibly to a subtidal reef over time if reef growth is outpaced by SLR. Yet another alternative is to design a reef or structure with a crest elevation suitable for current sea level conditions, but with a crest width that is large enough to accommodate the addition of material to its crest over time. Doing so allows the practitioner to optimize crest elevations for observed SLR instead of using SLR projections.

Ocean temperatures are known to affect coral reef systems. Rising ocean temperatures and ocean acidification decrease the long-term sustainability of coral reef systems (Hoegh-Guldberg et al. 2007).

Beaches and Dunes

Beaches have some natural capacity, depending on the sand supply, to keep pace with historical rates of SLR. Like coastal marshes, the ability of a beach to naturally respond to SLR depends on the availability of sediment and the ability to migrate landward. This is particularly true for barrier islands. Their ability to adapt to long-term SLR is governed by overwash during storms and natural island recovery during calmer periods. Established infrastructure, particularly coastal highways, may impede this process over time.

When retreat is not possible, beach nourishment and renourishment are excellent examples of direct actions that are incorporated in both the planning and design phases of a project to accommodate changes. Beach nourishment is an effective strategy used to combat shoreline retreat and erosion, and to reduce storm damage to upland infrastructure (Houston 2016). The presence of the infrastructure impedes the ability of the beach and dune system to retreat in response to anthropogenic, storm and SLR impacts. At the planning level, a management plan and financial commitment are established to maintain the feature over time. The maintenance frequency (i.e., renourishment interval) is determined during the design phase and adjusted during the life of the project as appropriate.

The required rates of nourishment vary by a factor of three from moderate to high future SLR projections. The costs of nourishment could therefore increase by similar amounts because of the increased volume of sand required to maintain shoreline position over time. Even if the increased project costs are appropriate for the benefits they provide, access to suitable quantities of beach-compatible sand is cited as a potential obstacle to long-term success (Parkinson and Ogurcak 2018). Therefore, the long-term viability of beach nourishment varies on a case-by-case basis, depending on site-specific requirements and reasonable projections of SLR and its impacts.

Traditional Structural Features

In contrast to nature-based solutions, traditional protective strategies lack the inherent ability to adapt to SLR over time. Bulkheads, revetments, and seawalls may be designed in such a way as to accommodate future SLR impacts. For example, you can increase the cap elevation of a seawall to accommodate a MSL position that is higher at the end of the expected project design life than at its beginning. One could elect to increase the armor stone used in a rock revetment to accommodate potentially larger wave heights in the future as depths at the structure increase with SLR. While accommodating SLR in infrastructure design is possible, the actual outcomes are uncertain. Furthermore, for much of its design life, that structure may possess more capacity than is required to meet resilience needs. This is one of the defining hallmarks that distinguishes traditional approaches from properly designed nature-based solutions: the latter have the capacity to adapt naturally over time, on their own, through biological, ecological, and geological processes.

3. PLANNING AND FUNDING

3.1 Transportation Planning

Incorporating nature-based solutions into transportation planning has several advantages, three of which are highlighted below:

Nature-based solutions could contribute to meeting transportation planning requirements. As covered in the section below on Federal Requirements and Relevant Policies, transportation agencies are required to consider approaches to increase the resilience of the transportation system.[2] Agencies also are required to include a discussion of potential environmental mitigation activities and potential areas in which to carry out these activities in their long-range transportation plans.[3] Where nature-based solutions are based on the existing habitat types in the project area, they have the potential to serve as environmental mitigation activities while increasing roadway resilience, which makes them a practical way to partially address these requirements.

Transportation planners can facilitate coordination and collaboration with stakeholders to mobilize larger projects. Conducting planning at the system level allows identification of potential large-scale, nature-based projects that may be implemented in coordination with other agencies, as discussed in Section 3.2, Stakeholder Engagement. For example, the development of a programmatic mitigation plan may allow stakeholders to identify opportunities and pool resources to accomplish a project that serves multiple purposes. Transportation planners also can help facilitate coordination with other coastal plans and studies, such as Hazard Mitigation Plans, State Coastal Management Plans, and USACE flood risk studies.

The planning process allows nature-based solutions to be considered in a systematic manner across a planning area or State. Following the FHWA Eco-Logical approach (see Using an Ecosystem Approach) and developing a Regional Ecosystem Framework allow the pre-identification of locations where nature-based solutions may be appropriate given existing natural resources. This information can be overlaid with transportation planning scenarios to understand opportunities, screen transportation projects, spark discussion with partners, and be provided to engineers for use in project development and design.

Federal Requirements and Relevant Policies

There are two Federal requirements that could, in part, be addressed through the consideration and planning of nature-based solutions. There also is the option to create a programmatic mitigation plan, which can incorporate nature-based solutions.

Discuss potential environmental mitigation activities and locations. The 20-year metropolitan transportation plan (MTP) and long-range statewide transportation plan (LRSTP)

[2] 23 CFR § 450.206(a).
[3] 23 CFR § 450.216, Development and content of the long-range statewide transportation plan and 23 CFR § 450.324, Development and content of the metropolitan transportation plan.

must include:

> *"[a] discussion of types of potential environmental mitigation activities and potential areas to carry out these activities, including activities that may have the greatest potential to restore and maintain the environmental functions affected by the [MTP and LRSTP]. The discussion may focus on policies, programs, or strategies, rather than at the project level. The [State and metropolitan planning organization (MPO)] shall develop the discussion in consultation with applicable Federal, State, regional, local and Tribal land management, wildlife, and regulatory agencies."*[4]

As you are considering environmental mitigation activities and locations during transportation planning, consider their resilience functions. Are there natural areas that make sense to restore or protect because they are providing a resilience value to a road in addition to providing critical habitat?

Improve the resiliency of the transportation system to natural hazards. 23 CFR § 450.206(a) calls for State DOTs and MPOs to "carry out a continuous, cooperative, and comprehensive statewide planning process that provides for consideration and implementation of projects, strategies, and services that will … improve the resiliency and reliability of the transportation system and reduce or mitigate stormwater impacts of surface transportation." As described in this guide, nature-based solutions can serve as a first line of defense and improve the resilience of roads in the coastal environment. For example, if properly designed, investing in the preservation, enhancement, and/or construction of natural shorelines can enhance the resilience of transportation assets protected by that shoreline.

Consider developing a programmatic mitigation plan. Transportation agencies may choose to develop a programmatic mitigation plan in consultation with partner agencies with jurisdiction and special expertise in the resource areas, as part of the statewide and metropolitan transportation planning process. Programmatic mitigation plans address the potential environmental impacts of future transportation projects on a regional scale.[5] These collaborative plans allow transportation and resource agencies to eliminate redundant investments, share data, and identify potential mitigation sites more effectively. The creation of this regional plan should reduce the level of coordination required on individual projects and reduce uncertainty around the level of effort needed to address potential ecological impacts. Another benefit of programmatic mitigation plans is that the plan recommendations will be given substantial weight during the environmental review and permitting process.[6] Consider identifying opportunities for nature-based solutions in a programmatic mitigation plan, which could make it easier to apply them to individual projects and reduce the need for offsite mitigation. Section 6 provides more information on mitigation

[4] 23 CFR § 450.216, Development and content of the long-range statewide transportation plan and 23 CFR § 450.324, Development and content of the metropolitan transportation plan.
[5] 23 CFR § 450.214, Development of programmatic mitigation plans and 23 CFR § 450.320, Development of programmatic mitigation plans.
[6] 23 CFR §§ 450.214 and 320.

opportunities.

Using an Ecosystem Approach

An ecosystem planning approach focuses on sustaining or restoring impaired ecological systems, ecological functions, and their values. Instead of project boundaries, an ecosystem approach is applied within a geographic framework defined mostly by ecological boundaries. In the coastal environment, boundaries may be defined by ecology, geology, or by sediment transport (often called a *littoral cell* or *littoral system*).

Planning beyond the project boundaries allows habitat conservation to be considered on a broader, ecosystem scale, and can lead to more cost-effective opportunities to avoid and minimize impacts. This form of ecosystem-based management allows the consideration of a specific project's connection to the broader system, which is key to enhancing the economic, social, and ecological resilience provided by nature-based solutions (Wowk and Yoskowitz 2017).

To integrate ecosystem planning with transportation planning, FHWA, Federal environmental permitting agencies, and four State DOTs[7] together developed the Eco-Logical approach, which is a landscape-scale approach to environmental systems planning (FHWA 2019c). The Eco-Logical framework provides an excellent model for the planning and implementation of nature-based solutions. Eco-Logical articulates a vision of how to integrate infrastructure development and ecosystem conservation to harmonize objectives and accelerate project delivery. Figure 3-1 displays a map of locations across the country that have implemented Eco-Logical, See the FHWA Eco-Logical toolkit for more information on the successes of each organization.

Figure 3-1. Map of locations that have implemented Eco-Logical (FHWA 2019c).

[7] Representatives from the Bureau of Land Management, U.S. Environmental Protection Agency, FHWA, NOAA Fisheries Service, National Park Service, USACE, U.S. Department of Agriculture Forest Service, U.S. Fish and Wildlife Service, the Knik Arm Bridge and Toll Authority, and several State DOTs, including North Carolina DOT, Vermont Agency of Transportation, and Washington DOT contributed to the completion of Eco-Logical.

The Eco-Logical framework organizes current methods for addressing natural resource identification, avoidance, minimization, and mitigation into a systematic, step-wise process that starts at the beginning of the transportation planning process and concludes with establishing programmatic approaches to recurring natural resource issues that are implemented at the project level. The nine-step framework is intended to be implemented through collaboration and coordination with other agencies. The framework is shown graphically in Figure 3-2 and the steps are listed below:

1. Build and strengthen collaborative partnerships and vision.
2. Characterize resource status.
3. Create a regional ecosystem framework.
4. Assess land use and transportation effects.
5. Establish and prioritize ecological actions.
6. Develop crediting strategy.
7. Develop programmatic consultation, biological opinion, or permit.
8. Implement agreements and adaptive management.
9. Update the Regional Ecosystem Framework.

Figure 3-2. FHWA Eco-Logical framework (FHWA 2019c).

Central to the Eco-Logical framework is Step 3, Develop a Regional Ecosystem Framework (REF). A REF typically consists of geographic information system (GIS) layers identifying existing natural resources, such as wetlands and priority locations for mitigation and conservation. For States that already have a REF, they can easily leverage it for identifying areas for nature-based solutions. For States that have not yet developed a REF, doing so will both help them in environmental compliance and permitting, as well as in identifying opportunities for flood risk mitigation through nature-based features.

Importantly, the REF, or similar GIS-based approaches, will identify existing nature-based features (e.g., marshes, reefs, mangroves, beaches, dunes) that are already providing resilience to coastal highways. If the features are performing well, no direct action is required. Simple, periodic assessment of their condition is advised. If the features show signs of distress, such as considerable marsh or beach erosion, a plan for stabilizing or restoring their function can be developed and implemented. Maintaining existing nature-based features will, in general, be less expensive than complete replacement/restoration. The regulatory effort associated with maintaining existing features is typically not as great either, particularly when there are concerns regarding habitat conversion.

Examples of agencies that are using REFs and GIS-based maps to identify areas for nature-based solutions include the following:

- NOAA's Coastal Flood Exposure Mapper is an online visualization tool that creates a collection of user-defined maps that show the people, places, and natural resources exposed to coastal flooding. The maps can be saved, downloaded, or shared to communicate flood exposure, potential impacts, and opportunities for nature-based solutions. In addition, the tool provides guidance for using these maps to engage community members and stakeholders.
- The Virginia Institute of Marine Science’s Center for Coastal Resources Management has developed comprehensive shoreline management tools that provide users with recommendations for land-use management and shoreline best management practices (VIMS 2019). For each locality in Virginia, there is an interactive mapping tool that includes information on shoreline conditions, shoreline access and protection structures, tidal marshes, beaches, bathymetry, topographic elevations, and SLR and flooding.
- The Nature Conservancy has developed a living shorelines tool for the State of North Carolina as part of their Coastal Resilience web-based tool. The North Carolina Living Shorelines Explorer provides information regarding living shoreline suitability as a function of location (The Nature Conservancy 2019). Suitability is described in terms of areas recommended for marshes alone or oyster reef, combinations of marshes with structures (i.e., a hybrid project), and areas that are not candidates for living shorelines.
- The State of Maryland’s Department of Natural Resources maintains an online data portal, the Coastal Atlas, that contains shoreline erosion rates, projected area of flooding from storm surge and SLR, habitat types, shoreline types, areas of future wetland conversion, and so forth (Maryland Dept. Natural Resources 2019).
- The Maryland Watershed Resources Registry is a partnership project supported by U.S. Environmental Protection Agency (USEPA) Region 3’s Water Protection Division. The tool allows agencies to cooperatively evaluate projects and employ consistent spatial

datasets. Figure 3-3 provides an example of how the tool can be used to identify candidate areas for nature-based solutions.

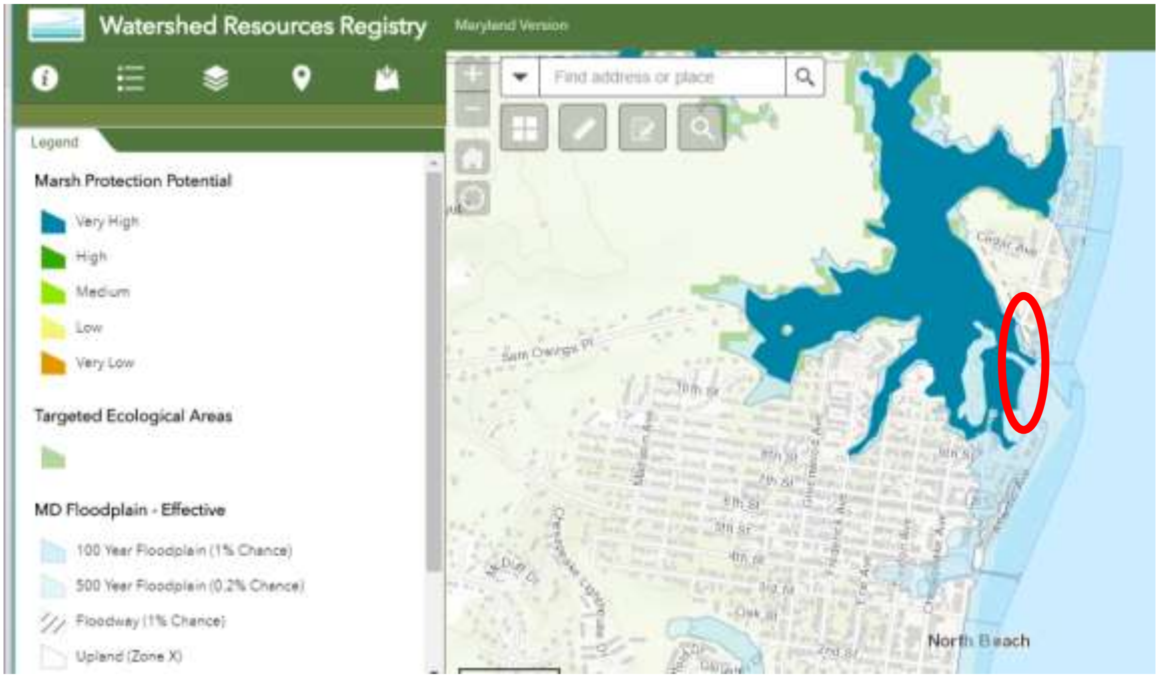


Figure 3-3. A screenshot from the Maryland Watershed Resources Registry shows how this and similar REFs can be used to identify candidate areas for nature-based solutions. The GIS layers indicate that the segment of MD-261/Bay Avenue circled in red is in (1) the 100-year floodplain, (2) an area of "high marsh protection potential," and (3) a "targeted ecological area." Source: Maryland Watershed Resources Registry.

Integrating Nature-Based Solutions Into the Transportation Planning Process

Planners can align the Eco-Logical framework with the transportation planning process to help identify locations for consideration of nature-based solutions. This integration encourages consideration of both large-scale projects, such as those discussed in Section 3.2 Stakeholder Engagement below, and smaller projects that can be used to reduce erosion or increase storm resilience at a particular transportation project site.

Specific approaches for considering nature-based solutions in the transportation planning process are indicated in Figure 3-4. Although integrating nature-based solutions into each step of the transportation planning process is not required, this guide provides options that transportation agencies may consider, if appropriate. More information on each step is provided after the figure.

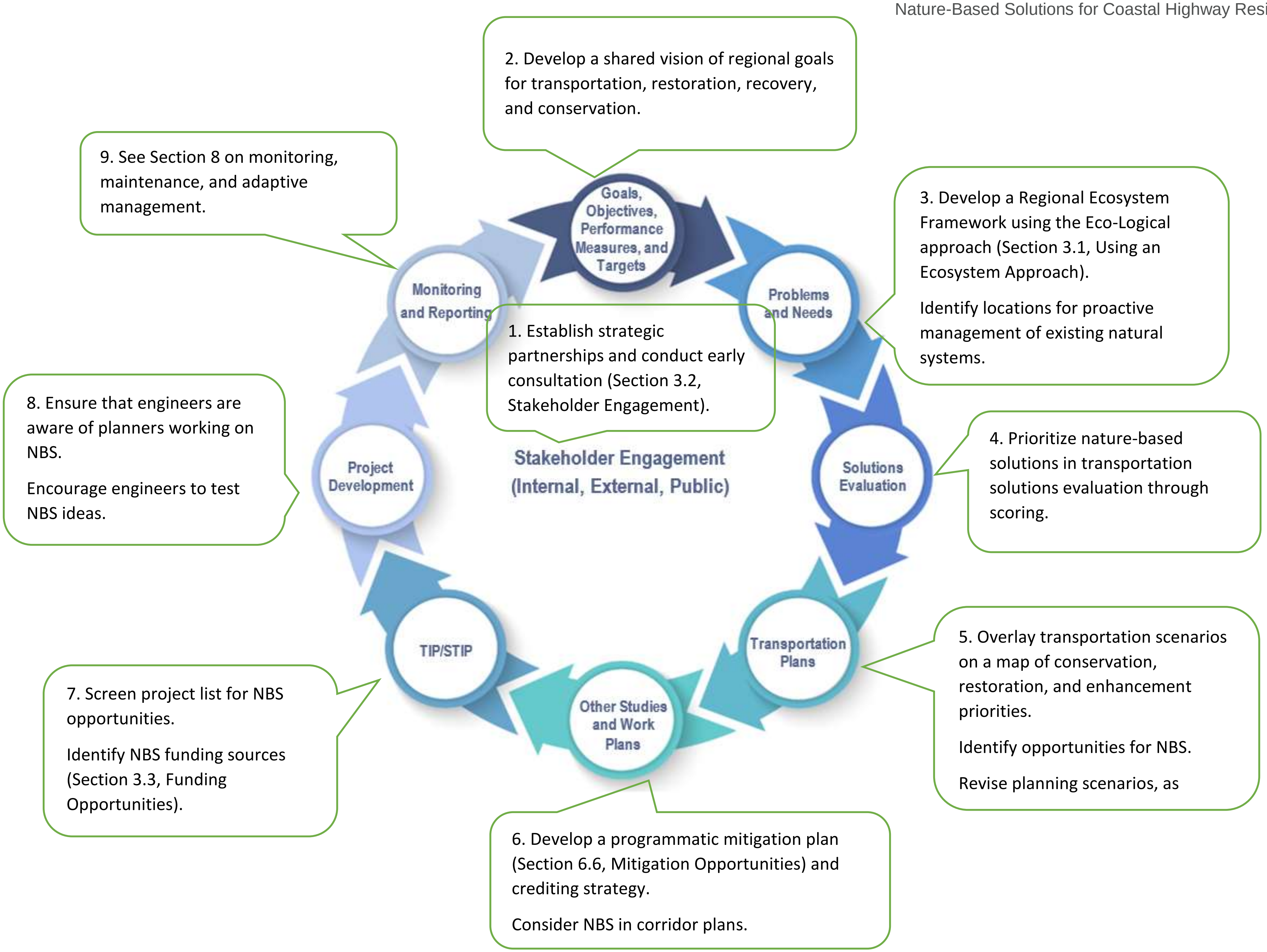


Figure 3-4. The transportation planning process consists of nine major steps that repeat as a (frequently non-linear) cycle. Stakeholder engagement occurs at every stage of the transportation planning process.

1. **Public and Stakeholder Engagement:** By engaging in strategic partnerships and conducting early consultations with local stakeholders and the public, the odds of successful nature-based solutions, large and small, are significantly increased. Transportation agencies should engage in open dialogue and establish mutual objectives to increase project benefits, gain access to additional resources, and ensure a smooth approval process. There is more information on the value of stakeholder engagement in Section 3.2.
2. **Goals, Objectives, Performance Measures, and Targets:** Consider how nature-based solutions can be part of the region's vision for the future, and how they may help accomplish the broader environmental and conservation-related goals of transportation and partner agencies. By establishing a collective vision that integrates considerations regarding the natural environment, it is more likely that decision-makers will understand the value of nature-based solutions when they are proposed for individual sites.
3. **Problems and Needs:** As discussed above, developing a REF enables the identification of healthy natural areas that currently offer resilience benefits to transportation assets, and areas that require stabilization to offer the performance benefits described in Section 2. By developing or reviewing a REF during the Problems and Needs step in the planning process, transportation agencies can identify those locations for stabilization investment.
4. **Solutions Evaluation:** If desired, transportation agencies can encourage the consideration and implementation of nature-based solutions by offering additional evaluation "points" to proposed projects with natural elements. The availability of these points should be communicated to stakeholders during the call for projects process.
5. **Transportation Plans:** Once a suite of planning scenarios is developed, overlay the projects on the REF maps to identify projects that fall within or near priority conservation, restoration, and enhancement areas. At those locations, transportation agencies may consider whether nature-based solutions could meet the project objectives. If so, make modifications to the preferred alternative to document the desire to further explore the potential for nature-based solutions.
6. **Other Studies and Work Plans:** Nature-based solutions could be considered in additional planning processes, such as corridor plans, programmatic mitigation plans, and so forth.
7. **Transportation Improvement Program:** If projects were not screened for nature-based solution potential during the transportation plan development process, the development of the transportation improvement program offers another opportunity to do so. To fund the identified projects, consider developing strategic partnerships, and/or pursuing grant opportunities, as discussed in Section 3.3, Funding Opportunities.
8. **Project Development:** Project development of nature-based solutions is the focus of the remainder of this implementation guide. However, it is valuable for planners who have worked on nature-based solutions to communicate their research, thinking, and findings to the engineers designing the project. By doing so, planners can encourage engineers to test the feasibility of nature-based solutions.
9. **Monitoring and Reporting:** To learn from constructed projects, planners should stay apprised of their performance. This will enable them to better screen for and recommend appropriate locations for nature-based solutions in the future. Section 8 provides more information on monitoring and reporting, and explains the importance of initiating development of the monitoring plan during the planning phase of a project.

3.2 Stakeholder Engagement

Strategic Partnerships

Partnerships enable transportation agencies to tap into larger, landscape-scale projects that utilize land and areas outside of the control of transportation agencies to protect all upland assets. These large-scale projects can protect roads, as well as other upland infrastructure and buildings. Transportation agencies should be involved in the partnerships that develop these types of projects so that they can be part of the planning and funding discussions to ensure that their needs are met when these projects are being designed and implemented. If transportation agencies are the ones spearheading the project, Section 5.1, Assembling the Team, provides more information on recommended team members for the design and implementation of nature-based solutions.

Partnership Spotlight
Project GreenShores is a multimillion-dollar habitat restoration and creation project in downtown Pensacola, FL. The project, located along the urban Pensacola Bay shoreline, also enhances the resilience of the Bayfront Parkway. This project involved partnerships among the Florida Department of Environmental Protection's Northwest Florida Aquatic Preserves, the City of Pensacola, Escambia County, the Ecosystem Restoration Support Organization, the USEPA Gulf of Mexico Program, the National Fish and Wildlife Foundation, the U.S. Fish and Wildlife Service, NOAA, Gulf Power, local agencies, businesses, and volunteers in a community-based effort to restore oyster reef, salt marsh, and seagrass habitat within the Pensacola Bay System.

The Eco-Logical framework discussed earlier in this section focuses on building and strengthening collaborative partnerships for landscape-scale projects. The initial steps for building partnerships include the following:

- **Identifying and contacting potential partners:** Contact potential partners to learn more about their work and to develop an understanding of their knowledge, expertise, and potential concerns.
- **Formalize partnerships:** Consider formalizing working partnerships through a memorandum of understanding. Establishing and solidifying common, long-term goals will ensure that everyone is making better and more inclusive decisions when planning projects on any scale.
- **Establish team responsibilities:** Transportation agencies may play more of a supporting role for landscape-scale projects. Therefore, they may not be required to particiapte in all aspects of landscape-scale planning, such as the science-based components. This division of labor ensures that the planning process is not overly burdensome.

Gaining Access to the Expertise Required for Nature-Based Solutions
Many State DOTs currently lack the expertise required to plan, design, implement, and maintain a nature-based solution on their own. Building long-term strategic partnerships with or among Federal, State, local, private, and nongovernmental organizations will help overcome this obstacle. These partnerships can provide the technical, regulatory, and/or financial assistance necessary to implement nature-based solutions. This is true of all phases of the project, from planning and funding to monitoring and maintenance.

State DOTs looking for potential partners in the implementation of nature-based solutions are encouraged to reach out to their State Coastal Management Program office and their nearest NOAA Sea Grant program office (NOAA 2019). These programs are often the best first contact for understanding potential partnership (and funding) opportunities in a specific State or region. Many coastal States also have National Estuary Programs (NEPs) or National Estuarine Research Reserves (NERRs) that have expertise related to nature-based solutions. Indeed, programs such as NEP and NERR often perform or support this type of work and can be of great help to transportation agencies. While not an exhaustive list, other pertinent Federal, State, and other organizations are listed below:

- Federal Agencies
  - U.S. Department of the Interior
  - National Oceanic and Atmospheric Administration
  - U.S. Environmental Protection Agency
  - U.S. Army Corps of Engineers
- State Agencies
  - Coastal zone management program
  - National Estuarine Research Reserve
  - State lands agency
  - State environmental protection agency
  - State conservation/natural resource agency
- Other Organizations
  - National Fish and Wildlife Foundation
  - Restore America's Estuaries
  - The Nature Conservancy
  - Environmental Defense Fund
  - Naturally Resilient Communities Partnership
  - Sea Grant Federal-University Partnership Program

Early Consultations With Regulators and Stakeholders

Early consultation with regulators enables concerns and differences in approaches to be heard and solved early in the process. One way to ensure that this consultation occurs is by establishing an integrated planning approach, as specified in the Eco-Logical framework. This process should result in clear benefits at the project level by ensuring that resource agencies are informed of the projects that are under consideration and development. If the transportation agency is planning a project consistent with the REF, the resource agency response(s) should be predictable.

Engaging stakeholders (e.g., relevant conservation NGOs and/or local groups working in the area) and providing the public (e.g., adjacent landowners, business owners that earn revenue from the estuary, recreational visitors) with information about nature-based solutions is an important part of the planning process. Lack of advocacy and the absence of a broader context for making shoreline management decisions are often barriers to implementation of nature-based solutions (RAE 2015). These barriers can be overcome through education and outreach during a transportation project's public engagement process. For example, public notification meetings provide opportunities to describe potential nature-based solutions, as well as their specific role in the project, and solicit stakeholder feedback. Doing so presents an opportunity for the community to better understand the impacts on the ecosystem and the need for resilient transportation infrastructure. More ways to communicate with the public during and after construction, and set expectations for the project, are provided in Section 7.3, Phases of Construction.

Soliciting stakeholder feedback also can be used to garner public support for a specific project and, in some cases, it can create opportunities for volunteerism. In their report on implementation barriers, the Restore America's Estuaries group specifically recommends the deliberate use of volunteers for project implementation. Doing so provides obvious economic benefits in terms of reduced labor costs and, at the same time, educates the public in a manner that raises awareness and expands the advocacy base (RAE 2015).

Figure 3-5. Participants at Alabama Peer Exchange (photo courtesy of FHWA).

In addition, Tribal consultation may be required if cultural resources are present, which is common along the coast. Tribal governments may have significant interest, input, and knowledge of natural habitats that could lend support to successful nature-based solutions.

3.3 Funding Opportunities

The multiple benefits of nature-based solutions for highways open up eligibility for funding from at least three sectors: transportation, coastal restoration, and hazard mitigation. Strategies that use multiple funding sources and organizations can accomplish larger efforts than could be accomplished alone. Transportation agencies are encouraged to work closely with their project partners to creatively identify and pursue funding for nature-based solutions. The text box below provides one example of cost-sharing (Tabb 2019).

Pulling Together a Wide Range of Funding Sources
Funding nature-based projects can require pulling together disparate funding sources, with all project partners working together. For example, in Kitty Hawk, NC, local residents and Federal, State, and local governments all pooled resources to construct a living shoreline to protect a local road and several residences (Tabb 2019). The $270,000 in funding included the following sources:

- NOAA cost share grant for living shorelines with private property owners
- Town of Kitty Hawk
- NCDOT ($30,000)
- Dare County Soil and Water Community Conservation Assistance Program grant

Activities to plan, design, and construct features to protect highways from current and future hazards, such as flooding, are generally eligible under major FHWA funding programs, which total more than $40 billion per year nationwide (FHWA 2012). That said, there are many competing needs for highway maintenance and construction, and State DOTs and MPOs generally have more project ideas than they are able to fund.

Transportation planning for nature-based solutions is eligible for Metropolitan Planning funds, Statewide Planning and Research funds, and the Surface Transportation Block Grant Program. Consideration of nature-based solutions in the transportation planning phase of a project is not only encouraged, it can be used to address the resilience considerations formalized under the Fixing America's Surface Transportation (FAST) Act.

Current sources of coastal restoration funding include the following:

- NOAA Community-Based Restoration Program
- NOAA Sea Grant
- National Fish and Wildlife Foundation National Coastal Resilience Fund
- FEMA's Hazard Mitigation Grant Program explicitly includes eligibility for green infrastructure projects.
- USACE's Engineering With Nature® (EWN) initiative encourages the use of EWN strategies and natural and nature-based features when pursuing flood risk-reduction projects. USACE districts have funding to provide States with flood risk mitigation analysis under USACE's Continuing Authorities Program and tangentially through the Silver Jackets proposals.
- On the Gulf Coast, the RESTORE Act has recently been a large source of funding for coastal restoration projects (Restore the Gulf 2019).
- Many of the partners listed previously in Section 3.2 Strategic Partnerships, such as the State coastal management programs, may periodically release funding opportunities that could cover nature-based solutions.

Finally, to the extent that a nature-based solution can qualify for compensatory mitigation that the DOT would otherwise need to pay for, it essentially provides a direct monetary benefit. For example, on the Northwest Florida Panhandle, mitigation credits for tidal marshes range from $130,000 to $330,000 per acre. If a DOT were able to use a 4-acre nature-based solution as out-of-kind mitigation for affected areas, they could potentially save $520,000 to $1.32 million in mitigation credits. More information on mitigation opportunities is provided in Section 6.6 Mitigation Opportunities.

4. SITE ASSESSMENT

Selecting an appropriate nature-based solution requires at least two critical steps: (1) site characterization, and (2) resilience characterization. These steps help determine what type of solution will best fit project needs. This section provides an overview of each step and points the reader to additional resources in Appendix A. The reader also will learn about some of the important regional considerations that make the design of nature-based solutions somewhat unique around the United States.

4.1 Site Characterization

The process of site characterization allows you to identify and better understand the conditions at your site. These conditions ultimately determine the processes that your selected nature-based solution will experience in that setting. Resilience characterization, which often occurs prior to or during the planning phase, identifies your transportation resilience needs (i.e., flood reduction, erosion reduction, shoreline stabilization, wave attenuation) and determines what environmental benefits an appropriate nature-based solution may provide.

Site characterization is the process of developing an understanding of historical and present site conditions, and, in some cases, projecting those conditions into the future. Site characterization allows you to place present site conditions within the context of what has happened over time while identifying the relevant physical, ecological, and geological processes at play. In other words, this process answers the simple question, What does nature support at this location? When thinking about nature-based solutions, it is best to let nature be your guide.

The practitioner typically characterizes site conditions in at least two phases: first, through preliminary or desktop analysis, and, second, through extended analysis and/or site visits. During the desktop analysis phase, you can use available datasets, maps, charts, imagery, and whatever other information you can obtain about your site to develop an initial characterization. While helpful, there are certain characteristics of a site that are not obvious on a photo or a map. Thus, you should use site visits to refine your understanding of site conditions, particularly the conditions of adjacent sites and shorelines that may affect or be affected by your project. A site visit is also an excellent opportunity to collect additional information about the conditions at your location, and possibly even take measurements of some key elements to fill in gaps from the desktop analysis.

Desktop Analysis
Developing an understanding of your site and its history starts with desktop analysis. The NOAA Digital Coast platform is an online repository of geospatial data that is often the best “first place” to look for pertinent information: https://coast.noaa.gov/digitalcoast/

It is often necessary to visit a site many times because the time of day, season, and weather play important roles in site characterization. If possible, you should perform site visits at low tide and high tide (see for example Figure 4-1); during calm and breezy days (wave action); on a weekday and on a weekend (boat wakes); and during the summer/fall and again during the winter/spring to capture seasonal changes in light availability, water levels, the presence of ice, and other factors.

Substituting some of these site visits with appropriate data and/or measurements taken at or near your site is acceptable.

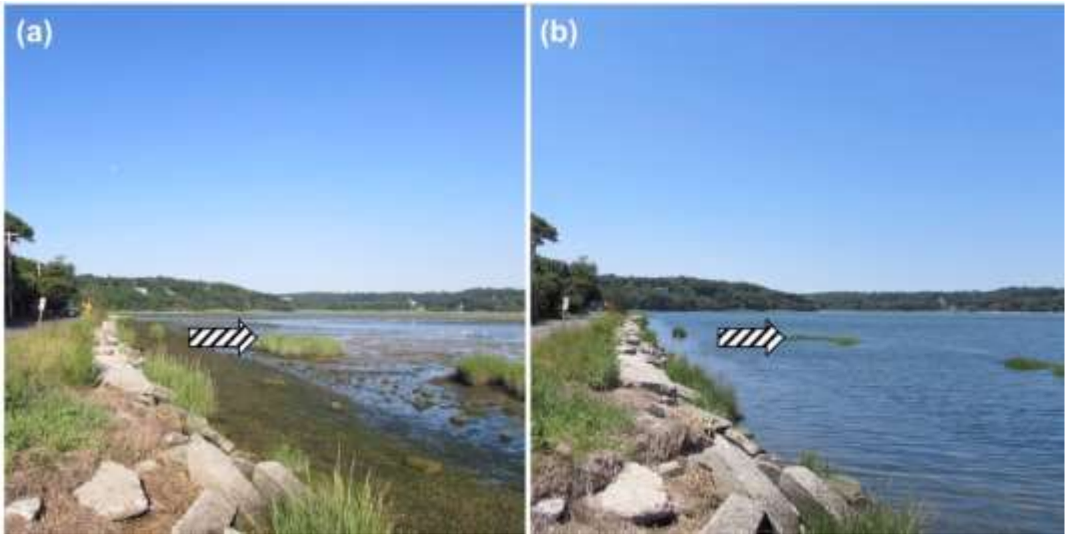


Figure 4-1. Photos showing site characteristics during (a) low tide and (b) high tide along a coastal road on Long Island, NY with arrows indicating the top of marsh grass for visual comparison (photo courtesy of Bret Webb).

This guide is written for a geographically diverse audience, including transportation professionals across all regions and territories of the United States. As such, presenting specific information for every State, region, island, and territory is unrealistic. The information provided in this section should therefore serve as a framework by which to characterize your site. You may substitute your own information to customize the process, as needed. We will borrow the site characterization framework of Miller et al. (2015) with some minor modifications. The site characterization framework from Hardaway et al. (2017) could also be used for this process.

The site characterization framework of Miller et al. (2015) uses five categories to organize the typical site condition requirements: system parameters, hydrodynamic parameters, terrestrial parameters, ecological parameters, and additional parameters. Table 4-1 lists some of the key site characterization parameters in each of the five categories. Table 4-2 lists typical values for each of these parameters using a simple scale of low/mild, moderate, and high/steep.

Table 4-1. Key site characterization parameters for nature-based solutions

System Parameters	Hydrodynamic Parameters	Terrestrial Parameters	Ecological Parameters	Additional Parameters
1. Shoreline Type 2. Infrastructure 3. Erosion Rate 4. Sea Level Rise 5. Tide Range	1. Wind Waves 2. Boat Wakes 3. Currents 4. Ice 5. Storm Surge	1. Upland Slope 2. Shoreline Slope 3. Width 4. Nearshore Slope 5. Water Depth 6. Soil Strength	1. Water Quality 2. Soil Type 3. Sunlight 4. Salinity	1. Permits 2. End Effects 3. Constructability 4. Species 5. Debris 6. Monitoring

Table 4-2. Site characterization evaluation criterion and key parameter values

Parameter Name		Evaluation Criterion		
		Low (L)	**Moderate (M)**	**High (H)**
System	Shoreline Type	High Bank	Low Bank	Open Coast Shoreline
System	Infrastructure	Minor Road, Drainage	Highway, Causeway	Evac, Bridge, Tunnel
System	Erosion Rate	< 2 feet/year	2–4 feet/year	> 4 feet/year
System	Sea Level Rise	< 0.2 inch/year	0.2–0.4 inch/year	> 0.4 inch/year
System	Tide Range	< 1.5 feet	1.5–4.0 feet	> 4 feet
Hydrodynamic	Wind Waves (Fetch)	< 1 foot / < 1 mile fetch	1–3 feet / 1–5 miles fetch	> 3 feet / 5–15 miles fetch
Hydrodynamic	Boat Wakes	< 1 feet	1–3 feet	> 3 feet
Hydrodynamic	Currents	< 1.25 knots	1.25–4.75 knots	> 4.75 knots
Hydrodynamic	Ice	< 2 inches	2–6 inches	> 6 inches
Hydrodynamic	Storm Surge	< 1 feet	1–3 feet	> 3 feet
Terrestrial	Upland Slope (V:H)	< 1:30	1:30–1:10	> 1:10
Terrestrial	Shoreline Slope	< 1:15	1:15–1:5	> 1:5
Terrestrial	Width	< 30 feet	30–60 feet	> 60 feet
Terrestrial	Nearshore Slope	< 1:30	1:30–1:10	> 1:10
Terrestrial	Water Depth	< 2 feet	2–5 feet	> 5 feet
Terrestrial	Soil Strength	< 500 lbf/ft^2	500–1,500 lbf/ft^2	> 1,500 lbf/ft^2
Ecological	Water Quality	Poor	Fair	Adequate
Ecological	Soil Type	Fine, organic material	Medium to coarse sand	Coarse sand to cobble
Ecological	Sunlight Exposure	< 2 hours/day	2–10 hours/day	> 10 hours/day
Ecological	Salinity	< 5 ppt	5–18 ppt	> 18 ppt

Key: lbf/ft^2 = pounds force per square foot; ppt = parts per thousand

Table 4-3 provides additional context regarding how selected (general) nature-based solutions relate to the values of key site characterization parameters (from Table 4-2). This table aids in the decision-making process in two ways: first, it enables the practitioner to quickly identify nature-based solutions that most closely match the conditions at their project site, and, second, it provides a framework by which to compare and select various alternatives and site locations.

Table 4-3. Nature-based solutions by parameter threshold categories L, M, and H (use in conjunction with Table 4-2)

Parameter Name		Marsh	Marsh and Sill or Reef	Mangrove and Reef	Reef	Beach and Dune	Pocket Beach	Cobble Beach	Maritime Forest
System	Shoreline Type	L/M	L/M/H	L/M/H	M/H	M/H	L/M	M/H	L/M/H
System	Infrastructure	L	L/M	L/M	L/M	M	L/M	L/M	M/H
System	Erosion Rate	L	L/M	L/M	L	M	L/M	M/H	L/M
System	Sea Level Rise	L/M	L/M	L/M	L/M	L/M/H	L/M	L/M	L/M/H
System	Tide Range	M	L/M	L	L/M	L/M/H	L/M	L/M/H	n/a
Hydrodynamic	Wind Waves (Fetch)	L	L/M	L/M	L/M/H	L/M/H	L/M/H	L/M/H	L/M/H
Hydrodynamic	Boat Wakes	L	L/M	L/M	L/M/H	L/M/H	L/M/H	L/M/H	n/a
Hydrodynamic	Currents	L	L/M	L/M	L/M	L/M/H	L/M/H	L/M/H	n/a
Hydrodynamic	Ice[1]	L	L	n/a	L	L/M/H	L/M	L/M/H	n/a
Hydrodynamic	Storm Surge	L/M/H	L/M/H	L/M/H	L/M	L/M/H	L/M	L/M	L/M/H
Terrestrial	Upland Slope	L/M	L/M	L	L/M	L/M/H	L/M/H	L/M/H	L/M
Terrestrial	Shoreline Slope	L/M	L/M	L/M	L/M	L/M	L/M	M/H	L/M/H
Terrestrial	Width	H	M/H	M/H	M/H	H	M/H	L/M/H	L/M/H
Terrestrial	Nearshore Slope	L/M	L/M	L/M	L/M/H	L/M/H	L/M/H	L/M/H	n/a
Terrestrial	Water Depth	L/M	L/M	L/M	L/M	L/M/H	M/H	M/H	n/a
Terrestrial	Soil Strength	L	M/H	L	L/M	L/M	M/H	M/H	n/a
Ecological	Water Quality	L/M/H	L/M/H	L/M/H	M/H	L/M/H	L/M/H	L/M/H	n/a
Ecological	Soil Type	L/M	L/M	M	M	M/H	M/H	M/H	M
Ecological	Sunlight Exposure	M/H	M/H	M/H	M/H	L/M/H	L/M/H	L/M/H	M/H
Ecological	Salinity[2]	L/M/H	L/M/H	M/H	M/H	L/M/H	L/M/H	L/M/H	n/a

[1] Ice: Mangroves and corals exist in tropical and subtropical settings where ice is not present; oyster reefs can tolerate intermittent ice.
[2] Salinity: Select the appropriate plant and/or reef type for the salinity, exposure, and setting.
n/a: Not applicable for the parameter or feature

The following subsections describe the key site characterization parameters outlined in Section 4.1. Table 10-1 in Appendix A provides recommendations to help the reader locate or identify appropriate data or methods for evaluating the key site characterization parameters.

System Parameters

System parameters relate to large-scale or regional conditions generated or influenced by external factors. Some examples include shoreline type, infrastructure, erosion rate, sea level rise, and tide range.

Shoreline Type refers to the characteristics of the existing shoreline and its susceptibility to inundation and erosion. Examples of shoreline type include low banks composed of sand, cobble, or vegetation; high banks of similar composition; coastal bluffs; and open ocean coastline. Susceptibility to erosion is directly correlated with exposure to wave energy. Assessment of shoreline type and condition typically requires a site visit unless recent aerial imagery is available.

Infrastructure refers to the type of coastal highway infrastructure being considered. Examples include less critical drainage infrastructure (e.g., conveyance channels, culverts, hydraulic structures) and minor/local roads; somewhat critical major roads (highways) and causeways; and critical bridges, tunnels, and evacuation routes. Document the full suite of transportation infrastructure and supporting services within the project area to ensure that all components are considered in project design.

Erosion Rate may refer to a vertical change in grade and/or lateral shoreline retreat. For coastal highways, the latter is of greater importance. Erosion rate has dimensions of length per time (e.g., feet per year). Historical shoreline positions, maps, aerial imagery, and topographic survey data, collected at two or more times in the past, provide the information needed to estimate a rate of erosion (or retreat). Use topographic survey data to estimate vertical erosion rates.

Sea Level Rise is the long-term change in the globally averaged mean sea level position. Sea level rise is an important factor when designing nature-based solutions because many components—both natural and constructed—are sensitive to mean sea level. Estimates of sea level rise at a project location must account for vertical land movement (subsidence or uplift) and other regional processes that combine to yield local variations in sea level rise, either larger or smaller rates than global mean sea level rise (GMSLR). Local factors produce RSLR. Local RSLR rates vary considerably throughout the United States. The NOAA/CO-OPS Tides & Currents website (NOAA 2018) provides measurements of historical RSLR trends at long-term tide gauges along the U.S. coastline. However, future projections are for higher rates of RSLR in most regions of the United States. Consider using the USACE Sea-Level Change Curve Calculator (USACE 2019c) and an appropriate scenario-based projection of RSLR, such as Sweet et al. (2017), for your location. This online tool considers the combined effects of GMSLR, as well as local and/or regional contributions that add to or subtract from that rate.

Tide Range is the vertical distance between the average high tide and average low tide at a specific location. Nature-based solutions are sensitive to tide range (Figure 4-2). The tide range often determines where certain natural elements exist on the landscape (e.g., vegetation and reefs). Tide range also is a critical factor in regulating wave energy dissipation by structural features. Tidal data, including tide ranges and tidal datums, are available on the NOAA/CO-OPS Tides & Currents website (NOAA 2018) at hundreds of locations across the United States. Tidal datums refer to the 18.6-year average of tidal positions at a specific location. Examples include mean higher high water (MHHW), mean high water (MHW), mean sea level (MSL), mean low water (MLW), and mean lower low water (MLLW). See FHWA (2008) for more information on tides and tidal datums.

