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Developing a Shoreline Restoration Suitability Model for North Indian River and Mosquito Lagoon, Phase II

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Developing a Shoreline Restoration Suitability Model for North Indian River and Mosquito Lagoon, Phase II

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1. EXECUTIVE SUMMARY

This project successfully created a living shoreline restoration prioritization model and a mangrove hydrodynamic habitat suitability model for 180 miles of estuarine shorelines in Mosquito Lagoon and northern Indian River. Shoreline model data are available for direct download as a spatial dataset (https://stars.library.ucf.edu/shorelines/), or for online viewing in a GIS storymap: (https://ucfonline.maps.arcgis.com/apps/MapSeries/index.html?appid=45caa29e80e6441c8bf6f75c542860af).

New empirical wave data were created through hydrodynamic modeling. Frequency analysis was applied to characterize wave climate in study area shorelines. Wind-wave measurements observed in the field validated that actual wave heights above 2 cm were well represented by the model. Modelled hydrodynamic data were combined with shoreline data (collected in the field during the project Phase I) to develop fundamental knowledge regarding hydrodynamic habitat suitability of IRL shoreline species. Through this analysis, strong relationships between mangrove presence and wind wave hydrodynamics were illuminated, such that the probability of mangrove persistence was predicted at the project site scale based on wave climate. Additionally, the influential role of site intertidal slope and its interaction with site hydrodynamics was confirmed. This is a transformative source of information from the perspective of Planning, Design and Engineering (PD&E) of shoreline stabilization projects and regional-scale restoration planning.

Mangroves were found on shorelines with overall lower incoming wave height distributions as compared to shorelines without mangrove vegetation. Mangrove presence became less likely as wave height increased, suggesting that there is a critical wave magnitude-frequency combination above which it is increasingly unlikely that mangrove vegetation will persist. Where wave heights exceeded 5 cm 20% of time, there was over an 80% chance of mangrove persistence. Where wave heights were 8 cm 20% of time, chance of mangrove persistence dropped to 50%. Where wave heights were over 15 cm 20% of time, there was less than 10% chance of mangrove persistence.

While wave climate was found to explain the greatest variance within a generalized linear model of mangrove distribution, the influence of shoreline slope was also found to be significant. Low shoreline intertidal slopes were found to increase the threshold wave climate mangroves can survive. For example, the 80th percentile wave height associated with 50% probability of mangrove survival was 8 cm when slope was 0.2, increased to 9 cm when slope was lower than 0.2, and decreased to 4 cm when slope was greater.

The presence of oysters or seagrasses at the shoreline were also correlated with wave height; however, conditions within the project area were insufficient to create robust hydrodynamic habitat thresholds for these important coastal ecosystem engineers. There are therefore future research opportunities to apply frameworks developed herein to broader study areas, which will potentially lead to discovery of flow-ecology relationships for a more diverse suite of coastal ecosystem engineers.

All study shorelines were classified within a prioritization model according to need and urgency of stabilization. Shoreline sites classified in Urgent need (18% of study shoreline) should be triaged for immediate stabilization. Shoreline sites classified as Priority (10% of study shoreline) will eventually move to the Urgent category without intervention. Shorelines classified as Vulnerable (6% of study shorelines) are sites for pre-emptive restoration. Sites within the Wetland category (38% of study shorelines) do not need to be restored at this time and can serve as reference sites for living shoreline stabilization. Shorelines with hard armoring (28% of study shorelines) may represent opportunities to increase long-term shoreline resilience or restore shoreline ecotone functionality. Analysis of Hardened shorelines in context of local wave climate and slope indicate that many hardened shorelines in the project study area may not actually require armoring. Living shoreline containing mangrove forest could be expected to stabilize many currently hardened shorelines.

All study shorelines were classified according to likelihood of mangrove persistence based on hydrodynamic habitat suitability. Within the study area, 68% of the shoreline was characterized by 50% or greater probability of mangrove persistence. At the site scale, likelihood of mangrove persistence can also be increased by design of an equilibrium shoreline slope, adding elasticity to stabilization site designs in areas that are on the borderline of mangrove hydrodynamic habitat suitability. Severe erosion was three times more likely to be observed on shorelines without mangrove vegetation, where over 60% of sites had escarpment heights greater than 30 cm. Similarly, shorelines with mangrove were more than two times as likely to be characterized by no to low levels of erosion.

Managers and practitioners within and outside of the direct project area can benefit from this work. First, the actual hydrodynamic habitat thresholds for mangrove discovered in this study can be transferred to other locations within and outside of the Indian River Lagoon system. Locations throughout Florida that fit within the mangrove temperature, salinity and hydrology habitat zones may apply the hydrodynamic habitat knowledge developed herein to site-scale project planning. Second, the synergy between regional-scale project prioritization data and site-scale habitat suitability design tools demonstrated in this project can be a framework for future restoration planning efforts. Provision of information both at a broad geographic scale for use in regional planning, and making the information sufficiently detailed such that it can be applied at the site scale can help managers and practitioners understand when and where restoration is needed, and also the appropriateness of nature-based or green-grey hybrid designs on a site-by-site basis. Widespread investment in this type of information, and dedicated strategies to adopt such information in project PD&E may increase restoration success and impact on a regional scale.

2. Project Background and Justification

Situated at the interface of aquatic and terrestrial environments, the estuarine shoreline ecotone is a hotspot zone of ecosystem services, beneficial for both lagoon and human health. Natural and human communities also overlap along shorelines of developed estuaries in Florida, making shorelines one of the most degraded and altered coastal habitats. In the Indian River Lagoon system, alteration of shorelines has been extensive and includes impounding, filling, hard-armoring, modified hydrology, and introduction of non-native species. For example, detailed field assessment of 375 miles of IRL shorelines along navigational channels from Ponce de Leon to Sebastian Inlets found that 95% of evaluated shorelines had been modified by human activity (Donnelly et al. 2018). Over 50% of the shoreline was hard-armored, and 45% of the remaining shoreline had been artificially steepened, often leading to severely eroded escarpments where non-native plants *Schinus terebinthifolius* (Brazilian pepper) and *Casuarina equisetifolia* (Australian pine) replaced native vegetation. Only 5% of evaluated shorelines met the classification of wetland shoreline, with native hydrophytic vegetation and an equilibrium slope.

The lost potential of the IRL shoreline ecotone has innumerable impacts to lagoon water quality, biodiversity, and the security of coastal communities. The wetland zone at the shoreline provides outsized ecosystem services, vastly exceeding the actual area occupied by the shoreline ecotone. Rates of biogeochemical transformation are particularly high within the shoreline ecotone (McClain et al. 2003, Vidon and Hill, 2004) and in nearshore features such as oyster reefs (Chambers et al. 2018), which constitute 'hot spots' for processes vital to lagoon water quality, including denitrification. Denitrification rates are closely tied to both hydrology and sequestration of carbon within wetland soils (Bernard-Jannin et al. 2017, Dosskey et al. 2010). Shoreline morphology (e.g. slope) directly controls hydrology, and thereby width of the ecotone, which is created by shifting periods of saturation (during high tides, high seasonal water levels) and drying. For instance, the same water level regime imposed on shorelines with low and high gradients will produce respectively wide and narrow shoreline ecotones. Chronically over-steepened shoreline (as documented in IRL) limit zones for key biogeochemical transformations (Bernard-Jannin et al. 2017) or development of habitats to support lagoon biodiversity. In addition, steep shoreline slopes above the equilibrium gradient (i.e. the slope that can be maintained under the prevailing sediment and hydrodynamic transport regime) are also susceptible to erosion and collapse, particularly when vegetation is removed, by humans or bank erosion.

Functional wetland shoreline ecotones are a necessary precondition for coastal ecosystem adjustments in the face of climatic and sea level changes (Erwin 2009). Wetland shorelines with emergent vegetation and nearshore habitats with oyster reefs and submerged vegetation retain sediments and organic matter more efficiently than nearby areas that lack these features (Kibler et al. 2019; Kitsikoudis et al. 2020; Chambers et al. 2018). These coastal features are not only important storage zones for carbon, but also allow shorelines to better maintain position as sea levels rise. The Florida Fish and Wildlife Conservation Commission's State Wildlife Action Plan (2019) has identified shoreline hardening as a major threat to coastal habitats and cited the development and application of living shoreline methods as a way to reverse this threat. Hard-armored shorelines often lack diversity, whereas natural and stabilized "living shorelines" provide structural complexity and support high levels of biodiversity. As resources are increasingly allocated to restore degraded shoreline habitats, restoration practitioners are in need of information to guide restoration planning, as well as site-level project design and engineering.

Data-driven tools for restoration site prioritization are often a primary need for environmental management communities. Prioritization provides a good starting point from the perspective of restoration planning, answering the questions of where and when shoreline stabilization resources should be dedicated based on ranked urgency within a regional portfolio of shorelines. However, prioritization does not address the next logical question practitioners have: How? How should a particular site be stabilized or restored? Which species and stabilization designs are likely to be robust to a site's unique hydrodynamic and geomorphic conditions? Because this question links directly to project success, understanding habitat suitability for species utilized in coastal resilience strategies is a critical component to effective shoreline management, successful habitat restoration efforts, and appropriate coastal development.

Though broadly recognized as an influential part of overall habitat suitability, hydrodynamic habitat suitability for shoreline species is often poorly understood and therefore difficult to apply in the context of restoration design. Hydrodynamic habitat suitability describes the range and frequency of occurrence of hydrodynamic variables (e.g. water depth, current speed, wave height) to which a given species is adapted. A particular species will persist and be competitive within a specific hydrodynamic niche. Where hydrodynamic conditions exceed the ecological thresholds of a given species, the organism will fail to persist. When organisms are utilized as ecosystem engineers in green infrastructure designs, such as living shoreline stabilizations, projects must be designed to match site conditions with organisms likely to be robust to the range and frequency of hydrodynamic forces characterized at the site scale. This is often a challenging task for restoration practitioners, as both pieces of information needed (species' habitat thresholds and site-scale hydrodynamic characterization) may be unknown. However, failure of the environmental management community to mandate the implementation of robust designs will inevitably lead to some level of unsuccessful restoration efforts. While it is unrealistic to expect that every project will be successful and high-impact, the restoration and management community recognizes that unsuccessful restoration efforts damage restoration capital, including the public trust in restoration efficacy. Thus, design tools that may broadly increase the success and impact of restoration efforts (for instance, regional hydrodynamic characterizations combined with ecological thresholds for species commonly used as ecosystem engineers), are timely. This project was undertaken with the objective of demonstrating the potential synergy of combined prioritization and hydrodynamic design information that can be delivered at a broad regional scale, but is also sufficiently granular to apply to the Planning, Design and Engineering (PD&E) of individual projects at the site scale.

3. Research Objectives and Project Task breakdown

The project goal was to create a living shoreline restoration prioritization and suitability model for 125 miles of estuarine shorelines in Mosquito Lagoon and northern Indian River (Figure 1). The final shoreline map included 180 miles of shoreline. To reach this goal, three research objectives were fulfilled: (1) create new empirical data regarding wave erosion hazards in the study area, (2) develop fundamental knowledge regarding hydrodynamic habitats of IRL shoreline species, and (3) integrate new data/knowledge with shoreline data collected during project Phase I to create comprehensive restoration suitability models in the study area (Table 1).

Table 1: Outline of project tasks, research objectives, and deliverables.

Task	**Research objective**	**Deliverables**
TASK 1. Quarterly Progress Reports	Project Administration and Reporting	Quarterly Progress Reports
TASK 2. Wave Modeling for Shoreline Assessment	Create new empirical data regarding wave erosion hazards along 125 miles of shoreline of the Mosquito Lagoon and northern Indian River.	Quantitative characterization of wave height and frequency of occurrence every 70 m of shoreline along 180 miles of shoreline of the Mosquito Lagoon and northern Indian River
TASK 3. Shoreline Vulnerability Assessment	Create fundamental knowledge regarding hydrodynamic habitat limits of IRL shoreline species.	Quantitative hydrodynamic habitat suitability thresholds for shoreline species
TASK 4. Comprehensive Shoreline Restoration Suitability Model	Create a comprehensive restoration suitability model to prioritize sites for stabilization and suggest suitability for shoreline species along 125 miles of shoreline of the Mosquito Lagoon and northern Indian River.	For 125 miles of shoreline in Mosquito Lagoon and northern Indian River: - Final restoration prioritization model - Final hydrodynamic habitat suitability model
TASK 5. Data Management	All project data are QA/QC'd, and access is provided via UCF's STARS Repository.	Data summary and link to file location access through the UCF STARS Repository
TASK 6. Project Administration and Final Report	Project Administration and Reporting	Project Final Report

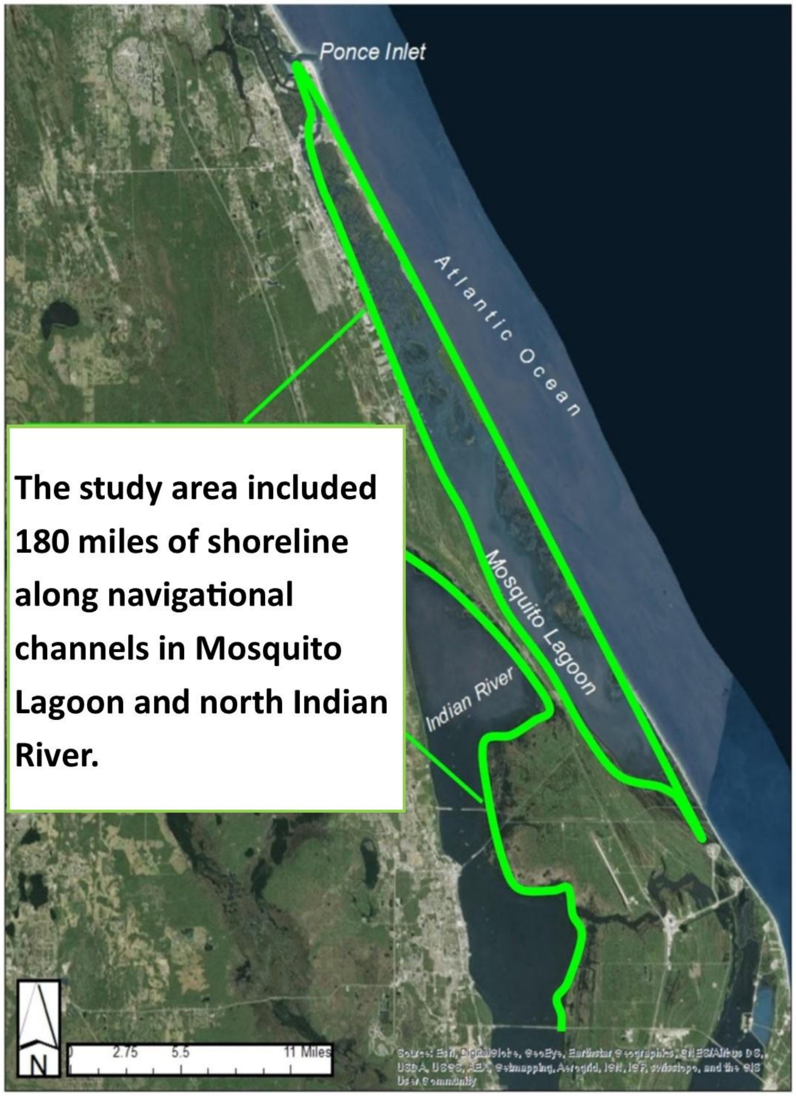


Figure 1: Project study area.

