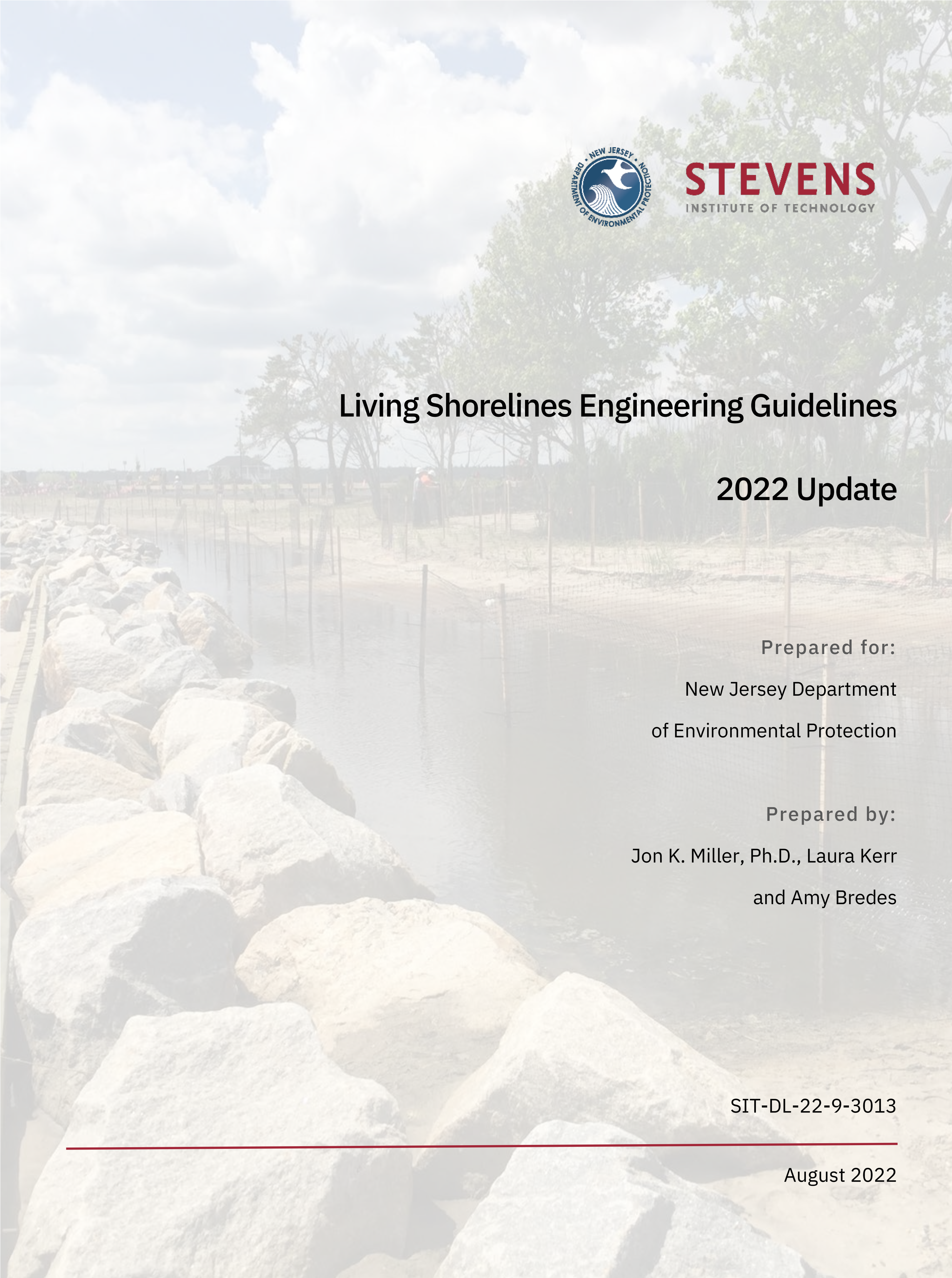

Living Shorelines Engineering Guidelines

2022 Update

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New Jersey Department

of Environmental Protection

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Contents

Version History

Version	Date	Description
1	February 2015	The original version of the New Jersey Living Shorelines Engineering Guidelines was released.
2	February 2016	The document was updated to reflect changes to the NJ Administrative Code made in July 2015 which resulted in a “Coastal GP 29” being renumbered as “Coastal GP 24”.
3	August 2022	The document was updated to reflect advances appearing in both peer-reviewed and gray literature since the original document was published. Appendix C identifying current information gaps was also added.

Introduction

Over the past century intensive development in the coastal zone has resulted in the proliferation of traditional "hard" shoreline stabilization measures such as bulkheads, seawalls, and revetments. While these approaches have proven to be successful at stabilizing shorelines when designed and constructed properly, they can also have a number of less desirable impacts on adjacent shorelines and critical intertidal and nearshore habitats. More recently, a variety of new shoreline stabilization approaches have been developed that attempt to incorporate natural features and reduce erosion by mimicking features of the natural environment. These approaches have come to be known by a variety of names including "living shorelines", "green shores", "ecologically enhanced shorelines", and "natural and nature-based features (NNBF)", among others. Originally developed in the Chesapeake Bay nearly two decades ago, the "living shorelines" approach has gradually gained momentum and has spread nationwide. In 2007, the National Academies Press released the report, *Mitigating Shore Erosion along Sheltered Coasts* (National Research Council, 2007), which advocated the development of a new management framework within which decision makers would be encouraged to consider the full spectrum of options available. More recently, the US Army Corps of Engineers (USACE) released a report on coastal risk reduction and resilience which advocates for an integrated approach to risk reduction that draws from the full array of measures available (US Army Corps of Engineers, 2013). Both documents strongly encourage greater consideration of projects such as living shorelines projects which have the dual benefit of shoreline stabilization and habitat creation.

While this technique was originally applied only to low-profile stone or natural breakwaters known as marsh sills, the term "living shoreline" has evolved to take on a broader meaning which encompasses a wide variety of projects that incorporate ecological principles into engineering design. Several examples of projects which are frequently included in the modern definition of living shorelines are shown in Figure 1. Panel A depicts a HESCO basket breakwater in Forked River Beach, NJ. Each HESCO unit is filled with a combination of rock and recycled shell. Panel B shows an Oyster Castle breakwater in Gandys Beach, NJ. Each breakwater segment consists of four individual reef structures constructed using ecologically enhanced concrete blocks. Panel C shows a traditional rock sill with a non-traditional bulkhead spine in Little Egg Harbor Township, NJ. New Jersey's Coastal Zone Management Rules define a living shoreline as a "shoreline management practice that addresses the loss of vegetated shorelines, beaches, and habitat in the littoral zone by providing for the protection, restoration or enhancement of these habitats" (N.J.A.C. 7:7-1.5). **It is important to note that the primary function of a living shoreline is the stabilization of the shoreline edge; while flood mitigation is needed in many coastal and riverine areas, a living shoreline is often not the most appropriate tool for addressing flooding issues.**

The objective of this document is to provide guidance to the engineering and regulatory community on the engineering components involved in the design of living shorelines projects that is consistent with the most up-to-date research. While the document is intended to provide the framework for the engineering design of living shorelines projects, the nature of these projects is such that diversity and innovation should be encouraged rather than discouraged. Innovation is identified in both the Waterfront Alliance's *Waterfront Edge Design Guidelines (WEDG)* (Waterfront Alliance, 2018) and the USACE's *International Guidelines on the use of Natural and Nature-based Features for Flood Risk Management (IGNNBF)* (Bridges, et al. 2021) as critical to the advancement of nature-based shoreline design.

The document is organized as follows. First, the Purpose and need for the engineering guidelines is discussed. The subsequent section outlines the Design Approach used to create the guidelines. Next a discussion of the Site Characterization parameters critical for the design of living shorelines projects is presented; these include System, Hydrodynamic, Terrestrial and Ecological Parameters. A section is then provided on Additional Considerations for living shoreline projects. A Glossary of terms that readers may be unfamiliar with is provided at the end of the main body of the report. Three appendices are also included. Appendix A: Approach Specific Design Guidance outlines the application of the engineering guidelines to five common types of living shorelines projects. Appendix B: Technical Excerpts contains excerpts from some of the design manuals referred to throughout this document. Lastly, Appendix C: Remaining Gaps contains a list of identified gaps in knowledge and research questions.

Figure 1: Example Living Shorelines Projects (From left to right: breakwaters, an oyster castle breakwater, and a marsh sill)

Purpose

Many documents have been developed with the objective of educating policymakers, regulators, and property owners on the engineering and ecological aspects of living shorelines. The guidance presented here was developed specifically for engineering consultants, regulators, and private-property owners to ensure that living shorelines projects built within the State of New Jersey are designed, permitted, and constructed in a consistent manner using the best available information. The guidance is being developed at a critical time when living shorelines projects are becoming an increasingly popular alternative for stabilizing shorelines and restoring natural habitat. In July 2013, the State of New Jersey officially adopted Coastal General Permit 24 (N.J.A.C. 7:7-6.24) – commonly referred to as the Living Shorelines General Permit - which was written to encourage "habitat creation, restoration, enhancement, and living shoreline activities" and to remove some of the regulatory impediments for these projects. The guidance provided in this document is intended to be consistent with the statutes and limitations outlined in Coastal General Permit 24. The guidelines that have been developed are intended to identify the parameters critical to the success of living shorelines projects, to outline the level of analysis required to understand those parameters, and to provide guidance on how to incorporate them into a successful project design. The objective is to reduce the number of poorly engineered or improperly designed structures, while at the same time recognizing that some living shorelines projects do not need the same level of detailed engineering analysis as traditional approaches. Moreover, the intent is to provide a document that can serve as a common starting point for both project designers and regulators, such that the framework, design process, and expectations are more clearly understood by both parties at the outset of a project. Due to the underdeveloped state of knowledge about living shorelines projects in the Northeast (north of Maryland), it is expected that these guidelines will continue to evolve as more information becomes available. It is also expected that from time-to-time projects may be constructed as functional experiments and that there may be reasons to deviate from the proposed guidelines to achieve a specific research objective.

Design Approach

Living shorelines differ from traditional gray infrastructure projects in that they attempt to restore or mimic natural processes which are inherently dynamic. As a result, the typical engineering design process needs to be modified accordingly. The IGNNBF recommend the 11-step process illustrated in Figure 2 for identifying and implementing an appropriate nature-based design alternative. They simplify the process into a five-segment design framework that incorporates: scoping, planning, decision-making, implementation, and operations. At each level, different information is required to move a project forward. During the **Scoping Phase**, a general understanding of the site and a clear understanding of the intended outcomes is required. During the **Planning Phase**, more detailed information about the site conditions is required to develop conceptual designs. At the **Implementation Phase** further analysis is often required to refine and generate final designs and construction specifications. In the IGNNBF framework,

Figure 2: IGNNBF process for identifying and implementing the preferred nature-based alternative

monitoring is performed during the **Operations Phase** and is used to inform maintenance and adaptive management actions. This updated version of the New Jersey Living Shorelines Engineering Guidelines adopts this simplified IGNNBF terminology, in place of the building block approach originally used, to be more in line with the broader community.

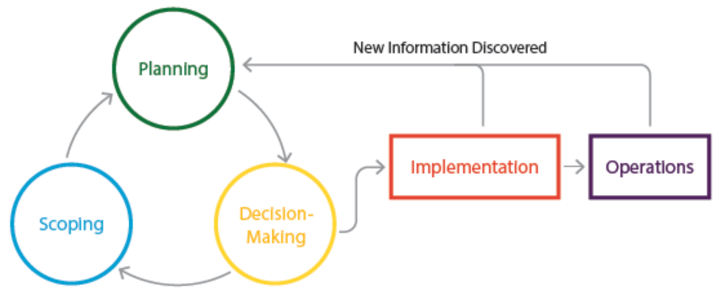


Figure 3: IGNNBF simplified 5-phase design process

Design Parameters

Living shoreline projects tend to be very diverse and, as such, each project may have its own set of unique factors that need to be considered. Based on a review of current literature, there are, however, several site characteristics which play a critical role in the success or failure of most living shoreline projects. These characteristics can be grouped into four categories and include both traditional engineering site characteristics as well as less traditional parameters. **System Characteristics** are more regional in nature and include factors such as erosion history, sea level rise, and tidal range. **Hydrodynamic Characteristics** are factors which relate to the erosional forcing at a site and include wind waves, wakes, currents, ice, and storm water level. **Terrestrial Characteristics** are the physical characteristics of the land on which a project will be built, and include upland slope, shoreline slope, nearshore slope, width, offshore depth, and soil bearing capacity. **Ecological Characteristics** are parameters that mainly affect the ability of organisms to utilize the site and include water quality, soil type, and sunlight exposure. It should be noted that the separation of these variables into groups is done for convenience and that there is some overlap. For example, tidal range is critically important for determining the appropriate vegetation, even though it is listed as a system parameter rather than an ecological parameter.

In addition to the physical site characteristics, there are a number of other considerations which play a significant role in the selection and design of an appropriate living shorelines project. These include:

- permits/regulatory factors,
- end effects,
- constructability,
- native/invasive species,
- debris impact,
- project monitoring,
- adaptive management, and
- beneficial reuse.

These site characteristics and additional project considerations are discussed in detail further into the document.

Scoping Phase

At the scoping stage, generally only a limited amount of information is needed to assess the possibility of applying a nature-based technique at a site. **At this stage it is critically important that the project objectives, as well as any potential limitations associated with the potential techniques being considered, be communicated.** Over the past decade, several tools have been developed to assist in this type of high-level analysis; the description of several follows. Once an alternative(s) has been selected, the project designer is encouraged to contact the New Jersey Department of Environmental Protection (NJDEP) Office of Policy and Coastal Management so that potential regulatory issues can be identified. Once any issues have been discussed, a conceptual design(s) should be developed.

Restoration Explorer

Restoration Explorer is a web-based application that allows users to visualize current and future risk and subsequently identify which nature-based technique(s) could work best in reducing coastal erosion, while also promoting the multiple benefits of healthy coastal habitats. Currently, the Restoration Explorer suggests the following six living shoreline techniques: beach restoration, nature-based living shoreline, marsh sill, ecologically enhanced revetment, living reef breakwater, and breakwater. The Restoration Explorer walks the user through a decision tree that guides the user to input their county and municipality of interest, the shoreline type, and disturbance process. Users may zoom into a square on the map representing 10-meter length of shoreline. Here the proposed shoreline enhancements are ranked and shown along with the option to view information on the individual restoration techniques. If selected, users are provided with information on the environmental conditions for the site and can investigate the applicability of restoration techniques for those conditions. The Restoration Explorer application is intended to support collaborative discussion about how to begin the process of considering the implementation of a living shoreline project. It is part of the The Nature Conservancy's larger Coast Resilience Tool platform.

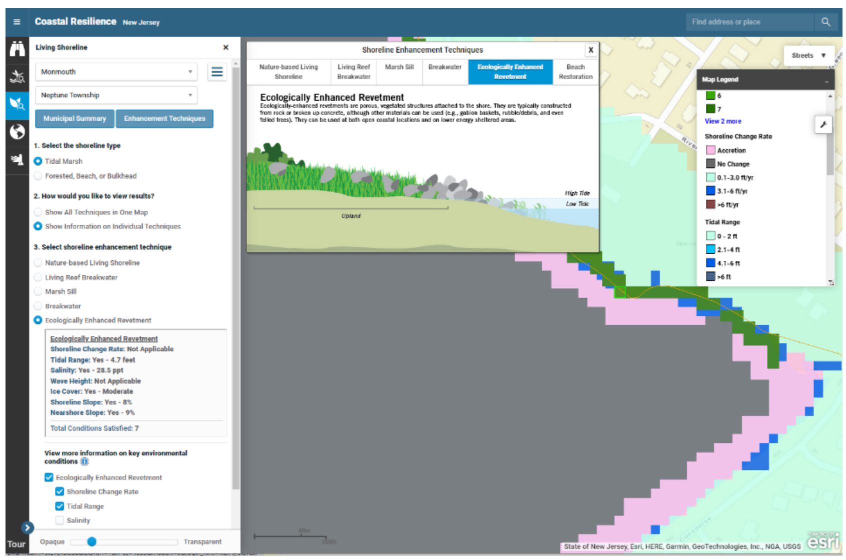


Figure 4: Restoration Explorer, a web-based application, provides a high-level evaluation of a shoreline and suggests, and describes, appropriate nature-based restoration technique(s) from a set of six.

WATCH

The Wetland Assessment Tool for Condition and Health, or WATCH, is a comprehensive framework that unites and evaluates site-specific data for six specific attributes (vertical position, horizontal position, biology, hydrology, soil condition, and water chemistry) that are the foundation of healthy salt marsh function. Users can apply this structured tool to holistically assess the condition of a specific salt marsh by selecting an appropriate metric for each attribute and then providing current data for the attribute. WATCH evaluates the user-provided data against user-defined goals and delivers a summary of the deficiencies of the site. Where available, a user may include trajectory data (rates of change) to forecast future vulnerabilities. Attribute-specific deficiencies are integrated to identify unique combinations that are indicative of site-wide diminished functionalities. WATCH also provides interpretive guidance and a list of additional considerations. The goals of the tool are: 1**. Restoration Project Planning -** users identify qualities that are likely either currently deficient and/or on a negative trajectory which allows for the prioritization for intervention; and 2. **Proposed Project Evaluation** – users are provided with a summary of quantitative findings alongside user-contributed justifications for all data selection/collection activities and decisions. Ultimately, WATCH seeks to assist the user in making informed decisions regarding the management, protection, and enhancement of salt marshes. The metrics and methods used in WATCH align with various monitoring guidelines, including *A Framework for Developing Monitoring Plans for Coastal Wetland Restoration and Living Shoreline Projects in New Jersey*.

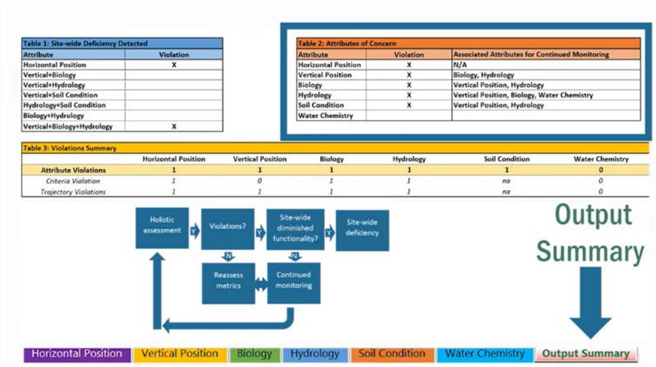


Figure 5: WATCH is a comprehensive framework that unites and evaluates site-specific data for six specific attributes to assess salt marsh functioning.

CERAP

The New Jersey Coastal Ecological Restoration and Adaptation Plan (CERAP) seeks to define priority sites and projects throughout NJ's coastal marshes, estuaries, and back bays based on their value in enhancing for ecological projects that will produce significant net carbon sequestration, ecosystem health, and/or built community resilience. Both ecological areas of concern and specific projects are nominated by coastal stakeholders and are evaluated and characterized based on the following suite of coastal issues of concern:

- coastal ecosystem degradation and habitat loss,
- shoreline erosion,
- coastal flood damage,
- nuisance flooding,
- coastal storm damage,
- water quality degradation,

- loss of CO_2 sequestration, and
- social vulnerability.

The result of this effort will be a mapped catalogue of sites and projects to help inform stakeholders on where resources could be best allocated for future projects.

MACWA

The Mid-Atlantic Coastal Wetlands Assessment (MACWA) is a wetland program that studies tidal wetland health in the Delaware Estuary and Barnegat Bay. The goal of MACWA is to supply coastal managers with data to help plan wetland recovery and protection. It consists of remote sensing analysis, rapid assessments, and the fixed-station monitoring of wetlands. MACWA is a 4-tier monitoring and assessment program envisioned to provide rigorous, comparable data across all tidal wetlands of the Mid-Atlantic. As the tiers progress data complexity and the number of metrics assessed increases while the spatial scale of the data collection decreases. A summary of the four tiers is as follows:

- Tier 1: Using remote sensing, landscape-level changes, inventories, and land or habitat classifications can be performed.
- Tier 2: Ground truthing is performed using a specific Rapid Assessment Method (RAM) that evaluates metrics that gauge stress and discern habitat condition, specifically for a suite of variables that represent four categories important for the maintenance of a wetland:
    - habitat and biotics,
    - hydrology,
    - buffers, and
    - shoreline dynamics.
- Tier 3: Intensive studies are discrete projects that address research questions related to wetland condition, function, ecosystem services, and/or restoration. Some example topics include blue carbon, shellfish services, and a tool called Marsh Futures.
- Tier 4: Site-specific intensive monitoring is designed to track changes in physical, chemical, and biological conditions with the goal of relating any changes to sea level rise and other stressors. Surveying the same locations for several years allows researchers to track and compare changes over time. Principal core metrics include biological integrity and biomass, and surface elevations, and physical conditions. Monitoring for geomorphology, biota, and water quality was designed to describe both structural and functional properties and overall integrity.

These data sets are suitable for providing input into tools such as WATCH and for later in the design process in the Planning Phase.

National Assessment Tools

Many additional tools are available at a national scale. These tools can also be useful in the Scoping Phase; some may provide data that could be useful in the Planning Phase as well. Examples of these national assessment tools include:

- United States Fish and Wildlife Service (USFWS) Wetlands Mapper – The Wetlands Mapper integrates digital map data along with other resource information to produce current information on the status, extent, characteristics, and functions of wetlands and disseminates wetlands data and information to resource managers and the public.
- United States Geological Survey (USGS) The National Map – The National Map is a suite of products and services that provide nationally consistent geospatial data access to describe the landscape of the United States and its territories. Supporting themes include boundaries, elevation, geographic names, hydrography, land cover, orthoimagery, structures, and transportation; other types of georeferenced or mapping information can be also added.
- Coastal Change Analysis Program (C-CAP) Land Cover Atlas – The C-CAP Land Cover Atlas is an online, browser-based data viewer that provides access to regional land cover and land cover change information developed through NOAA's Coastal Change Analysis Program (C-CAP). It does not require desktop geographic information system software or advanced technical expertise. The tool summarizes general change trends and can highlight specific changes of interest, such as salt marsh losses to open water.

Planning Phase

A base level of information about a site's physical characteristics and the additional considerations described above are typically sufficient to begin narrowing down potential alternative approaches. This basic information is determined through what is referred to throughout this document as a Planning Level analysis. Planning Level techniques are primarily desk-top analyses which rely on existing data to characterize a site and assess project specific additional considerations. **It is strongly recommended that a site visit be performed; a primary goal of the visit at this stage is to both confirm the information obtained through the desk-top analysis and to look for important details which may not have been captured by the data utilized in the analysis.**

Table 1 contains information on the conditions under which three common living shoreline project types are typically considered suitable based on a review of the existing literature. These three project types are described in more detail in Appendix A: Approach Specific Design Guidance. The information contained in Table 1 is purposefully qualitative in nature, as strict thresholds have yet to be established for most parameters. In Table 2, recommended quantitative boundaries are provided based on a review of the existing literature and New Jersey project experience. **It is stressed that these "boundaries" are provided for guidance only and that specific site conditions may dictate applying a technique outside of the recommended range.** As more research/data becomes available, specifically for projects constructed in New Jersey, these ranges should be updated accordingly. More information on the critical design parameters listed in the tables as well as suggestions on analysis can be found in the Site Characterization section of these Guidelines.

Table 1: Appropriate conditions for four common living shoreline approaches. Bold italic font is used to denote parameters of greater importance for specific techniques.

	Marsh Sill	Breakwater	Living Reef
System Characteristics			
Erosion History	***Low-Med***	***Med-High***	***Low-Med***
Sea Level Rise	Low-Mod	Mod-High	Low-Mod
Tidal Range	***Low-High***	Low-High	***Low-Mod***
Hydrodynamic Characteristics			
Wind Waves	***Low-Mod***	***Mod-High***	***Low-Mod***
Wakes	***Low-Mod***	***Mod-High***	***Low-Mod***
Currents	Low-Mod	Low-High	Low-Mod
Ice	***Low***	Low-High	***Low***
Storm Water Level	Low	***Mod-High***	Low
Terrestrial Characteristics			
Upland Slope	Mild-Mod	Mod-Steep	Mild-Mod
Shoreline Slope	***Mild-Mod***	***Mild-Steep***	***Mild-Mod***
Width	***Mod-High***	***Mod-High***	***Mod-High***
Nearshore Slope	***Mild-Mod***	***Mild-Mod***	***Mild-Mod***
Offshore Depth	Shallow-Mod	Mod-Deep	Shallow-Mod
Soil Bearing	Mod-High	***High***	Low-Mod
Ecological Characteristics			
Water Quality	Poor-Good	Poor-Good	***Good***
Soil Type	***Any***	Any	Any
Sunlight Exposure	***Mod-High***	Low-High	***Mod-High***

Table 2: Approximate quantitative bounds corresponding to the qualitative parameter ranges

	Criterion		
Parameter	**Low/Mild**	**Medium/Moderate**	**High/Steep**
System Characteristics			
Erosion History	<2 ft/yr	2 ft/yr to 6 ft/yr	>6 ft/yr
Sea Level Rise	<0.2 in/yr	0.2 in/yr to 0.4 in/yr	>0.4 in/yr
Tidal Range	< 1.5 ft	1.5 ft to 4 ft	> 4 ft
Hydrodynamic Characteristics			
Waves	< 1 ft	1 ft to 3 ft	> 3 ft
Wakes	< 1 ft	1 ft to 3 ft	> 3 ft
Currents	< 1.25 kts	1.25 kts to 4.75 kts	> 4.75 kts
Ice	< 2 in	2 in to 6 in	> 6 in
Storm Water Level	<25 yr	25 yr to 50 yr	> 50 yr
Terrestrial Characteristics			
Upland Slope	<1 on 30	1 on 30 to 1 on 10	>1 on 10
Shoreline Slope	<1 on 15	1 on 15 to 1 on 5	> 1 on 5
Width	<30 ft	30 ft to 60 ft	>60 ft
Nearshore Slope	<1 on 30	1 on 30 to 1 on 10	>1 on 10

Offshore Depth	< 2 ft	2 ft to 5 ft	> 5 ft
Soil Bearing Capacity	< 500 psf	500 psf - 1500 psf	> 1500 psf
Ecological Characteristics			
Water Quality	-	-	-
Soil Type	-	-	-
Sunlight Exposure	<2 hrs/day	2 to 6 hrs/day	>6 hrs/day

Planning Level analyses typically culminate in the development of one or more conceptual designs. Conceptual designs will typically consist of an overall project plan or layout and cross-sections illustrating approximate structure sizes and locations, planting zones, etc. One or more conceptual designs may be developed depending on the complexity of the project and the available budget. At this stage, it is recommended that a Pre-Application (Pre-App) Conference be held with the NJDEP Division of Land Resource Protection. Details on the process can be found on the NJDEP website.

