Modeling Site Suitability of Living Shorelines in the Albemarle-Pamlico Estuarine System

by

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June, 2013

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Shoreline erosion and associated land loss are major concerns for coastal land owners and resource managers. Traditional methods of shoreline stabilization using permanent, hard structures can have adverse environmental impacts. Living shorelines offer an alternative to these traditional methods and sometimes provide additional benefits to the surrounding environment. This study examines the suitability for living shorelines in the Albemarle-Pamlico Estuarine System (APES) by creating and testing spatial modeling for living shorelines using suitability indices. The results of this modeling show that the majority of the shoreline in the APES is suitable for living shorelines.

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CHAPTER 1: INTRODUCTION

This chapter begins with an introduction to shoreline change. It provides a synopsis of the processes that lead to this phenomenon and the characteristics of at risk shorelines. The chapter concludes with an overview of shoreline stabilization methods and their associated beneficial and adverse impacts.

Shoreline Change

Shorelines are dynamic features that are continually reshaped by coastal erosion and deposition. Land is removed by both short-term processes, such as erosion caused by storm events, wakes from boating traffic, and tidal currents, and long-term processes associated with sea- level rise (SLR). SLR does not directly cause the loss of land, but it is responsible for changing the relationship between sea-level and land elevation (Atlantic States Marine Fisheries Commission [ASMFC] 2010; Bosch et al. 2006; Broome et al. 1992;Chesapeake Bay Foundation 2007; Corbett et al. 2008; Cowart et al. 2010;Mcleod et al. 2010;Nordstrom 1989; North Carolina Estuarine Biological and Physical Processes Work Group [NCBPPWG] and North Carolina Division of Coastal Management [NCDCM] 2006; North Carolina National Estuarine Research Reserve [NCNERR]; Poulter et al. 2009). Estimates for SLR at the end of the twenty-first century range from 0.18 to five meters (Craft et al. 2009; Harper et al. 2008; Mcleod et al. 2010; Meehl et al. 2005; Overpeck et al. 2006; Poulter et al. 2009; Ramstorf 2007). The impacts of SLR include inundation and landward migration of wetlands and low-lying areas, increased coastal erosion, increased coastal flooding, and saltwater intrusion into estuaries, deltas, and aquifers (Craft et al. 2009; Mcleod et al. 2010: 507; Moorehead and Brinson 1995; NCEBPPWG 2006; Park et al. 1991).

Shorelines found in more exposed areas are typically more erosion prone given higher and stronger waves (Bosch et al. 2006). Corbett et al. (2008) identifies eight physical variables that influence the shaping of estuarine shorelines: fetch, offshore bottom character, geometry of the shoreline, height of sediment bank composition of the sediment bank, fringing vegetation, boat wakes, and storms (Table 1)(adapted from Riggs and Ames 2003). Erosion is also accelerated by intensive use and mismanagement of coastal areas by humans (ASMFC 2010; Broome et al. 2006). In lower energy systems such as bays and estuaries, erosion rates are less rapid than at locations facing the open ocean. However, generally post storm deposits are generally insufficient to replace sediment losses making estuarine erosion more persistent (Bosch et al. 2006; Nordstrom 1989).

Shoreline Variables	**Definition**	**Potential for Erosion**	
		Low	**High**
Fetch	Average distance of open water in front of a shoreline	Short fetch (<1000 feet)	Long fetch (>1000 feet)
Offshore bottom character	Water depth and bottom slope in the nearshore area	Shallow, gradual slope (<3 feet)	Deep, steep slope (>3 feet)
Geometry of shoreline	Shape and regularity of a shoreline (sinuosity)	Highly irregular or in a cove	Straight or on a headland
Height of sediment bank	Bank height at shoreline or immediately behind sand beach	High (> 6 feet)	Low (< 6 feet)
Composition of sediment bank	Composition and degree of cementation of bank sedements	Rock, tight clay	Unconsolidated sand, peat
Fringing vegetation	Type and abundance of vegetation (aqutic plants, marsh grasses, shrubs, trees, etc.) occurring in front of sediment bank	Very abundant, dense	Absent
Boat wakes	Proximity of property, and frequency of adjoining boat channel use	Absence of boats	Marinas, intracoastal waterway
Storms	Storms are the single most important factor determining specific erosional events	Depends on type, intensity, duration and frequency of storms	

Table 1. Physical Variables Shaping Shoreline Change.

Shoreline Stabilization

Because shoreline use is so important to humans for housing, fishing, and other commercial and recreational activities, land loss stemming from erosion at the shoreline is viewed as a negative process. Planners and property owners often use shoreline stabilization structures to halt or reduce erosion (ASMFC 2010; Bosch et al. 2006; NCNERR). Using artificial or engineered structures to control erosion is often referred to as *Hard stabilization*. Although these methods can potentially limit the loss of land for the properties where they are installed, they also can have adverse impacts on adjacent properties and the surrounding environmental systems (ASMFC 2010; Berman et al. 2005; Berman and Rudnicky 2008; Birkeneier 1980; Broderick and Ahrens 1982; Broome et al. 1992; Currin et al. 2011; Odom 1970; Watts 1987).

Hard stabilization structures are popular and diverse in design but also pose problems. Bulkheads and seawalls are vertical structures placed along the shoreline in order to retain the sediment behind the structure. Bulkheads are normally made of wood and are typically smaller and less expensive than seawalls (Figure 1). Seawalls are made of concrete or steel sheet pilings and provide better resistant protection from severe wave action than bulkheads (ASMFC 2010). Even though bulkheads and seawalls are intended to prevent and reduce erosion they can increase erosion at adjacent shorelines (ASMFC 2010; Berman et al. 2005). Bulkheading can accelerate erosion, withhold sediment from downdrift shores, degrade shallow intertidal bottoms and fringing marshes, induce scouring, and increase turbidity in nearshore waters (Figure 2) (ASMFC 2010; Berman and Rudnicky 2008; Birkeneier 1980; Bozek and Burdick 2005; Currin et al. 2011; National Research Council [NRC] 2007; Odom 1970; Pilkey and Wright 1989; Pilkey et al. 1998; Rogers and Skrabal 2001; Woodhouse et al. 1976).

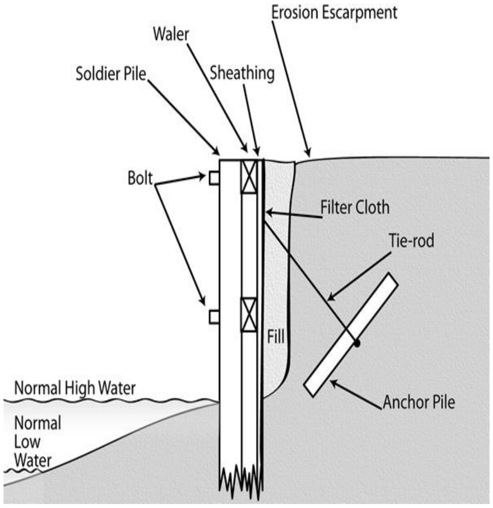

Figure 1. Bulkhead profile.

Source: North Carolina Division of Coastal Management.

The construction of bulkheads and seawalls destroys vegetation, and rather than allowing natural vegetation to recolonize property owners often replace them with landscape shrubs and lawn grasses that are less effective at reducing the effects of runoff (Currin et al. 2011; NRC 2007;Watts 1987). Scouring results from waves breaking against structures, reflecting energy both upwards and downwards, increasing current velocity leading to increased erosion at the base of the structure. This, in addition to increased turbidity, can cause existing wetlands and submerged aquatic vegetation (SAV) beds in front of the structure to be destroyed by undercutting root masses and deepening adjacent water (ASMFC 2010; Currin et al. 2011; Bozek and Burdick 2005; Riggs 2001). One study found sixty-three percent loss of marsh vegetation seaward of bulkheads owing to the increase of turbulence and scouring (Garbisch et al. 1973). The shoreward migration of fringing wetlands as a response to SLR is also prohibited by the placement of vertical structures, effecting *Placement loss* or the loss of potentially migrating shore zones following the construction of permanent structures. As a consequence wetlands will be lost due to drowning (Bozek and Burdick 2005; Currin et al. 2011; NRC 2007; Titus 1998).

The changes in bathymetry and vegetation also affect fish populations. The deepening of waters makes it possible for large piscivorous fish to access previously shallow nursery areas (Rozas 1987). By fixing the hard structure at a location the immobility of shoreline transition landward will also result in the loss of spawning and nursery habitats for certain species of fish (Currin 2011; O'Rear 1983).

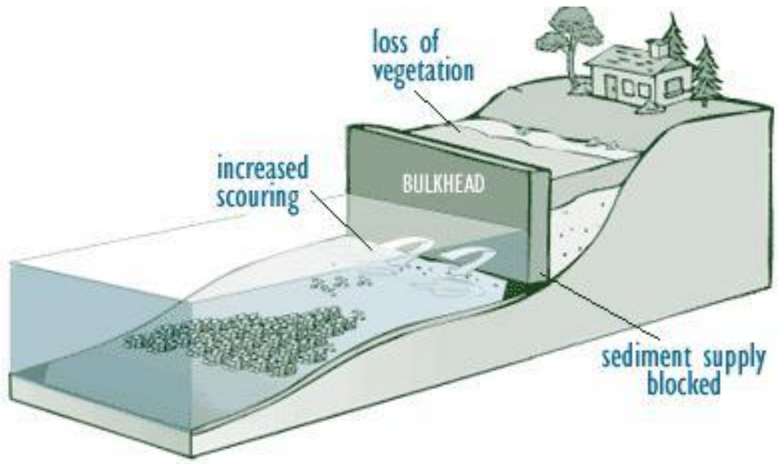

Figure 2. Adverse effects of bulkheads.

Source: Washington State Department of Ecology

Riprap (rock) revetments are similar to bulkheads and seawalls but are designed to have sloping surfaces that break waves more gradually. They are constructed by grading the shoreline and adding layers of large rocks to armor and maintain property behind the structure (Figure 3). Revetments must be built high enough to withstand the waves, and the rocks used for their construction must be large enough not to be displaced by powerful waves. Common complaints against revetments are that they have wide footprints and they often fail because of poor design (ASMFC 2010). The environmental effects of revetments are similar to those associated with bulkheads and seawalls (Broderick and Ahrens 1982).

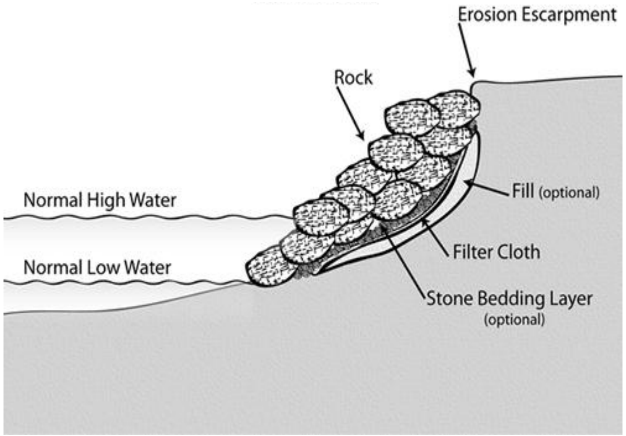

Figure 3. Revetment profile.

Source: North Carolina DCM

Breakwaters are structures built parallel to the shoreline in open water to cause waves to break prematurely. They are intended to control erosion by dissipating wave energy and building up sediment behind the structure by interrupting alongshore sediment transport. Breakwaters do not provide the same amount of protection as bulkheads and revetments because they allow wave action to reach the shore (ASMFC 2010).

Sills are similar to breakwaters but are normally smaller and placed closer to the shore (Figure 4). Sills are used to protect marshes by dissipating wave energy. They have effects on habitat similar to breakwaters in that dry beaches will be replaced by marshes. However, larger waves can pass over sills allowing for some natural movement of sediments behind the sills. Constructed of rock or other natural materials, such as oyster shell, sills rise six to twelve inches above normal high water level. In providing outstanding hard structure for live oyster and other shellfish, oyster sills can also promote water quality and clarity (ASMFC 2010).

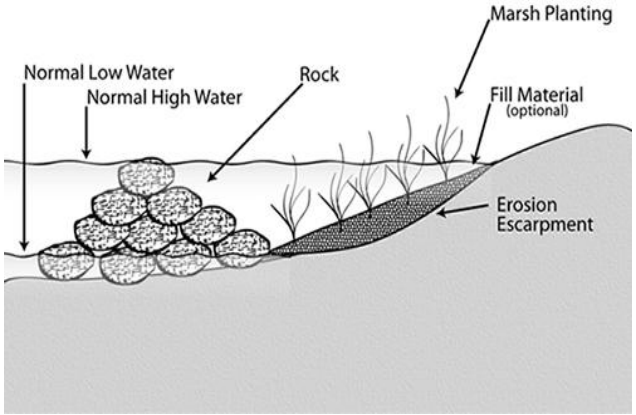

Figure 4. Sill profile.

Source: North Carolina DCM

Living shorelines provide an alternative to hardening shorelines, by using more *natural* and *environmentally friendly* stabilization techniques. They address the problem of shoreline erosion by providing long-term protection of coastal property, with the added benefits of ecological restoration and preservation of vegetated shoreline habitats (ASMFC 2010; Bermen et al. 2005; Berman et al. 2005; Center for Coastal Resources Management [CCRM] 2006; CBF 2007; Currin et al. 2011; NCNERR).

CHAPTER 2: BACKGROUND INFORMTION

This chapter provides an overview of literature that directly pertains to this study. First, the term “Living shoreline,” will be defined. An overview of how living shorelines work to prevent shoreline erosion is provided as well as their additional environmental benefits. Next, suitability requirements for successful living shorelines are discussed. The chapter concludes with examples of current living shoreline installations and their results.

Living shoreline is a popularized term that has been used to describe a wide variety of shoreline stabilization techniques that use natural elements and create a living space for coastal estuarine organisms (Figures 5 & 6) (ASMFC 2010; Berman and Rudnicky 2008) (Berman et al. 2005; Burke et al. 2005; Center for Coastal Resources Management [CCRM] 2006 ; Chesapeake Bay Foundation [CBF] 2007; Currin et al. 2008; Currin et al. 2011; Duhring et al. 2006; NERR).

Figure 5. Living shoreline with a rock sill at Roanoke Island Festival Park in Manteo, North Carolina.

Source: North Carolina Coastal Federation (NCCF)

Figure 6. Living shoreline with an oyster sill at Morris Landing in Onslow County, North Carolina.

Source: North Carolina Coastal Federation (NCCF)

Definitions for living shorelines include:

> "Living shorelines are an alternative erosion control treatment that advocates the use of natural materials to protect eroding fastland. The practice includes marsh restoration, marsh planting in conjunction with low profile sills, and bio-logs. Also known as soft stabilization, the treatments encourage restoration or preservation of fringe marsh to baffle wave energy and reduce chronic erosion problems" (Berman et al. 2005: 1).
>
> "The term *living shoreline* was coined to describe the preferred condition of the shoreline, wherein the shoreline provides living space for coastal and estuarine organisms, such as beach, marsh, submerged aquatic vegetation (SAV), or oyster reef" (ASMFC 2010: 2).
>
> "An alternative to hardening, living shorelines employ natural habitat elements to protect shorelines from erosion while also providing critical habitat for wildlife and water quality benefits" (Virginia Coastal Zone Management Program [VA CZM]: 1).
>
> "A living shoreline utilizes a management practice that addresses erosion by providing for long-term protection, restoration or enhancement of vegetated shoreline habitats. This is accomplished through the strategic placement of plants, stone, sand fill and/or other structural and organic materials. Living shorelines do not utilize structures that sever natural connections between riparian, intertidal and subaqueous areas" (CCRM 2006: 1).
>
> "Living shorelines are more natural alternatives to erosion control than hard structures like rock walls and wooden bulkheads. They use strategically placed native plants, stone, sand fill and other organic material to minimize erosion while also enhancing habitat for fish and other wildlife." (North Carolina Coastal Federation [NCCF] 2011).

Unlike vertical structures that reflect wave energy and retain sediment behind them, living shorelines use stabilization techniques that absorb and dissipate wave energy (ASMFC 2010; Bricker et al. 1989; Broome et al. 1992; CCRM2006; NCNERR). This is carried out by planting wetland vegetation, shrubs, and trees along the shoreline. In cases where wave energy is too strong for vegetation alone the plantings are protected sills and biologs (e.g. coconut-fiber rolls). As waves move through densely vegetated marshes they drag through stems and leaves causing them to break and reduce in height (ASMFC 2010; Bricker et al. 1989; Broome et al. 1992;

CCRM2006; NCNERR). One study claims that fifty percent of wave energy is dissipated in the first eight feet of marshes and is completely dissipated in 100 feet (Broome et al. 1992). SAV beds also reduce wave energy and stabilize sediments in place in similar fashion (ASMFC 2010). Root matrixes hold sediments in place and trap suspended sediments in resulting in accretion (Figure 7).

Figure 7. St. Johns College living shoreline site before and after living shoreline installation.

Source: NOAA Habitat Conservation

Not only do living shorelines combat shoreline erosion by providing long term protection, restoration, and enhancement of vegetated shoreline habitats, they also create a living space for coastal estuarine organisms, enhance their surrounding ecosystems, and can provide a more aesthetically pleasing landscape (ASMFC 2010; Bermen et al. 2005; Berman et al. 2005; Center for Coastal Resources Management [CCRM] 2006; CBF 2007; Currin et al. 2011; NCNERR). Shade provided by vegetation used keeps water temperatures cooler which increases oxygen levels for aquatic species (CBF 2008). Emergent vegetation traps sediment from runoff to sieve pollutants and uptake nutrients that contribute to eutrophication. Root systems trap and hold sediments in place cutting down on sediment re-suspension which results in improved water quality. The use of oyster reef sills also provides similar benefits in habitat provision and improved water quality and clarity (Figure 8)(ASMFC 2010).

Figure 8. Oyster sills at Bodie Island, North Carolina.

Source: US Fish and Wildlife Service

Living Shoreline Treatment Types

Living shorelines are separated into two general treatment categories: soft (non-structural) and hybrid. Soft stabilization treatments involve only the implementation of vegetation installation to address sedimentation and nourishment of existing beaches to control erosion. Hybrid treatments refer to the combining of techniques of non-structural, soft stabilization treatments with permanent structures to provide protection for marsh vegetation while it becomes established in areas where stresses from stronger wave energy and erosion would normally prevent growth (Berman and Rudnicky 2008;Burke and Hardaway;Currin et al. 2011). Hybrid design treatments include installing a low riprap revetment at the toe of a marsh or using stone, oyster, or wooden sills (ASMFC 2010; Berman and Rudnicky 2008; Broome 1992).

Suitable Conditions for Successful Living Shorelines

Although living shorelines need to be designed to meet site-specific conditions of wave energy, elevation, and surrounding ecology and geomorphology, there are some generally accepted guidelines for determining what type of methods to apply (Table 2). In areas with less wave energy because of lower fetch, shallower water at the shoreline usually does not require additional protection beyond the installation of vegetation stabilization methods. Sills become necessary in situations with medium energy. In high energy locations living shorelines are ineffective for shoreline stabilization (Bosch et al. 2006; Broome et al. 1992; CBF 2008; CCRM2010; Currin et al. 2011; NCDCM).

Energy Environment	**Low Energy**	**Medium Energy**	**High Energy**
Water Depth (feet (meters))	-1.0 (-0.3)	-1.0 (-0.3) to -4.0 (-1.2)	-4.0 (-1.2) to -15.0 (-4.6
Fetch (miles (kilometers))	0.5 (0.8)	1.0 (0.8) to 2.0 (3.2)	2.0 (3.2) +
Erosion rate (feet (meters) per year)	2 (0.6) or less	2 (0.6) to 8 (2.4)	8 (2.4) to 20 (6.1)

Table 2. Approximations of conditions for suitable living shoreline environments.

