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Modeling Site Suitability of Living Shoreline Design Options in Connecticut

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Modeling Site Suitability of Living Shoreline Design Options in Connecticut

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Abstract

Erosion is both a natural and anthropogenic phenomenon that threatens many properties along the coast. Installing hard structures has been the *status quo* method to protect waterfront property. However, structural barriers such as seawalls and groins have adverse environmental impacts on coastal processes and ecosystem services, such as food, recreation, and storm protection. Living shorelines are viable alternatives to shoreline armoring in low to moderate wave energy climates. Living shorelines are nature-based shoreline protection strategies which also enhance natural habitat and promote ecosystem services. In an attempt to improve coastal resilience in Connecticut, this study developed an automated geospatial model which determined the suitability of various living shoreline designs along Connecticut's Long Island Sound shoreline. The model uses coastal conditions and site characteristics to determine stretches of coastline suitable for living shorelines. Inputs such as fetch, bathymetry, erosion rates, marsh, and beach are taken into consideration in producing living shoreline site suitability. Outputs from the geospatial model include *beach enhancement* and *marsh enhancement*, as well as two hybrid design options –*offshore breakwaters* and *marsh with structures*. Results from this study reveal that overall 47% of the Connecticut shoreline is suitable for living shoreline design options. The model is a crucial first step for environmental planners, homeowners, environmental engineers, and consultants in considering shoreline protection alternatives to shoreline hardening.

Chapter 1: Introduction

1.1 The Problem

Shoreline erosion is a major risk to coastal property owners and environmental planners along sheltered coasts like that of Connecticut. Erosion is caused by many natural processes that result in associated land loss. Long-term weathering processes undercut dunes and bluffs while winds, waves, and tidal currents also all contribute towards a moving and constantly reshaping shoreline (National Research Council [NRC], 2007). Short-term events like high-energy storms and hurricanes are often significant erosion events that severely impact and damage the coast (Atlantic States Marine Fisheries Commission [ASMFC], 2010). Erosion is not an issue, however, until property or infrastructure are threatened. Recent storms like Hurricane Irene, in 2011, and Hurricane Sandy, in 2012, have brought the issue of erosion and coastal resilience to local, state, federal, and even national attention. Hurricane Irene and "Super Storm" Sandy caused much erosion when powerful waves and surge produced from these storms breached shoreline structures and transported away substantial quantities of sediment, exposing the Connecticut coast to flooding, property loss and damage. Additionally, climate change poses a major threat to the shoreline – sea level rise worsens erosion by changing the dynamics between the land-water interface, resulting in a "landward shoreline movement" (NRC, 2007, p. 34). Human activities, such as boat traffic, can also exacerbate the effects of erosion through boat wakes. The most common approach to mitigate shoreline erosion is to "harden" the shoreline.

Traditional methods of shoreline stabilization utilize hard structures such as sea walls, groins, jetties and bulkheads, which have adverse environmental consequences. Shoreline armoring or the installation of these hard structural features can actually lead to an increase in erosion on adjacent properties and cause scouring in front of the armored shore, oftentimes

negatively impacting beaches, fringing marsh and riparian habitats (Erdle et al., 2008; ASMFC, 2010). Shoreline armoring mitigation strategies result in loss of ecosystem services such as sediment stabilization, nursery areas for important species of fish, shellfish, and migratory birds, and filtering of pollutants from land-based runoff (NRC, 2007; United States Army Corps of Engineers [USACE], 2014). However, there are nature-based alternatives to shoreline armoring that provide ecosystem services and may even be more effective for some sites.

Living shorelines are an innovative and environmentally-friendly alternative to reduce coastal risk from both anthropogenic and natural causes of erosion. Living shoreline are nature-based shoreline protection strategies that are well-suited for sheltered coasts or areas that experience low to moderate wave energy (Figure 1-1). The Connecticut Department of Energy and Environmental Protection (DEEP) has a working definition of living shorelines:

> "A shoreline erosion control management practice which also restores, enhances, maintains, or creates natural coastal or riparian habitat, functions and processes. Coastal and riparian habitats include but are not limited to intertidal flats, tidal marsh, beach/dune systems, and bluffs. Living shorelines may include structural features that are combined with natural components to attenuate wave energy and currents" (Jacobson, 2015).

A living shoreline must restore, create or enhance natural habitats. Living shorelines may include soft, non-structural options such as beach nourishment and dune restoration, marsh restoration, bank-grading or planting of vegetation. A living shoreline may also include hybrid design options, as mentioned in DEEP's working definition, which include a man-made structure to attenuate wave energy in front of the natural shoreline. These hybrid designs include marsh with riprap, marsh with sills, and even breakwaters and reef balls. Living shoreline approaches

have proven successful in sheltered coastal areas such as Chesapeake Bay in Maryland and Virginia, North Carolina, as well as Gulf Coast states like Florida, Alabama, and Mississippi.

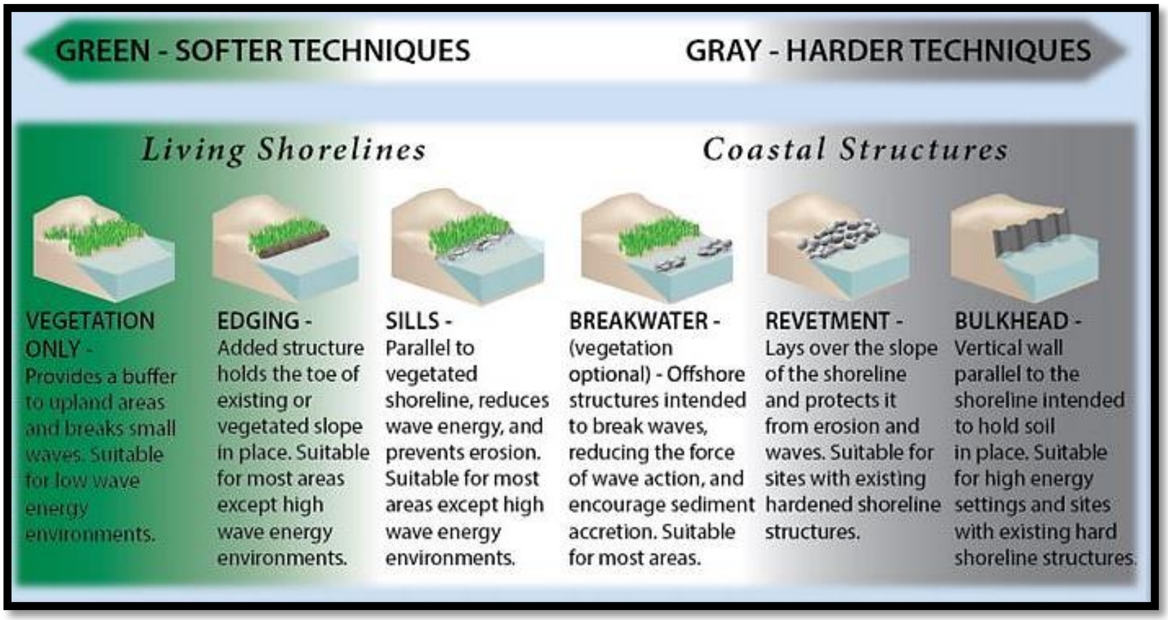


Figure 1-1. Erosion Control Structure Gradient
Source: National Oceanic and Atmospheric Administration (NOAA)

The concept of living shorelines for Connecticut is still relatively new. Effective October 1, 2012, Connecticut passed *An Act Concerning the Coastal Management Act and Shoreline Flood and Erosion Control Structures* which limits the amount of shoreline hardening allowed in the state of Connecticut. Connecticut provides a new interpretation of the Coastal Management Act which states "feasible, less environmentally damaging alternative(s)" must be considered when addressing shoreline protection strategies (Connecticut stat. §§ 12-101 (2012)). This legislation provides significant opportunity for implementing living shoreline strategies.

1.2 Purpose and Approach

In an attempt to improve coastal resilience in Connecticut, this study resulted in the development of an automated geospatial model which determines the suitability of various living

shoreline options for Connecticut's Long Island Sound shoreline. The primary purpose of the living shoreline site suitability model is a screening tool for nature-based erosion control options. The model takes into consideration regional, hydrodynamic, and terrestrial parameters in assessing the suitability for living shoreline techniques. Outputs from the geospatial model include both soft and hybrid design options which may help in expanding the use of living shorelines to Connecticut. The model is a crucial first step for environmental planners, homeowners, environmental engineers, and consultants in considering erosion control alternatives to shoreline hardening.

The living shoreline site suitability model follows a similar approach to other living shoreline models that have been developed for other regions and states like Carey's (2013) *Modeling Site Suitability of Living Shorelines in the Albemarle-Pamlico Estuarine System* and Berman and Rudnicky's (2008) *Living Shoreline Suitability Model* created for Worcester County, Maryland. The living shoreline site suitability model is a GIS raster-based binary model which determines viable sites for living shoreline options based on an unweighted spatial overlay analysis through a set of Python scripts. Five layers in this analysis are taken into consideration: fetch, bathymetry, erosion history, marsh, and beach. Layers are reclassified to living shoreline design guidelines based on adjustments to Miller et al.'s (2015) *Living Shoreline Engineering Guidelines* by the Stevens Institute of Technology. Once layers are reclassified to a common scale, layers are combined to produce living shoreline methods –*beach enhancement, marsh enhancement, marsh with structures,* and *offshore breakwaters*. Suitability is binary. It is either suitable for one of these shoreline stabilization methods based on the engineering guidelines, or it is not. All outputs are produced at 3-foot spatial resolution which allows for the potential employment of living shorelines on a property-by-property basis.

1.3 Objectives

The objectives of this study are as follows:

- Automate geoprocessing workflows to model site suitability of living shorelines along the Connecticut coast.
- Determine how much of the Connecticut shoreline, as defined by this study, is suitable for soft and hybrid living shoreline design options.
- Expand and encourage use of living shoreline treatments in Connecticut through development of a decision support tool.
- Define model limitations and determine which data are needed to refine the analysis further.

Chapter 2: Literature Review

The shoreline is constantly shifting as a result of natural processes such as winds, waves, sediment supply, rises and decreases in sea level, as well as man-made activities, including, for example, dredge and fill operations and boat wakes from boat traffic. Hurricanes and coastal storms have devastated coastal areas in recent years, significantly increasing economically-related losses in these regions (USACE, 2014). Some stretches of shoreline may migrate landwards while other stretches of shoreline may migrate waterwards (ASFMC, 2010). Many of the processes dictating erosion on the open water are also applicable to sheltered coasts (NRC, 2007). Sheltered coasts are typically considered a lower energy shoreline that face a smaller body of water such as a bay or estuary (NRC, 2007). The main difference between open coasts and sheltered coasts are that sheltered coasts have lower wave energy than open coasts and, therefore, salt marsh and mudflat habitats are able to develop and promote ecosystem services, whereas open coasts do not allow for these habitats to develop (NRC, 2007). Sheltered areas provide vital habitat for many species of shellfish, fish, and migratory birds, which also creates hotspots for fishing, housing, and recreational activities (ASFMC, 2010). However, human activities such as boat traffic, dredge and fill operations, and wetland drainage accelerate the rates of erosion (NRC, 2007). With a high demand for waterfront property and development, many strategies to mitigate erosion have been taken. This chapter will discuss the physical processes controlling erosion and related erosion mitigation strategies with a primary focus on nature-based alternatives such as living shoreline designs.

2.1 Shoreline Erosion

According to ASMFC (2010), erosion is “the natural, ongoing process in coastal areas in which sediment moves away from one part of the shore and is transported elsewhere” (p. 1).

Erosion occurs at sites of divergence, which is where sediment loss exceeds the amount deposited while accretion occurs as sites of convergence, which is where sediment deposited exceeds sediment loss (CT DEEP, 1979; USACE, 1984). The effects of erosion can be described as the movement of shore contours (NRC, 2007). There are many physical processes governing erosion along sheltered coasts.

Sediment is categorized based on grain size, the four major classes being gravel (greater than 0.08 in), sand (.0025 - 0.08 in), silt (0.00015 – 0.0025 in, and clay (less than 0.00015 in) (USACE, 1984; NRC, 2007). Due to the unique geomorphic and regional variability found within a sheltered coast, each of the four grain-size classes of sediment are well-represented. Beaches are typically composed of sand and “cobble-sized” sediment, while mudflats are composed of finer sediments like clays, and bluffs are a mixture of sand, gravel, and clay (NRC, 2007). Sheltered coasts range from unconsolidated sediment to partially-cemented rock to exposed bedrock (NRC, 2007; Erdle et al., 2008). Sediment is categorized based on size because size is an indicator of water’s ability either to entrain or to transport sediment. The NRC (2007) note that understanding the sediment transport process is fundamental to mitigate erosion.

The transport of sediment depends on the initial sediment threshold conditions, the hydrodynamic and geological processes that move sediment after sediment is initially dislodged, as well as processes of sediment being deposited. Entrainment, or the threshold of sediment motion, is where particles exceed a threshold from waves and currents and are lifted from settled sediment (NRC, 2007). The threshold of sediment motion is dependent on the size and density of the grain. Typically, finer sediments like clays and silts are more cohesive which decreases their chances of transport (NRC, 2007). Sheltered coasts are composed of fine sediments like mudflats and vegetated mudflats (marsh) so they typically only surpass the sediment threshold during

hurricanes and coastal storms (NRC, 2007). Once sediment is freed, it is carried along the nearshore through wave action and tidal currents, which is a complicated process either resulting in landward or waterward migration of geologic materials.

The main hydrodynamic factor behind the transport of sediment in sheltered coasts is wind-driven waves. Waves in sheltered shores are dependent upon the strength of the wind and the distance wind can travel over open water before reaching shore, also known as fetch (NRC, 2007). The wave energy generated during extreme events is usually limited by the fetch. Additionally, as mentioned in Chapter 1, boat traffic exacerbates the effects of erosion, but it is quite difficult to quantify the wave energy generated from boat wakes (ASFMC, 2010).

2.1.1 Erosion in Connecticut

Connecticut's shoreline spans the northern extent of Long Island Sound and is considered an estuarine embayment (CT DEEP, 1979). Geologically, Connecticut's coast is considered a "submerging, primary coast of glacial deposition" (CT DEEP, 1979, p.3). Connecticut's shoreline is divided into seven shoreline districts based on geological influences. District A, from Greenwich to Norwalk, is characterized by rock and drift. Erosion is less common due to the bedrock composition of this area. There is significant artificial fill and shoreline hardening projects, which is where erosion is more pronounced (CT DEEP, 1979; CT DEEP; 2012). District B, from Norwalk to Milford is characterized by glacial drift and beaches. These beaches are significantly affected by erosion (CT DEEP 1979). District C, from Milford to New Haven, is characterized by glacial drift and rock. Erosion along the north-south shoreline has been an issue exacerbated by hard structures on adjacent properties, in this district (CT DEEP 1979; CT DEEP 2012). District D, New Haven to Guilford, is characterized by rock and marsh where most of the shoreline is stable (CT DEEP, 2012). District E, from Guilford to Old Lyme, is characterized by

glacial drift and beaches where erosion along bluffs and beaches is common. Shoreline hardening along this district is common which prevents natural shoreline processes from occurring. Accelerated erosion along beaches and bluffs is common (CT DEEP, 1979; CT DEEP, 2012). District F, from Old Lyme to Groton, consists of glacial drift and rock where regional erosion is minimal, except along a few beaches and barrier beaches (CT DEEP, 1979; CT DEEP, 2012). Finally, District G, from Groton to Stonington, consists of rock and marshes where the main threat is sea level rise encroaching upon marsh. Most of the shoreline is protected from erosion by its rocky composition (CT DEEP, 1979; CT DEEP, 2012).

In 2014, O'Brien, Stocker, Barrett, and Hyde released *Analysis of Shoreline Change in Connecticut*. O'Brien et al. (2014) provide a GIS-based time-series analysis using orthoimagery between 1880 and 2006 which describes detailed and quantifiable trends in erosion and accretion for Connecticut's shoreline (Figure 2-1). Figure 2-1 shows erosion at a unique fill site at Fenwick Point, Connecticut which falls under the District E shoreline district.

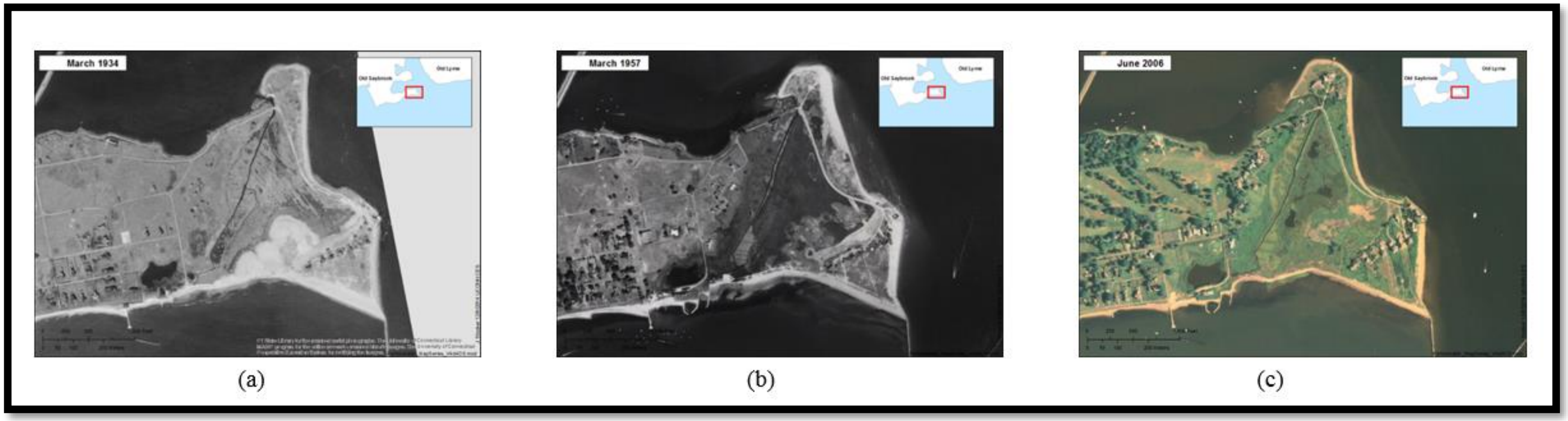


Figure 2-1. Connecticut Shoreline Change Analysis Time-Series at Fenwick Point, Old Saybrook, CT: Using orthoimagery, it is clear that this site, situated at the mouth of the Connecticut River, was filled between 1934 and 1957 (a and b, respectively). The June 2006 orthoimagery (c) shows that the shoreline has reverted back to its pre-fill original state.
Source: Joel Stocker, Center for Land Use Educator and Research (CLEAR) – University of Connecticut (UConn)
http://clear3.uconn.edu/coastalchange/mapsets/mapsFenwick/CM141208133417.htm

2.1.2 Current Coastal Risk Management Strategies

In general, there are three approaches towards mitigating erosion along sheltered coasts. The first, as explained by the USACE (2014), involves traditional methods of shoreline hardening which have adverse environmental consequences. Hard structures like seawalls, bulkheads, revetments, and groins are intended to "hold the front." The second set of strategies involves nature-based solutions that attenuate wave energy while providing critical habitat for estuarine species. These living shoreline options range from planting of vegetation to hybrid design options like marsh with man-made features to *offshore breakwaters*. The third set of strategies includes land-use planning techniques that minimize risk within coastal areas by limiting development to especially vulnerable areas (USACE, 2014).

Oftentimes, the decision for implementing a shoreline stabilization option is a balance between the cost of the project and the level of protection provided by the design (Maryland Department of Natural Resources, 2006). The cost is dependent upon construction materials, length of project, as well as cost of risk and consequence of failure (Maryland Department of Natural Resources, 2006). According to USACE (2014), risk refers to the "potential for hazards to cause adverse effects on our lives; health; economic well-being; social, environmental, and cultural assets; infrastructure; and the services expected from institutions and the environment" (NRC, 2012c; p. 17). Whereas, consequence refers to the effect(s) caused by the natural hazard (USACE, 2014). The *de facto* method to minimize shoreline erosion has been shoreline armoring.

2.2 Shoreline Armoring

Shoreline hardening is the most common approach towards mitigating erosion for water property owners because they are "immediately effective at reducing erosion" and are much

easier to permit and regulate (USFMC, 2010, p.2). Hard structures are commonly used to address shoreline erosion along Connecticut's coast. These structures are designed for high wave energy environments and are engineered to prevent flooding from extreme events like hurricanes and Nor'Easters (USACE, 2014). Shoreline armoring is especially popular in highly urbanized areas as a way to minimize risk to property and infrastructure (USACE, 2014,). Shore-parallel features like seawalls and bulkheads are common techniques for property owners with sandy shorelines where the beach has been nearly or entirely eliminated, or areas with very narrow intertidal regions as a way to protect the upland area (USACE, 2014). Another common hardening approach along sheltered coasts includes placement of structures perpendicular to the shoreline like groins, where the purpose is to build up sediment (ASFMC, 2010) (Section 2.2.5).

2.2.1 Seawalls and Bulkheads

One of the most traditional shoreline armoring techniques along sheltered coasts in the northeast is the use of seawalls, which are vertical structures placed parallel to the shore typically constructed of poured concrete, steel sheet pile, or local rock (USACE 1984; NRC, 2007; USACE, 2014) (Figure 2-2). Linham et al. (2010) discovered a seawall can cost anywhere between $0.6 million per mile to $44 million per mile depending on the level of protection and related building materials (USACE, 2014). Seawalls are designed to withstand high wave energy.

Figure 2-2. Seawall at Fenwick Point, Old Saybrook, CT
Source: Joel Stocker, CLEAR – UConn

Bulkheads are structures usually constructed of wood and serve a purpose similar to seawalls, but are generally less expensive and provide less protection (ASFMC, 2010). Bulkheads prevent upland sediment from being deposited seaward and provide stability at the toe (USACE, 1984). Their main purpose is to reinforce the soil bank (Figure 2-3). Although seawalls and bulkheads are designed to provide erosion control through protection of the upland, these structures may still contribute to additional sources of erosion.

Figure 2-3. Wooden Bulkhead at Fenwick Point, Old Saybrook, CT
Source: Joel Stocker, CLEAR – UConn

Erosion and accompanying loss of ecosystem services are often side-effects of vertical shoreline hardening structures. Dean (1986) noted that coastal armoring structures placed in an area with high rates of erosion will significantly disrupt the littoral transport process. As a result, seawalls and bulkheads often cause higher rates of erosion to adjacent properties and create problems downdrift because they prevent the beach from providing sediment to the rest of the nearshore region (Dean, 1986; USACE, 2014). Furthermore, vertical shoreline structures are intended to protect the upland, but over time will destroy the beach profile seaward of the armoring (Figure 2-4). A possible adverse effect is that the beach profile fronting a seawall or bulkhead steepens and decreases in width as the structure experiences scouring at the toe (Dean, 1986; Kraus and McDougal, 1996; USACE, 2014). Furthermore, Dean (1986) suggested that shoreline armoring structures recover slowly post-storm. As vertical structures interrupt the littoral transport system, oversteepen the beach profile, and reduce or eliminate the intertidal region, these structures significantly reduce ecosystem services provided by sheltered coasts.

According to NOAA Habitat Conservation, ecosystem services are “the contributions that a biological community and its habitat provide to our day-to-day lives” (NOAA). Ecosystem services provided by estuarine habitat include food, recreation, medicine, and storm protection (Erdle et al., 2008). However, vertical hardening structures considerably deteriorate the quality and quantity of these vital sheltered shoreline habitats, thus decreasing ecosystem service production. Wetlands and submerged aquatic vegetation (SAV) beds fronting hard structures can be eroded away due to scouring action at the base (ASFMC, 2010). Loss of water-filtering wetlands leads to an increase in land-based runoff and reduced water quality which ultimately leads to a decrease in marsh habitat (ASFMC, 2010). Additionally, vertical hardening structures cause deep water zones which have been shown to lower concentrations of detritus, reduce phytoplankton production, and lower quantities of benthic organisms (Odum 1970; ASFMC, 2010). As the water deepens seaward of the structure, the dynamics of the intertidal region change to one that favors invasive species. For instance, these deep water zones leave juvenile fish vulnerable to predatory species that were once inaccessible to their shallow nursing areas. (ASFMC, 2010). Furthermore, bulkheads constructed from wood have been known to contain chromated copper arsenate (CCA), which is a preservative that leaches out of the wood and reduces quality of the tidal ecosystem (ASFMC, 2010). Therefore, seawalls and bulkheads can lower species abundance and diversity.

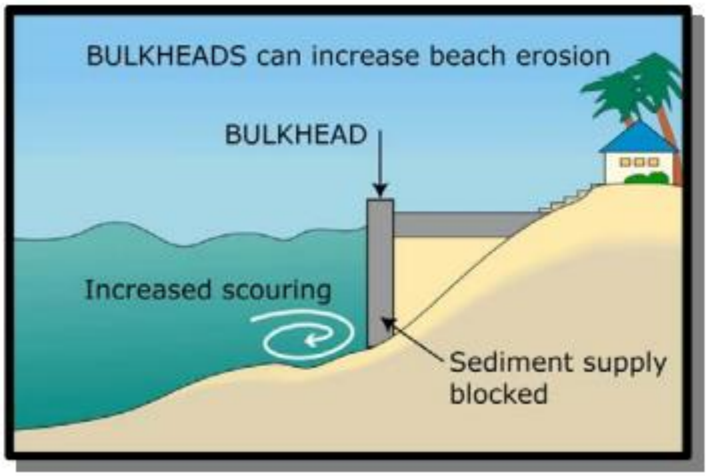


Figure 2-4. Scouring Action Seaward of Bulkhead
Source: ASFMC, 2010 from USGS

2.2.2 Revetments

Riprap (rock) revetments are structures placed parallel to an existing slope or embankment (USACE, 1984). Like bulkheads and seawalls, revetment features protect the upland from waves and strong currents (Figure 2-5). Unlike bulkheads and seawalls, most revetments do not interfere with the littoral transport process because they are built at a gentler slope (USACE, 1984). Revetments provide toe protection to embankments and are usually porous, which allows for water to pass through and wave energy to dissipate properly (USACE, 1984). If improperly installed, riprap revetments can destabilize the bank and increase erosion (ASFMC, 2010).

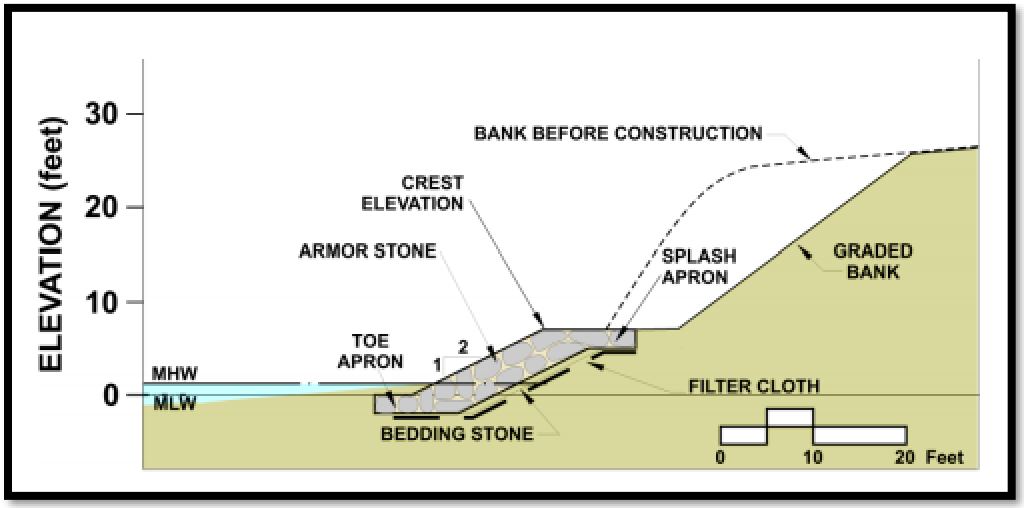


Figure 2-5. Cross-Section of Riprap Revetment
Source: Hardaway and Byrne, 1999

2.2.3 Sills

Sills are low-profile structures placed parallel to the shore near the Mean-High Water (MHW) line constructed of either armorstone, grout-filled bags, sheetpiling, or, in recent years, oyster reefs (USACE, 1984; ASFMC, 2010). Sills are typically engineered with gaps to dissipate wave energy and allow for natural movement of sediment behind the structure (ASFMC, 2010). In sheltered coasts, sills are commonly used to restore or enhance fringing marsh (ASFMC, 2010). Environmental consequences of sills include changing the habitat from a dry beach to a marsh system and potentially increasing erosion on adjacent shorelines (Figure 2-6). However, there are also many advantages of sills for enhancing natural habitat, which will later be discussed (See Section 2.3).

Figure 2-6. Stone Sill
Source: Karen A. Duhring, Center for Coastal Resource Management (CCRM) – Virginia Institute of Marine Science (VIMS)

2.2.4 Offshore Breakwaters

Breakwaters are shore-parallel structures built in open water that attenuate wave energy before reaching the shoreline (ASFMC, 2010). Breakwaters are similar in design and purpose to sills, but the main difference is that they are placed farther offshore and are larger and, consequently, more expensive (ASFMC, 2010). Breakwaters can be engineered using poured concrete, riprap, as well as oyster shells (ASFMC, 2010). Breakwaters can be attached, also known as a headland breakwaters, or detached, which is when they are placed farther offshore (Figure 2-7). Breakwaters allow sediment to accumulate landward of the structure(s) by interrupting natural transport of sediment nearshore. In general, breakwaters do not provide the same level of protection as seawalls and bulkheads because breakwaters allow for some wave action to penetrate the shoreline (USACE, 1984). An adverse effect from breakwaters is that they

can cause erosion downdrift of the structure (ASFMC, 2010). However, if properly engineered, breakwaters can promote development of ecosystem services (See Section 2.3).

Figure 2-7. Headlands Breakwater at Ocean Beach, New London, CT
Source:Joel Stocker

2.2.5 Groins

Groins are usually stone or rock structures placed perpendicular to the shore and extend out into the water. Groins trap sediment updrift, which exacerbates erosion downdrift of the structure (ASFMC, 2010). They are effective where the longshore transport is predominantly from one direction (USACE, 1984; ASFMC, 2010). Groins are often constructed on adjacent properties, resulting in a “groin field” that nourishes the beach between the features but ultimately alters the shoreline alignment (Figure 2-8) (ASFMC, 2010, p. 9). Groins provide low

to moderate protection from wave energy and storm events and often decreases health of benthic organisms and bottom habitat (ASFMC, 2010).

