

Suitability Analysis for Living Shorelines Development in Southeast Florida's Estuarine Systems



Technical Report

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EXECUTIVE SUMMARY

Coastal hazards including storm damage and sea level rise threaten coastal cities and may drive major shifts in urban development patterns. With elevations of 3 to 4 feet, South Florida is one of the most vulnerable coastal regions in the world. Areas at risk are likely to see increased shoreline armoring which may have long-term environmental impacts on the health of our estuaries and the ecosystem services they provide. The hard-armoring approach is known to reduce sediment sources by interrupting natural sediment transport, affect water quality, reduce habitat viability, and fundamentally disrupt the connectivity between terrestrial and estuarine and marine ecosystems. Shoreline restoration and enhancement techniques have been shown to provide comparable protection under suitable landscape and environmental conditions. An emerging approach to shoreline stabilization is to create “living shorelines” in which natural habitats are incorporated into a resilient shoreline stabilization design.

The Southeast Florida (SEFL) Regional Climate Change Compact Shoreline Resilience Working Group (SRWG) provided the impetus for this effort as well as invaluable expertise, input and feedback. The spatial extent of the database encompasses the estuarine areas alongside inland waters in Broward County, Miami-Dade County, Palm Beach County, and the Blowing Rocks Preserve in Martin County. This database was created based on our understanding of the importance of nature-based shoreline stabilization options at reducing the impacts of coastal hazards, and their contribution to the health of estuarine and marine environments, and protection of economic and cultural resources. Several shoreline stabilization projects included in the database use a range of naturally occurring features to stabilize and protect shorelines.

Drawing upon the scientific literature, expert opinion and shoreline management best practices, we propose a decision framework for multiclass suitability classification of generic project types that use a range of naturally occurring features to stabilize and protect shorelines. We apply a modified version of the InVEST Coastal Vulnerability model (Sharp et al. 2015) to calculate an exposure index based on spatial attributes such as wind/wave exposure, boat wake, nearshore slope, storm surge, water depth, nearshore habitat, and distance to inlet. An expert opinion survey was conducted to elicit parameter weights. The calculated Exposure Index was then used to develop a suitability framework based on decision trees for multi-criteria evaluation to facilitate future efforts to establish the use of vegetated shorelines or a combination of plant communities and stabilization to attenuate wave action, dissipate wave energy, and mitigate erosional forces. The results of the analysis will facilitate decisions regarding the use of vegetated shorelines or a combination of plant communities and structural stabilization to attenuate wave action, mitigate erosional forces, and reduce storm damage. The successful implementation of innovative shoreline stabilization techniques is particularly important in the context of sea level rise which will most likely amplify the flood management challenges faced by residents, planners, coastal managers, and decision-makers. Re-evaluation of the existing regulatory

basis for including living shorelines provisions and demonstration projects on public and private lands will increase awareness and acceptance of these alternative shoreline stabilization options. As a step in this direction, section 2(a)(2) of Executive Order 11988 was recently amended to include the use of natural systems and ecosystem services in the development of flood control alternatives (EO 13690/Jan. 30, 2015, FR 80 (23)/6425-28/Feb. 4, 2015). Living shorelines have the potential to enhance ecosystem services in estuaries and other sheltered shorelines which are particularly vulnerable to the effects of development and hardening. The management challenge here is to find ways to allow property owners to protect their valuable real estate while at the same time minimize long-term environmental impacts on the health of our estuaries and the ecosystem services they provide. The benefits can be mutual as a waterfront lot with natural wetlands and living shorelines is more aesthetically pleasing and hence potentially more valuable leading to increased property values and tax base.

Section 1 provides an overview of the pertinent literature with a focus on alternative approaches to shoreline stabilization. Factors that affect the establishment of nature-based approaches are discussed and the objectives of the study are formulated. In Section 2, the Southeast Florida context and the methods employed in this study are discussed. Section 3 contains the results of the analysis. Appendix 1 lists the shoreline description together with the proposed stabilization option for each shoreline type. Appendix 2 includes several maps displaying locations where alternative solutions to hard armoring could be implemented. A synopsis of attribute labels, attribute type, attribute definition, and attribute data source of the Exposure Index shapefile is given in Appendix 3. Appendix 4 contains the research participation invitation. Appendix 5 includes the survey instrument. Appendix 6 contains the report generated by Qualtrics.

ACKNOWLEDGMENTS

We gratefully acknowledge the contribution of many individuals and organizations. First and foremost, we would like to thank the members of the Southeast Florida Climate Compact Shoreline Resilience Working Group who provided invaluable support in all phases of the project.



DISCLAIMER

This study is based on publicly available data sources and expert knowledge. The results from this study are not intended to create or constitute any legally binding obligation and no party shall have any liability or obligation to another with respect to using the result from the analysis as is. All users should carefully consider scale, purpose and intended uses and consult the best available data sources as certain assumptions developed under the project may not be suitable for all purposes, tasks and/or planned objectives.

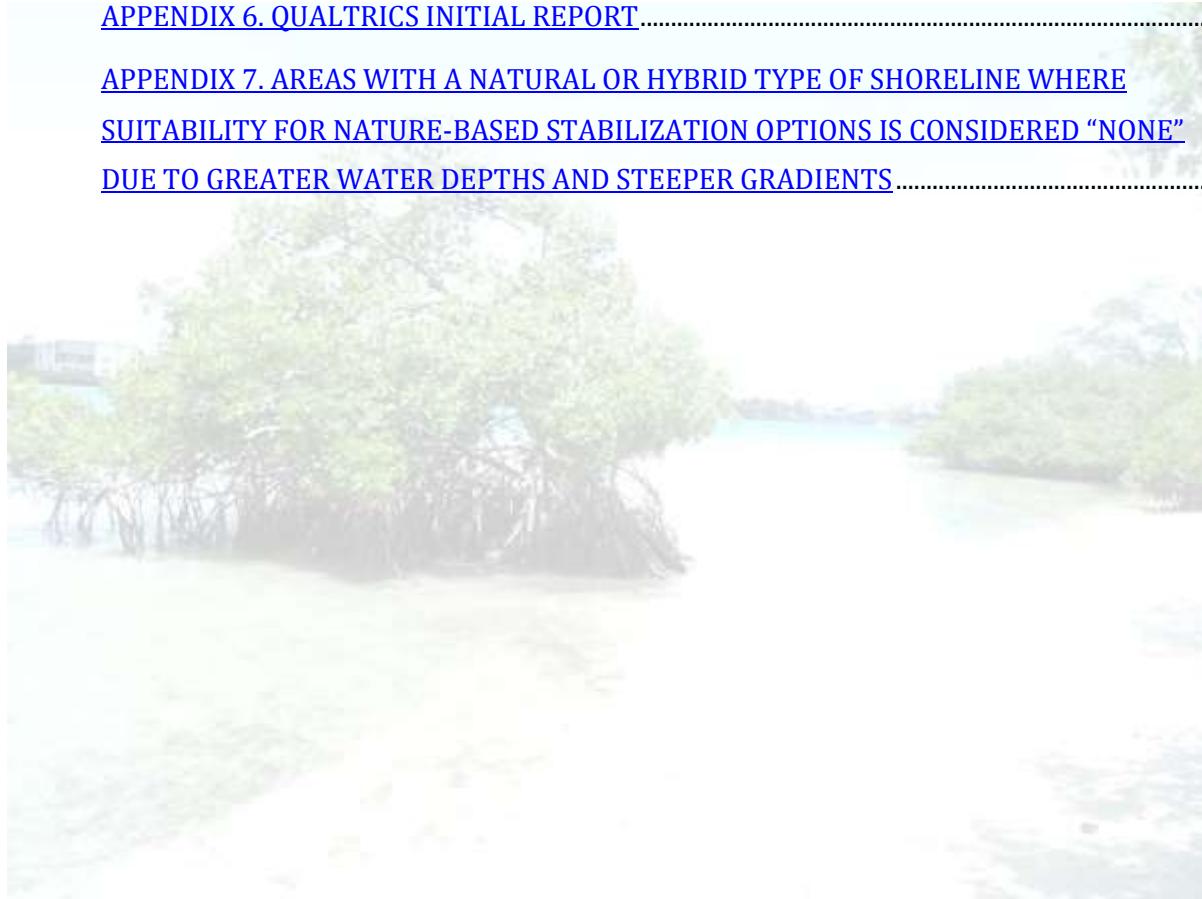
Data for shoreline restoration, enhancement and stabilization projects in the study area were not generally available through public data sources. The data were obtained through direct communication and data requests, or derived from historical documents. Data for several parameters used in the suitability analysis were available only in permits and reports. Every effort was made to ensure the completeness and accuracy of the information in each spatial layer. However, some discrepancies may still persist due to the variety of sources used to compile the information. Some spatial layers may not be as comprehensive as others because such data were not produced by the owner of the data source.



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1. INTRODUCTION

Coastal regions are some of the most vulnerable to disasters and ecosystem disturbances due to co-location of critical infrastructure, high population densities, and major resource use to maintain vital economic activities (Walker et al. 2004, Adger et al. 2005, Adger 2006, Becker 2012, Beichler et al. 2014). In fact, the linkages between socio-economic and ecological systems in coastal areas are so intertwined that the very concept of socio-ecological resilience draws upon the ability of interconnected social-ecological systems to withstand, mitigate, absorb shocks, and recover from extreme events while simultaneously maintaining the functionality of human infrastructures and allowing for provision of essential societal services (Walker et al. 2004, Adger et al., 2005, Beichler et al. 2014). Recent studies evaluating the risks of climate change on coastal regions highlight increased exposure and vulnerability due to continued population growth and placement of critical economic resources in harm's way (Nicholls 2004, Adger et al. 2005, Rosenberg and McLeod 2005, Leslie and McLeod 2007, McGranahan et al. 2007, UNEP 2009). In 2007, scientists at the Center for International Earth Science Information Network and the International Institute for Environment and Development published a study of the global population at risk of sea level rise impacts (McGranahan et al. 2007). The study found that over 600 million people live in coastal areas at an elevation of less than 10 meters (McGranahan et al. 2007). In addition, the largest and most populous urban areas around the globe are situated, partially or entirely, in the low-lying coastal zone (McGranahan et al. 2007). More recently, data from the UN Atlas of the Oceans developed by six UN agencies in collaboration with various partners from the private and public sectors indicated that currently, 44 percent of the global population resides in coastal areas (UN Atlas of the Oceans 2015) with an expected increase to 50 percent by 2030 (Nicholls 2004, Adger et al. 2005).

The increasing pressures on coastal ecosystems due to accelerating pace of urban development have led to the degradation of many of the ecosystem functions on which human prosperity and well-being depend (MA 2005, Rosenberg and McLeod 2005, Leslie and McLeod 2007, UNEP 2009). The Millennium Ecosystem Assessment concluded that 15 out of the 24 most important ecosystem services have been critically impacted by human activities over the past 50 years (MA 2005). UNEP (2009) prioritized 11 of the 15 declining ecosystem services placing climate, natural hazards, water, energy, and nutrient cycling at the top of the priority list. Pew Oceans Commission (2003) estimated that more than 20,000 acres of coastal wetlands and estuaries that support habitat for fisheries, birds and other aquatic and terrestrial species have been destroyed as a result of the coastal zone overdevelopment. Recognizing the need for change in current sector-based approaches, both the US Commission on Ocean Policy (2004) and UNEP (2006) proposed several recommendations that highlight the importance of ecosystem-based approaches and integrated coastal resources management to improve the health and enhance coastal habitats while at the same time provide the nature-based services necessary to strengthen our response to hazards and climate change, decrease pollution, and create conditions for successful economic development, increased food security, and protection of human health.

In the wake of hurricane Sandy, the U.S. Army Corps of Engineers published the North Atlantic Coast Comprehensive Study (NACCS) which formulates several principles and strategies for enhancing coastal resilience. The report draws particular attention to the need for undertaking "a systems approach" that validates the interaction between natural, social, and built dimensions (USACE 2015, p. ii). The full array of proposed solutions includes engineered as well as nonstructural nature-based approaches to reduce vulnerability to coastal hazards (USACE 2013, USACE 2015). Restoration and shoreline enhancement projects provide both ecosystem services and potential for shoreline protection against the threats of sea level rise. A meta-analysis of living shoreline research showed overwhelmingly that marsh and mangrove vegetation can effectively attenuate wave action and protect people, property, and infrastructure (Gedan et al. 2011, Click et al. 2014). Mangroves fringe swamps are key habitat for the survival of many species and provide a natural defense against hurricanes and erosion (FDEP 2011). These resilient, pioneer tree communities can buffer wave action

generated by high winds and are particularly adept at accreting sediment at rates likely to keep pace with average sea level rise (Alongi 2008, Kirwan and Magonigal 2013). In the context of sea level rise, shoreline restoration projects and natural defenses are considered in several recommendations addressing the designation and implementation of Adaptation Action Areas (SEFL-CCC 2012b). More specifically, the Southeast Florida Regional Climate Action Plan suggests that adaptation actions with respect to natural systems be based on “monitoring, management, and conservation programs designed to protect natural systems and improve their capacity for climate adaptation” (SEFL-CCC, 2012b, p. 32). Recommended actions NS-2, NS-5, NS-6, and NS-7 of the Compact’s Regional Climate Action Plan include protection of natural areas, restoration of coastal wetlands, and use of “living shorelines” and other types of natural infrastructure to “create and maintain resilience and adaptive capacity” (SEFL-CCC, 2012b, p. 33).

1.1 Shoreline Processes

The coastal zone is a fundamentally dynamic and shifting system influenced by the wind, wave action, upland disturbances, and underlying morphology and geology. Shore erosion is a natural phenomenon involving “detachment and transportation of sediment particles from the shore, resulting in the landward retreat of the land-water boundary” (Byrne and Anderson 1979). Erosion can occur gradually over time as a result of sea level rise and continuous wave action or suddenly in the event of a storm. Littoral drift is the movement of sand both perpendicularly to the shore or parallel to it due to wave dynamics. The forces affecting littoral drift are complex and human activities can often disturb the sand transfer equilibrium along the shore which can result in sand accretion or sand loss (Burke and Hardaway, 2007). In addition to littoral drift, shoreline dynamics are influenced by the wave climate which is determined by prevailing winds, frequency and magnitude of storms, and bathymetry (WMO 1998). Waves are limited by wind duration and fetch distance (FDOT-FHA 2011). Fetch is the distance over which wind can blow over open water seaward from a shoreline to the next landmass (Burke and Hardaway 2007). Shorelines can be generally categorized by their fetch exposure as low-energy, medium energy or high-energy depending on fetch distance (Byrne and Hardaway 1999). Diffraction due to gradients in the bathymetry is another important factor to consider as local wave growth over shallow, enclosed areas can be influenced by nearshore hardbottom. In such cases, the nearshore bottom provides sufficient attenuation to limit finite-depth wave growth (Van der Westhuysen 2012) and offset the effect of longer fetch distances as is the case of Biscayne Bay, Florida. Tidal cycles, boat wakes, and occurrence of extreme events such as hurricanes and storm surge can affect changes in shoreline position over relatively short periods of time. Sea level rise can be a contributing factor to shoreline change in the long run as it affects the position of the land-water interface (ASMFC 2010, Craft et al. 2008).

1.2 Approaches to Shoreline Stabilization

Engineering approaches including structural shoreline armoring have been widely used to protect development on the coastline (Berman et al. 2007). Hardening control measures include riprap revetments, breakwater systems, seawalls, and spurs. While often very effective especially in high wave energy systems, a review of the scientific literature suggests that bulkhead erosion control methods can lead to accelerated erosion, toe scouring, habitat degradation, and inability to adapt to changing stressors in the natural environment (Currin et al. 2010). This hard-armoring approach is known to reduce sediment sources by interrupting natural sediment transport, affect water quality and reduce habitat viability in adjacent water bodies, and fundamentally disrupt the connection between coastal and offshore ecosystems. These structures are also associated with decreasing wetland ecosystem services (Berman et al. 2007) as the resulting high energy environment around the bulkheads creates poor quality habitat for fish and other species (Peterson and Lowe 2009). Seawalls

in California, for instance, have been shown to reduce habitat quality by narrowing the upper intertidal and mid-intertidal zones in front of armoring structures with accompanying losses in intertidal invertebrate and avian biodiversity (Komar 2000, Dugan and Hubbard 2010). With the anticipated effects of more intense storm damage and flooding as a result of sea level rise and climate change, armoring of shorelines is likely to increase (Defeo et al. 2009).

Recognition of the pitfalls of traditional coastline management approaches has led to a shift toward more holistic practices (Currin et al. 2010). A recent report by the National Wildlife Federation emphasizes the benefits of preserving and restoring natural infrastructure for reducing the vulnerability of local communities to flood and hurricane risks, in addition to numerous ecological and economic benefits (Glick et al. 2014). The report highlights the important role that healthy natural ecosystems can play in building resilient communities and provides several examples of successful implementation of nature-based strategies to counteract the damaging effects of extreme events. In 2011, Virginia state law incorporated living shoreline techniques as the preferred method of shore stabilization. In Jamaica Bay, New York, for example, 150 acres of restored wetlands helped mitigate the destructive backwash waves brought about by super-storm Sandy (Glick et al. 2014). In 2014, USACE issued “A Design Manual for Engineering with Nature Using Native Plant Communities” which describes specific tools and techniques for native plant use in design elements for engineered water resource projects (Bailey 2014).



Figure 1. A hybrid shoreline stabilization using limestone riprap and mangrove planting, Oleta River State Park, Miami-Dade County

Studies have shown the beneficial effects of coastal wetlands and vegetated shorelines on wave propagating time, wave height and damaging wave energy of coastal storms thus affording additional protection beyond what a hard structure can provide (Wamsley et al. 2009, Wamsley et al. 2010). Creating living shorelines is also a major effort in the Chesapeake Bay to restore fisheries habitats. Applying soft armoring techniques, including living shorelines, is consistent with NOAA shoreline management planning policies that support shoreline protection with a “no net loss” of the shoreline ecological functions (NOAA, 2012). Shoreline restoration and enhancement techniques have been shown to provide comparable protection under suitable landscape and environmental

conditions (Berman et al. 2007; Burke and Hardaway 2007; Swann 2008). An emerging alternative is to sustain “living shorelines” in which natural habitats are incorporated into the shoreline stabilization design (Berman and Rudnicky 2008; FDEP 2008, Reay and Lerberg 2008, Currin et al. 2010; McGuire 2011). This approach allows for the long-term protection, restoration and/or enhancement of vegetated shoreline habitats, even during tropical storms.



Figure 2. Mangrove planting and dune vegetation at the Blowing Rocks Preserve, The Nature Conservancy

Living shoreline practices use a range of naturally occurring features to stabilize and protect shorelines, including vegetated buffers; beach nourishment; reefs, oyster beds, and mangrove habitat restoration. Dense vegetation (e.g., seagrasses and mangroves) can attenuate wave action, dissipate wave energy, and mitigate the erosion of the underlying substrate. Studies of living shorelines' efficiency show measurably improved erosion rates compared to nearby upstream and downstream reaches, giving evidence of living shorelines viability as an erosion control measure (Berman et al. 2007). Whalen et al. (2012) review the provisions for living shoreline implementation adopted by multiple states in planning and coastal resource management. While living shoreline techniques can be highly effective in most coastal conditions, high wave energy conditions or risk from flooding can make hardened structures necessary (Mitsova and Esnard 2012). Even under these conditions, living shorelines can provide additional protection by extending the life of the hard structure. Subsequently, living shorelines can become part of hybrid shoreline stabilization solutions which combine vegetation with a stabilizing structure, and while these may be more appropriate in higher energy systems (Currin et al. 2010), there are possible tradeoffs in biodiversity and habitat services that must be considered when choosing hybrid over purely natural stabilization technique (Bilkovic and Mitchell 2013).

1.3 Suitability models for living shorelines

One of the first living shorelines suitability models was developed by the Center for Coastal Resources Management (CCRM) at the Virginia Institute of Marine Science (VIMS) to assist the shoreline management decision-making process (Berman and Rudnick 2008). VIMS-CCRM has compiled a series of indexed, coded shoreline maps for the Chesapeake Bay Foundation showing where and which types of shoreline stabilization techniques were used. The maps also indicate proposed treatments for candidate locations and provide helpful suggestions to landowners who may be considering living shoreline treatments (Burke and Hardaway 2007). Virginia Institute of Marine Sciences (VIMS) was contracted by the Virginia Marine Resources Commission to create a GIS-based Living Shoreline Suitability Model which brings together information on ecosystem-based approaches and site conditions to guide coastal managers (VIMS-CCRM 2012). A scorecard is developed to aid decision-makers in identifying site-specific living shoreline alternatives (VIMS-CCRM 2012). The model considers two types of living shoreline treatments; *soft stabilization* associated with planting fringing vegetation to stabilize unaltered shorelines, and *hybrid treatments* which include any combination of soft stabilization with permanent structures such as riprap revetments, breakwaters, stone, oyster or wooden sills, and bio-logs (Berman and Rudnick 2008, Hardaway and Duhring 2010, Currin et al. 2011). The suitability model is based on the following six parameters: fetch, bathymetry, beach presence, marsh presence, bank condition, and presence/absence of vegetation. Carey (2013) adapted the CCRM model with a few modifications. The model is based on two criteria: wave energy and presence/absence of vegetation. Wave energy is determined based on fetch, boat traffic, and nearshore water depth. The vegetation component includes the presence of marshes and submerged aquatic vegetation (SAV). Fetch distances are calculated for 225° and 10°, southwest, and north-northeast, respectively, to account for prevailing winds (Carey 2013).

2.4 Research Objectives

Our study builds upon these efforts with recognition of the distinctive challenges and opportunities presented by the unique ecosystems of South Florida. The considerations and technique for assessing the suitability of the shoreline for a specific type of stabilization option differ based on the type and characteristics of the shoreline (Brown et al. 2011, Daniels 1996, Coates and Mason 2001).

The project has two specific objectives:

- (1) develop a generic suitability model for nature-based shoreline stabilization options in estuarine environments specific to South Florida; and
- (2) assess the feasibility of the generic model to a range of shoreline types, including developed, undeveloped, and protected.

2. CONTEXT AND METHODS

This section of the report provides an overview of the South Florida context and the methods employed in the analysis.

2.1 The South Florida context

The spatial extent of the study area was based on the South Florida Water Management District's delineation of the coastal ecosystems of South Florida watersheds (SFWMD 2015). Florida is likely to suffer great impacts from climate change. Its low-lying topography, extensive coastline, and high coastal population density make it especially vulnerable to sea-level rise, flooding and extreme weather events. According to Sylvia Earle, marine biologist and former chief scientists at the National Oceanic and Atmospheric Administration (NOAA), "Florida can and must be a leader not only in curbing the build-up of CO₂ and other greenhouse gases in the atmosphere, but also implementing smart, common-sense coastal and ocean policies that will help preserve the state's natural coastal and ocean heritage" (Glick & FCOC 2008).

Florida faces multiple challenges in the years ahead. Unrestrained population growth and development patterns have already significantly degraded our coastal and marine systems. This degradation makes us all the more vulnerable to the upcoming effects of climate change. In its 2008 report, the Florida Coastal and Ocean Coalition (FCOC) recommended that we use a more ecosystem-based approach to managing Florida's coasts and it provided specific suggestions for scientifically based action steps we can take to face climate change. Increasing urban development in the shore zone has resulted in substantial shoreline armoring, water quality impairment due to sedimentation and pollution, and loss of habitat and intertidal ecological functions (FDEP 2011). Probabilistic models of sea-level change scenarios for Florida predict a shift in return period for major storms wherein 1-in-50-year storm events may become as frequent as 1-in-5-year storms (Park et al. 2011). Changing climate and sea level rise will most likely amplify the shoreline management challenges faced by residents, planners, coastal managers, and decision-makers. The Southeast Florida Regional Climate Change Compact Inundation Mapping and Vulnerability Assessment (SEFL-CCC 2012a) indicates the magnitude of the anticipated sea level rise impacts. The study is based on high-resolution LiDAR data, infrastructure, and tidal gauge data and identifies locations where priority action is needed.

Nature-Based Coastal Defenses in Southeast Florida (TNC 2014) is a compilation of seven case studies that showcase shoreline restoration and enhancement efforts in southeast Florida. The report is a collaborative publication of The Nature Conservancy and the Southeast Florida Regional Climate Change Compact Shoreline Resilience Working Group (TNC 2014). Building shoreline resilience using natural infrastructure provides immediate ecological benefits (Jancaitis 2008, Glick et al. 2014). Soft armoring and living shoreline techniques can provide site-specific solutions. Achievement of regional sustainability and resilience requires an integrated approach to shoreline management and understanding of policy and planning processes at regional scales (Leafe 1998).

