Living Shorelines Engineering Guidelines

Prepared for:

New Jersey Department
of Environmental Protection

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Contents

REVISION HISTORY

Revision Number	Date	Description
1	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”.

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", and "ecologically enhanced shorelines". 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 released a report on coastal risk reduction and resilience which advocates 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 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 traditional marsh sill which is designed to reduce the wave energy at the marsh edge and to allow sediment to accrete behind the structure. Panel B shows a joint-planted revetment which is an ecologically enhanced version of a traditional stone revetment. In the revetment, the stone provides the backbone or the structural spine, while the plantings are designed to enhance the ecological value of the project and provide increased stability to the soil substrate. Panel C shows an oyster reef which is a variation on the marsh sill concept illustrated in Panel A, where the oyster reef provides the wave dissipation effect. Finally Panel D shows a series of Reef Balls, which are concrete elements designed to attenuate wave energy and serve as the backbone of a natural reef.

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. 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. The document is organized as follows. In the next section, the need for, and the purpose of the engineering guidelines is discussed. The subsequent section outlines the approach used to create the guidelines. Next a discussion of the parameters critical for the design of living shorelines projects is presented. The final section describes different methods for determining the design parameters. Two appendices are also included. The first outlines the application of the engineering guidelines to five common types of living shorelines projects, while the second contains excerpts from some of the design manuals referred to throughout the document.

Figure 1: Example Living Shorelines Projects (A - Marsh Sill, B - Joint Planted Revetment, C - Oyster Reef, D - Reef Balls)

PURPOSE

Many documents have been developed with the objective of educating policy-makers, 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 under-engineered or improperly designed structures, while at the same time recognizing that some living shorelines projects may 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 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.

APPROACH

The approach taken in developing the engineering guidelines was to first identify the set of factors which are critical to the success or failure of a living shorelines project, and then to outline a methodology for taking these factors into consideration during the design of a project. Living shorelines projects tend to be fairly diverse, and as such, each project may have its own set of unique factors that need to be considered. The critical parameters that influence the selection and design of most living shorelines projects are presented in Table 1. The parameters have been grouped into four categories, and include both traditional engineering parameters such as wave height and water level, as well as less traditional engineering parameters such as water quality and sunlight exposure. As will be discussed in more detail below, even some of the more familiar engineering variables such as elevation which engineers typically reference to a geodetic datum, are utilized differently in a living shorelines project where they are typically referenced to a tidal datum. In addition to the parameters listed in Table 1, there are a number of other considerations which play a significant role in the selection and design of an appropriate living shorelines project. Some of the more important factors are listed in Table 2.

Table 1: Parameters Typically Used in the Design of Living Shorelines Projects.

System Parameters	Ecological Parameters
Erosion History	Water Quality
Sea Level Rise	Soil Type
Tidal Range	Sunlight Exposure
Hydrodynamic Parameters	**Terrestrial Parameters**
Wind Waves	Upland Slope
Wakes	Shoreline Slope
Currents	Width
Ice	Nearshore Slope
Storm Surge	Offshore Depth
	Soil Bearing Capacity

Table 2: Additional Considerations for the Design of Living Shorelines Projects.

Additional Considerations
Permits/Regulatory
End Effects
Constructability
Native/Invasive Species
Debris Impact
Project Monitoring

The methodology prescribed for the selection and ultimately the design of a living shorelines project utilizes the building block approach illustrated in Figure 2. A base level of information about the parameters listed is typically sufficient to begin narrowing down the alternatives. This basic information is determined through what is referred to throughout this document as a Level 1 analysis. Level 1 techniques are primarily desk-top analyses which rely on existing data to characterize a site. Whenever possible, site visits should be used to confirm the information obtained during the desk-top analyses, and to look for important details which may not have been captured in the data collected. Table 3 contains information on the conditions under which the five alternatives examined in the appendix are typically considered suitable based on a review of the existing literature. In Table 4 an attempt has been made to put quantitative bounds on the somewhat subjective limits imposed in Table 3. Guidance on specific limiting values for many of the relevant parameters used in the design of living shoreline projects is limited. The ranges defined in Table 4 were established by combining limits found in the literature, with engineering experience. As more research/data becomes available, specifically for projects constructed in New Jersey, these ranges should be updated accordingly.

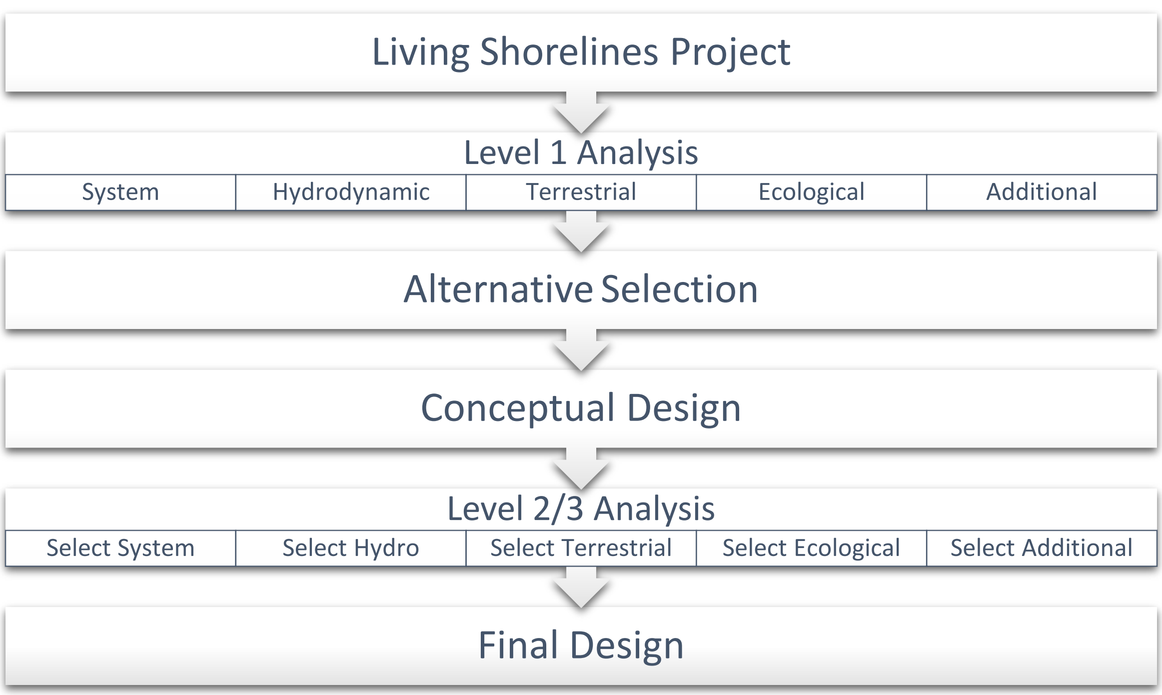

Figure 2: Summary of Building Block Approach

Table 3: Appropriate Conditions for Various Living Shoreline Approaches

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

Table 4: Criteria Ranges

	Criterion		
Parameter	Low/Mild	Moderate	High/Steep
System Parameters			
Erosion History	<2 ft/yr	2 ft/yr to 4 ft/yr	>4 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 Parameters			
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 Surge	<1 ft	1 ft to 3 ft	>3 ft
Terrestrial Parameters			
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 Parameters			
Water Quality	-	-	-
Soil Type	-	-	-
Sunlight Exposure	<2 hrs/day	2 to 10 hrs/day	>10 hrs/day

Once an alternative(s) has been selected, the project designer is encouraged to contact the NJDEP living shorelines projects coordinator so that potential regulatory issues can be identified. Once any issues have been discussed, a conceptual design(s) should be developed. Generally the information obtained from the initial site visit along with the Level 1 desk-top analyses is sufficient to develop a conceptual layout of the project. The conceptual design will typically consist of an overall project plan and select profiles 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. For all but the simplest projects, the next step will be to refine the conceptual design based upon gathering additional information and/or performing additional analyses for several of the most critical design parameters. In Table 3, the most critical design parameters for each technique are identified in bold, italicized text. Depending on the complexity/cost involved, these additional analyses are termed Level 2 or Level 3 analyses. 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. A more detailed discussion of each of these parameters and a description of various approaches for obtaining the required design information is presented below.

LIVING SHORELINES SITE PARAMETERS

The term "living shorelines" can refer to a wide range of shoreline stabilization/restoration projects. Some of these are very similar to traditional engineering projects such as joint planted revetments or breakwaters, while others such as living reefs and Reef Balls are more unique. Due to the diversity of the techniques which can be included under the living shorelines umbrella, the number of parameters that are relevant to their design is quite large. Many variables that influence the growth and survivability of vegetation may be uncommon to engineers and many of the common engineering variables may be uncommon to landscape architects and marsh ecologists. In addition, common variables may have a different meaning to the two communities. For example, landscape derived datums are often used by landscape architects and ecologists in defining planting zones, while engineers typically prefer to design to precisely defined geodetic datums.

To simplify the guidelines, the relevant parameters have been divided into five categories. System parameters are large scale phenomena that effect the performance of a shoreline within the coastal system of which it is a part. System parameters include the erosion history of the site, tidal range, and sea level rise. Hydrodynamic criteria represent the primary forces acting on the shoreline and include wind waves, wakes, currents, ice, and storm surge. Terrestrial variables strongly influence the response of a shoreline to the forcing parameters, and include slope (upland, shoreline, and nearshore), shore width, offshore depth, and soil bearing capacity. Ecological variables are those that are most relevant to the performance of the natural elements of a project and include water quality, sunlight exposure, and soil type. The fifth category is slightly different than the first four in that it represents factors that should be considered in the design of a living shorelines project, but that are not necessarily a part of the conditions at the site. 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.

One parameter which is noticeably absent is "length". 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. 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.

DETERMINATION OF DESIGN CONDITIONS

Generally there are multiple ways of evaluating each of the parameters identified in Table 4, ranging from simple desk-top analyses, to time-consuming and expensive numerical modeling and/or field data collection. The level of analysis of the parameters that is 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 each of the parameters identified in Table 1. The methodologies are presented in order of the level of complexity and often expense involved in performing the analysis. Level 1 analyses are representative of desk-top analyses, and represent the type of analyses that should be performed in support of a conceptual design. Level 2 and Level 3 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 represent large scale or regional processes which are not necessarily confined to the project site. 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.

Level 1 Analysis – Desk-top 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 free resources that can assist in determining the erosion history of a site including:

- Google Earth – Google Earth (www.googleearth.com) 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 5 and 10 aerials dating back to the early 1990's.
- Nationwide Environmental Title Research, LLC (NETR) online database (www.historicaerials.com) – The NETR website database contains a series of historic aerial photographs and topographic maps that typically dates back to the early 1900's. 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 a number of local, county, state, and federal sources. Two relevant datasets available from the NJ Department of Environmental Protection (http://www.state.nj.us/dep/gis/) are the shoreline structure dataset and the historic shoreline dataset.
- Bing Maps – Bing maps (http://www.bing.com/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.
- 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. Several federal and state agencies such as the NOAA Coastal Services Center (http://www.csc.noaa.gov) maintain and disseminate Lidar data for use by the public. While currently, the number of available Lidar datasets is small, data collection is becoming more common particularly after large storm events. These post-storm datasets can be extremely useful in helping to understand how large storms impact prospective project sites.
- Other Sources – The sources listed above represent a fairly thorough list of information sources for establishing the erosional history of a site. Additional sources of information may include local libraries and historic maps maintained by the county, state, or university (http://mapmaker.rutgers.edu/MAPS.html).

Level 2 Analysis – Personal Interviews

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 land owners, 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.

Sea Level Rise

Sea levels have risen approximately 1.3 ft along the coast of New Jersey in the past century. Projections of future sea levels vary; however all are consistent in that they indicate future sea levels will be higher than they are today. Living shorelines projects are particularly sensitive to sea level rise due to the living elements of the projects, therefore it is particularly critical to take this information into account during project design. Currently no official State guidance exists on the incorporation of sea level rise into the design of living shorelines projects. Until official guidance is developed, it is suggested that the project designer discuss all assumptions with regards to sea level rise (rate, time frame, etc.) with the State's living shorelines project coordinator.

Level 1 Analysis – Desk-top Analysis

The simplest approach is to assume that the existing regional sea level trend will persist into the future. NOAA maintains information on sea level trends on its *Tides and Currents* website (http://tidesandcurrents.noaa.gov/). The sea level trends calculated for New Jersey's three long-term tide gauges are as follows:

- Sandy Hook – 3.90 mm/yr, or 1.28 ft/century
- Atlantic City – 3.99 mm/yr or 1.31 ft/century
- Cape May – 4.06 mm/yr or 1.33 ft/century

A first order estimate of the potential sea level rise at a living shoreline project site can be made by simply applying these values.

Level 2 Analysis – Adopt Federal Guidance

The historic trends provide one estimation of future water levels; however there is considerable uncertainty as to whether the currents trends will persist into the future. One method of accounting for this uncertainty is outlined in a guidance document prepared by the US Army Corps of Engineers (US Army Corps of Engineers, 2011). The approach advocated by the Corps of Engineers was also referenced by NOAA in a report outlining guidance for planning for sea level rise in tidal wetland restoration projects (National Oceanic and Atmospheric Administration Restoration Center, 2011). The robust methodology outlined by the Corps of Engineers provides a roadmap for calculating future sea levels considering low (current trend), medium, and high rates of sea level rise. Incorporation of these results into the Corps of Engineers design process is also discussed. The document is available at: http://www.corpsclimate.us/docs/EC_1165-2-212%20-Final_10_Nov_2011.pdf.