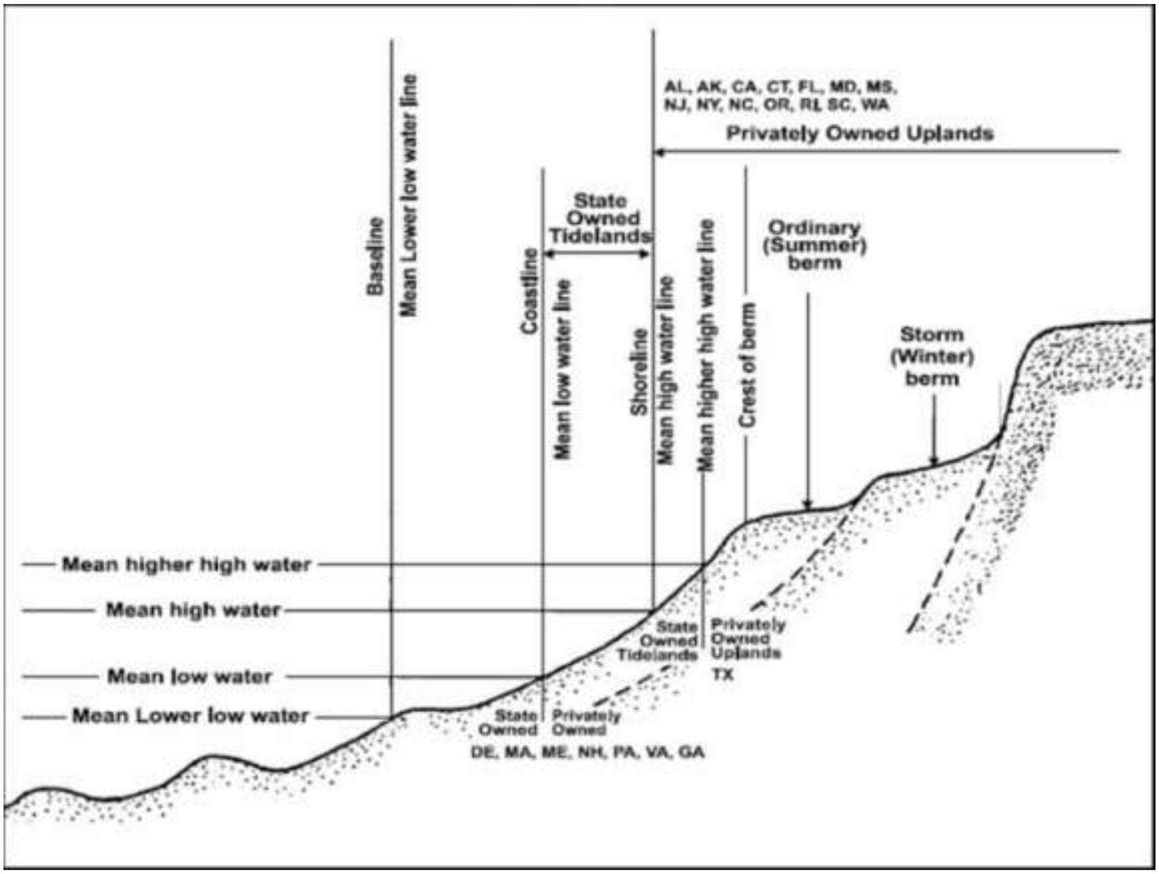


Figure 4-2. Definition sketch for tidal datums and the nearshore profile (NRC 2007).

Hydrodynamic Parameters

Hydrodynamic parameters represent the local "forces" that influence the type and condition of your shoreline, as well as the local geology and ecology of your site. Hydrodynamic parameters serve as the basis of most engineering and ecological design in nature-based solutions.

Wind Waves are waves that travel across a body of water as the result of local and/or distant meteorological conditions (wind and pressure). These are often the most persistent and largest waves that affect shorelines and infrastructure. Wind wave characteristics, namely wave height and wave period as defined in Figure 4-3, are a function of wind speed, wind duration, water depth, and fetch length. Fetch length refers to the distance that wind blows over the surface of the water to "build" the wave. Fetch is often the limiting factor for wave development. Accordingly, these waves are called "fetch-limited" waves. FHWA (2008, 2014) provide tools for estimating fetch-limited waves. Section 5 contains more information on wave characteristics for the purpose of engineering and ecological design.

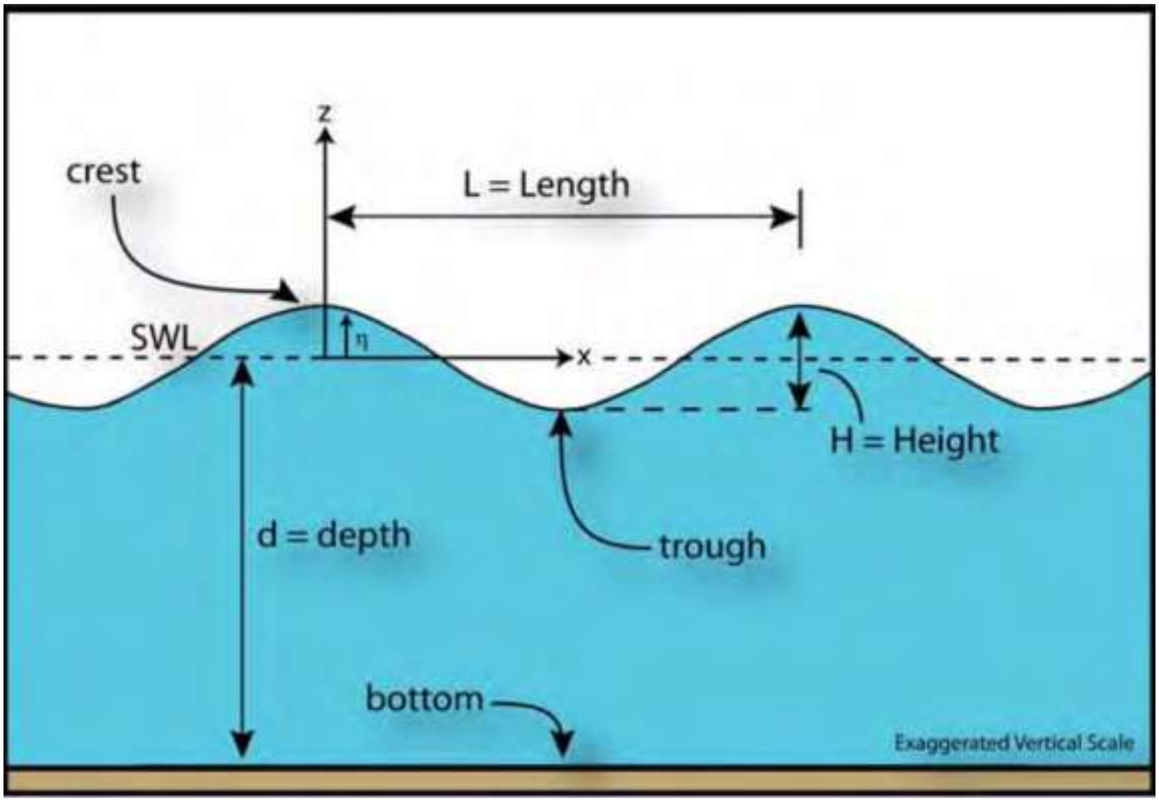


Figure 4-3. Definition sketch of a wave (FHWA 2008).

Boat Wakes are ship- or vessel-generated waves. Boat wakes are sometimes the "design waves" along shorelines with small fetches, but near waterways, navigation channels, marinas, harbors, and boat launches. Like wind waves, wave height and period are the descriptive properties of boat wakes. There are fewer tools for estimating boat wake magnitude and frequency at a specific location. Miller, et al. (2015) provides a method for estimating boat wakes, but often a visual survey of boat wake activity is more appropriate.

Currents refer to the movement or flow of water along the shoreline. Currents, like velocities, have dimensions of length per time (e.g., feet per second, meters per second). Currents sometimes affect the design of nature-based solutions, particularly near tidal inlets, along the shorelines of tributaries and tidal creeks, and when the project uses nearshore structures such as breakwaters (see Section 5 for more information). Strong shore-parallel currents uproot vegetation, erode the bank, and transport large floating debris that can damage structures and vegetation, including floating ice blocks in some regions. Current data are unavailable for most project locations. You can supplement the lack of current data with visual observations, simple or sophisticated measurements, and/or hydrodynamic modeling, when necessary.

Ice presents a substantial threat to nature-based solutions. Like floating debris, ice blocks impose large impact forces on structures. Ice accumulation on vegetation and/or structures induces uplift, through ice buoyancy, with the rising tide, and it increases the chances of overturning on a falling tide. Ice accumulation on riprap during high tide results in an overturning moment when the water level falls, and possible movement of the stone; some refer to this as "ice picking" (FHWA 2014).

Storm Surge is the increase in the time-averaged (still) water level position as the result of all meteorological forcing. Storm surge includes the contributions of wind, pressure, waves, currents, and freshwater input to the coast, and exists on top of the astronomical tides at a given location. Their combination is referred to as the storm tide or total water level. Determining the magnitudes of storm surge and the magnitudes of each contributing factor is important for selecting an appropriate nature-based solution and for evaluating its flood-reduction benefits. Regulatory flood maps show extreme event (i.e., 1 percent and 0.2 percent annual chance) still water elevations. The corresponding Flood Insurance Study documents will often contain additional return period water levels. Some NOAA tide stations provide return period water level estimates (most do not contain the effects of waves, which can be significant). The USACE Coastal Hazards System website provides high-resolution stormwater level data in some regions (USACE 2019d).

Terrestrial Parameters

Terrestrial parameters characterize the condition of the upland, land-water interface (i.e., the shoreline) and the nearshore (i.e., submerged) regions. The combination of terrestrial and hydrodynamic parameters dictates the shoreline type, condition, and resilience. Successful nature-based solutions attempt to mimic, through engineering design and construction, the terrestrial parameters of nearby stable shorelines. Figure 4-4 shows the location of the terrestrial parameters relative to the coastal profile.

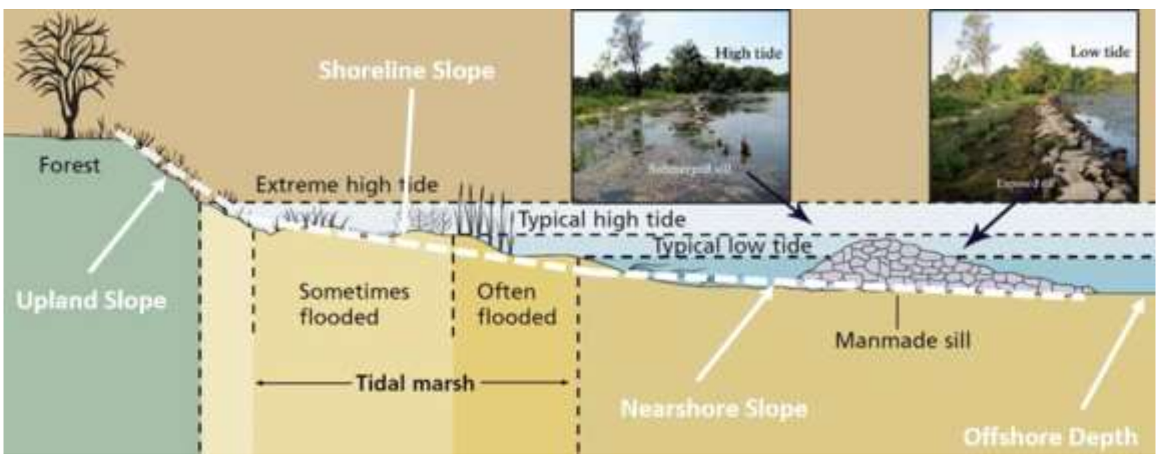


Figure 4-4. Profile schematic for selected terrestrial parameters (Miller et al. 2015).

Upland Slope is generally the slope of the land between the MHHW tidal elevation and the point at which the upland attains a mostly constant elevation. Upland slope often determines the vegetative communities and susceptibility to severe erosion, or scarping, during storm events. Milder slopes are more vulnerable to flooding, but less vulnerable to extreme erosion. Stormwater runoff over steep upland slopes contributes to profile erosion and should be mitigated through traditional stormwater management techniques on the upland. Topographic survey data provide upland slope values. You can also use Light Detection and Ranging (LiDAR) measurements, of adequate resolution, to calculate upland slope.

Shoreline Slope is the slope of the intertidal shoreline between the MLLW and MHHW datums. Nature-based solutions, particularly those involving vegetation, are very sensitive to shoreline slope (see Section 5 for more information). LiDAR data are not always useful for calculating shoreline slope. A traditional survey conducted at low tide is the best way to measure shoreline slope.

Nearshore Slope is generally taken as the slope from the MLLW tidal datum to where the adjacent water bottoms attain a relatively constant depth. The nearshore slope affects many of the hydrodynamic site parameters, including the magnitude of storm surge, the balance between wave reflection and energy dissipation, the location of wave breaking, and the size of the active sand transport system (parallel and perpendicular to the shoreline). Steep nearshore slopes are less susceptible to storm surge, reflect more wave energy than they dissipate, and experience wave breaking closer to shore. Steep slopes are more vulnerable to wave runup and wave setup. The use of nearshore structures on steep slopes presents substantial engineering challenges. Milder nearshore slopes experience larger storm surges, dissipate wave energy, and force large waves to break further from the shoreline. The only way to measure the nearshore slope reliably is through traditional survey methods, including wading surveys and vessel surveys.

Width refers to the horizontal distance between the upland or infrastructure and the mean shoreline position. Along sheltered shorelines, minimum beach widths fall in the range of 40 to 60 feet for moderate tide ranges, while marshes may require 40 to 70 feet of width under similar conditions (Hardaway and Byrne 1999). Acceptable project width increases with tide range, wave exposure, and infrastructure sensitivity. Minimum beach widths along ocean shorelines may be 100 feet or more. Generally, infrastructure resilience increases in direct proportion to its distance from the shoreline (as mentioned in Section 2). Obtaining the preferred project width requires moving the upland/infrastructure landward or advancing the shoreline position seaward. Depending on easement and right-of-way ownership, advancing the shoreline seaward may be easier than moving the infrastructure.

Water Depth is the vertical distance from the water level, under normal conditions, to the seabed at or near the base of the nearshore slope. Water depth is reported on nautical charts, provided in many comprehensive digital elevation model datasets, and also easily measured with conventional tools. Shallow offshore water depths provide more natural dissipation of energy as waves approach your site, typically experience slower currents, and are active regions of sediment transport. The deeper the offshore water depth, the larger a wave can be at your project site. This is true of both wind waves and boat wakes, since the deeper water allows boats to travel closer to your project site. Greater water depths typically require more materials (e.g., fill, structural materials), but provide advantages when construction is performed from the water-side (see Section 7 for notes on construction). Shallower depths require less construction material, but water-side construction is more challenging because of the limited draft for barges and vessels. Section 5 identifies additional technical challenges associated with the construction of stone structures in shallow water depths.

Soil Strength refers to the bearing capacity of marine soils, which varies considerably across the United States, and sometimes even across a project site! The bearing capacity is an important factor in the design of structural elements in nature-based solutions. Structures that are placed on, or driven into, the seabed have the potential to settle, rotate, slide, or otherwise “move” when soil conditions are poor. Even moderately sized riprap can easily disappear when placed on poor soil. When gravity structures, such as breakwaters, sills, proprietary habitat units, and reefs, exert a pressure that exceeds a soil’s bearing capacity, the structure will settle, and its effectiveness will diminish unless accounted for or mitigated. An example mitigation effort would be using advanced geotextiles, geofabrics, and geogrids laid under the structure, which will distribute the force over a larger area and reduce the pressure on the soil. Soil strength data are typically not accessible in the desktop analysis phase. Instead, one must perform direct measurements in the field (static cone penetrometer) or in the laboratory after gathering a soil sample or core sample.

Non-Rock Alternatives

Engineers designing projects in extremely poor soil conditions, such as on the Louisiana coast, are evaluating “non-rock” alternatives for breakwaters, and fish and reef habitats. These alternatives to rock are made of materials ranging from steel and special concrete mixtures to recycled plastics and others. These are typically proprietary devices sold by a commercial business. Examples include Reef Ball, ReefBLK℠, WAD®, OysterBreak™, EcoSystems, and Coastal Havens™.

Ecological Parameters

Ecological parameters reflect the habitat conditions at a site. They often determine the type of biological and ecological communities, or habitats, which nature-based solutions seek to mimic and provide. Nature-based solutions both depend on and are directly influenced by ecological parameters, including water quality, soil type, sunlight exposure, salinity, and habitat.

Water Quality refers to the composition of the water in terms of its constituents, including the presence of nutrients, dissolved materials, and suspended solids. Basic water quality parameters include water temperature, salinity (addressed separately), pH, dissolved oxygen, and turbidity. The value of each parameter will dictate the presence, absence, success, or failure of biological and ecological communities in a nature-based solution. Other relevant water quality parameters include total inorganic nitrogen and total inorganic phosphorous. Some water quality data are found online at NOAA and/or U.S. Geological Survey (USGS) websites, but it is always preferable to obtain measurements from your site during project planning, design, and implementation.

Soil Type refers to the sediment characteristics at your site. Typical characteristics include median diameter, grain size distribution, angularity, carbonate content, and color. Median grain size and the percentage of fines (passing the number 200 sieve) determine project performance, particularly for beach nourishment projects. In such projects, matching the native grain size and keeping the percentage of fines to 1–2 percent or less are critical for project success. Using fill material that is smaller than the native material produces nearshore and shoreline slopes that are too mild. This translates to minor gains in project width. Using fill material that is larger than the native material produces nearshore and shoreline slopes that are too steep. Overly steep slopes result in scarping and poor performance of vegetated (marsh) slopes. Soil type is determined through standard geotechnical testing of “grab” samples taken from your project site.

Sunlight refers to the amount of available sunlight, or sunlight exposure, along the intertidal shoreline and in the water in the case of submerged aquatic vegetation. Large shade trees along the bank can reduce the available sunlight for emergent intertidal vegetation. High values of turbidity prevent or limit light penetration through the water column, limiting the photosynthetic activity of submerged aquatic vegetation.

Salinity refers to the amount of dissolved salt in the water. It is represented in parts per thousand (ppt) or partial salinity units (PSU), both having roughly the same scale where 0 ppt/PSU represents freshwater and 35 ppt/PSU represents oceanic seawater. The salinity at a site determines the types of vegetation (emergent and submerged) present at a location, the fish assemblages, and the presence of mollusks and crustaceans. You should obtain multiple salinity measurements at your site using a handheld water quality probe, and/or perform research regarding the variability of salinity at your project site. Knowing your typical salinity, and salinity range, is an important part of specifying the “natural” features in any nature-based solution.

How Salty?
Estuarine and ocean environments are often characterized by their salinity. Here’s the general distribution:

< 0.5 ppt	Freshwater
0.5–5 ppt	Oligohaline
5–18 ppt	Mesohaline
18–30 ppt	Polyhaline
> 30 ppt	Euhaline (ocean)

Additional Considerations

There are additional considerations during the site characterization and conceptual design phases. These parameters may dictate the type, layout, and dimensions of the most appropriate nature-based solution for your site and need. Some of these considerations include permits, end effects, constructability, species, debris, and monitoring.

Permits are necessary for nature-based solutions. Any work performed seaward of the regulatory tidal datum, which is typically MHW, usually requires a Joint Coastal Permit from the authorized State coastal zone management agency and the district office of USACE, in addition to any appropriate local, municipal, county, or watershed permit or authorization. At a minimum, nature-based solutions will receive three permits upon successful conclusion of the permit review process: a water quality certification permit (from the State), a biological opinion from USACE, and a permit to fill or affect State lands. Section 6 provides more information on permitting. Early engagement of regulatory officials will aid in the selection of appropriate nature-based solutions.

End Effects refer to the interaction between the “ends” of your nature-based solution and the adjoining shorelines. Project planning and design should consider the potential for adjoining undefended shorelines (i.e., natural) to negatively affect your project’s performance. You should also consider, and minimize or avoid, all negative impacts of your project on adjoining shorelines. This includes, but is not limited to, the potential for structures to redirect wave energy to adjacent shorelines; inhibit and/or trap the natural movement of sediment, both parallel and perpendicular, to your shoreline; and the potential for your project to exacerbate flooding on adjoining properties.

Constructability refers to the viability of constructing your preferred project. A desirable nature-based solution is one that is technically feasible, reasonable, justifiable, and, most importantly, constructible. If site conditions prohibit construction of the project, then ultimately that project design will not work for that location. Constructability touches on many aspects, including site accessibility (by land or by water), safety, access to qualified contractors, availability of materials, time of year, regulatory restrictions, and potentially other factors. Section 7 provides additional information about construction means and methods.

Species refers to the presence and abundance of native, non-native, and/or invasive species at a project site. We mostly think of upland plants when we use this language, but non-native and invasive aquatic species and vegetation exist and may negatively affect project performance. Plant, wetland, and fisheries ecologists should be involved to characterize the species abundance, richness, and coverage for the project site. Mimicking healthy nearby plant communities is a key to project success. For example, management of invasive species may be a key component of project maintenance (see Section 8 for more information on monitoring and maintenance).

Debris, particularly large floating debris, damages structures and emergent vegetation during storm events. There are no simple preventative controls for limiting debris impacts during storms, but their effects should be considered during project design. When structure crests are left low in elevation, debris may pass over during storm events and ultimately end up damaging the shoreline or vegetation. Removal of large debris from the wrack line following a storm event prevents repetitive damage during future events (see Figure 4-5). When structure crests are kept high relative to stormwater levels, the practitioner should orient the structure in a way that minimizes impact forces as much as practicable.

What's a Wrack Line?
In marine lingo, the wrack line is a line of debris that accumulates after a high tide or storm event. The elevation of the wrack line is an excellent post-storm indicator of the still water elevation at your site during the peak of the storm.

Monitoring refers to the routine collection of project parameter values and conditional assessments of performance for some time period following construction. Monitoring plans range from very simple to very complex. Monitoring is required under some permit conditions, but, in many cases, is optional. However, even basic, low-level routine monitoring provides critical data for performing preventative maintenance in order to stave off major problems. Section 8 is devoted to a discussion of monitoring, maintenance, and adaptive management.

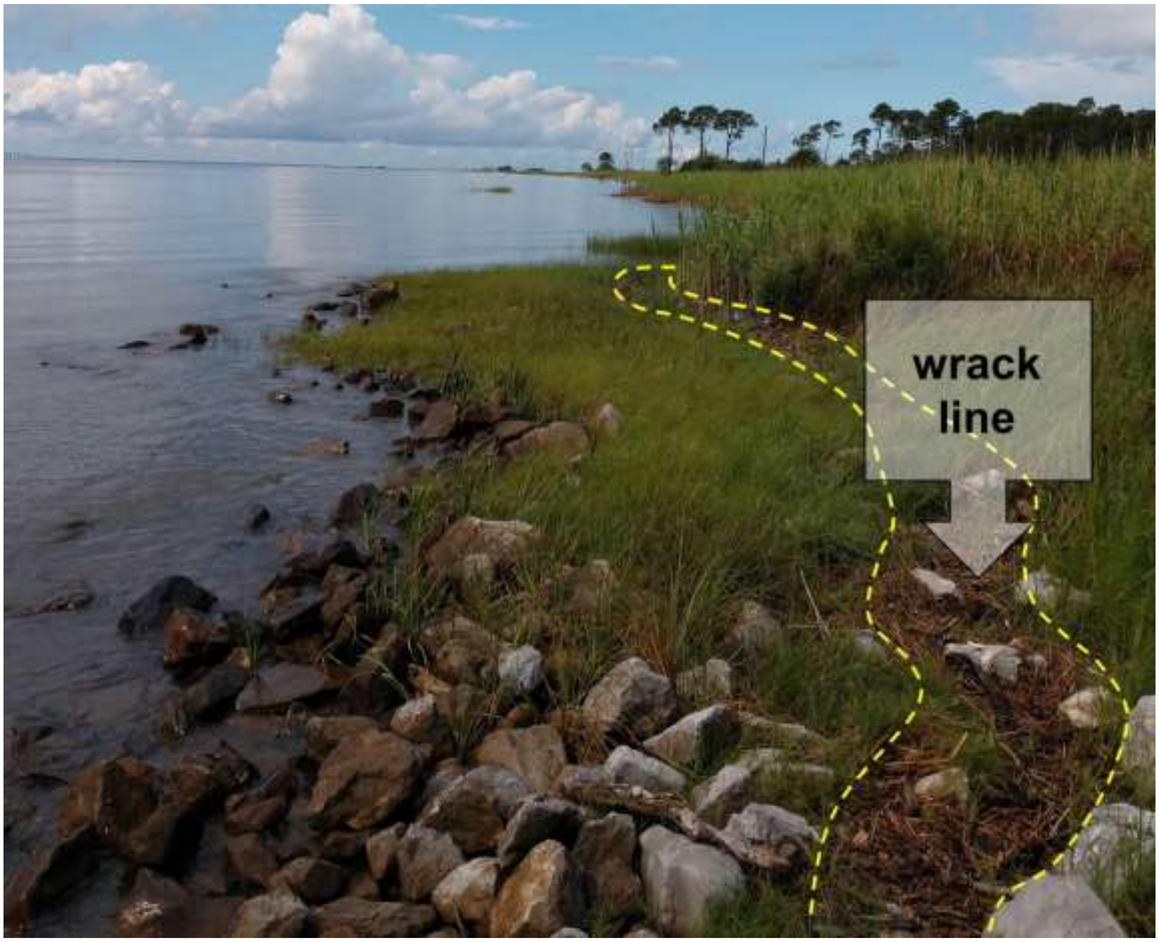


Figure 4-5. Photograph of a storm wrack line in a tidal marsh (photo courtesy of Bret Webb).

4.2 Resilience Characterization

Resilience characterization is simply identifying and/or assessing coastal highway vulnerabilities, and then determining their resilience requirements. Resilience needs may include flood reduction, wave attenuation, erosion reduction, shoreline stabilization, and possibly many others.

Table 4-4 lists some common coastal highway vulnerabilities. More information on identifying and assessing the vulnerability of coastal highways to extreme events and sea level rise can be found in FHWA (2014) and FHWA (2019a).

Table 4-4. Common coastal highway vulnerabilities

Highway Hydraulics	Coastal Roadways	Coastal Bridges	Coastal Tunnels
1. Sea Level Rise (SLR) 2. Increased Flooding from SLR 3. Storm Surge 4. Sedimentation	1. Sea Level Rise 2. Increased Flooding from SLR 3. Storm Surge 4. Wave Action 5. Erosion 6. Shoreline Retreat	1. Sea Level Rise 2. Storm Surge 3. Wave Action 4. Erosion	1. Sea Level Rise 2. Storm Surge 3. Wave Action

Resilience Example: Causeway Affected by Sea Level Rise Flooding

Under an intermediate to high future sea level rise projection, the U.S. Route 1B causeway in New Castle, NH (Figure 4-6), would be inundated 188 times in 2060 and 338 times in 2065. As documented in FHWA (2018d), New Hampshire DOT studied the flood reduction and ecological benefits of a range of options: (1) no action, (2) enhancing salt marsh habitat in the vicinity, (3) elevating the causeway, (4) elevating the causeway and enhancing surrounding marsh habitat, and (5) constructing a bridge.

Figure 4-6. U.S. Route 1B causeway in New Castle, NH (photo courtesy of New Hampshire DOT).

Resilience Example: Coastal Roadway Affected by Erosion

Laguna Shores Road in Corpus Christi, TX, runs parallel to Laguna Madre, a lagoon within the western region of the Gulf of Mexico. Shoreline erosion has undermined the roadway in multiple locations, which has direct negative impacts on project life cycle, maintenance costs, and public safety. These locations are particularly susceptible to the impacts of storm surge and extreme weather events, and this vulnerability will increase in the face of sea level rise. In addition, several locations along Laguna Shores Road are subject to periodic inundation under spring tide and other typical (non-storm) conditions. The City of Corpus Christi is rebuilding three segments of Laguna Shores Road to improve the level of service and reduce susceptibility to erosion and inundation. Reconstruction of the roadway includes increasing the elevation of the roadway surface. A coastal engineer is designing shoreline protection options for the roadway that include natural and engineered materials such as sand fill, marsh plantings, and stone.

Figure 4-7. Laguna Shores Road under typical (non-storm) conditions. Note the irregular edge of pavement and proximity to open water (photo courtesy of Corpus Christi MPO).

Resilience Strategies for Coastal Highways

No single nature-based solution addresses all of the vulnerabilities listed in Table 4-4, not independently and certainly not simultaneously. Thus, you should provision resilience accordingly, using the entire suite of management strategies presented in Table 2-1. Policy, structural, and nature-based solutions are appropriate for varying degrees of infrastructure criticality, and for infrastructure sensitivity to flood, wave, or erosion hazards.

Consider the conceptual diagram showing the entire resilience strategy space for coastal highways in Figure 4-8a. This figure shows, schematically, how varying magnitudes of system criticality and system sensitivity combine to suggest an appropriate resilience action or suite of actions. For example, a nature-based solution may be appropriate for a system with moderate sensitivity and moderate criticality; however, if the system is moderately sensitive but highly critical, then an appropriate course of action may involve some combination of nature-based solutions and structural features.

The presence of policy measures at opposite corners of the resilience space is intentional. Systems that are neither critical nor sensitive may not require any direct action for some time. Before action is needed, policy measures could, for example, focus on right-of-way acquisition for future realignment of the roadway. Alternatively, policy measures may be the most pragmatic solution for systems that are both critical and sensitive when other methods do not yield the desired level of resilience. Note that Figure 4-8a is intentionally non-quantitative and overly generalized; it is simply a suggested approach to considering how one balances sensitivity and criticality in the resilience decision-making process.

We can further refine the concept of resilience management strategies by considering the sensitivity of coastal highways to specific hazards: sea level rise, coastal flooding, wave action, and erosion or shoreline retreat (Figure 4-8b–d). Doing so allows us to more objectively define the ranges over which different nature-based solutions are appropriate. In other words, we can better describe the potential distribution of “effectiveness” within the nature-based solution strategy space. Beyond this space, we consider major structural features such as flood barriers, retrofits, or armoring, and/or policy measures such as retreat, abandonment, or advanced flood warnings.

Two reference points are indicated (1 and 2) on each of the hazard figures to serve as descriptive examples for this text. First consider infrastructure sensitivity to flooding in Figure 4-8b. For a project that is not critical but has some moderate sensitivity to flooding (point 1), preservation, conservation, or establishment of a maritime forest may provide appropriate flood-reduction benefits. However, a more critical project with the same sensitivity to flooding may require additional flood protection through establishment of an elevated feature, such as a constructed dune or berm, perhaps in conjunction with a structural feature such as a parapet wall or sheet pile wall. For sensitivity to waves, Figure 4-8c includes two points representing projects with the same level of criticality, but with lower (point 1) and higher (point 2) sensitivities to waves and wave-related damage. While a vegetated feature, such as a coastal marsh may provide the desired level of wave height reduction for the project at point 1, a higher sensitivity to waves may require some form of an offshore reef or breakwater to dissipate additional wave energy for point 2. For sensitivity to erosion or shoreline retreat, Figure 4-8d shows reference points for projects with unique levels of criticality and sensitivity. For low criticality and moderate sensitivity to erosion, a coastal marsh or mangroves may provide the level of stabilization required at point 1. However, increasing both parameters may warrant the establishment or enhancement of a beach and dune system, possibly combined with an appropriate structural element, such as a buried revetment or seawall.

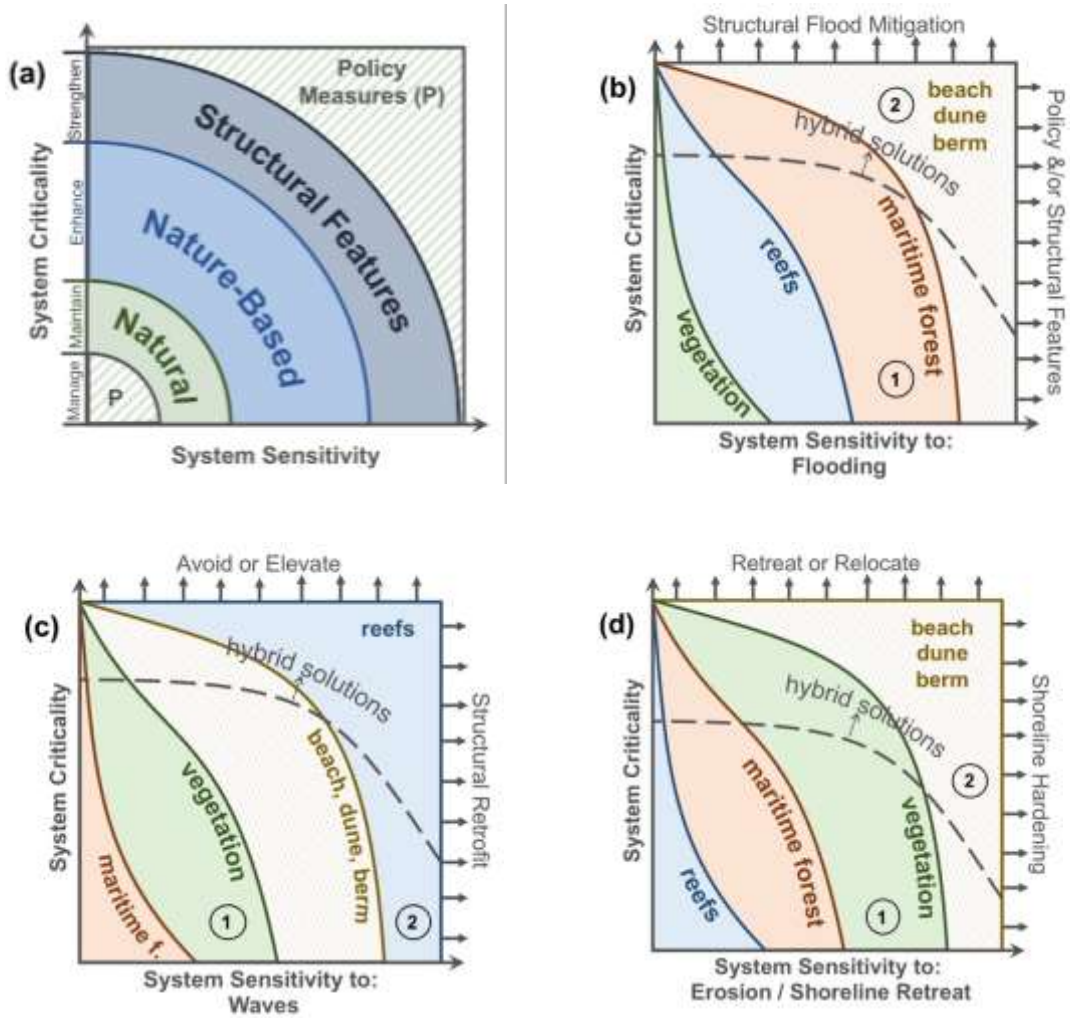


Figure 4-8. Resilience strategies for coastal highways: (a) complete strategy space, (b) nature-based strategies for flood resilience, (c) nature-based strategies for wave mitigation, and (d) nature-based strategies for erosion mitigation and shoreline stabilization.

The resilience strategies diagrammed in Figure 4-8b–d are non-quantitative and intentionally stylized. We do not know exactly how the various nature-based features will provision resilience in a way that addresses criticality and sensitivity concerns. However, the information presented in Section 2, and more specifically in Table 2-1, provides reasonable guidance on the performance of various natural and nature-based features at mitigating the vulnerabilities shown in Table 4-4. Each of the schematics shown in Figure 4-8b–d is roughly partitioned by the gray dashed line, above which you should consider hybrid solutions given high system criticality.

4.3 Selecting the Right Solution

The information gathered during site characterization and resilience characterization provide the necessary inputs for identifying potential resilience management strategies. At this point, you should have some conceptual ideas about what strategies are appropriate for your project location and needs. This section builds on that information and generally describes some important concepts for selecting an appropriate nature-based solution. The reader is directed to Appendix B for decision trees that help inform policy, and nature-based/hybrid and/or structural solutions to address flood, wave, and erosion hazards for coastal highways.

NOAA Green Infrastructure Effectiveness Database

When determining the best nature-based solution to address project needs, consider using the NOAA Green Infrastructure Effectiveness Database. This online, searchable database contains a wide range of resources, including peer-reviewed journal articles, reports, web-based tools and resources, gray literature, and information on 32 different types of coastal green infrastructure and nature-based solutions. Users can filter results by type, hazard, region, State, source name, or type, in addition to standard bibliographic data such as title, author, year, and keywords. Access the database at https://coast.noaa.gov/digitalcoast/training/gi-database.html

The selection process requires an understanding of two major issues: (1) the type of nature-based solution that your site will support (e.g., Is it a beach or a marsh?), and (2) the infrastructure vulnerabilities or risks you seek to mitigate through project implementation. Once you determine the management strategy that best fits your location and needs, consider the various alternatives that maximize benefits, minimize costs, and meet other priorities. Also, be sure to answer these four questions before moving ahead to the full design phase:

- Is it technically feasible?
- Is it reasonable?
- Is it justifiable?
- Is it constructible?

Table 4-5 presents coastal hazards (column 1), relevant asset types (column 2), and representative examples of possible management strategies (policy, nature-based, structural, and hybrid) as a function of vulnerability and type of infrastructure (columns 3–6). The vulnerabilities shown in Table 4-5 are slightly refined versions of those shown in Table 4-4. These suggestions are based on what we know about the flood-reduction benefits of nature-based solutions (Section 2), the general types of vulnerabilities listed by infrastructure type in Table 4-4, and the decision-making framework shown in Figure 4-8. Many other options are possible, and those options are unique in almost every region and territory of the United States. We address regional considerations in a subsequent section.

SITE ASSESSMENT

Table 4-5. Representative examples of management strategies by vulnerability and infrastructure type

Issue	Application	Policy	Natural and Nature-Based	Structural	Hybrid (possible examples)
Increased Flooding because of SLR	Roads Causeways Drainage	Accommodate Relocate Abandon	Dunes Berm	Elevate Bulkhead Seawall Flood Barrier	Dunes + Bulkhead/Seawall/Barrier Berm + Bulkhead/Seawall/Barrier
Storm Flooding	Roads Causeways Bridges Tunnels Drainage	Accommodate Relocate Abandon	Beach Dunes Maritime Forest Marsh Mangroves	Elevate Bulkhead Seawall Flood Barrier	Beach + Dunes + Seawall/Barrier Marsh/Mangrove + Seawall/Barrier
Wave Runup and Overtopping	Roads Causeways Tunnels	Accommodate Relocate Abandon	Dunes Marsh Mangroves Reefs	Elevate Revetment Flood Barrier Breakwaters Sill	Dunes + Seawall/Barrier Marsh/Mangrove + Revetment Marsh/Mangrove + Sill Marsh/Mangrove + Reef/Breakwater
Wave Forces	Bridges Revetments	Relocate Abandon	Marsh Mangroves Reefs	Elevate Breakwaters	Beach + Dunes + Reef/Breakwater Marsh/Mangrove + Reef/Breakwater
Erosion	Roads Causeways Bridges	Relocate Abandon	Dunes Marsh Mangroves Reefs	Revetment Armoring Sill	Dunes + Vegetation Marsh/Mangrove + Sill Marsh/Mangrove + Revetment
Shoreline Retreat	Roads Bridges	Relocate Abandon	Beach Marsh Mangroves Reefs	Bulkhead Seawall Revetment Breakwaters	Beach + Reef/Breakwater Marsh/Mangrove + Reef/Breakwater Beach + Revetment/Wall Marsh/Mangrove + Revetment/Wall

Feasibility and Constraints

There are feasibility considerations and constraints that often need to be addressed and resolved during the planning and design phases. Some of these issues—namely permitting, end effects, and constructability—were identified in Table 4-1 as “Additional Parameters”. Additional constraints include easement and right-of-way ownership issues, impacts on submerged lands (permitting issue), habitat tradeoffs, habitat impact offset requirements, liability concerns, and hazards to navigation (when using nearshore or offshore structures). Design professionals can overcome these potential pitfalls, but only when they are considered early in the implementation process.

4.4 Regional Considerations

There are other factors in addition to the site characterization parameters, infrastructure type, and infrastructure resilience needs that affect the selection process. For example, each of the four (or perhaps five) site characterization parameters face unique issues and challenges in various regions and territories of the United States. The variability in project design, project elements, materials, and construction are a function of the regional setting in which they exist, and careful consideration must be given to regional specifics and differences. For example, plant species being considered for restoration purposes may be native to and/or protected in some parts of North America, while being highly invasive species in other States or regions. Table 4-6 describes how States and territories are regionally categorized for this discussion. Some brief comments regarding the viability of nature-based solutions in each region follow Table 4-6.

Table 4-6. Regional categorization of coastal States and territories

Northeast	Mid-Atlantic	Southeast	Great Lakes	Gulf of Mexico	Pacific / Northwest	Hawaii and Pacific Islands
NJ NY CT RI MA NH ME	VA MD DE	PR USVI FL Keys FL (East) GA SC NC	NY PA OH MI MN IN IL WI	TX LA MS AL FL (West)	AK WA OR **Pacific / Southwest** CA[1]	HI AS FM GU MH MP PW

[1] California is somewhat unique on the Pacific Coast and belongs in its own category, as described below.

The **Northeast** region has a comparatively short history of using nature-based solutions for coastal resilience (except for beach nourishment). Tideland ownership and policies in some States have historically inhibited encroaching on State-owned water bottoms, making many nature-based solutions difficult to implement. With some exceptions, the wave energies in this region vary from moderate to high because of the long, open ocean coastline and larger sounds and estuaries with considerably long fetches. The tide range varies considerably across the region, as do the shoreline types: ranging from low bank, sandy shorelines to coastal bluffs and rocky cliffs. There is a growing network of design professionals and practitioners in this region, and access to materials and qualified contractors is good. Major vulnerabilities in this region include sea level rise, storm surge, extra-tropical storms (nor'easters), wave action, bluff erosion, ice impacts (frequent), and invasive species. Habitat types include marshes, oyster reefs, maritime forests, beaches, and dunes. More specific information about the use of nature-based solutions in this region is found in Miller et al. (2015), NYSDEC (2017), and Woods Hole Group (2017).

The **Mid-Atlantic** region has the longest track record when it comes to nature-based solutions. Unlike other regions, this region has more estuarine and sheltered shoreline (i.e., the Chesapeake and Delaware Bays) than it does open coast, high wave energy shoreline (Atlantic Coast). Wave energy exposures for most of the region vary from low to moderate. The tide range is moderate and does not change substantially within the region, and there are comparatively fewer habitat types. Tideland ownership and policies vary considerably between States. Maryland owns land below the MHW tidal datum, including tidal wetlands. Virginia owns land below the MLW datum and tidal wetlands are privately owned. Maryland and Virginia have specific legislative policies that facilitate the use of living shorelines over shoreline armoring (see Section 6 for more information). There is an established network of design professionals and practitioners in this region, and access to materials and qualified contractors is good to excellent. Major vulnerabilities in this region include sea level rise, storm surge, bluff erosion, boat wakes, ice impacts (infrequent), and invasive species. For example, *Vitex rotundifolia* (beach vitex) is native to Hawaii, but non-native and invasive in Mid-Atlantic States, where it smothers native plants on the coastlines of States, including Virginia. Habitat types include marshes, oyster reefs, maritime forests, beaches, and dunes. More specific information about the use of nature-based solutions in this region is found in PDE (2013), Hardaway et al. (2017), and Schrass and Mehta (2017).

The **Southeast** region, excluding North Carolina, has a shorter history regarding the formal design and construction of nature-based solutions. Shoreline hardening along the east coast of Florida is very common, except for the open ocean coast. However, North Carolina has a relatively long record of building marshes and low timber sills along estuarine and sheltered shorelines. This region has a very large range of wave energy exposures, a wide distribution of tidal ranges, and multiple habitat types. Tideland ownership and policies vary somewhat from State to State. There is a growing network of design professionals and practitioners in this region, particularly in Florida and North and South Carolina. Major vulnerabilities in this region include sea level rise, storm surge, boat wakes, dense coastal development, and invasive species. Ice negatively impacts the performance of marsh sills and structures in North Carolina but does so infrequently. Habitat types include marshes, mangroves, reefs (oyster and coral), beaches, and dunes. More specific information about the use of nature-based solutions in this region is found in GDNR (2013) and Schiavinato and Kalo (2014).

The **Great Lakes** region has a shorter track record with formal implementation of nature-based solutions, although shoreline and marsh restoration projects do exist. The wave energies in this region can be extremely high along the primary lake shorelines because of the large fetches. While the lakes do not necessarily experience storm surge, they do experience surge-like events in the form of meteotsunamis and squall line surge events. Shoreline types vary considerably throughout these lakes, including low sandy banks, high coastal bluffs, and freshwater emergent marshes. There is no substantial astronomical tide in the Great Lakes and sea level change does not apply. However, the Great Lakes do experience considerable fluctuations in water levels associated with redistributions of water within the broader hydrologic cycle. Major vulnerabilities in this region include major lake-level fluctuations, extra-tropical storms, wave action, bluff erosion, ice impacts (frequent), and invasive species. For example, many wetlands of the Great Lakes region are experiencing problems with the cattail *Typha glauca*, which is a hybrid of the native cattail *Typha latifolia* (native to much of North America), and the introduced cattail *Typha angustifolia*. Habitat types include freshwater marshes, maritime forests, beaches, and dunes. More specific information about the use of nature-based solutions in this region is found in Lulloff and Keillor (2016) and USACE (2017).

Meteo-what?

A meteorological tsunami, or meteotsunami, is a tsunami-like wave event that is triggered by a weather event. This can be a significant drop in atmospheric pressure, rapid movement of a weather front across the surface of the water body, or rapid relaxation of the water surface “sloshing” back following a strong wind event.

The **Gulf of Mexico** region has a relatively long record (~20 years) of nature-based solutions built across a wide range of wave energy exposures, habitat types, and permitting options. Tideland ownership and policies vary somewhat from State to State. There is a healthy network of design professionals and practitioners in this region, adequate access to materials and contractors, and a growing body of knowledge to assist in project implementation. Major vulnerabilities in this region include sea level rise, storm surge, dense coastal development, and invasive species. Habitat types include marshes, mangroves (non-native in specific areas of some States), maritime forests, reefs (oyster and coral), beaches, and dunes. More specific information about the use of nature-based solutions in this region is found in GBF (2011), MBNEP (2014), and Bryars (2016).

The **Pacific Northwest** region has a relatively short track record with formal implementation of nature-based solutions, although some examples exist. The wave energies in this region are extremely high along the open ocean shorelines, and more moderate along the estuarine shorelines of Puget Sound (but by no means mild). Tide ranges are typically large in this region. Tideland ownership and policies vary from State to State. There are fewer coastal design professionals and practitioners in this region. Major vulnerabilities in this region include sea level rise, flooding during “king tide” events, wave runup and overtopping, tsunamis, ice impacts, and invasive species. For example, smooth cordgrass (*Spartina alterniflora*) is invasive on Pacific Coast mudflats and waterways, while being an important native component of Gulf of Mexico and Atlantic Coast coastal ecology. Habitat types include marshes, beaches (sandy and cobble/shingle), berms, dunes, bluffs, and rocky coasts. More specific information about the use of some nature-based solutions in this region is found in Allan et al. (2005a, 2005b) and Johannessen et al. (2014).

