THE GEO PROJECT
GEOSPATIAL EDUCATION & OUTREACH

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TECHNICAL REPORT
NO. 5094

A REVIEW OF LIVING SHORELINE SITE SUITABILITY MODELS APPLIED TO COASTAL AREAS OF THE ATLANTIC OCEAN AND NORTHERN GULF OF MEXICO

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JULY 2022

This work was supported through funding by the National Oceanic and Atmospheric Administration Regional Geospatial Modeling Grant, Award # NA19NOS4730207.

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The Geospatial Education and Outreach Project (GEO Project) is a collaborative effort among the Geosystems Research Institute (GRI), the Northern Gulf Institute (a NOAA Cooperative Institute), and the Mississippi State University Extension Service. The purpose of the project is to serve as the primary source for geospatial education and technical information for Mississippi.

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INTRODUCTION

Living Shorelines are erosion control practices that restore or enhance vegetated shoreline habitats to provide long-term stabilization. These soft stabilization methods baffle wave energy through the strategic placement of marsh plants, stone structures, sand fill, low profile sills, biodegradable coir logs, and other material in a manner that does not sever the natural connections between riparian, intertidal, and subaqueous areas (Berman et al. 2005, Center for Coastal Resource Management 2006). These practices are considered ecologically friendly alternatives to traditional armoring.

Landowners considering a living shoreline management option can consult written guides and decision support tools that explain how local features such as wave energy, slope, existing structures, and vegetation affect suitability (Mississippi-Alabama Sea Grant Consortium 2022, Virginia Institute of Marine Science 2022, Miller et al. 2016). The same features can be mapped to rapidly assess suitability for living shorelines in large landscapes. This report summarizes eight independent index-based living shoreline site suitability models and eight variations on the Shoreline Management Model developed by the Virginia Institute of Marine Science (VIMS SMM), which does not rank locations with an index valuation but instead generates descriptions of recommended practices based on combinations of input factors.

This report is intended to be used as a guide for users of living shoreline suitability models who are considering adapting existing or developing new models. This document aggregates information, such as general approaches, specific input datasets, and produced outputs, from documented living shoreline suitability models applied to coastlines of the Atlantic Coast and

Gulf of Mexico in the United States. Information is aggregated here so that such users can proceed with a fuller understanding of current practices.

Living Shoreline Models Reviewed in this Report:

- Connecticut
- Florida: Southeast Florida (four counties)
- Florida: Sarasota County
- Maine
- Maryland: Prince George's County
- New Hampshire
- North Carolina: Pamlico – Albemarle Estuarine Complex
- Texas
- VIMS SMM (adaptations and applications):
  - Virginia: Entire coastline
  - Mississippi: Biloxi and St. Louis Bays
  - Florida: Tampa Bay
  - Texas: Galveston Bay
  - Alabama: Perdido Bay Complex
  - Louisiana: Lake Pontchartrain
  - Alabama: Mobile Bay
  - Maryland: Worcester County

GENERAL SUMMARY OF MODELS

The models reviewed here are designed to evaluate shoreline segments regarding suitability for living shoreline and other stabilization practices. The models produce output recommendations along a gradient from soft approaches using vegetation only, through hybrid approaches that use vegetation and incorporate structural components, to hard solutions that are purely structural. All models agree that wave energy, shallow water, and the presence of or potential for vegetation are the driving factors for ranking shoreline segments on the soft-to-hard spectrum. The living shoreline option is most likely to succeed where wave energy is low and vegetation either already exists or can be added without significant land modification, both conditions are associated with shallow nearshore water.

Wave Energy

Direct measure of wave energy at all locations is not feasible, so proxy datasets are used to estimate high, medium, and low values for wave energy. Fetch (the distance traveled by wind or waves across open water to the opposite shore) is the most widely used proxy for wave energy. Most of the models reviewed here use the USGS Wind Fetch and Wave Model (Rohweder et al. 2012). The VIMS SMM is an exception: it includes a stand-alone fetch model that creates points and corresponding perpendicular bearing arcs along a shoreline and calculates distances at which the bearing arcs crossing a water polygon intersects a land polygon. The VIMS SMM reinforces the distinction between high and low energy by forcing shoreline segments in tidal creeks into the low exposure class in a separate calculation. Other exceptions are the Maryland

(Prince George's County) model, which ignores fetch since it addresses riparian shorelines only, and the Florida (Sarasota County) model, which classifies water body types (bayou, creek, bay, gulf, etc.) into wave energy bins based on general size of features rather than fetch. Boat wakes contribute to wave energy, and proxies for real-time measures of boat activity include maps of boat restricted areas and no-wake zones, proximity to shipping channels, proximity to boat ramps, and proximity to inlet (based on assumed contribution of vessel clustering to wave energy).

Models differ on how sharply they distinguish the contribution of wave energy from other factors, since it is functionally closely related to the other important variables of nearshore shallow water and present or potential vegetation. Areas with shallow water and low wave energy are more biologically active and produce more vegetation. The North Carolina model considers submerged aquatic vegetation (SAV) to be a proxy for low wave energy, whereas VIMS considers SAV a trigger of regulatory restrictions and recommends expert advice. Environmental Sensitivity Index (ESI) values, based on combined information about wave energy, water depth, and vegetation, are used in the Florida, Maine, and Texas models. The VIMS SMM and the model for the entire state of Texas developed by the General Land Office are the only other examples of non-indexed models among those reviewed here.

The Theoretical Framework: Property Protection and Policy

The living shoreline models reviewed here were created in a framework of planning, permitting, and policy, and therefore assume that some form of management for shoreline stabilization is under consideration at all locations. The models were generally created by agencies and institutions wanting to promote living shorelines and soft stabilization methods as alternatives to traditional armoring. For the most part, the model parameters are adapted from practical and permitting guides developed for individual landowners. The models clearly identify areas where wave energy is so high that living shorelines are unsuitable and armoring is the best option. However, criteria and processes for analyzing and generating a "do nothing" recommendation for the opposite condition - low wave energy and abundant vegetation making stabilization unnecessary - are not well-developed. The VIMS model is unique in providing a "no action needed" output for low energy vegetated areas where stabilization occurs naturally, but that recommendation is triggered by a single feature: the presence of extensive marsh or marsh islands. Users of shoreline stabilization models should consider other combinations of features to indicate areas where action is unnecessary.

Geophysical vs Sociopolitical Factors

All models agree that suitability is driven primarily by the geophysical factors that cause erosion. Three of the nine models reviewed here also address important sociopolitical factors. The New Hampshire project presents two models: a geophysical model that generates numerical index values, and a separate, qualitative, sociopolitical model that uses ecological values assigned by stakeholders, landowner capacity and interest, likelihood of demand for stabilization, and potential impacts to regulated resources as inputs to generate recommendations rather than a quantitative index. The Maryland (Prince George's County) model uses two sociopolitical inputs, parcel ownership and cultural resource impacts, along with nine geophysical features, assigning scores to all in the same matrix before calculating an unweighted cumulative index. The Florida (Sarasota County) model uses population density and land value with the rationale that a positive linear correlation exists between these factors and suitability from the lowest to maximum values. In that model, valuable land supporting human population may be more suitable than less valuable land with no people, but that doesn't necessarily mean that the most expensive land with highest population density is the most suitable for living shoreline practices.

Erosion Trend

Only three of the nine models (Connecticut, Maryland, and New Hampshire) address erosion trend. This is because reliable estimates of the rate of change covering multiple counties of entire state coastlines are uncommon. The lack of an erosion trend variable input increases the likelihood that a model will generate a management action recommendation in the absence of an actual threat. The VIMS SMM, the only model packaged for easy exportation and application in other locations, does not include an erosion trend variable. This may be due to limited access to the necessary data for most locations.

The following section summarizes living shoreline suitability models developed for locations on the Atlantic and Gulf of Mexico coastlines. The format addresses four elements of each model: source information, geographical features of the area, model approach (inputs and outputs), and notes about the particular model and/or the process of developing it.