Source: MD Department of Natural Resources

Modeling Living Shoreline Suitability

The Center for Coastal Resources Management (CCRM) at the Virginia Institute of Marine Science (VIMS) developed a Living Shoreline Suitability Model (LSSM) to encourage and increase the use of living shorelines to control shoreline erosion. The model was created to support management decisions and assist implementation of management programs. More specifically, the model's output is meant to be used as a tool to advise a regulatory or management action seeking an erosion control technique (Berman and Rudnicky 2008).

Three categories are used by the model to classify living shoreline suit suitabity: 1) shorelines suitable for soft stabilization, 2) suitable for hybrid treatments, and 3) those that are not suitable for a living shoreline. The model also expands the hybrid category to identify treatments that may be used given specific site conditions. These sub-types include marsh toe revetments, marsh plantings combined with the use of marsh shills, and modifications to the riparian upland. There are six attributes used to determine shoreline classification: 1) fetch, 2) bathymetry, 3) marsh presence, 4) beach presence, 5) bank condition, and 6) tree canopy presence. Studies by CCRM (2007) and Durhing et al. (2005) were used to establish the criteria for mapping living shoreline treatments (Table 3) (Berman and Rudnicky 2008).

Attribute	**Value**
Fetch	Low (0-1.0 mile/ 0-1.6 kilometers) Moderate (1.0-5.0 miles/ 1.6 – 8.0 kilometers) High (> 5.0 miles/ 8.0 kilometers)
Bathymetry	1m contour > 10m 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 Presence	Present/absent

Table 3. CCRM Living Shoreline Suitability Model criteria.

There are two limitations associated with the model. The first is that the model does not depict site-specific anthropogenic conditions. Even though the morphologic and biologic conditions of a site may indicate an area is suitable for a living shoreline treatment, a field assessment may show that it is unsuitable because of conditions the model input data cannot capture. These are site-specific scenarios brought on by property owners and communities that cannot be predicted. An example of this is parcel characteristics such as telephone poles or buildings located too close to the shore that would prohibit necessary grading of the bank for treatment construction. The second major limitation is the accuracy of data layers used in the model. In addition to accurate data, the data inventory used in the model must be as current as possible in order for the model output to be accurate. If a landscape has been altered since data collection or classified incorrectly, the model output will be no longer reliable for making recommendations (Berman and Rudnicky 2008).

Current Examples of Living Shorelines

A study by Currin et al. (2008) of three living shoreline projects in North Carolina showed that sediment accretion rates in the marshes behind stone sills were nearly twice as much as those observed in adjacent natural marshes. Currin et al. state that it is possible that this elevation increase could result in the conversion of low marsh into high marsh. Currin and colleagues continued their study of sediment accretion rates and surface elevation changes of living shorelines with stone sills using the Surface Elevation Table (SET) methodology (Cahoon et al. 2004). Changes in marsh surface elevation were observed every fall and spring between March 2005 and March 2008 in four living shorelines with stone sills and adjacent natural fringing marshes. Not only were the rates of sediment increase of the living shorelines higher than in the natural fringing marshes, but they were almost twice the rate of relative sea level rise. Lower marsh vegetation moved seaward toward the rock sill, while in some cases the upper marsh began to exhibit vegetation change (Currin et al. 2011). A study of thirty six living shoreline projects in Virginia reported that there was little accretion behind the sills and that there was an unvegetated gap between the sills in marshes at several sites (Duhring et al. 2006).

At Point Peter Road on the eastern edge of the Alligator River National Wildlife Refuge (North Carolina) oyster reefs were constructed as part of a SLR adaptation study by the Nature Conservancy (TNC) and the U.S. Fish and Wildlife Service (FWS) (Figure 9). The reefs are intended to dissipate energy on the shoreline and slow erosion of the shoreline (Strawser 2010). Unlike most oyster sill treatments, these reefs are set approximately 30 meters out from the shoreline because the soft peat bottom close to shore would not support their weight. This technique has been effective in slowing the rate of erosion from approximately five meters per year to less than one meter per year (Boutin 2011).

Figure 9. Aerial view of Point Peter Road oyster sills.

Source: US Fish and Wildlife Service

A study of twenty-seven marsh sills in North Carolina by Fear and Bendell (2011) showed that they were effective (Figure 10). Eighty-nine percent of the marsh sills did not show signs of damage or erosion, and ninety-five percent property owners were happy with the performance of their marsh sills. However, it was unclear whether or not marsh sills caused erosion on adjacent properties. Field reports stated that erosion occurred at thirty-one percent of sills, no erosion at forty-six percent of sills, and at the remaining twenty-three percent of sills reporters were “unsure”. Property owners unanimously responded that they did not believe their sills not have any detrimental effect on their neighbors’ property. Forty-two percent thought that their sills had no impact and fifty-eight percent stated that the sills had beneficial impacts. Additionally, it was found that oysters colonized eighty percent of observed sills and seventy-three percent of the marshes behind the sills were described as “dense and healthy”

Figure 10. Marsh sill sites from Fear and Bendell (2011) study.

Source: Fear and Bendell 2011

CHAPTER 3: APPROACH

This chapter provides an overview of the objective of this study and introduces the area where this study takes place. It provides an overview of the area's natural environment and its importance. The chapter concludes with an explanation of why this area was selected for this study.

Objective

To develop a screening tool to aid in determining the potential suitability and constraints of living shoreline treatments for shoreline stabilization in the Albemarle-Pamlico Estuarine System, North Carolina.

Research Questions

1. How much of the shoreline is suitable for employing soft stabilization living shorelines techniques for shoreline stabilization?
2. How much of the shoreline is suitable for employing hybrid stabilization living shorelines techniques for shoreline stabilization?

Study Area: Albemarle-Pamlico Estuarine System

Extending from Cape Lookout to Virginia Beach the Albemarle-Pamlico Estuary of North Carolina is the second largest estuary in the United States (Wells and Kim 1989; Murphy 2002; Corbett et al. 2008)(Figure 11). It compromises 7,770 square kilometers of estuarine water composed of eight sounds: Albemarle, Pamlico, Back, Bogue, Croatan, Currituck, Core, and Roanoke Sounds (Albemarle-Pamlico National Estuarine Program [APNEP] 2012; Martin et al. 1987). The Outer Banks barrier island chain separates the estuary from the Atlantic Ocean.

Because the chain only has four “permanent” inlets there is minimal exchange between these shallow fresh-brackish bodies of water and the ocean (Wells and Kim 1989).

The estuary is supported by a watershed of approximately 80,290 square kilometers, consisting of water drained from forty-three counties in North Carolina and thirty-eight counties and cities in Virginia (Figure 12). Major river systems in this watershed include: the Pasquotank, Chowan, Roanoke, Tar-Pamlico, Neuse, and White Oak.

Depths in the Albemarle Sound gradually increase away from the shore to a maximum depth of 9.1 meters with an average of 5.3meters. Depths in the Croatan Sound are typically less than 3.6meters. The Pamlico Sound is divided into two basins. The northern basin dips smoothly towards the center with a maximum depth of approximately 7.3 meters, and the southern basin has an average depth of 5.4 meters (Wells and Kim 1989).

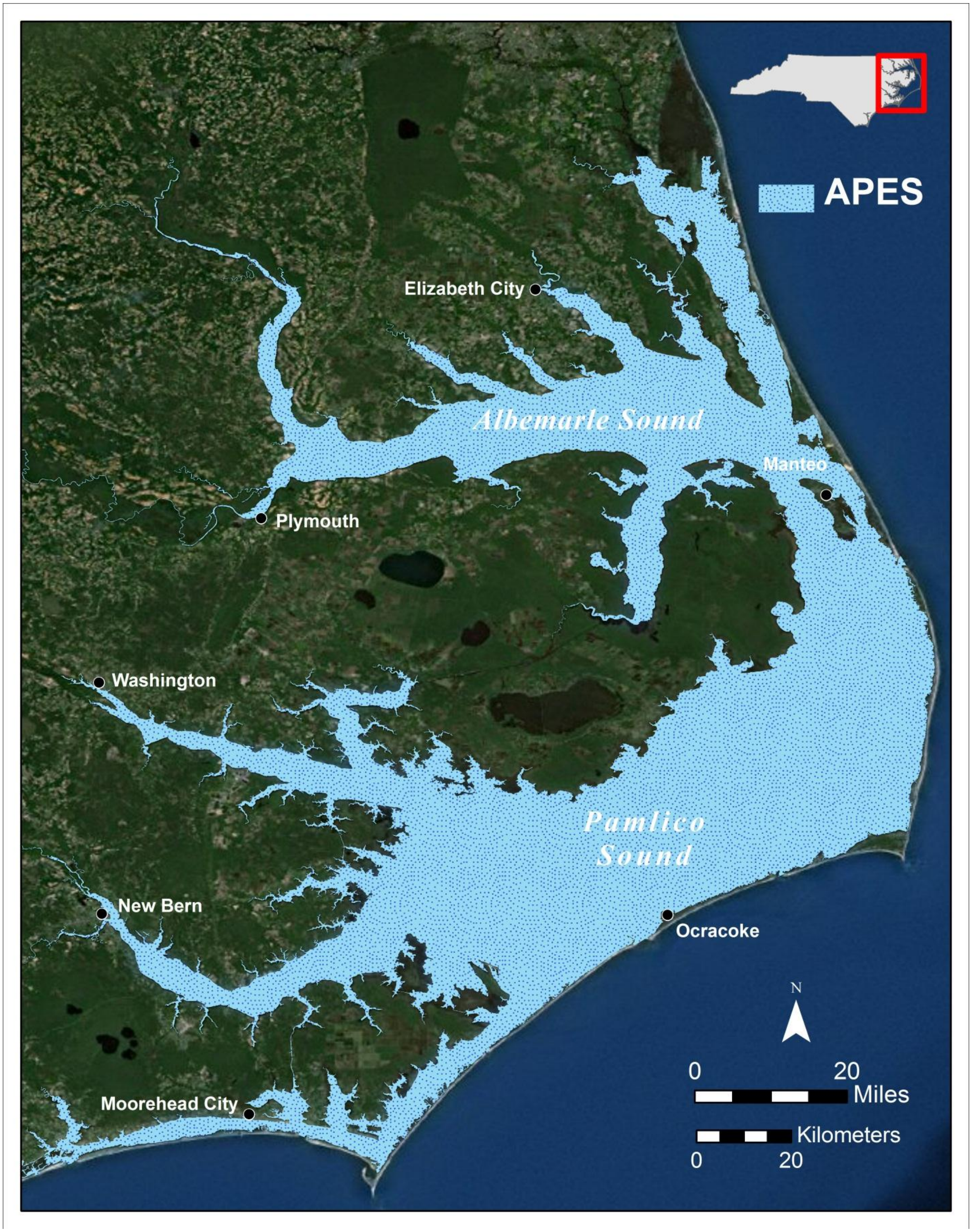

Figure 11. Albemarle-Pamlico Estuarine System, North Carolina.

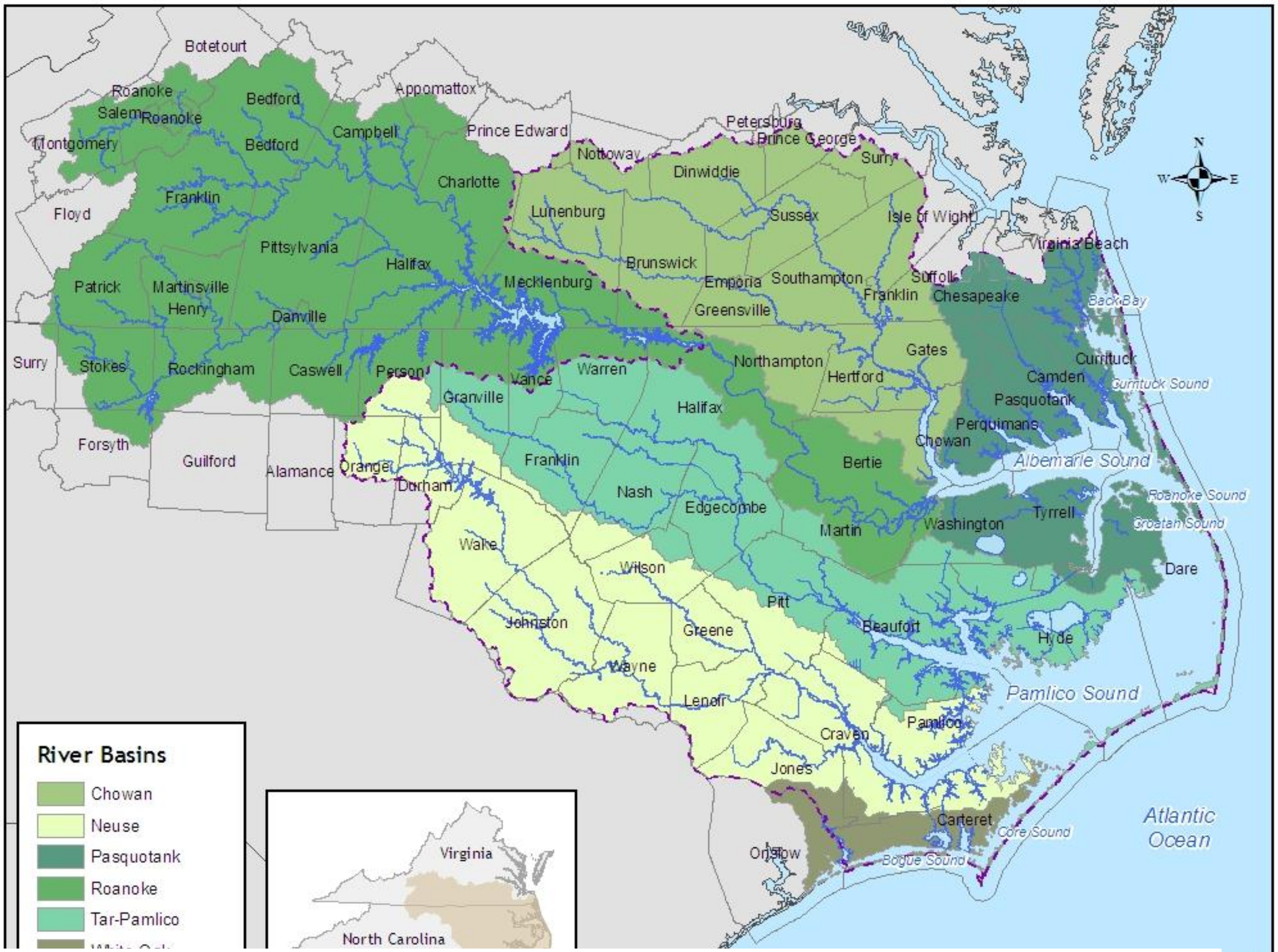

Figure 12. Counties, independent cities, and river basins of the Albemarle-Pamlico Region.

Source: Albemarle-Pamlico National Estuarine Program

The estuary is characterized by wind-driven tides that affect circulation patterns within its sounds and saltwater concentrations in their tributaries. These wind tides are variable and contribute to unpredictable changes in water levels and erosion patterns along the coast (APNEP 2012). The maximum tide range is approximately one meter around inlets, but in most of the system it is ten centimeters or less (Wells and Kim 1989). The dominant wind directions in the region blow from the south to southwest from April to August and north to north west from September to February.

The Albemarle-Pamlico estuary is very important to the residents and guests of North Carolina (APNEP 2012). Its sounds provide a sense of place to the counties and municipalities located along their shorelines. Towns such as Bath, Edenton, Manteo, and New Born each have unique identities and histories that are tied to the surrounding ecosystem. Tourists visit from all over the world to watersports, relax in the sun, sample the coastal cuisine, and explore the region’s parks, forests, and wildlife refuges. The estuary also supports North Carolina’s commercial fishing industry.

The estuary system also provides other benefits that are not quite as easy to see (APENAP 2012). Coastal wetlands filter water supplies and act as a protective buffer against storms and hurricanes. Submerged aquatic vegetation beds provide habitat for most fish and shellfish species in the sounds, while improving water quality by creating oxygen and removing excess nutrients in the water. Oysters, clams, and other shellfish filter the water column and are provide a food source for both humans and animals. The estuary supports billions of dollars in economic activity and natural services each year. Damages or losses to this system would be detrimental environmentally and economically.

Like the majority of shorelines in North Carolina, shorelines in the APES are subject to erosion. Much of estuarine shoreline erosion in the region responds to the interaction of storms and sea-level rise. However, previous studies indicate that shoreline erosion is extremely variable from site to site with significant ranges in erosion rates evident over short distances (Riggs, 2001; Riggs and Ames, 2003). In a study by Riggs and Ames (2003) Point Peter was found to have the highest average rate of erosion with an average rate of -2.3 meters per year (Figure 13). The lowest average erosion rate was found along the bluff shoreline at Bay Hills with a rate of less than 0.3 meters a year. Additionally, shoreline change rates varied from zero meters of erosion per year during periods of low storm activity to a high of 7.9 meters per year along the sand bluffs at the north end of Roanoke Island during periods of high storm activity. Riggs and Ames (2003) determined that the average annual estuarine shoreline change rates for specific shoreline types ranged between 0.2 feet per year of accretion for back-barrier beaches to one meter of erosion per year for the mainland marshes.

Figure 13. Locations from Riggs and Ames (2003) study.

This study focuses on the center of the system, using 145.68 kilometers of shoreline of the Croatan and northern Pamlico Sounds to represent the rest of the APES (Figure 14). This area includes the shorelines of the eastern Albemarle-Pamlico Peninsula and Roanoke Island. This stretch of shoreline provides examples of both developed and undeveloped shorelines (Figures 15 & 16).

Figure 14. Central APES shorelines used for suitability index .

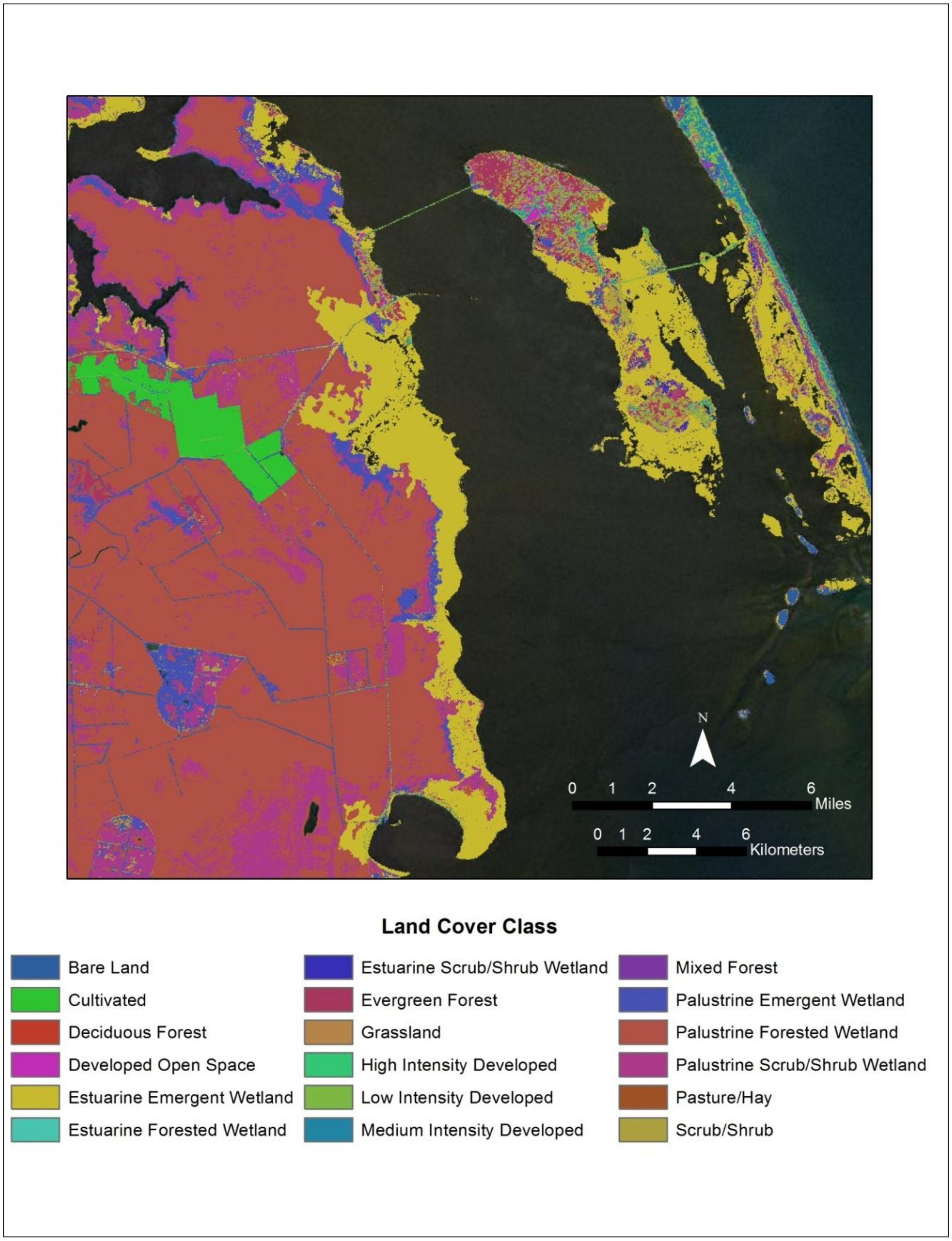

Figure 15. 2006 Central APES NOAA Coastal Change Analysis Program (C-CAP) landcover classification.