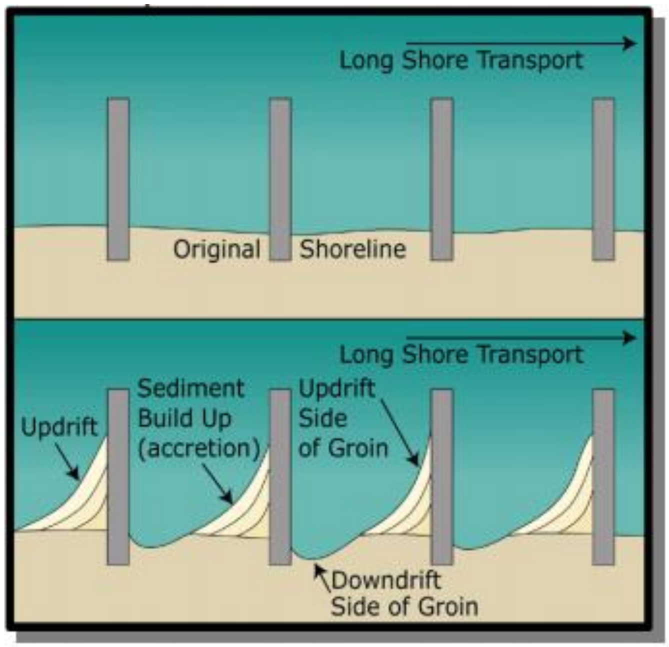


Figure 2-8. Diagram of Sediment Transport Along Groin Field
Source: NOAA; ASMFC, 2010

2.3 Living Shorelines

Living shorelines are nature-based shoreline stabilization strategies that also provide ecosystem services. Living shoreline techniques prevent shoreline erosion while maintaining important natural physical, geological and biological processes of a natural shoreline (Virginia Coastal Zone Management Program [VA CZM], 2012). Living shorelines are viable options for sheltered coasts and protected creeks and rivers where there is low to moderate wave energy and minimal erosion (Chesapeake Bay Foundation, 2009). Key aspects of living shoreline designs include riparian buffers, tidal wetlands, and native plant species, as well as submerged aquatic

vegetation (Chesapeake Bay Foundation, 2009) (Figure 2-9). Many living shoreline techniques have been employed along sheltered coasts in Maryland, Virginia, North Carolina, and Gulf Coast states. However, living shorelines are still relatively a new concept for Connecticut shorelines.

Living shorelines maintain, enhance, or restore riparian habitat. A riparian area refers to the "transition between aquatic and terrestrial environments" (ASFMC, 2010, p. 15). Maintaining a healthy riparian habitat is especially important because riparian buffers along tidal shorelines trap and filter sediments, nutrients, and chemicals from land-based runoff (Hardaway et al., 2010). Riparian buffers also stabilize the bank and nutrients in the soil help convert nitrate into nitrogen gas, also known as "denitrification" (Hardaway et al., 2010). Living shorelines provide key habitat for fish and shellfish, as well as nesting and foraging areas for resident and migratory birds (Galveston Bay Foundation, 2014). Other benefits of nature-based approaches include aesthetically-pleasant views and recreational opportunities for boating and fishing (VA CZM, 2012). Living shoreline designs contribute to less bank erosion and property loss and often perform better than traditional methods of shoreline armoring during storm events (See Section 2.4.3). Most importantly for waterfront property owners, living shorelines may even cost less to construct and maintain compared to traditional shoreline hardening techniques (VA CZM, 2012).

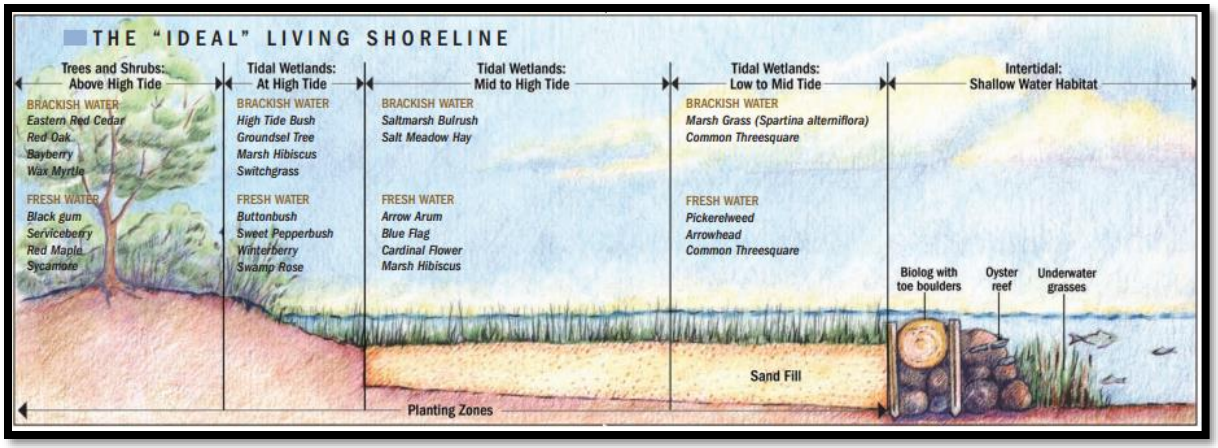


Figure 2-9. The "Ideal" Living Shoreline
Source: Chesapeake Bay Foundation, 2007

2.4 Living Shoreline Design Options

Living shorelines can be either nonstructural in design or incorporate engineered structures, also known as "hybrid" designs. Nonstructural options include planting of native vegetation species, beach nourishment, bank grading, and coir fiber logs or other natural materials. Nonstructural, or "soft", techniques stabilize bank erosion and restore wetland habitat in lower wave energy climates, whereas, hybrid living shoreline stabilization techniques incorporate structural features that provide higher levels of protection to natural erosion buffers like wetlands and beach (Duhring, 2006). Hybrid design options include marsh sills or marsh toe revetments, offshore breakwater systems, as well as oyster shell/natural reefs (Duhring, 2006; Galveston Bay Foundation, 2014). In the case of living shoreline site suitability for Connecticut, this study focuses on the living shoreline design outputs from the site suitability model – *marsh enhancement, beach enhancement, marsh with structures,* and *offshore breakwaters.*

2.4.1 Marsh Enhancement

Marsh enhancement refers to nonstructural design options such as tidal marsh creation or enhancement, which is appropriate for low wave energy shorelines. Marsh restoration is the process of adding new marsh plants to barren or eroding marsh areas or replacing marsh plants washed out from storm events (Duhring, 2006; Hardaway et al., 2010). Water depth and sunlight are key factors in restoring tidal wetlands (Duhring, 2006; Hardaway et al., 2010). Marsh creation refers to creating marsh where marsh does not naturally exist or augmenting marsh where small patches of marsh have begun to develop. This method usually requires bank grading of non-vegetated intertidal areas (Duhring, 2006). Planting of tidal marsh is dependent upon the local salinity range, tidal amplitude, as well as the wave climate (Duhring, 2006; Hardaway et al., 2010). One of the most common tidal marsh grasses for marsh creation includes *Spartina alterniflora,* which is a low marsh plant species. Marsh enhancement techniques control erosion while providing many benefits to the ecosystem.

Tidal wetlands mitigate erosion primarily through three mechanisms (ASFMC, 2010): (1) marsh vegetation stabilizes the shoreline by holding sediment in place via the root system (2) marsh vegetation allows for wave energy to dissipate, which, (3) decreases velocity from wave energy and allows sediment to deposit. Tidal wetlands provide many benefits to the ecosystem including filtering of pollutants from upland runoff and providing habitat for juvenile fish, invertebrates, and nesting and foraging areas for migratory birds (ASFMC, 2010).

Figure 2-10. Planted Marsh at VIMS
Source: Karen A. Duhring, CCRM – VIMS

2.4.2 Beach Enhancement

Beach enhancement refers to nonstructural design options such as beach nourishment and dune restoration, which is appropriate for low wave energy shorelines. Duhring (2006) defines beach nourishment as "the addition of sand to a beach to raise its elevation and increase its width to enhance its ability to buffer the upland from wave action" (p. 14). Whereas, dune restoration refers to the process of using planted vegetation to stabilize a dune system, usually as part of a beach nourishment project (Duhring, 2006; Hardaway et al., 2010). Important considerations include matching sand grain sizes and planting native plant species to ensure success of design (Duhring, 2006; Hardaway et al., 2010).

USACE (2014) assert that beach nourishment and dune restoration are key components of their coastal risk reduction strategy through the protection and ecological benefits they provide. Beach nourishment and dune restoration projects do not prevent erosion (USACE,

2014). However, beach nourishment projects slow the processes of erosion by providing additional sediment that counteracts erosion processes (USACE, 2014). Therefore, the greater the volume and width provided by the beach nourishment project, the greater level of protection against shoreline erosion. Rogers (2007) ascertained that Hurricanes Dennis and Floyd in 1999 did not cause damage at three USACE-constructed beach nourishment and dune restoration projects in North Carolina, but adjacent areas outside these shoreline stabilization strategies resulted in damage to 900 buildings. Success of beach nourishment projects is dependent upon clean sediment that matches the local beach characteristics, such as the grain size and shape of native materials (USACE, 2014). If properly installed, these sites provide potential for new habitats to become established.

Figure 2-11. Beach Nourishment and Dune Planting at Yorktown, VA
Source: Karen A. Duhring, CCRM – VIMS

2.4.3 Marsh with Structures

Marsh with structures refers to marsh hybrid design options such as marsh toe revetments, marsh sills, or marsh with groins. Hybrid marsh designs incorporate structures designed for areas that experience higher levels of wave energy than marsh enhancement. Marsh toe revetments, also known as “marsh edge stabilization,” involves the process of using freestanding low-profile structures placed at the eroding edge of marsh near the Mean Low Water (MLW) line (Duhring, 2006; Hardaway et al., 2010). Marsh sills are a similar type of low-profile stone structure but create new marsh where it does not naturally exist – areas along graded banks and failed bulkheads (Figure 2-12). These are also placed near the MLW mark (Duhring, 2006; Hardaway et al., 2010). These structures are placed in shallow water so they receive adequate tidal flow, which allows marsh vegetation to grow. Marsh with groins are similar to marsh sills, but, instead of placing these structures parallel to MLW, groins are placed perpendicular to the shoreline (Duhring, 2006; Hardaway et al., 2010). A groin is best used to trap sand moving along the beach, which increases sediment over time, whereas, a sill may utilize sand fill to establish marsh growth behind the structure. Hybrid marsh techniques promote marsh habitat and its accompanying ecosystem services.

Gittman et al. (2014) note that engineering performance and cost-effectiveness are decisive factors for waterfront property owners when choosing shoreline stabilization strategies. Gittman et al. (2014) suggest that marshes with and without sills are more resilient and provide better erosion control than bulkheads in a Category 1 hurricane. After Hurricane Irene, bulkheads were the only shoreline stabilization technique that showed visual damage at the study sites in Central Outer Banks, North Carolina. Immediately following Hurricane Irene, there was substantial marsh loss at both hybrid and unmodified marsh sites, but there was nearly a full

recovery within 13 months, with hybrid marsh designs recovering more completely, which suggests that marsh, especially hybrid marsh designs, are more resilient than shoreline hardening techniques (Gittman et al., 2014). Gittman et al. (2014) found that marshes less than 10 m in width can reduce wave heights by 80% for waves less than 0.5 m in height and can reduce wave heights by 50% for waves greater than 0.5 m in height (p. 100). This study also found that marshes promoted vertical sediment accretion, reduced overall sediment loss, and maintained elevation of the shoreline (Gittman et al., 2014). Hybrid marsh techniques maintain key marsh habitat.

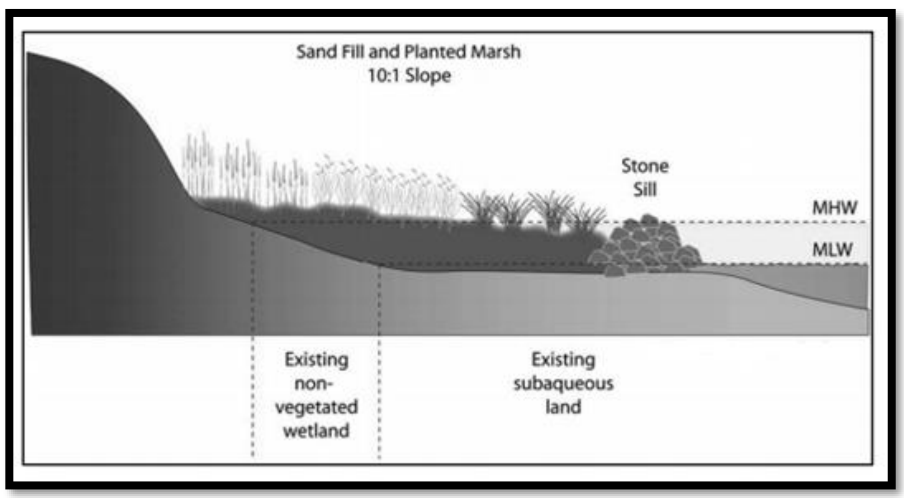


Figure 2-12. Cross-Section of Marsh Sill
Source: Karen A. Duhring, CCRM – VIMS

2.4.4 Offshore Breakwaters

Offshore breakwaters refers to hybrid design options for beaches, such as artificial reefs and living breakwaters. These are either a series of stone or shell structures strategically placed offshore that enhance the ability for stable pocket beaches to develop in moderate to high wave energy environments (Figure 2-13).

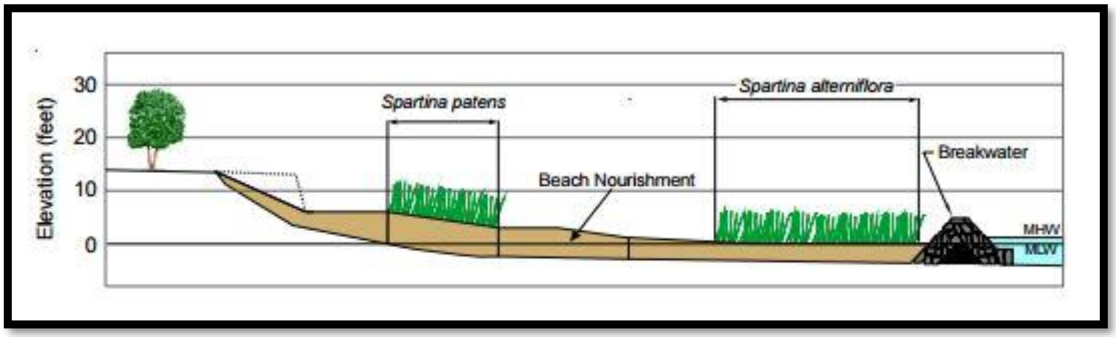


Figure 2-13. Typical Cross Section of Living Breakwater System
Source: Hardaway and Byrne, 1999

Offshore breakwaters may require beach nourishment or dune restoration landward of structures. Offshore breakwaters provide substantial levels of erosion protection and are known to enhance estuarine habitat (Duhring, 2006; Hardaway et al., 2010). Living breakwaters may provide habitat for terrestrial and aquatic wildlife, including shorebirds and turtles, as well as colonization of oysters and mussels on the structures (Duhring, 2006; Hardaway et al., 2010). Additionally, oyster reefs improve water quality through filtration which promotes SAV growth and enhances bottom habitat (Figure 2-14) (ASFMC, 2010). Scyphers et al. (2011) examined the effects that oyster reefs have on nearshore fish and shellfish communities in Mobile Bay, Alabama. Scyphers et al. (2011) discovered enhanced habitat for several economically-important species including blue crabs, sea trout, and flounder which shows living breakwaters provide important ecosystem services, in addition to erosion control.

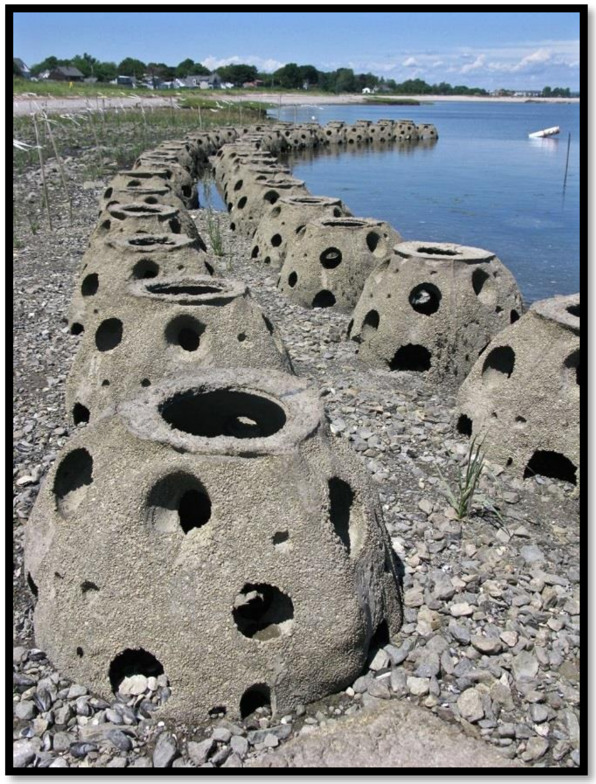


Figure 2-14. Reef Balls at Stratford Point, CT
Source: Judy Preston, Connecticut Sea Grant – Uconn

2.5 Design Considerations for Living Shorelines

Implementing a living shoreline design is extremely site-specific to system, hydrodynamic, terrestrial, and ecological parameters (Miller et al., 2015). Miller et al. (2015) provide living shoreline engineering guidelines that are intended not only to educate decision-makers and waterfront property owners about engineering and ecological aspects of living shorelines, but also to provide a methodology for considering the system, hydrodynamic, terrestrial, and ecological factors that are critical to the success of living shoreline stabilization techniques. System parameters are large scale phenomena that influence shoreline stabilization such as erosion history, tidal range, and sea level rise (Miller et al., 2015). Hydrodynamic parameters, such as waves, wakes, tidal currents, and storm surge, relate to the factors impacting

the existing shoreline condition (Mill et al., 2015). Terrestrial parameters represent “the condition of the land both below and above the water” (Miller et al., 2015, p.23). This includes the upland, shoreline, nearshore slopes, and offshore depth. Ecological parameters determine the performance of the design and “represent the biogeochemical conditions at the site” such as water quality, sunlight exposure, and sediment type (Miller et al. 2015, p. 28). Miller et al.’s (2015) guidelines address the “underdeveloped state of knowledge” about living shorelines in the Northeast (p. 7).

It is important to understand that “one size does not fit all” with regards to employing living shoreline techniques (Galveston Bay Foundation, 2014). Hardaway et al. (2010) explain that shoreline variables considered in living shoreline designs can be categorized into two sets – map parameters and site visit parameters. Map parameters include factors such as fetch, depth offshore, shoreline geometry and orientation, nearshore morphology, presence of marsh and SAV, erosion history, design wave determination, and storm surge frequency. Whereas, site visit parameters, such as boat wakes, impacts of existing shoreline structures on local erosion processes, and bank condition and composition, are factors not easily mapped (Hardaway et al., 2010). This study aims to address the map parameters critical to living shoreline design and implementation.

Carey (2013) noted that there are some generally accepted guidelines through these map parameters listed above, despite the site-specific nature of living shoreline projects. Living shoreline site suitability is a function of wave energy and presence of vegetation (Carey, 2013). Areas that experience low wave energy based on low fetch exposure and a shallow and gently-sloping nearshore region may indicate sites suitable for soft non-structural living shoreline techniques. Sites that experience a moderate wave energy may incorporate hybrid designs, and

sites that experience high wave energy are not suitable for living shorelines (Hardaway et al., 2010; Carey, 2013). Important map parameters in living shoreline site suitability include erosion history, wind-driven waves, and bathymetry.

2.5.1 Erosion Rates

Erosion rates are system parameters indicative of the shoreline stability and are an important factor in successfully designing, installing, and maintaining a living shoreline technique. Miller et al. (2015) explain that if the source of erosion can be better identified, then an appropriate shoreline stabilization method can be established to provide erosion control. A popular method to determine trends in erosion history involves studying historic aerial photographs, as well as digitized shorelines at the project site (Miller et al., 2015). Determining erosion history may also incorporate personal interviews where locals can provide detailed knowledge, oftentimes not captured in the aerial photographs that better identifies the cause(s) of erosion (Miller et al., 2015). Miller et al. (2015) categorize erosion rates into three categories which are important when considering specific designs – less than 2 feet per year is considered low/mild, 2 to 4 feet per year is moderate, and greater than 4 feet per year is steep.

2.5.2 Fetch

Wind-driven waves are perhaps the most important hydrodynamic factor that determines shoreline stability. Rohweder et al.(2012) define fetch as “the unobstructed distance that wind can travel over water in a constant direction” (p. 5). Wave energy along sheltered coasts is mostly limited by fetch (Miller et al., 2015). Therefore, fetch is used as a proxy for wave energy. The greater the distance that wind travels over open water, the stronger the waves will be. Both Hardaway et al. (2010) and Miller et al. (2015) advise that there are two assessments of fetch that

determine the project design – the longest fetch and the average fetch. The longest fetch is indicative of wave energy experienced during extreme events, which is a strategy commonly used for design of traditional coastal engineering projects (Miller et al., 2015). However, living shorelines are not designed to withstand large storm events – they are often inundated during these scenarios – so longest fetch is less relevant to living shoreline applications. Rather, average fetch, representing normal conditions for waves, is more appropriate for living shoreline applications. Hardaway and Byrne (1999) categorize fetch exposure into very low (less than 0.5 mi), low (0.5 – 1.0 mi), medium (1.0 – 5.0 mi), and high (5.0 – 15.0 mi). These fetch classifications are suited for sheltered shorelines. If fetch surpasses 15 miles at river inlets or along a bay, then it is classified as very high (Hardaway and Byrne, 1999; Miller et al. 2015).

2.5.3 Bathymetry

Underwater topography or bathymetry is an important consideration for living shoreline design. Miller et al. (2015) state that nearshore slope "plays a critical role in determining the behavior of waves and currents immediately offshore of the site" (p. 26). A gentler slope properly absorbs and dissipates wave energy, whereas, steep slopes tend to deflect energy. Also, the offshore depth is an important factor in determining wave response – deeper water allows waves to develop more energy, which increases the impact those waves have on the shoreline. Similarly, deeper water allows for passage of larger ships which increases boat wake action, thus increasing erosion along the shore (Millet et al., 2015). Therefore, shallow water on a gradual slope may be immediately effective for consideration of soft-nonstructural designs. Deep water and larger slope gradients may require fill and structural support (Hardaway et al., 2010; Miller et al., 2015).

2.6 Site Suitability Models

Previous GIS-based studies have modeled site suitability of living shoreline designs. Carey (2013) modeled site suitability of living shorelines in the Albemarle-Pamlico Estuarine System in North Carolina. Boyd and Dutta (2014) took a GIS- and remote sensing-approach for site suitability in Mobile Bay, Alabama. These models were based on adjustments from the earliest example of living shoreline site suitability assessment, which was performed by Berman and Rudnicky (2008) at the Center for Coastal Resources Management (CCRM) at the Virginia Institute of Marine Science (VIMS) for Worcester County, Maryland. This section highlights the key factors for delineating shoreline suitable for living shoreline methods.

2.6.1 Purpose

Berman and Rudnicky (2008) explain that their Living Shoreline Suitability Model (LSSM) is a tool to be used by decision-makers and coastal managers when considering alternatives to shoreline hardening. Their model is particularly useful to waterfront property owners who seek to be actively involved in implementing a shoreline stabilization strategy, which can save time and money for coastal land owners (Berman and Rudnicky, 2008). Their site suitability model encourages and expands the use of living shoreline treatments where coastal managers, property owners, and decision-makers, alike, can consider their options through an interactive mapping interface (Berman and Rudnicky, 2008; Boyd and Dutta, 2014).

2.6.2 Limitations

There are many limitations associated with the living shoreline site suitability models, which is to be expected for a GIS-based approach that generalizes the complex nature of site-specific parameters. Most notably, the previous living shoreline site suitability models did not

consider anthropogenic conditions (Carey, 2013). The effects of man-made coastal structures and infrastructure were not considered on coastal processes. For example, a seawall installed adjacent to a replenished beach may exacerbate the forces of erosion at the nonstructural site during storm events. Also, infrastructure upland of the coastal engineering application may limit design options – buildings too close to the riparian area may limit necessary bank grading (Carey, 2013). Furthermore, none of the models consider a “Do Nothing” approach, which means these models assume that erosion is a problem for the shoreline and needs to be addressed (Berman and Rudnicky, 2008; Carey, 2013, Boyd and Dutta, 2014). In real-life scenarios, if erosion is minimal and the shoreline naturally provides habitat, then strategies to reduce erosion are unnecessary. Also, Berman and Rudnicky (2008) did not provide recommendations for shorelines unsuitable for living shoreline techniques. In all cases, the model is only as accurate as the data inputs and the time period for which the data were captured, which hints at the static nature of a living shoreline site suitability decision support tool (Berman and Rudnicky, 2008; Carey, 2013; Boyd and Dutta, 2014).

2.6.3 Approach

Based on six attributes (fetch, bathymetry, presence of marsh, presence of beach, bank condition, and tree canopy) Berman and Rudnicky (2008) categorize the shoreline into three classes: suitable for soft stabilization, suitable for hybrid design, and not suitable for living shoreline application. Layers were reclassified to living shoreline design guidelines which determined into which shoreline stabilization category the site was placed (Table 2-1).

Attribute	Values
Fetch	Low (0-1.0 miles) Moderate (1.0-5.0 miles) High (>5.0 miles)
Bathymetry	1m contour > 10 m from shoreline
Marsh Presence	Present/Absent
Beach Presence	Present/Absent
Bank Condition	High: Observed Erosion Low: No Observed Erosion Undercut: Bank Toe Erosion
Tree Canopy	Present/Absent

Table 2-1. Berman and Rudnicky's (2008) Living Shoreline Site Suitability Design Criteria
Source: Modified from Berman and Rudnicky, 2008

Carey (2013) took a similar approach as Berman and Rudnicky (2008), using unweighted and weighted indices to calculate suitability scores for soft, hybrid, and unsuitable categories. Carey's model did not consider bank condition, tree canopy presence or beach presence, however. Rather, these variables were exchanged with other factors such as boat wakes and SAV (Figure 2-15). His model determined suitability based on wave energy and presence of vegetation.

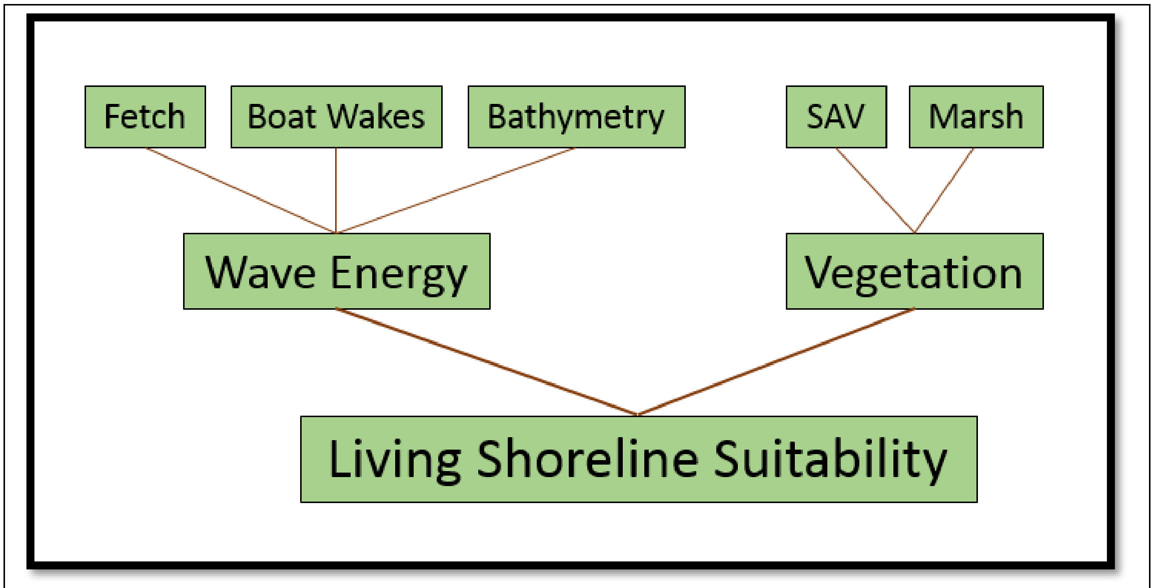


Figure 2-15. Carey's (2013) Living Shoreline Site Suitability Methodology
Source: Modified from Carey, 2013

Boyd and Dutta’s (2014) study was also very similar in data layers and approach to earlier models. Boyd and Dutta (2014) performed a weighted overlay analysis which incorporated bathymetry, shoreline condition, erosion, soil, and fetch and outputted into one of three categories: soft, hybrid, or hard structure/unsuitable. The key geoprocessing technique for all GIS-based site suitability models is the overlay analysis.

2.7 Overlay Analysis

Criteria for a single objective multi-criteria evaluation are either continuous factors or Boolean constraints (Eastman et al., 1993). Continuous factors are criteria scaled to a standardized range and then weighted against all other factors (Eastman et al., 1993). An example of a factor may include something like distance to road in a site suitability analysis for selecting a fast-food restaurant, where the development of a fast-food restaurant is more suitable closer to the road. Boolean constraints are binary criteria that results in either one of two options and is represented by values like 1 and 0 (Eastman et al., 1993). An example of a Boolean constraint in multi-criteria evaluation is presence or absence of flat land in selecting a camping site, where flat land is suitable and land that is not flat is unsuitable.

Chang (2014) explains that the outputs from multi-criteria evaluation may be classified as binary models or index models. Chang (2014) notes that a binary model “uses logical expressions to select target areas from a composite feature layer or multiple rasters” (p.394). A binary model results in either ‘yes or no’, ‘true or false’, or ‘acceptable or unacceptable’. Criteria selection is the most important step in developing a binary model, which is often based on literature review (Change, 2014). A binary model may be vector-based or raster-based. Vector-based binary models combine feature classes by overlay and then queries the composite feature layer based on the aggregate geometries and attributes (Chang, 2014). A raster-based method

requires input rasters (at the same spatial resolution) and allows for more complex calculations (Chang, 2014). Applications of binary models include, most commonly, site selection analysis which is based on well-defined or "crisp" threshold values (Chang, 2014).

An index model is similar to a binary model, but produces an index value (score or rating) for each unit area and a ranked map based on the index values (Chang, 2014, p. 397). Weighted linear combination is a common approach to an index model. Weighted linear combination is a method that "computes the index value for each unit area by summing the products of the standardized value and the weight for each criterion" (Chang, 2014, p. 406). Chang (2014) notes that weighted linear combination index models require evaluation at three distinctive levels: (1) rating the importance of each factor against each other; (2) standardizing the values of each data layer to a common scale (Figure 2-16); and (3) calculating the index value by dividing the summation of weighted values by the summation of the total weights (Figure 2-17) (Chang, 2014). Applications of index models include suitability analysis and vulnerability analysis. Thus, a site selection suitability analysis determines sites on a degree-of-suitability.

$$S_i = \frac{(X_i - X_{min})}{(X_{max} - X_{min})}$$

$$I = \frac{\sum_{i=1}^{n} w_i x_i}{\sum_{i=1}^{n} w_i}$$

Figure 2-16. Standardizing Each Criterion (Left) and Figure 2-17. Index Value Equation (Right): Left – Where S_i is the standardized value of X_i, X_{min} is the lowest original value, and X_{max} is the highest original value; Right – Where I is the index value, n is the number of criteria, w_i is the weight for criterion i, and x_i is the standardized criterion Source: Modified from Chang, 2014

2.8 Role of This Study

This study applies techniques and procedures from previous living shoreline site suitability models, as well as additional methodologies, to determine sites suitable for soft or

hybrid living shoreline design applications along Connecticut's Long Island Sound shoreline. Previous studies focus on index scores to categorize shoreline stabilization methods. This study incorporates Miller et al.'s (2015) living shoreline engineering guidelines to determine site-specific methods – beach enhancement, marsh enhancement, marsh with structures, and offshore breakwaters. Similar in purpose to studies for other regions, the role of this study is to encourage and expand the use of living shoreline treatment options to Connecticut. The final output is a decision-support tool for coastal engineers, decision-makers, and waterfront property owners that considers shoreline armoring alternatives.