ACRONYMS

BMP: Best Management Practices
CCI: Comprehensive Coastal Inventory
CCRM: Center for Coastal Management, Virginia Institute of Marine Sciences
ESI: Environmental Sensitivity Index from Florida Cooperative Land Cover
FWCC: Florida Fish and Wildlife Conservation Commission
HRI: Harte Research Institute
LS: Living Shorelines
MHW: Mean High Water. Often used as a proxy for shoreline
NH GRANIT: New Hampshire's statewide GIS clearinghouse
NOAA: National Oceanic and Atmospheric Administration
NRCS: Natural Resources Conservation Service
SAV: Submerged Aquatic Vegetation
SLR: Sea Level Rise
SMM: Shoreline Management Model
UNH-CCOM: University of New Hampshire Center for Coastal and Ocean Mapping
USACE: US Army Corps of Engineers
USDA: US Department of Agriculture
USGS: US Geological Survey
VIMS: Virginia Institute of Marine Science

MODEL SUMMARIES

Connecticut

1. Information Source: A detailed website includes an overview with a list of references and individual story maps dedicated to the model's four principal output recommendations: https://www.arcgis.com/apps/MapSeries/index.html?appid=150edfcff35d4103afe8a20856067c05
2. Geography: Connecticut's coastline faces Long Island Sound, which occupies 1320 square miles, contributes over $9 billion to the regional economy, and provides habitat to over 1200 species of invertebrates (Zylberman 2022). The Sound is separated from the Atlantic Ocean by Long Island, a wide land mass compared to the barrier islands typical of the coastlines represented in this report. The project study area is a 300-foot buffer of the 24 coastal communities, also known as New England Towns (Connecticut does not have County-level government), which contains roughly 400 miles of shoreline.
3. The Model: Raster based unweighted spatial overlay analysis. Processing is done in a set of Python scripts. Inputs are reclassified to living shoreline design guidelines following Miller et al. (2015).
    a. Inputs:
        i. Shoreline: NOAA Continually Updated Shoreline Product (CUSP). ESRI shapefile, seamless polyline.
        ii. Fetch: USGS Wind Fetch and Wave Model (Rohweder et al. 2012).
        iii. Bathymetry from the Connecticut Department of Energy and Environmental Protection (DEEP) GIS data page. The contour layer was converted to raster using the ArcGIS "Topo to Raster" tool.
        iv. Erosion History from O'Brien et al. (2014), a GIS-based long term (1880-2006) and short-term (1983-2006) time-series analysis of erosion trends.
        v. Marsh from Hoover (2009). Used as a proxy for vegetation under the assumption that marsh attenuates wave energy and limits erosion
        vi. Beach created via on-screen digitizing of 2012 Ortho Imagery from the Center for Land Use Education and Research (CLEAR). Beach presence indicates potential for living shoreline design options.
    b. Outputs:
        i. Beach enhancement: nonstructural options, beach nourishment (addition of sand), dune restoration (shaping dunes, adding plants). Determined by low fetch, low rate of erosion, shallow water, presence of beach.
        ii. Marsh enhancement: nonstructural option, process of adding new plants or replacing plants lost in storm events, usually requires grading of bank in non-vegetated areas. Determined by low fetch, low rate of erosion, shallow water, presence of marsh.
        iii. Marsh enhancement with structures: hybrid options, marsh tow revetments, marsh sills, marsh groins. Determined by moderate to high fetch, low to high erosion, shallow water, presence of marsh.

   iv. Offshore breakwaters: hybrid design for beaches. May require beach nourishment or dune restoration landward of structures. Determined by moderate to high fetch, low to high erosion, shallow water, presence of beach.

4. Notes:
   a. Connecticut has a state law (Shoreline Management Act) that limits the use of hardened structures and mandates the consideration of "less environmentally damaging alternatives."
   b. This model does not calculate an index but instead processes reclassified inputs to sort them into the four output classes.

Florida: Southeast

1. Information Source: A Technical Report (Mitsova et al. 2016). https://maps.coastalresilience.org/seflorida/methods/Living_Shorelines_Final_Report_05_06_16.pdf
2. Geography: Estuarine areas alongside inland waters in Broward County, Miami Date County, Palm Beach County, and the Blowing Rocks Preserve in Martin County. This is a highly populated area with a high density of material assets historically vulnerable to storms and sea level rise.
3. The Model: A modified version of the InVEST Coastal Vulnerability Model which produces an exposure index rank representing the relative exposure of different coastline segments to erosion and inundation caused by storms. This project uses some of the same variables as InVEST to calculate vulnerability, but processes them differently, using the weighted ranking average rather than the rankings geometric mean. Variables related to shoreline properties and feasibility are added, and the Analytic Hierarchy Process (AHP), is used to assign weights to the variables based on expert responses to surveys. 65 experts from diverse backgrounds, all working in four-county study area of Southeast Florida, were invited to participate in the surveys and 33 responded. The AHP uses a reciprocal matrix of pairwise comparisons in the structure of the survey eliciting the expert responses. The weights are based on eigenvectors derived from the squared reciprocal matrix. The weighted variables are summed, and the results are sorted to six proposed alternatives to armoring plus the armoring option for the highest exposure index class.
   a. Inputs:
      i. Shoreline type: six classes described by FWCC are lumped into natural, hybrid, and armored
      ii. Average nearshore slope, calculated using elevation data from South Florida Water Management District and topobathymetric LiDAR from Taylor Engineering for FEMA (unofficial release)
      iii. Boat wake and boat speed from FWCC Boating Restricted Areas
      iv. Storm surge from FEMA SLOSH model, calculated for both Category 3 and Category 5 hurricanes
      v. Distance to inlet, based on assumed contribution to wave energy by vessel clustering

    vi. USGS Wind Fetch and Wave Model (Rohweder et al. 2012)

b. Outputs:
    i. The modified InVEST Coastal Vulnerability Model produced two sets of index values: one representing prevailing conditions and another showing the impact of a Category 3 hurricane.
    ii. The parameter aggregation and decision tree analysis mapped proposed alternatives to armoring in the study area:
        - Soft, with vegetation only
        - Soft, with vegetation and potentially sediment only
        - Enhancement, with vegetation only
        - Enhancement, with harder features and vegetation
        - Hybrid, with softer features
        - Hybrid, with harder features
        - None, water depth and slope too great

5. Notes:
    a. A separate calculation of Exposure Index values for a hurricane event is an interesting exercise, but the text is unclear about which category is used in the analysis. Results are shown for the Category 3 calculation, Appendix 3 indicates that results were calculated for both Category 3 and Category 5 storms.
    b. The estimated lengths of possible alternatives to armoring are given by the county. Presumably, these lengths were derived from the index values created in the "prevailing conditions" model, not the hurricane model. The inclusion of maps depicting the results of the hurricane model risks encouraging more armoring, as property owners prepare for the worst in response to maps showing exposure well above normal across many locations.
    c. The use of a survey of local experts and the AHP process to derive weights for the input variables strengthens this model's application to a specific location, but this feature is not easily exported. Users seeking to repeat this type of analysis will require extra resources and capacity to do so effectively.
    d. Calculating slope from the shoreline to a bathymetric contour seems like an unnecessary step. Nearshore deep water can be identified easily by an intersection of a buffer of a depth contour representing deep water (e.g., one meter) with the shoreline. All other models use this method with the exception of Prince George's County Maryland, which addressed riparian shores only and assumes all near-shore water to be shallow.

Florida: Sarasota County

1. Information Source: Dobbs et al. 2017. http://www.ccsenet.org/journal/index.php/jsd/article/view/64068
2. Geography: Sarasota County is in West Central Florida south of Tampa Bay. The mainland is separated from barrier islands by narrow bays less than a mile wide. The model addresses estuarine areas and Gulf-facing beaches, plus a section of the Myakka River that flows southeast out of the county to Gasparilla Sound.