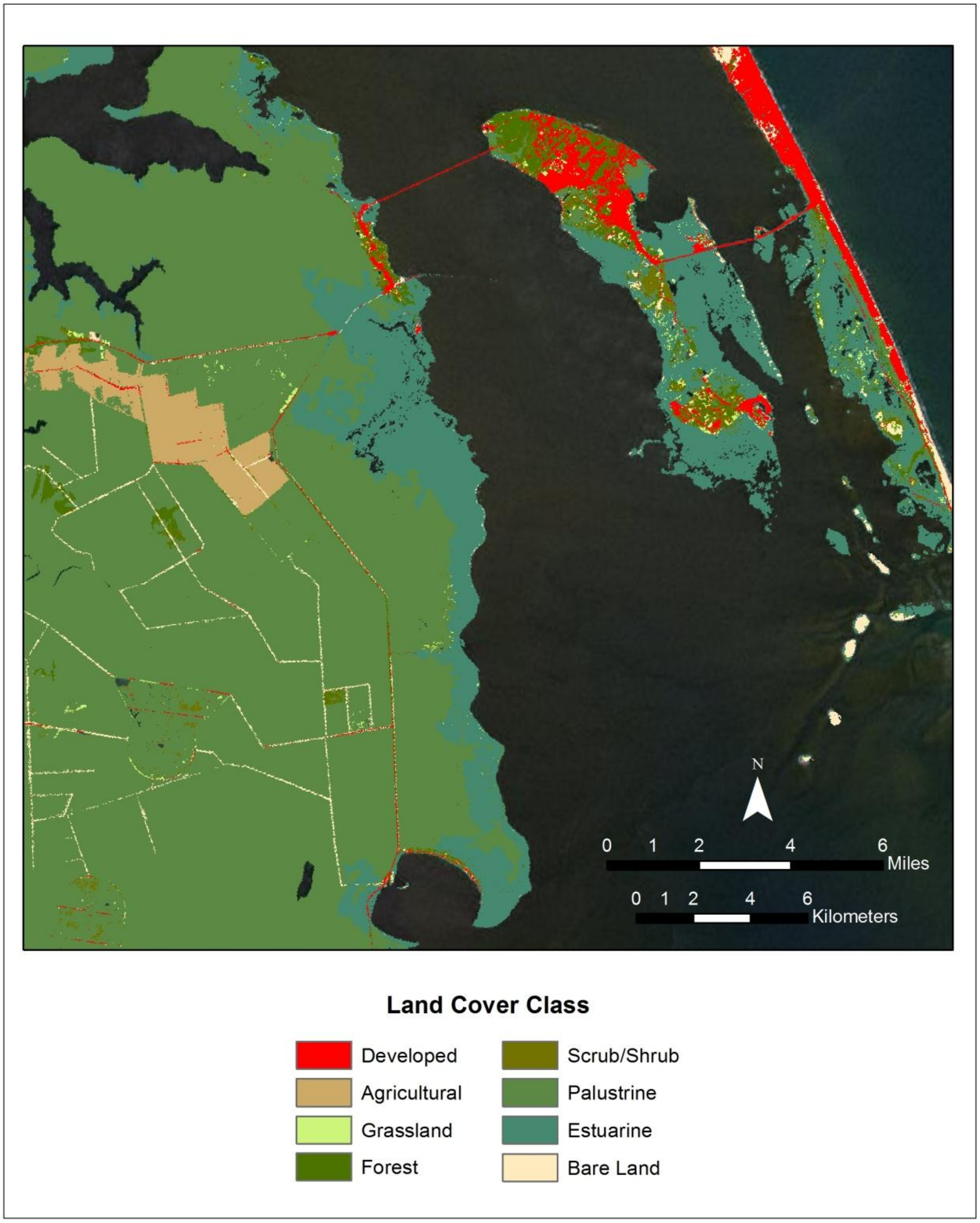

Figure 16. Central APES simplified land cover classification.

There are four communities located in the study area: Manns Harbor, Stumpy Point, Manteo, and Wanchese (Figure 17). Manns Harbor is an unincorporated village with a population of 935. Stumpy Point is also an unincorporated village that has a population of 323. The Town of Manteo is the county seat of Dare County and has a population of 1,266. Wanchese is a census-designated place and has a population of 1,466.

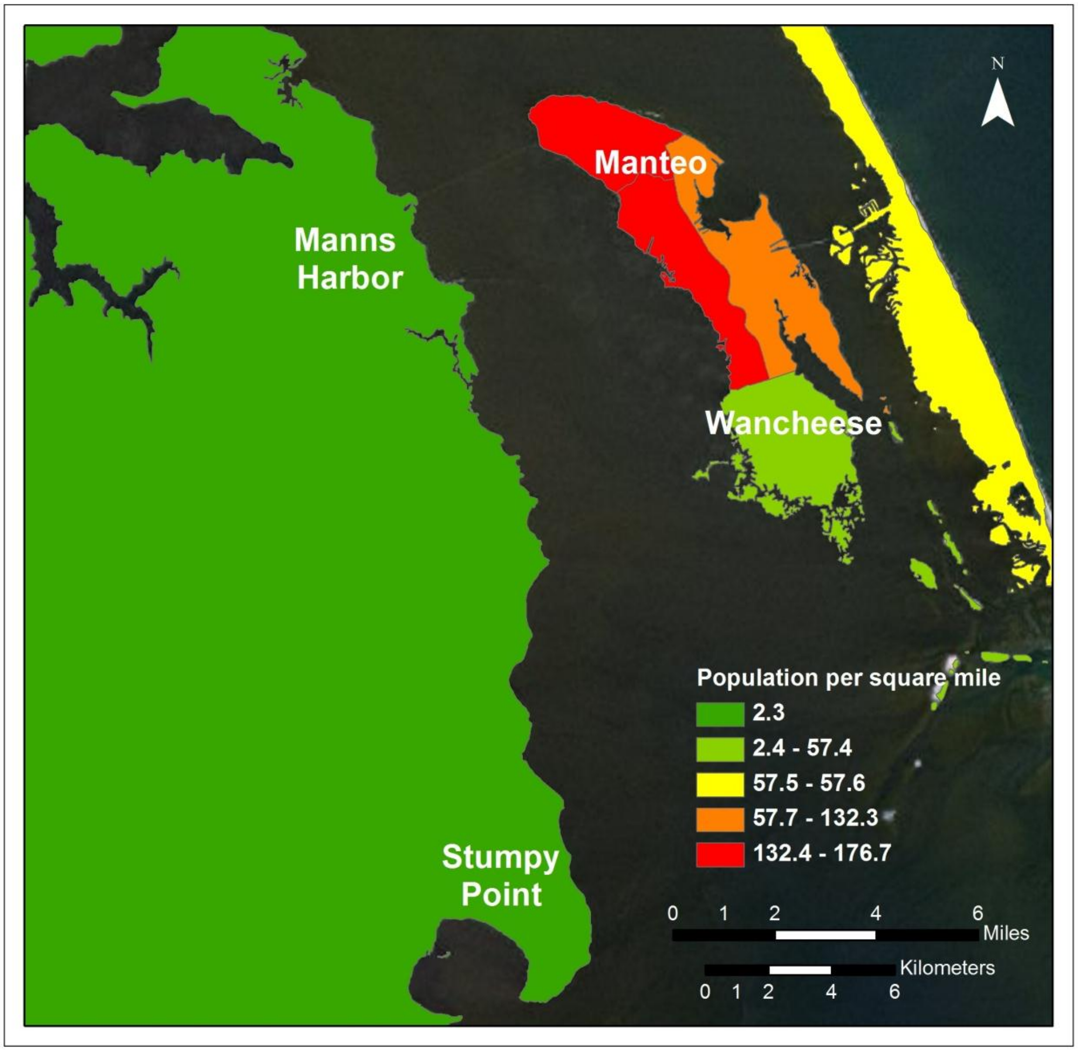

Figure 17. Central APES 2010 block group population density.

Also included within the study area is the Alligator River National Wildlife Refuge (Figure 18). The refuge covers approximately 616 square kilometers of Dare and Hyde Counties. It is bordered by the Alligator River to the west, the Albemarle Sound to the north, and the Croatan and Pamlico sounds to the east and south. The U.S. Fish and Wildlife service established the refuge in 1984 to protect and conserve migratory birds and other wildlife resources through the protection of wetlands (United States Fish and Wildlife Service [FWS] 2008; Fish and Wildlife Act of 1956; Refuge Recreation Act of 1952; National Wildlife Refuge System Administration Act of 1966; Emergency Wetland Resources Act of 1986; FWS 2011).

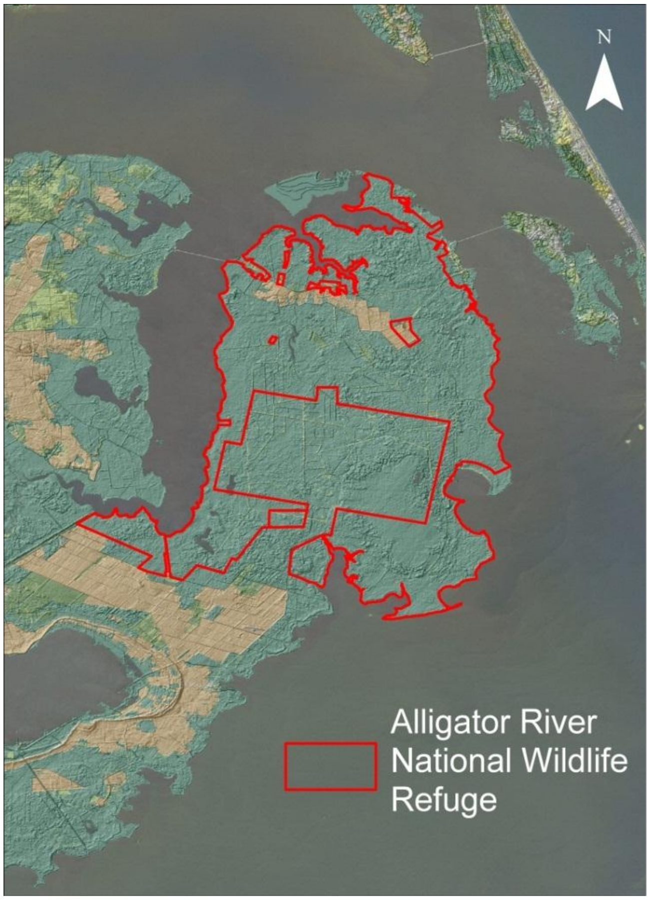

Figure 18. Alligator National Wildlife Refuge boundary.

The refuge is an ecologically diverse area. There is a wide variety of habitats found within the refuge including: high and low pocosin, bogs, fresh and brackish water marshes, hardwood swamps, and Atlantic White Cedar swamps. The refuge supports wildlife species that are deemed important from both regional and national viewpoints (Noffsinger et al. 1984). It is part of the northern border of the American Alligators habitat range and is one of the last remaining strongholds for the black bear on the Eastern Seaboard. The refuge is visited by approximately 250 species of birds regularly and is the midpoint of the Atlantic Flyway. The fisheries found on and surrounding the refuge are very diverse and productive. The open water areas are used as spawning grounds, nurseries and foraging habitat. Several federally listed threatened and endangered species are found within the refuge, including red-cockaded woodpecker, red wolf, bald eagle, and the American Alligator. The refuge is also host to the Red Wolf Recovery Program that is using the site for reintroducing red wolves into the wild (FWS 2011; FWS 2008).

Additionally the refuge is heavily utilized by humans. Approximately 45,000 visitors come to the refuge annually. Visitors use the refuge for hunting, fishing, wildlife observation and photography, and environmental education (FWS 2011; FWS 2008).

The refuge is facing the risk of being lost as a result of SLR (Figure 9). It is projected that within the next 100 to 150 years the vast majority of the area will be underwater. In response to this threat, TNC and the refuge jointly planned a project as a way to "buy some time for the wildlife and their habitats to the rapidly changing environments" (Strawser 2010: 1) as well as to better understand the effects of climate change and ways of adapting to those changes (Strawser 2010).

CHAPTER 4: METHODOLOGY

This chapter provides an overview of the methodology to assess the suitability of living shoreline treatments for estuarine shoreline stabilization. The data and steps used to determine the likelihood of shorelines to successfully support living shorelines will be discussed in detail. The chapter concludes with an overview of the formula used to create a suitability index for living shoreline treatments.

Overview

The suitability index used in this study is an adaptation of the VIMS CCRM's Living Shoreline Suitability Model. Combining wave energy and environmental attributes a suitability index is calculated (Figure 19). However, the variables from this index are tailored to be site specific to the Chesapeake Bay area. To better represent the study area the index for this study also incorporates Corbett et al. (2008) variables that influence shoreline change in North Carolina. Both unweighted and weighted indexes are used to calculate suitability scores.

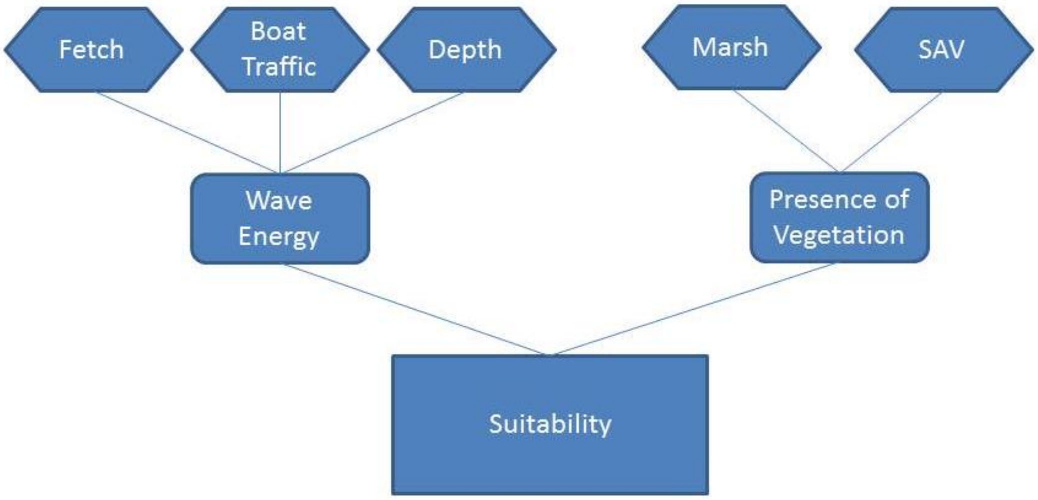

Figure 19. Overview of attributes for living shoreline suitability.

Representing the Shoreline

The North Carolina Department of Transportation's shoreline polyline (2011) was used to represent the shoreline of the study area. This file was created using United States Geological quadrangles and ground survey information, and the North Carolina Geodetic Survey verified and updated lines that have been surveyed and approved by their respective counties. The polyline was split into at its vertices for analytical purposes using the Editor tool to split. This method was chosen because although the shoreline segments are not uniform in size they represent variations in shoreline geometry such as coves and harbors (Figure 20).

Figure 20. Close-up of shoreline segments used for analysis in Manteo and Southern Roanoke Island, North Carolina.

Wave Climate

The stress from wind drive waves and boat wakes is the primary factor in determining whether or not a living shoreline treatment will be successful (Hardaway et al. 1985; Broome et al. 1986; CCRM 2006; MDE 2008; CCRM 2012). Stronger wave climates can also make it difficult for marsh seedlings to root before they are washed away (Rogers 1994). The energy of a wind wave is a product of fetch and bathymetry. Areas with deeper bathymetry and exposed to greater fetches will have the highest energy waves. Shorelines that are in proximity with heavy boat traffic will be susceptible to damage from boat wakes.

Fetch

Fetch is the distance that wind travels across a body of water to generate waves. Greater fetch creates larger more powerful waves and therefore lessens the likelihood of successful living shoreline treatments (Broome et al.).

The fetch of a shoreline was calculated using United States Geological Survey (USGS) *Wind Fetch Model for Habitat Rehabilitation and Enhancement Projects* (Rohwerder et al. 2008). This tool uses *landraster* inputs where pixel values greater than “0” are evaluated as land and values less than “0” are evaluated as water. Wind fetch is calculated by spreading nine radials (Figure 21) around the desired wind direction in three degree increments. The resulting wind fetch is the arithmetic mean of these radials. The wind origin for fetch is measured in degrees with north being 0˚ and south being 180˚.

The North Carolina Department of Transportation’s (NCDOT) county boundaries with shoreline polygon file was converted to a raster file to serve as the landraster for this analysis.

Figure 21. Wind Fetch Model for Habitat Rehabilitation and Enhancement Projects Fetch Model radials.

Because the dominant winds in the area come from the southwest and north-northeast, fetches were calculated for 225° and 10°. This produced two raster files for the fetch distance values for the study area (Figures 22 & 23). The mean fetch value for each segment was calculated and exported into a table with Zonal Statistics (Figures 24& 25).

