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A geospatial modeling approach to assess site suitability of living shorelines and emphasize best shoreline management practices

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ABSTRACT

The Shoreline Management Model (SMM) is a novel geospatial approach used to assess conditions along a shoreline, and recommend best management practices for defended and undefended shorelines. The SMM models available spatial data in order to identify areas where the use of living shorelines would be suitable to address shoreline erosion. The model was developed to support and inform decision-making by shoreline managers responsible for management of shoreline resources, shorefront property owners, and tidal habitat restoration actions. Recommended erosion control strategies are based on scientific knowledge of how shorelines respond to natural conditions and anthropogenic measures used to stabilize shorelines. The SMM uses input variables representing current conditions and recommends a strategy that falls into one of three general categories: living shorelines, traditional approaches, and special considerations. Areas of special consideration are areas where the model may not be able to provide an appropriate recommendation due to ecological, geological, or highly developed conditions. These areas are given recommendations that include the instruction to seek expert advice. Data required to run the model include presence of tidal marsh, beach, submerged aquatic vegetation (SAV), riparian land cover, bank height, nearshore bathymetry, fetch, and shoreline erosion control structures. The model has been calibrated and validated along Virginia's Chesapeake Bay shoreline, USA. The model results are largely consistent with field recommendations (i.e., shoreline management recommendations made by scientists based on on-site observations during shoreline evaluation visits). The SMM performed with an overall accuracy of 82.5%. The SMM is exportable; the model code can be adapted to other systems. This geospatial model provides a robust screening tool for local and state governments, coastal and environmental planners and engineers, as well as property owners, when considering best management practices, including living shorelines as an alternative for erosion control.

1. Introduction

Shoreline erosion is a major issue for property owners and environmental planners. It occurs over a full range of time scales, including short-term events such as waves, tides, and storms, and long-term changes due to sea-level rise (National Research Council, 2007). Shoreline hardening (e.g., bulkhead, revetments) has been the industry standard for controlling shoreline erosion problems (Gittman et al., 2015). Several studies have shown that the construction of erosion control structures (i.e., armoring or shoreline hardening) results in the decrease, and permanent loss in some cases, of living resources along impacted shorelines (e.g., Bilkovic and Roggero, 2008; Myszewski and Alber, 2016; Tavares et al., 2020). If this trend persists, the areal extent of intertidal habitats will continue to decrease, and the ecological and aesthetic character of streams and rivers will be altered forever.

There is an increasing trend in the coastal management community to adopt and implement strategies using living shorelines as alternatives to conventional hardening for erosion protection, with minimum losses to riparian and intertidal habitats (Polk and Eulie, 2018; Dugan et al., 2018; Silliman et al., 2019; Toft et al., 2021). In the past decade, the concept of living shorelines has started to gain more attention in many coastal communities (e.g., Meyer et al., 1997; Bulleri and Chapman, 2010; Peterson and Bruno, 2012; De Roo and Troch, 2015; Narayan et al., 2016; Borsje et al., 2017; Winters et al., 2020). Natural and nature-

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based approaches to shoreline protection (i.e., living shorelines) are being encouraged through various government policies as alternatives to armoring that not only provide protective services, but also can adapt to rising seas and provide numerous societal and ecosystem benefits. (Narayan et al., 2016; Borsje et al., 2017; Dugan et al., 2018; Winters et al., 2020; Toft et al., 2021). Living shorelines incorporate the use of "non-structural" or "soft- structural" control for shoreline stabilization. Vegetating shorelines with marsh grasses can offer comparable levels of protection against shoreline erosion as revetments and bulkheads (Borsje et al., 2017; Smith et al., 2018). These approaches are considered to provide a balance between private shoreline erosion protection and the public benefits derived from natural shoreline features by having little adverse effect and the likely potential for increased ecosystem services (Isdell et al., 2021). With the incorporation of newly created marsh, living shorelines can offset historical and projected marsh loss (Leo et al., 2019; Mitchell and Bilkovic, 2019) and have been shown to mimic services provided by natural marshes: erosion protection (Scyphers et al., 2011; Gittman et al., 2014; Narayan et al., 2016; Esteves and Williams, 2017), habitat services (Bacchiocchi and Airoldi, 2003; Bilkovic et al., 2016; Sharma et al., 2016; Browne and Chapman, 2017; Onorevole et al., 2018), biodiversity (Isdell et al., 2021), fisheries benefits (Bilkovic et al., 2021), and combined co-benefits to support coastal resilience (Morris et al., 2018; Currin, 2019).