4. Research Activities and Results

4.1. Research Objective 1: Hydrodynamic modeling along study shorelines

A High-Performance Computing Cluster was used to run the Simulating WAves Nearshore (SWAN) model across the study area at a 70 m resolution. The SWAN model, developed by Delft University of Technology, uses input bathymetry, wind, and current data to model nearshore wave heights by solving the wave action balance equation, which accounts for non-linear wave-wave interactions, white-capping, bottom friction, and depth induced wave breaking (Booij, et al. 1999; Ris, et al. 1999). Mosquito Lagoon is a particularly challenging modeling environment for SWAN, due to the heterogeneity of habitats found in the lagoon. North Mosquito Lagoon is less of an open water body and more of a system of channels running through vegetated islands. In order to obtain accurate wave heights, these islands must be represented within the modeling domain. To address this concern, the precise borders of the lagoon shorelines and all vegetated islands were delineated based on 2017 imagery (Figure 2). Lagoon water levels were estimated based on records collected at the Haulover Canal gauge (USGS 02248380, 2010-2018) and integrated with bathymetry (NOAA National Centers for Environmental Information (NCEI), with resolution of 1/9 arc-second) to estimate appropriate water depths within the model domain. Based on statistical analysis, median water level observed at Haulover Canal gauge is -0.47 ft relative to the North American Vertical Datum (NAVD), 90th percentile is 0.06 ft NAVD, and mean water level is -0.448 ft NAVD.

Two-dimensional stationary wave modelling was performed assuming negligible current influence and uniform wind forcing across the model domain. Historic reanalysis wind data (1979 - 2018) were obtained from the North American Land Data Assimilation System (NLDAS) at a temporal and spatial resolution of 1 hour and 0.125°, respectively. Frequency analysis of wind data revealed little spatial variation in wind speeds (mean: 4 m/s; max: 12 m/s) and directions throughout northern IRL (Figure 3), promoting the use of a uniform, spatially-averaged wind field to model waves within the study area. The SWAN model was run in stationary mode with 70 m rectangular grid spacing using each possible combination of observed integer windspeed (1 – 12 m/s) and direction (0-360°; 20° increments) for a total of 216 model scenarios. Finally, modeled wave heights for each scenario were integrated with wind speed/direction probability distributions compiled across the 40-year wind data record, producing cumulative probability estimates of wave occurrence at each grid point (Figure 4).

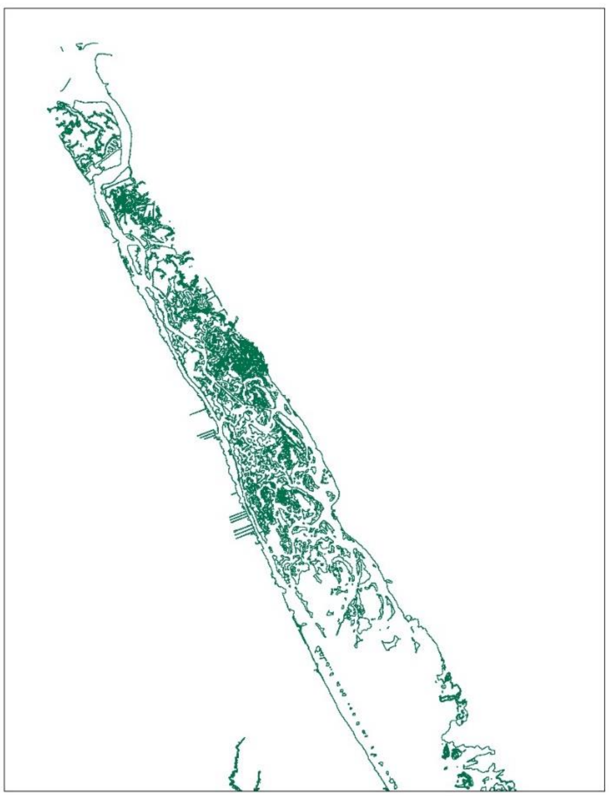


Figure 2. Detailed shoreline for modelling domain in Mosquito Lagoon.

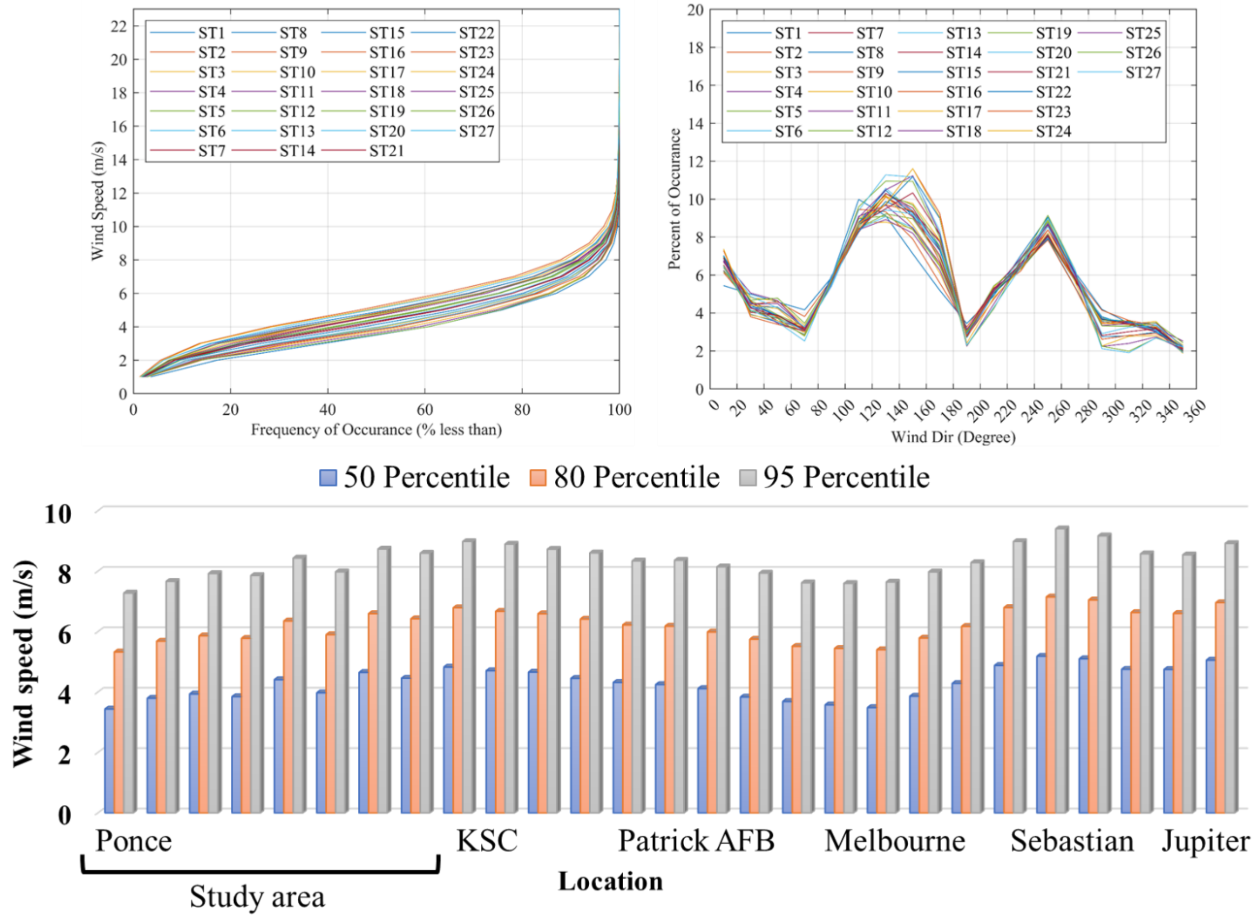


Figure 3. Wind speed and direction frequency distributions from Ponce de Leon Inlet (ST1) to Jupiter Inlet (ST27). Distributions of wind speed and direction vary little over the study area and IRL in general.

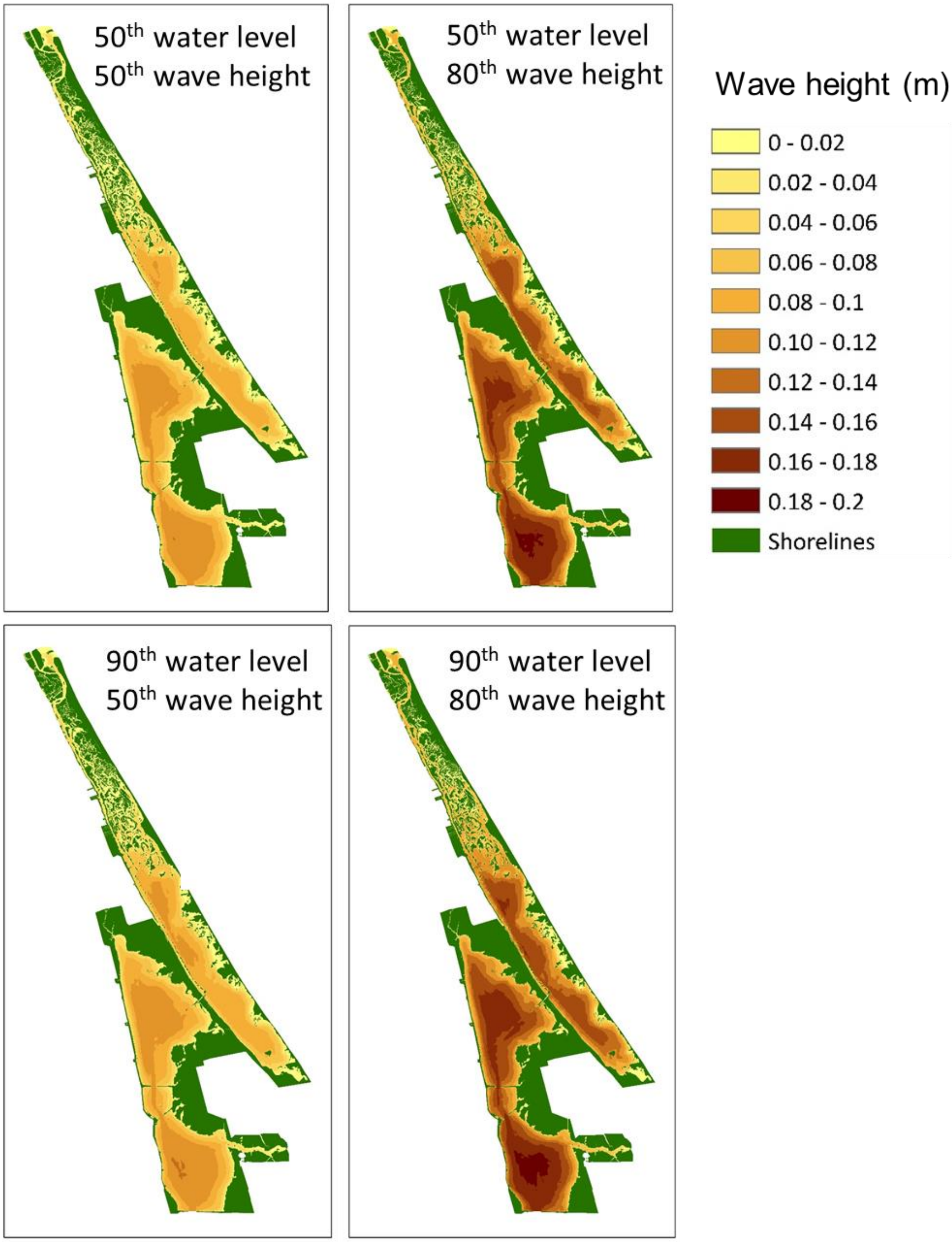


Figure 4. Modelled wave heights over the study area: 50th and 80th percentile wave heights in meters, modelled with 50th and 90th percentile water levels.

4.1.1. Model validation

Coupled wind-wave data were collected in two locations (on Merritt Island, Indian River Lagoon, and in Canaveral National Seashore, Mosquito Lagoon) and used to validate model performance. The equipment at each station consisted of wave sensors (Ocean Systems) positioned above the water surface that measure water surface deformation (wave height) at a frequency of

32 Hz (Figure 5). Windspeed and direction were simultaneously recorded using marine-grade anemometers and wind vanes.

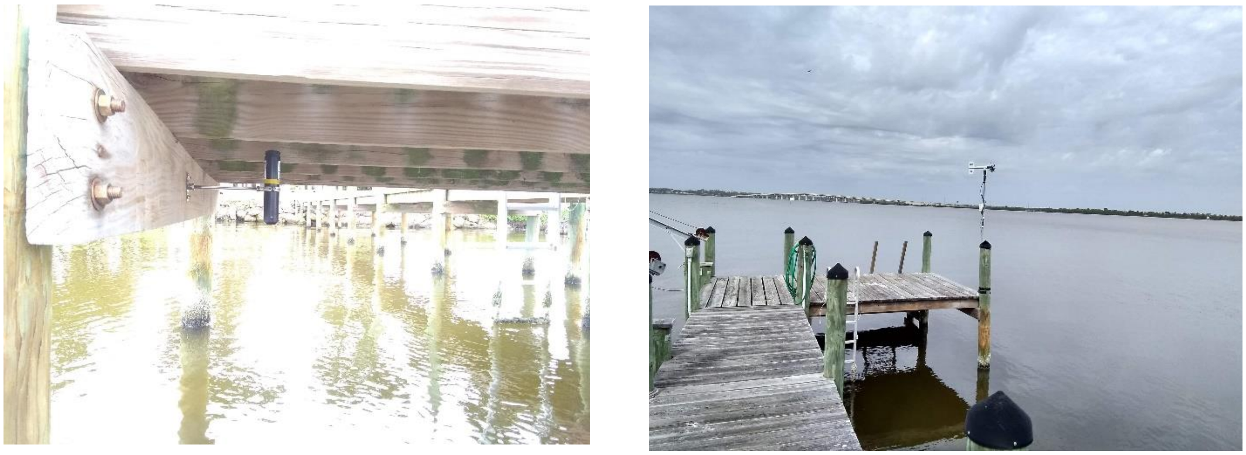


Figure 5. Two coupled wind-wave monitoring stations were established to validate model results.