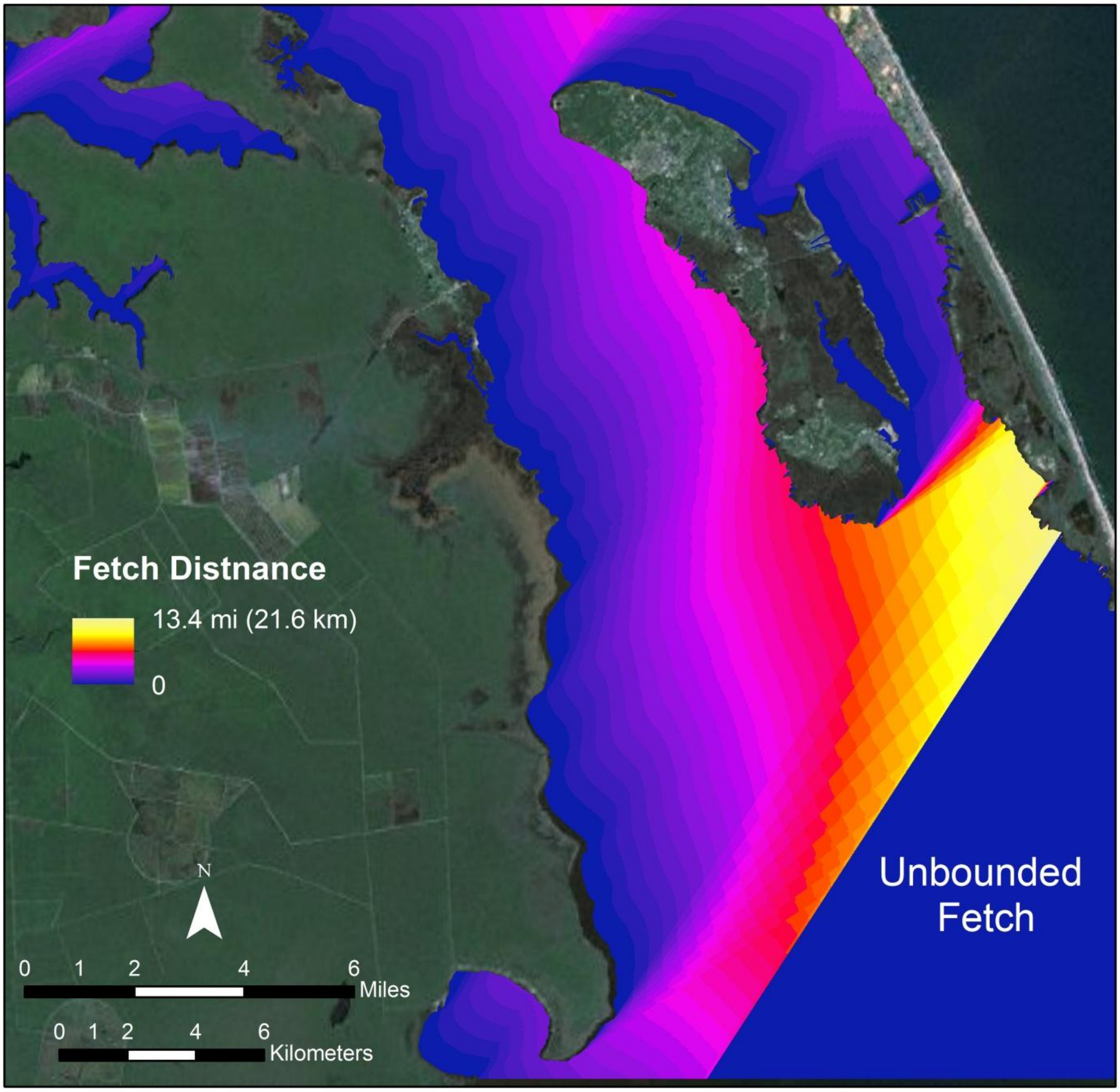

Figure 22. Fetch distance from the southwest (225˚).

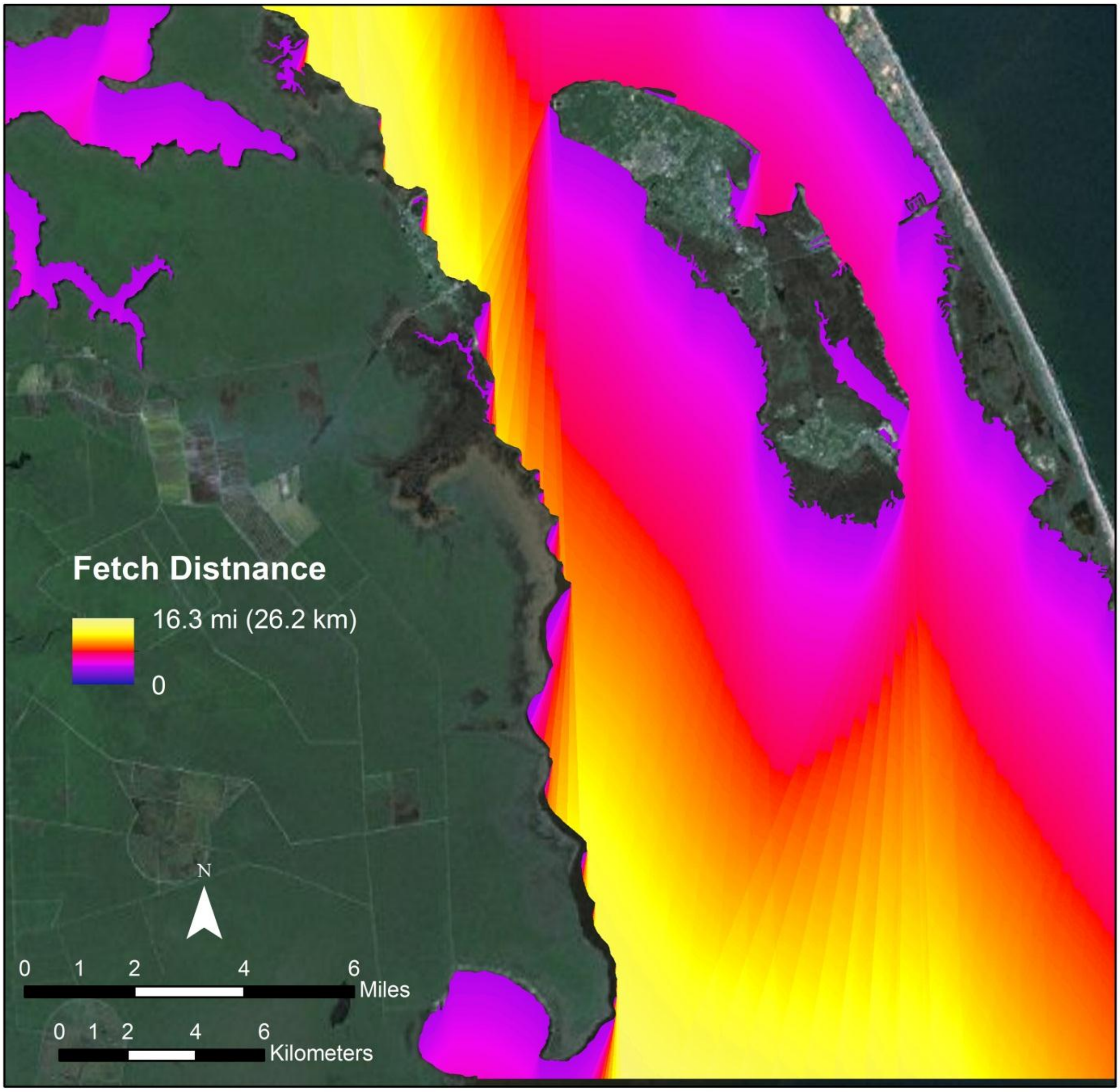

Figure 23. Fetch distance from the north-northeast (10˚).

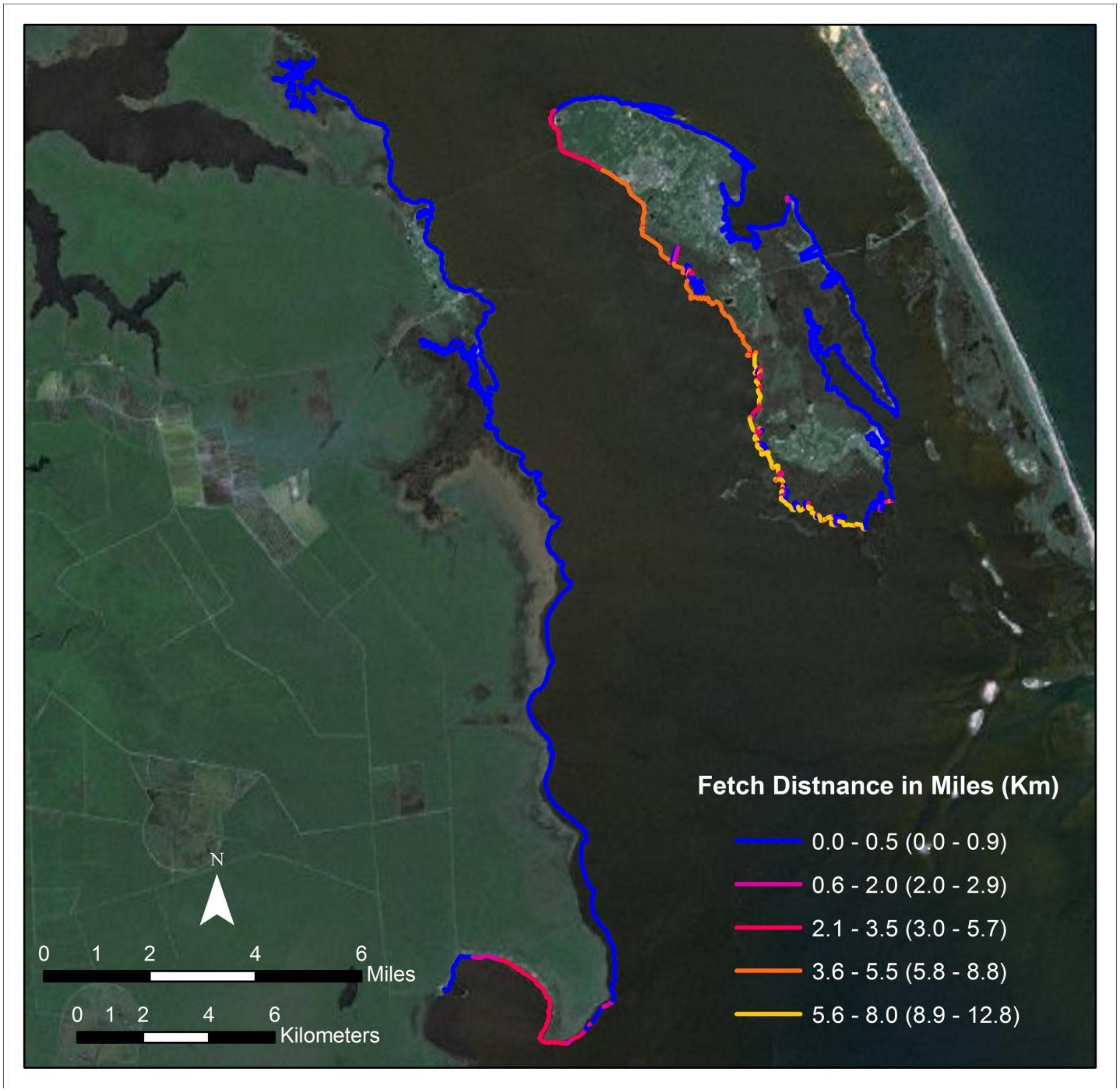

Figure 24. Average shoreline segment fetch distance from southwest (225˚).

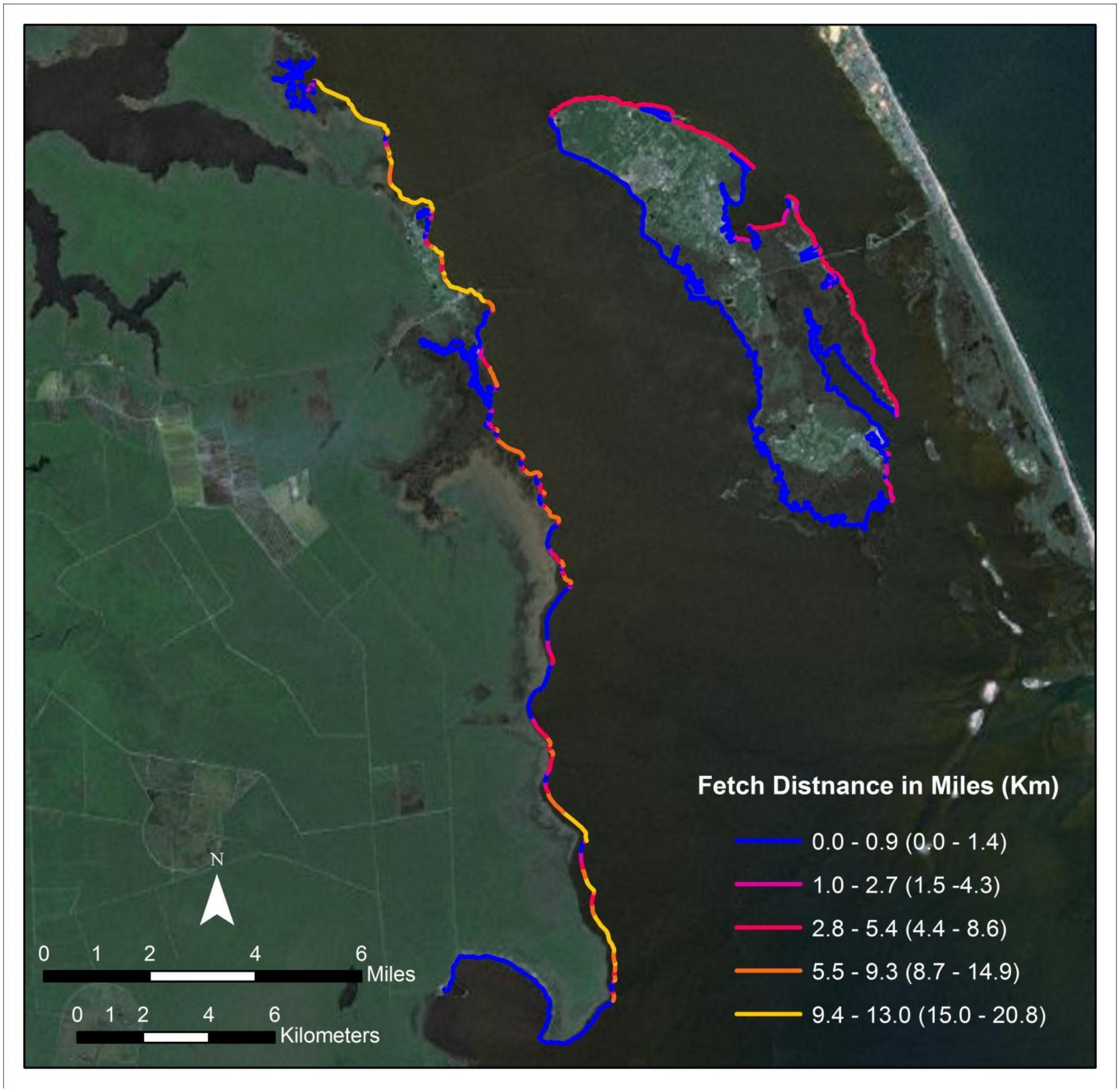

Figure 25. Average shoreline segment fetch distance from north-northeast (10˚).

An attribute query was run to select which shoreline segments had suitable values for living shoreline treatments. The values were the reassigned using the Field Calculator. Segments with suitable fetch values were given a value of “1” and those that were unsuitable were assigned values of “0”.

Bathymetry

Bathymetry is the measurement of depth from the bottom of a body of water to its surface. In in other words it is underwater topography. This was modeled using elevation points from the Advanced Circulation (*ADCIRC)* model obtained from the Renaissance Computing Institute (RENCI) at UNC-Chapel Hill, NCDOT’s shoreline polyline file, and polygon file of the estuaries of North Carolina created from the NCDOT’s county boundaries with shoreline polygon file.

The ADCIRC model is a finite element hydrodynamic model for coastal oceans, inlets, rivers and floodplains (Figure 26). The model is a system of computer programs for solving time dependent, free surface circulation and transport problems in two and three dimensions. These programs utilize the finite element method in space allowing the use of highly flexible, unstructured grids. *ADCIRC* was developed by Rick Leuttich and Joannes Westerink. Other developers include Randall Kolar and Cline Dawson, along with support from various other groups around the country (ADCIRC 2011).

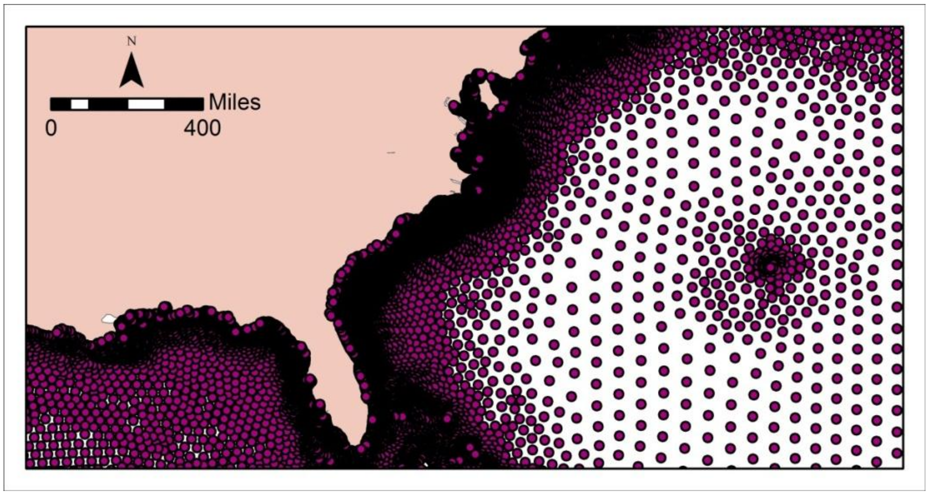

Figure 26. ADCIRC grid node distribution.

Using a spatial query all the ADIRC grid nodes that were within the estuary polygon were selected and exported into a new feature file. The shoreline file was then converted to a point file by using the feature to point tool. Field calculator was used to give the points elevation values of "0". These points were merged with the extracted ADCIRC grid nodes to create a single point file representing depths for the Albemarle-Pamlico sound. Depth values were unchanged from provided vertical datum of mean tide level (MTL.)

The spline tool was then used to interpolate bathymetry for the sound based on the elevation value of each point. This method estimates values using a mathematical function that minimizes overall surface curvature, and results in a smooth surface that passes exactly through the input points (ESRI 2010). The resulting output was a raster file of the modeled bathymetry (Figure 27). The mean nearshore depth for each segment was calculated and exported into a table using Zonal Statistics (Figure 28). Shoreline segments with suitable values were given values of "1" and those that were unsuitable were given values of "0.

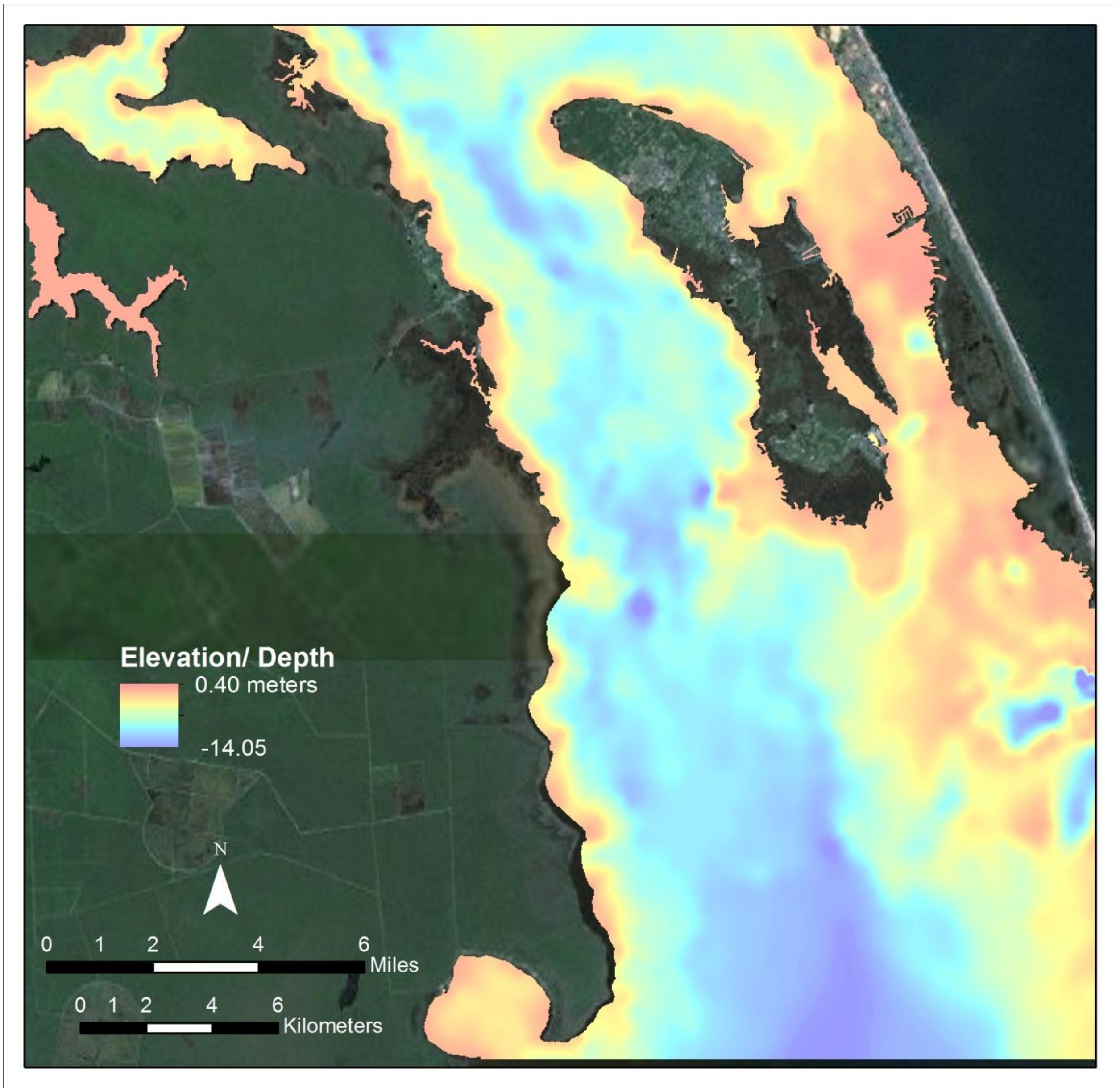

Figure 27. Central APES bathymetry model.