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 or small breakwaters, the position of the crest relative to the water level plays a role in the amount of energy dissipation that can be expected and the amount of force the structure is subjected to. Tidal range is also critically important for any "living" portion of a living shorelines project. Selection of the appropriate vegetation is highly dependent on the placement of the vegetation with respect to local tidal datums. Likewise, the growth of living reef elements such as mussels and oysters will be dependent on their location with respect to the water surface.

Level 1 Analysis – Desk-top 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 or by utilizing NOAA's VDatum tool (http://vdatum.noaa.gov/). Users of the VDatum tool are cautioned that significant errors can occur during the transformations (http://vdatum.noaa.gov/docs/est_uncertainties.html). There are many sources of tidal information including, NOAA (http://tidesandcurrents.noaa.gov/), the USGS (http://waterdata.usgs.gov/nj/nwis/current/?type=tide&group_key=NONE) , and local universities (http://hudson.dl.stevens-tech.edu/maritimeforecast/PRESENT/data.shtml, http://njwrri.rutgers.edu/RealTime.htm). 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 the 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.

Level 2 Analysis – Field Data Collection

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).

Level 3 Analysis – Model Water Levels

If the project budget allows, a circulation model could be used to determine the required tidal elevations. Any model should be calibrated and validated prior to its application. The procedure for establishing tidal datums from numerical model results over shorter time frames is similar to that described above for short observational records.

Hydrodynamic Parameters

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

Wind Waves

Waves generated by local winds and meteorological conditions tend to be one of the dominant forces impacting shorelines, and are typically considered in all engineered shoreline improvements. As the wind blows over the surface of a body of water its energy is transferred to the water. 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 open ocean coastlines. When designing a living shoreline project, there are generally two design waves which may be important. The first is the maximum expected or extreme wave. This is the wave height typically used in most traditional coastal engineering applications; however for living shorelines this wave may not represent the critical condition because during an extreme storm the entire project may be submerged. The second relevant wave height should represent a more frequently encountered condition. (Shafer, et al., 2003) in an evaluation of several sites in Texas and Alabama found that the presence or absence of marsh vegetation was most sensitive to the wave height exceeded 20% of the time. Unfortunately, for most sheltered water bodies, minimal if any wave observations exist.

Level 1 Analysis – Desk-top 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 5. Although there is no direct correlation with the ranges in Table 3 and Table 4, the medium energy conditions presented in Table 5 are roughly consistent with the moderate conditions in the prior tables.

Table 5: Fetch categorization according to Hardaway (1984).

Energy	Fetch (mi)	Weight (lb)	Diameter (ft)	Sill/Marsh BW/Beach	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 slightly more rigorous approach also discussed by (Hardaway, et al., 2010) is to factor in the wind climate using an approach such as the SMB method (US Army Corps of Engineers, 2002). There are a number of different variations of the SMB method ranging from deep water to shallow water, and from restricted fetch to unconfined fetch. Reviews of several of the variations are contained in (US Army Corps of Engineers, 1984) and (Etemad-Shahidi, et al., 2009). Most living shorelines projects are constructed in relatively shallow water bodies, therefore a shallow water approach is typically most appropriate.

Level 2 Analysis – Collect Wave Measurements

Wave measurements may be carried out either independently, or as a means to verify wave predictions from an SMB (Level 1 Analysis) method or hydrodynamic model (Level 3 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 1.5-7 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.

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 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 & 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.

Alternate Approaches

A number of 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. The plaster cast approach relates the wave energy to the erosion of a plaster cast which has previously been calibrated in the lab.

Level 3 Analysis – Wave Modeling

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 modes are included as a part of a modeling package containing fully 3-D hydrodynamic and morphologic models (Delft 3D, 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. 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. Two of the more commonly used nearshore modeling packages which include waves are: Delft3D (http://oss.deltares.nl/web/delft3d) and Mike21 (http://www.mikepoweredbydhi.com/). Locally, Stevens operates an operational version of the Ecomsed model, known as NYHOPS (http://hudson.dl.stevens-tech.edu/maritimeforecast/) which is capable of simulating both waves and currents.

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 3. 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 generally 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 taken into account during design in a physically satisfying manner, due to a lack of readily available wake measurements.

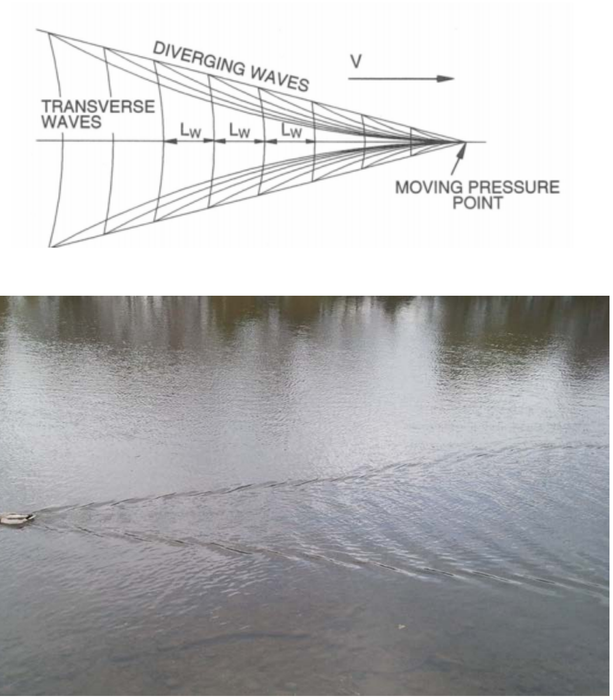

Figure 3: Typical Wake Wave Pattern

Level 1 Analysis – Desk-top Analysis

The ability to perform a desk-top analysis of wakes is limited by the scarcity of archived wake data. In spite of its importance to the design of inland shoreline stabilization and restoration works, little to no wake data exists. At the Level 1 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. 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), respectively.

Level 2 Analysis – Visual Wake Analysis

To obtain a basic sense of the wake energy at a site, simple, low-cost methods can be used. (Rella, et al., 2014) describe a very basic visual observation technique which was used to measure wakes at dozens of sites along the Hudson River. The approach consisted of mounting a graduated rod to a fixed structure or the river bottom and then visually recording the water surface oscillations as depicted in Figure 4. Video recordings can be made to check initial observations and to obtain a better estimate of the wake period. One of the advantages of the visual technique is that the wakes can easily be distinguished from the ambient wind waves. In order to get a true sense of the wake energy at a site, the measurements should be repeated several times to reduce bias due to factors like variations in boat traffic due to seasonality 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.

Figure 4: Visual Wake Measurement near a Bulkhead

Level 3 Analysis – Advance Wake Measurement

Many of the instruments discussed above for measuring wind waves 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. If it is desired to separate wind and wake measurements, visual observations of the water body are typically required to supplement the measurements as the heights and periods of both types of waves tend to be very similar. In order to get a true sense of the wake energy at a site, the measurements should be repeated several times to reduce bias due to factors like variations in boat traffic due to seasonality 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.

Level 3 Analysis – Extension of Analytical Approach

The empirical approaches described above under "Level 1 Analysis – Desk-top Analysis" can be extended. The existing empirical relationships for vessel generated wakes primarily calculate the wake near the point of generation. As the wake propagates away from this point it will be transformed by the local processes until it encounters the shoreline. Depending on the vessel's distance from shore, the local currents, and the nearshore bathymetry, the wave impacting the shoreline may look significantly different than the original wave. In addition, while the empirical results provide an estimate for a single vessel passage, consideration should be given to the relative frequency of different vessel types passing the project site. For living shorelines projects where wakes are expected to be a primary driver of shoreline behavior, a wave transformation study should be performed to estimate the nearshore wave heights.

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 sites located near tidal inlets or along riverbanks. 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 similar to debris can scour the shoreline.

Level 1 – Desk-top Analysis

It is rare that sufficient current data exists to perform a desk-top analysis. General data can be obtained from NOAA (http://tidesandcurrents.noaa.gov/curr_pred.html), the USGS (http://waterdata.usgs.gov/nj/nwis/rt), and the U.S. Army Corps of Engineers (http://cirp.usace.army.mil/); however none of the sources provides enough localized detail for final design. For some locations, detailed hydrodynamic models exist, from which typical or even storm currents may be extracted. NYHOPS (http://hudson.dl.stevens-tech.edu/maritimeforecast/) is one such model, however generally there is insufficient 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 Sustainable Shorelines Project (http://www.hrnerr.org/geospatial/).

Level 2 Analysis – Current 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. 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). A review of one promising technology for overcoming the blanking distance limitation by (Gartner & Ganju, 2002) illustrated the need for approaching "technological breakthroughs" with caution. While other high-tech approaches exist for measuring currents such as surface radar/Lidar, particle tracking, and drone deployment, these approaches are rarely used in bayshore/estuarine environments.

Level 3 Analysis – Current Modeling

If the complexity and scale of the project requires it, 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 the 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 (http://oss.deltares.nl/web/delft3d), Mike21 (http://www.mikebydhi.com/Products/CoastAndSea/MIKE21.aspx), and Ecomsed (http://www.hydroqual.com/ehst_ecomsed.html). Both Delft3D and Mike21 are also capable of modeling waves. Locally, Stevens operates an operational version of the Ecomsed model, known as NYHOPS (http://hudson.dl.stevens-tech.edu/maritimeforecast/) 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

Like wakes, ice is known to have a significant impact on shoreline and coastal structure stability, yet just like wakes, our knowledge on the process of ice-structure interaction is lacking. This is particularly true for living shorelines projects which thus far have predominantly been constructed in locations such as the Chesapeake Bay and Gulf of Mexico where ice is not a concern. Floating ice acts similarly to other types of floating debris and can impose large impact forces to shorelines and structures which need to be accounted for in design. 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 a living shorelines project. Additional research needs to be performed to help anticipate the amount of ice, as well as the expected forces accompanying it, in any areas where living shorelines are being considered an option.

Level 1 Analysis – Desk-top Analysis

In some locations records of ice are collected by organizations such as the coast guard; however these records are sparse, 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 (http://www.hrnerr.org/hudson-river-sustainable-shorelines/shorelines-engineering/ice-conditions/) which contains information from the Upper Hudson River Estuary.

The National Ice Center archives ice cover within Delaware Bay, with records available at http://www.natice.noaa.gov/index.html. The data set is based on an analysis of MODIS (Moderate Resolution Imaging Spectroradiometer) imagery (http://modis.gsfc.nasa.gov/) and provides estimates of ice presence but not thickness. Similarly, the Corps of Engineers maintains an archive of historic ice jams (http://icejams.crrel.usace.army.mil/); 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 due to heat transfer can be found in (US Army Corps of Engineers Cold Regions Research and Engineering Laboratory, 2004).

Level 2 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 in order to be considered reasonably representative.

Storm Surge

For traditional engineering designs, determination of the storm surge plays a critical role in the design of coastal structures. For living shorelines however, the storm surge takes on less significance because most of the approaches are low lying and will be overtopped during extreme storms. For those approaches which require an estimation of the storm surge, traditional engineering approaches are sufficient.

Level 1 Desk-top Approach

A first order approach is to use the existing FEMA Flood Information Study (FIS) reports and Flood Insurance Rate Maps (FIRMS) to estimate the water level during the 1% annual chance of occurrence storm (nominally, the 1 in 100 year storm). The most recent data for New Jersey is available from http://www.region2coastal.com/. The FIRMS (or preliminary versions) accessible via the website split the coast into zones based on the type of flooding and wave activity expected during a 100-yr storm as shown in Figure 5. 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 storm. The elevations specified on the FIRMs represent the Base Flood Elevation (BFE) expected during the 1% annual chance of occurrence storm. The BFE is the 100-yr still water elevation plus the larger of the wave run-up or the wave crest elevation. The resulting BFE's are often several feet higher than the still water elevation near the coast. Still water elevations (which include the effect of wave setup) for the 10%, 2%, 1%, and 0.2% annual chance of occurrence storms can be obtained from the accompanying FIS reports.

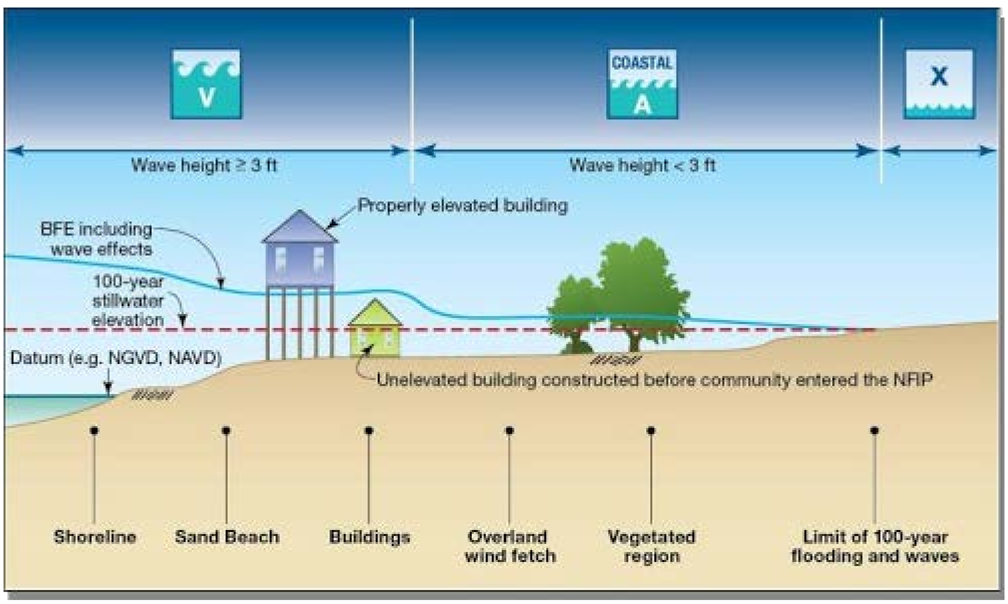

Figure 5: Definition Sketch Showing Flood Zone and BFE Delineation

NOAA provides estimates of extreme water level for each of their long term stations at http://tidesandcurrents.noaa.gov/est/. Unlike FEMA's BFEs, The NOAA estimates do not explicitly take into account wave effects. As such the NOAA estimates are more representative of the still water elevation than the BFE appearing on a FIRM.