California has a moderate history of formal implementation of nature-based solutions, particularly along sheltered shorelines. The wave energies in this region are extremely high along the open ocean shorelines, and moderate along the estuarine shorelines of San Francisco Bay. Tide ranges are large in this region. There is a large group of coastal design professionals and practitioners in this region. Major vulnerabilities in this region include sea level rise, flooding during “king tide” events, wave runup and overtopping, tsunamis, ice impacts (less frequent), and invasive species. Habitat types include marshes, beaches (mostly sandy), dunes, bluffs, and rocky coasts. More specific information about the use of nature-based solutions in California is found in Newkirk et al. (2018).

The **Hawaiian and Pacific Islands** region has perhaps one of the most interesting histories with respect to nature-based solutions. Native Hawaiians have historically managed their shorelines and coastal regions using a comprehensive, systems-type approach. Locally, the strategy is known as “ridge to reef” management. This approach is equivalent to watershed management. An example of an old, Hawaiian nature-based solution is the fish pond (Figure 4-9). Fish ponds, some of which are more than 800 years old, are strategies that comprehensively manage fisheries, watershed contributions to the coast, storm surge impacts (relatively minor), and wave-induced shoreline erosion (significant). The porous lava rock used to build the pond wall allows exchange of seawater and freshwater, serves as a sort of broad crested weir during rainfall runoff events, and as a reef and/or breakwater during elevated ocean water level and large wave events. Hawaii and other Pacific Island territories experience relatively minor tide ranges, but all are subject to extreme winter swell wave energy and wave runup along the coast. Storm surge is typically smaller in this region because of the steep nearshore slopes. Wave breaking over reefs contribute to setup along the coast that significantly exceeds that of storm surge. Some islands in this region are more vulnerable to sea level rise than others. Major vulnerabilities in this region include wave runup and overtopping, tsunamis, and invasive species. For example, the mangrove (*Rhizophora mangle*) is highly invasive in Hawaii and other Pacific Islands (as well as specific areas of some Gulf Coast States) but is native to North America; it is protected in Florida and vital for that State’s coastal stability and ecosystem integrity. Habitat types include non-native mangrove forests, extensive coral reef systems, beaches (mostly sandy), dunes, and some rocky/volcanic coasts. More specific information about the use of nature-based solutions in this region is found in DLNR (2013) and USACE (2018).

Figure 4-9. Example of a fish pond from He’eia State Park in Kaneohe Bay, Oahu, HI (photo courtesy of Bret Webb).

5. ENGINEERING AND ECOLOGICAL DESIGN CONSIDERATIONS

With the site and resilience characterization steps now complete and having selected one or more potential nature-based solutions for evaluation, it is time to design the engineering and ecological elements of your project. After reading this section, you will better understand the design considerations, tools, methods, and strategies for addressing the engineering and ecological needs of your nature-based solution. Design examples of existing and proposed nature-based solutions appear at the end of this section.

5.1 Assembling the Team

There is no "one size fits all" and no two sites are ever the same. Therefore, it is imperative that you rely on the appropriate professional expertise and experience when it comes to project design. To that end, the assembled team of professionals must have someone who is knowledgeable about planning, designing, and implementing nature-based solutions. Successful nature-based solutions also benefit from a wide variety of technical expertise throughout implementation, including, at a minimum, transportation professionals, coastal engineers, and coastal scientists. Figure 5-1 briefly describes the elements of a successful nature-based solution and, ideally, how the different professionals should interact: at the intersection of all three circles!

Figure 5-1. Suggested expertise for the implementation of nature-based solutions.

Implementing nature-based solutions for coastal highway resilience requires active participation and involvement from the spectrum of transportation professionals: planners, ecologists, environmental scientists, pre-construction engineers, design engineers, maintenance engineers, financial experts, and regulatory compliance staff. This is likely the broadest set of expertise required among the three groups and for good reason. Transportation projects are complex and an appropriate assessment of the project life cycle and how nature-based solutions will address broader transportation system needs is critical to success. In short, transportation professionals identify system needs, preferences, and project constraints. They convey that information to the nature-based solution design team, which consists of practitioners of coastal engineering and coastal sciences, including ecology, biology, geology, and perhaps oceanography. The coastal team then develops a nature-based solution, or a suite of alternatives, that meet the transportation requirements and are technically feasible, reasonable, justifiable, permittable, and constructible.

5.2 Addressing Tie-Ins to Surrounding Areas

Before designing your nature-based solution, consider addressing issues and/or making improvements to the upland and/or surrounding areas. In some cases, erosion issues are resolved by (1) implementing appropriate stormwater best management practices on the upland, (2) managing the coastal or riparian buffer, and (3) regrading overly steep banks. Addressing these three issues also plays an important role in the function and performance of your nature-based solution.

Stormwater Management

Basic stormwater management best management practices (BMPs) play an important role in the success and performance of nature-based solutions. Unmanaged stormwater runoff will erode the upland and intertidal slopes and possibly uproot emergent vegetation as runoff flows to the shoreline. In addition to the volume and rate of overland flow, stormwater runoff contains nitrogen and phosphorous, as well as heavy metals, chemicals, and bacteria that attach to sediment particles as they are transported to the coastal environment. Application of traditional stormwater BMPs on the upland and/or transportation infrastructure will reduce or eliminate many of these issues (USEPA 2015a). Transportation agencies should consider whether their own stormwater BMPs accommodate nature-based solutions and, if not, modify them appropriately as part of the construction process.

Coastal Buffer Management

Management of the coastal (riparian) buffer refers to maintaining, enhancing, or restoring the coverage, density, and composition of vegetation (e.g., ground cover, shrubs, understory, trees) found on the face of the bank and near the top of the bank or bluff. Like smaller versions of maritime forests, the coastal buffer reduces coastal flooding and wave action, stabilizes banks and slopes, and reduces the rate of stormwater runoff. Effective buffers extend approximately 100 feet landward from the top of the bank. This target width of 100 feet is not always practical for some transportation settings with narrow easements. However, conservation and maintenance of existing coastal buffers benefit transportation resilience and improve the performance of nature-based solutions along the shoreline. Effective buffer management requires a plan and dedicated funding to perform routine maintenance, particularly when large trees shade the shoreline and limit sunlight exposure to emergent intertidal marsh or beach plants.

Bank Grading

Bank grading is used to stabilize steep or eroding upland slopes. Grading the bank reduces erosion from upland stormwater runoff and promotes wave runup on the slope as opposed to undercutting at the toe of the bank or bluff. Bank grading also provides space for the shoreline to migrate in response to sea level rise. Limit bank grading only to areas experiencing erosion, making sure not to disturb stable soil and vegetation, or create a hazard for adjacent properties. Bank grading should attain a slope of 3:1 (H:V) or flatter. Constraints on bank grading include feasibility, space, and accessibility to the bank and shoreline. In some cases, good material excavated from the bank can be used to increase planform elevation and/or width to create or enhance the natural feature. It is more common to dispose of that material on the upland or in some other location, but remember that the eroding bank or bluff is most often the primary source of material for the shoreline at its base. Continually removing that material from the bank effectively cuts off the shoreline from at least one of its long-term sediment supplies. A more effective strategy for managing that excavated material is to place it directly on the shoreline below (if the sediment is compatible and appropriate permits are obtained).

5.3 Engineering Design Considerations for Common Nature-Based Materials and Techniques

After completing the site characterization (Sections 4.1 and 4.2) and determining the primary materials and techniques you will use based on that characterization (Section 4.3), the next stage is to advance your conceptual design to a draft design. While transportation agencies will likely hire a coastal engineer for this step, it is still important for the transportation practitioner to understand the steps and considerations in order to properly oversee the work.

A Note on Technical Guidance
The USACE (2002) *Coastal Engineering Manual* provides many of the tools and methods required for designing the structural elements used as part of a nature-based solution. Specific regional design guidance, best practices, and recommendations related to nature-based solutions were previously mentioned in Section 4.4.

The design team must determine the placement, size, and combinations of materials based on desired risk reduction and ecological performance. Below we describe some design considerations for these particular materials and techniques:

- Marsh Sills and Toe Revetments
- Vertical Sills
- Breakwaters
- Vegetation
- Geotextiles
- Reefs

- Dunes
- Beach Nourishment
- Sediments for Beaches and Dunes

Marsh Sills and Toe Revetments

Marsh sills are relatively small structures, often trapezoidal in cross-section, placed seaward (channelward) of a shoreline for the purposes of stabilizing newly placed fill and attenuating wave energy (Figure 5-2). Materials used in the construction of marsh sills range from stone (riprap) to bagged oyster shells and manufactured (concrete or other structural material) habitat devices. Fill is added landward of the marsh sill to establish appropriate nearshore and shoreline slopes. For intertidal marsh habitat, an appropriate target design slope from the sill to the upland is 10:1 (H:V), although steeper slopes may be adequate in some cases. If that value does not seem to be correct for your region, perform an elevation survey of a nearby, healthy intertidal marsh and mimic that value in your project.

Design of Marsh Sills
The States of Maryland and Virginia have nearly 40 years of experience using marsh sills and marsh toe revetments. Consider their design guidance to determine whether it is appropriate for your area (see MDE 2008 and Hardaway et al. 2017). If the conditions in your area are different, try to find an appropriate way to adapt their guidance to fit your needs or find other appropriate State or regional guidance (see Miller et al. 2015 for New York/New Jersey).

The design of the structure depends on wave energy exposure. If you are constructing a marsh where fetch is less than 1 mile, a sill will be sufficient. However, if fetch is less than about 15 miles, nearshore segmented breakwaters would be more appropriate. If the fetch is significantly larger than 15 miles, the size and cost of the necessary structure may become undesirable (this is not uniformly true and must be evaluated on a case-by-case basis).

Figure 5-2. Stone sill and constructed marsh at Morris Landing, NC (photo courtesy of Bret Webb).

The marsh sill design requires determination of an appropriate stone weight, crest elevation and width, side slopes, structure length, the size of gaps (if used), and the appropriate geotextile or filter fabric on which to build the structure. You can use Hudson's equation, described in FHWA (2008), to size armor stone for marsh sills. A simple approximation of Hudson's equation for quarried granite stone (specific weight = 165 lbf/ft^3) is:

$$W_{50} = (16.7 \times H^3) / \cot(\theta), \qquad \text{(Eq. 1)}$$

where H is the design wave height, and cot(θ) is the side slope of your structure such that a side slope (H:V) of 2:1 is equal to cot(θ) = 2.0.

Side slopes of 1.5:1 have been used at sites with very low fetches and/or on the landward-facing slopes, where appropriate. Unless the marsh sill is located adjacent to deep water (unlikely), the design wave height will likely be a depth-limited wave height equivalent to 80 percent of the design water depth condition. An example appears in the text box below.

Example of Sizing Armor Stone for Marsh Sills, Toe Revetments, and Breakwaters

A small marsh sill will be built in a shallow offshore water depth of 2 ft (MSL). The crest elevation is set at 2 ft above MSL. Wave forces acting on the stones will reach a maximum when the design water level is just below the crest elevation of the structure. Therefore, assume a design water depth of 4 ft. Calculate the median armor unit weight using Hudson's equation, specify an appropriate gradation, and approximate the stone dimensions.

Step 1: Find the design wave height assuming depth-limited conditions.

$H_{max} = (0.8) * (4 \text{ ft}) = 3.2 \text{ ft}$

Step 2: Specify the side slope of the structure and apply Hudson's equation.

Use 2:1 (H:V) side slopes.

$W_{50} = (16.7) * (3.2 \text{ ft})^3 / (2) = 273.6$ lb or approximately 275 lb

Step 3: Specify an appropriate gradation based on FHWA (2008).

$0.125 \times W_{50} < W_{50} < 4 \times W_{50}$

$(0.125) * (275 \text{ lb}) < W_{50} < (4) * (275 \text{ lb})$

$35 \text{ lb} < W_{50} < 1{,}100 \text{ lb}$

Step 4: Approximate the stone dimensions assuming a cubic shape and a specific weight of 165 lbf/ft^3.

$D_{low} = [(35 \text{ lb}) / (165 \text{ lbf/ft}^3)]^{1/3} = 0.6 \text{ ft}$

$D_{50} = [(1{,}100 \text{ lb}) / (165 \text{ lbf/ft}^3)]^{1/3} = 1.2 \text{ ft}$

$D_{high} = [(1{,}100 \text{ lb}) / (165 \text{ lbf/ft}^3)]^{1/3} = 1.9 \text{ ft}$

Step 5: Evaluate the feasibility and constructability of your design.

Marsh sills and other smaller rubble mound structures are difficult to construct in shallow depths purely because the dimensions of the armor stones are so large. In this example, we could potentially stack about three or four median stones on top of one another before reaching the desired 4-ft structure height. The 35-lb stones are small enough to be moved around by waves, so use them to construct the core of the marsh sill or as a bedding layer over the geotextile.

In addition, a marsh toe revetment can be used to protect an eroding marsh shoreline (i.e., when the addition of fill is not necessary to establish a new marsh). The marsh toe revetment should be placed slightly seaward (channelward) of the MLW tidal datum, and no stone should be placed directly on the marsh edge or marsh surface. The crest elevation of a marsh toe revetment is typically at the MHW tidal datum for low wave energy settings (fetch < 1 mile), and about 1 foot above MHW for moderate wave energy settings (1 mile < fetch < 5 miles). These are simply suggestions and the appropriate toe and crest elevations for a marsh toe revetment may vary on a case-by-case basis.

Vertical Sills

A vertical sill, made of timber or sheet pile, is designed to stabilize sediments and attenuate wave energy (Figure 5-3). Vertical sills are often deployed within 10 to 30 feet of the marsh edge and/or in relatively shallow water depths (~3 to 4 feet or less). North Carolina frequently uses vertical sills for marsh shoreline stabilization. Unlike marsh sills and marsh toe revetments that affect a substantial portion of the benthic habitat, vertical sills have much smaller footprints on the seabed and, therefore, fewer (but measurable) benthic impacts.

Design considerations for vertical sills include wave loads, soil-bearing capacity, wave transmission past the structure, ice uplift, and constructability. As flat-faced, rigid structures, vertical sills are vulnerable to wave loads that lead to overturning in poor soil conditions. The *Coastal Engineering Manual* provides many formulas for estimating wave loads on vertical walls (USACE 2002). Ice formation on timber is known to cause uplift forces on vertical sills as the tide rises.

Wave transmission past a vertical sill is a function of structure porosity. For timber structures, porosity is related to the size of and spacing between vertical boards. The equation for porosity is the gap distance divided by the center-to-center timber spacing. For example, a sill using 2 inch by 6 inch vertical boards and 1-inch gaps has a porosity of 14 percent (e.g., 1 inch / [3 inches + 1 inch + 3 inches] = 1 / 7). Gaps smaller than 1-inch fill with marine growth over time. Timber sills with porosities of less than 15 percent reduce wave height by more than 50 percent. A porosity of 20 percent will only reduce wave heights by 20 percent to 30 percent. Smith and Kriebel (2004) provide additional guidance on porosity calculations and designs. Figure 5-4 shows a typical timber sill design. Some vertical sills use vinyl sheet pile, which has zero porosity, but may still allow wave transmission via wave overtopping during high tide.

Figure 5-3. Vertical timber sill protecting a marsh (NCDEQ 2019).

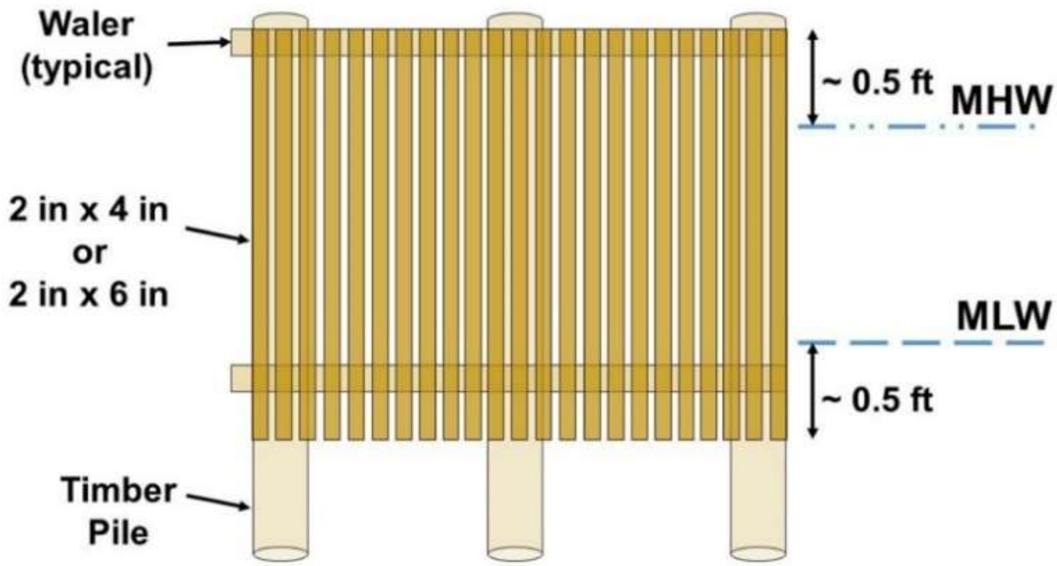


Figure 5-4. Typical vertical timber sill design in shallow water (Bryars 2016).

Breakwaters

Breakwaters are used to “break” or reduce wave heights through multiple wave transformation processes: reflection, dissipation, and diffraction. Breakwaters reduce wave heights and redirect waves, thus modifying the position and shape of nearby shorelines.

Breakwaters are used in many different settings and are deployed in many different configurations. There are floating breakwaters, timber breakwaters, stone breakwaters, concrete breakwaters, and many other types. Some are placed some distance offshore, and typically parallel to it, segmented with gaps to facilitate water circulation, habitat ingress/egress, recreation, and other hydrodynamic processes. Others are placed directly on the shore, or very close to it, to establish permanent connectivity between the shore and the structure. The literature refers to these types of breakwaters as headlands, headland structures, and headland breakwaters (Figure 5-5).

Lesson Learned: Using Structures

The size, characteristics, and location of a structure must account for the project objectives. Common design mistakes include:

- Under- or over-designing structures for their intended application.
- Using non-traditional structures (e.g., alternatives to rock breakwaters) where the performance is not well understood.
- Placing structures at sites where they may exacerbate shoreline erosion.
- Other unintended or unanticipated adverse effects.

Figure 5-5. Offshore segmented breakwaters and beach nourishment protecting Louisiana Highway 82 in Holly Beach (source: FHWA 2019a).

For the purposes of this guide, we limit the discussion of breakwaters to relatively small breakwaters constructed from stone—so-called rubble mound structures. Hudson's equation, discussed in an earlier textbox, provides reasonable estimates of median armor stone weight for small to moderately sized breakwaters. In nature-based solutions, breakwaters are often combined with constructed marshes or sandy shorelines to create an irregular, but stable, shoreline position. The bending, or diffraction, of waves around the ends of breakwaters and through breakwater gaps leads to the formation of stable, crenulate-shaped pockets (Hardaway and Gunn 2002). The geometry of these pockets, or "pocket beaches," is somewhat predictable in the case of sandy shorelines. The formation of pocket beaches mimics the naturally occurring beaches that form in between rocky headlands or outcrops in the Northeast and Pacific Northwest.

In the literature, there are numerous empirical methods for estimating the pocket geometry based on the gap width between breakwaters, the dominant wave direction(s), the tide range, and the expected storm tide. For example, Hardaway and Gunn (2011) summarize some of the most commonly used methods; Bodge (2003) presents a comprehensive multi-step process for designing pocket beaches; and Rosati (1990) gives a comprehensive overview of functional shoreline structure design. As shown in Figure 5-6, the relationship that most determines the geometry of the pocket is the gap width between adjacent breakwaters. The relationship between the gap width and pocket indentation varies based on the wave energy exposure and coastal setting. Hardaway et al. (2017) report an average value for Chesapeake Bay as M_b:G_b = 1:1.65. On some coasts, this ratio can increase to M_b:G_b = 1:3 (Hardaway and Gunn 2011). The pocket shape establishes its equilibrium position as a function of both the average annual and storm wave conditions, as described schematically in Figure 5-7.

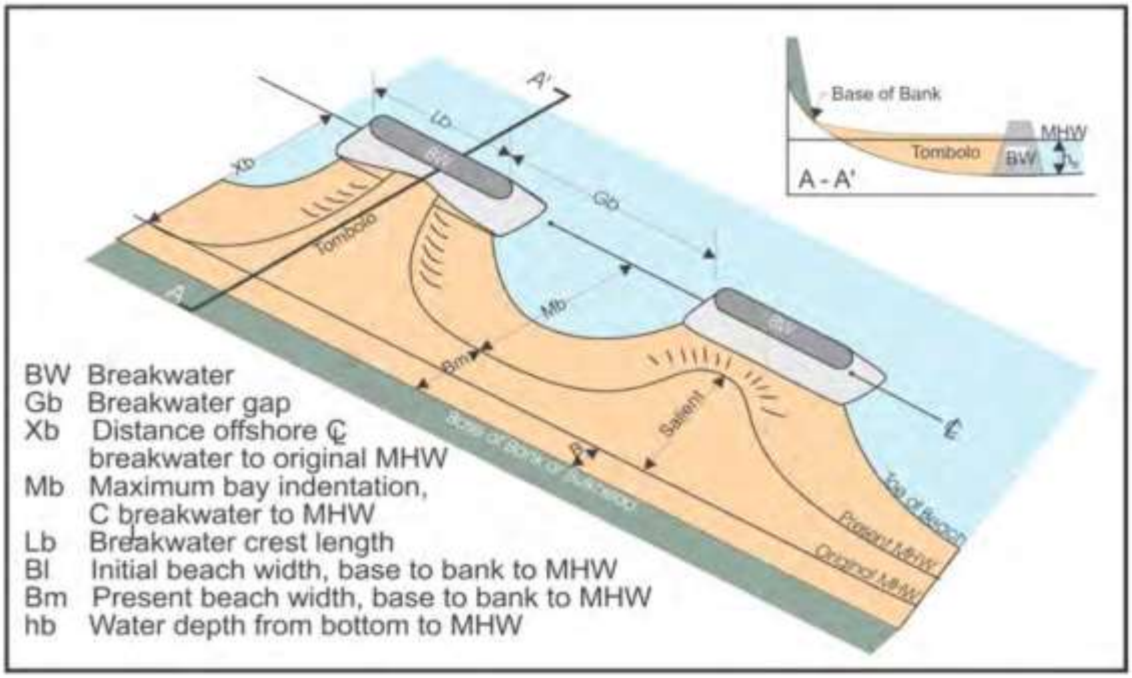


Figure 5-6. Headland breakwater design parameters (Hardaway and Byrne 1999; Hardaway et al. 2017).

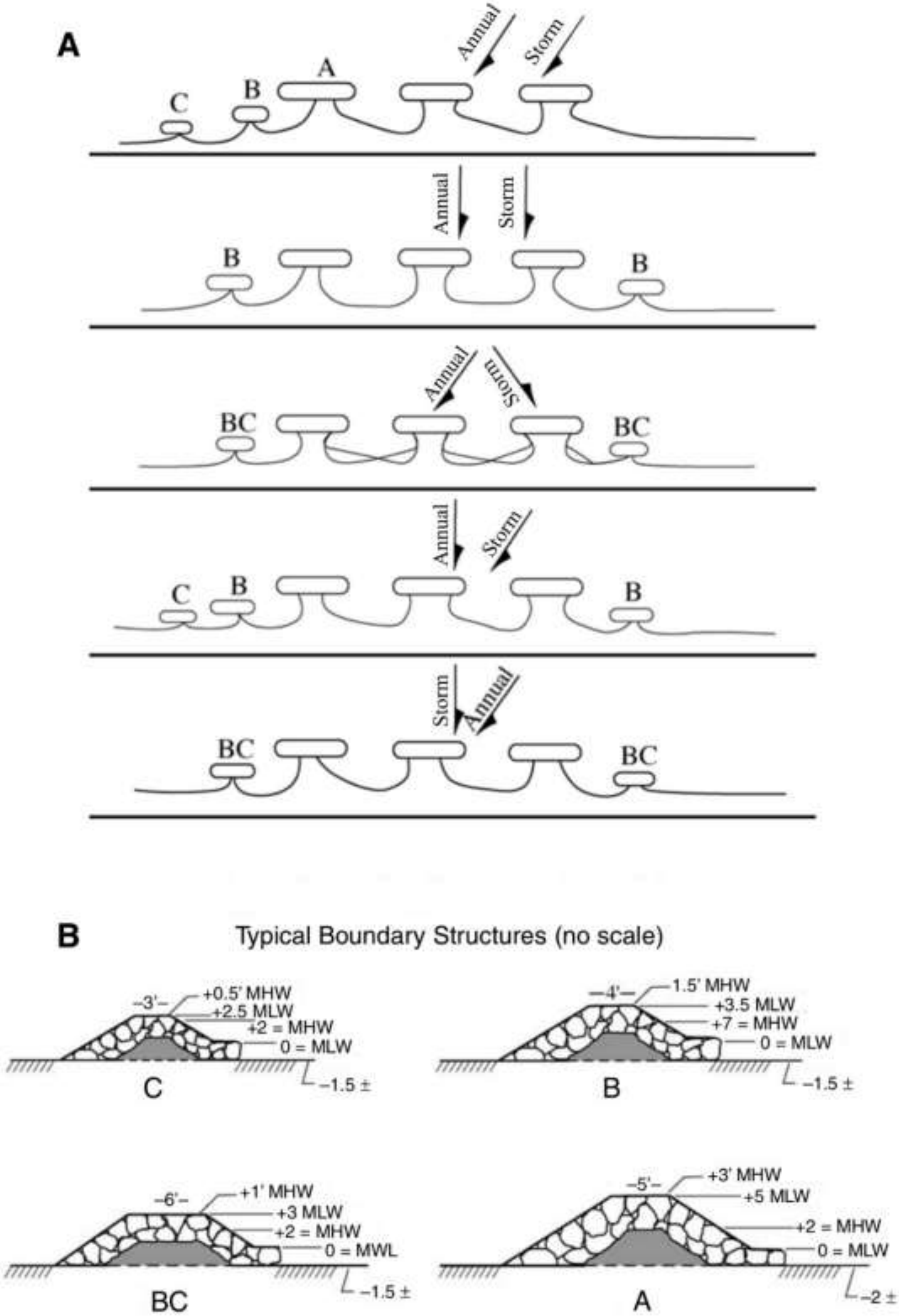


Figure 5-7. (A) Equilibrium pocket beach shoreline positions as a function of wave conditions; (B) Corresponding breakwater cross-sections for type A, type B, type C, and type BC structures shown in (A). These unique cross-sections demonstrate how site-specific conditions, such as the annual and storm wave conditions, lead to changes in project design (Hardaway et al. 1993; NRC 2007).

Vegetation

The appropriate use of vegetation in a nature-based solution depends on specific site factors, including the following:

- Region
- Historic and current native habitat conditions
- Extent, rate, and cause of erosion
- Elevation, slope, orientation, light availability, and soil characteristics
- Average wind speed, duration, and fetch and peaks during storm events
- Tidal range
- Exposure and characterization of wave action and timing, including by storms and boat traffic
- Type of body of water, water depth, salinity, prevailing currents, and fetch
- Wildlife species existing within the site or desired within the site

The species of vegetation will vary by region of the United States and are targeted for a given level of inundation, salt-tolerance, and desired vegetation community/habitat type, including submerged aquatic vegetation (SAV), emergent vegetation (e.g., marshes), riparian, and upland terrestrial species. Figure 5-8 is one such example for vegetation in Gulf Coast marshes.

Lesson Learned: Marsh Erosion
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 most of the time, in addition to considering those associated with infrequent but extreme events.

In addition to establishing appropriate elevations and required levels of wave attenuation, there are other considerations to address in the project design. Some of these considerations include establishing the appropriate slope, planting density, availability and use of donor plants, and protection from foraging. Intertidal marsh vegetation often prefers mild slopes of 10:1 (H:V). The track record of marshes planted on substantially milder or steeper slopes is poor. Furthermore, many practitioners recommend waiting at least 1 to 3 weeks to plant following the placement of fill. The newly placed fill will equilibrate to the site-specific hydrodynamic conditions during that waiting period.

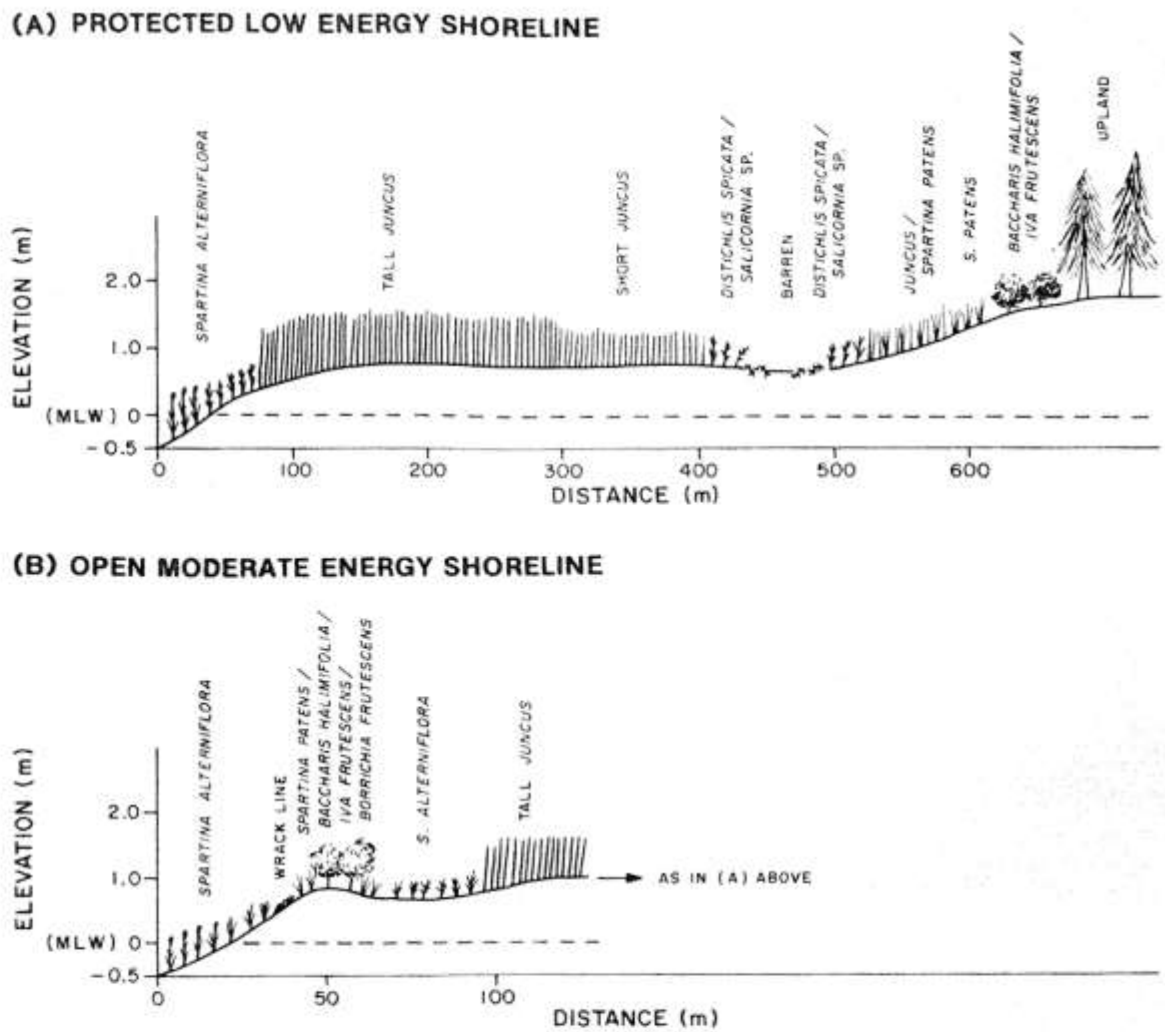


Figure 5-8. General diagrams of salt marshes on (A) Protected low energy shoreline, and (B) Open moderate energy shoreline of the Gulf Coast (Stout 1984).

Planting strategies are often designed to achieve a certain initial coverage. For example, plants are often installed with 1-foot, 1.5-foot, or 2-foot center spacing (plant-to-plant). Some anecdotal evidence suggests that plant clustering yields more desirable benefits than plant spacing (FHWA 2018b). Similarly, mixing plants excavated from a donor marsh near the project site with nursery plants is known to contribute to success (Sharma et al. 2016). The use of a donor marsh, however, requires approval from State and Federal regulatory agencies and cannot always be guaranteed. Often overlooked in nature-based design, newly planted vegetation is a desirable food source for birds and marine mammals. Some project designs incorporate nets, cages, or fencing that attempt to prevent or limit foraging early in the plant's development. Maintenance of vegetation is critical for the success of nature-based solutions and may include invasive/exotic plant and animal species removal, replanting of vegetation when needed, trimming of vegetation, and removing debris.

The existence and health of emergent saltwater marshes is regulated by a variety of factors, including sediment type and supply, elevation, nutrient levels, and wave conditions. A study by Roland and Douglass (2005) quantifies the wave tolerance of *Spartina 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 both significant wave height and frequency of occurrence in Figure 5-9. 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 foot) and a corresponding 80th percentile significant wave height of 0.2 meter (0.66 foot). In other words, marsh vegetation is stable when significant wave heights are less than 0.2 meter (0.66 foot) 80 percent of the time and less than 0.3 meter (1 foot) 95 percent of the time.

The Roland and Douglass (2005) findings are generally consistent with a "rule of thumb" that marsh grasses exist where maximum storm wave heights are less than 1 foot. These values serve as practical engineering guidance on the wave tolerance of typical marsh vegetation to incident waves. Sills or breakwaters provide the necessary attenuation of wave energy when incident wave heights are greater than these limits. The hatched area between the two regions in Figure 5-9 reflects locations with eroding and marginal marsh vegetation.

Geotextiles

The use of geotextile fabrics or geotextile grids is common in the design of nature-based solutions. Figure 5-10 shows contractors stretching, aligning, and placing geotextile fabric to serve as the base for construction of an offshore rock breakwater. Geotextile materials are most often used to prevent or reduce the loss of sediments behind or under a structure, provide additional bearing capacity in poor soil conditions, or serve as a sand-retaining structure (e.g., geotube). The use of hybrid geotextiles that better accommodate vegetation is becoming more commonplace.

The selection of an appropriate geotextile material depends on sediment size and gradation, existing and required soil-bearing capacities, and exposure to sunlight. Many geotextile materials are vulnerable to ultraviolet (UV) degradation and must remain buried to avoid direct sunlight exposure. Material manufacturers are developing new products that are less sensitive to UV degradation and the appropriate geotextile should be selected for a given application.

In some settings, placement of a suitable geotextile fabric is impractical or even impossible (e.g., an area with strong currents). Substituting the geotextile fabric for a suitable underlayer that provides the necessary foundation strength and filtering requirements is allowable. In fact, it is not uncommon for contractors to use a layer of bedding stone to hold the geotextile in place.

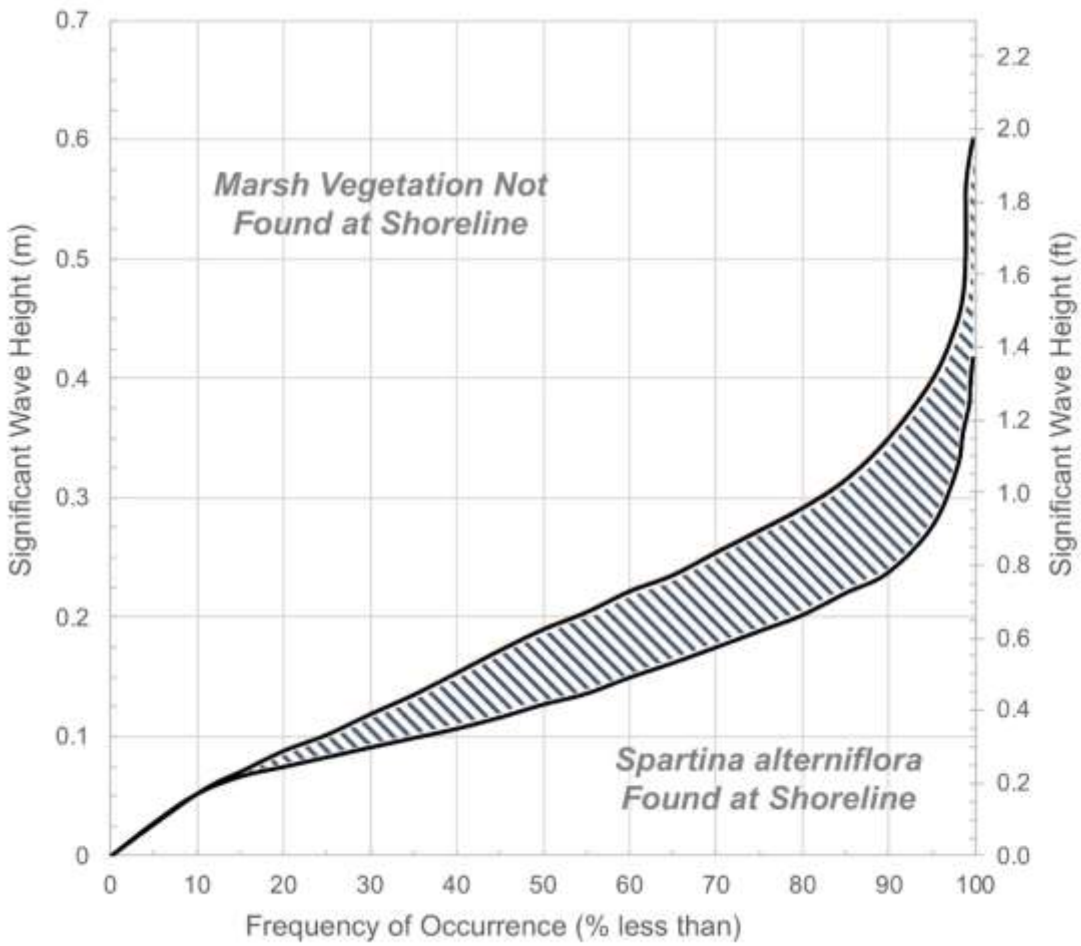


Figure 5-9. Wave tolerance of Spartina alterniflora as a function of significant wave height and frequency of occurrence (based on Roland and Douglass 2005).

Figure 5-10. Contractors placing geotextile fabric for the foundation of an offshore rock breakwater (photo courtesy of Sam St. John).

Reefs and Reef Restoration

Alternatives to traditional breakwater materials and traditional coastal structures are growing in practice. These materials are presented as alternatives that provide performance, habitat value, or an ecosystem service that is (or claims to be) superior to traditional materials and structures. For example, the use of artificial reef units as “living breakwaters” is becoming more common (Allen and Webb 2011; Webb and Allen 2015), even in lieu of accepted performance criteria and design standards. In some cases, Federal agencies, such as USACE, are facilitating the consideration of non-rock alternatives through performance-based design criteria that address, among other things, stability under wave attack, wave attenuation, constructability, durability, and cost.

Lesson Learned: Working With Oyster Shell and Loose Material
Loose substrate (e.g., oyster shell), coir fiber logs, and woody debris have not performed well when exposed to wave action. For example, loose oyster shell substrate tends to degrade over time because of 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 because of abrasion of the encapsulating netting against the stakes and strapping used to secure them to the ground.

Dunes

Dunes serve two critical functions during storm events: (1) they delay and reduce coastal flooding, and (2) minimize the duration and intensity of wave action and wave-induced flooding. Figure 5-11 shows an artificial sand dune constructed seaward of a coast-parallel highway to protect the road from flooding and damage. Dune erosion during a major storm removes all wave protection afforded by a small dune. Two important characteristics of dunes are their volume above stormwater levels and the elevation of their crest. Hallermeier and Rhodes (1989) provide an equation relating dune erosion to storm return period for specifying minimum dune volume densities. This equation generally describes the dune volume required to protect against a storm having a *T*-year return period:

$$V = 86.1T^{0.4}, \qquad \text{(Eq. 2)}$$

where *V* is dune volume above the still water level in cubic feet per foot of shoreline, and *T* is the storm return period in years. The equation continues to be used despite considerable uncertainty in the formula.

Figure 5-11. Artificial sand dune constructed seaward of North Carolina Highway 12 to protect the roadway from flooding and damage (FHWA 2008).

No engineering tools specifically account for the positive effects of vegetation on dune performance. However, in most published studies, dune vegetation substantially decreases dune erosion and retreat rates (Figlus et al. 2014), and is effective at reducing wave runup, overtopping, and overwashing (Gralher et al. 2012; Kim et al. 2016; Kobayashi et al. 2013; Silva et al. 2016). USACE is supporting enhanced research in this area to better understand and quantify the role of vegetation in dune resilience (Bryant et al. 2018).

Beach Nourishment

Beach nourishment is protecting many coastal highways in the United States. Beach nourishment is the direct placement of clean, compatible sand on the beach to widen the beach and advance the shoreline seaward (Dean 2003). Beach-quality sand fill is used for (re)establishing the preferred shoreline and/or upland slope and required grade elevation. For example, a constructed intertidal marsh will often require the use of sand fill to establish appropriate slopes and elevations for the marsh vegetation. On sandy shorelines of considerable width, sand fill is added to create or restore dune features or amend the shoreline berm elevation and location.

Beach nourishment (with or without dunes) is an appropriate shoreline management strategy along gently sloping sandy shorelines and in areas where the hydrodynamic parameters, including nearshore sediment transport, support a sandy beach (Figure 5-12). Beach nourishment is typically a preferred management strategy for facilitating shoreline recreation, and it is an effective strategy for mitigating risks to coastal highways vulnerable to shoreline retreat.

Not All Beaches Are Sandy Beaches

Beaches and beach nourishment are not exclusive to the use of sand. In Oregon and other parts of the United States, cobble and shingle beaches exist along the coastline. The use of dynamic revetments to simulate a cobble beach, while providing the functional performance of a revetment, is growing in popularity and some technical guidance exists (Allan et al. 2005a, 2005b).

The performance of beach nourishment projects depends on the background erosion rate, storm frequency and intensity, characteristics of the fill or nourishment material, project design, and the use of coastal structures. See Dean (2003) for a comprehensive guide to the theory and practice of beach nourishment.

The background erosion rate and storm-induced beach erosion factor into the design beach width and design beach volume in order to meet performance requirements. Beach nourishment projects consider two volumes of fill: the design beach volume and the advance mitigation volume. The design beach volume and width are the desired, minimum targets for maintaining a healthy beach system. The advance mitigation volume is provided to allow initial beach profile equilibration, accounting for expected storm impacts and factoring in the background erosion rate. These factors are considered over a specified period in order to determine the beach renourishment interval required to maintain the design beach width. A very simple example of the calculation for a beach nourishment project without structures is given in a text box on the following page.

Figure 5-12. Active beach nourishment in North Carolina showing the dredge pipeline discharging sand and water directly onto the shore. The dredge ship is visible in the background (photo courtesy of Tina Hodges).

Beach Nourishment Performance Example

A small beach nourishment project (without structures) is considered to protect a four-lane divided coastal highway. The minimum desired beach width is 50 feet. The background erosion rate is 2 feet per year. The erosion for a 10-year return period storm event is estimated as 10 feet. The initial profile adjustment erosion is 15 feet. Assuming that the storm event occurs exactly once over a 10-year period, determine the additional beach width required to meet the minimum beach width requirement.

Step 1: Find the total amount of background erosion.

E_{be} = (10 yr) * (2 ft/yr) = 20 ft

Step 2: Find the total amount of erosion over the 10-year interval.

$E_t = E_{be}$ + 10 ft + 15 ft = 20 ft + 10 ft + 15 ft = 45 ft

Step 3: Determine the total beach nourishment width at the time of construction.

W_{bn} = 50 ft + E_t = 50 ft + 45 ft = 95 ft

The half-life of a beach nourishment project—the time at which 50 percent of the beach nourishment volume remains—is directly proportional to the length of the project squared. In other words, a 2,000-foot-long project has a half-life that is four times longer than a 1,000-foot-long project. The use of coastal structures such as breakwaters and groins considerably extends the life of small beach nourishment projects (NRC 1995). Theoretically, these projects have an indefinite half-life since very little of the material ever leaves the project site.

Sediment for Beaches and Dunes

The performance of beaches and dunes is very sensitive to sediment characteristics. Sediment from borrow sources must match the native sediment characteristics as closely as possible. The three characteristics that drive physical performance include median sediment diameter (d_{50}), sediment gradation, and percentage of fines. Using sediment that is smaller than the native material will lead to less emergent dry beach or require larger volumes of sediment to meet the design requirements. Using material that is slightly larger than the native grain size is often preferred over a smaller grain size; however, material that is too large will produce a beach slope that is out of equilibrium with the wave conditions. In terms of gradation, a suitable borrow source consists of well-sorted (poorly graded) material with a very low percentage of fines (e.g., < 1 or 2 percent). Sediment texture, as well as its mineral content, also is important, but it is less of a performance concern. Sediment color can be an important factor for aesthetic reasons; it is standardized based on the Munsell color system.

Finding suitable sediments that are compatible with the project beach, in large enough volumes for your project needs, may be challenging. The most suitable material is found near the project site, often in the offshore areas. However, nearshore dredging of seabed sediments for beach nourishment is often prohibited. Viable sediment sources include upland quarries, bank or bluff materials, beneficial use of dredge material, and dredging offshore borrow areas. The design engineer must consider the total cost of finding suitable sand, evaluate its characteristics, assess the feasibility of transporting it to your site, and plan for future renourishment events prior to selecting the material source. For example, offshore borrow areas may contain relatively inexpensive sand (e.g., $8/cubic yard) compared to upland quarries (e.g., $12/cubic yard); however, mobilizing a hydraulic dredge may cost $1 million or more. In this example, you would break even at 250,000 cubic yards of sand.

5.4 Analyze Protection Levels and Adjust Design as Needed

For some nature-based designs, the sizing and estimates for the level of protection can be made based on the formulas and techniques described in Section 5.3. This is the case for marsh sills and toe revetments, breakwaters, dunes, and beach nourishment.

For other designs, especially those incorporating larger landscape features, there may be value in hydrodynamic modeling or other analyses to estimate the level of protection, or equivalent risk reduction, offered by the nature-based solution(s).