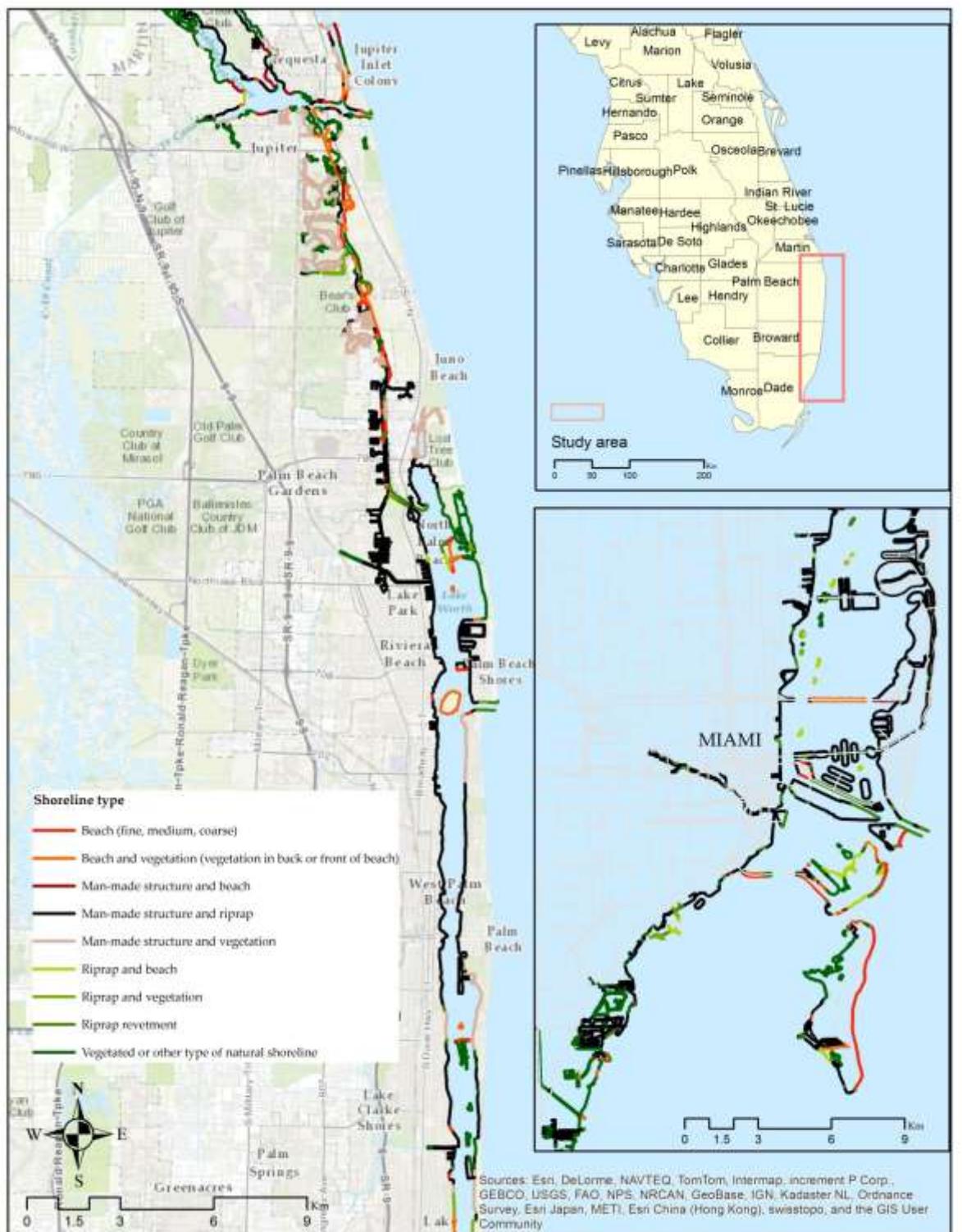


Figure 3. Study area map with estuarine shoreline descriptions (*Data source:* FFWCC, NOAA)

2.2 Decision framework for nature-based shoreline stabilization options

Each shoreline type is evaluated in terms of its exposure to wind/wave action, boat wakes, storm surge, tidal influence and vessel clustering due to inlet proximity, nearshore slope, and the presence of habitat. To facilitate the analysis, the exposure index composite scores were calculated (section 2.3) and reclassified to low, medium and high as shown in Table 1. Generic project types were developed based on expert knowledge and review of the literature. The project types discussed in this study are specific to the subtropical environment of South Florida.

Table 1. Decision framework for nature-based shoreline stabilization options

Existing Shoreline Type	Exposure	Generic Project Type
Natural and erodible	High	Hybrid, with harder features
	Med	Hybrid, with softer features
	Low	Soft, with vegetation only
Unnatural and erodible	High	Hybrid, with harder features
	Med	Hybrid, with softer features
	Low	Soft, with vegetation and potentially sediment only
Armored but permeable (riprap, etc.)	High	Enhancement, with harder features and vegetation
	Med	Enhancement, with harder features and vegetation
	Low	Enhancement, with vegetation only
Armored with wall/impermeable	High	Enhancement, with harder features and vegetation
	Med	Enhancement, with harder features and vegetation
	Low	Enhancement, with vegetation only

According to the *Florida Ecological Restoration Inventory* (FERI) (FDEP 2011) *shoreline restoration* involves fill removal or scraping, clearance of exotic vegetation, slope re-grading, the creation of flushing channels, and re-vegetating with native plants. *Shoreline stabilization* refers to structural armoring, most commonly achieved through the construction of seawalls and bulkheads, but often achievable with hybrid approaches. *Shoreline enhancement* refers to vegetation planting and replanting, and may involve some removal of exotic species (FDEP 2011). *Natural shoreline* refers to a shoreline unaltered by human activities. It is consistent with FLUCCS classification classes of mangrove swamp, freshwater marsh, saltwater marsh, exotic wetland hardwood, maritime hammock, beach dune, and developed unarmored shoreline. Natural or restored shorelines that are relatively stable and not modified by continual wave action are not considered candidates for living shorelines or other treatments at this time, but sea level rise impacts may change this decision in the future. Table 2 provides further details on the rationale of the decision analysis.

Armored shorelines in shallow environments with gradual nearshore slope may be suitable for shoreline enhancement, that is, application of soft stabilization or riprap seaward of existing seawalls to improve both protection and habitat quality. If the structures are exposed to constant wave action, scour typically occurs and seawall toe protection is needed. Mangrove fringing can mitigate these processes. Enhancement of existing seawalls may require some additional fill and vegetation planting. A low profile revetment can be placed at the toe of a seawall and planted with mangroves to help reduce the scouring effect of wave action.

Shorelines with low exposure and nearshore gradient of less than 1:10 are considered suitable for soft stabilization. Those shoreline treatments will provide moderate to high erosion protection and a high level of ecosystem services. Soft stabilization involves the use of native plants and sometimes sediment to help reduce erosion rates and provide ecosystem services. For sandy beaches threatened by erosion, appropriate treatments may include vegetated sand dune restoration or creation and in some cases, beach nourishment.

Mangroves and other salt-tolerant species such as smooth cordgrass (*Spartina alterniflora*), found at lower elevations that are regularly flooded, and salt meadow cordgrass (*Spartina patens*), typically found at slightly higher elevations subject to periodic inundation. Other salt-tolerant species typically found in South Florida include Bay Bean (*Canavalia rosea*), Bay Cedar (*Suriana maritima*), Beach Creeper (*Ernodea littoralis*), Beach Elder (*Iva imbricate*), Beach Morning Glory (*Ipomoea pes-caprae*), Beach Sunflower (*Helianthus debilis*), Black Needlerush (*Juncus roemerianus*), Cabbage Palm (*Sabal palmetto*), Cocoplum (*Chrysobalanus icaco*), Green Buttonwood (*Conocarpus erectus*), Gulfcoast Spikerush (*Eleocharis*), Inkberry (*Scaevola plumieri*), Lantana (*Lantana depressa*), Mangrove Spiderlily (*Hymenocallis latifolia*), Sand Cordgrass (*Spartina bakeri*), Saw Palmetto (*Serenoa repens*), Sawgrass (*Cladium jamaicense*), Sea Lavender (*Limonium carolinianum*), Sea Oats (*Uniola paniculata*), Sea Ox-eye Daisy (*Borrichia frutescens*), Sea Purslane (*Sesuvium portulacastrum*), Seagrapes (*Coccoloba uvifera*), and Silver Buttonwood (*Conocarpus sericeus*).

Shorelines with a medium to high level of exposure and shallow nearshore waters are suitable for hybrid stabilization. Those shoreline treatments will provide a higher level of erosion control and, depending on other environmental constraints, a moderate to high level of ecosystem services. Hybrid stabilization usually consists of two elements: some type of wave attenuating, sediment retaining structure (most commonly, a riprap revetment), and vegetation planting. Hybrid stabilization with harder features typically uses permeable structures such as riprap revetments and/or breakwaters made of rock. Revetments are placed on the shore while breakwaters are placed offshore. In addition to natural limestone and other rock materials, revetments and breakwaters can be constructed from precast concrete (Swann 2008). Hybrid stabilization with softer features may incorporate the use of vegetation, sand backfill or dredged material, oyster shells bags, geotubes, coir logs, and geotextile (straw and coconut fabrics).

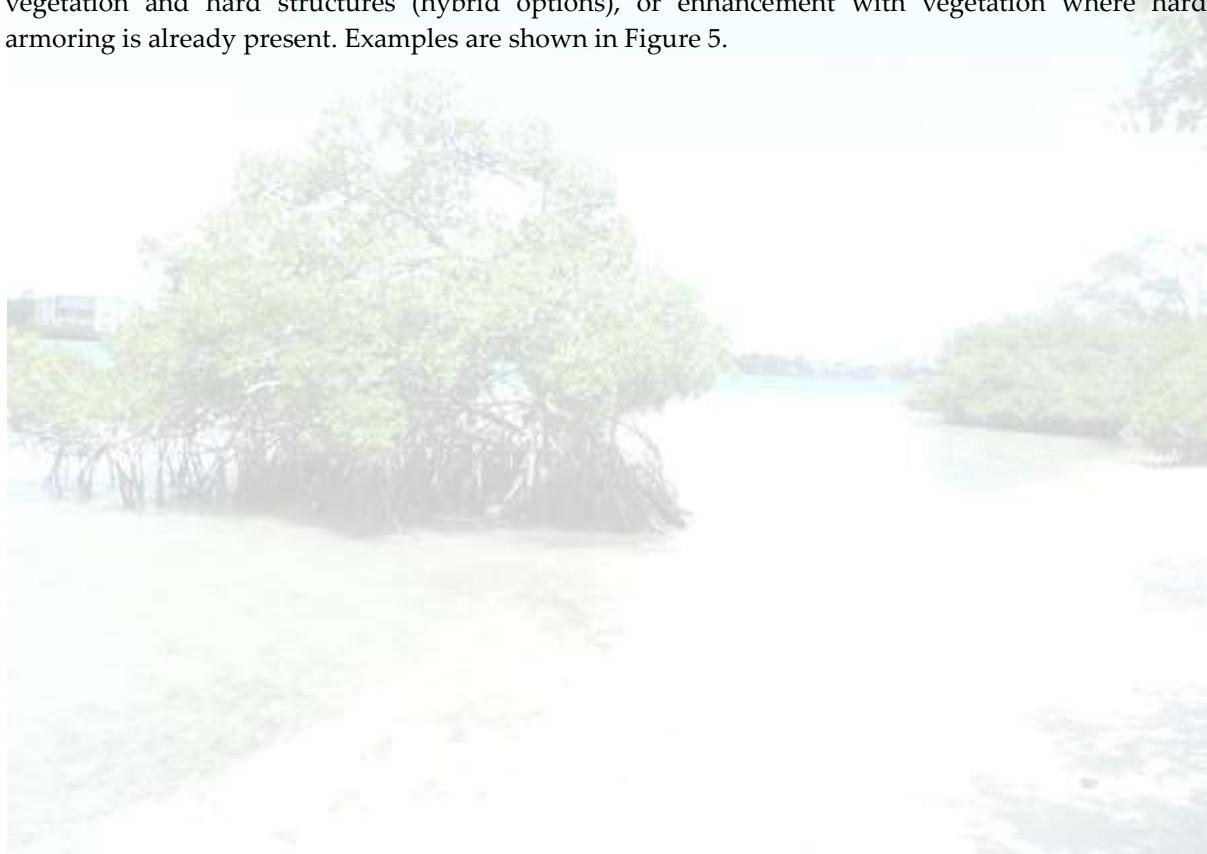
2.2.1 Suitability Analysis

Corbett et al. (2009) identified eight physical variables that characterize the potential for erosion in estuarine shorelines. The factors include: fetch, nearshore bottom, bathymetry, shoreline configuration/ geometry, elevation, sediment type, fringing vegetation, boat wakes, and storms. High fetch values or average distance of open water of more than 1000 feet are associated with higher erosion potential. Lower elevations and unconsolidated sand/ peat are associated with higher erosion rates (Corbett et al. 2009). Shallow water depth and gradual slopes in nearshore areas reduce the erosion potential compared to deeper water and steep slopes (Corbett et al. (2009)). The straight-line configuration of the shoreline and location on a headland is considered more conducive to erosion compared to irregularly shaped shorelines. Abundant and dense fringing vegetation (aquatic plants, marsh grasses, shrubs, trees, etc.) occurring at or in front of the shoreline reduce the erosion potential (Corbett et al. 2009). The proximity of the property to marinas and intra-coastal waterways as well as the level of boat channel use also play roles in determining the susceptibility of a shoreline to erosion (Bosch et al. 2006). It is generally accepted that low wave energy systems such as bays and estuaries are less susceptible to erosion than open ocean shorelines. However, boat traffic and less abundant sediment deposits can contribute to persistent trends in estuarine erosion (Bosch et al. 2006). Storms, including, intensity, duration and frequency remain the single most important factor determining the occurrence of severe erosional events (Corbett et al. 2009).

The generic suitability model for nature-based shoreline stabilization options in estuarine environments incorporates three components: (1) shoreline exposure parameters; (2) prioritization and assignment of weights to the exposure parameters using an expert opinion survey; and (3) multi-objective/ multi-criteria suitability analysis and mapping. The exposure index calculation includes six parameters: wind/wave exposure, intensity of boat wake traffic, nearshore slope, water depth, presence/absence of nearshore habitat, and distance to inlet. We weighed these parameters based on answers obtained via an expert opinion survey. We computed these weights using the Analytic Hierarchy Process (AHP) (Saaty 1990), a multi-criteria decision-making approach based on pairwise

comparison of expert answers. The results from the exposure index calculation ranged from 1 (low) to 5 (high). These results were then evaluated in relation to existing shoreline type, presence/absence of existing structures, and land use and ownership to identify shoreline segments suitable for soft stabilization, hybrid treatments, or shoreline enhancements and assess the ease of access. The generic model was applied to a range of shoreline types including developed, undeveloped, and protected. Figure 4 describes the decision objectives, criteria, parameters, and alternative solutions.

Figure 4 illustrates the decision hierarchy organized around a goal, objectives, parameters, and alternative solutions. In this study, the overall goal is to develop a framework for suitability analysis of nature-based shoreline stabilization options. The objectives include (1) understanding of the shoreline properties, (2) developing an algorithm for exposure as a determinant of the shoreline vulnerability to natural and man-made disturbances, and (3) understanding of feasibility and ease of implementation issues when all other favorable environmental factors are present. The parameters are data-driven characteristics of the shoreline and its interaction with the natural and built environments. The alternative solutions are various combinations of vegetation ("soft" armoring), vegetation and hard structures (hybrid options), or enhancement with vegetation where hard armoring is already present. Examples are shown in Figure 5.



2.2.2 Decision hierarchy process

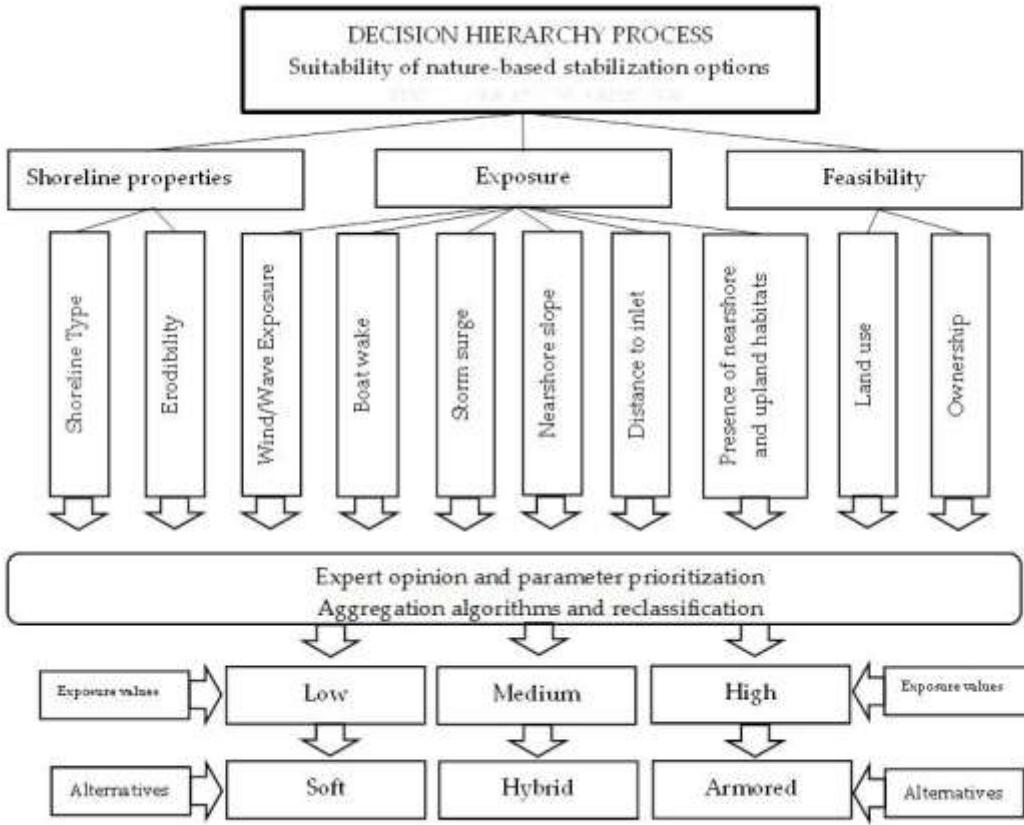


Figure 4. The analytic hierarchy process for shoreline suitability using nature-based stabilization options.

In this study, we use a scientifically established method to aggregate responses from survey data known as the Analytic Hierarchy Process (AHP) (Saaty 1990). The purpose of AHP is to facilitate the decision-making process by disaggregating a problem into a set of hierarchically ordered components (Figure 4). AHP is conducted in three steps (Meng et al. 2011). First, the decision-making process is structured as a hierarchy of goals, objectives, parameters, and alternative solutions (Meng et al. 2011). In the second step, a reciprocal matrix of pairwise comparisons is developed to elicit parameter weights from expert responses. The weights are based on eigenvectors derived from the squared reciprocal matrix. In the third step, the weights derived in step 2 are incorporated in Equation 1.

2.3 Exposure Index calculation

The Exposure Index calculation was partly based on the methodology developed by the Natural Capital Project for the InVEST Coastal Vulnerability Model (Sharp et al. 2015). In this case, we have used the weighted rankings average instead of the rankings geometric mean:

$$EI = \left(\sum_{i=1}^n R_i w_i \right) / n \quad (1)$$

where n denotes the number of variables, R_i is the ranking of each variable according to its contribution to exposure defined on a scale of 1 (low) to 5 (high), and w_i is the weight of the parameter derived from the expert opinion survey and the Analytic Hierarchy Process. Table 2 provides an overview of the variables included in the exposure analysis.

Shoreline descriptions were derived from the Environmental Sensitivity Index data developed by NOAA's Office of Response and Restoration (NOAA 2012). The data were obtained from the Florida Fish and Wildlife Conservation Commission (FFWCC 2012). The shoreline descriptions included in the Environmental Sensitivity Index (ESI) were updated using the 2013 aerial photography and expert opinion. In order to estimate exposure, the shoreline file was converted to a point file with equally spaced features. The point features were spaced 100 meters.

Elevation and slope is an important factor in species distribution of mangroves and marsh plants and must be considered when replanting restoration sites. Due to Florida history of disturbance and urbanization, many restoration sites require clearance of exotic vegetation and re-grading by scraping back soils to elevations appropriate for native plants to recruit (FWS 1999).

Table 2. A list of the exposure index variables and proposed categorization.

Rank/ Variable	Very low (1)	Low (2)	Moderate (3)	High (4)	Very high (5)
Average nearshore slope Wave height (m)	Less than 5 percent	5 to 7 percent	7 -8 percent	9-10 percent	above 10 percent
	0 to 20 percentile	20 to 40 Percentile	40 to 60 Percentile	60 to 80 Percentile	80 to 100 Percentile
Boat wakes	No wake zones		Medium boat wake exposure		High boat wake exposure
Storm surge Category 5	No storm surge	No storm surge	Less than 2 m	2 to 3 m	Above 3 m
Distance to inlet	No tidal influence				Tidal influence within 3 miles
Presence of habitat	Presence of nearshore and upland habitat				No habitat

The elevation of each point was extracted from LiDAR data obtained from the South Florida Water Management District (SFWMD 2009). A topobathymetric LiDAR compiled by Taylor Engineering for FEMA (unofficial release) was used to extract water depths at a distance of 10 meters from each shoreline point. Elevations were also obtained from points located 10 meters from the shoreline point in a landward direction. The elevation points were then used to calculate nearshore and landward slopes. The slope angle was found using the equation:

$$(\alpha) = \tan^{-1} \left(\frac{y}{x} \right) \quad (2)$$

where y = Zvalue (Shoreline_point) - Zvalue (Water_point), and x = NEAR_Distance value estimated using the *Near* function wizard in ArcGIS. The slope angle was then used to estimate slope. If the slope angle is $\sim 6.0^\circ$ and the grade is less than 1 in 10 (i.e., the water depth was less than 1 meter approximately 10 meters from the shoreline), then the nearshore environment was considered "shallow" and suitable for living shorelines. Wave exposure was computed as a compilation of wind/wave modeling, boat wake regulations, and vessel traffic reports. Wind/wave exposure was computed using the Wave Exposure Model in InVEST for points spaced 300 meters. The output was written into the baseline shoreline point file attributes using the *Near* function in ArcGIS. Calculated fetch distances, prevailing wind direction, and estimated water depths provided the inputs for the wind/wave modeling. The FEMA SLOSH model output for Category 5 hurricane storm surge was also included in the analysis. With respect to storm surge the shoreline was reclassified as follows: very low exposure (no storm surge); medium exposure (up to 2 meters), high exposure (between 2 and 3 meters); and very high exposure (above 3 meters). The presence of nearshore and upland

habitat was included in the analysis as an indicator that enabling conditions are already present to support the establishment of nature-based stabilization options (Table 2).





(a)



(b)



(c)



(d)



(e)



(f)

Figure 5. Examples of generic project types for living shorelines in Southeast Florida: (a) Mangrove planting on a restored shoreline at the Blowing Rock Preserve managed by The Nature Conservancy; (b) shoreline restoration at Coral Cove Park on the Intracoastal Waterway in Palm Beach County; (c) A seawall enhanced with mangrove vegetation at Lake Worth Lagoon, Palm Beach County; (d) cordgrass planting at Blowing Rock Preserve; (e) An innovative crib rip-rap to protect eroding wetlands at West Lake Park, Broward County, and (d) a vegetated riprap at the Oleta River State Park, Miami-Dade County.

2.4 Expert opinion survey and elicitation of parameter weights

A common concern in any type of multi-criteria evaluation is to measure the relative importance of each criterion. Assigning weights to the variables included in the analysis involves ranking the criteria in order of their perceived influence on the composite score. Indices can be built with both unweighted and weighted variables. Research has shown that unweighted and weighted indices can yield statistically different results depending on weight distribution (Carey 2013). There are several mathematical algorithms for criterion weighting and ranking such as *rank sum*, *rank reciprocal*, or *rank exponential* (Carey 2013). A common weakness of these widely used methods is that the final decision on weight distribution is at the discretion of the analyst. Conversely, involving stakeholders and experts in the process of determining parameter weights has the potential to overcome this limitation. The scientifically established methods of expert opinion elicitation have proven its usefulness in achieving consensus and addressing uncertainty in the decision-making process (Meng et al. 2011).

For the purposes of this study, the list of experts was compiled by the Shoreline Resilience Working Group. Overall, 85 experts with diverse background were invited to participate in the survey nationally. The survey was anonymous. The participants were asked questions about their educational background, areas of expertise and years of experience in coastal management, coastal hazard mitigation efforts, ecosystem restoration, and hazard response. Shoreline type and exposure parameters were grouped in ten sets of pairwise comparisons. The survey respondents were asked to evaluate each pair and make a judgment of the relative importance of each parameter. Three options were given: (1) parameter x is more important than parameter y ; (2) parameter y is more important than parameter x , and (3) both are equally important.

The participants were also asked to suggest optimum distance to inlet as a proxy for tidal influence, overall circulation patterns, and observed boat traffic. In addition, the participants were requested to assess the feasibility of nature-based shoreline stabilization options based on land use and ownership. Malczewski (1999) explains in detail the process of GIS-based Multi-Criteria Decision Analysis (GIS-MCDA) and AHP. The process combines geographical analysis with value judgments to prioritize and assign weights to the evaluation criteria (Meng et al. 2011). Responses are entered in a reciprocal pairwise comparison matrix in the form of $\mathbf{AA}^{-1} = \mathbf{I}$, whereas $\mathbf{A} = [\eta_{ab}]_{nxn}$, η_{ab} is the pairwise comparison value for attributes a and b , and the matrix is inverted so that $\eta_{ab} = \eta_{ab}^{-1}$ (Lipschutz 2013, Meng et al. 2011). The weights are derived by squaring the matrix and normalizing the row values for each alternative. The eigenvector solution provides the weight distribution.

2.5 Parameter aggregation and decision tree analysis

The Exposure Index variables were aggregated into a composite score using the equation below:

$$EI = [(0.315WWE + 0.072BWE + 0.199NS + 0.234ST + 0.148NH + 0.017PNH + 0.015DI) + StormSurgeCat] / n \quad (3)$$

where *WWE*, *BWE*, *NS*, *NH*, *PNH*, and *DI* are the variables described in Table 2, *n* is the number of variables in the exposure sub-index and *StormSurgeCat* are the reclassified storm surge heights as described in sub-section 2.3.2. Due to the destructive force of a Category 5 hurricane, this parameter was not weighted against the other variables in the Exposure Index calculation. Table 2 provides a summary of the decision criteria. The existing shoreline types were subdivided into four major categories: (1) natural, undisturbed and erodible shoreline, (2) erodible shorelines on spoil islands and other shoreline segments developed as a result of dredge and fill activities, (3) armored but permeable shorelines such as riprap revetments which provide some favorable environmental conditions for living shorelines, and (4) shorelines that are armored with hard structures such as bulkheads and seawalls.

3. SHORELINE SUITABILITY FOR ALTERNATIVE STABILIZATION OPTIONS

Table 3 provides a summary of the initial screening of the shoreline types in the study area. The summary statistics indicate that 61.4 percent of the estuarine shorelines stretching from the Loxahatchee River/Southern Indian River Lagoon Estuary to the lower portion of Miami-Dade County have been altered using traditional hard armoring approaches. The percentage of man-made structures such as seawalls and bulkheads is the highest in Broward County (~84%), followed by Palm Beach County (~63%) and Miami-Dade County (~59%). Approximately one-third of the estuarine shoreline (28.5%) consists of natural and undeveloped or restored shorelines where no armoring is currently present. Miami-Dade County has the highest percentage of undeveloped shoreline (~32%) followed by Palm Beach County (~21%) and Broward County (~13%). Palm Beach and Miami-Dade counties each have between three and five kilometers of estuarine beach areas as a result of restoration projects or natural sand deposition. In Miami-Dade and Palm Beach between 4% and 5% percent of the shoreline is fortified with ripraps and other permeable structures which are suitable for hybrid stabilization with vegetation enhancement. Table 3 describes the shoreline type with the corresponding percentage of total shoreline length in each county.

Table 3. The length of shoreline in percent per shoreline type.