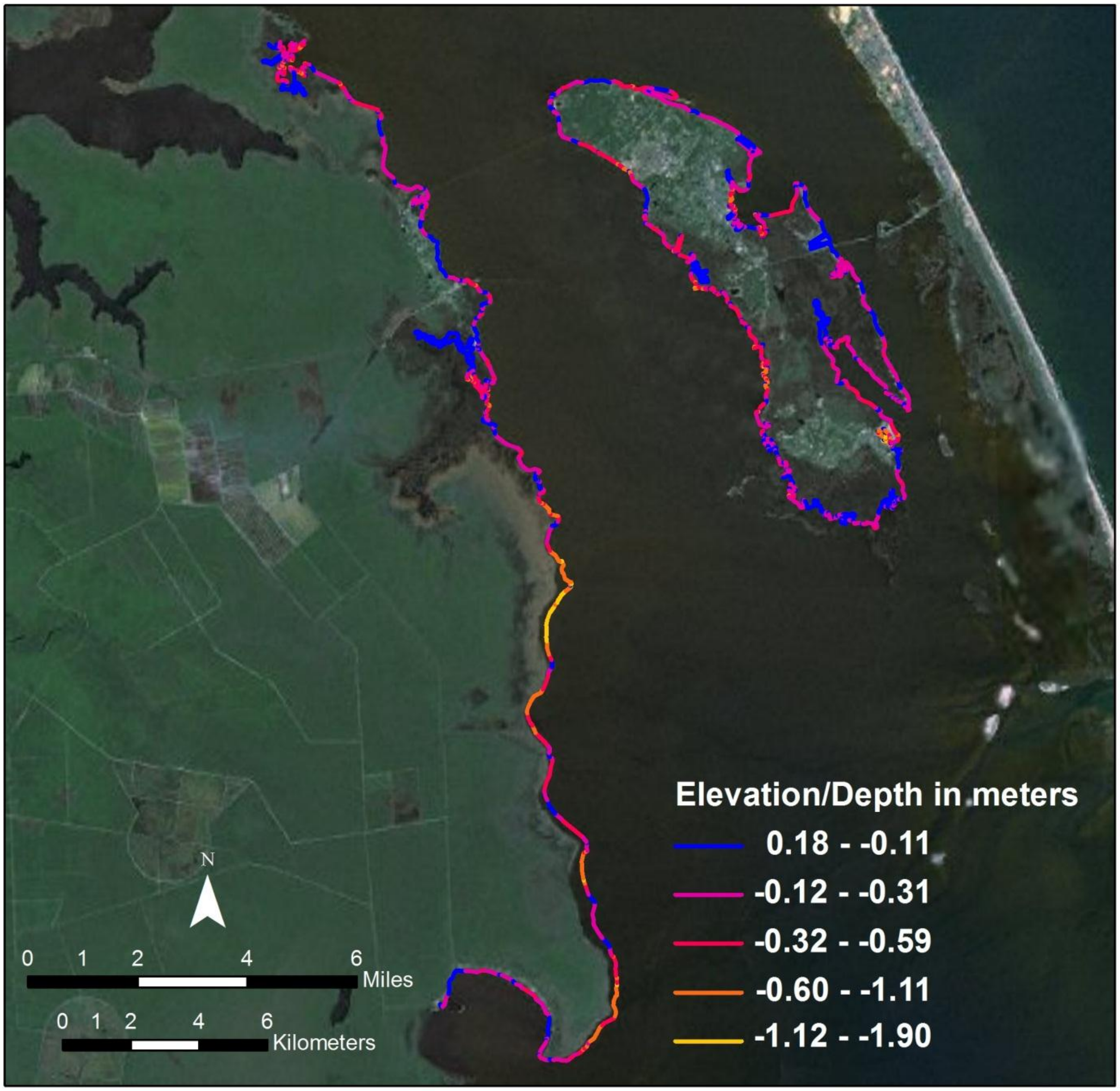

Figure 28. Average shoreline segment elevation/depth.

Boat Traffic

Wakes from boat traffic can place stress on plants used in living shoreline. For the purposes of this study, shorelines within two miles (3.2 kilometers) to boat access ramps were to have heavy boat traffic are unsuitable for living shorelines. Boat access locations were obtained from the North Carolina Wildlife Resources Commission (NCWRC) point file of public boating accesses (NWRC 2011).

A spatial query was run to select shorelines located within one mile of the boat access points (Figure 29). These shorelines were given a value of “0” to represent that they are unsuitable for living shorelines. Shorelines outside of the buffer zone were give values of “1”.

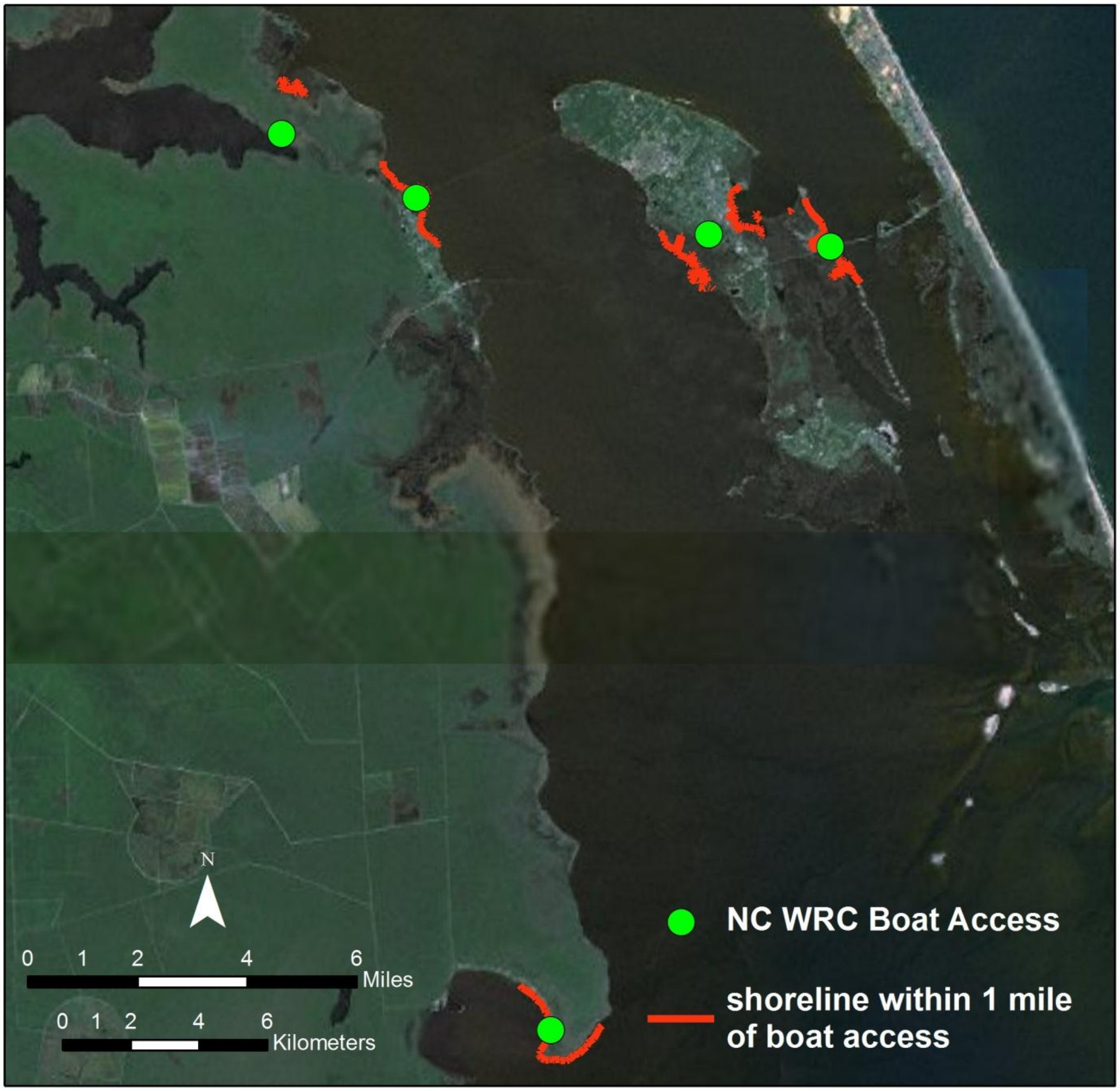

Figure 29. Public boat access locations.

Presence of Vegetation

The presence of vegetation at a shoreline suggests that its environmental conditions are favorable for growth (CCRM 2008). Therefore, the presence of vegetation indicates that growth from new plantings would succeed at a shoreline.

Preexisting Marshes

Wetland data was obtained from the North Carolina Division of Coastal Management's Wetlands Type polygon file (Figure 30). The data's classification scheme is based on both vegetative cover and hydrogeomorphic character. Wetland classes include: Salt/Brackish Marsh, Estuarine Shrub-Shrub, Estuarine Forest, Maritime Swamp Forest, Freshwater Marsh, Pocosin, Bottomland Hardwood, Swamp Forest, Headwater Swamp, Hardwood Flat, Pine Flat, Managed Pineland, Human Impacted (DCM 2003).

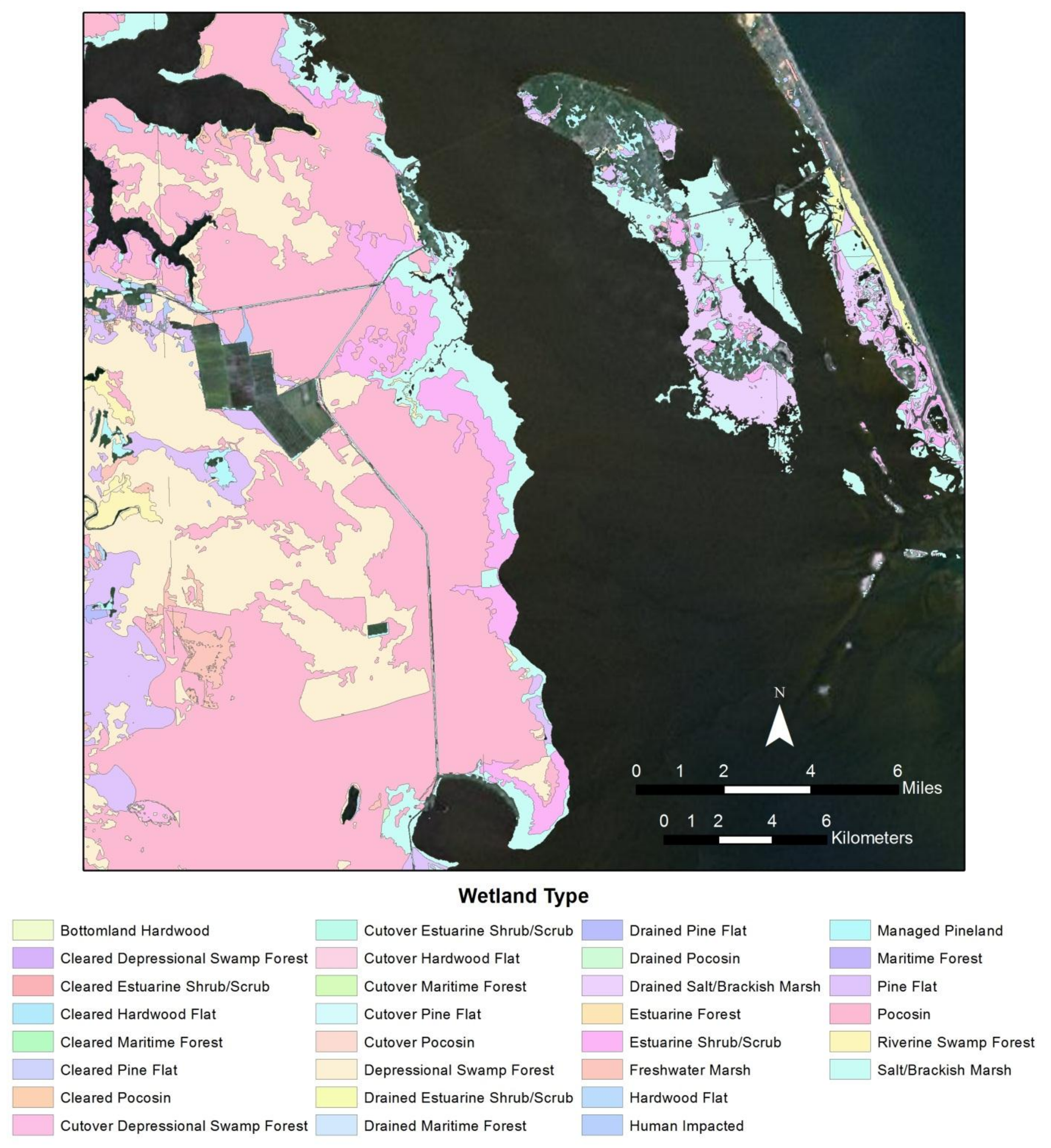

Figure 30. Central APES U.S. Fish and Wildlife Service National Wetland Inventory (NWI) classifications.

An attribute query was run to select all marsh wetland types (drained salt/brackish marsh, fresh water marsh, and salt/brackish marsh). The selection was exported to create a polygon of preexisting marshes.

A spatial query was run to select all shoreline segments within ten feet (three meters) of preexisting marshes (Figure 31). The selected shoreline segments were given a value of “1” using the field calculator. And, unselected shorelines were given a value of “0.

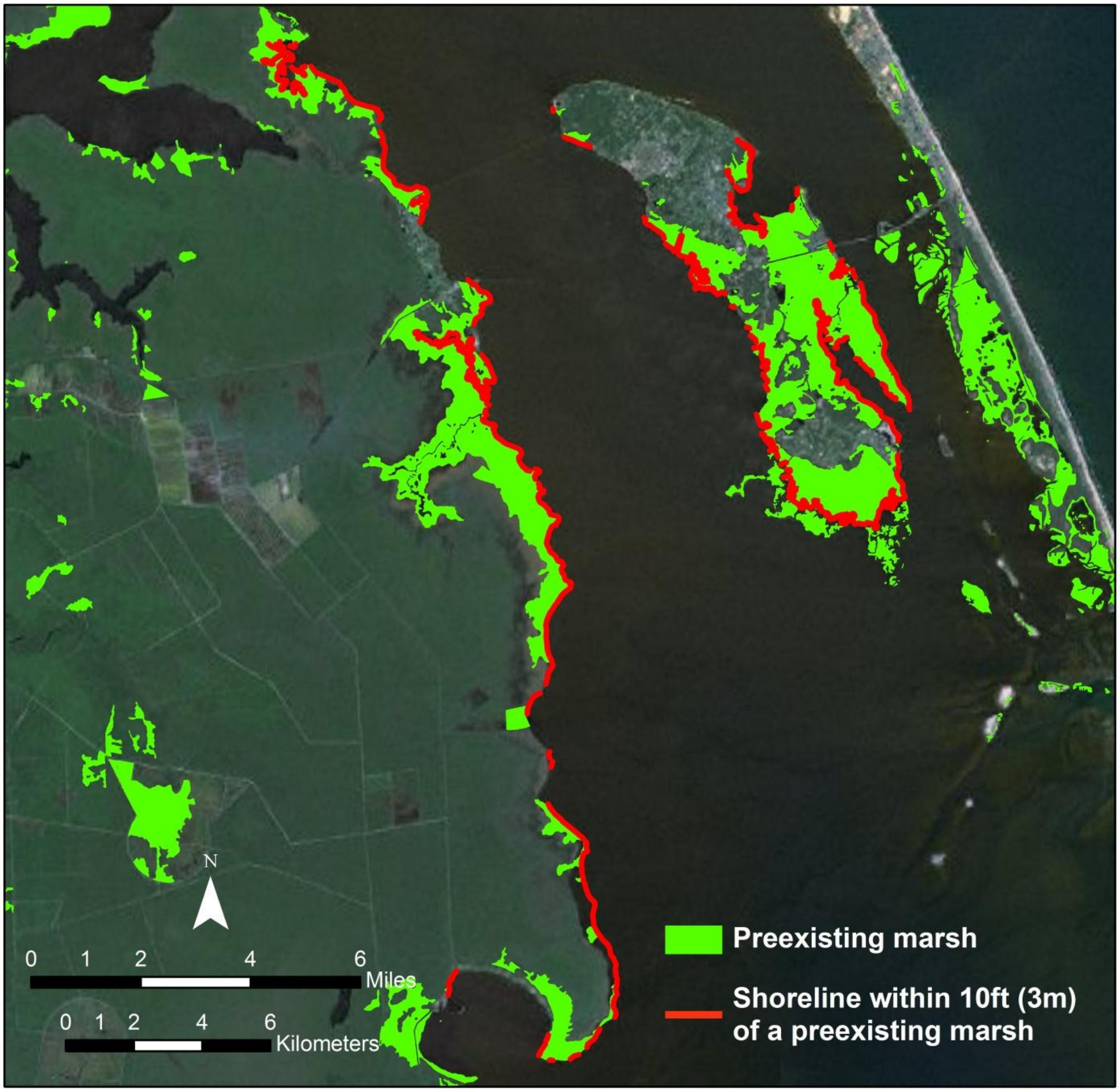

Figure 31. Preexisting marsh locations.

Submerged Aquatic Vegetation

The presence of submerged aquatic vegetation (SAV) can have a significant impact on the reduction of wave energy by causing the waves to break prematurely. But more importantly they serve as an indicator of the wave energy climate. SAV beds only develop in areas that have relatively low wave energy.

The SAV polygon (2011) file was provided by the Albemarle-Pamlico National Estuary Program (APNEP). The file was created using aerial imagery from 2007 and 2008 that depicted the red and green bands. SAV beds were mapped with a minimum mapping unit of fifteen meters. Any SAV beds that did not meet this requirement were omitted (APNEP 2011).

A spatial query was to select the shorelines that were within the one hundred foot buffer (Figure 32). Using the field calculator these shorelines were given a value of “1” to signify their suitability. The non-selected shorelines were given a value of “0”.