Implementation Phase

For all but the simplest projects, the next step will be to refine the conceptual design. This typically requires collecting and/or analyzing additional information on the critical design parameters. This is what is referred to throughout this document as an Implementation Level analysis. Implementation Level analyses may require field data collection and/or numerical modeling. In Table 1 the critical design parameters for each of the three techniques are identified in bold, italicized text. The level of additional analysis required for these critical parameters should be dependent on factors such as project size, complexity, cost, setting, and upland use, and should be agreed upon by the project designer and all appropriate regulatory agencies. Implementation Level analyses should lead to a final design suitable for permitting and construction.

Site Characterization

An understanding of the characteristics of a site is critically important to developing an appropriate living shoreline solution. As described above there are several levels of analysis, that can occur, each appropriate with different phases. Generally, there are multiple ways of evaluating the site characteristics, ranging from simple desk-top analyses to time-consuming and expensive numerical modeling and/or field data collection. The level of analysis required is a function of the stage of the design (conceptual/final), the parameter type (critical/non-critical), and the size, scope, and intent of the project. It is advisable that prior to the development of final detailed plans, the project designer, and the regulatory body(ies) come to a consensus on the level of analysis required for the critical parameters.

What follows below is a description of some of the more common methodologies for evaluating site characteristics. The methodologies are presented in order of the level of complexity (and often expense) involved in performing the analysis. Planning Level analyses are typically desk-top analyses that can be used to develop a conceptual design(s). **Note, it is strongly**

recommended that all Planning Level analyses include a site visit. Implementation Level analyses typically involve more advanced computational techniques, modelling, or field data collection. It should be noted that not all parameters have a higher level of analysis, and that while the different levels of analysis identified represent a comprehensive list, innovative methods should not be excluded.

System Parameters

System Parameters are parameters that either a) represent large scale or regional processes or b) represent the impact of several processes, some of which are large-scale or regional in nature. In some cases, these parameters can be observed/measured locally however they originate or have impacts outside of the immediate project area.

Erosion History

Understanding the erosion history of the site is important if a successful living shorelines project is to be designed and constructed. In some cases, erosion is a consistent, long-term process, while in others it is episodic and/or related to specific changes to the environment surrounding a project site. If the cause of the erosional problem can be identified, more appropriate solutions can be found.

Erosion rates vary widely in New Jersey, especially in marshes which are often the site of living shoreline projects. Weis, et al. (2021) found that erosion was the primary driver of marsh loss in Barnegat and Delaware Bays at rates of 0.5 m/yr and 2 to 5 m/yr, respectively. Conversely, they found that erosion was not the primary driver of marsh loss in New York/New Jersey Harbor. Marsh edge erosion is a complex process that varies between and even within each marsh due to the natural heterogeneity of these ecosystems. Erosion is largely dependent on average wave power, not wave height, with a documented linear relationship (Feagin, et al. 2009; McLoughlin, et al., 2015; Priestas, et al. 2015; Leonardi, et al. 2015). There is no identified wave power threshold that causes sudden or extreme marsh edge erosion, such as during a large storm. Indicating that in most cases, marsh edge erosion is a constant process. In addition to wave power, marsh erosion is also a function of marsh sediment cohesion and the ratio between scarp elevation and water depth (Marani, et al. 2011). While understanding historic and current erosion rates and conditions is important, these rates must be combined with a wind wave analysis to assign the appropriate solution to erosion of the marsh edge.

Planning Level Analysis

The erosion history of a site can often be determined by examining historic aerial photography and/or digitized shorelines of the project site. There are many resources that can assist in determining erosion history including:

- Google Earth – Google Earth is a free geographical information program that stitches together satellite imagery, aerial photography, and geographic information systems 3-D globe. One of the useful features within Google Earth is the ability to “go back in time” and view historic aerial photographs of an area. The availability of aerial photography varies from location to location; however, most of New Jersey's coastal regions have between five and ten aerials dating back to the early 1990s.

- Nationwide Environmental Title Research, LLC (NETR) online database – The NETR website database contains a series of historic aerial photographs and topographic maps that typically dates to the early 1900s. Aerial photographs from different periods can be overlain on one another using a tool on the website which facilitates the process of visualizing and comparing the images.
- GIS Data Repositories – Historic shorelines are typically available in GIS form from local, county, state, and federal sources. Two relevant datasets available from the NJDEP are the shoreline structure dataset and the historic shoreline dataset.
- Bing Maps – Bing maps is a useful source for obtaining current high-resolution "birdseye" photographs of shoreline sites. While only the most recent photograph of a given area is displayed, the level of detail is often such that important features (even those underwater) can be identified.
- New Jersey Geographic Information Network (NJGIN) - The New Jersey Geographic Information Network archives and serves a variety of geospatial data including high resolution aerial photographs, lidar elevation data, and derived Digital Elevation Models (DEMs).
- Lidar Data – Lidar is high-resolution survey data typically collected from an airplane. Due to the expense involved in collecting and processing the data, the number of available datasets is limited. The US Interagency Elevation Inventory archives and provides access to national elevation datasets as does the National Ocean and Atmospheric Administration (NOAA) Office for Coastal Management Digital Coast. Historically the number of available data sets was small due to the expense involved in collecting, processing, and serving the information; however recent technological advancements have reduced costs, resulting in more frequent data collection.
- Other Sources – Additional sources of information may include local libraries and historic maps maintained by the county, state, or local universities. The Cartography Center at Rutgers University maintains an extensive set of historic maps of New Jersey.

Implementation Level Analysis - Measurement

The data sources and basic analyses described above can often be supplemented with high-resolution data collected using advanced techniques. These data sources and techniques include the following:

- Structure from Motion (SfM) – SfM is a technique whereby three-dimensional elevation models are created from a series of two-dimensional pictures. The pictures used in geospatial applications of SfM are typically taken by an Unmanned Aerial Vehicle (UAV) or drone. SfM tracks points common to one or more images and combines that information with data on the camera and UAV motions to create accurate centimeter scale three-dimensional maps (Zimmerman, et al. 2020). Most commercial grade (<$2000) UAVs can take photographs suitable for analysis with SfM. Likewise, there are many commercially available software packages capable of performing SfM analysis. Short-term erosion rates can be calculated by comparing two or more data sets collected using SfM.

- Real-Time Kinematic Global Positioning Systems (RTK GPS) – A popular approach for tracking shoreline/edge changes is GPS. GPS uses satellite positioning technology to determine the coordinates of features such as the shoreline or marsh edge at a site. Survey-grade GPS units capable of centimeter scale accuracy can cost $10,000 or more. Short-term erosion rates can be calculated by comparing two or more data sets collected using RTK GPS.
- Satellite-Derived Shorelines (SDS) – SDS generally uses machine-learning based algorithms to detect shorelines from satellite data. (Vos, et al. 2019) developed the CoastSat system for detecting shorelines on sandy beaches and demonstrated its accuracy. Methods for using SDS on marsh shorelines are significantly less advanced, however this is a field of active research that promises to advance significantly over the next decade. Short-term erosion rates can be calculated by comparing two or more data sets collected using SDS.
- Low-cost Techniques - Simpler approaches such as a theodolite and prism or rod can also be used to track shoreline erosion. Findlay, et al. (2018) describe low-cost surveying methods including several for estimating erosion and feature (the shoreline in this case) displacement as part of a rapid assessment protocol developed for the Hudson River Sustainable Shorelines Project.

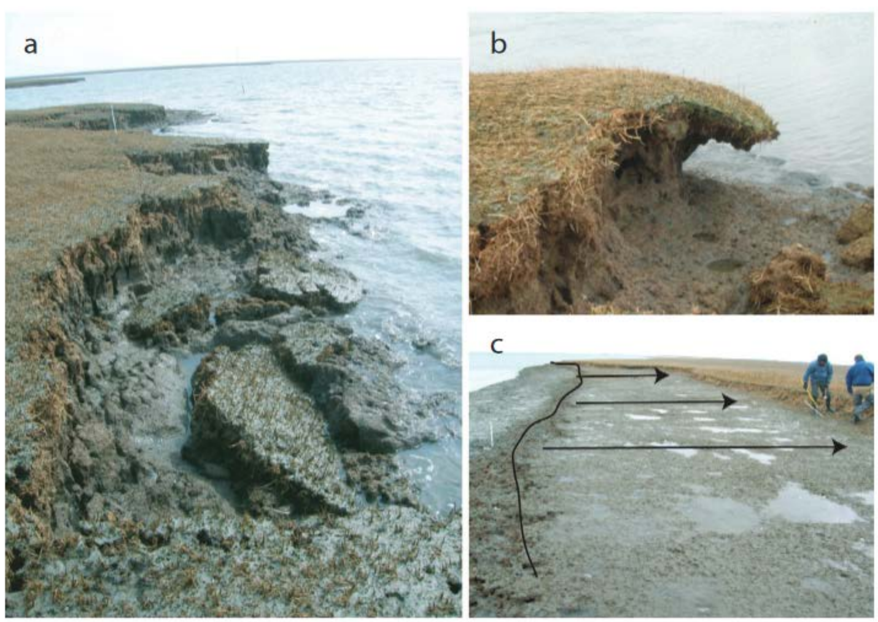


Figure 6: Examples of marsh edge erosion; (a) slumping, (b) undercutting, (c) root scaling. Adapted from Fagherazzi, et al. (2013).

While a desk-top analysis can reveal a wealth of information about a site, local knowledge can often add significantly to the understanding of the erosional history of a site. Oftentimes factors not readily observable in aerial photographs, such as the construction of a dam, or the dredging of a waterway may have a significant influence on the coastal processes at a site. Interviewing public works directors, adjacent landowners, environmental commission members, etc. can often provide invaluable information on factors such as these that may have a significant influence on the design and performance of a living shorelines project.

Observing a marsh shoreline in the field can also provide insight into the health of the marsh edge. Steep and high marsh scarps are more likely to erode than shorter and sloped or terraced marsh scarps. Root scalping, undercutting, slumping, and a concave scarp slope are all indicators of an eroding marsh edge. The type of marsh edge erosion observed is largely a function of water level and marsh cohesion. While growth of marsh grasses may make the top layer of sediment strong, it does not increase the cohesion of the layer below the root mat. Animal burrows often weaken marsh edges while mussel growth assists in stability. When completing field observations, note these different conditions to assess what section of marsh needs more intervention.

Sea Level Rise

Since 1911, sea levels along the New Jersey coast have risen approximately 1.5 ft or on average 1.7 inches per decade (Kopp, et al. 2019). Projections of future sea levels depend on greenhouse gas emissions; however, regardless of emissions, future sea levels along the New Jersey coast will be higher than they are today. Living shoreline projects are particularly sensitive to sea level rise due to the living elements of the projects; therefore, it is particularly critical to appropriately account for this information at the design phase. Marshes, in particular, require adequate sediment supply to maintain elevation and keep pace with sea level rise. Consideration should be given to whether sediment supply will be reduced with the addition of living shorelines on the edge. If this is the case, placing dredge material on the marsh platform (beneficial reuse) may help it keep pace with sea level rise.

Planning Level Analysis – Desk-top Analysis

NOAA maintains numerous coastal tide gauges, including three in New Jersey with long-term records. The rate of sea level rise calculated by NOAA for each of these stations is:

- Sandy Hook – 4.17 mm/yr, or 1.37 ft/century
- Atlantic City – 4.16 mm/yr or 1.36 ft/century
- Cape May – 4.84 mm/yr or 1.59 ft/century

At a minimum, it should be expected that these trends will continue into the future; however, Kopp, et al. (2019) found that the rate sea level rise has increased over the past half-century.

As part of a series of resilience planning efforts taking place in the state, a Science and Technical Advisory Panel (STAP) on Coastal Storms and Rising Seas was convened by the NJDEP. The panel was charged with evaluating the latest science and producing sea level rise estimates specific to New Jersey (Kopp, et al. 2019). After considering the science, the STAP settled on the estimates shown in Figure 7. In addition to the estimates, the STAP concluded that over shorter timeframes (<30 yrs) consistent with the life expectancy of most living shoreline projects, greenhouse gas emissions scenarios only have a minimal impact on the expected amount of sea level rise.

In 2021, New Jersey published an official sea level rise guidance document based on the findings contained in the STAP report. Although the guidance document recognizes the existence of other sea level rise estimates (IPCC for example), it recommends using the moderate emissions scenario contained in the STAP report for planning purposes. An expanded version of the STAP moderate emissions results is provided in Figure 8. The guidance further recommends that risk tolerance be used to determine whether the low-end, likely, or high-end values are used. For most living shorelines projects, the risk tolerance is likely to be high; therefore, it is recommended that values in the low-end to likely range be utilized for the design of most living shorelines projects.

		2030	2050	2070			2100			2150		
				Emissions								
	Chance SLR Exceeds			Low	Mod.	High	Low	Mod.	High	Low	Mod.	High
Low End	> 95% chance	0.3	0.7	0.9	1	1.1	1.0	1.3	1.5	1.3	2.1	2.9
Likely Range	> 83% chance	0.5	0.9	1.3	1.4	1.5	1.7	2.0	2.3	2.4	3.1	3.8
	~50 % chance	0.8	1.4	1.9	2.2	2.4	2.8	3.3	3.9	4.2	5.2	6.2
	<17% chance	1.1	2.1	2.7	3.1	3.5	3.9	5.1	6.3	6.3	8.3	10.3
High End	< 5% chance	1.3	2.6	3.2	3.8	4.4	5.0	6.9	8.8	8.0	13.8	19.6

Figure 7: Sea level rise estimates contained in (Kopp, et al. 2019).

Year	Low End	At least a 66% chance between			High End
	Greater than a 95% chance SLR exceeds	*Greater than an 83% chance SLR exceeds*	*~50% chance SLR exceeds*	*Less than a 17% chance SLR exceeds*	*Less than a 5% chance SLR exceeds*
2000			0		
2010			0.2 ft		
2020	0.1 ft	0.3 ft	0.5 ft	0.7 ft	0.9 ft
2030	0.3 ft	0.5 ft	0.8 ft	1.1 ft	1.3 ft
2040	0.5 ft	0.7 ft	1.1 ft	1.5 ft	1.9 ft
2050	0.7 ft	0.9 ft	1.4 ft	2.1 ft	2.6 ft
2060	0.8 ft	1.2 ft	1.8 ft	2.5 ft	3.1 ft
2070	1.0 ft	1.4 ft	2.2 ft	3.1 ft	3.8 ft
2080	1.1 ft	1.6 ft	2.6 ft	3.8 ft	4.8 ft
2090	1.2 ft	1.8 ft	3.0 ft	4.4 ft	5.8 ft
2100	1.3 ft	2.0 ft	3.3 ft	5.1 ft	6.9 ft
2110	1.6 ft	2.3 ft	3.7 ft	5.7 ft	8.1 ft
2120	1.6 ft	2.4 ft	4.1 ft	6.4 ft	9.4 ft
2130	1.7 ft	2.6 ft	4.5 ft	7.1 ft	10.9 ft
2140	1.9 ft	2.9 ft	4.9 ft	7.7 ft	12.4 ft
2150	2.1 ft	3.1 ft	5.2 ft	8.3 ft	13.8 ft

Notes: All values are 19-year means and are measured with respect to a 1991-2009 baseline. Projections are 19-year averages based on Kopp et al. (2014), Rasmussen et al. (2018), and Bamber et al. (2019). Moderate emissions are interpolated between the high and low emissions scenarios. Rows correspond to different projection probabilities. For example, the 'Likely Range' rows correspond to at least a 2-in-3 (66-100% chance) chance of sea-level rise from the relevant projections considered, consistent with the terms used by the Intergovernmental Panel on Climate Change (Mastrandrea et al., 2010). Note alternative methods may yield higher or lower estimates of the chances of low-end and high-end outcomes.

Figure 8: Sea level rise estimates for the moderate emissions scenario (adapted from Kopp, et al. 2019).

Additional estimates of sea level rise can be found on the USACE Sea Level Change Curve Calculator. This web-based tool facilitates estimation and comparison of future water levels based on sea level rise projections from:

- NOAA Global Sea Level Rise Scenarios for the United States National Climate Assessment (2012),
- USACE (2013),
- Strategic Environmental Research and Development Program (2016),
- NOAA US Global Change Research Program (2017), and
- NJ STAP (2019)

Current New Jersey state planning efforts include plans for revising sea level rise estimates on a regular basis to reflect the most recent science. It is recommended that all living shoreline projects in the state be designed with the most recent New Jersey state guidance in mind, and that whenever possible adaptability be incorporated into project designs such that modifications can be made if necessary.

Tidal Range

Tidal range is a critical factor in the design of most living shorelines projects. For submerged or low-crested structures such as sills, living reefs, or even small breakwaters, the position of the crest relative to the water level and wave heights (relative freeboard) and the width of the crest relative to the wave heights (relative crest width) determine the effectiveness of the structure in dissipating wave energy. The effect of crest width is even more pronounced when structures are submerged. At sites with a large tidal range this needs to be considered at the design phase as the effectiveness of the structure can vary appreciably over the course of a tidal cycle. Care should be taken when choosing design equations to ensure that the relative freeboard and relative crest width are within the applicable ranges of that equation.

Tidal range is also critically important for the living portion of living shorelines projects. Reestablishment of vegetation, whether natural or placed is highly dependent on the relative elevation of the substrate. Typically, high marsh is only inundated periodically during storms or spring tides, while low marsh is inundated regularly with water. In New Jersey, *Spartina patens* and *Phragmites australis* are two species typical of a high marsh, while *Spartina alterniflora* is typical of a low marsh. Likewise, the growth of living reef elements such as mussels and oysters will be dependent on their location with respect to the water surface. The Atlantic oyster (*Crassostrea virginica*) is the most common on the eastern seaboard and often is submerged 60-80% of the time; however, it can survive submerged at little as 50% of the time (Morris et al 2021).

Planning Level Analysis

A first order assessment of the tidal datums and variation at a site can be obtained by identifying nearby gauges and assuming that the local conditions are the same. There are many sources of tidal information. NOAA maintains a series of coastal tide gauges with established datums and has recently (2021) modernized their tide tables and made them available digitally. Tidal ranges for subordinate stations can be calculated by applying the height offset factors provided in the tide tables to the appropriate reference stations. NOAA also offers its VDatum tool. VDatum is a software tool for converting geospatial data between a variety of tidal, orthometric and ellipsoidal vertical datums. VDatum models the water surface between known stations and therefore has known uncertainties.

Other sources of tidal information include the United States Geological Survey (USGS), and local universities such as Stevens and Rutgers. Unfortunately, many of these stations do not have established tidal datums. For short tide gauge records without established tidal datums, the methodology outlined in NOAA's *Computational Techniques for Tidal Datums Handbook* (National Oceanic and Atmospheric Administration, 2003) is recommended for accurately establishing tidal datums.

It should be noted that significant water level variations can occur over relatively small distances, in rivers and coastal bays, therefore higher-level analyses are recommended for establishing final design elevations.

Implementation Level Analysis - Measurements

Because significant water level variations can occur over relatively short distances, field sampling of water levels is recommended to establish the local tidal variation at the project site. While short term records will provide an indication of the daily fluctuations, the methodology outlined in NOAA's *Computational Techniques for Tidal Datums Handbook* (National Oceanic and Atmospheric Administration, 2003) is recommended for establishing local tidal datums. Observations should be made for a minimum of one month according to the procedures outlined in the manual. For East Coast stations, (Swanson, 1974) estimated the accuracy of tidal datums based on short time series at between 0.13 ft (1-month record) and 0.05 ft (12-month record).

Implementation Level Analysis - Modeling

Tidal elevations can also be obtained from circulation models such as Stevens New York Harbor Observation and Prediction System (NYHOPS) model. The procedure for establishing tidal datums from numerical model results over shorter time frames is like that described above for short observational records. Models can also be used to understand how changes in natural processes (e.g., sea level rise (Blyth Lee, 2017), increasing/decreasing ice (Georgas, 2012) and human interventions (e.g., dredging (Ralston, et al. 2019), storm surge barriers (Orton, et al. 2019)) impact tidal fluctuations. It is important that any model used for any purpose be properly calibrated and validated.

Hydrodynamic Parameters

Generally, the hydrodynamic parameters at a site represent the dominant forcing mechanism contributing to the existing shoreline condition and influencing the proposed living shorelines project. Understanding the hydrodynamic conditions at a site is critical to designing a successful living shoreline project.

Wind Waves

In New Jersey most potential living shorelines sites are impacted by a combination of natural, wind-driven waves, and human-induced boat wakes. Although measurements of wind driven waves are uncommon, the process of wind wave growth is well understood and there are many methods of estimating the wind-wave climate. Wind waves are formed when wind blows over the water surface generating surface currents and waves. The wind speed, the duration of the wind, and the open-water distance over which it acts (fetch) will determine how large the waves grow. At most inland sites wave growth will be limited by the available fetch, and as a result wave heights and periods are generally much less than those observed on ocean coastlines. Exceptions may occur near inlets or along exposed bays where oceanic swell may reach the shoreline.

When designing a living shoreline project, there are generally two wave heights which are important. The first is the maximum expected or extreme wave height. This is the wave height typically used to design traditional coastal engineering structures that are designed to function and survive these conditions. Recent studies of eroding marshes however suggest that the most marsh edge erosion occurs during typical rather than extreme conditions (Leonardi, et al. 2015). (Shafer, et al. 2003) found that the presence or absence of marsh vegetation along the Texas and Alabama coasts was most sensitive to the wave height exceeded approximately 20% of the time. (Leonardi, et al. 2015) suggest that marsh edge erosion is most sensitive to the average wave power attacking the marsh and suggest using the 2.5-month storm wave conditions as a proxy. As a result, living shorelines need to consider a second, more common, operational wave height. Generally, living shorelines should be designed to function in the operational condition and survive the extreme condition.

Planning Level Analysis

There are several desk-top approaches for estimating the wave conditions or "energy" expected at a living shorelines site. The simplest approach developed by (Hardaway Jr., et al. 1984) and refined by (Hardaway Jr. & Byrne, 1999) simply relates the relative energy at the site to the fetch. It is recommended that both the average fetch and the longest fetch are considered when designing a living shorelines project. Based on the energy regime, recommended stone sizes (weight and diameter), structure/habitat combinations, and backshore widths were provided as shown in Table 3. Although there is no direct correlation with the ranges in Table 1 and Table 2, the medium energy conditions presented in Table 3 are roughly consistent with the moderate conditions in the prior tables.

Table 3: Fetch categorization according to Hardaway (1984)

Energy	Fetch (mi)	Weight (lb)	Diameter (ft)	Sill/Marsh	Width(ft)
Very Low	<0.5	300-900	1.4-2.0	Sill/Marsh	-
Low	0.5 - 1.0	300-900	1.4-2.0	Sill/Marsh	-
Medium	1.0 – 5.0	400-1,200	1.5-2.1	Sill/Marsh	40-70
Medium	1.0-5.0	800-2,000	2.0-2.6	BW/Beach	35-45
High	5.0 - 15.0	2,000-5,000	2.6-3.5	BW/Beach	45-65

Very High	>15.0	2,000-5,000	2.6-3.5	BW/Beach	45-65

A shortcoming of the above approach is that it does not take into consideration wind direction. In New Jersey, for example, the strongest winds in most locations come from the Northeast and Northwest quadrants and are typically associated with winter storms. Longer fetches in these directions tend to create bigger waves due to the (generally) stronger winds. A slightly more rigorous approach also discussed by (Hardaway, et al. 2010) is to factor in the wind climate. Several empirical methods for doing this are discussed in the USACE Coastal Engineering Manual (US Army Corps of Engineers, 2002) and The Rock Manual (CIRIA, et al. 2012). One of the more common methods is the shallow-water SMB method. Comparisons of variations of the SMB approach with several other formulas are found in (US Army Corps of Engineers, 1984) and (Etemad-Shahidi, et al. 2009). The various formulas generally produce consistent results, specifically for the range of conditions for which living shorelines projects are designed.

Implementation Level Analysis - Measurements

Wave measurements may be carried out either independently, or to verify wave predictions from a Planning Level Analysis or hydrodynamic modeling (Implementation Level Analysis). When measuring waves in sheltered water bodies, it should be kept in mind that wave periods tend to be small and that the selected instrumentation should be capable of capturing water surface fluctuations in the 1.5 - 10 second range. Any wave data collection will only capture a snapshot of the conditions during the instrument's deployment; therefore, deciding on an appropriate sampling interval and duration are critical. Some of the instruments typically used to measure wave data are described below.

Pressure Gauge

Pressure gauges work by recording the fluctuating pressure underneath a wave. Pressure gauges are typically secured to the bottom using an anchor or elastic ties where they measure the total pressure above the gauge. Through processing the data, the dynamic pressure related to the presence of the waves can be isolated. Due to pressure attenuation effects, pressure gauges placed in deep water can have difficulty measuring short period waves. Pressure gauge measurements are typically non-directional unless they are placed in an array. In addition to commercial gauges, guidance for constructing, deploying, and the analyzing data from low-cost pressure gauges is becoming more readily available.

Accelerometer Buoy

Accelerometer buoys are more often used to collect wave data in deep-water environments; however, they can also be used in shallow water. The buoy is typically anchored to the bed and uses an accelerometer placed within the buoy to measure the rate at which the buoy rises and falls (correlating with the passing waves). Integrating with respect to time the data can then be converted to displacement. Through incorporating additional sensors, the buoys can be made directional. Since they ride on the surface, accelerometer buoys are generally capable of measuring even very short period waves.

Acoustic Wave Gauge

Acoustic wave gauges are typically fixed to the bed, mounted on a piling or attached to a buoy and utilize pressure and acoustics to generate directional wave measurements. The traditional approach combines measurements of pressure (from which the wave heights can be determined), and u and v current velocities (from which the direction can be derived) to create the directional wave record. Unfortunately, this approach is subject to the same limitations as pressure gauges when it comes to measuring short period waves. More recently gauges have been developed that use acoustics to directly measure the air-water interface. These measurements can be combined with traditional velocity measurements in the same way that pressure has been traditionally used to generate directional measurements with fewer depth and wave period limitations.