Shoreline type	Study area (length in percent)	Palm Beach County (length in percent)	Broward County (length in percent)	Miami-Dade County (length in percent)
Beach (fine, medium, coarse)	4.0%	6.0%	0.8%	4.4%
Man-made structure and beach	0.5%	0.9%	0.2%	0.0%
Man-made structure and riprap	61.4%	63.0%	84.2%	58.6%
Man-made structure and vegetation	1.6%	5.0%	0.1%	0.1%
Riprap/ Riprap and vegetation	4.2%	4.0%	2.0%	5.0%
Vegetated or other types of shoreline	28.5%	21.0%	12.6%	32.0%

3.1 Exposure variables

3.1.1 Wind/wave exposure

The mean wave height for sheltered shorelines in the study area was 0.12 meters. The 99th percentile of the wind generated wave height in the estuary was found to be approximately 0.48 meters. Higher mean wave heights (1.38 m) were found in exposed areas near the inlets.

3.1.2 Boat wake and distance to inlet

The idle speed restrictions apply to approximately 20 kilometers of inland waters between the Jupiter Inlet and South Miami-Dade County. The slow speed restrictions apply to roughly 15 km of the estuarine shoreline. The longest stretch of the shoreline (roughly 6.6 km) where speed limitations on recreational boating apply is located in Broward County. Previous studies found higher clustering of vessels near Jupiter Inlet, Peanut Island and Blue Heron Bridge near Lake Worth Inlet, Pompano Inlet in southern Lake Worth and Boca Raton Inlets in Palm Beach County,

along the lower portions of the New River and Stranahan River (Port Everglades Inlet?) in Broward County, and near Haulover Park (Haulover Inlet) in Miami-Dade County [47,48,49].

3.1.3 Water depth and nearshore slope

The results indicate that despite the intensive urban development in the coastal zone, most of the natural and/or restored shorelines in the sheltered embayments and waterways of the study area have a nearshore slope of less than 5.71 percent which corresponds to a grade of 1 to 10. Undeveloped shorelines constitute roughly one-third of the shorelines on the study area. Shallow water depths and gradual nearshore slopes in these areas are particularly suitable for soft or hybrid stabilization depending on wind and wave exposure, boat wakes influence, and storm action. About 10 percent of the armored shorelines may also be suitable for vegetation enhancement since the nearshore environment is relatively shallow and the nearshore gradient is not excessively steep.

3.1.4 Storm surge

The output of the SLOSH model indicates that at least one-fourth of the estuarine shoreline in the study area will be impacted by a storm surge induced by a Category 1 hurricane. The model predictions range from 0.6 m to 2 m depending on elevation, bathymetry, exposure and location of the shoreline segments. Storm surge resulting from category 3 hurricanes will impact nearly 90% of the estuarine shoreline while during a category 5 hurricane the storm-induced surge at a level predicted to exceed 6 m will affect nearly 98.7% of the area.

3.1.5 Presence of nearshore or upland habitat

The root system of submerged aquatic vegetation (SAV) helps stabilize estuarine sediments, increases the amount of dissolved oxygen and nutrients, helps improve water quality, and enhances the habitat. The SAV presence is an important indication of the general health of the estuarine ecosystem. Submerged aquatic vegetation was found in close proximity to approximately 16.3 percent of the estuarine shorelines in the study area. Table 4 provides an overview of the SAV distribution near various types of shoreline. Approximately 50% of the SAV patches were found near vegetated or other types of natural shorelines including beach areas. Nearly 16% are located in close proximity to permeable hard structures such as riprap, and 30% are near seawalls and bulkheads. The SAV presence along with the shallow environment and upland vegetation create favorable environmental conditions for the establishment of living shorelines [28,29].

Table 4. Presence of submerged aquatic vegetation

Shoreline Type	Percent of shoreline	Average water depth (m)
Beach (fine, medium, coarse)	5.5%	-0.264
Beach and vegetation (vegetation in back or front of beach)	7.0%	-0.298
Man-made structure and beach	2.0%	-0.315
Man-made structure and riprap	30.0%	-0.442
Man-made structure and vegetation	5.0%	-0.410
Riprap and beach	6.8%	-0.147
Riprap and vegetation	3.7%	-0.233
Riprap revetment	6.0%	-0.349
Vegetated or another type of natural shoreline	34.0%	-0.251

3.2 Expert opinion survey and assignment of parameter weights

The response rate of the expert opinion survey was 38.8 percent. Thirty percent of the participants reported to have worked mostly in the public sector, 9% have worked mostly in the private sector, and 61% have worked in both sectors. The areas of expertise included coastal engineering, coastal science, restoration and systems ecology, marine biology and habitat restoration, community resilience, urban planning and sustainability, coastal hydrology, stormwater management and drainage, and architecture. Eighty-one percent of the respondents reported prior involvement in coastal management projects. Fifty-four percent reported having over 20 years of experience in coastal restoration and coastal management, out of which thirty percent had over thirty years of experience in the field. Thirty-nine percent took part in a response effort to a coastal flooding event or other coastal hazards in their respective community in the past 5 years, 47% in the past 10 years, and 34% in the past 25 years. Hazards in which the experts were involved included hurricanes, inland and coastal flooding, storm surge, wind/ice/snow, tornadoes, sea level rise, coastal erosion, emergency response and long-term planning, restoration projects, and regional hazard preparation efforts for wildlife protection.

Table 5 displays the reciprocal pairwise matrix derived from the expert responses and the eigenvector solution which was used to determine the parameter weights. The results indicate that wind/wave exposure received the highest weight followed by shoreline type, nearshore slope, nearshore habitat, and boat wake. Public lands and educational institutions were singled out by the experts as the topmost choices in terms of feasibility and ease of implementation, followed by private golf courses. Right-of-ways, marinas, commercial hotel/time share and office, mixed use, and residential low density were considered next while residential high density and multi-family residential uses and condominiums were believed to offer the least in terms of ease of implementation.

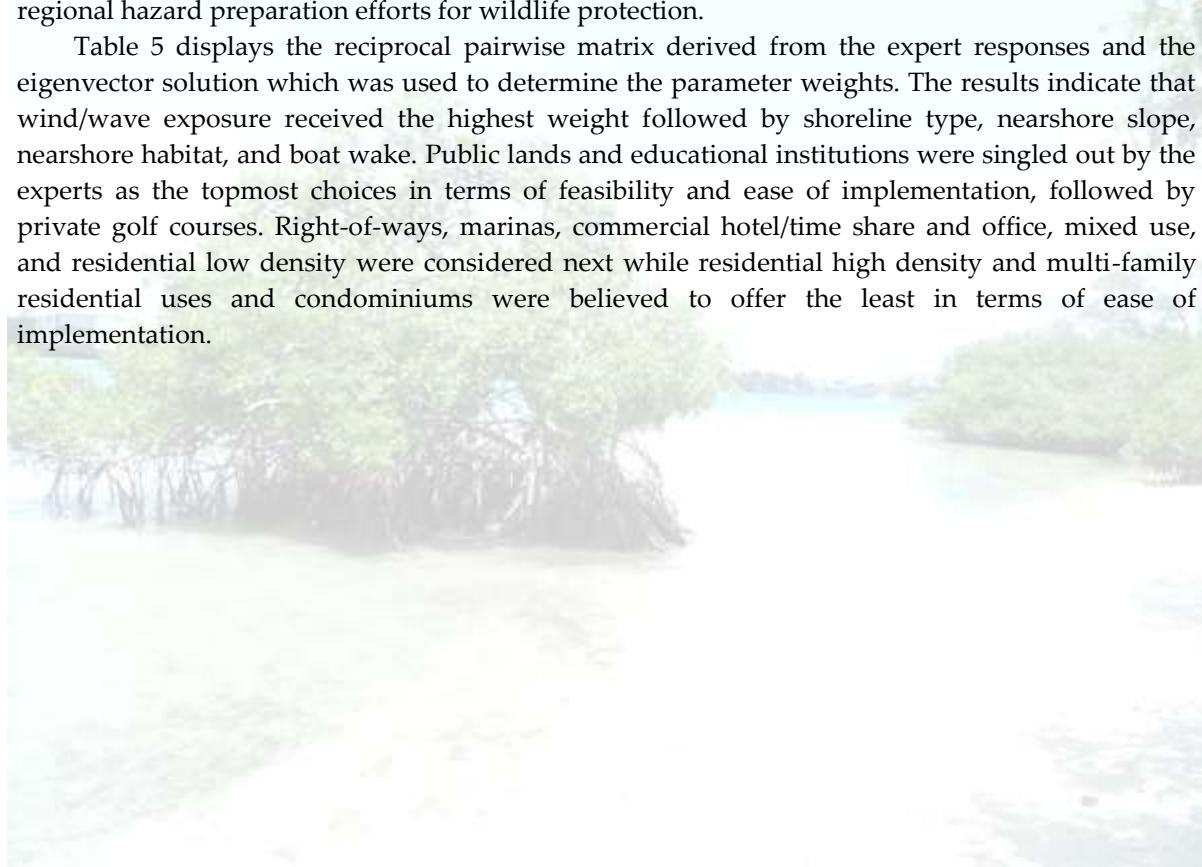


Table 5. Pairwise matrix derived from the expert opinion survey and the eigenvector solution used to determine parameter weights.

	Wind/Wave Exposure (WWE)	Boat wake exposure (BWE)	Nearshore slope (NS)	Shoreline Type (ST) (natural, armored, hybrid)	Nearshore habitat (NH)	Presence of upland natural habitat (PNH)	Distance to inlet	Eigenvector
Wind/Wave Exposure (WWE)	1.000	2.086	1.259	1.159	1.460	4.294	4.563	0.315
Boat wake exposure (BWE)	0.479	1.000	0.603	0.556	0.700	2.059	2.188	0.072
Nearshore slope (NS)	0.795	1.657	1.000	0.921	1.160	3.412	3.625	0.199
Shoreline type (ST) (natural, armored, hybrid)	0.863	1.800	1.086	1.000	1.260	3.706	3.938	0.234
Nearshore habitat (NH)	0.685	1.429	0.862	0.794	1.000	2.941	3.125	0.148
Presence of upland natural habitat (PNH)	0.233	0.486	0.293	0.270	0.340	1.000	1.063	0.017
Distance to inlet	0.219	0.457	0.276	0.254	0.320	0.941	1.000	0.015

The participants in the survey were also asked to assess the perceived ease of implementation of nature-based approaches to various land use categories. The respondents indicated that some land uses such as publicly-owned parks or educational institutions are perceived as allowing easier access and implementation of nature-based restoration and stabilization projects while residential uses are considered more likely to opt in favor of hard armoring or hybrid shoreline stabilization. Figure 6 shows the rankings for each land use category included in the survey. The scale indicates the perceived ease of action regarding the establishment of project types other than traditional armoring where 1 indicates a very low chance of implementing a project type other than traditional armoring, and 5 indicates a very high chance of implementing such a project, all other favorable conditions being present.

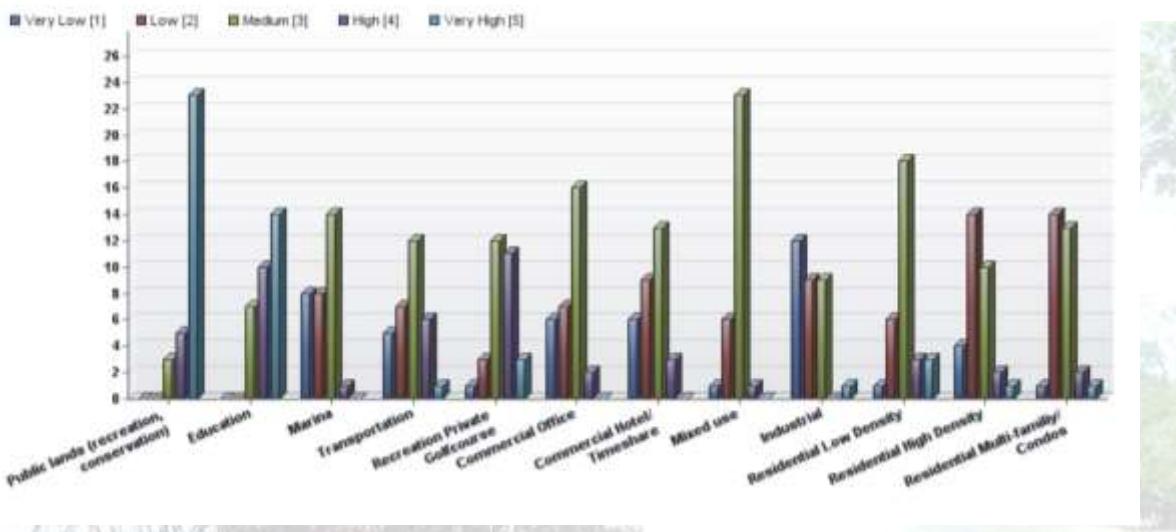


Figure 6. Survey responses indicating the perceived ease of implementation of nature-based approaches for various land use categories.

3.3 Results from the exposure index calculation

We estimated two subsets of the exposure index values for the estuarine shorelines in the study area. The first subset accounts for average exposure under the prevailing wind and wave conditions. The second subset takes into account the impact of a storm surge driven by a Category 3 hurricane. In both cases, the index values are scaled to a maximum value of 5. The average exposure values for the estuarine shorelines in the study area vary from 0.93 to 4.45 whereas a value of 5 stands for the highest possible score. The scores of the average exposure sub-index were reclassified to low (0.93 to 2.25), medium (2.25 to 3.50), and high (above 3.50) (Figures 7 and 8). The results indicate low average exposure for 70% of the estuarine shoreline, medium exposure for 28% of the shoreline, and high exposure for 2% of the shoreline (mainly near the inlets exposed to unbounded fetch).

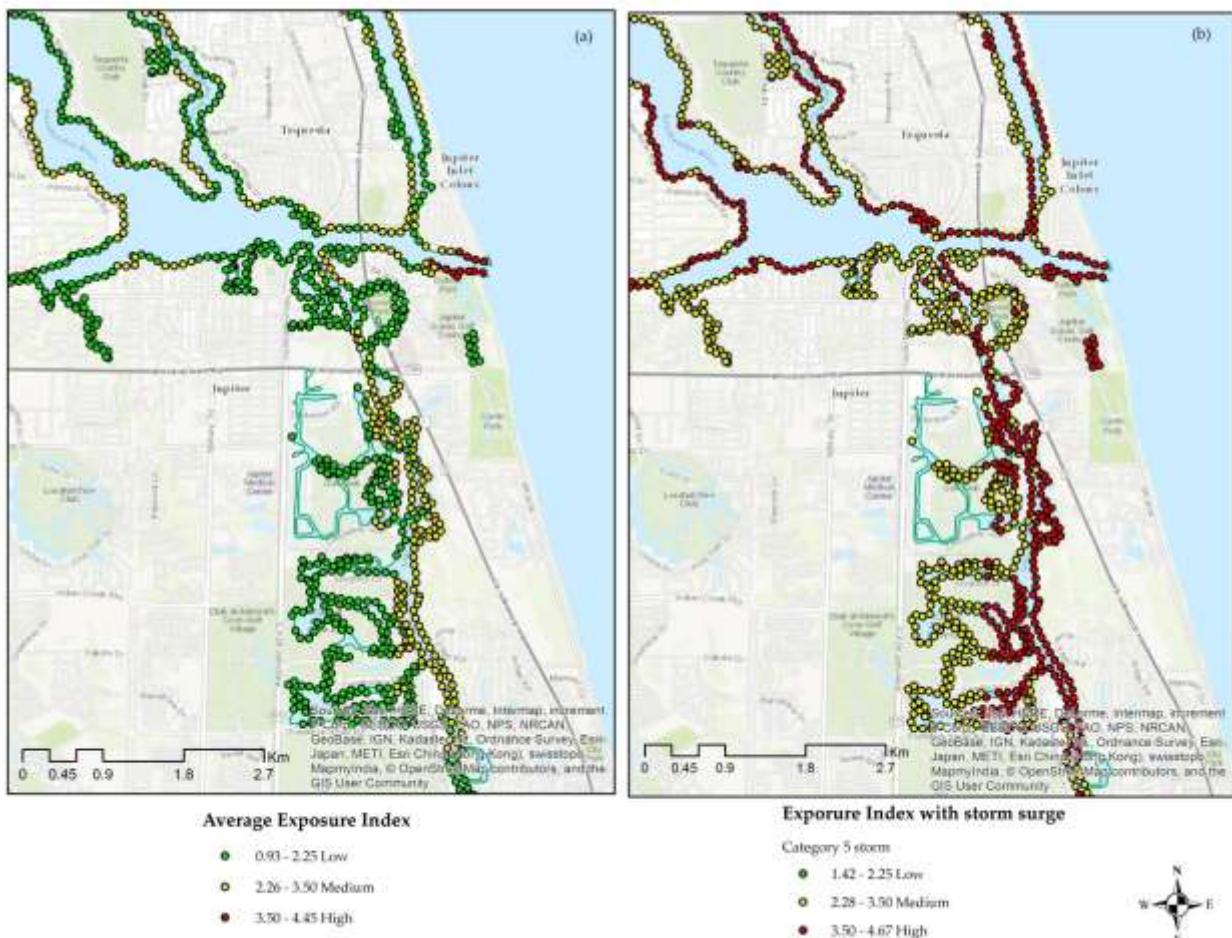


Figure 7. Two subsets of the Exposure index values near Jupiter Inlet, Florida: (a) average exposure index factoring in wind and wave exposure, boat wake influence, nearshore slope, presence/absence of SAV, presence/absence of upland habitat, type of shoreline, and distance to inlet; and (b) exposure with the compounding effect of the storm surge driven by a category 5 storm.

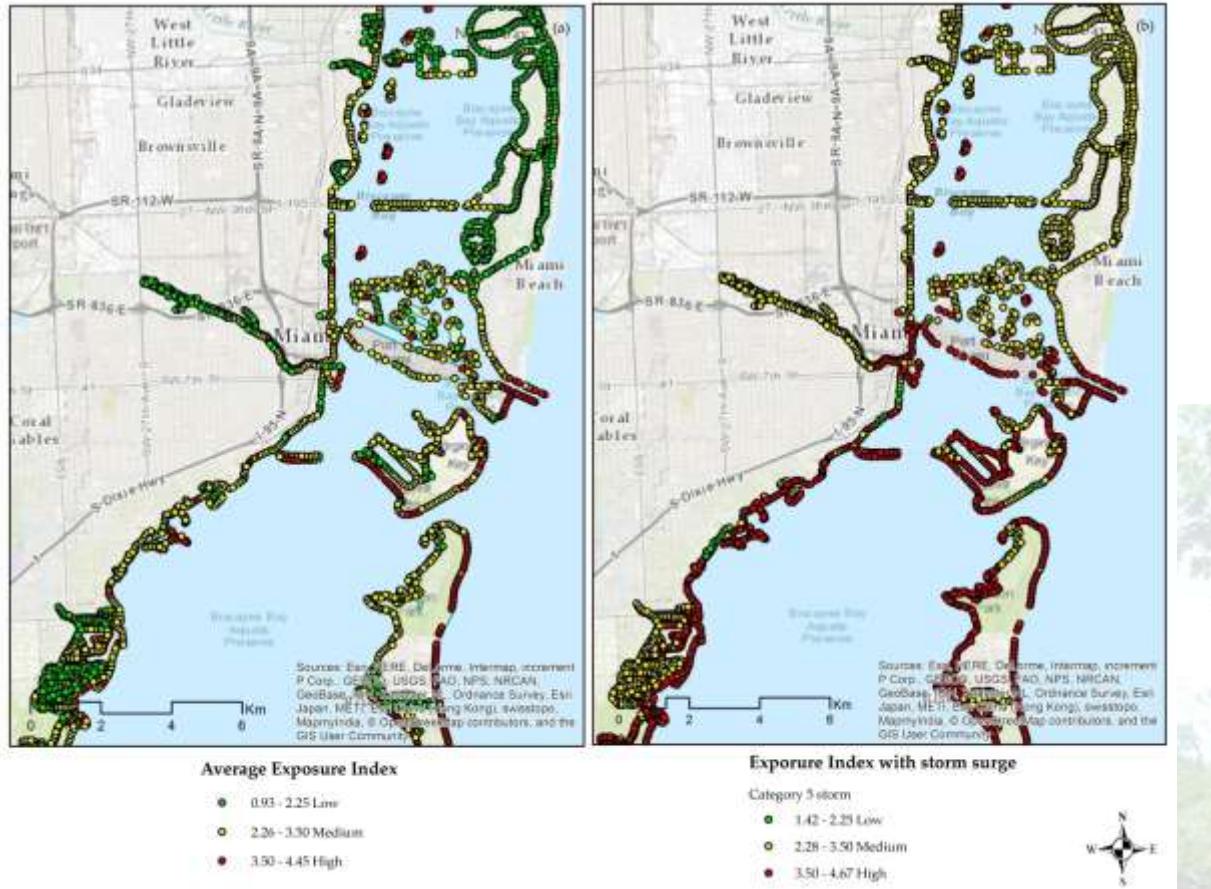


Figure 8. Two subsets of the Exposure index values near Miami, Florida: (a) average exposure index factoring in wind and wave exposure, boat wake influence, nearshore slope, presence/absence of SAV, presence/absence of upland habitat, type of shoreline, and distance to inlet; and (b) exposure with the compounding effect of the storm surge driven by a category 5 storm.

The values of the exposure index under extreme events range from 1.42 to 4.67. Adding storm surge for category 3 hurricane to the exposure index calculation depicts a different type of exposure. Although the range of values is quite similar, the frequency distribution of the exposure estimates differs noticeably. Under this extreme condition, only 1.5% of the estuarine shoreline is within the range of low exposure, 67.5% is subject to medium exposure, and 31% receives high exposure values. Figures 7 and 8 illustrate two subsets of the exposure index values near Jupiter Inlet, Florida. The map on the left shows average exposure index based on wind and wave exposure, boat wake influence, nearshore slope, presence/absence of SAV, presence/absence of upland habitat, type of shoreline, and distance to inlet. The map on the right depicts exposure index values with the compounding effect of the storm surge driven by a category 5 storm.

3.4 Results from the parameter aggregation and decision tree analysis

Table 6 provides a summary of the length of the shoreline segments suitable for various shoreline stabilization options. The results indicate that nearly 20% of the estuarine shoreline is not suitable for any type of alternative stabilization due to water depths greater than 3 feet and a slope gradient greater than 1:10. To create these water depths, enhancement with harder features and vegetation can be a suitable option for existing seawalls and bulkheads. Approximately 18% of the already hardened estuarine shoreline may be suitable for this alternative solution. A riprap revetment with limestone boulders placed

near the seawall can extend the life of the hard structure as it will mitigate the scouring effect of wave action. In addition, a riprap will allow for the establishment of mangroves and create habitat. A riprap built to an appropriate elevation (e.g., 0.30 m to 0.50 m NGVD) can facilitate self-recruitment of mangrove species.

Table 6. Estimated length of possible alternatives to hard armoring in the study area.

Suitability	Length (km)
Palm Beach County	
Soft, with vegetation and potentially sediment only	3.5
Hybrid, with harder features	0.1
Enhancement, with harder features and vegetation	19.7
Enhancement, with vegetation only	13.0
Hybrid, with harder features	3.5
Soft, with vegetation only	8.5
None, water depth > 3.0 feet, slope > 1:10	25.4
Broward County	
Enhancement, with harder features and vegetation	16.9
Hybrid, with softer features	6.8
Enhancement, with vegetation only	13.7
Soft, with vegetation only	1.9
None, water depth > 3.0 feet, slope > 1:10	26.8
Miami-Dade County	
Soft, with vegetation and potentially sediment only	0.5
Enhancement, with harder features and vegetation	12.9
Enhancement, with vegetation only	14.9
Hybrid, with softer features	3.7
Soft, with vegetation only	8.5
None, water depth > 3.0 feet, slope > 1:10	12.6



Figure 9. Undeveloped shorelines suitable locations for soft stabilization.

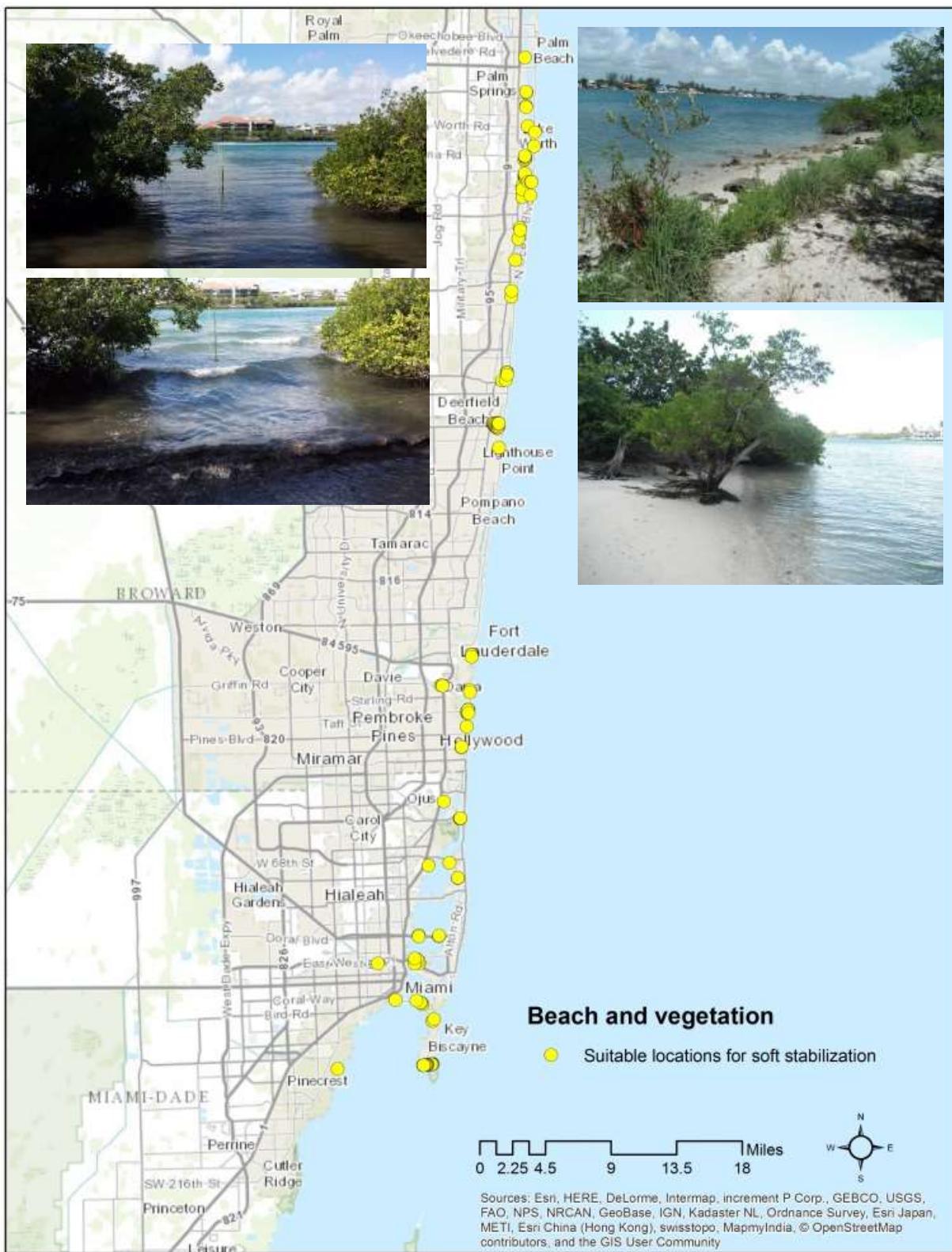


Figure 10. Areas where beach and vegetation are present with high suitability score for soft stabilization.