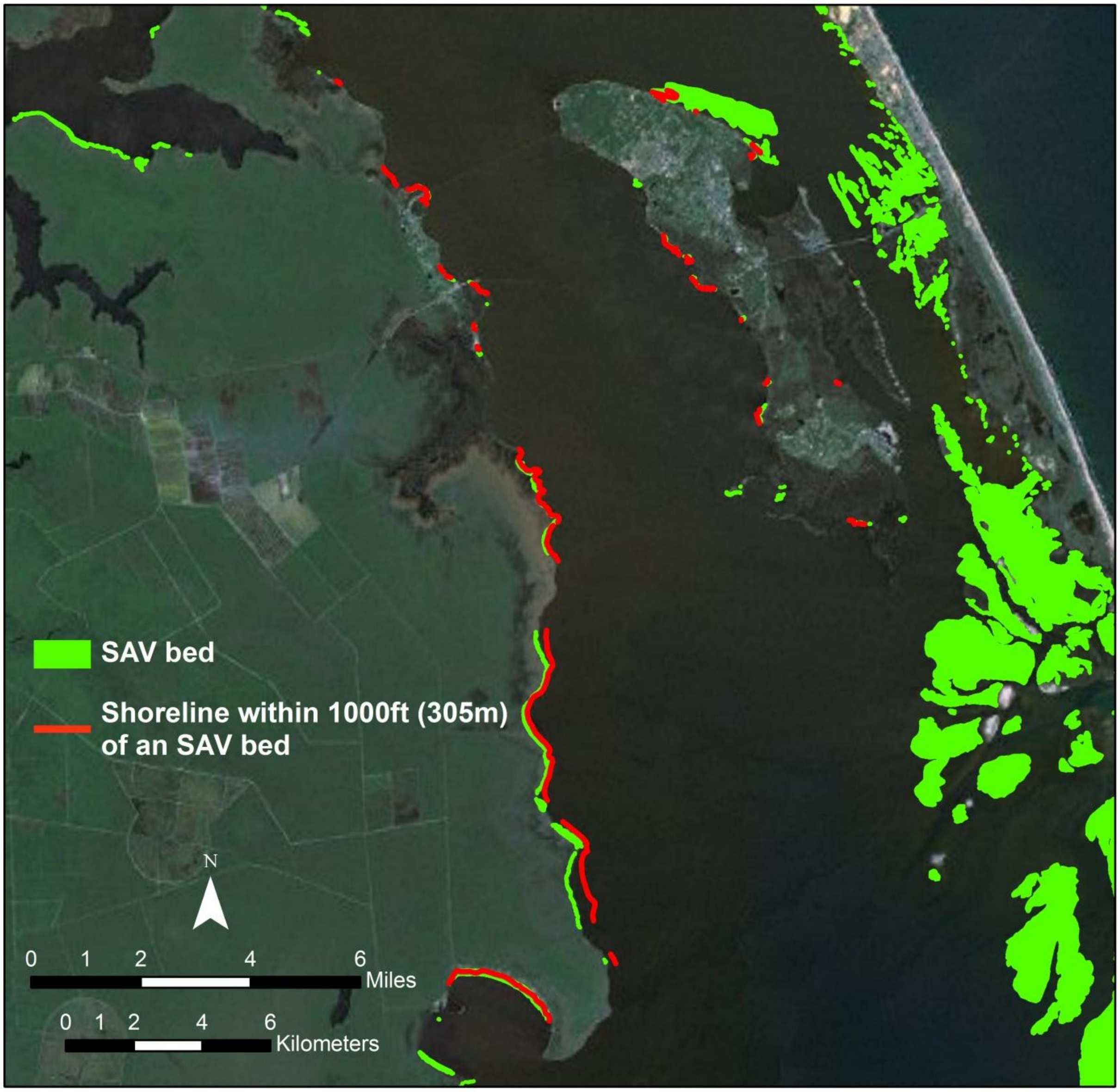

Figure 32. Submerged aquatic vegetation locations.

Calculating the Suitability Index

For this study, a suitability index was calculated for each of the 1,800 shoreline segments. Both weighted and unweighted calculations were used based on six different criteria: the two primary wind directions' fetch distances, nearshore depth, proximity to boat wakes, and the presence of wetland vegetation and SAV. This was done to calculate suitability scores for both soft and hybrid stabilization methods.

For each criterion shoreline segments were given a value of "1" if they met the standards mentioned previously. Values of "0" were given to segments that did not meet these standards. The sums of the assigned values for each segment were then calculated to produce an unweighted suitability score for each shoreline segment.

$$s = 225^{\circ}\, fetch + 10^{\circ}\, fetch + nearshore\ dpth + boat\ traffic + presence\ of\ pre - existing\ marshes + presence\ of\ SAV$$

A second suitability index was calculated by incorporating weights created using rank weighting (Malczewski 1999; Belka 2005). This involves ranking the criteria in order of importance (1= most important, 2 = second most important, etc.). After the ranks are established there are several procedures for calculating numerical weights can be used. The simplest and most popular is rank sum. This approach calculates weights based on the following formula:

$$w_i = \frac{n - rj + 1}{\sum(n - r_{k+1})}$$

Where w is the normalized weight for the jth criterion, n is the number of criteria under consideration ($k = 1,2, \ldots, n$), and r is the rank position of the criterion. Each criterion is weighted (n- r + 1) and then is normalized by the sum of all weights, that Is, $\sum(n - r_k + 1)$.

Using this method the criteria were then placed in order of importance: 1) fetch distance of southwest winds (225°) 2) fetch distance of north winds (10°) 3) nearshore depth 4) presence of wetland vegetation 5) boat traffic 6) presence of SAV. And their weights were calculated. The resulting dividends were then multiplied by "100" in order to produce a suitability index of zero to one hundred (Table 4).

n	rj	$n - rj + 1$	$\sum rj$	$\frac{n - rj + 1}{\sum(n - rj + 1)}$	$100 \times \frac{n - rj + 1}{\sum(n - rj + 1)}$
fetch distance of southwest winds (225°)	1	6	21	0.2857	28.57
fetch distance of north winds (10°)	2	5	21	0.2381	23.81
nearshore depth	3	4	21	0.1905	19.05
presence of preexisting marsh	4	3	21	0.1429	14.29
boat traffic	5	2	21	0.0952	9.52
presence of SAV	6	1	21	0.0476	4.76

Table 4. Criterion weighting for living shoreline suitability index.

$$s = 28.57(x_1) + 23.81(x_2) + 19.05(x_3) + 9.52(x_4) + 14.29(x_5) + 4.76(x_6)$$

CHAPTER 5: RESULTS

This chapter presents the results of the suitability index for living shoreline treatments. It begins by showing results and discussing the suitablility of the individual criteria in binary form (suitable vs. not suitable). Then, composite unweighted and weighted suitability maps are shown. The chapter concludes by comparing the results of the unweighted and weighted suitability indexes.

Off the 1800 shoreline segments, 1415 (78.61%) satisfy the 225 ˚ fetch criteria for soft stabilization(Figure 33). The total length of shoreline that meets this criteria is 116.27 kilometers. This is 79.81% of th total shoreline legnth of the study area.

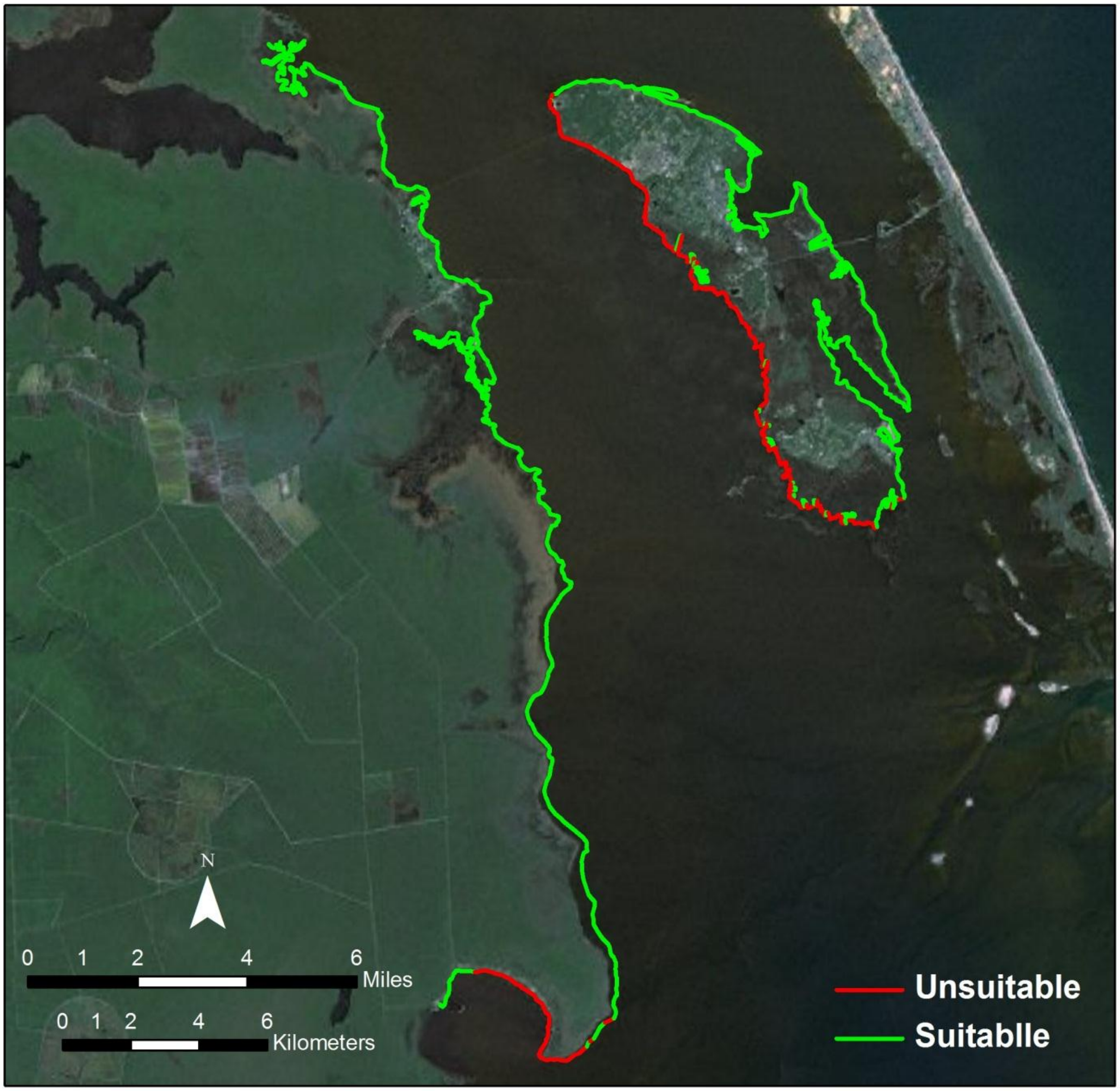

Figure 33. Southwest (225˚) Fetch suitability for soft stabilization living shoreline treatments.

Of the 1800 shoreline segments, 1652 (91.78%) satisfy the 225 ˚ fetch criteria for hybrid stabilization (Figure 34). The total length of shoreline that meets this criteria is 135.89 kilometers. This is 93.28% of th total shoreline legnth of the study area.

Figure 34. Southwest (225˚) Fetch suitability for hybrid stabilization living shoreline treatments.

Of the 1800 shoreline segments 1345, (74.72%) satisfy the 10 ° fetch criteria for soft stabilization (Figure 35). The total length of shoreline that meets this criteria is 100.13 kilometers. This is 68.73% of th total shoreline length of the study area.

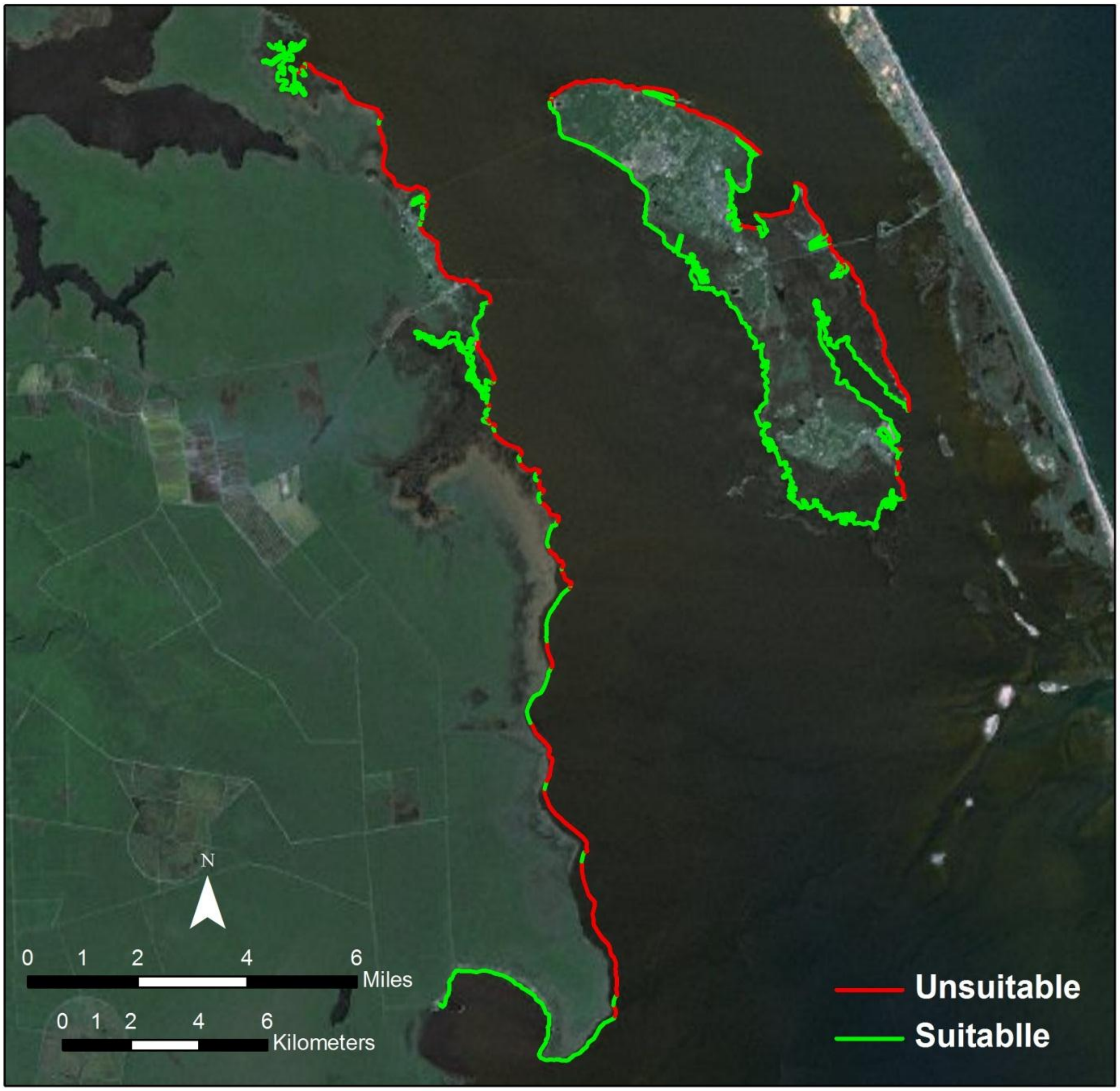

Figure 35. North-northeast (10˚) Fetch Suitability for soft stabilization living shoreline treatments.

Of the 1800 shoreline segments 1603, (89.06%) satisfy the 10˚ fetch criteria for hybrid stabilization (Figure 36). The total length of shoreline that meets this criteria is 125.34 kilometers. This is 86.04% of th total shoreline legnth of the study area.

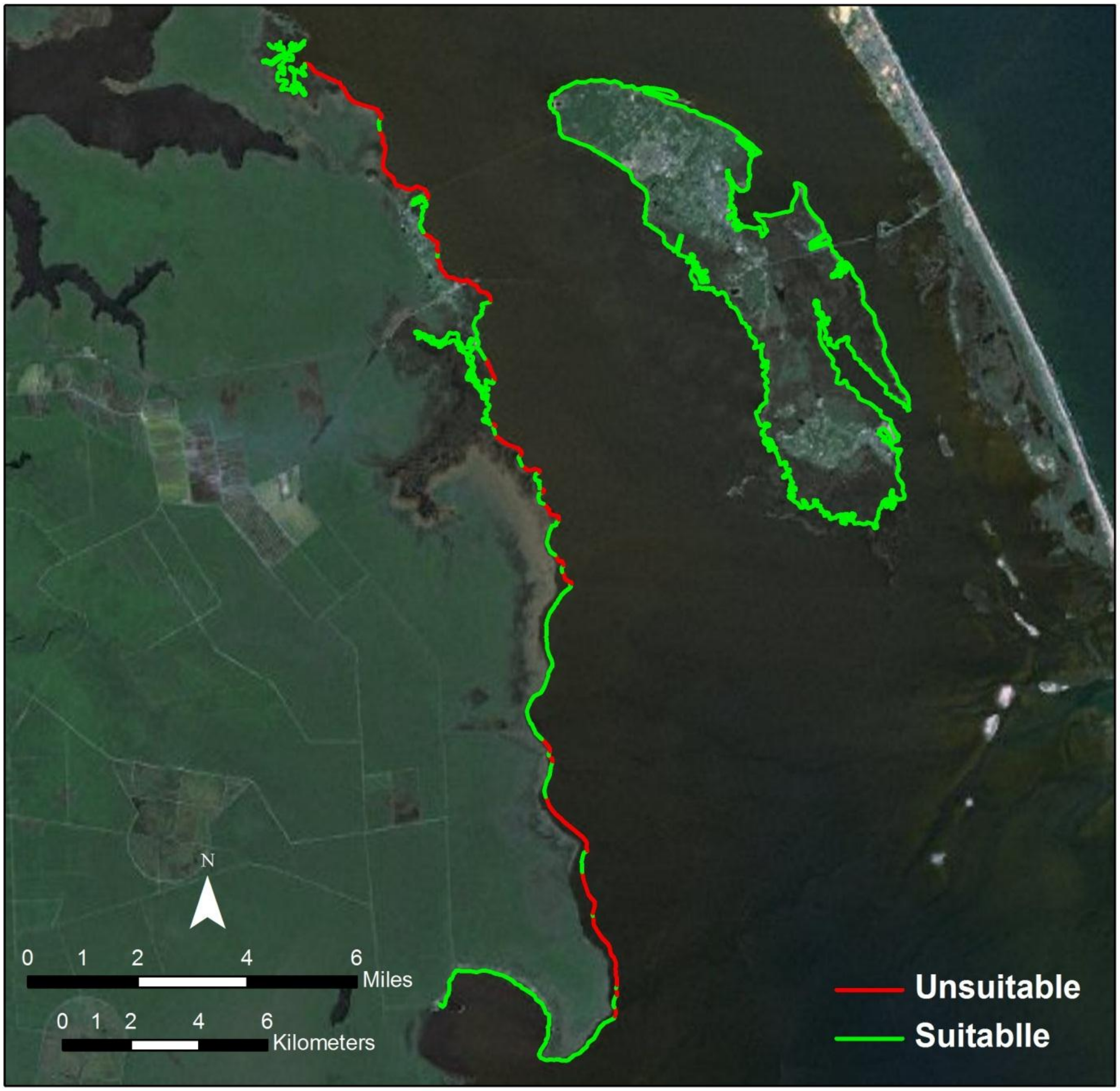

Figure 36. North-northeast (10˚) fetch suitability for hybrid stabilization living shoreline treatments.