Chapter 3: Data and Methodologies

This chapter provides an overview of the data and methods incorporated to generate living shoreline site suitability for the 24 coastal communities of Connecticut. This chapter introduces the study area, provides detailed information on the data inputs, and presents the scripting for reclassification and the overlay analysis. This chapter also highlights two methods for measuring shoreline distances: which will be defined as the "transect intersect method" and the "clip method." Methods incorporated in this chapter are adjustments from the living shoreline site suitability models by Carey (2013) and Berman and Rudnicky (2008). There are four living shoreline design techniques created from this model: beach enhancement, marsh enhancement, marsh with structures, and offshore breakwaters. Outputs are in raster-format at 3-foot spatial resolution. ArcGIS 10.2 was used for data processing, data creation, and overall model development. The Python programming language was used to automate geoprocessing tasks including, but not limited to, reclassifying and overlaying input layers to produce site suitability outputs.

3.1 General Methodology

Similar to Carey (2013), living shoreline site suitability in this study is considered to be a function of wave energy and presence of vegetation. Areas that have low to moderate wave energy with potential for vegetation growth are more suitable for living shoreline designs. Sites that experience high wave energy and more significant erosion rates may not be suitable for a living shoreline stabilization technique. There are five layers considered in the living shoreline site suitability analysis which are fetch, erosion, bathymetry, presence of beach, and presence of marsh. All layers were processed to a common data format, value, and scale on a town-by-town

basis to better manage processing time. Once layers were pre-processed, data inputs were clipped to each town's study area to limit further processing time and produce manageable file sizes. After clipping to the study area, layers were reclassified to threshold values established in the living shoreline site suitability literature. The resulting outputs from the multi-criteria evaluation include both soft and hybrid living shoreline designs (Figure 3-1).

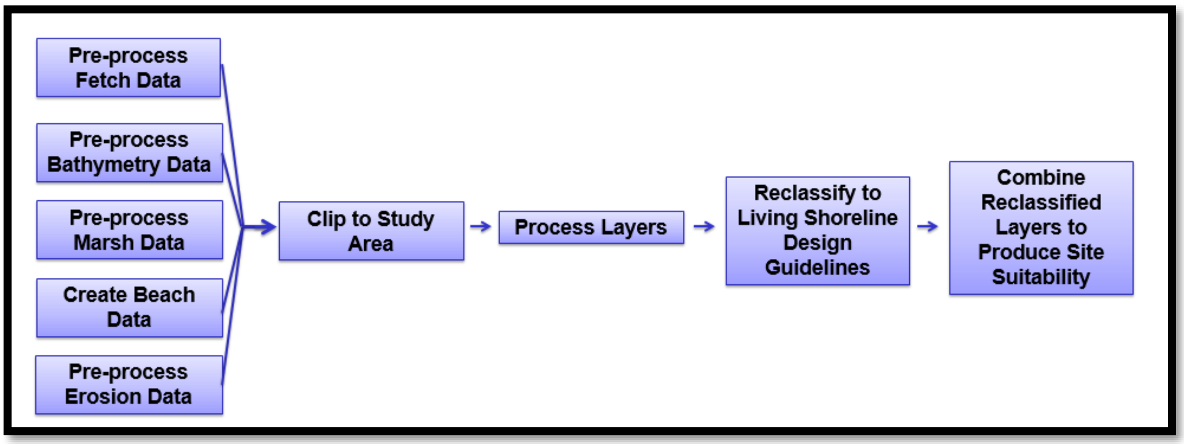


Figure 3-1. Living Shoreline General Methodology

3.2 Study Area

The study area is a 300-foot buffer, in both seaward and landward directions from the shoreline, for each of the 24 coastal town shorelines adjacent to Long Island Sound for Connecticut. The 24 towns included in analysis, from west to east, are Greenwich, Stamford, Darien, Norwalk, Westport, Fairfield, Bridgeport, Stratford, Milford, West Haven, New Haven, East Haven, Branford, Guilford, Madison, Clinton, Westbrook, Old Saybrook, Old Lyme, East Lyme, Waterford, New London, Groton, and Stonington (Figure 3-2).

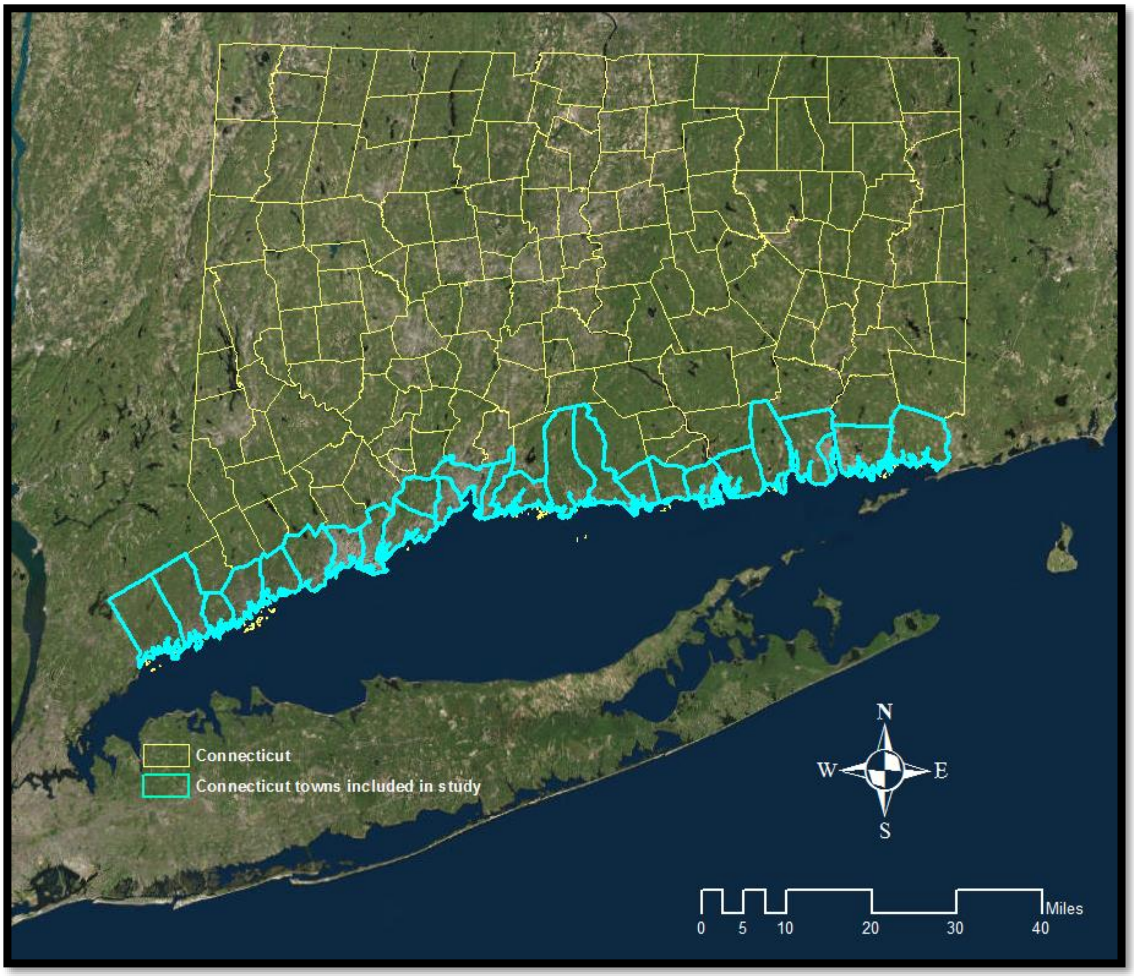


Figure 3-2. Coastal Towns Included in Living Shoreline Site Suitability Analysis
Source: Modified from CT DEEP; Esri background imagery

The town boundaries were acquired from the Connecticut town polygon shapefile on the Connecticut Department of Energy and Environmental Protection's (DEEP) *GIS Data* download page[1]. Once the Connecticut town polygon shapefile was acquired, data were checked to ensure that they were projected in the 1983 North American Datum (NAD) Connecticut State Plane US Feet coordinate system, the coordinate system for all data in this study. Next, the 24 coastal towns were selected by the attribute "TOWN" and exported to create a new shapefile named "Connecticut coastal towns."

[1] http://www.ct.gov/deep/cwp/view.asp?a=2698&q=322898&deepNav_GID=1707%20

In the Connecticut coastal towns layer, there was an attribute called “COAST_POLY” which indicated whether the polygon was an inland or island polygon. There were 640 records attributed to “COAST_POLY” type. However, in this study, only inland polygons and island polygons that had road access to inland features were included in deriving the final study area. Also, small barrier islands were included because these islands have the ability to attenuate wave energy depending on their orientation to the shoreline. In the end, 120 of the 640 polygons were kept in the Connecticut coastal towns shapefile. Using the “Dissolve” ArcGIS tool, the 120 island and inland polygons were aggregated by “TOWN” to produce 24 distinct town boundaries.

The dissolved Connecticut coastal towns layer was then converted to a polyline feature using the “Feature to Line” tool and named “Connecticut coastal line”. This polyline output represented the outline for each of the 24 town boundaries. Town boundaries that were not directly adjacent to the coastline in the Connecticut coastal line polyline feature class were removed. This edited polyline feature class represented the coastline for each town. Next, the coastline was buffered 300 feet, both seaward and landward, using the “Buffer” tool, and a new shapefile was generated for each of the 24 buffered towns. Smaller inlets and tributaries were removed from each town buffer using the “Editor” tool because this study focuses primarily on shoreline adjacent to Long Island Sound. The final edited buffer represents the study area in this analysis. Figure 3-3 shows an example of the shoreline buffer.

Figure 3-3. Study Area, in Teal, along Fenwick Point, Old Saybrook, CT
Source: Study area draped over 2012 orthoimagery

3.3 Fetch

Fetch is the unobstructed distance that wind can travel over open water in any given direction. In sheltered coasts, wave energy is limited by fetch. Therefore, the higher the fetch exposure is, the greater the wave energy generated from the wind will be. Fetch exposure was calculated using the United States Geological Survey (USGS) *Wind Fetch Model for Habitat Rehabilitation and Enhancement Projects* (Rohweder et al., 2012). The wind fetch model is an ArcGIS tool that requires ArcGIS 10.x and a Spatial Analyst license.

The wind fetch tool requires two inputs. First, it requires a land cover raster where land is aggregated to one class and given a value greater than 0 while water is given a value equal to 0. Rohweder et al. (2012) explain that water not completely surrounded by land pixels results in

unbounded fetch, which are artifacts from the tool. Spatial scale from the reclassified land raster plays an important role in processing time and file size (Rohweder et al., 2012). The finer the spatial resolution of the land cover raster, the longer the processing time and the larger the files produced. Second, the wind fetch tool requires a comma delimited text file that contains wind directions and percentages from that direction. Wind direction is measured in azimuthal degrees, where 0 degrees is due north. When calculating fetch from the wind frequency distributions, the percentages must sum to 100 (Rohweder et al., 2012).

The wind fetch tool calculates a weighted fetch based on the recommended methodology from the USACE (1984) *Shore Protection Manual* (SPM). The SPM calculation method "spreads nine radials around the desired wind direction at three-degree increments" where "the resultant wind fetch is the arithmetic mean of these nine radial measurements" (Rohweder et al., 2012, p. 7) (Figure 3-4). This tool ignores nearshore processes such as shoaling, breaking, reflection, refraction, and diffraction (Rohweder et al., 2012).

Figure 3-4. Wind Fetch Model *Shore Protection Manual (1984)* Method
Source: Modified from Rohweder et al., 2012

3.3.1 Data

Land cover data were acquired from the Center for Land Use Education and Research (CLEAR) Connecticut's Changing Landscape (CCL) project[2]. The CCL project land cover imagery were derived from 30 meter Landsat imagery and the spatial resolution of the resulting land cover are 100 feet. Once 2010 land cover data were acquired from CLEAR's CCL data download page, the data were reclassified so that water was 0 and all other classes were 1.

Wind information was acquired from NOAA's National Data Buoy Center (NDBC). A 10-year climatology for wind frequency distributions between 2005 and 2014 was produced for Buoy 44039 – the Central Long Island Sound Buoy. Data were used from this buoy and not for other buoys or land stations because this buoy is most centrally-located in Long Island Sound, which may better represent wind conditions for Long Island Sound. In order to produce a wind rose climatology, the standard meteorological text files from 2005 to 2014 for Buoy 44039 were imported into Microsoft Excel using the "Text Import Wizard." Records were separated into two columns: date and "WDIR." WDIR is the ten-minute average wind direction measurements in degrees clockwise from true north. Next, a "PivotTable" was created for each year that determined which percentage of time wind came from any given direction. An "IF" statement was assigned to each wind direction to a related point on a 16-point cardinal compass. This process was repeated for each year from 2005 to 2014 and a final 10-year average wind frequency distribution was produced from these data. The climatology reveals that wind for central Long Island Sound comes from a westerly direction more often than from an easterly direction (Figure 3-5).

[2] http://clear.uconn.edu/projects/landscape/index.htm

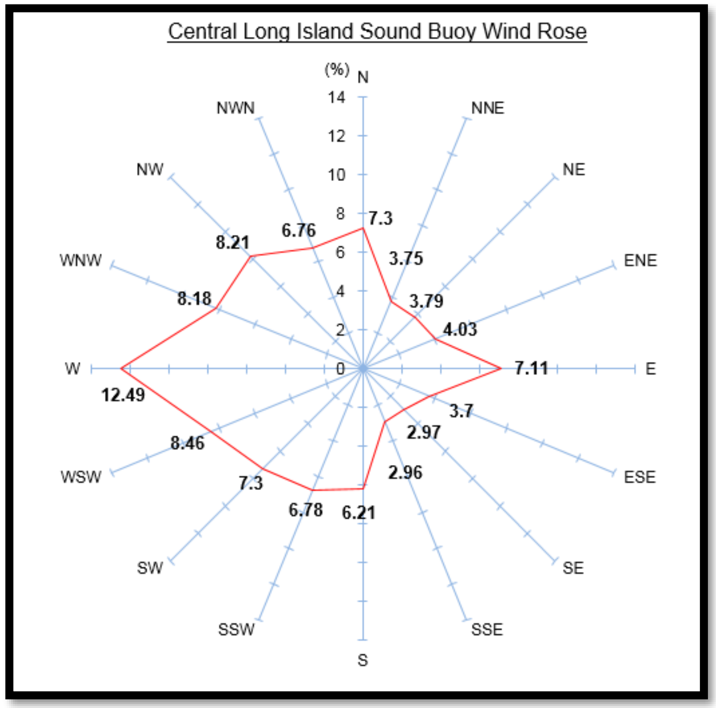


Figure 3-5. 10-Year Climatology for Central Long Island Sound Station 44039

3.3.2 Methods

Once the wind data and land cover data were prepared, the wind fetch tool was initiated to calculate fetch for Long Island Sound (Figure 3-6).

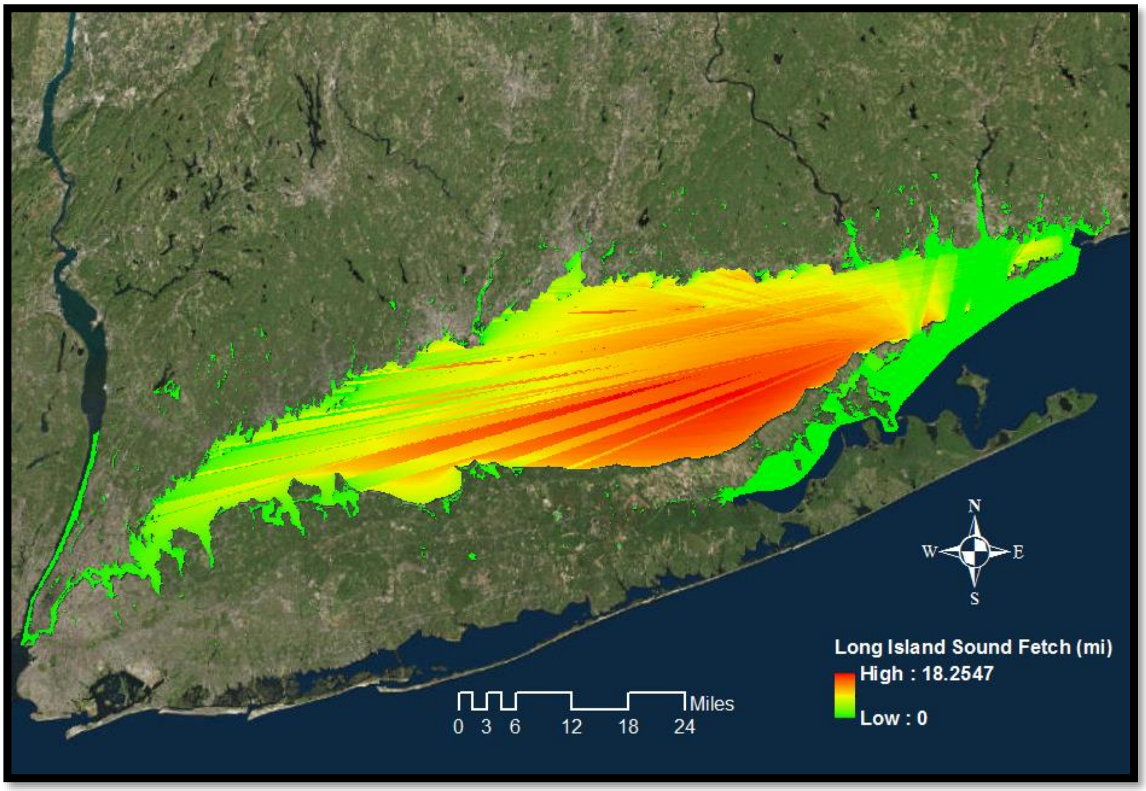


Figure 3-6. Long Island Sound Fetch
Source: Output from USGS fetch tool based on historic Long Island Sound wind data

There were a couple issues incorporating fetch into the site suitability analysis. The first was there were negative fetch values in the resulting fetch output. As mentioned in Rohweder et al. (2012), negative fetch values are artifacts of the fetch model. These values were removed from the fetch raster. Second, fetch is a water-based layer whereas other data inputs (presence of beach and marsh) are land-based. All layers in an overlay analysis must overlay to successfully perform a site selection analysis. Therefore, pixels from the fetch raster had to be shifted over-land. This was accomplished by interpolating fetch landward.

There were a few steps involved to interpolate a fetch surface over the study area. First, the “Raster Calculator” tool was used to convert the fetch output values from feet into miles by dividing the fetch pixel values by 5280 feet. Next, all fetch values along each town’s study area were extracted using the “Extract by Mask” tool, then, the raster was converted to points using

the “Raster to Point” tool. These points were used in a spatial interpolation along the entire study area using the “IDW” Spatial Analyst tool based on the fetch values at 3-foot spatial resolution. IDW – Inverse Distance Weighted – is “an exact method that enforces the condition that the estimated value of a point is influenced more by nearby known points than by those farther away” (Chang, 2014, p. 322). All predicted values from an IDW interpolation are within the maximum and minimum values of the known points. Once interpolated, the continuous surface was smoothed using the “Focal Statistics” low-pass filter (Figure 3-7). Data were then ready to be classified based on the living shoreline engineering guidelines.

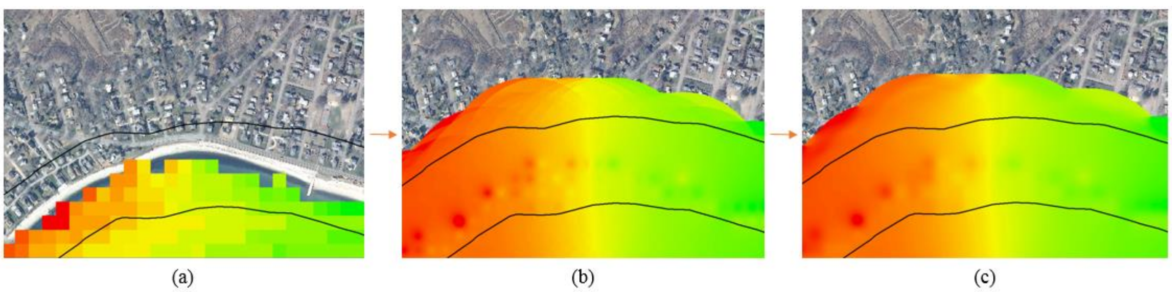


Figure 3-7. Fetch Interpolation along Study Area: Interpolating fetch grid (a) along the study area using IDW (b) and smoothing (c) with Focal Statistics, where green is lower fetch exposure and red is high

3.4 Erosion History

Erosion rates play an important role in living shoreline site suitability. Lower trends in erosion are locations suitable for living shorelines, whereas higher erosion rates indicate sites unsuitable for living shorelines and may require further action to protect property. Erosion data for Connecticut were acquired from the *Analysis of Shoreline Change in Connecticut* (O’Brien et al., 2014). O’Brien et al. (2014) performed a GIS-based time-series analysis on short-term and long-term trends in erosion history between 1880 and 2006 for Connecticut's shoreline using digitized shorelines and orthoimagery. Transects for historical shoreline data were created using

the USGS Digital Shoreline Analysis Software (DSAS) for ArcGIS 10.x (O'Brien et al., 2014). The short-term "End Point Rates" (EPR), which represent the net movement in shoreline between two time periods –1983 and 2006 – were used in the site suitability analysis. The short-term trends were preferred for this study because short-term erosion is a more accurate proxy for storm-induced erosion (O'Brien et al., 2014). Accretion and erosion trends from O'Brien et al. (2014) refer to horizontal movement of the shoreline, as opposed to vertical movement. There are a couple of caveats associated with these data. First, the data are intended to identify historic trends in accretion and erosion, not provide absolute certainty on changes in erosion at any given site (O'Brien et al., 2014). Secondly, it does not explain the cause of erosion at any site. Therefore, fill sites which are historically more vulnerable to erosion were not labeled as fill (See Figure 2-1).

3.4.1 Data and Methods

Data from the *Analysis of Shoreline Change in Connecticut* are point shapefile layers (Figure 3-8). The Connecticut short-term (1983-2006) shoreline change point shapefile feature class was clipped to each town's study area (Figure 3-8). Next, a new attribute field was added in each town's erosion point shapefile that converted the EPR attribute from meters to feet because this study is done in Connecticut State Plane feet. Also, if the value was 1 in the "omit" attribute field, these attributes were removed from the point shapefiles. A value of 1 represents industrialized waterfront, which were areas omitted from rate-based erosion assessments in O'Brien et al.'s (2014) study.

Figure 3-8. Short-Term (1983-2006) Shoreline Change Point Shapefile at Old Saybrook, CT
Source: Modified from O'Brien et al. (2014) draped over 2012 orthoimagery

Although O'Brien et al. (2014) provide a comprehensive data source for erosion and accretion trends in Connecticut, data in areas along sheltered bodies of water such as coves and tributaries were not included in their study, as their report focused on Long Island Sound shoreline. O'Brien et al. (2014) assume that these bodies of water were low wave energy, so erosion was likely to be negligible at these locations. However, some of these sheltered bodies of water were included in the living shoreline site suitability study area, so data had to be provided for these locations. Connecticut historical aerial photographs from University of Connecticut Libraries' MAGIC[3] (Map and Geographic Information Center) was reviewed at these locations

[3] http://magic.lib.uconn.edu/connecticut_data.html#apindex1985

for 1985-1986 and 2006. These time periods represent approximately the same time period for short-term erosion rates generated by O'Brien et al. (2014). If there was a high level of user-based certainty that erosional forces at these natural sites were low or negligible, then data were appended along the shoreline at these locations.

Similar in approach to the fetch pre-processing, erosion data had to be interpolated along the study area. The IDW interpolation method was used to produce a continuous erosion surface, along the study area. Next the surface was smoothed using the "Focal Statistics" mean function (Figure 3-9). The erosion data were, then, ready to be classified, according to the living shoreline design thresholds.

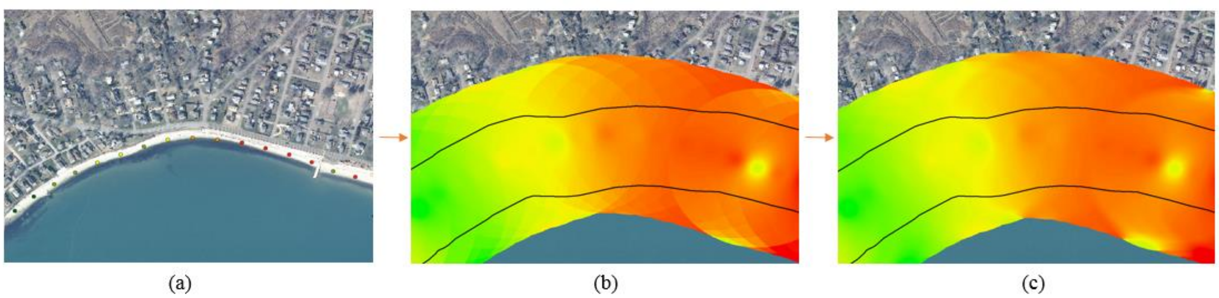


Figure 3-9 Erosion Interpolation along Study Area: Interpolating erosion points (a) along the study area using IDW (b) and smoothing (c) with Focal Statistics, where red is erosion and green is accretion

3.5 Bathymetry

Bathymetry refers to underwater topography. Sites that are shallow and have a more gradual nearshore slope are more suitable for living shoreline design options. Bathymetric data were acquired from Connecticut DEEP's *GIS Data* download page[4]. The bathymetric data are a contour dataset, measured in meters, developed from NOAA bathymetry and USGS topographic-bathymetric maps (Figure 3-10).

[4] http://www.ct.gov/deep/cwp/view.asp?a=2698&q=322898&deepNav_GID=1707%20

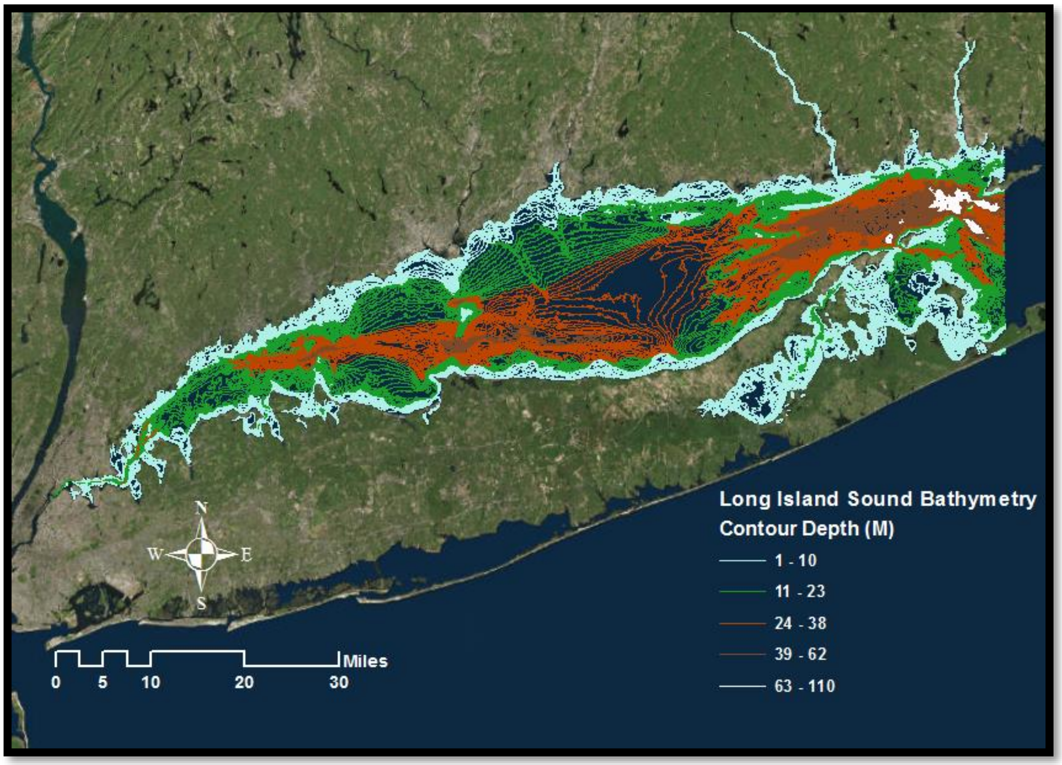


Figure 3-10. Long Island Sound Bathymetry Contours
Source: NOAA Long Island Sound "T-sheets" bathymetric contours draped over Esri background imagery

Pre-processing was also required to convert the contour dataset to a raster grid. First, the MHW line from NOAA's Continually Updated Shoreline Product (CUSP) was appended into the bathymetric contour dataset. The MHW received a value of 0 within the bathymetry layer, which represented the shoreline. Next, each town's study area was buffered 0.5 mi and all contour lines were clipped along this enlarged study area using the "Clip" Analysis tool. The bathymetry captured within this half-mile range represents the nearshore bathymetry. The "Topo to Raster" Spatial Analyst tool was used to create a hydrologically-correct raster surface from the bathymetric dataset (Figure 3-11). This process was done on a town-by-town basis to limit processing time.