Wave Wire

Wave wires are gauges typically used in the nearshore that use either resistance or capacitance to directly measure water surface oscillations. Resistance gauges simply measure the resistance in a wire to which a voltage is applied. Seawater shorts the underwater portion of the wire leading to time variations in the resistivity. In capacitance wave gauges, the seawater is used as one plate of a coaxial capacitor. As the water level changes, the capacitance in the staff changes.

Lidar and Radar

Advanced remote sensing techniques including lidar and radar can be used to measure nearshore wave heights. Both systems operate on similar principles, where an energy source is emitted, and a receiver observes the reflection of that energy. The properties of the reflected energy provide information about the objects they encounter, including their distance from the source and their relative speed. Lidar systems use lasers as the source of energy, while radar systems rely on sound.

Low-Cost Approaches

Several simpler, low-cost approaches exist for estimating wave energy as well. Many of these approaches have been used traditionally during the design of living shorelines projects. Wave heights can be directly measured by recording water level oscillations on a graduated staff as shown in Figure 9. (Rella, et al. 2014) describe a very basic visual observation technique which was used to measure boat wakes at dozens of sites along the Hudson River. (Findlay, et al. 2018) describe the use of plaster casts to assess the overall energy at a site. Note this technique does not distinguish between wind wave, boat wake and current energy and is typically only used to make qualitative observations.

Implementation Level Analysis – Modeling

Figure 9: Visual Wake Measurement near a Bulkhead

For complex projects, sophisticated wave models can be used to provide a detailed analysis of the wave patterns in and around a site. Wave modeling typically takes a significant amount of effort but may be warranted depending on the complexity of the project. For application to most living shorelines projects, shallow water wave models that can accurately represent important processes, like shoaling, refraction, dissipation, diffraction, etc. should be used. Some wave models are included as a part of a modeling package containing fully 3-D hydrodynamic and morphologic models (Delft3D and Mike21 for example). These models will have the advantage of being able to consider more complicated processes and even predict the sediment transport and coastal evolution with and without the proposed project. Standalone phase-averaged models that can be applied in bay/estuarine environments include SWAN and STWAVE. These models estimate the evolution of the wave energy spectrum and can be used to derive design parameters such as wave height, period, and direction. For highly complex projects more advanced techniques such as Boussinesq wave modeling or Smoothed Particle Hydrodynamics (SPH) can be used to model individual waves; however, these approaches are typically outside of the scope for most living shoreline projects. Regardless of the model selected, a thorough calibration and validation procedure should be followed to ensure that the model results accurately reproduce the physical measurements.

Wakes

Wakes or ship-generated waves can be one of the most significant sources of wave energy within sheltered water bodies. As ships pass, two distinct types of waves are generated as depicted in Figure 10. Divergent waves are waves generated by the bow of the vessel as it moves through the water. Transverse waves are waves generated by the stern and propellers. The largest wakes are generated at the point where the two types of waves intersect along the cusp locus line, which occurs at an angle of 19.3 degrees from the sailing line. For large, slow-moving ships such as barges the transverse wakes will generally be dominant, while for smaller, faster moving vessels the divergent wakes will dominate. Once generated, wakes will propagate away from the point of generation where they will be modified by the local conditions including the wind and bathymetry. Wakes are rarely if ever considered during design in a physically satisfying manner, due to a lack of measurements and reliable design formulas.

Planning Level Analysis

The ability to perform a desk-top analysis of wakes is limited by the scarcity of archived wake data. Despite its importance to the design of inland shoreline stabilization and restoration works, little to no wake data exists. At the Planning Level Analysis stage, a cursory evaluation of the potential importance of wakes can be made by identifying features such as nearby marinas or navigation channels that will influence the size and frequency of ship traffic. Records for larger boats can be found on the [Automatic Identification Systems (AIS)](#) online portal. AIS is required equipment on

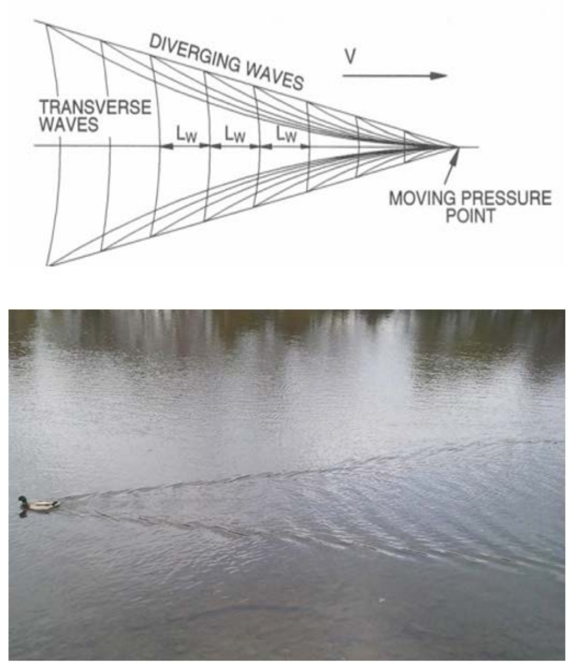


Figure 10: Typical wake wave pattern.

- ships larger than 500 gross tons,
- ships larger than 300 gross tons that travel internationally,
- commercial ships longer than 65 feet,
- towing ships of 26 feet or more in length and more than 600 hp, and
- ships that carry more than 150 passengers.

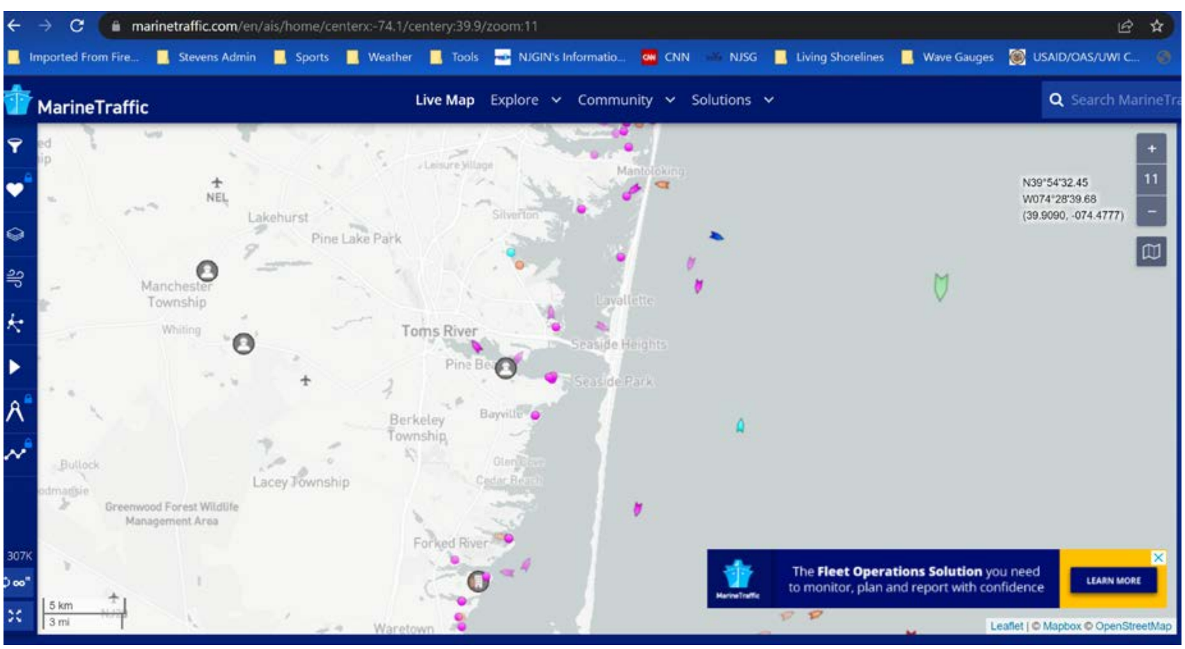


Figure 11: Sample AIS output.

Most recreational ships however will not be captured by the AIS system. Although the reliability of empirical wake estimations is questionable, methods for estimating the divergent and transverse wakes based on the characteristics of the vessel and waterbody can be found in (Sorensen, 1997), and (CIRIA; CUR; CETMF, 2012).

Recently, the USACE has developed a Vessel Wake Prediction Tool (VWPT) that provides a rapid, low-order assessment of the potential impacts of vessel wakes in comparison to other forcing at a site. The tool provides an exploratory assessment on the relative contribution of energy dissipation due to vessel wake compared to the ambient dissipation caused by tidal and river flow. The USACE recommends that VWPT be used in conjunction with other more quantitative methods (e.g., measurements) to help explore 'what if' scenarios where vessel wake is important.

Implementation Level Analysis – Measurements

The instruments described above in the wind wave section can also be used to collect wake data. As with wind generated waves, the periods of wakes tend to be small (1.5-4 sec) so an appropriate instrument with the proper settings should be selected. Due to the shallow depths and short-wave periods, pressure transducers, wave wires, and surface-attached acoustic gauges are most common. As wakes are inherently more irregular, it is often necessary to analyze the data in the time domain (as opposed to the frequency domain) to capture individual wake events. To get a true sense of the wake energy at a site, measurements should be taken over several deployment windows to reduce bias due to factors like variations in boat traffic due to seasonality, weather, or other factors. For sites where critical vessels (ferries, barges) are encountered, the measurement plan should be sure to include time periods where these wakes will be encountered.

Implementation Level Analysis – Modeling

Although less common, numerical models can be used to assess wake impacts. El Safty and Marsoolli (2020) illustrated the potential of phase-resolving wave models to estimate boat-wake induced erosion in Jamaica Bay. Their work indicated that cumulative erosion increased rapidly and potentially non-linearly with the number of passing vessels. They found that the magnitude of bed erosion after the passage of ten vessels was two to three times larger than that after the passage of five vessels. As with all models, models for predicting boat wakes should be calibrated and validated prior to use.

Currents

Although waves are generally considered to be the primary force impacting the design of coastal structures, currents also play an important role, particularly for living shorelines projects located near tidal inlets, riverbanks or natural/engineered drainage features. Erosion rates are typically higher in regions of high current. Currents have the capacity to uproot vegetation, scour the bank, and during storms can transport debris which increases the scour potential. In areas subject to freezing, currents can also transport blocks of ice, which like debris can scour the shoreline.

Planning Level Analysis

It is rare that sufficient current data exists to perform a desk-top analysis of currents. General data can be obtained from NOAA, the USGS, and the USACE; however, none of these sources provides enough localized detail for final design. In some cases, discharge measurements can be converted into crude estimates of velocity by dividing by the channel cross-sectional area. For some locations, detailed hydrodynamic models exist, from which typical or even storm currents may be extracted. Stevens NYHOPS model is one such example; however, the model generally lacks detail in New Jersey's coastal inlets and bays. In extremely rare cases, statistical summaries or climatologies based on measured and/or modeled data may exist. An example is the physical forces climatology developed for the Hudson River through the Hudson River Sustainable Shorelines Project.

Implementation Level Analysis – Measurements

Current measurements can be collected at a site using a variety of instruments. Typically, an Acoustic Doppler Velocimeter (ADV) or an Acoustic Doppler Current Profiler (ADCP) would be used. Both instruments are generally bottom mounted and use the physical properties of sound to deduce the current velocity. ADCPs offer an advantage over ADVs in that the vertical variation of the current is measured rather than taking a measurement at a single elevation. This vertical variability can be important for calculating things like forces on structures, sediment transport, and scour potential. ADCPs can be towed across or along a channel to create a current velocity transect such as that shown in Figure 12. A limiting factor for both ADCPs and ADVs in shallow water is the fact that measurements taken too close to the transducer heads are invalid (the so-called blanking distance).

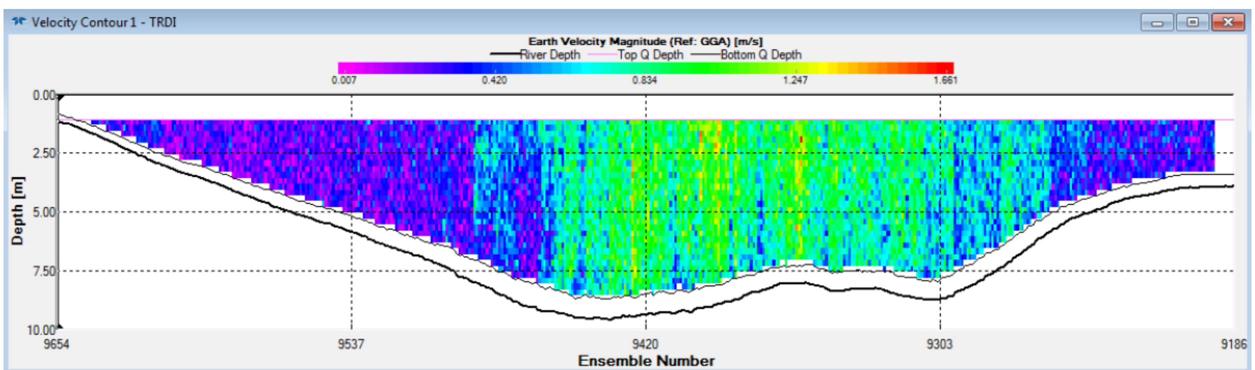


Figure 12: Example towed ADCP velocity profile transect

Other approaches exist for measuring currents ranging from high-tech methods such as surface radar/lidar and particle tracking, to low-tech methods such as current drifters. An example of surface current data collected using low-cost (< $200) GPS drifters are shown in Figure 13.

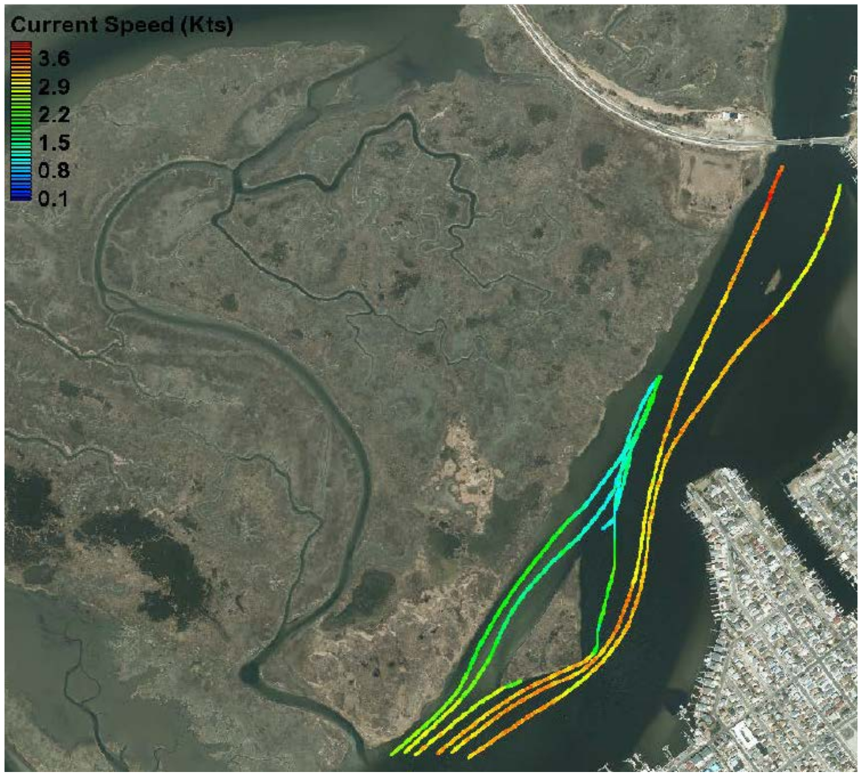


Figure 13: Example surface current data collected using low-cost GPS drifters.

Implementation Level Analysis – Modeling

If the complexity and scale of the project requires, sophisticated circulation models can be used to provide an extremely detailed look at the current patterns in and around a site. Hydrodynamic modeling typically takes a significant amount of effort but may be warranted depending on the complexity of the site. For application to most living shorelines projects, shallow water models capable of representing the flow patterns close to shore should be used. While both 2-D and 3-D models exist, in a nearshore estuarine/bayshore environment 3-D models provide significantly more detail and are much more capable in the shallow water/nearshore settings where living shorelines projects are likely to be constructed. Some of the more commonly used nearshore modeling packages include Delft3D, Mike21, and ECOMSED. Both Delft3D and Mike21 are also capable of modeling waves. Locally, Stevens operates an operational version of the ECOMSED model, known as NYHOPS which is capable of simulating currents and waves. Regardless of the model selected, a thorough calibration and validation procedure should be followed to ensure that the model results accurately reproduce the physical measurements.

Ice

Ice is known to have a significant impact on shorelines and coastal structures; however, design guidance for dealing with ice impact is limited. This is particularly true for living shorelines projects which historically have been constructed in locations where ice is less of a concern. Floating ice acts similarly to other types of floating debris and can impose large impact forces to shorelines and structures. Additionally, when ice becomes frozen to either vegetation or a structure, the uplift produced by buoyant forces related to tidal fluctuations can cause significant damage. To improve design, additional research is needed on methods of predicting ice formation, and design methodologies for dealing with it. In the short-term living shorelines design strategies for ice typically fall into one of two categories: 1) designing with a factor of safety and/or 2) trying to prevent ice from reaching the project.

Planning Level Analysis

In some locations records of ice are collected by organizations such as the United States Coast Guard (USCG); however, these records are rare, and the authors are unaware of any data available for New Jersey. An example of the type of information that can be used to aid living shorelines projects designers is the Hudson River Sustainable Shorelines Ice Climatology which contains information collected by the USCG on the Upper Hudson River Estuary.

The National Ice Center archives ice cover within Delaware Bay based on MODIS (Moderate Resolution Imaging Spectroradiometer) satellite imagery and provides estimates of ice presence but not thickness. Similarly, the USACE maintains an archive of historic ice jams; however, the level of detail is generally insufficient to be of much use in the design of living shorelines. An approach for estimating ice thickness based on procedure for calculating ice growth (US Army Corps of Engineers Cold Regions Research and Engineering Laboratory, 2004) can be found in Appendix B: Technical Excerpts.

Implementation Level Analysis – Measurements

A variety of techniques and tools exist for measuring ice directly and indirectly. Typically, the instruments use measurements of pressure (depth) and range (distance) to estimate the ice thickness. The major drawback in any attempt to measure ice is that ice coverage, type, and thickness varies significantly from year to year. Ideally, measurements need to span several ice seasons to be considered reasonably representative.

Storm Water Level

The water level experienced during storms plays a significant role in the design of living shoreline projects. When designing traditional coastal structures, it is common to consider the water level during extreme events such as the 50, 100, or even 500-year (return period) storm. While these rare storms may also be considered for living shoreline projects, it is much more common to consider return periods of between 10 and 50 years, as during exceptionally large storms most living shoreline projects and the features they protect are submerged. Recognition of this fact can allow for smaller, less-expensive structures.

Planning Level Analysis

NOAA provides estimates of extreme water levels for each of their long-term tide gauges on its Tides and Currents website. The estimates for the three New Jersey gauges are provided in Table 4.

Table 4: Annual exceedance probabilities for NOAA tide gauges

Annual Exceedance Probability	Sandy Hook (m MSL)	Atlantic City (m MSL)	Cape May (m MSL)
1%	2.96	2.29	2.06
10%	2.10	1.85	1.87
50%	1.68	1.55	1.66
99%	1.40	1.31	1.39

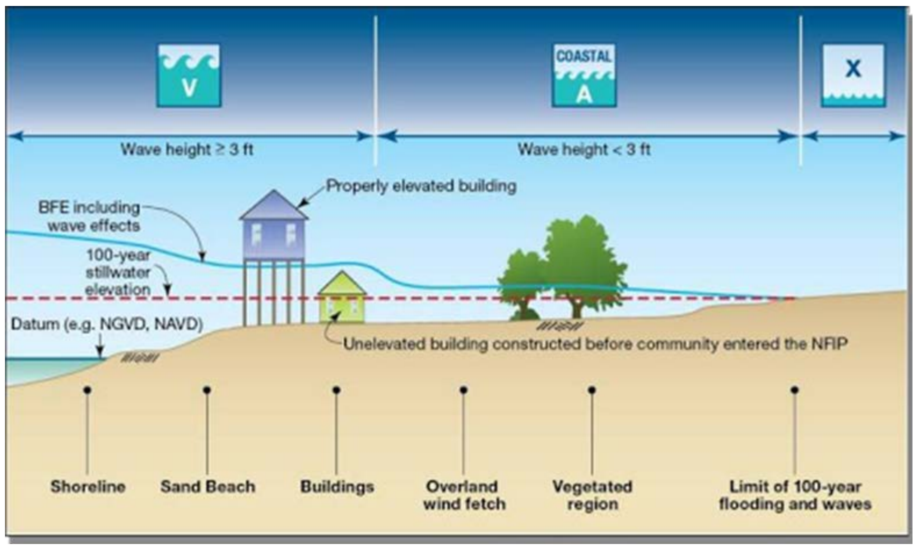
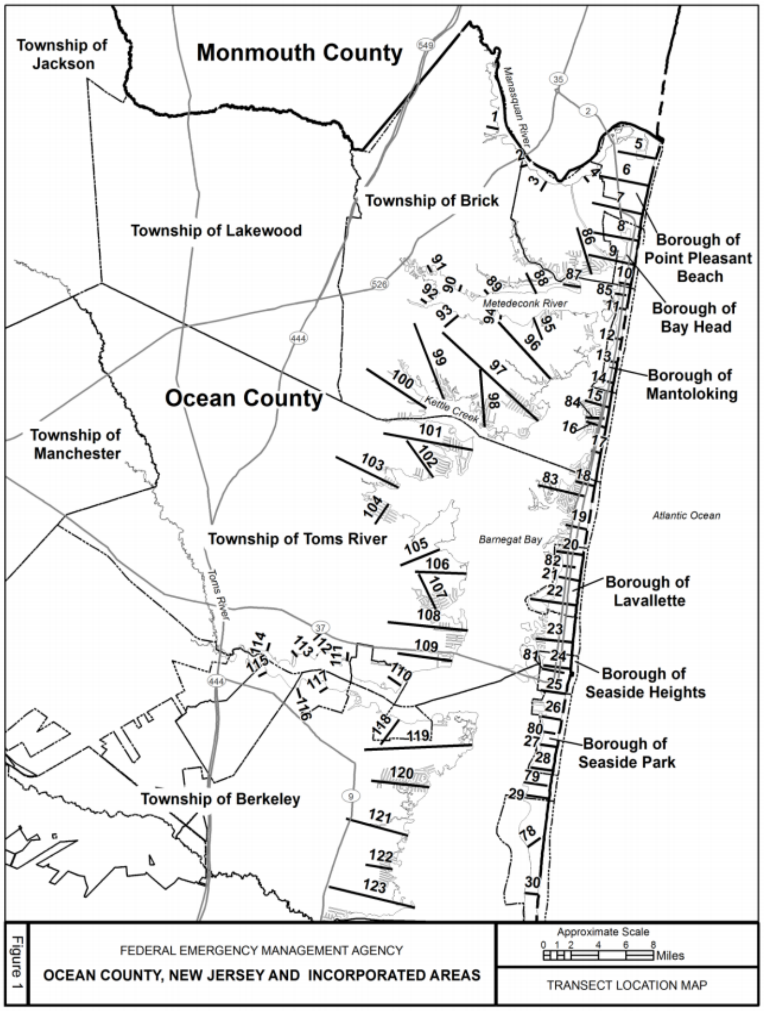


Figure 14: FIRMs Definition sketch showing flood zone and BFE designation

Estimates of the water level expected during storm events can be obtained from FEMA Flood Information Study (FIS) reports and Flood Insurance Rate Maps (FIRMs). The reports and maps are available on the FEMA website. The FIRMs split the coast into zones based on the type of flooding and wave activity expected during a 100-yr storm as shown in Figure 14. Most living shoreline projects will be located in special flood hazard areas (A zones) or coastal high hazard areas (V zones). V zones delineate areas where high velocity flow, or 3-foot wave heights are expected during the 1% annual chance of occurrence or the 100-year storm. The elevations depicted on the FIRMs represent the Base Flood Elevation (BFE), which is the 100-year still water elevation plus a contribution from the waves (the larger of the wave run-up or the wave crest elevation). Still water elevations (which include the effect of wave setup, but not wave runup or crest elevations) for the 10%, 2%, 1%, and 0.2% annual chance of occurrence storms can be obtained from the accompanying FIS reports. Examples of a transect location map and the corresponding wave and water level information are shown in Figure 15.



Flood Source	Transect	Starting Wave Conditions for the 1% Annual Chance			Starting Stillwater Elevations (ft NAVD88) Range of Stillwater Elevations* (ft NAVD88)			
		Coordinates	Significant Wave Height	Peak Wave Period	10% Annual Chance	2% Annual Chance	1% Annual Chance	0.2% Annual Chance
Atlantic Ocean	13	N 40.035303 W 74.049881	18.86	13.99	7.1 3.8 - 7.1	9.2 6.3 - 9.2	10 7.3 - 10	12.2 9.7 - 12.2
Atlantic Ocean	14	N 40.029256 W 74.051492	18.92	14.00	7.1 4 - 7.1	9.2 6.4 - 9.2	10.1 7.4 - 10.1	12.2 9.6 - 12.2
Atlantic Ocean	15	N 40.021936 W 74.053220	19.15	13.98	7.1 3.9 - 7.1	9.2 6.3 - 9.2	10.0 7.3 - 10.0	12.2 9.5 - 12.2
Atlantic Ocean	16	N 40.015948 W 74.054657	19.44	14.00	7.2 4.0 - 7.2	9.3 6.3 - 9.3	10.1 7.3 - 10.2	12.2 9.5 - 12.3
Atlantic Ocean	17	N 40.008315 W 74.056716	19.28	14.07	7.3	9.3 6.2 - 9.3	10.1 7.2 - 10.2	12.2 9.5 - 12.2
Atlantic Ocean	18	N 39.998537 W 74.059064	19.75	14.05	7.2 3.9 - 7.2	9.3 6.2 - 9.3	10.1 7.2 - 10.1	12.1 9.4 - 12.1
Atlantic Ocean	19	N 39.985632 W 74.062109	19.98	13.89	7.2 3.8 - 7.2	9.3 6.1 - 9.3	10.1 7.0 - 10.1	12.1 9.2 - 12.1

Figure 15: Example FEMA FIS transect data

Another useful source of storm water level information is the [USACE Coastal Hazards System](#) (CHS). The CHS is a national coastal storm hazard data resource that supports probabilistic coastal hazard assessment. The CHS database stores numerical and probabilistic modeling results including storm surge, astronomical tide, waves, currents, and wind from high-resolution numerical modeling of coastal storms spanning the practical probability and forcing parameter space. The New Jersey modeling was performed in the wake of Hurricane Sandy as part of the North Atlantic Coast Comprehensive Study (NACCS) (US Army Corps of Engineers, 2015). Of particular relevance to the design of living shorelines are the archived wave height and water level data, an example of which is shown in Figure 16. Most of the CHS save points are in open water; therefore, the results are comparable to FEMA still water levels, minus the wave setup and runup contributions.