Level 2 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 yr). 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 Emergencey Management Administration, 2002). (Arns, et al., 2013) reviewed a number of 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 in how the selected treatment will respond to the local conditions. The terrestrial parameters which include the upland, shoreline, and nearshore slopes, the offshore depth and the soil bearing capacity are defined in Figure 6. Generally, the most appropriate shoreline modification will be the one which mimics surrounding naturally stable shorelines.

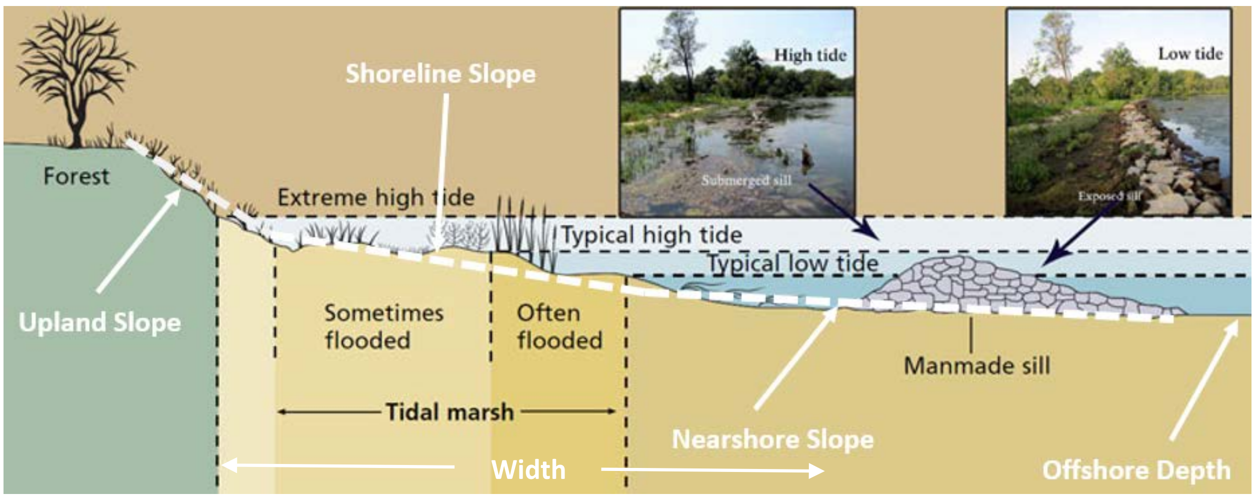

Figure 6: Terrestrial Parameters Definition

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.

Level 1 Analysis – Desk-top Analysis

It is often possible to obtain a sense of the upland slope by examining existing data sources. Topographic maps, digital elevation models (DEMs), and Lidar data sets are frequently available online. USGS topographic maps can be obtained from: http://store.usgs.gov/b2c_usgs/usgs/maplocator/(ctype=areaDetails&xcm=r3standardpitrex_prd&carea=%24ROOT&layout=6_1_61_48&uiarea=2)/.do. The State of New Jersey maintains an online collection of GIS resources at http://www.state.nj.us/dep/gis/, which contains among other things a 10m grid DEM. Typically several sets of Lidar data for most coastal locations in New Jersey can be obtained from NOAA's Coastal Services Center (http://www.csc.noaa.gov/).

Level 2 Analysis – Survey

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 due to the expense involved in collecting the data, 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. In order 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. Standard surveying equipment can be used to survey the upland area down to the water's edge. A common approach is to use survey grade GPS equipment; however simpler approaches such as a theodolite and prism or rod and level can be used as well. If the tidal rage at the site is large, upland surveys should be conducted at low tide to maximize the walkable survey area.

Shoreline Slope

The shoreline or intertidal slope is important in determining the appropriate shoreline stabilization 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).

Level 1 Desk-top Analysis

It can be more difficult to determine shoreline slopes via a desk-top analysis than upland slopes because the area of interest lies along the boundary between two separate 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.

Level 2 Analysis – Wading Survey

Estimates of the shoreline slope obtained via desk-top analysis will generally be very coarse and potentially inaccurate due to the possibility for errors introduced when merging different data sets together. On a developed eroding coast the frequency of data collection poses a problem as well due to the rapid pace of erosion and human modification of the shore zone. In order 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. In order to capture the shoreline slope, it is often necessary to conduct a wading survey in which standard surveying equipment is utilized to survey the area out to at least mean low water (MLW). A common approach is to use survey grade GPS equipment; however simpler approaches such as a theodolite and prism or rod and level can be used as well. 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. In order for a living shorelines 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 reproduced in Table 5. 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 through the use of 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.

Level 1 Analysis – Desk-top 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 (www.googleearth.com) 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 a number of local, county, state, and federal sources. Relevant datasets available from the NJ Department of Environmental Protection include the shoreline structure dataset, the historic shoreline dataset, and the 1977 tidelands base map. The data can be accessed from several websites including:
    - http://www.state.nj.us/dep/gis/
    - http://www.state.nj.us/dep/gis/geowebsplash.htm
    - https://njgin.state.nj.us/NJ_NJGINExplorer/jviewer.jsp?pg=wms_instruct
- Bing Maps – Bing maps (http://www.bing.com/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 the NOAA Coastal Services Center (http://www.csc.noaa.gov) maintain and disseminate Lidar data for use by the public. Shore widths can typically be measured directly from lidar datasets.

Level 2 Analysis – Survey

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 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.

Level 1 Analysis – Desk-top 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 on line, the resolution is typically insufficient for design purposes. Coarse sets of bathymetry data for New Jersey can be found at: http://www.charts.noaa.gov/OnLineViewer/AtlanticCoastViewerTable.shtml or http://nj.usharbors.com/explore/harb or-guide. Both sites provide bathymetric charts from which nearshore slopes can be inferred. The NOAA Coastal Services Center maintains a database of estuarine bathymetry data (DEMs) created by merging multiple surveys collected over time together (http://estuarinebathymetry.noaa.gov/midatlantic.html). 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.

Level 2 Analysis – Bathymetric Survey

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 (https://www.youtube.com/watch?v=3ZraiYGmgZM), 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 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 larger ships which are generally capable of generating larger wakes. Depending on the living shoreline approach selected, water depth will also impact the amount of fill material and the size of the structure required.

Level 1 – Desk-top 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 http://nj.usharbors.com/explore/harb or-guide or http://www.charts.noaa.gov/OnLineViewer/AtlanticCoastViewerTable.shtml. Both sites provide bathymetric charts from which nearshore slopes can be inferred. The NOAA Coastal Services Center maintains a database of estuarine bathymetry data (DEMs) created by merging multiple surveys collected over time together (http://estuarinebathymetry.noaa.gov/midatlantic.html). 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.

Level 2 Analysis – Bathymetric Survey

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 (https://www.youtube.com/watch?v=3ZraiYGmgZM), 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.

Level 1 Analysis – Desk-top 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. 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.

Level 2 Analysis – Detailed Geotechnical Investigation

There are a number of 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, 2005).

Ecological Parameters

The success or failure of any habitat which the living shorelines project intends to restore, enhance or develop will ultimately be dependent 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 have an understanding of 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 significant factors that must be considered when planning any habitat preservation or restoration. Specific habitat types (i.e marsh plantings, oysters, 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 – 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 in order 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 also among water body classifications. The standards for New Jersey as reported in (HEP, 2011) are presented below in Table 6.

Table 6: New Jersey State Surface Water Quality Criteria (as reported in (HEP, 2011)

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 – 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 – 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. Similar to 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 – 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 (Steinberg et al. 2004). 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 water bed.

Level 1 Analysis – Desk-top 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 (http://nj.usgs.gov/infodata/waterquality.html), the EPA (http://iaspub.epa.gov/tmdl/attains_state.control?p_state=NJ&p_cycle=2006), the NJDEP (http://www.state.nj.us/dep/wms/wqde/), local universities (http://www.monmouth.edu/university/coastal-water-quality-real-time-monitoring-program-ver-2.aspx), and environmental organizations (http://nynjbaykeeper.org/resources-programs/advocacy-legal-campaigns/how-is-the-water/). Data archived from operational circulation models (http://hudson.dl.stevens-tech.edu/maritimeforecast/) can often be used to supplement this observational data.

Level 2 Analysis –Water Quality Sampling

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 of 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, 2005).

Soil Type

Soil type plays an important role in determining the rate of vegetation growth and the penetration and heartiness of the root system. A strong root system is essential for providing erosion resistance during large storms; therefore selecting the right type of soil for use in living shorelines projects is critical.

Level 1 Analysis – Desk-top Analysis

Typically only a limited amount of information about the characteristics of the soil at a site exist prior to the collection of project-specific geotechnical information. Some 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. 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.

Level 2 Analysis – Grab Samples

In order 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, 2005).

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.

Level 1 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 (www.googleearth.com) 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 (http://www.bing.com/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

Level 2 Analysis – Field Survey

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 U.S. Army Corps of Engineers 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. In an effort to promote living shorelines projects within the State, a living shorelines working group was created within the NJDEP to assist potential applicants in navigating the regulatory process. Project designers are encouraged to contact the State's living shorelines project coordinator during the preliminary design phase so that potential State regulatory barriers can be identified and addressed during the early phases of project planning and design. The State's living shoreline coordinator is located within the NJDEP Coastal Management Program (http://www.state.nj.us/dep/cmp/).

End Effects

The influence of end effects 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 end effects associated with adjacent projects are a contributing factor to the erosion experienced on unstabilized sections of coast. By recognizing existing end effects in the pre-design phase their influence can be addressed more effectively during the design phase. The second perspective has to do with the potential for end effects associated with the proposed living shorelines project 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 shorelines projects tend to have smaller end effects as compared to traditionally engineered shoreline stabilization projects, they should be evaluated and if necessary steps should be taken to mitigate any negative effects on neighboring shorelines. Generally end effects can be limited by tying into adjacent shore protection works on stabilized coasts, or by gradually transitioning back to a natural coastline on unstabilized coastlines.

Constructability

Even when a project is feasible or even preferred from an engineering stand point 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. 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 construct-able. However, as decisions made in the preliminary design phases will implications to the contractor and thus ultimately the price of the project, 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 be upland based (equipment based on land, and if required, reaching into the waterway) or water based (equipment based on a barge or similar). While several factors such as tide range, water depths at the site, distance from shore, slope, site access, permitting requirements, contractor selection and available equipment will factor in the decision of the construction method, it is usually most cost effective to utilize upland based construction. Upland based construction does however require the owner to designate a contractor staging area, site access and material storage areas. Similarly water based construction may require mooring of work and material storage barges and should be coordinated with appropriate authorities including USCG and the local Harbormaster.

Native/invasive Species

The existing ground cover at a site or on adjacent properties often provides clues as to what vegetation will thrive and which will struggle to survive. Every effort should be made to mimic the conditions in which the natural vegetation is thriving. The presence of invasive species should be noted, and every attempt should be made to replace these invasive species with natural vegetation. The NJDEP maintains a list of common invasive species at http://www.nj.gov/dep/njisc/Factsheets/. A list of common native species commonly used in restoration projects can be found on the USDA Plant Materials Center website at http://www.nrcs.usda.gov/wps/portal/nrcs/pmreleases/plantmaterials/pmc/northeast/njpmc/cp/.

Debris Impact

Recent analyses on the impact of Hurricanes Irene, Lee, and Sandy on shoreline stabilization projects in the State of New York has identified debris impact as one of the major reasons for the extensive damage that was caused (Miller, et al., 2015). Currently no engineering guidance exists on the best approach for incorporating potential debris impact into the design of coastal structures. Until further guidance is developed, it is suggested that living shorelines projects designed and constructed in New Jersey recognize the possibility of similar impacts, and where possible, take steps to address them.

Project Monitoring

Recent analyses on the impact of Hurricanes Irene, Lee, and Sandy on shoreline stabilization projects in the State of New York has identified project monitoring and maintenance as a critical factor in minimizing the damage sustained by several living shorelines sites. (Miller, et al., 2015). One of the recommendations from that report is that monitoring plans be included at the design stage and that sufficient funds be set aside to ensure that the plan is followed. Currently several groups including the State of New Jersey are working on the development of metrics and monitoring protocols for living shorelines projects. In the event that the State of New Jersey adopts an official standard for monitoring living shorelines projects, that protocol would take precedence over any of the suggestions put forth in this document.

Many of the relevant factors in the development of a monitoring plan are discussed in (Kreeger & Moody, 2014). 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 approach have been developed (Smith, 2002). Critical considerations 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 (diurnal or seasonal for example) 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.

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.

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 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 1/3rd of wave heights in a record.