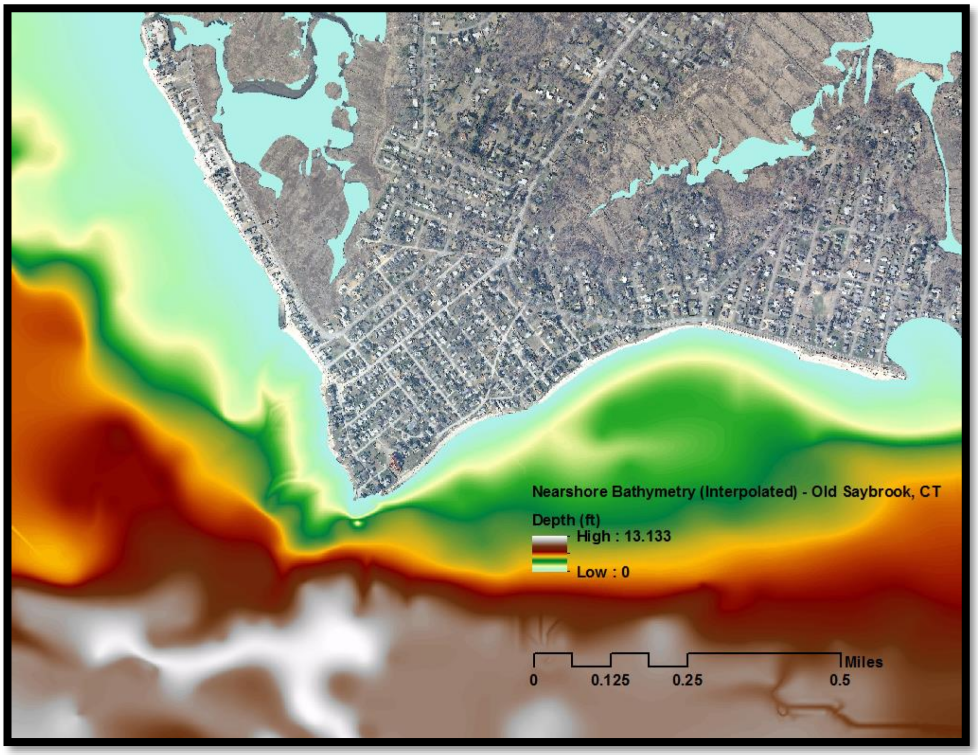
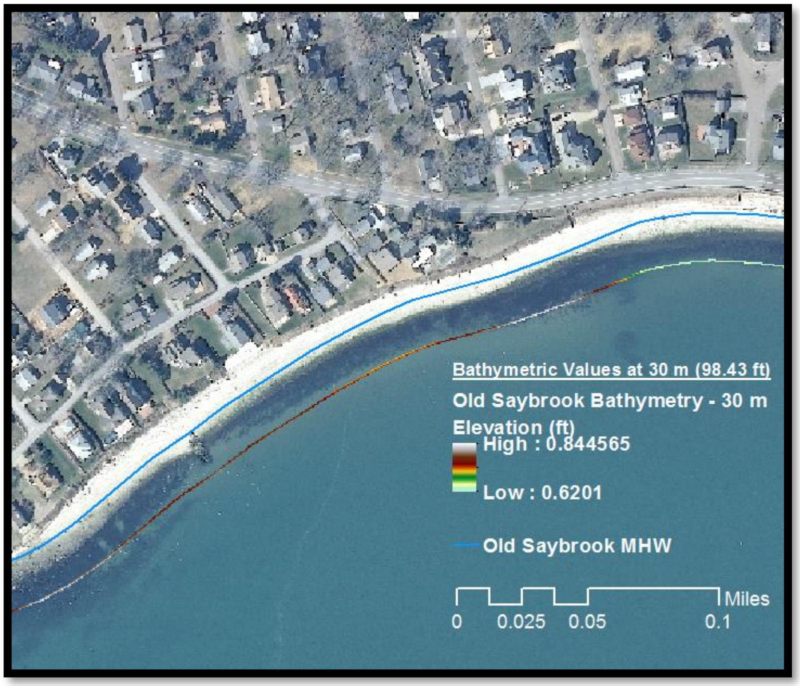


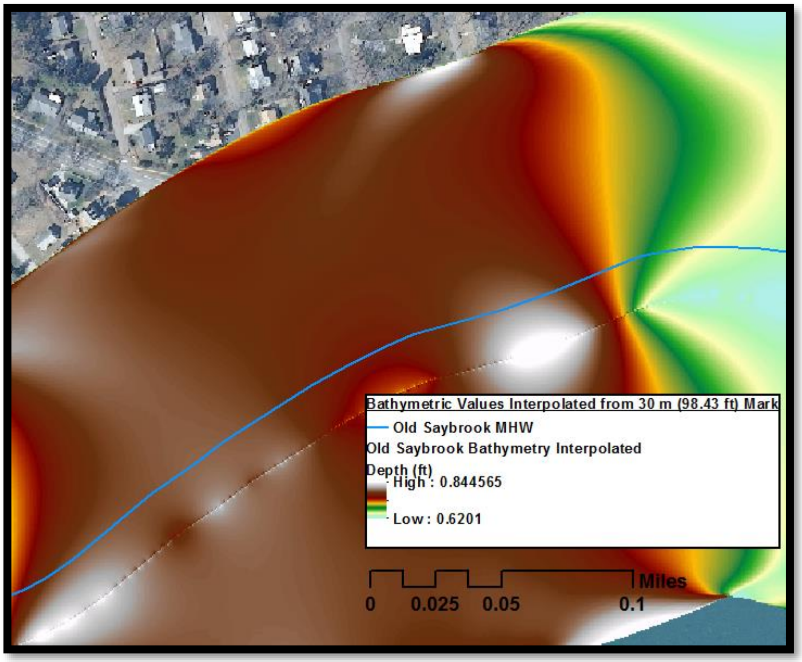
Figure 3-11. Old Saybrook Nearshore Bathymetry Interpolated
Source: Output from "Topo to Raster" interpolation based on NOAA 1-m contour dataset and NOAA CUSP dataset draped over 2012 orthoimagery

Once the nearshore bathymetry was represented in raster format, additional processing was required to shift the water-based layer landward, which follows the same approach as the fetch and erosion layers. First, the NOAA CUSP polyline was buffered 30 m (98.43 ft). Next, using the "Extract by Mask" function, all bathymetric cells along the 30-m buffered shoreline were extracted. This is because living shorelines are suitable where the 1-m contour is greater than 30 m from the shoreline (Miller et al., 2015). Therefore, bathymetry depths equal to or less than 1 m at the 30-m mark are suitable for a living shoreline design. So, bathymetric values along the 30-m mark were selected to determine if underwater topography was shallow enough for a living shoreline design. Next, the bathymetry cells were converted to points with the "Raster to Point" tool and interpolated based on elevation value (ft) using the "IDW" Spatial

Analyst method. The resulting data were ready to be classified according to living shoreline engineering guidelines (Figure 3-12).



(a)



(b)

Figure 3-12. Bathymetry Interpolated to 1 on 30 Gradient: Elevation values extracted 30 m from shoreline (a) and subsequent interpolation (b) from values at 30-m mark using IDW

3.6 Marsh

Marsh is a proxy for vegetation in living shoreline site suitability. The best indicator of where tidal marsh vegetation can grow is where it is already present. In terms of living shoreline design, marsh has the capability to attenuate wave energy, and stabilize sediment, thereby limiting erosion. Marsh data were acquired from Hoover's (2009) *Connecticut's changing salt marshes: A remote sensing approach to sea level rise and possible salt migration* (Figure 3-13). The four classes of marsh from Hoover's research (Low Marsh, High Marsh, *Iva frutescens*, and *Phragmites australis*) were aggregated together and resampled from 2-foot resolution to 3-foot resolution to match resolution of other layers used in site selection.

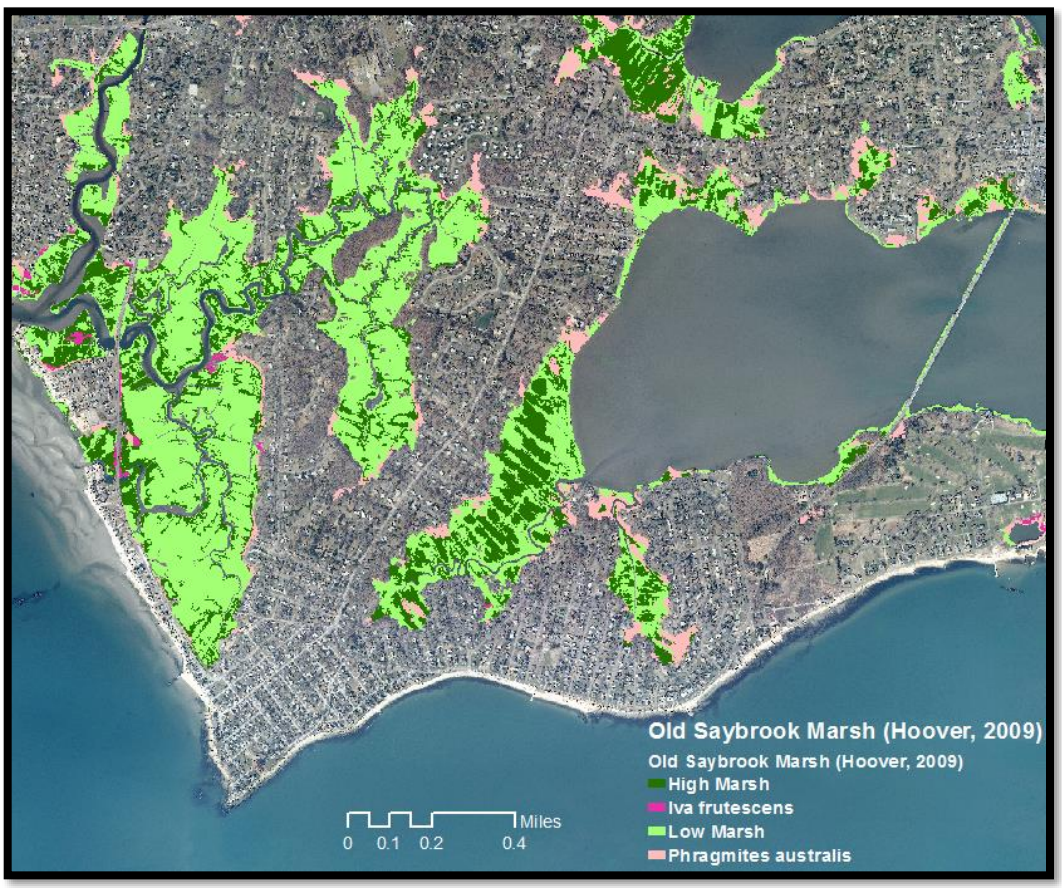


Figure 3-13. Coastal Marsh Data at Old Saybrook, CT
Source: Hoover, 2009 draped over 2012 orthoimagery

Once marsh data were aggregated to one class, marsh within 25 feet of the MHW shoreline were selected. To accomplish this task, the NOAA CUSP dataset was buffered 25 feet in each direction, and the “Clip” Data Management tool was used to select a subset of the marsh raster within that 25 foot buffer (Figure 3-14). Marsh was only selected within this specified distance to distinguish between marshes at the eroding edge of a shoreline as opposed to wetlands farther inland.

Figure 3-14. Old Saybrook Wetlands within 25 ft of MHW Shore
Source: Modified from Hoover, 2009 draped over 2012 orthoimagery

3.7 Beach

Presence of beach indicates sites suitable for beach nourishment and dune restoration designs. In order to produce a highly detailed beach layer for Connecticut, beach was manually digitized using an “on-screen digitizing” method. Chang (2014) defines on-screen digitizing as

“manual digitizing on the computer monitor using a data source such as Google Maps or DOQ as the background” (105). Using 2012 orthoimagery from Connecticut Environmental Conditions Online (CT ECO) “app3” GIS Server[5] as the backdrop and the NOAA CUSP as the MHW shoreline, a beach layer was created for each of the 24 coastal communities drawn at an average scale between 1:200 and 1:500. Beaches were drawn landward of the MHW shoreline. Sandy and rocky beaches are both included in this beach layer. Once the shapefiles were created, they were converted to raster format using the “Raster to Polygon” tool and resulting rasters were output at 3-foot spatial resolution (Figure 3-15).

Figure 3-15. Old Saybrook Beaches Digitized
Source: On-screen digitized in ArcMap 10.2 using 2012 orthoimagery and NOAA CUSP dataset

[5] http://www.ctecoapp3.uconn.edu/arcgis/rest/services/images/ortho_2012/ImageServer

3.8 Reclassification

After the five input layers were pre-processed to 3-foot raster grids, each of the criteria were classified to living shoreline threshold values established from the literature (Table 3-1). Continuous values for the input layers were classified between 1 and 0. A criterion such as presence of beach and marsh is considered a Boolean constraint and were given values of 1 where present and 0 where absent. Areas where bathymetry is shallow are necessary for living shoreline designs, so it is considered a constraint and received a value of 1 where shallow and 0 where not shallow. Erosion rates and fetch are factors and were scaled to a standardized range of values of 1, 0.7, 0.3, and 0, where a value of 1 represents most suitable, 0.7 represents areas moderately suitable, 0.3 has low suitability, and 0 is unsuitable. A value of 0 in the erosion raster may refer to areas missing data where the interpolation could not produce results or areas classified as industrialized waterfront by O'Brien et al (2014). A value of 0 in the fetch raster are areas where the fetch tool produced unbounded fetch or negative fetch values, which are artifacts from the fetch model where water is not completely enclosed by land pixels.

Each criterion was reclassified using Python's "RasterToNumPyArray" function (Appendices A-E). Data were converted from raster format to a numpy array where data were categorized by reclassification value. After data were characterized based on the array value, the array was converted back to raster format and saved to be combined in the multi-criteria evaluation.

Attribute	Category	Reclassification Value
Fetch	Low (0-1.0 miles) Moderate (1.0-5.0 miles) High (>5.0 miles)	Low = 1 Moderate = 0.7 High = 0.3 Unsuitable = 0
Rate of Erosion	Low (<2 feet per year) Moderate (2-4 feet per year) High (>4 feet per year)	Low = 1 Moderate = 0.7 High = 0.3 Unsuitable = 0
Bathymetry	1-m contour > 30m from the shoreline	Shallow = 1 Not Shallow = 0
Marsh Presence	Present within 25 feet of MHW Absent within 25 feet of MHW	Present = 1 Absent = 0
Beach Presence	Present Absent	Present = 1 Absent = 0

Table 3-1. Living Shoreline Reclassification Table
Source: Adjustments from Berman and Rudnicky, 2008; Carey, 2013; Miller et al., 2015

3.9 Site Suitability Analysis

One Python script was used to combine reclassified layers and produce soft and hybrid living shoreline outputs (Appendix F) (Table3-2). Beach enhancement and marsh enhancement are soft, nature-based approaches to mitigate erosion. Sites deemed suitable for beach enhancement and marsh enhancement contain existing beach or marsh, respectively, and are areas that experience low fetch exposure and low rates of erosion. Marsh with structures and offshore breakwaters refer to hybrid design options that include engineered structures to provide higher levels of protection and erosion control. Marsh with structures requires presence of existing marsh while offshore breakwaters requires presence of beach. Both hybrid designs experience moderate to high fetch exposure and low to high erosion. All living shoreline designs must adhere to bathymetric readings where the 1-m contour is greater than 30 m from the shoreline. If the depth is shallower than this threshold below 30 m, then it is suitable for living shoreline designs.

Attribute	Beach Enhancement	Marsh Enhancement	Marsh with Structures	Offshore Breakwaters
Fetch	Low	Low	Moderate – High	Moderate – High
Rate of Erosion	Low	Low	Low – High	Low – High
Bathymetry	Shallow	Shallow	Shallow	Shallow
Marsh Presence	---	Present	Present	---
Beach Presence	Present	---	---	Present

Table 3-2. Living Shoreline Design Output Table
Source: Adjustments from Berman and Rudnicky, 2008; Carey, 2013; Miller et al., 2015

There were several steps in manipulating the reclassified criteria to produce site suitability (Figure 3-16). First, constraints (bathymetry, marsh and beach) were multiplied by each other to produce a combined constraints layer. Then, factors (erosion and fetch) were standardized by an equal weight and added together to produce a combined factors layer. The combined factors and combined constraints were multiplied by each other which generated a suitability rating, and then the 1 and 0 values were extracted from the suitability rating to produce binary results. These binary results represent each of the four living shoreline design techniques.

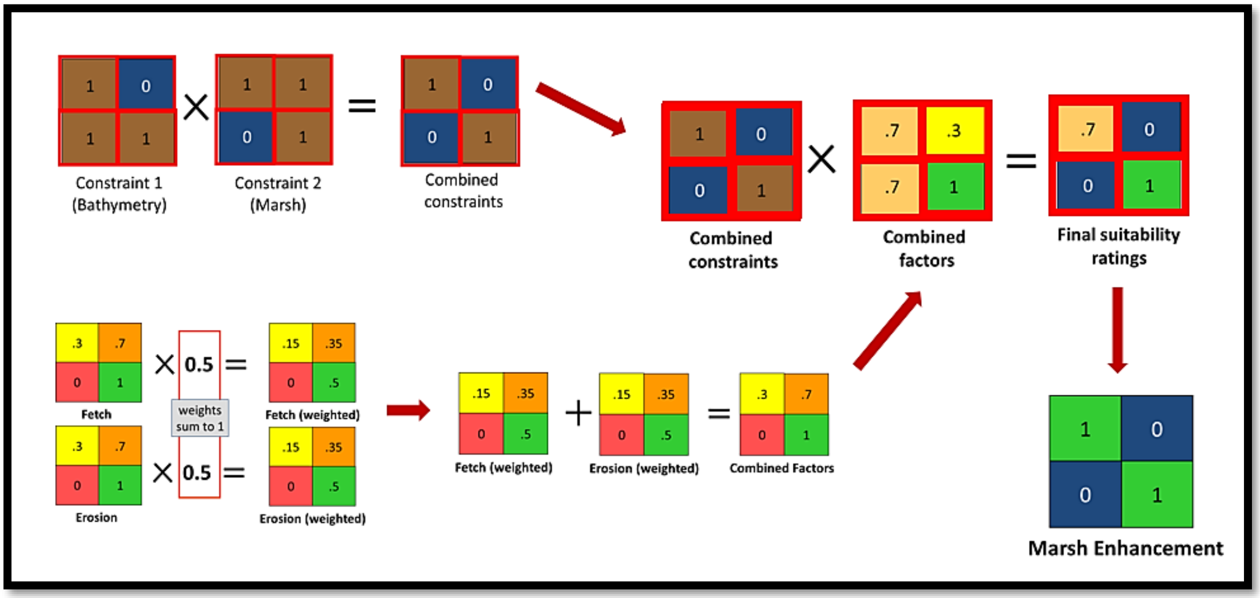


Figure 3-16. Marsh Enhancement Raster Procedure

3.10 Transect Intersect Method

Once living shoreline results were generated for the entire Connecticut coastline, the transect intersect method was established to measure the length of shoreline suitable for each of the living shoreline output methods, as well as the bathymetry, marsh, and beach data input layers. This method converts the NOAA CUSP MHW polyline to perpendicular transects and counts the number of transects that intersect the feature class (which represents an approximation of shoreline length for that feature class). This methodology was established to avoid issues where the raster layers could not be extracted along the MHW polyline due to the different spatial accuracies between polyline features and raster layers (Figure 3-17). The MHW polyline, therefore, could not be used to "Extract by Mask" the length of the raster along the polyline feature, hence the transect intersect method was established.

Figure 3-17. Extract by Mask Shoreline Length Complication: The beach enhancement living shoreline output produced at 3-foot resolution does not fully align with the MHW polyline – Notice the small gaps between the red line and green polygon
Source: Beach enhancement living shoreline output and NOAA CUSP polyline draped over Esri's background imagery

3.10.1 Methods

First, all reclassified input data layers and living shoreline site suitability outputs were converted from raster format to shapefile feature classes using the "Raster to Polygon" Conversion tool. Next, perpendicular transects were created from each town's NOAA CUSP MHW shoreline using a transect tool available freely online (Ferreira, 2014). Transects were spaced every three feet, which represents the pixel size of the original raster output, and were extended 25 feet in each direction (Figure 3-18).

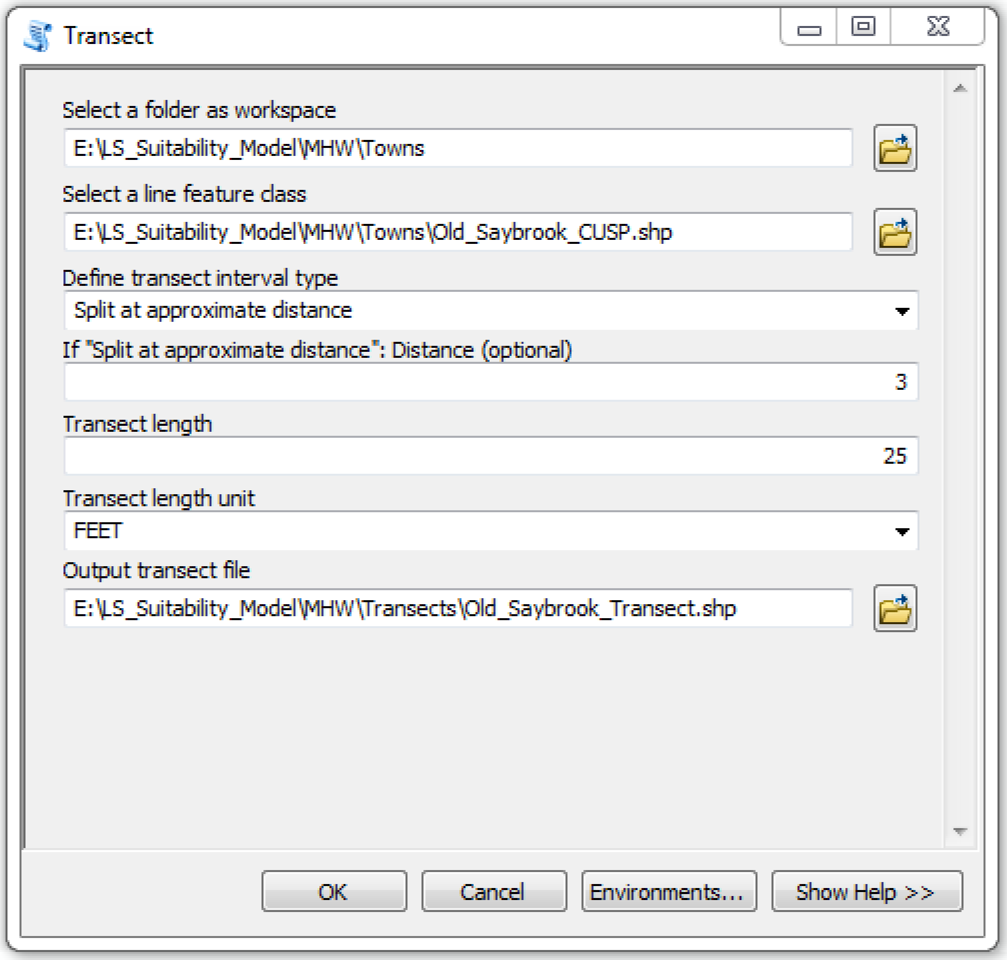


Figure 3-18. Perpendicular Transect Tool
Source: Ferreira, 2014

Once perpendicular transects were created, the shapefile living shoreline output was intersected with the perpendicular transect feature class using the “Intersect” Analysis tool. The intersected transects were summed and multiplied by three. Since transects were spaced every three feet, this calculation represents the shoreline length in feet of that living shoreline output (Figure 3-19).

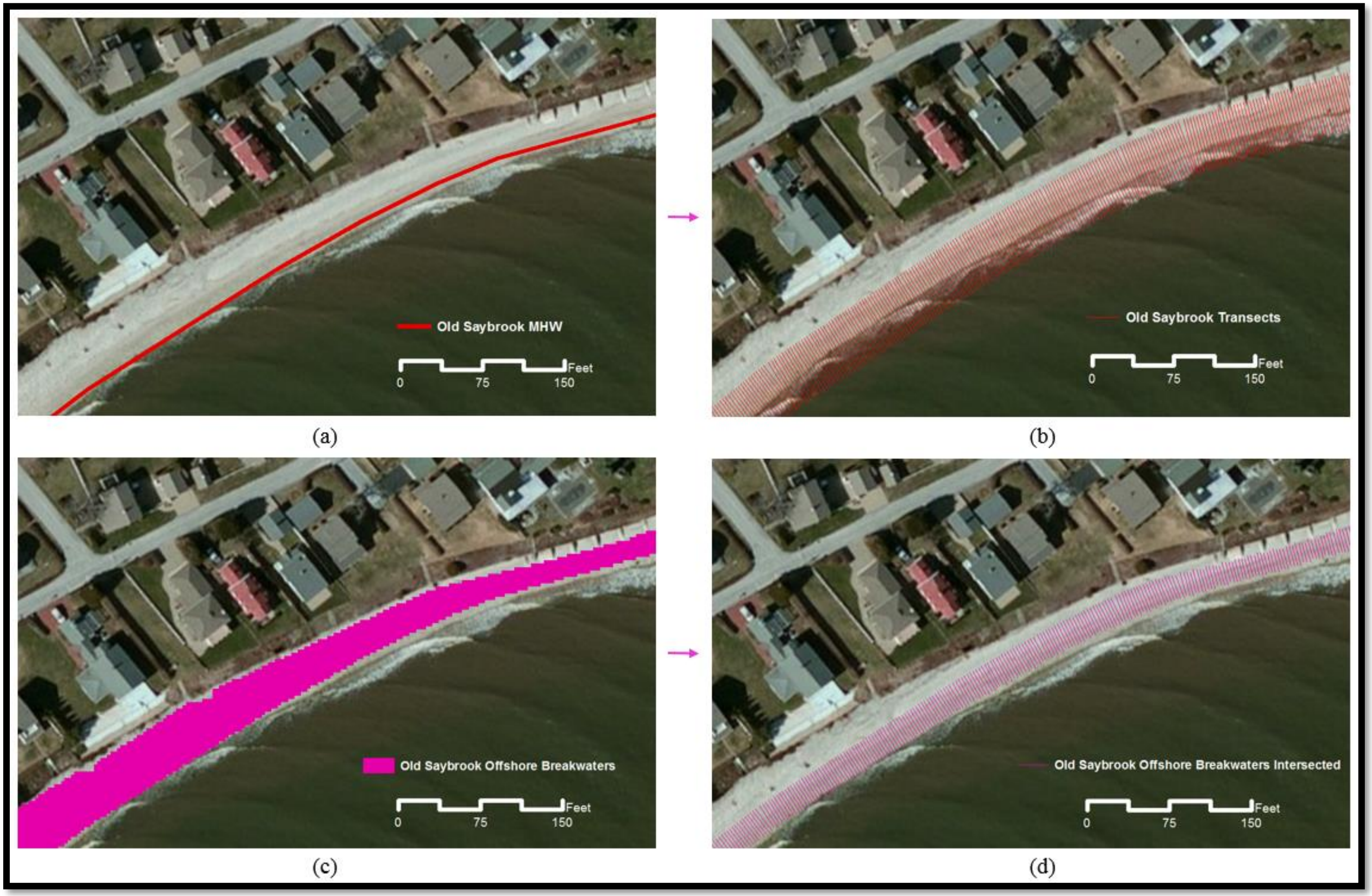


Figure 3-19. Representing Shoreline Length via Transect Intersect Method: Converting NOAA CUSP MHW (a) to perpendicular transects (b) and intersecting living shoreline output (c) with transects (d)
Source: NOAA CUSP dataset and living shoreline outputs draped over Esri background imagery

The transect intersect method is an accurate approximation to calculate shoreline length for binary shapefiles. However, the transect tool creates overlap where there were extreme curvatures (bends) in the NOAA CUSP dataset. These sharp bends are primarily caused by hard shoreline structures such as seawalls, jetties, and groins that shift orientation quickly over short distances. Although these areas are not the focus of this study, they caused overlap in the transect output, which results in inaccurate calculations for these problematic areas (Figure 3-20). This problem was exacerbated for scaled factors such as fetch and erosion and a separate methodology was created to address this issue for those layers.

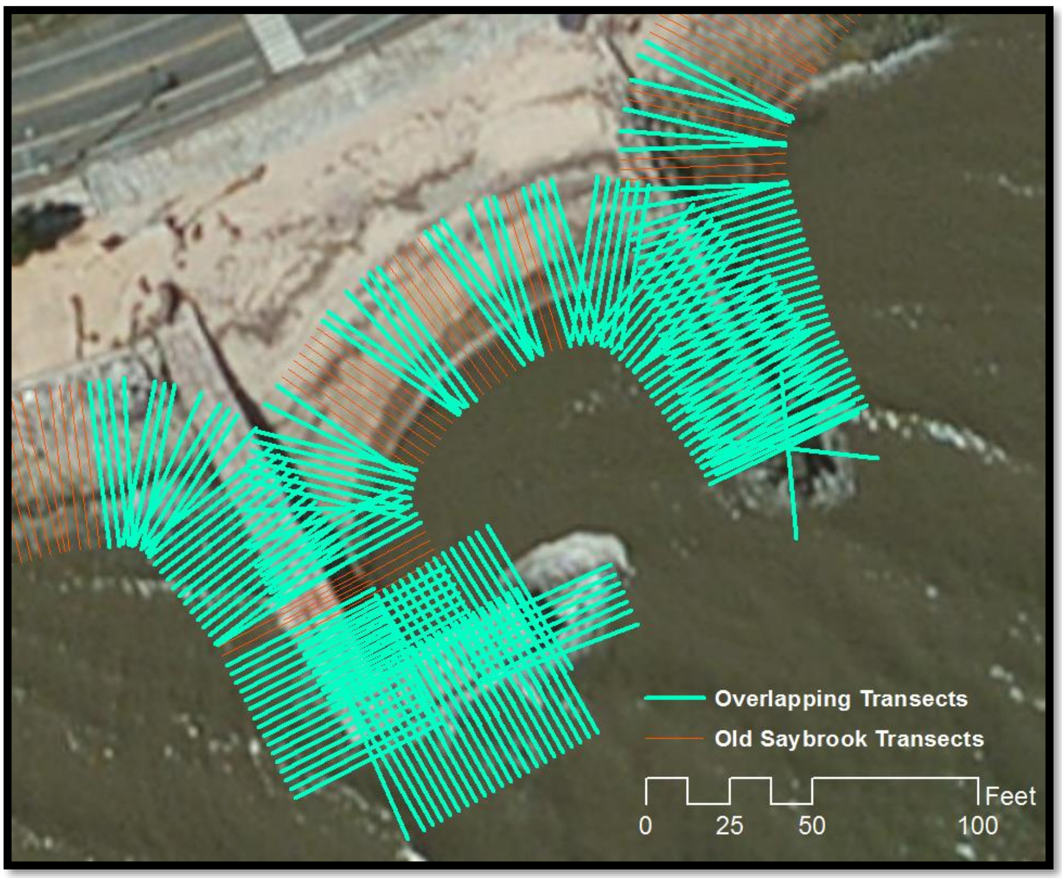


Figure 3-20. Overlapping Transects
Source: Transect output draped over Esri background imagery

3.11 Clip Method

The clip method was established to calculate shoreline distance for the erosion and fetch reclassified raster layers. The clip method is a much more direct method for measuring shoreline length where each town's NOAA CUSP MHW shoreline is clipped to the erosion and fetch shapefile outputs via the "Clip" Analysis tool and, then, the clipped shoreline segments are summed (Figure 3-21). The summed shoreline represents the length of shoreline per town suitable for the erosion and fetch reclassified layers.