While hydrodynamic modeling can incorporate larger landscape features well, such as barrier islands, large expanses of wetlands, and larger topographic features, more specialized hydrodynamic modeling is needed to resolve smaller features, such as a narrow band of constructed marsh or a breakwater. Such an example is provided in Hayward et al. (2018), who used a combination of three sophisticated hydrodynamic models to evaluate the erosion-reduction benefits of nature-based solutions along the coast of Rhode Island.

Development and Evaluation of Alternatives
As part of the conceptual design of a nature-based solution for the realignment of U.S. 98 across Mobile Bay, AL, the design team developed and evaluated multiple alternatives (Section 5.7). Development of alternatives focused on nature-based solutions that reflected the geological and ecological setting of the estuary, namely tidal marsh and submerged aquatic vegetation. The design team evaluated and scored each alternative using six criteria: (1) material cost, (2) length of revetment converted to natural shoreline, (3) cost savings associated with revetment conversion, (4) amount of wave attenuation, (5) area of habitat created, and (6) amount of habitat affected. The alternative with the best score was selected for conceptual design. This simple approach provided an opportunity to objectively compare each alternative.

This leaves us with the category of features for which we do not have detailed engineering guidance and which are too small to be modeled well without highly specialized tools. The main nature-based features falling in this category are those relying heavily on vegetation, such as constructed marshes, mangroves, and reefs. For these features, we have general estimates from the research literature on wave, erosion, and flood attenuation. Under these circumstances, we use empirical methods that are available in the literature to develop estimates for the risk mitigation potential of our design, while exercising caution not to overpromise given the greater uncertainties.

Hydrodynamic Modeling

The FHWA document, *A Primer on Modeling in the Coastal Environment*, introduces transportation engineering professionals to coastal hydrodynamic modeling and can serve as a useful reference (FHWA 2017).

A vulnerability assessment for a coastal bridge in Mississippi provides an example of how hydrodynamic modeling may be useful in identifying appropriate nature-based solutions. As part of an FHWA pilot, analysts used a suite of three hydrodynamic models (ADCIRC, SWAN, and XBeach) to simulate the water levels, velocities, and waves during Hurricane Katrina. The model grids are shown in Figure 5-13. In FHWA (2018a), the results of this modeling exercise showed that a bridge abutment and low-elevation approach spans were vulnerable to damage from strong flows during extreme events. Those results led the research team to develop conceptual designs for vegetated berms running parallel to the lowest bridge spans. The purpose of the berms was to displace, or shift, the strong currents to higher elevation portions of the bridge alignment. The research team also used these modeling results to determine that this displacement of flows would not lead to damage elsewhere.

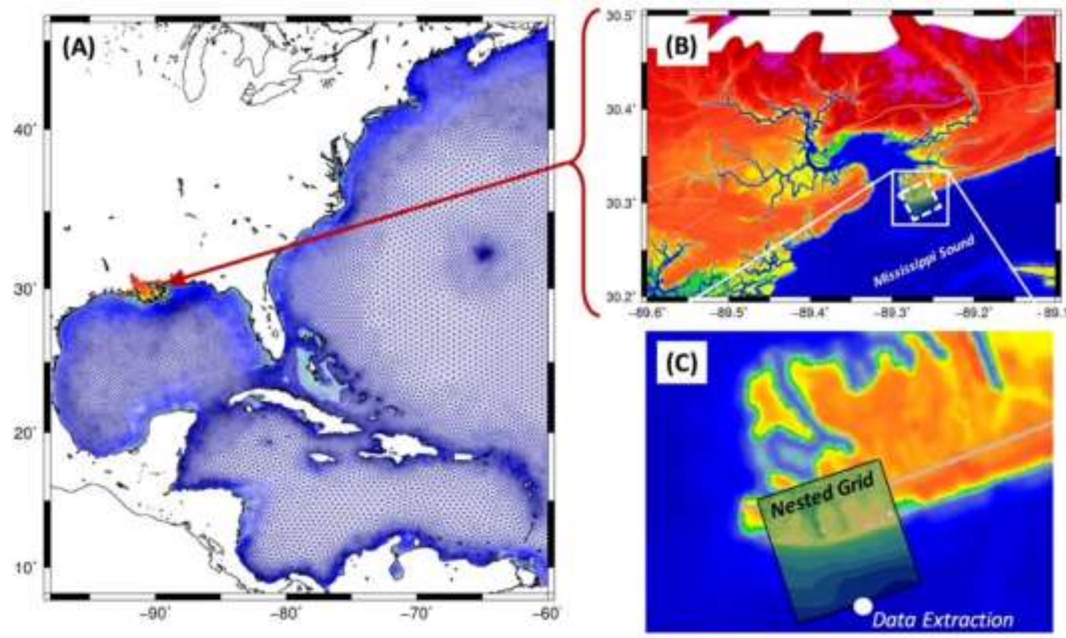


Figure 5-13. (A) Full ADCIRC+SWAN unstructured mesh with local refinement in Mississippi and Louisiana, (B) a detailed view of elevation contours near the study site at Henderson Point, and (C) the location of the nested XBeach model grid relative to the larger mesh (FHWA 2018a).

As another example, after developing conceptual designs for nature-based solutions to protect segments of U.S. 101, Oregon DOT partnered with another State agency, the Oregon Department of Geology and Mineral Industries, to perform wave runup analysis for each of their three project sites to gauge the effectiveness of the designs. The analyst extracted data for the 10-, 25-, 50-, and 100-year extreme total water levels (combined wave runup and tides) using the methodology found in the Coastal Flood Hazard Study for Lincoln County, OR (Allan et al. 2015). The analysis incorporated a projected sea level rise of 19 inches for the 2050 high range scenario. The analysis showed that for one of the three sites, Ona Beach, the nature-based design provided the desired level of protection. For another site, Beverly Beach, the hydrodynamic analysis showed that the design provided insufficient protection and that substantially larger amounts of materials and space would be needed. For the third site, Lost Beach, the analysis showed that the design did not provide the desired level of protection; however, only a slight increase in elevation of the cobble beach and artificial dune would be needed to meet the desired level (ODOT 2017). This project is highlighted as a design example in Section 5.7.

Using Empirical Data and Methods

Section 2 described the benefits of nature-based solutions and what they can provide in the way of flood, wave, and erosion mitigation. Most of the methods used to describe those benefits are based on empirical measurements and observations from the field and/or laboratory. They can be used, with or without hydrodynamic modeling, to estimate the risk reduction they provide. If we understand the magnitude of a hazard value generated by a specific storm event (e.g., a 10-year return period storm water level or wave height), then we can reasonably predict how much the nature-based solution will reduce it using the empirical methods. Comparing the reduced value to the hazard magnitude associated with storms of lower (or higher) return periods allows us to evaluate the level of protection the solutions offer. This assumes that the nature-based solution is resilient to the storm event and survives. As such, we should analyze the literature and use practical experience to determine what type of events the vegetation is capable of surviving. For instance, marsh vegetation is more likely to survive during events where storm surge has submerged the marsh and wave forces are not affecting the vegetation than when wave forces are affecting the vegetation directly.

Reliability

Nature-based solutions are effective at reducing the impacts associated with frequent and low-intensity storm events. They continue to provide some benefits during extreme events. Their impacts on project performance and resilience can be accounted for during the design phase.

The potential for nature-based solutions to reduce an event return period is illustrated in Figure 5-14. In this example, we show a series of return period wave heights for a specific location ("Without NBS" curve). Assuming that we want to know the level of protection and risk reduction provided by a coastal marsh, we use Anderson et al. (2013) to find that the constructed marsh will reduce wave heights by 30 percent ("With NBS" curve). In this case, the marsh (Arrow A) reduces the 5-year return period wave height to that of a (Arrow B) 2-year return period wave height for the design. In other words, the marsh reduces the design wave height. In terms of risk reduction, what is currently a 5-year return period wave height without the marsh shifts to (Arrow C) a 60-year return period event value with the marsh. Assuming a 30-year expected life of the marsh, implementation of the marsh reduces your risk of experiencing the "Without NBS" wave height from 79 percent to 39 percent.

The procedure used to develop Figure 5-14 is completely transferable to other nature-based solutions and other hazard types. You need two pieces of information to complete this type of assessment. First, you need to know the design hazard value without the nature-based solution. This is likely the hazard value under existing site conditions. You do not necessarily need to know how the hazard value changes with the return period. Second, you need a tool, method, or equation that describes how the selected nature-based solution will modify the hazard magnitude. This might be a reduction in flood depth, a decrease in wave height, or a decrease in the rate of shoreline erosion. Use the characteristics of your project (e.g., width, length, height, type), along with the appropriate tool, method, or equation, in order to determine its impact on the selected hazard. Compare your "without NBS" and "with NBS" hazard values to determine the additional resilience provided by your nature-based solution. Consider whether that change might allow you to modify or improve some other portion of your project design, such as reducing the size of riprap in a revetment.

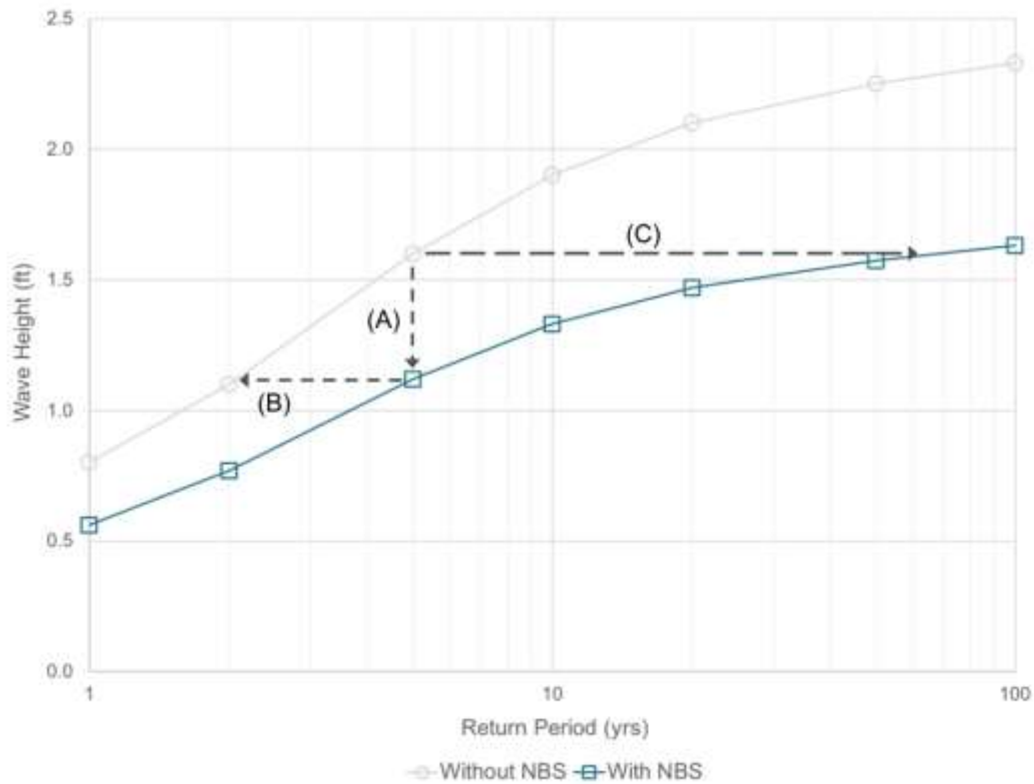


Figure 5-14. Conceptual reduction in the event return period because of a nature-based solution.

5.5 Ecological Design Considerations

This section discusses some considerations regarding the ecological design of nature-based solutions as it is important to understand how the design components being considered will affect the local ecosystem and to understand what ecosystem services the design features may provide. The text relies heavily on several published guidance documents on living shorelines. Nature-based solutions may provide important habitat for economically and ecologically important species, including fish, shellfish, marine plants, invertebrates, reptiles, amphibians, and birds. They also may improve or restore the vegetative diversity of local habitats, may reduce surface water runoff or erosion problems to the benefit of humans and habitats, and may improve water quality through groundwater filtration.

General categories of areas to consider ecologically during project design include the following:

- Habitats/vegetation communities present and desired
- Connectivity effects on adjacent and nearby habitats
- Construction timing effects on vegetative growing season or wildlife reproduction and life cycles
- Plant and wildlife species present and desired
- Invasive plant and wildlife species requiring removal, maintenance, and monitoring
- Effects of monitoring and debris removal on plant and wildlife species and water quality
- Public access to and uses of habitat, current and desired

Habitats/Vegetation Communities

An assessment of the vegetation communities and habitats present onsite and that are appropriate for preservation, enhancement, or installation is important for project design. In some cases, certain habitat elements may need to be removed or reduced; for example, excessive large woody vegetation can shade out vulnerable marsh vegetation, and may need to be trimmed or removed in order to allow successful growth of the desired habitat type and the achievement of project implementation goals. Various shoreline and upland habitats provide a variety of ecosystem services, including nesting, spawning, nursery, foraging, and shelter habitat for a wide range of plants and animals in addition to providing the means for the shoreline to absorb wave energy and reduce coastal flooding.

Double Duty
Vegetation communities and habitats targeted for implementation may be for the dual purposes of shoreline protection and species conservation. Marsh and SAV, for example, provide important varieties of ecological services, including shelter for fish and invertebrates, nursery habitats for recreationally and commercially important finfish and shellfish species, food sources for mammals and migratory over-wintering waterfowl species, and protection from erosion via sediment stabilization.

The intertidal marsh zone provides various ecosystem services benefits and supports ecologically, recreationally, and commercially important invertebrate, shellfish, and finfish fisheries, such as white and brown shrimp, crabs, oysters, red drum, and spotted sea trout. Some habitats may be considered to be sensitive by regulatory entities. Therefore, measures for avoiding or minimizing impacts may be required in certain areas in order to protect ecologically valuable aquatic habitat, including, for example, submerged aquatic vegetation beds; coral reefs, shellfish beds, and oyster reefs; tidal wetlands dominated by native species; or habitat used by federally threatened or endangered species.

In addition to establishing native vegetation communities and establishing native living structures, including corals and oyster reefs, ecological design considerations should also consider the need for integrating hard structure features such as functional wildlife and fish habitat. Examples include adding fish habitat enhancement structures to bulkheads, incorporating openings in hard structural components (excluding bulkheads and seawalls) to allow aquatic organisms access to nearshore and shoreline habitat (e.g., fish and turtles for upland nesting), and incorporating oyster or clam shell bags or marine-safe concrete that encourages shellfish attachment.

The condition of existing habitats within a project area can provide information regarding the potential success of a nature-based approach; for example, the presence of a healthy marsh habitat with dense vegetation may be a suitable site for a desired management approach, whereas a less dense marsh or hardscape-converted habitat near a healthy marsh may be enhanced with removal of hardscape, and with vegetation installation, trimming, and removal of debris and non-native invasive species. Soil assessments are important also, as some soils, for example, are not appropriate for particular vegetation communities or may not be able to support the weight of structural components, such as marsh sills, and the settling of the soils beneath the structures sometimes destroy structures or reduce their effectiveness.

Connectivity Effects

A nature-based project can have positive and negative effects on nearby habitats and species, both during construction activities and following project completion, and the condition and components of adjacent properties may, in turn, affect the suitability of living shoreline approaches. Careful consideration of the adjacent properties and how they will interact with the project components is critical for project success. For example, the presence of a nearby healthy marsh may indicate that the project site has suitability for marsh creation or restoration, and the installation of marsh within the project would increase the extent of the overall marsh acreage and therefore the extent of coastal protection, and increase habitat and potentially improve habitat connectivity to nearby habitats; whereas the presence of nearby human-made coastal stabilization structures may limit the effectiveness of a nature-based project or necessitate engineering that incorporates those nearby structures appropriately into the design. It is important to maintain connectivity between habitats for species to successfully complete their life cycles and to maintain population levels, and this includes maintaining links between aquatic and upland habitats; maintaining connectivity, in some cases, may involve culverts or overpasses to ensure adequate and safe movement of species between fragmented habitat patches or bodies of water.

Plant and Wildlife Species

Nature-based designs should consider multiple vegetation community types and multiple habitat elements to maximize plant and animal species diversity and to maximize the functional value of the components. Watersheds naturally transition from freshwater to saltwater environments, and support a variety of wetland ecosystems, including scrub-shrub wetlands, forested wetlands, fresh wetlands, swamps, marshes, and non-fresh or saltwater emergent wetlands, as they transition to uplands; each of these communities supports unique and overlapping species that depend on their resources for their livelihoods. A multitude of invertebrates, reptiles and amphibians, finfish and shellfish, turtles and tortoises, birds, and mammals utilize one or more of these habitats permanently or seasonally, or during migration. In many cases, the health of a vegetation community can be at least partially assessed by surveying the wildlife species that are present within the habitat. As discussed in earlier sections, the ability of native plant species to become established or to persist depends on multiple factors. Marsh plant species, for example, are highly dependent on salinity, which results in distinct zones of plant species based on elevation and the resultant flooding of saltwater. Oysters are a species often used in nature-based designs because oyster reefs can provide the same erosion control as rock sills; however, they offer the additional ecosystem benefits of building reef structures that provide protection naturally over time, in addition to improving water quality by removing sediment and algae, and offering refuge for fish, shrimp, molting blue crabs, and other species.

Invasive Plant and Wildlife Species

The presence of invasive species within the project area and on adjacent and upstream properties should be documented, and the invasive species should be removed and replaced with native vegetation. Employing a combination of prevention and control measures is important for the management of invasive species, and weedy or invasive species often need to be controlled before and after installation of native plant material. Control methods may include manual, mechanical, chemical, biological, and cultural components. Thorough site evaluation is important to determine the life-cycle characteristics of the invasive species and the effects of control methods on native plant and animal species and on water resources. When limited resources, species-specific challenges, or the degree of infestation make eradication unattainable, a more realistic management goal may be to control the invasive species by reducing the density and abundance to levels that allow native species to eventually dominate to a degree that provides for a healthy ecosystem. Many State agencies maintain lists of invasive plant species.

5.6 Monitoring, Maintenance, and Public Access Needs

The overall project design should include design elements that will be needed to facilitate monitoring and maintenance. Examples include implementation of temporary pathways or boardwalks through the habitat during the maintenance and monitoring period to avoid trampling; delineation of temporary staging areas for equipment and vehicles; specifying ingress/egress areas; specifying the timing of maintenance and monitoring events to avoid disturbance during sensitive breeding, nursery, and nesting times; and restrictions on noise, smoking, and animals.

Public use of natural areas may include activities such as general day use, picnicking, birdwatching, fishing, hiking, biking, and boating. Public use of natural areas often results in degradation of the natural habitat because of a variety of factors, including trampling of vegetation and disturbance of wildlife, introduction of trash, and contamination of water and soils by humans and pets—all of which can result in erosion and project failure. Use of boats in some areas may introduce wakes that are larger than waves caused by wind. The expected use and frequency of public recreation; the expected size, use, and frequency of vessels in the area; and the proximity of the site to a boat launch, a marina, or navigational channel are important design considerations for nature-based solutions.

5.7 Design Examples

Nature-based solutions come in many different configurations. The design elements depend on the system components, hydrodynamic conditions, terrestrial setting, and ecological needs—the key parameters from Section 2 . This section shows some design examples and cross-sections of nature-based solutions. Their purpose in this document is to convey, graphically, their scale and composition. These selected examples are not an exhaustive list of nature-based solutions, and some of them are conceptual and have not yet been implemented. However, these design examples illustrate the diversity of nature-based solutions and their application to coastal highway resilience.

Pocket Beach: Yorktown, Virginia

Region: Mid-Atlantic
Coastal Risks Addressed: Waves, erosion, flooding

Along Water Street in Yorktown, VA (37.2370ºN 76.5068ºW), York County led a shoreline protection project that placed clean sand fill and rock breakwaters to form a series of pocket beaches—beaches stabilized by artificial or natural headlands (see location overview on Figure 5-15). The project provides protection to approximately 1,600 feet of Route 1020 (Water Street) along the York River and serves as a recreational amenity for the Yorktown waterfront. This shoreline experiences an average fetch of 10 miles across the mouth of the York River and wave energy from across Chesapeake Bay, with a maximum fetch totaling 30 miles. Figure 5-16 shows positions of the shoreline before and many years after construction.

The County of York was the primary sponsor of this project, which was completed as part of a historic waterfront revitalization in conjunction with the Virginia Board on Conservation of Public Beaches. Virginia DOT participated in the project formulation and provided funding proportional to the extent of the State-maintained highway mileage that was previously exposed at the east end of the project.

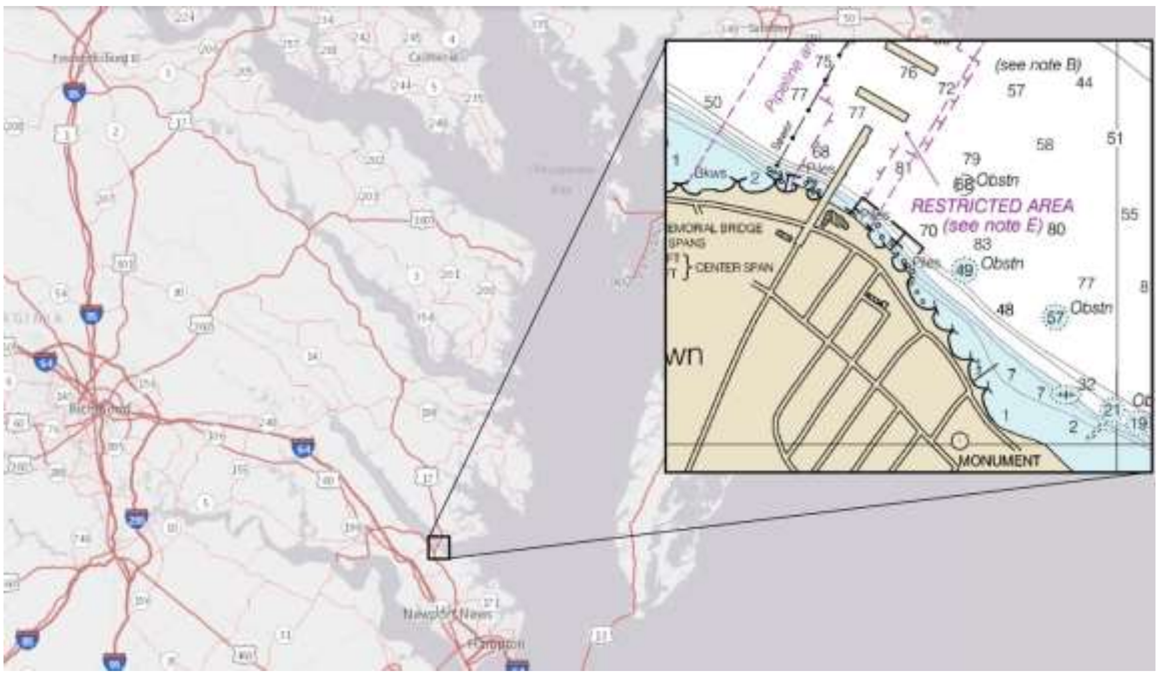


Figure 5-15. Yorktown, VA, location overview (NOAA Nautical Chart 12241 inset, depths in feet).

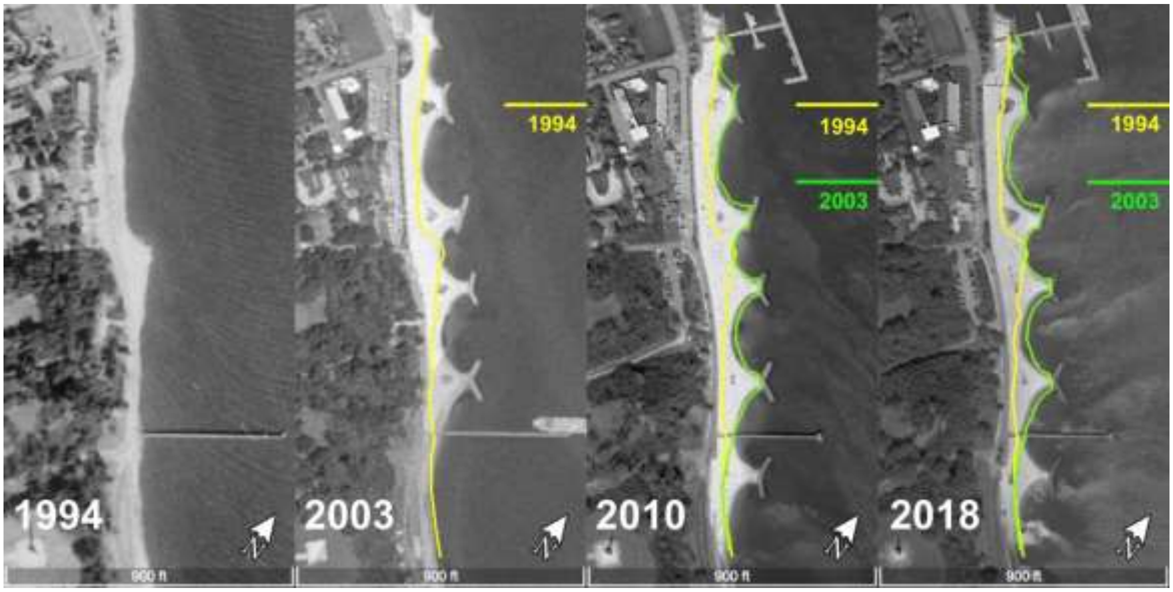


Figure 5-16. Recent history of shoreline positions at Yorktown, VA (photo courtesy of Google Earth).

Figure 5-17 shows a general cross-section schematic of the pocket beach. 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 1996). The project was designed for a 50-year return period storm. Hurricane Isabel (2003), an approximately 100-year return period storm event for this area, resulted in sand losses and local scour, but without significantly affecting project performance. The beach required an additional 3,500 cubic yards of sand to re-establish its pre-storm condition (Milligan et al. 2005). During Hurricane Isabel, the project successfully decreased wave energy that would have otherwise damaged upland commercial infrastructure.

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 more than two decades. The beach and vegetation provide intertidal habitat and shore bird habitat. The addition of a raised stone wall running parallel to the sidewalk mitigates flooding of Water Street during storms. Storms have not damaged the sidewalks and roads since construction of the original pocket beach project (Milligan 1996).

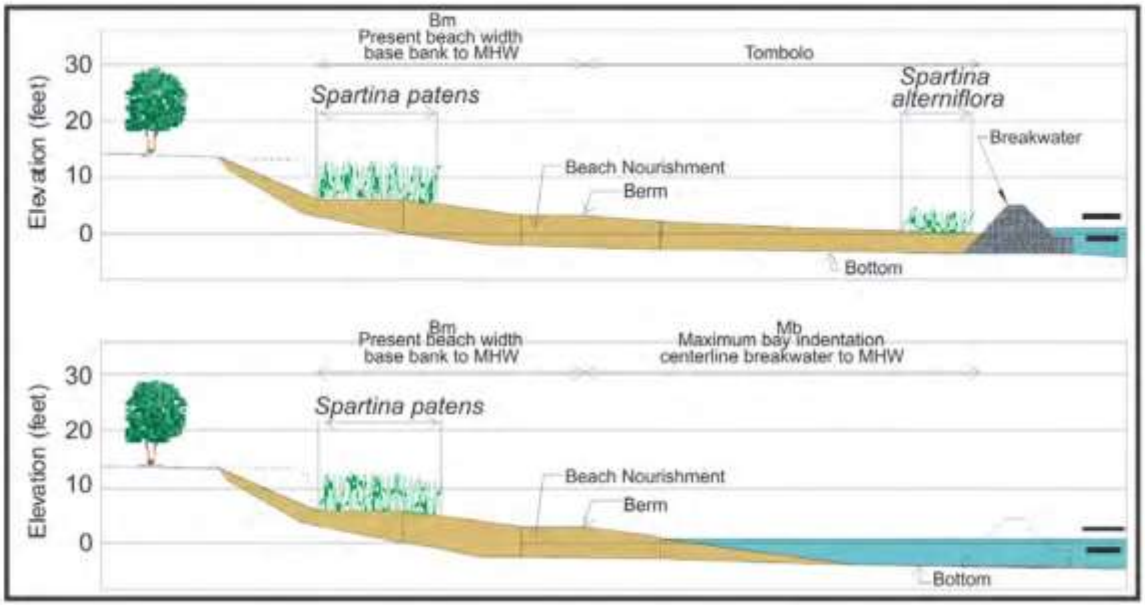


Figure 5-17. Conceptual cross-section of the Yorktown Pocket Beach (Hardaway and Byrne 1999).

Constructed Marsh With Breakwaters: Mobile Bay, Alabama

Region: Gulf Coast
Coastal Risks Addressed: Erosion, waves

Alabama DOT considered a nature-based solution as part of a bridge replacement and highway realignment project across Mobile Bay, AL (see location on Figure 5-18). The replacement of an existing bridge necessitates a new eastbound alignment and bridge to carry U.S. 98 across the confluence of the Tensaw River with the Mobile Bay estuary. The proposed realignment will alter approximately 2,200 feet of bay shoreline within the project footprint. Establishment of the new alignment will result in the loss of benthic habitat, aquatic resources, and SAVs (~1 acre). Alabama DOT considered the use of a nature-based solution in order to enhance the resilience of U.S. 98 and to potentially offset unavoidable impacts on aquatic resources. The existing shoreline is hardened with a vertical concrete seawall.

Shorelines within the study area are subject to a small tide range (~1.5 feet), considerable water level fluctuations as a result of storms, and considerable exposure to wave energy. The wave energy exposure is high because of the 30+-mile-long fetches that stretch to the south. Large shoals are directly offshore from the study area and water depths beyond are typically shallow (< 9 feet). The intertidal and nearshore slopes here are both low. This part of the estuary exhibits low salinity levels and nearby shorelines are a combination of sand and intertidal marsh vegetation. Submerged vegetation exists in shallow water depths adjacent to the site.

The resilience requirements for this highway included shoreline and embankment stabilization during minor to extreme events. Alabama DOT considered using a continuous rock revetment from the edge of the pavement down to the existing bay bottom on a slope of 3:1 (H:V).

Figure 5-18. Mobile Bay, AL, location overview (NOAA Nautical Chart 11376 inset, depths in feet).

Further analysis revealed that placing a nature-based solution consisting of stone breakwaters and planted marsh in front of the planned revetment (Figure 5-19) would provide multiple benefits. These benefits include:

- Reducing the amount of rock needed for the revetment, thus reducing the cost of the revetment by $1.2 million.
- Reducing storm impacts on the revetment and roadway by reducing wave heights by more than 50 percent during a moderate storm event.
- Providing environmental benefits, including conversion of nearly 2,000 feet of (proposed) hardened shoreline into a natural intertidal marsh, and creation of more than five new acres of marsh and/or SAV habitat with resulting pollutant uptake and fisheries benefits.
- Providing recreation and education opportunities.
- Offsetting impacts on aquatic resources from the highway project, potentially allowing Alabama DOT to meet compensatory mitigation requirements, saving Alabama DOT more than $0.5 million by not having to purchase credits from a tidal wetlands mitigation bank.

The material cost of the nature-based solution is approximately $1.2 million. Since it would reduce the cost of the revetment by $1.2 million, it is essentially cost neutral, although it would require additional maintenance and monitoring.

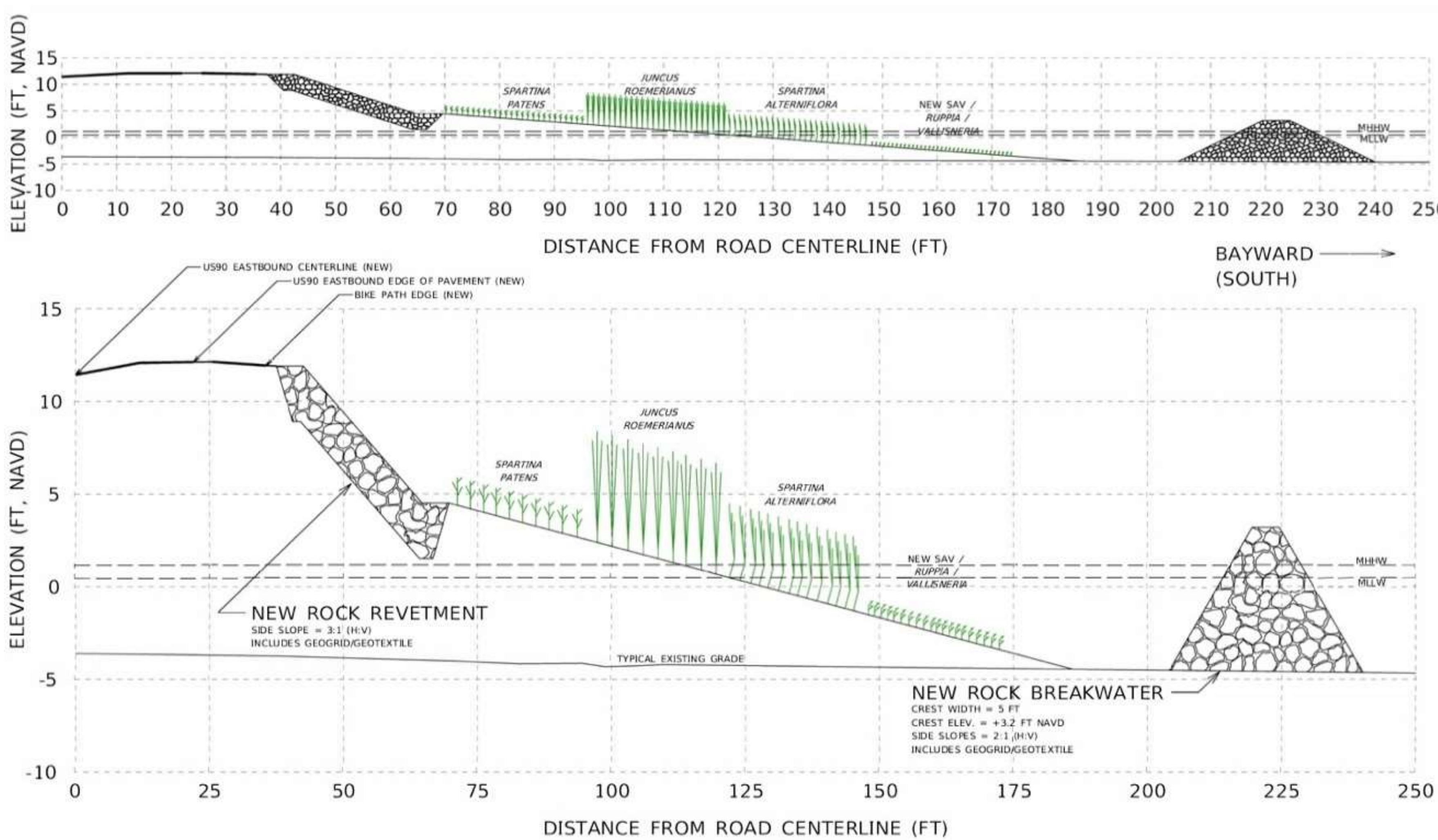


Figure 5-19. Conceptual cross-section diagram of a constructed marsh and breakwater system in Mobile Bay, AL.

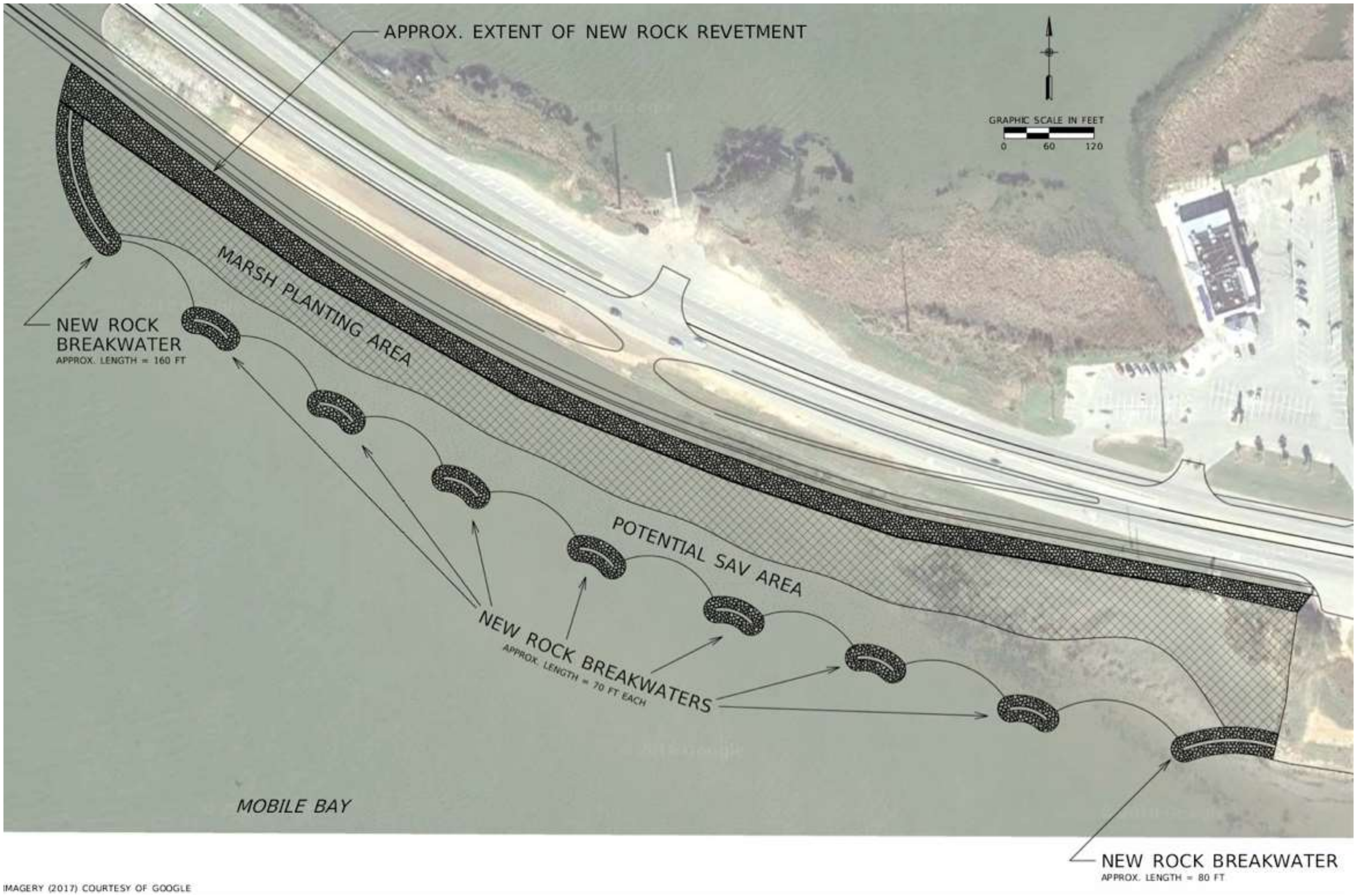


Figure 5-20. Conceptual planform diagram of a constructed marsh and breakwater system for Mobile Bay, AL. (Credit: FHWA)

Marsh Enhancement With Toe Protection: Great Egg Harbor Bay, NJ

Region: Northeast

Coastal Risks Addressed: Erosion, waves

New Jersey DOT stabilized approximately 1 mile of bay island shorelines as part of a transportation project near Ocean City, NJ (see location overview on Figure 5-21). Replacement of the Route 52 causeway across Great Egg Harbor Bay required realignment of two existing navigation channels, exposing quickly eroding marsh shorelines to additional boat wakes (Traylor 2017). New Jersey DOT implemented nature-based solutions to stabilize the eroding marsh banks to address these boat wake concerns raised by the New Jersey Department of Environmental Protection and USACE.

The marsh shorelines are subjected to boat wakes and wind waves of moderate height, resulting from fetch lengths of approximately 3 miles or less. The estuarine conditions, experiencing a moderate tide range of less than 4 feet, support recreationally and commercially important fisheries, shellfish resources, and wildlife. Prior to project implementation, eroding marsh shorelines were severely scarped.

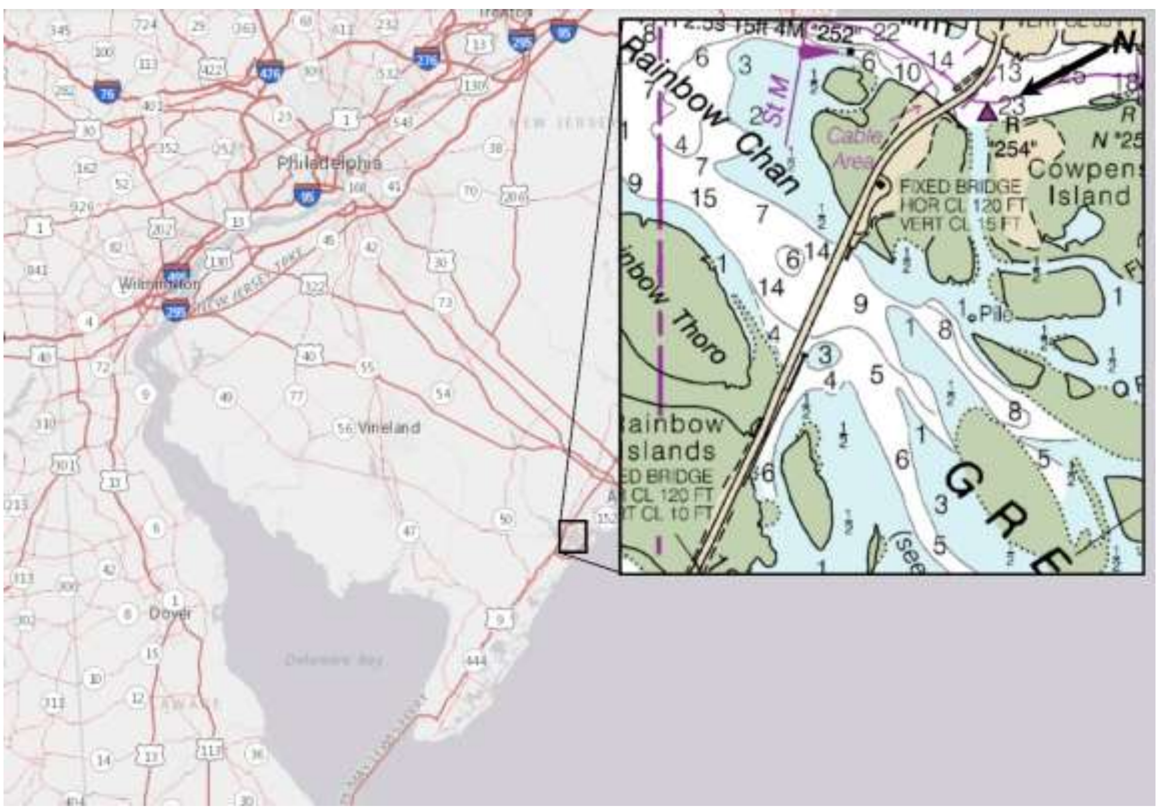


Figure 5-21. Great Egg Harbor, NJ, location overview (NOAA Nautical Chart 12316 inset, depths in feet).

New Jersey DOT developed four unique nature-based solution designs to mitigate the marsh shoreline erosion and to correct the over-steepened intertidal shoreline (see Figure 5-22 and Figure 5-23). Each design accommodated a different level of wave energy exposure, with high energy sites incorporating structural features to further stabilize the restored marsh edge. The designs generally consisted of shoreline regrading using available onsite material, coir fascine edging to stabilize the marsh toe, and planting of *Spartina alterniflora* landward of the coir fascine. A stone marsh toe revetment and a sheet pile wall were incorporated into the design details for shorelines experiencing higher wave energies.

The first installations occurred in summer 2010, but experienced mixed results because of implementation issues, environmental conditions, and material performance. Projects exposed to lower wave energies and/or in sandy substrate generally performed better than those subject to higher wave energies and/or overlying silty substrate. Adaptive management techniques were used to address shortcomings and improve project performance. The coir fascines were re-installed at higher elevations, pre-vegetated coir mattresses were substituted for marsh plugs, riprap sizes were increased, and the contractor was given more flexibility. Routine monitoring was performed for 5 years. After the first 3 years of monitoring, all sites experienced increases in marsh coverage, average stem height, and average plant density. The sites were undamaged by Hurricane Sandy (2012), which affected the area only a few months following implementation of the adaptive management techniques (Traylor 2017).

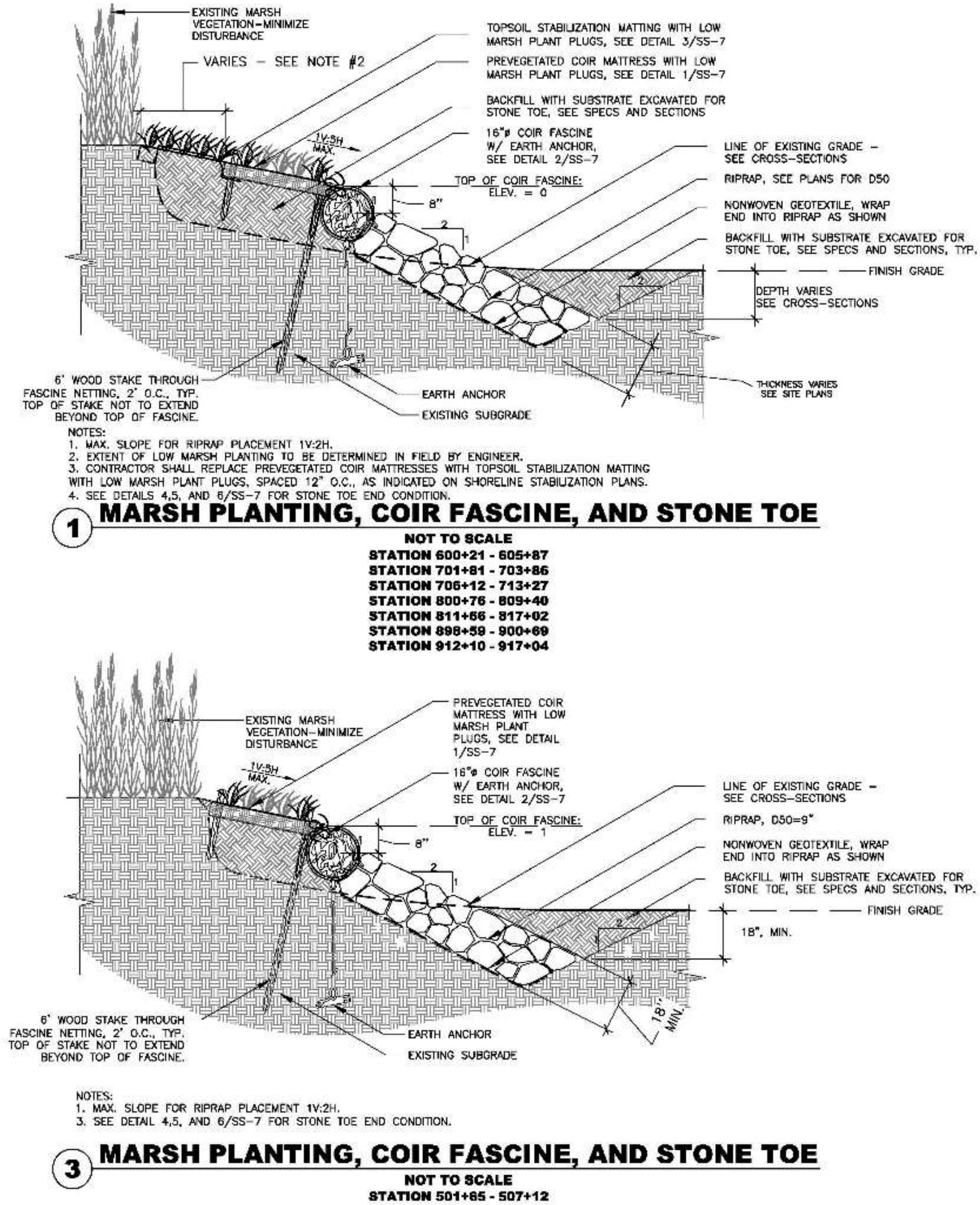


Figure 5-22. Cross-section design details for marsh shoreline stabilization in Great Egg Harbor Bay, NJ (Traylor 2017; NJDOT 2009). Details 1 and 3 were used in high wave energy locations.