Small beach areas along inland waters can be enhanced with vegetation and potentially some sediment. Several relatively short stretches of this type of shoreline are found in Palm Beach County. Enhancement with vegetation only is an appropriate technique for different types of altered shorelines where wave energy exposure is relatively low. Hybrid options are a suitable solution for shorelines with medium to high wave exposure. Natural and restored shorelines in low and medium wave energy environments can be maintained with soft stabilization using various types of coastal vegetation. Figures 9 through 12 illustrate potential alternatives based on existing conditions and exposure.

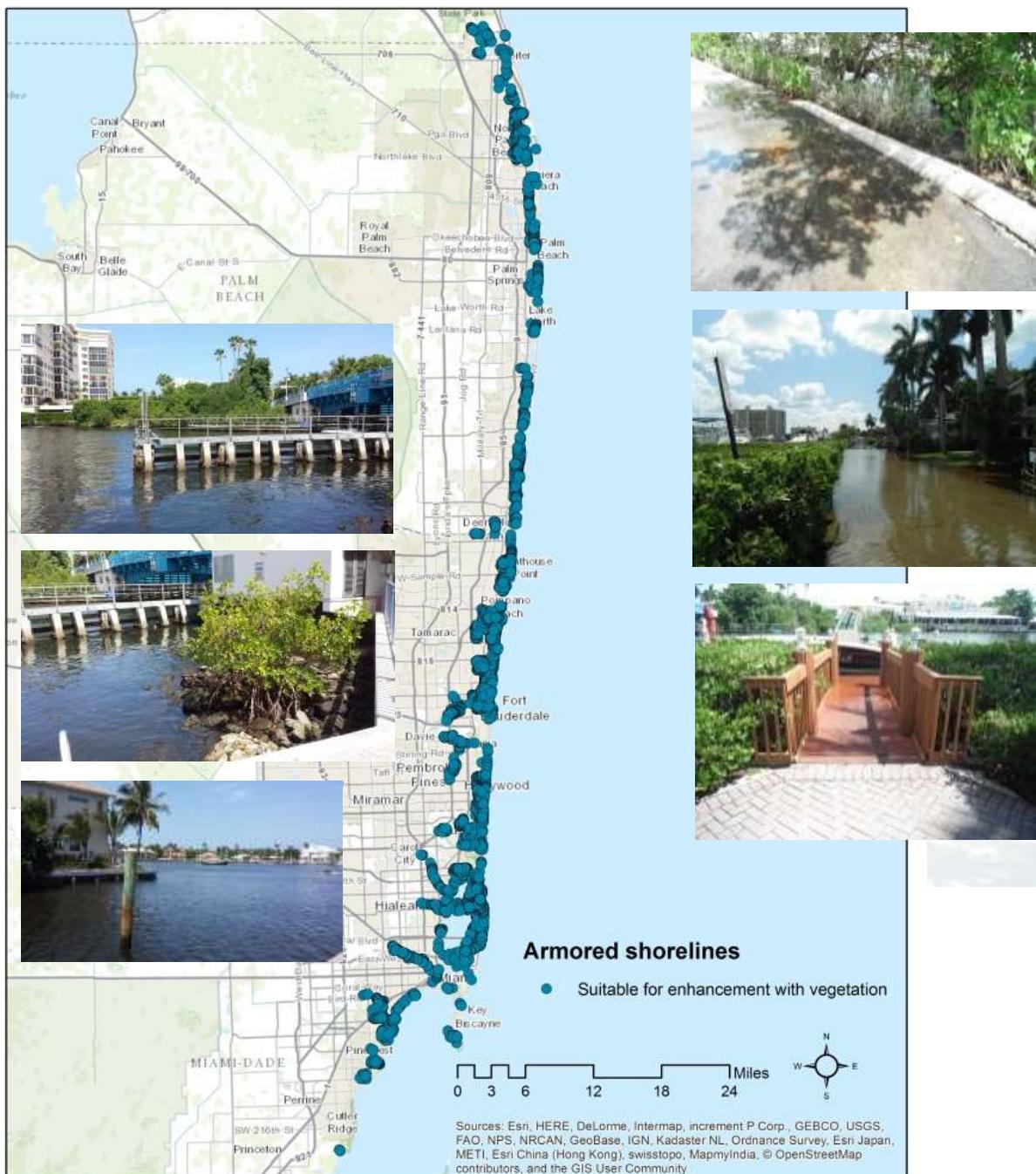


Figure 11. Armored shorelines suitable for enhancement with vegetation.

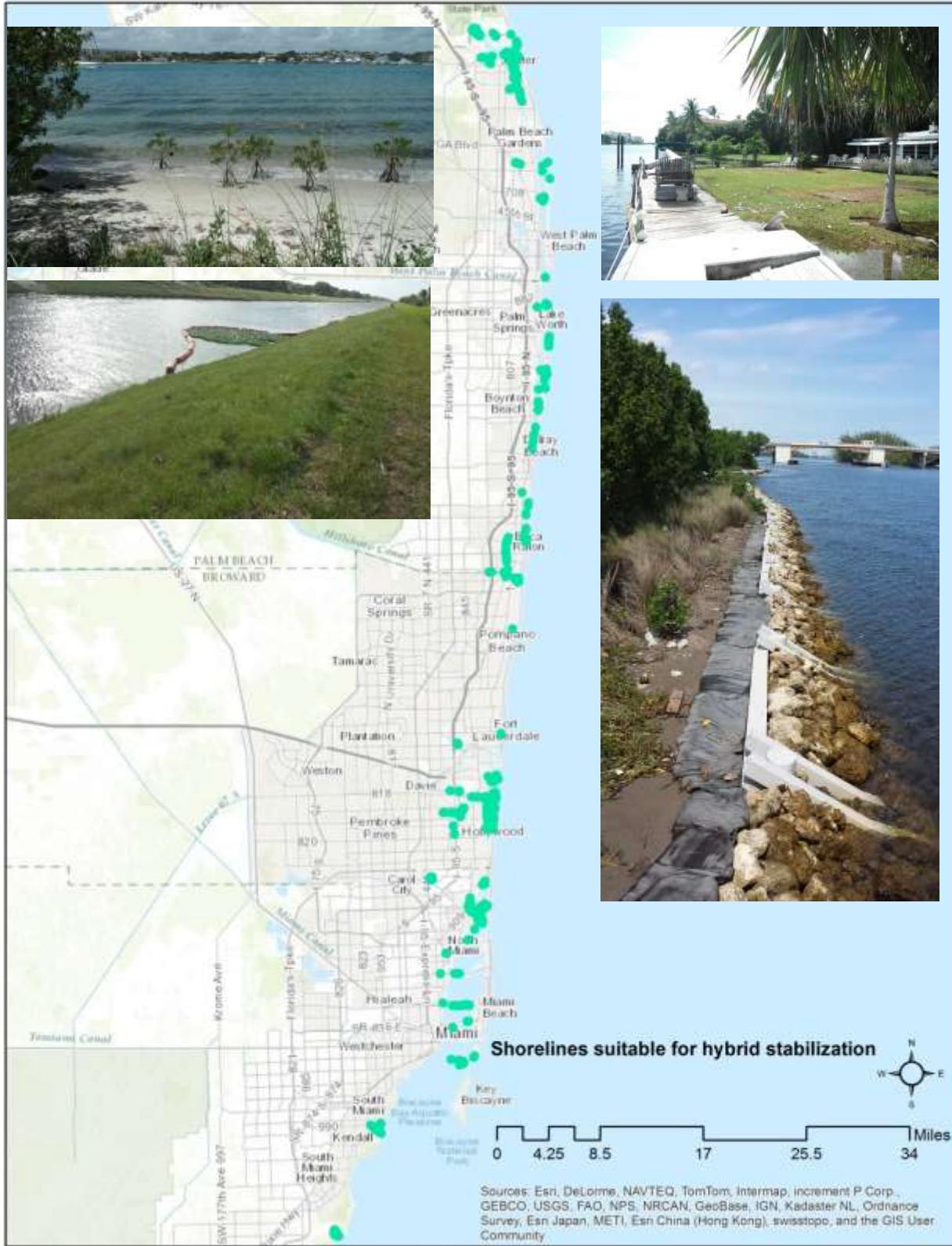


Figure 12. Shorelines suitable for hybrid stabilization

The results from this study indicate that overall suitable conditions are present at several locations that would allow for successful implementation of nature-based solutions to shoreline stabilization. Nearly 30 percent of the natural shorelines in inland waters in South Florida are found on publicly owned land. Local governments have already established and continue to develop alternatives to hard armoring along some of these natural shorelines. In approximately 10% of the armored shorelines, favorable conditions are present for enhancement of existing seawalls and bulkheads with vegetation such as creating a mangrove fringe. These conditions include gently sloping gradient, presence of submerged aquatic vegetation, some presence of upland vegetation, and shallow water depths. Two subdivisions in Palm Beach County, *Jonathan's Landing* and *Admiral's Cove*, have incorporated enhancement with vegetation alongside riprap revetments and seawalls. Another approach to protecting existing natural shorelines from erosion resulting from wave action is creating breakwaters at a proper distance from the shoreline. A single headland breakwater or a system of detached breakwaters strategically placed in medium and high wave energy environments can replicate the effect of "natural bars, reefs or nearshore islands" creating a sheltered area behind the breakwater where sand can accumulate. Areas with active vertical erosion near existing bulkheads and seawalls are suitable for hybrid stabilization with the placement of ripraps and vegetation. Hybrid stabilization options in high wave energy environments offer numerous benefits including; reducing the scouring effect of the wave action on the hard structure and protecting the toe of the seawall, preserving the functionality of the intertidal zone, supporting natural processes, and providing habitat for aquatic flora and fauna species. Hybrid options with vegetation enhancement can reduce the erosion rates, protect and prolong the life of the hard structure, provide visual/ aesthetic value for waterfront homeowners, filter stormwater runoff, and even provide cost-effective solutions outside the traditional hard armoring approach. Figures 13 and 14 show the existing conditions and suitable shoreline enhancement options.

South Florida coastal ecosystems are highly susceptible to erosion/sedimentation, fragmentation, and habitat degradation due to dredging/ fill and land conversion to urban and housing development (FFWCC 2005). Due to Florida's history of disturbance and urbanization, many restoration sites require re-grading by scraping back non-native soils to elevations appropriate for intertidal native plants to recruit (FWS 1999). The elevation is an important factor in species distribution of mangroves and marsh plants and must be considered when replanting restoration sites. Mangrove swamps are essential for the health of estuarine and marine environments in South Florida (FWS 1999). They provide habitat for over one thousand species of intertidal, subtidal, and arboreal animals (FWS 1999). They also serve as nesting sites; nurseries for fish, shellfish, and crustaceans; and are a major source of detritus which provides the basis of the marine food system (FWS 1999). Their root systems stabilize shorelines; buffer wind action; reduce turbidity and increase water clarity, and cause accretion by catching sediment and debris (Kirwan and Megonigal 2013). Red mangrove (*Rhizophora mangle*), black mangrove (*Avicennia germinans*), white mangrove (*Laguncularia racemosa*), black needlerush (*Juncus roemerianus*), and smooth cordgrass (*Spartina spartinae*) are commonly used in wetlands and mangrove restoration projects (FWS 1999). Using the National Geodetic Vertical Datum (NGVD), red mangroves are planted in the elevation range 1.0'-1.2', black mangrove 1.25'-1.5', white mangrove 1.5'-2.0', and gulf cordgrass in the range 2.1'-2.5'. Habitat may also be created by reconstruction of a more natural hydrology, such as re-establishing inter-tidal flushing creek connections.

A number of spoil island restoration projects have been successfully implemented in Miami-Dade County since the 1990s (Milano 1999, 2000). Dredged material disposal during the construction of the Atlantic Intracoastal Waterway which began in the early 1900s resulted in the creation of spoil islands (Milano 2000). They have been dominated for decades by exotic invasive species and have been known as a source of sedimentation and water quality degradation (Milano 2000). Spoil island restoration involves fill removal, clearance of exotic species, a creation of flushing channels, planting mangroves and native upland species, and shoreline stabilization (Milano 2000). Rip-raps are commonly used as "a riprap

revetment can be part of a “living shoreline”, as a substrate for aquatic plants and animals or as part of a “planter” for vegetation” (MDC - personal communication, 2011, 2014).

Development of barrier islands in South Florida negatively affected many of the maritime hammock communities. In South Florida, the maritime hammock is characterized by tropical, broad-leaved hardwoods such as live oak, cabbage palmetto, red bay, silver palm, and black bead (FWS 1999). Species of concern which inhabit this habitat include the Florida panther, peregrine falcon, Florida prairie warbler, and several species of prickly apple (FWS 1999). South Florida hammock restoration projects are generally not planted as a monoculture, but rather as a mix. The most common species used in restoration are gumbo limbo (*Bursera simaruba*), buttonwood (*Conocarpus erectus*), strangler fig (*Ficus aurea*), false mastic (*Sideroxylon foetidissimum*) and Jamaican dogwood (*Piscidia piscipula*) (FWS 1999, MDC, personal communication, 2014). Freshwater wetlands are also part of ongoing restoration efforts in South Florida. These marshes consist mostly of herbaceous plants and grass of which sawgrass, pickerelweed, arrowhead, and spike rush are the most abundant (MDC 2013). Many of these important ecosystems have been degraded or lost due to alteration of hydrologic conditions (MDC 2013).

Development of alternative solutions to hard armoring requires removing regulatory obstacles and establishment of a permitting system that incorporates and facilitates nature-based approaches. Best management practices indicate that permits can be sought for restoration or protection (NJDEP 2009). Planning for living shoreline also requires revision of the existing coastal management plans. Outreach and information campaigns should be put in place to engage both contractors and property owners. Currently, a failing seawall will most likely be repaired or replaced by a new hard structure. In many cases, this might be the only solution. However, if it is determined that the site characteristics would not prevent the successful implementation of alternative nature-based solutions, such options should be given priority and pursued, and appropriate techniques and materials identified and included in the permitting process.

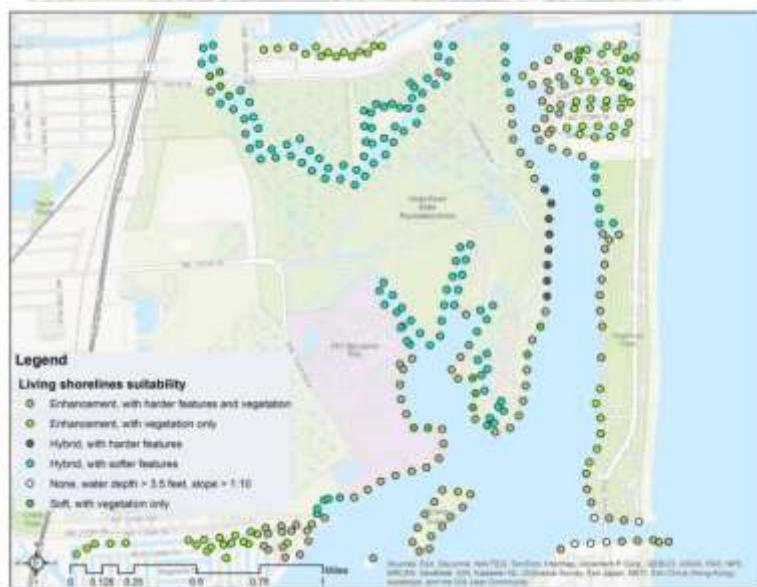


Figure 13. Results from the suitability analysis for the Oleta River State Park shoreline

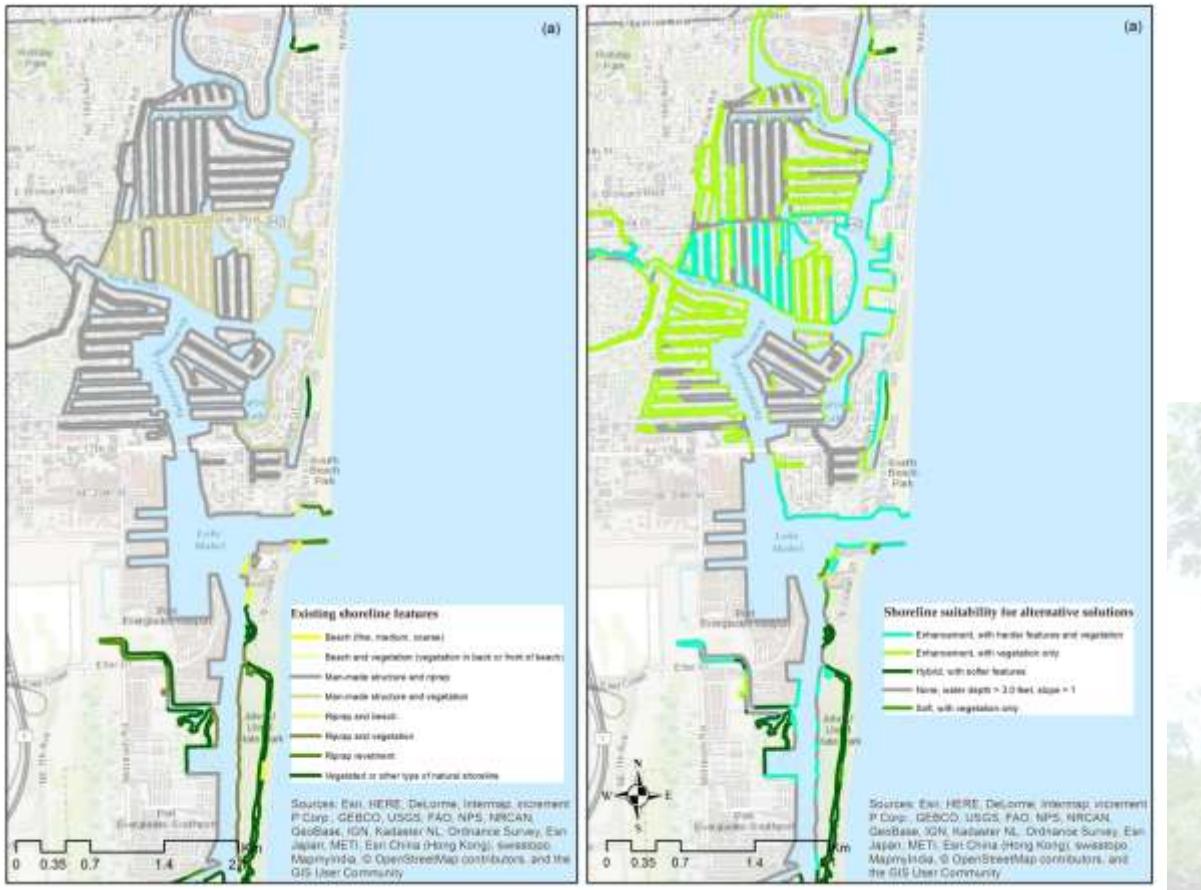


Figure 14. Shoreline type and proposed alternative stabilization options based on the results of the suitability model (City of Fort Lauderdale, FL): (a) existing shoreline features, (b) suitable alternatives.

4. Conclusion

In this study, we developed a GIS-based multi-criteria decision framework for nature-based shoreline stabilization options. Our focus is on living shorelines in estuarine and tidally-influenced environments. More specifically, we combined the tools of spatial analysis with value judgments derived from an expert opinion survey to assign weights to the model variables. The existing shoreline type derived from an updated version of the NOS Environmental Sensitivity Index was evaluated using the exposure index aggregated scores, and generic project types for each set of possible combinations of shoreline features and exposure were proposed. Although armoring of the shoreline is still the dominant trend, the results indicate that there are valuable living shoreline alternatives available in Southeast Florida. Existing coastal restoration and living shoreline projects in South Florida provide examples of successful implementation of nature-based strategies to counteract the damaging effects of erosion and extreme events.

The results from this study should be interpreted as a screening and planning tool for identification of potential sites for closer examination. In each specific case where a living shoreline is considered, further detailed site-specific analysis should be conducted. This study has been conducted on a regional scale. Its main objective was to identify potentially suitable areas for alternative shoreline stabilization options along the inland waters of Southeast Florida using the best available digital data. Site-specific

implementation of living shorelines may be constrained by several factors not considered in this analysis. These factors can potentially make the implementation impossible or impractical. These additional considerations include narrow channels with high boat traffic where placement of living shorelines may obstruct navigation, areas designated for commercial vessel berthing and areas used for loading and unloading operations, areas that are easily accessible which may dramatically increase the cost of restoration, and areas with inadequate width to support soft armoring despite all other favorable conditions being present (NJDEP 2009). Site-specific analyses should also consider other physical constraints including adverse effects of tidal flushing, insufficient land area for grading and establishing suitable elevations for native species recruitment (NJDEP 2009).

Other factors to consider are land regulations and policies. In order to be successfully implemented on a larger regional scale, nature-based alternatives to hard armoring should become part of the coastal element of the county and municipal comprehensive plans. A pertinent permitting process should be put in place. As part of future research efforts, site-specific evaluation of the effectiveness of existing living shorelines should be conducted under various conditions to improve response and design requirements as their buffering properties are not as predictable as hard bulkheads and seawalls and may require lengthier planning horizons and careful design to be effective. Continued research on this topic is particularly important in the context of sea level rise as living shorelines and habitat restoration offer a host of strategies that planners, coastal resource managers, and decision-makers can use to mitigate hazards, protect property values, secure the tax base, prevent processes of shrinking and divestiture, and enhance habitat value. Examples from South Florida indicate that dune planting, coastal strand, and mangrove fringes can help stabilize existing natural shorelines and enhance habitat along existing armoring structures. South Florida's coastal ecosystems offer unique opportunities to develop shoreline management techniques that can create appropriate habitat conditions and increase the resilience of the built environment to existing and future threats.

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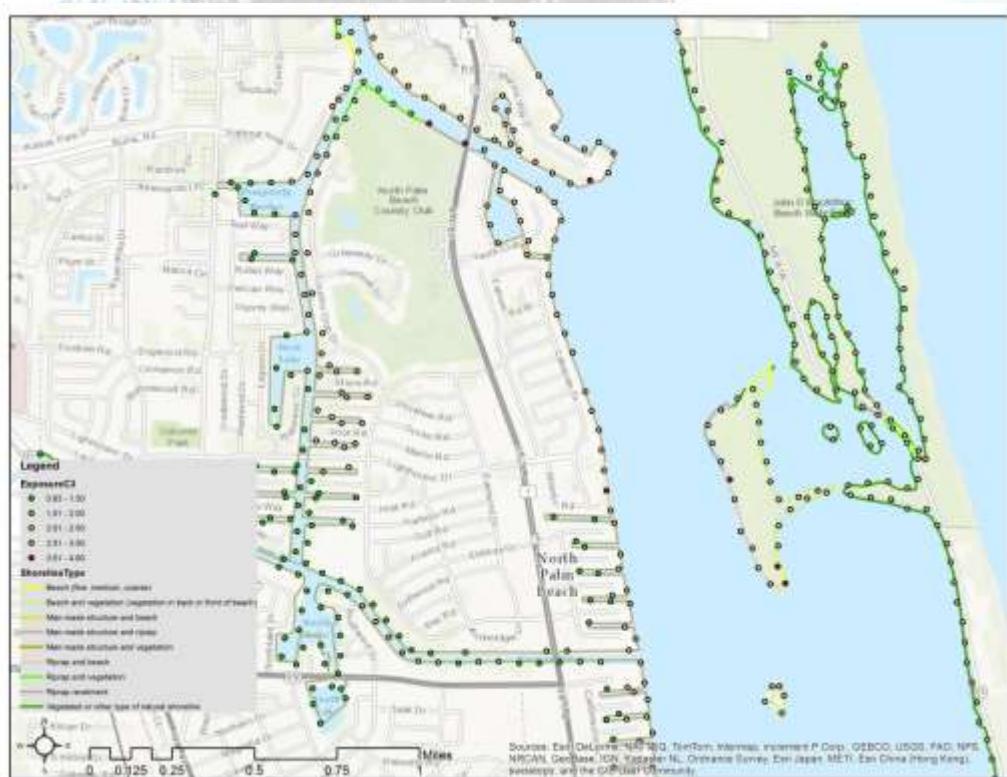
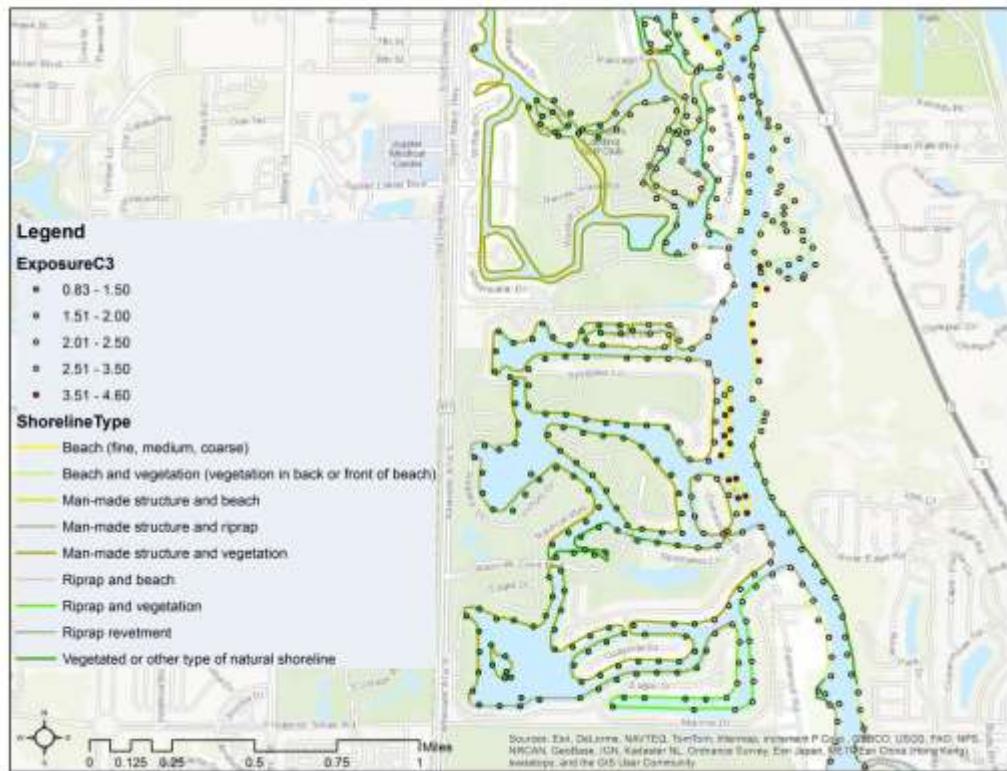
Appendix 1. Study area shorelines types and proposed stabilization options