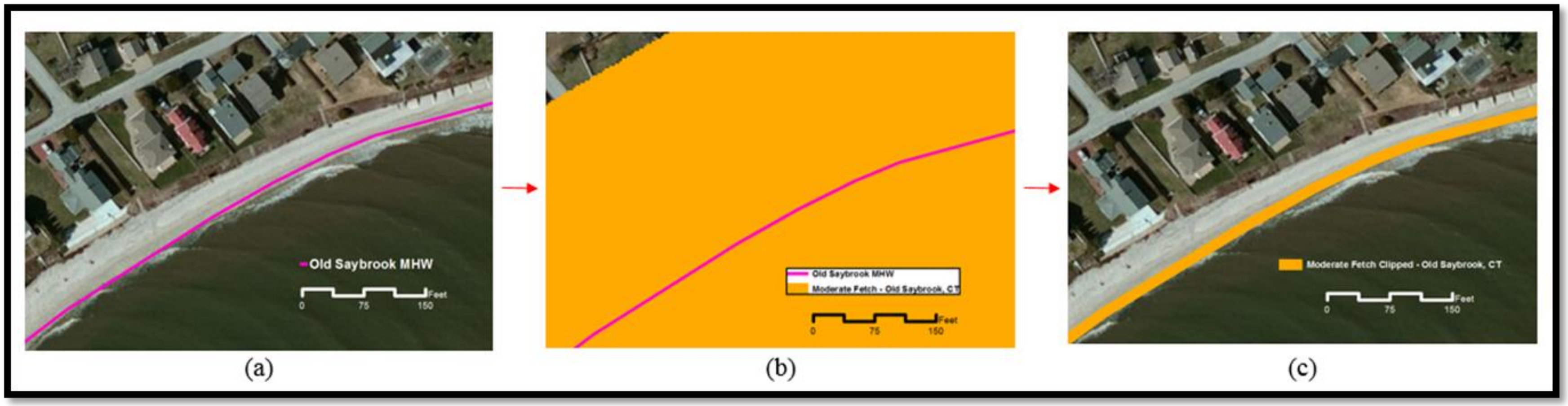


Figure 3-21. Representing Shoreline Length via Clip Method: NOAA CUSP MHW polyline (a) along moderate erosion (b) and resulting clipped shoreline length output (c)
Source: NOAA CUSP dataset and fetch outputs draped over Esri background imagery

Overlap is also an issue for the clip method, although not as significant as in the transect intersect method. As mentioned earlier, polylines maintain extremely high horizontal accuracy. The erosion and fetch reclassified rasters used in this analysis were 3-foot resolution and the pixels were snapped together. Therefore, when these data were converted to shapefiles, the accuracy and location were transferred, as well, which caused minor overlap between resulting clips (Figure 3-22). To mitigate this effect, the “XY Tolerance” was specified to 3 feet in the Clip Analysis tool.

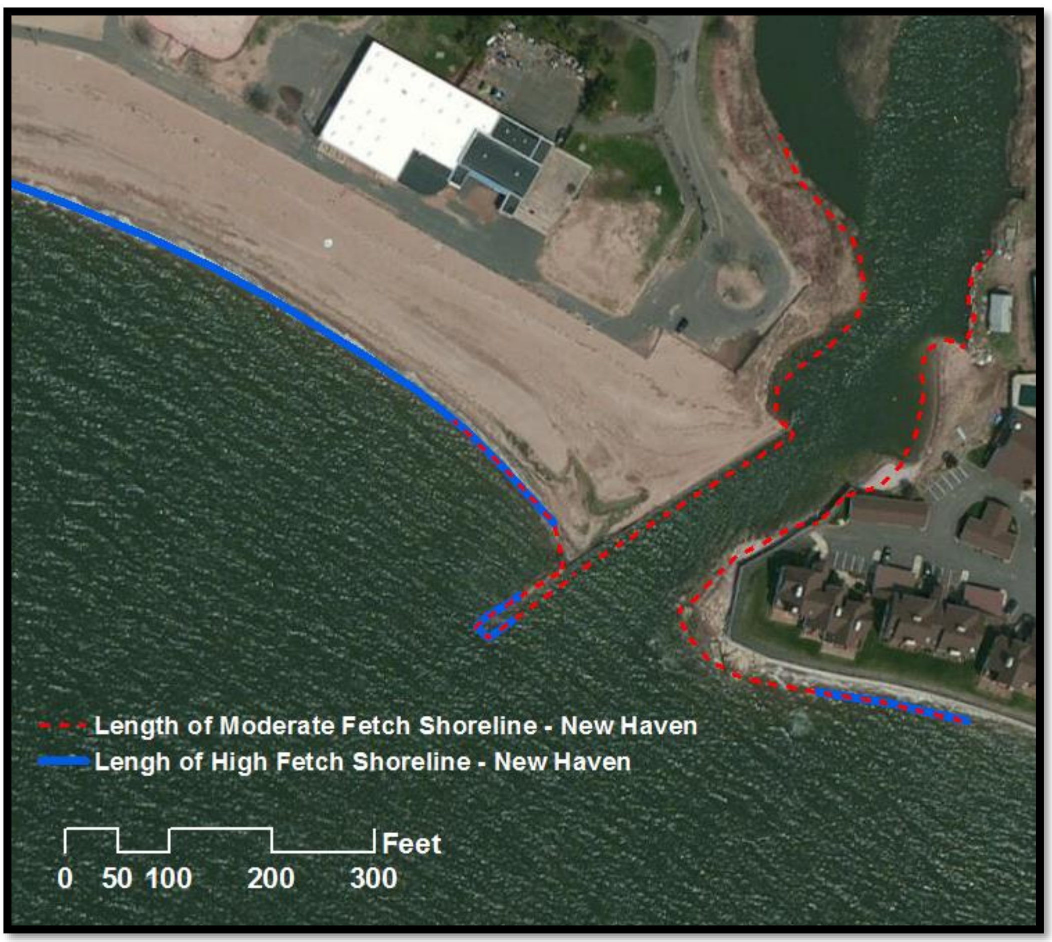


Figure 3-22. Overlap between Clipped Shoreline Lengths
Source: Fetch shoreline length outputs draped over Esri background imagery

Chapter 4: Results

This chapter focuses on results derived from the living shoreline site suitability outputs for the entire coast of Connecticut. This chapter, first, compares the two methods for measuring shoreline distances: the transect intersect method and clip method. Based on these two methodologies, results for the five reclassified input layers were generated, and results from the four living shoreline output methods were produced.

4.1 Comparing Shoreline Length Calculation Methods

The clip method and transect intersect method were compared to ensure that these methods produced highly-comparable results. The two methods were tested on each town's original beach shapefile and then a regression analysis was performed to determine the percent of variance explained between the methodologies, also known as the R-squared statistical measure. The R^2 value for this test was 0.986 (Figure 4-1). The percentage of unexplained variance is most likely due to the difference in the amount of overlap derived between the two methods. Thus, these two methods were appropriate for producing results from this study.

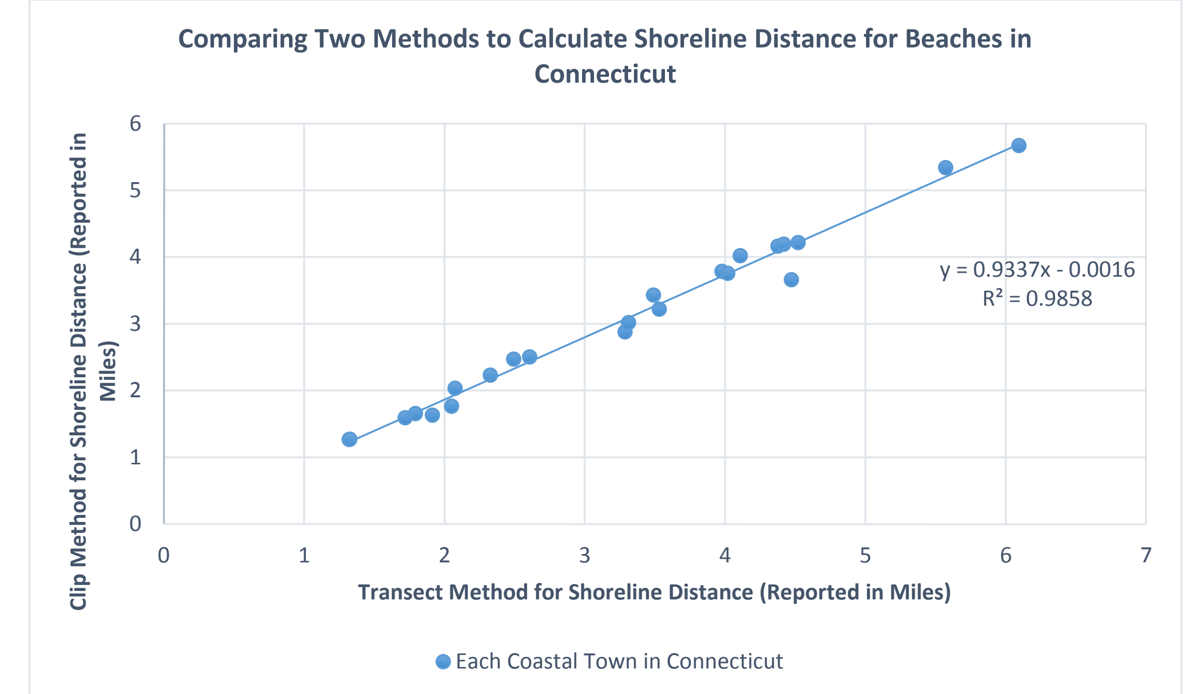


Figure 4-1. Comparing Two Methods to Calculate Shoreline Distance

4.2 Reclassified Input Layer Results

This section highlights results for the five reclassified raster layers created in producing living shoreline site suitability. These five layers include beach, marsh, bathymetry, erosion, and fetch. Statewide map outputs are provided, and tabular data are also listed for each layer. All results are reported in length of shoreline, measured in miles. The total shoreline distance for the study area in Connecticut is 432.21 miles, which excludes the town of Stonington. Stonington had missing bathymetric data necessary to perform the living shoreline site suitability analysis, so the total shoreline distance excludes results for Stonington.

4.2.1 Beach Results

Beach results were generated using the transect intersect method. Of the 432.21 miles of shoreline for the study area in Connecticut, 74.59 miles (17.26%) of the shoreline consists of rocky and sandy beaches (Figure 4-2) (Table 4-1).

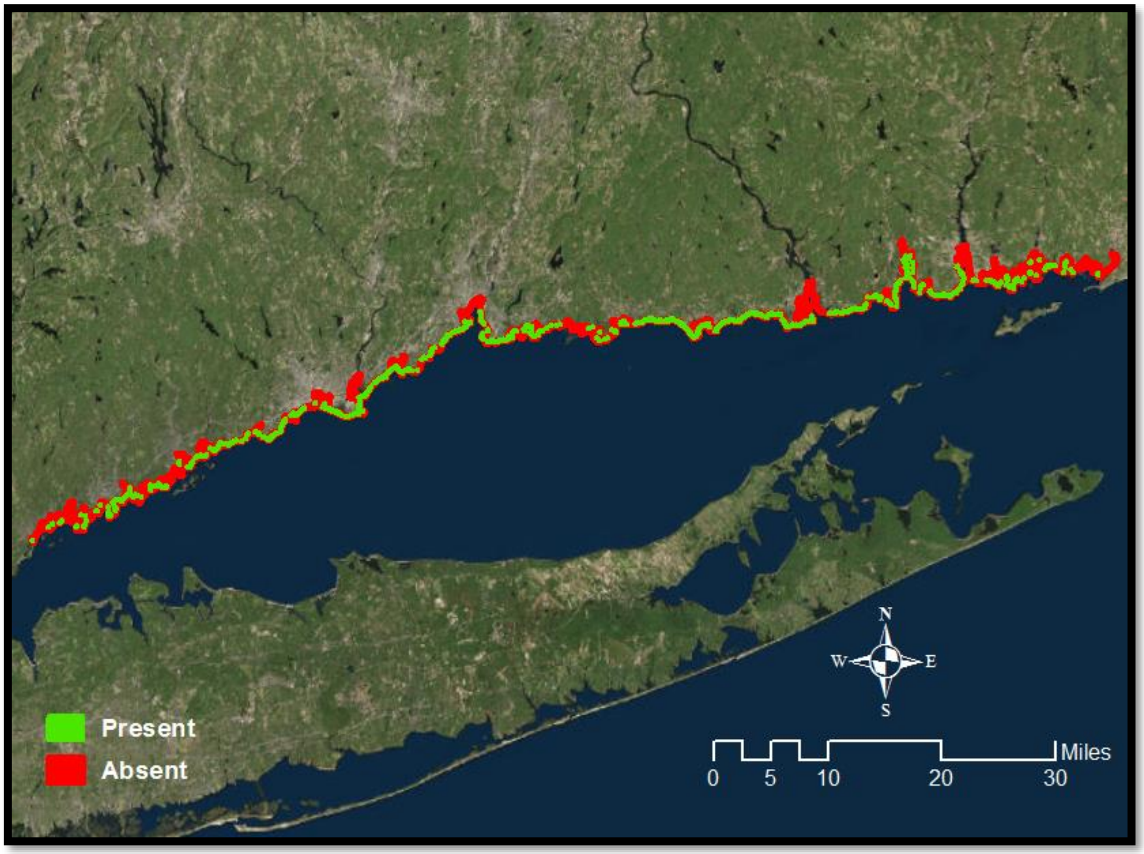


Figure 4-2. Presence of Beach within Connecticut
Source: Reclassified beach draped over Esri's background imagery

Town	Total Shoreline (mi)	Beach Present (mi)	Beach Absent (mi)	Present %	Absent %
Branford	31.41	2.60	28.81	8.28	91.72
Bridgeport	15.68	2.49	13.19	15.90	84.10
Clinton	7.63	1.91	5.72	25.07	74.93
Darien	19.25	1.31	17.94	6.80	93.20
East Haven	4.76	1.79	2.97	37.69	62.31
East Lyme	24.89	4.51	20.39	18.10	81.90
Fairfield	13.02	3.98	9.05	30.54	69.46
Greenwich	40.65	1.69	38.95	4.17	95.83
Groton	51.49	3.49	48.00	6.78	93.22
Guilford	27.90	1.32	26.58	4.74	95.26
Madison	12.79	5.54	7.25	43.34	56.66
Milford	23.57	6.09	17.48	25.84	74.16
New Haven	10.66	2.03	8.64	19.00	81.00
New London	10.60	2.07	8.53	19.55	80.45
Norwalk	22.61	2.32	20.29	10.25	89.75
Old Lyme	12.25	3.52	8.73	28.75	71.25
Old Saybrook	23.03	4.46	18.57	19.36	80.64
Stamford	14.64	3.27	11.38	22.30	77.70
Stratford	13.91	4.10	9.81	29.48	70.52
Waterford	19.57	4.37	15.21	22.31	77.69
Westbrook	5.49	3.31	2.18	60.31	39.69
Westport	17.07	4.00	13.07	23.45	76.55
West Haven	9.31	4.42	4.89	47.44	52.56
TOTAL	432.21	74.59	357.61	17.26	82.74

Table 4-1. Presence of Beach Results within Connecticut by Town

4.2.2 Marsh Results

Marsh results were generated using the transect intersect method. Of the 432.21 miles of shoreline for the study area in Connecticut, 172.16 miles (39.83%) of the shoreline consists of marsh (Figure 4-3) (Table 4-2).

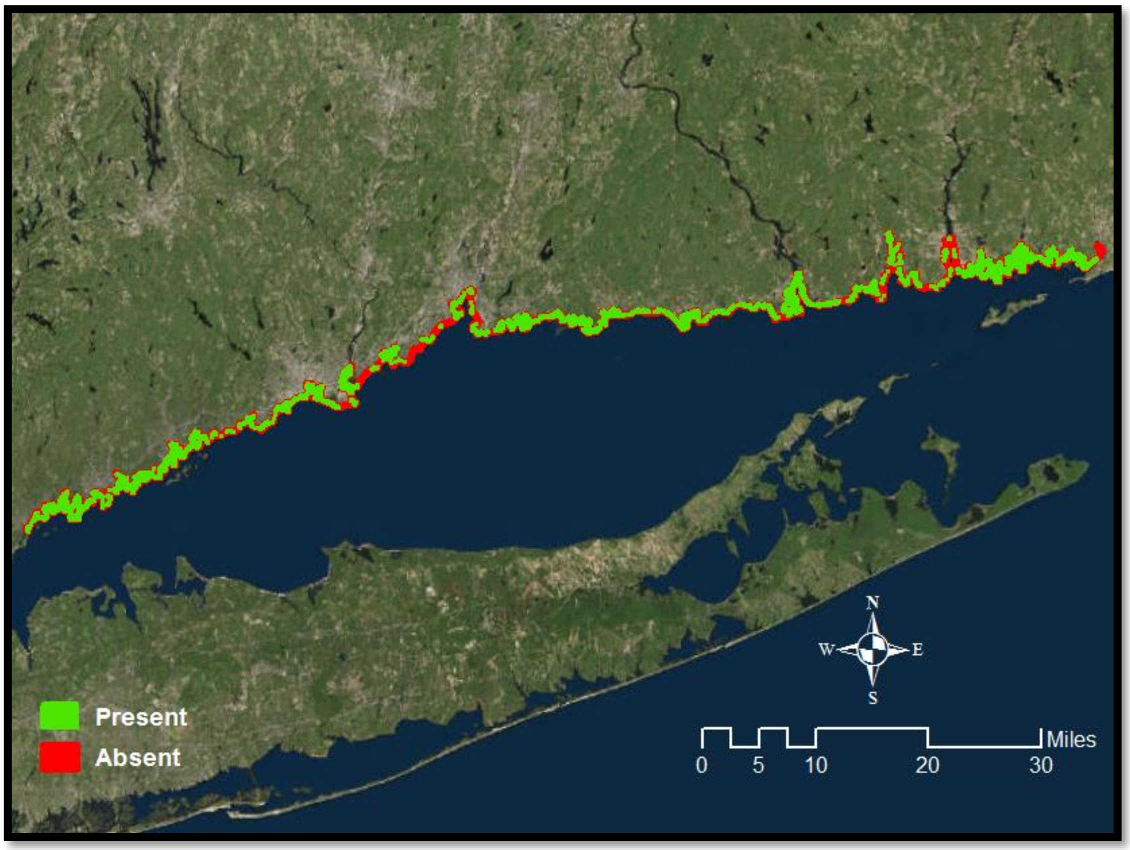


Figure 4-3. Presence of Marsh within Connecticut
Source: Reclassified marsh draped over Esri's background imagery

Town	Total Shoreline (mi)	Marsh Present (mi)	Marsh Absent (mi)	Present %	Absent %
Branford	31.41	13.55	17.87	43.13	56.87
Bridgeport	15.68	4.92	10.76	31.39	68.61
Clinton	7.63	3.75	3.88	49.14	50.86
Darien	19.25	8.41	10.84	43.70	56.30
East Haven	4.76	0.75	4.01	15.75	84.25
East Lyme	24.89	10.28	14.62	41.29	58.71
Fairfield	13.02	2.96	10.06	22.73	77.27
Greenwich	40.65	15.77	24.88	38.80	61.20
Groton	51.49	25.98	25.51	50.45	49.55
Guilford	27.90	15.45	12.45	55.38	44.62
Madison	12.79	4.76	8.03	37.22	62.78
Milford	23.57	9.85	13.72	41.80	58.20
New Haven	10.66	2.04	8.62	19.11	80.89
New London	10.60	0.98	9.63	9.22	90.78
Norwalk	22.61	11.97	10.63	52.97	47.03
Old Lyme	12.25	5.88	6.37	48.02	51.98
Old Saybrook	23.03	13.85	9.18	60.12	39.88
Stamford	14.64	2.04	12.60	13.91	86.09
Stratford	13.91	6.64	7.27	47.72	52.28
Waterford	19.57	2.92	16.65	14.93	85.07
Westbrook	5.49	1.08	4.40	19.71	80.29
Westport	17.07	5.90	11.17	34.58	65.42
West Haven	9.31	2.42	6.88	26.04	73.96
TOTAL	432.21	172.16	260.04	39.83	60.17

Table 4-2. Presence of Marsh Results within Connecticut by Town

4.2.3 Bathymetry Results

Bathymetry results were generated using the transect intersect method. Of the 432.21 miles of shoreline for the study area in Connecticut, 421.42 miles (97.50%) of the shoreline satisfies the living shoreline design requirement for nearshore depth (Figure 4-4) (Table 4-3).

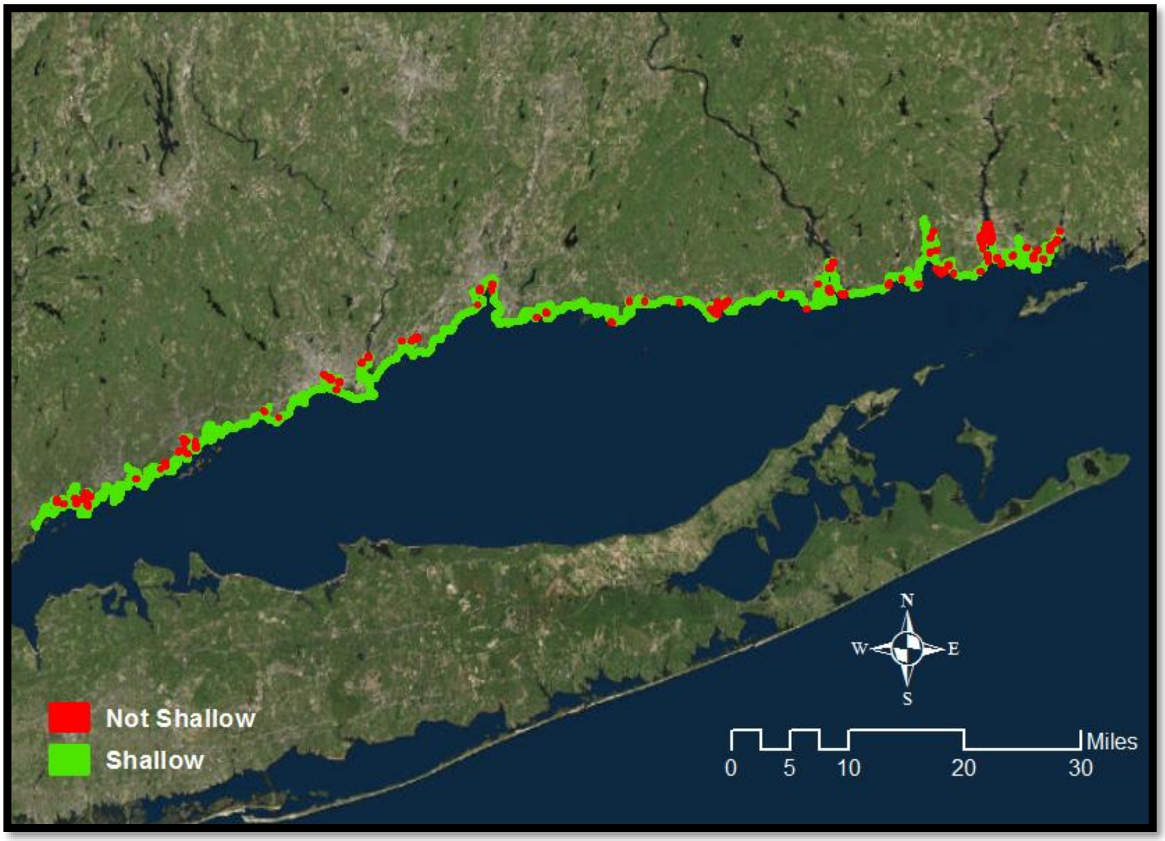


Figure 4-4. Nearshore Depth Suitable for Living Shorelines within Connecticut
Source: Reclassified bathymetry draped over Esri's background imagery

Town	Total Shoreline (mi)	Bathymetry Suitable (mi)	Bathymetry Unsuitable (mi)	Suitable %	Unsuitable %
Branford	31.41	31.41	0.00	100.00	0.00
Bridgeport	15.68	15.54	0.14	99.08	0.92
Clinton	7.63	7.53	0.11	98.58	1.42
Darien	19.25	19.25	0.00	100.00	0.00
East Haven	4.76	4.76	0.00	100.00	0.00
East Lyme	24.89	24.72	0.18	99.29	0.71
Fairfield	13.02	13.02	0.00	100.00	0.00
Greenwich	40.65	40.20	0.44	98.91	1.09
Groton	51.49	48.03	3.46	93.29	6.71
Guilford	27.90	27.86	0.04	99.85	0.15
Madison	12.79	12.64	0.15	98.84	1.16
Milford	23.57	23.36	0.22	99.09	0.91
New Haven	10.66	10.37	0.29	97.28	2.72
New London	10.60	7.58	3.02	71.51	28.49
Norwalk	22.61	21.28	1.32	94.16	5.84
Old Lyme	12.25	11.88	0.37	97.01	2.99
Old Saybrook	23.03	22.35	0.68	97.05	2.95
Stamford	14.64	14.64	0.00	100.00	0.00
Stratford	13.91	13.91	0.00	100.00	0.00
Waterford	19.57	19.24	0.33	98.31	1.69
Westbrook	5.49	5.45	0.04	99.26	0.74
Westport	17.07	17.07	0.00	100.00	0.00
West Haven	9.31	9.31	0.00	100.00	0.00
TOTAL	432.21	421.42	10.79	97.50	2.50

Table 4-3. Nearshore Bathymetry Results for Connecticut by Town

4.2.4 Erosion Results

Erosion results were generated using the clip method. Of the 432.21 miles of shoreline for the study area in Connecticut, 344.39 miles (79.68%) of the shoreline experienced low erosion, 25.65 miles (5.93%) of the shoreline experiences moderate erosion, 4.35 miles (1.01%) of the shoreline experiences high erosion, and 57.82 miles (13.38%) of the shoreline is unsuitable, as based on data from the 1983-2006 short-term erosion trends provided by O'Brien et al. (Figure 4-5) (Table 4-4).

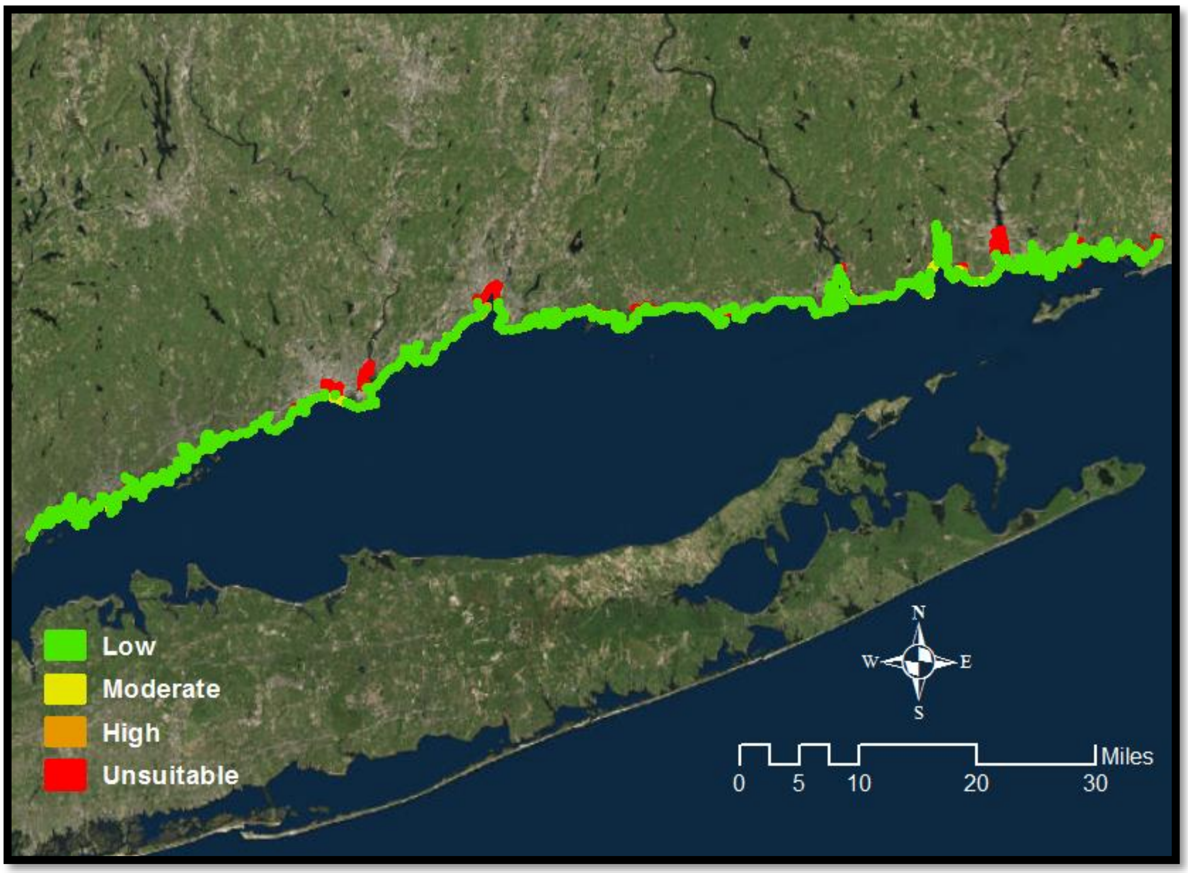


Figure 4-5. Living Shoreline Erosion Classifications for Connecticut
Source: Erosion reclassified layers draped over Esri's background imagery

Town	Total Shoreline (mi)	Low (mi)	Mod (mi)	High (mi)	Unsuitable (mi)	Low %	Mod %	High %	Unsuitable %
Branford	31.41	27.29	1.82	0.00	2.30	86.88	5.80	0.00	7.32
Bridgeport	15.68	6.59	1.30	0.02	7.77	42.01	8.31	0.14	49.53
Clinton	7.63	7.52	0.12	0.00	0.00	98.47	1.52	0.00	0.01
Darien	19.25	18.75	0.07	0.00	0.44	97.37	0.35	0.00	2.29
East Haven	4.76	4.76	0.00	0.00	0.00	99.98	0.00	0.00	0.02
East Lyme	24.89	20.53	3.09	0.20	1.07	82.48	12.43	0.81	4.28
Fairfield	13.02	11.03	1.02	0.00	0.97	84.73	7.86	0.00	7.42
Greenwich	40.65	38.31	1.42	0.00	0.92	94.24	3.49	0.00	2.26
Groton	51.49	42.10	2.32	0.25	6.81	81.78	4.52	0.48	13.22
Guilford	27.90	20.23	0.37	0.00	7.30	72.51	1.34	0.00	26.16
Madison	12.79	11.51	0.55	0.00	0.74	89.93	4.30	0.00	5.77
Milford	23.57	19.36	0.34	0.38	3.49	82.14	1.45	1.62	14.79
New Haven	10.66	3.89	0.02	0.00	6.75	36.47	0.22	0.00	63.31
New London	10.60	2.43	1.53	0.01	6.63	22.92	14.45	0.11	62.52
Norwalk	22.61	21.47	0.16	0.00	0.97	95.00	0.71	0.00	4.29
Old Lyme	12.25	8.51	1.43	0.67	1.64	69.43	11.69	5.45	13.42
Old Saybrook	23.03	22.52	0.51	0.00	0.00	97.77	2.21	0.00	0.01
Stamford	14.64	11.07	1.38	0.03	2.16	75.61	9.44	0.21	14.74
Stratford	13.91	6.54	1.70	0.24	5.42	47.04	12.22	1.76	38.99
Waterford	19.57	13.30	3.51	0.99	1.77	67.97	17.93	5.08	9.02
Westbrook	5.49	5.45	0.00	0.00	0.04	99.28	0.00	0.00	0.72
Westport	17.07	15.05	1.58	0.33	0.12	88.14	9.25	1.91	0.70
West Haven	9.31	6.18	1.38	1.22	0.53	66.36	14.82	13.16	5.67
TOTAL	432.21	344.39	25.65	4.35	57.82	79.68	5.93	1.01	13.38

Table 4-4. Results for Erosion Classifications within Connecticut Reported as Miles and Percentages by Town

4.2.5 Fetch Results

Fetch results were generated using the clip method. Of the 432.21 miles of shoreline for the study area in Connecticut, 236.70 miles (54.77%) of the shoreline faces low fetch exposure, 135.49 miles (31.35%) of the shoreline faces moderate fetch exposure, 38.53 miles (8.91%) of the shoreline faces high fetch exposure, and 21.48 miles (8.91%) of the shoreline is unsuitable (Figure 4-6) (Table 4-5).