Raw surface fluctuations were used to estimate significant wave heights (H_s) following Holthuijsen (2007), where $H_s = 4\sigma_s$ and σ_s is standard deviation of surface elevations calculated using 5 minute measurement windows with 50% overlap. Time series of hourly mean and maximum wave heights were used to generate observed wave distributions at the monitoring station, allowing for direct comparison with co-located SWAN modelled wave distributions (Figure 6). Estimated cumulative distribution functions (CDFs) for observed and modelled waves were poorly matched below the 50th percentile (CDF $\leq$ 0.50), indicating that the model underpredicted waves when actual wave heights were below 2 cm. Such poor characterization of very low waves is typical behavior for hydrodynamic models, where precision of 2 cm is standard. However, when actual wave heights exceeded 2 cm, model predictive skill was greater. Within the upper 20% of the distribution (0.80 $\leq$ CDF $\leq$ 0.99), waves were well represented by the model, with modelled results falling within the 95% CI of the hourly maximum wave height distributions.

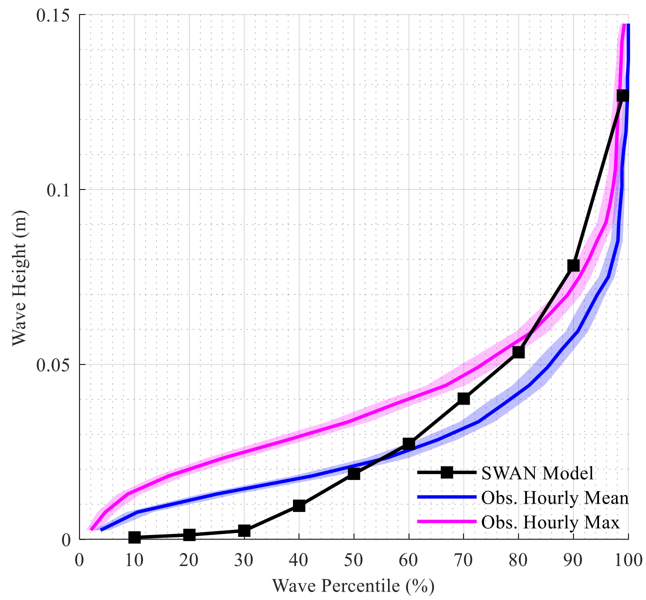


Figure 6: Empirical cumulative density functions (CDF) of hourly mean (blue) and maximum (magenta) wave heights as observed at the CANA field station, as compared to modelled wave heights (black) in same location. Shaded regions represent bootstrapped 95% confidence intervals for observed CDFs.

4.2. Research Objective 2: Hydrodynamic habitat suitability for IRL shoreline species

To address the second research objective, study sites were selected from the full set of shoreline survey data (described in detail in Donnelly et al. 2018) for observational experiments querying the hydrodynamic impact of waves on distributions of shoreline species, including mangrove, oyster, and seagrasses. Study sites with no hard armoring in the intertidal zone, with low risk of boat wake incidence, and with locations far (> 50 m) from intertidal oyster reefs were included in the study. Sites with high boat wake risk or within proximity to intertidal oyster reefs were excluded, as the hydrodynamic signatures of such sites may not be reasonably represented in the output of wind wave models.

In estuaries and other fetch-limited water bodies where wind waves are generally small, boat wakes can play a significant role in driving near-shore hydrodynamics (Anderson 1974; Bauer et al, 2002; Parnell et al 2007). In the current study, a boat wake hazard index was developed to account for both the frequency and magnitude of boat wakes incidence along the shoreline. Wake frequency was estimated using direct boat traffic observations where available (Sidman et al., 2007), which were extended to regions without direct traffic observations (i.e. north Mosquito Lagoon, Volusia County) using observed correlations between boat traffic and bathymetry and the locations of known boating channels. Potential boat wake magnitudes were inferred from speed regulations in the waterway (i.e. no wake zones). Wake magnitude and frequency were combined to develop a composite risk factor (RI_w) for each 70 m cell in the modelling domain. Each parameter was weighted equally to account for low frequency, extreme magnitude events as well as high frequency, moderate magnitude events (Wolman and Miller 1960). A cumulative boat wake hazard index ($BWHI = \sum_{l=0}^{n} RI_w/d$) was calculated for each shoreline site by integrating the composite risk along a perpendicular shoreline transect using a distance decay function ($1/d$), which assumed that the effect of boat wake decreases linearly with distance from the boat (Kofoed-Hanson et al., 1999). Shorelines potentially subjected to high boat wake hazards (17% of sites in study area) were excluded from analysis, as were sites within 50 m of intertidal oyster reefs, which were identified by a 2018 reef mapping survey. The final dataset consisted of shoreline sites without hard armoring, without high risk of boat wake, and far from intertidal oyster reef (Table 2, Figure 7).

Table 2: Sites selected for observational study of mangrove, oyster and seagrass hydrodynamic habitat thresholds.

Biota	**Number of sites**
Sites with mangrove	750
Sites with no mangrove	138
Sites with oyster	231
Sites with no oyster	541
Sites with seagrass	318
Sites with no seagrass	293

4.2.1. Shoreline and hydrodynamic characteristics within study area

Mangrove vegetation was found on shorelines throughout the study area while oyster and seagrasses were largely segregated according to latitude (Figure 7). Shoreline oysters were observed mainly in the northern part of Mosquito Lagoon and seagrasses were mostly found from central Mosquito Lagoon south. There were very few sites in the study area at which both shoreline oysters and seagrasses were found (Figure 7). Wave heights also varied with location in the waterbodies, with overall smaller wave height distributions found in north Mosquito Lagoon, likely due to the low fetch of north Mosquito Lagoon as compared to study areas further south. Areas on the west banks of waterbodies were characterized by greater wave height distributions due to prevailing wind patterns.

4.2.2. Hydrodynamic habitat for mangrove

The presence of shoreline mangrove vegetation was strongly correlated with wave height distribution (Figure 8). Mangroves were found on shorelines with lower incoming wave height distributions (mean ± 95% CI: 7.1 ± 0.2 cm) as compared to shorelines without mangrove (9.2 ± 0.4 cm). Mangroves were observed at 88% of shorelines where the 80th percentile wave height (H_{80}) was less than 4 cm. By contrast, shorelines characterized by large wave height distributions (H_{80} > 12 cm) were associated with a near complete absence (14%) of mangrove vegetation. Although there is considerable overlap in wave distributions of shorelines with and without mangrove (Figure 9), mangrove presence becomes less likely as wave height increases, suggesting that there is a "critical" wave magnitude-frequency combination above which it is increasingly unlikely that mangrove vegetation will persist.

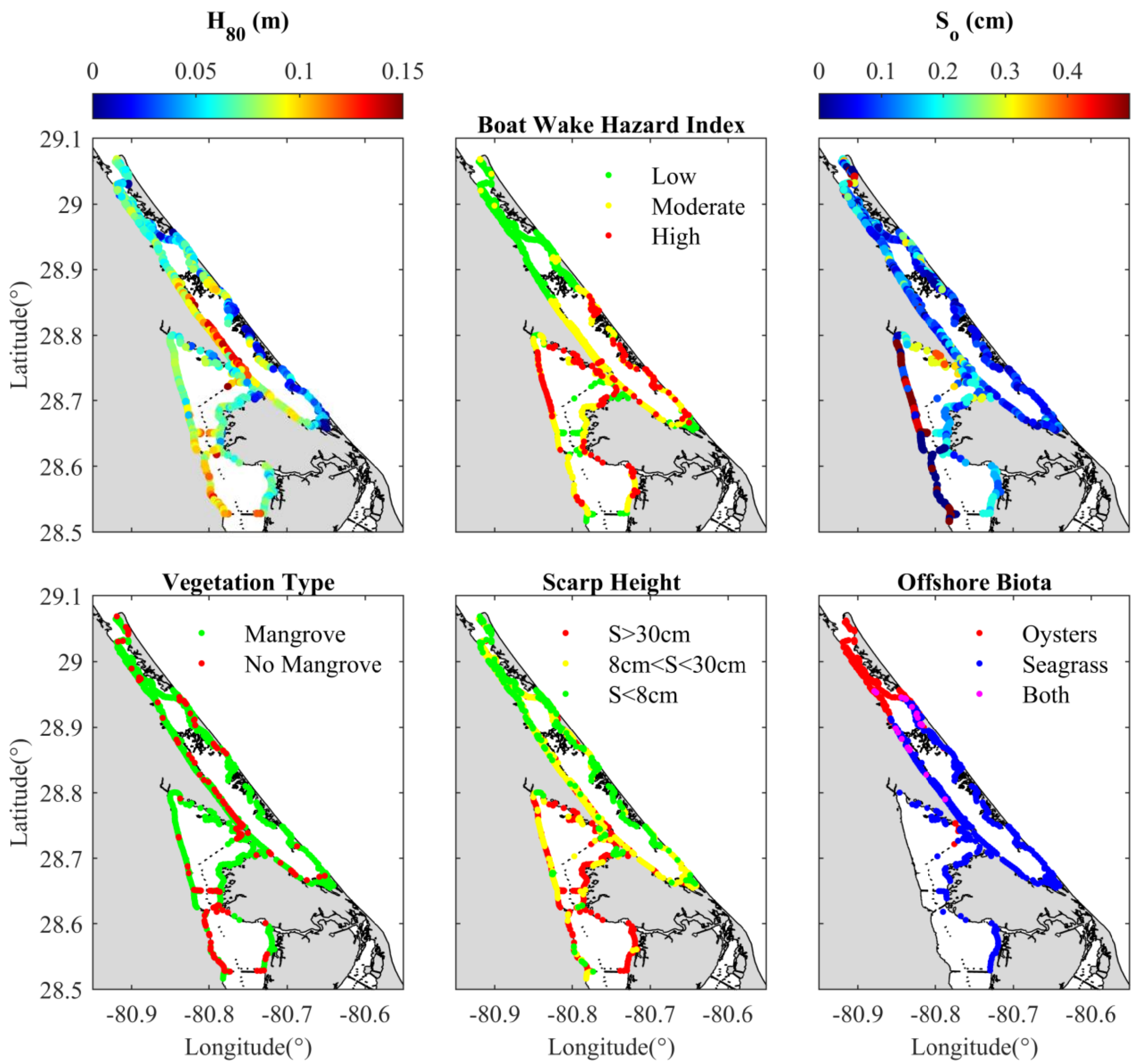


Figure 7: Shoreline characterization within study area: (a) 80th percentile wave height (H_{80}) based on wind-wave modelling, (b) boat wake hazard index, (c) shoreline slope measured across intertidal width (S_o), (d) presence or absence of mangrove observed in intertidal zone, (e) erosion index based on measured scarp height, and (f) presence or absence of oyster and seagrass.

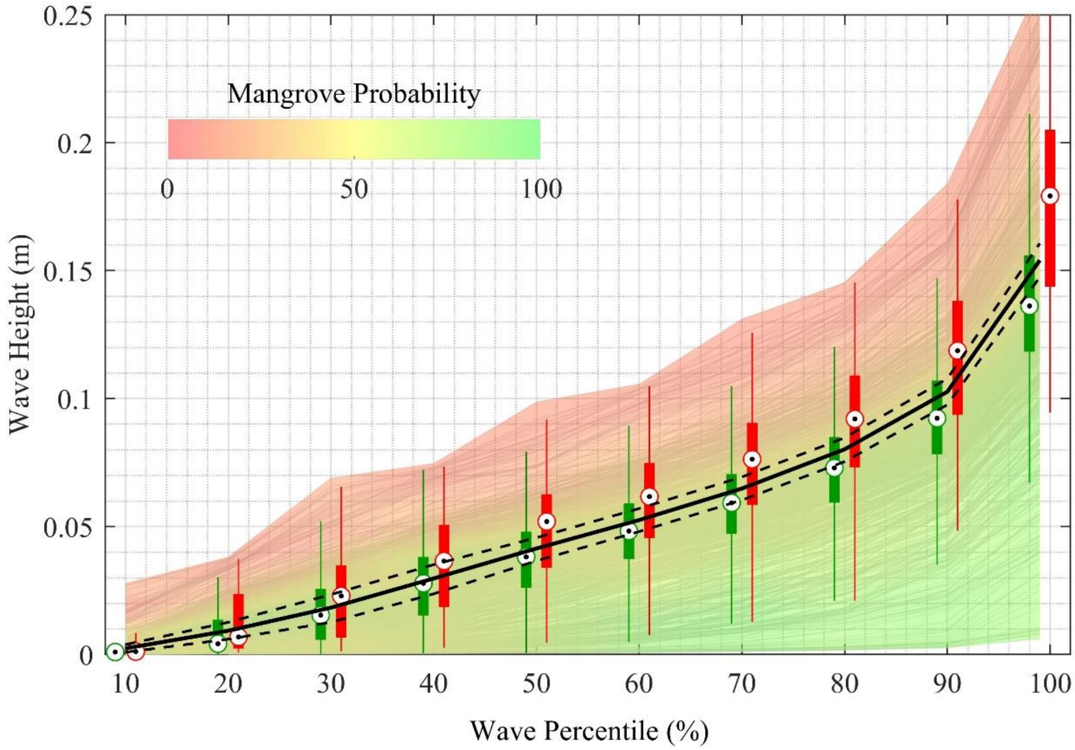


Figure 8: Estimated hydrodynamic wave tolerance of mangrove. Faint gray lines are wave height CDFs modelled at each shoreline site; background shading indicates the weighted probability of mangrove vegetation within each wave height region. Boxplots are wave distributions for mangrove (green) and no mangrove (red) sites at each wave reoccurrence percentile. Black lines represent the 50% logistic threshold (solid: mean; dashed: 95% CI) for mangrove wave height tolerance. Mangroves have less than 50% chance of occurrence at sites with wave heights above this threshold; more than 50% chance of occurring at sites below this threshold.