3. The Model: It uses a shoreline from the Florida Fish and Wildlife Conservation Commission clipped to a 400m buffer of Sarasota County. All data inputs were converted to raster with 10m cell size. Rasters were reclassified to values of 0-3 with three describing suitability for living shoreline with no structural components, two describing a hybrid solution with minimal structural components, one a hybrid solution incorporating vegetation and structural components, and zero entirely unsuitable for living shorelines. A weighted overlay analysis summed the inputs after multiplying each by the weight of importance. Eight inputs were used, so the equal weight analysis used a weight of 1/8 = 0.125. A separate unequal weighted analysis assigned a weight of 0.155 to the five environmental inputs and 0.075 to the three anthropogenic attributes. These weights result in output index values scaled to the same range as the inputs (0-3).
    a. Inputs: All inputs are converted to raster and reclassified to suitability values ranging from 0-3, with 3 being most suitable.
        i. Bathymetry from NOAA was used to classify nearshore slope with 0-3% considered suitable (3), 3-6% (2), 6-10% (1) and >10% unsuitable (0).
        ii. Land Use from FWCC's Cooperative Land Cover. High intensity urban use is assigned highest score (3), then low intensity urban use (2), then rural (1), then any class of land cover (as opposed to land use) is assigned a value of zero, with no rationale given.
        iii. Land values from the US Census. The writers assume that higher land values are indicative of landowners "more comfortable investing money to protect their property." This input is classified into three bins instead of four, with no justification
        iv. Population from the US Census. The writers assume living shorelines in more populated areas will create opportunities for educational exhibits. Four bins of people per acre (0-1, 1-3, 3-9, and 9-175), were reclassified to input values from zero (unsuitable) to three (suitable).
        v. Environmental Sensitivity Index (ESI) from FWCC. This index calculates the sensitivity of coastal environments and species to oil spills. Environments with low biological productivity and high wave energy generally rank lowest on the index, while areas with high biological activity and low wave energy rank highest. Since the same is true of living shoreline suitability indexes, the writers simply re-scaled the ESI values to fit 0-3 range of the model.
        vi. Shoreline habitat from Florida Cooperative Land Cover. Freshwater and estuarine marsh was given the highest value, then other types capable of producing vegetation, such as cypress and mangrove swamps. All other types were assigned the zero value. Clearly this conflicts with land value and population inputs.
        vii. Tree canopy from the 2011 National Land Cover Database. Marsh grasses and other vegetation used in living shorelines require abundant sunlight, so the percent tree canopy cover values were reclassified into three bins with the highest values indicating the least suitability. The writers acknowledge in the discussion section that the use of three bins instead of the model

standard of four was an unintentional oversight that impinged the validity of the results.

viii. Wave energy input obtained by reclassifying a map of water body types from Sarasota County. Bayou, lagoon, creek, slough, and canal were given a value of three, inlet, pass, waterway, and basin, were given a value of two, and gulf, channel and bay were classed as highest energy with a value of one. All other classes, which were non-shore water bodies such as freshwater lakes and detention ponds, were classified as zero.

b. Outputs: From the sum of weighted inputs, the outputs ranged from 0-3 and were rounded to the nearest integer. The results of the weighted and unweighted overlay calculations were very similar, describing about 3% of the total shoreline as unsuitable, 97% in the two hybrid classes, and no areas suitable for living shoreline options.

4. Notes:
   a. A living shoreline suitability model that fails to identify any areas suitable for living shorelines in an entire county is obviously problematic. The limitations of the process are mentioned in the discussion section, and users might rightfully wonder why they weren't addressed before publication. Despite these serious limitations, the model deserves some consideration for including land value and population data inputs. The correlation is likely not as linear as the authors assume: areas with more people who have more money may be generally more suitable than areas with fewer people and less money, but the positive correlation may level off such that areas of greatest wealth and density are not the most suitable. If the relationship were better understood, land values and population density might be useful inputs.
   b. As with the Southeastern Florida example, calculating slope from the shoreline to a bathymetric contour seems like an unnecessary step. Nearshore deep water can be identified easily by an intersection of a buffer of a depth contour representing deep water (e.g., one meter) with the shoreline. All other models use this method, with the exception of Prince George's County, Maryland, which addressed riparian shores only and assumes all near-shore water to be shallow.

Maine

1. Information Source: Living Shoreline Decision Support Tool hosted on the website of the Maine Department of Agriculture, Conservation & Forestry. Interactive map, data description and video tutorial:
   https://www.maine.gov/dacf/mgs/hazards/living_shoreline/index.shtml
   No published literature or technical reports associated with this model could be found. Balasubramanyam, & Howard (2019) refer to it and cite Pete Slovinsky by personal communication.
2. Geography: Casco Bay, also coastline from South Bristol to Frenchman Bay. Only 2% of Maine's coast is sandy beach. Most (58%) is hard rock. 40%, or 1,400 miles, is unconsolidated bluffs composed of rock, gravel, clay, or sand that erodes easily (Slovinsky and Schmitt 2011).

3. The Model: The shoreline is represented by a point file with evenly spaced points 15 meters apart. The GIS processes are not described in detail, but we can assume the input datasets were converted to index scores (shown in a table on the website's FAQ page) and those scores were aggregated to the output in an overlay analysis using procedures such as spatial join or extract values to points. Suitability scores range from 0-44, binned into five classes from "probably not suitable" to "highly suitable." There are seven input layers contributing to the score, and the map viewer displays information about two additional unscored characteristics, special habitat type and structure proximity. The interactive mapper also displays the seven scored input layers.
    a. Inputs:
        i. Fetch: USGS Wind Fetch and Wave Model (Rohweder et al. 2012).
        ii. Nearshore Bathymetry: NOAA 1/3 AS DEM. 100 feet seaward from point, <1m depth = shallow, >1m depth = deep.
        iii. Landward Shoreline Type: Environmental Sensitivity Index data layer from NOAA: wetlands, swamps, marsh, beach, scarps, sheltered hard, exposed hard.
        iv. Seaward Shoreline Type: Environmental Sensitivity Index data layer from NOAA supplemented by Maine Geological Survey Coastal Marine Geologic Environments data: marsh, flats, beaches, dunes, low energy channels, moderate/high energy channels, sheltered hard, exposed hard, man-made land.
        v. Relief (Difference between elevation at point 50 feet from MHW and elevation at MHW): From LiDAR. Four bins of elevation in feet. Higher = less suitable.
        vi. Percent slope (50 feet from MHW): From LiDAR. Five bins. 0-3 = most suitable, >30 = least suitable.
        vii. Aspect. From LiDAR. S, SE, SW most suitable, N least.
    b. Outputs: Suitability scores 0-44 binned in five classes from a Natural Breaks scheme:
        i. Probably not suitable: 0-15
        ii. Likely not suitable: 15-22
        iii. Possibly suitable: 23-28
        iv. Moderately suitable: 29-35
        v. Highly suitable: 36-44
4. Notes:
    a. In their review of LS suitability models, Balasubramanyam, & Howard (2019) note that Maine's model is most comparable and transferable to New Hampshire's shoreline condition. The New Hampshire model is therefore a highly refined and data-rich version of Maine's model.

Maryland: Prince George's County

1. Information Source: Presentation by Anthony Dowell of AECOM in Coastal GeoTools 2019 (Dowell 2019). https://coastalgeotools.org/wp-content/uploads/Dowell.pdf

2. Geography: Prince George’s County includes part of the Washington metropolitan area and is densely populated (967,201 according to the 2020 US Census). The 120 miles of shoreline addressed in this model are on rivers: the Patuxent, which forms the eastern boundary of the county, the Potomac, which forms part of the western boundary, and the Anacostia, a tributary of the Potomac inside the beltway.
3. The Model: One goal of this model is to obtain credits to meet US EPA Total Maximum Daily Load (TMDL) requirements for Chesapeake Bay. One hundred linear feet of living shoreline is equal to four impervious acre credits. The model processes LS suitability criteria for shoreline segments in a relational database. There are ten criteria, and the score for each ranges from 0-10. Higher scores indicate greater suitability. The model uses cumulative unweighted scores to rate suitability in a range from 0-100. Dowell (2019) refers to efforts to convert the relational database to a geoprocessing tool.
    a. Inputs:
        i. Shoreline polyline segmented by parcel. The source for this dataset is not identified.
        ii. Erosion rates and trends, Maryland Geologic Survey
        iii. Bank Height, State of Maryland
        iv. Shoreline orientation and fetch, internal
        v. Geology (sand, clay, mud, gravel) and waters (tidal, nontidal), USGS
        vi. Vegetative cover, USGS
        vii. Projected sea level rise, NOAA
        viii. SAV presence, Maryland Department of Natural Resources
        ix. Blue/Green infrastructure (network of land and water supporting ecological functions), Maryland Department of Natural Resources
        x. Cultural Resource Impacts, Maryland Historical Trust
        xi. Parcel ownership, Maryland Department of Planning
        xii. Adjacent parcel ownership and land use, Maryland Department of Planning
    b. Outputs: The unweighted sum of input scores for each shoreline segment, potential score range is 0-100. This output is unique among the models reviewed here in that there is no effort to bin the output scores into classes of suitability or a gradient of soft-to-hard stabilization practices.
4. Notes:
    a. Maryland has a state law (2008 Living Shoreline Protection Act) that requires shoreline property owners to use non-structural shoreline stabilization methods unless they can demonstrate that such methods are not feasible.
    b. Of the models reviewed here, this is the only one that assigns points for being connected to an ecologically functioning network (Blue/Green infrastructure).