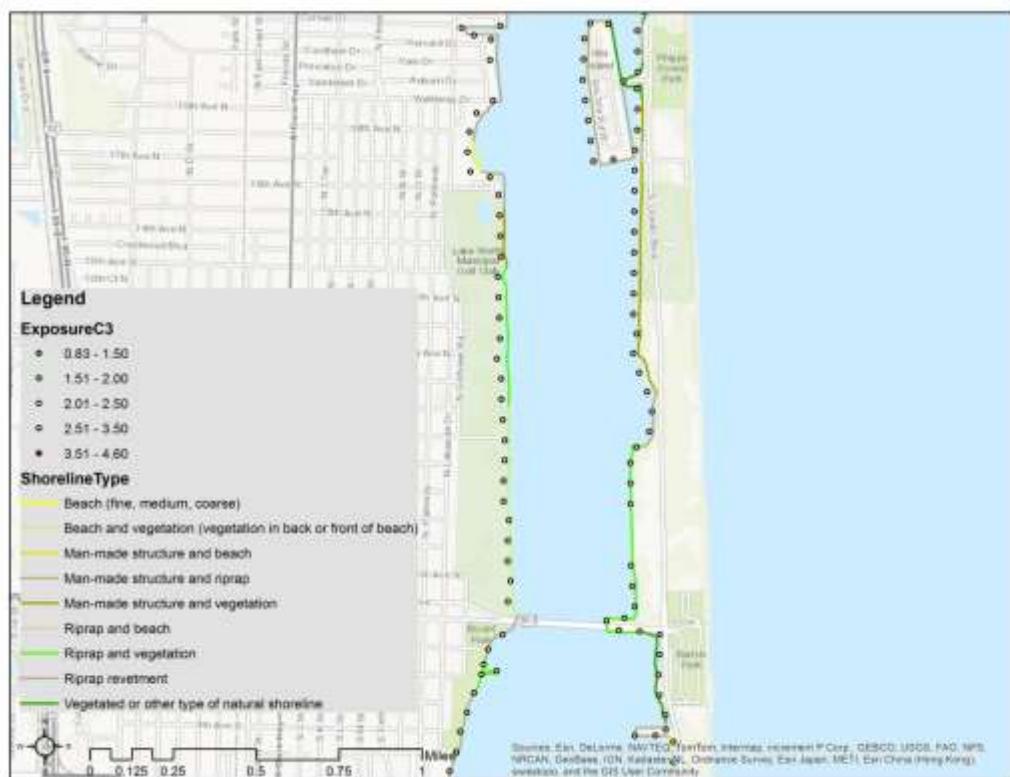
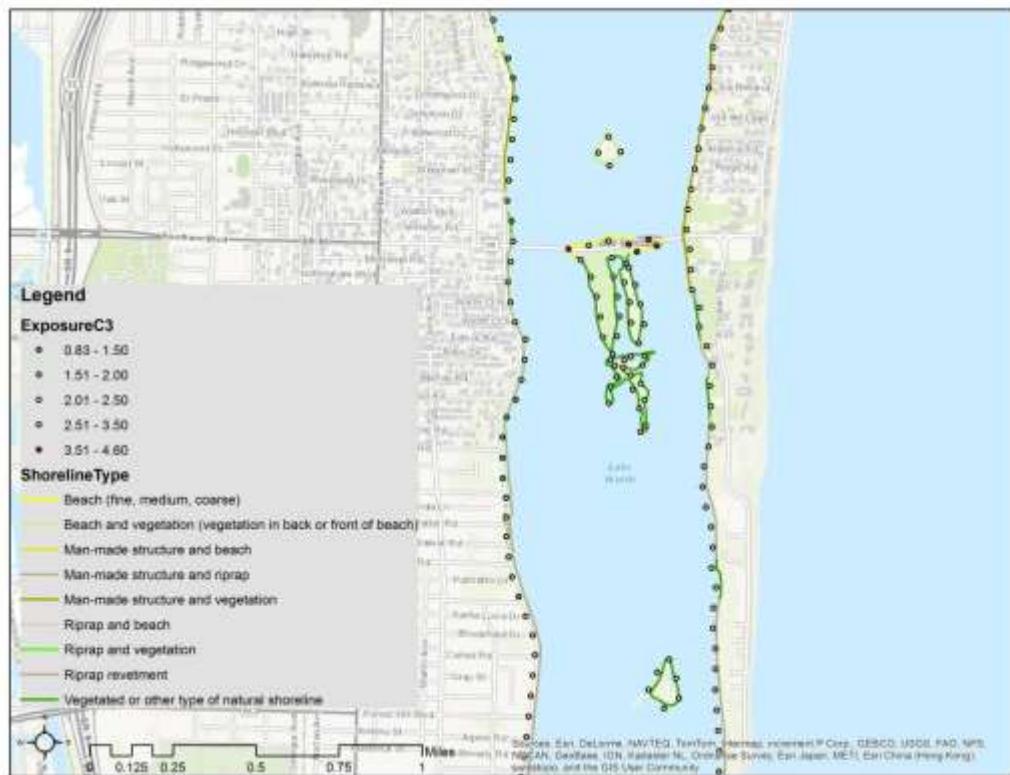
	<i>Landward</i>	<i>Seaward</i>	
Shoreline Code	Shoreline Type	Category	Stabilization Type
10A/10D/9A	Salt- and Brackish-water Marshes/ Scrub-shrub Wetlands/ Sheltered Tidal Flats	Natural	None
10A/10D	Salt- and Brackish-water Marshes/ Scrub-shrub Wetlands	Natural	None
10A/4	Salt- and Brackish-water Marshes/ Coarse-grained Sand Beaches	Natural	Soft
10A/5	Salt- and Brackish-water Marshes/ Mixed Sand and Gravel Beaches	Natural	Soft
10A/8B	Salt- and Brackish-water Marshes/ Sheltered, Solid Man-made Structures	Man-made	Hybrid/ Soft (enhancement)
10A/9A	Salt- and Brackish-water Marshes/ Sheltered Tidal Flats	Natural	None
10A	Salt- and Brackish-water Marshes	Natural	None
10B/10D	Freshwater Marshes/ Scrub-shrub Wetlands	Natural	None
10B	Freshwater Marshes	Natural	Soft
10C/10D	Swamps/ Scrub-shrub Wetlands	Natural	None/Soft
10C/8A	Swamps/ Sheltered Rocky Shores and Sheltered Scarps in Bedrock, Mud, or Clay	Natural	None/ Soft
10C	Swamps	Natural	None
10D/1B	Scrub-shrub Wetlands / Exposed, Solid Man-made Structures	Man-made	Armored/ Hybrid
10D/2A	Scrub-shrub Wetlands/ Exposed Wave-cut Platforms in Bedrock, Mud, or Clay	Natural	None
10D/2B	Scrub-shrub Wetlands / Exposed Scarps and Steep Slopes in Clay	Natural	None
10D/3A	Scrub-shrub Wetlands/ Fine- to Medium-grained Sand Beaches	Natural	None/ Soft
10D/3B	Scrub-shrub Wetlands/ Scarps and Steep Slopes in Sand	Natural	None/Soft
10D/4/7	Scrub-shrub Wetlands/ Coarse-grained Sand Beaches/ Exposed Tidal Flats	Natural	None/Soft
10D/4	Scrub-shrub Wetlands/ Coarse-grained Sand Beaches	Natural	None/ Soft
10D/5	Scrub-shrub Wetlands/ Mixed Sand and Gravel Beaches	Natural	None/ Soft
10D/6B	Scrub-shrub Wetlands/ Riprap	Man-made	Soft/ Hybrid
10D/7	Scrub-shrub Wetlands/ Exposed Tidal Flats	Natural	None
10D/8A	Scrub-shrub Wetlands/ Sheltered Rocky Shores and Sheltered Scarps in Bedrock, Mud, or Clay	Natural	None
10D/8B	Scrub-shrub Wetlands/ Sheltered, Solid Man-made Structures	Man-made	Soft/ Hybrid (enhancement)
10D/8C	Scrub-shrub Wetlands/ Sheltered Riprap	Man-made	Soft/ Hybrid

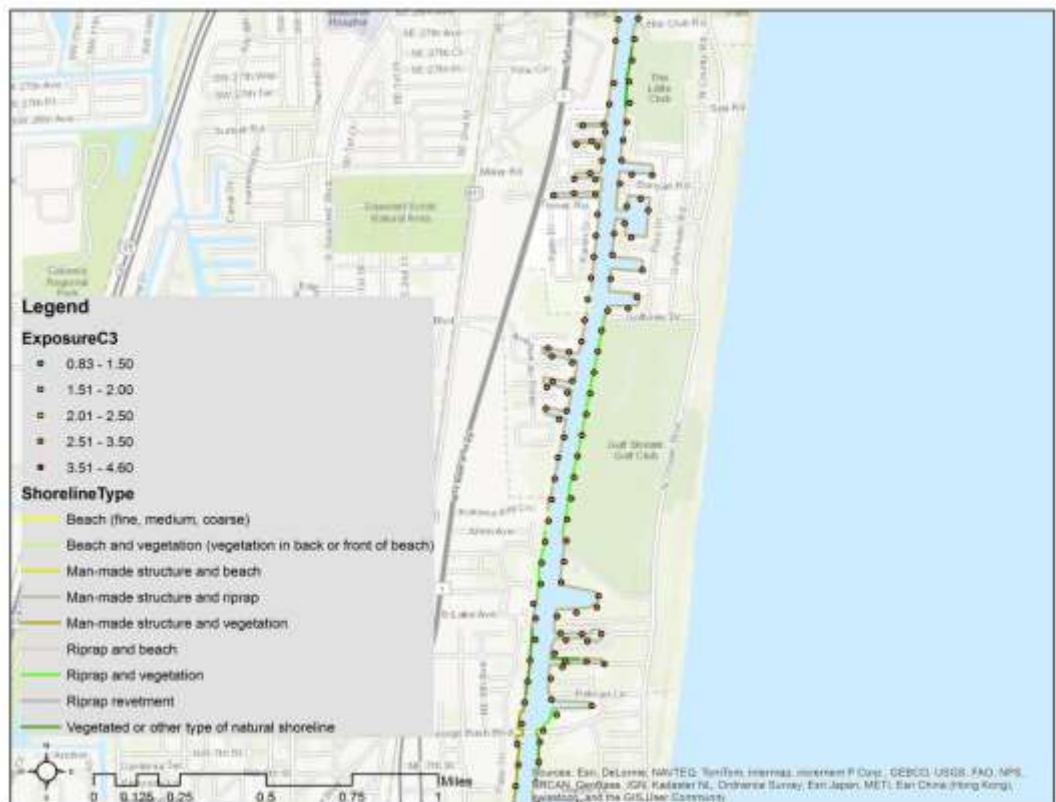
10D/2B	Scrub-shrub Wetlands/ Exposed Scarps and Steep Slopes in Clay	Natural	None
1B/10D	Exposed, Solid Man-made Structures /Scrub-shrub Wetlands	Man-made	Soft/ Hybrid
10D/2A	Scrub-shrub Wetlands/ Exposed Wave-cut Platforms in Bedrock, Mud, or Clay	Natural	None
1B/2A	Exposed, Solid Man-made Structures / Exposed Wave-cut Platforms in Bedrock, Mud, or Clay	Man-made	Hybrid/None
2B/3A	Exposed Scarps and Steep Slopes in Clay / Fine- to Medium-grained Sand Beaches	Natural	None/ Soft
3A/1B	Fine- to Medium-grained Sand Beaches / Exposed, Solid Man-made Structures		Soft/ Armored/ Hybrid (enhancement)
3A/2A	Fine- to Medium-grained Sand Beaches / Exposed Wave-cut Platforms in Bedrock, Mud, or Clay	Natural	None
3A/6B	Fine- to Medium-grained Sand Beaches / Exposed riprap	Man-made	Soft/ Hybrid
3A/7	Fine- to Medium-grained Sand Beaches / Exposed Tidal Flats	Natural	None/ Soft
3A	Fine- to Medium-grained Sand Beaches	Natural	None/ Soft
3B	Scarps and Steep Slopes in Sand	Natural	None/ Soft
4/1B	Coarse-grained Sand Beaches/ Exposed, Solid Man-made Structures	Man-made	Hybrid
4/2A	Coarse-grained Sand Beaches / Exposed Wave-cut Platforms in Bedrock, Mud, or Clay	Natural	None
4/6B	Coarse-grained Sand Beaches / Exposed riprap	Man-made	Hybrid
4/7	Coarse-grained Sand Beaches / Exposed Tidal Flats	Natural	None/ Soft
4/8C	Coarse-grained Sand Beaches/ Sheltered Riprap	Man-made	Soft/ Hybrid
4	Coarse-grained Sand Beaches	Natural	None/ Soft
5/10D	Mixed Sand and Gravel Beaches /Scrub-shrub Wetlands	Natural	None/ Soft
5/6B	Mixed Sand and Gravel Beaches / Exposed riprap	Man-made	Soft/ Hybrid
5/7	Mixed Sand and Gravel Beaches/ Exposed Tidal Flats	Natural	None
5	Mixed Sand and Gravel Beaches	Natural	None/ Soft
6B/10A	Exposed riprap/ Salt- and Brackish-water Marshes	Man-made	Hybrid/ Soft
6B/10D	Exposed riprap / Scrub-shrub Wetlands	Man-made	Hybrid/ Soft
6B/2A	Exposed riprap/ Exposed Wave-cut Platforms in Bedrock, Mud, or Clay	Man-made	Hybrid
6B/3A	Exposed riprap/ Fine- to Medium-grained Sand Beaches	Man-made	Hybrid/ Soft
6B/4	Exposed riprap/ Coarse-grained Sand Beaches	Man-made	Hybrid/ Soft
6B/5	Exposed riprap/ Mixed Sand and Gravel Beaches	Man-made	Hybrid/ Soft
6B/7	Exposed riprap / Exposed Tidal Flats	Man-made	Hybrid/ Soft
6B	Exposed riprap	Man-made	Hybrid/ Soft
8A/10D	Sheltered Rocky Shores and Sheltered Scarps in Bedrock, Mud, or Clay /Scrub-shrub Wetlands	Natural	None
8A	Sheltered Rocky Shores and Sheltered Scarps in	Natural	None

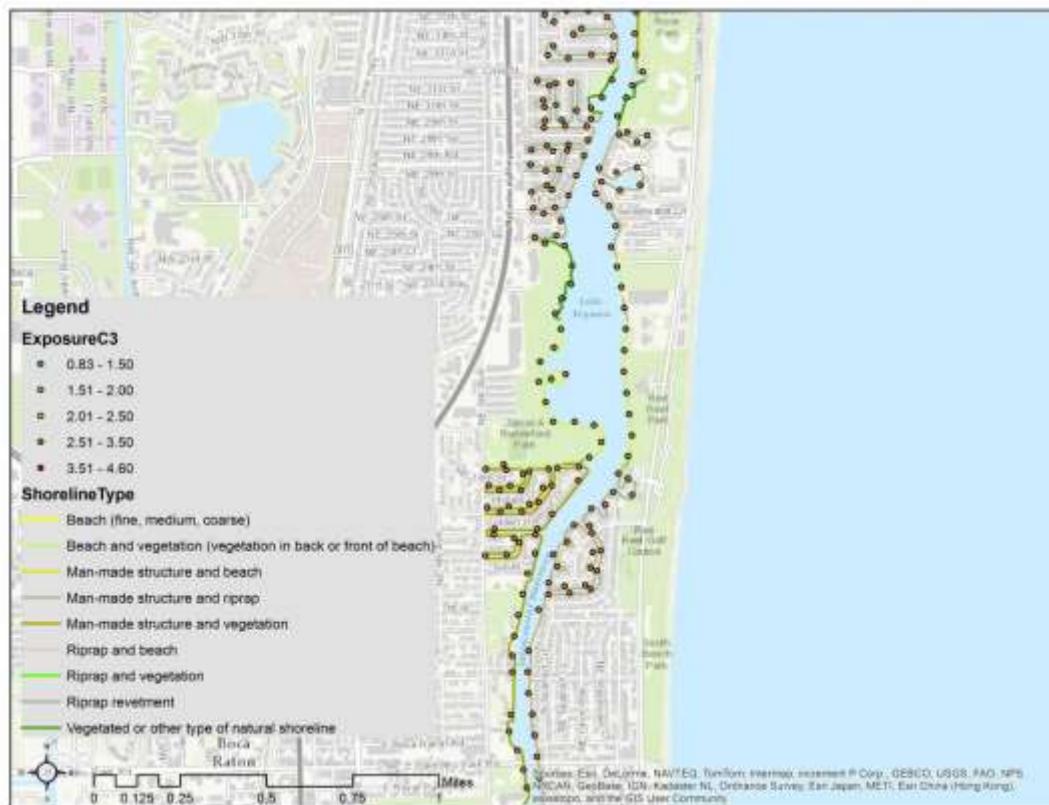
	Bedrock, Mud, or Clay		
8B/10D	Sheltered, Solid Man-made Structures/ Sheltered Rocky Shores and Sheltered Scarps in Bedrock, Mud, or Clay	Man-made	Hybrid
8B/3A	Sheltered, Solid Man-made Structures/ Fine- to Medium-grained Sand Beaches	Man-made	Hybrid/ Soft
8B/4	Sheltered, Solid Man-made Structures/ Coarse-grained Sand Beaches	Man-made	Hybrid/ Soft
8B/6B	Sheltered, Solid Man-made Structures / Exposed rip-rap	Man-made	Hybrid (enhancement)
8B/7	Sheltered, Solid Man-made Structures / Exposed Tidal Flats	Man-made	Hybrid/ Soft
8B/8C	Sheltered, Solid Man-made Structures/ Sheltered Riprap	Man-made	Hybrid/ Soft
8B/9A	Sheltered, Solid Man-made Structures/ Sheltered Tidal Flats	Man-made	Hybrid/ Soft
8B/9B	Sheltered, Solid Man-made Structures/ Vegetated Low Banks	Man-made	Hybrid/ Soft
8B	Sheltered, Solid Man-made Structures	Man-made	Hybrid
8C/10D	Sheltered Riprap/ Sheltered Rocky Shores and Sheltered Scarps in Bedrock, Mud, or Clay	Man-made	Hybrid/ None
8C/3A	Sheltered Riprap/ Fine- to Medium-grained Sand Beaches	Man-made	Hybrid/ Soft
8C/4	Sheltered Riprap / Coarse-grained Sand Beaches	Man-made	Hybrid/ Soft
8C/5	Sheltered Riprap / Mixed Sand and Gravel Beaches	Man-made	Hybrid/ Soft
8C	Sheltered riprap	Man-made	Hybrid/ Soft
9B/3A	Vegetated Low Banks/ Fine- to Medium-grained Sand Beaches	Natural	None/ Soft
9B/4	Vegetated Low Banks / Coarse-grained Sand Beaches	Natural	None/ Soft
9B/5	Vegetated Low Banks / Mixed Sand and Gravel Beaches	Natural	None/ Soft
9B/6B	Vegetated Low Banks / Exposed rip-rap	Man-made	Hybrid/ Soft
9B/5	Vegetated Low Banks / Mixed Sand and Gravel Beaches	Natural	Hybrid/ Soft
9B/6B	Vegetated Low Banks/ Exposed riprap	Man-made	Hybrid
9B/8C	Vegetated Low Banks / Sheltered Riprap	Man-made	Hybrid
9B	Vegetated Low Banks	Natural	None/ Soft
9C	Hypersaline Tidal Flats	Natural	None

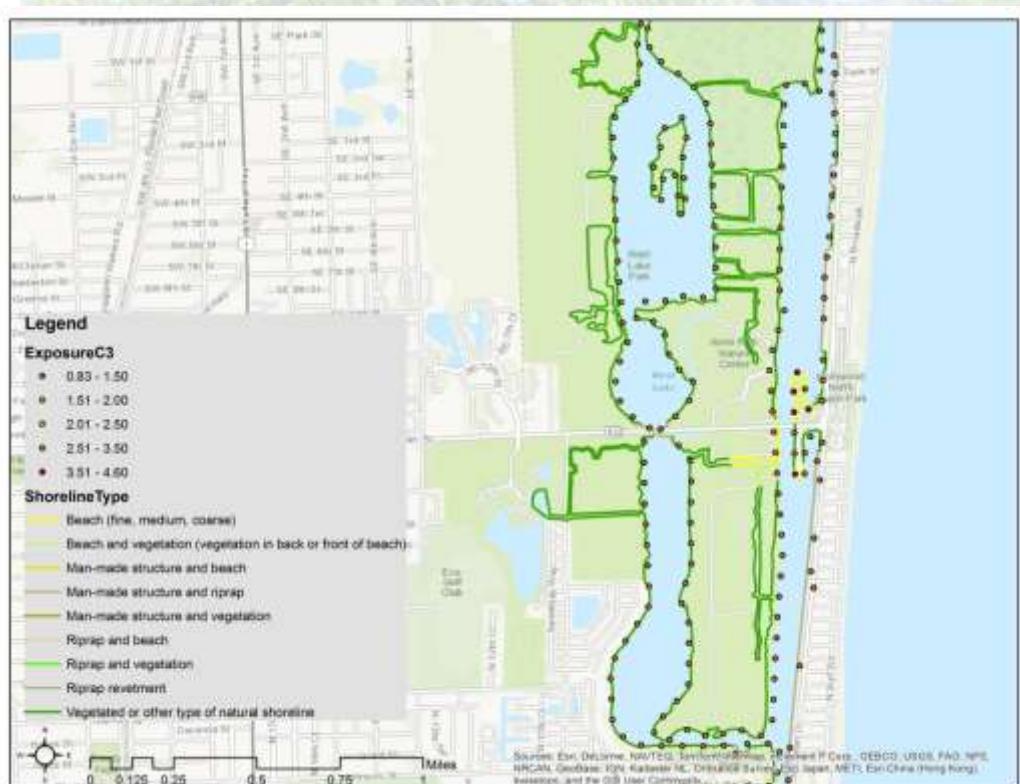
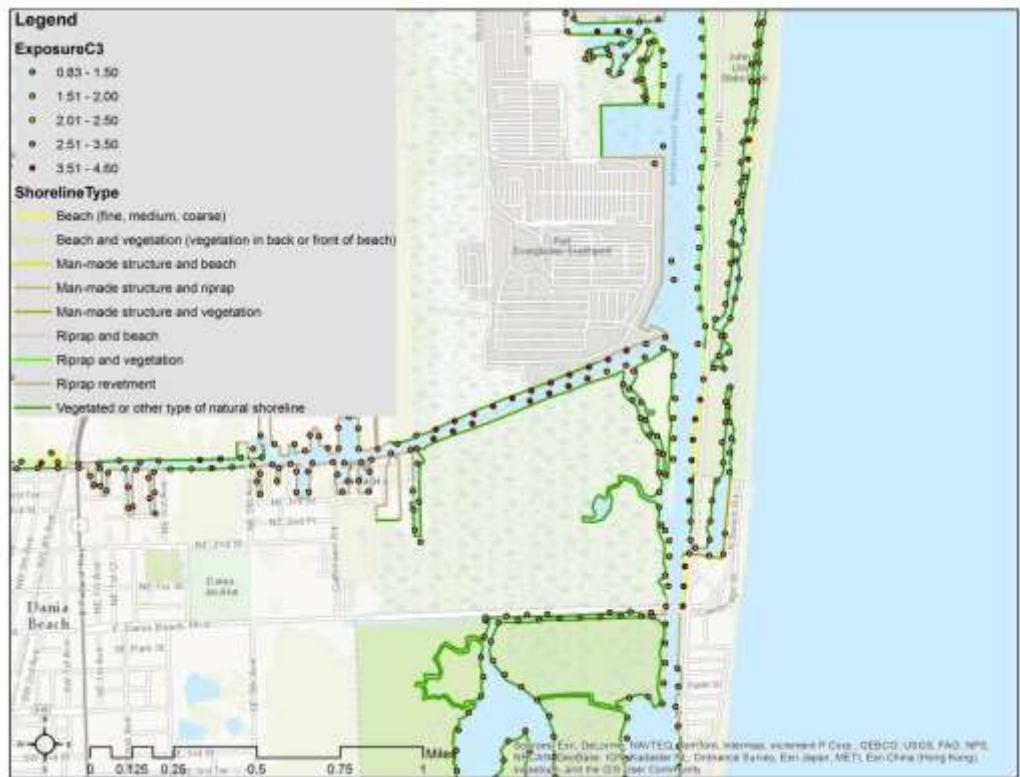
Appendix 2. Examples of potential sites to consider for soft and hybrid stabilization





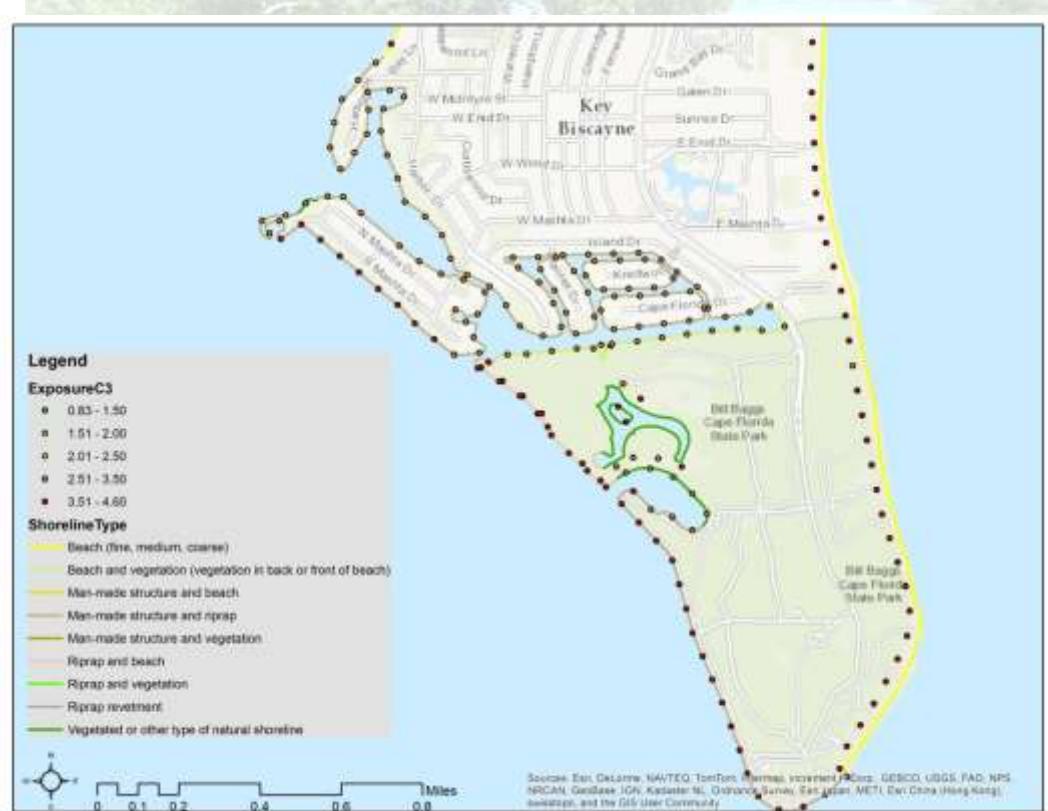












Appendix 3. Attribute label, attribute type, attribute definition and attribute definition source