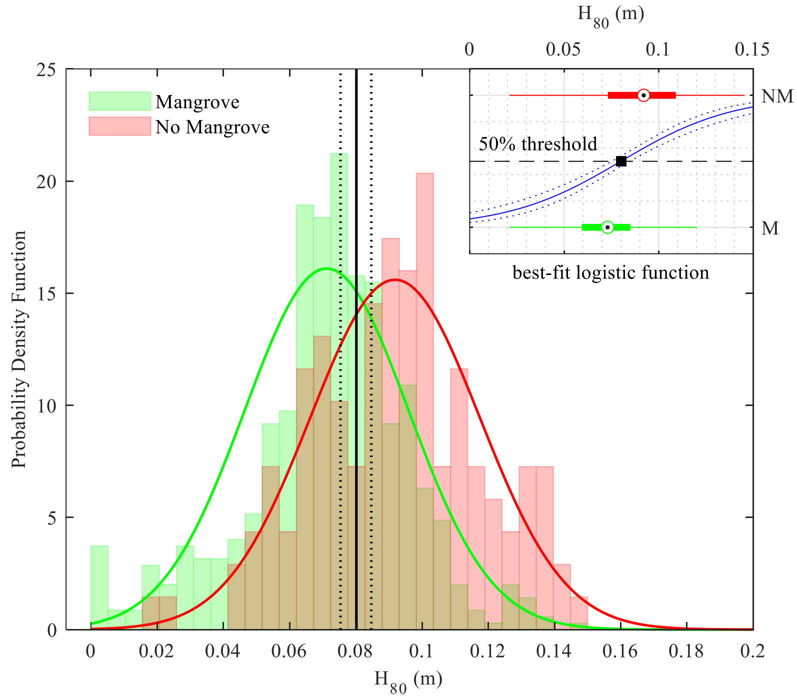


Figure 9: Example of mangrove wave threshold detection using observed vegetation types and modelled wave heights. Raw PDFs of 80th percentile wave heights modelled at shorelines with mangrove (green) and no mangrove (red) are shown overlain with best-fit normal distributions. The wave threshold, estimated using binomial logistic regression (see inlay figure), is shown with a solid vertical line along with estimated 95% confidence intervals (dotted lines).

Using population-weighted univariate logistic regression (Figure 9), the 80th percentile wave threshold at which the probability of mangrove presence was 50% was estimated to be 8.0 ± 0.5cm (Figure 9). This threshold can be interpreted as the 80th percentile wave height at which it is equally likely for a shoreline within the study area to contain mangrove vegetation, or no mangrove vegetation. As H_{80} increases, likelihood of mangrove vegetation persistence decreases (Figure 9). In the same way, as the wave climate becomes milder and H_{80} decreases, mangrove vegetation becomes increasingly likely. Results suggest that mangrove survival is influenced by the wave climate at all recurrence rates (e.g. 10th-99th percentiles), with a median wave threshold of H_{50}^{T50}= 4.2 ± 0.4cm. Critical wave thresholds calculated for all wave recurrence percentiles provide estimates of a critical wave climate (Figure 10a; black line), where mangroves have less than a 50% chance of occurrence at sites with wave heights above this threshold and more than 50% chance of occurring at sites below this threshold. Probability of mangrove vegetation persistence can thereby be predicted at the site scale, based only on the site's hydrodynamic climate (Figure 10b). For instance, this analysis suggests that when wave heights are over 15 cm more than 20% of time, there is less than 10% chance of mangrove persistence. When wave heights are 8 cm 20% of time, there is a 50% chance of mangrove persistence. When wave heights exceed 5 cm 20% of time, there is over an 80% chance of mangrove persistence.

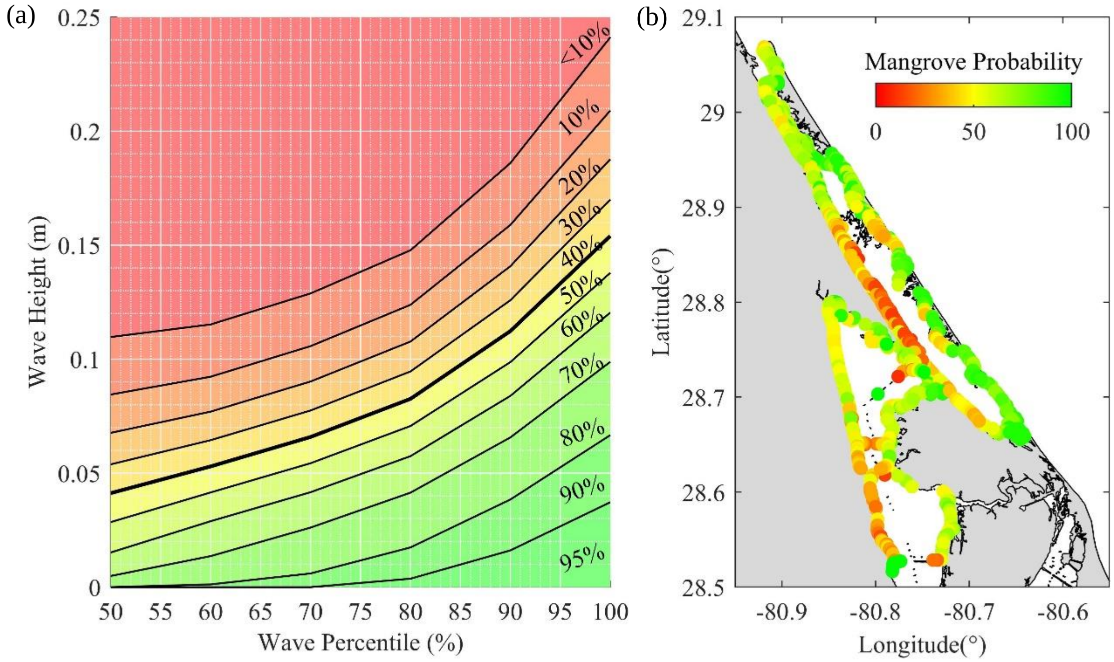


Figure 10: (a) Wave tolerance for mangroves in Indian River Lagoon under 10-95% logistic thresholds. Background shading represents the population-weighted mangrove likelihood. The critical wave climate contour (as shown in Figure 8) is included for reference (bold line). (b) Based on hydrodynamic climate alone, probability of mangrove vegetation persistence can be predicted at the site scale.

4.2.3. Shoreline stability and mangrove habitat

To identify factors correlated with mangrove distribution in the study area, shoreline characteristics (intertidal slope, 80th percentile wind wave height (H_{80}), distance to oyster reef and boat wake risk) were compared at non-hardened shorelines with and without mangroves using a generalized linear model with binomial distribution. Wave height ($p<0.001$), intertidal slope ($p=0.003$), and high levels of boat wake risk ($p<0.001$) were identified as significant factors influencing mangrove presence on shorelines. While wave climate was the most significant predictor of mangrove distribution in the study area, shoreline stability parameters also potentially influenced mangrove distribution. Unlike hydrodynamics, which act as a “top-down” control on mangrove habitat, the direct and indirect influences of shoreline stability are more complicated. Alterations to intertidal slopes can decrease stability of shorelines by changing hydrodynamic and sediment transport processes and extent of intertidal habitat for mangroves and other wetland plants. This is perhaps most evident in the strong correlation between high scarp heights (potentially an indicator of active erosion) and mangrove absence (Figure 11). Severe erosion was significantly more likely to be observed on mangrove-free shorelines, where over 60% of sites had scarp heights greater than 30 cm. In contrast, only 21% of shorelines with mangroves had scarp heights exceeding 30 cm, suggesting that there is a nearly threefold decrease in the probability of severe shoreline erosion when mangroves are present. The inverse was also true, with mangrove presence increasing the likelihood of shoreline erosion being classified as either moderate (mangrove: 45%, vs. no mangrove: 23%) or minor (mangrove: 33%, vs. no mangrove: 15%). This correlation has two related but competing implications: (1) mangroves reduce shoreline erosion through mechanical soil stabilization and/or increased wave attenuation, and (2) the probability of successful mangrove recruitment and survival is diminished along eroded or eroding shorelines. While it is impossible to decouple these effects in the present study, the results have important implications for coastal management and warrant further discussion.

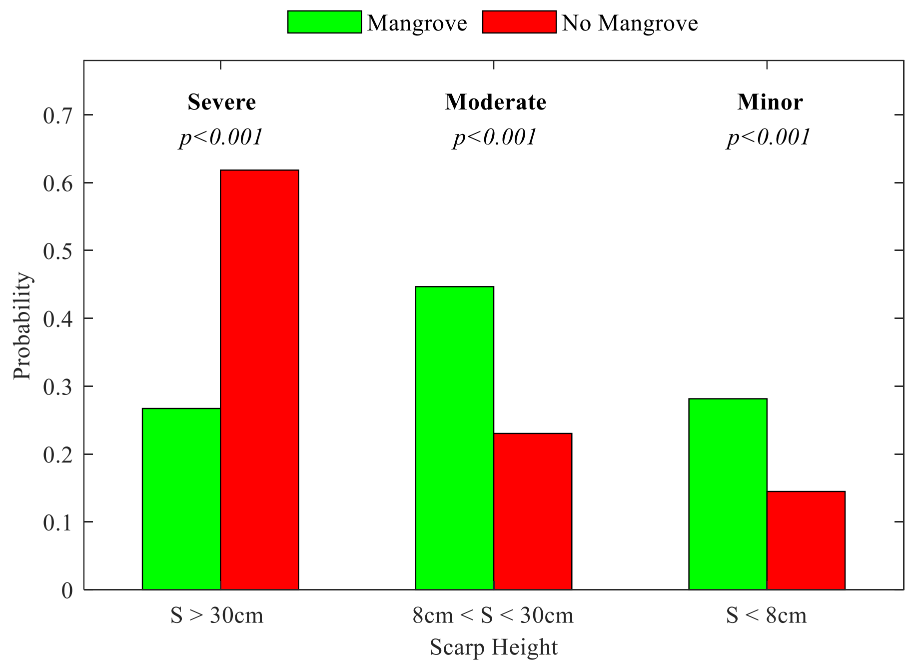


Figure 11: Scarp height probability for sample sites with (green) and without (red) mangroves. The associated erosion category (*severe, moderate,* or *minor*) and within-category χ^2 test p-value are included for reference.

A two-variable logistic function fit to observed shoreline slopes (S_o) and modelled 80th percentile wave heights (H_{80}) suggests that wave heights and shoreline slopes influence mangrove analogously (Figure 12); increases in both parameters reduce the likelihood that mangroves will be observed at a given location. The lowest mangrove probability occurs where wave heights and slopes are high, supporting results of the generalized linear model analysis which identified both wave heights (p<0.001) and intertidal slope (p=0.003) as significant factors for mangrove distribution. While the majority of variance was explained by wave heights alone, addition of the intertidal slope information modified mangrove probability contours slightly. For any given shoreline, ignoring the effect of intertidal slope was likely to result in an overly optimistic mangrove likelihood estimate, reflecting the typical slopes of study shorelines, which were below 0.2. For instance, while a shoreline with an 8 cm H_{80} wave height has a 50% chance of supporting mangroves when S_o<0.2, the probability drops to 30% when the slope increases to 0.5. Following the critical wave-slope threshold represented by the 50% likelihood contour (Figure 8), low shoreline slopes increase the threshold wave climate mangroves can survive (H_{80}^{T50}= 9 cm; S_o= 0) while high slopes decrease the threshold (H_{80}^{T50}= 4 cm; S_o= 1).

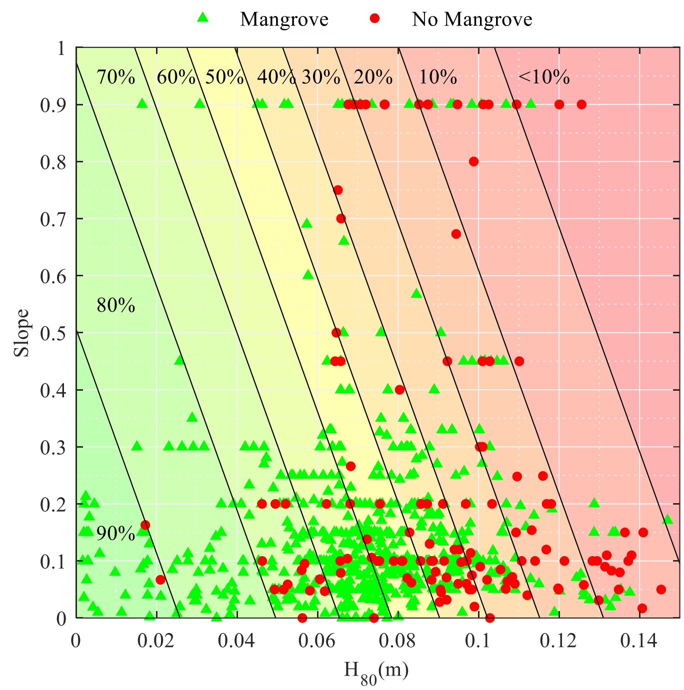


Figure 12: Wave and shoreline slope tolerance for mangroves in Indian River Lagoon under various logistic thresholds (10-90%). Background shading represents the population-weighted likelihood (labeled percentages) that mangroves were observed under combinations of wave height and slope. Observations for shorelines with (green triangle) and without (red circle) mangroves are included for reference.

4.2.4. Hydrodynamic habitat for oyster and seagrass

The presence of oysters or seagrasses at the shoreline were also correlated with wave height (Figure 13 and 14). However, in the case of oyster and seagrasses, the correlations detected do not necessarily indicate causation, due to latitudinal collinearity in wave heights and the distributions of oyster and seagrass. In the study area, oysters on the shoreline are observed primarily in north Mosquito Lagoon, closely associated with where intertidal oyster reefs are found (Figure 7). Places where oyster are found tend to have less energetic wave climate due to limited fetch. Seagrasses are observed further to the south, mainly in locations without oyster, and in areas that have more diverse hydrodynamic signatures. However, it is impossible to conclude that the observed distributions of seagrass or oyster are strongly influenced by hydrodynamics, since the latitudinal segregation of oyster and seagrasses happen to coincide with different wave climates in a manner that confounds the current study approach. Expanding the data set to a broader set of site conditions (for instance, by including information from the entire IRL system) may yield a robust set of hydrodynamic thresholds for oyster and seagrasses, similar to what is possible for mangrove.