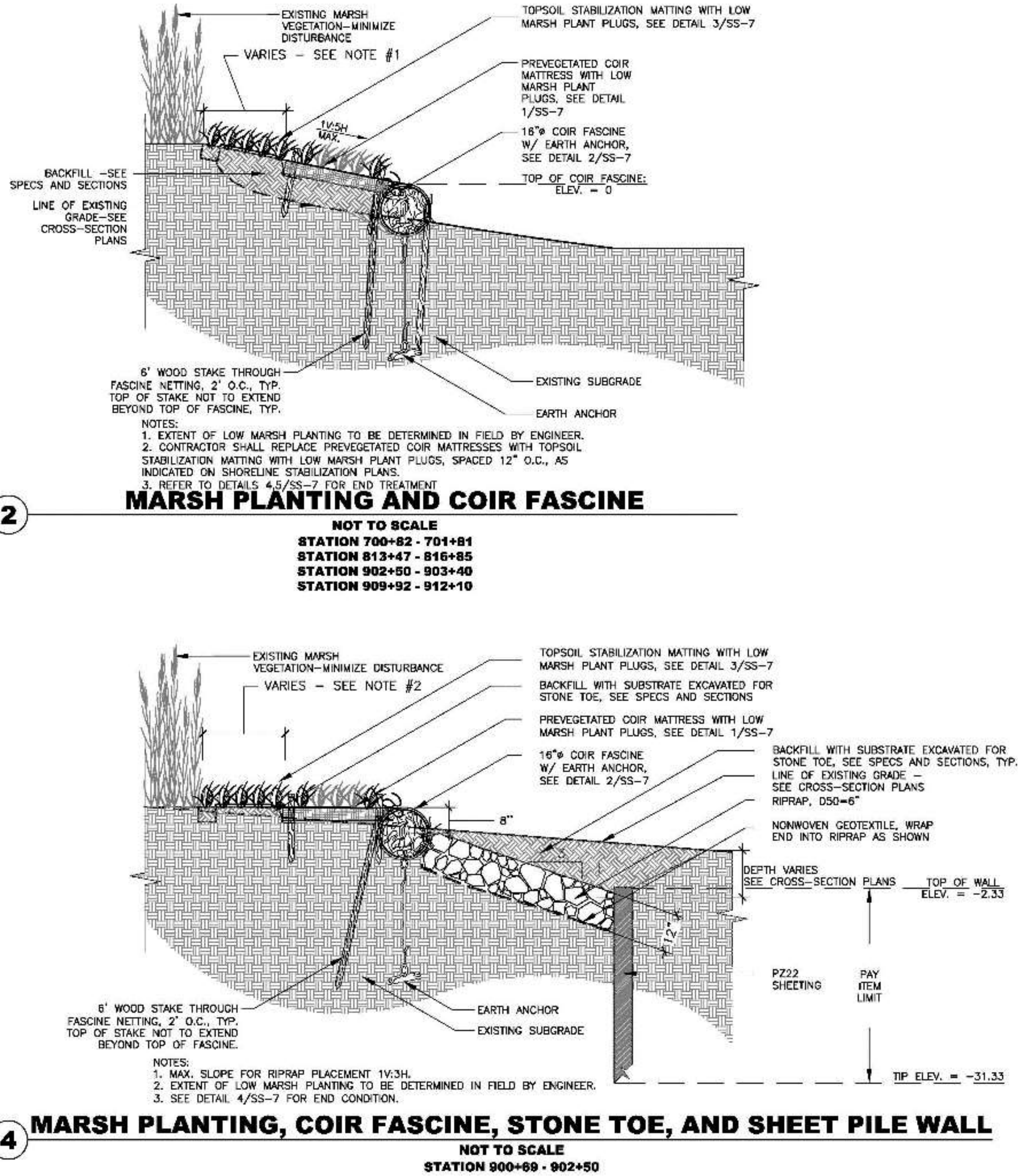


Figure 5-23: Cross-section design details for marsh shoreline stabilization in Great Egg Harbor Bay, NJ (Traylor 2017; NJDOT 2009). Detail 2 was used along shorelines with the lowest wave energy exposure. The project engineers specifically designed Detail 4 to address increased exposure to boat wake energy as a result of navigation channel realignment.

Cobble Beach, Berm, and Dune Enhancements: Pacific Coast, OR

Region: West Coast
Coastal Risks Addressed: Erosion, wave runup, flooding

Oregon DOT designed several nature-based solutions for the purpose of protecting the Oregon Coast Highway (U.S. 101) from the impacts of extreme events and coastal bluff erosion (ODOT 2017). The Oregon Coast Highway is an important 363-mile-long coastal transportation corridor connecting the States of California and Washington. The highway, in many places, runs along high cliffs and beaches, and through State Park lands. In many places, there is limited space between the shoreline and roadway, making many forms of roadway management and maintenance more difficult. The limited space and easement constraints favor a protection strategy; however, Oregon's coastal and land-use policies require completion of a complicated regulatory exceptions process when coastal armoring is necessary. Oregon DOT worked collaboratively with regulatory and resource agencies, as part of this process, to develop a suite of nature-based solutions that existing rules and regulations would allow.

Oregon DOT focused on three sites vulnerable to erosion, surge, and wave runup in Lincoln County (see location overview on Figure 5-24). These sites represent a small fraction of the more than 20 miles of coastal highway that Oregon DOT identified as highly vulnerable to coastal bluff erosion and wave attack. The conditions at the three subject sites are, however, representative of the many constraints and vulnerabilities found at other locations along U.S. 101. The three sites chosen for this study were Beverly Beach to the north of Newport, and Lost Creek and Ona Beach to the south of Newport. The diversity of sites allowed Oregon DOT to address unique constraints, as well as the timeliness of resilience enhancements. The Beverly Beach site required more immediate intervention, while the Lost Creek and Ona Beach sites were of concern over a longer timeframe.

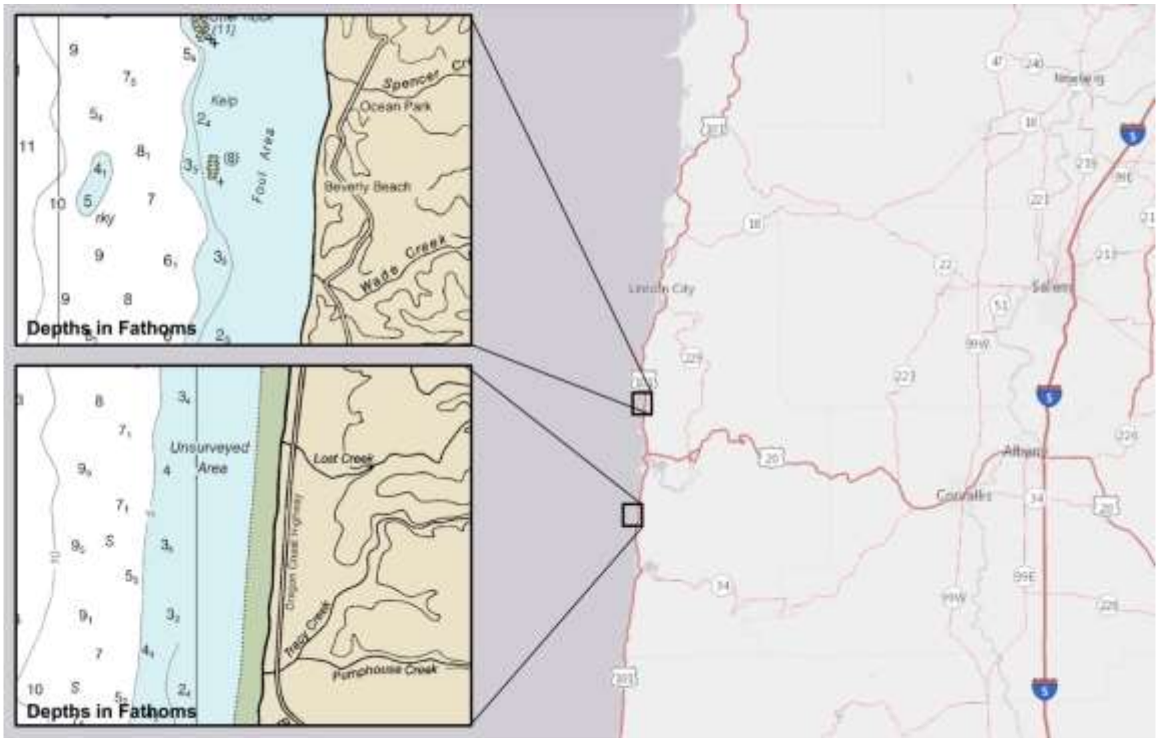


Figure 5-24. Oregon coast location overview (NOAA Nautical Chart 18561 inset, depths in fathoms).

Oregon DOT capitalized on their previous research on dynamic revetments to inform many of the nature-based designs for their study. The Oregon coast consists of natural cobble beaches in many locations. These cobble beaches provide a natural form of wave protection along the backshore and respond to extreme events in a dynamic manner that makes them resilient to ocean forcing. Given its exposure to Pacific Ocean swell and storm waves, and deep offshore depths, nature-based solutions along the Oregon coast are more constrained than they are along sheltered shorelines. Oregon DOT selected a high-range sea level rise scenario to 2050 along with a 100-year return period storm event as the basis for their design—an extreme set of requirements for nature-based solutions.

Oregon DOT designs focused on replicating the naturally occurring beach materials and morphologic features, while incorporating structural features to enhance the resilience of the natural system and their transportation infrastructure. Each design incorporates a restored cobble beach with some other protective or stabilizing feature to address the vulnerabilities and hazards unique to a specific site:

- **Beverly Beach** is currently very narrow, affected by high energy waves, and lacks substantial sand input from natural processes. The highway is threatened by coastal bluff erosion at this site. The hybrid design for this site includes a cobble beach covering large stone keyed in with piles at the toe of the coastal bluff (Figure 5-25). Bluff slope stabilization is achieved using a mechanically stabilized earth (MSE) wall with planted terraces. The total cost estimate is $41 million for the 2,100-foot-long project, resulting in a unit cost of approximately $19,500 per linear foot.
- **Lost Creek** is a low-lying portion of U.S. 101 vulnerable to flooding, storm surge, and sea level rise. The highway at this location has experienced overtopping during significant

storm events in the past. The nature-based design selected for this site includes a cobble beach seaward of an artificial dune (Figure 5-26). The total cost estimate for this 600-foot-long repair, including the cost of replacing a culvert on the opposite side of the road, is $2.8 million. The approximate unit cost is $4,700 per linear foot.

- **Ona Beach** is another low-lying portion of U.S. 101 just south of Lost Creek. The vulnerabilities and hazards at Ona Beach are like those at Lost Creek. The site-specific design here incorporates a cobble beach, MSE slopes, and a core of sand-filled geotextiles (i.e., geotubes) for added stability (Figure 5-27). The total cost estimate for this 1,150-foot-long repair is $5.9 million, resulting in a unit cost of approximately $5,000 per linear foot.

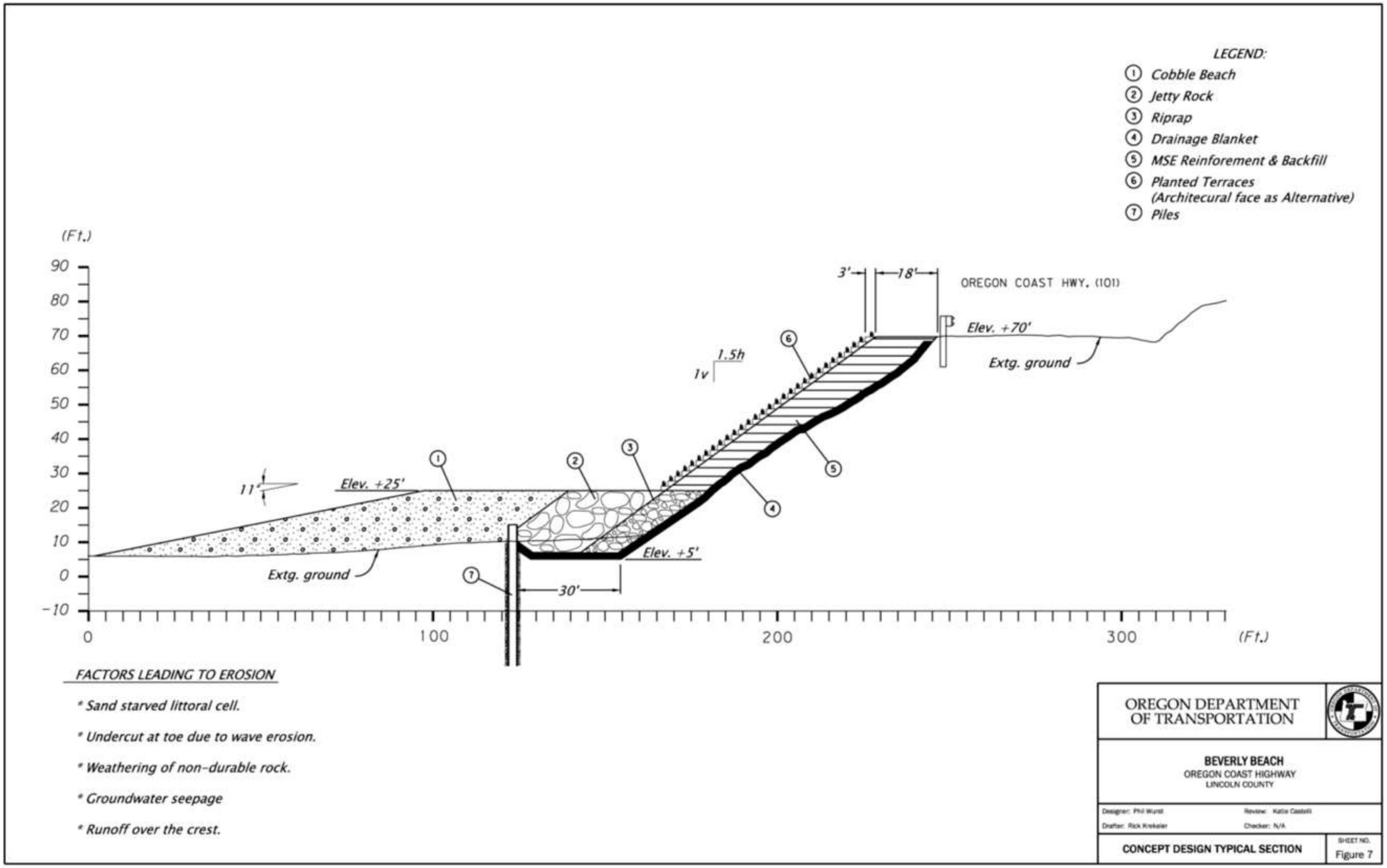


Figure 5-25. Cross-section diagram of the nature-based protection at Beverly Beach, OR (ODOT 2017).

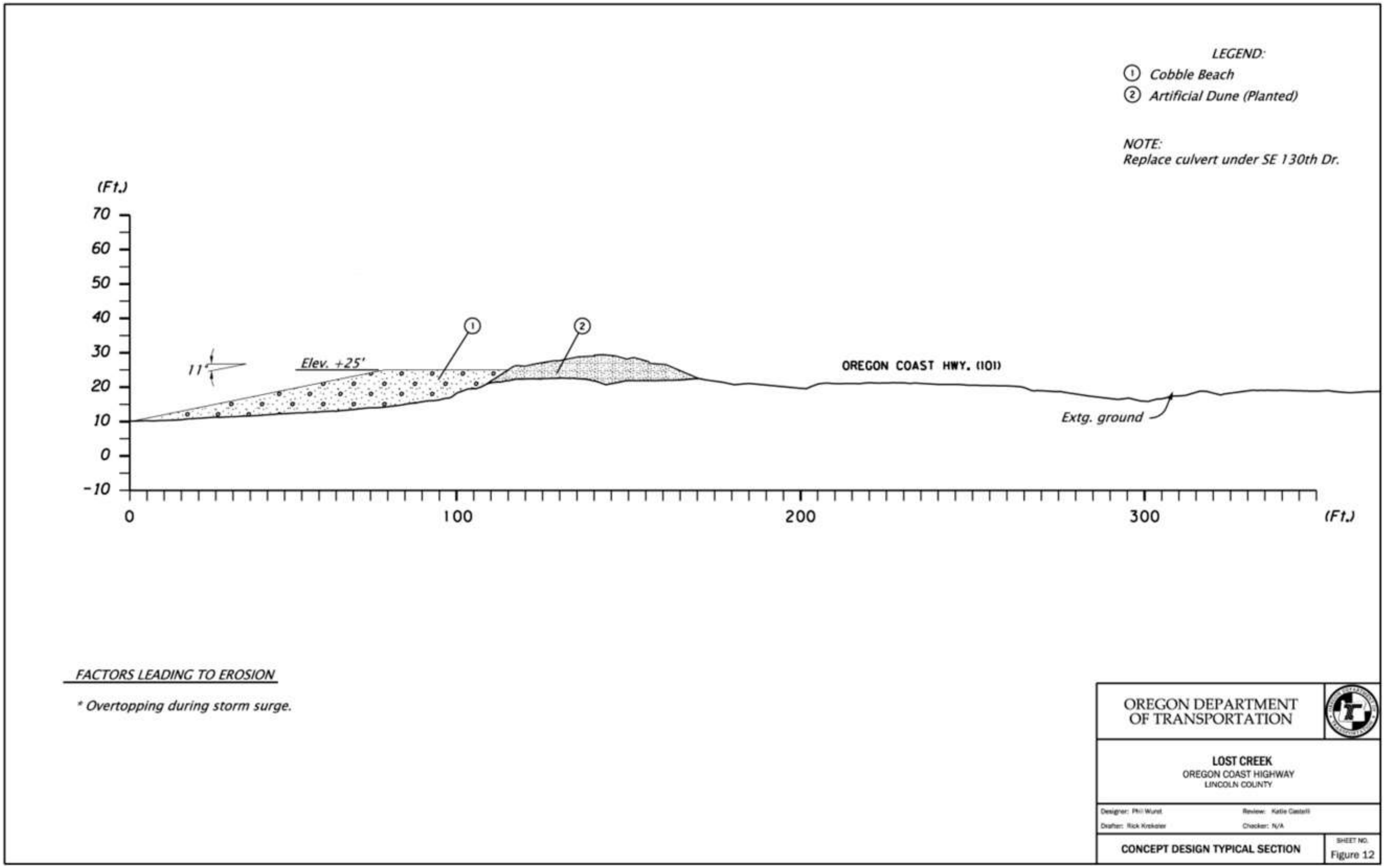


Figure 5-26. Cross-section diagram of the nature-based protection at Lost Creek, OR (ODOT 2017).

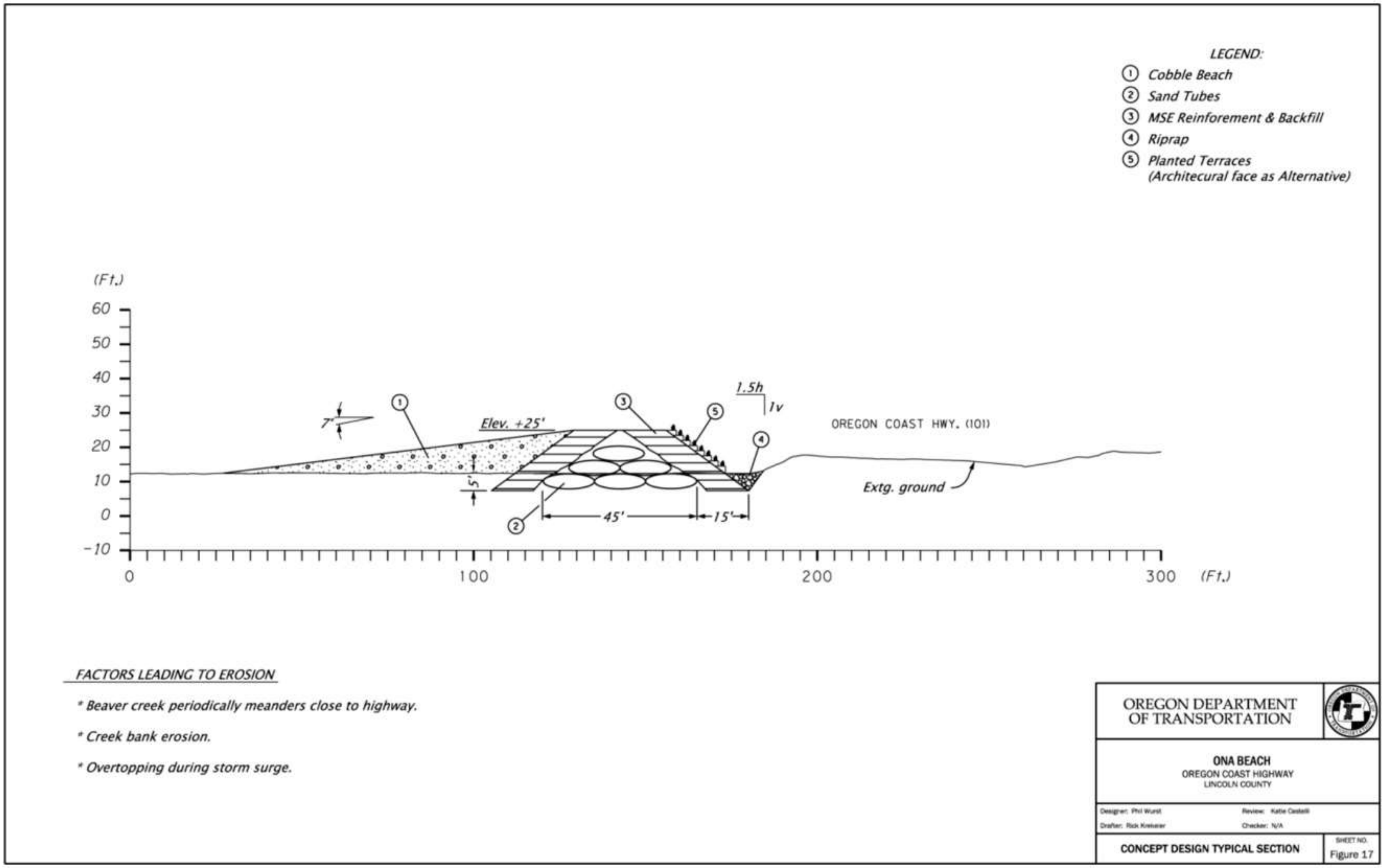


Figure 5-27. Cross-section diagram of the nature-based protection at Ona Beach, OR (ODOT 2017).

Vegetated Dune and Buried Revetment: Maui, HI

Region: Hawaii and Pacific Islands
Coastal Risks Addressed: Erosion, wave runup, flooding

The Wailuku-Kahului Wastewater Reclamation Facility on the island of Maui is critical infrastructure for the local public. Certain parts of the facility were in danger of failing or being seriously compromised within a 1- to 10-year timeframe because of chronic shoreline erosion. Failure of the injection wells and a chlorine tank would have resulted in a substantial environmental disaster for the County of Maui and a major impact on their wastewater services.

The county opted for a nature-based solution to provide risk-reduction benefits for the facility (Boudreau et al. 2018). The preferred design at this site included a buried revetment, some beach nourishment, dune restoration, and vegetative plantings. The revetment will protect the reclamation facilities against shoreline retreat. Simultaneously, the dune and vegetation reduce the frequency and magnitude of wave-induced flooding (from wave runup) while also providing sandy beach habitat. This nature-based solution provides shoreline protection for critical public infrastructure and incorporates multiple adaptation strategies to provide resilience from future sea level rise. For example, the county opted to give up land by placing the buried revetment well landward, thereby increasing the amount of time until future shoreline retreat would intercept the protective feature. In addition, the beach nourishment project advanced the shoreline seaward, further increasing its resilience to erosion, flooding from wave runup, and sea level rise impacts.

Three years of monitoring data illustrate that the nature-based solution performed well and accomplished its goals of stabilizing the shoreline position. Seasonal shoreline fluctuations remained stable and were consistent with pre-project values. The shoreline position has advanced seaward in portions of the project area with accretion occurring over some of the beach nourishment profiles. This accretion has led to a temporary reduction in the annual erosion rate.

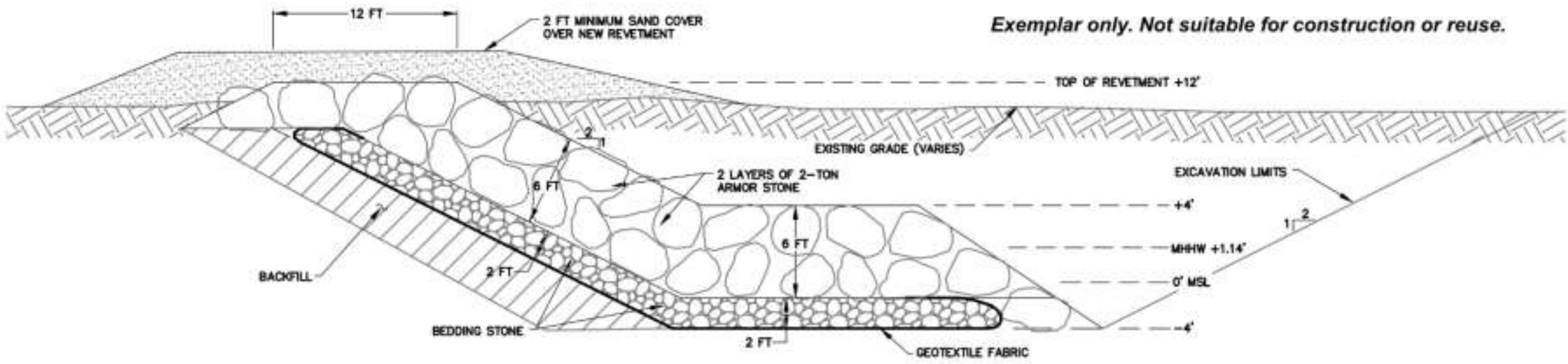


Figure 5-28. Sample cross-section of buried revetment and dune restoration (Boudreau et al. 2018).

Wetland Shelf, Stone Toe, and Sill: Lake Huron, MI

Region: Great Lakes
Coastal Risks Addressed: Erosion, waves

Figure 5-29 shows yet another nature-based solution with a transportation application, but this time in the Great Lakes. This project was implemented along the St. Clair River in Marysville, MI, a tributary to Lake Huron, and replaced 1,900 feet of failing steel seawall, which is visible in Figure 5-29b taken prior to implementation. The roadway visible at the top left of that figure is Interstate 94. This shoreline is a major feature of the City of Marysville and it is used for both passive and active recreation. A heavily used walking path along the shoreline was relocated as part of this project.

This nature-based design, used to stabilize the roadway embankment and reduce erosion from wave action, includes a large stone toe, emergent wetland shelf/bench with more than 10,000 native plants, embankment revetment with toe protection, and vegetation near the edge of pavement. This site is subject to large fluctuations in lake level, with low and high water conditions visible in Figure 5-29c and Figure 5-29d, respectively. The large water level fluctuations necessitated a substantial toe channelward of the wetland shelf.

This nature-based solution provides multiple benefits. Removal of the seawall allows connectivity between the upland and the waterway. As lake levels rise, the land-water interface extends over the wetland bench and stone toe, which provide wave attenuation. The presence of the wetland plants also improves water quality associated with stormwater runoff from the roadway. The improved land-water connectivity also provides enhanced recreational opportunities along the riverfront.

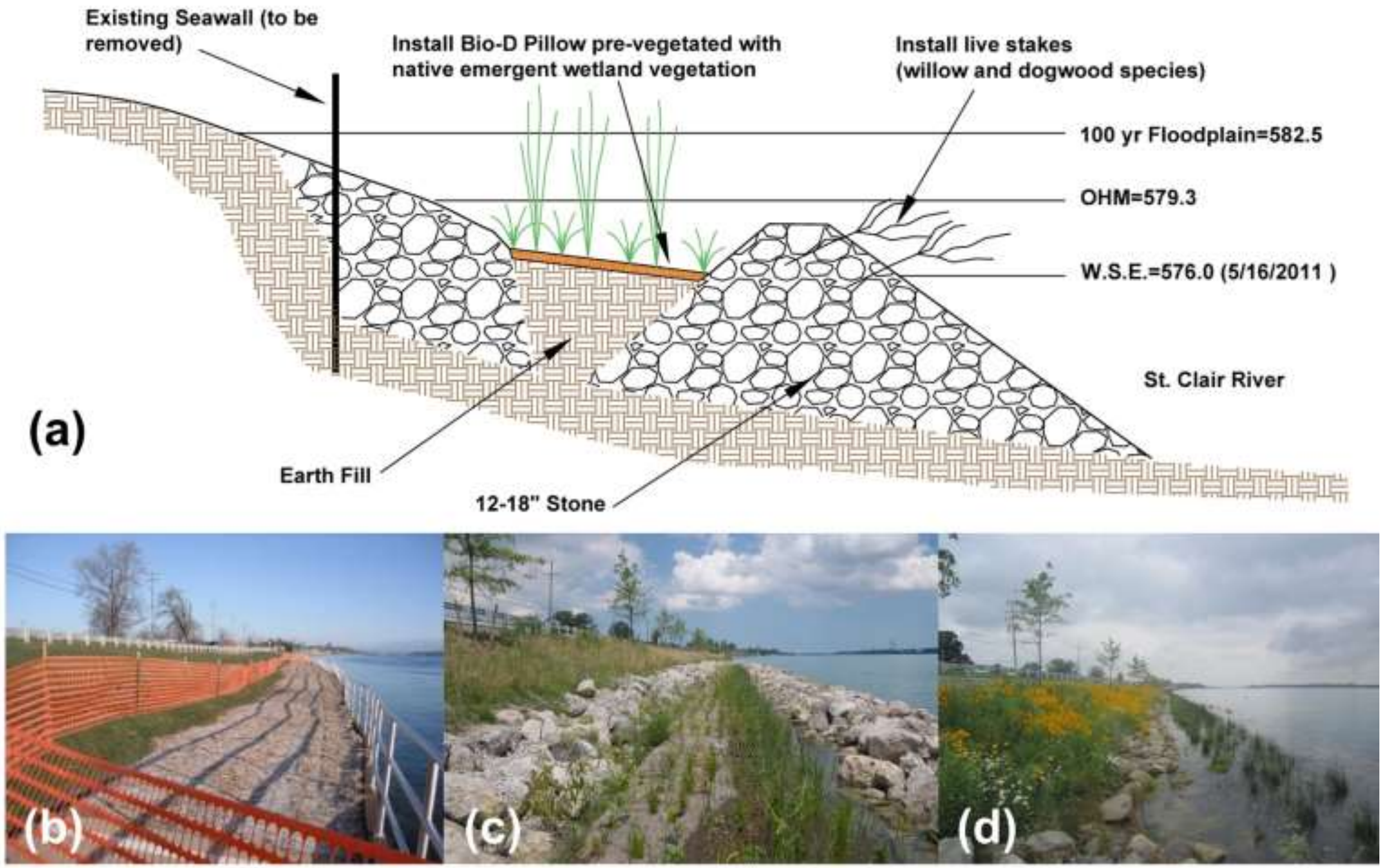


Figure 5-29. Sample cross-section of an emergent wetland shelf with stone toe protection and sill (diagram and photos courtesy of Brian Majka and Scott Dierks).

6. PERMITTING FOR NATURE-BASED SOLUTIONS

This section focuses on the permitting process for nature-based solutions. This, however, should not be the first time during the design phase when you establish contact with the pertinent regulatory agencies. That initial contact should have occurred during the planning and/or conceptual design phases of your work. Meeting with regulatory agencies early in the process can minimize the amount of time spent revising and refining the design of your nature-based solution. After reading this section you will better understand some of the Federal and State regulations that apply to nature-based solutions, the types of permits commonly used, the general workflow associated with submitting and obtaining permits, NEPA compliance issues, and opportunities for meeting compensatory mitigation requirements.

6.1 Federal Regulations

Civil works projects in the coastal environment, including nature-based solutions, are subject to several Federal laws, policies, and regulations. This section describes some of the most common Federal regulations that govern the permitting of nature-based solutions. Where appropriate, the text also names the Federal agencies that administer or assist with administration of those regulations. Figure 6-1 summarizes the relevant Federal regulations described in this section.

Almost every project involving work and/or activities in coastal areas is subject to the Clean Water Act (CWA) of 1972, which is administered by the U.S. Environmental Protection Agency (USEPA). The CWA is the primary Federal statute governing protection of the Nation's waters. Nature-based solutions are often subject to section 404 of the CWA, which regulates the discharge of dredged or fill material in waters of the United States, including wetlands. This includes the use of dredged or fill material for development, water resource projects, infrastructure development (e.g., roads, bridges), and for the construction of nature-based solutions. USACE handles the day-to-day permitting and enforcement of the section 404 program. Under circumstances where section 404 is required, permit applicants must also obtain a section 401 certification from the State in which the discharge of dredged or fill material originates. The section 401 certification ensures that materials discharged to waters of the United States will comply with relevant provisions of the CWA, including water quality standards.

Transportation infrastructure projects and nature-based solutions are also subject to section 9 and section 10 of the Rivers and Harbors Act of 1899. Section 9 of this act restricts the construction of any bridge, dam, dike, or causeway over or in navigable waterways of the United States. Section 10 of this act restricts the building of any wharf, pier, jetty, breakwater, bulkhead, or other structure, as well as excavation and/or fill within navigable waterways. Potential discharges associated with activities restricted by section 9 and section 10 of this act are also subject to the CWA.

Clean Water Act	o For: discharge of dredged or fill material o Lead: USACE o Assisting: USEPA, USFWS, NMFS
Rivers & Harbors Act	o For: structures (bridge, causeway, breakwater, bulkhead, jetty) or work (building structures, dredging) o Lead: USACE o Assisting: USCG (bridges, causeways), USACE (other)
Coastal Zone Management Act	o For: management of coastal resources o Lead: State CZMP agency o Assisting: NOAA
National Environmental Policy Act	o For: prevent/eliminate environmental damage o Lead: Council on Environmental Quality o Assisting: all Federal agencies participate
Endangered Species Act	o For: protection of imperiled species & ecosystems o Lead: USFWS, NMFS o Assisting: n/a
Magnuson-Stevens Fishery Conservation & Management Act	o For: essential fish habitat, fisheries management o Lead: NMFS o Assisting: n/a
Marine Mammal Protection Act	o For: protection of marine mammals o Lead: NFMS, USFWS, Marine Mammal Commission o Assisting: n/a
National Historic Preservation Act	o For: historic preservation, cultural resources o Lead: State Historic Preservation Office o Assisting: n/a

Figure 6-1. Summary of Federal policies relevant to the permitting of nature-based solutions.

With the exception of bridges and causeways, USACE is responsible for maintaining the standards set by the Rivers and Harbors Act, and for issuing permits. The U.S. Coast Guard (USCG) is responsible for issuing the permits needed to build bridges and causeways in navigable waters. Relevant Federal laws related to bridge permits include section 9 of the Rivers and Harbors Act, as well as the General Bridge Act of 1946. Additional considerations with respect to bridges and bridge permits are described in 23 CFR § 650 Subpart H (§ 650.801–§ 650.809), where FHWA is granted specific exemptions for permits when certain conditions are met.

Transportation and nature-based projects are also subject to the FHWA floodplain regulations described in 23 CFR § 650 Subpart A. These regulations capture the NEPA-aligned requirements and FHWA design standards (§ 650.115/650.117) regarding the location and hydraulic design of encroachments on floodplains.

Nature-based solutions have the potential to affect fish, wildlife, and/or marine mammals. The Endangered Species Act (ESA) protects and recovers imperiled species and the ecosystems on which they depend. The ESA is administered and enforced by the U.S. Fish and Wildlife Service (USFWS) and the NOAA National Marine Fisheries Service (NMFS) (Services). The USFWS and NMFS review public notices and environmental documents (e.g., environmental assessments, environmental impact statements) released by the lead Federal agency for compliance with the ESA, and they also conduct consultations with the lead Federal agency when a proposed project may affect federally endangered or threatened species. The level of USFWS or NMFS involvement in a project depends on the affected species and the nature and extent of anticipated impacts (direct and indirect) on that species and its designated critical habitat. If "take"[8] of a federally listed species is anticipated, USFWS or NMFS will issue a biological opinion, the terms and conditions of which are generally binding on the lead Federal agency. The duration of consultations with USFWS and NMFS varies, but under circumstances where take is anticipated, the statutory timeline allows for up to 135 days from initiation of consultation to issuance of the biological opinion. The Services have substantial discretion in determining whether a consultation request is considered incomplete (e.g., because of insufficient survey data or impact analysis), which may result in additional delays. Accordingly, as described below, early coordination is highly recommended to identify listed species and their designated critical habitats (https://ecos.fws.gov/ipac/) that may be affected by a proposed project, the need for additional surveys, appropriate survey windows, and avoidance and minimization measures that could be integrated into the project early in the planning and design stages.

The Magnuson-Stevens Fishery Conservation and Management Act, or more simply the Magnuson-Stevens Act (MSA), governs commercial and recreational fisheries in U.S. Federal waters. The MSA may apply to nature-based solutions because they have the potential to negatively affect Essential Fish Habitat (EFH).[9] Similar to administration of the ESA, NMFS reviews public notices and environmental documents for compliance with the MSA, and also conducts consultations with the lead Federal agency when a proposed project may adversely affect EFH. There is no statutory timeline for EFH compliance; however, in general, consultations can be completed within 2 to 3 months. Similar to ESA compliance, early coordination is highly recommended. In order to receive substantive feedback from NMFS, literature searches should be conducted prior to coordination.

While less common, the Marine Mammal Protection Act (MMPA) may apply to nature-based solutions that have the potential to harm or impair marine mammal species. Implementation of the MMPA is jointly shared by NMFS, USFWS, and the Marine Mammal Commission, which provides independent oversight of Federal agencies.

Federal permit actions for nature-based solutions can be subject to the Coastal Zone Management Act (CZMA) and the National Historic Preservation Act (NHPA). As with the ESA and MSA, it is the responsibility of the lead agency to demonstrate compliance with these

[8] *Take* as defined under the ESA means "to harass, harm, pursue, hunt, shoot, wound, kill, trap, capture, or collect, or to attempt to engage in any such conduct" (16 U.S.C. § 1531 et seq.).
[9] Essential Fish Habitat is defined under the 1996 amendments to the Magnuson-Stevens Fishery Conservation and Management Act, or Magnuson-Stevens Act, as "those waters and substrate necessary to fish for spawning, breeding, feeding or growth to maturity" (16 U.S.C. § 1801 et seq.).

statutes, while the administration and enforcement of CZMA and NHPA lies with other Federal authorities. NOAA is responsible for programmatic administration of the CZMA at the national level, but relies on its 34 Coastal Zone Management Programs (CZMPs) for ensuring project compliance for CZMA consistency at the State level (see next section) and for issuance of project approvals. Similarly, the NHPA is handled at the State level. State Historic Preservation Offices (SHPOs) or Officers ensure that permitted projects do not adversely affect historic buildings, sites, structures, or cultural resources. For example, replacement of a historic bridge or causeway may constitute an adverse effect, therefore the lead agency may be required to consult directly with the SHPO. Similarly, dredging projects may pose a risk to cultural resources, and thus may also require agency-to-agency consultation, as well as notification to federally recognized tribes. With respect to timelines, the CZMA allows the State coastal zone management agency up to 6 months for review and approval of a consistency determination provided by either the applicant or the lead Federal agency. There is no statutory timeline for NHPA compliance, although the SHPO may have established protocols with the Federal lead (e.g., USACE, FHWA) to help guide the review and approval processes. In general, consultations can be completed within 3 to 4 months. Similar to ESA and MSA compliance, early coordination is highly recommended. In order to receive substantive feedback from the SHPO, literature searches (e.g., survey records from regional Information Centers) should be conducted prior to coordination.

6.2 State Regulations

The number and types of regulations applicable to coastal projects, including nature-based solutions, varies from State to State. A description of the applicable State regulations for the 35 coastal States and territories is beyond the scope of this guide. Instead, this section of the guide generally describes the two primary issues that often apply to coastal projects in coastal States or territories: coastal zone management and impacts on State-owned lands. The text also provides a brief overview of unique State policies that encourage or support nature-based solutions.

Coastal States Organization
Anyone unsure of who to contact regarding coastal zone management, coastal policies, or coastal regulations can contact the Coastal States Organization and they will help you connect with the appropriate State resource agency. For more information, visit http://www.coastalstates.org

Coastal Zone Management

All work performed in the “coastal zone” is subject to specific rules and regulations of that State’s or territory’s coastal zone management program, as authorized by the CZMA. As defined in the CZMA, the coastal zone includes coastal waters extending to the outer limit of State submerged land title and ownership, adjacent shorelines, and land extending inward to the extent necessary to control shorelines. The coastal zone boundary is defined differently across States and territories, but generally extends from on-shore (inland) areas to near-shore (marine) waters. The goal of coastal zone management is to balance environmental protection and coastal development. As these issues are often unique from State to State, each State or territory develops its own coastal zone management regulations.

Coastal infrastructure projects, including nature-based solutions, are subject to coastal zone management regulations. Applicable portions of the regulations apply to dredging and filling, the use and construction of structures, shoreline stabilization, and other activities that may result in direct or indirect impacts on tidal and non-tidal aquatic resources located within a designated coastal zone boundary. As described in Section 6.3, the State coastal zone management agency is involved in the review of environmental compliance documentation (e.g., environmental impact reports, environmental impact statements) and permit applications for proposed activities in the coastal zone. In this role, the State agency is charged with ensuring that a project meets coastal zone consistency requirements and, if so, issues the appropriate approval. Table 10-11 in Appendix D provides a list of State agencies charged with administration of the CZMA and links to their websites.

Impacts on State-Owned Lands

Nature-based solutions are subject to regulations that limit or manage impacts on State-owned lands. These regulations can severely limit the type, size, and characteristics of a nature-based solution. For example, dredging, filling, and the construction of bridge or revetment structures may directly or indirectly impact the submerged or subaqueous lands of a State or territory, or the public's use of such lands. A prescribed tidal datum often serves as the delineation between private and State-owned land. A tidal datum represents the 18.6-year average (i.e., tidal epoch) of a specific stage, or elevation, of the tide. The Mean High Tide Line or Mean Higher High Water are commonly referenced in State regulations as the delineation between private and public lands. The State agency charged with managing State-owned lands must approve any work performed, or impacts on, submerged lands seaward of their regulatory boundary. The ability to perform work seaward of the regulatory boundary varies from State to State, as do the limitations on impacts, the potential fees associated with those impacts, and mitigation requirements to offset impacts. In some States, property owners are required to sign a legal affidavit waiving their right to ownership for all new lands created either as part of the project (i.e., initial creation of new land) or as a result of the project (i.e., long-term accretion). While owners maintain their riparian rights to the new land, it is not recorded as part of their legal property description and they do not have the right to erect permanent structures on it.

Unique State Policies

Currently, some States have specific laws, regulations, and/or policies that require or encourage the use of nature-based solutions, such as living shorelines, over traditional shoreline stabilization practices for the purpose of erosion control. Examples include policies in Maryland, North Carolina, and Virginia, which are briefly summarized below. Other States are currently developing similar policies or provide specific exemptions that encourage the use of nature-based approaches for shoreline management (e.g., Florida).

- **Maryland's Living Shoreline Protections Act.** This legislation requires property owners to implement non-structural shoreline stabilization measures wherever technologically and ecologically appropriate. The law specifically mentions living shorelines as an example of non-structural shoreline stabilization; however, generally, any appropriate nature-based solution can be justified. When opting for traditional shoreline armoring, the permittee must demonstrate that a nature-based solution could not be substituted feasibly.

- **North Carolina's Coastal Area Management Act.** This legislation enables the State of North Carolina to develop regulations and permits that specifically encourage the use of natural and sustainable shoreline practices.
- **Virginia Senate Bill 964.** This legislation enables the State of Virginia to establish regulations that authorize and encourage the use of living shorelines as the preferred method for managing tidal shorelines within Virginia.

6.3 Types of Permits

As described above, most nature-based solutions are subject to regulatory review by Federal and State agencies for compliance with CWA section 404, CWA section 401, ESA, NHPA, and CZMA. USACE generally acts as the Federal clearinghouse for infrastructure projects occurring predominantly within aquatic (tidal and non-tidal) areas, coordinating with each of the agencies to demonstrate compliance with these statutes prior to issuing a permit. When USACE is not the lead Federal agency (e.g., for long, linear projects with substantial upland components), the responsibility for compliance with these statutes lies with the lead Federal agency. Under these circumstances, USACE limits its review and permit authority to project work occurring within and adjacent to aquatic (jurisdictional) areas. Given the importance of USACE's role, this guidance document highlights the USACE permitting process below for (in order of increasing complexity) nationwide permits, regional or programmatic general permits, and individual permits.