Attribute Label	Attribute Type	Attribute Definition	Attribute Definition Source
OBJECTID	OID	Internal feature number	ESRI
Shape	String	Feature type	ESRI
S_NEAR_DIS	Double	Distance between the shoreline point and the water/landward point (in meters)	generated by ArcGIS Near function , used to calculate slope
S_NEAR_X	Double	X-coordinate	ESRI
S_NEAR_Y	String	Y-coordinate	ESRI
S_Z_M	Double	Elevation for the shoreline point feature (in meters)	<p>Data sources:</p> <p>Layer Name: Broward_10ft (2007 Broward 10-ft DEM in NAVD 1988, Release Version 1) Originators: South Florida Water Management District (SFWMD) Publication date: November 23, 2009 Data type: Fgdb raster digital data Data location: \\ad.sfwmd.gov\dfsroot\data\lida\\2007_FDEM\DEM_Releases\Broward\ReleaseV1\merged\fgdb\Broward_Merged_10ft.gdb</p> <p>Layer Name: MiamiDade_10ft (2007-08 Miami-Dade 5-ft DEM in NAVD 1988, Release Version 1) Originators: South Florida Water Management District (SFWMD) Publication date: November 23, 2009 Data type: Fgdb raster digital data Data location: http://www.sfwmd.gov</p> <p>Layer Name: PBEast_10ft Broward_10ft (2007-08 Palm Beach East 10-ft DEM in NAVD 1988, Release Version 1) Originators: South Florida Water Management District (SFWMD) Publication date: May 14, 2010 Data type: Fgdb raster digital data Data location: \\ad.sfwmd.gov\dfsroot\data\lida\\2007_FDEM\DEM_Releases\PalmBeachEast\ReleaseV1\merge\\fgdb\PBEast_Merged_10ft.gdb</p>
S_Z_FT	Double	Mean elevation for each shoreline feature	Data sources (see S_Z_M field entry)
L_Z_M	Double	Mean elevation for a point ~ 10 m landward from the shoreline feature	Data sources (see S_Z_M field entry)
L_Z_FT	Double	Mean elevation for a point ~ 10 m landward from the shoreline feature	Data sources (see S_Z_M field entry)
W_Z_M	Double	Mean elevation for a point ~ 10 m seaward from the shoreline feature	Data sources (see S_Z_M field entry)
W_Z_FT	Double	Mean elevation for a point ~ 10 m seaward from the	Data sources (see S_Z_M field entry)

		shoreline feature	
LS_PC	Double	Landward slope in percent	Calculated field
WS_PC	Double	Seaward slope	Calculated field
SeagrassDE	String	Description, presence/absence of seagrasses	<p>Layer Name: SEAGRS_2011, FLORIDA'S STATEWIDE SEAGRASS – 2011</p> <p>Originators: Florida Fish and Wildlife Conservation Commission-Fish and Wildlife Research Institute</p> <p>Publication date: October 21, 2011</p> <p>Data type: vector digital data</p> <p>Data location: http://www.fgdl.org/metadataexplorer/explorer.jsp</p>
MOST_SENS	String	Environmental Sensitivity Index (NOAA 2012) code of the most sensitive plant community	<p>Layer Name: SENSHR_2013, FLORIDA'S ENVIRONMENTALLY SENSITIVE SHORELINES - 2013</p> <p>Originators: Florida Fish and Wildlife Conservation Commission-Fish and Wildlife Research Institute</p> <p>Publication date: August 1, 2014</p> <p>Data type: vector digital data</p> <p>Data location: http://www.fgdl.org/metadataexplorer/explorer.jsp</p>
Descript2	String	Environmental Sensitivity Index (NOAA 2012) code of the most sensitive plant community	Data source (see above)
W_Z_feet	Double	Water depth 10 m from the shoreline	Derived from topobathymetric LiDAR using the Value to Point function in ArcGIS.
BoatWake	String	Describes three categories of boat wake influence – no wake, medium and high boat wake	<p>Layer Name: State_Boating_Safety_Zones_Florida, This data set represents the FWC Boating Restricted Areas as described in Florida Administrative Code Chapter 68D-24.</p> <p>Originators: Florida Fish and Wildlife Conservation Commission-Fish and Wildlife Research Institute</p> <p>Publication date: January 1, 2011; updated 2015</p> <p>Data type: vector digital data</p> <p>Data location: http://geodata.myfwc.com/datasets/663fd68e205445da97800b5a5f9ae561_13</p>
SpeedRule	String	Boating safety speeds rule	<p>Layer Name: State_Boating_Safety_Zones_Florida, This data set represents the FWC Boating Restricted Areas as described in Florida Administrative Code Chapter 68D-24.</p> <p>Originators: Florida Fish and Wildlife Conservation Commission-Fish and Wildlife Research Institute</p> <p>Publication date: January 1, 2011; updated 2015</p> <p>Data type: vector digital data</p> <p>Data location: http://geodata.myfwc.com/datasets/663fd68e205445da97800b5a5f9ae561_13</p> <p>Gorzelany 2005, 2009; PBS&J 2009</p>
DistInlt3mi	String	Binary variable (Yes/No) to	Calculated

		indicate if a shoreline point is within 3 miles from an inlet	
Fetch_cat	String	Very low < 0.25 mi; Low 0.25 to 0.5mi; Medium 0.5 to 1.0 mi; High 1.0 mi to 3.0 mi; Unbounded	The average fetch in miles was calculated using the <i>Application of Wind Fetch and Wave Models for Habitat Rehabilitation and Enhancement Projects</i> (Rohweder et al. 2012). The application <i>Waves2012.tbx</i> is a toolbox for @ArcGIS 10.0/10.1 based on the methodology described in the <i>USACE Shore Protection Manual</i> (USACE 1984).
Poly_ID	String	SLOSH model output	Available reports, permits and other documents, expert knowledge
i_index	Short integer	A free text field to place general comments	Available reports, permits and other documents, expert knowledge
c1_mean	Double	Modeled height of storm surge	SLOSH
c1_high	Double	Modeled height of storm surge	SLOSH
c2_mean	Double	Modeled height of storm surge	SLOSH
c2_high	Double	Modeled height of storm surge	SLOSH
c3_mean	Double	Modeled height of storm surge	SLOSH
c3_high	Double	Modeled height of storm surge	SLOSH
c4_mean	Double	Modeled height of storm surge	SLOSH
c4_high	Double	Modeled height of storm surge	SLOSH
c5_mean	Double	Modeled height of storm surge	SLOSH
c5_high	Double	Modeled height of storm surge	SLOSH
ShorelineType	String	Environmental Sensitivity Index (NOAA 2012) code of the most sensitive plant community	UPDATED
REI	Double	InVEST output	InVEST outout
Wave_Exp	Double	InVEST output	InVEST output
ExposureX	Double	Exposure Index	Calculated
ExposureC3	Double	Exposure Index + exposure to storm surge for category 3 hurricane (mean)	Calculated
ExposureC5	Double	Exposure Index + exposure to storm surge for category 5 hurricane (high)	Calculated
SuitabilityX	String	Alternative shoreline stabilization options	Based on the decision tree analysis

Appendix 4. Research Participation Invitation

To: dmitsova@fau.edu; cbergh@tnc.org

BCC: email addresses from the expert list (to avoid disclosing the email addresses of potential research subjects to others, it is an IRB requirement)

From: dmitsova@fau.edu; cbergh@tnc.org

Subject: Research Participation Invitation – Living Shorelines Suitability Analysis for Estuarine Systems

You have been asked to complete this survey as part of a research project conducted by FAU with support from The Nature Conservancy. This email message is an approved request for participation in research titled **SUITABILITY ANALYSIS FOR LIVING SHORELINES IN SOUTHEAST FLORIDA ESTUARINE SYSTEMS** which has been declared exempt or non-human subjects research by the Florida Atlantic University Institutional Review Board. We conduct a Multi-objective / Multi-criteria suitability analysis. A common concern in multi-criteria evaluation is to measure the relative importance of each criterion. This questionnaire is intended to provide insight and input to the prioritization and assignment of weights to the suitability criteria.

The survey will take about 10 minutes to complete. Your responses are entirely voluntary, and you may refuse to complete any part or all of this survey, by skipping a question or checking “I prefer not to answer.” This survey is designed to be anonymous, meaning that there should be no way to connect your responses with you. Toward that end, please do not sign your name to the survey or include any information in your responses that makes it easy to identify you. By completing and submitting the survey, you affirm that you are at least 18 years old and that you give your consent for the Principal Investigator to use your answers as part of this research. If you have any questions about this research before or after you complete the survey, please contact the principal investigator Diana Mitsova at dmitsova@fau.edu or (561) 297-4279. If you have any concerns or questions about your rights as a participant in this research, please contact the Florida Atlantic University Division of Research at (561) 297-0777.

The survey can be accessed through the link below:

http://faucdsi.az1.qualtrics.com/jfe/form/SV_eKYZwTTvVEWYnqZ

Thank you for your participation.

Diana Mitsova, Ph.D.

Associate Professor
School of Urban & Regional Planning
Florida Atlantic University
Phone: 561-297-4285

Chris Bergh

South Florida Conservation Director
The Nature Conservancy
Chair, Shoreline Resilience Working Group
SE FL Regional Climate Compact

Appendix 5. Survey instrument

Questionnaire

In response to the erosion of shorelines, as well as potentially more intense storm damage and flooding as a result of sea level rise and climate change, armoring of shorelines is likely to increase using traditional engineered approaches and structures. This hard-armoring approach is known to reduce sediment sources by interrupting natural sediment transport, affect water quality and reduce habitat in adjacent water bodies, and fundamentally disrupt the connection between coastal and offshore ecosystems. Alternative and viable approaches to shoreline stabilization techniques and land use practices that minimize structural and environmental problems associated with hard-armored shorelines are becoming an accepted practice inshore zone management. Alternative stabilization techniques have been shown to provide comparable protection under suitable landscape and environmental conditions. These approaches allow for the long-term protection, restoration and/or enhancement of vegetated shoreline habitats, even during tropical storms. We conduct a Multi-objective / Multi-criteria suitability analysis and mapping for such alternative approaches: A common concern in multi-criteria evaluation is to measure the relative importance of each criterion. This questionnaire is intended to provide insight and input to the prioritization and assignment of weights to the suitability criteria (see pp. 3-4 of this questionnaire).

The survey will take about 10 minutes to complete. Your participation to this survey is voluntary. You may skip any question that makes you uncomfortable by checking "I prefer not to answer." The risks involved with participation in this study are no more than one would experience in regular daily activities since your survey responses are anonymous (i.e. there are no personal identifiers). For other questions about the study, contact the principal investigator Diana Mitsova at dmitsova@fau.edu or (561) 297-4279.

1. County_____

2. How many years of experience do you have in the field? I prefer not to answer_____

3. Which sector have you worked for?
a. Public
b. Private
c. Both

4. What is your area of expertise? I prefer not to answer_____

5. What is your educational background?
a. Coastal Engineering _____
b. Geoscience and GIS _____
c. Environmental science _____
d. Urban Planning _____
e. Architecture/ Design _____
f. Social science _____
g. Business _____
h. Other (please specify) _____

6. Have you been involved in coastal management projects?
- a. Yes b. No
- If yes, for how many years? _____
7. Have you been part of a response effort to a coastal flooding event or other coastal hazards in your community in the past 5 years? I prefer not to answer _____
- a. No
b. Yes
- If yes, what type of hazard? _____
8. Have you been part of a response effort to a coastal flooding event or other coastal hazards in your community in the past 10 years? I prefer not to answer _____
- a. No
b. Yes
- If yes, what type of hazard? _____
9. Have you been part of a response effort to a coastal flooding event or other coastal hazards in your community in the past 25 years? I prefer not to answer _____
- a. No
b. Yes
- If yes, what type of hazard? _____
10. One of the parameters included in the living shoreline suitability analysis for SE FL estuarine environments is “Distance to inlet.” This parameter will be used as a proxy for currents and salinity conditions within a specified shoreline feature. To this respect , which of the following should be the maximum distance to inlet to be considered in the analysis (please circle one):
- a. 0.25 mi
b. 0.5 mi
c. 1.0 mi
d. 2.0 mi
e. 3.0 mi
f. Other (please specify) _____
g. I don't know
11. Listed on the next page are various land use categories. Some uses such as publicly-owned parks or golf courses are known to allow easier access and implementation of various restoration and stabilization projects. Others tend to be more cautious in their approach. For example, public lands, public parks, and conservation areas are more likely to facilitate soft stabilization while private property owners may be more inclined to support hard armoring or hybrid shoreline stabilization. The scale below indicates the perceived ease of action regarding the establishment of project types other than traditional armoring. On a scale of 1 to 5, please indicate how easy you think it will be to implement nature-based approaches (where 1 indicates a very low chance of implementing a project type other than traditional armoring, while 5 indicates a very high chance of implementing such a project, all other favorable conditions being present):

Very low 1	Low 2	Moderate 3	High 4	Very high 5
---------------	----------	---------------	-----------	----------------

Public lands (Recreation/ Conservation)

1	2	3	4	5
---	---	---	---	---

Education

1	2	3	4	5
---	---	---	---	---

Marina

1	2	3	4	5
---	---	---	---	---

Transportation

1	2	3	4	5
---	---	---	---	---

Recreation private Golfcourse

1	2	3	4	5
---	---	---	---	---

Commercial Hotel/Timeshare

1	2	3	4	5
---	---	---	---	---

Industrial

1	2	3	4	5
---	---	---	---	---

Mixed Use

1	2	3	4	5
---	---	---	---	---

Office / Commercial

1	2	3	4	5
---	---	---	---	---

Residential High Density

1	2	3	4	5
---	---	---	---	---

Residential Low Density

1	2	3	4	5
---	---	---	---	---

Residential Multifamily/ Condos

1	2	3	4	5
---	---	---	---	---

12. Suitability analysis usually relies on multiple factors. Some of these factors are more important for the proposed action than others, therefore, they carry more weight. The next few questions are intended to elicit your expert opinion on the importance of some of the factors included in the suitability analysis for living shorelines in SE FL estuarine environments. We will use pairwise comparisons to gain an insight of which factor is considered more important and thus have higher weight. Weights will be extracted on the basis of these pairwise comparisons.

a. Wind/Wave Exposure (WWE) vs. Boat wake exposure (BWE)
 WWE _____ BWE _____ Both _____

b. Boat wake exposure (BWE) vs. Distance to inlet (DI)
 BWE _____ DI _____ Both _____

c. Nearshore slope vs. Shoreline Type (ST) (natural, armored, hybrid)
 Nearshore slope _____ ST _____ Both _____

d. Nearshore slope vs. Distance to inlet (DI)
 Nearshore slope _____ DI _____ Both _____

e. Shoreline type (ST) (natural, armored, hybrid) vs. Nearshore habitat (NH)
 ST _____ Nearshore habitat _____ Both _____

f. Nearshore slope vs. Nearshore habitat (NH)

Nearshore slope _____ Nearshore habitat _____ Both _____

g. Presence of upland natural habitat (PNH) vs. Shoreline Type (ST) (natural, armored, hybrid)
Upland NH _____ ST _____ Both _____

h. Nearshore habitat (NH) vs. Wind/Wave Exposure (WWE))
Nearshore habitat _____ WWE _____ Both _____

i. Wind/Wave Exposure (WWE) vs. Presence of upland natural habitat (Upland NH)
WWE _____ Upland NH _____ Both _____

j. Ownership (public or private) vs. Land use (LU)
Ownership _____ LU _____ Both _____



Appendix 6. Qualtrics initial report

Last Modified: 11/01/2015

#	Answer		Response	%
1	I consent to participate in this study		33	100%
2	I do not consent to participate in this study		0	0%
	Total		33	100%

Statistic	Value
Min Value	1
Max Value	1
Mean	1.00
Variance	0.00
Standard Deviation	0.00
Total Responses	33

2. County (enter the name of the County where you are employed)

Text Response

Santa Barbara

Dade

Miami-Dade

Miami-Dade

Monroe

Miami - Dade

Miami-Dade

USA

Leon

United States

Broward

Indian River

Santa Cruz, CA

Monroe

Leon

Miami-Dade

Miami-Dade County

Palm Beach

Volusia

Broward

Broward

Palm Beach

Palm Beach

Broward

Miami-Dade

Palm Beach

Palm Beach

Broward

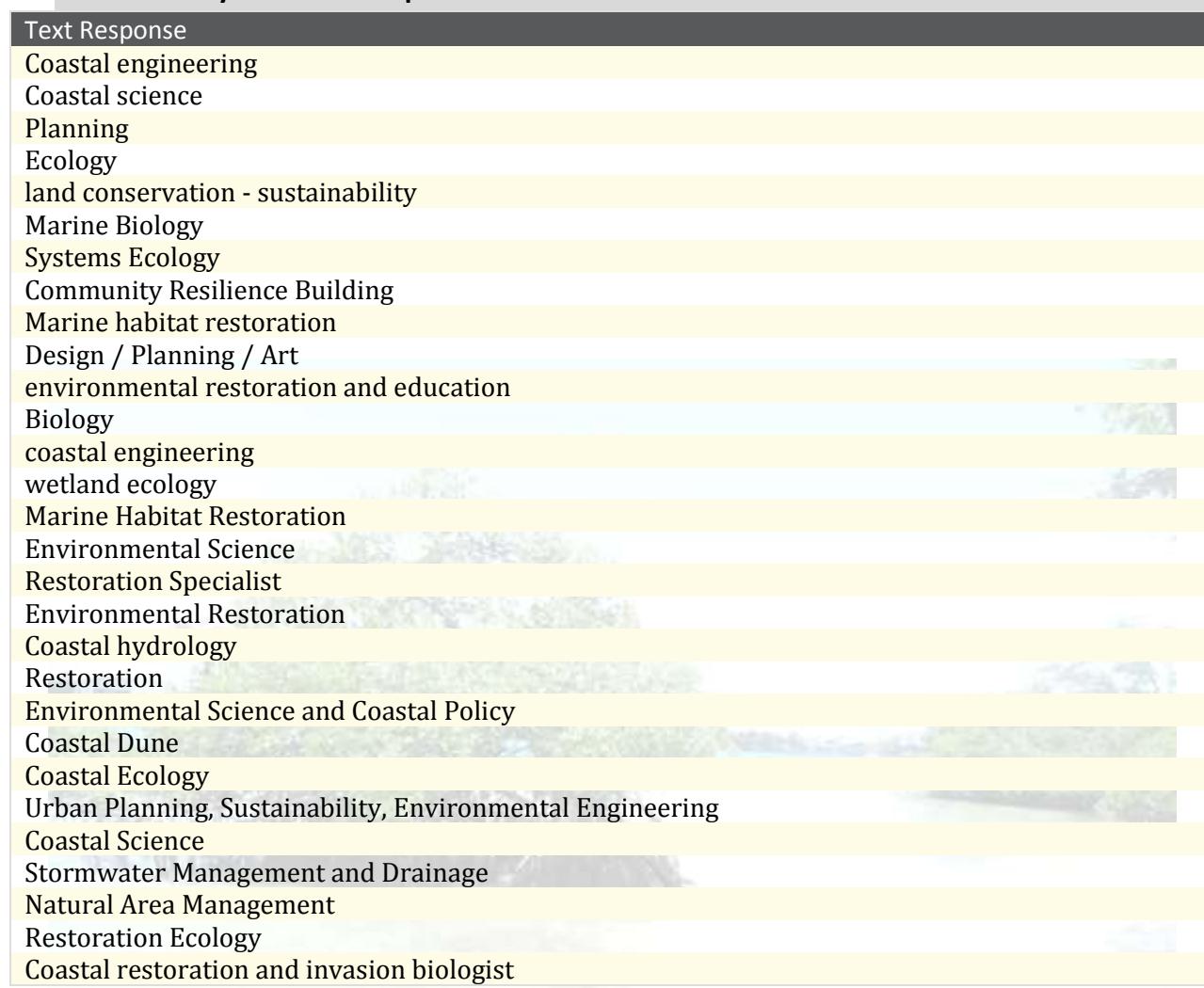
Monroe

Miami-Dade

Martin

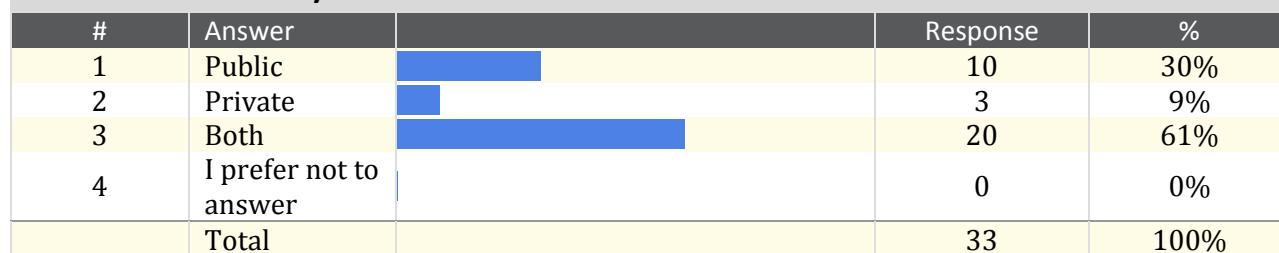
Statistic	Value
Total Responses	31

1. What is your area of expertise?



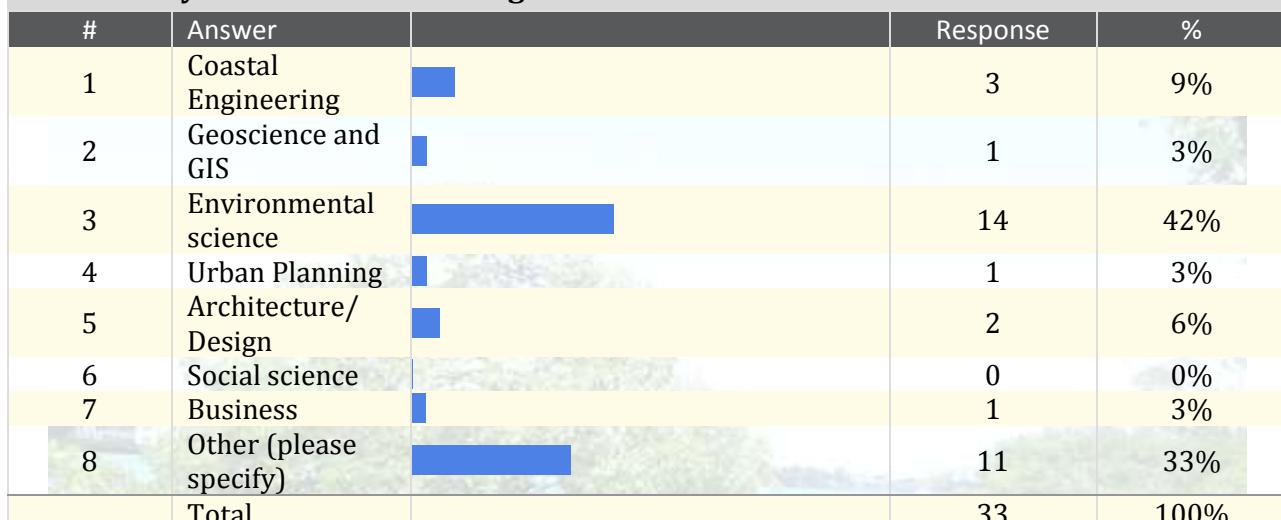
Statistic	Value
Total Responses	29

4. Which sector have you worked for?



Statistic	Value
Min Value	1
Max Value	3
Mean	2.30
Variance	0.84
Standard Deviation	0.92
Total Responses	33

5. What is your educational background?



Other (please specify)

Regional & urban planning
Biology
ecology
Limnology
Ecology/Biology
Coastal Zone Management
Marine Biology and Coastal Zone Mgmt
Civil ad Environmental Engineering
Biology
plant biologist

Statistic	Value
Min Value	1
Max Value	8
Mean	4.73
Variance	6.70
Standard Deviation	2.59
Total Responses	33

6. How many years of experience do you have in the field?



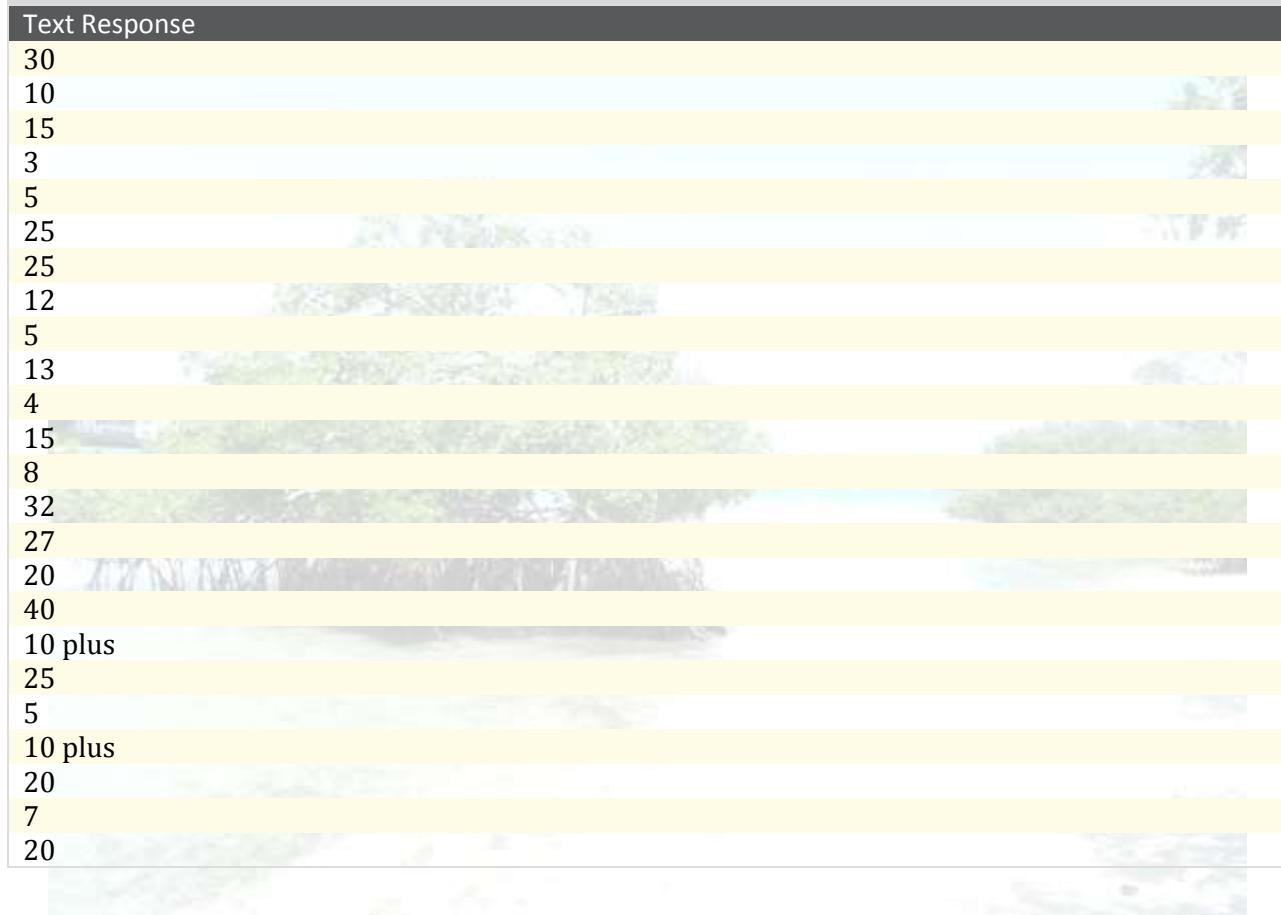
Statistic	Value
Total Responses	32

7. Have you been involved in coastal management projects?

#	Answer	Response	%
1	No	6	19%
2	Yes	26	81%
	Total	32	100%

Statistic	Value
Min Value	1
Max Value	2
Mean	1.81
Variance	0.16
Standard Deviation	0.40
Total Responses	32

8. If yes, for how many years:



Statistic	Value
Total Responses	24

9. Have you been part of a response effort to a coastal flooding event or other coastal hazards in your community in the past 5 years?