Development of shoreline and coastal management decision support tools has increased in recent years. A few living shoreline models are available via web-based visualizations (e.g., in the USA: Casco Bay, Maine, Texas, and portions of North Carolina); however, most guidance is found in documents and reports available on-line, lacking modeled applications or viewers (e.g.,

Tidal Wetlands Guidance Document: Living Shoreline Techniques in the Marine District of New York State [New York Department of Conservation, 2017]; Site Evaluation for Living Shoreline Projects in Delaware [Delaware Living Shorelines Committee, 2020]; NOAA Guidance for Considering the Use of Living Shorelines [NOAA, 2015]; A Community Resource Guide for Planning Living Shorelines Projects [New Jersey Resilient Coastlines Initiative, 2018]). For example, the Texas model (Bezore et al., 2020) uses a rule-based spatial model calling on bio-physical criteria to produce five living shoreline recommendations, the Casco Bay model produces a ranked score for suitability for living shorelines (*Phase One,* 2021), while The Nature Conservancy's Coastal Resilience Viewer, Living Shorelines Explorer App (*Phase One,* 2021), currently available for two counties in North Carolina, derives living shoreline suitability from three elements; wave and boat wake energy plus existing marsh proximity. These tools provide for informed decision-making relevant to living shorelines uses. Focused only on living shorelines, these tools do not produce management recommendations for shorelines where living shorelines are not suitable. A slightly different shoreline management decision support tool called InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) (Sharp et al., 2020), is a suite of models designed to inform decisions about natural resource management in terrestrial, coastal, and marine systems. The uniqueness of InVEST is that it allows valuation of ecosystem services using environmental data to explore how changes in ecosystems may affect the return of benefits to people, enabling decision makers to assess the tradeoffs associated with alternative choices. Nevertheless, InVEST does not identify shoreline best management practices, but could be used to supplement and support other modeling efforts by identifying areas where investment in living shorelines could enhance human well-being and development (Caro et al., 2020).

To support a more comprehensive coastal management approach, we have developed a geospatial Shoreline Management Model (SMM) to inform, assist, enhance, and streamline regulatory decisions by identifying best management practices (BMP) for tidal shoreline erosion control. The SMM is a spatially-explicit model, which uses a suite of fine scale coastal conditions and characteristics to provide shoreline management recommendations, and specifically where living shorelines are suitable methods for erosion control. The model output is served via a web-based map viewer, which allows the end-user to determine appropriate shoreline best management practices from their desktops and identify the criteria incorporated in the modeled output. The assessment is conducted at parcel level scale (spatial unit considered in the model), but the SMM output represents a reach based or cumulative approach to shoreline management. This geospatial model offers a robust screening tool for local and state governments, coastal and environmental planners, property owners, as well as environmental engineers, when considering erosion control alternatives to shoreline hardening, and promoting the use of natural and nature-based features to support ecological resilience in the face of climate change.

2. Methods

2.1. Study area

Shorelines along Virginia's coast, USA (Fig. 1) were selected (13,779 km) for model development, calibration, and validation. Virginia is a state located in the Mid-Atlantic region of the USA, along the shores of the Chesapeake Bay, the destination of the major tributary rivers. Virginia has a broad range of geophysical, biological, and anthropogenic characteristics, from extremely low energy marsh and organic sediment dominated shorelines, to high energy Atlantic Ocean and Bay facing sandy beach and dune complexes, and natural unmanaged shores to highly managed and commercially developed shorelines (Hobbs et al., 2015).

2.2. Shoreline Management Model (SMM)

Work on the SMM was initiated in 2007 (Berman et al., 2007) as a living shoreline suitability model for undeveloped shoreline. It proceeded with multiple iterations (not published) as a part of the calibration process, each improving upon the output and process, including the incorporation of feedback received by end-users at workshops and through other communications. The SMM work presented here represents the most comprehensive and validated iteration, using the most recent technologies, scientific understanding, and shoreline management policy.

The SMM is a geospatial model run in ArcGIS that provides a recommended approach for tidal shoreline erosion control and identifies where living shorelines are suitable (Fig. 1). Recommended erosion control strategies are based on decision trees (https://www.vims.edu/ccrm/ccrmp/bmp/decision_tools/index.php) developed to inform shoreline decision-making, which are reflective of current scientific knowledge of how shorelines respond to natural conditions and anthropogenic measures, the direct and cumulative impacts of conventional shoreline stabilization, and best professional judgment from over 4000 shoreline site visits. The logic workflow of the SMM is derived from the decision trees as shown in Fig. 3 and Appendices A, B, and C.