New Hampshire

1. Information Source: A technical report (Balasubramanyam, & Howard 2019). https://www.des.nh.gov/sites/g/files/ehbemt341/files/documents/2020-01/r-wd-19-19.pdf
2. Geography: The ocean-facing coastline is one of the shortest in this report at only 18 miles. An inventory of New Hampshire shoreline protection structures encompasses all tidally influenced areas, including the Atlantic Coast, Great Bay, Portsmouth Harbor, eight rivers, and intertidal marshes, and calculates a shoreline length of 326 miles (Blondin 2016).
3. The Model: Two models are presented, one addressing biophysical suitability by assigning numerical scores to input datasets and one addressing sociopolitical feasibility by assigning written recommendations to combinations of inputs without scores or weights. Both use a common shoreline, a LiDAR-derived Mean Higher High Water (MHHW) dataset processed to generate a set of points ten feet apart. Procedures such as spatial join, extract values to points, and near were used to aggregate the input datasets to the MHHW points. The biophysical model processes weighted inputs to calculate a suitability index. The index range is from one (may be suitable with significant structural components) to six (highly suitable for living shoreline with no structural components).
    a. Inputs:
        i. Biophysical suitability model from Balasubramanyam, & Howard (2019):
            - Shoreline (MHHW) derived from LiDAR from GRANIT
            - Northeast fetch (proxy for storm effects) from USGS Wind Fetch and Wave Model (Rohweder et al. 2012)
            - Northwest fetch (proxy for ice effects) from USGS Wind Fetch and Wave Model (Rohweder et al. 2012)
            - Tidal crossing proximity (proxy for high-velocity areas) from New Hampshire Coastal Program Tidal Crossing Assessment
            - Current velocity (maximum flood current at spring tide, proxy for scouring effects) from Dr. Tom Lippman, UNH-CCOM
            - Distance from federal navigation channels (proxy for boat wakes which is in turn proxy for erosion) from USACE
            - Aspect (proxy for sunlight exposure, identifying sunlit slopes) from USGS LiDAR
            - Distance from eelgrass beds (proxy for wave attenuation in sheltered coastlines) from UNH-CCOM
            - Landward shore type (to characterize habitat type) from the Environmental Sensitivity Index, NOAA Office of Response and Restoration, plus delineated and digitized dunes from Hampton-Seabrook Estuary Restoration Compendium
            - Seaward shore type (to characterize habitat type) from the Environmental Sensitivity Index, NOAA Office of Response and Restoration
            - Future salt marsh potential (identify areas that allow marsh migration) from the Sea Level Affecting Marshes Model (SLAMM)

    - Engineered shoreline structure presence (negative influence on adjacent shoreline) from the New Hampshire Department of Environmental Services Coastal Program
    - Steep bank presence (to understand the degree of modification required) from USGS LiDAR
    - Beach volumetric change (measure of erosion) from Olson and Chormann (2017)
    - Seaward slope (proxy for wave energy) from several datasets pieced together from UNH-CCOM, USACE, NOAA, GRANIT
    - Soil erodibility (measure of erosion) from USDA NRCS
  - ii. Sociopolitical feasibility model:
    - Likelihood of demand for stabilization, from maps of recreational trails from NH Office of Energy and Planning and NH Fish and Game Department, and from buildout scenarios for impervious cover from Earth Systems Research Center, University of New Hampshire, and suggested site location information solicited directly from stakeholders
    - Owner capacity/interest from maps of public lands from the Society for the Protection of NH Forests, the NH Office of Strategic Initiatives, and the Earth Systems Research Center at the University of New Hampshire
    - Vulnerability to sea level rise using a two-foot contour derived from LiDAR from GRANIT in a simple bathtub model approach
    - Potential impacts to some regulated resources from mapped eelgrass extent (UNH CCOM) and mapped shellfish beds (NH Department of Environmental Services)
    - Ecological value assigned by stakeholders from Wildlife Action Plan, Coastal Conservation Plan, and Water Resources Conservation Plan

b. Outputs:
  - i. Biophysical model (index score, description, structural components):
    - 6, highly suitable for living shorelines, none
    - 5, suitable for living shorelines, none to minimal
    - 4, suitable for living shoreline hybrid solutions, minimal
    - 3, suitable for living shoreline hybrid solutions, moderate
    - 2, may be suitable for living shorelines with hybrid components and/or significant site modification, significant
    - 1, may be suitable for living shorelines with very significant hybrid components and/or site modification, very significant
  - ii. Sociopolitical feasibility model:
    - An attribute table aggregating input information and describing “indications” such as vulnerability to sea-level rise, possibility of lower regulatory barriers, potential public interest, desire, or

demand, ecological function, and accessibility for construction equipment.

4. Notes:
    a. The New Hampshire project identifies and uses as inputs factors that are more applicable (they say "unique") to New England Coasts compared to other Atlantic and Gulf states: short growing season, ice, nor'easters, and large tidal range.
    b. The development process included a qualitative field check. At 45 publicly accessible sites, suitability numbers were assigned based on a visual site inspection. These numbers were compared with suitability index numbers generated by the model and the results were used to inform the description of the limitations of the model.
    c. The model assumes living shoreline management practices in some form are appropriate at all locations. Even the least suitable sites can support some vegetation. There is no possibility of returning a recommendation of "no action needed," meaning that hypothetically erosion is a threat everywhere and the shoreline needs management everywhere. In other words, the model assumes that areas with low wave energy, shallow near-shore waters, abundant vegetation, and no risk of erosion do not exist. In the discussion section of the report, the authors say that scores of 4-6 may indicate suitability for no stabilization action (Balasubramanyam, & Howard 2019). They also say that certain results in the sociopolitical feasibility model, such as location within an area of conservation priority, can support doing nothing. Just as the suggested interpretation of index scores doesn't allow for "no action needed," they also don't allow for purely structural armoring: the least suitable class is described as "may be suitable for living shorelines with very significant hybrid components."
    d. The Technical Report (Balasubramanyam, & Howard 2019) Appendix II includes a review of seven living shoreline suitability models described here: Connecticut, Southeast Florida, Sarasota County Florida, Maine, Worcester County, Maryland, Maine, and North Carolina. The summary is in the form of a table and addresses some elements not addressed here, such as model goals, questions answered, model assumptions, and intended audiences.
    e. The Technical Report (Balasubramanyam, & Howard 2019) includes a section of data recommendations that could inform development of new models and adaptations of existing models. Some of the recommendations inform the Future Directions section of this report.

North Carolina: Albermarl-Pamlico Estuarine System

1. Information Source: Master's Thesis by Matthew Carey (Carey 2013).
2. Geography: The Albemarle-Pamlico Estuarine System is the second-largest estuarine system in the US, after Chesapeake Bay. It is fed by six river basins: Pasquotank, Chowan, Roanoke, Tar-Pamlico, Neuse, and White Oak. Barrier Islands separate the estuarine waters from the Atlantic Ocean, but exchange of ocean water with brackish water is minimal since there are only four "permanent" inlets. The entire system contains roughly 7770 sq km of estuarine

water. This model focuses on a small area of 146 km of shoreline in Croatan Sound, which connects Albemarle Sound in the north to Pamlico Sound in the south.