#	Answer	Response	%
1	No	19	61%
2	Yes	12	39%
	Total	31	100%

Statistic	Value
Min Value	1
Max Value	2
Mean	1.39
Variance	0.25
Standard Deviation	0.50
Total Responses	31

10. If yes, what type of hazard?

Text Response

Flooding, sea level rise
 storm surge, wind/ice/snow, tornado, sea level rise, inland flooding
 Flooding
 Storm Events
 Flooding
 SLR, Tidal
 Flooding and Erosion
 TS Isaac Flood Response and Emergency Ops Center response
 Oil Spill, Storm
 Shoreline erosion

Statistic	Value
Total Responses	10

11. Have you been part of a response effort to a coastal flooding event or other coastal hazards in your community in the past 10 years?

#	Answer	Response	%
1	No	17	53%
2	Yes	15	47%
	Total	32	100%

Statistic	Value
Min Value	1
Max Value	2
Mean	1.47
Variance	0.26
Standard Deviation	0.51
Total Responses	32

12. If yes, what type of hazard?

Text Response
Flooding, sea level rise
same as above for 5 years
Hurricane
hurricanes
Flooding
Storm Events
Flooding from Isaac
Hurricanes in 2004 - work extended through 2006
Flooding
But involved in USCG regional hazard prep efforts for wildlife protection
Flooding and Erosion
Coastal erosion, emergency response and long-term planning, and restoration projects
Storm
Past Hurricane Damage Assessments
Shoreline erosion

Statistic	Value
Total Responses	15

13. Have you been part of a response effort to a coastal flooding event or other coastal hazards in your community in the past 25 years?

#	Answer	Response	%
1	No	19	66%
2	Yes	10	34%
	Total	29	100%

Statistic	Value
Min Value	1
Max Value	2
Mean	1.34
Variance	0.23
Standard Deviation	0.48
Total Responses	29

14. If yes, what type of hazard?

Text Response

Flooding & storm surge
 storm surge, inland flooding
 Hurricane
 Storm Events
 coastal flooding due to a tropical storm (unnamed)
 Same as 7 and 8
 Storm
 Past Hurricane Damage Assessments
 Coastal flooding, saltwater intrusion

Statistic	Value
Total Responses	9

15. One of the parameters included in the living shoreline suitability analysis for SE FL estuarine environments is “Distance to inlet.” This parameter will be used as a proxy for boat traffic and circulation conditions within a specified distance from a shoreline feature. To your knowledge, which of the following should be the maximum distance to inlet to be considered in the analysis (please check one):

#	Answer	Response	%
1	0.25 mi	3	17%
2	0.5 mi	0	0%
3	1.0 mi	1	6%
4	2.0 mi	1	6%
5	3.0 mi	5	28%
6	Other	8	44%
Total		18	100%

Other

This is inlet-dependent
 if possible otherwise 0.25mi - more is better to minimize wake but properly designed living shorelines can reduce a wake in very close proximity however, they then may cause navigational hazards which are not to cool

depends on floodplain....consider floodplain maps

Distance should be based on historical information on erosion in a particular system. However for planning purposes, in south Florida tidal influence in the estuarine waters can be considered to be within 3 miles.

Not Applicable

Depends on the type of shoreline and purpose of project. Could be a variable or not.

10 miles

Varies depending on location and other factors

Statistic	Value
Min Value	1
Max Value	6
Mean	4.61
Variance	3.43
Standard Deviation	1.85
Total Responses	18



16. Listed below are various land use categories. Some uses such as publicly-owned parks or golf courses are known to allow easier access and implementation of various restoration and stabilization projects. Others tend to be more cautious in their approach. For example, public lands, public parks, and conservation areas are more likely to facilitate soft stabilization while private property owners may be more inclined to support hard armoring or hybrid shoreline stabilization. The scale below indicates the perceived ease of action regarding the establishment of project types other than traditional armoring. On a scale of 1 to 5, please indicate how easy you think it will be to implement nature-based approaches (where 1 indicates a very low chance of implementing a project type other than traditional armoring, while 5 indicates a very high chance of implementing such a project, all other favorable conditions being present):

#	Question	Very Low [1]	Low [2]	Medium [3]	High [4]	Very High [5]	Total Responses	Mean
1	Public lands (recreation, conservation)	0	0	3	5	23	31	4.65
2	Education	0	0	7	10	14	31	4.23
3	Marina	8	8	14	1	0	31	2.26
4	Transportation	5	7	12	6	1	31	2.71
5	Recreation Private Golfcourse	1	3	12	11	3	30	3.40
6	Commercial Office	6	7	16	2	0	31	2.45
7	Commercial Hotel/Timeshare	6	9	13	3	0	31	2.42
8	Mixed use	1	6	23	1	0	31	2.77
9	Industrial	12	9	9	0	1	31	2.00
10	Residential Low Density	1	6	18	3	3	31	3.03
11	Residential High Density	4	14	10	2	1	31	2.42
12	Residential Multi-familiy/Condos	1	14	13	2	1	31	2.61

Statistic	Public lands (recreation, conservation)	Education	Maria	Transportation	Recreation Private Golfcourse	Commercial Office	Commercial Hotel / Timeshare	Mixed-use	Industrial	Residential Low Density	Residential High Density	Residential Multi-familiy/ Condos
Min Value	3	3	1	1	1	1	1	1	1	1	1	1
Max Value	5	5	4	5	5	4	4	4	5	5	5	5
Mean	4.65	4.23	2.26	2.71	3.40	2.45	2.42	2.77	2.00	3.03	2.42	2.61
Variance	0.44	0.65	0.80	1.15	0.87	0.79	0.85	0.31	1.00	0.83	0.85	0.65
Standard Deviation	0.66	0.80	0.89	1.07	0.93	0.89	0.92	0.56	1.00	0.91	0.92	0.80
Total Responses	31	31	31	31	30	31	31	31	31	31	31	31

17. Suitability analysis usually relies on multiple factors. Some of these factors are more important for the proposed action than others, therefore, they carry more weight. The next few questions are intended to elicit your expert opinion on the importance of the factors included in the suitability analysis. We will use pairwise comparisons to gain an insight of which factor is considered more important and thus have higher weight. Weights will be extracted on the basis of these pairwise comparisons. Consider the first statement " Wind/Wave Exposure (WWE) vs. Boat wake exposure (BWE)." In this statement, WWE is Parameter 1 while BWE is Parameter 2. Check the radio button to indicate whether you consider WWE having more influence than BWE, BWE having more influence than WWE or both being equally important.

#	Question	Parameter 1	Parameter 2	Both	Total Responses	Mean
1	Wind/Wave Exposure (WWE) vs. Boat wake exposure (BWE)	12	2	15	29	2.10
2	Boat wake exposure (BWE) vs. Distance to inlet (DI)	15	6	5	26	1.62
3	Nearshore slope (NS) vs. Shoreline Type (ST) (natural, armored, hybrid)	5	11	11	27	2.22
4	Nearshore slope (NS) vs. Distance to inlet (DI)	17	5	4	26	1.50
5	Shoreline type (ST) (natural, armored, hybrid) vs. Nearshore habitat (NH)	13	5	9	27	1.85
6	Nearshore slope vs. Nearshore	9	5	12	26	2.12

	habitat (NH)					
7	Presence of upland natural habitat (PNH) vs. Shoreline Type (ST) (natural, armored, hybrid)	7	16	4	27	1.89
8	Nearshore habitat (NH) vs. Wind/Wave Exposure (WWE)	3	15	8	26	2.19
9	Wind/Wave Exposure (WWE) vs. Presence of upland natural habitat (Upland NH)	20	3	3	26	1.35
10	Ownership (public or private) vs. Land use (LU)	7	4	15	26	2.31

Statistic	Wind/Wave Exposure (WWE) vs. Boat wake exposure (BWE)	Boat wake exposure (BWE) vs. Distance to inlet (DI)	Nearshore slope (NS) vs. Shoreline Type (ST)	Nearshore slope (NS) vs. Distance to inlet (DI)	Shoreline type (ST) (natural, armored, hybrid) vs. Nearshore habitat (NH)	Nearshore slope vs. Nearshore habitat (NH)	Presence of upland natural habitat (PNH) vs. Shoreline Type (ST) (natural, armored, hybrid)	Nearshore habitat (NH) vs. Wind/Wave Exposure (WWE)	Wind/Wave Exposure (WWE) vs. Presence of upland natural habitat (Upland NH)	Ownership (public or private) vs. Land use (LU)
Min Value	1	1	1	1	1	1	1	1	1	1
Max Value	3	3	3	3	3	3	3	3	3	3
Mean Variance	2.10	1.62	2.22	1.50	1.85	2.12	1.89	2.19	1.35	2.31
Standard Deviation	0.95	0.65	0.56	0.58	0.82	0.83	0.41	0.40	0.48	0.78
Total Responses	29	26	27	26	27	26	27	26	26	26

18. In this section, we will give you the opportunity to share comments and suggestions.

Text Response

If you have good policy, all can be easier.

I did not understand the last question....consider natural floodplain in the analysis, education is necessary as the way to disseminate information to landowners so they understand how living shorelines will protect their assets....also consider plants and pruning that will not impact view too much, that will help.

The selections in the previous section depend on the circumstances. For example, wind/wave exposure is more important in open areas exposed to the wind but not as important in a protected narrow channel setting. In the narrow channel setting, boat wakes play a bigger role.

After reading through and answering the questions I realized that (I think) we are not talking about beach erosion. A living shoreline on an ocean beach can be effective for erosion control but I assumed oceanfront projects are not the subject of this survey.

Answers came from hard copy of the survey

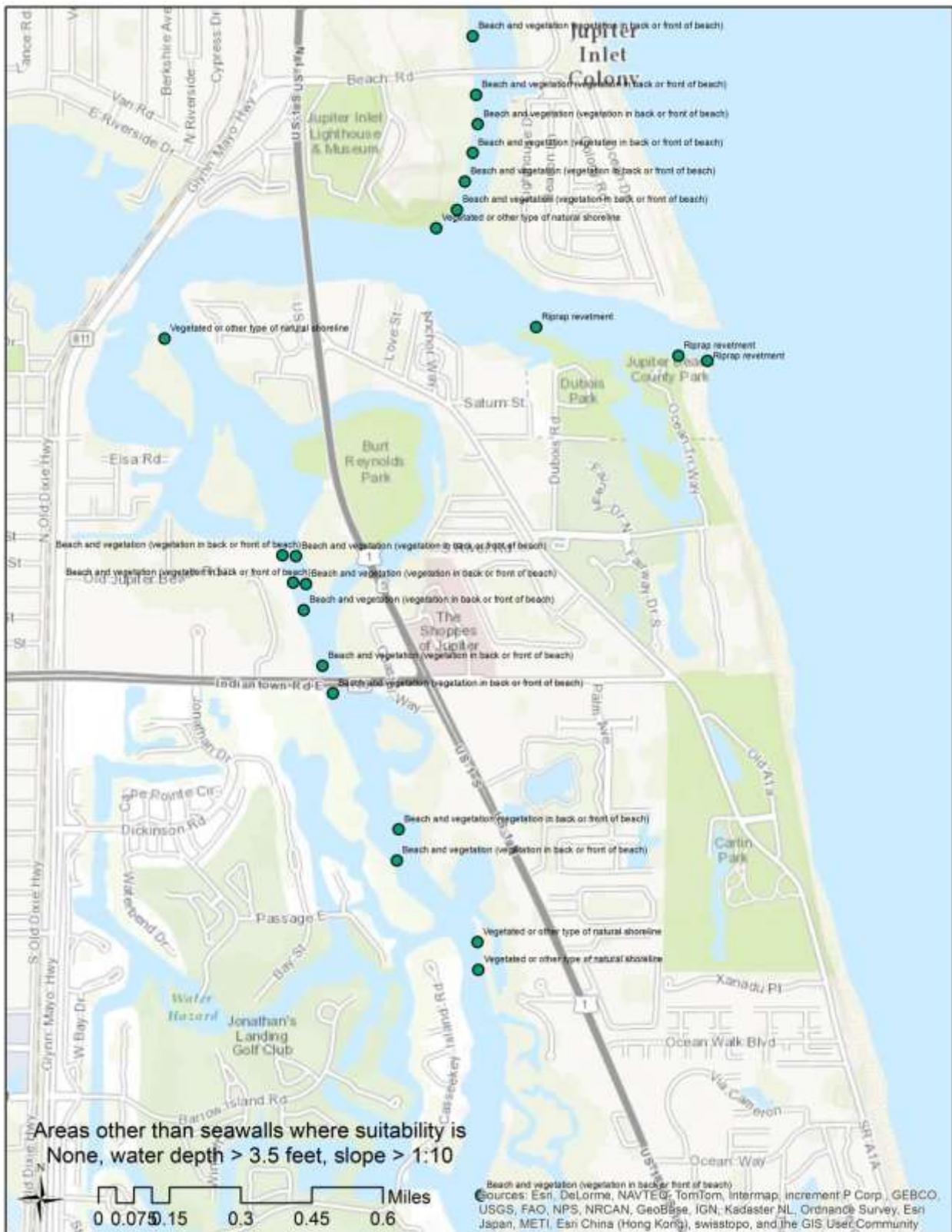
Answers came from a hard copy of the survey. Pair-wise comparisons were noted to be site dependent and boat wake exposure and distance to inlet was said to not be a logical factor. All land use categories were also said by the respondent to be possible in today's regulatory world.

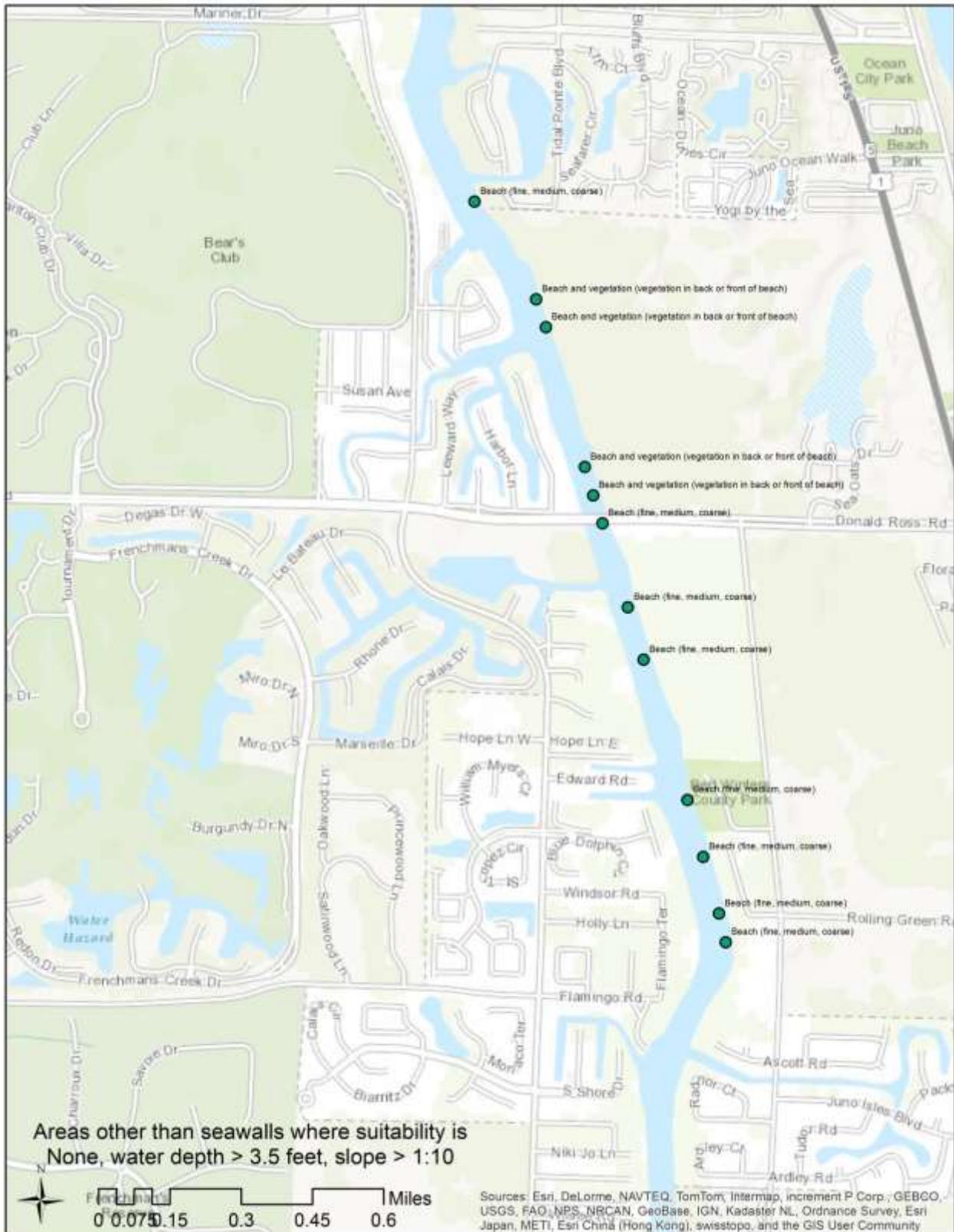


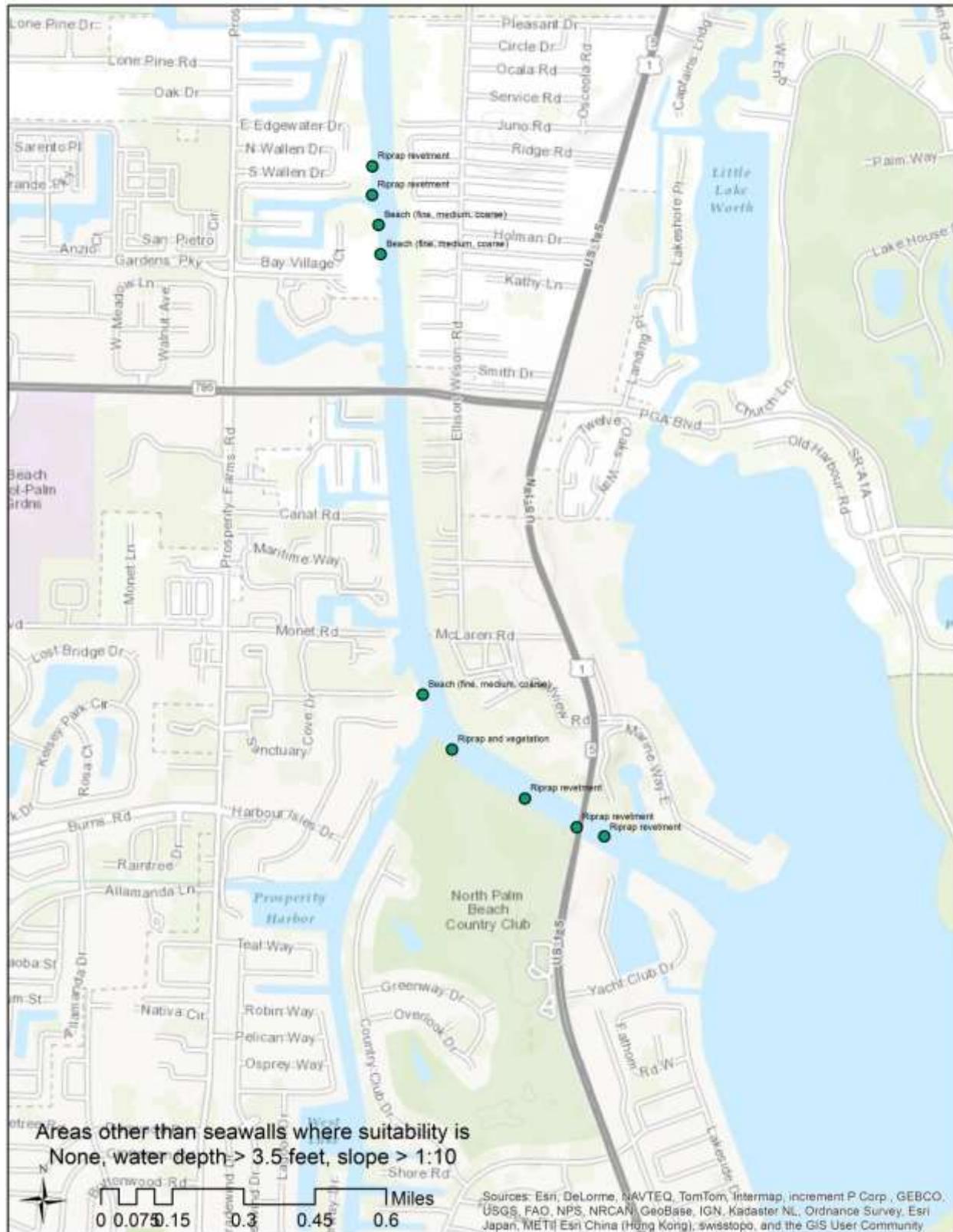
Appendix 7. Areas with a natural or hybrid type of shoreline where suitability for nature-based stabilization options is considered “none” due to greater water depths and steeper gradients

NOTE: Due to sediment movement caused by currents, storms, boat traffic, and construction activities, changes in sediment erosion and deposition rates may occur at the specified locations over time.