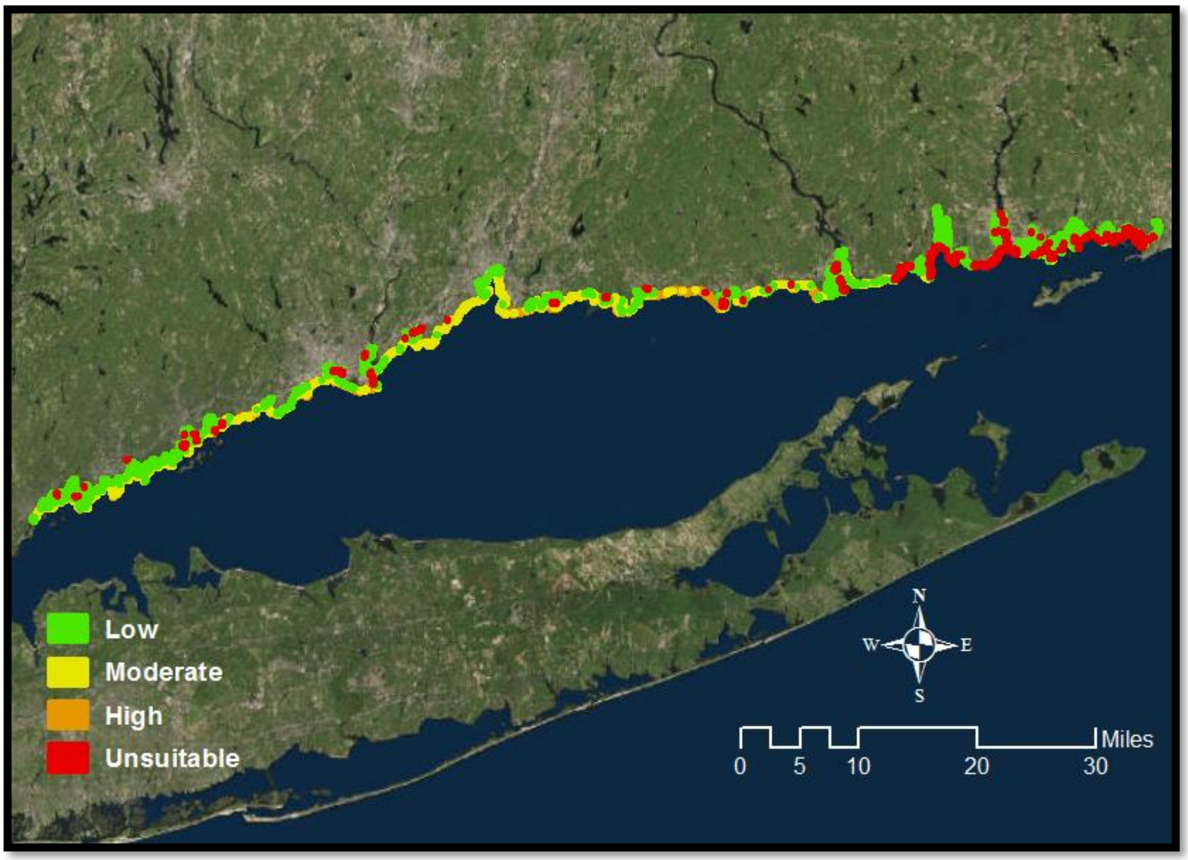


Figure 4-6. Living Shoreline Fetch Classifications for Connecticut
Source: Fetch reclassified layers draped over Esri's background imagery

Town	Total Shoreline (mi)	Low (mi)	Mod (mi)	High (mi)	Unsuitable (mi)	Low %	Mod %	High %	Unsuitable %
Branford	31.41	8.63	16.19	4.98	1.62	27.46	51.52	15.85	5.16
Bridgeport	15.68	7.58	6.00	2.08	0.02	48.32	38.24	13.29	0.14
Clinton	7.63	4.30	2.66	0.67	0.01	56.28	34.87	8.74	0.11
Darien	19.25	12.67	6.54	0.01	0.03	65.80	33.98	0.07	0.15
East Haven	4.76	0.54	1.16	3.14	-0.07*	11.24	24.42	65.86	-1.52
East Lyme	24.89	16.96	3.16	0.15	4.62	68.14	12.68	0.61	18.58
Fairfield	13.02	6.38	5.60	1.07	-0.03*	49.02	43.04	8.18	-0.24
Greenwich	40.65	30.12	10.18	0.20	0.14	74.11	25.04	0.50	0.35
Groton	51.49	44.07	3.52	0.00	3.90	85.60	6.83	0.00	7.57
Guilford	27.90	9.67	14.33	3.71	0.20	34.64	51.35	13.30	0.71
Madison	12.79	1.40	2.03	8.87	0.50	10.92	15.87	69.32	3.88
Milford	23.57	12.14	9.39	2.02	0.02	51.51	39.84	8.58	0.07
New Haven	10.66	3.97	6.47	0.30	-0.07*	37.21	60.68	2.80	-0.69
New London	10.60	8.74	0.00	0.00	1.87	82.40	0.00	0.00	17.60
Norwalk	22.61	14.83	6.45	0.00	1.33	65.61	28.52	0.00	5.87
Old Lyme	12.25	4.86	5.65	0.33	1.42	39.64	46.14	2.67	11.55
Old Saybrook	23.03	14.77	3.19	3.28	1.79	64.13	13.85	14.25	7.77
Stamford	14.64	5.08	9.42	0.14	0.00	34.68	64.36	0.95	0.01
Stratford	13.91	6.44	3.18	3.58	0.71	46.27	22.84	25.76	5.14
Waterford	19.57	13.96	2.40	0.00	3.21	71.34	12.25	0.00	16.41
Westbrook	5.49	0.92	3.31	1.21	0.04	16.80	60.33	22.06	0.82
Westport	17.07	6.13	8.21	2.49	0.23	35.93	48.12	14.60	1.36
West Haven	9.31	2.55	6.46	0.29	0.00	27.43	69.44	3.12	0.01
TOTAL	432.21	236.70	135.49	38.53	21.48	54.77	31.35	8.91	4.97

Table. 4-5. Results for Fetch Classifications within Connecticut Reported as Miles and Percentages by Town

* Caused by overlap in clip calculations. Refer to Section 3.11 for more information.

4.3 Living Shoreline Results

This section highlights results generated from the living shoreline site suitability outputs. Calculations for suitable/unsuitable length of shoreline are provided for each town for beach enhancement, marsh enhancement, marsh with structures, and offshore breakwaters. It is important to note that excluded areas in analysis are treated the same as unsuitable areas which lower the overall suitability for each living shoreline treatment option. Excluded areas include unbounded fetch, areas classified as industrialized waterfront or missing data in the erosion layer, as well as missing data in the bathymetry dataset. These excluded areas were not removed from the analysis because data were still contained for other reclassified input layers at these locations.

4.3.1 Beach Enhancement Results

Beach enhancement results were generated using the transect intersect method. Of the 432.21 miles of shoreline for the study area in Connecticut, 13.94 miles (3.23%) of the shoreline is potentially suitable for soft, non-structural Beach enhancement living shoreline treatments (Figure 4-7) (Table 4-6).

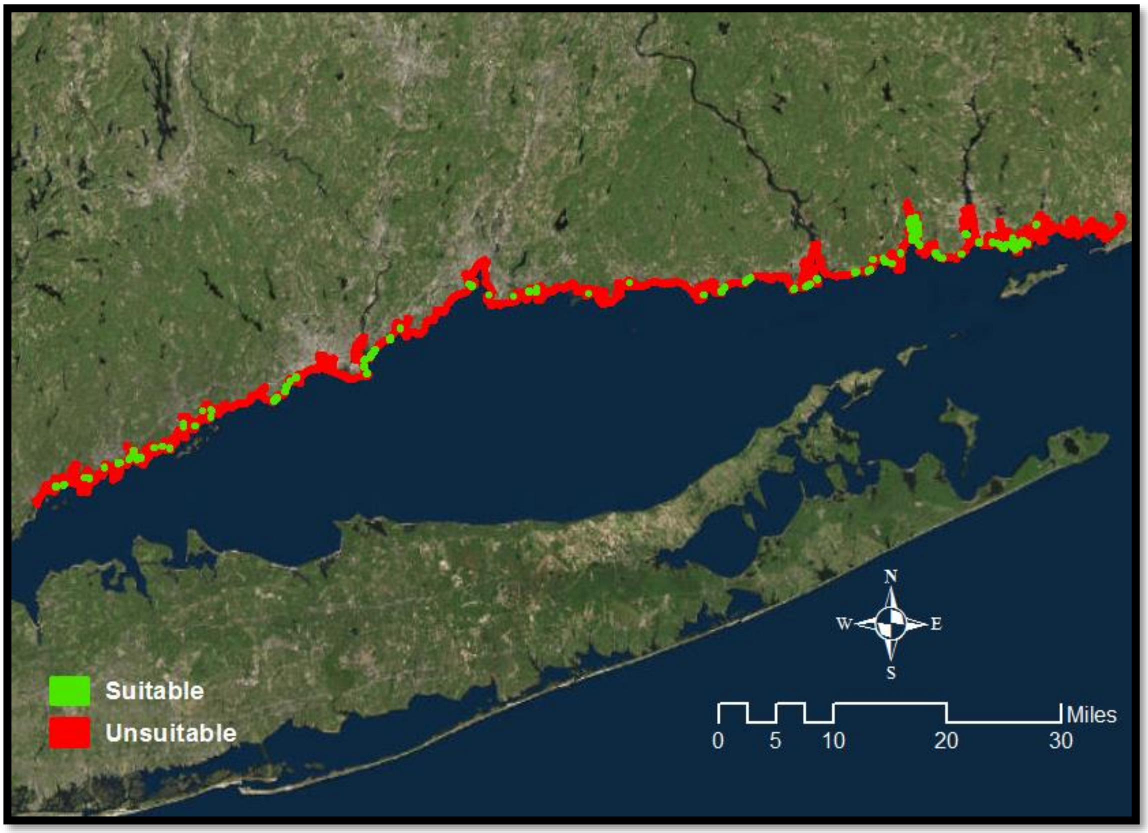


Figure 4-7. Suitable Sites for Beach Enhancement Living Shoreline Techniques within Connecticut
Source: Beach enhancement output draped over Esri's background imagery

Town	Total Shoreline (mi)	Beach Enhancement (mi)	Beach Enhancement %
Branford	31.41	0.12	0.37
Bridgeport	15.68	0.39	2.52
Clinton	7.63	0.64	8.38
Darien	19.25	0.32	1.66
East Haven	4.76	0.02	0.44
East Lyme	24.89	1.89	7.57
Fairfield	13.02	1.09	8.36
Greenwich	40.65	0.56	1.39
Groton	51.49	1.96	3.81
Guilford	27.90	0.07	0.26
Madison	12.79	0.05	0.38
Milford	23.57	1.10	4.68
New Haven	10.66	0.00	0.04
New London	10.60	0.46	4.29
Norwalk	22.61	0.64	2.84
Old Lyme	12.25	0.54	4.39
Old Saybrook	23.03	0.76	3.31
Stamford	14.64	0.36	2.49
Stratford	13.91	0.31	2.20
Waterford	19.57	1.60	8.15
Westbrook	5.49	0.61	11.20
Westport	17.07	0.23	1.32
West Haven	9.31	0.22	2.33
TOTAL	432.21	13.94	3.23

Table 4-6. Beach Enhancement Results for Connecticut by Town

4.3.2 Marsh Enhancement Results

Marsh enhancement results were generated using the transect intersect method. Of the 432.21 miles of shoreline for the study area in Connecticut, 94.26 miles (21.81%) of the shoreline is potentially suitable for soft, non-structural marsh enhancement living shoreline treatments (Figure 4-8) (Table 4-7).

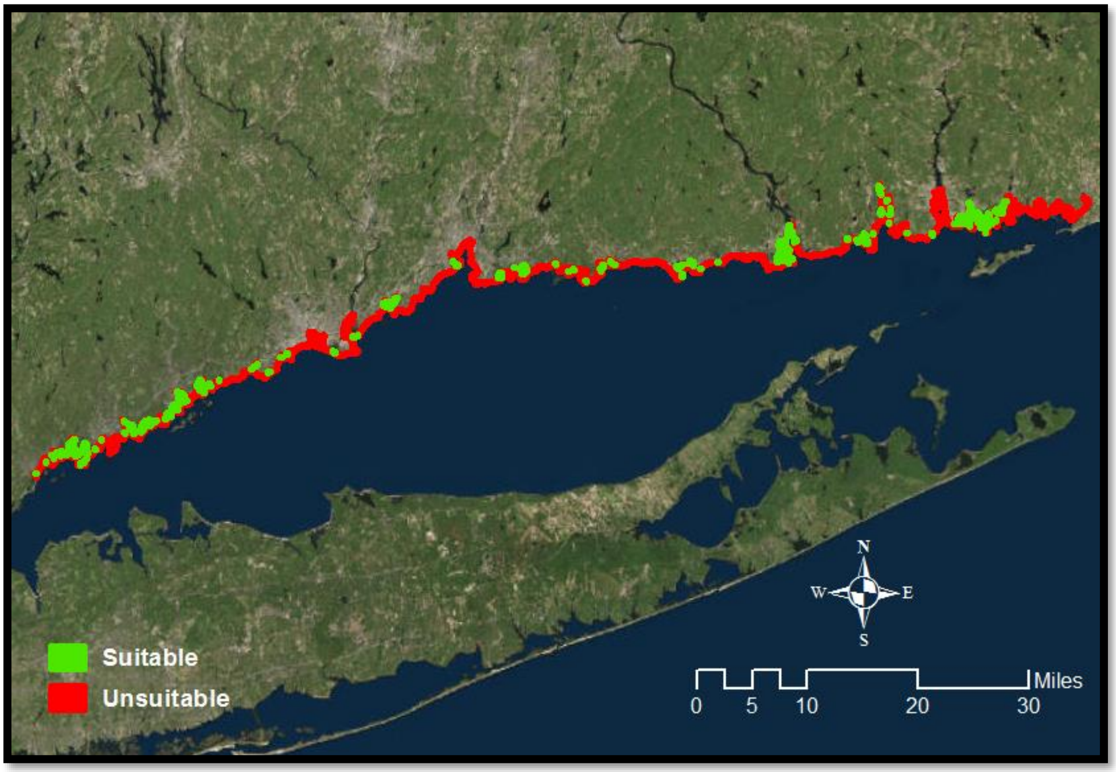


Figure 4-8. Suitable Sites for Marsh Enhancement Living Shoreline Techniques within Connecticut
Source: Marsh enhancement output draped over Esri's background imagery

Town	Total Shoreline (mi)	Marsh Enhancement (mi)	Marsh Enhancement %
Branford	31.41	5.23	16.64
Bridgeport	15.68	0.50	3.19
Clinton	7.63	2.83	37.04
Darien	19.25	6.57	34.10
East Haven	4.76	0.32	6.68
East Lyme	24.89	8.52	34.22
Fairfield	13.02	0.84	6.47
Greenwich	40.65	12.06	29.66
Groton	51.49	21.06	40.91
Guilford	27.90	2.12	7.61
Madison	12.79	1.22	9.54
Milford	23.57	5.29	22.44
New Haven	10.66	0.00	0.00
New London	10.60	0.15	1.40
Norwalk	22.61	8.16	36.08
Old Lyme	12.25	2.15	17.52
Old Saybrook	23.03	11.22	48.71
Stamford	14.64	0.74	5.06
Stratford	13.91	0.34	2.46
Waterford	19.57	1.01	5.17
Westbrook	5.49	0.16	2.90
Westport	17.07	2.76	16.19
West Haven	9.31	1.01	10.90
TOTAL	432.21	94.26	21.81

Table 4-7. Marsh Enhancement Results for Connecticut by Town

4.3.3 Marsh with Structures Results

Marsh with structures results were generated using the transect intersect method. Of the 432.21 miles of shoreline for the study area in Connecticut, 41.52 miles (9.61%) of the shoreline is potentially suitable for hybrid marsh with structures living shoreline treatments (Figure 4-15) (Table 4-9).

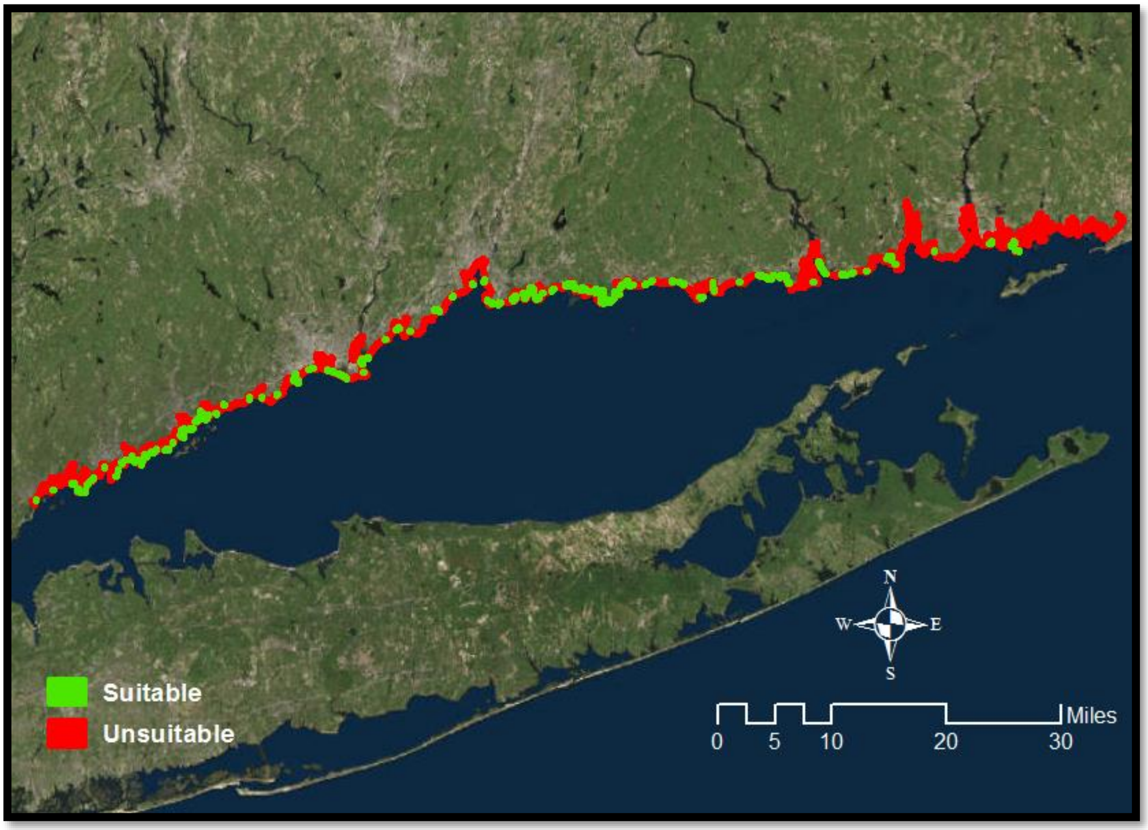


Figure 4-9. Suitable Sites for Marsh with Structures Living Shoreline Techniques within Connecticut
Source: Marsh with structures output draped over Esri's background imagery

Town	Total Shoreline (mi)	Marsh with Structures (mi)	Marsh with Structures %
Branford	31.41	5.14	16.37
Bridgeport	15.68	1.32	8.43
Clinton	7.63	0.93	12.18
Darien	19.25	1.71	8.90
East Haven	4.76	0.43	9.07
East Lyme	24.89	0.91	3.64
Fairfield	13.02	1.40	10.72
Greenwich	40.65	2.78	6.83
Groton	51.49	1.82	3.53
Guilford	27.90	6.57	23.54
Madison	12.79	2.67	20.83
Milford	23.57	1.44	6.09
New Haven	10.66	0.41	3.83
New London	10.60	0.00	0.00
Norwalk	22.61	2.24	9.90
Old Lyme	12.25	2.47	20.12
Old Saybrook	23.03	1.53	6.63
Stamford	14.64	0.86	5.85
Stratford	13.91	2.01	14.48
Waterford	19.57	0.18	0.94
Westbrook	5.49	0.89	16.21
Westport	17.07	3.04	17.79
West Haven	9.31	0.79	8.47
TOTAL	432.21	41.52	9.61

Table 4-8. Marsh with Structures Results for Connecticut by Town

4.3.4 Offshore Breakwaters Results

Offshore breakwaters results were generated using the transect intersect method. Of the 432.21 miles of shoreline for the study area in Connecticut, 51.35 miles (11.88%) of the shoreline is potentially suitable for hybrid offshore breakwaters living shoreline treatments (Figure 4-10) (Table 4-9).

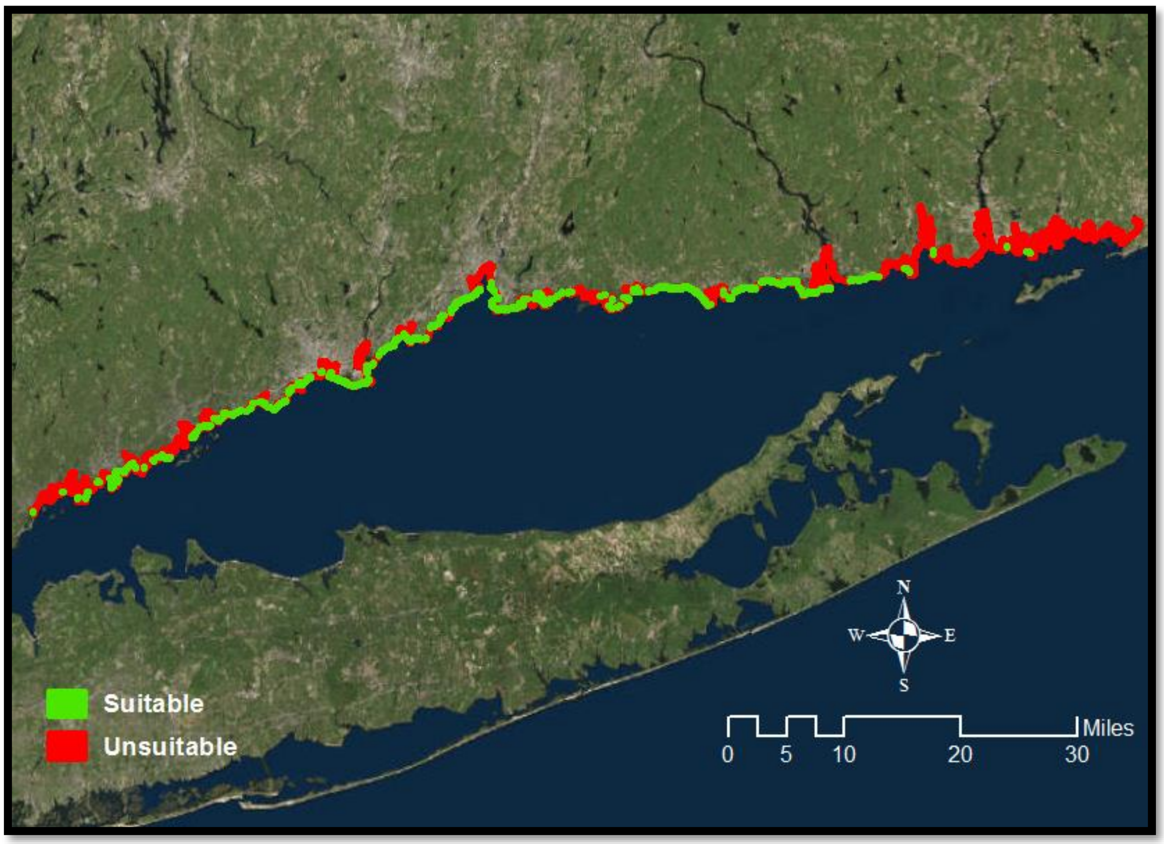


Figure 4-10. Suitable Sites for Offshore Breakwaters Living Shoreline Techniques within Connecticut
Source: Offshore breakwaters output draped over Esri's background imagery

Town	Total Shoreline (mi)	Offshore Breakwaters (mi)	Offshore Breakwaters %
Branford	31.41	2.46	7.83
Bridgeport	15.68	2.11	13.44
Clinton	7.63	1.28	16.73
Darien	19.25	0.99	5.16
East Haven	4.76	1.68	35.32
East Lyme	24.89	0.43	1.72
Fairfield	13.02	2.80	21.54
Greenwich	40.65	1.09	2.68
Groton	51.49	0.42	0.82
Guilford	27.90	1.27	4.53
Madison	12.79	5.37	41.96
Milford	23.57	5.01	21.27
New Haven	10.66	1.76	16.47
New London	10.60	0.00	0.00
Norwalk	22.61	1.66	7.36
Old Lyme	12.25	2.57	20.94
Old Saybrook	23.03	3.52	15.28
Stamford	14.64	2.90	19.78
Stratford	13.91	3.31	23.78
Waterford	19.57	0.46	2.37
Westbrook	5.49	2.62	47.81
Westport	17.07	3.72	21.77
West Haven	9.31	3.93	42.22
TOTAL	432.21	51.35	11.88

Table 4-9. Offshore Breakwaters Results for Connecticut by Town

4.3.5 Overall Results

Of the 432.21 miles of shoreline for the study area in Connecticut, 201.06 miles (46.52%) of the shoreline is potentially suitable for living shoreline treatments (Table 4-10). Based on results from this study, there is significant potential for both soft and hybrid living shoreline designs in Connecticut. Overall, 108.20 (25.04%) miles is suitable for soft, nonstructural living shoreline techniques. Overall, 92.87 (21.49%) miles is suitable for hybrid living shoreline techniques. Of the 74.59 miles of rocky and sandy beach within Connecticut, the potential for beach enhancement and offshore breakwaters totals 65.29 miles of shoreline, which is 87.53% of beach in Connecticut. Of the 172.16 miles of wetlands within Connecticut, the potential for marsh enhancement and marsh with structures totals 135.78 miles of shoreline, which is 78.87% of wetlands in Connecticut. However, it is important to be made aware of limitations associated with this study.

Town	Total Shoreline (mi)	Total Suitable (mi)	Total % Suitable
Branford	31.41	12.95	41.21
Bridgeport	15.68	4.32	27.57
Clinton	7.63	5.68	74.34
Darien	19.25	9.59	49.83
East Haven	4.76	2.45	51.51
East Lyme	24.89	11.74	47.15
Fairfield	13.02	6.13	47.09
Greenwich	40.65	16.49	40.56
Groton	51.49	25.27	49.08
Guilford	27.90	10.03	35.94
Madison	12.79	9.30	72.72
Milford	23.57	12.84	54.48
New Haven	10.66	2.17	20.33
New London	10.60	0.60	5.70
Norwalk	22.61	12.70	56.19
Old Lyme	12.25	7.71	62.97
Old Saybrook	23.03	17.03	73.92
Stamford	14.64	4.86	33.17
Stratford	13.91	5.97	42.92
Waterford	19.57	3.26	16.64
Westbrook	5.49	4.29	78.11
Westport	17.07	9.74	57.07
West Haven	9.31	5.95	63.93
TOTAL	432.21	201.06	46.52

Table 4-10. Total Shoreline Suitable for Living Shorelines within Connecticut by Town

Chapter 5: Discussion

This chapter analyzes key results produced from the living shoreline site model. This chapter also discusses limitations of this GIS-based analysis and ways to refine further the site suitability model. Challenges of living shoreline implementation, in terms of education/outreach, cost, and permitting, are also discussed, and some solutions to address these issues are presented

5.1 Living Shoreline Site Suitability Analysis

The living shoreline site suitability analysis delineates sites that are primarily natural shoreline. Beach and marsh are important factors in determining site suitability because existing wetlands and beaches indicate where site conditions allow for the development of these habitats, which are, thereby, suitable sites for living shoreline stabilization techniques. This section highlights the effects of input layers in deriving living shoreline site suitability.

Erosion results produced from O'Brien et al.'s (2014) short-term erosion (1983-2006) are generally consistent with geological shoreline district classifications for Connecticut. Beaches and bluffs directly exposed to Long Island Sound experienced higher rates of erosion than tidal wetlands and sheltered coves and inlets between the 1983 and 2006 period. Also, sites of artificial fill, based on O'Brien et al.'s (2014) study, experienced abnormally high erosion. This analysis categorizes these highly erodible areas into hybrid site suitability outputs or areas that require man-made structures to provide additional support to natural riparian buffers. Highly erodible areas (sites where erosion was greater than 2 feet per year between 1983 and 2006) make up a small portion of the Connecticut shoreline – 30 miles or 6.94% of the entire shoreline (O'Brien et al., 2014).

Fetch also strongly influences site suitability. Offshore winds are predominantly westerly which greatly impacts the USGS fetch model calculations where the shoreline geometry of

Connecticut's Long Island Sound shoreline faces west-south-west to east-north-east (DEEP, 1979). As fetch results are generated along the shoreline from west to east, results may be biased since wind information is provided from a westerly direction. The east-north-east aspect and irregular geometry of an eastern Connecticut coastal town such as Stonington produces unbounded fetch from the USGS fetch tool's SPM calculation method.

Results reveal that more than half of Connecticut's shoreline experiences low fetch exposure. However, moderate (31.35%) and high (8.91%) fetch exposure is notable along open beaches and barrier beaches, as well as along bluffs. Qualitatively, based on observation from orthoimagery, sites that experience higher fetch exposure along Connecticut's shoreline are areas where the upland is already protected by hard structures. This study delineates areas that experience higher fetch exposure as sites potentially suitable for hybrid design options – sites that require at least minimal hard structures. However, given the irregularity of Connecticut's shoreline, wave energy studies should be conducted on site before implementing any shoreline stabilization strategy.

Near shore depth is an important consideration when designing a living shoreline. Results from the bathymetry data reveal that 97.50% of the coastline, excluding Stonington, is suitable for living shoreline techniques. Areas that were not shallow for design include, most prominently, marinas, harbors, and headland areas, and these areas lowered the overall suitability for living shoreline designs.

Based on results from this study, there is substantial potential for both soft and hybrid living shoreline designs in Connecticut. Overall, 108.20 miles (25.04%) are suitable for soft, nonstructural living shoreline techniques. Overall, 92.87 miles (21.49%) are suitable for hybrid

living shoreline techniques. However, it is important to be made aware of limitations associated with this study.