3. The Model: A shoreline polyline is segmented at vertices. The segments are not of equal length but represent local-scale geographical features (e.g., beach, marsh, cove). Each input criterion ultimately contributes a value of either zero (unsuitable) or one (suitable) to the segment. The model is run twice, once with unweighted raw scores producing potential output scores of 0-6, and once with raw scores weighted by rank sum (weight = ([number of criteria, in this case 6] – [rank] +1) divided by (sum of ranks = 1+2+3+4+5+6 = 21)) and standardized to produce potential scores ranging from 0-100.
    a. Inputs: (after shoreline, inputs are in rank order, fetch being the most important, SAV the least)
        i. Shoreline from the NC Department of Transportation, segmented at vertices that represent changes in local geographical features
        ii. Fetch from the USGS Wind Fetch and Wave Model (Rohweder et al. 2012). Fetch is calculated for north-northeast (10') and southwest (225') wind, these being the dominant winds. How the fetch values are converted to index values of zero (unsuitable) and one (suitable) is not explained. The two fetch distance outputs are used as two SL shoreline suitability inputs with the highest weights.
        iii. Near-shore water depth from interpolated bathymetry point data from the Renaissance Computing Institute (RENCI) at the University of North Carolina at Chapel Hill. Values for distance from shore and for water depth are not described, but the point data values are summarized for the shoreline segments by zonal statistics before being converted to zero (unsuitable) and one (suitable) index scores.
        iv. Boat traffic, a proxy for wave energy, indicates less suitable conditions. A spatial query selected shoreline segments within one mile of boat ramps, these segments were coded zero (unsuitable) and all others coded one (suitable).
        v. Marsh presence indicates conditions are suitable. The North Carolina Division of Coastal Management's Wetland Type polygon file was used to create a new polygon of marsh presence. A spatial query selects shoreline segments within three meters of marsh, selected segments were coded one (suitable), all others zero (unsuitable)
        vi. Submerged Aquatic Vegetation: Indicates low wave energy and good conditions. Dataset from Albemarle-Pamlico National Estuary Program. A spatial query selected shoreline segments within 100 feet SAV, these segments were coded one (suitable), all others zero (unsuitable)
    b. Outputs: Scores for the individual inputs are processed, then the weighted and unweighted total scores are summed to indicate levels of suitability for soft stabilization and for hybrid stabilization, producing four outputs:

    i. Suitability for soft stabilization: unweighted scores potentially ranging from 0-6, (results range 1-6), weighted and standardized scores potentially ranging from 0-100 (results range 24-100).
    ii. Suitability for hybrid stabilization: unweighted scores potentially ranging from 0-6 (results range 2-6), weighted and standardized scores potentially ranging from 0-100 (results range 48-100).

4. Notes:
    a. Distance to boat ramps seems like a very good proxy for wave energy from boat ramps. The fact that no other models use this variable is surprising, especially considering many of them cite this one. A binary, yes-or-no metric based on a one-mile threshold seems coarse, however. Users should consider binning the distance into high, medium, and low metrics for a more meaningful index input.
    b. The model documentation (Carey 2013) lacks a clear description of how soft and hybrid scores were calculated differently. It also lacks interpretation of the index scores to guide users, either by binning into high, medium, and low levels of suitability or into recommended practices. It would be much clearer for the user to derive one single index rather than four, and then to interpret those results in terms of soft and hybrid recommendations, rather than evaluate soft and hybrid practices separately for the entire study area.

Texas: Entire Coastline

1. Information Source:
    a. Story map from the Texas General Land Office: https://storymaps.arcgis.com/stories/d6989e741253424584c06ead83078c5d
    b. Presentation by the Harte Research Institute for Gulf of Mexico Studies, shows inputs and outputs and a decision tree in a section of shoreline at Espiritu Santo Bay, Matagorda Bay, and East Matagorda Bay (Bezore et al. 2022). https://www.glo.texas.gov/coast/coastal-management/forms/files/living-shoreline/presentations-2020/living-shoreline-site-suitability-model.pdf
    c. A Guide to Living Shorelines in Texas (General Land Office 2020). A description of the five factors the model uses is found in Appendix A.
2. Geography: Coastal areas of the entire state of Texas, excluding rivers and Gulf-facing beaches. The area assessed is a series of bays connected by natural and man-made channels.
3. The Model: Decision tree logic is used in this model. The first two tests place all segments near deep water and bordering shipping channels in the "not suitable" class. The remaining branches filter the segments into soft or hybrid stabilization classes based on erosion rate, exposure, scarp presence, and proximity to shipping channels. Finally, locations lacking beach or marsh are classed as needing a "retrofit" stabilization solution. The output is a polyline segmented according to recommended stabilization methods. The input base shoreline layer, and whether and how it is segmented, is not described (Bezore et al. 2022).
    a. Inputs: (in order addressed in the decision tree) with sources.
        i. Nearshore water depth, from USACE

    ii. Whether location borders a shipping channel, from the HRI Channel Polygon
    iii. Erosion rate, from Bureau of Economic Geology Historic Shorelines
    iv. Fetch/exposure, from NOAA wind gauges and USGS fetch model (Rohweder et al. 2012)
    v. Shoreline type, beach or marsh, scarp presence (a proxy for wave energy), from the HRI mapped Environmental Sensitivity Index
    vi. Proximity to the shipping channel, from the HRI Channel Polygon
    vii. Beach presence, from the HRI mapped Environmental Sensitivity Index
  b. Outputs: Segments are sorted by the decision tree tests into four classes. The "retrofit" qualifier is applied when the test for the presence of beach or marsh results in "no."
    i. Soft stabilization
    ii. Retrofit soft stabilization
    iii. Hybrid stabilization
    iv. Retrofit hybrid stabilization
    v. Not suitable

4. Notes:
  a. The decision tree logic used here is the simplest and perhaps most easily repeated of the models reviewed here.
  b. The major weakness of this model is a lack of detailed written documentation. Information about the origin and format of the shoreline base layer, that is, the dataset that is sent through the tests of the decision tree, and whether those tests are applied to existing line segments (as with all other independent models reviewed in this section) or whether the tests create new segment new segment breaks (as is the case with the variations on VIMS SMM described in the next section) would be helpful for users.

Virginia Institute of Marine Sciences Shoreline Management Model (VIMS SMM): Six Adaptations/Applications

This section treats the eight applications of VIMS SMM in the same format (source, geography, model, notes) as the independent models are treated above, given the available information. The applications are presented in reverse chronological order, with the latest and most comprehensive iteration first.

The VIMS SMM was developed by the Center for Coastal Resources Management at the Virginia Institute of Marine Science. The current version (v5.1) is available as a zipped folder including model documentation and toolboxes here: https://www.vims.edu/ccrm/ccrmp/bmp/smm/. The model runs in the ArcMap ModelBuilder application. The user codes all the relevant data into the attribute table of a shoreline feature class. The application uses decision tree logic to classify each segment of shoreline into one of eight management recommendation classes based on combinations of features.

Four of the adaptations reviewed here (Perdido Bay Complex, Tampa Bay, Lake Pontchartrain, and Galveston Bay) were originally targeted for a VIMS SMM application study by the RESTORE Science Program project led by Dr. Chris Boyd of Troy University. Information about that project and a one-hour "lessons learned" webinar recorded in 2020 can be found here: https://restoreactscienceprogram.noaa.gov/projects/living-shoreline-tool

The Galveston Bay and Tampa Bay projects received funding outside the RESTORE Program and took on greater scope involving stakeholders and experts outside of Dr. Boyd's team. The Galveston Bay project ultimately was funded by The Harte Research Institute and the Galveston Bay Foundation, while the Tampa Bay project was funded by the Gulf of Mexico Alliance.

Virginia: Entire Coastline

1. Information Source: Nunez et al. (2022). https://doi.org/10.1016/j.ecoleng.2022.106617
2. Geography: Shorelines (13,779 km) along Virginia's coast. The shoreline has a broad range of physical characteristics, from low energy, highly organic marsh areas to beach and dune complexes, and from natural unmanaged shores to highly developed areas (Nunez et al. 2022).
3. The Model:
    a. Inputs: Sourced from the CCI developed by CCRM / VIMS:
        i. Bank height
        ii. Beach presence
        iii. Canals
        iv. Fetch
        v. Nearshore bathymetry
        vi. Permanent structures
        vii. Public boat ramps
        viii. Riparian land use
        ix. Roads
        x. Sand spits
        xi. Shoreline protection structures
        xii. SAV
        xiii. Tidal marsh
        xiv. Tributary designation
    b. Outputs:
        i. Maintain beach or offshore breakwater with beach nourishment
        ii. Non-structural living shoreline
        iii. Plant marsh with sill
        iv. Groin field with beach nourishment
        v. Revetment
        vi. Revetment/bulkhead toe revetment
        vii. Ecological conflicts
        viii. Highly modified area
        ix. Land use management

        x. No action needed
        xi. Special geomorphic features.

4. Notes:
    a. Nunez et al. (2022) should be considered the authoritative comprehensive description of VIMS SMM as of the date of this report.
    b. The project included a validation/ground truthing procedure involving 40 shoreline sites and a resulting error matrix showing overall accuracy of 82.5% and a Kappa statistic of 0.72.