As shown in Figure 6-2, there are three types of permits: nationwide general, regional/programmatic general, and individual. These permits have different requirements and you should determine, in consultation with your permit coordinator(s), which one is most appropriate for your project. More details about each permit type and their requirements are outlined below.

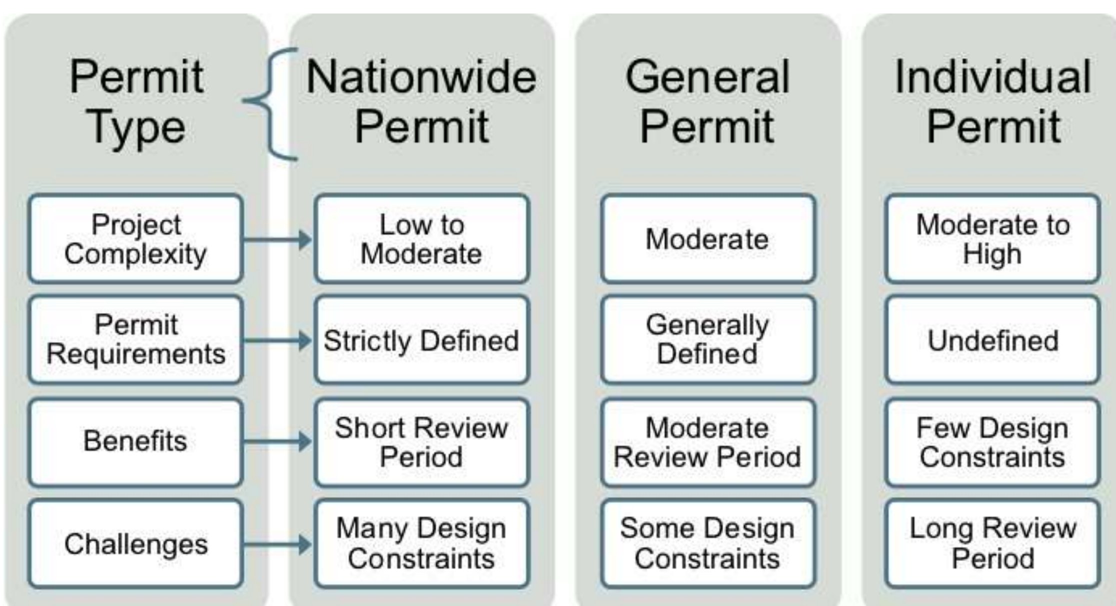


Figure 6-2. Summary of key points for USACE nationwide general, regional/programmatic general, and individual permits.

Individual permits are evaluated on a case-by-case basis, take longer to process (i.e., 4 to 12 months), and are subject to a 30-day public comment period. Individual permits are typically used for larger, more complex nature-based projects that do not qualify for a general permit. Until recently, individual permits were the only available option for permitting nature-based solutions. Approval timelines depend largely on the level of coordination required to demonstrate compliance with other relevant Federal statutes (e.g., ESA, MSA, NHPA), thus emphasizing the importance of early coordination with the lead Federal agency.

General permits provide a more streamlined permitting process for projects that are similar in nature, and are expected to result in minimal individual and cumulative impacts on the aquatic environment (40 CFR § 230.7(a)). In order to ensure minimal individual and cumulative impacts, work eligible for a particular general permit needs to adhere to multiple general conditions. Individual authorizations under a general permit typically have shorter review periods (< 2 months if mitigation and other Federal agency coordination is minimal) and are not subject to a public review period. However, all such authorizations may still be subject to interagency consultation if there are issues related to ESA, EFH, or NHPA.

There are two broad categories of general permits. Regional or programmatic general permits are issued by the District Engineer of the local USACE district on a regional or State basis. A USACE district may issue a regional or programmatic general permit to address activities not covered by a nationwide general permit (see below). Some States have general permits that set forth specific guidance and requirements for nature-based approaches to shoreline management. These requirements may limit the size, location, and materials used in the nature-based solution.

Nationwide permits are issued to the public at large for common categories of project activities (e.g., linear transportation projects, minor discharges) that fall under certain impact thresholds (e.g., 0.5-acre permanent impacts on the waters of the United States). There are four nationwide permits that are relevant to the implementation of nature-based solutions:

- **Nationwide Permit 14: Linear Transportation Projects.** This permit applies to activities required for the construction, expansion, modification, or improvement of linear transportation projects (e.g., roads, highways). For linear transportation projects in non-tidal waters, the project cannot cause the (permanent) loss of greater than ½ acre of waters of the United States. For linear transportation projects in tidal waters, the project cannot cause the (permanent) loss of greater than 1/3 acre of waters of the United States.
- **Nationwide Permit 13: Bank Stabilization.** This permit applies to bank stabilization activities used for erosion control or prevention, including natural, nature-based, and structural measures, as well as their combinations in hybrid approaches. The permitted activity cannot exceed 500 feet in length along the bank and cannot exceed an average of 1 cubic yard of fill per running foot, unless the District Engineer waives these criteria.
- **Nationwide Permit 27: Aquatic Habitat Restoration, Enhancement, and Establishment Activities.** This permit applies to the restoration, enhancement, and establishment of tidal wetlands and (non-tidal) riparian areas, tidal streams, and tidal open waters under the provision that such activities result in the net increase in aquatic resource functions and services.

- **Nationwide Permit 54: Living Shorelines.** This permit applies to the use of structures and to discharges of dredged or fill materials in waters of the United States for the construction and maintenance of living shorelines that stabilize banks and shores in coastal waters, including the Great Lakes. The permitted activity cannot exceed 500 feet in length along the bank and cannot extend into a body of water more than 30 feet from the mean low water line in tidal waters or the ordinary high-water mark in the Great Lakes, unless the District Engineer waives these criteria. This nationwide permit is relatively new, dating to 2017. As of August 2018, it had been granted 63 times, primarily in Florida, Virginia, Texas, North Carolina, New York, and New Jersey. (USACE 2018)

Nationwide permits have been regionally conditioned or revoked in some USACE districts. Specific regional conditions may require additional agency coordination and unique design considerations. For instance, there is significant regional variation in implementation of Nationwide Permit 54. Alabama and Maryland use state-specific general permits that were developed prior to Nationwide Permit 54. Washington, Ohio, Louisiana, and Texas have regional conditions on Nationwide Permit 54. (Boyd et. al. 2017) Before pursuing a nationwide permit for nature-based solutions, check with your USACE district office and State environmental agencies to determine which, if any, are available in your State.

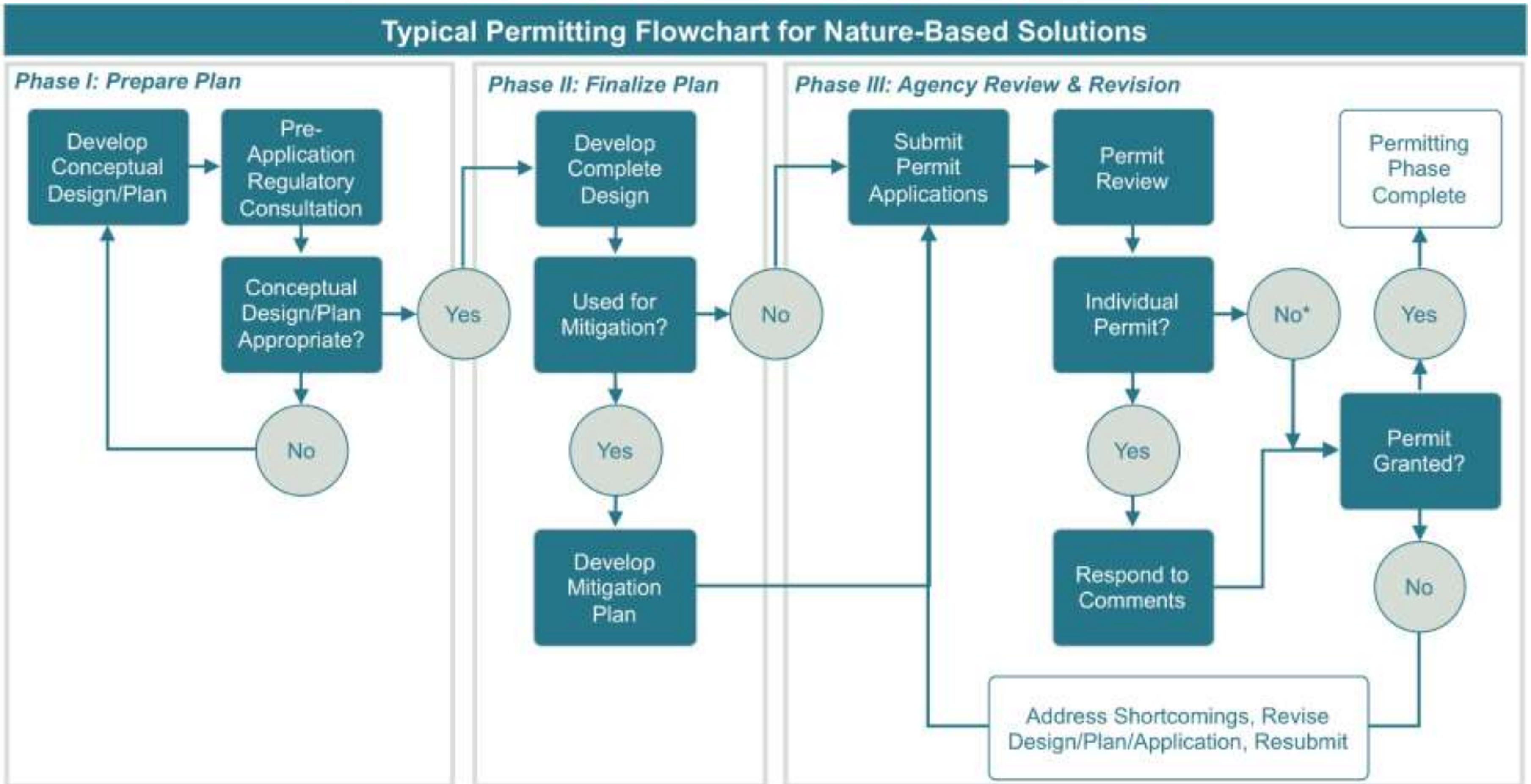
6.4 Typical Permit Workflow

Nature-based projects often follow unique permitting timelines, but many follow a similar workflow from beginning to end. Figure 6-3 provides an example of a permitting workflow for a typical nature-based solution. This workflow consists of three distinct phases: plan preparation, finalizing the plan, and agency review.

During plan preparation, the permittee develops (at a minimum) a conceptual design or plan for the nature-based solution and conducts a pre-application meeting with Federal and State regulatory agencies to discuss the project location, design, and potential environmental constraints. The permittee may need to revise the conceptual design or plan based on the results of the pre-application meeting. If the changes to the plan are substantial, a second pre-application meeting may be warranted.

Once there is agreement on the general characteristics of the nature-based solution and having determined the permits and other approvals required for the work, the permittee finalizes their design or plan. At a minimum, the permit application will include the design or plan (e.g., dimensions, areas, amount of fill used, profile and planform drawings), a written project description, the purpose and need for the project, a jurisdictional delineation, proposed impacts on the waters of the United States, and possibly additional technical studies documenting existing environmental conditions (i.e., biological, historic, and cultural resources). It is recommended that a mitigation proposal and plan are prepared prior to finalizing the design plan and submitting the permit application, with input from the USACE district mitigation lead.

The permittee submits their application to the appropriate Federal and State agencies in the final phase of the workflow. The agencies review and provide feedback and/or a permit decision during this final phase. In the case of an individual permit, the applicant will likely respond to comments submitted by the public and consulting Federal agencies. Successful resolution of these comments may require more investigation, justification of the project purpose and need, or modification of the project design or mitigation plan. No public comments are submitted in the case of general permits and nationwide permits. However, USACE and relevant State agencies may ask the applicant for more information about, or clarification of, a specific issue.



*It may be necessary to respond to comments for Nationwide and General Permits. These comments will come form USACE and relevant State agencies. Individual permits typically require responses to questions/comments from the public and consulting Federal and/or State agencies.

Figure 6-3. Typical permitting flowchart for nature-based solutions.

PERMITTING FOR NATURE-BASED SOLUTIONS

6.5 NEPA Compliance

Projects or policy changes involving Federal actions, including Federal assistance, leases or easements, and permitting, are required to demonstrate compliance with the National Environmental Policy Act (NEPA). NEPA is administered by the Council on Environmental Quality (CEQ), a Federal office tasked with oversight and development of policies and guidance tools regarding NEPA implementation and compliance. CEQ is also responsible for resolving disputes between lead or cooperating Federal agencies.

NEPA provides Federal agencies with a framework for the evaluation of environmental impacts, alternatives, mitigation measures, and comments from agencies and the general public. During the NEPA process, the lead Federal agency concurrently demonstrate compliance with other Federal laws, regulations, and orders, including the Endangered Species Act and the National Historic Preservation Act. In terms of project timeline, preparation of the NEPA compliance documentation is either conducted in advance of, or concurrent with, permitting, depending on the lead Federal agency, the category of permit, and the need for interagency consultations.

Common categories of NEPA compliance documentation include, in descending order of complexity:

- **Environmental Impact Statement (EIS).** This document is the most rigorous environmental review, applicable to major projects or policy changes that may result in significant impacts on one or more categories of the “human environment,” including environmental or social factors.
- **Environmental Assessment (EA).** This document is a lower level of environmental review than the EIS, applicable to projects or policy changes not expected to result in significant effects to the human environment, but also may be used to determine whether an EIS is required.
- **Categorical Exclusion (CatEx).** This is the lowest level of environmental review, limited to a brief decision document and, potentially, public notification. Examples of actions qualifying for a CatEx may include small or minor new activities/facilities, routine maintenance, and budgetary and administrative actions.

Under circumstances where USACE is the lead Federal agency, the timing of NEPA compliance depends largely on the category of permit being sought. For nationwide permits and other general permits (e.g., regional general permits) issued for categories of activities, NEPA is satisfied programmatically on a national or regional scale, respectively, prior to application submission. USACE prepares an EA at the time of the establishment of the general permit. During the 5-year authorization period, individual activities that are eligible for the general permit do not need to undertake a separate NEPA review. However, the applicant still needs to demonstrate compliance with the terms and conditions of the permit, as well as compliance with other relevant Federal statutes (e.g., EFH, ESA, NHPA, CZMA) in order to receive a section 404, section 9, or section 10 permit. For individual permits, USACE conducts project-specific NEPA compliance documentation concurrent with permit processing (i.e., after an application is submitted). Depending on the size and complexity of a project, as well as the anticipated impacts, USACE may elect to prepare either an EA (~99.7 percent of the time) or an EIS (if the impacts are significant). Under circumstances where another Federal agency is the lead (e.g., FHWA), compliance with NEPA is often conducted prior to submission of permit applications.

Material requirements for EISs and EAs include the following: a detailed project description, purpose, and need; alternatives analysis, plans, and specifications (level of detail varies); impact evaluation for relevant environmental and social factors; solicitation of public comments; identification of mitigation measures; and demonstration of compliance with other Federal laws, regulations, and orders.

For major infrastructure projects (i.e., those that may require an EIS), Executive Order (EO) 13807 requires Federal agencies with purview over a given project to conduct environmental reviews and authorization processes in a coordinated, consistent, predictable, and timely manner, culminating in One Federal Decision. The EO directs Federal agencies to develop a single EIS and Record of Decision (ROD), and issue all necessary authorizations within 90 days of completion of the ROD. An overarching goal of EO 13807 is to complete all reviews and authorization decisions for major infrastructure projects within a 2-year timeframe. For additional information, see the following:

- Presidential Executive Order on Establishing Discipline and Accountability in the Environmental Review and Permitting Process for Infrastructure (Trump 2017)
- Implementing One Federal Decision Under Executive Order 13807 (White House 2018)

For nature-based solutions, relevant portions of EO 11988 (floodplain management) and EO 11990 (protection of wetlands) also apply.

In the context of nature-based solutions, early identification of opportunities to integrate habitat restoration, creation, and enhancement within a project design is critical. In addition, as discussed in Section 5.1, Assembling the Team, early coordination with State and Federal resource and regulatory agencies (e.g., USFWS, NMFS, USACE) provides insight and expertise on special-status species, habitat requirements, and regional priorities, and also has the potential to streamline agency review of infrastructure projects during both the planning and permitting

Additional Permitting Resources

Additional resources on NEPA and CEQ are available at http://ceq.doe.gov, including guidance for Federal agencies and information on NEPA training opportunities. CEQ's Frequently Asked Questions are available at https://www.energy.gov/sites/prod/files/G-CEQ-40Questions.pdf

An FHWA overview of NEPA, as it applies to transportation projects, is available at https://www.fhwa.dot.gov/federal-aidessentials/catmod.cfm?category=environm.

The FHWA Eco-Logical approach provides a framework for collaborative decision making in support of nature-based solutions, including decision tools and resources for assistance, is available at https://www.environment.fhwa.dot.gov/env_initiatives/eco-logical.aspx

The One Federal Decision Framework for the Environmental Review and Authorization Process for Major Infrastructure Projects is available at https://ceq.doe.gov/docs/ceq-regulations-and-guidance/One_Federal_Decision_Framework_Guidance_(M-18-13)_2018-03-20.pdf stages. For example, a project may qualify for streamlined permitting with USACE if it meets the terms and conditions of a nationwide permit or regional general permit. Efficiencies are often gained through the early identification of project objectives and data needs that serve to satisfy the statutory requirements of the agencies with purview over the project. Additional opportunities to avoid or minimize adverse effects to sensitive resources, as well as sources of funding or technical assistance, may also be identified through such advance planning strategies.

6.6 Mitigation Opportunities

The construction of new transportation infrastructure projects, or modifications to existing infrastructure, may require compensatory mitigation. As defined by USEPA (2015b), compensatory mitigation "… refers to the restoration, establishment, enhancement, or in certain circumstances preservation of wetlands, streams or other aquatic resources for the purpose of offsetting unavoidable adverse impacts." Transportation agencies may elect to create, adopt, or integrate programmatic mitigation plans as part of statewide transportation planning in order to address potential impacts of future projects.[10]

Transportation professionals can incorporate nature-based solutions to meet mitigation requirements, gain mitigation credits, offset environmental impacts, or meet permit requirements (e.g., section 404, Endangered Species Act, Total Maximum Daily Load, National Pollutant Discharge Elimination System). Pursuing compensatory opportunities for nature-based solutions can provide an additional incentive for implementation. The eligibility of a specific project, however, is determined on a case-by-case basis. Early engagement between the transportation agency and its USACE district mitigation lead is important. The following subsections describe how nature-based solutions can be used to meet environmental regulatory requirements. A summary of mitigation opportunities and challenges is presented in Table 6-1.

Water Quality Improvements

Many nature-based solutions provide measurable water quality improvements. For example:

- As a means of stabilizing eroding shorelines, a nature-based solution may improve water quality through reduced sediment loading.
- Nature-based solutions containing a vegetative component, such as a tidal marsh, may reduce nutrient loading. Deposition of suspended solids improves tidal marsh stability and light penetration needed for growth of submerged aquatic vegetation.
- The presence of reefs may play a faciliatory role by enhancing sediment deposition.

[10] Programmatic mitigation planning is addressed in 23 CFR § 450.214, Development of Programmatic Mitigation Plans.

Table 6-1. Compensatory mitigation opportunities and challenges

Mitigation Option	Opportunity	Challenge
Permittee Responsible Mitigation	▪ Can be used to provide resilience for project ▪ More control over type of project and implementation	▪ Management requirement ▪ Lack of expertise required to design and implement nature-based project
In-Lieu Fee (ILF) Mitigation	▪ Credits purchased from an ILF program ▪ No long-term responsibility from the permittee ▪ No specific nature-based expertise required	▪ May not benefit transportation project ▪ Cost could be high
Mitigation Banking	Same as ILF plus … ▪ Credits purchased from established bank ▪ Bank/Site can be chosen	Same as ILF plus … ▪ Limited opportunities for coastal banks ▪ Impact ratios could be high

The benefits provided by nature-based solutions may assist in meeting Total Maximum Daily Load (TMDL) requirements for impaired bodies of water under 303(d) of the Clean Water Act. A TMDL is calculated as the maximum amount of a pollutant allowed to enter a waterway while maintaining water quality standards in a receiving body of water. If the current pollutant loading rates exceed the maximum allowable value, then the TMDL is used to determine a pollutant reduction target and load reductions are subsequently allocated to sources.

Virginia Department of Transportation (VDOT) Spotlight
As part of the Chesapeake Bay TMDL Action Plan, VDOT will be using shoreline stabilization techniques to meet 20 percent of their Total Nitrogen and 70 percent of the Total Phosphorus reduction targets. The 2 miles of shoreline stabilization and 5.4 acres of marsh plantings, primarily on State park lands, will reduce Total Nitrogen input by more than 5,600 pounds per year (Harmon 2018). These projects are simultaneously benefiting the State parks through erosion control and are creating recreational opportunities for park visitors.

Some States now permit the use of qualifying shoreline management practices to meet sediment and nutrient load reduction targets as part of a TMDL program. For example, Maryland and Virginia have established guidance for determining sediment and nutrient load reduction targets for existing urban development under the Chesapeake Bay TMDL program (Forand et al. 2015; Harmon 2018). Load reduction values are determined using simple, conditional equations that are functions of the length of shoreline stabilized and/or acres of tidal marsh created.

Permittee Responsible Mitigation

Many State DOTs have direct experience using Permittee Responsible Mitigation (PRM) to meet compensatory mitigation requirements. Under PRM, a State DOT has direct control of, and ongoing responsibility for, the mitigation action or project. A transportation agency may implement a nature-based solution under PRM in such a way as to simultaneously meet mitigation requirements and enhance the resilience of their transportation infrastructure.

The ability of a nature-based solution to meet compensatory mitigation requirements is determined through consultation between the permittee (e.g., DOT, MPO, municipality) and the regulatory agencies. Initial consultation with the regulatory agencies will often inform the activities described in a mitigation proposal. In the proposal, a permittee may elect to perform in-kind or out-of-kind mitigation. In-kind mitigation activities are those in which adverse impacts on a specific habitat type are mitigated through the establishment, restoration, or enhancement of that same habitat type. Out-of-kind mitigation projects address adverse impacts on one habitat type (e.g., submerged aquatic vegetation) through the establishment, restoration, or enhancement of another habitat type (e.g., tidal marsh).

A permittee must be able to provide continued management of their mitigation project as part of the PRM process. Providing continued management requires both the ability to access the project for the purpose of performing monitoring and maintenance, and the dedicated financing to do so. PRM often requires specific monitoring and maintenance requirements that seek to ensure long-term project success. See Section 8 for more information on monitoring requirements.

In-Lieu Fee Mitigation

In-Lieu Fee (ILF) mitigation is another type of mitigation that compensates for impacts on certain habitat types. Under ILF mitigation, the permittee provides funding to an ILF sponsor. The sponsor, which is often a public agency or nonprofit organization, collects the fees from multiple permittees to build and/or maintain mitigation sites. This type of mitigation is often “offsite,” meaning that it does not occur at or near the actual impacts. The mitigation frequently occurs after the permitted activity is complete.

Mitigation Banking

Mitigation banking is another form of compensatory mitigation that addresses unavoidable impacts on natural resources and the environment. Under this form of mitigation, a permittee purchases credits from an established “mitigation bank,” which is the preservation, enhancement, restoration, or establishment of a wetland, stream, or habitat conservation area that compensates for adverse impacts on nearby ecosystems. Compared with freshwater streams and wetlands, opportunities for coastal mitigation bank credits are fewer in number and the cost of credits is often greater. USACE maintains an online geodatabase called the Regulatory In-Lieu Fee and Banking Information Tracking System, or RIBITS (USACE 2019a). The RIBITS database contains information on mitigation and conservation banking and ILF programs nationally.

CONSTRUCTION

7. CONSTRUCTION

Now that you have your permits in hand, it is time to build your project! Before you can build the project, however, you must first select a contracting method and then identify potential contractors. This section addresses these issues and also provides a description of the phases of construction and some special considerations for constructing nature-based solutions.

7.1 Who to Contact

Before initiating contact with a marine contractor, reach out to your coastal resource agency or local/regional groups that are knowledgeable regarding nature-based solutions. They will often provide excellent recommendations, or at least a list of marine contractors with experience constructing nature-based solutions. The percentage of marine contractors with nature-based experience is relatively small (but growing).

> **Need Help?**
> If you are unsure who to contact, look no further than the Living Shorelines Academy Professional Directory. This web-based directory allows a user to search by name, affiliation, profession, and/or State.
>
> Living Shorelines Academy
> http://livingshorelinesacademy.org

The construction team should include appropriate engineering and ecological expertise to resolve construction issues as they arise. Site conditions change often, and onsite modifications are often made quickly to prevent work stoppage. You may wish to hire a construction manager and other appropriate experts for very complex projects (Duhring 2016).

Narrow down your list of potential contractors and invite them to your site. While there, review the design plan, evaluate construction access and staging areas, assess site conditions, convey your expectations, and inquire about their availability. Once you have contacted your preferred contractor, determine the project schedule, availability of materials, probable costs, and other appropriate issues prior to entering into a binding contract for services.

7.2 Procurement Considerations

Procurement for construction of nature-based solutions will generally follow established transportation agency procurement methods, though there are some considerations specific to nature-based solutions that warrant discussion. One of these considerations is whether to choose a performance-based contract or a more traditional, method-based contract. Method-based contracts describe how to do the work, what materials to use, the treatments to apply, specific activities, and potentially other issues. Performance-based procurement methods focus on what the project must achieve, rather than how the contractor will achieve it.

Performance-based contracts can promote innovation in construction techniques, which is often helpful when constructing nature-based solutions. Performance-based contracts can also be helpful in developing contracts that not only include initial construction, but also maintenance. AASHTO’s “Guidelines for Vegetation Management” contains procurement advice that is relevant to nature-based solutions, including information on selecting performance measures for performance-based contracts. Table 7-1 is a very brief example of what performance measures may look like for nature-based solutions.

Table 7-1. Example measures for performance-based contracts (adapted from AASHTO 2011)

Activity[1]	Condition Indicator	Performance Measure	Threshold[2]					Acceptable[3] Threshold
			A	B	C	D	E	
Vegetation Stem Density	Mean stem density for *Spartina alterniflora*	stems per m^2	90	80	70	60	50	C
Vegetation Stem Height	Mean stem height for *Spartina alterniflora*	cm	110	100	90	80	70	C
Sediment Elevation	Deviation of sediment elevation from plan (for vegetation planting)	%	±0	±2	±4	±5	±6	C
Structure Elevation	Deviation of structure elevation from plan	%	0	-2	-5	-7	-10	C

[1] These activity categories are provided as examples only. This is not a complete list, and some of these may not be applicable for a given project. See Section 8 for more information.
[2] These threshold values are fictitious and provided as examples only. See Section 8 for more information.
[3] These acceptable threshold values are assumptions and placeholders only. See Section 8 for more information.

One potential complication with a performance-based contract is the amount of time that must elapse before, or in between, performance assessments. For example, if a performance standard is written for a healthy, mature marsh (to continue the example from above), then the contractor may not meet those targets for as many as 3 years following planting. In that case, a performance payment may be held back for a period that aligns with monitoring and performance assessment windows. In other words, construction contracting for nature-based solutions may require two contracts: one that pays for labor and materials, and another that pays for performance (the contractor's "fee" estimate for the work).

Full performance-based contracts can be difficult to administer because of the amount of experience required for selecting performance criteria, the availability of qualified inspectors, and an understanding that the biological and ecological elements of a nature-based solution do not always behave as expected. Alternatively, some States use selected performance measures in their methods-based contracts to reduce complexity.

Leung et al. (2018) provides a comprehensive procurement guide to nature-based solutions that transportation professionals may find helpful. Their guide outlines format and content for request for proposals (RFPs), provides sample language on nature-based solutions, and gives helpful information regarding selection criteria and the evaluation process.

7.3 Phases of Construction

This section organizes expectations into three phases of construction: the pre-construction phase, the construction phase, and the post-construction phase. Discussion of the construction phase also includes an overview of a typical construction sequence.

Pre-Construction Phase

Pre-construction refers to the period prior to starting construction. The pre-construction phase includes the preceding project steps, such as project design and permitting. This is an excellent time to address construction-related items as well. The pre-construction phase is an opportune time to develop the monitoring and maintenance plan, prepare the site, resolve construction access issues, and develop an agreement for restoring the site to a suitable condition (Duhring 2016).

Construction Phase

Aside from performing the construction, frequent communication between parties is a significant part of the construction phase. It is important to maintain collaboration among the contractor, design engineer/practitioner, biologists, ecologists, and other scientists (as appropriate) throughout the construction phase (O'Donnell et al. 2018).

For projects in highly visible areas, communication with the public is equally important. Poor public perception or a misunderstanding of the project and the construction process can endanger project success and opportunities for future projects. The construction phase is not necessarily pleasant: It is noisy, it is disruptive, and it is dirty. Installing temporary signage during the construction process is a productive public engagement tool. For example, the Delaware Department of Natural Resources and Environmental Control (DNREC) installed the low-cost sign shown in Figure 7-1 at their project sites during the construction phase. DNREC staff believe that these signs are effective tools for public engagement and communication. The signage also provides a contact number for DNREC that the public can call for more information.

Figure 7-1. Living shoreline construction notification signage for the public (photo courtesy Eli Chen, Delaware Public Media).

There is no uniform sequence or schedule for performing construction. However, construction projects do follow a somewhat logical progression of tasks and there are some requirements that go along with those tasks. For the purposes of this guide, we are breaking down the construction sequence into four distinct actions: plan, prepare, build, and leave. Figure 7-2 shows this sequence graphically and provides related comments for each action.

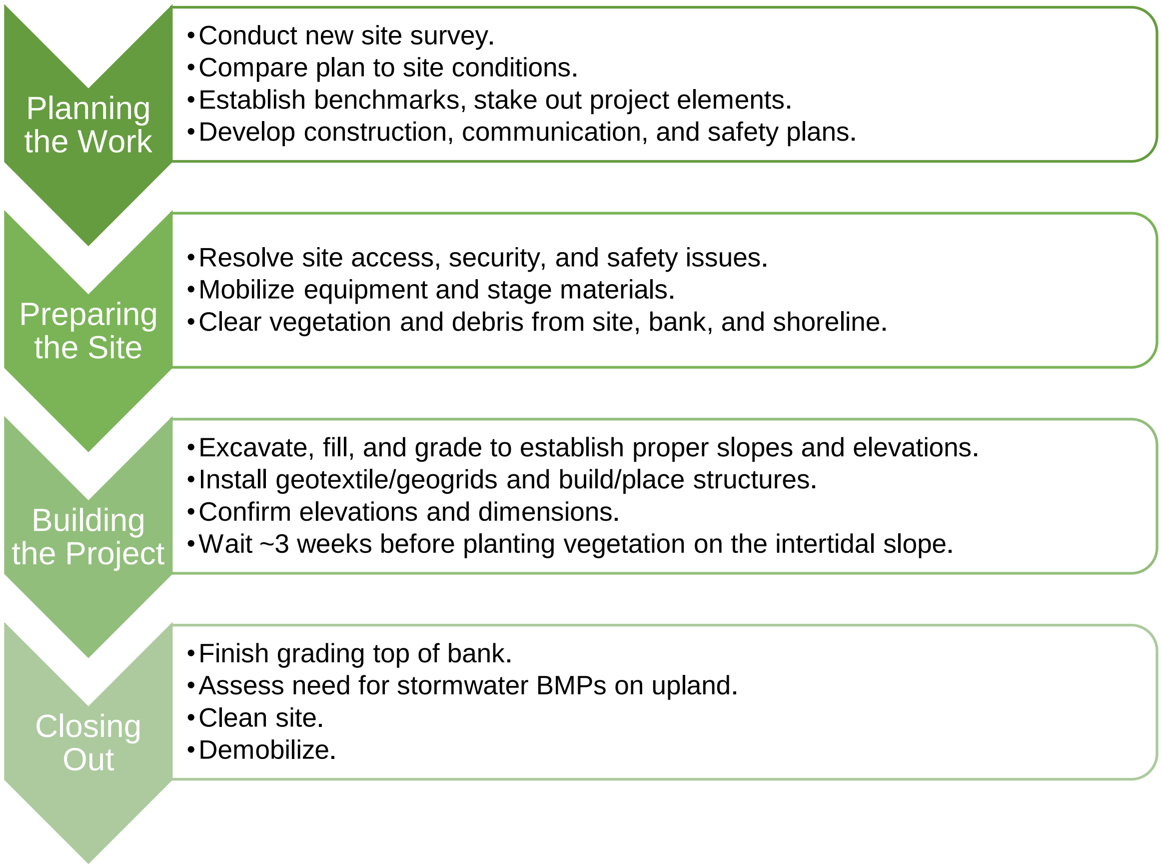


Figure 7-2. Typical construction sequence for a simple nature-based solution (adapted from GDNR 2013).

It is possible to further subdivide the third action—building the project—into distinct steps for nature-based construction. These four sequential steps convey the order in which elements of the project are constructed. Figure 7-3 shows this general four-step sequence for construction of a tidal marsh and stone sill using land-based construction methods. In this case, the contractor used some of the marsh fill to establish a bench along the shoreline from which the track-mounted excavator could reach the material pile (of riprap) and the structure site (in the water). When working from the water, construction of the sill may have been performed earlier in the project sequence, depending on the staging of materials, water depths, barge draft, or other factors.

Figure 7-3. General sequence for building a nature-based solution (adapted from Duhring 2016).

Post-Construction Phase

Post-construction does not mean project completion. A project is not complete until the entire scope of work is complete, and all contractual obligations are fulfilled. There are several issues to address following construction, and they are handled in the post-construction phase. The first step is to obtain an as-built, post-construction survey of your project (including biological/ecological surveys) immediately after all elements are installed. This will serve as your performance baseline for project monitoring. The contractor will sometimes request or perform an intermediate survey following the completion of structures, and/or the placement of fill material. These are often “pay quantities” in contracts; the contractor will want to ensure that they are paid for what was placed in the project area, not what was remaining after 4 weeks. This is particularly true for sand fill projects since some percentage of sand will leave the project almost immediately. Once all tasks are complete, use the as-built survey to confirm design specifications and compliance with the permitted activities (Duhring 2016).

For high-visibility projects, consider installing permanent informational and educational signage at your project site. Figure 7-4 shows an example of a large informational sign installed at a living shoreline demonstration project at Bayfront Park in Sarasota, FL. The sign introduces the living shoreline concept, its various elements, and what they provide and accomplish. The sign also has a Quick Response code that directs people to the Sarasota Bay Estuary Program website to further educate the public about living shoreline benefits.

Figure 7-4. Example of informational signage installed at a project site (photo courtesy of Dianne Rosensweig, ESA).

7.4 Special Considerations and Constraints

Construction Access

Confirm construction and site access with the contractor prior to starting work. Site access, adequate staging area, and security can delay the start of the project. Site accessibility depends on how easy and/or safe it is for the contractor to mobilize his or her equipment, crew, and materials to the project site by land or by sea. In cases where site access is particularly limited, you may have to modify your design plan based on equipment accessibility (Duhring 2016).

Construction accessibility ranges from *easy* to *difficult* to *impossible* (Priest 2006). *Easy* access means that the contractor will not need to do much, if any, clearing, grading, or grubbing to reach the site by land. By sea, *easy* access refers to the availability of water depths that accommodate the draft of work boats, equipment barges, and material scows. *Difficult* land and water access situations refer to generally difficult or adverse conditions, such as considerable site work on land and shallow drafts at sea. *Impossible* means that access is just that—not possible to reach (Priest 2006).

Assuming that access issues are non-existent or possible to overcome, the contractor must exercise caution using heavy machinery on the site and near the project area. It is not uncommon for heavy equipment such as excavators to sink in soft subsurface soils (Miller et al. 2015). Based on the nature of the work, heavy equipment will have to function in and around marshes; on unstable shoreline banks; on newly placed, unconsolidated materials; and/or directly in the water. The contractor must exercise caution to ensure the safety of his or her crew and equipment. The use of large timber construction mats is common on these types of construction projects and they should be used in coastal buffers and marshes (Priest 2006; Duhring 2016).

Additional considerations for long-term access should also be part of the overall project design. Most projects will require long-term access for the purpose of monitoring and maintenance (see Section 8 for more information).

Equipment and Methods

There are two general construction methods for nature-based solutions: land-based construction and water-based construction. Similar types of heavy equipment are used with both methods, namely track-mounted dozers (land), long-reach excavators (land and water), and dump trucks (land). Staging of materials for land-based construction is done on the upland, whereas materials are stored on scows and moored offshore of the site for water-based work. For land-based work, the access roads and upland property must be adequate to support the weight of the equipment and materials. On the water, the depth over the full tidal cycle must accommodate the loaded draft of the equipment barge and material scows. The draft of most barges is approximately 4 feet (Miller et al. 2015). Mooring of these barges often requires coordination with USCG and your State Marine Police division.

Land-based construction of most nature-based elements is possible since the features are relatively close to the existing shoreline. There are some exceptions, however. First, if materials are transported to the site by water, then the contractor will either work from the water or spend additional time moving materials from the barges to the upland. Second, for offshore structures such as breakwaters, their distance from the shoreline is generally too great to overcome with a long-reach excavator and the work is performed on water-based platforms. Third, the contractor may elect to erect a temporary structure for the purpose of accessing offshore locations using traditional land-based methods. If large, use of the temporary structures may be prohibited by the regulatory agencies.

Timing

Construction of nature-based solutions presents interesting logistical challenges that are sometimes very difficult to overcome. There are very real physical barriers that limit your ability to do some work: the tides! Most contractors will try to perform their work during low tide if performing land-based construction. However, low tide only occurs for a few hours out of each day. In locations with very large tide ranges (e.g., Georgia, Northeast, Alaska, and others), the tide also moves swiftly and creates hazardous conditions for equipment and workers when in or near the water.

How Low Can You Go?
NOAA produces tidal predictions at hundreds of locations around the United States. Do you need to know when low tide will occur and for how long it will last? Visit the NOAA Tides & Currents website and find the location nearest your project:

NOAA Tide Predictions
https://tidesandcurrents.noaa.gov/tide_predictions.html

In order to maximize the availability of low-water conditions (for land-based work), marine contractors often like to begin construction during the winter months. This greatly depends on your region of the country. In the Gulf of Mexico, construction often begins between November and January, and marsh plants are installed February through May. This allows the plants to experience a few months of in-place growth prior to their first winter and prior to the most active part of the tropical cyclone season (GBF 2011). In comparison, the recommended months for planting in the Northeast are slightly later than those of the Gulf of Mexico. For projects focused on natural recruitment of oyster spat or other bivalves on reef substrate, the timing must account for the spawning cycles of target species (Miller et al. 2015).

The installation of a nature-based project could positively and negatively affect onsite and nearby habitats and species during construction activities and following project completion. Construction activities can disrupt, fragment, or destroy habitat, and noise, trampling, and the presence of humans and equipment can cause habitat or nest abandonment or failure. Consideration should be given to the breeding, nesting, spawning, and growing seasons of wildlife and plant species in order to minimize disturbance and maximize success. For example, the construction of an oyster reef that is late by 1 month can delay oyster recruitment by an entire year. Thoughtful planning can include the life cycles of species and could involve the salvage and storage of plant and soil material for later use in the project. Successful nature-based shorelines stabilize over time as plants, roots, and oyster reefs grow and sediments deposit; however, inappropriately installed fill material has the potential to bury aquatic plants and animals, and sills and breakwaters installed without appropriate consideration for nearby effects have the potential to damage nearshore habitats and species, and offshore vegetation and aquatic species.

8. MONITORING, MAINTENANCE, AND ADAPTIVE MANAGEMENT

Congratulations on the construction of your project! The prior section gave some helpful tips on construction-related issues associated with nature-based solutions. But the end of construction is not the end of your project. In fact, your project is only now beginning. This next phase of your project life cycle involves monitoring project performance and impacts, maintaining the features of your project so that they will continue to provide the expected benefits, and implementing adaptive management if or when those benefits are not realized. After reading this section, you will better understand performance monitoring requirements and methods, common maintenance issues and costs, and tips for tracking project performance.

8.1 Performance Monitoring

Nature-based solutions that provide flood and/or erosion benefits will often affect aquatic resources, landforms, property values, private or public infrastructure, and local and/or regional sediment transport characteristics, as well as critical habitats (NRC 2007). Monitoring a project's performance provides an opportunity to measure and assess these impacts.

Three Phases of Monitoring
Performance monitoring takes place over three phases:

1. Pre-construction
2. Construction (as-built)
3. Post-construction (performance)

The pre-construction survey serves as a baseline. The construction, or as-built, survey and monitoring describe the "improved" condition immediately following the time of construction. The post-construction, or performance, phase may last indefinitely; however, most agencies report monitoring timeframes of 7 years or less.

Performance monitoring provides an opportunity to assess the project against performance metrics, identify potential adaptive management needs, and refine designs for future projects. Some form of performance monitoring is required when nature-based solutions provide compensatory mitigation. Funding agencies may also require performance monitoring. This guide recommends some basic data collection and visual observation for all projects, regardless of whether it is required. Monitoring data allows the project team to determine whether the project meets performance expectations. If performance falls short of expectations, the monitoring data informs the design and implementation of corrective actions. The process of monitoring and assessing project performance is critical for the continuous improvement of nature-based solutions (Yepsen et al. 2016).

Performance monitoring is seldom uniform across projects. Monitoring type, frequency, and methods are a function of project goals and objectives, which are often unique for every nature-based project. The design and implementation of performance monitoring is guided by a monitoring plan, which requires input from both the project team (e.g., design practitioners, compliance professionals, maintenance engineers) and stakeholders (e.g., regulatory agencies, funding agencies, NGOs, public). Initiating development of the monitoring plan in the project planning phase allows practitioners and stakeholders to provide their input on the process.

Starting early is important for another reason: The project design may need to incorporate access provisions, monitoring stations, work platforms, and/or monitoring measurement locations.

This guide recommends following the framework of Yepsen et al. (2016) for developing a monitoring plan. Plan development is a multi-step process. These steps are briefly described in the following sections:

1. Identifying project type and goals.
2. Identifying relevant performance metrics.
3. Selecting appropriate measurement methods.
4. Developing the monitoring plan.

Plan execution logically follows plan development. In all cases, plan execution will require dedicated annual funding for the duration of the monitoring period. Some States, such as Virginia, include permit-required performance monitoring as a line item in their biennial budgets, which provides enough funds to execute monitoring plans. In other cases, performance monitoring is paid through appropriations requests, or through grant funding.

Identify Project Type and Goals

The Yepsen et al. (2016) framework is based on two common project types: living shorelines and tidal wetland restoration. Living shorelines—a type of nature-based solution—are often smaller, more focused projects aimed at shoreline stabilization and erosion control, but they also provide co-benefits such as habitat enhancement, water quality improvement, enhanced resilience, and other ecosystem services benefits. Tidal wetland restoration is often much larger in scale and is focused on restoring the extent and/or ecological function of tidal marshes. The purpose of tidal wetland restoration is not shoreline stabilization, although it is often an indirect benefit. The restoration of tidal wetlands can lead to habitat enhancement, water quality improvements, and resilience enhancements, as well as hydrologic improvements, and socioeconomic benefits at a much larger scale than living shorelines. While there are certainly other types of projects, these are used to describe some of the goals and monitoring metrics covered below. Other large-scale project types that can improve coastal highway resilience include programmatic dune restoration and beach nourishment, mangrove restoration, maritime forest conservation, and reef (coral and/or oyster) restoration.

Tidal Wetlands Restoration
These restorative actions seek to re-establish appropriate marsh elevations, natural tidal hydrology, and wetland plant and wildlife communities. Restoration practices include beneficial use of dredged material to elevate the marsh platform, restoring hydrologic function and tidal connectivity impaired by human activities, and rebuilding native plant communities. Installing and/or improving culverts under roadways and causeways is one component of tidal wetlands restoration. Reorientation of causeways or replacement with bridges are considerations for more comprehensive restoration projects.

The project types listed previously share many of the same goals. Project goals correspond to the type of project and its primary purpose. Project goals should be SMART—specific, measurable, achievable, relevant, and time-bound—to enable assessment and implementation of corrective actions. Assessment requires comparing performance monitoring data to project goals. Corrective action occurs when the assessment reveals that a project is not meeting, or not going to meet, a specific goal within the desired timeframe.

The Yepsen et al. (2016) framework is based on five categories of goals, appearing as the first five items in the list below. Here, we include a sixth category focused on transportation, which is relevant for readers of this guide. The categories of goals are as follows:

- Erosion control
- Water quality improvements
- Habitat (e.g., fisheries, wildlife) enhancement
- Hydrologic enhancement
- Socioeconomic enhancement
- Transportation resilience

Erosion control is a goal common to many types of nature-based solutions. The objectives of erosion control are to reduce excessive sediment inputs to adjacent waters; stabilize the bank or slope; and, in some cases, manage shoreline retreat. The goal of erosion control, and shoreline stabilization more specifically, is relevant for coastal highway infrastructure. Erosion threatens the stability of coastal highway embankments, drainage infrastructure, and bridge approaches. Shoreline retreat threatens the stability of shore- and coast-parallel highways at many locations across the United States (FHWA 2008).

Water quality improvements involve steps to reduce concentrations of nutrients, contaminants, and/or suspended solids in receiving waters. Improving water quality is an important component of section 303(d) of the Clean Water Act. Transportation organizations are familiar with section 303(d) requirements and utilize stormwater BMPs to meet water quality standards and TMDL requirements for threatened and impaired waters of the United States. Nature-based solutions can often provide the desired water quality improvements.

Examples of Success Criteria

Examples of success criteria used in compensatory wetland mitigation projects include percentage of canopy cover, percentage of plant survival, plant vigor, percentage of native species, period of tidal inundation, stability of designed features, wildlife usage, plant heights, and others. The metrics used to measure the success of a goal or criteria are a function of the project type and project function (NRC 2007).

Habitat enhancement goals focus on restoring or improving critical or essential habitat for wildlife; ecologically important, threatened, and/or protected species; and commercially or recreationally important fisheries. Associated goals focus on increasing habitat area, abundance, biodiversity, and so forth. Habitat enhancement may not be a primary goal for transportation-oriented projects, but it can be used as part of compensatory mitigation efforts.