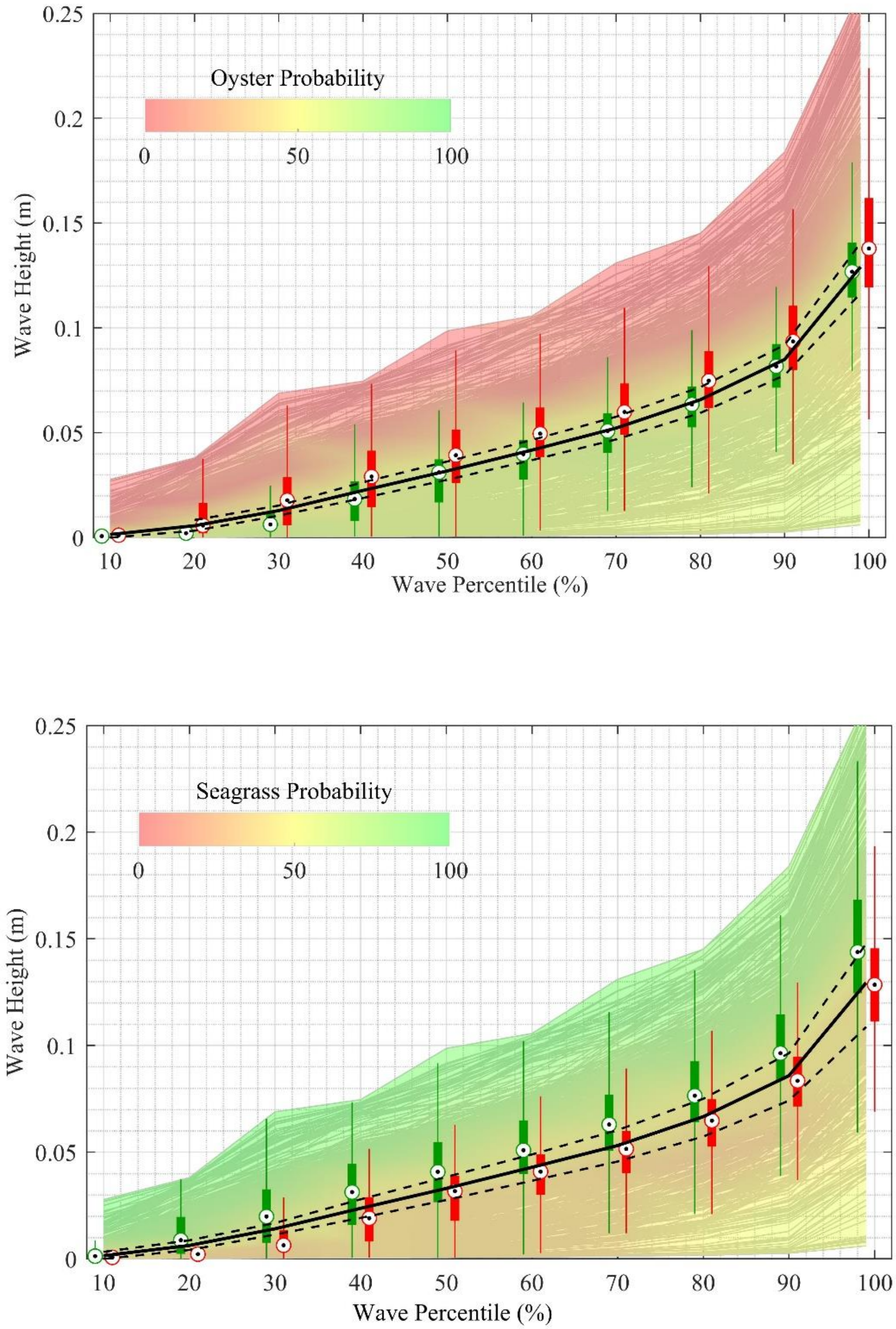
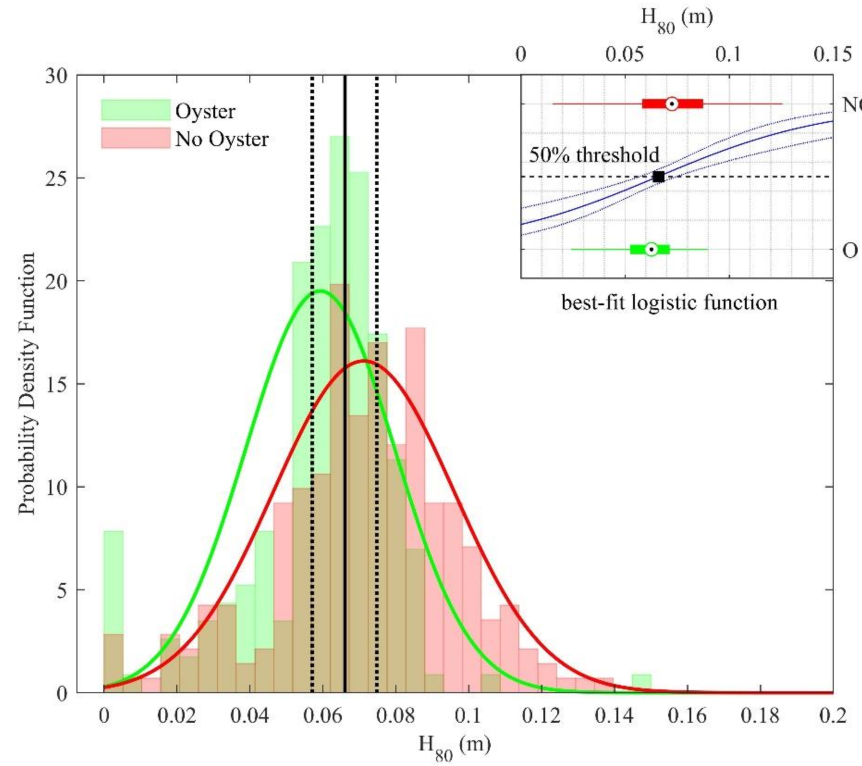


Figure 13: Distributions of oyster and seagrass with wave height. Faint gray lines are wave height CDFs modelled at each shoreline site; background shading indicates the weighted probability of biota within each wave height region. Boxplots are wave distributions for sites with oyster/seagrasses (green) and no oyster/seagrass (red) at each wave reoccurrence percentile. Black lines represent the 50% logistic threshold (solid: mean; dashed: 95% CI) for wave height.



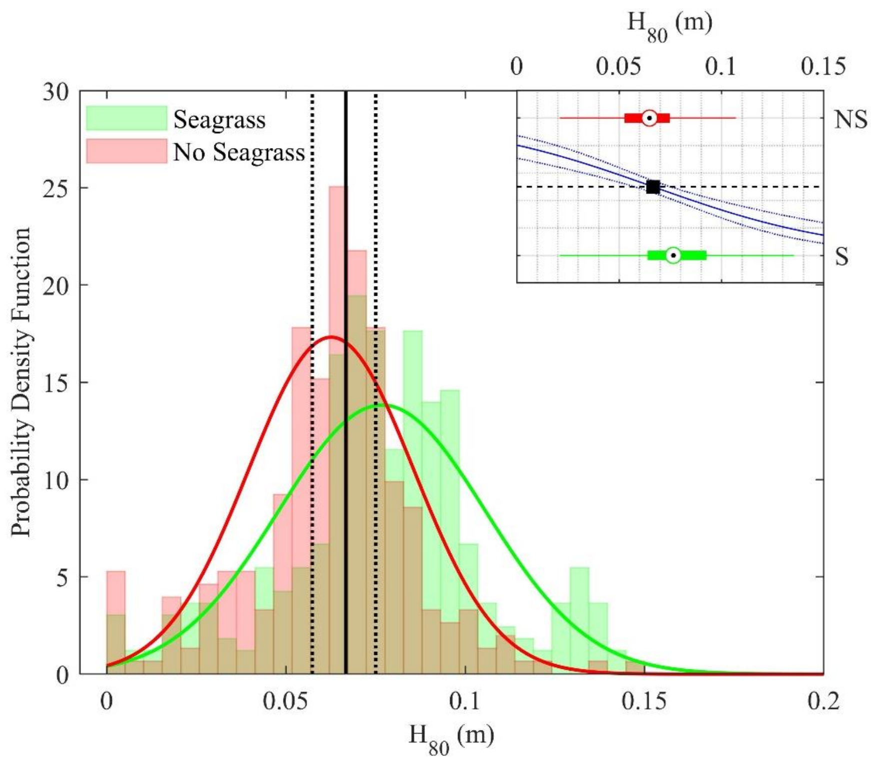


Figure 14: Distributions of oyster and seagrass with wave height.

4.3. Research Objective 3: Creation of restoration suitability models

The living shoreline suitability models consists of two parts: (1) a restoration prioritization model, and (2) a hydrodynamic habitat suitability model for mangrove. The prioritization model ranks shorelines according to urgency of stabilization and the habitat suitability model indicates the likelihood for persistence of mangrove vegetation on a given site.

4.3.1. Prioritization of shorelines for stabilization

All study shorelines were classified as Hardened, Urgent, Priority, Vulnerable, or Wetland according to need and urgency of stabilization (Figure 15, Appendix A), which is assessed at the site scale according to a suite of algorithms (Table 3). In addition to maps provided with this report (Figure 15 and Appendix A), shoreline prioritization data are additionally available for online viewing in a GIS storymap: (https://ucfonline.maps.arcgis.com/apps/MapSeries/index.html?appid=45caa29e80e6441c8bf6f75c542860af) or for direct download (https://stars.library.ucf.edu/shorelines/).

Shorelines classified as Hardened currently have a hardened structure within the intertidal zone. Within the study area, 50.6 miles of shoreline (28% of study shorelines) were classified as Hardened (Table 4). For the objective of prioritization, we assume that hardened sites are currently stabilized. However, managers and property owners wishing to increase long-term shoreline resilience or restore shoreline functionality may wish to consider restoration opportunities presented by currently hardened shorelines (See Section 5).

Shorelines classified as Urgent have no hardened structure, contain no intertidal wetland vegetation and are likely actively eroding (i.e. evidence suggesting active erosion was observed during the site visit). A total of 33.2 miles (18%) of shoreline was classified as Urgent. Sites classified as Urgent should be triaged for immediate stabilization.

Shorelines classified as Priority either contain no intertidal wetland vegetation, or contain wetland vegetation but are above a critical slope and are likely actively eroding. Shorelines in the Priority category totaled 17.3 miles (10% of study shoreline). Without intervention, it is likely that Priority sites will eventually move to the Urgent category.

Shorelines classified as Vulnerable are sites for pre-emptive restoration. Vulnerable sites currently have wetland vegetation within the intertidal zone, but either have a slope above a critical value or are actively eroding. A total 11.5 miles of shoreline (6% of study shorelines) were classified as Vulnerable.

Shorelines classified as Wetland currently have wetland vegetation within the intertidal zone, have a slope at or below the maximum wetland slope (0.2 m/m), and are not actively eroding. The Wetland category comprised 68.1 miles (38%) of study shorelines. Wetland shoreline sites do not need to be restored at this time and can serve as reference sites for stabilization of shorelines classified as Urgent, Priority, or Vulnerable.

Table 3: Prioritization algorithms for shoreline stabilization

Shoreline Type	Algorithm	Priority
Hardened	IF shoreline has: hard structure within intertidal zone	THEN: Hardened
Unhardened	IF shoreline has: no vegetation AND is eroding AND slope is > 0.2; OR no vegetation AND is eroding AND slope is ≤ 0.2; OR no vegetation AND is not eroding AND slope is > 0.2	THEN: Urgent
	IF shoreline has: no vegetation; OR slope > 0.2 AND is eroding	THEN: Priority
	IF shoreline has: vegetation AND slope ≤ 0.2 AND is eroding; OR vegetation AND is not eroding AND slope > 0.2	THEN: Vulnerable
	IF shoreline has: vegetation AND slope ≤ 0.2 AND is not eroding	THEN: Wetland

Table 4. Total shoreline lengths in each priorization category.

Priority Classification	Shoreline Length (miles)	Shoreline Length (km)	Percent of Shoreline Length (%)
Hardened	50.6	81.4	28%
Urgent	33.2	53.4	18%
Priority	17.3	27.8	10%
Vulnerable	11.6	18.7	6%
Wetland	68.1	109.6	38%
Total	180.8	291.0	100%

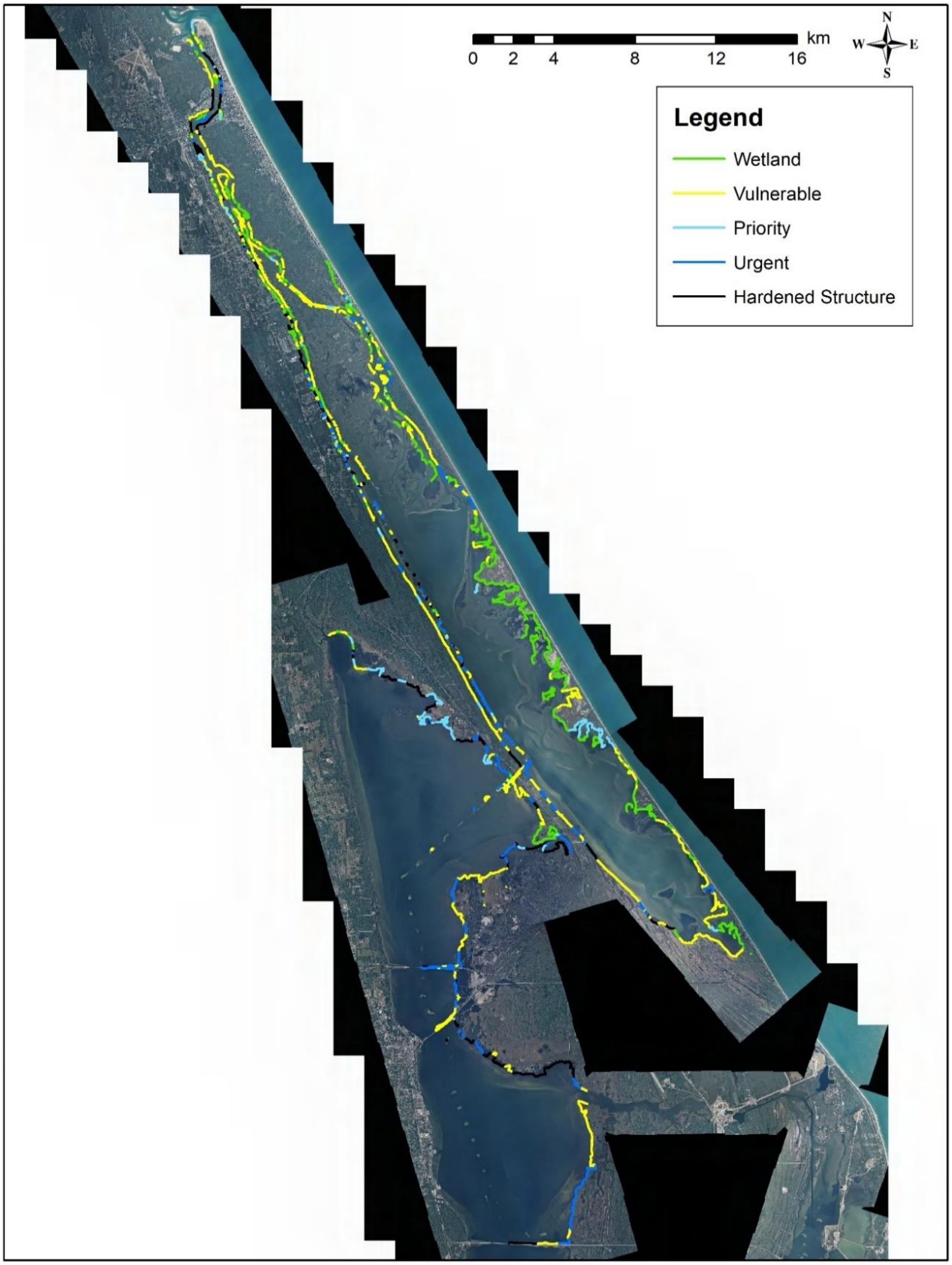


Figure 15: Shoreline prioritization for stabilization in study area. Maps of shoreline prioritization at larger scale are given in Appendix A. Data are additionally available for online viewing in a GIS storymap: (https://ucfonline.maps.arcgis.com/apps/MapSeries/index.html?appid=45caa29e80e6441c8bf6f75c542860af) or for direct download (https://stars.library.ucf.edu/shorelines/).