Silt – fine-grained material, such as sand; 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, typically stone structures that are constructed in the water parallel to the existing shoreline. Sills are often used as armoring for fringe marshes or wetlands that require a higher degree of protection. Sills dissipate wave energy and reduce bank erosion, causing waves to break on the offshore structure, rather than upon 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. 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 7.

Figure 7: Typical Sill

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 (Chesepeake Bay Foundation, 2007). The current recommendation is to use a more conservative value 4 ft/yr until an inventory of successful, well-studied New Jersey projects can be developed.

Sea Level Rise

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. When designing sills for living shorelines projects it is recommended that the guidance provided by the Corps of Engineers is followed (US Army Corps of Engineers, 2011). The guidance recommends that the impact of low, medium, and high sea level rise scenarios be considered during design, and that the final design balance structural considerations (size, placement, etc) with other factors (economic, ecological, etc).

Sills themselves are adaptable in that their crest elevations and widths can be modified relatively easily to reduce some of the problems associated with sea level rise; however the marsh systems that develop behind the sill can be less capable of adapting. In 2011, NOAA produced a report (National Oceanic and Atmospheric Administration, 2011) that described sea level rise considerations for wetland restoration projects. Although the focus was different, the recommendations were similar to those contained in the Corps of Engineers report. Specifically, the report advises considering the low, medium, and high sea level rise scenarios, and ultimately including sea level rise in the project design in a way that maximizes ecological benefits, while minimizing adverse consequences such as risks to human life and safety over the life of the project.

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. When the tidal range becomes too large, the structure will function as a marsh toe revetment during the majority of the tidal cycle, and should be designed as such.

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

Approaches for designing marsh sills for wave heights range from the simple fetch based approaches presented in the main body of these guidelines, to more traditional engineering approaches based on a design wave height. Traditional engineering approaches for the design of rubble mound structures 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, the size of the armor units, the amount of energy dissipation, spacing (for segmented sills), and scour potential. The two most frequently used approaches to select the appropriate armor stone based on the structure geometry and the incident wave conditions are the (Hudson, 1959) and (Van der Meer, 1988) formulas. Both are provided for reference in Appendix B, although inexperienced designers are encouraged to refer to the source documents for a more complete discussion.

The amount of wave height transmission through or around the sill will have a significant impact on marsh development behind the structure. Traditional approaches found in either the Coastal Engineering Manual or the Rock Manual can be used to estimate the energy on the leeside of the structure. Recent work on marsh stability thresholds can be used to set wave height reduction targets. (Shafer, et al., 2003) in their study of Gulf Coast marshes found that the 20% wave height - $H_{20\%}$ (value only exceeded 20% of the time) - was critical to marsh stability. They identified a value of $H_{20\%}$ of between 0.5 ft and 1.0 ft as the threshold for supporting marsh vegetation. Specifically for Spartina alterniflora, (Roland & Douglass, 2005) identified a limiting median significant wave height 0.33 ft for marsh stability in Alabama, which was associated with a corresponding 80^{th} percentile significant wave height of 0.65 ft.

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).

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 Surge

Sills are low-crested structures that will be submerged during large storm events. During most design storm surge events (the 50 or 100 yr storm event for example), the marsh behind the breakwater will be completely submerged and therefore not directly impacted by the storm waves. Theoretically, there is no sill design limitation based on storm surge; however large storm surges will lead to increased overtopping and wave transmission. Data compiled and presented in (D'Angremond, et al., 1996) illustrate that once the freeboard reaches approximately 1.25 times the incident wave height, the wave energy dissipation is minimal. It is important to note that individual marsh sill projects will have a negligible impact on reducing storm surge.

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 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 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 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 the vegetation 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 marshhay cordgrass (Spartina patens) can tolerate regular inundations with 0 to 35 parts per thousand salinity (USDA).

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). 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). More expansive lists of flora native to the New Jersey region are available from multiple sources, including the following: http://www.cumauriceriver.org/botany/saltveg.html, http://rsgisias.crrel.usace.army.mil/nwpl_static/data/DOC/lists_2014/States/pdf/NJ_2014v1.pdf , http://www.environment.fhwa.dot.gov/ecosystems/vegmgmt_rd_nj.asp.

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 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, in particular the living shorelines working group is suggested. Project designers are encouraged to contact the State's living shorelines project coordinator during the preliminary design phase so that potential State regulatory barriers can be identified and addressed during the early phases of project planning and design. The specific regulatory requirements are site and project dependent; however there are several common regulatory issues that are associated with marsh sill projects. Among these are:

- Covering critical nearshore habitat
- Filling beyond the 1977 tidelands boundary
- Impacts to adjacent properties

- Nature and quality of fill material
- Navigation hazard

End Effects

A sill is subject to the typical modes of failure that impact all sloping-front rock structures. As waves reflect off the front and ends of the sill, the resulting turbulence will generate scour along the toe and flanks of the structure. Scour is common and if severe, may cause the entire structure to slump. If this occurs, the stability of the structure may be compromised and its effectiveness reduced. If identified during routine inspections, slumping can typically be corrected by repositioning the existing stones and or adding new stone to the sill.

A properly designed sill will contain windows or gaps along the structure to allow for circulation. While it is possible for water to access a marsh bordered by a living reef through overtopping or the macro-pores or spaces in the reef, 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 into 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, staggering the openings, and turning the orientation of reef 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 the sill minimizes the disturbance to the natural environment, which minimizes the associated end effect erosion. If a marsh builds out behind the sill and ultimately connects to the sill, the end effect erosion can be exacerbated on the downdrift side due to the disruption of the natural littoral transport.

Constructability

Sills can be constructed via upland based or water based construction techniques; however the marsh fill will almost exclusively need to be constructed via upland based machinery. Typically, for all but the smallest projects, the use of an excavator equipped with an articulating claw for armor stone placement will be required. Provisions for site access for earth hauling equipment, such as dump trucks and/or loaders should be considered for the placement of sandy fill on the marsh as required. Consideration should be made to ensure the access road is stable and considers site specific environmental considerations. On projects with poor subsurface soils, heavy equipment such as excavators have been known to sink. Depending on the dimensions of the sill, it is not uncommon for a temporary earthen bridge to be constructed from land, enabling the excavator to move along the crest as it is constructed. Ultimately, upon project completion, the excavator back tracks along the crest, and removes the access bridge. In a recent analysis of the impacts of severe storms on vegetated shorelines in New York, the maturity of the vegetation was identified as critical to its stability (Miller, et al., 2015). Vegetation installation should be sequenced to allow maximum root penetration and growth during the first growing season.

For water based construction, 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 the barges during the full tidal cycle or else sequencing of the work around the tidal cycle may be required. Alternatively, long reach excavators can also be used however the lift capacity of a long boom is greatly reduced and may limit the weight of the individual stones. 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 spring 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 NJDEP maintains a list of common invasive species at http://www.nj.gov/dep/njisc/Factsheets/. The USDA Cape May Plant Materials Center maintains a list of the plants it releases to commercial growers specifically for resource conservation needs at http://www.nrcs.usda.gov/wps/portal/nrcs/pmreleases/plantmaterials/pmc/northeast/njpmc/cp/. A fact sheet is provided for each plant describing its native range and preferred growing conditions.

Debris Impacts

Recent analyses on the impact of Hurricanes Irene, Lee, and Sandy on shoreline stabilization projects in the State of New York has identified debris impact as one of the primary factors relating to the poor performance of several living shorelines projects during Sandy (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 no specific design criteria exists for debris impact, it is recommended that the potential for debris impact is considered in the design phase. One alternative 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.

Project Monitoring

Recent analyses on the impact of Hurricanes Irene, Lee, and Sandy on shoreline stabilization projects in the State of New York has identified project monitoring and maintenance as a critical factor in minimizing the damage sustained by several living shorelines sites. (Miller, et al., 2015). One of the recommendations from that report is that monitoring plans be included at the design stage and that sufficient funds be set aside to ensure that the plan is followed.

Sills are generally designed to be statically stable structures with minimal movement of the structural elements. Inspections should be performed regularly after major storms and particularly intense winters with heavy ice development. 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 sills 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.

Joint Planted Revetment

Description

Revetments are shore-attached structures built along the shoreline to prevent erosion of the bank. Revetments are typically constructed from rock or concrete armor units, although alternative materials such as gabion baskets, rubble/debris, and even felled trees can also be used. Revetments are designed to armor the existing bank and to dissipate the incident wave energy on their sloping face. Revetments can be used at both open coastal locations as on lower energy sheltered coasts. Revetments differ from rip-rap covered slopes in that revetments are typically designed more rigorously and have more clearly defined layers and stone sizes. As part of a living shorelines strategy, the interstitial spaces in a traditional revetment can be planted. Incorporating vegetation within the revetment can provide valuable ecological benefits and help to stabilize the soil under the revetment. An example of a joint planted revetment is shown in Figure 8.

Figure 8: Typical Joint Planted Revetment

Design Guidance

System Parameters

Erosion History

Properly designed revetments can be extremely successful in stopping shoreline erosion. Revetments have been implemented as coastal protection on many open sea coastlines where the expected wave heights far exceed anything likely to be experienced at a living shorelines site. In living shorelines applications, where wave energy (wind or wake) is the primary driver of erosion, an appropriately sized and placed revetment should be capable of mitigating the erosional problem.

Sea Level Rise

As sea level rises, a joint-planted revetment will provide less protection and overtoping will become more frequent. 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. When designing larger revetments it is recommended that the guidance provided by the Corps of Engineers is followed (US Army Corps of Engineers, 2011). The guidance recommends that the impact of low, medium, and high sea level rise scenarios be considered during design, and that the final design balance structural considerations (size, placement, etc) with other factors (economic, ecological, etc). While revetments themselves are adaptable in that their crest elevations and widths can be modified relatively easily to reduce some of the problems associated with sea level rise, joint plantings will eventually die out as they become submerged.

Tidal Range

Revetments can be constructed in a wide range of tidal environments, including those most common in New Jersey. Tidal range will dictate specific characteristics of a joint planted revetment such as stone size and placement and geometry in the same manner as it would for a traditional revetment. Tidal range will additionally affect the selection, placement and growth of vegetation for a joint planted revetment. At sites with large tidal ranges, specific attention should be paid to the selection of plants such that species capable of tolerating frequent, heavy inundation are selected.

Hydrodynamic Parameters

Wind Waves

Revetments 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, wave heights will not limit the applicability of revetments. Traditional engineering approaches for designing rubble mound structures such as revetments 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, the size of the armor units, the amount of energy dissipation, and scour potential. The two most frequently used approaches to select the appropriate armor stone based on the structure geometry and the incident wave conditions are the (Hudson, 1959) and (Van der Meer, 1988) formulas. Excerpts are provided in Appendix B. When selecting the vegetation for the joint planting, care must be taken to select hearty plants capable of withstanding the expected wave climate.

Wave runup and overtopping should also be evaluated using the methods in either of the two design manuals. Recent analyses by (Miller, et al., 2015) identified scour related to overtopping and the power of the receding storm surge as a common cause of structural failure during Superstorm Sandy. Based on these observations, it is recommended that the crest stability be considered during design. Approaches that can be used to reinforce the crest include adding a geotextile fabric crest extension, extending the armor stone inland, or planting the surface with hearty vegetation.

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 joint planted revetment, the design should proceed as discussed above, considering the wake heights in addition to the wind wave heights.

Currents

In most cases where revetments are being considered, wave heights represent the primary design consideration and currents are assumed to be negligible. In the types of environments where joint planted revetments 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 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 joint planted revetments are reported velocity thresholds for live fascines and live willow stakes of between 6 and 10 ft/sec (3.6 to 5.9 kts) and for 12-24 inch rip-rap of 10 to 18 ft/sec (5.9 to 10.7 kts).

Ice

Guidance for designing structures to resist ice impacts is scarce. 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°. During extreme winters, it should be expected that ice riding up the slope will uproot the joint plantings. A successful monitoring and maintenance program can help identify and restore the vegetation. 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 Surge

Storm surge typically factors into the design of a joint planted revetment in two ways. Elevated water levels increase the water depths offshore and at the toe of the structure, potentially leading to larger wave impacts. These wave impacts need to be factored into the design as discussed above under the wind wave subheading. Storm surge also impacts run up and overtopping, and is typically a factor in setting the elevation of the crest of the structure. For most living shorelines projects however, the crest elevation will be fixed by the elevation of the adjacent upland. Since most joint planted revetments will be overtopped during significant storms due to their lower (in general) crest elevations, backside scour is a concern. Backside scour occurs when the waves and/or surge overtopping a structure scour out the land immediately behind the structure. The depression that is formed can focus energy on the backside of the structure as the floodwaters recede (Miller, et al., 2015). Robust vegetation can help minimize backside scour.

Terrestrial Parameters

Upland Slope

Revetments are typically constructed to protect an upland region and can be constructed either at the shoreline or inland of the existing shoreline. When constructed inland of the existing shoreline, the revetment is typically constructed on or to replace the existing upland slope. Modern revetment design guidelines call for maximum revetment slopes of 1(V):1.5(H).

Width

Revetments are constructed directly on the upland slope; therefore width is irrelevant in revetment design.

Shoreline Slope
Revetments are typically constructed to protect an upland region and can be constructed either at the shoreline or inland of the existing shoreline. When constructed at the shoreline, the revetment typically replaces the existing shoreline slope. Modern revetment design guidelines call for maximum revetment slopes of 1(V):1.5(H).

Nearshore Slope
Revetments are typically constructed on the existing upland slope or near the shoreline. Nearshore slopes should be mild enough to support the constructed revetment.