Hydrologic enhancement goals focus on re-establishing hydrologic (upland) and hydraulic (tidal) functions and connections that development and human modifications have altered over time. Hydrologic improvements seek to restore the extent, depth, and duration of tidal inundation.

Transportation corridors along the coast have historically affected tidal bodies of water and wetlands by modifying the “hydroperiods” of tidal wetlands and other estuarine environments. The hydroperiod corresponds to daily (tidal) and seasonal patterns of water levels within a tidal marsh.

Socioeconomic enhancement goals seek to enhance environmental attributes that contribute to social and/or economic well-being. These goals are the result of improved ecological function, but require different types of data collection in order to assess performance (if so desired). Some consideration should be given to tracking social and economic co-benefits, even if they are not the primary purpose of the project; the benefits may be of sufficient magnitude to warrant assessment and may be relevant for other project partners and stakeholders.

Transportation resilience goals are not part of the Yepsen et al. (2016) framework, but are obviously relevant for transportation agencies. Appropriate transportation resilience goals might include the following:

- Reductions in flooding (extent, duration, and event frequency)
- Reductions in maintenance (repair cost and/or frequency)
- Reductions in service disruption (increase system reliability)
- Reductions in recovery times following extreme events

Identify Relevant Metrics

The Yepsen et al. (2016) framework describes monitoring metrics as “… specific parameters used to assess project success and gauge attainment of project goals.” Their framework considers two categories of metrics: **project-type metrics** associated with a specific type of restoration project, and **goal-based metrics** associated with the specific project goals. Project-type metrics assess the effectiveness of the restoration technique. Goal-based metrics are specific to project goals. Tracking goal-based metrics are necessary for assessing project success and developing adaptive management strategies that correct performance shortcomings.

The project- and goal-oriented metrics are further subdivided into **core** metrics and **conditional** metrics (Figure 8-1). The core concerns represent a small number of metrics that are collected on all projects of a certain type. The conditional concerns represent more specific metrics that can be assessed for all projects, but depend on the specific project site and design. Figure 8-2 provides an example of how the general hierarchy of metrics applies to a living shoreline that is used to improve water quality. Suggested core and conditional metrics are presented in Appendix C (Table 10-2 through Table 10-8), and are provided only as an illustrative example. While the tabulated metrics are appropriate for many project types and goals, the project team must carefully consider whether some are unnecessary, and if any critical metrics are missing. Table 8-1 lists some common metrics associated with the six project goals. A more complete list is found in Appendix C (Table 10-2 through Table 10-8).

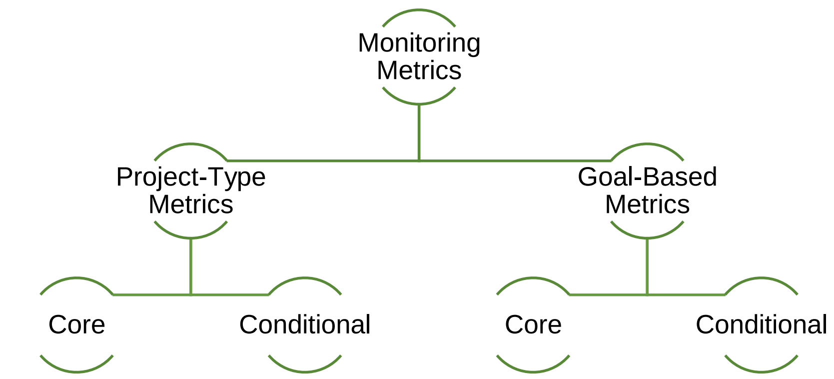


Figure 8-1. Hierarchy of metrics in the monitoring framework (adapted from Yepsen et al. 2016).

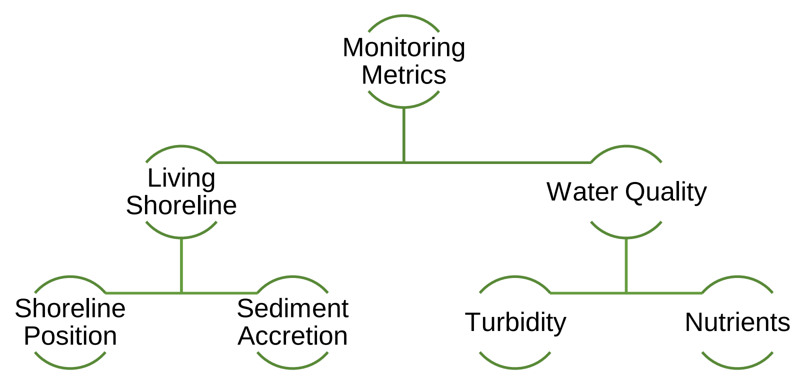


Figure 8-2. Example of monitoring metrics for a living shoreline used to improve water quality.

Select Appropriate Methods

> **Engage the Public in Monitoring**
> Coastal restoration projects are engaging the public in their monitoring activities by encouraging them to take photos of the site and email them to a point of contact or web service. Every person with a smartphone is a potential citizen scientist who can assist with your routine monitoring!

Monitoring methods represent the measurement techniques for a specific metric. Yepsen et al. (2016) suggest a range of methods, from simple to advanced, with the express goal of making performance monitoring accessible to all participants, and feasible for all projects. Many of the suggested methods are simple enough for volunteers and citizen scientists to perform. Yepsen et al. (2016) cite the value of citizen scientists at more than $20 per hour, resulting in significant cost savings and/or cost-share value. In a study published by Currin et al. (2008), volunteer data collection accounted for 223 out of 309 total worker-hours, which resulted in substantial cost savings and provided public engagement opportunities.

Transportation organizations will have in-house expertise and equipment for tackling some of the monitoring methods listed in Appendix C (Table 10-2 through Table 10-8). However, transportation professionals will require additional training and/or equipment for some of the methods. Overly complex monitoring methods may require outside help, which could come from local groups (e.g., NERRS, National Estuary Programs, coastal resource managers, local universities and their extension services).

Table 8-1. Representative sample metrics for different project goals

Goal	Sample Metrics
Erosion Control	Shoreline Position, Profile Volume, Intertidal Slope
Water Quality	Water Temperature, Salinity, Dissolved Oxygen
Habitat Enhancement	Vegetation Height, Density, Composition, Coverage, Species Biodiversity, Species Characteristics
Hydrologic Enhancement	Streamflow, Creek/Channel Morphology, Hydroperiod, Salinity
Socioeconomic Enhancement	Damages Avoided, Change in Property Value, Tourism, Fisheries Harvest
Transportation Resilience	Maintenance Cost and Frequency, Number of Flood Events, Number of Service Disruptions, Restoration/Recovery Time

One of the most important monitoring protocols is also the easiest and least expensive: visual inspection of the site. Routine and preventative maintenance is as simple as visiting the site and looking for signs of trouble or distress, removing trash, clearing large debris from the wrack line, looking for signs of damage from recreational use (foot paths), inspecting the bank, noting signs of excessive erosion (vertical scarp in the bank or shoreline), and many others. Other than a bit of time and possibly a camera, the level of effort and difficulty for routine site visits is low. Also, most smartphones now have high-resolution cameras that automatically geo-reference photos when a user enables location services on their phone.

Yepsen et al. (2016) provide helpful comments regarding “additional user considerations” as they relate to the recommended monitoring methods. In addition to technical expertise, other considerations include temporal requirements for monitoring, data collection effort and investment of time, the cost of monitoring, and special cases that require permitting. Additional review of this document would provide more detailed information.

Develop the Monitoring Plan

The monitoring plan documents and describes the process for measuring, assessing, and possibly tracking project performance over time. Yepsen et al. (2016) recommend implementation of the monitoring plan prior to construction. See the textbox for an example of a monitoring protocol called BACI (Before-After-Control-Impact) (Baggett et al. 2015; Yepsen et al. 2016). The plan should summarize the specific monitoring metrics and methods, experimental or data collection plans (e.g., data collection frequency, location, time of year), the specific roles and responsibilities of each person involved in implementation of the plan, the quality assurance and quality control plans, data archival and storage methods, and some indication as to how to summarize and report project performance on a continual basis. A monitoring plan of this scope is useful when developing a Quality Assurance Project Plan, which Federal agencies often require when funding projects. The monitoring plan should be able to address the questions posed in Figure 8-3.

Considerations for *BACI* Designs

A *BACI* monitoring protocol is one where monitoring is performed before and after restoration, at a control site, and at your impact site (Baggett et al. 2015; Yepsen et al. 2016). Select your control site so that it is close enough to your project/impact site to experience similar conditions and have similar baseline characteristics, but not so close that it will be affected by your project (positively or negatively). Shorelines immediately adjacent to your project will experience “end effects” that are known to bias the *BACI* comparisons. Furthermore, successful nature-based solutions are thought to have a “halo effect” where positive benefits extend some distance from the project itself.

Yepsen et al. (2016) recommend the following outline and structure for a monitoring plan:

- Project Overview
  - Describes the restoration project, design, location, partners, and goals.
- Monitoring Metrics
  - Identifies and describes monitoring metrics for the project.
  - Lists performance targets (interim and/or end targets).
- Monitoring Design
  - Describes the data collection plan in detail.
  - Identifies the frequency, location, and time (season) of measurement.
- Detailed Methods
  - Documents field and lab procedures completely.
  - Provides step-by-step documentation so that procedures are replicated.
- Data Management
  - Describes procedures to ensure and maintain data quality (QA/QC protocols).
  - Documents how and where data are stored.
- Data Analysis and Reporting
  - Describes how to use the data.
  - Documents the statistical analyses performed, equations used, and tests applied.
  - Identifies opportunities for sharing data synthesis with other professionals.
- References
  - Lists citations for specific methodologies, standards, protocols, and procedures.
- Appendix

– Used as appropriate for standardized field/lab sheets, project maps, sampling locations, and site conditions.

Figure 8-3. Questions that the monitoring plan should answer (adapted from Yepsen et al. 2016).

8.2 Maintenance Requirements

Maintenance requirements vary by project type and setting. Projects that are more exposed to wave energy or have higher recreational uses often require more maintenance. However, successful, high-functioning projects may only require preventative maintenance. Miller et al. (2015) note that the nature-based projects that sustained the least amount of damage overall during hurricanes Irene, Lee, and Sandy were those with routine monitoring and maintenance plans in place. Some comments regarding maintenance of specific nature-based solution components are provided below.

Living Reefs

Once established, there should be little maintenance required for living reef systems (Miller et al. 2015). Some restoration sites across the United States use stacked, bagged oyster shell as a substitute for stone in sills, toe revetments, and breakwaters. Experience has shown that the bags are susceptible to tearing/breakage, causing oyster shell to spill out. The failure of bags results in reduced crest elevation and/or a steepening of the structure side slopes. Also, loose oyster shell exposed to persistent wave action will degrade over time, resulting in very small shell fragments that easily escape their containment structures and containment bags, leading to unintended marine debris.

Beaches and Dunes

Beach nourishment projects will require periodic renourishment, depending on the rate of background erosion, as well as the frequency and magnitude of storm events. The use of structures in combination with beach nourishment greatly extends the life of the project and reduces renourishment requirements. Aside from renourishment activities, beaches require no routine maintenance. Like beaches, dunes may require maintenance and repair following a storm event. This would include repairing damage to a dune core (when present), reconstructing the dune, replacing dune vegetation, and repairing dune fencing (where present). Maintaining dune walkovers or dedicated footpaths is necessary for preserving dune and dune vegetation integrity.

Vegetation

Marsh vegetation may fail, or die off, for several reasons even when managed routinely. Some common problems are as follows:

- Vegetation planted too low or too high on the profile
- Ponding and poor drainage at low tide
- Rapid sediment accretion, which buries the marsh
- Too much wave energy or currents are too strong
- Too much upland runoff (poor stormwater BMPs)
- Disturbance from foot traffic and recreational uses

Therefore, vegetative components of nature-based solutions tend to require the most maintenance. Just like any plant, marsh vegetation requires adequate light, water, and nutrients to maintain its productivity. Table 8-2 lists actions recommended by Duhring (2016) as part of routine and preventative marsh maintenance.

Stone Structures

Stone structures, such as sills, breakwaters, and revetments, do not require much routine maintenance. Replacement of displaced or dislodged stones is a common form of maintenance following storm events. Adding more stones to the structure crest to maintain its design elevation can be a longer term maintenance requirement. Structure settlement and/or sea level rise may require this form of maintenance, which can be a form of adaptive management.

Table 8-2. Suggested actions for routine and preventative marsh maintenance

Action	Comment
Remove Excess Debris and Trash	Trash degrades marsh health and water quality over time and encourages foraging. Large debris in the wrack line will damage and dislodge vegetation.
Replace Plugs	Newly planted marsh plugs may wash out because of excessive upland runoff or too much wave action. Replant the plug by burying it deeply in the soil.
Prune Shade Trees	Overhanging branches may shade marsh vegetation and reduce sunlight availability. Regularly prune branches and shade trees adjacent to the marsh.
Remove Non-Native and Invasive Species	Frequently remove non-native, invasive, and nuisance species as often as you see them.
Do Not Mow!	This should be obvious, but do not mow your marsh!
Avoid Chemicals	Do not apply herbicides, pesticides, or other chemicals to your marsh. Be cautious in application to adjacent upland lawns and vegetation, and protect the marsh from runoff.
Discourage Foraging	Animals, such as geese, love to eat marsh grass! Discourage foraging whenever possible. Movement of survey tape, affixed to stakes or nearby trees, in the wind is an effective deterrent for geese and other species.

8.3 Maintenance Costs

Routine maintenance costs for well-designed and well-built nature-based solutions should be minimal but are unlikely to be zero. It is unfair to generally state that the maintenance costs of nature-based solutions are less than those of traditional approaches (Duhring 2006).

Comparison of Annual Maintenance Costs
According to Beavers et al. (2016), the annual maintenance cost for a constructed tidal marsh and stone sill is approximately $100 per foot. Stamski (2005) states that the annual maintenance cost of shoreline structures ranges from 2 percent to 15 percent of initial cost. Using the synthesized unit cost data in Table 2-4, the annual maintenance costs for shoreline structures may range from as low as $2 per foot (vinyl bulkhead, 2 percent) to as high as $300 per foot (seawall, 15 percent).

Maintenance costs and maintenance intervals vary by approach (e.g., structural, natural, nature-based, hybrid). A simple example below illustrates the concept of estimated maintenance costs for a nature-based solution and a structural feature (Beavers et al. 2016; Stamski 2005).

It is difficult to find accurate data and reports on maintenance costs for nature-based solutions. This is certainly a knowledge gap that needs to be filled through improved record keeping. Some specific values and ranges of maintenance costs are available in the literature, although they are often provided in qualitative terms (low, moderate, and high). Table 8-3 attempts to describe the annual maintenance costs and maintenance intervals, as well as replacement costs, for many of the features this guide describes. These subjective assessments are the result of synthesizing information and values given in Sutton-Grier et al. (2018), Faulkner (2010), Nichols and Brzozowski (2014), Beavers et al. (2016), Stamski (2005), and Miller et al. (2015)

Table 8-3. Comparison of maintenance cost, maintenance interval, and replacement cost for structural and nature-based features

Feature	Maintenance Cost	Maintenance Interval	Replacement Cost
Bulkhead/Seawall[1]	Low	Low	High
Revetment	Low	Low	Moderate
Breakwater	Low	Low	Low
Sill (stone)	Low	Low	Low
Vertical Sill (vinyl)	Low	Moderate	Moderate
Vertical Sill (timber)	Low	Moderate	High
Reefs	Low	Low	Low
Vegetation	Low	Moderate	Low
Beach Nourishment	High	Moderate	High
Coastal Bank[2]	Moderate	Moderate	Moderate
Hybrid Solutions	Moderate	Moderate	Moderate

[1] Maintenance interval assumes that the project adequately meets the design conditions. Replacement cost may vary from moderate for partial replacement to high for complete replacement.
[2] Refers to maintaining the bank slope and vegetation.

When executing a project, you should consider the entire life-cycle cost of resilience and mitigation measures. In doing so, the replacement cost of structural features tends to overwhelm those for nature-based solutions (Sutton-Grier et al. 2018). Successful nature-based solutions will be more self-sustaining over the long term, since the shared goal of all nature-based solutions is to restore and/or provide natural ecosystem functions. Projects used to restore natural functions face the same stresses that resulted in the degradation of the original feature. Yet, routine maintenance will help mitigate these “background” or pre-existing stresses. Projects used to provide natural function will experience both chronic stresses (e.g., lack of sediment supply, impact of adjacent projects, sea level rise) and acute impacts (e.g., coastal storms, floods, droughts, fires), and routine maintenance addresses these impacts on project performance.

8.4 Tracking Performance

Performance tracking and assessment represent opportunities to implement adaptive management practices if a project is under-performing. Tracking performance requires collecting monitoring data, generating maintenance reports, and synthesizing these sets of information in a manner that provides an assessment of performance relative to an expected goal or outcome. As mentioned previously, the goals of the project tend to fall into (broadly) one of the six categories: erosion, water quality, habitat, hydrologic, socioeconomic, and transportation. Each goal will have a quantitative measure related to performance. Some measures are defined by permitting or regulatory requirements. Stakeholders may define other measures of success. A final group of measures are the goals of the transportation organization. For example, consider this common regulatory requirement for tidal wetlands mitigation: achieve 80 percent wetland vegetative coverage by year 5. If vegetative coverage at the time of the first post-construction survey is 20 percent, then plant coverage must increase at least 12 percent per year (Year 1: 32%, Year 2: 44%, Year 3: 56%, Year 4: 68%, and Year 5: 80%). If the year 1 monitoring data show that coverage is 30%, then your coverage condition is behind schedule and you may consider some form of corrective action to increase coverage in the next growing season.

Project Assessment Example
As part of the Hurricane Sandy Mitigation and Resilience Program, the U.S. Department of Interior Metrics Expert Group (MEG) developed a set of recommendations for assessing project impacts on ecological systems and infrastructure resilience in the coastal Northeast region of the United States. That report DOI (2015) provides helpful information on resilience performance metrics, strategies for addressing long-term change, a framework for integrating environmental monitoring, an approach for linking ecological and socioeconomic conditions, and recommendations for post-assessment monitoring.

Performance monitoring data are only useful if they are used! One way to ensure that they are useful is to assess each performance goal on an annual basis, even for goals that do not have annual or interim targets. Synthesize monitoring measurements into simple tables and/or explanatory figures. It is helpful to show parameter values from each monitoring phase (pre-construction, as-built, and performance period) to compare trends to interim and end target goals. Figure 8-4 shows one such example for an assessment of restored *Spartina alterniflora* at three sites (DUML, NCMM, PKS) by Currin et al. (2008). The figure clearly shows the trends in mean percentage plant coverage over time at each site, the difference between the natural (control) marsh and restored (impact) marsh at each site, and the standard error for each measurement.

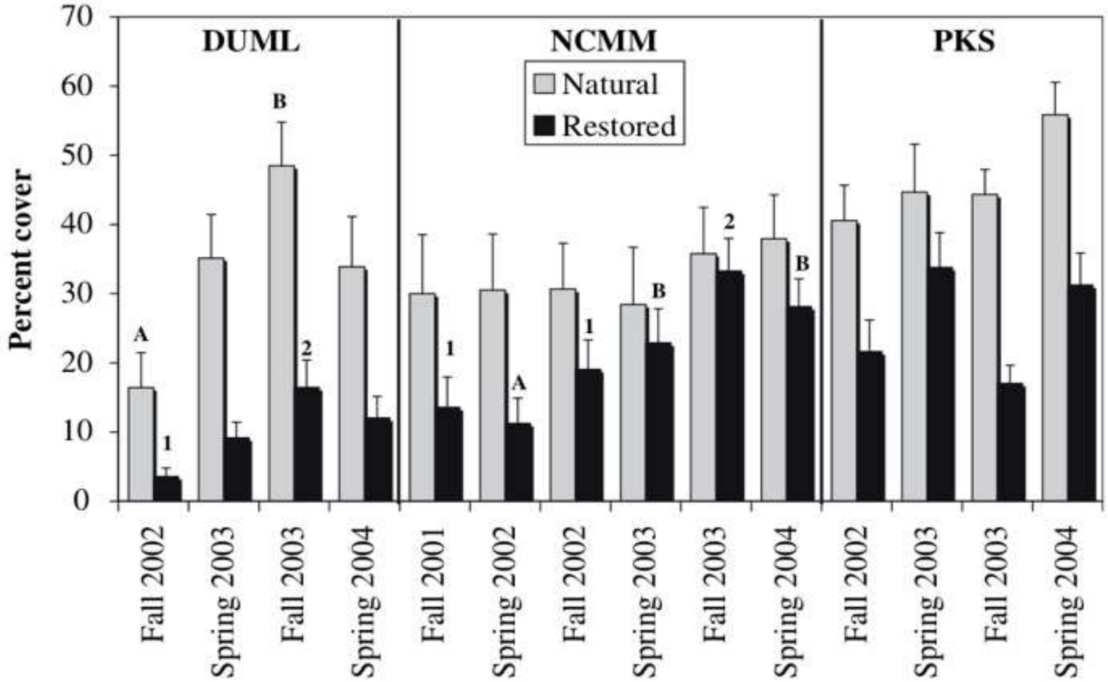


Figure 8-4. Mean percentage of cover (columns) and standard error (error bars) of restored and natural Spartina alterniflora at three different sites (Currin et al. 2018).

8.5 Making Adjustments

When monitoring data or observations indicate signs of trouble, try to take corrective actions as quickly as possible. Making small adjustments, through adaptive management, can aid in achieving interim and end target goals. Adaptive management acknowledges the uncertainty of natural and nature-based systems; it integrates monitoring and evaluation into an iterative decision-making process for management of the project. Incorporate results from the monitoring plan and program into subsequent planning activities to support adaptive management as a mechanism to consistently evaluate and refine plans (NRC 2007). Also, consider forward-looking adaptive management needs and opportunities. For example, will combining a structural feature with a nature-based solution provide the infrastructure resilience needed for a longer period? Or perhaps decrease the sensitivity of the infrastructure to uncertainty at future sea levels or storm frequency and magnitude? An example of proactive adaptive management is provided below.

The vegetative components of nature-based solutions are often prime candidates for adaptive management (Whalen et al. 2011), especially newly planted or distressed plants. For example, a storm event shortly following construction may remove newly planted marsh plugs and sediment from the project. Adding fill to re-establish the slope and repair low spots, and supplementing with new plugs, is the suggested form of corrective action. On the other hand, storms, strong currents, and upland runoff can deposit too much sediment that smothers marsh plants. According to Whalen et al. (2011), the subsequent change in slope and/or elevation can alter vegetative communities and sometimes facilitate the invasion of unwanted species, such as *Phragmites*. In that case, you may need to regrade the slope to ensure that a majority of the marsh area is below the MHW tidal datum; this discourages, but does not prevent, many nuisance plant species.

Structural components of nature-based solutions do not typically require routine maintenance, but they may require adaptive management. It may be necessary to modify the structure's design when it is not providing the expected benefits, or if it is having unintended consequences. Duhring (2016) notes that some restored tidal marshes fail because of excessively long periods of inundation associated with inadequate drainage and tidal flushing. Continuous structural enhancements that stabilize the marsh edge, such as sills, toe revetments, and edging material, have the potential to prevent drainage from the tidal marsh during the falling tide. Corrective actions, in this case, include modifying the features to promote better flushing and drainage, which may require removal or lowering of their crest elevation.

Proactive Management

When considering how sea level rise and changes in temperature and precipitation patterns may affect coastal highway vulnerability over different timeframes, one may also need to consider similar changes in the performance, resilience, or reliability of natural features that have historically mitigated damage. For example, at what future time will an existing marsh that protects a roadway no longer be viable because of sea level rise? Answering this question provides an opportunity to support and accommodate the existing marsh for a period of time, after which alternative methods for preventing erosion and flooding will be required. Identifying so-called "tipping points" is one way to identify such opportunities.

A tipping point is defined here as a point in space, or in time, beyond which some alternative approach is required. Consider a marsh in front of a causeway. Assuming that the causeway is fixed in space with a set elevation that cannot be changed, sea level rise will impede migration of the marsh. Over time, the marsh will drown in place. At a specific elevation, the marsh will no longer provide protection for the causeway, and the road will experience flooding—first from wave runup and overtopping during storms because of the lack of wave attenuation by the marsh, then possibly during very high astronomical tides, and sometime later under daily high tides. That specific elevation is the tipping point and it may occur at different times in the future under various sea level rise projections. Implementation of a structural (e.g., roadway modification) or policy solution, before reaching that tipping point, could address the roadway's increasing vulnerability to flooding.

The "Living Shoreline Along Coastal Roadways Exposed to Sea Level Rise" case study provides an example of a tipping point analysis for a coastal roadway along Mount Sinai Harbor on Long Island, NY (FHWA 2016b). The study describes when, and potentially how, the use of structural and long-term management options can enhance the nature-based resilience provisions of a constructed tidal marsh. The roadway's existing elevation (+6 feet NAVD88) will prevent daily, high-tide flooding until 2065 under a higher sea level rise scenario (Figure 8-5). The road does experience flooding now under minor, but frequent, storm events (e.g., 1-year and 2-year return periods). Frequent wave-induced flooding (i.e., wave overtopping) may occur as early as 2025 without intervention. The proposed intertidal marsh with toe protection, represented in cross-section in Figure 8-6 and planform in Figure 8-7, delays the onset of wave-induced flooding by about 40 years, at which time the road experiences the daily flooding mentioned earlier. Prior to reaching those tipping points of elevation (+6 feet NAVD88 and/or 2065), implementation of a structural feature or strategy will similarly delay the onset of daily flooding. Potential solutions include raising the roadway elevation or adding a parapet wall along the edge of the pavement. Increasing either elevation by +1 foot or +2 feet delays the onset of daily flooding to 2080 and 2095, respectively.

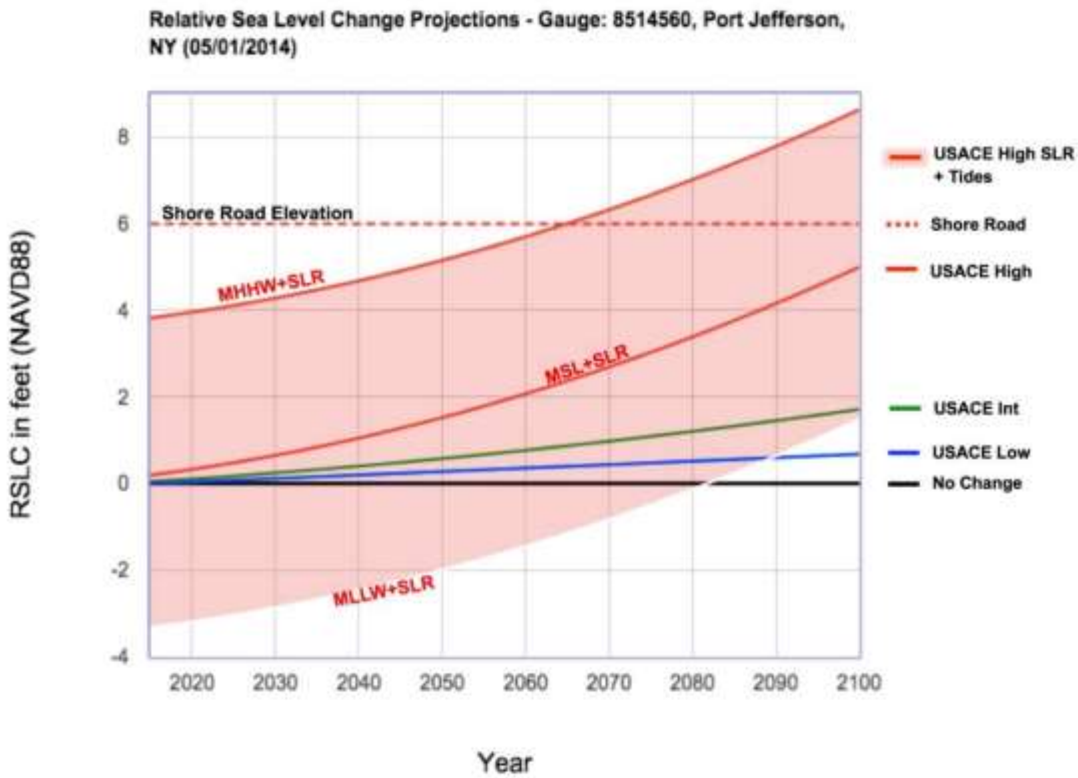


Figure 8-5. Relative sea level projections for three scenarios from 2015 to 2100 (FHWA 2016b).

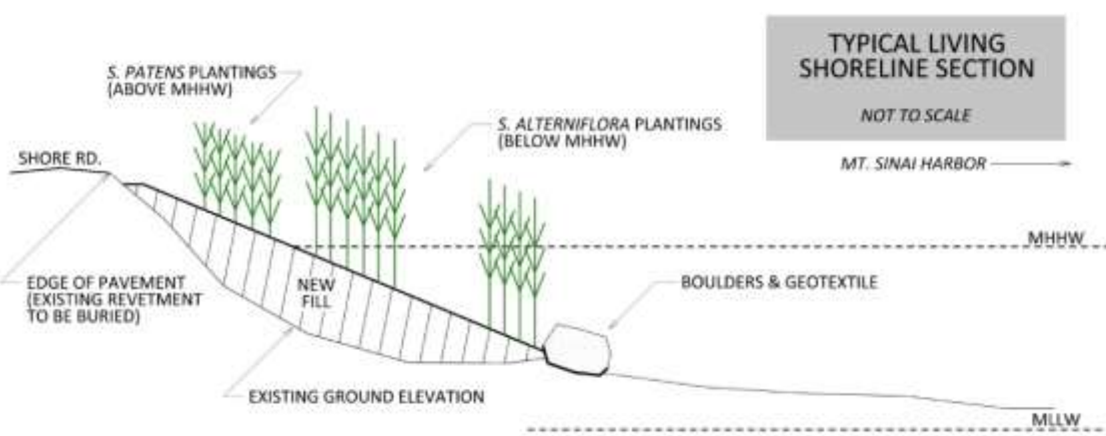


Figure 8-6. Conceptual cross-section diagram of a constructed intertidal marsh with segmented toe protection boulders (FHWA 2016b).

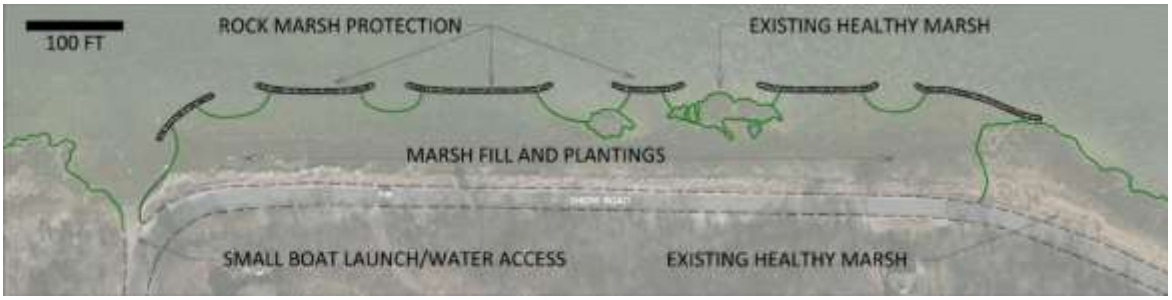


Figure 8-7. Conceptual planform diagram of a constructed marsh with segmented toe protection for shore road (FHWA 2016b).

9. CONCLUSIONS

Nature-based solutions can play an important role within a systems-based approach to mitigating extreme weather risks for highways in the coastal environment. Either independently or when used in combination with policy measures and/or structural features, nature-based solutions simultaneously provide risk-reduction, ecological, water quality, and recreational benefits to transportation agencies and the broader community.

Incorporating nature-based solutions into coastal highway planning and design can increase resilience to a broad spectrum of coastal hazards that are known to disrupt or damage transportation infrastructure. Examples highlighted in this document include storm flooding, wave damage, erosion, and shoreline retreat. Many of the over 60,000 miles of coastal highways in the United States are exposed to and occasionally experience these types of hazards. The vulnerability of these coastal highway miles may increase over time with future sea level rise. By embracing the dynamic design of nature-based solutions, their adaptive capacity can serve to mitigate some of these hazards in a manner that can be self-sustaining if properly designed.

Transportation organizations will not always be able to implement nature-based solutions on their own. To overcome this obstacle, transportation organizations need to develop partnerships with other Federal and State agencies, as well as NGOs, who plan, fund, design, and implement nature-based solutions. Through collaboration and cooperation, these partnerships can lead to the development of agreements and an appropriate accounting of benefits that broaden funding sources and improve the likelihood of implementation. Partnerships also enable larger, landscape scale nature-based solutions, including areas outside of highway right-of-way. Larger scale solutions can provide higher levels of protection. Given that many transportation organizations lack the in-house expertise to design nature-based solutions, these partnerships play a crucial role in identifying the appropriate subject matter experts for implementing these projects.

This guide describes some common nature-based solutions and provided a few design examples with unique characteristics from different regions of the United States. While each of these solutions is somewhat unique, they all seek to address the site-specific conditions and project-specific needs while mimicking the local coastal ecology and geology. Do not misinterpret the examples in this guide as the “only” nature-based solutions. It is important to develop a somewhat broad interpretation of that terminology so that possible project alternatives are not overly constrained. Working with the local, State, university, NGO, and Federal partners can help frame the suite of nature-based solutions and identify additional implementation guidance that is most appropriate for your region.

10. APPENDICES

APPENDIX A: Site Characterization Resources

Section 4.1 describes the key site characterization parameters to consider at the desktop analysis and extended analysis or site visit phases of a nature-based project. Table 10-1 provides a list of tools and other resources to assist in gathering the information needed to describe each of those parameters.

Table 10-1. Tools and resources for site characterization

Parameter Name		Site Characterization Tools & Resources	
		Desktop Analysis	Extended Analysis
System	Shoreline Type	Historical aerial imagery, online image servers/software (e.g., Google Earth™[1])	Site visit, review of historical maps
System	Infrastructure	GIS, transportation inventory data, National Bridge Inventory	Site visit, maintenance and repair records, design details
System	Erosion Rate	Historical aerial imagery, shoreline positions, LiDAR data, NOAA Digital Coast https://coast.noaa.gov/digitalcoast/	Site visit, conduct interviews, consult historical maps and charts
System	Sea Level Rise	Evaluate historical values: https://tidesandcurrents.noaa.gov/sltrends/sltrends.html Consider future scenarios: http://corpsmapu.usace.army.mil/rccinfo/slc/slcc_calc.html https://coast.noaa.gov/digitalcoast/tools/flood-exposure.html https://coast.noaa.gov/slr/#/layer/slr	
System	Tide Range	Nearby tide station (https://tidesandcurrents.noaa.gov), NOAA VDatum tool (https://vdatum.noaa.gov/)	Measure at site; numerical modeling of tides in project area
Hydrodynamic	Wind Waves (Fetch)	Use parametric wind-wave equations in USACE (2002) and/or FHWA (2008). Use the CHS database (USACE 2019d).	Collect wave measurements at the site. Perform numerical modeling of waves.
Hydrodynamic	Boat Wakes	Unreliable. Assume a depth-limited wave height for conceptual design (FHWA 2008).	Collect wake measurements at site.
Hydrodynamic	Currents	Limited. Use operational forecast model data, near real-time measurements, or the CHS database (USACE, 2019b). https://tidesandcurrents.noaa.gov/forecast_info.html, https://ioos.noaa.gov/	Collect measurements at site. Perform numerical modeling of tidal currents.
Hydrodynamic	Ice	Limited. Evaluate online resources. https://www.natice.noaa.gov/index.html, https://icejam.sec.usace.army.mil	Measure typical ice thickness and assess coverage and persistence at site.

Parameter Name		Site Characterization Tools & Resources	
		Desktop Analysis	**Extended Analysis**
	Storm Surge	Review return period surge elevations in latest FEMA Flood Insurance Study report. Consult online resources from NOAA (2018), USACE (2019d).	Numerical modeling of storm surge and/or wave runup and overtopping, as appropriate. See FHWA (2014), Webb (2017).
Terrestrial	Upland Slope (V:H)	Use LiDAR data, digital elevation models, existing site survey data, etc. Search NOAA Digital Coast for elevation data. https://coast.noaa.gov/digitalcoast/	Perform traditional site survey using rod and level, total station, or GPS.
Terrestrial	Shoreline Slope	Same as for upland slope. Be cautious regarding data limitations, especially in regions with large tide ranges.	Perform wading survey using appropriate methods.
Terrestrial	Width	Imagery, maps, GIS tools, and/or tools such as Google Earth™	Measure at site. Large areas may require a boat or vessel, total station, GPS, and/or depth measurement capabilities.
Terrestrial	Nearshore Slope	Use existing digital elevation models and/or bathymetric datasets, where available. Approximate from nautical charts if digital data are unavailable. https://coast.noaa.gov/digitalcoast/, https://charts.noaa.gov/ChartCatalog/MapSelect.html	Perform a bathymetric survey using a vessel and appropriate depth-sounding instruments and a GPS for positioning.
Terrestrial	Water Depth	Same as for nearshore slope.	Same as for nearshore slope.
Terrestrial	Soil Strength	Limited. Search for soil maps, boring logs, sediment analyses, sand characterization data, dredge records, etc.	Collect measurements at the site. Obtain sediment cores (borings) for laboratory testing. Perform cone penetrometer or vane shear stress test in the field.
Ecological	Water Quality	Online resources, including NOAA, USGS, and State agencies responsible for water quality. https://tidesandcurrents.noaa.gov/met_info.html https://ioos.noaa.gov/	Collect measurements at the site using handheld devices or collect samples for laboratory testing.
Ecological	Soil Type	Same as soil strength.	Collect measurements at the site and send to laboratory for evaluation and granulometric analysis.
Ecological	Sunlight Exposure	Limited. Consider using historical aerial imagery, online image services, or tools such as Google Earth™ or https://www.suncalc.org	Conduct site visit during spring, summer, or fall when vegetation is mature. Assess exposure conditions and plant conditions.
Ecological	Salinity	Same as for water quality.	Same as for water quality.

[1] Be cautious when using aerial imagery to assess shoreline position or rates of erosion. The time of year (season) and the tide stage greatly affect interpretation of shoreline position.

APPENDIX B: NATURE-BASED SOLUTION DECISION TREES

APPENDIX B: Nature-Based Solution Decision Trees

Figure 10-1–Figure 10-4 are suggested decision trees for determining possible resilience strategies for coastal highways exposed to flood, erosion, and/or wave hazards. These decision trees include policy, nature-based, and structural approaches. The decision trees lead to an approach based on site constraints and vulnerability. For nature-based solutions, an appropriate strategy will also depend on the hazard and site characteristics. These decision trees are adaptable to various regions or problems by altering the recommendations in the white boxes.

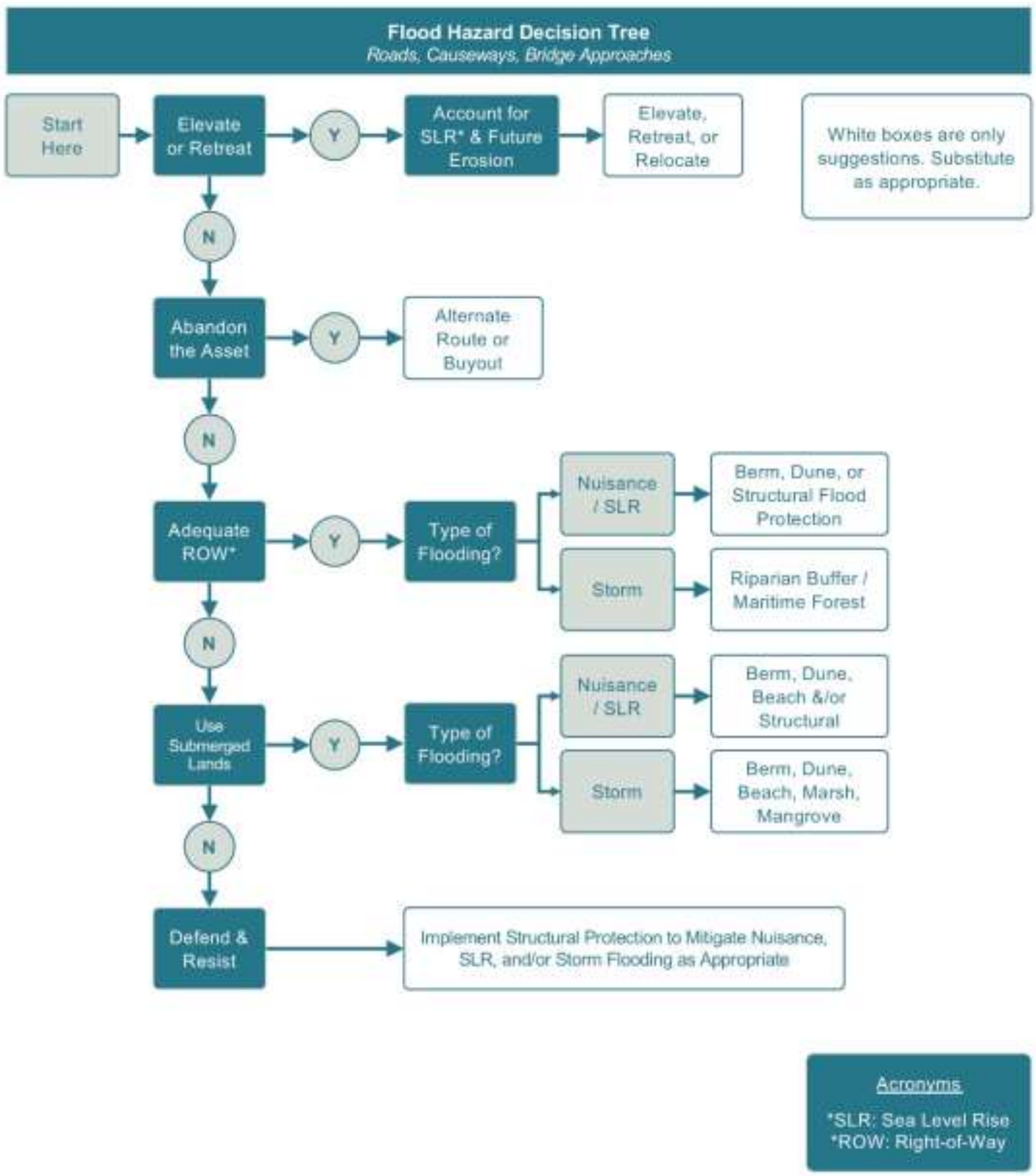


Figure 10-1. Flood hazard decision tree for roads, causeways, and bridge approaches.

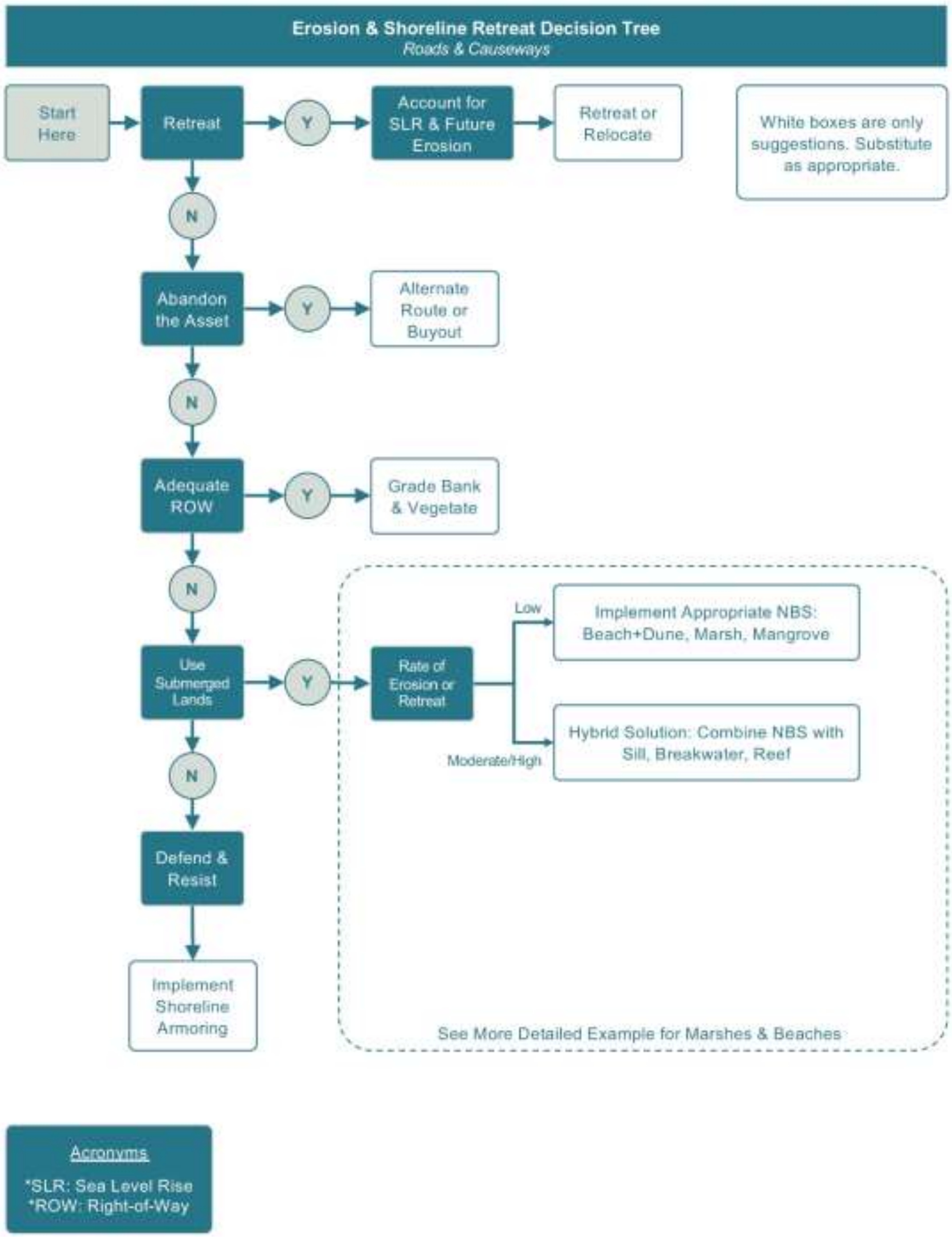


Figure 10-2. Erosion and shoreline retreat decision tree for roadways and causeways.