Of the 1800 shoreline segments, 1439 (79.94%) satisfy the nearshore depth criteria for soft stabilization (Figure 37). The total length of shoreline that meets this criteria is 114.11 kilometers. This is 78.33% of th total shoreline legnth of the study area.

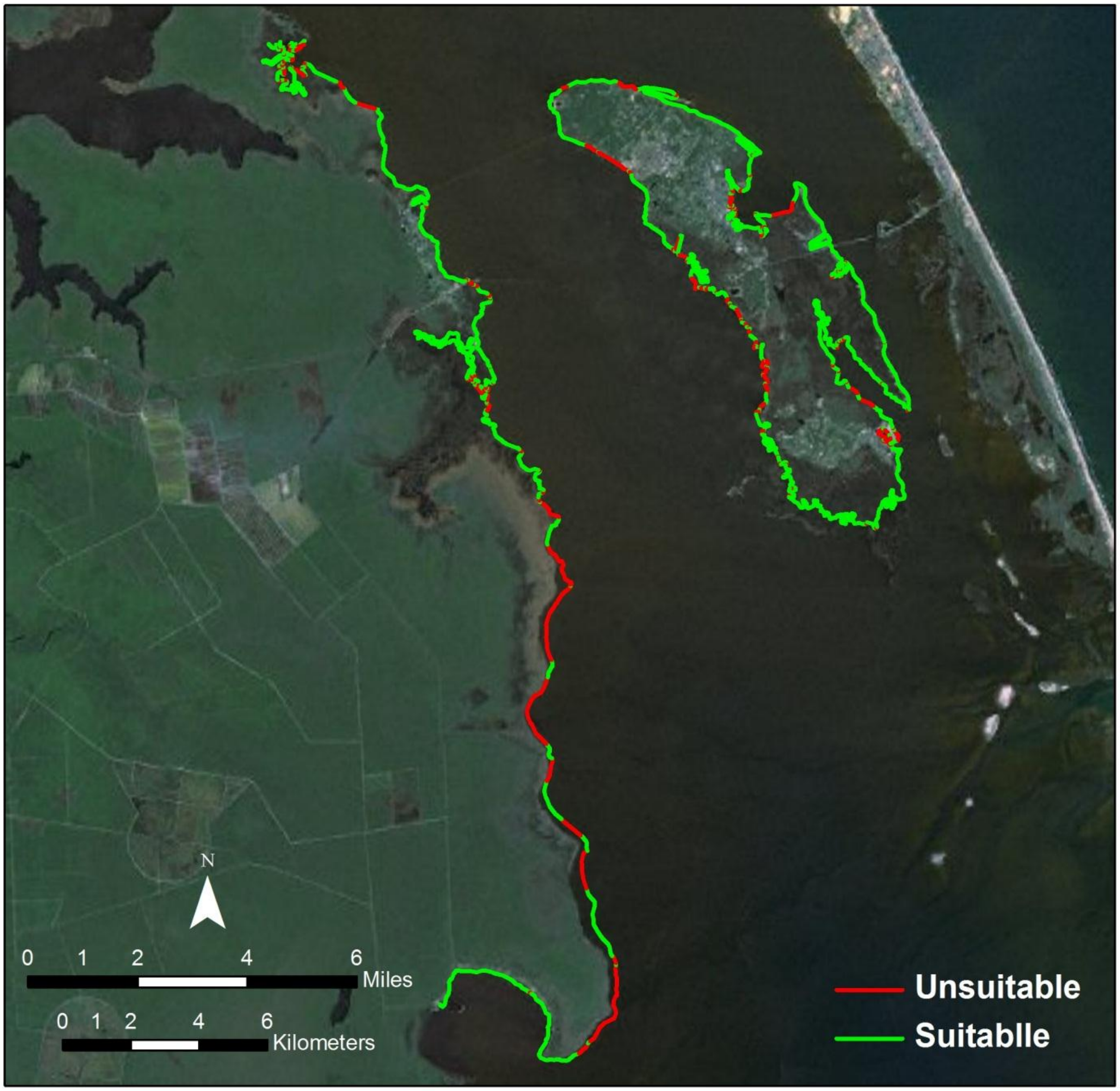

Figure 37. Nearshore depth suitability for soft stabilization living shoreline treatments.

Of the 1800 shoreline segments, 1773 (98.50%) satisfy the nearshore depth for hybrid stabilization (Figure 38). The total length of shoreline that meets this criteria is 143.61 kilometers. This is 98.58% of th total shoreline legnth of the study area.

Figure 38. Nearshore depth suitability for hybrid stabilization living shoreline treatments.

Of the 1800 shoreline segments, 1406 (78.11%) satisfy the proximity to boat traffic critrion (Figure 39). The total length of shoreline that meets this criteria is 115.39 kilometers. This is 79.21% of th total shoreline legnth of the study area.

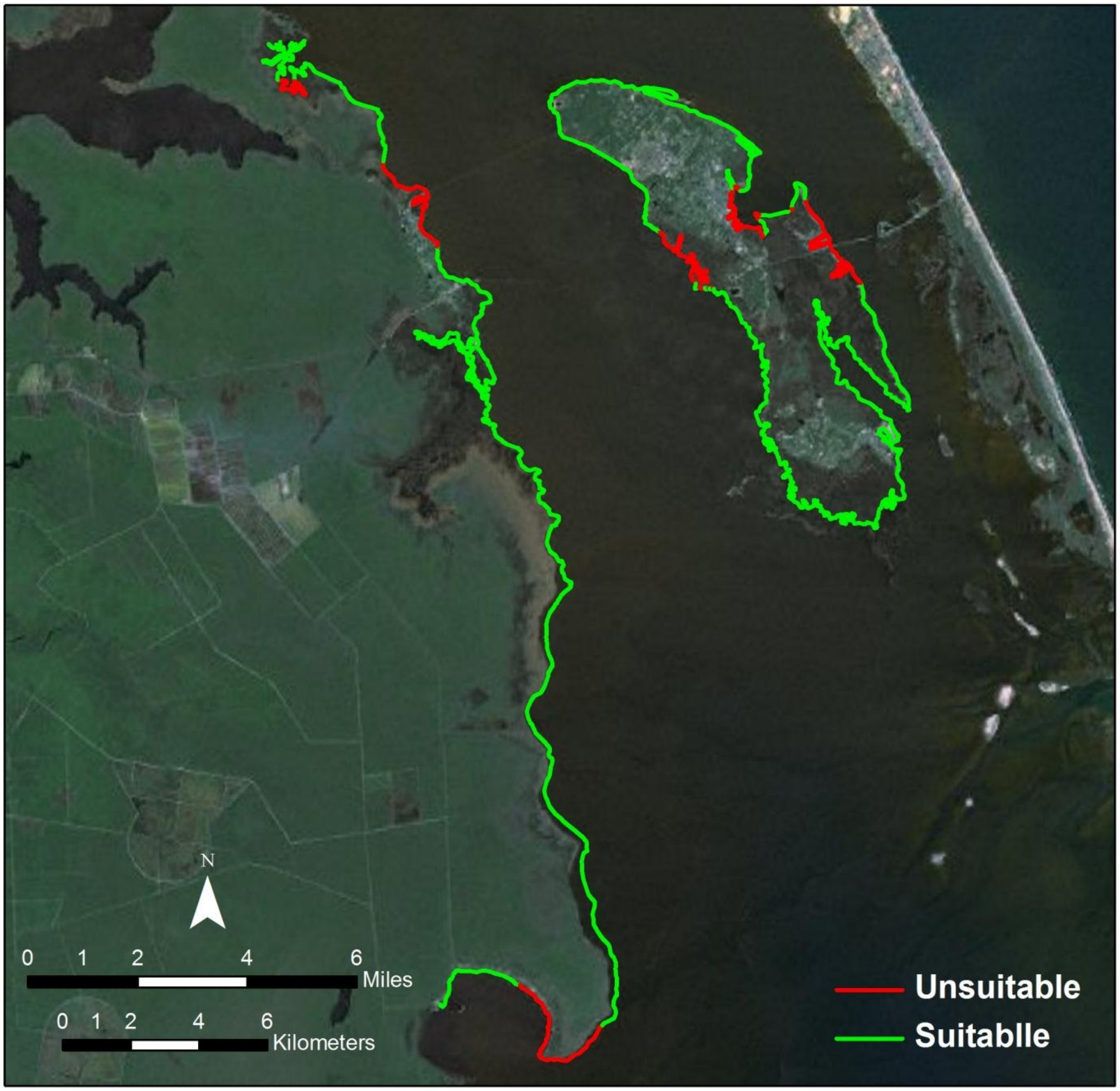

Figure 39. Boat traffic suitability for living shoreline treatments.

Of the 1800 shoreline segments, 1127 (62.61%) satisfy the marsh presence critrion (Figure 40). The total length of shoreline that meets this criteria is 89.08 kilometers. This is 61.15% of th total shoreline legnth of the study area.

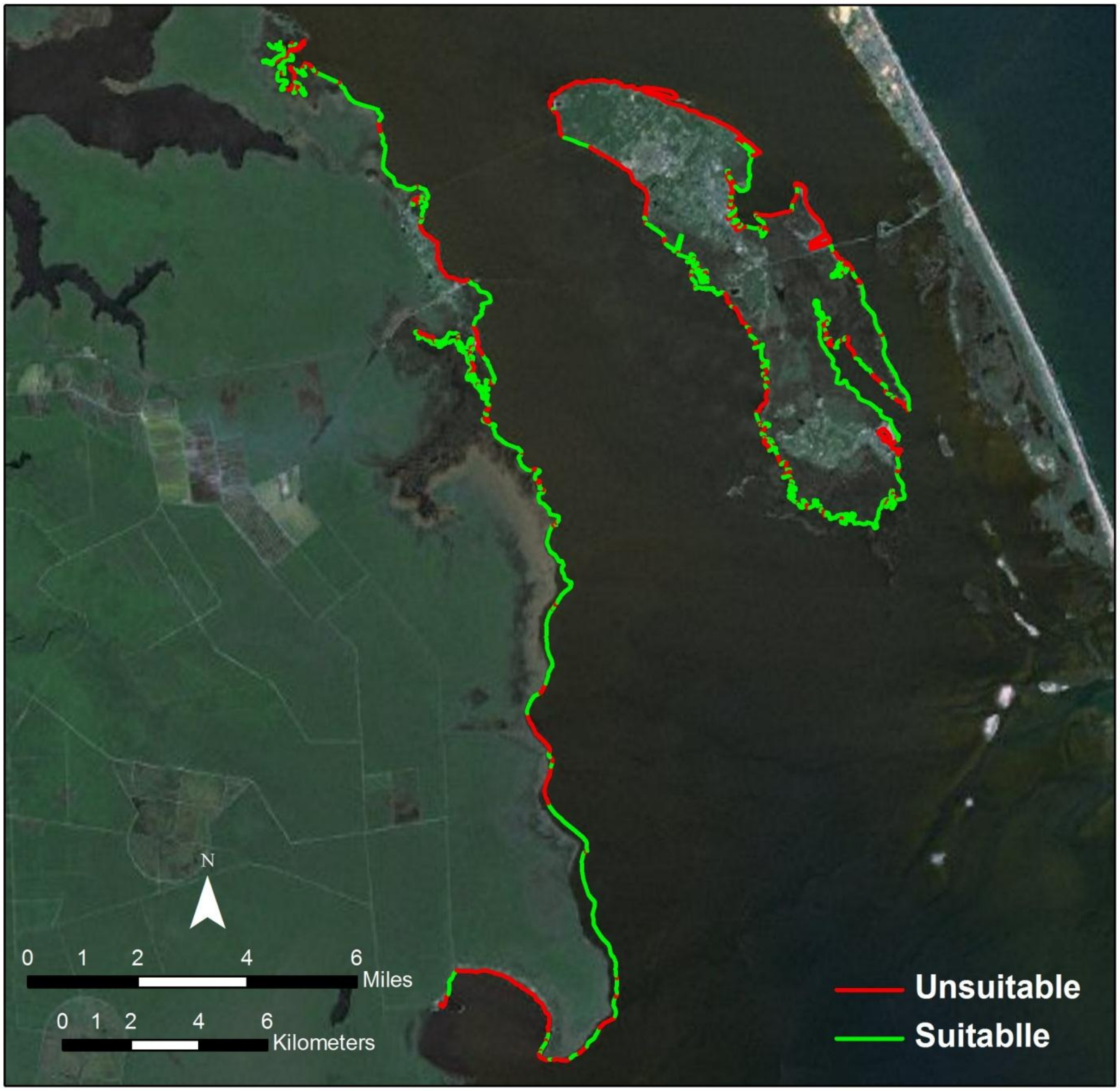

Figure 40. Preexisting marsh suitability for living shoreline treatments.

Of the 1800 shoreline segments 262, (14.56%) satisfy the presence of SAV criterion (Figure 41). The total length of shoreline that meets this criteria is 25.56 kilometers. This is 17.55% of th total shoreline legnth of the study area.

Figure 41. Submerged aquatic vegetation suitability for living shoreline treatments.

Comparing Un-weighted and Weighted Scores

The un weighted suitability calculations for both soft and hybrid stabilization practices created suitability scores for each shoreline segments ranging from one to six (Figures 42 & 43). The weighted suitability calculations for both soft and hybrid stabilization practices created suitability scores for each shoreline segments ranging from 23.81 to one hundred (Figures 44 & 45).

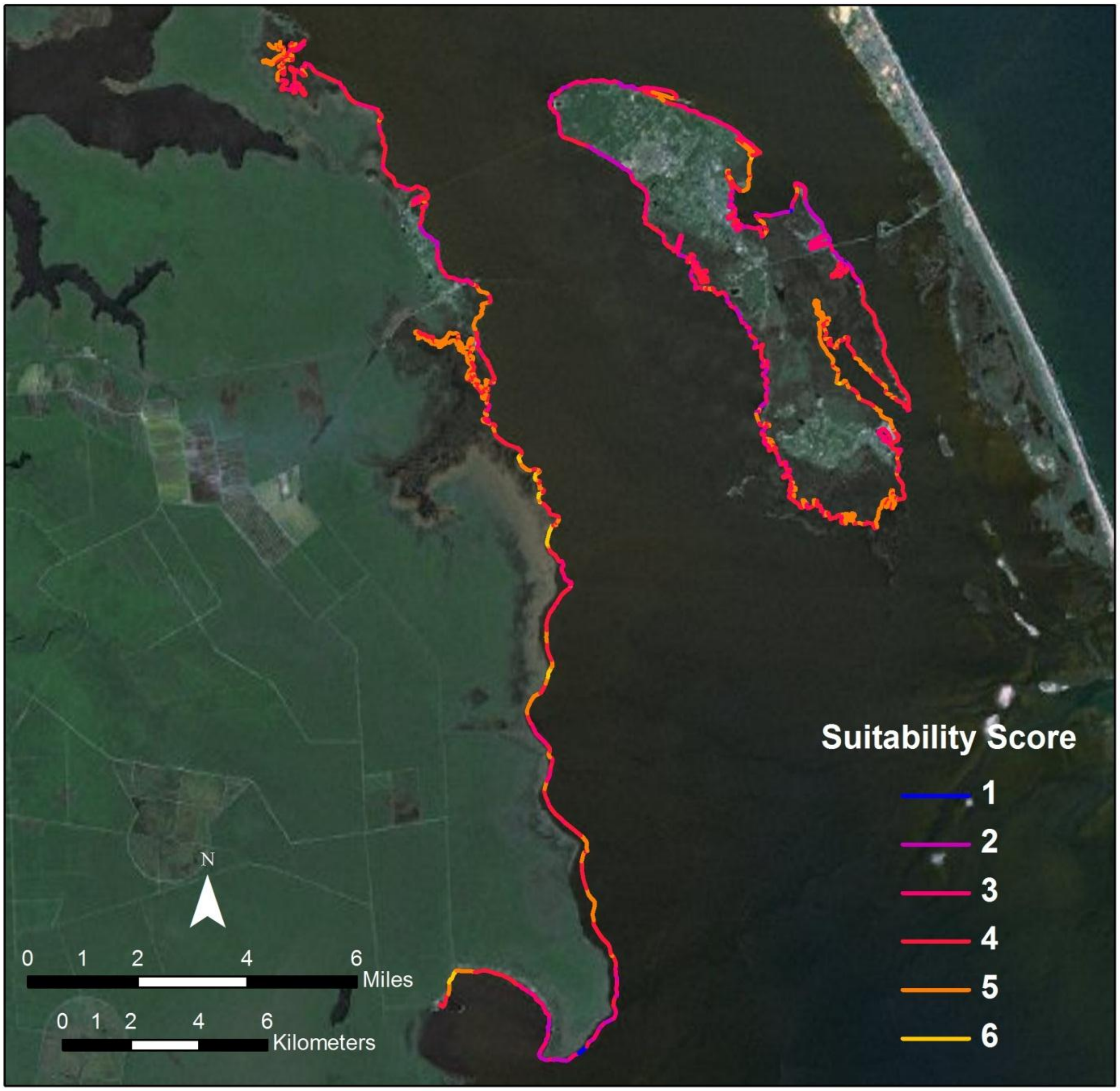

Figure 42. Unweighted suitability index for soft stabilization living shoreline treatments.

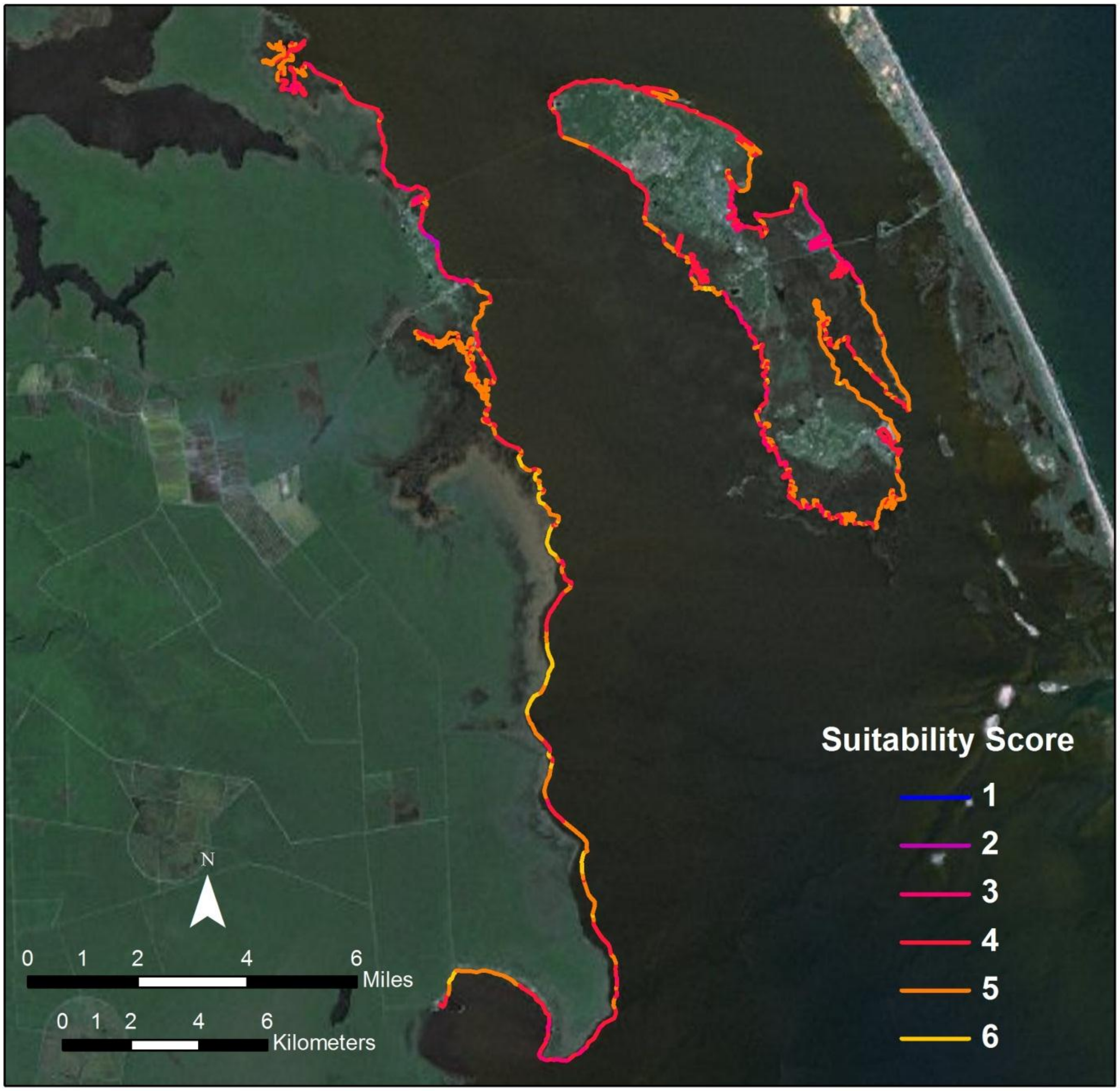

Figure 43. Unweighted suitability index for hybrid stabilization living shoreline treatments.