Offshore Depth
Revetments have been constructed in extremely energetic environments, where the offshore water depths are much greater than those that will be encountered during the construction of living shorelines project. Offshore depth is not considered a limiting factor for revetment design; however it 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 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 if the revetment 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 revetment. Depending on the size of the structure and the strength of the underlying soils, the foundation layer may consist of a geotextile membrane and/or a gravel base.

Ecological Parameters

Water Quality
Water quality parameters will not affect the stone part of a joint planted revetment; however the vegetation will be sensitive to water quality. Salinity limitations should be obtained for all joint plantings prior to design and planting to ensure survival. Willow wattle, or willow acacia, is commonly used in joint planted revetments (U.S. Department of Transportation Federal Highway Administration, 2011). It prefers full sun and low water (Arizona Municipal Water Users Association, 2014) and can tolerate any salinity (Florabank, 2014).

Soil Type
Revetments can be constructed on any type of soil with the appropriate bearing capacity, but the growth of the joint plantings will be influenced by the substrate. Willow wattle, or willow acacia, tolerates any soil pH and any salinity. It is suitable for use in any type of clay soil, loam, sandy loam, or sand (Florabank, 2014).

Sunlight Exposure

Sunlight exposure will not impact the rock part of the revetment structure. The sunlight requirements of the joint plantings should be taken into account. Willow wattle, or willow acacia, grows best in exposure to full sunlight (Arizona Municipal Water Users Association, 2014)

Additional Considerations

Permits/Regulatory

Close coordination with the NJDEP, in particular the living shorelines working group is suggested. Project designers are encouraged to contact the State's living shorelines project coordinator during the preliminary design phase so that potential State regulatory barriers can be identified and addressed during the early phases of project planning and design. The specific regulatory requirements are site and project specific; however there are several common regulatory issues that are associated with joint planted revetments. Among these are:

- Impacts to adjacent properties

End Effects

A joint planted revetment is subject to the typical modes of failure that occur with sloping-front structures. Scour is one of these. As waves reflect from the front and ends of the stone structure, the water's motion will scour the toe and flanks of the structure. Scour around any stone structure is typical and continued erosion may result in the structure slumping or the movement of the stones. This will decrease the effectiveness of the structure but can be prevented with routine inspections.

End effects are a significant concern with hard shore-attached structures such as revetments. Adjacent shorelines typically erode at a greater rate due to the presence of the structure. The enhanced erosion results from a combination of increased turbulence at the ends of the structure, and the disruption of the natural littoral transport system. The magnitude and the extent of edge related erosion is dependent upon the existing wave and current conditions, the erodability of the soil, and the characteristics (material, geometry, etc) of the structure. Methods for reducing edge related impacts include tying into existing structures on stabilized coastlines and incorporating gradual transitions on natural coastlines.

Constructability

Joint planted revetments can be constructed via upland or water based construction techniques. Typically, for all but the smallest projects, the use of an excavator equipped with an articulating claw for armor placement will be required. Consideration needs to be given to the stability of access roads and any site specific environmental constraints. On projects with poor subsurface soils, heavy equipment such as excavators have been known to sink. Plantings are usually performed by hand from the upland area. Use of steel or pipe embedded in the armor layer to allow larger plantings have been recently utilized on projects, however, the ultimate effect on the armor stability during design events is not fully understood at this time. In a recent analysis of the impacts of severe storms on vegetated shorelines in New York, the maturity of the vegetation was identified as critical to its stability (Miller, et al., 2015). Vegetation installation should be sequenced to allow maximum root penetration and growth during the first growing season.

Native/Invasive Species

Joint planted revetments should incorporate appropriate native vegetation for the interstitial plantings. Ideally an ecologist with experience working on bank stabilization should be consulted to identify appropriate plant species and planting zones. The NJDEP maintains a list of common invasive species at http://www.nj.gov/dep/njisc/Factsheets/. The USDA Cape May Plant Materials Center maintains a list of the plants it releases to commercial growers specifically for resource conservation needs at http://www.nrcs.usda.gov/wps/portal/nrcs/pmreleases/plantmaterials/pmc/northeast/njpmc/cp/. A fact sheet is provided for each plant describing its native range and preferred growing conditions. A list of vegetation species suitable for bioengineered shoreline projects is also available at http://www.state.nj.us/agriculture/divisions/anr/pdf/26_Soil%20Bioengineering%202011.pdf.

Debris Impacts

Recent analyses on the impact of Hurricanes Irene, Lee, and Sandy on shoreline stabilization projects in the State of New York has identified debris impact as one of the primary factors relating to the poor performance of several living shorelines projects during Sandy (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 revetments tend to be fairly robust structures capable of withstanding minor debris impact, joint plantings (especially new plantings that have not had time to develop robust root systems) are particularly vulnerable to scour from floating debris. While no specific design criteria exists for debris impact, it is recommended that the potential for debris impact is considered in the design phase. 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.

Project Monitoring

Recent analyses on the impact of Hurricanes Irene, Lee, and Sandy on shoreline stabilization projects in the State of New York has identified project monitoring and maintenance as a critical factor in minimizing the damage sustained by several living shorelines sites. (Miller, et al., 2015). One of the recommendations from that report is that monitoring plans be included at the design stage and that sufficient funds be set aside to ensure that the plan is followed.

Revetments are designed to be statically stable structures with minimal maintenance requirements. It is uncommon to conduct regular revetment inspections; however inspections should be performed after major storms, and particularly harsh winters with heavy ice development. Common concerns to be evaluated during an inspection include the displacement of individual stones, settling of the structure, the development of scour/erosion, removal of vegetation, and the potential overgrowth of vegetation. Maintenance of joint planted revetments typically consists of the resetting of displaced stones, replanting of vegetation that has been removed or is in poor condition, and potentially cutting back any vegetation that has grown so big that it threatens the integrity of the underlying stone structure.

Breakwater

Description

Figure 9: Typical Breakwater Project

Breakwaters are coastal engineering structures typically constructed parallel to the shoreline that are designed to reduce the amount of wave energy experienced by 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 tend to be slightly larger. An example of a breakwater field and salient formation is shown in Figure 9.

Design Guidance

System Parameters

Erosion History

Properly designed breakwaters can be extremely successful in stopping 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. Assuming that wave energy (wind or wake) is the primary driver of coastal erosion at the site, an appropriately sized and placed breakwater should be capable of mitigating the erosional problem under most conditions.

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. When designing large/critical breakwaters for living shorelines projects it is recommended that the guidance provided by the US Army Corps of Engineers is followed (US Army Corps of Engineers, 2011). The guidance recommends that the impact of low, medium, and high sea level rise scenarios be considered during design, and that the final design balance structural considerations (size, placement, etc) with other factors (economic, ecological, etc).

Breakwaters themselves are adaptable in that their crest elevations and widths can be modified relatively easily to reduce some of the problems associated with sea level rise; however the adaptability of any marsh development in the lee of the structure is less certain. In 2011, NOAA produced a report (National Oceanic and Atmospheric Administration, 2011) which provides guidance on including sea level rise in wetland restoration projects in the northeast. The guidance is similar to that found in the document produced by the US Army Corps of Engineers, in that it suggests considering low, medium, and high sea level rise scenarios, and ultimately including sea level rise in the project design in a way that maximizes ecological benefits, while minimizing adverse consequences such as risks to human life and safety over the life of the project.

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 be subjected to, 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. A study done in England (Department for Environment, 2010) has shown that larger tidal ranges generally result in shorter salient lengths behind the breakwater. The relatively small tidal fluctuations at most New Jersey sites will not significantly impact the structural component of breakwaters designed for living shorelines projects; however it will have a much larger effect on the vegetative component. At sites with large tidal ranges, specific attention should be paid to the selection of plants such that species capable of tolerating frequent inundation and specific salinities are selected.

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 for wave height range from the simple fetch based approaches presented in the main body of these guidelines, to more traditional engineering approaches 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, the size of the armor units, the amount of energy dissipation, spacing (for segmented breakwaters), and scour potential. The two most frequently used approaches to select the appropriate armor stone based on the structure geometry and the incident wave conditions are the (Hudson, 1959) and (Van der Meer, 1988) formulas. Both are provided for reference in Appendix B, although inexperienced designers are encouraged to refer to the source documents for a more complete discussion.

The amount of wave height transmission through or around the breakwater will have a significant impact on marsh development behind the structure. Traditional approaches found in either the Coastal Engineering Manual or the Rock Manual can be used to estimate the energy on the leeside of the structure. Recent work on marsh stability thresholds can be used to set wave height reduction targets. (Shafer, et al., 2003) in their study of Gulf Coast marshes found that the 20%

wave height – $H_{20\%}$ (value only exceeded 20% of the time) - was critical to marsh stability. They identified a value of $H_{20\%}$ of between 0.5 ft and 1.0 ft as the threshold for supporting marsh vegetation. Specifically for Spartina alterniflora, (Roland & Douglass, 2005) identified a limiting median significant wave height 0.33 ft for marsh stability in Alabama, which was associated with a corresponding 80^{th} percentile significant wave height of 0.65 ft.

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 where breakwaters are being considered, wave heights represent the primary design consideration and currents are assumed to be negligible. In the types of environments where living shoreline projects 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 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 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).

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. 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 Surge

Theoretically, there is no breakwater design limitation based on storm surge; however large storm surges will lead to increased overtopping and wave transmission. Large storm surges will also modify the local wave climate potentially delaying the breaking process and changing the breaker type. In cases where the breakwater becomes completely submerged, it will function as a submerged structure, rather than as an emergent structure. This will reduce the hydrodynamic force on the individual armor stones, but also reduce the structure's effectiveness. Data compiled and presented in (D'Angremond, et al., 1996) illustrate that once the freeboard reaches approximately 1.25 times the incident wave height, the wave energy dissipation is minimal. Breakwaters should be designed to withstand a critical condition which considers a combination of storm surge and wave impacts. During most design storm surge events (the 50 or 100 yr storm event for example), the marsh behind the breakwater will be completely submerged and therefore not directly impacted by the storm waves.

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 developing behind the breakwater will be highly dependent on the local conditions. It is typical for either a tombolo or a salient (see Figure 10) to form behind offshore breakwaters, depending 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 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.

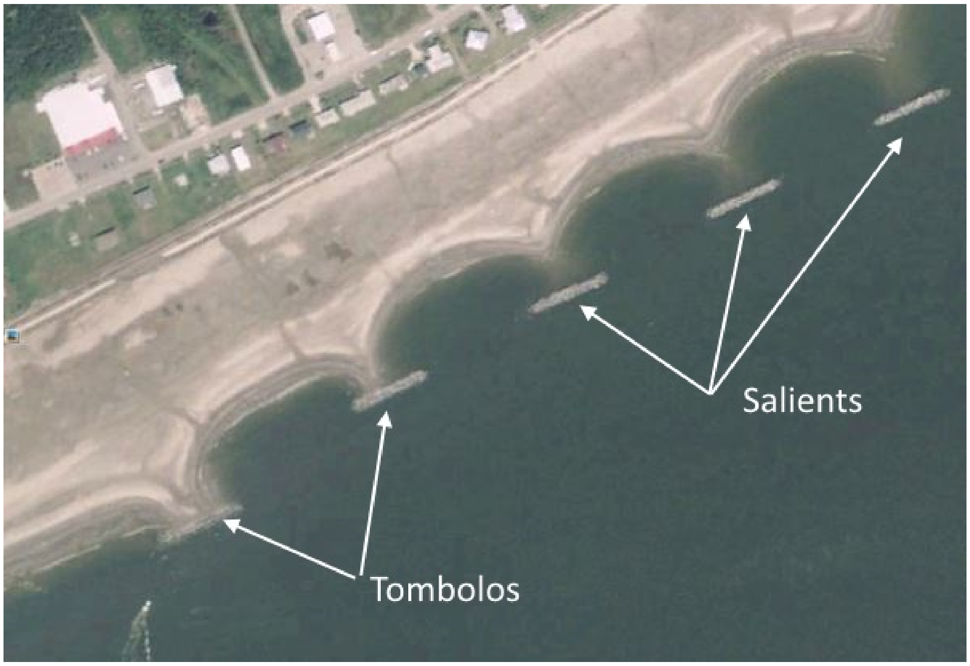

Figure 10: Definition of tombolo and salient.

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 thus 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 expected to be a limiting factor. Breakwaters are common on open sea coastlines where the water depths far exceed those expected to be encountered offshore of a living shorelines project. 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 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 breakwater settles, the interlocking between neighboring stones can be reduced. The interlocking contributes significantly to the breakwater's strength. If the breakwater degrades over time, its ability to dissipate wave energy will be reduced, and the stability of the marsh behind it will be threatened. 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, a gravel base, or a flexible gabion mattress.

Ecological Parameters

Water Quality

Water quality parameters will not affect the breakwater itself; however if vegetation is included landward of the structure it will be sensitive to water quality. Salinity and inundation limitations should be obtained for all marsh plantings prior to design and planting to ensure survival. Two of the more common marsh plants used in living shorelines projects are smooth cordgrass (Spartina alterniflora) and marshhay cordgrass (Spartina patens). Both can tolerate regular inundations with 0 to 35 parts per thousand salinity (USDA).