4.3.2. Hydrodynamic habitat suitability for mangrove vegetation

All study shorelines were characterized for mangrove hydrodynamic habitat suitability (Figure 16 and Appendix B) according to likelihood for persistence of mangrove vegetation, as predicted by wave climate (e.g. Figure 10). Data are also available for online viewing in a GIS storymap: https://ucfonline.maps.arcgis.com/apps/MapSeries/index.html?appid=45caa29e80e6441c8bf6f75c542860af or for direct download: https://stars.library.ucf.edu/shorelines/.

Within the study area, 68% (121.7 miles) of the total evaluated shoreline was characterized with 50% or greater probability of mangrove persistence (Table 5). It is important to note that the interaction of many habitat variables (reviewed in Krauss et al. 2008) will determine the overall habitat suitability for mangrove at a given site. Temperature, salinity, nutrient availability and ecological controls of competition and predation are examples of mangrove habitat suitability metrics that were not considered in this study of hydrodynamic habitat suitability. It is the site-scale variation in all habitat suitability metrics that leads to the large observed overlap in distributions of sites with and without mangrove vegetation (Figures 8 and 9). This is why predicting overall site suitability based on examination of one metric is best presented probabilistically (e.g. there is a 50% vs. 10% change of persistence). Even sites with acceptable hydrodynamic conditions may fail to support mangrove vegetation due to deficiency in another critical habitat component. That being said, this study does confirm the influence of hydrodynamics in habitat suitability of mangrove, and does establish hydrodynamic habitat thresholds in that can be applied as one piece of overall habitat suitability characterization. Mangrove vegetation established within sites classified above 50% probability will not likely be subjected to unsuitable hydrodynamic conditions due to wind-generated waves. It is likely that these shorelines will support mangrove vegetation. Shorelines characterized by lower probability of mangrove persistence, or in areas facing other hydrodynamics stresses (e.g. boat generated wakes) may require additional stabilization materials, such as a wave break, in order to improve suitability of shoreline hydrodynamics for mangrove establishment and survival.

Table 5. Total study shoreline length according to probability of mangrove persistence.

Probability of Mangrove Persistence	**Shoreline Length (miles)**	**Shoreline Length (km)**	**Percent of Shoreline Length (%)**
<10%	14.9	24.0	8%
10-19%	5.0	8.0	3%
20-29%	4.8	7.7	3%
30-39%	10.3	16.6	6%
40-49%	23.1	37.2	13%
50-59%	32.3	52.0	18%
60-69%	32.9	52.9	18%
70-79%	20.5	33.0	11%
80-89%	27.3	43.9	15%
90-100%	8.7	14.0	5%
Total	179.8	289.4	100%

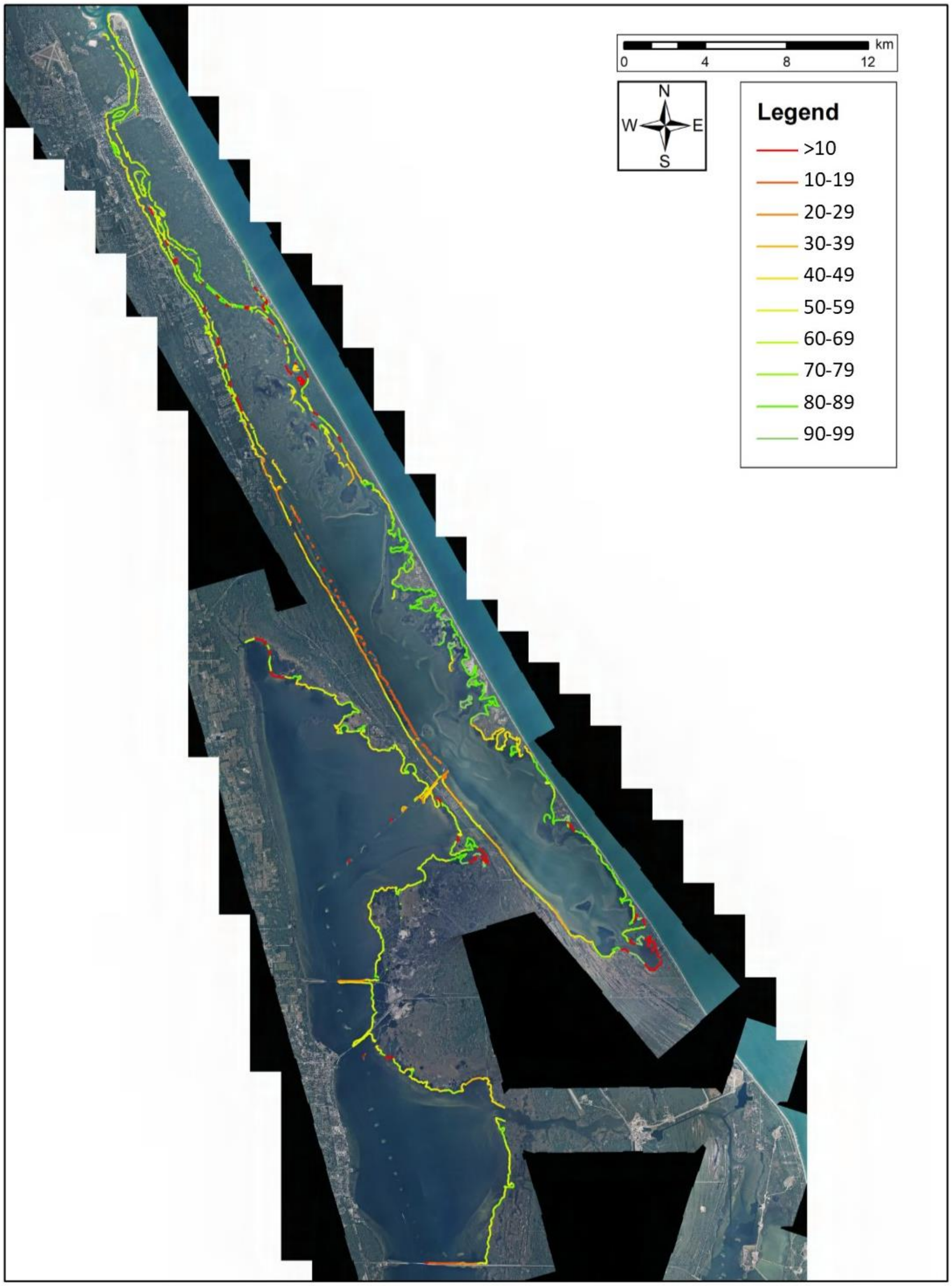


Figure 16: Shoreline hydrodynamic habitat suitability for mangrove in study area. Maps of mangrove hydrodynamic habitat suitability at larger scale are given in Appendix B. Data are additionally available for online viewing in a GIS storymap (https://ucfonline.maps.arcgis.com/apps/MapSeries/index.html?appid=45caa29e80e6441c8bf6f75c542860af) or for direct download (https://stars.library.ucf.edu/shorelines/).

5. Research Conclusions and Applications

This project successfully created a living shoreline restoration prioritization and mangrove habitat suitability model for 180 miles of estuarine shorelines in Mosquito Lagoon and northern Indian River. New empirical wind wave data created through hydrodynamic modeling and frequency analysis were applied to characterize wave climate in study area shorelines. Modelled hydrodynamic data were combined with shoreline data collected in the field during the project Phase I to develop fundamental knowledge regarding hydrodynamic habitat suitability of IRL shoreline species. Through this analysis, strong relationships between mangrove presence and wind wave hydrodynamics were illuminated, such that probability of mangrove persistence was predicted at the project site scale based on wave climate. Additionally, the influential role of site intertidal slope and its interaction with site hydrodynamics was confirmed. This is a transformative source of information from the perspective of Planning, Design and Engineering (PD&E) of shoreline stabilization and regional-scale restoration planning.

Managers and practitioners working within the direct project study area can immediately begin to apply the tools developed herein to shoreline stabilization within the study area. For example, managers may find that the prioritization model delivers a succinct plan for future resource distribution. Furthermore, for managers seeking water quality or habitat enhancement opportunities, the mangrove habitat suitability information can assist in restoring function to shorelines that are overly steepened or currently hardened. Options for restoration of hardened sites currently include hybrid restoration techniques, where the structure or hardening remains in place, or removal of the hard structure to restore hydrologic processes that control intertidal ecotone functions. Because hybrid restoration options will often not fully restore these hydrologic processes, hybrid options are unlikely to fully restore ecotone functionality. However, hybrid solutions may often be preferable to the public or homeowners, as removal of shoreline armoring structure may appear risky. Using the mangrove habitat suitability data, stability risks associated with structure removal could be assessed based on where a living shoreline containing mangrove vegetation could be predicted to successfully replace a hardened shoreline (Figure 17).

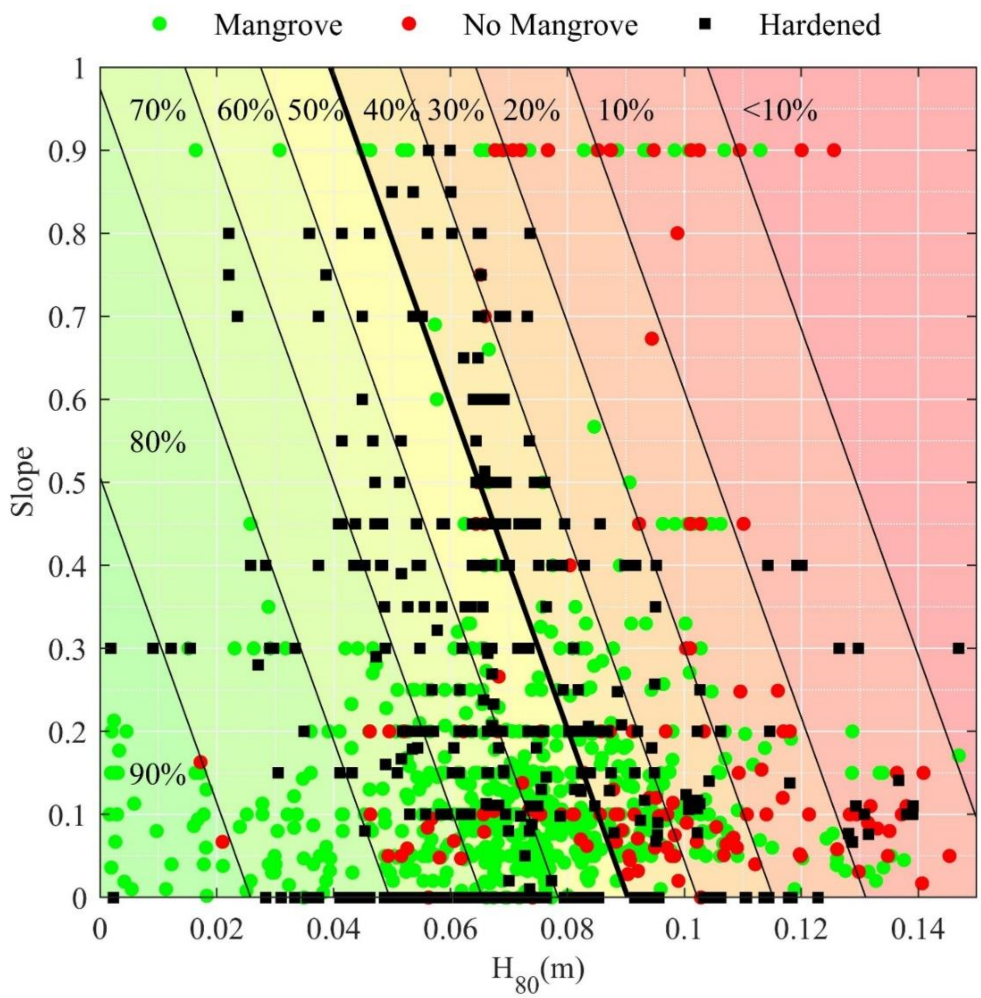


Figure 17: Hardened shorelines within the project study area, projected on multivariate mangrove hydrodynamic habitat suitability space. These data indicate that many hardened shorelines in the project study area do not actually require armoring. Living shoreline containing mangrove forest could be expected to stabilize many hardened shorelines. This information identifies opportunities where shoreline hardening and structures may be removed and replaced with living shorelines containing mangrove vegetation to restore shoreline ecotone functionality.

Managers and practitioners outside of the direct project area will also benefit, as this work can be transferred more broadly. First, the actual hydrodynamic habitat thresholds for mangrove discovered in this study can be transferred to other locations within and outside of the IRL system. Locations throughout Florida that fit within the mangrove temperature, salinity and hydrology habitat zones may use the knowledge developed herein for site-scale project planning. Application of hydrodynamic habitat thresholds will allow managers to predict site suitability for mangrove after undertaking work to characterize shoreline hydrodynamics at the site scale. Second, the synergy between regional-scale project prioritization and site-scale habitat suitability design tools demonstrated in this project can be a framework for future restoration planning efforts. Provision of information both at a broad geographic scale for use in regional planning, and making the information sufficiently detailed such that it can be applied at the site scale can help managers and practitioners understand when and where restoration is needed, and also the appropriateness of nature-based or green-grey hybrid designs on a site by site basis. Widespread investment in this type of information, and dedicated strategies to adopt such information in project PD&E may increase restoration success and impact on a regional scale.