Mississippi: Biloxi Bay, St. Louis Bay

1. Information Source: The GEO Project at Mississippi State University applied the VIMS SMM (v5.1) to Biloxi Bay and St. Louis Bay (Gray et al. 2022a, Gray et al. 2022b).
2. Geography: Biloxi Bay is in Harrison and Jackson Counties and contains about 28.5 square km (11 square miles) of open water. St. Louis Bay, located in Harrison and Hancock Counties, consists of about 43.3 square km (16.7 square miles) of shallow water.
3. Following the written handbook provided with the model, the input features were coded to multiple copies of a vector shoreline. All copies were combined into a single layer, and the model generated a new output layer with management classes based on the data in the attribute table. The single adaptation to local geography was a change in the way bank height was classified.
    a. Inputs:
        i. Shoreline: In Biloxi Bay, the NOAA Composite Shoreline was adjusted by hand to align with the latest imagery. In St. Louis Bay the shoreline was extracted from a digital elevation model (DEM) derived from 2015 LiDAR from the Mississippi Department of Environmental Quality (MDEQ)
        ii. Riparian Land Use, obtained by visual inspection of aerial imagery
        iii. Beach, Wide Beach from imagery
        iv. Canals, from imagery
        v. Public boat ramps, from online inventories confirmed by imagery
        vi. Roads and Permanent structures, from imagery
        vii. Bathymetry (nearshore water depth) from NOAA
        viii. Shoreline protection structures, from imagery
        ix. Fetch, from visual inspection of a scaled symbol of threshold distances applied to the map surface
        x. SAV, from Mississippi State University Coastal Marine Extension Program, limited to a small area of Biloxi Bay.
        xi. Marsh, visual inspection of imagery, coded in the Riparian Land Use field
        xii. Tributary designation, visual inspection of the shape of the shoreline. Classified segments as tidal creek, major tributary, and bay as a proxy for wave energy.
    b. Outputs: The output for Biloxi Bay is documented as a story map: https://storymaps.arcgis.com/stories/9d84164198ef47068455379e4af56fe7
        i. Ecological conflicts, seek regulatory advice

    ii. Groin field with beach renourishment
    iii. Highly modified area, seek expert advice
    iv. Maintain beach or offshore breakwater with beach renourishment
    v. No action needed
    vi. Non-structural living shoreline
    vii. Plant marsh with sill
    viii. Revetment
    ix. Revetment/Bulkhead toe revetment
    x. Special Geomorphic feature, seek expert advice

Alabama: Perdido Bay Complex

1. Information Source: No written information was found. The model output is available via interactive mapper here: https://www.gsa.state.al.us/apps/CASIS/index.html
2. Geography: A network of small bays and bayous on the boundary between Florida and Alabama, separated from the Gulf of Mexico by barrier islands Perdido Key and Ono Island. This project addresses the shorelines in Alabama only.
3. The Model: Assumed to be the version of VIMS SMM during the RESTORE project 2017-2020.
    a. Inputs: unavailable
    b. Outputs: The stabilization methods as seen with the interactive mapper:
        i. Ecological conflicts, seek regulatory advice
        ii. Groin field with beach renourishment
        iii. Highly modified area, seek expert advice
        iv. Land use management, seek expert advice
        v. Maintain beach or offshore breakwater with beach renourishment
        vi. No action needed
        vii. Non-structural living shoreline
        viii. Plant marsh with sill
        ix. Revetment
        x. Revetment/Bulkhead toe revetment
        xi. Special Geomorphic feature, seek expert advice

Florida: Tampa Bay

1. Information Source: Florida Fish and Wildlife Conservation Commission has a website with a description of the project, a link to the results in story map format, and a link to a written report by Boland and O'Keife (2018). https://myfwc.com/research/gis/regional-projects/living-shorelines/
2. Geography: Tampa Bay is an estuary on the west-central coast of Florida that includes roughly 1036 square km (400 square miles) of surface water. The three counties of the region, Hillsborough, Manatee, and Pinellas, have a population of 2.7 million residents (Boland and O'Keife 2018). The connection to the Gulf is unimpeded (no barrier islands) relative to the other estuaries in this report.

3. The Model: Initially part of the Troy University RESTORE project but was ultimately funded by the Gulf of Mexico Alliance and managed by the FWCC. The model design differs from the current version of VIMS SMM in that input datasets and output recommendations are separated into "shoreline" and "upland" categories. FWCC worked with the VIMS staff to adapt the model to account for the presence of mangrove forests. Information on inputs and outputs were obtained from Boland and O'Keife (2018).
    a. Inputs: *Indicates an input not included in VIMS SMM v5.1.
        i. Vector shoreline
        ii. Riparian land use from ESI shoreline classification and aerial imagery
        iii. Bathymetry from USGS Tampa Bay Topobathy (2006)
        iv. Marsh presence from ESI shoreline classification
        v. Bank height from USGS Tampa Bay Topobathy (2006)
        vi. Canals from ESI shoreline classification
        vii. Sand spits from aerial imagery
        viii. Forested shoreline from ESI shoreline classification*
        ix. Shoreline protection structures (Bulkhead, Marina, Wharf, etc.) from ESI
        x. Offshore erosion control structures from ESI
        xi. Defended shoreline from ESI shoreline classification
        xii. Exposure (fetch) from manual measurements taken in ArcGIS
        xiii. Roads from the Florida Department of Transportation (FDOT) and aerial imagery
        xiv. Permanent Structures from FDOT and aerial imagery
        xv. Beach, wide beach from ESI shoreline classification
        xvi. Tributaries, tidal creeks, from aerial imagery
    b. Outputs:
        i. Upland BMP: Land use management (this term is undefined in the document)
        ii. Upland BMP: Maintain/Enhance/Restore riparian buffer
        iii. Upland BMP: Area of special concern
        iv. Upland BMP: No action needed
        v. Shoreline BMP: Maintain/Enhance/Create marsh
        vi. Shoreline BMP: Plant marsh with sill
        vii. Shoreline BMP: Maintain beach OR offshore breakwaters with beach renourishment
        viii. Shoreline BMP: Groin field with beach renourishment
        ix. Shoreline BMP: Revetment
4. Notes:
    a. Tampa Bay is the southernmost location of the models reviewed here and the only one supporting mangrove forests. This adaption of VIMS addresses the presence of mangroves, but no details are provided (Boland and O'Keife 2018).
    b. This project included a series of public meetings to share model outputs and elicit feedback from stakeholders.

Louisiana: Lake Pontchartrain

1. Information Source: No information about this specific application was found other than an interactive mapper showing the model output: https://troygeoamtics.maps.arcgis.com/apps/webappviewer/index.html?id=f10332f81b9547bb956272c088b282e4
2. Geography: Lake Pontchartrain covers 1600 square km (630 square miles) of open water in Southwest Louisiana. The lake is separated from the Gulf of Mexico by the Rigolets strait and Lake Borgne, a large lagoon.
3. The Model: Assumed to be the version of VIMS SMM during the RESTORE project 2017-2020. Inputs and outputs were obtained from the interactive mapper mentioned above. Sources for the inputs were unavailable:
    a. Inputs:
        i. Boat ramps
        ii. Beach
        iii. Marsh
        iv. SAV
        v. Canals
        vi. Existing shoreline protection structures
        vii. Riparian land use
        viii. Fetch
    b. Outputs:
        i. Ecological conflicts, seek regulatory advice
        ii. Groin field with beach renourishment
        iii. Highly modified area, seek expert advice
        iv. Maintain beach or offshore breakwater with beach nourishment
        v. No action needed
        vi. Non-structural living shoreline
        vii. Plant marsh with sill
        viii. Revetment

Texas: Galveston Bay

1. Information Source: The Harte Research Institute at Texas A&M University Corpus Christi hosts a web page "Integrated Living Shoreline Tools and Community Outreach" https://www.harte.org/project/integrated-living-shoreline-tools-and-community-outreach.
    a. This page briefly describes the Galveston Bay Shoreline Protection Model and has a link to the map viewer showing the model output. Information can also be found in the metadata for the output data layer: http://cmap2.vims.edu/arcgis/rest/services/GalvestonBay/GalvestonBayLSSM/MapServer/0
2. Geography: Galveston Bay has a surface area of roughly 1554 square km (600 square miles). It connects the Port of Houston, the third-largest port in the United States, to the Gulf of Mexico. Almost four million people live in the counties surrounding the bay (National Coastal Condition Report II, 2004).