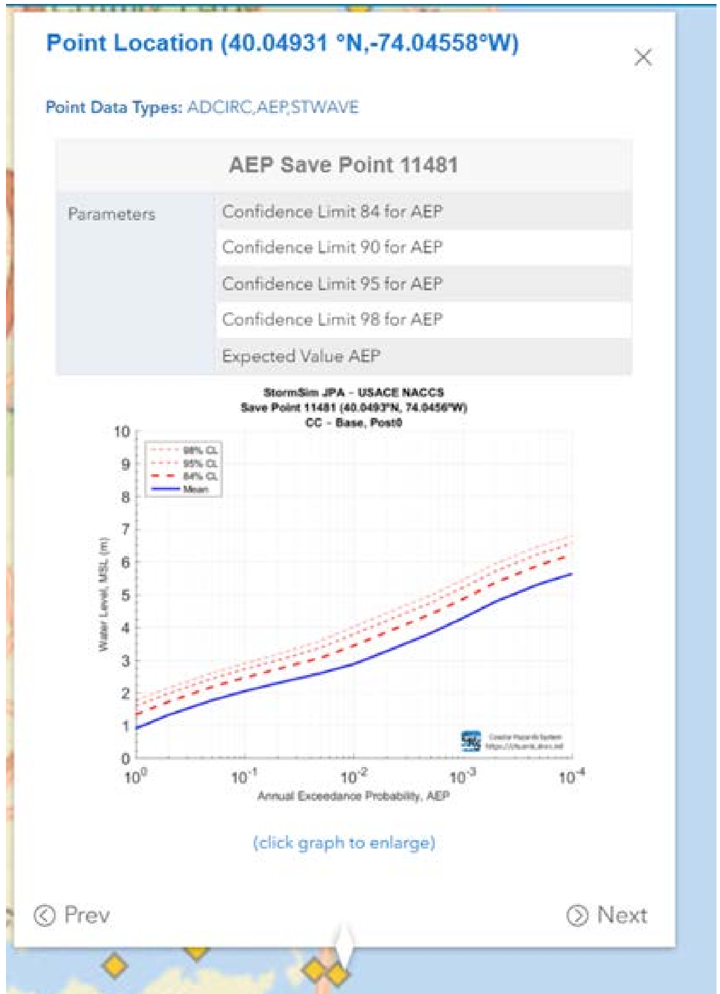


Figure 16: Example Coastal Hazards System data

Implementation Level Extreme Value Analysis

When the project site is located in the vicinity of a tide gauge with a long-term record, an extreme value analysis can be performed to estimate the water level associated with the design storm (typically 50 or 100 year). A thorough review of extreme value analysis approaches and methodologies can be found in Appendix D of FEMA's *Guidelines and Specifications for Flood Hazard Mapping Partners* (Federal Emergency Management Administration, 2002). (Arns, et al. 2013) reviewed several different approaches for estimating extremes and concluded that a peaks over threshold approach with an objective model setup produced the most consistent results.

Terrestrial Parameters

Terrestrial parameters represent the condition of the land both below and above the water. It is the relationship between the terrestrial parameters, which represent the existing condition, and the hydrodynamic parameters which represent the forcing that generally determines a given shoreline's behavior. Terrestrial parameters play a significant role in dictating what type of shoreline modification is appropriate and how the selected treatment will respond to the local conditions. Terrestrial parameters include the upland, shoreline, and nearshore slopes, project width, and the offshore depth (defined in Figure 17) and the soil bearing capacity. Generally, the most appropriate shoreline modification will be the one which mimics surrounding naturally stable shorelines.

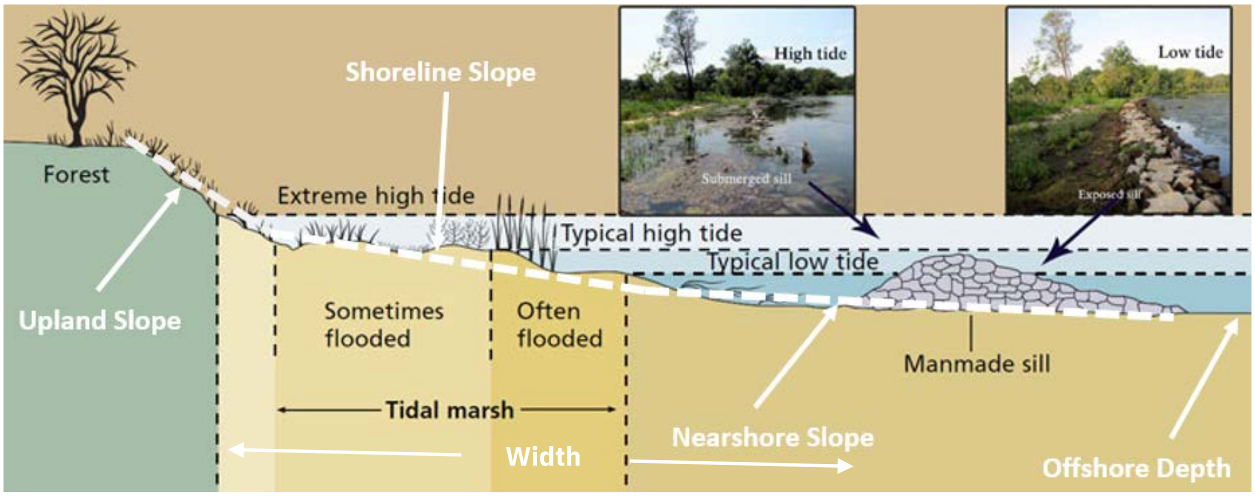


Figure 17: Terrestrial parameters definition

Upland Slope

Here the upland slope is defined as the slope of the land from approximately the spring high water elevation to the point at which the upland levels off. The upland slope is critical for determining the type of vegetation that can be supported and the likelihood of scarping during storms. In general, gentler slopes are more susceptible to inundation and less susceptible to erosion, while steeper slopes will act as a barrier to marsh migration.

Planning Level Analysis

It is often possible to obtain a sense of the upland slope by examining existing data sources. Topographic maps, DEMs, and lidar data sets are frequently available online. The USGS maintains an extensive online database of topographic maps. State resources including 10m grid DEMs can be found on the NJDEP Bureau of GIS website. Typically, several sets of lidar data for most coastal locations in New Jersey can be obtained from the NOAA Digital Coast.

Implementation Level Analysis - Measurement

Data obtained from a desk-top analysis will often have one of two limitations. Estimates of the upland slope obtained from topographic maps or DEMs will generally be very coarse. Lidar data sets typically have much higher resolution; however, they are collected relatively infrequently. On a developed eroding coast, the frequency of data collection poses a problem due to the rapid pace of erosion and human modification of the shore zone. To ensure that living shorelines projects are designed based on the most accurate and up to date conditions, a pre-design site survey is recommended. The SfM, RTK GPS, and low-cost surveying techniques described above under Erosion History can also be used to determine the upland slope. Upland slope surveys should generally take place at low tide to maximize the survey area.

Shoreline Slope

The shoreline or intertidal slope is important in determining the appropriate living shoreline technique for a particular site. Here the shoreline slope is defined as the slope from approximately Mean Lower Low Water (MLLW) to the Spring High Water line. Most living shorelines projects require gentle shoreline slopes so that marsh vegetation can be established. A recent analysis of the performance of several stabilized shorelines in New York State during Hurricanes Irene, Lee, and Sandy determined that oversteepened slopes contributed to the loss of vegetation and subsequently to the development of erosion at the site (Miller, et al. 2015).

Planning Level Analysis

Determining shoreline slopes is more difficult because the area of interest often lies along the boundary between two different data sets. The topographic data sources discussed above provide information above water, while the bathymetric data sets discussed below provide information below water. Some of the data sets however span the shoreline region, including modern topographic and bathymetric Lidar systems which use a dual laser system to penetrate the water's surface. Estimating the shoreline slope can be done either by working with a data set such as lidar that covers the area of interest or by patching together a topographic and a bathymetric data set. If the patchwork approach is selected, particular attention should be paid to the datums to ensure that they are consistent. In the wake of Hurricane Sandy, the USGS and NOAA developed a three dimensional topobathymetric elevation model of the New Jersey and Delaware coasts, a portion of which is depicted in Figure 18.

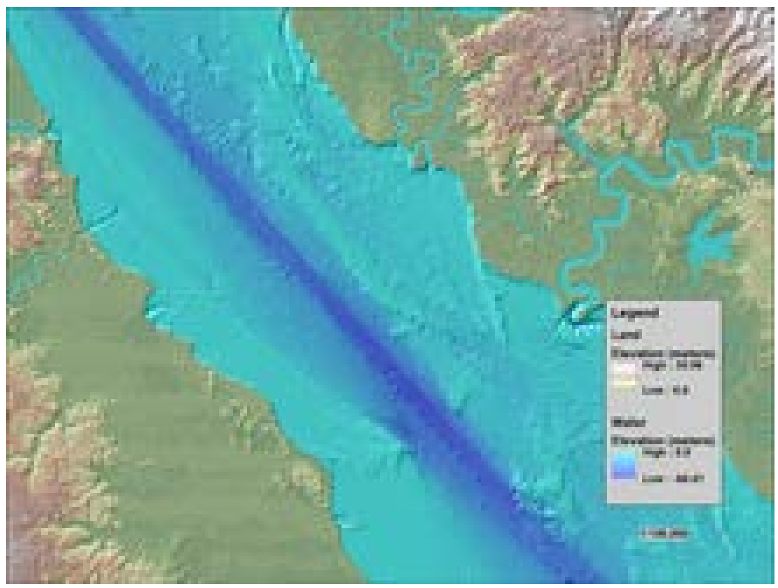


Figure 18: USGS and NOAA Topobathymetric model of a portion of the Delaware River https://www.usgs.gov/media/images/topobathymetric-elevation-model-delaware-river-basin

Implementation Level Analysis - Measurements

The topobathymetric model described above is an excellent source of information; however, due to the costs involved such datsets are updated infrequently. This poses a problem on developed and/or eroding coasts, where things change rapidly, especially near the shoreline. To ensure that living shorelines projects are designed based on the most accurate and up to date conditions, a pre-design site survey is recommended. The RTK GPS and low-cost surveying techniques described above under Erosion History can also be used to determine the shoreline slope; however, this will typically involve wading out into the water or surveying at an extremely low tide. Surveying as close to low tide as possible will minimize the wading depths encountered during the survey.

Width

Along developed coastlines, the horizontal space between the developed area and the water's edge is often reduced or eliminated. For a living shoreline project to be successful, the amount of available space must meet or exceed that required for the project. Minimum recommended beach/marsh widths were provided in (Hardaway Jr. & Byrne, 1999) and are reported in Table 3. When space is not available, generally two options exist for creating it. The first is to landscape back into the site at an appropriate slope. The second is to advance the shoreline using fill. In New Jersey, as in most states, there are strict regulations prohibiting the placement of fill below the mean high water (MHW) line; however, the Living Shorelines General Permit (GP 24) provides an exception for wetland restoration projects. The exception allows fill placement out to the shoreline delineated on the 1977 tidelands map for the purposes of habitat enhancement.

Planning Level Analysis

The available width at a site can often be determined by examining aerial photography and/or digitized shorelines of the project site. There are many free resources that can assist in determining the width at a site including:

- Google Earth – Google Earth is a free geographical information program that stitches together satellite imagery, aerial photography, and geographic information systems 3-D globe. Google Earth contains a measurement tool that allows for a quick estimation of the distance between discernable features such as the upland and the shoreline. Caution is urged however in that features such as the shoreline may not always be distinguishable and can sometimes be misinterpreted.
- GIS Data Repositories – Current and historic shorelines are typically available in GIS form from several local, county, state, and federal sources. Relevant datasets available from the NJDEP include the shoreline structure dataset, the historic shoreline dataset, and the 1977 tidelands base map. The data can be accessed from the NJDEP Bureau of GIS, New Jersey Geological and Water Survey, and the New Jersey Geographic Information Network websites.
- Bing maps– Bing Maps is a useful source for obtaining current high-resolution "birdseye" photographs of shoreline sites. While the level of detail is typically very high, the photographs cannot be used for measurements since they are not orthorectified.
- Lidar Data – Lidar is a method of obtaining high resolution surface elevation data over vast areas. Large datasets are typically collected from a plane and require significant post-processing making them relatively expensive to obtain. As a result, only a limited number of datasets is typically available for a given area. Several federal and state

agencies, such as NOAA Digital Coast, maintain and disseminate lidar data for use by the public. Shore widths can typically be measured directly from lidar datasets.

Implementation Level Analysis – Measurements

A more accurate estimate of the shore width can be determined from a nearshore survey. Depending on the slopes at the site of interest, the survey may require a bathymetric component.

Nearshore Slope

The nearshore slope, typically the tidal flat slope in a marsh environment, plays a critical role in determining the behavior of the waves and currents immediately offshore of the site. The offshore contours will affect the size of waves impacting the shore, where the waves will break, and the amount of scour or sediment transport that should be expected. Steeper slopes generally reflect energy, while milder slopes tend to absorb and dissipate energy. Steeper sloping nearshore areas may require more fill if fill is a requirement of the project and may also make structures less stable. Understanding the bathymetry or under-water conditions is crucial for fully understanding the site and for structure selection/design.

Planning Level Analysis

It is often possible to get a preliminary sense of the nearshore bathymetry at a site from a desk-top analysis. While many freely available bathymetry data sets exist online, the resolution is typically insufficient for design purposes. Coarse sets of bathymetry data for New Jersey are available from NOAA's National Centers for Environmental Information, the New Jersey Geological and Water Survey, and the New Jersey Geographic Information Network websites. Both sites provide bathymetric data from which nearshore slopes can be inferred. The NOAA Digital Coast maintains a database of estuarine bathymetry data (DEMs) created by merging multiple surveys collected over time together. The data set includes several of New Jersey's larger bays/estuaries including Barnegat Bay, Delaware Bay, Raritan Bay, the Hudson River, and several of the inland bays in Atlantic and Cape May counties.

Implementation Level Analysis – Measurements

Estimates of nearshore slope obtained from bathymetric charts or DEMs are typically insufficient for a final design. In addition, the nearshore region tends to be dynamic and older surveys may be missing important nearshore features. Project specific bathymetric surveys can be conducted using a jet-ski, boat or kayak (Hampson, et al. 2011), equipped with GPS and sonar. To maximize the amount of area that can be covered during the hydrographic survey, the survey should be performed at high tide.

Offshore Depth

Offshore water depths, including tidal flat depths, are important in the design of living shorelines projects for several reasons. Deeper water reduces the amount of energy dissipation a wave experiences as it travels towards the shoreline. In addition, deep water allows the passage of larger ships which are generally capable of generating larger wakes that will impact the shoreline. The depth and extent of the tidal flat is critical in determining the size of waves that can approach the shore. Additionally, large shallow tidal flats are less likely to be the site of aggressive open water conversion of marshes (Mariotti and Fagherazzi, 2013). The larger and deeper a tidal flat is, the larger the waves, and the more likely the marsh along that tidal flat will erode. A critical size of tidal flat, strongly dependent on sediment availability, determines if the marsh will convert to open water or not. With enough sediment availability, marshes can propagate seaward and counteract wave erosion. Depending on the living shoreline approach selected, offshore water depth will also impact the amount of fill material and the size of the structure required.

Planning Level Analysis

The datasets available for assessing offshore water depths are essentially the same as those discussed above for nearshore slopes; however, the resolution issues are generally less of a concern when determining offshore depths. Bathymetry data for New Jersey can be found at NOAA's National Centers for Environmental Information, the New Jersey Geological and Water Survey, and the New Jersey Geographic Information Network websites. The NOAA Digital Coast maintains a database of estuarine bathymetry data (DEMs) created by merging multiple surveys collected over time together. The data set includes several of New Jersey's larger bays/estuaries including Barnegat Bay, Delaware Bay, Raritan Bay, the Hudson River, and several of the inland bays in Atlantic and Cape May counties.

Implementation Level Analysis – Measurements

The approach for obtaining site specific offshore depth information is generally the same as that discussed above for determining nearshore slopes. Estimates of nearshore slope obtained from bathymetric charts or DEMs are typically insufficient for a final design. In addition, the nearshore region tends to be dynamic and older surveys may be missing important nearshore features. Project specific bathymetric surveys can be conducted using a jet-ski, boat or kayak (Hampson, et al. 2011), equipped with GPS and sonar. To maximize the amount of area that can be covered during the hydrographic survey, the survey should be performed at high tide.

Soil Bearing Capacity

Soil bearing capacity is an important, often overlooked factor in the design of living shorelines projects. Most living shorelines projects are constructed in areas where the soil conditions would be considered poor to very poor, based on traditional construction standards. Although the size of the materials used in living shorelines projects is typically small compared to traditional engineered approaches, the additional load imposed by structural elements consisting of stone, concrete, or even natural reefs needs to be taken into consideration. If not accounted for properly in the design phase, these additional loadings can cause undesirable settlement which can compromise the performance of the project.

Planning Level Analysis

Typically, only a limited amount of information about the characteristics of the soil at a site exists prior to the collection of project-specific geotechnical information. Some potential sources of information that may be used to get a very general sense of the conditions expected at a site are topographic and geologic maps, groundwater maps, previously published geotechnical studies, and dredging/disposal records. Some of this type of information for New Jersey can be found at the New Jersey Geological and Water Survey, and the NJDEP Bureau of GIS websites. Specifically in areas likely to be a candidate for living shorelines projects, dredging records may give an indication of the type of material accumulated on the bed, or in some cases, disposed of on the shore. An initial estimate of soil bearing capacity can be made by walking the project site including shallow water areas to determine the type and consistency of the soil.

Implementation Level Analysis – Measurements

There are several *in situ* and laboratory tests which can be used to assess the quality of the underlying sediments. The specific tests performed should reflect the types and scale of the project being undertaken. Large underwater areas can be mapped using seismic reflection surveys and side-scan sonar in combination with bathymetric soundings. On dry land, electro-resistivity and electro-magnetic techniques can be used in addition to the seismic approaches. Collection of a small number of *in situ* borings typically helps confirm the analysis of these techniques. More local and direct approaches include penetration tests and vane shear stress tests to measure *in situ* soil strength, nuclear densometers and sand cone devices for measuring density, specialized permeability and pore pressure tests, and measurement of soil response vibratory and impulse loading. All samples should be collected in accordance with the procedures outlined in the NJDEP's *Field Sampling Procedures Manual* (New Jersey Department of Environmental Protection, 2022).

Ecological Parameters

The success or failure of any habitat for which a living shorelines project intends to restore, enhance, or develop will ultimately depend upon a series of ecological parameters. These parameters generally represent the biogeochemical conditions at the site and will determine the suitability of the growing conditions for living elements of the project. Water quality, which can be determined according to parameters such as dissolved oxygen, turbidity, or salinity, is extremely important; however, less apparent factors such as sunlight exposure and soil composition/type also play an important role. It is vital to understand the role of each of these factors when implementing a living shoreline. These ecological parameters may be unfamiliar to engineers as they are not typically assessed as part of the engineering design of traditional shoreline structures.

Water Quality

Habitat development is extremely dependent upon water quality. Dissolved oxygen concentrations, water temperature, salinity, and turbidity are important parameters that must be considered when planning any habitat preservation or restoration. Specific organisms (i.e., marsh grasses, shellfish, fish) each have optimal conditions under which they flourish. The surface water quality standards for New Jersey appear in N.J.A.C. 7:9B.

Dissolved oxygen (DO) concentration is a key parameter that defines the quality of a water body (HEP, 2011). Fish and other aquatic organisms utilize microscopic bubbles of oxygen gas dissolved in the water to survive. Oxygen is a product of photosynthesis and is consumed during respiration and decomposition. The amount of oxygen that is dissolved in the water column dictates both the abundance and types of aquatic life that can survive and reproduce in a water body. DO varies according to the time of day, tidal cycle, season, and depth. Low dissolved oxygen levels leave aquatic organisms in a weakened physical state and more susceptible to disease, parasites, and other pollutants (ETE, 2004). Dissolved oxygen water quality standards are based either on daily averages or individual sampling events, rather than seasonal averages. The values of these water quality standards vary depending on NY and NJ State standards and among water body classifications. The standards for New Jersey are presented below in Table 5.

Table 5: New Jersey state surface water quality criteria (N.J.A.C.7:9B)

Water Class Use	DO mg/L
FW2-NT	24hr AVG ≥ 5.0 Never < 4.0
SE1 (Shellfish/Bathing)	24hr AVG ≥ 5.0 Never < 4.0
SE2 (Fishing/Propagation)	Never < 4.0
SE3 (Fishing/Fish Migration)	Never < 3.0
FW2-NT - Maintenance; migration and propagation of the natural and established biota; primary and secondary contact recreation; industrial and agricultural water supply; public potable water supply after conventional filtration treatment and disinfection; and any other reasonable uses.	
SE1 - Shellfish harvesting; maintenance, migration and propagation of the natural and established biota; primary and secondary contact recreation; and any other reasonable uses.	
SE2 - Maintenance; migration and propagation of the natural and established biota; migration of diadromous fish; maintenance of wildlife; secondary contact recreation; and any other reasonable uses.	
SE3 - Secondary contact recreation; maintenance and migration of fish populations; migration of diadromous fish; maintenance of wildlife; any other reasonable uses.	

Water temperature has a large influence on biological activity and the growth of marine flora or fauna. Fish, insects, zooplankton, phytoplankton, and other aquatic species all have a preferred temperature range (USGS, 2014). Temperature is also important because of its influence on water chemistry and its ability to increase the rate of chemical reactions at higher temperatures. Metabolic rates of aquatic plants increase with greater water temperature and therefore increases their demand for oxygen (ETE, 2004). Warm water additionally becomes saturated more easily with oxygen and therefore is less capable of holding dissolved oxygen. For this reason, the warmer top portions of a lake can have critically low levels of oxygen during summer months (USGS, 2014).

Salinity measures the amount of salt dissolved in the water. Water molecules prefer to associate with salt rather than oxygen; therefore, DO levels decrease as salinity increases. Like temperature, salinity plays an important role in determining the type of growth that can be expected in and along a given body of water.

Turbidity measures the amount of particles or solids suspended in water. These particles can include organic matter, waste, pollution, sediment, or anything light enough not to settle. Turbidity is measured in NTU's (Nephelometric Turbidity Units). Excess sediment and contaminants in runoff caused by an increase in paved surfaces can reduce water clarity and quality and impact sensitive habitats, like oyster reefs and eelgrass beds. Reduced water clarity can also affect fish and aquatic invertebrates, such as zooplankton, by interfering with their ability to feed or by changing the composition of prey species and phytoplankton. Due to the settling of sediment out of the water column and decreased water velocities, higher turbidity levels can be expected deeper in the water column, close to the bed.

Planning Level Analysis

An initial desk-top analysis of the water quality in the vicinity of proposed living shorelines projects can typically be performed. Increasing regulations on water quality standards and an emphasis on transparency and accountability has resulted in the collection and dissemination of a significant amount of observational data. Sources include the USGS, the EPA, the NJDEP, and environmental organizations such as the Meadowlands Research and Restoration Institute (MERI) and the Jacques Cousteau National Estuarine Research Reserve (JCNERRS). Data archived from operational circulation models such as Stevens NYHOPS model can often be used to supplement this observational data.

Implementation Level Analysis –Measurement

While the sources mentioned above provide an indication of the water quality within a region, it is often necessary to conduct project specific measurements to assess the water quality in the immediate vicinity of a living shorelines project. The exact type and duration of the measurements to be made depends on the scale of the project and the requirements of the living elements of the project. Care should be taken to perform measurements that capture all the relevant scales of variability. All samples should be collected in accordance with the procedures outlined in the NJDEP's *Field Sampling Procedures Manual* (New Jersey Department of Environmental Protection, 2022).

Soil Type

Soil type plays an important role in determining the rate of vegetation growth, the penetration and heartiness of the root system, and the cohesion of the marsh edge. However, marsh cohesion is very complex and there is not a clear consensus on the most important soil parameters necessary for a more cohesive and resistant marsh edge. When selecting soil type if any sediment is being added, it is best to attempt to mimic the native soil when possible due to the lack of consensus. The correct soil type for a marsh will help to create a strong root system and healthier flora. Strong root systems are an important part of marsh cohesion and are essential for providing erosion resistance during large storms; therefore, selecting the right type of soil for use in living shorelines projects is critical.

Planning Level Analysis

The USDA Natural Resources Conservation Service hosts a web soil survey tool which contains a wealth of soil information. The tool allows users to import or enter an Area of Interest (AOI), then query that AOI for relevant soils data. Information on soil type, including both physical and chemical properties, are available. Other potential sources of information that may be used to get a general sense of the conditions expected at a site are topographic and geologic maps, groundwater maps, previously published geotechnical studies, and dredging/disposal records. Some of this type of information for New Jersey can be found at the New Jersey Geological and Water Survey, and the NJDEP Bureau of GIS websites. Specifically in areas likely to be a candidate for living shorelines projects, dredging records may give an indication of the type of material accumulated on the bed, or in some cases, disposed of on the shoreline.

Implementation Level Analysis – Measurements

To determine the soil type and soil chemistry, grab samples should be taken along the shoreline and offshore. If fill is to be imported, samples should be taken to ensure compatibility of the fill material with the native sediments. All samples should be collected in accordance with the procedures outlined in the NJDEP's *Field Sampling Procedures Manual* (New Jersey Department of Environmental Protection, 2022).