6. Future Research Opportunities

Though this project attempted to discover hydrodynamic habitat suitability metrics for intertidal oysters and seagrasses, conditions within the project area were insufficient to reach robust conclusions regarding these important coastal ecosystem engineers. There are therefore future research opportunities to apply frameworks developed herein to broader study areas, which will potentially lead to discovery of flow-ecology relationships for a broader suite of coastal ecosystem engineers.

Furthermore, shoreline hydrodynamics in other areas may be influenced by a more diverse set of hydrodynamic forces. Exploring the interaction of currents, waves, and boat wakes to understand how species persist under the influence of more diverse hydrodynamic habitats is an important research direction needed to expand this work to other coastal areas. The model for boat wake risk developed within this project represents a good conceptual start, but more research is needed to characterize boat wake hydrodynamics with more rigor. In particular, more empirical data regarding boat traffic frequency and improved methods to estimate wake magnitudes at shorelines are needed to enable boat wake modelling for management applications.

The synergy between regional-scale project prioritization and site-scale habitat suitability design tools demonstrated in this project can be a framework for future restoration planning support efforts. The framework, models, and new flow-ecology information demonstrated in this project can be scaled up to the entire IRL system to provide a common baseline of information to managers and restoration practitioners in the IRL.

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8. Appendices

8.1. Appendix A – Shoreline site prioritization maps

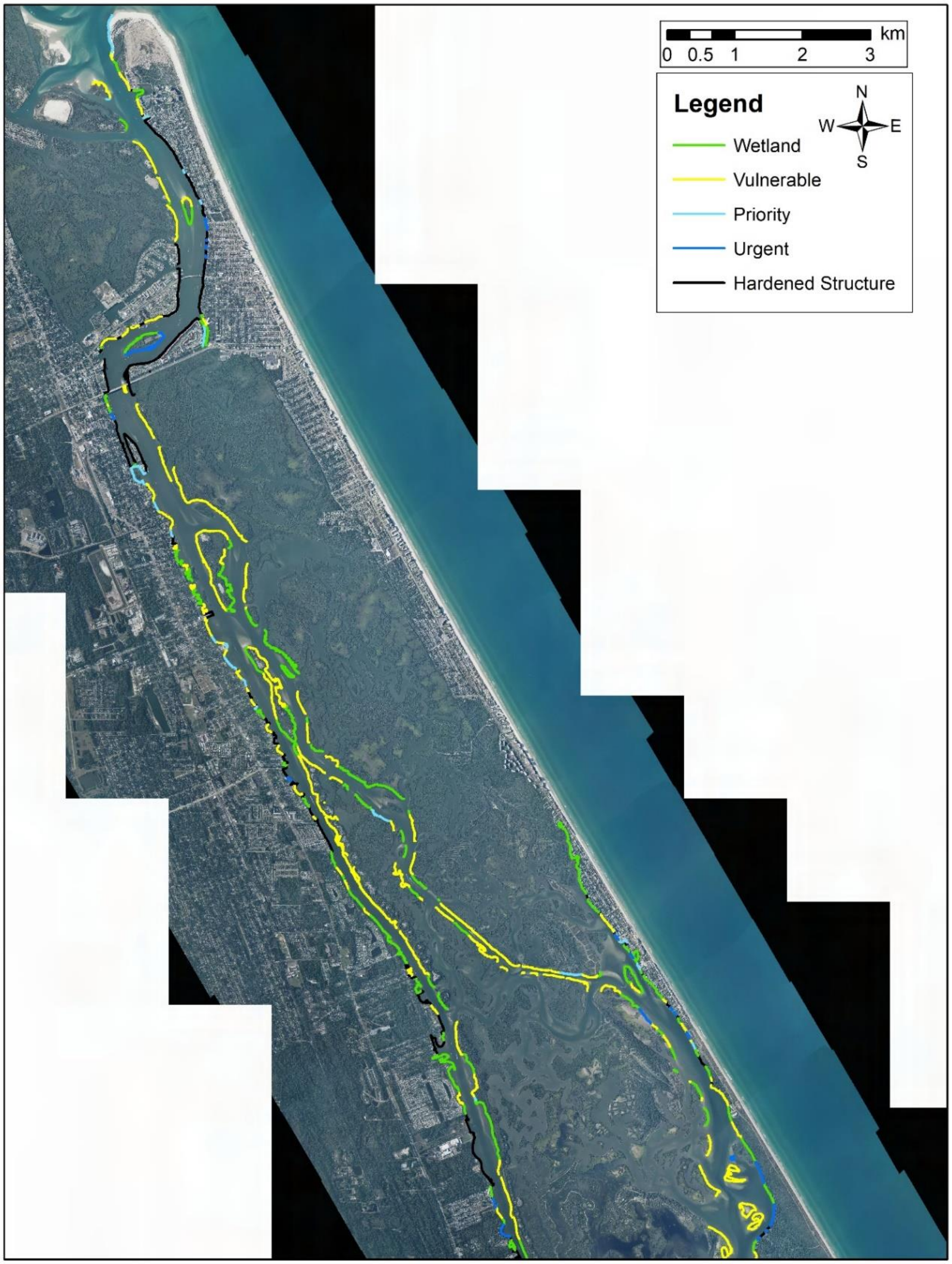

Figure A1: Shoreline prioritization for northern Mosquito Lagoon.

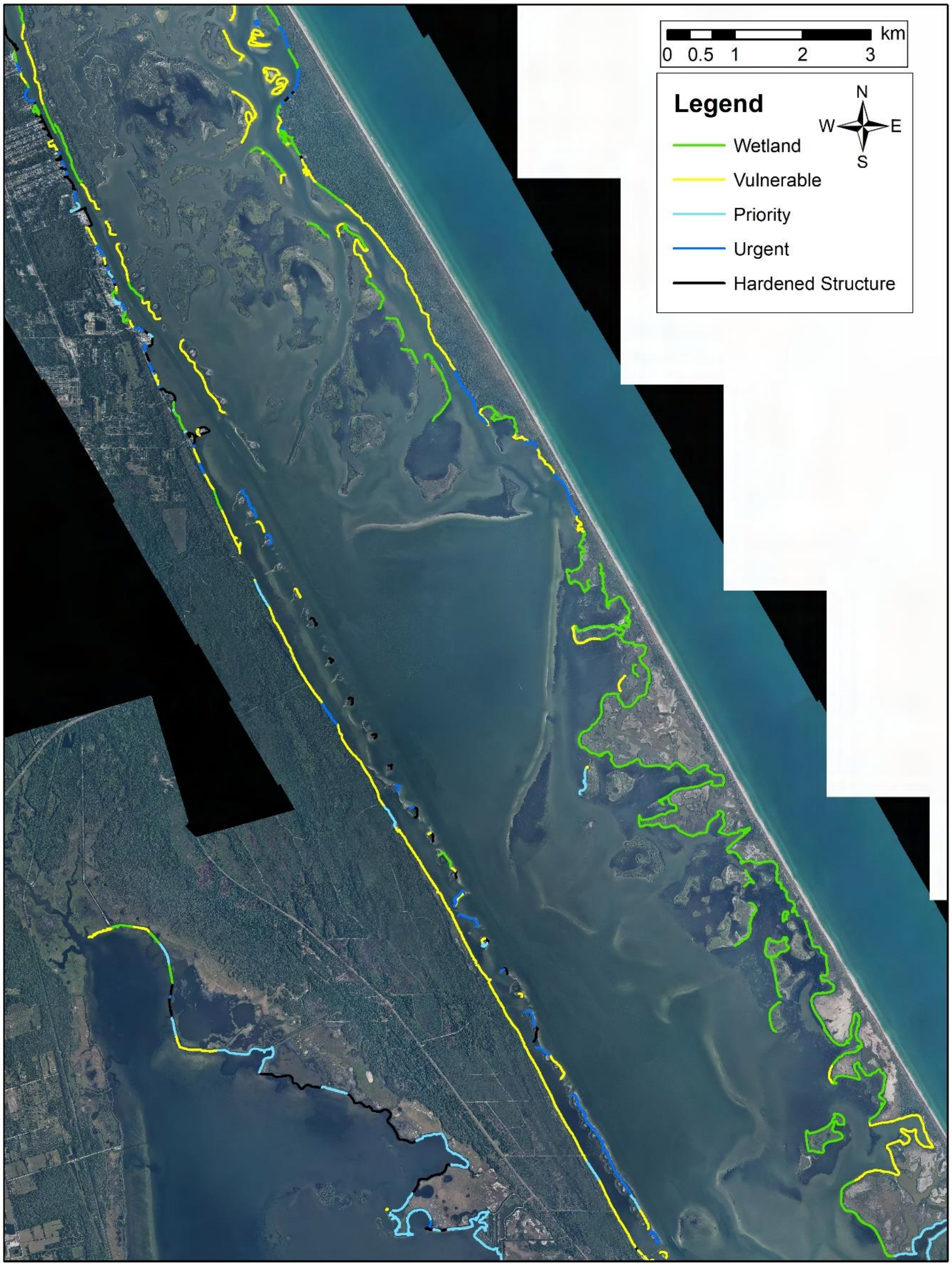

Figure A2: Shoreline prioritization for central Mosquito Lagoon.

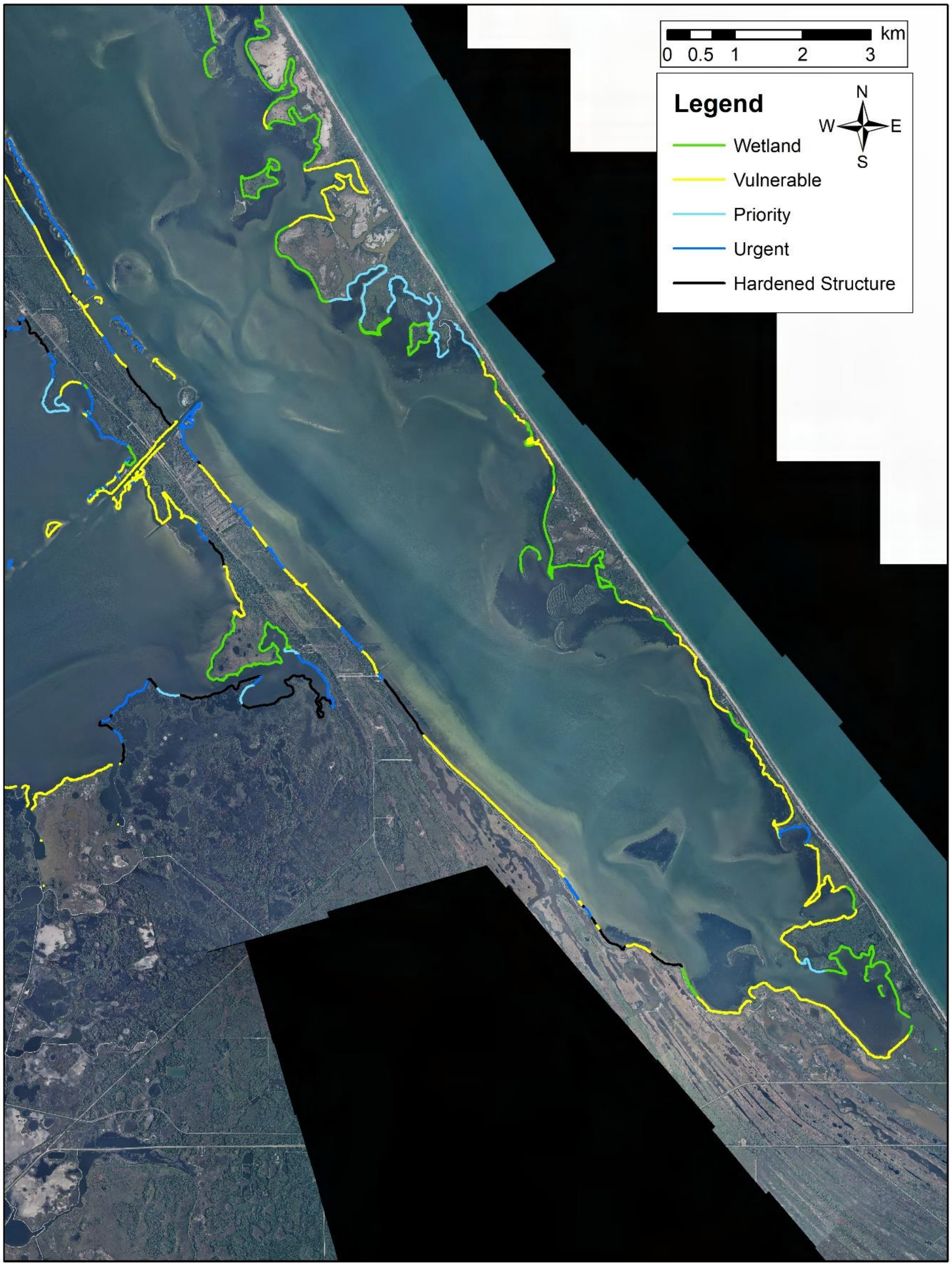

Figure A3: Shoreline prioritization for southern Mosquito Lagoon and Haulover Canal area.

Figure A4: Shoreline prioritization for east bank of northern Indian River and Haulover Canal vicinity.

Figure A5: Shoreline prioritization for east bank Indian River, Max Brewer Bridge to NASA Causeway.