Soil Type

Breakwaters can be constructed on any type of soil as long as the bearing capacity issues are addressed. If marsh development or marsh planting is included as a part of the project, the growth and development of the plants will be highly dependent on the substrate. Two of the more common marsh plants used in living shorelines projects are smooth cordgrass (Spartina alterniflora) and marshhay cordgrass (Spartina patens). Spartina alterniflora generally prefers sandy aerobic or anaerobic soils with pH values ranging from 3.7 to 7.9 (USDA). 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). In spite of the ability of marsh vegetation to take root in a variety of soils, sand is recommended to enhance root development and increase stability early in the growth cycle. More expansive lists of flora native to the New Jersey region are available from multiple public sources, including the following: http://www.cumauriceriver.org/botany/saltveg.html, http://rsgisias.crrel.usace.army.mil/nwpl_static/data/DOC/lists_2014/States/pdf/NJ_2014v1.pdf, http://www.environment.fhwa.dot.gov/ecosystems/vegmgmt_rd_nj.asp.

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, in particular the living shorelines working group is suggested. Project designers are encouraged to contact the State's living shorelines project coordinator during the preliminary design phase so that potential State regulatory barriers can be identified and addressed during the early phases of project planning and design. The specific regulatory requirements are site and project dependent; however there are several common regulatory issues that are associated with breakwater projects. Among these are:

- Covering critical nearshore habitat

- Filling beyond the 1977 tidelands boundary
- Impacts to adjacent properties
- Nature and quality of fill material
- Navigation hazard

End Effects

A breakwater is subject to the typical modes of failure that occur with sloping-front structures. Scour is one of these. As waves reflect off the front and ends of the stone structure, the water's motion will scour the toe and flanks of the structure. Scour around stone structures is typical and continued erosion may result in the structure slumping or the movement of the stones. This will decrease the effectiveness of the structure but can be prevented with routine inspections and repairs.

Although the end effects associated with breakwaters tend not to be as severe as those associated with shoreface armoring, any sand that builds up to form a tombolo or salient comes from the adjacent beaches. The amount of erosion 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

Emergent breakwaters can be constructed via upland or water based construction techniques, while submerged breakwaters are usually constructed via water based construction techniques. Typically, for all but the smallest projects, the use of an excavator equipped with an articulating claw for armor placement or a hoist for concrete units will be required. If constructed via land based techniques accessibility issues for any equipment should be considered. For water based construction, 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 the barges during the full tidal cycle or else sequencing of the work around the tidal cycle may be required. Alternatively, long reach excavators can also be used however the lift capacity of a long boom is greatly reduced and may limit the weight of the individual stones. 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 spring tidal cycle.

If marsh restoration is to take place in conjunction with the construction of the breakwater, access for the required heavy equipment should be considered. Consideration needs to be given to the stability of access roads and any site specific environmental constraints. On projects with poor subsurface soils, heavy equipment such as excavators have been known to sink. In a recent analysis of the impacts of severe storms on vegetated shorelines in New York, the maturity of the vegetation was identified as critical to its stability (Miller, et al., 2015). Vegetation installation should be sequenced to allow maximum root penetration and growth during the first growing season.

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 NJDEP maintains a list of common invasive species at http://www.nj.gov/dep/njisc/Factsheets/. The USDA Cape May Plant Materials Center maintains a list of the plants it releases to commercial growers specifically for resource conservation needs at http://www.nrcs.usda.gov/wps/portal/nrcs/pmreleases/plantmaterials/pmc/northeast/njpmc/cp/. A fact sheet is provided for each plant describing its native range and preferred growing conditions.

Debris Impacts

Recent analyses on the impact of Hurricanes Irene, Lee, and Sandy on shoreline stabilization projects in the State of New York has identified debris impact as one of the primary factors relating to the poor performance of several living shorelines projects during Sandy (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 fairly robust structures capable of withstanding minor debris impact, the marsh areas they protect are particularly vulnerable to scour from floating debris. While no specific design criteria exists for debris impact, it is recommended that the potential for debris impact be considered in the design phase. 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.

Project Monitoring

Recent analyses on the impact of Hurricanes Irene, Lee, and Sandy on shoreline stabilization projects in the State of New York has identified project monitoring and maintenance as a critical factor in minimizing the damage sustained by several living shorelines sites. (Miller, et al., 2015). One of the recommendations from that report is that monitoring plans be included at the design stage and that sufficient funds be set aside to ensure that the plan is followed.

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.

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 breakwater/marsh living shorelines project might include filling in low spots, thin-layer spreading of dredge material, and supplementing the original vegetation.

Living Reef

Description

Offshore living reef breakwaters and low lying living reef sills have recently become a popular method for protecting and stabilizing shorelines in sheltered areas. More commonly constructed in the southern United States, these submerged aquatic habitats function in a similar manner to constructed breakwaters or sills. Living breakwaters in the northeast are typically constructed with oysters or mussels (Figure 11) being used as the dominant species. Both species are capable of growing rapidly in brackish water, near estuarine river mouths and in near shore areas. 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. Lacking a native community for supporting reef growth, current projects typically begin in a controlled environment (remote setting) and are then placed at the project site for "grow out". Natural recruitment occurs when larvae at the project site settle upon the supplied substrate. With time, generations of the species continue to grow and large reef structures are eventually formed. As these reefs develop, they not only serve as a natural breakwater, but also provide critical aquatic habitat. Similar to sills, deposition commonly occurs in the quiescent areas behind the reefs and vegetation takes root (Rella & Miller, 2012). It should be noted that while the results discussed below focus on traditional living reef projects, living elements are being incorporated into a wide array of projects. One such example is the living breakwater proposed during the Rebuild by Design competition for protecting the southern shore of Staten Island.

Figure 11: Typical 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). The current recommendation is to use a more conservative value 4 ft/yr until an inventory of successful living reef projects have been implemented, monitored, and documented.

Sea Level Rise

Living reef breakwaters have some capacity to adapt to changing conditions; however they are particularly sensitive to changes in water quality. As long as 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 behind the increase in sea level, the effectiveness of the living reef in dissipating wave energy will be reduced as well and larger waves will impact the reef and marsh. Marsh vegetation which may be included as a part of a living reef project, is also highly susceptible to the changes associated with sea level rise, i.e. drowning of root systems and salt intrusion. For larger living reef projects, the guidance provided by NOAA in a 2011 report suggesting that low, medium, and high sea level rise scenarios be considered and included in a way that maximizes the ecological benefits while minimizing the adverse consequences, should be followed (National Oceanic and Atmospheric Administration, 2011).

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

Living materials, such as oysters and mussels can be used either to enhance or used exclusively to construct sill, revetment, or breakwater structures. Naturally occurring, well established reefs that have developed over long periods of time have the advantage of being firmly bound together. As oyster reefs grow their calcium carbonate shells cement them together, adding incredible stability to the stabilization technique. Mussels are only bound to the substrate and each other by hair like cilia and tend to be less stable than oyster reefs. 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 and exposed to wave energy need special consideration for their design. When developing a living marsh sill with oysters and mussels in a moderate wave energy environment, gabion baskets constructed from wire or geogrid material should be used to contain larger masses of shell to add increased stability to the structure. The stone sizes recommended in the guidelines for each structure type; sill, revetment, breakwater, should be referenced when determining the required weight of each gabion basket. When developing living reefs in areas exposed to intense levels of wave action, it is recommendable to seed the surface of heavily weighted pre-cast concrete forms with larvae in a laboratory setting.

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 a low to moderate wave energy locations. Similar to submerged breakwaters, the transmission coefficient for natural reefs strongly depends on the structure height and crest width. Results from laboratory experiments performed by (Allen & Webb, 2011) demonstrated that the wave height could be attenuated up by 90% on natural reefs. Recent work on marsh stability thresholds can be used to set wave height reduction targets. (Shafer, et al., 2003) in their study of Gulf Coast marshes found that the 20% wave height - $H_{20\%}$ (value only exceeded 20% of the time) - was critical to marsh stability. They identified a value of $H_{20\%}$ of between 0.5 ft and 1.0 ft as the threshold for supporting marsh vegetation. Specifically for Spartina alterniflora, (Roland & Douglass, 2005) identified a limiting median significant wave height 0.33 ft for marsh stability in Alabama, which was associated with a corresponding 80th percentile significant wave height of 0.65 ft.

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 the majority of 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). Excessive velocities however, can reduce the oyster's ability to filter the water and inhibit the growth process. In locations where there is a high velocity of water flow, oysters grow in size very quickly but have extremely thin shells, limiting their effectiveness to withstand 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 Surge

When determining the crest height of a living reef, the structure should be designed to mimic nearby naturally occurring features. 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. During large storm surges, living reefs will experience significant overtopping, reducing their effectiveness in dissipating the waves. Data compiled and presented in (D'Angremond, et al., 1996) illustrate that once the freeboard reaches approximately 1.25 times the incident wave height, the wave energy dissipation over submerged structures is minimal.

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 or gabions 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 in order 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 estuary or bay, is the oyster's susceptibility to freshets, or pulsed freshwater events from melting snow and ice at the end of the winter. A freshet 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, decrease parasite infection intensities, resulting in a decrease in mortality rates. Growth however, is positively correlated with salinity. Oyster valves close during low salinity events, which in turn reduces feeding and has a direct impact on 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 thin because they must grow quickly to keep their open end from being covered; while oysters grown on more stable bottom 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 the 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; 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). 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). More expansive lists of flora native to the New Jersey region are available from multiple public sources, including the following: http://www.cumauriceriver.org/botany/saltveg.html, http://rsgisias.crrel.usace.army.mil/nwpl_static/data/DOC/lists_2014/States/pdf/NJ_2014v1.pdf, http://www.environment.fhwa.dot.gov/ecosystems/vegmgmt_rd_nj.asp.

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 any aquatic organisms that are incapable of moving to more suitable areas (SOW, 2007). Chlorophyll directly effects the levels of phytoplankton in the water. Phytoplankton are microscopic organisms that inhabit the surface waters of most bodies of water and serve as a main food source for oysters and mussels. 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, in particular the living shorelines working group is suggested. Project designers are encouraged to contact the State's living shorelines project coordinator during the preliminary design phase so that potential State regulatory barriers can be identified and addressed during the early phases of project planning and design. The specific regulatory requirements are site and project specific; however there are several common regulatory issues that are typically associated with living reef projects. Among these are:

- 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

End Effects

A living reef is subject to many of the same modes of failure as other sloping-front offshore structures. As waves reflect from the front and ends of the reef, the water motion will scour the toe and flanks of the structure. Although this effect will be reduced compared to traditional structures due to the increased surface complexity, continued erosion may cause the reef to slump, negatively impacting further growth, and reducing its effectiveness in dissipating wave energy.

A properly designed living reef project will contain windows or gaps along the structure to allow for circulation. While it is possible for water to access a marsh bordered by a living reef through overtopping or the macro-pores or spaces in the reef, 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 into 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 turning the orientation of 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 dissipates rather than reflects energy. In addition, living reefs generally terminate in a more natural manner than man-made structures, reducing the erosive impacts associated with an abrupt edge.

Constructability

Living reefs can be constructed with water or land based construction techniques. If constructed with land based techniques, consideration should be given to the stability of access roads and any site specific environmental constraints. On projects with poor subsurface soils, heavy equipment such as excavators have been known to sink. When utilizing water based construction techniques, 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 the barges during the full tidal cycle. If water depth is a concern, sequencing of the work around the tidal cycle may be required. 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 spring tidal cycle. If the intent of the project is to encourage natural recruitment, installation should be timed that all substrates have been placed in time for the spawning cycles of target species. When integrating vegetation into a shoreline stabilization project, planting should take place during the spring and summer growing seasons to allow root systems adequate time to strengthen prior to the winter season, which is normally accompanied by intense storm conditions when compared to the summer months. In a recent analysis of the impacts of severe storms on vegetated shorelines in New York, the maturity of the vegetation was identified as critical to its stability (Miller, et al., 2015).

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 NJDEP maintains a list of common invasive species at http://www.nj.gov/dep/njisc/Factsheets/. The USDA Cape May Plant Materials Center maintains a list of the plants it releases to commercial growers specifically for resource conservation needs at http://www.nrcs.usda.gov/wps/portal/nrcs/pmreleases/plantmaterials/pmc/northeast/njpmc/cp/. A fact sheet is provided for each plant describing its native range and preferred growing conditions.

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

Recent analyses on the impact of Hurricanes Irene, Lee, and Sandy on shoreline stabilization projects in the State of New York have identified debris impact as one of the primary factors leading to the poor performance of numerous living shoreline projects during Sandy (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 (gradually sloping intertidal zones). The calcium carbonate shells of oysters can endure more intense forces than the more fragile mussels; however, fast floating debris is capable of crushing the shells comprising the reef, as well as dislodge large portions of the living structure. The marsh areas behind the living reef are particularly vulnerable to scour from floating debris. Unlike stone structures, these living components have the ability to 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.

Project Monitoring

Recent analyses considering the impact of Hurricanes Irene, Lee, and Post-Tropical Storm Sandy on shoreline stabilization projects in the State of New York, have identified project monitoring and maintenance as a critical factor when attempting to minimize the damage sustained by several living shorelines sites. (Miller, et al., 2015). One of the recommendations listed in the report is that monitoring plans be included from the design stage and that sufficient funds be set aside to ensure that the plan is followed accurately.

Living reefs are generally designed to be self-sustaining, stable structures with minimal maintenance requirements once the living elements have been established. Although once historically naturally present, living reefs have not been commonly constructed in this region. It is uncommon to conduct regular living reef inspections; however, inspections should be performed after major storms, and winters with particularly heavy icing conditions. Likely concerns to be evaluated during a living structure's inspection include: an evaluation of the health of the mussel/oyster community, settling of the reef, and the development of scour/erosion related to the reef. Once successfully established, maintenance of living reefs tends to be minimal.