Sunlight Exposure

The amount of sunlight available is an important parameter both for aquatic and terrestrial habitat development. Photosynthesis only occurs in the presence of sunlight, which directly affects water quality and ultimately the level of biological production in the water. On land, the amount of daily sunlight directly affects the growth rate of vegetation included in the project. Particular attention should be paid to existing and proposed large woody vegetation that may shade out vulnerable incipient marsh vegetation. While some guidance specifically identifies south facing shorelines as favorable, the reality is that many flat, mild sloping northward facing shorelines also experience excellent growing conditions.

Planning Level Analysis – Desk-top Analysis

A desk-top analysis of sunlight exposure can typically be performed using readily available aerial images. Some potential sources include:

- Google Earth – Google Earth is a free geographical information program that stitches together satellite imagery, aerial photography and geographic information systems 3-D globe. Google Earth images are "flat" however trained ecologists can typically identify vegetation type and the potential for shading from these photographs
- Bing maps– Bing Maps is a useful source for obtaining current high-resolution "birdseye" photographs of shoreline sites. The perspective view offered by the birdseye photographs is useful in identifying shade potential

Implementation Level Analysis – Measurement

A field survey should be conducted to confirm the results of the desk-top analysis. The field survey should be conducted during the spring, summer or fall while the existing vegetation is fullest (after leaf out and prior to dropping their leaves).

Additional Considerations

Oftentimes in the design/implementation of a living shorelines project there are additional factors which must be considered in the engineering design phase before the project design can be finalized. These factors are more general and are typically evaluated or considered differently than the parameters described above.

Permits/Regulatory

Acceptable living shoreline projects should meet not only the engineering criteria discussed above, but also all regulatory requirements. The specific permit requirements will vary from project to project; however, the two most common permits that will be required for living shorelines projects will be a Regular or Nationwide General Permit from the USACE and either an Individual or General Permit from the State of New Jersey.

Coastal General Permit 24 (N.J.A.C. 7:7-6.24) was specifically designed to encourage "habitat creation, restoration, enhancement, and living shoreline activities" and to remove some of the regulatory impediments for these projects. Coastal GP 24 has several unique conditions.

- Projects must have the endorsement of a "sponsor" with experience designing and implementing living shorelines projects.
- Projects must have a reasonable likelihood of success unless they are constructed as a research project with a university partner.
- The project area below the mean high-water line must be one acre or less unless the applicant is a county, State or Federal agency that demonstrates the necessity of a larger project.
- Projects must minimize disturbance to special areas as defined in N.J.A.C. 7:7-9, unless the proposed activities are deemed sufficiently environmentally beneficial as to outweigh the negative environmental impacts of reduction.
- Projects intended to restore an existing shoreline must limit fill to the footprint of the shoreline shown on the applicable Tidelands Map, except for structural components intended to reduce wave energy.

Nationwide Permit 54 (NWP 54) was created for many of the same reasons. NWP 54 authorizes construction and maintenance of living shorelines for shore erosion control. Special conditions for NWP 54 include the following.

- Projects must have a substantial biological component.
- Projects including sand fills, sills, breakwaters, or reefs, cannot extend into the waterbody more than 30 feet from the mean low water line in tidal waters.

- Projects must be no more than 500 feet in length along the bank.
- Discharges of dredged or fill material into waters of the United States, and oyster or mussel reef structures in navigable waters, must be the minimum necessary for the establishment and maintenance of the living shoreline.
- Additionally if sills, breakwaters, or other structures must be constructed to protect fringe wetlands for the living shoreline, those structures must be the minimum size necessary.
- Projects must be properly maintained, which may require periodic repair of structures, replacement of sand fills, or replanting of vegetation.

In New Jersey there may be additional restrictions related to the use of shellfish in living shorelines projects. Historically, limitations have been placed on the use of oysters specifically due to the threat of poaching. The NJDEP Bureau of Marine Water Monitoring maintains a map of water classification according to the National Shellfish Sanitation Program.

Project designers are encouraged to contact the NJDEP Office of Policy and Coastal Management during the preliminary design phase so that water quality and other potential regulatory barriers can be identified and addressed during the early phases of project planning and design.

Scour

The influence of scour on proposed living shorelines projects should be considered from two perspectives. The first has to do with the pre-project conditions and the potential influence of adjacent engineering works on the project shoreline. Oftentimes edge scour or "end effects" associated with adjacent projects are a contributing factor to the erosion experienced on unstabilized shorelines. If edge scour is identified as a cause of erosion early on, it can be addressed more effectively during the design phase. The second perspective has to do with the potential for scour associated with proposed living shoreline projects to adversely impact neighboring properties. Poorly designed coastal structures have contributed significantly to the erosion experienced on ocean, bay, and riverine shorelines in the State of New Jersey. While living shoreline projects tend to cause less scour than traditional gray shoreline stabilization techniques, scour needs to be considered, and steps taken to mitigate any potential negative effects on neighboring shorelines. Generally, scour can be limited by tying living shorelines projects into adjacent shore protection works on stabilized coasts, or by gradually transitioning to a natural coastline on unstabilized coastlines.

Constructability

Even when a project is feasible, or even preferred from an engineering standpoint, based on an analysis of the design conditions, the ability to actually construct the project must also be considered. Typically, specific details regarding the method of construction are determined by the contractor's means and methods and, ultimately, influence the cost of the project. Significant variation from site to site and contractor to contractor is to be expected. In most cases, the project designer may review and approve the contractor's means and methods for critical components or materials but is not responsible for providing the means and methods - only a design that is considered constructable. Decisions made in the preliminary design phases will have implications for the contractor's options and, thus, ultimately the price of the project. Therefore, it is important to have a broad sense of the requirements and limitations of each type of project when selecting a solution.

As a general overview, construction of living shorelines projects can either be land based with equipment reaching out into the waterway when necessary, or water based using a barge or similar. While factors such as tidal range, water depth, distance from shore, slope, site access, permit requirements, contractor skill and available equipment will factor into the decision, it is typically most cost effective to utilize land based construction methods. Some of the potential disadvantages of working from land include difficult site access often over/through sensitive habitats, the need to stage material, and uncertain/unstable terrain. Water based construction is not without its own difficulties which may include the need to moor work boats and material barges, water depth restrictions, and weather impacts.

Native/Invasive Species

The existing ground cover at a site or on adjacent properties often provides clues as to what types of vegetation a site will support. In locations where natural vegetation is thriving, living shorelines projects should attempt to reproduce those conditions. In locations where invasives are more prevalent, consideration needs to be given as to whether the intent is to convert the system back to a more natural system or protect the existing modified system. Invasives are opportunists and may revegetate cleared areas quickly; therefore if the intent is to restore the natural system, replanting with native species is often necessary. The US Department of Agriculture (USDA) National Invasive Species Information Center maintains a list of resources specific to New Jersey. Among these are a 2022 list of invasive species compiled by the New Jersey Invasive Species Strike Team, a list of aquatic invasive species maintained by NJ Fish and Wildlife, and a list of native plants maintained by the Native Plant Society of New Jersey. The USDA Cape May Plant Materials Center also maintains a list of plants released to commercial growers to meet specific restoration needs.

Debris Impact

An analysis of the impact of three significant hurricanes (Irene, Lee, and Sandy) on sustainable (living) shoreline projects constructed in New York state identified debris impact as one of the major causes of damage (Miller, et al. 2015). Debris impact occurs when man made or natural material strikes a shoreline with such force that it can erode sediment, dislodge vegetation, and damage coastal structures. Examples include floating ice and/or logs propelled by tidal currents, boat wakes, or waves. Unfortunately, at present there is limited guidance on how to incorporate debris impact into the design of traditional and non-traditional coastal structures. Until further guidance is developed, it is suggested that living shorelines projects designed and constructed in New Jersey recognize the possibility of debris impact, and take steps to address it.

Project Monitoring

Project monitoring has always been recognized by living shorelines practitioners as critical for documenting project successes and failures; however, its importance has been elevated in some of the recent peer-reviewed and gray literature. Miller (2015) recommended that monitoring plans be included at the design stage for all living shorelines projects. The recently released IGNNBF goes one step further, recommending that funds be set aside during the implementation phase for long-term (10-year) monitoring of implemented projects. It is recommended that at a minimum, monitoring plans that include evaluation criteria and key success metrics should be developed for all living shoreline projects.

Many of the relevant factors in the development of a monitoring plan are discussed in (Kreeger & Moody, 2014 and Yepsen, et al. 2016). Some of these include the project objective, budget, and the technical capability of the entity carrying out the monitoring. Generally, the project objective will help define the core set of metrics which will be used to help evaluate the success of the project. The project budget and the technical capabilities of the group responsible for the monitoring will drive the type and frequency of the measurements used to evaluate the metrics. Regardless of the sophistication of the measurements utilized, an appropriate sampling protocol should be adopted to ensure that the results have relevance. Several formal methods such as the BACI (Before-After-Control-Impact) approach have been developed (Smith, 2002). Critical aspects include the incorporation of before and after surveys and the inclusion of a control site so that valid comparisons can be made. Consideration should be given to short term variations (e.g., diurnal or seasonal) as well as anthropogenic factors that may influence the results. Recent studies have indicated that living shorelines projects typically don't begin to thrive until several years after construction. Based on this observation, monitoring is suggested through at least the first several growing seasons.

Adaptive Management

Current best practice calls for incorporating adaptive management into the design and permitting of living shorelines. The advantages of adaptive management are discussed extensively in Chapter 7 of the IGNNBF. Specifically, adaptive management is discussed as a way of managing risk related to uncertainties related to climate change and future interactions between various aspects of the hydrodynamic, morphologic, ecological, economic, and social landscapes. Adaptive management:

- prevents overbuilding at the design phase;
- reduces upfront costs by allowing management of unknowns over time;
- allows phasing of projects;
- provides flexibility to adjust project goals over time as the needs of the site change;
- facilitates environmental permitting, acknowledging uncertainties regarding impacts;
- improves design life via asset resilience;
- allows lessons learned to be incorporated into management actions; and
- allows design to evolve with the science leading to innovation.

Effective implementation of adaptive management requires 1) designing with future adaptive management in mind, 2) a commitment to project monitoring and 3) a regulatory environment which facilitates adaptive management.

Beneficial Reuse

Living shorelines are most commonly used in areas where significant erosion has occurred. When constructed along waterbodies with high concentrations of suspended sediment, some types of living shoreline projects (sills, breakwaters, living reefs) promote sedimentation (Liu et, al., 2021). These projects typically reduce wave/current energy below the threshold required to keep sediment in suspension. For other project types, or in areas where the natural supply of sediment is limited, marsh restoration may require importing sediment. In these cases, beneficial reuse of dredged sediments should be explored. Sediment quantity and quality should be matched to project goals, and all beneficially reused sediment should undergo the appropriate testing to ensure it is appropriate for the intended application. New Jersey regulations generally allow fill below Mean High Water (MHW) out to the shoreline shown on the 1977 tidelands claim maps (subject to the constraints outlined in N.J.A.C. 7:7-6.24). For most edge restoration activities fill should contain a higher percentage of coarse material. New Jersey regulations require 75 percent or greater sand content for beach nourishment (N.J.A.C. 7:7E-4.8). Although *Spartina alterniflora* will grow in both fine and coarse textured sediment, fines may be more easily eroded in a higher energy environment (Christian, et al. 2020). It is recommended that dredged material with a higher percentage of fines be considered for alternate uses, such as marsh platform improvements or planted soon after placement to increase its stability.

Glossary

Aerobic – requiring the use of air or oxygen.

Anaerobic – without the use of air or oxygen.

Anthropogenic – originating from human activity.

Aquaculture – farming or cultivating aquatic plants or animals, such as seaweed and shellfish.

Armor Unit – hard, concrete units designed to be placed together and layered to form a protective coastal structure, such as a revetment, jetty, or breakwater.

Biota – the living organisms and vegetation of a specific region, geological period, or habitat.

Brackish – water that is slightly salty; typically present in estuaries where river water and seawater mix.

Chloroplasts – a chlorophyll containing plastid present in green plant cells, where photosynthesis takes place.

Crest – the highest point on a wave, where the displacement is at a maximum.

DEM – digital elevation model

Diffraction – when waves partially wrap around into the lee side of an object they encounter; when waves extend outward after moving through a narrow opening.

Diurnal – daily.

Fetch – open water distance over which wave growth occurs as energy is transferred from the wind to the water surface.

Freeboard – the height of the watertight portion of a structure above a given water level.

Freshet – a freshwater stream flowing into a body of water; often caused by heavy rainfalls or melting ice.

Gabion – a metal-wired cage, often filled with rock, and can be layered to form retaining walls or barriers.

Geodetic Datum – a coordinate system with a set of reference points used to as a basis to define other locations on the earth.

Geotextile Fabric – a permeable textile material, typically installed underneath a rock structure to help prevent scouring and increase soil stability.

Geogrid Material – a synthetic material, usually fabricated into woven grids with large voids, used to provide reinforcement in fill behind a retaining wall.

$H_{20\%}$ - wave height that is exceeded 20% of the observed time.

In-Situ – in the original location.

Interstitial Heterogeneity – diverse sizes and shapes of voids in between grains or pieces of a layer, material, or sediment.

Intertidal Zone – the area of the shoreline that is underwater during high tide and exposed during low tide.

Lee – the sheltered side of an object or land from wind, weather, or waves.

Lidar – Light Detection and Ranging; a remote sensing method used to measure ranges on the earth using light from a laser.

Macropores – large cavities in a soil that are usually greater than 0.08 mm in diameter.

Mariculture – the cultivation of marine life for food in a sea environment, whether it is in the open ocean, in cages in the ocean, or in tanks filled with seawater.

Marine Mattress – a large, rectangular, rock-filled geogrid container; units are typically laid together on the ground to provide erosion or scour protection, or to disperse the weight of a larger rock structure placed on top (such as a breakwater).

Mortality Rates – the number of deaths in a given area within a given time frame.

Natural Recruitment – the natural increase in animal or vegetation population within a habitat.

Overtopping – the passing of water over top of an object or structure upon impact.

Peaks Over Threshold – an approach used to study trends in a dataset consisting of extreme values; it is used to find the probability of events that are more extreme than those within the dataset.

Peat – an organic material composed of decomposed vegetation matter; usually brown in color with soil-like characteristics.(

Perched Beach – a beach that exists at an elevation higher than the normal profile and is typically retained by a structure parallel to the shoreline.

PSU – practical salinity unit

Quiescent – in an inactive or dormant state.

Refraction – the bending of waves due to varying water depths; the section of wave in shallower water will move slower than that in deeper water, creating a visible bend in the wave.

Shelf – a flat section or ledge along a strip of land or seabed.

Theodolite – an instrument used for land surveying to measure horizontal and vertical angles.

Tidal Datum – a standard vertical elevation used as a reference to measure local water levels.

Tombolo – a land mass forming in response to the placement of an offshore structure, where the mass connects to the structure. If the land mass does not reach the structure it is known as a salient.

Turbidity – the measure of water clarity; the amount of suspended material in a water column.

Sailing Line – the direction in which a vessel, such as a boat or ship, is traveling.

Salient – a bump in the shoreline that forms in response to the placement of an offshore structure. If the salient builds out and connects to the structure it becomes a tombolo.

Scarp – a very steep slope or cut in a bank, resulting from erosion.

Significant Wave Height – the average of the largest $1/3^{rd}$ of wave heights in a record.

Silt – fine-grained material; can be easily carried and transported by moving water.

Slumping – the gradual or sudden leaning or spreading out of a structure composed of individual units, or a pile of sediment; a decrease in slope.

SMB – Sverdup-Munk-Bretchneider method for predicting wave heights based on a known fetch and windspeed. Several SMB type prediction approaches exist.

Substrate – an underlying material or substance, typically where organisms grow.

Wave Attenuation – the gradual loss in intensity of waves, or wave energy.

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Appendix A: Approach Specific Design Guidance

Marsh Sill

Description

Sills are low-elevation, structures constructed parallel to the shoreline for the purpose of reducing the erosional pressure along the natural shoreline. Sills are often used as armoring for fringe marshes or wetlands that require a higher degree of protection or shallow water nearshore breakwaters. Sills dissipate wave energy and reduce bank erosion, causing waves to break on the structure, rather than on the natural, more fragile shore. The quiescent area of water that is created by the sill often allows sand and sediment to accumulate between the structure and the shoreline. With time this process can eventually raise the elevation of the bottom and create a perched beach or cause the marsh to build out to the structure. This unique effect not only serves to further stabilize the shoreline or marsh behind the sill but replaces lost and eroded land. Often the area between the sill and the shoreline is filled during construction to accelerate the development of the perched beach. Marsh plantings are often added to further stabilize the reclaimed land. A typical sill is illustrated in Figure 19.

Figure 19: Example marsh sill
http://ccrm.vims.edu/livingshorelines/design_options/structural.html

Design Guidance

System Parameters

Erosion History

Sills are appropriate at sites with a low-moderate erosion rate. The Chesapeake Bay Foundation suggests hybrid approaches such as sills are appropriate at sites with erosion rates of between 2 and 8 ft/yr (Chesapeake Bay Foundation, 2007). Based on the success of several New Jersey projects along higher energy shorelines, the recommended limit in New Jersey has been raised from 4 ft/yr to 6 ft/yr.

Sea Level Rise

Sills rely on their exposed crest to reduce wave energy on shore. In general, the effectiveness of a sill will be reduced over time as sea level rise gradually reduces the freeboard of the structure. If sea level increase rapidly, eventually the structure may become submerged at which point its ability to reduce wave heights will be reduced significantly. Sea level rise will also allow larger waves to impact the structure and may change the location and characteristics of the breaking waves. These possibilities should be considered during design. It is recommended that the latest guidance provided by the

NJDEP be used to design marsh sills in New Jersey. Currently that guidance suggests using the STAP sea level rise estimates associated with the moderate emissions scenario. Depending on the project setting and risk tolerance, values in the low-end to likely range may be appropriate for marsh sills. Adaptive management should be considered at the design phase, to mitigate any unexpected impacts from sea level rise.

Tidal Range

Sills are generally constructed at sites with a small to moderate tidal range. Sills are intended to be low-crested structures with a freeboard of between 0 and 1 ft above MHW. Wave attenuation is highly dependent on relative crest width and relative freeboard. Recent work by Bredes, et al. (2022) highlighted the variability in wave attenuation characteristics for a sill structure in Delaware Bay with a six-foot tidal range.

Marsh vegetation is also sensitive to the tidal range, with only select species being able to withstand extended periods of significant inundation. Adjacent mashes should be checked to help identify the appropriate plants and their preferred elevations.

Hydrodynamic Parameters

Wind Waves

Waves (both wind and wake) generally represent the primary force driving marsh and/or beach erosion and are therefore typically the most significant design consideration. Approaches for designing marsh sills range from the simple fetch-based approaches discussed in (Hardaway Jr. & Byrne, 1999), to more traditional coastal engineering methods based on a design wave height. Traditional engineering approaches are discussed in the *Coastal Engineering Manual* (US Army Corps of Engineers, 2002) and *The Rock Manual* (CIRIA; CUR; CETMF, 2012). Relevant considerations include the geometry of the structure, stone size, the amount of energy dissipation, spacing (for segmented sills), scour potential, and orientation. The appropriate design methodology depends on the complexity and scale of the project.

The Van der Meer (1988) formula which appears in both design manuals is one of the more common formulas used to design the stone size for frequently overtopped structures such as a sill. The design formula is provided for reference in Appendix B; however, inexperienced designers are encouraged to refer to the source documents for a more complete discussion.

The amount of wave height transmission through, around, or over a sill will have a significant impact on marsh and/or beach stability. Although traditional approaches can be used to estimate the wave attenuation characteristics of sills, recent work by Bredes, et al. (2022) and others point to some of the deficiencies in the design formulas when structures become submerged. Typically, vegetation stability thresholds are used to set wave height reduction targets. (Shafer, et al. 2003) in their study of Gulf Coast marshes found that the wave height exceeded 20% of the time ($H_{20\%}$) was critical to marsh stability, and that a value of $H_{20\%}$ of between 0.5 and 1.0 ft was the threshold for supporting marsh vegetation. Specifically, for Spartina Alterniflora, (Roland & Douglass, 2005) identified a limiting median significant wave height 0.33 ft (and an associated $H_{80\%}$ significant wave height of 0.65 ft) for marsh stability in Alabama and Texas. Nearly all wave transmission equations assume continuous structures. Marsh sills constructed with gaps need to account for additional wave energy transmission through the gaps. To maximize effectiveness, sills should be oriented perpendicular to the dominant incoming wave direction. If waves come from multiple directions, chevron shaped structures or staggered zig-zag structures can be used.

Although the current state of practice in living shoreline design focuses on wave height reduction, wave power has been found to be the primary driver of marsh edge erosion. While wave power is related to the wave height, the two are not exactly the same. Wave power is the wave energy multiplied by the group velocity. Recently, some researchers have suggested reducing wave power below 1-3 W/m to prevent marsh edge erosion (Mariotti & Fagherazzi, 2010; Bendoni, et al. 2016). In the short term, sill design will likely proceed with wave height reduction targets; however, as the science advances, the state of practice should move towards more physically meaningful wave power reduction targets.

Wakes

Currently no guidance exists other than to modify the expected wave heights if wakes are expected to be the dominant force acting at a site. If wakes are expected to play a critical role in the stability and performance of the marsh sill, the design should proceed as discussed above under waves, considering the wake heights in addition to the wind wave heights.

Currents

In most cases, wave heights represent the primary design consideration and currents are assumed to be negligible. In the types of environments where marsh sills are likely to be constructed, this may not always be the case. Section 5.2.3 of *The Rock Manual* (CIRIA; CUR; CETMF, 2012) provides specific design guidance for coastal/river structures subjected to currents. In most cases, the required armor stone size is shown to be proportional to some measure of the current velocity (typically depth averaged, or bottom) squared. Section 5.2.3 also addresses current related scour for rock structures. (Fischenich, 2001) summarized research on the stability thresholds of various materials used in stream bank restoration. Of relevance to marsh sill projects are reported velocity thresholds for short and long native grasses and reed fascines of between 3 and 6 ft/sec (1.8 to 3.6 kts) and for 12-24 inch rip-rap of 10 to 18 ft/sec (5.9 to 10.7 kts). Currents can also be created by water draining off of the marsh through natural and/or engineered channels (such as mosquito trenches). These currents will likely change how waves propagate after passing the sill and may also contribute to erosion of the marsh. The velocity of these currents should also be considered when designing a structure.

Ice

Guidance for designing structures to resist ice impacts is significantly lacking. Currently a number of ad hoc "rule of thumb" criteria exist which serve as the basis for ice resistant design. Although these rules of thumb were not developed for living shoreline projects application to living shorelines project design is recommended until more robust criteria are developed. Current guidance suggests sizing stone so that the median stone diameter is two to three times the maximum expected ice thickness (Sodhi & Donnelly, 1999). Additional guidance is provided in *The Rock Manual* Section 5.2.4 (CIRIA; CUR; CETMF, 2012), which recommends that the slope of the armor layer should be less than 30° and the slope of the breakwater (sill) below the water line should be less steep than the slope above the waterline. An alternative to increasing the resistance of the structure itself to ice is the strategic placement of auxiliary project elements designed to break up or deflect the ice. Common elements include timber piles or large rocks placed offshore of the main structure.

Storm Water Level

Sills are low-crested structures that are generally submerged during large storm events. When constructed to protect marshes and/or beaches those features are generally submerged as well. This submergence reduces the wave forces on the structures themselves and the shorelines they are intended to protect. For this reason, it is common to design sills to a lower survivability standard than traditional coastal structures. To determine an appropriate design storm, it is recommended that the proposed elevation of the sill and any inland features it is intended to protect are compared to design water elevations. For most marsh sill projects it is expected that the design storm water level will be associated with a 20-30 yr return period storm.

Terrestrial Parameters

Upland Slope

Sills are constructed offshore and as such the upland slope is not a factor in their design. An adequately designed sill and marsh system will prevent erosion of the upland bank. If the upland slope is to be vegetated, the vegetation selected should be appropriate for the existing/designed slope.

Shoreline Slope

Shoreline slope is an important factor for the development of a marsh landward of the sill structure. While the sill itself will not be impacted by the shoreline slope, slopes of between 1 on 8 and 1 on 10 or milder have been identified as optimal for the marsh development (Hardaway, et al. 2010). In general, the wider the intertidal zone, the more effective the marsh is at dissipating wave energy. (Knutson, et al. 1982) in his study of the wave dampening characteristics of Spartina alterniflora found that for small waves, 50% of their energy was dissipated within the first 8 feet of marsh, and that 100% was dissipated within 100 ft. While overall mild slopes are preferred, a small gradient needs to be maintained for drainage purposes. (Priest, 2006) recommends that areas of standing water larger than 100 ft^2 be avoided to prevent the drowning and die off of pockets of marsh vegetation.

Width

The width of the marsh developing behind the sill structure will be highly dependent on the local conditions. Marsh width will determine the amount of additional energy dissipation that will occur for transmitted waves. (Hardaway Jr. & Byrne, 1999) recommends a minimum width of between 30 and 70 ft for low-moderate energy sites. It is expected that the intense coastal development in New Jersey may make it difficult to achieve the desired widths without extending the shoreline seaward. Under the conditions set forth in Coastal General Permit 24, any fill taking place in conjunction with a living shorelines project must occur landward of the shoreline depicted on the 1977 tidelands map.

Nearshore Slope

Marsh sills are generally constructed on an existing nearshore slope. Once the marsh platform is developed, the shoreline slope typically abuts the landward side of the sill. The nearshore slope influences wave breaking at the structure and should be considered in the wave analysis. A broad flat nearshore slope is preferable and will help to dissipate wave energy.

Offshore Depth

Sills are typically constructed in in areas where the offshore depths are less than 6 ft. Shallow offshore depths are one of the factors that limits wave exposure and creates the low-medium energy conditions required for marsh sill projects.

Soil Bearing Capacity

A geotechnical investigation should be carried out to assess the bearing capacity of the underlying soils. The sedimentary processes in marsh/wetland systems are such that it is not uncommon to encounter layers of sediments with markedly different properties. Generally, there are two areas of concern, one is the initial settlement, and the other is the long-term settlement. Initial settlement is often of less concern because the issue can be addressed during construction. Long term settlement can be more problematic because as the sill settles, its structural integrity and ability to dissipate wave energy will be reduced, and the stability of the marsh will be threatened. If settlement is expected, the designer should incorporate a foundation layer to distribute the weight of the sill. Depending on the size of the structure and the strength of the underlying soils, the foundation layer may consist of a geotextile membrane, a gravel base, or a flexible gabion mattress.