5.2 Caveats

The living shoreline site suitability analysis determines site suitability based on proxies for wave energy and presence of vegetation. Unfortunately, it is not possible to consider every factor that may determine the site-specific nature of implementing a living shoreline protection strategy. “One size does not fit all” in terms of recommending erosion control methods at any given site. Rather, this research takes a simplified approach to be used as a screening tool and supplemental guide to assist natural resource managers and property owners in considering nature-based shoreline stabilization options. This model does not consider the contribution of existing structures to erosion. Mapping each structure along the coast and determining the effects of said structure on coastal processes is not possible at the scale of this study. Similarly, the model uses the best GIS data available. Accordingly, the results are only as accurate as the data layers and data tools used to produce site suitability outputs. For example, fetch is based on only wind information from the central Long Island Sound buoy, and does not incorporate other buoys or land stations. Therefore, fetch derived from the USGS fetch tool is only as accurate as the wind information input into the tool, which is a data limitation from this analysis. This analysis does not consider a "Do Nothing" approach. It assumes that some action may be required to prevent erosion.

5.3 Future Considerations

Many other variables could be potentially incorporated into living shoreline site suitability assessment. Surficial materials and soil maps could be used to indicate the level of

erosion at sites, as well as provide insight to which plants could be utilized in living shoreline design. Another consideration for selecting plant species is salinity tolerance, however, spatially-represented salinity data do not exist for the entire extent of Connecticut's shoreline. Also bottom type could indicate whether or not an area can support the weight of a sill or breakwater (Carey, 2013). Additionally, tidal amplitude and upland land-use are important considerations for specific shoreline stabilization designs. Another important factor is the level of grading required for a specific site which requires high-resolution elevation data such as LiDAR (Light Detection and Ranging).

Current and accurate data are perhaps the most important factors in determining site suitability of living shorelines. As Connecticut continues to experience extreme coastal storm events similar to Hurricane Irene or Hurricane Sandy, all data must be updated to account for changes in shoreline alignment. Also, as sea level continues to rise, more research should be conducted to determine the ability of tidal wetlands to accrete peat or to migrate landward since vegetation and wetland grasses are a key component of living shoreline design. The ability of tidal wetlands to migrate landward is also dependent on upland land-use. Similarly, sea level rise will exacerbate the effects of erosion along beaches, which will impact shoreline stabilization strategies recommended by coastal planners and natural resource managers. For instance, sea level rise may shift employment of living shoreline strategies from soft-nonstructural designs like beach replenishment to hybrid breakwater systems where the goal is not simply to slow down the effects of erosion but build up sediment. Future studies should focus on living shoreline strategies that also take into consideration sea level rise. Environmental planners should also consider land-use planning that limits development in areas highly vulnerable to

inundation from erosion, although this task will be highly contested by various stakeholders. Certainly, there are many challenges towards living shoreline implementation.

5.4 Challenges of Living Shoreline Implementation

According to Mason (2014), there are three sets of challenges to implementing living shorelines. Challenges include education and outreach, cost/financial concerns, and regulatory obstacles (Mason, 2014). This section highlights some of these major concerns identified by property owners, municipalities, state agencies, and environmental groups which are generally of the same concern to Connecticut.

5.4.1 Education and Outreach

Mason (2014) notes that provision of educational information is a major challenge in employing living shoreline stabilization options. A key question for waterfront property owners and natural resource decision makers is *where do living shorelines work*? Organizations such as VIMS CCRM provide decision support tools[6] to help answer this question. The CCRM website provides a decision tree for erosion control structures along sheltered coasts, for both protected and unprotected shorelines (VIMS, 2010). CCRM also provides a GIS model called the Shoreline Assessment Mapper[7] similar in approach to this study. There are also many resources available online such as the Chesapeake Bay Foundation[8], NOAA's Habitat Conservation Center[9], the Maryland Department of Natural Resources[10], and the Living Shorelines Academy[11] by the North Carolina Coastal Federation. These sources provide accurate information related to

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[6] http://ccrm.vims.edu/livingshorelines/design_options/index.html
[7] http://cmap.vims.edu/ShorelineAssessmentMapper_SL/ShorelineAssessmentMapperTestPage.html
[8] http://www.cbf.org/
[9] http://www.habitat.noaa.gov/restoration/index.html
[10] http://dnr2.maryland.gov/ccs/Pages/livingshorelines.aspx
[11] http://livingshorelinesacademy.org/

definitions, design, research, policy and permitting (Mason, 2014). Obtaining accurate and reliable information is the first step to implementing living shorelines. Mason notes that "word-of-mouth" is another popular method for learning about shoreline erosion control.

Property owners often learn about shoreline protection through friends and contractors (Mason, 2014). According to a questionnaire done by CCRM, most people interested in erosion control seek advice from friends and family, as well as from contractors (Mason, 2014). However, the main issue with this is that shoreline hardening is the norm so it is most commonly recommended. Similarly, contractors may know less about the effectiveness of living shorelines. As living shoreline projects are implemented, people will have the opportunity to observe and assess the effectiveness of living shorelines, which will ultimately help promote these methods (Mason, 2014).

5.4.2 Cost

Shoreline protection is a trade-off between level of protection and cost. For example, if home-owners require protection against a Category 3 hurricane – the most powerful yet observed in Connecticut – then living shorelines are not the preferred method. However, as level of protection increases, so does the cost of shoreline protection structures. Fortunately, living shorelines have been proven to be a cost-effective method towards mitigating erosion along sheltered coasts. Gittman et al. (2014) observe that marsh with or without sills perform better than bulkheads during a Category 1 hurricane at their study sites in the Central Outer Banks, North Carolina, while bulkheads were the least cost effective method of erosion control. As living shoreline demonstration projects, like that, by Gittman et al. (2014) become more common, their effectiveness towards mitigating erosion will be better observed and understood.

Living shorelines may also be less expernsive to install and maintain than traditional hard structures. (Linham et al., 2010; VCZM, 2012, Mason, 2014). Mason (2014) explains that living shorelines enhance the ecological value of the property. The long-term value added from promoting ecosystem services provided through living shoreline design is a benefit not often considered when choosing a shoreline stabilization technique. Living shorelines maintain the natural quality of the shoreline – living shorelines increase water quality and enhance habitat for economically-important shellfish and fish which, in return, promotes commercial and recreational boating and fishing activities. Living shorelines may provide a larger return per dollar invested than traditional hardening techniques.

5.4.3 Permitting

Regulatory obstacles are a major challenge to living shoreline implementation. Shoreline erosion structures may require permitting at the local, state, and federal levels. The complex – and sometimes conflicting – permit processes are a major difficulty for coastal engineering firms and waterfront property owners (Mason, 2014). Another issue with permitting is the timing of the review process. For example, planting of tidal wetland vegetation is best in the spring, so successfully timing living shoreline implementation with permitting is a challenging process. Acquisition of native plants for living shorelines may also be a problem certain times of year if not properly coordinated with the review process. However, perhaps the biggest threat to living shoreline implementation will be the increase in requests for hard structures as sea level rises and coastal storms intensify (New Jersey Department of Environmental Protection [NJDEP], 2009). The current national permitting framework provides a reactive approach where shoreline stabilization is not usually considered until after a storm event occurs. Thus, streamlining living shoreline permitting as an innovative, proactive measure against shoreline erosion requires

reworking of current shoreline management laws and regulations (NJDEP, 2009). Local and state agencies may be more familiar with permitting for hard structures, so shifting towards living shoreline implementation is an enormous task.

5.5 Solutions to Living Shoreline Implementation

This study addresses the key issue of providing baseline information for living shoreline implementation. As a first step in considering nature-based approaches to mitigate erosion, this study provides a decision support tool to waterfront property owners, local municipalities, and the state of Connecticut to determine where living shorelines may work along the Connecticut coast. This study also recommends that the state of Connecticut builds decision support tools similar, in approach, to the CCRM decision trees, geospatial models, and waterfront property owner shoreline erosion control guidelines used by other state agencies.

The DEEP Office of Long Island Sound Programs (OLISP) released the *Connecticut Coastal Management Manual* in September 2000, which currently reflects the reactive and outdated nature of implementing hard shoreline structures. OLISP provides a “Municipal Coastal Management Review Process Flowchart” which highlights the major steps towards achieving project compliance (2000, p. 6). This study recommends updating this flowchart to reflect statutes set forth in the 2012 *An Act Concerning the Coastal Management Act and Shoreline Flood and Erosion Control Structures* where nature-based erosion control practices must be considered. Additionally, the first question the flowchart asks: “Is the project site in the coastal boundary?” This study also recommends implementing a GIS viewer that delineates local boundaries, the state of Connecticut’s Coastal Jurisdiction Line, and federal boundaries. Hydrographically-based coastal boundaries can be delineated using LiDAR, orthoimagery, and

by using a uniform tidal datum. A GIS viewer that shows these boundaries may help to avoid jurisdictional disputes and streamline the permitting process.

Another recommendation for Connecticut is to create official guidelines that prescribe shoreline erosion stabilization techniques for waterfront property owners consistent with current state and federal laws and regulations and local ordinances. On the OLISP website, Planning Report No. 29 *Shoreline Erosion Analysis and Recommended Planning Process*[12] outlines best management practices that include revetments and bulkheads (DEEP, 1979). Although this report is an excellent source for understanding local, hydrodynamic, and regional parameters impacting erosion in Long Island Sound, an updated report must be created that considers living shoreline designs. The Maryland Department of Natural Resources (2006) *Shoreline Erosion Control guidelines for Waterfront Property Owners* and the North Carolina Division of Coastal Management (2011) *Weighing Your Options – How to Protect Your Property from Shoreline Erosion: A handbook for estuarine property owners in North Carolina* both serve as excellent examples towards creating erosion control guidelines for coastal landowners here in Connecticut.

[12] http://www.ct.gov/deep/lib/deep/long_island_sound/coastal_hazards/plngreport29.pdf

Chapter 6: Conclusion

Long Island Sound is one of Connecticut's most important natural resources. As sea level rises and coastal storms intensify, associated land loss from erosion will be a major issue for Connecticut's Long Island Sound shoreline. The traditional method to protect waterfront property has been shoreline armoring. However, the 2012 legislation, *An Act Concerning the Coastal Management and Shoreline Flood and Erosion Control Structures*, restricts shoreline hardening in the state of Connecticut due to the adverse environmental consequences caused from hard structures like seawalls and bulkheads. This legislation provides the opportunity to implement nature-based shoreline stabilization strategies like living shorelines in Connecticut.

Living shorelines mimic coastal processes of a natural shoreline while restoring, enhancing, or creating natural habitats. Living shorelines develop in low to moderate wave energy climates, and offer many ecosystem services such as food, recreation, and storm protection. Living shorelines can include non-structural techniques, designed for low wave energy shorelines, such as beach nourishment and dune restoration, marsh restoration or marsh creation, as well as bank grading of natural riparian buffers. Living shorelines can also include hybrid design options where the goal is to provide higher levels of protection than non-structural shoreline stabilization techniques. Hybrid options include marsh sills, marsh toe revetments, breakwaters, and shell or artificial reefs. Living shorelines are a popular technique along sheltered coasts like those of North Carolina, Maryland, Virginia, and the Gulf Coast. Research from these areas suggest that living shorelines are more resilient than shoreline hardening techniques and are more cost-efficient than hardening strategies.

This report supports coastal resilience efforts by modeling site suitability of living shorelines along Connecticut's Long Island Sound shoreline. This is the first report for

Connecticut that determines the suitability of various living shoreline design options in Connecticut, based on previous living shoreline suitability studies for other regions and Miller et al.'s (2015) living shoreline engineering guidelines. Using ArcGIS 10.2 and Python programming, this study has established a methodology to automate geoprocessing workflows in deriving site suitability. Results from this study reveals that there is significant potential for both soft, non-structural design options and hybrid living shoreline strategies. Overall, 46.52% of the shoreline, as defined by this study, is potentially suitable for living shoreline treatments.

Living shoreline strategies face many challenges, in terms of outreach, cost, and permitting, ahead of living shoreline implementation in Connecticut. Moving towards a national framework that promotes living shoreline strategies as part of community coastal resilience plans will require significant effort. However, as climate change looms and development within coastal regions booms, it will be absolutely necessary. This study provides that crucial first step to expand and encourage the use of living shoreline treatment options in Connecticut. The model offers an important screening tool for environmental planners, homeowners, environmental engineers, and consultants in considering erosion control alternatives to shoreline hardening.

Literature Cited

An Act Concerning the Coastal Management Act and Shoreline Flood and Erosion Control Structures. Connecticut stat. §§ 12-101 (2012).

Atlantic States Marine Fisheries Commission. (2010). Living shorelines: impacts of erosion control strategies on coastal habitats. Habitat Management Series 10.

Berman, M. and Rudnicky, T. (2008). The living shoreline suitability model Worcester County, Maryland. Coastal Zone Management Program.

Boyd, Chris A., Dutta, Saranee, and Jones, Stephen. (2014). Living shoreline site suitability modeling for Mobile Bay: a GIS & remote sensing-based approach. *Grand Bay National Estuarine Research Reserve*. Retrieved October 24, 2014, from http://grandbaynerr.org/wp-content/uploads/2014/06/Status-of-research_Boyd.pdf

Carey, M. (2013). Modeling site suitability of living shorelines in the Albemarle-Pamlico estuarine system. Masters of Art Thesis, East Carolina University.

Chang, K. (2014). *Introduction to Geographic Information Systems, Seventh Edition*. New York, NY: McGraw-Hill.

Chesapeake Bay Foundation. (2007). *Living shorelines for the Chesapeake Bay watershed.* Philip Merrill Environmental Center: Annapolis, Maryland. Retrieved September, 27, 2014, from http://www.cbf.org/Document.Doc?id=60

Connecticut Department of Environmental Protection. (1979). Shoreline erosion analysis and recommended planning process. The Connecticut Coastal Area Management Program. Retrieved January 3, 2016, from http://www.ct.gov/deep/lib/deep/long_island_sound/coastal_hazards/plngreport29.pdf

Connecticut Department of Environmental Protection. (2002). *Connecticut Coastal Management Manual*. Office of Long Island Sound Programs, Coastal Programs. Retrieved January 5, 2016, from http://www.ct.gov/deep/lib/deep/long_island_sound/coastal_management_manual/manual_08.pdf

Connecticut Department of Environmental Protection. *Tidal Wetlands Buffer Guidance Document*. Office of Long Island Sound Programs. Retrieved January 5, 2016, from http://www.ct.gov/deep/lib/deep/long_island_sound/coastal_management/twbufferguidance.pdf

Connecticut Department of Energy & Environmental Protection. (2012). Coastal Jurisdiction Line – Fact Sheet. Retrieved January 3, 2016, from http://www.ct.gov/DEep/cwp/view.asp?a=2705&Q=511544&deepNAV_GID=1622

Connecticut Department of Energy & Environmental Protection. (2012). Long Island Sound. Retrieved January 3, 2016, from http://www.ct.gov/DEep/cwp/view.asp?a=2705&q=323790&deepNav_GID=1635

Currin, C.A., Chappell, W.S., and Deaton, A. (2010). Developing alternative shoreline armoring strategies: The living shoreline approach in North Carolina, *in* Shipman, H., Dethier, M.N., Gelfenbaum, G., Fresh, K.L., & Dinicola, R.S. (2010). Puget Sound Shorelines and the Impacts of Armoring—Proceedings of a State of the Science Workshop, May 2009: *U.S. Geological Survey Scientific Investigations Report* 2010-5254, 91-102.

Dean, R. G. (1986). *Coastal Armoring: Effects, Principles and Mitigation*. Proceedings of 20th Coastal Engineering Conference, American Society of Civil Engineers, p.1843-1857.

Duhring, Karen A. (2006). Overview of Living Shoreline Design Options for Erosion Protection on Tidal Shorelines, *in* Erdle, S.Y., J.L.D. Davis, and K.G. Sellner, eds. (2008). Management, Policy, Science and Engineering of Nonstructural Erosion Control in the Chesapeake Bay: Proceedings of the 2006 Living Shoreline Summit. Tools and Decision-Making: Facilitating and Encouraging Living Shoreline Implementation. *CRC* Publ. No. 08-164, Gloucester Point, VA, 13-18.

Eastman, J.R., Kyem, P.A.K., and Toledano, J. (1993). A procedure for multi-objective decision making in GIS under conditions of competing objectives. *Proceedings, EGIS'93*, 438-447.

Erdle, S.Y., J.L.D. Davis, and K.G. Sellner, eds. (2008). Management, Policy, Science and Engineering of Nonstructural Erosion Control in the Chesapeake Bay: Proceedings of the 2006 Living Shoreline Summit. CRC Publ. No. 08-164, Gloucester Point, VA, 136p.

Ferreira, M. (2014). Transect tool for ArcGIS 10.1 available online at http://gis4geomorphology.com/stream-transects-partial/

Frizzera, Dorina. (2009). Mitigating shoreline erosion along New Jersey's sheltered coast: overcoming regulatory obstacles to allow for living shorelines. New Jersey Department of Environmental Protection, Office of Coastal Management. Retrieved October 24, 2014, from http://www.nj.gov/dep/cmp/docs/living-shorelines2011.pdf

Galveston Bay Foundation. (2014). LIVING SHORELINES: a natural approach to erosion control. Webster, TX. Retrieved September 20, 2014, from http://galvbay.org/root/htdocs/

Gittman, Rachel K., Popowich, Alyssa M., Bruno, John F., Peterson, and Charles H. (2014). Marshes with and without sills protect estuarine shorelines from erosion better than bulkheads during a Category 1 hurricane. *Elsevier: Ocean & Coastal Management*, 102(2014), 94-102. DOI: 10.1016/j.ocecoaman.2014.09.016

Hardaway, C. S. Jr. and R.J. Byrne. (1999). Shoreline Management in Chesapeake Bay. Special Report in Applied Marine Science and Ocean Engineering Number 356, Virginia Sea Grant Publication VSG- 99-11. October 1999. 54 pp.

Hardaway, C. Scott & Duhring, Karen. (2010). Living Shoreline Design Guidelines for Shore Protection in Virginia's Estuarine Environments, Version 1.2. Virginia Institute of Marine Science. College of William & Mary: Gloucester Point, Virginia. Retrieved October 24, 2014, from http://web.vims.edu/physical/research/shoreline/docs/LS_Design_final_v1.2.pdf

Hoover, Mark. (2009). Connecticut's changing salt marshes. A remote sensing approach to sea level rise and possible salt marsh migration. Master of Science Thesis, University of Connecticut.

Jacobson, Sue. (2015). *Permitting Living Shorelines in Connecticut* [PowerPoint Slides]. Retrieved May 2, 2016, from http://clear.uconn.edu/climate/docs/living-shorelines/1-2015/JacobsonLivingShorelines.pdf

Kraus, N. C., & William G. McDougal. (1996). The Effects of Seawalls on the Beach: Part I, An Updated Literature Review.*Journal of Coastal Research*, *12*(3), 691–701. Retrieved from http://www.jstor.org/stable/4298517

Linham, M., Green, C., and Nicholls, R. (2010). Costs of Adaptation to the Effects of Climate Change in the World's Large Port Cities. Work stream 2, Report 14 of the AVOID programme (AV/WS2/D1/R14).

Mason, Pam. (2014). Living shoreline implementation: challenges and solutions. *Rivers & Coast*, 9(2), 1-11.

Maryland Department of Natural Resources. (2007). *Shore Erosion Control Guidelines for Waterfront Property Owners*. Coastal Resources Division, Tidewater Administration. Retrieved October 24, 2014, from http://www.seagrant.umaine.edu/files/chg/MDwaterfrontpropertyownersguide.pdf

Miller, John K., Rella, Andrew, Williams, Amy, and Sproule, Erin. (2015). Living Shoreline Engineering Guidelines. Stevens Institute of Technology: Davidson Laboratory, Center for Maritime Systems.

National Research Council. (2007). *Mitigating Shore Erosion on Sheltered Coasts*. Washington, D.C.: The National Academies Press, 188p.

National Oceanic and Atmospheric Administration. (2015). Guidance for Considering the Use of Living Shorelines. Retrieved November 27, 2015, from http://www.habitat.noaa.gov/pdf/noaa_guidance_for_considering_the_use_of_living_shorelines_2015.pdf

National Oceanic and Atmospheric Administration. (2016). Tides and Currents website. Retrieved on October 24, 2014, from http://www.habitat.noaa.gov/index.html

O'Brien, K., Stocker, J., Barrett, J., and Hyde, B. (2014). Analysis of Shoreline Change in Connecticut. A cooperative effort between the Connecticut Department of Energy & Environmental Protection (DEEP), the Connecticut Sea Grant (CT Sea Grant), and the University of Connecticut Center for Land Use Education and Research (UConn - CLEAR). 51p.

Odum, W.E. (1970). Insidious alteration of the estuarine environment. *Transactions of the American Fisheries Society*. 4, 836-847.

Ondiviela, Barbara, Losada, Inigo J., Lara, Javier L., Maza, Maria, Galvan, Christina, Bouma, Tjeerd J., and Belzen, Jim van. (2013). The role of seagrasses in coastal protection in a changing climate. *Elsevier: Coastal Engineering*, 87(2014), 158-168. Doi: 10.1016/j.coastaleng.2013.11.005

Restore America's Estuaries. (2014). *Living Shorelines: From Barriers to Opportunities.* Draft Report Available for Comment. Retrieved November 25, 2014, from http://www.estuaries.org/LivingShorelines/Draft_Opportunities_Report.pdf

Rohweder, J., Rogala, J. T., Johnson, B. L., Anderson, D., Clark, S., Chamberlin, F., Potter, D., and Runyon, K. (2012). Application of Wind Fetch and Wave Models for Habitat Rehabilitation and Enhancement Projects – 2012 Update. Contract report prepared for U.S. Army Corps of Engineers' Upper Mississippi River Restoration – Environmental Management Program. 52 p.

Rogers, S. M. (2007). Beach nourishment for hurricane protection: North Carolina project performance in Hurricanes Dennis and Floyd. *Shore and Beach*, 75(1).

Seachange Consulting. (2011). *Weighing Your Options, How To Protect Your Property from Shoreline Erosion: A handbook for estuarine property owners in North Carolina.* Division of Coastal Management, NC, 51 pp.

Scyphers SB, Powers SP, Heck KL Jr, and Byron D. (2011). Oyster reefs as natural breakwaters mitigate shoreline loss and facilitate fisheries. PLoS ONE 6(8): e22396. doi:10.1371/journal.pone.0022396

Virginia Institute of Marine Science. (2010). *Education: Living Shoreline Design – A Class for Marine Contractors. Module 2: understanding and predicting site suitability*. Center for Coastal Resources Management: Gloucester Point, Virginia. Retrieved October 24, 2014, from http://ccrm.vims.edu/education/ls_design_class/index.html

Virginia Institute of Marine Science. (2010). *VIMS – CCRM Coastal Management Decision Tools, Decision Tree for Undefended Shorelines and Those with Failed Structures*. Center for Coastal Resources Management: Gloucester Point, Virginia. Retrieved

October 24, 2014, from http://ccrm.vims.edu/education/workshops_events/april2010/Decision%20Trees%20Descriptions%20and%20Explanations-3May2010.pdf

Virginia Coastal Zone Management Program. (2012). *Living Shorelines: The Preferred Approach to Shoreline Erosion Protection*. Retrieved October 24, 2014, from http://www.deq.virginia.gov/Portals/0/DEQ/CoastalZoneManagement/Living%20Shorelines%20Fact%20Sheet.pdf

United States Army Corps of Engineers. (1984). *Shore Protection Manual*. U.S. Government Printing Office, Washington, DC, Vol II, 480 p., Appendices.

United States Army Corps of Engineers. (2014). *Reducing Coastal Risk on the East and Gulf Coasts*. Washington, DC: The National Academies Press.

Appendix A:
Bathymetry Reclassification Script

```
# LIVING SHORELINE SITE SUITABILITY ANALYSIS
# Updated October 08, 2015
# By Jason Zylberman
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# University of Connecticut


# Layers for suitability analysis
# 1 - Beach
# 2 - Marsh
# 3 - Bathymetry
# 4 - Fetch
# 5 - Erosion Rate


## Section 1.--------------------------------------------------------------------------------
## Ignore; Move to next Section 2.

# Import modules and set up geoprocessor
from datetime import datetime
start_time = datetime.now()
import arcpy, os, os.path
from arcpy import env
# allow outputs to be overwritten
env.overwriteOutput = 1
# checking out spatial analyst extension
arcpy.CheckOutExtension("Spatial")
# import spatial analyst keys
from arcpy.sa import *


## Section 2. Set inputs and variables ---------------------------------------------------------
## Here is where you will input your layers to initiate living shoreline site suitability analysis.

# Set the Workspace; This is where processed data is placed.
# Make sure it is the same workspace as the other reclassify scripts.
env.workspace = r"E:\LS_Results\Westport" #change folder as necessary

# Inputs:
CUSP = r"E:\LS_Suitability_Model\MHW\Towns\Westport_CUSP.shp" # import the MHW
shoreline from the NOAA CUSP dataset
```

```
Marsh = r"E:\CT_Marsh\Processed\Towns\Westport_Marsh.img" # *absolutely necessary for
snap raster*
Bathymetry =
r"E:\LS_Suitability_Model\Bathymetry\Towns\Interpolation\Westport_Bathymetry_Interpolated
.img" # add bathymetry raster

### Set a variable for Study Area on where analysis is to be performed
StudyArea = r"E:\LS_Suitability_Model\Study_Area\Westport_Study_Area.shp"


## Section 3. Analysis Output Folder / Environments ---------------------------------------------------
-------
# This code creates a subfolder within the workspace for final processed layers.  Also creates
Scratch Workspace,
# sets Processing Extent, sets Snap Raster, and sets Output Coordinate System. Move to section
4 if your
# input data uses Connecticut State Plane (US Feet) Coordinates. Change the spatial reference, if
not.

# Set the Output Coordinate System
## desc = arcpy.Describe(ProcessingExtent)
## spatRef = desc.spatialreference
env.outputCoordinateSystem = arcpy.SpatialReference(2234) # Change Factory Code as Needed

# Cell Size for Interpolations/Raster Creation
CellSize = 3

# Create variable for town name based on BeachFC
Town_name = os.path.basename(StudyArea)
town = Town_name[:-15]
print town

analysisDir = env.workspace + "\\" + town + "_Layers_for_Analysis"
if not os.path.exists(analysisDir):
	os.makedirs(analysisDir)
print analysisDir

env.scratchWorkspace = env.workspace + "\\" + "Temp"

env.extent = StudyArea

# Set Snap Raster based on Marsh Input Layer
env.snapRaster = Marsh

# Print Set Environments for Analysis
print "Set Environments for Analysis"
```

```
print "----------------------"

## Section 4. Layer 3: Bathymetry ----------------------------------------------------------
## GOAL - Reclassify bathymetry so that if the 1 meter contour line is greater than 30 feet
offshore,
## bathymetry is considered shallow and set to a value of 1.

# Buffer CUSP 98.4252 feet (30 meters).
CUSPdist = "98.4252 Feet"
buffCUSP = env.workspace + "\\" + town + "_CUSP_Buffered.shp"
arcpy.Buffer_analysis (CUSP, buffCUSP, CUSPdist)
print buffCUSP

# Dissolve buffCUSP to remove all the lines
dissolveCUSP = env.workspace + "\\" + town + "_CUSP_Dissolved.shp"
arcpy.Dissolve_management (buffCUSP, dissolveCUSP)
print dissolveCUSP

# Convert dissolveCUSP to polyline
lineCUSP = env.workspace + "\\" + town + "_CUSP_30mLine.shp"
arcpy.PolygonToLine_management (dissolveCUSP, lineCUSP)
print lineCUSP

# Extract by mask values that lie along lineCUSP.
bathExtracted = arcpy.sa.ExtractByMask(Bathymetry, lineCUSP)
bathExtracted.save(env.workspace + "\\" + town + "_bath_30mExtracted.img")
print bathExtracted

# Extract positive values from bathExtracted
desc3 = arcpy.Describe(bathExtracted)
xMin3 = desc3.Extent.XMin
yMin3 = desc3.Extent.YMin
cellsize3 = desc3.MeanCellWidth
refPnt3 = arcpy.Point(xMin3,yMin3)

bathymetryArray = arcpy.RasterToNumPyArray(bathExtracted)

bathymetryArray[bathymetryArray > 0]
bathymetryArray[bathymetryArray <= 0] = -9999

BathPos = arcpy.NumPyArrayToRaster(bathymetryArray, refPnt3, cellsize3, cellsize3,
value_to_nodata = -9999)

# Save the Reclassified Raster
BathPos.save(env.workspace + "\\" + town + "_BathPositive.img")
# Print BathPos
```

```
print BathPos

# BathRec represents a nearshore depth. However, for purpose of analysis, BathRec must be
interpolated
# landware. First, convert BathRec to Point Shapefile
bathPnt = env.workspace + "\\" + town + "_bathPts.shp"
arcpy.RasterToPoint_conversion (BathPos, bathPnt)
print bathPnt

# Interpolate a raster surface from bathPnt using Inverse distance weighted
# (IDW) interpolation.  IDW determines cell values using a linearly weighted combination
# of a set of sample points. This method assumes that the variable being mapped decreases
# in influence with distance from its sample location. The average cannot be greater than
# its highest input or lower than its lowest input.
SearchRadius = RadiusFixed(600,"")
bathZField = "grid_code"
power = 2
bathIDW = arcpy.sa.Idw (bathPnt, bathZField, CellSize, power, SearchRadius)

# Save the output
bathIDW.save(env.workspace + "\\" + town + "_bathIDW.img")
print bathIDW

# Living shorelines are suitable where the 1m contour is > 30m than the shore.
# Therefore extract values that are less than 3.28084 ft from bathIDW.
bathIDW = env.workspace + "\\" + town + "_bathIDW.img"
desc4 = arcpy.Describe(bathIDW)
xMin4 = desc4.Extent.XMin
yMin4 = desc4.Extent.YMin
cellsize4 = desc4.MeanCellWidth
refPnt4 = arcpy.Point(xMin4,yMin4)

bathymetryArray2 = arcpy.RasterToNumPyArray(bathIDW, nodata_to_value = 0)

bathymetryArray2[bathymetryArray2 > 3.28084] = 0
bathymetryArray2[(bathymetryArray2 > 0) & (bathymetryArray2 <=3.28084)] = 1

BathRec = arcpy.NumPyArrayToRaster(bathymetryArray2, refPnt4, cellsize4, cellsize4)

# Save the Reclassified Raster
BathRec.save(env.workspace + "\\" + town + "_BathRec.img")
# Print BathRec
print BathRec

# Clip BathRec to the Study Area
Final_Bath = analysisDir + "\\" + town + "_Final_Bathymetry.img"
```

```
arcpy.Clip_management (BathRec, "#", Final_Bath, StudyArea, "", "ClippingGeometry")
print Final_Bath
# Print "Bathymetry Reclassify Complete"
print "Bathymetry Reclassify Complete"
print "----------------------"


end_time = datetime.now()

print("Duration: {}".format(end_time - start_time))
```

Appendix B:

Beach Reclassification Script

```
# LIVING SHORELINE SITE SUITABILITY ANALYSIS
# Updated October 08, 2015
# By Jason Zylberman
# Natural Resources and the Environment
# University of Connecticut


# Layers for suitability analysis
# 1 - Beach
# 2 - Marsh
# 3 - Bathymetry
# 4 - Fetch
# 5 - Erosion Rate


## Section 1.--------------------------------------------------------------------------------
## Ignore; Move to next Section 2.

# Import modules and set up geoprocessor
from datetime import datetime
start_time = datetime.now()
import arcpy, os, os.path
from arcpy import env
# allow outputs to be overwritten
env.overwriteOutput = 1
# checking out spatial analyst extension
arcpy.CheckOutExtension("Spatial")
# import spatial analyst keys
from arcpy.sa import *


## Section 2. Set inputs and variables -------------------------------------------------------
## Here is where you will input your layers to initiate living shoreline site suitability analysis.

# Set the Workspace; This is where processed data is placed.
# Make sure it is the same workspace as the other reclassify scripts.
env.workspace = r"E:\LS_Results\Westport" #change folder as necessary

# Inputs:
Marsh = r"E:\CT_Marsh\Processed\Towns\Westport_Marsh.img" # *absolutely necessary for
snap raster*
```

```
BeachFC = r"E:\LS_Suitability_Model\Beach\Town\Westport_Beaches.shp" # add beach
shapefile;
### Set a variable for Study Area on where analysis is to be performed
StudyArea = r"E:\LS_Suitability_Model\Study_Area\Westport_Study_Area.shp"


## Section 3. Analysis Output Folder / Environments --------------------------------------------------
-------
# This code creates a subfolder within the workspace for final processed layers.  Also creates
Scratch Workspace,
# sets Processing Extent, sets Snap Raster, and sets Output Coordinate System. Move to section
4 if your
# input data uses Connecticut State Plane (US Feet) Coordinates. Change the spatial reference, if
not.

# Set the Output Coordinate System
## desc = arcpy.Describe(ProcessingExtent)
## spatRef = desc.spatialreference
env.outputCoordinateSystem = arcpy.SpatialReference(2234) # Change Factory Code as Needed

# Cell Size for Interpolations/Raster Creation
CellSize = 3

# Create variable for town name based on BeachFC
Town_name = os.path.basename(StudyArea)
town = Town_name[:-15]
print town

analysisDir = env.workspace + "\\" + town + "_Layers_for_Analysis"
if not os.path.exists(analysisDir):
	os.makedirs(analysisDir)
print analysisDir

env.scratchWorkspace = env.workspace + "\\" + "Temp"

### Set the processing extent environment by Buffering the StudyArea 0.5 Miles
##ProcessingExtent = env.workspace + "\\" + town + "_ProcessingExtent.shp"
##BufferStudy = "2640 Feet"
##
##arcpy.Buffer_analysis(StudyArea, ProcessingExtent, BufferStudy)
##print ProcessingExtent

env.extent = StudyArea

# Set Snap Raster based on Marsh Input Layer
env.snapRaster = Marsh
```

```
# Print Set Environments for Analysis
print "Set Environments for Analysis"
print "----------------------"


## Section 4. Layer 1: BEACHES ---------------------------------------------------------------

# GOAL - To reclassify beaches so that area within beaches is suitable for living shorelines and
set to a value of 1.

# Add Field to BeachFC called "GridVal"
arcpy.AddField_management(BeachFC, "GridVal", "SHORT")
# Give "GridVal" a value of 5
arcpy.CalculateField_management(BeachFC, "GridVal", 1)

# Convert BeachFC to Raster
BeachRaster = env.workspace + "\\" + town + "_BeachRas.img"
arcpy.PolygonToRaster_conversion (BeachFC, "GridVal", BeachRaster, "", "", CellSize)
print BeachRaster

# Reclassify BeachRaster to a value of 1 and set NoData value = 0

desc1 = arcpy.Describe(BeachRaster)
xMin1 = desc1.Extent.XMin
yMin1 = desc1.Extent.YMin
cellsize1 = desc1.MeanCellWidth
refPnt1 = arcpy.Point(xMin1,yMin1)

beachArray = arcpy.RasterToNumPyArray(BeachRaster, nodata_to_value = 0)

BeachRec = arcpy.NumPyArrayToRaster(beachArray, refPnt1, cellsize1, cellsize1)

# Save the Reclassified Raster
BeachRec.save(env.workspace + "\\" + town + "_BeachRec.img")
# Print BeachRec
print BeachRec

# Clip the Reclassified Beach raster to the Study Area and send to a new folder
# called "Layers_for_Analysis"
Final_Beach = analysisDir + "\\" + town + "_Final_Beach.img"

arcpy.Clip_management (BeachRec, "#", Final_Beach, StudyArea, "", "ClippingGeometry")
print Final_Beach

# Print "Beach Reclassify Complete"
```

```
print "Beach Reclassify Complete"
print "----------------------"
end_time = datetime.now()

print("Duration: {}".format(end_time - start_time))
```

Appendix C:
Erosion Reclassification Script

```
# LIVING SHORELINE SITE SUITABILITY ANALYSIS
# Updated October 08, 2015
# By Jason Zylberman
# Natural Resources and the Environment
# University of Connecticut


# Layers for suitability analysis
# 1 - Beach
# 2 - Marsh
# 3 - Bathymetry
# 4 - Fetch
# 5 - Erosion Rate


## Section 1.--------------------------------------------------------------------------------
## Ignore; Move to next Section 2.

# Import modules and set up geoprocessor
from datetime import datetime
start_time = datetime.now()
import arcpy, os, os.path
from arcpy import env
# allow outputs to be overwritten
env.overwriteOutput = 1
# checking out spatial analyst extension
arcpy.CheckOutExtension("Spatial")
# import spatial analyst keys
from arcpy.sa import *

## Section 2. Set inputs and variables ---------------------------------------------------------
## Here is where you will input your layers, set workspace to initiate living shoreline site
suitability analysis.

# Set the Workspace; This is where processed data is placed.
# Make sure it is the same workspace as the other reclassify scripts.
env.workspace = r"E:\LS_Results\Westport" #change folder as necessary

# Inputs:
Marsh = r"E:\CT_Marsh\Processed\Towns\Westport_Marsh.img" # *absolutely necessary for
snap raster*
```

```
Erosion = r"E:\LS_Suitability_Model\DSAS\Erosion_Correction\Towns\Westport_Erosion.shp"
#add erosion rate from DSAS by CLEAR/DEEP
### Set a variable for Study Area on where analysis is to be performed
StudyArea = r"E:\LS_Suitability_Model\Study_Area\Westport_Study_Area.shp"


## Section 3. Analysis Output Folder / Environments ---------------------------------------------------
-------
# This code creates a subfolder within the workspace for final processed layers.  Also creates
Scratch Workspace,
# sets Processing Extent, sets Snap Raster, and sets Output Coordinate System. Move to section
4 if your
# input data uses Connecticut State Plane (US Feet) Coordinates. Change the spatial reference, if
not.

# Set the Output Coordinate System
## desc = arcpy.Describe(ProcessingExtent)
## spatRef = desc.spatialreference
env.outputCoordinateSystem = arcpy.SpatialReference(2234) # Change Factory Code as Needed

# Cell Size for Interpolations/Raster Creation
CellSize = 3

# Create variable for town name based on BeachFC
Town_name = os.path.basename(StudyArea)
town = Town_name[:-15]
print town

analysisDir = env.workspace + "\\" + town + "_Layers_for_Analysis"
if not os.path.exists(analysisDir):
	os.makedirs(analysisDir)
print analysisDir

env.scratchWorkspace = env.workspace + "\\" + "Temp"

### Set the processing extent environment by Buffering the StudyArea 0.5 Miles
##ProcessingExtent = env.workspace + "\\" + town + "_ProcessingExtent.shp"
##BufferStudy = "2640 Feet"
##
##arcpy.Buffer_analysis(StudyArea, ProcessingExtent, BufferStudy)
##print ProcessingExtent

env.extent = StudyArea

# Set Snap Raster based on Marsh Input Layer
env.snapRaster = Marsh
```

```
# Print Set Environments for Analysis
print "Set Environments for Analysis"
print "----------------------"


# Section 4. Layer 5: Erosion Rate ------------------------------------------------------------
## Goal - Interpolate fetch transects to represent erosion continuously along shoreline. Reclassify erosion to the
## extent of Study Area so that > -2 miles (Low) is set to a value of 1, -2 - -4 miles (Moderate) is set to a value of .5,
## > -4 miles (High) is set to a value of 0, and the rest is set to 0.  The higher the rate of erosion,
## the less suitable area for a living shoreline.

# Create a copy of the erosion layer so that you are not deleting attributes of the original erosion layer
Erosion_Copy = env.workspace + "\\" + town + "_erosionCopy.shp"
arcpy.CopyFeatures_management (Erosion, Erosion_Copy)
print Erosion_Copy


# Create Update cursor to remove industrialized waterfront from DSAS Erosion Layer.
rows = arcpy.UpdateCursor(Erosion_Copy)

# for each row object
for row in rows:

    # get the value of the omit category. Omit Category 1 - which is industrialized waterfront
    # and not suitable for analysis
    Omit = row.getValue("omit")

    # delete rows that have 1 in omit category
    if Omit == 1:
        rows.deleteRow(row)

# delete cursor and row objects
del rows, row

# print Erosion_Copy conversions/querying complete
print Erosion_Copy

## Interpolate Erosion along the Study Area using IDW.
erosionZfield = "EPR_FT"
power = 2
SearchRadius = RadiusFixed(600,"")
erosionIDW = arcpy.sa.Idw(Erosion_Copy, erosionZfield, CellSize, power, SearchRadius)
```

```
erosionIDW.save(env.workspace + "\\" + town + "_erosionIDW.img")
print erosionIDW
# Smooth FetchExtract using Focal Statistics
Stat_smooth = "MEAN"
erosionSmooth = arcpy.sa.FocalStatistics(erosionIDW, "Rectangle 25 25 CELL", Stat_smooth,
"DATA")
erosionSmooth.save(env.workspace + "\\" + town + "_erosionSmooth.img")
print erosionSmooth

# Reclassify Erosion so that erosion > 2 feet per year is set to a value of 1, erosion 2-4 feet per
year
# is set to a value of .5, and greater than 4 feet per year is set to a value of 0.
erosionSmooth = env.workspace + "\\" + town + "_erosionSmooth.img"
desc6 = arcpy.Describe(erosionSmooth)
xMin6 = desc6.Extent.XMin
yMin6 = desc6.Extent.YMin
cellsize6 = desc6.MeanCellWidth
refPnt6 = arcpy.Point(xMin6,yMin6)

erosionArray = arcpy.RasterToNumPyArray(erosionSmooth)

erosionArray[erosionArray >= 0] = 1
erosionArray[(erosionArray >= -2) & (erosionArray < 0)] = 1
erosionArray[(erosionArray > -4) & (erosionArray < -2)] = 0.7
erosionArray[(erosionArray <= -4)& (erosionArray > -50)] = 0.3
erosionArray[erosionArray <= -50] = 0

ErosionRec = arcpy.NumPyArrayToRaster(erosionArray, refPnt6, cellsize6, cellsize6)

# Save the Reclassified Raster
ErosionRec.save(env.workspace + "\\" + town + "_erosionRec.img")
# Print erosionRec
print ErosionRec

# Clip FetchRec to the Study Area
Final_Erosion = analysisDir + "\\" + town + "_Final_Erosion.img"
arcpy.Clip_management (ErosionRec, "#", Final_Erosion, StudyArea, "", "ClippingGeometry")
print Final_Erosion

# Print "Erosion Reclassify Complete"
print "Erosion Reclassify Complete"
print "----------------------"


end_time = datetime.now()
```

```
print("Duration: {}".format(end_time - start_time))
```

Appendix D:
Fetch Reclassification Script

```
# LIVING SHORELINE SITE SUITABILITY ANALYSIS
# Updated October 08, 2015
# By Jason Zylberman
# Natural Resources and the Environment
# University of Connecticut


# Layers for suitability analysis
# 1 - Beach
# 2 - Marsh
# 3 - Bathymetry
# 4 - Fetch
# 5 - Erosion Rate


## Section 1.--------------------------------------------------------------------------------
## Ignore; Move to next Section 2.

# Import modules and set up geoprocessor
from datetime import datetime
start_time = datetime.now()
import arcpy, os, os.path
from arcpy import env
# allow outputs to be overwritten
env.overwriteOutput = 1
# checking out spatial analyst extension
arcpy.CheckOutExtension("Spatial")
# import spatial analyst keys
from arcpy.sa import *


## Section 2. Set inputs and variables -----------------------------------------------------------
## Here is where you will input your layers to initiate living shoreline site suitability analysis.

# Set the Workspace; This is where processed data is placed.
env.workspace = r"E:\LS_Results\Westport" #change folder as necessary

# Inputs:
Marsh = r"E:\CT_Marsh\Processed\Towns\Westport_Marsh.img" # *absolutely necessary for
snap raster*
meanFetch = r"E:\LS_Suitability_Model\Fetch\LIS_Fetch\lis_fetw_mean" #add fetch layer
created from USGS Application of Wind Fetch Model
```

```
### Set a variable for Study Area on where analysis is to be performed
StudyArea = r"E:\LS_Suitability_Model\Study_Area\Westport_Study_Area.shp"


## Section 3. Analysis Output Folder / Environments ---------------------------------------------------
-------
# This code creates a subfolder within the workspace for final processed layers.  Also creates
Scratch Workspace,
# sets Processing Extent, sets Snap Raster, and sets Output Coordinate System. Move to section
4 if your
# input data uses Connecticut State Plane (US Feet) Coordinates. Change the spatial reference, if
not.

# Set the Output Coordinate System
## desc = arcpy.Describe(ProcessingExtent)
## spatRef = desc.spatialreference
env.outputCoordinateSystem = arcpy.SpatialReference(2234) # Change Factory Code as Needed

# Cell Size for Interpolations/Raster Creation
CellSize = 3

# Create variable for town name based on BeachFC
Town_name = os.path.basename(StudyArea)
town = Town_name[:-15]
print town

analysisDir = env.workspace + "\\" + town + "_Layers_for_Analysis"
if not os.path.exists(analysisDir):
	os.makedirs(analysisDir)
print analysisDir

env.scratchWorkspace = env.workspace + "\\" + "Temp"

env.extent = StudyArea

# Set Snap Raster based on Marsh Input Layer
env.snapRaster = Marsh

# Print Set Environments for Analysis
print "Set Environments for Analysis"
print "----------------------"
```

```
## Section 4. Layer 4: Fetch ----------------------------------------------------------------

## GOAL - Interpolate fetch raster to retrieve fetch values along shoreline.  Reclassify fetch to
the
## extent of Study Area so that 0-1 Miles (Low) is set to a value of 1, 1-5 Miles (Moderate) is set
to a value of .7,
## 5-6 miles (High) is set to a value of .3, and the rest is set to 0.  The higher the fetch distance,
## the less suitable area for a living shoreline.

# The fetch values are in feet. Convert feet to miles.
Miles = float(5280)
fetchMiles = arcpy.sa.Divide (meanFetch, Miles)
fetchMiles.save(env.workspace + "\\" + town + "_fetw_sum_miles.img")
print fetchMiles

# Unbounded fetches are artifacts from calculating fetch lengths on a raster and are represented
by
# negetative values. Remove negative values or unbounded fetches from fetchMiles.

desc4 = arcpy.Describe(fetchMiles)
xMin4 = desc4.Extent.XMin
yMin4 = desc4.Extent.YMin
cellsize4 = desc4.MeanCellWidth
refPnt4 = arcpy.Point(xMin4,yMin4)

unboundArray = arcpy.RasterToNumPyArray(fetchMiles)
unboundArray[unboundArray > 0] = 1
unboundArray[unboundArray <= 0] = 999

fetchBurnRec = arcpy.NumPyArrayToRaster(unboundArray, refPnt4, cellsize4, cellsize4,
value_to_nodata = 999)

# Save the Reclassified Raster
fetchBurnRec.save(env.workspace + "\\" + town + "_fetchBurnRec2.img")
# Print fetchBurnRec
print fetchBurnRec

# Multiply fetchBurnRec by fetchMiles to burn out the negative fetch (unbounded fetch) values
from fetchMiles.
fetchBurnoutMiles = (fetchBurnRec*fetchMiles)
fetchBurnoutMiles.save(env.workspace + "\\" + town + "_fetchBurnoutMiles.img")
print fetchBurnoutMiles

# fetchMiles represents the fetch for the entire Long Island Sound. Extract by mask the values
# that intersect the coast.
```

```
# Extract by mask the fetchBurnoutMiles values that are contained within the Study Area.
# This represents the fetch along the town's coast.
fetchExtract = arcpy.sa.ExtractByMask (fetchBurnoutMiles, StudyArea)
fetchExtract.save(env.workspace + "\\" + town + "_Final_Extract_Fetch_in_Miles.img")
print fetchExtract

# Convert fetchExtract to Point Shapefile
fetchPnt = env.workspace + "\\" + town + "_Final_Extract_Fetch_Points.shp"
arcpy.RasterToPoint_conversion (fetchExtract, fetchPnt)
print fetchPnt

# Interpolate a raster surface from fetchPnt_clip using Inverse distance weighted
# (IDW) interpolation.  IDW determines cell values using a linearly weighted combination
# of a set of sample points. This method assumes that the variable being mapped decreases
# in influence with distance from its sample location. The average cannot be greater than
# its highest input or lower than its lowest input.
SearchRadius = RadiusFixed(600,"")
fetchZField = "grid_code"
power = 2
fetchIDW = arcpy.sa.Idw (fetchPnt, fetchZField, CellSize, power, SearchRadius)

# Save the output
fetchIDW.save(env.workspace + "\\" + town + "_fetchIDW.img")
print fetchIDW

# Smooth fetchIDW using Focal Statistics
Stat_smooth = "MEAN"
fetchSmooth = arcpy.sa.FocalStatistics(fetchIDW, "Rectangle 25 25 CELL", Stat_smooth,
"DATA")
fetchSmooth.save(env.workspace + "\\" + town + "_fetchSmoothed.img")
print fetchSmooth

## Reclassify fetchExtract so that 0-1 miles is set to a value of 1, 1-5 Miles is set to a value of .7,
and
## > 5 miles is set to a value of .3, while all other values are set to 0.

desc5 = arcpy.Describe(fetchSmooth)
xMin5 = desc5.Extent.XMin
yMin5 = desc5.Extent.YMin
cellsize5 = desc5.MeanCellWidth
refPnt5 = arcpy.Point(xMin5,yMin5)

fetchArray = arcpy.RasterToNumPyArray(fetchSmooth)

fetchArray[fetchArray <= 0] = 0
```

```
fetchArray[(fetchArray > 0) & (fetchArray <= 1)] = 1
fetchArray[(fetchArray > 1) & (fetchArray <= 5)] = 0.7
fetchArray[fetchArray > 5] = 0.3

FetchRec = arcpy.NumPyArrayToRaster(fetchArray, refPnt5, cellsize5, cellsize5)

# Save the Reclassified Raster
FetchRec.save(env.workspace + "\\" + town + "_FetchRec.img")
# Print FetchRec
print FetchRec

# Clip FetchRec to the Study Area
Final_Fetch = analysisDir + "\\" + town + "_Final_Fetch.img"
arcpy.Clip_management (FetchRec, "#", Final_Fetch, StudyArea, "", "ClippingGeometry")
print Final_Fetch

# Print "Fetch Reclassify Complete"
print "Fetch Reclassify Complete"
print "----------------------"


end_time = datetime.now()

print("Duration: {}".format(end_time - start_time))
```

Appendix E:

Marsh Reclassification Script

```
# LIVING SHORELINE SITE SUITABILITY ANALYSIS
# Updated October 08, 2015
# By Jason Zylberman
# Natural Resources and the Environment
# University of Connecticut


# Layers for suitability analysis
# 1 - Beach
# 2 - Marsh
# 3 - Bathymetry
# 4 - Fetch
# 5 - Erosion Rate


## Section 1.-------------------------------------------------------------------------------
## Ignore; Move to next Section 2.

# Import modules and set up geoprocessor
from datetime import datetime
start_time = datetime.now()
import arcpy, os, os.path
from arcpy import env
# allow outputs to be overwritten
env.overwriteOutput = 1
# checking out spatial analyst extension
arcpy.CheckOutExtension("Spatial")
# import spatial analyst keys
from arcpy.sa import *


## Section 2. Set inputs and variables -------------------------------------------------------
## Here is where you will input your layers to initiate living shoreline site suitability analysis.

# Set the Workspace; This is where processed data is placed.
env.workspace = r"E:\LS_Results\Westport" #change folder as necessary

# Inputs:

Marsh = r"E:\CT_Marsh\Processed\Towns\Westport_Marsh.img" # add marsh raster
```

CUSP = r"E:\LS_Suitability_Model\MHW\Towns\Westport_CUSP.shp" # add MHW shoreline from NOAA CUSP dataset
Set a variable for Study Area on where analysis is to be performed
StudyArea = r"E:\LS_Suitability_Model\Study_Area\Westport_Study_Area.shp"

Section 3. Analysis Output Folder / Environments --
This code creates a subfolder within the workspace for final processed layers. Also creates Scratch Workspace,
sets Processing Extent, sets Snap Raster, and sets Output Coordinate System. Move to section 4 if your
input data uses Connecticut State Plane (US Feet) Coordinates. Change the spatial reference, if not.

Set the Output Coordinate System
desc = arcpy.Describe(ProcessingExtent)
spatRef = desc.spatialreference
env.outputCoordinateSystem = arcpy.SpatialReference(2234) # Change Factory Code as Needed

# Cell Size for Interpolations/Raster Creation
CellSize = 3

# Create variable for town name based on BeachFC
Town_name = os.path.basename(StudyArea)
town = Town_name[:-15]
print town

analysisDir = env.workspace + "\\" + town + "_Layers_for_Analysis"
if not os.path.exists(analysisDir):
    os.makedirs(analysisDir)
print analysisDir

env.scratchWorkspace = env.workspace + "\\" + "Temp"

env.extent = StudyArea

# Set Snap Raster based on Marsh Input Layer
env.snapRaster = Marsh

Print Set Environments for Analysis
print "Set Environments for Analysis"
print "----------------------"

Setion 4. Layer 2: MARSH ---

```
## GOAL - Reclassify marsh within 25 feet of shoreline and give a value of 1.
# Buffer the shoreline 25 feet
CUSPbuff = env.workspace + "\\" + town + "_MHW_Buffered_25ft.shp"
arcpy.Buffer_analysis(CUSP, CUSPbuff, "25 FEET")
print CUSPbuff

# Dissolve the buffered shoreline
CUSPdissolve = env.workspace + "\\" + town + "_MHW_Buffered_and_Dissolved.shp"
arcpy.Dissolve_management(CUSPbuff, CUSPdissolve)
print CUSPdissolve

# Clip the Reclassified Marsh raster to the Buffered Shoreline
MarshClip = env.workspace + "\\" + town + "_MarshClip.img"
arcpy.Clip_management (Marsh, "#", MarshClip, CUSPdissolve, "", "ClippingGeometry")
print MarshClip

# Reclassify Marsh to a value of 1 and set NoData = 0

desc2 = arcpy.Describe(MarshClip)
xMin2 = desc2.Extent.XMin
yMin2 = desc2.Extent.YMin
cellsize2 = desc2.MeanCellWidth
refPnt2 = arcpy.Point(xMin2,yMin2)

marshArray = arcpy.RasterToNumPyArray(MarshClip, nodata_to_value = 0)

MarshRec = arcpy.NumPyArrayToRaster(marshArray, refPnt2, cellsize2, cellsize2)

#Save the Reclassified Raster
MarshRec.save(env.workspace + "\\" + town + "_MarshRec.img")
# Print MarshRec
print MarshRec

# Clip the Reclassified Marsh raster to the Study Area and send to a new folder
# called "Layers_for_Analysis"
Final_Marsh = analysisDir + "\\" + town + "_Final_Marsh.img"
arcpy.Clip_management (MarshRec, "#", Final_Marsh, StudyArea, "", "ClippingGeometry")
print Final_Marsh

# Print "Marsh Reclassify Complete"
print "Marsh Reclassify Complete"
print "----------------------"


end_time = datetime.now()
```

```
print("Duration: {}".format(end_time - start_time))
```

Appendix F:
Living Shoreline Site Suitability Script

```
# LIVING SHORELINE SITE SUITABILITY ANALYSIS
# Updated October 08, 2015
# By Jason Zylberman
# Natural Resources and the Environment
# University of Connecticut


## This script produces suitable sites for the following living shoreline methods:
# 1) Beach Nourishment
# 2) Marsh Restoration/Enhancement
# 3) Marsh with Structure
# 4) Breakwater


## Section 1.--------------------------------------------------------------------------------
## Ignore; Move to next Section 2.

# Import modules and set up geoprocessor
from datetime import datetime
start_time = datetime.now()
import arcpy, os, os.path
from arcpy import env
# allow outputs to be overwritten
env.overwriteOutput = 1
# checking out spatial analyst extension
arcpy.CheckOutExtension("Spatial")
# import spatial analyst keys
from arcpy.sa import *


## Section 2. Set inputs and variables ----------------------------------------------------------
## Here is where you will input your layers to perform living shoreline site suitability analysis.

# This is your only input. Set analysisDir from reclassification scripts as workspace.
env.workspace = r"E:\LS_Results\New_Haven\New_Haven_Layers_for_Analysis"


## Section 3. Analysis Output Folder / Environments ----------------------------------------------------
-------
# This code creates a subfolder within the workspace for final processed layers.  Also creates
Scratch Workspace,
```

```
# sets Processing Extent, sets Snap Raster, and sets output Output Coordinate System. Move to
section 4 if your
# input data uses Connecticut State Plane (US Feet) Coordinates. Change the spatial reference, if
not.

env.outputCoordinateSystem = arcpy.SpatialReference(2234)

suitabilityDir = env.workspace + "\\" + "Suitability"
if not os.path.exists(suitabilityDir):
   os.makedirs(suitabilityDir)
print suitabilityDir

recLayers = arcpy.ListRasters()
Bathymetry = recLayers[0]
BathymetryObj = arcpy.sa.Raster(Bathymetry)
print BathymetryObj
Beach = recLayers[1]
BeachObj = arcpy.sa.Raster(Beach)
print BeachObj
Erosion = recLayers[2]
ErosionObj = arcpy.sa.Raster(Erosion)
print ErosionObj
Fetch = recLayers[3]
FetchObj = arcpy.sa.Raster(Fetch)
print FetchObj
Marsh = recLayers[4]
MarshObj = arcpy.sa.Raster(Marsh)
print MarshObj

env.extent = Fetch
env.snapRaster = Marsh

# Create variable for town name based on layers
town = Bathymetry[:-21]
print town

# Print Set Environments for Analysis
print "Set Environments for Analysis"
print "----------------------"


## Section 4: Beach Nourishment ---------------------------------------------------------------
## Beach Nourishment is suitable where all reclassified layers have a value of 1.

# First combine Beach constraints
Beach_constr = BathymetryObj * BeachObj
```

```
# Second combine Beach factors
Beach_fact = ErosionObj * FetchObj

# Multiply Beach constraints by Beach factors
Beach_mult = Beach_constr * Beach_fact

# Extract 1 values from Marsh_mult
Beach_nourishment = Beach_mult == 1

# Save Marsh_rest
Beach_nourishment.save(suitabilityDir + "\\" + town + "_Beach_Nourishment.img")
print Beach_nourishment


## Section 5: Marsh Restoration ----------------------------------------------------------------
## Marsh Restoration is suitable where all reclassified layers have a value of 1.

# First combine Marsh constraints
Marsh_constr = BathymetryObj * MarshObj

# Second combine Marsh factors
Marsh_fact = ErosionObj * FetchObj

# Multiply Marsh constraints by Marsh factors
Marsh_mult = Marsh_constr * Marsh_fact

# Extract 1 values from Marsh_mult
Marsh_restoration = Marsh_mult == 1

# Save Marsh_rest
Marsh_restoration.save(suitabilityDir + "\\" + town + "_Marsh_Restoration.img")
print Marsh_restoration

## Section 6: Marsh with Structure ----------------------------------------------------------------
## Marsh with Structure is suitable where erosion reclassified layers have low to moderate
erosion
## and reclassified fetch layers have moderate to high fetch.

# Extract Low (Value = 1) to Moderate (Value = .7) Erosion
Low_to_Mod_erosion = ErosionObj >= 0.68

# Extract Moderate (Value = .7) to High (Value = .3) Fetch
Mod_to_High_fetch = (FetchObj > .29) & (FetchObj < .71)

# Multiply Erosion and Fetch factors
```

```
Marsh_fact2 = Low_to_Mod_erosion * Mod_to_High_fetch

# Multiply Marsh constraints by Marsh factors
Marsh_structure = Marsh_constr * Marsh_fact2

# Save Marsh_structure
Marsh_structure.save(suitabilityDir + "\\" + town + "_Marsh_with_Structures.img")
print Marsh_structure


## Section 7: Breakwater ------------------------------------------------------------------
## Marsh with Structure is suitable where erosion reclassified layers have low to high erosion
## and reclassified fetch layers have moderate to high fetch.

# Extract Low (Value = 1) to High (Value = .3) Erosion
Low_to_High_erosion = ErosionObj >= 0.29

# Multiply Erosion and Fetch factors
Beach_fact2 = Low_to_High_erosion * Mod_to_High_fetch

# Multiply Beach constraints by Beach factors
Breakwater = Beach_constr * Beach_fact2

# Save Breakwater
Breakwater.save(suitabilityDir + "\\" + town + "_Offshore_Breakwater.img")
print Breakwater


## ---------------------------------------------------------------------------------------

# Print "Living Shoreline Site Suitability Analysis Complete !!"
print "Living Shoreline Site Suitability Analysis Complete"
print "----------------------"


end_time = datetime.now()

print("Duration: {}".format(end_time - start_time))
```

Appendix G:

Written Permission for Use of Figures

Below is an email correspondence from Karen A. Duhring of the Center for Coastal Resource Management (CCRM) at the Virginia Institute of Marine Science (VIMS) indicating permission for use of her figures. Permission was granted for Figure 2-6, Figure 2-10, and Figure 2-11 (All other figures were within “fair use”):

karend@vims.edu on Tuesday, February 9, 2016 at 9:50 AM RE: Living Shoreline Research:

> *“Hi Jason – I think these are OK. I took all 3 photos. You have my permission to use them cost and royalty free for your Master’s thesis, a living shoreline site suitability model for Connecticut, and an ArcGIS StoryMap. Please include proper credit, here is a suggestion K. Duhring, CCRM-VIMS.*
>
> *Here is additional information about each photo:*
>
> *1. Gapped sills maintain tidal connections between shallow water and natural marsh habitats*
>
> *2. Low-profile marsh sill with a wide planted tidal marsh*
>
> *3. Beach nourishment and dune planting at Yorktown, VA public beach*
>
> *Good luck with your project. If it’s not too much trouble, I would like to see the results.*
>
> *Karen”*