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, 2005). Ravit et. al 2005 suggests water column samples should be collected from a depth of approximately one meter. Depending on the spatial span on the structure, multiple samples should be collected throughout the project space for each desired parameter; which at a minimum should include dissolved oxygen, turbidity, and salinity. Multiple repetitions should be collected to account for collection and sampling errors. Additional parameters that may be tested include, pH, chlorophyll, concentrations of ammonia, nitrogen and phosphorous, and the presence of fecal coliform (Ravit, et al., 2012).

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 living reef project might include removing debris, filling in low spots, thin-layer spreading of dredge material, and supplementing the original vegetation.

Reef Balls

Description

Figure 12 Typical Reef Ball

Reef Balls provide a durable substrate for reef development in areas with intense wave conditions. Ideally, generations of reef species grow over time and large reef structures are eventually formed. Reef Ball breakwaters function similarly to submerged breakwaters, sills, and living reefs, and are more common in the Caribbean and southern United States than the northeast. The few projects that have been constructed in the northeast indicate that reef development and natural recruitment is much less vigorous in this region. In New Jersey, oysters and/or mussels would be expected to colonize deployed Reef Ball units. Both species are capable of growing rapidly in brackish water, near estuarine river mouths and in near shore areas. The larvae of the species naturally seek out hard surfaces to settle upon, making Reef Balls ideal under certain conditions. As a reef created by Reef Ball units develops, it not only serves as a natural breakwater, but also provide critical aquatic habitat capable of providing numerous ecosystem services. For the purposes of the description below, it is assumed that Reef Ball units are placed in a manner that results in significant wave attenuation, and that a beach or marsh platform is created and planted behind the units. A cluster of Reef Ball units is shown in Figure 12.

Design Guidance

System Parameters

Erosion History

Reef Balls have been shown to attenuate wave energy and reduce erosion in low to moderate wave energy locations (Harris, 2001). Quantitative estimates with regards to erosion rate for Reef Balls are difficult to find. The Chesapeake Bay Foundation suggests hybrid approaches are appropriate at sites with erosion rates of between 2 and 8 ft/yr (Chesepeake Bay Foundation, 2007). The current recommendation is to use a more conservative value 4 ft/yr until an inventory of successful Reef Ball projects have been implemented, monitored, and documented.

Sea Level Rise

Living reefs or breakwaters utilizing Reef Balls have some capacity to adapt to changing conditions; however, the sessile organisms inhabiting their surface are particularly sensitive to changes in water quality. As long as parameters such as dissolved oxygen, water temperature, salinity, and turbidity, remain within the range required by the constituent species occupying the Reef Balls, the reefs they support 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 behind the increase in sea level, the effectiveness of the Reef Balls in dissipating wave energy will be reduced as well and larger waves will impact the structure and marsh. If marsh restoration is being performed in addition to the placement of the Reef Ball units, the guidance provided in a 2011 NOAA report that suggests considering low, medium, and high scenarios, and ultimately including sea level rise in the project design in a way that maximizes ecological benefits, while minimizing adverse consequences such as risks to human life and safety over the life of the project, should be followed (National Oceanic and Atmospheric Administration, 2011).

Tidal Range

Knowing the expected daily tidal range, as well as the spring tide and storm surge related extremes, is vital when planning any aquatic habitat project involving Reef Balls. It is imperative that the oysters/mussels, utilizing the Reef Balls as substrate, 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). If the Reef Ball structure is intended to serve as a substrate for oyster recruitment, the top of the "growing zone" must be below mean lower low water (MLLW) to prevent the oysters from freezing during winter (Rella, 2014). When relying upon natural recruitment as a means to populating a reef, proper seasonal planning is necessary to maximize oyster larvae settlement (Risinger, 2012). 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

Reef Balls are generally very stable under most wave conditions due to the size and weight of the units, and have been shown to attenuate wave energy and reduce erosion in a low to moderate wave energy locations. In their study, (Armono & Hall, 2003) found that Reef Balls could reduce incident wave heights by up to 60%. (Harris, 2001) found that wave transmission strongly depended on the relationship between the wave height and the freeboard (difference between the still water level and the structure height) and the number of rows of units that were utilized. Some of the results are reproduced in Table 7. Harris found that by utilizing six rows of Reef Ball units incident wave heights could be reduced by over 70%. This result formed the basis of a recommendation that at least six rows of Reef Ball units be used when shoreline stabilization is the primary objective. More recently, several researchers including (Buccino, et al., 2013) have developed empirical relationships that can be used to estimate transmission coefficients for design. Recent work on marsh stability thresholds can be used to set wave height reduction targets. (Shafer, et al., 2003) in their study of Gulf Coast marshes found that the 20% wave height - $H_{20\%}$ (value only exceeded 20% of the time) - was critical to marsh stability. They identified a value of $H_{20\%}$ of between 0.5 ft and 1.0 ft as the threshold for supporting marsh vegetation. Specifically for Spartina alterniflora, (Roland & Douglass, 2005) identified a limiting median significant wave height 0.33 ft for marsh stability in Alabama, which was associated with a corresponding 80th percentile significant wave height of 0.65 ft.

Wakes

Currently no guidance exists other than to modify the expected design 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 project performance, the design considerations and process of considering wake forces in living shoreline projects should proceed as discussed above under waves.

Table 7: Reef Ball transmission coefficients.

Wave Transmission Coefficients for Reef Balls			
wave height = H (feet)	**4 rows**	**5 rows**	**6 rows**
1.64	0.33	0.31	0.3
2.46	0.31	0.29	0.27
3.28	0.33	0.29	0.27
4.10	0.36	0.31	0.28
4.92	0.39	0.34	0.3

Currents

For Reef Ball breakwater design, wave heights typically represent the primary design consideration; however, currents can also be important in the environments where Reef Ball projects are likely to be constructed. Section 5.2.3 of *The Rock Manual* (CIRIA; CUR; CETMF, 2012) provides design guidance for coastal/river structures subjected to currents. In most cases, the required armor unit size for stability 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. In absence of Reef Ball specific design guidance, similar relationships can be assumed for Reef Ball stability.

(Fischenich, 2001) summarized research on the stability thresholds of various materials used in stream bank restoration. Of relevance to the establishment of a marsh behind a Reef Ball structure 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).

Ice

Most of the original Reef Ball projects were constructed in temperate climates, therefore specific guidance on the ability of Reef Ball units to resist icing conditions is lacking. Floating ice acts similar to other types of floating debris, and can apply large forces to the living organisms attached to the Reef Ball units, potentially crushing them. Additionally, if ice becomes frozen to individual units, they 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. Currently a number of ad hoc "rule of thumb" criteria exist which serve as the basis for ice resistant design of rock structures. Although these criteria were not developed for living shoreline projects, their consideration in 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). Although most Reef Ball units will exceed this dimension, the rule of thumb provides a useful cross-check. 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 Surge

Unlike traditional stone structures, where only the maximum water levels are considered, the minimum expected water levels must be also be considered for Reef Ball projects. If the Reef Ball units are placed too high in the intertidal zone the sessile organisms will dry out and be unable to survive. Oysters/mussels can remain out of the water up to 6 hours in cool or wet weather, and 2 to 4 hours in warm and dry weather (NY/NJ Baykeeper, 2005). During large storm surges, the Reef Ball units will experience significant overtopping, reducing their effectiveness in dissipating the waves.

Terrestrial Parameters

Upland Slope

Reef Balls are generally placed offshore and as such the upland slope is not typically a factor in their design. An adequately designed Reef Ball 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 Reef Ball 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 developing behind the Reef Ball structure will be highly dependent on the local conditions. Marsh width will determine the amount of additional energy dissipation that will occur for waves transmitted past the Reef Ball structure. (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

The flatter the nearshore slope between the Reef Ball breakwater and the exposed shoreline or marsh toe, the cheaper the structure will be due to the shallower depths. A broad flat shelf will also help to dissipate any remaining energy once the wave field moves through the breakwater. The nearshore slope should be flat enough or modified to provide a stable platform for the Reef Ball units.

Offshore Depth

Living breakwaters consisting of Reef Ball units can be constructed in fairly deep water, but sunlight penetration should be evaluated for proper habitat development; oyster growth is heavily dependent upon their position within the water column. Ideally the crest of the units should remain submerged. Like all submerged breakwaters, the amount of wave energy dissipation decreases with the depth of water above the structure. Currently, the tallest standard Reef Ball unit is the Goliath which stands 5 feet tall (Reef Beach Co. Ltd., 2014).

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 Reef Balls settle, their 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 Reef Ball units. Depending on the size of the units 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 Reef Balls themselves; however, it will dictate their ability to provide habitat. Oyster/mussel reef systems require specific conditions in order for the species to thrive and become self-sustaining. Regulatory issues must be carefully considered. One oyster restoration project in New Jersey was terminated in 2010 after it was determined that the potential illegal harvesting of oysters used to create a breakwater in impaired waters posed a threat to the New Jersey seafood industry. Salinity is the most important factor influencing the growth and survival of oysters/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 estuary or bay, is the oyster's susceptibility to freshets, or pulsed freshwater events from melting snow and ice at the end of the winter. A freshet 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, decrease parasite infection intensities, resulting in a decrease in mortality rates. Growth; however, is positively correlated with salinity. Oyster valves close during low salinity events, which in turn reduces feeding and has a direct impact on growth (Rella, 2014).

If marsh restoration is included as a part of the Reef Ball project, salinity limitations 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

Reef Balls can be placed on any type of soil; however, sedimentation from being too close to the bottom can affect both the growth and mortality rates of the oysters/mussels. Oysters grown on muddy substrates tend to be thin because they must grow quickly to keep their open end from being covered; while oysters grown on more stable bottoms tend to be thicker (Wheaton, 2007). Reef Balls may provide a more suitable alternative substrate in muddy conditions.

If marsh plantings are included in the project design, their growth will be primarily dependent on the substrate/medium in which they are growing. Sand is the best medium for establishing vegetation as rapidly as possible. It not only provides a good anchor for the roots, but also allows for rapid growth and provides 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; 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). 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). More expansive lists of flora native to the New Jersey region are available from multiple public sources, including the following: http://www.cumauriceriver.org/botany/saltveg.html, http://rsgisias.crrel.usace.army.mil/nwpl_static/data/DOC/lists_2014/States/pdf/NJ_2014v1.pdf, http://www.environment.fhwa.dot.gov/ecosystems/vegmgmt_rd_nj.asp.

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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

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- 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

End Effects

As waves reflect from the front and ends of the Reef Balls, the water's motion will scour the toe and flanks of the reef. Scour around any stone structure is typical and continued erosion may result in the structure slumping, or the movement of the individual units. This will decrease the effectiveness of the structure but can be prevented with routine inspections. Depending on the amount of wave energy dissipation that occurs, the shoreline behind a Reef Ball deployment may develop a salient (see the discussion on breakwaters). In doing so, sediment accumulates from the adjacent beaches, which erode as a result. Generally both the amount of accumulation behind Reef Ball structures and the amount of erosion experienced on adjacent beaches is minimal.

Constructability

Reef Ball units are precast prior to construction and are usually placed in the form of reef via water based construction techniques. Typically, the individual units are placed using an excavator or crane operating from a barge. 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 the barges during the full tidal cycle or else sequencing of the work around the tidal cycle may be required. Alternatively, long reach excavators can be used; however, the lift capacity of a long boom is greatly reduced and may limit the unit size. 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 spring tidal cycle. If the intent of the project is to encourage rapid natural recruitment, installation should be timed to coincide with the spawning cycles of the target species. It is also possible to remote set the Reef Balls with oyster spat at a local aquaculture facility prior to onsite placement.

If marsh restoration is to take place in conjunction with the placement of the Reef Ball units, access for any required heavy equipment must be provided. Consideration should be given to the stability of access roads and any site specific environmental constraints. On projects with poor subsurface soils, heavy equipment such as excavators have been known to sink. In a recent analysis of the impacts of severe storms on vegetated shorelines in New York, the maturity of the vegetation was identified as critical to its stability (Miller, et al., 2015). Vegetation installation should be sequenced to allow maximum root penetration and growth during the first growing season.

Native/Invasive Species

Native species should be considered in the design of the Reef Ball unit itself. Specifically the units should be designed to attract species typical for the area in which they are to be placed. Unit size, spacing, and composition will impact which organisms are attracted. The units should be designed such that native species are able to outcompete invasive species.

Reef Ball 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 NJDEP maintains a list of common invasive species at http://www.nj.gov/dep/njisc/Factsheets/. The USDA Cape May Plant Materials Center maintains a list of the plants it releases to commercial growers specifically for resource conservation needs at http://www.nrcs.usda.gov/wps/portal/nrcs/pmreleases/plantmaterials/pmc/northeast/njpmc/cp/. A fact sheet is provided for each plant describing its native range and preferred growing conditions.

Debris Impacts

Recent analyses on the impact of Hurricanes Irene, Lee, and Sandy on shoreline stabilization projects in the State of New York have identified debris impact as one of the primary factors relating to the poor performance of multiple living shorelines projects during Sandy (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 (gradual sloping shores with wide intertidal zones). The concrete used to make Reef Balls, combined with its domed shape creates a high strength, abrasion resistant structure which is less likely to be negatively affected by debris. Furthermore, as the units are colonized, the oysters/mussels cement to each other, and in essence lock the structure together, strengthening it, as well as protecting it from the erosional force of the waves (Risinger, 2012). Although generally resistant to debris impact, fast-moving, floating debris is capable of damaging the units, as well as dislodging large portions of the developed reefs. Marsh areas protected by the Reef Balls are particularly vulnerable to scour from floating debris. While no specific design criteria exists for debris impact, it is recommended that the potential for damage from debris impact is considered in the design phase. One alternative 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.