Ecological Parameters

Water Quality

Water quality parameters will not affect the stone part of marsh sill structures; however, flora and fauna will be sensitive to water quality. Salinity limitations should be obtained for all marsh plantings prior to design and planting to ensure survival. Smooth cordgrass (Spartina alterniflora) and marsh hay cordgrass (Spartina patens) can tolerate regular inundations with 0 to 35 parts per thousand salinity (USDA, 2002). Additionally, species living interior to breakwater or sill structures require certain temperature, salinity, and dissolved oxygen conditions to survive. It is also important to allow for water to circulate to maintain good water quality. This can be achieved through the addition of gaps between structures or porosity within a structure.

Soil Type

Sills can be constructed on any type of soil; however, the growth of marsh plants will be dependent on the substrate. Two of the most common marsh plants used in the northeast are Spartina alterniflora and Spartina patens. Spartina alterniflora generally prefers sandy aerobic or anaerobic soils with pH values ranging from 3.7 to 7.9 (USDA, 2002). Spartina patens is adapted to a wide range of soils from coarse sands to silty clays with pH values ranging from 3.7 to 7.9 (USDA, 2002). More expansive lists of flora native to the New Jersey region are available from regional and national sources including Citizens United to Protect the Maurice River and the Federal Highway Administration.

Sunlight Exposure

Sunlight exposure will not impact the sill part of the marsh sill structure; however, marsh plants generally require at least six hours of direct sunlight per day (Whalen, et al. 2011). This should be considered during design and marsh plantings should be avoided where large trees or ancillary structures (docks for example) will prevent adequate sunlight exposure.

Additional Considerations

Permits/Regulatory

Close coordination with the NJDEP and other relevant regulatory agencies is suggested. Project designers are encouraged to contact NJDEP during the scoping and/or planning phase so that potential State regulatory barriers can be identified and addressed. Specific regulatory requirements are site and project dependent; however, there are several common regulatory issues associated with marsh sill projects including:

- covering critical nearshore habitat
- filling beyond the 1977 tidelands boundary
- impacts to adjacent properties
- nature and quality of fill material
- navigation hazard

Scour

Sills are subject to the typical modes of failure that impact all sloping rock structures, including scour. As waves reflect off the front and sides of sills, the resulting turbulence generates scour along the toe (base) and flanks (edges) of the structure. Such scour is typical and if excessive may result in slumping or settlement which can reduce the effectiveness of the sill and compromise its integrity. Engineering methods for reducing such impacts should be considered for all sills. If slumping or settlement is identified during routine inspections, it can typically be corrected by repositioning the existing stones and/or adding new stones to the sill.

Many sills contain windows or gaps along the structure to allow for water circulation and animal/human movement. While it is possible for water to access areas behind an uninterrupted sill through pore spaces or via overtopping, gaps should always be included along larger projects to allow access for marine fauna (i.e. fish and turtles). Limited research has been performed to determine optimum gap width and frequency, but a general empirical guide recommends windows at least every 100 feet (Hardaway, et al. 2010). Factors that influence window spacing include drainage, elevation change, recreational access, and bends in the project. Scour is generally observed along the shoreline behind the windows as waves are allowed to penetrate this area. Diffraction diagrams, and crenulate bay stability formulas have been shown to be successful in predicting the equilibrium planform of these indentations. An analysis of living shoreline projects in Virginia has suggested a ratio of 1:1.65 between the indentation and gap width (Hardaway & Gunn, 2000). Options for limiting or reducing the scour behind openings include lining the shoreline with small cobble or stones, staggering the openings, and angling structures away from shore before the gap (Hardaway, et al. 2010).

It is not uncommon for marsh sill projects to cause some erosion on adjacent properties; however, the amount is typically much less than what would be expected with a traditional structure. The low profile of sills minimizes the disturbance to the natural environment, which minimizes the associated edge scour. If the marsh behind a sill connects to the sill either through natural or artificial means, end effect erosion can be exacerbated on the downdrift side due to the disruption of the natural littoral transport.

Constructability

Sills can be constructed using either land based or water based construction techniques. If land based techniques are used, an excavator equipped with an articulating claw can be used to place larger stones. If long reach excavators are required, the lift capacity will be reduced which limits the weight of individual stones that can be handled. Depending on the dimensions of the sill, it is not uncommon for a temporary earthen bridge to be constructed, which enables a traditional excavator to move along the crest as it works. In such cases, the excavator back tracks along the crest, and removes the access bridge once the project is completed.

For projects that include fill, access to the site must be provided for earth hauling equipment such as dump trucks and/or loaders. In remote areas this may require establishing temporary “roadways” across unsuitable terrain with strict environmental constraints. If planting is included as part of the project, it should be sequenced to allow maximum root penetration and growth during the first growing season. (Miller, et al. 2015) identified vegetation maturity as critical to its stability.

For water based construction, a key consideration will be the local water depth. The draft of most construction barges is on the order of 4 ft. Water depths at the project site need to be sufficient to accommodate barges, which may necessitate scheduling construction around the tides. For large projects, additional considerations need to be made for onsite material storage. If stored on material barges, care should be taken to moor the barges in areas with sufficient depth to accommodate the draft through the full tidal cycle.

Native/Invasive Species

Marsh sill projects should incorporate appropriate native vegetation for the marsh platform and upland areas if they are to be planted. Ideally an ecologist with experience working in a marsh environment should be consulted to identify appropriate plant species and planting zones. The US Department of Agriculture (USDA) National Invasive Species Information Center maintains a list of resources specific to New Jersey. Among these are a 2022 list of invasive species compiled by the New Jersey Invasive Species Strike Team, a list of aquatic invasive species maintained by NJ Fish and Wildlife, and a list of native plants maintained by the Native Plant Society of New Jersey. The USDA Cape May Plant Materials Center also maintains a list of plants released to commercial growers to meet specific restoration needs.

Debris Impacts

An analysis of the impact of three significant hurricanes (Irene, Lee, and Sandy) on sustainable (living) shoreline projects constructed in New York state identified debris impact as one of the major causes of damage (Miller, et al. 2015). In New Jersey, Sandy was responsible for producing an extraordinary amount of debris, much of which ended up in and along the types of shorelines ideally suited for living shorelines projects. While sills tend to be submerged during the types of storms likely to generate significant debris, the marsh and upland areas behind them are particularly vulnerable to scour from floating debris. While specific design criteria for debris impact does not exist, it is recommended that debris impact be considered during the design phase. One alternative that has been shown to be successful along shorelines prone to ice impact, is the inclusion of auxiliary project elements such as large boulders to deflect debris.

Project Monitoring

Sills should be monitored to assess both the system performance and the structural performance (Bridges, et al. 2021). System performance assesses the degree to which the sill is performing its intended function (reducing waves, stabilizing the edge, promoting vegetation growth), while structural performance measures the degree to which the sill is holding up to environmental stressors. A simple low-cost method for conducting such an analysis is described in Findlay, et al. (2018).

Sills are generally designed to be statically stable structures with minimal movement of the structural elements. Inspections of sills should be performed regularly, after major storms, and after particularly intense winters with heavy icing. Common concerns to be evaluated during the inspection of a sill include the displacement of individual stones, settling of the structure, and the development of scour/erosion related to the structure. Sill maintenance tends to be minimal and most typically consists of the resetting of displaced stones.

As with all living shorelines that contain a vegetative component, monitoring and maintenance of the vegetation can be key to the success of the project. Marsh monitoring should consist of at a minimum an inventory of all vegetation, a survey of the offshore and marsh bed elevations, and a shoreline survey. Provisions should be made to ensure that any identified deficiencies are addressed in an expedient manner. Typical maintenance activities related to the vegetative component of a marsh sill project might include filling in low spots, thin-layer spreading of dredge material, and supplementing the original vegetation.

While monitoring has always been recognized by living shorelines practitioners as critical for documenting both project successes and failures, its importance has been elevated in some of the recent literature. In particular, the IGNNBF stresses the importance of monitoring for both assessment purposes and adaptive management. Assessment is deemed critical for both documenting the benefits of NNBF/living shorelines and improving future design. The IGNNBF goes so far as to recommend that funds be set aside during the implementation phase for long-term (10-year) monitoring of implemented projects. A similar recommendation was made by Miller, et al. (2015).

Many of the relevant factors in the development of a monitoring plan are discussed in (Kreeger & Moody, 2014; Yepsen, et al. 2016). Some of these include the project objective, budget, and the technical capability of the entity carrying out the monitoring. Generally, the project objective will help define the core set of metrics which will be used to help evaluate the success of the project. The project budget and the technical capabilities of the group responsible for the monitoring will drive the type and frequency of the measurements used to evaluate the metrics. Regardless of the sophistication of the measurements utilized, an appropriate sampling protocol should be adopted to ensure that the results have relevance. Several formal methods such as the BACI (Before-After-Control-Impact) approach have been developed (Smith, 2002). Critical aspects include the incorporation of before and after surveys and the inclusion of a control site so that valid comparisons can be made. Consideration should be given to short term variations (e.g., diurnal or seasonal) as well as anthropogenic factors that may influence the results. Recent studies have indicated that living shorelines projects typically don't begin to thrive until several years after construction. Based on this observation, monitoring is suggested through at least the first several growing seasons.

Adaptive Management

Marsh sills should be designed with adaptive management in mind. This may involve creating wider structures so that additional elements can be added at a future time. To help maintain the marsh behind the sill, sediment management plans including consideration of beneficial reuse of dredged material should be discussed at the planning and/or implementation phase.

Beneficial Reuse

In areas where marsh and/or beach restoration is desired and the natural supply of sediment is limited, beneficial reuse of dredged material should be considered for restoring the shoreline. GP 24 currently allows for habitat restoration out to the shoreline shown on the 1977 tidelands map. If shoreline restoration via the beneficial reuse of dredged material is included as part of a marsh sill project, coarse material should be placed along the shoreline. Finer grained material should be reserved for interior marsh improvements.

Breakwater

Description

Figure 20: Example breakwater

Breakwaters are coastal engineering structures typically constructed parallel to the shoreline that are designed to reduce wave energy in the area directly behind them. Breakwaters are frequently used in marinas and harbors as well as along open coasts. When utilized on an open coast in a sediment rich environment, the resulting wave diffraction patterns typically cause sediment to accumulate in the shadow zone behind the structure creating features known as tombolos and salients. When utilized as a part of a living shorelines project, breakwaters are designed to reduce the wave energy to acceptable levels to allow the establishment of a beach or vegetated (typically marsh) shoreline in its lee. Breakwaters are distinguished from sills in that they are typically constructed in deeper water, further from shore, in more energetic wave climates, and therefore tend to be larger. An example of a breakwater field and salient formation is shown in Figure 20.

Design Guidance

System Parameters

Erosion History

Properly designed breakwaters can be successful in addressing shoreline erosion. Breakwaters have been implemented as coastal protection on many open sea coastlines where offshore wave heights exceed 30 ft. At sites where living shoreline projects are being considered, the wave energy will be significantly less. Due to their larger size, breakwaters can be used along high energy coastlines with erosion rates in the moderate-high range.

Sea Level Rise

In general, the effectiveness of a breakwater will be reduced over time as sea level rise gradually reduces the freeboard of the structure. If sea levels increase rapidly, eventually the structure may become submerged at which point its ability to dissipate the incoming waves will be reduced significantly. Sea level rise will also allow larger waves to impact the structure and may change the location and characteristics of the breaking waves. These possibilities should be considered during design. It is recommended that the latest guidance provided by the NJDEP be used to design living shoreline projects in New Jersey. Currently that guidance suggests using the STAP sea level rise estimates associated with the moderate emissions scenario. Depending on the project setting and risk tolerance, values in the likely to high-end range may be appropriate for breakwaters. Adaptive management should be considered at the design phase, to mitigate any unexpected impacts from sea level rise.

Tidal Range

Breakwaters can be constructed in a wide range of tidal environments, including those most common in New Jersey. Tidal range affects the water depth in front of the structure and controls the size and type of waves it will encounter, as well as the amount of overtopping likely to occur. Tidal range has been shown to influence the type of landform that develops behind a breakwater, with larger tidal ranges being associated with shorter salient lengths on sandy beaches (Department for Environment, 2010). Most potential living shoreline site in New Jersey are micro-macro tidal; therefore, tidal fluctuations will not be a limiting factor in breakwater design. Project designers should however account for overtopping and wave impact at various stages of the tide. If marsh restoration is completed along with breakwater construction specific attention need to be given to the planting plan. Marsh vegetation is sensitive to tidal range, with only select species being able to withstand extended periods of significant inundation. Adjacent mashes should be checked to help identify the appropriate plants and their preferred elevations. If ecological enhancements are incorporated into the breakwater design, specific attention needs to be given to the habitat needs of the native fauna. For example, if enhancements are added to encourage oysters/mussel colonization, the enhancements must remain submerged at all times if growth is to continue during periods of low tide.

Hydrodynamic Parameters

Wind Waves

Breakwaters have been used on open sea coastlines with extremely high wave energy. In the much lower wave energy conditions likely to be experienced at proposed living shorelines sites in New Jersey, wave heights will not limit the applicability of breakwaters. Approaches for designing breakwaters range from the simple fetch-based approaches discussed in (Hardaway Jr. & Byrne, 1999), to more traditional coastal engineering methods based on a design wave height. Traditional engineering approaches are discussed in the *Coastal Engineering Manual* (US Army Corps of Engineers, 2002) and *The Rock Manual* (CIRIA; CUR; CETMF, 2012). Relevant considerations include the geometry of the structure, stone size, the amount of energy dissipation, spacing (for segmented breakwaters), scour potential, and orientation. Breakwaters are typically constructed in higher energy environments with larger erosion rates and tend to be larger structures; therefore, a more rigorous design approach is recommended.

The two most frequently used approaches for designing the required stone size for breakwaters are the (Hudson, 1959) and (Van der Meer, 1988) formulas. Both formulas appear in both design manuals. The Van der Meer formula is provided for reference in

Appendix B; however, inexperienced designers are encouraged to refer to the source documents for a more complete discussion.

The amount of wave height transmission through, around, or over a breakwater will have a significant impact on marsh and/or beach stability. Traditional approaches found in either of the design manuals can be used to estimate the wave energy behind a breakwater. Typically, vegetation stability thresholds are used to set wave height reduction targets. (Shafer, et al. 2003) in their study of Gulf Coast marshes found that the wave height exceeded 20% of the time ($H_{20\%}$) was critical to marsh stability, and that a value of $H_{20\%}$ of between 0.5 and 1.0 ft was the threshold for supporting marsh vegetation. Specifically, for Spartina Alterniflora, (Roland & Douglass, 2005) identified a limiting median significant wave height 0.33 ft (and an associated $H_{80\%}$ significant wave height of 0.65 ft) for marsh stability in Alabama and Texas. Nearly all wave transmission equations assume continuous structures. Breakwaters constructed with gaps need to account for additional wave energy transmission through the gaps. To maximize effectiveness, breakwaters should be oriented perpendicular to the dominant incoming wave direction. If waves come from multiple directions, chevron shaped structures or staggered zig-zag structures can be used.

Although the current state of practice in living shoreline design focuses on wave height reduction, wave power has been found to be the primary driver of marsh edge erosion. While wave power is related to the wave height, the two are not exactly the same. Wave power is the wave energy multiplied by the group velocity. Recently, some researchers have suggested reducing wave power below 1-3 W/m to prevent marsh edge erosion (Mariotti & Fagherazzi, 2010; Bendoni, et al. 2016). In the short term, breakwater design will likely proceed with wave height reduction targets; however, as the science advances, the state of practice should move towards more physically meaningful wave power reduction targets.

Wakes

Currently no guidance exists other than to modify the expected wave heights if wakes are expected to be the dominant force acting at a site. If wakes are expected to play a critical role in the stability and performance of the breakwater, the design should proceed as discussed above, considering the wake heights in addition to the wind wave heights.

Currents

In most cases, wave heights represent the primary design consideration and currents are assumed to be negligible. In the types of environments where living shoreline breakwaters are likely to be constructed, this may not always be the case. Section 5.2.3 of *The Rock Manual* (CIRIA; CUR; CETMF, 2012) provides specific design guidance for coastal/river structures subjected to currents. In most cases, the required armor stone size is shown to be proportional to some measure of the current velocity (typically depth averaged, or bottom) squared. Section 5.2.3 also addresses current related scour for rock structures. (Fischenich, 2001) summarized research on the stability thresholds of various materials used in stream bank restoration. Of relevance to living shoreline breakwater projects are reported velocity thresholds for short and long native grasses and reed fascines of between 3 and 6 ft/sec (1.8 to 3.6 kts) and for 12-24 inch rip-rap of 10 to 18 ft/sec (5.9 to 10.7 kts). Currents can also be created by water draining off of the marsh through natural and/or engineered channels (such as mosquito trenches). These currents will likely change how waves propagate after passing the breakwater and may also contribute to erosion of the marsh. The velocity of these currents should also be considered when designing a structure.

Ice

Guidance for designing structures to resist ice impacts is lacking. Currently a number of ad hoc "rule of thumb" criteria exist which serve as the basis for ice resistant design. Although these rules of thumb were not developed for living shoreline projects, application to living shorelines project design is recommended until more robust criteria are developed. Current guidance suggests sizing stone so that the median stone diameter is two to three times the maximum expected ice thickness (Sodhi & Donnelly, 1999). Additional guidance is provided in *The Rock Manual* Section 5.2.4 (CIRIA; CUR; CETMF, 2012), which recommends that the slope of the armor layer should be less than 30° and the slope of the breakwater below the water line should be less steep than the slope above the waterline.

Storm Water Level

In the environments in which living shoreline breakwaters will be designed, storm water level will not be a limiting factor. Breakwaters on ocean coastlines are subjected to much more intense conditions than will be experienced in living shoreline project settings. Increased water levels during storms however will lead to larger waves at the structure and increased overtopping and wave transmission. Breakwaters should be designed to withstand a critical condition which considers a combination of storm surge and wave impacts. While it is recommended that breakwaters be designed to withstand a 50-100 yr storm, in may not necessarily need to maintain its function. Depending on the elevation of the upland it is designed to protect, a portion or all of the upland may be submerged during larger storms. If this is the case, the erosional pressure may be reduced to the point which wave attenuation is no longer needed during those storms.

low-crested structures that are generally submerged during large storm events. When constructed to protect marshes and/or beaches those features are generally submerged as well. This submergence reduces the wave forces on the structures themselves and the shorelines they are intended to protect. For this reason, it is common to design sills to a lower survivability standard than traditional coastal structures. To determine an appropriate design storm, it is recommended that the proposed elevation of the sill and any inland features it is intended to protect are compared to design water elevations. For most marsh sill projects it is expected that the design storm water level will be associated with a 20-30 yr return period storm.

Terrestrial Parameters

Upland Slope

Breakwaters are constructed well offshore and as such the upland slope is not a factor in their design. An adequately designed breakwater and marsh system will prevent erosion of the upland bank. If the upland slope is to be vegetated, the vegetation selected should be appropriate for the existing/designed slope.

Shoreline Slope

Shoreline slope is an important factor for the development of a marsh landward of the breakwater structure. While the breakwater itself will not be impacted by the shoreline slope, slopes of between 1 on 8 and 1 on 10 or milder have been identified as optimal for the marsh development (Hardaway, et al. 2010). In general, the wider the intertidal zone, the more effective the marsh is at dissipating wave energy. (Knutson, et al. 1982) in his study of the wave dampening characteristics of Spartina alterniflora found that for small waves, 50% of their energy was dissipated within the first 8 feet of marsh, and that 100% was dissipated within 100 ft. While overall mild slopes are preferred, a small gradient needs to be maintained for drainage purposes. (Priest, 2006) recommends that areas of standing water larger than 100 ft^2 be avoided to prevent the drowning and die off of pockets of marsh vegetation.

Width

The width of the marsh and/or beach behind a breakwater will be highly dependent on the local conditions. On sandy beaches, it is typical for either a tombolo or a salient (see Figure 21) to form behind offshore breakwaters. The type of feature depends on the spacing between the structures, the distance to the shoreline, and length of the structure relative to the wavelength of the incident waves. Tombolos are more likely to form when breakwaters are closer to shore, are large relative to the wavelength of the incident waves, and when the gaps between adjacent structures are smaller. When the ratio of the length of the breakwater to the distance between the breakwater and the nourished

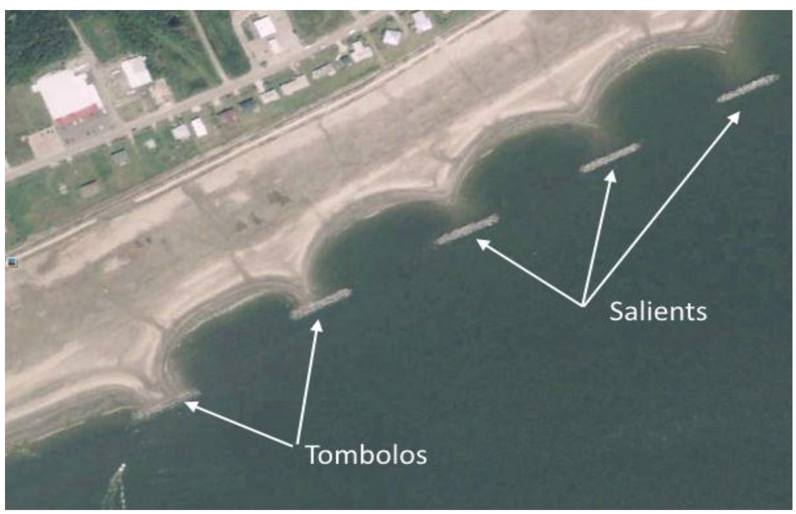

Figure 21: Definition of tombolo and salient

shore is greater than 1-2, the conditions favor tombolo formation. When the ratio is less than 1, conditions favor salient formation (US Army Corps of Engineers, 2002).

(Hardaway Jr. & Byrne, 1999) recommends a minimum beach width of between 45 and 65 ft for moderate to high energy sites. It is expected that the intense coastal development in New Jersey may make it difficult to achieve the desired widths without extending the shoreline seaward. Under the conditions set forth in Coastal General Permit 24, any fill taking place in conjunction with a living shorelines project must occur landward of the shoreline depicted on the 1977 tidelands map.

Nearshore Slope

Breakwaters are generally constructed on an existing nearshore slope. The nearshore slope will influence the size and type of waves that impact the structure and should be considered in the wave analysis. A broad flat nearshore slope is preferable and will help to dissipate any wave energy transmitted past the breakwater. For constructability purposes, the nearshore slope needs to be flat enough to provide a stable platform for the breakwater. The flatter the nearshore slope between the breakwater and the marsh toe, the less expensive the structure will be due to the shallower depths.

Offshore Depth

For breakwaters constructed as a part of a living shorelines project, offshore depth is not a limiting factor. Breakwaters are common on open sea coastlines where the water depths far exceed those expected to be encountered in most living shorelines projects. The offshore depth will influence the wave climate and should be considered during the wave analysis.

Soil Bearing Capacity

A geotechnical investigation should be carried out to assess the bearing capacity of the underlying soils. The sedimentary processes in marsh/wetland systems are such that it is not uncommon to encounter layers of sediments with widely varying properties. Generally, there are two areas of concern, one is the initial settlement, and the other is the long-term settlement. Initial settlement is often the lesser of the two concerns, because it is often identified and addressed during construction. Long term settlement can be more problematic because if the breakwater settles differentially, the interlocking of the stones can be compromised, weakening the structure. If settlement is expected, the designer should incorporate a foundation layer to distribute the weight of the breakwater. Depending on the size of the structure and the strength of the underlying soils, the foundation layer may consist of a geotextile membrane, gravel base or marine mattress. Additional information is contained in the two design manuals.

Ecological Parameters

Water Quality

Water quality parameters will not affect the breakwater itself; however, flora and fauna will be sensitive to water quality. Salinity limitations should be obtained for all marsh plantings prior to design and planting to ensure survival. Smooth cordgrass (Spartina alterniflora) and marsh hay cordgrass (Spartina patens) can tolerate regular inundations with 0 to 35 parts per thousand salinity (USDA, 2002). Additionally, species living interior to breakwater or sill structures require certain temperature, salinity, and dissolved oxygen conditions to survive. It is also important to allow for water to circulate to maintain good water quality. This can be achieved through the addition of gaps between structures or porosity within a structure.

Soil Type

Breakwaters can be constructed on any type of soil as long as the bearing capacity issues are addressed; however, the growth of marsh plants will be dependent on the substrate. Two of the most common marsh plants used in the northeast are Spartina alterniflora and Spartina patens. Spartina alterniflora generally prefers sandy aerobic or anaerobic soils with pH values ranging from 3.7 to 7.9 (USDA, 2002). Spartina patens is adapted to a wide range of soils from coarse sands to silty clays with pH values ranging from 3.7 to 7.9 (USDA, 2002). More expansive lists of flora native to the New Jersey region are available from regional and national sources including Citizens United to Protect the Maurice River and the Federal Highway Administration.

Sunlight Exposure

Sunlight exposure will not impact the breakwater itself; however marsh plants generally require at least six hours of direct sunlight per day (Whalen, et al. 2011). This should be taken into account if marsh restoration is performed leeward of the structure.

Additional Considerations

Permits/Regulatory

Close coordination with the NJDEP and other relevant regulatory agencies is suggested. Project designers are encouraged to contact NJDEP during the scoping and/or planning phase so that potential State regulatory barriers can be identified and addressed. Specific regulatory requirements are site and project dependent; however, there are several common regulatory issues associated with marsh sill projects including:

- covering critical nearshore habitat
- filling beyond the 1977 tidelands boundary
- creating impacts to adjacent properties
- nature and quality of fill material
- creating a navigation hazard

Scour

Breakwaters are subject to the typical modes of failure that impact all sloping rock structures, including scour. As waves reflect off the front and sides of breakwaters, the resulting turbulence generates scour along the toe (base) and flanks (edges) of the structure. Such scour is typical and if excessive may result in slumping or settlement which can reduce the effectiveness of the structure and compromise its integrity.

Engineering methods for reducing such impacts should be considered for all breakwater structures.