8.2. Appendix B – Shoreline mangrove habitat suitability maps

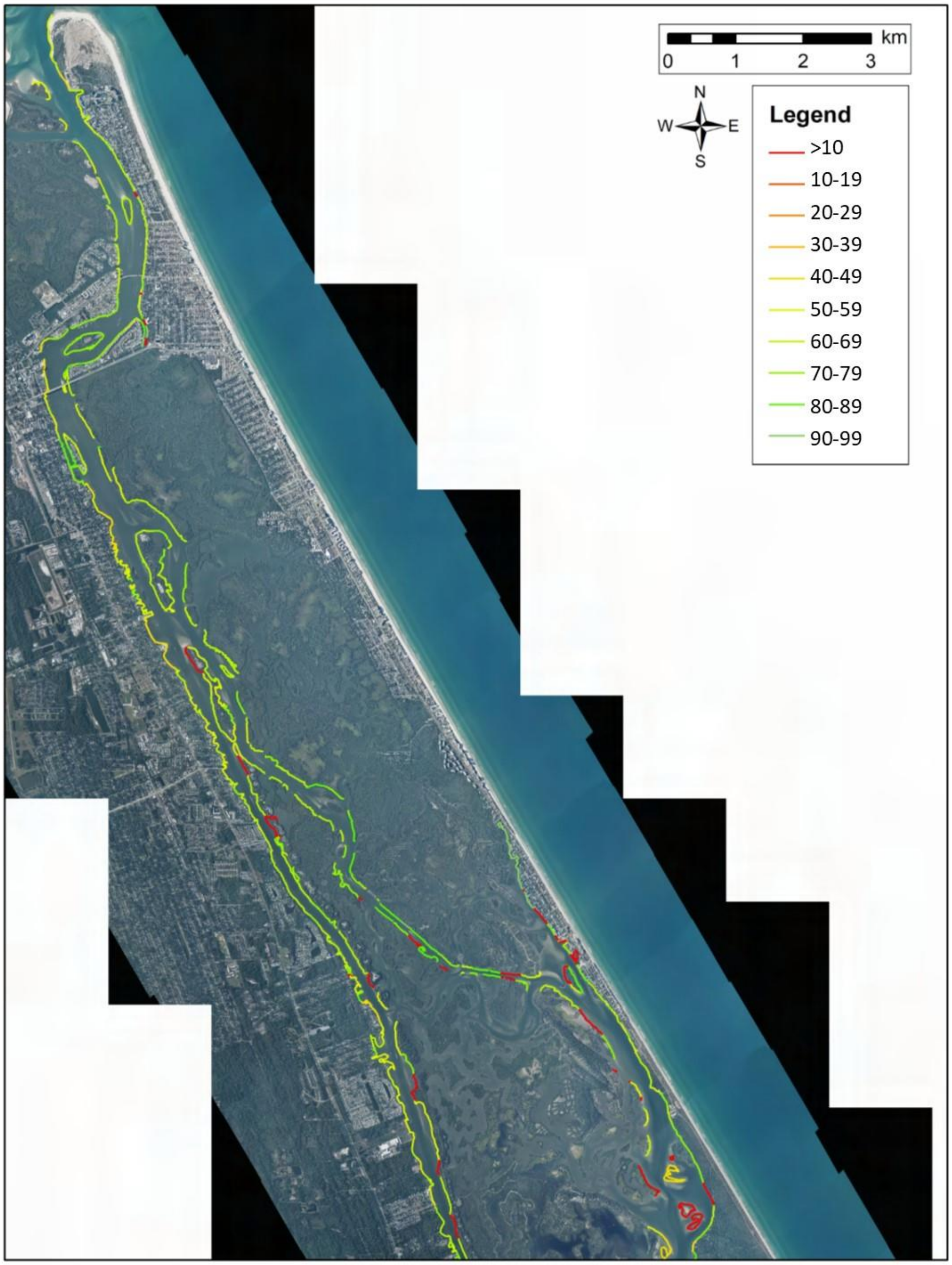

Figure B1: Shoreline mangrove habitat suitability for northern Mosquito Lagoon.

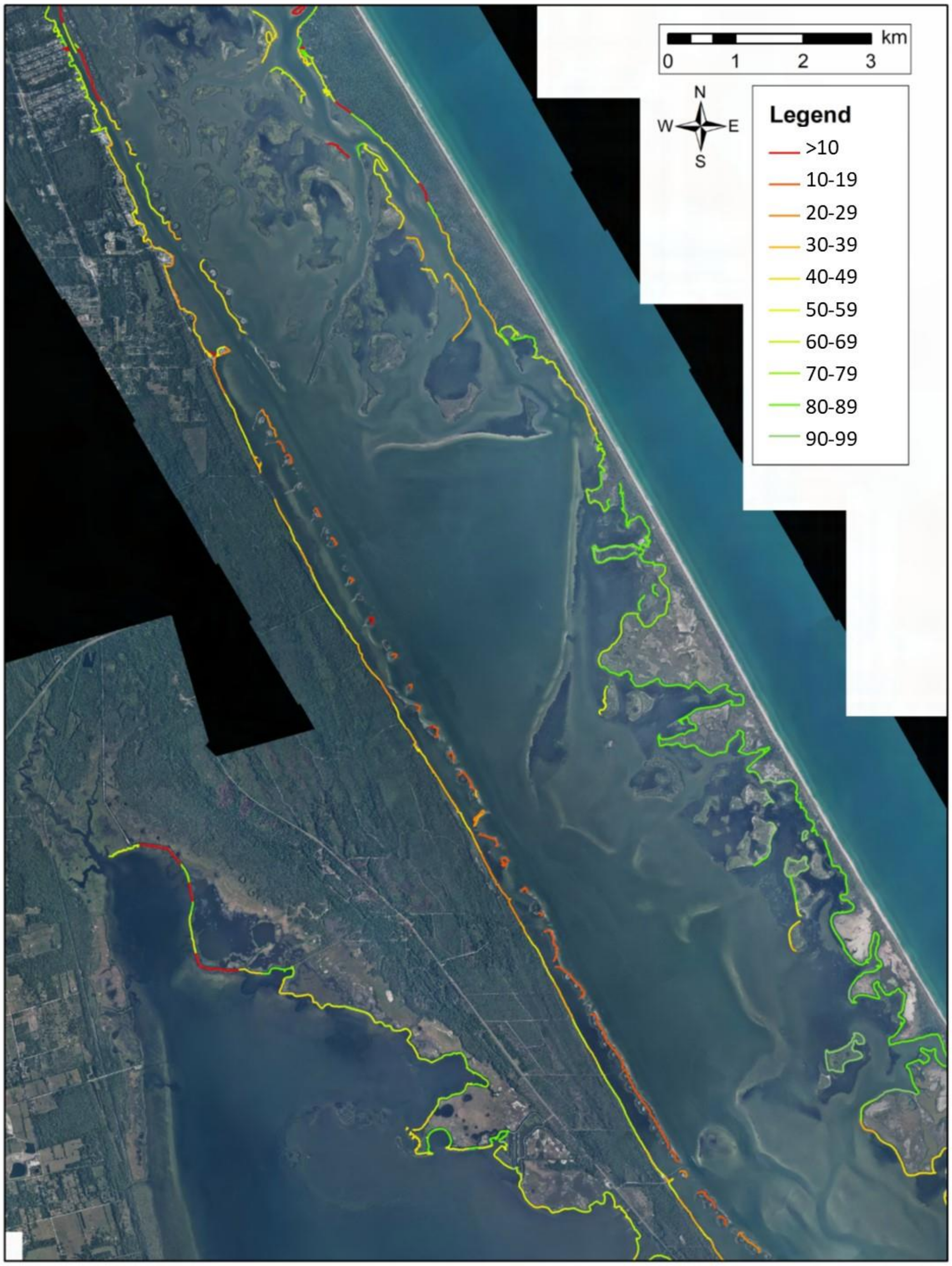

Figure B2: Shoreline mangrove habitat suitability for central Mosquito Lagoon.

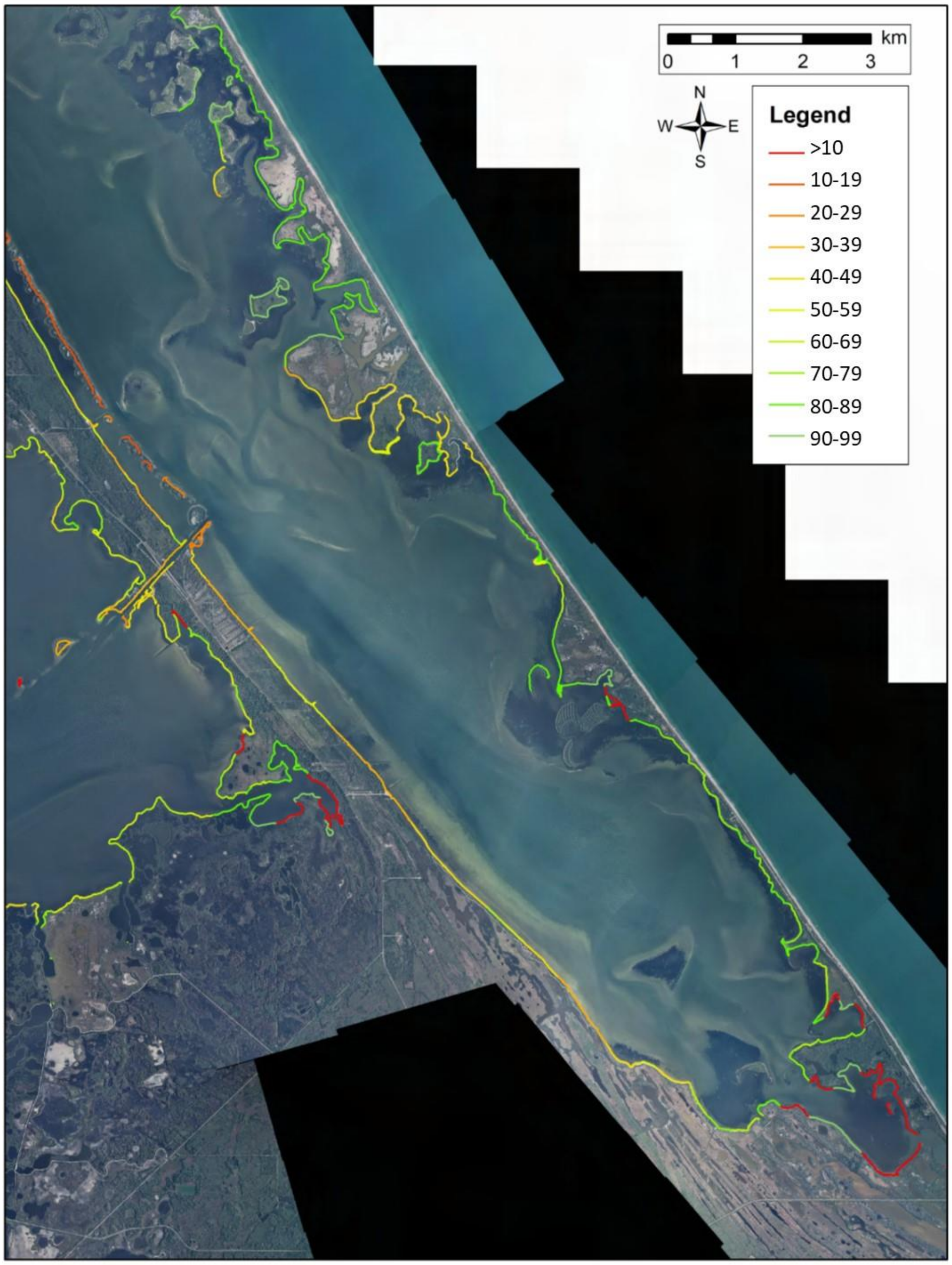

Figure B3: Shoreline mangrove habitat suitability for southern Mosquito Lagoon and Haulover Canal area.

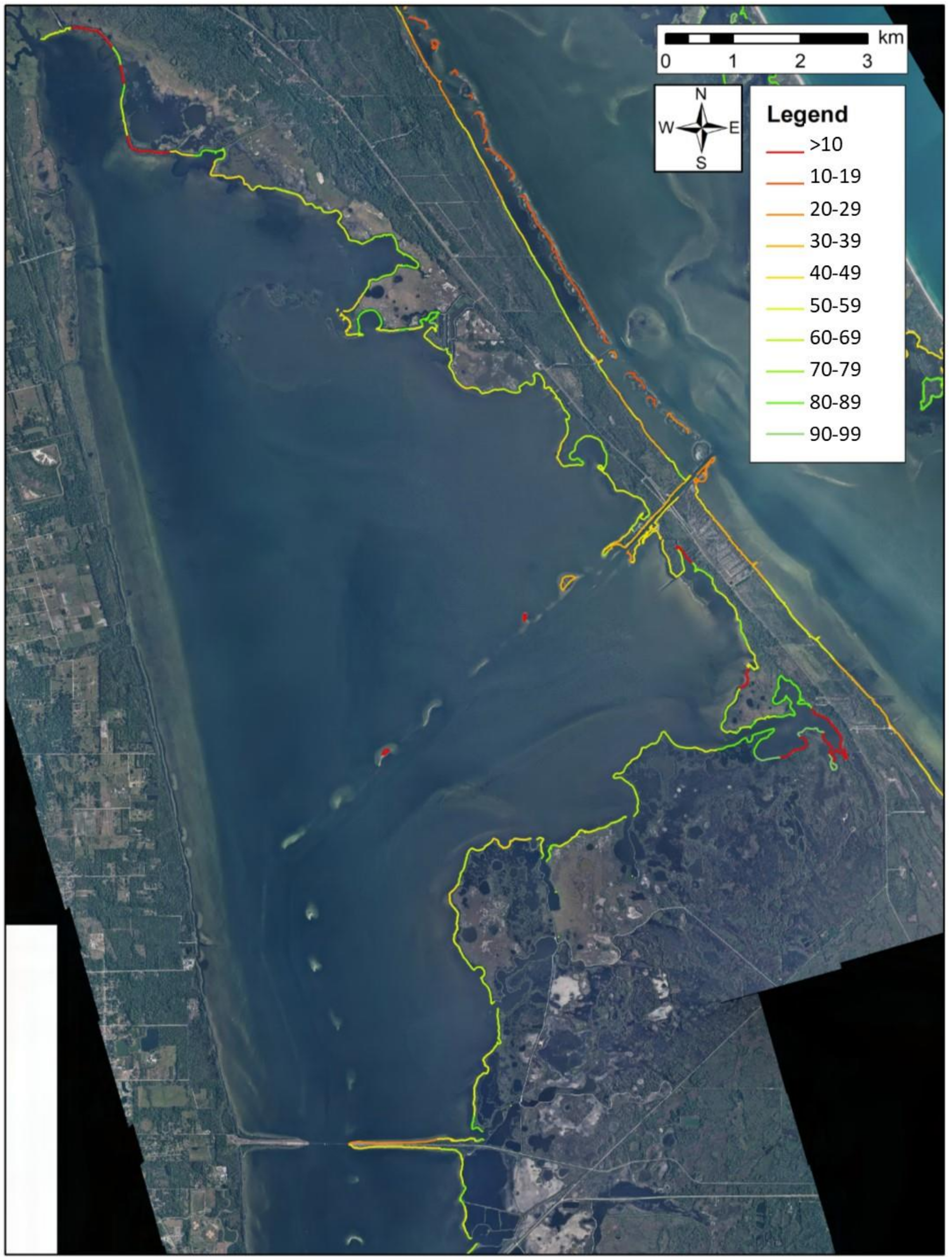

Figure B4: Shoreline mangrove habitat suitability for east bank of northern Indian River and Haulover Canal vicinity.

Figure B5: Shoreline mangrove habitat suitability for east bank Indian River, Max Brewer Bridge to NASA Causeway.