Project Monitoring

Recent analyses on the impact of Hurricanes Irene, Lee, and Sandy on shoreline stabilization projects in the State of New York has identified project monitoring and maintenance as a critical factor in minimizing the damage sustained by living shorelines sites. (Miller, et al., 2015). One of the recommendations from that report is that monitoring plans be included at the design stage and that sufficient funds be set aside to ensure that the plan is followed.

Reef Ball breakwaters are generally designed to be stable structures with minimal maintenance requirements. It is uncommon to conduct regular Reef Ball unit inspections; however, inspections should be performed after major storms and winters with particularly heavy icing conditions, to ensure that the units have not been moved or damaged. During an inspection the health of the mussel/oyster community settling on the units should be evaluated (growth and survivability). Once established, maintenance of the Reef Ball units tends to be minimal.

When developing pilot projects aimed to test the ecological impact of Reef Ball 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, 2005). Ravit et. al 2005 suggests water column samples should be collected from a depth of approximately one meter. Depending on the spatial span on the structure, multiple samples should be collected throughout the project space for each desired parameter; which at a minimum should include dissolved oxygen, turbidity, and salinity. Multiple repetitions should be collected to account for collection and sampling errors. Additional parameters that may be tested include, pH, chlorophyll, concentrations of ammonia, nitrogen and phosphorous, and the presence of fecal coliform (Ravit, et al., 2012).

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 Reef Ball project might include removing debris, filling in low spots, thin-layer spreading of dredge material, and supplementing the original vegetation.

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. In general, the most commonly cited source is the *Coastal Engineering Manual* (CEM) USACE EM 1110-2-1100 (US Army Corps of Engineers, 2002) produced by the US Army Corps of Engineers. The CEM is updated regularly to reflect advances in coastal/ocean engineering. Individual chapters of the CEM can be downloaded from the US Army Corps of Engineers Coastal & Hydraulics Laboratory's (CHL) website at:

http://chl.erdc.usace.army.mil/cem

A second source that is used quite frequently in coastal engineering 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 used more frequently in Europe. The Rock Manual 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 on the following topics:

- Estimating Ice Thickness
- Sea Level Rise
- Wind Wave Generation (two approaches)
- Selection of Stone Size (two approaches)
- Wind Speed Adjustment
- Primary Wake Calculation
- Secondary Wake Calculation (two approaches)

Ice Thickness Estimation

The U.S. Army Corps of Engineers has developed guidance on estimating the thickness of river ice as a result of heat transfer processes. As discussed in the technical note the process of ice formation is complex; therefore the resulting estimates should be considered carefully before application.

Extracted from the U.S. Army Corps of Engineers TN 04-3 (US Army Corps of Engineers Cold Regions Research and Engineering Laboratory, 2004)

The growth of ice thickness in inches is dependent on the number of accumulated freezing degree days in a given winter. Freezing degree days are calculated for each day of the winter season.

$$FDD = (32 - T_a)$$

Where:

FDD = Freezing degree days
T_a = Average daily air temperature in Fahrenheit

Thickness is estimated using the Stefan equation:

$$t_i = C(AFDD)^{0.5}$$

Where:

AFDD = Accumulated freezing degree days (sum of FDD beginning at a point in late fall or early winter when the temperatures are consistently below freezing)
C = Coefficient (see table below)
T_i = Estimated thickness

Condition	Typical value for C
Windy lake with no snow	0.8
Average lake with snow	0.5 to 0.7
Average river with snow	0.12 to 0.15
Sheltered small river	0.21 to 0.41

Sea Level Rise

The U.S. Army Corps of Engineers has issued guidance on incorporating sea level rise into their projects. The procedure outlined below comes from ER-1165-2-212 (US Army Corps of Engineers, 2011). Additional information on the procedure can be found in the source document. It should be noted that on June 30, 2014 updated guidance was issued by the Corps of Engineers, and that that guidance is not reflected in ER-1165-2-212.

Extracted from ER-1165-2-212 (US Army Corps of Engineers, 2011)

Step 1: Is the project in the coastal/tidal estuarine zone, or does it border those zones such that project features or outputs are now or may be in the future subject to influence by continued or accelerated rate of local relative sea-level change?

a. If YES, go to Step 2
b. If NO, continue with product development process without considering sea-level change

Step 2: Locate the nearest tide station(s) with a current period of record. Is the period of record at least 40 years?

a. If YES, go to Step 4
b. If NO, go to Step 3

Step 3: Identify next closest long-term gauge. Assess whether or not the long-term gauge can be used to artificially extend the record of the short-term gauge.

a. If YES, go to Step 4.
b. If NO, consult with a tidal hydrodynamics expert such as the Center for Operational Oceanographic Products and Services (CO-OPS)

Step 4: Assess whether identified long-term gauges can be used to adequately represent local sea-level conditions at project site.

a. If YES, go to Step 5.
b. If NO, consult with a tidal hydrodynamics expert such as CO-OPS.

Step 5: Assess whether project site and gauge site have similar physical conditions (coastal/estuarine location, bathymetry, topography, shoreline geometry, and hydrodynamic conditions).

a. If YES, go to Step 6.
b. If NO, consult with a tidal hydrodynamics expert such as CO-OPS.

Step 6: Calculate local historic trends for Mean Sea Level (MSL), Mean High Water (MHW), and Mean Higher High Water (MHHW) at long-term gauge. Use CO-OPS values, if available. If not available, use CO-OPS method for sea-level trend analysis (described in NOAA Technical Report NOS CO-OPS 36, *Sea Level Variations of the United States 1854-1999* (National Oceanic and Atmospheric Administration, 2009). This historic trend is now the low or baseline trend rate for project alternative analysis (see 8(a)). Continue to Step 7.

Step 7: Calculate standard error of the linear trend line (use CO-OPS values, if available). Go to Step 8.

Step 8: The next step is to evaluate whether there is a regional mean sea-level trend (see definition) that is different from the eustatic mean sea-level trend of 1.7 mm/year (+/- 0.5 mm/year, (Intergovernmental Panel on Climate Change, 2007). Considering regional geology, is it possible to identify a vertically stable geologic platform within the same region as the project site?

(Eustatic mean sea-level rise – Eustatic sea-level rise is a change in global average sea level brought about by an increase in the volume of the world ocean (Intergovernmental Panel on Climate Change, 2007)

a. If YES, go to Step 9.
b. If NO, go to Step 11.

Step 9: Calculate regional MSL trend for the identified vertically stable geologic platform within the region and continue to Step 10.

Step 10: Estimate local rate of vertical land movement by subtracting regional MSL trend from local MSL trend. Go to Step 12.

Step 11: Assume the regional mean sea-level trend is equal to the eustatic mean sea-level trend of 1.77 mm/year (+/- 0.5 mm/year) and estimate local rate of vertical land movement by subtracting eustatic MSL trend from local MSL trend. Go to Step 12.

Step 12: Calculate future values for sea-level change for low (historic or baseline) rate: extrapolate historic linear trend into future at 5 year increments OR reasonable increments based on both period of analysis and scope of study. Go to Step 13.

Step 13: Calculate future values for sea-level change for intermediate rate (based on the modified NRC Curve I (National Research Council, 1987)). Calculate future sea level-change values at 5-year increments OR reasonable increments based on both the period of analysis and the scope of the study by combining incremental values from the following equation for the eustatic sea level change in meters, E(t), with values obtained by extrapolating the local rate of vertical land movement.

$$E(t_2) - E(t_1) = 0.0017(t_2 - t_1) + b(t_2^2 - t_1^2)$$

In the above equation, t_1 is the time between the projects construction date and 1992, and t_2 is the time between the future date for which the estimate of sea level rise is required and 1992. For the modified NRC Curve I, the coefficient b = $2.71E^{-5}$. Additional details are provided in the source document. Go to Step 14.

Step 14: Calculate future values for sea-level change for high rate (based on the modified NRC Curve III (National Research Council, 1987)). Calculate future sea level-change values at 5-year increments OR reasonable increments based on both period of analysis and scope of study by combining incremental values from the following equation for the eustatic sea level change in meters, E(t), with values obtained by extrapolating the local rate of vertical land movement.

$$E(t_2) - E(t_1) = 0.0017(t_2 - t_1) + b(t_2^2 - t_1^2)$$

In the above equation, t_1 is the time between the projects construction date and 1992, and t_2 is the time between the future date for which the estimate of sea level rise is required and 1992. For the modified

NRC Curve III, the coefficient b = $1.13E^{-4}$. Additional details are provided in the source document. Go to Step 15.

Step 15: Assess project performance for each sea-level change scenario developed in Steps 12, 13, and 14. This assessment and Steps 15-18 can occur at any point in the project life-cycle, and this applies to existing as well as proposed projects. Go to Step 16.

Step 16: Calculate the risk for each project design alternative combined with each sea-level change scenario as developed in steps 12, 13, and 14 at 5-year increments OR reasonable increments based on both period of analysis and scope of study. Go to Step 17.

Step 17: Assess risk (policies are under development) and reevaluate project design alternatives. Consider at a minimum: planning for adaptive management, designing to facilitate further modifications, and designing for a more aggressive future sea-level change scenario. Go to Step 18.

Step 18: Select project designs that best accommodate the range of sea-level change scenarios throughout the project life cycle.

Simplified Wind Wave Generation

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 Simplified Wave Generation Equation:

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.

Extracted from (Etemad-Shahidi, et al., 2009)

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

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

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:

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

Where:

θ = angle with respect to shore normal

Stone Size - Van der Meer

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.

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

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

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

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

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 = *r*elative 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} = *d*eep water wavelength corresponding to mean wave period

Validity:

1) Equations are valid for non-depth-limited waves. For depth limited waves, H_s is replaced by $H_{2\%}/1.4$.
2) For cot (α) ≥ 4.0, only the plunging wave equation should be used.
3) $N_z \leq 7{,}500$ after which number equilibrium damage is more or less reached.
4) $0.1 \leq P \leq 0.6$, $0.005 \leq s_m \leq 0.06$, 2.0 tonne/m$^3 \leq \rho \leq$ 3.1 tonne/m^3
5) 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.

Stone Size - Hudson

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 (Hudson, 1974) and can be found in Part VI Chapter V.

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

$$\frac{H}{\Delta D_{n50}} = (K_D \cot(\alpha))^{1/3} \quad \text{or} \quad M_{50} = \frac{p_s H^3}{K_D (\frac{p_s}{p_w} - 1)^3 \cot(\alpha)}$$

Where:

H = characteristic wave height (H_s or $H_{1/10}$)
D_{n50} = equivalent cube length of median rock
M_{50} = medium mass of rocks, $M_{50} = \rho_s D^3_{n50}$
ρ_s = mass density of rocks
ρ_w = mass density of water
$\Delta = (\rho_s/\rho_w) - 1$
α = slope angle
K_D = stability coefficient

K_D – values by SPM 1977, $H = H_s$, for slope angles $1.5 < \cot \alpha \leq 3.0$

(Based entirely on regular wave tests)

		Damage, D[(4)]			
Stone shape	**Placement**	**0-5% Breaking waves[(1)]**	**0-5% Non-Breaking waves[(2)]**	**5-10% Non-breaking waves**	**10-15% Non-breaking waves**
Smooth rounded	Random	2.1	2.4	3.0	3.6
Rough angular	Random	3.5	4.0	4.9	6.6
Rough angular	Special[(3)]	4.8	5.5	-	-

K_D – values by SPM 1984, $H = H_{1/10}$

		Damage, D^4 = 0-5%	
Stone shape	**Placement**	**Breaking waves(1)**	**Non-breaking waves(2)**
Smooth rounded Rough angular	Random	1.2	2.4
Rough angular	Random	2.0	4.0
Rough angular	Special(3)	5.8	7.0

1. Breaking waves means depth limited i.e., wave breaking takes place in front of the armor slope (critical case for shallow-water structures).
2. No depth-limited wave breaking takes place in front of armored slope
3. Special placement with long axis of stone places perpendicular to the slope face
4. D is defined according to SPM 1984 as follows: The percent damage based on the volume of armor units displaced from the breakwater zone of active armor unit removal for a specific wave height. This zone extends from middle of breakwater crest down the seaward face to depth equivalent to the wave height, causing *zero* damage below still-water level

Wind Speed Adjustment

It is frequently necessary to adjust the wind speeds measured at elevations other than the meteorological standard of 10 meters above the surface to an equivalent 10 meter wind speed. 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

Primary Wake Generation:

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:

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

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

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):

$$U_r = V_s\,(A_c/A_c^* - 1)$$

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

$$\frac{\Delta\hat{h}}{\Delta h} = \begin{cases} 1 + 2A_w^* \text{ for } b_w/L_s < 1.5 \\ 1 + 4A_w^* \text{ for } b_w/L_s \geq 1.5 \end{cases}$$

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

$$\frac{\widehat{U_r}}{U_r} = \begin{cases} 1 + A_w^* \text{ for} \frac{b_w}{L_s} < 1.5 \\ 1 + 3A_w^* \text{ for} \frac{b_w}{L_s} \geq 1.5 \end{cases}$$

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}.

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

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

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

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 Wake Generation - 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 US Army Corps of Engineers (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