Although edge scour associated with breakwaters tends not to be as severe as the edge scour associated with shoreface armoring (bulkheads, seawalls, revetments), if sediment builds up behind the breakwater a tombolo or salient may form. These accretional features are formed as the sand from adjacent beaches is rearranged in response to the modified wave/current patterns. The amount of erosion induced on the neighboring beaches is directly linked to the size of the accretional feature that develops. In the case where a tombolo forms, the resulting sand “bridge” can effectively cut off the longshore sediment transport, resulting in more severe downdrift erosion.

Constructability

Breakwaters are generally constructed using water based construction techniques. For water based construction, water depth is a critical consideration. Shallow water may limit site access, while deep water may create unsafe working conditions. Most construction barges require working depths of at least 4 ft, which may limit site access during periods of lower tides. For larger projects, material may need to be stored on site. If material barges are used, they should be moored in areas with sufficient depth to accommodate the loaded barge’s draft through the full tidal cycle.

For projects that include fill, access to the site must be provided for earth hauling equipment such as dump trucks and/or loaders. In remote areas this may require establishing temporary “roadways” across unsuitable terrain with strict environmental constraints. If planting is included as part of the project, it should be sequenced to allow maximum root penetration and growth during the first growing season. (Miller, et al. 2015) identified vegetation maturity as critical to its stability.

Native/Invasive Species

Breakwater projects should incorporate appropriate native vegetation for the marsh platform and upland areas if they are to be planted. Ideally an ecologist with experience working in a marsh environment should be consulted to identify appropriate plant species and planting zones. The US Department of Agriculture (USDA) National Invasive Species Information Center maintains a list of resources specific to New Jersey. Among these are a 2022 list of invasive species compiled by the New Jersey Invasive Species Strike Team, a list of aquatic invasive species maintained by NJ Fish and Wildlife, and a list of native plants maintained by the Native Plant Society of New Jersey. The USDA Cape May Plant Materials Center also maintains a list of plants released to commercial growers to meet specific restoration needs.

Debris Impacts

An analysis of the impact of three significant hurricanes (Irene, Lee, and Sandy) on sustainable (living) shoreline projects constructed in New York state identified debris impact as one of the major causes of damage (Miller, et al. 2015). In New Jersey, Sandy was responsible for producing an extraordinary amount of debris, much of which ended up in and along the types of shorelines ideally suited for living shorelines projects. While breakwaters themselves tend to be robust structures capable of withstanding minor debris impact, the marsh areas they protect are particularly vulnerable to scour from floating debris. While specific design criteria for debris impact does not exist, it is recommended that debris impact be considered during the design phase. One alternative that has been shown to be successful along shorelines prone to ice impact, is the inclusion of auxiliary project elements such as large boulders to deflect debris.

Project Monitoring

Breakwaters should be monitored to assess both the system performance and the structural performance (Bridges, et al. 2021). System performance assesses the degree to which the breakwater is performing its intended function (reducing waves, stabilizing the edge), while structural performance measures the degree to which the breakwater is holding up to environmental stressors. A simple low-cost method for conducting such an analysis is described in Findlay, et al. (2018).

Breakwaters are generally designed to be statically stable structures with minimal maintenance requirements. It is uncommon to conduct regular breakwater inspections; however, inspections should be performed after major storms. Common concerns to be evaluated during an inspection include the displacement of individual stones, settling of the structure, and the development of scour/erosion related to the structure. Maintenance of breakwaters tends to be minimal and most typically consists of the resetting of stones displaced during a storm and/or addressing localized scour.

As with all living shorelines that contain a vegetative component, monitoring and maintenance of the vegetation can be key to the success of the project. Marsh monitoring should consist of at a minimum an inventory of all vegetation, a survey of the offshore and marsh platform elevations, and a shoreline survey. Provisions should be made to ensure that any identified deficiencies are addressed in an expedient manner. Typical maintenance activities related to the vegetative component of a breakwater/marsh living shorelines project might include filling in low spots, thin-layer placement of dredge material, and supplementing the original vegetation.

Adaptive Management

Breakwaters should be designed with adaptive management in mind. This may involve creating wider structures so that additional elements can be added at a future time. To help maintain the marsh behind the breakwater, sediment management plans including consideration of beneficial reuse of dredged material should be discussed at the planning and/or implementation phase.

Beneficial Reuse

In areas where marsh and/or beach restoration is desired and the natural supply of sediment is limited, beneficial reuse of dredged material should be considered for restoring the shoreline. GP 24 currently allows for habitat restoration out to the shoreline shown on the 1977 tidelands map. If shoreline restoration via the beneficial reuse of dredged material is included as part of a breakwater project, the coarser grained material should be placed along the shoreline with the finer grained material reserved for interior marsh improvements.

Living Reef

Description

Naturally occurring living reefs have always served to protect fragile shorelines and marshes but unfortunately many of the natural beds have disappeared either through natural or anthropogenic causes. Living reef breakwaters and sills have recently become a popular method for protecting and stabilizing shorelines, creating habitat, and improving water quality in sheltered areas. More common in the southern United States, these submerged aquatic habitats function like constructed breakwaters or sills. Living breakwaters in the northeast are typically constructed with oysters or mussels (Figure 22) and use an artificial substrate (Reef Ball, Oyster Castle, etc). The substrate is either placed with the intent of natural recruitment or seeded with organisms grown in a controlled environment (remote setting). When constructed in areas with strong natural recruitment, large reef structures can eventually form. Like constructed breakwaters and sills, sediment deposition can occur behind these living reefs, allowing vegetation to take root (Rella & Miller, 2012).

Figure 22: Example living reef

Design Guidance

System Parameters

Erosion History

Historically, mussel and oyster reefs provided protection for vast stretches of the New Jersey coastline. Living reef projects aim to restore some of the natural protective capacity that has been lost over time by encouraging the development of small low-crested mussel/oyster sills. Sills are appropriate at sites with a low-moderate erosion rate. The Chesapeake Bay Foundation suggests hybrid approaches such as living reefs are appropriate at sites with erosion rates of between 2 and 8 ft/yr (Chesepeake Bay Foundation, 2007). Based on the success of several New Jersey marsh sill projects along higher energy shorelines, the recommended limit for living reefs in New Jersey has been raised from 4 ft/yr to 6 ft/yr.

Sea Level Rise

Living reef breakwaters have some capacity to adapt to changing conditions; however, they are particularly sensitive to changes in water quality. If parameters such as water temperature, salinity, and turbidity, remain within the range required by the constituent species, living reefs can adapt naturally to slow changes in water level through natural growth/migration. If the changes are rapid however, they may outpace the ability of the natural system to respond (Rella & Miller, 2012). If the increase in reef elevation lags the increase in sea level, the effectiveness of the reef in dissipating waves will be reduced over time as sea level reduces the freeboard. Marsh vegetation which may be included as a part of a living reef project, is also highly susceptible to changes associated with sea level rise, i.e. drowning of root systems and salt intrusion. It is recommended that the latest guidance provided by the NJDEP be used to design living reefs in New Jersey. Currently that guidance suggests using the STAP sea level rise estimates associated with the moderate emissions scenario. Depending on the project setting, values in the low-end to likely range are considered appropriate for living reefs.

Tidal Range

Knowing the expected daily tidal range, as well as the spring tide and storm surge related extremes, is vital when planning any living reef project. It is imperative that the oysters/mussels forming the reef remain submerged at all times if growth is to continue during periods of low tide. In colder climates like the northeast, it is essential to keep the oysters/mussels submerged to prevent them from freezing during the winter months. Oysters can survive dormant in cold water but will die if exposed to cold air, so it is important to ensure that the oysters remain completely submerged during low tide (NY/NJ Baykeeper, 2005). Typically, the crest height for living reefs should be set at or below mean low water as oysters/mussels can only remain out of the water for between 2 and 6 hours depending on the weather conditions (NY/NJ Baykeeper, 2005). In order for marsh plantings developing behind the living reef to grow successfully, it is imperative that the roots of the marsh plantings are under water during periods of high tide and dry during times of low tide. The dominant salt marsh plantings do not grow well in permanently standing water because their roots need to breathe in order to survive (Priest, 2006).

Hydrodynamic Parameters

Wind Waves

Naturally occurring, well established living reefs are firmly bound together. As oyster reefs grow their calcium carbonate shells cement together, increasing their stability. Mussels on the other hand are only bound to the substrate and each other by hair like cilia and tend to be less stable. If completely submerged and under the influence of wave action, newly constructed reefs can be formed by simply placing individual shells on the bed in a trapezoidal shape. Reefs that are placed in the intertidal zone however are exposed to higher wave energy and need special consideration for their design. In such cases, artificial substrates such as shell filled gabion baskets or ecologically enhanced concrete structures are often used to provide a stable base for reef development. There is little to no design guidance for most of these artificial substrates with regards to stability. Generally the substrates should strong enough to withstand the expected forces and function as a wave attenuator with or without natural recruitment.

The wave attenuation characteristics of natural reefs will vary due to the irregularity of the underlying structure. On the smallest scale, oyster shell bags placed on the shore have been shown to attenuate wave energy and reduce erosion in low to moderate wave energy locations. Similar to submerged breakwaters, the transmission coefficient for submerged living reefs strongly depends on the height and width of the reef relative to the wave height. (Allen & Webb, 2011) demonstrated that in a laboratory, wave height could be attenuated by up to 90% on natural reefs.

Typically, vegetation stability thresholds are used to set wave height reduction targets. (Shafer, et al. 2003) in their study of Gulf Coast marshes found that the wave height exceeded 20% of the time ($H_{20\%}$) was critical to marsh stability, and that a value of $H_{20\%}$ of between 0.5 and 1.0 ft was the threshold for supporting marsh vegetation. Specifically, for Spartina Alterniflora, (Roland & Douglass, 2005) identified a limiting median significant wave height 0.33 ft (and an associated $H_{80\%}$ significant wave height of 0.65 ft) for marsh stability in Alabama and Texas.

If artificial substrate is placed as part of a living reef project, the individual reef elements should be oriented perpendicular to the dominant incoming wave direction. If waves come from multiple directions, chevron shaped structures or staggered zig-zag structures can be used.

Although the current state of practice in living shoreline design focuses on wave height reduction, wave power has been found to be the primary driver of marsh edge erosion. While wave power is related to the wave height, the two are not exactly the same. Wave power is the wave energy multiplied by the group velocity. Recently, some researchers have suggested reducing wave power below 1-3 W/m to prevent marsh edge erosion (Mariotti & Fagherazzi, 2010; Bendoni, et al. 2016). In the short term, living reef design will likely proceed with wave height reduction targets; however, as the science advances, the state of practice should move towards more physically meaningful wave power reduction targets.

Wakes

Currently no guidance exists other than to modify the expected wave heights if wakes are expected to be the dominant force acting at a site. If wakes are expected to play a critical role in the stability and performance of the living reef, the design should proceed as discussed above, considering the wake heights in addition to the wind wave heights.

Currents

In most cases where living reefs are being considered, wave heights represent the primary design consideration and currents are assumed to be negligible. Considering the varying types of environments where living reefs are likely to be constructed, this may not always be the case. The growth rates of mussel/oysters are heavily dependent upon the currents that they are exposed to (Riley, 2001). Generally, the stronger the current, the more food (phytoplankton) that will reach them and the greater the growth potential (Flimlin, 2002). If the current is too strong however, it can reduce the oyster's ability to filter water and inhibit the growth process. In locations where there fast moving currents, oysters have been found to grow in size very quickly but have extremely thin shells, which may limit their ability to withstand wave forces (Riley, 2001).

(Fischenich, 2001) summarized research on the stability thresholds of various materials used in stream bank restoration. Of relevance to living reef and marsh creation projects are reported velocity thresholds for short and long native grasses and reed fascines of between 3 and 6 ft/sec (1.8 to 3.6 kts). While velocity thresholds for natural reefs were not given, thresholds of between 10 and 19 ft/s (5.9 to 11.3 kts) were reported for rip-rap and gabion structures. Section 5.2.3 of *The Rock Manual* (CIRIA; CUR; CETMF, 2012) provides design guidance for coastal/river structures subjected to currents. Of particular relevance is Section 5.2.3 which addresses current related scour for rock structures.

Ice

Most of the early, successful living reef projects were constructed in temperate climates, therefore specific guidance on the ability of living reefs to resist ice is lacking. Floating ice acts similar to other types of floating debris, and can apply large forces to developing reefs. Additionally, if ice becomes frozen to the reef, individual sections may be uplifted due to buoyant forces. Another concern related to ice/freezing conditions, is the biota's susceptibility to freshets, or pulsed freshwater events from melting snow and ice at the end of the winter. An alternative to increasing the resistance of the structure itself to ice is the strategic placement of auxiliary project elements designed to break up or deflect the ice. Common elements include timber piles or large rocks placed offshore of the main structure.

Storm Water Level

When deploying artificial substrate as a part of a living reef project, the structure should be designed to mimic nearby naturally occurring reefs. Unlike inert structures where only the maximum water levels are typically considered, both the minimum and maximum expected water levels are relevant to the design of living reefs. If the reef is placed too high in the intertidal zone the organisms will dry out and won't be able to survive. No portion of the reef should be without water for any longer than six hours.

Living reefs are low-crested structures that are generally submerged during large storm events. When constructed to protect marshes and/or beaches those features are generally submerged as well. This submergence reduces the wave forces on the structures themselves and the shorelines they are intended to protect. For this reason, it is acceptable to design living reefs to a lower survivability standard than traditional coastal structures. To determine an appropriate design storm, it is recommended that the proposed elevation of the living reef and any inland features it is intended to protect are compared to design storm water elevations. For most living reef projects it is expected that the design storm water level will be associated with a 20-30 yr return period storm.

Terrestrial Parameters

Upland Slope

Living reefs are constructed offshore and as such the upland slope is not a factor in their design. An adequately designed living reef and marsh system will prevent erosion of the upland bank. If the upland slope is to be vegetated, the vegetation selected should be appropriate for the existing/designed slope.

Shoreline Slope

Shoreline slope is an important factor for the development of a marsh landward of the living reef structure. While the living reef itself will not be impacted by the shoreline slope, slopes of between 1 on 8 and 1 on 10 or milder have been identified as optimal for the marsh development (Hardaway, et al. 2010). In general, the wider the intertidal zone, the more effective the marsh will be at dissipating wave energy. (Knutson, et al. 1982) in his study of the wave dampening characteristics of Spartina alterniflora found that for small waves, 50% of their energy was dissipated within the first 8 feet of marsh, with 100% dissipated within 100 ft. While overall mild slopes are preferred, a small gradient needs to be maintained for drainage purposes. (Priest, 2006) recommends that areas of standing water larger than 100 ft^2 be avoided to prevent the drowning and die off of pockets of marsh vegetation.

Width

The width of the marsh developing behind the living reef structure will be highly dependent on the local conditions. Marsh width will determine the amount of additional energy dissipation that will occur for transmitted waves. (Hardaway Jr. & Byrne, 1999) recommends a minimum width of between 30 and 70 ft for low-moderate energy sites. It is expected that the intense coastal development in New Jersey may make it difficult to achieve the desired widths without extending the shoreline seaward. Under the conditions set forth in Coastal General Permit 24, any fill taking place in conjunction with a living shorelines project must occur landward of the shoreline depicted on the 1977 tidelands map.

Nearshore Slope

Living reefs are generally constructed on an existing nearshore slope. Once the marsh platform is developed, the shoreline slope typically abuts the landward side of the reef. The nearshore slope influences wave breaking at the structure and should be flat enough or modified to provide a stable platform for the reef.

Offshore Depth

Living reefs are typically constructed in areas where the offshore water depths are less than 6 ft. Shallow offshore depths are one of the primary factors that limit wave exposure and create the low-medium energy conditions required for living reefs to thrive.

Soil Bearing Capacity

Soil bearing capacity should be sufficient to prevent unwanted sinking or settling. Settling is less of a concern for natural placement; however if large shell bags, gabions , or concrete substrates are utilized, settlement may occur. A bedding layer, geotextile fabric, or marine mattress bed may be placed below the reef structure to reduce settling.

Ecological Parameters

Water Quality

The most important consideration when implementing a living reef and normally a limiting factor for success, is the local water quality. Both oyster and mussel reef systems require specific conditions for the species to thrive and become self-sustaining. Regulatory issues regarding water quality must be carefully considered. Salinity is the most important factor influencing the growth and survival of oysters and mussels. Oysters can tolerate a wide range of salinity in the intertidal zone (Risinger, 2012), ranging from 5 to 40 psu, with 14 to 28 psu being an optimal range (Galtsoff, 1964). One concern with developing oyster reefs in an estuarine environments, is the impact of freshets, or pulsed freshwater events from melting snow and ice during the spring. Freshets can have a large impact on the salinity of the lower portion of an estuary with a large river discharge like the Hudson, dramatically effecting key ecosystem processes. La Peyre, et al. (2009) proved through laboratory and field experiments that both low and high salinity events are necessary for optimal oyster growth. Low salinity events (less than 5 psu) were found to decrease parasite infection intensities, resulting in a decrease in mortality rates. Growth however, is positively correlated with salinity as oyster valves close during low salinity events, reducing feeding and stunting growth.

If marsh restoration is being performed in addition to the living reef, salinity thresholds should also be obtained for all marsh plantings prior to design and planting to ensure survival. Smooth cordgrass (Spartina alterniflora) and marshhay cordgrass (Spartina patens) can tolerate regular inundations with 0 to 35 parts per thousand salinity (USDA, 2002).

Soil Type

Oyster growth is heavily dependent upon their position within the water column. Oysters grown on muddy substrates tend to be thinner because they need to grow quickly to keep from being smothered, while oysters grown on more stable bottoms tend to be thicker (Wheaton, 2007). Sedimentation from being too close to the river bed can negatively affect both the growth and mortality rates of oysters. (NY/NJ Baykeeper, 2005) recommends keeping oyster cages between 1 and 2 feet from the sediment to prevent smothering.

Living reefs can be constructed on any type of soil; however, the growth of any vegetation planted behind the reef will be dependent on the substrate. Sand is the best medium for establishing robust vegetation. Sand not only provides a good anchor for the roots, but also allows for rapid growth and effective drainage. Coarser sand should be utilized in areas exposed to higher degrees of wave energy to limit sediment transport. Silt-clay and peat may also be considered but provide limited anchoring and are difficult during planting. Heavy plastic clays, organic amendments, topsoil and mulch should all be avoided as they are difficult mediums for planting and do not effectively anchor the plants (Priest, 2006). Two of the most common marsh plants used in the northeast are Spartina alterniflora and Spartina patens. Spartina alterniflora generally prefers sandy aerobic or anaerobic soils with pH values ranging from 3.7 to 7.9 (USDA, 2002). Spartina patens is adapted to a wide range of soils from coarse sands to silty clays with pH values ranging from 3.7 to 7.9(USDA, 2002). More expansive lists of flora native to the New Jersey region are available from regional and national sources including Citizens United to Protect the Maurice River and the Federal Highway Administration.

Sunlight Exposure

Chlorophyll is a green pigment found in chloroplasts and is a critical component in the process of photosynthesis. In water chlorophyll concentrations depend on the availability of nutrients and sunlight, as well as water temperatures (Rella, 2014). Without photosynthesis oxygen cannot be produced, ultimately resulting in the relocation of all mobile species and the death of sessile organisms such as oysters and mussels (SOW, 2007). Chlorophyll also directly effects the levels of phytoplankton in the water, which serve as the main food source for oysters. The availability of this food supply directly affects oyster/mussel growth and reef development.

Sunlight is also an important factor in the growth and propagation of marsh vegetation. Marsh plants generally require at least six hours of direct sunlight per day (Whalen, et al. 2011). This should be taken into account during design, and marsh plantings should be avoided where large trees or ancillary structures (docks for example) will prevent adequate sunlight exposure.

Additional Considerations

Permits/Regulatory

Close coordination with the NJDEP and other relevant regulatory agencies is suggested. Project designers are encouraged to contact NJDEP during the scoping and/or planning phase so that potential State regulatory barriers can be identified and addressed. Specific regulatory requirements are site and project dependent; however, there are several common regulatory issues associated with living reef projects including:

- covering critical nearshore habitat
- filling beyond the 1977 tidelands boundary
- impacts to adjacent properties
- nature and quality of fill material
- restrictions on the use of planting/seeding of commercial shellfish species (Eastern Oyster - *Crassostrea virginica* - or Blue mussels - *Mytilus edulis* - for example) in waters not approved for shellfish harvesting
- navigation hazard

Scour

Living reefs are subject to many of the same modes of failure as other sloped offshore structures. As waves reflect off the front and sides of living reefs, the resulting turbulence can generate scour along the toe (base) and flanks (edges) of the reef. Although this effect will be reduced compared to traditional structures due to the increased surface complexity, excessive erosion may cause the reef to slump, negatively impacting further growth, and reducing its effectiveness in dissipating wave energy.

Properly designed living reefs will contain windows or gaps along the structure to allow for circulation. While it is possible for water to access areas behind a living reef through pores spaces or via overtopping, gaps should always be included along larger projects to allow access for marine fauna (i.e. fish and turtles). Limited research has been performed to determine optimum gap width and frequency, but a general empirical guide recommends windows at least every 100 feet along the length of the project (Hardaway, et al. 2010). Factors that influence window spacing include drainage, elevation change, recreational access, and bends in the project. Scour is generally observed along the shoreline behind the windows as waves are allowed to penetrate this area. Diffraction diagrams, and crenulate bay stability formulas have been shown to be fairly successful in predicting the equilibrium planform of these indentations. An analysis of living shoreline projects in Virginia has suggested a ratio of 1:1.65 between the indentation and gap width (Hardaway & Gunn, 2000). Options for limiting or reducing the scour in the windowed section include lining the shoreline with small cobble or stones instead of sand, staggering the openings, and angling the reef away from shore before the gap (Hardaway, et al. 2010).

It is not uncommon for living reef projects to cause some erosion on adjacent properties; however, the amount is typically much less than what would be expected with a traditional structure. The irregularity and surface complexity created by the living elements of living reef structures generally increases energy dissipation and reduces reflection. This in turn reduces turbulence and scour compared to traditional offshore or shore-attached structures. Additionally, living reefs generally terminate in a more natural manner than man-made structures, reducing the erosive impacts associated with abrupt edges.

Constructability

Living reefs can be constructed using either land based or water based construction techniques. Constructed living reefs typically use artificial substrate to jumpstart the reef building process. There are numerous commercially available substrates including Oyster Castles, Reef Balls, and ECOncrete as well as several non-commercial substrates such as shell bags and gabion baskets. (Goelz, et al. 2020) reviewed the materials most commonly used as artificial substrate and concluded that project objectives should guide the selection. Ease of construction varies widely amongst the various substrate types. Shell bags and oyster castles can be placed by hand and are suitable for non-technical construction crews including volunteers, while Reef Balls and gabion baskets typically require heavy equipment and skilled contractors. For projects that require heavy equipment, access to the site must be provided. In remote areas this may require establishing temporary "roadways" across unsuitable terrain with strict environmental constraints.

For water based construction, water depth is a critical consideration. Shallow water may limit site access, while deep water may create unsafe working conditions. Most construction barges require working depths of at least 4 ft, which may limit site access during periods of lower tides. On the other hand, water depths of greater than 4 ft make working in the water difficult for most individuals. For larger projects, material may need to be stored on site. If material barges are used, they should be moored in areas with sufficient depth to accommodate the loaded barge's draft through the full tidal cycle.

For projects anticipating natural recruitment, substrate installation should be timed such that all substrates are in place in time for the spawning cycles of target species. If vegetation is included, planting should take place during the spring and summer growing seasons to allow root systems adequate time to strengthen prior to the winter (storm) season. (Miller, et al. 2015) identified vegetation maturity as critical to its ability to resist storm conditions.

Native/Invasive Species

Living reef projects should incorporate appropriate native vegetation for the marsh platform and upland areas if they are to be planted. Ideally an ecologist with experience working in a marsh environment should be consulted to identify appropriate plant species and planting zones. The US Department of Agriculture (USDA) National Invasive Species Information Center maintains a list of resources specific to New Jersey. Among these are a 2022 list of invasive species compiled by the New Jersey Invasive Species Strike Team, a list of aquatic invasive species maintained by NJ Fish and Wildlife, and a list of native plants maintained by the Native Plant Society of New Jersey. The USDA Cape May Plant Materials Center also maintains a list of plants released to commercial growers to meet specific restoration needs.

Native species should be considered in the design of the reef itself. Specifically oysters and/or ribbed mussels should be utilized in the environments in which they would naturally occur. This is important not only for natural recruitment and reef development, but also to prevent competition from invasive organisms.

Debris Impacts

The marsh areas behind the living reef are particularly vulnerable to scour from floating debris. Unlike stone structures, these living components can naturally recover with time without human intervention; however, the process often takes a considerable amount of time to occur. One alternative for preventing damage from floating debris is to strategically place auxiliary project elements to deflect large debris. Common elements include timber piles or large rocks placed offshore of the main structure.

An analysis of the impact of three significant hurricanes (Irene, Lee, and Sandy) on sustainable (living) shoreline projects constructed in New York state identified debris impact as one of the major causes of damage (Miller, et al. 2015). In New Jersey, Sandy was responsible for producing an extraordinary amount of debris, much of which ended up in and along the types of shorelines ideally suited for living shorelines projects. Living reefs, as well as the marshes they protect can be vulnerable to debris impact. The calcium carbonate content of oyster shells tends to make well established oyster reefs more resistant to damage than mussel reefs; however, fast floating debris can damage both types of reefs and dislodge large portions of the living structure. Marshes located behind living reefs are also vulnerable to scour from floating debris. Unlike stone structures, living reefs can naturally recover with time without human intervention; however, the process often takes a considerable amount of time. While specific design criteria for debris impact does not exist, it is recommended that debris impact be considered during the design phase. One alternative that has been shown to be successful along shorelines prone to ice impact, is the inclusion of auxiliary project elements such as large boulders to deflect debris.

Project Monitoring

Living reefs should be monitored to assess both the system performance and the structural performance (Bridges, et al. 2021). System performance assesses the degree to which the reef is performing its intended function (reducing waves, stabilizing the edge, promoting oyster growth, improving water quality), while structural performance measures the degree to which the reef is holding up to environmental stressors.