3. The Model: Developed through an agreement between the Galveston Bay Foundation, Troy University, and CCRM at VIMS to adapt the SMM for use in Galveston Bay using funding from the NOAA RESTORE Science Program. Since no detailed description of the process for adapting the VIMS model to local conditions is available, information about inputs and outputs was obtained from the displayed layers in the interactive mapper referenced above. Two of the inputs, tree canopy presence and oyster presence, are not part of the VIMS SMM v5.1 and are assumed to be adaptations.
    a. Inputs (sources unknown): *Indicates an input not included in VIMS SMM v5.1.
        i. Vector shoreline
        ii. Fetch
        iii. Nearshore bathymetry
        iv. Bank height
        v. Marsh presence
        vi. Beach presence
        vii. Tree canopy presence*
        viii. Permanent structures
        ix. Erosion control structures
        x. SAV presence
        xi. Oyster presence*
    b. Outputs:
        i. High-profile breakwater with marsh planting
        ii. Low-profile breakwater with marsh planting
        iii. Marsh planting with or without shoreline grading
        iv. Revetment
        v. Revetment or bulkhead with rock toe
        vi. Beach nourishment
        vii. Ecological conflicts. Seek regulatory advice.
        viii. Existing breakwater. Seek expert advice.
        ix. Highly modified area. Seek expert advice.
        x. Land use management. Seek expert advice.
        xi. No action needed
4. Notes:
    a. The notable difference between this adaptation and the VIMS SMM used by the GEO Project in Mississippi is the addition of tree presence and oyster presence as inputs.

Alabama: Mobile Bay

1. Information Source: Two presentations describe the project: Boyd and Jones (2016) and Jones (2018). The inputs and outputs are displayed in an online mapper hosted by GSA: https://www.gsa.state.al.us/apps/CASIS/index.html
2. Geography: Mobile Bay occupies about 1070 square km (413 square miles) in Baldwin and Mobile Counties. It connects to the Northern Gulf of Mexico through a 5 km-wide inlet between Dauphin Island and Fort Morgan peninsula.

3. The Model: An early version of VIMS SMM (v3 according to the GSA-hosted map), applied here by Dr. Chris Boyd and Geological Society of Alabama (GSA) geologist Stephen Jones before the RESTORE project. The presentations include detailed maps of armoring (28 categories) and shoreline type (artificial, organic, rock, sediment, vegetated, etc.) from GSA, plus erosion rate data from GSA and USGS.
    a. Inputs: *Indicates an input not included in VIMS SMM v5.1.
        i. Bathymetry
        ii. Marsh presence
        iii. Beach presence
        iv. Tree Fringe (yes or no)*
        v. Erosion rate*
        vi. Shoreline protection structures
        vii. Bank height
        viii. Tributaries
        ix. Canopy Cover (total, partial, bare)*
    b. Outputs:
        i. Shoreline BMPs
            1. Area of special concern
            2. Maintain beach or offshore breakwaters with beach nourishment
            3. Maintain/enhance/create marsh
            4. No action needed
            5. Plant marsh with sill
            6. Revetment
        ii. Upland BMPs
            1. Area of special concern
            2. Land use management
            3. Maintain/enhance/restore riparian buffer
            4. No action needed
4. Notes:
    a. The web mapper shows a VIMS SMM v5.1 update in addition to the v3 (2016) version described here.
    b. Marsh and beach presence involves the use of a 15-foot threshold value, although the effect that threshold has on the output is not described. In v5.1, a distinction between the beach and wide beach is made at 30 feet, and marsh is parsed out as marsh, extensive marsh, or marsh island, with no guidance regarding a threshold beyond which marsh is considered extensive. Current users might consider a quantifiable value such as used here to rule out very small patches, especially if coding over aerial imagery by hand.
    c. This project includes a ground-truthing/validation and a confusion matrix showing overall accuracy of 81% and a Kappa index of 0.67

Maryland: Worcester County

1. Information Source: Berman and Rudnicky (2008), a written report.
2. Geography: Entire mainland coastline faces sounds separated from the Atlantic Ocean by barrier islands with a single inlet at Ocean City. Assateague Island National Seashore dominates the southern portion of the coastline. The model did not address ocean-facing beaches, rather it processed sections of sound-facing estuarine shorelines and inland reaches of the Pocomoke River.
3. The Model: An early version of VIMS SMM from the Center for Coastal Resources Management (CCRM) that was later adapted and applied to five Gulf of Mexico locations. This version classifies the shoreline into three categories: suitable for soft stabilization, suitable for hybrid options, and not suitable for living shorelines. It does not have a "no action needed" category and assumes erosion is present or perceived present at all locations and all landowners and managers are considering taking action. Like the succeeding adaptations, the data is processed in ArcMap ModelBuilder.
    a. Inputs: *Indicates an input not included in VIMS SMM v5.1.
        i. Shoreline: the report does not describe how the shoreline vector was obtained or generated.
        ii. Fetch, CCRM exposure model, values binned low, moderate, high
        iii. Bathymetry from MD Geological Survey. One-meter contour >10m from sure indicates shallow and suitable, otherwise deep and unsuitable
        iv. Presence of marsh from CCRM and MD Dept. of Natural Resources, indicates shallow water and suitability
        v. Beach presence from CCRM, indicates shallow water and suitability
        vi. Bank Condition* from CCRM, three classes, a measure of erosion
        vii. Tree canopy* from Regional Earth Science Applications Center. Absence is deemed suitable for soft stabilization, but the rationale is not explained.
    b. Outputs:
        i. Treatment 1: Planted marsh on existing substrate or minor fill (fiber logs)
        ii. Treatment 2: Riparian modifications: selective tree removal, pruning, bank grading, vegetation restoration
        iii. Treatment 3: Marsh toe revetment: stone structure placed at eroding edge of existing marsh
        iv. Treatment 4: Marsh sill: stone structure with backfill and planted marsh or beach
        v. Unsuitable
4. Notes:
    a. The model was developed in the context of guiding management decisions in a regulatory environment.

TABULATED SUMMARIES OF INPUTS AND OUTPUTS

Table 1: Model Inputs. Models are represented by state name abbreviations. SE = Southeast, SC = Sarasota County.

Input	CT	ME	MD	NH	NC	FL-SE	FL-SC	TX	VIMS v5.1
Aspect (orientation in cardinal direction)		x	x						
Bank height		x	x	x					x
Bathymetry: Nearshore water depth	x	x		x	x			x	x
Beach presence	x							x	x
Blue/Green infrastructure			x						
Boat ramps (as a permanent structure preventing SL modification)									x
Boat traffic (borders a shipping channel)								x	
Boat traffic (distance to boat ramps)					x				
Boat traffic (distance to shipping channel)								x	
Boat traffic (from maps of boat restricted areas)						x			
Canals									x
Cultural resource impacts			x						
Current velocity (max flood current at spring tide)				x					
Distance to inlet						x			
Ecological value assigned by stakeholders				x					
Eelgrass beds				x					
Erosion history/trend/rate	x		x	x				x	
Fetch: distance and wind direction (USGS wind/wave model)	x	x			x	x		x	
Fetch: distance only (VIMS model or visual estimation)			x	x					x
Geology (sand, gravel, mud)			x						
Geology: erodible soil				x					
Land cover: landward and seaward distinct		x		x					
Landowner capacity/interest				x					
Land use and/or land cover			x				x		x
Land use (adjacent parcel)			x						
Land value							x		

Likelihood of demand for stabilization				x					
Marsh presence	x				x			x	x
Marsh: potential for future landward migration				x					
Navigation channels (distance from)				x					
Parcel ownership			x						
Population density							x		
Potential impacts to regulated resources				x					
Roads, permanent structures									x
SAV					x				x
Sea Level Rise			x	x					
Scarp presence (proxy for wave energy)								x	
Shoreline protection structures				x					x
Slope (landward from SL)		x							
Slope (seaward from SL)						x	x		
Storm surge						x			
Tidal crossings (culverts or bridges that convey tidal flow beneath a traveled way)				x					
Tributary designation			x						x
Vegetative cover (%)			x						

Table 2: Outputs for models that do NOT calculate suitability indices.