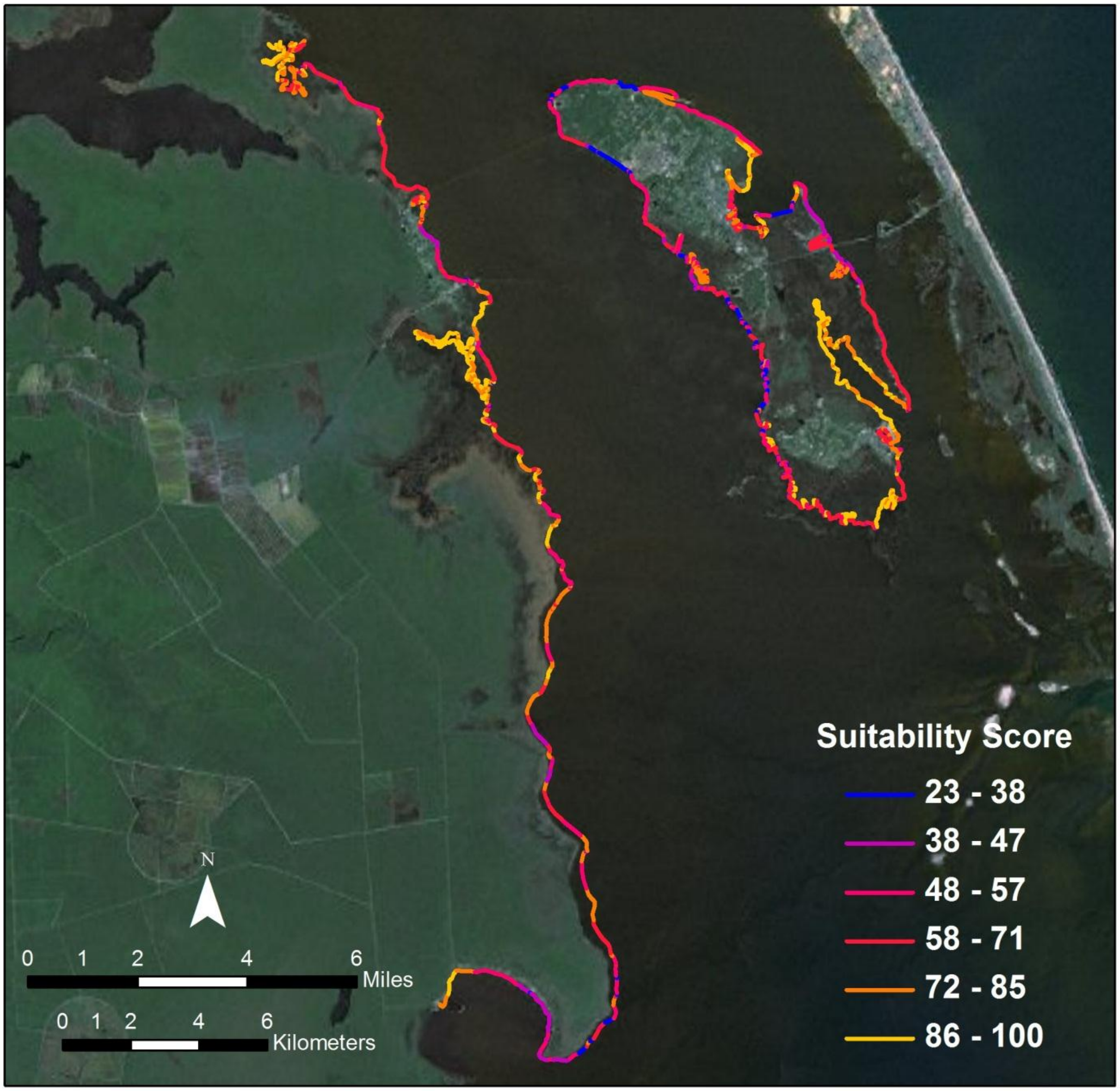

Figure 44. Weighted suitability index for soft stabilization living shoreline treatments.

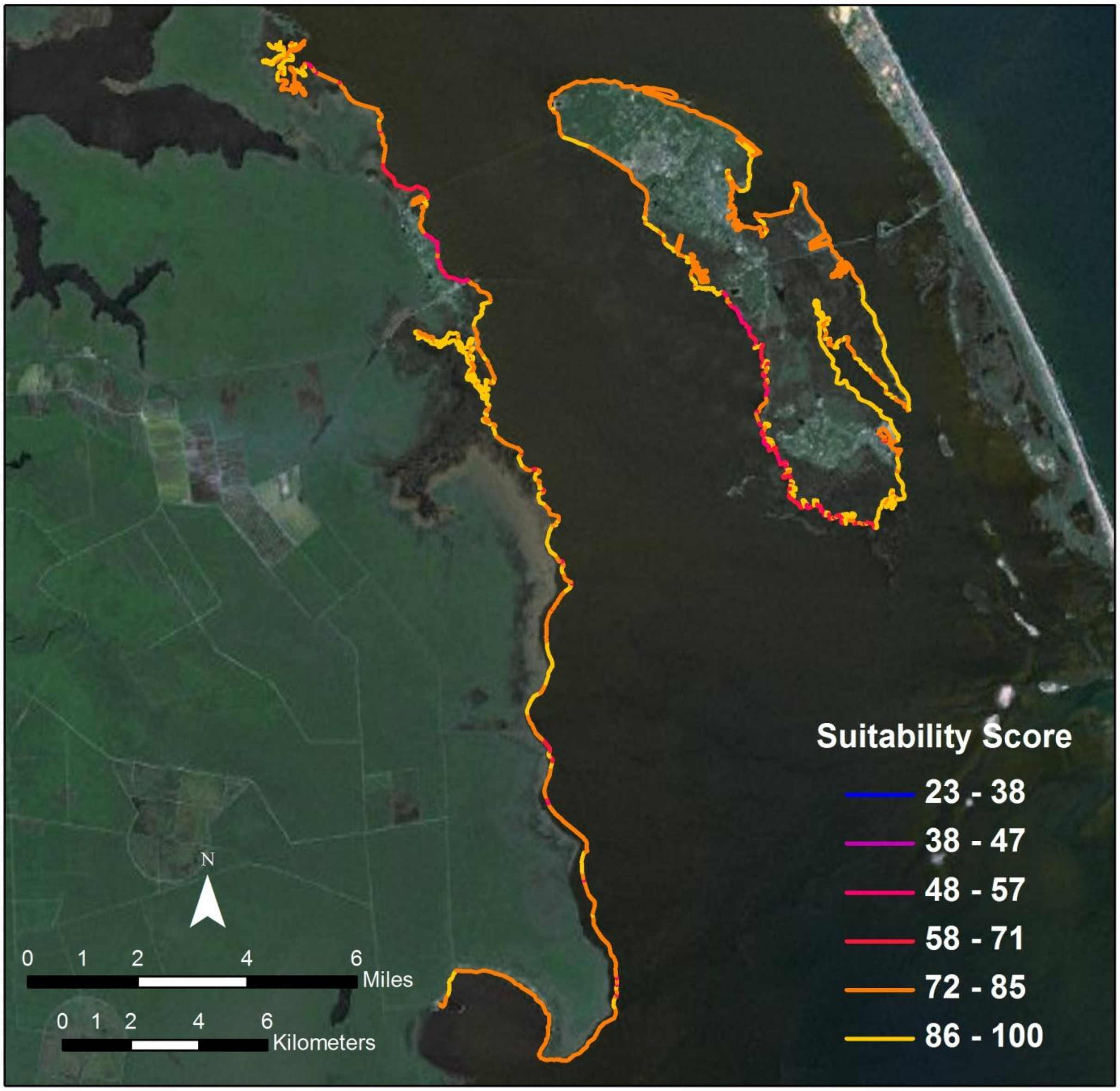

Figure 45. Weighted suitability index for hybrid stabilization living shoreline treatments.

Un-weighted Suitability Scores

Soft Stabilization

The minimum score is one. This shows that every shoreline segment satisfies at least one suitability criterion. The maximum score is six showing that there are shoreline segments that satisfy all the criteria. The mean score value is 3.89, which indicates that on average a shoreline segment will satisfy over half of the suitability criteria. The most common suitability score is four. There is a standard deviation of 0.97 between the data. Of the 1800 shoreline segments 1638 (91%) satisfy at least half of the suitability criteria for soft stabilization practices, making up 132.73 km (91%) of the shoreline. 523 (29.1%) of the shoreline segments have a suitability score of five or higher.

Minimum	1.00
Maximum	6.00
Mean	3.89
Mode	4.00
Standard Deviation	0.97

Table 5. Descriptive statistics for soft stabilization unweighted suitability scores.

Suitability Score	Number of Segments (Percentage of Total)	Shoreline Length (Percentage of Total)
1	7 (0.4%)	0.50 km (0.3%)
2	155 (8.6)	12.44 km (8.5%)
3	423 (23.5%)	37.09 km (25.5%)
4	692 (38.4%)	56.65 km (38.9%)
5	498 (27.7%)	36.66 km (25.2%)
6	25 (1.4%)	2.33 km (2.6%)

Table 6. Shoreline segment lengths and portions of the study area for soft stabilization un-weighted suitability scores.

Hybrid Stabilization

The minimum score is two, which shows that the every shore line segment satisfies at least two criteria. The maximum score is six showing that there are shoreline segments that satisfy all of the criteria. The mean score is 4.35, which indicates that the average shoreline will satisfy over four of the six criteria. The most common suitability score is four. The standard deviation between the data is 0.77. Of the 1800 shoreline segments 1790 (99.4%) satisfy at least half of the suitability criteria for hybrid stabilization practices, making up 144.79 km (99.6%) of the shoreline. 809 (44.9%) of the shoreline segments have a suitability score of five or higher.

Minimum	2.00
Maximum	6.00
Mean	4.35
Mode	4.00
Standard Deviation	0.77

Table 7. Descriptive statistics for hybrid stabilization un-weighted suitability Scores.

Suitability Score	Number of Segments (Percentage of Total)	Shoreline Length (Percentage of Total)
1	0 (0.0%)	0.00 km (0.0%)
2	10 (0.6%)	0.64 km (0.4%)
3	231 (12.8%)	17.49 km (12.0%)
4	750 (41.7%)	63.02 km (43.3%)
5	744 (41.3%)	58.04 km (39.9%)
6	65 (3.6%)	6.24 km (4.4%)

Table 8. Shoreline segment lengths and portions of the study area for hybrid stabilization un-weighted suitability scores.

Weighted Suitability Score

Soft Stabilization

The minimum score is 23.81 (Table 9). This shows that every shoreline segment satisfies at least one suitability criterion. The maximum score is 100 showing that there are shoreline segments that satisfy all the criteria. The mean score value is 72.56. The most common suitability score is 95.24. There is a standard deviation of 18.19 between the data. Of the 1800 shoreline segments 1294 (71.9%) have suitability score over 57 soft stabilization practices, making up 100.28 km (69.1%) of the shoreline (Table 10). 439 (20.8%) of the shoreline segments have a suitability score of five or higher.

Minimum	23.81
Maximum	100.00
Mean	72.56
Mode	95.24
Standard Deviation	18.19

Table 9. Descriptive statistics for soft stabilization weighted suitability scores.

Suitability Score	Number of Segments (Percentage of Total)	Shoreline Length (Percentage of Total)
23 - 38	77 (4.2%)	6.79 km (4.7%)
38 - 47	136 (7.6%)	10.95 km (7.5%)
48 - 57	293 (16.3%)	27.07 km (18.7%)
58 - 71	417 (23.2%)	36.99 km (25.5%)
72 - 85	438 (24.3%)	33.16 km (22.8%)
86 - 100	439 (24.4%)	30.13 km (20.8%)

Table 10. Shoreline segment lengths and portions of the study area for soft stabilization weighted suitability scores.

Hybrid Stabilization

The minimum score is 47.62 (Table 11). This shows that every shoreline segment satisfies at least one suitability criterion. The maximum score is 100 showing that there are shoreline segments that satisfy all the criteria. The mean score value is 83.27. The most common suitability score is 95.24. There is a standard deviation of 12.28 between the data. Of the 1800 shoreline segments 1705 (94.7%) have a suitability score over 58 for hybrid stabilization practices, making up 139.60 km (95.7%) of the shoreline (Table 12). 689 (38.3%) of the shoreline segments have a suitability score of 86 or higher.

Minimum	47.62
Maximum	100.0
Mean	83.27
Mode	95.24
Standard Deviation	12.28

Table 11. Descriptive statistics for hybrid stabilization weighted suitability scores.

Suitability Score	Number of Segments (Percentage of Total)	Shoreline Length (Percentage of Total)
23 - 38	0 (0.0%)	0.00 km (0.0%)
38 - 47	10 (0.5%)	0.64 km (0.1%)
48 - 57	85 (4.7%)	5.61 km (3.8%)
58 - 71	347 (19.3%)	30.02 km (20.6%)
72 - 85	669 (37.2%)	57.75 km (39.6%)
86 - 100	689 (38.3%)	51. 65 km (35.5%)

Table 12. Shoreline segment lengths and portions of the study area for hybrid stabilization weighted suitability scores

CHAPTER 6: DISCUSSION

This chapter begins with a discussion of the patterns of suitability for the variables of the suitability index and the suitability scores. This chapter also describes other considerations that could be taken into account in future living shoreline-suitability studies. It concludes with an overview of the significance of this research.

Suitability Patterns

The results show that the majority of the shorelines within the study area are suitable for both soft-stabilization and hybrid living shoreline treatments. Suitability scores are quite high owing to the three influential factors governing estuarine wave energy in the area.

Because the majority of the shorelines are East facing fetch from the dominant wind direction, southwest, is suitable for 79.8% of the shorelines. The areas that have fetches that exceed the suitable limit of are the Western side of Roanoke Island and eastern Stumpy Point Bay. 93.8% of the shorelines have suitable southwest fetches for hybrid treatments. The only shorelines that have unsuitable fetches are on the southwest shore of Roanoke Island. But, even this area has an interlacing of shorelines with suitable fetches due to the irregular geometry of the shoreline.

The geometry of both Roanoke Island and the eastern shore of the Albemarle-Pamlico Peninsula make for an interesting pattern for shoreline suitability for North-northeast fetches. Approximately 68% of the shorelines are suitable for soft-stabilization living shorelines. The Northwest to Southeast orientation of Roanoke Island creates a virtually uniform distribution of shorelines with suitable fetches. The northeast-facing shores are almost all unsuitable except for the sheltered shorelines in Shallowbag Bay. The scalloped shoreline of the Albemarle-Pamlico

Peninsula creates an alternating pattern of shorelines with suitable and unsuitable fetches. This is also the case for suitability hybrid living shoreline treatments. However, the Outer Banks provide shelter causing all of Roanoke Island's shorelines that have suitable fetches.

Nearshore depth played a significant factor in suitability scores. 78% of shorelines within of the study had suitable nearshore depths to support soft stabilization living shorelines. The main concentration of shorelines unsuitable depths is at the lower half of the Albemarle-Pamlico Peninsula where the Croatan and Pamlico Sounds meet. Nearly all (98.58%) of the shorelines are have suitable nearshore depths for hybrid stabilization living shorelines. The only segments that have unsuitable depths are at the center of the Albemarle-Pamlico Peninsula.

79.76% of the shorelines are not within a mile of public boat accesses. However, this variable is a little shaky because being close to or away from a boat access does not provide a definite approximation of boat traffic.

61.15% of the shorelines have pre-existing marshes. Only shorelines around the population centers of Manteo, Manns Harbor, and Stumpy do not have marshes present. Only 17.55% of the shorelines are near SAV beds. These are mostly found in the in the southern portion of the Albemarle-Pamlico Peninsula.

The outcome of this study is supported by findings of other studies that show that living shorelines can be successful in the Albemarle-Pamlico Estuarine system (Currin 2010; Fear and Bendell 2011). Albeit the majority of the living shorelines evaluated in these studies are found on shorelines with less wave exposure than what are found within this paper's study area. Additionally, these studies are limited to the success of hybrid stabilization living shorelines using marsh sills.

It appears that the shorelines of the Albemarle-Pamlico Estuarine system are suitable for use of hybrid stabilization techniques. However, although it appears that the majority shorelines in the region have high suitability scores for soft stabilization techniques, they may only be successful in areas with minimal fetches such as bays and creeks.

FUTURE CONSIDERATIONS

There are a few variables that could be included in future suitability indexes. Sediment type could be looked at to ensure that plants would be able to preserve or create natural and sustainable environments (Currin 2011). Bottom type could be taken into account because if bottoms are too soft they might not be able to support the weight of a sill (Boutin 2010). Additionally, to extend suitability screening into areas with forested shorelines in narrow tributaries or bluff shores that are susceptible to shading additional variables would need to be included.

It also would have been beneficial to test the suitability index results. Roloff and Kernohan (1999) state that the range and distribution of suitability index scores important to supporting the indexes validity. An analysis of variance (ANOVA) test could be used to show the scores' distribution.

Perhaps the biggest issue with this method in the future is the data used. It will be import to make sure that the most current data available is used. Also, it would be preferable to use data collected from the same time period with matching resolution.

SIGNIFCANCE OF RESEARCH

The need for effective forms of shoreline control is of great importance given the threat of land loss due to increased erosion. While traditional methods are usually effective in protecting the land immediately behind them they do tend to have significant adverse impacts. Conversely, living shorelines have less impact and evidence show that they can have beneficial impacts.

Currently, it is fairly difficult for living shorelines to be granted permits owing to many specifications that must be met for their success as well as compliance with property laws. This can lead to a very long process. To help expedite the decision making process, this type of research can be applied to help managers screen for areas that are suitable for living shoreline treatments. Based on the previously mentioned criteria areas could be screened to see if living shoreline treatments would be successful and then more closely looked at to determine how to tailor them for more specific treatments. Another possible use would be for organizations such as The Nature Conservancy to use this for identifying areas that would be potential candidates to use living shorelines for habitat restoration.

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Appendix A. Data Used

Data	Source	Year
Shoreline Polyline	North Carolina Department of Transportation	2011
North Carolina County Boundaries with Shoreline Polygon	North Carolina Department of Transportation	2011
Advanced Circulation Grid Nodes	ADCIRC	2003
Public Boating Access Points	North Carolina Resources Commission	2012
Wetlands Type Polygon	North Carolina Division of Coastal Management	2003
Submerged Aquatic Vegetation Polygon	Albemarle-Pamlico National Estuarine Program	2011
Coastal Change Analysis Program Landcover	NOAA Coastal Change Analysis Program	2006