Living reefs are generally designed to be self-sustaining, stable structures with minimal maintenance requirements once the living elements have been established. In New Jersey, living reefs are more commonly monitored for ecological purposes; however, it is important to also assess engineering criteria. At a minimum, living reefs should be monitored after major storms and extreme weather events. Typical performance related parameters that should be monitored include the health of the mussel/oyster community, settling of the reef, and the development of scour/erosion related to the reef. If deficiencies are identified the ability of living reefs to heal over time should be weighed against the costs/benefits of immediate intervention.

When developing pilot projects aimed to test the ecological impact of living reef breakwaters, it is important to follow a strict monitoring protocol. The exact type and duration of the measurements to be made depends on the type and scale of the project. Care should be taken to perform measurements that capture all of the relevant scales of variability. Growth and recruitment of target organisms and water quality should be monitored throughout the first two years to capture seasonal variations. All samples should be collected in accordance with the procedures outlined in the NJDEP's *Field Sampling Procedures Manual* (New Jersey Department of Environmental Protection, 2022).

As with all living shorelines that contain a vegetative component, monitoring and maintenance of the vegetation can be key to the success of the project. Marsh monitoring should consist of at a minimum an inventory of all vegetation, a survey of the offshore and marsh platform elevations, and a shoreline survey. Provisions should be made to ensure that any identified deficiencies are addressed in an expedient manner. Typical maintenance activities related to the vegetative component of a living reef project might include removing debris, filling in low spots, thin-layer spreading of dredge material, and supplementing the original vegetation.

Adaptive Management

Living reefs have been shown to keep pace with sea level rise under current sea level rise conditions. When artificial substrates are used to accelerate reef development, they should be designed with adaptive management in mind. This may involve creating wider structures so that additional substrate elements can be added at a future time, should the natural reef not be able to keep up with sea level rise. This can also be accomplished by beginning with an irregular surface with high and low spots designed for current/future colonization.

Beneficial Reuse

In areas where marsh and/or beach restoration is desired and the natural supply of sediment is limited, beneficial reuse of dredged material should be considered for restoring the shoreline. GP 24 currently allows for habitat restoration out to the shoreline shown on the 1977 tidelands map. If shoreline restoration via the beneficial reuse of dredged material is included as part of a living reef project, coarse material should be placed along the shoreline to reduce in water turbidity during placement. Finer grained material should be reserved for interior marsh improvements.

Appendix B: Technical Excerpts

Overview

The following equations, excerpts and technical information are provided in abbreviated form for reference and convenience. For a more complete discussion of the topics presented, the original source documents should be consulted. Although there is no definitive living shoreline design manual, most coastal structures in the United States are designed using techniques outlined in the *Coastal Engineering Manual* (CEM) USACE EM 1110-2-1100 (US Army Corps of Engineers, 2002). The CEM and a number of other potentially relevant publications can be found on the USACE publications website

- https://www.publications.usace.army.mil/USACE-Publications/Engineer-Manuals/

A similar document that is frequently used in Europe is *The Rock Manual. The Use of Rock in Hydraulic Engineering* (CIRIA; CUR; CETMF, 2012). The Rock Manual covers several topics not covered in the CEM and is available from the Construction Industry Research and Information Association (CIRIA) website at:

- http://www.ciria.org/ItemDetail?iProductCode=C683&Category=BOOK

This appendix contains information extracted from these two sources on the following topics:

- Wind Wave Height Estimation (2 methods)
- Armor Stone Size Calculation
- Wake Height Calculation (Primary and Secondary)

Wind Wave Height Estimation

In areas where wave data is limited, it is common to use empirical formulas to estimate the wave conditions (height and period) from wind speed and fetch (open water distance over which the wind conditions are reasonably constant).

Wind Speed Adjustment

Wind speed varies with distance above the Earth's surface; therefore, it is necessary to correct wind speeds measured at elevations other than the standard meteorological convention of 10 m. The standard approach which is presented in Part II, Chapter II of the Coastal Engineering Manual (US Army Corps of Engineers, 2002) is to assume a logarithmic wind speed profile and adjust the wind speed measurements according to the following.

Extracted from EM 1110-2-1100 Part II Chapter II (US Army Corps of Engineers, 2002)

Winds very close to a marine surface (within the constant-stress layer) generally follow some of the "law-of-the-wall" for near-boundary flows. To adjust winds measured at an arbitrary elevation to the 10-m reference level, the "1/7 Rule" can be applied

$$U_{10} = U_z \left(\frac{10}{z}\right)^{\frac{1}{7}}$$

Where:

U_z = wind speed at height z above the surface

z = elevation in m above the surface where U_z is measured

Wave Height Prediction

A simplified method for estimating fetch limited wind wave heights can be found in the Coastal Engineering Manual (US Army Corps of Engineers, 2002). The guidance below is extracted from Part II Chapter II.

Extracted from EM 1110-2-1100 Part II Chapter II (US Army Corps of Engineers, 2002)

The spectrally based significant wave height (H_{mo}) and peak period (T_p) can be calculated as follows for a known fetch (X) and wind speed (U_{10})

$$\frac{gH_{m_0}}{u_*^2} = 4.13 \times 10^{-2} * (\frac{gX}{u_*^2})^{1/2}$$

and

$$\frac{gT_p}{u_*} = 0.751(\frac{gX}{u_*^2})^{1/3}$$

$$C_D = \frac{u_*^2}{U_{10}^2}$$

$$C_D = 0.001(1.1 + 0.035U_{10})$$

Where:

C_D = drag coefficient

U_{10} = wind speed at elevation of 10 m (m/s)

u_* = friction velocity (m/s)

g = gravitational acceleration (m/s^2)

For fully developed wave conditions, the equations can be simplified,

$$\frac{gH_{m*}}{u_*^2} = 2.115x10^2$$

and

$$\frac{gT_p}{u_*} = 2.398x10^2$$

Where for shallow water conditions, the maximum (limiting) wave period is

$$T_p \approx 9.78\left(\frac{d}{g}\right)^{0.5}$$

Where:

d = water depth (m)

SMB Method

The SMB method is another approach for calculating fetch limited wave conditions based on the prevailing wind speeds. There are several versions of the SMB. The excerpt below was extracted from (Etemad-Shahidi, et al. 2009). Additional information on the SMB and alternate wind wave generation approaches can be found in the original article.

<u>*Extracted from* (Etemad-Shahidi, et al. 2009)</u>

The non-dimensional fetch limited wave height (H_s) is given as a function of wind speed (U) and the average fetch (X)

$$\frac{gH_s}{U^2} = 0.283\, tanh\, tanh \left[0.0125\left(\frac{gX}{U^2}\right)^{0.42}\right]$$

Where:

g = gravitational acceleration

and the average fetch, X, is calculated by considering the fetch in 6 degree intervals ±45 degrees from shore normal according to:

$$X = \frac{\sum_{i=1}^{15} \quad X_i cos\,(\theta)_i}{\sum_{i=1}^{15} \quad cos\,cos\,(\theta)_i}$$

Where:

ϑ = angle with respect to shore normal

Armor Stone Size Calculation

Van der Meer Equation

The Coastal Engineering Manual (US Army Corps of Engineers, 2002) presents several approaches for calculating the appropriate stone size for rubble mound structures. The approach discussed below is based on the method of (Van der Meer, 1988) and can be found in Part VI Chapter V.

<u>Extracted from EM 1110-2-1100 Part VI Chapter V (US Army Corps of Engineers, 2002)</u>

$$\frac{H_s}{\Delta D_{n50}} = 6.2 \cdot S^{0.2} P^{0.18} N_z^{-0.1}$$ Plunging waves: $\xi_m < \xi_{mc}$

$$\frac{H_s}{\Delta D_{n50}} = 1.0 \cdot S^{0.2} P^{-0.13} N_z^{-0.1} cot\ (\alpha)^{0.5} \xi_m^P$$ Surging waves: $\xi_m > \xi_{mc}$

$$\xi_m = s_m^{-0.5} tan\ (\alpha)$$

$$\xi_{mc} = (6.2 P^{0.31} (tan\ tan\ (\alpha)\ ^{0.5})^{1/(P+0.5)}$$

Where:

H_s = significant wave height

D_{n50} = equivalent cube length of median rock

ρ_s = mass density of rocks

ρ_w = mass density of water

$\Delta = (\rho_s/\rho_w) - 1$

S = relative eroded area (see Table VI-5-21 in CEM for nominal values)

P = notional permeability (see Figure VI-5-11 in CEM)

N_z = number of waves

α = slope angle

s_m = wave steepness $s_m = \frac{H_s}{L_{om}}$

L_{om} = deep water wavelength corresponding to mean wave period

Validity:

Equations are valid for non-depth-limited waves. For depth limited waves, H_s is replaced by $H_{2\%}/1.4$.

For cot (α) ≥ 4.0, only the plunging wave equation should be used.

N_z ≤ 7,500 after which number equilibrium damage is more or less reached.

$0.1 \leq P \leq 0.6$, $0.005 \leq s_m \leq 0.06$, $2.0 \text{ tonne/m}^3 \leq \rho \leq 3.1 \text{ tonne/m}^3$

For the 8 tests run with depth-limited waves, breaking conditions were limited to spilling breakers which are not as damaging as plunging breakers. Therefore, equations may not be conservative in some breaking wave conditions.

Wake Height Estimation

Primary wakes

A method for calculating the primary wake generated by a vessel is presented in the Rock Manual (CIRIA; CUR; CETMF, 2012).

Extracted from the Rock Manual Chapter 4 (CIRIA; CUR; CETMF, 2012)

Step 1: Determine the vessel's submerged cross-section, A_m

$$A_m = C_m B_s T_s$$

Where:

C_m = midship coefficient related to the cross section of the ship

C_m = 0.9 to 1.0 for push units and inland vessels

C_m = 0.9 to 0.7 for service vessels, tow boats and marine vessels

B_s = beam width of the ship (m)

T_s = draft of ship (m)

Step 2: Calculate limit speed of vessel, V_L

$$V_L = F_L \sqrt{\frac{gA_c}{b_w}}$$

Where:

$$F_L = [\tfrac{2}{3}\left(1 - \tfrac{A_m}{A_c} + 0.5F_L^2\right)]^{\frac{3}{2}}$$

A_C = cross sectional area of the waterway (m^2)

b_w = width of the waterway at the waterline (m)

g = gravitational acceleration (m/s^2)

Other relevant speed limits:

$$V_L = (\frac{gL_s}{2\pi})^{1/2}$$

$$V_L = (gh)^{1/2}$$

Where:

L_s = ship length (m)

h = water depth (m)

Step 3: Calculate actual speed

$$V_s = f_v V_L$$

Where:

f_v = 0.9 for unloaded ships

= 0.75 for loaded ships

Step 4: Calculate mean water level depression, Δh (m),

$$\Delta h = \frac{V_s^2}{2g}[\alpha_s \left(\frac{A_c}{A_c^*}\right)^2 - 1]$$

Where:

α_s = factor to express the effect of the sailing speed V_s relative to its maximum (-),

= $1.4 - 0.4V_s/V_L$

A_c^* = cross sectional area of the fairway next to the ship (m^2)
A_c = cross-sectional area of the fairway in the undisturbed situation (m^2)

Calculate the mean return flow velocity U_r (m/s):

$$U_r = V_s \frac{(A_c}{A_c^*} - 1)$$

Step 5: Calculate maximum water level depression $\Delta\hat{h}$ (m),

$$\frac{\Delta \hat{h}}{\Delta h} = \{1 + 2A_w^* \, for \, b_w/L_s < 1.5 \; 1 + 4A_w^* \, for \, b_w/L_s \geq 1.5$$

Where:

$$A_w^* = yh/A_c$$

and

y = ship position relative to the fairway axis (m)

Calculate the maximum return flow $\hat{U}_r$ (m/s), where if the ratio of A_c/A_m is smaller than 5 (comparable with b_w/B_s < 10) the flow field induced by sailing ships could be considered one dimensional, and $\hat{U}_r$ can be calculated

$$\frac{\widehat{U_r}}{U_r} = \{1 + \; A_w^* \, for \frac{b_w}{L_s} < 1.5 \; 1 + 3A_w^* \, for \frac{b_w}{L_s} \geq 1.5$$

For larger ratios, the field is two dimensional and the gradient in the return current and the water level depression between the ship and the bank must be taken into account

Step 6: Calculate front wave, Δh_f, and steepness, i_f.

$$\Delta h_f = 0.1\Delta h + \Delta\hat{h}$$

$$i_f = 0.03\Delta h_f$$

Step 7: Calculate the stern wave height, z_{max}, steepness, i_{max}, and velocity, u_{max}.

$$z_{max} = 1.5\Delta\hat{h}$$

$$i_{max} = \left(\frac{z_{max}}{z_0}\right)^2 \; with \; i_{max} < 0.15$$

$$u_{max} = V_s(1 - \Delta D_{50}/z_{max})$$

Where:

$$z_0 = 0.16y_s - c_2$$

y_s = ship position relative to the bank

$$= 0.5b_w - B_s - y$$

$$c_2 = 0.2 \; to \; 2.6$$

D_{50} = bed roughness (m)

Δ = relative buoyant density of the material (-).

Secondary Wakes - USACE

Many approaches exist for calculating secondary wake characteristics. Most of the formulae are specific to the type of vessel, the characteristics of the channel, and the maneuvering of the ship. What is presented below is an example of an equation employed by the USACE (US Army Corps of Engineers, 1980) for calculating the bow diverging wake height at the bank in a navigation canal.

Extracted from (US Army Corps of Engineers, 1980)*:*

The following equation can be used to predict the diverging wake heights (H_m) at the bank in a navigation canal:

$$H_m = 0.0448V^2\left(\frac{D}{L_v}\right)^{\frac{1}{2}}\left(\frac{S_C}{S_C - 1}\right)^{2.5}$$

Where:

D = vessel draft

S_c = channel section coefficient (channel cross-sectional area divided by the wetted cross-

sectional area of the vessel at midship)

L_v = vessel length

V = vessel speed

Secondary Wake Generation - PIANC

Many approaches exist for calculating secondary wake characteristics. Most of the formulae are specific to the type of vessel, the characteristics of the channel, and the maneuvering of the ship. What is presented below is an example of an equation employed by the Permanent International Association of Navigation Congresses (PIANC, 1987) for calculating waves generated by vessels in inland waterways.

Extracted from (PIANC, 1987):

The following equation can be used to predict the wake heights (H_m) generated by vessels in inland waterways:

$$H_m = A^{II} d \left(\frac{S}{d}\right)^{-0.33} F^4$$

Where:

A^{II} = coefficient

=1 for tugs, patrol boats, and loaded convention inland motor boats

=0.5 for empty European barges

=0.35 for empty conventional motor vessels

S = distance perpendicular to the sailing line from the vessel's side to the point at which the wake height is being calculated

d = water depth below the still water line

F = Froude number

The Froude number is calculated as:

$$F = \frac{V}{\sqrt{gL}}$$

Where:

V = vessel speed

g = gravitational acceleration

L = vessel length at the waterline

Appendix C: Remaining Gaps

Overview

In the process of compiling the 2022 update to the Living Shorelines Engineering Guidelines, the following gaps have been identified. A brief description of these knowledge gaps is provided below.

Science Gaps

In reviewing the literature for this document, the following gaps were identified that are specific to the engineering design of living shorelines projects.

Impacts of Climate Change/Sea Level Rise

There is broad consensus that the climate is changing and that sea levels are rising; however, there is less consensus on how rising sea levels will affect existing living shorelines projects. At the most basic level, rising seas threaten to inundate both built and natural landscapes. Most empirical equations predict that as structures become submerged, they lose their ability to attenuate waves. Some new research even suggests that as structures become submerged, they may actually amplify incoming waves (Bredes, et al. 2022). While natural reefs do have some ability to keep up with rising sea levels, this is highly dependent on the rate at which sea levels rise. Marsh platforms are similarly affected; they can keep pace with sea level rise through natural sedimentation/accretion up to a point, assuming there is enough sediment in the system. The concept of adaptive management is an approach for dealing with rising seas, which has gained momentum recently. Continued monitoring of existing living shoreline projects, natural reefs and marsh platforms will create data sets that will aid in future research of these effects.

Design Gaps

In reviewing the literature for this document, the following gaps were identified that are specific to the engineering design of living shorelines projects.

Adaptive Design

Adaptive management is a concept that has gained momentum recently. Adaptive management offers many advantages including:

- prevents overbuilding at the design phase;
- reduces upfront costs by allowing management of unknowns over time; and
- provides flexibility to adjust project goals over time as the needs of the site change.

To apply adaptive management most effectively, projects need to be designed and regulated with adaptive management in mind. Although many of the principles are well understood (e.g., need for shorter, wider structures) there is currently a lack of information on the adaptive living shoreline design strategies.

Appropriate Length Scales

Length in the context of living shoreline project design refers to the alongshore length of property required for a successful project. One of the problems in defining an appropriate longshore project length is that the criteria for determining the success of living shorelines projects are not well documented. From an engineering standpoint, success can be defined in terms of survivability, but from an ecological standpoint more is expected and often required than just a structure that is still standing. Small projects can be just as worthwhile as large projects depending on the objective of the individual project and the way in which it fits into municipal, county, or State plans for the region.

Urban and Developed Shoreline Design Guidance

To date, most of the existing design guidance for living shorelines has focused on traditional projects in more natural settings. As the field has evolved however, the core living shoreline design principles balancing engineering and ecology have been extended to more developed or urban environments. While there are many urban living shoreline projects, until recently there has been little in the way of comprehensive design guidance. Seeking to fill this gap, the NJ DEP commissioned a companion document focused on developed shorelines. *Ecoshorelines on Developed Coasts Guidance and Best Practices* (Miller, et al. 2022) provides guidance to the regulatory and design community on the implementation of living shorelines along developed shorelines. Three examples of living shoreline concepts applied to developed infrastructure that illustrate both the potential of these approaches as well as the need for further study are enhanced concrete structures, ecologically enhanced bulkheads, and oyster-reef pile encasements. The use of these examples in case studies are described in the *Ecoshorelines on Developed Coasts Guidance and Best Practices* document.

Enhanced Concrete Structures

Over 50 percent of coastal and marine infrastructure is made from Portland cement, a poor substrate for biological recruitment due to its highly basic alkalinity, leaching of toxic compounds into the water, and minimal surface complexity (Perkol-Finkel and Sella, 2013). Habitats that do develop are typically less diverse than natural systems and are commonly dominated by nuisance and invasive species. Enhanced concrete is concrete that has been altered to encourage biological recruitment along marine infrastructure. By modifying the chemical composition and/or surface texture of coastal or marine-infrastructure concrete it is possible to improve its capability of supporting enhanced marine fauna and flora. Chemical modification is typically accomplished through changing the concrete mix which ultimately influences the final properties of the concrete, including its tensile and compressive tolerances. By lowering the high surface alkalinity of concrete from its normal pH of approximately 13 to closer to 8 (the average pH of seawater) and by texturizing or increasing the complexity of the surface, a more diverse recruitment and increased growth can be achieved (Perkol-Finkel and Sella, 2013). Additionally, it is known that many organisms prefer complex surfaces (either on the macro or micro scale) that alter circulation patterns and allow for recruitment despite sometime turbulent conditions. While enhanced concrete projects have shown promise, more detailed engineering studies need to be completed before enhanced concrete is adopted more widely.

Ecologically Enhanced Bulkheads

Historically, urban waterways and waterfront infrastructure were designed and built with little or no ecological considerations, strongly reducing their ability to provide valuable ecosystem services to the marine environment (Bulleri & Chapman, 2010) (Munsch et al., 2014). Traditional urban shoreline edge designs that include steep slopes and homogeneous smooth surfaces such as metal and concrete, lead to reduced biodiversity and dominance of nuisance and invasive species. Recently, retrofits for existing bulkheads have been proposed that are designed to introduce sloped or terraced edges, shoreline sinuosity, surface complexity or material composition (Coombes et al., 2015) (Perkol-Finkel & Sella, 2015). Studies have shown that many of these alterations can have a significant impact on the local ecology (Chapman & Underwood, 2011) (Naylor & Viles, 2002). Similar studies need to be performed to assess the impact of proposed and constructed enhancements on the engineering performance of the units themselves and the structures to which they are attached.

Oyster Reef Pile Encasements

This innovative concept involves building oyster reefs around both new and degrading pile encasements to prevent the erosion of the underlying concrete. Under optimal environmental conditions eastern oysters (Crassotrea virginica) can biologically dominate artificial concrete reef structures (Risinger, 2012). As growth on a structure increases the oysters cement to each other and in essence lock the structure together, strengthening it as well as protecting it from the erosional forces of the waves. It has been shown that when oysters settle on concrete structures, they not only reinforce their structural integrity, but they also effectively dissipate wave energy (Risinger, 2012). While this idea has much promise the impact of the proposed encasements on the performance and function of the pile clusters to which they will be attached needs more study.

Beneficial Reuse and Thin Layer Placement

Many of the areas in New Jersey where a living shoreline may be an appropriate solution for stabilizing the shoreline are often sediment starved. As sea levels rise this lack of sediment will only exacerbate the erosion and degradation of these sites. In many cases these projects would benefit from the addition of sediment, potentially on a semi-regular basis, in addition to a shoreline stabilization technique. While this document specifically addresses the traditional living shoreline techniques used to stabilize eroding shorelines, there is also a need for guidance related to the beneficial reuse of dredged material. When used to fill behind an edge stabilization project the techniques are relatively straightforward; however, when material is placed on an active marsh platform a greater degree of precision is often required. This addition of sediment can be part of the primary design and permitting of the project or may be part of the adaptive management of the site. This use of sediment should further be worked into a regional sediment management plan for the region.

Ice

One of the primary environmental factors that requires consideration during the design and construction of living shorelines projects in the northeast is the presence of ice. The existing body of literature does not address the issue at all, and while ice may not be a primary consideration for traditional coastal structures, living shorelines projects are inherently more structurally fragile and, therefore, are more susceptible to damage during heavy ice conditions. Two aspects of this problem that need to be address are: 1. determining which areas of New Jersey typically experience ice, and 2. developing better guidance for designing living shorelines projects for ice impact. While some guidance on ice-resistant design exists, most of the work is based on studies of rock-lined embankments in the Arctic and is too restrictive for living shorelines projects. Alternative means of protecting living shoreline projects such as the incorporation of "ice breaks" should be included in the investigation of ice impacts.

Wakes

For many of the areas of New Jersey where living shorelines projects are likely to be considered, boat wakes are expected to be a significant concern and potentially even the dominant source of erosive energy at the site. Unfortunately, boat wake data is typically scarce, and oftentimes only very crude calculations or estimates of the wake energy at a site are used as input to designs. Traditional shore-protection design is typically driven by storm waves, meaning that these rough estimates of boat wake energy may be sufficient; however, for living shorelines projects in which the design is often driven by the service load, accurately characterizing the wake environment takes on added importance. Further research needs to be performed to assess the wake climate in regions in which living shorelines project are to be constructed. Ultimately, it may be possible to develop an empirical approach that could be used in combination with vessel traffic information to "model" the wake climate.

Regulatory Gaps

Adaptive Management

There is broad consensus that adaptive management of living shorelines projects can lead to improved outcomes; however, adaptive management can only occur if the regulatory framework allows it. State and federal regulatory frameworks must be modified to allow for innovative designs (e.g., wider adaptable structures, the addition of regular beneficially reused sediment nourishment on sediment starved marshes) and the adaptive management of these sites to assure that project goals are met. Ultimately, allowing for adaptive management techniques will only create more resilient shorelines for both habitats and human development.

Regulatory Consistency

One of the challenges to developing living shorelines is the regulatory boundaries. Regulation creates a challenge in the creation of habitat through living reefs or wider shoreline structures. The assessment of habitat destruction and creation needs to be examined to allow for habitat creating structures that may temporarily cause a disruption to the ecosystem during construction and ecological colonization but will ultimately create new habitat that is needed in the region. Additionally, regulation does not always allow for "new" or "cutting edge" designs to be built, reducing the ability to study wider or more ecologically beneficial structures. Conflicting regulations at the state and federal level need to be resolved. More emphasis needs to be placed on projects that do the most good, rather than those that do the least harm.

Assessment Gaps

Documentation of Benefits

One of the impediments to the more widespread adoption of living shorelines has been the lack of consistent documentation of their benefits. Very few projects have been monitored in a thorough and consistent manner; therefore, the extension of the results from one project to the next is difficult. Complicating matters is the fact that living shorelines projects have multiple benefits and often multiple objectives so defining the appropriate metrics to evaluate a project is not straightforward. Even after the metrics haven been defined, appropriate means of evaluating the metric need to be determined. Oftentimes this is dependent on the funding available as well as the technical capability of the group responsible for the monitoring. Regardless of the approach taken, it is essential that the measurements collected adequately assess the defined metrics, and that the metrics allow comparisons between projects.

Valuation

The valuation of ecosystem goods and services has garnered considerable attention in recent years and is particularly relevant to the ultimate valuation of living shorelines projects. In an increasingly competitive and cost-conscious world, return on investment is often a key metric in determining which projects get funded and which do not. Living shorelines projects frequently suffer in these discrete comparisons due to the inability to justifiably monetize the ecosystem benefits of the projects. The problem is twofold. First, while there has been a significant amount of work on the value of ecosystem goods and services, a unified or standard methodology for monetizing these benefits has yet to be developed. Second, there is a lack of case studies and monitoring as discussed above. Even if a well-vetted, standardized approach existed for monetizing ecosystem goods and services, living shorelines projects would still suffer from a lack of consistent, reliable long-term data on which to base the monetization.

Education

One of the commonly identified impediments to the adoption of the living shorelines in the region is the lack of knowledge about the approach. Landowners and developers may not even be aware of alternatives to bulkheads. Further, in part due to the lack of case studies and monitoring data, there is a general hesitancy to embrace living shorelines. Engineers and contractors are generally hesitant to suggest alternatives they are unfamiliar with. Likewise, regulators may be uncomfortable in permitting these alternatives for the same reason. The engineering guidelines (Miller, et al. 2022) recently developed by Stevens for the NJDEP, is intended to bridge this knowledge gap; however, additional education and outreach will be required. Outreach should focus on the availability of techniques and their proven successes but also present realistic goals that can be obtain through the application of a living shoreline; there should be an understanding that while a living shoreline is often less expense at the onset, it does also need to be monitored for regular adaptive management and upkeep. Education programs should first focus on the successful design and construction of living shorelines in New Jersey and secondly focus on techniques for adaptively managing these sites into the future.