Output	CT	TX	MD	VIMS v5.1
Beach enhancement with groin field				x
Beach enhancement: non-structural	x			
Beach enhancement: offshore structure optional				x
Ecological conflicts, seek expert advice				x
Groin field with beach renourishment				x
Highly modified area, seek expert advice				x
Hybrid stabilization		x		
Marsh enhancement with structures	x			x
Marsh enhancement with vegetation	x			x
No Action Needed				x
Non-structural living shoreline				x
Offshore structure	x			x
Retrofit hybrid stabilization		x		
Retrofit soft stabilization		x		
Revetment				x
Revetment/Bulkhead toe revetment				x
Soft stabilization		x		
Special geomorphic feature, seek expert advice				x
Output attribute table aggregating input "sociopolitical" information and describing “indications” such as vulnerability to sea-level rise, possibility of lower regulatory barriers, potential public interest/desire/demand, ecological function, and accessibility for construction equipment.			x	

Table 3: Output for models that calculate suitability indices.

Output	ME	MD	NH	NC	FL-SE	FL-SC
Index scores in seven bins, range 1-7, interpreted on a gradient from (1) being soft-w/veg only through levels of veg + structure hybrid to (7) being hard armoring with no veg					x	
Index scores in four bins, range 0-3 all scores rounded to integer, with zero being unsuitable and 3 being suitable. No shoreline segments with a score of 3 (suitable) were found.						x
Index score potential range 0-44, binned in five classes of probably not, likely not, possibly, moderately, and highly suitable for LS	x					
Index with potential score range 0-100. No use of bins to aid interpretation of scores.		x				
Index scores range 1-6, with (1) possibly suitable with significant structural components and (6) being highly suitable for LS, no structural components. Explicitly restricted to "biophysical" inputs.			x			
Four outputs: separate indexes for soft and hybrid stabilization using an unweighted raw score with potential range 0-6 and with a weighted & standardized index with potential range 0-100.				x		

LIMITATIONS AND FUTURE DIRECTIONS

Utility and Exportability of Models

Of the living shoreline suitability models reviewed here, the VIMS SMM is the only one packaged and available for immediate use. It is therefore the most easily exported and distributed model, but not necessarily the easiest to adapt for local conditions. The structure in the ArcGIS ModelBuilder application, the connected workflow that applies decision tree logic to process the data, is very complex, and a thorough knowledge of ModelBuilder is required if a user wishes to make changes. The index-based models (Maine, Connecticut, North Carolina, and Texas) use simpler procedures in which input layers are assigned suitability scores which are aggregated for locations through overlay processes that are transparent and repeatable.

Another advantage the index-based models have over VIMS SMM in terms of ease of use is their simpler approach to segmenting the shoreline for evaluation. VIMS SMM requires users to segment, either by hand or using intersections with input datasets, multiple copies of the vector shoreline. Each copy describes the existence of the relevant features within segments. Changes in features and corresponding segments break on vertices, and the breaks are rarely consistent across features. Consequently, when all shoreline copies are combined into a single layer, many small (< 1m) segments are created, and a preprocessing step identifying these segments and merging them with larger, adjacent segments is necessary. The index-based models, alternatively, segment the shoreline as an initial step, and the input data is aggregated to the segments, eliminating the need for creating new segments or eliminating extremely small segments where features overlap. Most use equal-distance spacing for the segments, ranging in spatial resolution from three feet (Connecticut) to fifteen meters (Maine). Prince George's County, Maryland segments the shoreline by parcel boundaries. Southeast Florida and North Carolina use shorelines classified and segmented by shoreline type and aggregate input data to those units. Information about the Texas model is unclear whether the shoreline is initially segmented by type or undergoes a re-segmentation during the decision tree tests. Initial arbitrary segmentation can provide the advantage of a simpler, quicker, less error-prone process than VIMS SMM. The advantage could be worth the loss in spatial resolution of feature edges VIMS SMM provides if a description of suitability at large landscape scales is prioritized over a precise parcel-by-parcel analysis.

Beyond Property Protection and Permitting: Ecological Contexts

Wetlands are frequently cited as being the most valuable parts of our landscape in terms of ecosystem services. They are sometimes described as *kidneys of the landscape* because of their function as downstream receivers of water and waste, and sometimes as *nature's supermarkets* because of their contribution to biodiversity and the food chain (Mitsch et al. 2015). Living shorelines contribute to the ecological functioning of coastal and estuarine wetlands by maintaining the land-water connection severed by traditional armoring. Regional planners and managers may consider expanding on the permitting and property protection approach taken by the models described here to incorporate prioritization for ecosystem services. Living shoreline practices serve the needs of property owners at the parcel level. When aggregated in a landscape context the practice can provide benefits to entire regions, provided they are configured in a way that improves network connectivity and function. The Maryland (Prince George's County) model is the only one reviewed here with an expressed ecosystem services goal, specifically the reduction of the amount of pollutant, or Total Maximum Daily Load described by the EPA, into the Chesapeake Bay. That model includes an input representing a segment's contribution to an ecologically functioning network using mapped "blue-green infrastructure" data. New Hampshire's model includes information about whether a segment has been designated as important to conservation stakeholders, but only in a stand-alone "sociopolitical" model that does not use numerical values. The regulatory framework is important here: models that express enhancing ecosystem services as a goal additionally mention state laws that restrict traditional armoring.

An additional element for evaluating a location's potential connection to a functioning ecological network is the assessment of the potential of locations to facilitate marsh migration landward in response to sea level rise. Certain types of land use and land cover, and urban use, in particular, constrain landward wetland migration. Areas that don't provide space for wetland migration risk losing the many ecosystem services wetlands provide (Borchet et al. 2018). New Hampshire's model is the only one reviewed here that considers inland future salt marsh potential as positively influencing suitability for living shorelines. The Sea Level Affecting Marshes Model (SLAMM), available from NOAA's Office for Coastal Management's Digital Coast, simulates the dominant processes involved in wetland conversions and shoreline modifications during long-term sea level rise. USGS Scientists have mapped potential corridors for wetland migration across most estuaries of the Northern Gulf of Mexico (Borchet et al. 2018). Particularly when it comes to quantifying the benefit of removal of armoring, living shoreline suitability models could incorporate some of the science and data resources surrounding marsh migration as they expand beyond the parcel permitting framework and into a context of regional ecosystem services.

Future Directions

As scientists and land managers develop new and adapt existing methods for rapidly assessing living shoreline suitability using geospatial data and processes, they should work continuously and iteratively with communities and constituencies to examine the ecological, geophysical, and sociopolitical framework. Who are we assessing suitability for and at what scale? Does a framework of permitting and regulations at a metro level (as with VIMS SMM) necessarily conflict with a framework of water quality and habitat for marine organisms (as with Prince George's County, Maryland)? While it is safe to assume that the significant drivers of suitability – exposure to wave energy, potential for vegetation, nearshore water depth, and bank height – are the same everywhere, the best ways to measure them or their proxies can vary by location. Users should exercise caution when transferring these exact metrics and thresholds to new environments. Erosion trend and rates of shoreline change are valuable inputs to suitability assessments, but good information about this factor can be difficult to obtain locally. The models here show that erosion trend is mapped opportunistically: if the community has access to the information, they use it. The feasibility, or balance of cost against benefit, of removing existing armored structures, is another factor that could greatly improve future assessments if better understood. The effect of boat traffic, the potential for real-time monitoring of the speed and size of crafts, better mapping of shipping lanes or wake-restricted zones, and better understanding of at what distance from traffic corridors boat wakes significantly contribute to erosion, all hold promise for improving the exposure assessments of the future. Finally, potential for improvement exists in developing the logic supporting a "do nothing" recommendation. VIMS SMM is the only model that attempts to define areas where action is not needed because erosion is highly unlikely, but the definition it uses is far too narrow to capture all such instances. No model reviewed here identifies circumstances where allowing the bank to erode naturally is the best option. New Hampshire is a possible exception: Balasubramanyam, & Howard (2019) write that sites deemed highly suitable by the biophysical model may be candidates for no action, especially if they meet certain criteria described in the sociopolitical model. However, the New Hampshire model doesn't generate that interpretation explicitly in the output, only by suggestion in the supporting literature. Refining model logic supporting no action would not only improve the ability of the models to better reflect the broad range of likely scenarios, it may also increase user's confidence that the models won't recommend unnecessary action or the unwise allocation of limited resources.

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