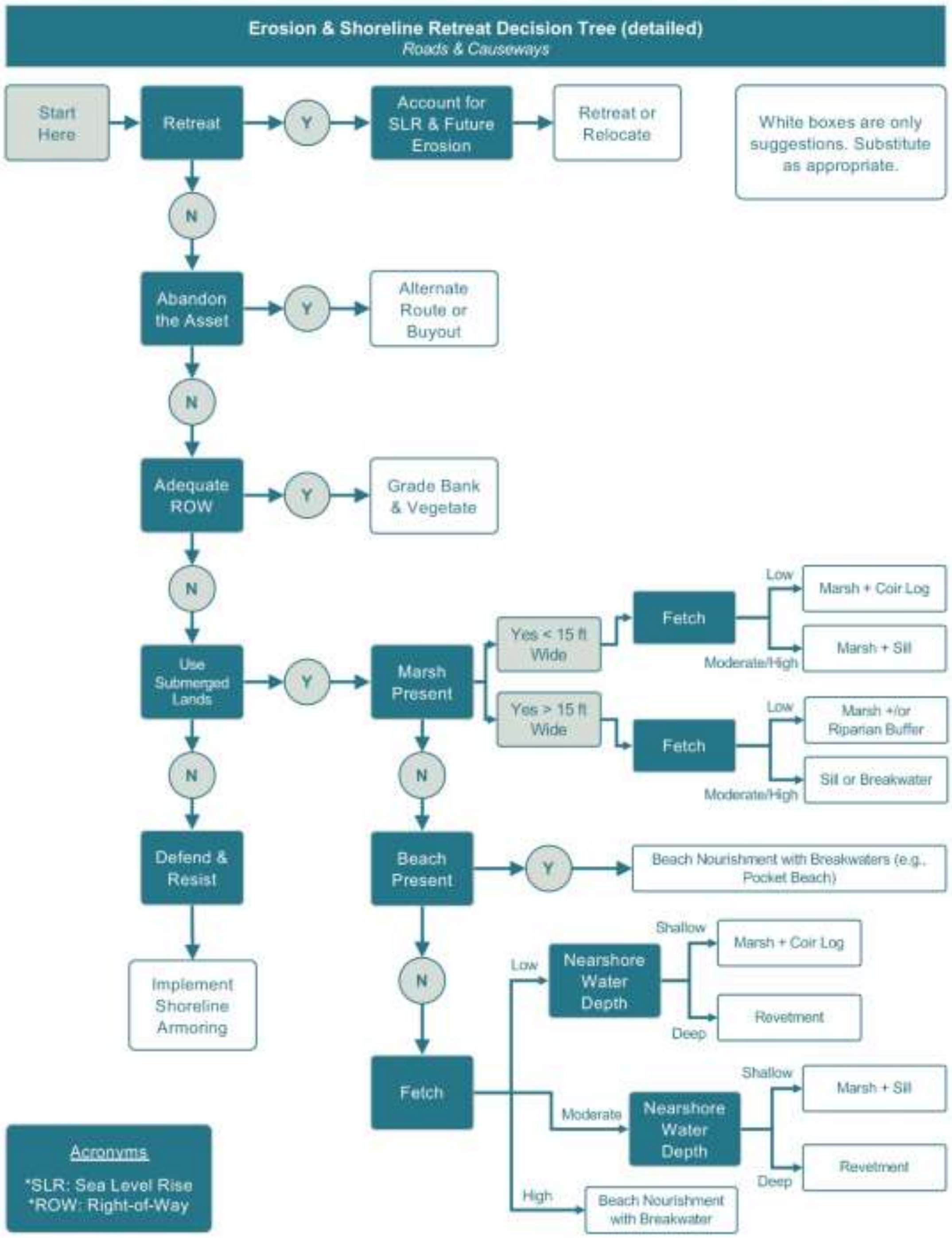


Figure 10-3. Detailed erosion and shoreline retreat decision tree for roads and causeways.

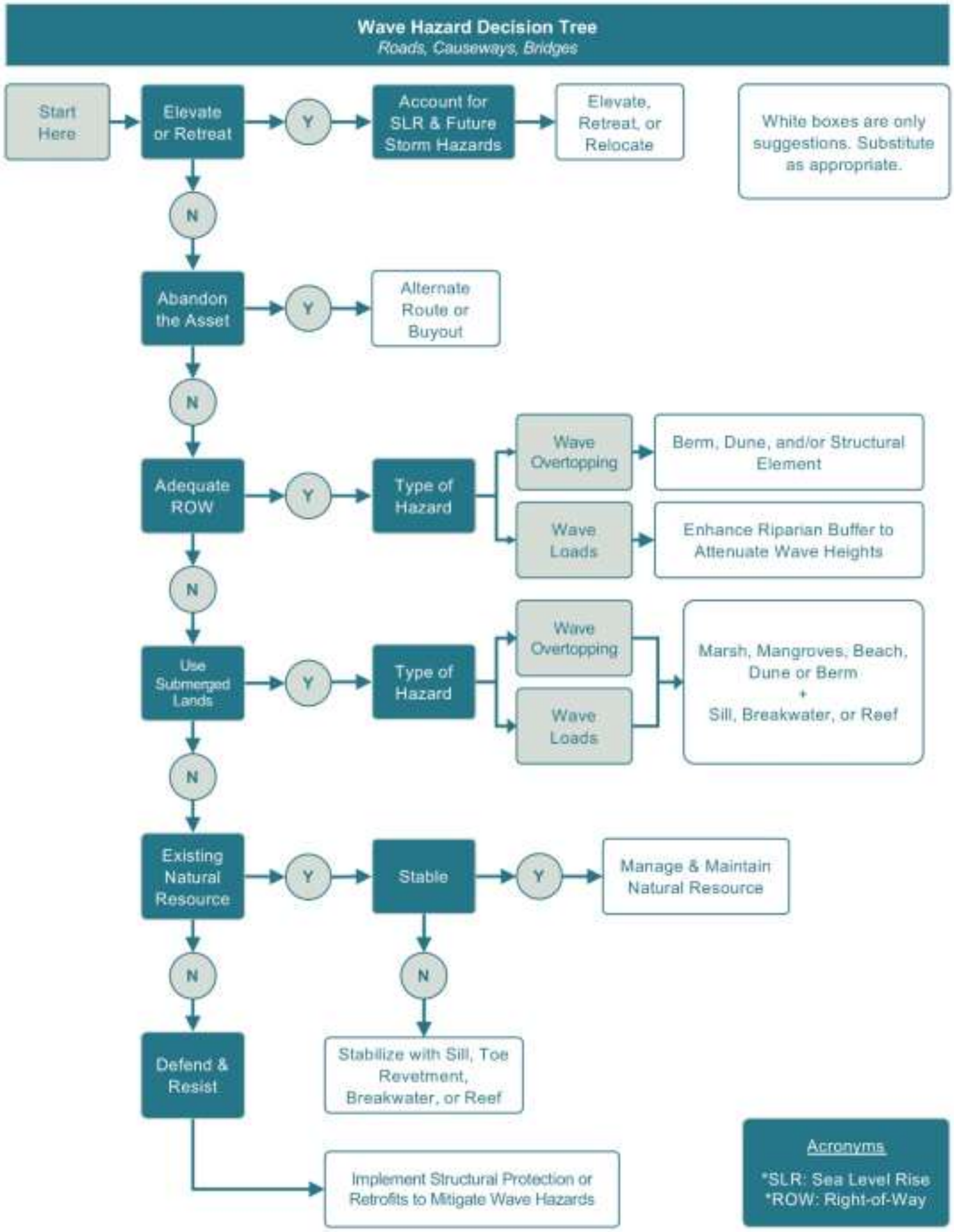


Figure 10-4. Wave hazard decision tree for roads, causeways, and bridges.

APPENDIX C: Performance Metrics for Monitoring

This appendix provides tables of potential monitoring performance metrics, as developed by Yepsen et al. (2016).

Table 10-2. Project-type metrics for a living shoreline

Class	Metric categories	Method options	Additional user considerations
Core	Position of living shoreline structure AND Lateral Position of Shoreline (i.e., horizontal change, erosion)	RTK GPS (m/y)	Technical expertise; cost/expense; specialized equipment
		Aerial photograph (m/y)	Technical expertise; temporal requirements; cost/expense; specialized equipment
		Surveying Instrument (barcode leveling)	Technical expertise; cost/expense; specialized equipment
		Distance from installed post or perm structure	Suited for all user groups
		LiDAR	Technical expertise; cost/expense; specialized equipment
	Vegetation Structure	Horizontal vegetative obstruction	Temporal requirements; specialized equipment
		Vertical light attenuation	Temporal requirements; specialized equipment
		Cover per m^2	Suited for all user groups; temporal requirements
		Number of stems per m^2	Temporal requirements; collection time investment
	Structural integrity of materials (e.g. how well is the breakwater holding together)	Observation	Suited for all user groups
		Photograph (fixed point)	Suited for all user groups
Conditional	Sediment capture/ accretion	Sedimentation disc/tile/plate/ marker horizon	Cost/expense (for some methods); temporal requirements; specialized equipment (for some methods)
		Measuring stick	Suited for all user groups
	Wave energy or height and amplitude (wind/wake)	Gauges and Buoys (e.g., Acoustic Doppler Current Profilers)	Technical expertise; cost/expense; collection time investment; specialized equipment
		Water level loggers	Technical expertise; cost/expense; temporal requirements; specialized equipment
		Graduated rod	Temporal requirement; collection time investment

		Plaster or gypsum ball/ clod card dissolution	Technical expertise; temporal requirements; collection time investment; specialized equipment
	Vegetation Productivity	Biomass (above and/or belowground)	Technical expertise; temporal requirements; collection time investment; cost/expense; specialized equipment
	Vegetation Community Composition	List of species found at site	Suited for all user groups; temporal requirements
	Nuisance species	Cover per m2, Stem counts per m2, or presence/absence	Suited for all user groups; temporal requirements
		Observation of grazing or other disturbance	Suited for all user groups
	Debris	Observation	Suited for all user groups
	Target species (e.g. Oysters…)	See habitat/ biodiversity goal table	
	Elevation (i.e. Vertical change): of the shoreline	RTK GPS (m/y)	Technical expertise; cost/expense; specialized equipment
		Lidar	Technical expertise; cost/expense; specialized equipment
		Laser level height relative to position on permanent post or other structure	Cost/expense; specialized equipment
		Thermal imaging	Technical expertise; temporal requirements; collection time investment; cost/expense; specialized equipment
		Surveying Instrument (barcode leveling)	Technical expertise; cost/expense; specialized equipment
	Foreshore slope	RTK GPS (m/y)	Technical expertise; cost/expense; specialized equipment
		Lidar	Technical expertise; cost/expense; specialized equipment
		Laser level height relative to position on permanent post or other structure	Cost/expense; specialized equipment
		Thermal imaging	Technical expertise; temporal requirements; collection time investment; cost/expense; specialized equipment
		Surveying Instrument (barcode leveling)	Technical expertise; cost/expense; specialized equipment
	Planted species (e.g. Mussels or vegetation)	Percent survival (of all if small area or quadrat samples if large area)	Suited for all user groups

Socioeconomic	Difference in cost between hardened structure and a living shoreline ($)	Data collection method: Project budgets and existing data sources; Analysis method: substitute cost method	Technical expertise and specialized software needed. *If using a BACI design*, may require a large collection time investment (need to wait several years to have enough weather events to compare changes in damage per storm over time).
	Cost-effectiveness of structure for shoreline stabilization (rate of erosion reduction per unit cost)	Data collection method: Project budgets; Analysis method: Cost effectiveness analysis	Technical expertise and specialized software needed. *If using a BACI design*, may require a large collection time investment (need to wait several years to have enough weather events to compare changes in damage per storm over time).
	Number of homes or structures benefitting (#)	Data collection methods: visual assessment or GIS analysis	Some technical expertise needed; may require additional collection time.
	Public awareness of living shorelines	Data collection methods: Surveys; focus group meetings; Analysis methods: NA	Note that the value placed on individual experience represents the *social value* of the visitor experience, or the value *beyond* the actual amount spent. Some technical expertise needed; may require additional collection time.

Table 10-3. Project-type metrics for tidal wetlands restoration

Class	Metric categories	Method options	Additional user considerations
Core	Elevation	RTK GPS	Technical expertise; cost/expense; specialized equipment
		Surface elevation table	Technical expertise; temporal requirements; collection time investment; cost/expense; specialized equipment
		Surveying Instrument (barcode leveling)	Technical expertise; cost/expense; specialized equipment
		Lidar	Technical expertise; cost/expense; specialized equipment
		Laser level height relative to position on permanent post or other structure	Suited for all user groups
	Vegetation structure	Horizontal vegetative obstruction	Temporal requirements; specialized equipment
		Vertical light attenuation	Temporal requirements; specialized equipment
		Cover per m^2	Suited for all user groups; Temporal Requirements
		Stem heights	Collection time investment; temporal requirements
		Number of stems per m^2	Collection time investment; temporal requirements
		Habitat Type %, 50m Radius (e.g., High marsh, low marsh, invasives, pannes and pools etc.)	Collection time investment; temporal requirements
	Vegetation community composition and diversity	List of species (plants)	Suited for all user groups, Temporal Requirements
Conditional	Hydroperiod (i.e. Flood duration)	Water level loggers	Technical expertise; cost/expense; temporal requirements; specialized equipment
	Vegetation productivity	Biomass (above and/ or belowground)	Technical expertise; temporal requirements; collection time investment; cost/expense; specialized equipment
		Photograph (fixed point)	Suited for all user groups; Temporal Requirements
		Plant tissue nutrient analysis (C/N)	Technical expertise; temporal requirements; collection time investment; cost/expense; specialized equipment
	Vegetation productivity (cont.)	LANDSAT/infrared imagery	Technical expertise; temporal requirements; collection time investment; cost/expense; specialized equipment
		Number of stems per m^2 and stem height of dominant species	Suited for all user groups; Temporal Requirements; Collection Time Investment

	Sediment capture (e.g. Capture, accretion)	Sedimentation disc/tile/ feldspar marker horizon	Cost/Expense (for some methods); Temporal Requirements; Specialized Equipment (for some methods)
		Measuring stick	Suited for all user groups
	Sediment supply (e.g. TSS)	Filtration	Technical expertise; cost/expense; temporal requirements; specialized equipment
		Turbidity meter	Cost/expense; specialized equipment
		Secchi disc	Suited for all user groups
	Erosion rate/ shoreline position	RTK GPS (m/y)	Technical expertise; cost/expense; specialized equipment
		Aerial photograph (m/y)	Technical expertise; temporal requirements; cost/expense; specialized equipment
		Surveying Instrument (barcode leveling)	Technical expertise; cost/expense; specialized equipment
		Distance from installed post or permanent structure to shoreline (m/y)	Suited for all user groups
		Lidar	Technical expertise; cost/expense; specialized equipment
		Aerial photographs (GIS analysis)	Technical expertise; temporal requirements; cost/expense; specialized equipment
	Foreshore slope	RTK GPS (m/y)	Technical expertise; cost/expense; specialized equipment
		Lidar	Technical expertise; cost/expense; specialized equipment
		Laser level height relative to position on permanent post or other structure	Cost/expense; specialized equipment
		Filtration	Technical expertise; temporal requirements; collection time investment; cost/expense; specialized equipment
		Surveying Instrument (barcode leveling)	Technical expertise; cost/expense; specialized equipment
	Drainage density/ position	Aerial photographs (GIS analysis)	Technical expertise; temporal requirements; cost/expense; specialized equipment
		RTK GPS	Technical expertise; cost/expense; specialized equipment
	Survival of planted species	Percent survival (all if small area or quadrat samples if large area)	Suited for all user groups
	Nuisance species (e.g. Invasives, herbivory)	Cover per m^2, number of stems per m^2, or presence/absence	Suited for all user groups; Temporal Requirements

		Observation of grazing and other disturbance	Suited for all user groups; Temporal Requirements
	Debris	Observation	Suited for all user groups
	Target habitat: salinity	Refractometer	Specialized equipment
		Meter (total dissolved solids)	Cost/expense/ specialized equipment
Socioeconomic	Damage costs avoided to surrounding homes ($)	Data collection method: Surveys; existing data sources; Analysis method: Avoided cost method; HAZUS modeling or other modeling that simulates changes in flood levels	Technical expertise and specialized software needed. If using a BACI design, may require a large collection time investment (need to wait several years to have enough weather events to compare changes in damage per storm over time).
	Damage costs avoided to surrounding structures, roads or other public infrastructure ($)	Data collection method: Surveys; existing data sources; Analysis method: Avoided cost method; HAZUS modeling or other modeling that simulates changes in flood levels	Technical expertise and specialized software needed. If using a BACI design, may require a large collection time investment (need to wait several years to have enough weather events to compare changes in damage per storm over time).
	Spending by birders ($)	Data collection methods: surveys; existing data sources; Data analysis methods: Economic impact assessment	Some technical expertise needed; may require additional collection time.
	Value of visitors place on the improved water quality (boaters, anglers, beach visitors, etc.) ($)	Data collection methods: surveys; existing data sources; Data analysis methods: Contingent valuation or choice experiment	Note that the value placed on individual experience represents the social value of the visitor experience, or the value beyond the actual amount spent. Some technical expertise needed; may require additional collection time.

Table 10-4. Goal-based metrics for erosion control

Class	Metric categories	Method options	Additional User Considerations
Core	Lateral position or shoreline or Erosion (i.e., horizontal change) of the shoreline (m/year)	RTK GPS	Technical expertise; cost/expense; specialized equipment
		Aerial photograph	Technical expertise; cost/expense; specialized equipment
		Lidar	Technical expertise; cost/expense; specialized equipment
		Surveying Instrument (barcode leveling)	Technical expertise; cost/expense; specialized equipment
		Distance from permanent post of other structure to shoreline	Suited for all user groups
	Elevation of shoreline (m/year)	Rtk gps	Technical expertise; cost/expense; specialized equipment
		Lidar	Technical expertise; cost/expense; specialized equipment
		Surveying Instrument (barcode leveling)	Technical expertise; cost/expense; specialized equipment
		Laser level height relative to position on permanent post or other structure	Cost/expense; specialized equipment
	Foreshore slope	Rtk gps	Technical expertise; cost/expense; specialized equipment
		Lidar	Technical expertise; cost/expense; specialized equipment
		Laser level height relative to position on permanent post or other structure	Cost/expense; specialized equipment
		Thermal imaging	Technical expertise; temporal requirements; collection time investment; cost/expense; specialized equipment
		Surveying Instrument (barcode leveling)	Technical expertise; cost/expense; specialized equipment
Conditional	Accretion (m/year)	Sedimentation disc/tile/plate/ marker horizon	Cost/Expense (for some methods); temporal requirements; specialized equipment (for some methods)
		Measuring stick	Suited for all user groups
	Wave energy or height and amplitude (wind/wake)	Gauges and buoys (e.g., acoustic doppler current profilers for wave energy and stream/ creek flow)	Technical expertise; cost/expense; collection time investment; specialized equipment
		Water level loggers	Technical expertise; cost/expense; temporal requirements;

			specialized equipment
		Graduated survey rod	Temporal requirement; collection time investment
		Plaster or gypsum ball/ clod card dissolution	Technical expertise; temporal requirements; collection time investment; specialized equipment
	Vegetation Structure	Horizontal vegetative obstruction	Temporal requirements; specialized equipment
		Vertical light attenuation	Temporal Requirements; Specialized Equipment
		Cover per m^2	Suited for all user groups; Temporal Requirements
		Number of stems per m^2	Temporal Requirements; Collection Time Investment
	Vegetation Productivity	Biomass (above and/ or belowground)	Technical Expertise; Temporal Requirements; Collection Time Investment; Cost/Expense; Specialized Equipment
Socioeconomic	Change in property value because of reduction in rate of erosion ($)	Data collection method: Existing data sources; Analysis method: Hedonic valuation	Technical expertise needed.
	Difference in cost between hardened structure (e.g. bulkhead) and a living shoreline ($)	Data collection method: Project budgets and existing data sources; Analysis method: substitute cost method	Little technical expertise required; this method is suited for most user groups.
	Number of homes or structures benefitting (#)	Data collection methods: visual assessment or GIS analysis; Analysis method: NA	Suited for all user groups. Note that this metric only shows number, not the magnitude of the benefit.

Table 10-5. Goal-based metrics for habitat enhancement

Class	Metric categories	Method options	Additional user considerations
Core	Vegetation community composition and diversity	List species found at site (plants)	Suited for all user groups; temporal requirements
	Vegetation Structure	Horizontal light obstruction	Temporal requirements; specialized equipment
		Vertical light attenuation	Temporal requirements; specialized equipment
		Cover per m2 (for each plant species or total cover by plant species)	Suited for all user groups; temporal requirements
		Stem heights of dominant species	Temporal requirements; collection time investment
		Number of stems per m2	Temporal requirements; collection time investment
		Habitat Type %, 50m Radius (e.g., High marsh, low marsh, invasives, pannes and pools etc.)	Temporal requirements; collection time investment
		Photographs (fixed point)	Suited for all user groups; temporal requirements
Conditional	Target species for restoration (e.g. black duck or oysters) or biodiversity	Observations (e.g., horseshoe crabs, terrapins)	Suited for all user groups; temporal requirements
		Biomass (wet weight or dry weight/ m2) (e.g., plants, nekton, mussels)	Technical expertise; temporal requirements; collection time investment; cost/expense; specialized equipment; permitting requirements
		Cover per m2 or # per m2 (e.g., percent cover of SAV, # of fiddler crab boroughs, # of fish in a sample, Ribbed mussel lip counts)	Suited for all user groups; temporal requirements
	Target species for restoration (e.g. black duck or oysters) or biodiversity (cont.)	Morphometric (e.g., length of nekton or oysters)	Technical expertise; temporal requirements; collection time investment; cost/expense; specialized equipment; permitting requirements
		Health (e.g., condition index, of bivalves)	Technical expertise; temporal requirements; collection time investment; cost/expense; specialized equipment; permitting requirements
		List of species found at site (e.g., nekton or benthic infauna)	Suited for all user groups; temporal requirements

		Recruitment (e.g., oysters)	Suited for all user groups; temporal requirements
		Feeding and breeding behavior (for avian target species)	Technical expertise; temporal requirements; collection time investment; permitting requirements
	Soil texture	Grain size and soil type analysis	Technical expertise; collection time investments; cost/expense; specialized equipment
	Belowground stability	Shear vane strength	Technical expertise; cost/expense; specialized equipment
		Bearing capacity	Specialized equipment
	Vegetation productivity	Photograph (fixed point)	Suited for all user groups; temporal requirements
		Plant tissue nutrient analysis (C/N)	Technical expertise; temporal requirements; collection time investment; cost/expense; specialized equipment
		LANDSAT/infrared imagery	Technical expertise; temporal requirements; collection time investment; cost/expense; specialized equipment
		Biomass (above and/or belowground)	Technical expertise; temporal requirements; collection time investment; cost/expense; specialized equipment
		Number of stems per m2 and stem height of dominant species	Collection time investment; temporal requirements
	Salinity	Refractometer	Specialized equipment
		Meter (total dissolved solids)	Cost/expense; specialized equipment
	Dissolved oxygen	Meter (total dissolved oxygen)	Cost/expense; specialized equipment
	Area of habitat	GPS	Cost/expense; specialized equipment
		Aerial photography	Technical expertise; temporal requirements; cost/expense; specialized equipment
	Nuisance species	Number of stems per m2	Collection time investment; temporal requirements
		Cover per m2	Suited for all user groups; Temporal Requirements
		Presence/absence	Suited for all user groups; Temporal Requirements
	Inhibition of fauna movement	Observations	Suited for all user groups; Temporal Requirements

Socioeconomic	Economic impact of ecotourism ($)	Data collection methods: surveys; existing data sources; Data analysis methods: IMPLAN or other regional economic modeling, such as input/output models	Technical expertise and specialized software needed; only relevant for large enough projects to have a meaningful impact; if existing data sources are not available, may require additional collection time.
	Spending by birders ($)	Data collection methods: surveys; existing data sources; Data analysis methods: Economic impact assessment	Some technical expertise needed; may require additional collection time.
	Revenues for commercial fisherman ($)	Data collection methods: surveys; interviews; existing data sources; Data analysis methods: Partial budget analysis	Some technical expertise needed; only relevant for large enough projects to have a meaningful impact.
	Value visitors to the site place on their experience ($)	Data collection methods: surveys; existing data sources; Data analysis methods: Contingent valuation or choice experiment	Note that the value placed on individual experience represents the social value of the visitor experience, or the value beyond the actual amount spent. Some technical expertise needed; may require additional collection time.
	Number of students benefiting from environmental education/research (#)	Data collection methods: Surveys; Focus group meetings; Tracking with a log; Data analysis methods: NA	Suited for all user groups.

Table 10-6. Goal-based metrics for water quality improvement

Class	Metrics: Target water quality parameter- select one or more based on project goals	Method options	Additional user considerations
Conditional	Dissolved Oxygen	Meter (DO)	Cost/expense; specialized equipment
		Titration kit	Cost/expense; specialized equipment
		Winkler titration	Technical expertise; cost/expense; temporal requirements; specialized equipment
	Turbidity	Meter (turbidity)	Cost/expense; specialized equipment
		Clarity tube	Suited for all user groups
		Secchi disc	Suited for all user groups
	Sediment supply / total suspended solids	Filtration	Technical expertise; cost/expense; temporal requirements; specialized equipment
	Nutrients nitrate, nitrite, ammonia	Filtration (lab tests TKN, etc.)	Technical expertise; cost/expense; temporal requirements; specialized equipment
		Laboratory Analysis	Technical expertise; cost/expense; temporal requirements; specialized equipment
		Colorimeter	Technical expertise; cost/expense; temporal requirements; specialized equipment
	Water - bacteria	Lab analysis (CFUs)	Technical expertise; cost/expense; temporal requirements; specialized equipment
	Nutrients: phosphates	Lab analysis	Technical expertise; cost/expense; temporal requirements; specialized equipment
	Ph	Titration kits	Cost/expense; specialized equipment
		Colorimeter	Cost/expense; specialized equipment
		Meter (pH)	Specialized equipment
	Salinity	Refractometer	Specialized equipment
		Meter (total dissolved solids)	Cost/expense; specialized equipment
	Algal bloom	Chl a tests (lab or sensor)	Technical expertise; cost/expense; temporal requirements; specialized equipment

	Water BOD	Dilution method EPA method 5210B	Technical expertise; cost/expense; temporal requirements; specialized equipment
	Pollutants	Manometric method	Technical expertise; cost/expense; temporal requirements; specialized equipment
	Temperature	Meter	Cost/expense; specialized equipment
		Thermometer	Suited for all user groups
Potential socioeconomic metrics	Number of beach closing days (#)	Data collection method: existing data sources; analysis method: NA	Suited for all user groups.
	Value of visitors place on the improved water quality (boaters, anglers, beach visitors, etc.) ($)	Data collection methods: surveys; existing data sources; data analysis methods: contingent valuation or choice experiment	The value placed on individual experience represents the social value of the visitor experience, or the value beyond the actual amount spent. Some technical expertise needed; may require additional collection time.
	Number of shellfisheries closing days (#)	Data collection method: existing data sources; analysis method: NA	Suited for all user groups.
	Delisting of a waterway from EPA 303d	Data collection method: existing data sources; analysis method: NA	Suited for all user groups. Note that this metric will only be relevant for large enough projects that would have a quantifiable impact on water quality.
	Change in property value because of water clarity improvements ($)	Data collection method: existing data sources; analysis method: hedonic valuation	Technical expertise needed. Note that this metric will only be relevant for large enough projects that would have a quantifiable impact on water quality.

Table 10-7. Goal-based metrics for hydrological enhancement

Class	Metrics	Method options	Additional user considerations
Core	Stream flow	Flowmeter	Technical expertise; cost/expense; temporal requirements; specialized equipment
		Gauges and Buoys (e.g., Acoustic Doppler Current Profilers)	Technical expertise; cost/expense; collection time investment; specialized equipment
	Creek/channel morphometry	Aerial Photography or satellite imagery	Technical expertise; temporal requirements; cost/expense; specialized equipment
		Survey instrument (barcode leveling)	Technical expertise; cost/expense; specialized equipment
		RTK GPS transects	Technical expertise; cost/expense; specialized equipment
Conditional	Hydroperiod	Water level loggers	Technical expertise; cost/expense; temporal requirements; specialized equipment
	Sediment supply (e.g., TSS)	Meter (turbidity)	Cost/expense; specialized equipment
		Secchi disc	Suited for all user groups
		Filtration	Technical expertise; cost/expense; temporal requirements; specialized equipment
	Sediment capture/ accretion	Sedimentation disc/tile/plate/ marker horizon	Cost/expense (for some methods); temporal requirements; specialized equipment (for some methods)
		Measuring stick	Suited for all user groups
	Salinity	Refractometer	Specialized equipment
		Meter (total dissolved solids)	Cost/expense; specialized equipment
	Dissolved oxygen	Meter (total dissolved solids)	Cost/expense; specialized equipment
	Vegetation community composition	List of plant species in site	Suited for all user groups; temporal requirements
	Vegetation structure	Horizontal vegetative obstruction	Temporal requirements; specialized equipment
		Vertical light attenuation	Temporal requirements; specialized equipment
		Cover per m2	Suited for all user groups; temporal requirements
		Number of stems per m2	Collection time investment; temporal requirements
		Stem heights	Collection time investment; temporal requirements
		Habitat Type %, 50m radius (e.g., high marsh, low marsh, invasives, pannes & pools etc.)	Collection time investment; temporal requirements
Socioeconomic	Damage costs avoided to surrounding structures, roads or other public infrastructure ($)	Data collection method: Surveys; existing data sources; Analysis method: Avoided cost method; HAZUS modeling or other modeling that simulates changes in flood levels	Technical expertise and specialized software needed. If using a BACI design, may require a large collection time investment (need to wait several years to have enough weather events to compare changes in damage per storm over time).
	Number of homes or structures benefitting (#)	Data collection methods: visual assessment or GIS analysis	Suited for all user groups. Note that this metric only shows number, not the magnitude of the benefit.

	Number of days per month that road is flooded (#)	Data collection method: Surveys; existing data sources; Analysis method: Modeling that simulates changes in flood levels	Some technical expertise required. Note that this metrics shows only the number of days, not the number of people benefitting.
	Change in property value because of decrease in flood risk ($)	Data collection method: Existing data sources; Analysis method: Hedonic valuation	Technical expertise needed.

Table 10-8. Goal-based metrics for socioeconomic improvements

Class	Metric categories	Method options	Additional user considerations
Community resilience	Damage costs avoided to surrounding structures, roads or other public infrastructure ($)	Data collection method: surveys; existing data sources; analysis method: avoided cost method; HAZUS modeling or other modeling that simulates changes in flood levels	Technical expertise and specialized software needed. If using a BACI design, may require a large collection time investment (need to wait several years to have enough weather events to compare changes in damage per storm over time).
	Damage costs avoided to surrounding homes ($)	Data collection method: surveys; existing data sources; analysis method: avoided cost method; HAZUS modeling or other modeling that simulates changes in flood levels	Technical expertise and specialized software needed. If using a BACI design, may require a large collection time investment (need to wait several years to have enough weather events to compare changes in damage per storm over time).
	Value of time saved by individuals driving on a road where flooding is reduced ($)	Data collection method: surveys; existing data sources; analysis method: avoided cost method	Technical expertise required; specialized software may be needed, depending upon if hydrological modeling is used to supplement the analysis.
	Change in property value because of decrease in flood risk ($)	Data collection method: existing data sources; analysis method: hedonic valuation	Technical expertise needed.
	Difference in cost between hardened structure (e.g. bulkhead) and a living shoreline ($)	Data collection method: project budgets and existing data sources; analysis method: substitute cost method	Little technical expertise required; this method is suited for most user groups.
	Number of homes or structures benefitting (#)	Data collection methods: visual assessment or GIS analysis	Suited for all user groups. Note that this metric only shows number, not the magnitude of the benefit.
	Change in property value because of reduction in rate of erosion ($)	Data collection method: existing data sources; analysis method: hedonic valuation	Technical expertise needed.
Recreation and tourism	Spending by birders, boaters or anglers ($)	Data collection methods: surveys; existing data sources; data analysis methods: economic impact assessment	Some technical expertise needed; may require additional collection time.
	Number of visitors to the restoration site (#)	Data collection methods: car counter; surveys; geospatially referenced social media methodology; analysis methods: NA	Suited for all user groups. Note that this metric only shows number, not the magnitude of the benefit.

Water quality	Number of shellfisheries closing days (#)	Data collection method: existing data sources; analysis method: NA	Suited for all user groups. Note that this metric will only be relevant for large enough projects that would have a quantifiable impact on water quality.

APPENDIX D: Additional Tools and Resources

Table 10-9 through Table 10-11 provide lists of additional tools and resources that can help you with planning and designing nature-based solutions. The tables are organized into nationwide resources, regional resources, and resources by State.

Table 10-9. Nationwide resources for the planning and design of nature-based solutions

Name	Source / Location	Brief Description
Coastal Resilience Tools	http://coastalresilience.org/tools/apps/	A collection of web-based tools for assessing shorelines, habitats, sea level rise effects, economics, and risk
NOAA Digital Coast	https://coast.noaa.gov/digitalcoast/tools/	A wide collection of tools and data on topics including adaptation, coastal hazards, resilience, and green infrastructure
NOAA Sea Level Rise Viewer	https://coast.noaa.gov/slr/#/layer/slr	A web-based tool for viewing sea level rise inundation, marsh migration predictions, social vulnerability data, and high tide flooding sensitivity
NOAA Office for Coastal Management	https://coast.noaa.gov/	A collection of coastal data, factsheets, and links to relevant programs that can be filtered by State or topic area
NOAA Green Infrastructure Effectiveness	https://coast.noaa.gov/digitalcoast/training/gi-database.html	An online database of trusted literature sources related to the effectiveness of green infrastructure at reducing the impacts of coastal hazards
NOAA National Centers for Coastal Ocean Science	https://coastalscience.noaa.gov/	Data, products, and tools relevant for the planning and design of nature-based solutions

Name	Source / Location	Brief Description
NOAA National Data Buoy Center	https://www.ndbc.noaa.gov/	Wave characteristics, meteorological data, water temperature, and salinity
NOAA Tides & Currents	https://tidesandcurrents.noaa.gov/	Tide projections, tidal datums, measured water levels, meteorological data, sea level rise trends
USEPA Green Infrastructure Resources	https://www.epa.gov/green-infrastructure/green-infrastructure-design-and-implementation	A collection of manuals, tools, and resources, curated by the U.S. Environmental Protection Agency, regarding green infrastructure
USACE Coastal Hazards System	https://chs.erdc.dren.mil/default.aspx	Hydrodynamic data including water levels, waves, and currents for many different storm conditions
USACE Engineering With Nature®	http://www.engineeringwithnature.org/	A collection of tools procured by USACE Engineering With Nature®, including information on Thin Layer Placement and Beneficial Use of Dredge Material
USGS Coastal Change Hazards Portal	https://marine.usgs.gov/coastalchangehazardsportal/	A national overview of extreme events, shoreline change, shoreline position, and sea level rise impacts
Living Shorelines Academy	https://livingshorelinesacademy.org/	A clearinghouse for information on living shorelines and nature-based solutions, including training, resources, guidance, project examples, and a directory of professionals

Name	Source / Location	Brief Description
SAGE	http://sagecoast.org/	Systems Approach to Geomorphic Engineering is a community of practice focused on furthering the use of green-gray/hybrid approaches for resilience
Adaptation Clearinghouse	https://www.adaptationclearinghouse.org/	An online database for finding relevant information and organizations related to adaptation

Table 10-10. Regional resources for the planning and design of nature-based solutions

Name	Source / Location	Brief Description
GulfTREE (Gulf)	http://www.gulftree.org/	A decision support search engine for identifying tools for adaptation
USACE NACCS Study Data (NE)	https://www.nad.usace.army.mil/CompStudy/	Geodatabase containing exposure and risk analysis, future sea level inundation mapping, and housing density projections
VIMS-CCRM (MA)	http://www.vims.edu/ccrm/	A number of useful resources related to living shorelines and nature-based solutions for Virginia and the Chesapeake Bay
Integrated Ocean Observing System	https://ioos.noaa.gov	Coastal and ocean observing data for all coastal regions of the United States

Table 10-11. Coastal Zone Management Program governmental contacts by State

Name	Source / Location	Agency
Alabama	http://www.adem.state.al.us/programs/coastal/default.cnt	Alabama Department of Environmental Management
Alaska	n/a	Alaska withdrew from the CZMP in 2011
American Samoa	http://www.doc.as/resource-management/ascmp/	American Samoa Government Department of Commerce
California	https://www.coastal.ca.gov/	California Coastal Commission
Connecticut	https://www.ct.gov/deep/cwp/view.asp?a=2705&q=323536&deepNav_GID=1622	Connecticut Department of Energy & Environmental Protection
Delaware	https://dnrec.alpha.delaware.gov/coastal-zone-act/	Delaware Department of Natural Resources and Environmental Control
Florida	https://floridadep.gov/rcp/fcmp	Florida Department of Environmental Protection
Georgia	https://coastalgadnr.org/CoastalManagement	Georgia Department of Natural Resources
Guam	http://bsp.guam.gov/guam-coastal-management-program/	Guam Bureau of Statistics and Plans

Name	Source / Location	Agency
Hawaii	http://planning.hawaii.gov/czm/	Hawaii Office of Planning
Illinois	https://www.dnr.illinois.gov/cmp/Pages/default.aspx	Illinois Department of Natural Resources
Indiana	https://www.in.gov/dnr/lakemich/	Indiana Department of Natural Resources
Louisiana	http://www.dnr.louisiana.gov	Louisiana Department of Natural Resources
Maine	https://www.maine.gov/dmr/mcp/	Maine Department of Marine Resources
Maryland	http://dnr.maryland.gov/ccs/Pages/funding/czma.aspx	Maryland Department of Natural Resources
Massachusetts	https://www.mass.gov/orgs/massachusetts-office-of-coastal-zone-management	Massachusetts Office of Coastal Zone Management
Michigan	https://www.michigan.gov/egle/http://www.michigan.gov/deq/	Michigan Department of Environment, Great Lakes, and Energy
Minnesota	https://www.dnr.state.mn.us/waters/lakesuperior/index.html	Minnesota Department of Natural Resources
Mississippi	http://www.dmr.ms.gov/index.php/coastal-resources-management	Mississippi Department of Marine Resources

Name	Source / Location	Agency
New Hampshire	http://des.nh.gov/organization/divisions/water/wmb/coastal/index.htm	New Hampshire Department of Environmental Services
New Jersey	http://www.state.nj.us/dep/cmp/	New Jersey Department of Environmental Protection
New York	https://www.dos.ny.gov/opd/	New York Office of Planning & Development
North Carolina	https://deq.nc.gov/about/divisions/coastal-management	North Carolina Department of Environmental Quality; Division of Coastal Management
Northern Mariana Islands	https://dcrm.gov.mp/	Northern Mariana Islands Department of Coastal Resources Management
Ohio	http://coastal.ohiodnr.gov/	Ohio Department of Natural Resources Office of Coastal Management
Oregon	https://www.oregon.gov/lcd/Pages/index.aspx	Oregon Department of Land Conservation & Development
Pennsylvania	http://www.dep.state.pa.us/river/czmp.htm	Pennsylvania Department of Environmental Protection
Puerto Rico	http://drna.pr.gov/	Puerto Rico Department of Natural and Environmental Resources

Name	Source / Location	Agency
Rhode Island	http://www.crmc.ri.gov/	Rhode Island Coastal Resources Management Council
South Carolina	https://www.scdhec.gov	South Carolina Department of Health and Environmental Control
Texas	http://www.glo.texas.gov/coast/grant-projects/cmp/index.html	Texas General Land Office
Virgin Islands	https://dpnr.vi.gov/	USVI Department of Planning & Natural Resources
Virginia	https://www.deq.virginia.gov/Programs/CoastalZoneManagement.aspx	Virginia Department of Environmental Quality
Washington	http://www.ecy.wa.gov/programs/sea/czm/index.html	Washington Department of Ecology
Wisconsin	https://doa.wi.gov/Pages/LocalGovtsGrants/CoastalManagement.aspx	Wisconsin Department of Administration Coastal Management Program

11. GLOSSARY

Accretion	The accumulation or gain of land by the action of natural forces. On a beach, the deposition of beach material by wave action, tidal currents, or littoral currents.
Adaptive capacity	The degree to which the system containing the asset can adjust or mitigate the potential for damage or service interruption by climatic hazards.
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.
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).
Benthic	Referring to the habitat-rich zone at the bottom of a body of water.
Bottom friction	The momentum transfer caused by the interaction of a body of water with the bottom surface.
Breakwater	A structure protecting a shore area, harbor, anchorage, or basin from waves.
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 engineering	The planning, design, construction, and operation of infrastructure in the wave, tide, and sand environment that is unique to the coast. A well-established specialty area of civil engineering that focuses on the coastal zone and coastal processes.
Coir logs	Tube-shaped erosion-control devices filled with straw, flax, rice, coconut fiber material, or composted material.
Depth-limited wave height	A wave height that is limited by the local depth of water.
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.
Edging	The stabilization of a marsh edge.
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 saltwater of the sea and receives both fluvial and littoral sediment influx. (2) The part of a river that is affected by tides.

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Fascine	A bundle of material, especially in a log shape. See *Coir logs*.
Fetch	The distance or area in which wind blows across the water, thus forming waves.
Floodwall	A long, narrow concrete or masonry embankment usually built to protect land from flooding.
Geomorphology	(1) That branch of physical geography that deals with the form of the Earth, the general configuration of its surface, the distribution of the land and water, etc. (2) The investigation of the history of geologic changes through the interpretation of topographic forms.
Hybrid approach	An integrated approach to shoreline stabilization that combines nature-based solutions with structures and possibly policy measures.
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.
Littoral cell	An area of shoreline and associated topography/bathymetry wherein the movement of sediment is driven by waves and currents.
Living breakwater	A structure that provides potential habitat within it and functions like a breakwater to reduce wave energy on the shoreline.
Living shoreline	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.
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 a range of salt spray.
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.
Meteotsunami	Long-wave motions principally caused by meteorologically induced disturbances, including those associated with pressure jumps, frontal passages, and squalls.
Nonlinear	Occurring as a result of a mathematical operation that is not linear.
Nuisance flooding	Minor, recurrent flooding that occurs at high tide or during minor storms.
Nutrient loading	The quantity of nutrients (such as nitrogen or phosphorous) entering an ecosystem in a given timeframe.
Nutrient uptake	The process of plants absorbing, usually through the roots, nutrients from the surrounding environment.
Ocean acidification	A reduction in the pH of the ocean over an extended period of time, caused primarily by uptake of carbon dioxide (CO_2) from the atmosphere.

GLOSSARY

Overtopping	Passing of water over the top of a structure (e.g., seawall, roadway), usually as a result of wave runup 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.
Poorly graded	See *Well sorted*.
reef	Offshore consolidated rock. Often refers to coral fringing reefs in tropical waters, but may also include shellfish reefs such as oyster.
Return period	A concept used to define the average length of time between occurrences in which the value of the random variable, typically flood level, is equaled or exceeded.
Revetment	A layer or layers of stone, concrete, etc. that protect(s) an embankment, or shore structure, against erosion by wave action or currents.
Rhizome	A root-like, usually horizontal, stem growing under or along the ground. Roots sprout from the lower surface, and stems and leaves sprout from the top surface.
Risk	Chance or probability of failure resulting from 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.
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. It often retains earth against its shoreward face. A seawall is typically more massive and capable of resisting greater wave forces than a bulkhead.
Sediment transport	The movement of (beach) sediments. Longshore sand transport occurs primarily parallel to the shoreline.
Sheet pile	Interlocking boards or planks of steel, vinyl, concrete, wood, or other materials that are driven into the ground to form a wall.
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.
Stem density	A measurement of the average number of plant stems found in a given area.
Storm surge	A rise in average (typically over several minutes) water level above the normal astronomical tide level because of the action of a storm. Storm surge results from wind stress, atmospheric pressure reduction, and wave setup.

Subtidal	Refers to a feature that is always submerged, even at low tide.
Suspended solids	Particulate matter that is dispersed in a body of water.
Tidal restriction	A reduction of the tidal flow to and from a hydrologic feature, such as a marsh.
Tipping point	A point in space, or in time, beyond which some alternative approach is required.
Tsunami	A long-period wave, or series of waves, caused by an underwater disturbance, such as a volcanic eruption or earthquake. Commonly miscalled a *tidal wave*.
Tsunami runup	The large amount of water that a tsunami pushes onshore.
Water quality	The composition of the water in terms of its constituents, including the presence of nutrients, dissolved materials, and suspended solids.
Wave	A ridge, deformation, or undulation of the surface of a liquid.
Wave attenuation	To lessen the height or amplitude of a wave, wave-like feature, or velocity.
Wave breaking	Reduction in wave energy and height. In the surf zone, breaking is because of limited water depth.
Wave height	The vertical distance between a crest and the preceding trough.
Wave period	The time for a wave crest to traverse a distance equal to one wavelength. The time for two successive wave crests to pass a fixed point.
Wave runup	The upper level reached by a wave on a beach or coastal structure, relative to the still water level.
Wave setup	Superelevation of the water surface over normal surge elevation because of onshore mass transport of the water by wave action alone.
Wave transmission	The movement of a wave through some porous obstruction, which usually causes some attenuation of the wave.
Well sorted	A characterization of soil representing a very narrow (low variance) grain size distribution.

12. ACKNOWLEDGMENTS

The Federal Highway Administration would like to express appreciation to the members of the Technical Review Committee, whom contributed valuable input and technical expertise during the development of this implementation guide. The members were:

- Rick Bennett, Ph.D., US Fish and Wildlife Service;
- Geoff Crook, Oregon Department of Transportation;
- LaTonya Gilliam, P.E., Delaware Department of Transportation;
- Maria Honeycutt, Ph.D., National Oceanic and Atmospheric Administration;
- Jeffrey King, Ph.D., P.E., US Army Corps of Engineers;
- Pam Mason, Virginia Institute of Marine Science;
- Michelle Mattson, US Army Corps of Engineers; and
- Kim Penn, National Oceanic and Atmospheric Administration.

The Federal Highway Administration would also like to express appreciation to the participants in the four regional peer exchanges that informed the development of this guide. The list of participants is included in Peer Exchange Report: Nature-based Solutions for Coastal Highways.

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