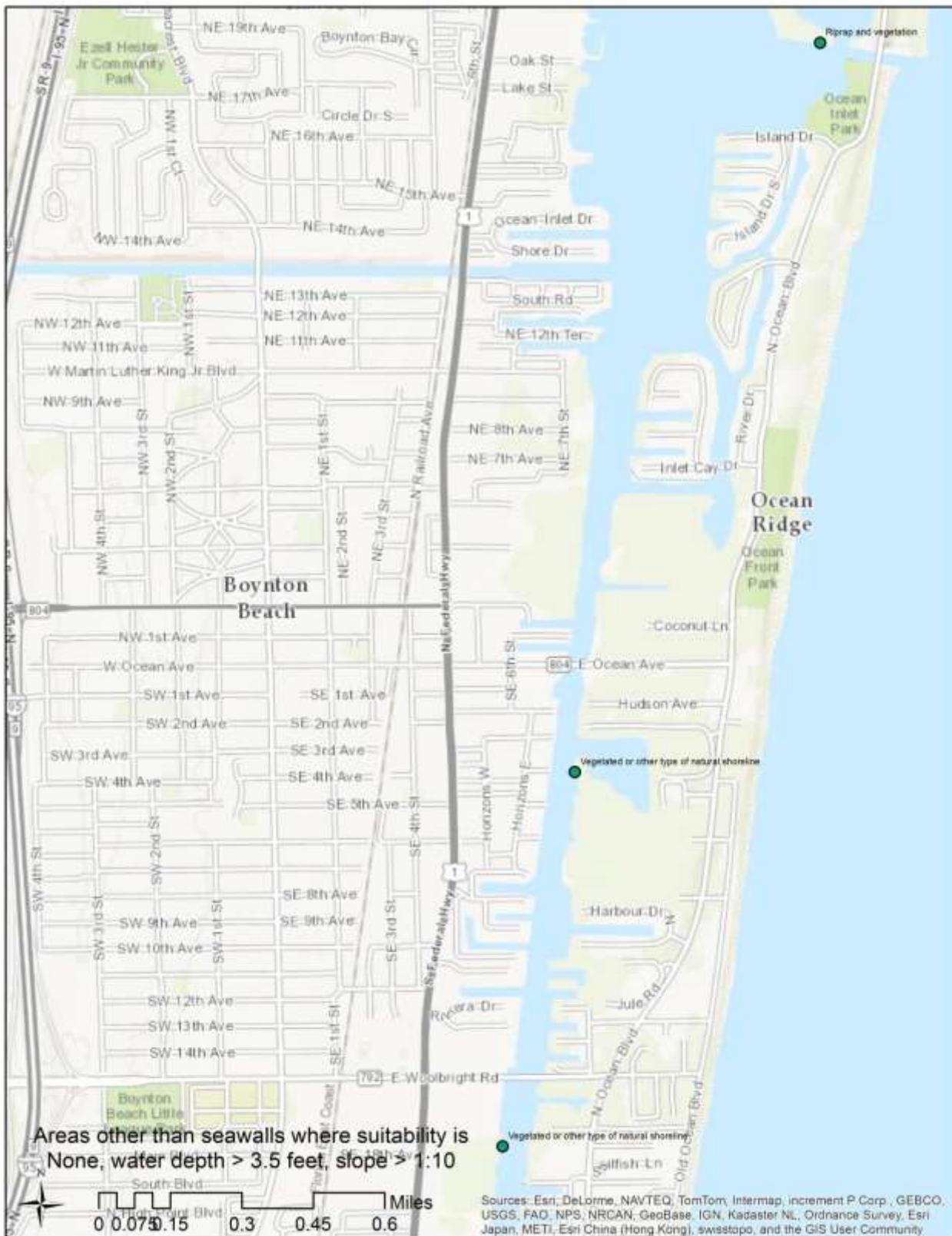


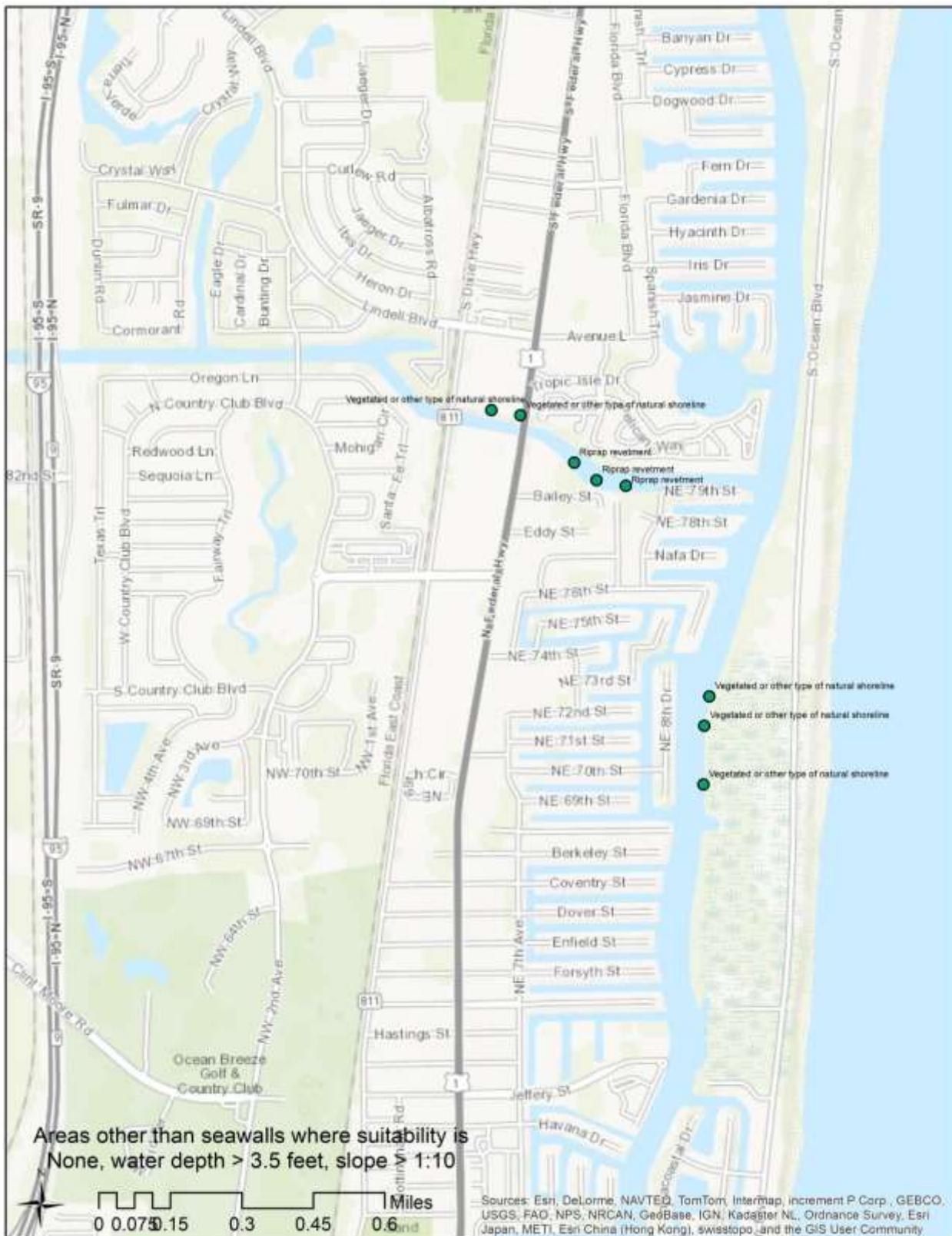






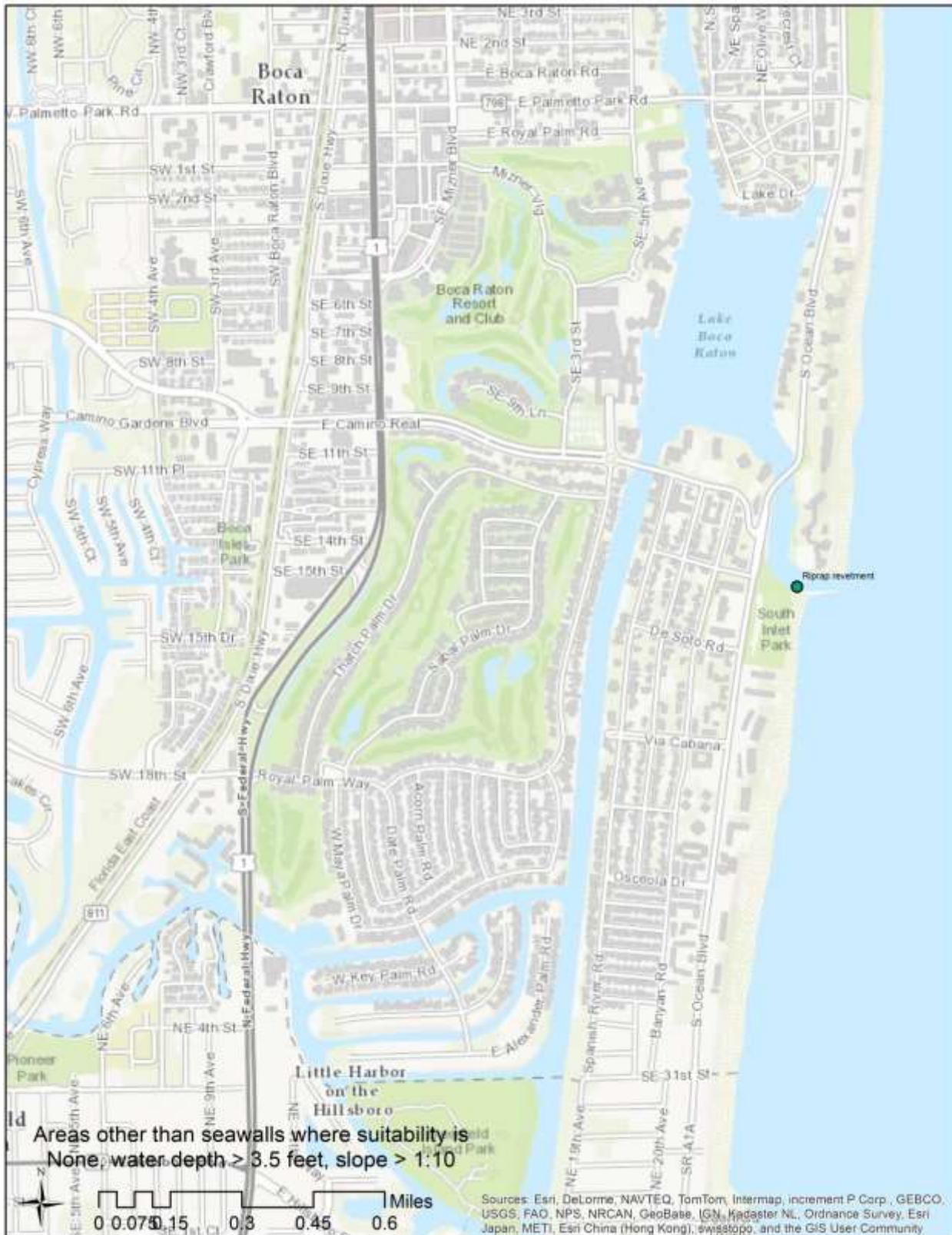


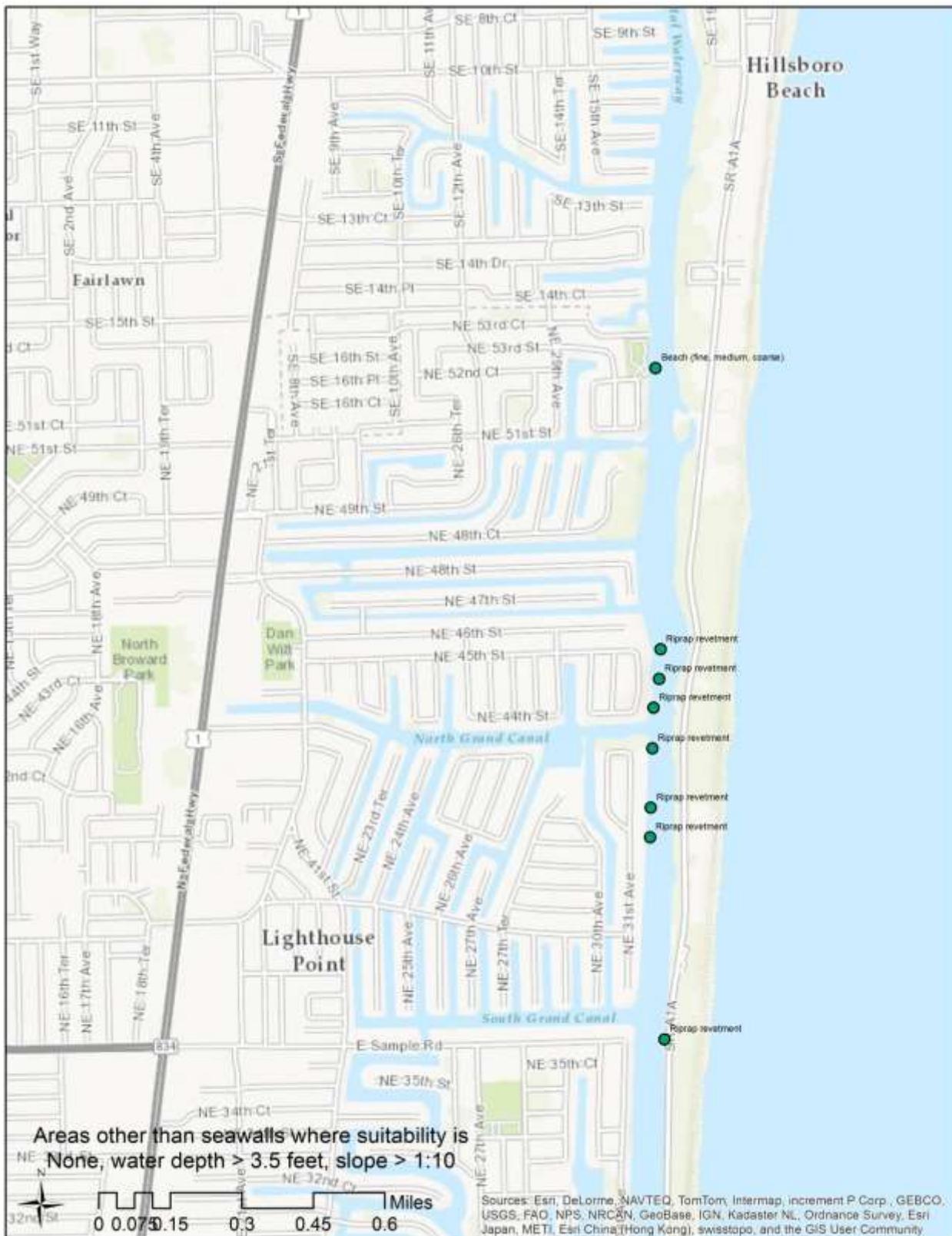


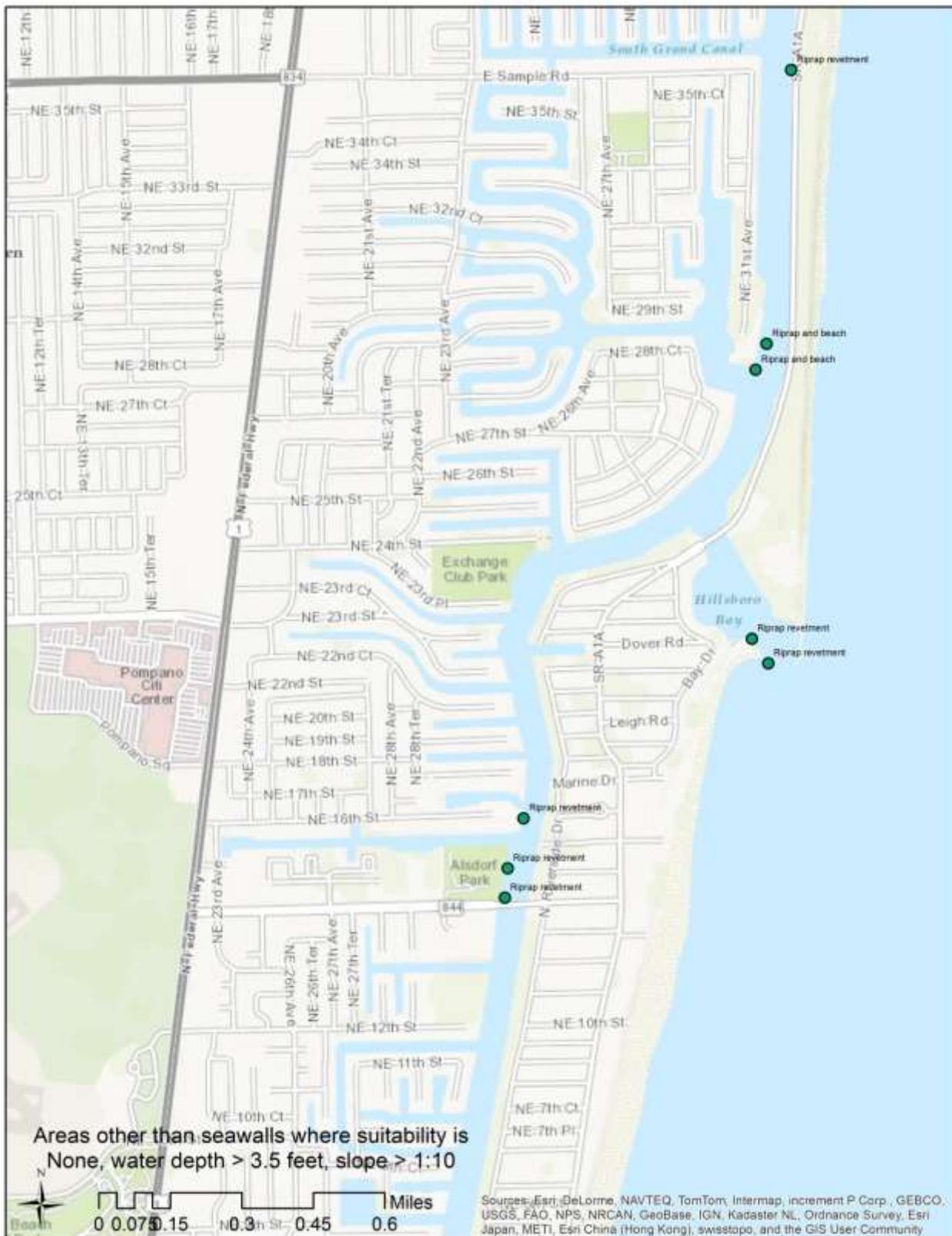




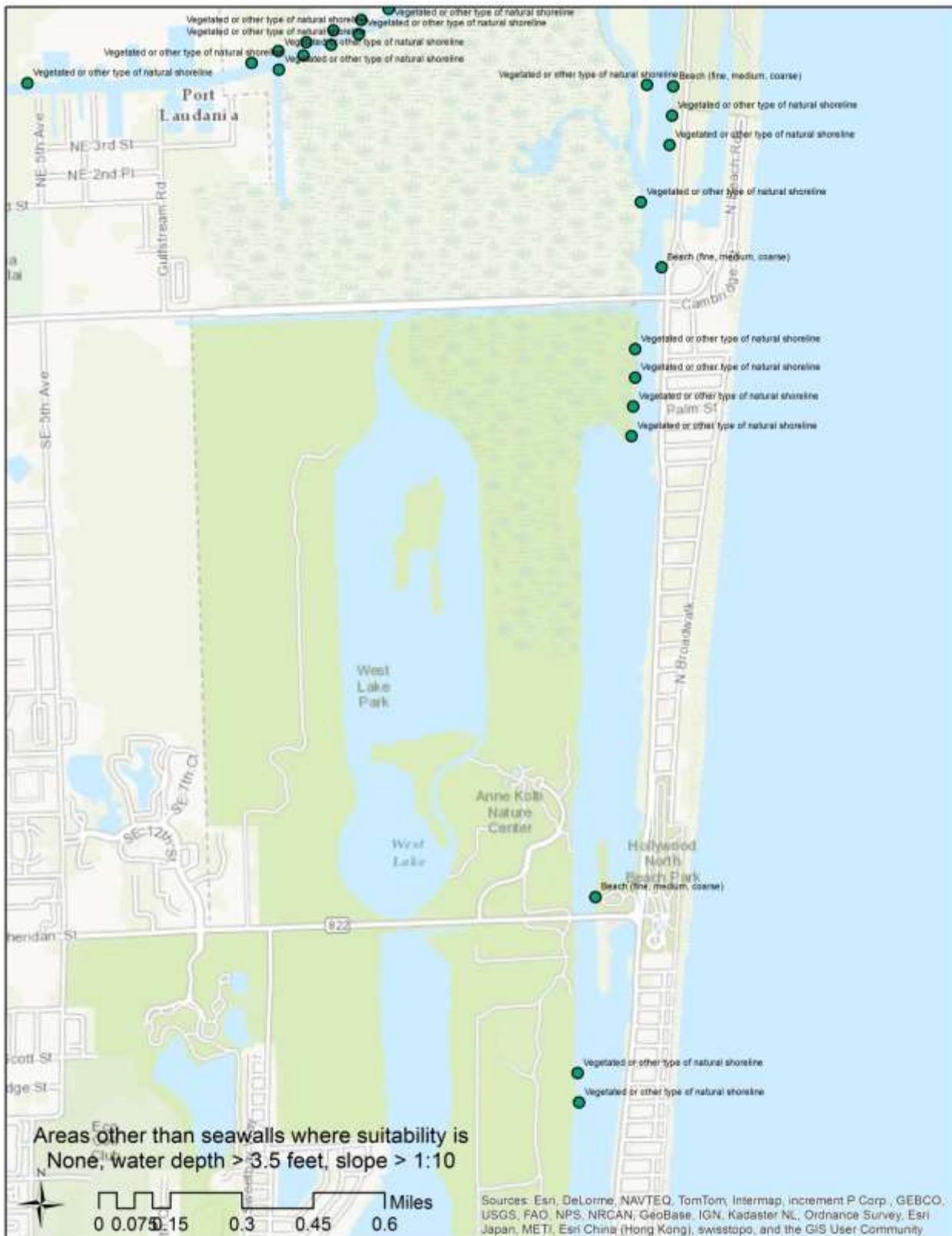


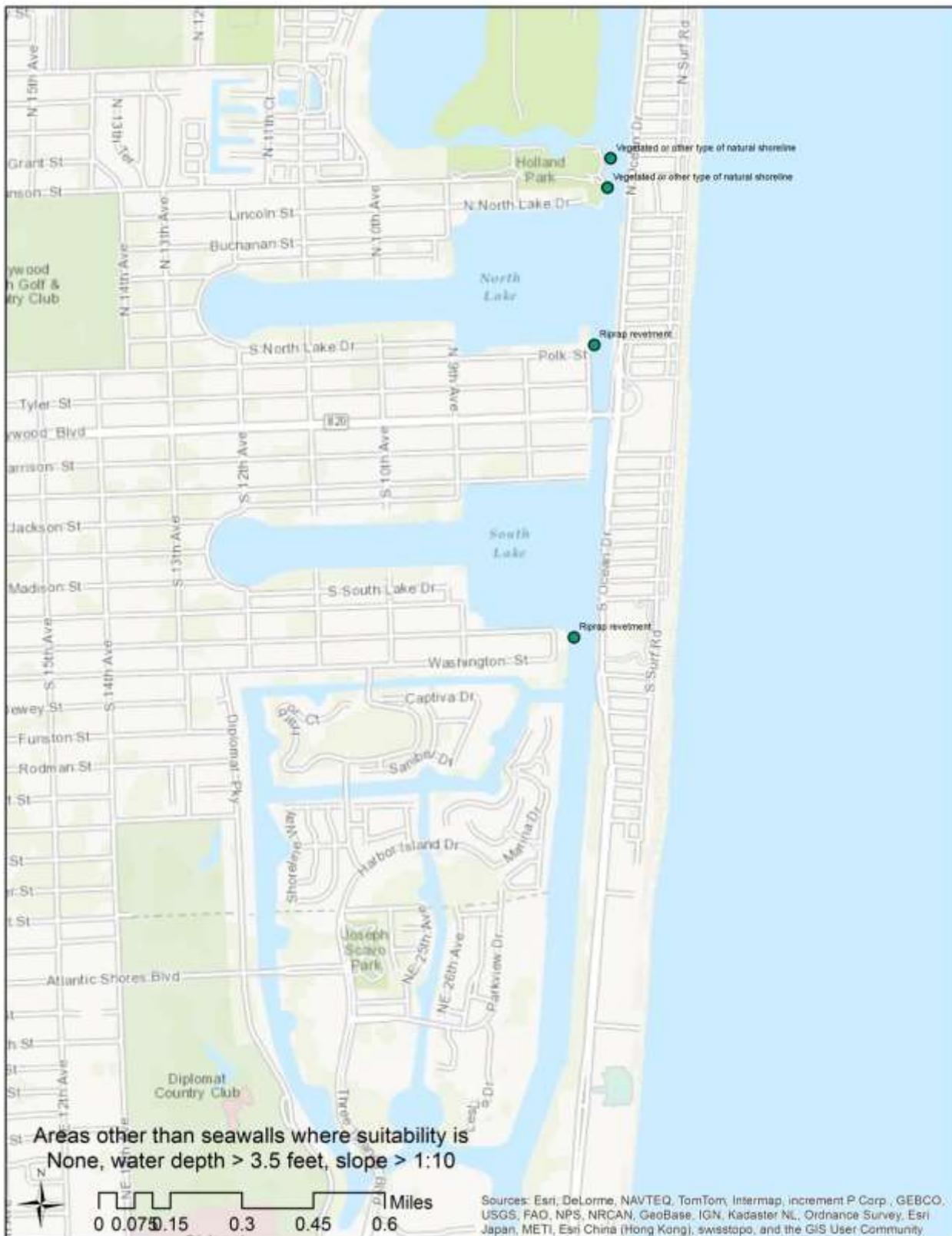


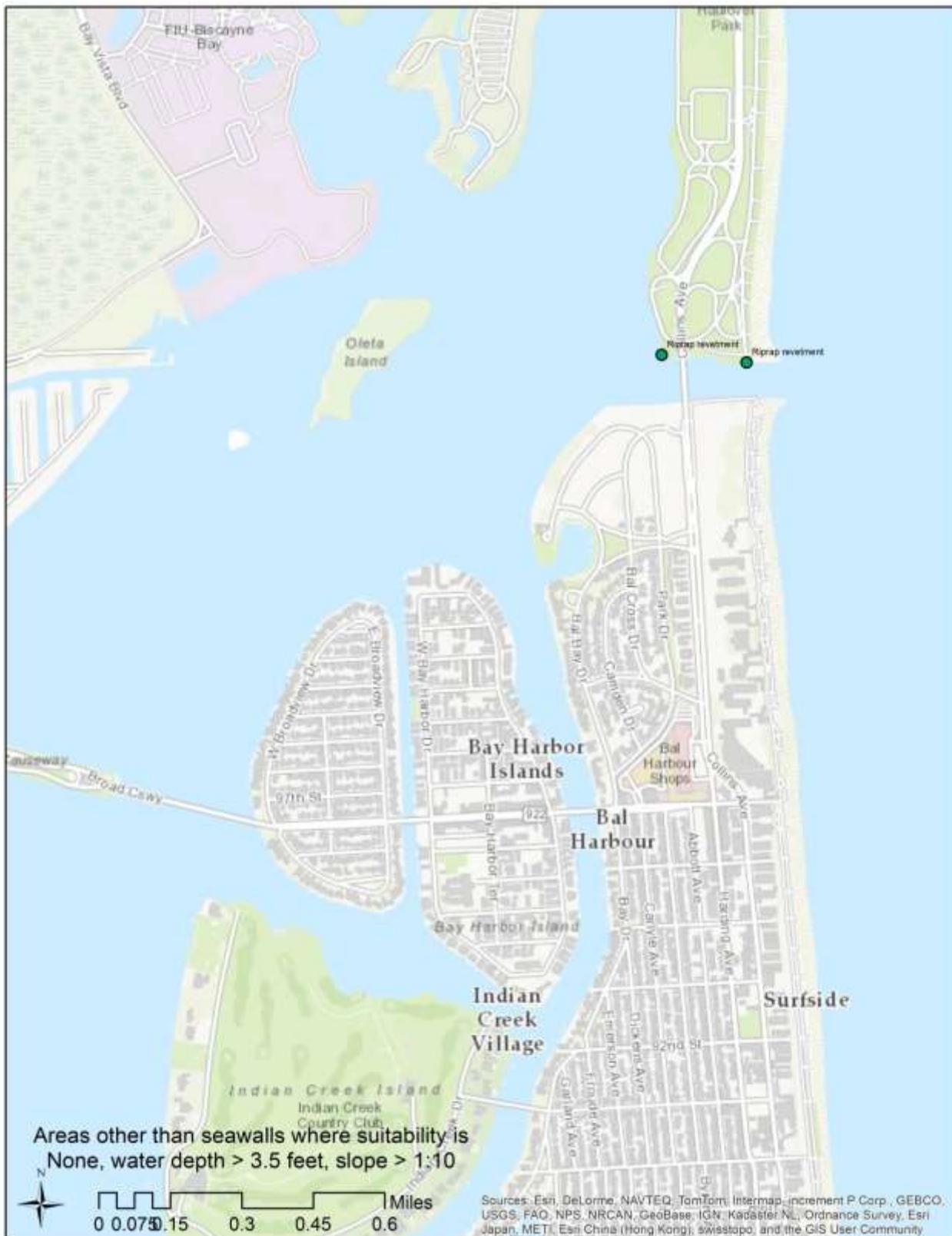












Suitability Analysis for Living Shorelines Development in Southeast Florida's Estuarine Systems



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