The model outputs eleven possible recommendations for Virginia: three living shoreline options (non-structural living shoreline, maintain beach or offshore breakwater with beach nourishment, plant marsh with sill), three traditional management approaches (revetment, bulkhead with toe revetment, groin field with beach nourishment), and five cases of special consideration (where it is advised to seek expert advice; for example, due to ecological conflicts). The SMM is comprised of three sub-models (Fig. 2). The models were built in ArcMap version 10.6.1 using ModelBuilder. The core part of the SMM (Fig. 3) calls on the three sub-models: SMM – Existing Bulkhead (Appendix A), SMM – Existing Revetment (Appendix B), and SMM – Undefended (Appendix C). The sub-models have been created separately, primarily for ease of management. Running the SMM creates a new feature class (i.e., a new file) with recommended preferred shoreline best management practices for defended and undefended shoreline (definitions displayed in Appendix D). The SMM uses input variables representing the most current

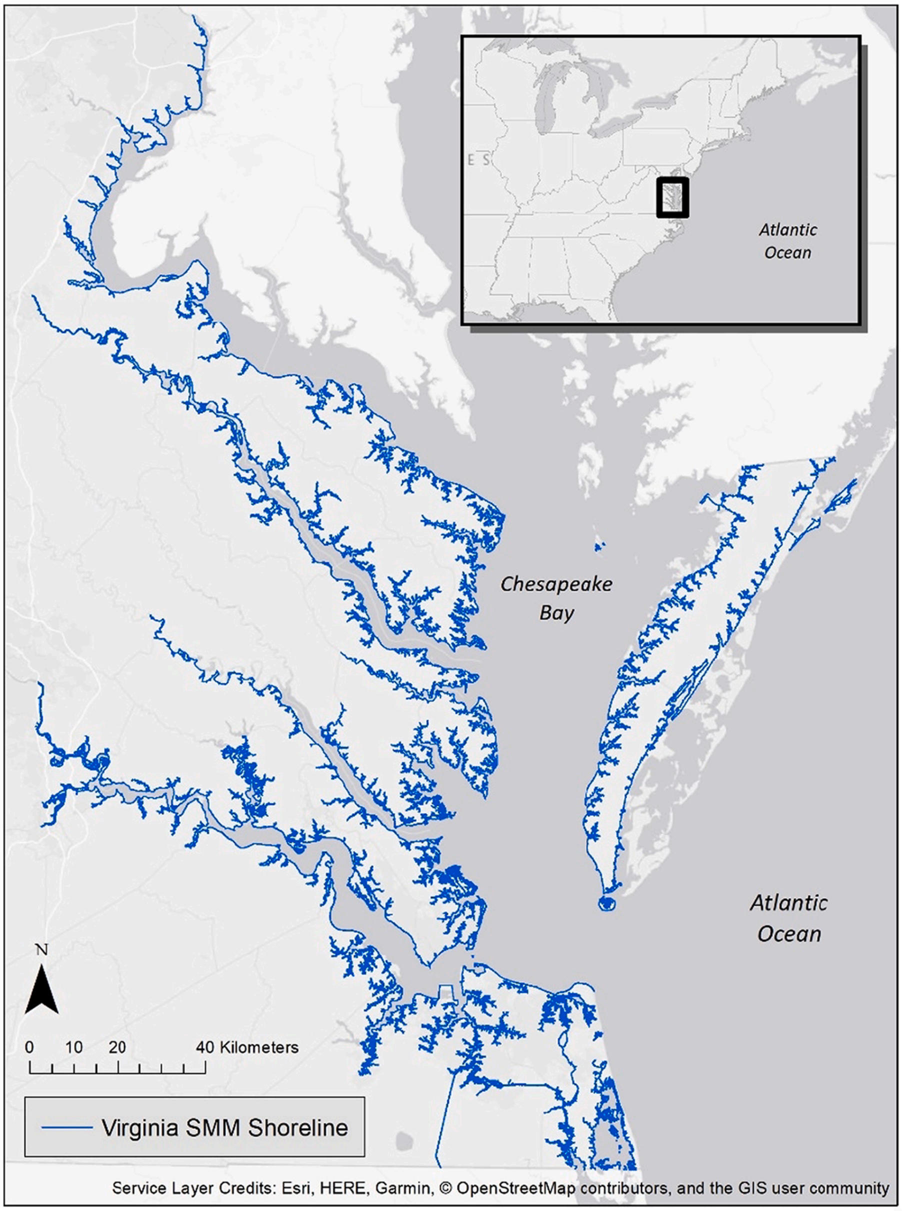

Fig. 1. Shorelines along Virginia's coast, USA, where the SMM was applied. Note, the SMM has been developed to support tidal shoreline decision-making to address erosion along tidal shorelines. Due to data availability during model development, the open Atlantic shoreline was not considered in this study.

shoreline and riparian conditions at the time the model is run.

The model output can be downloaded as a shapefile (geospatial vector data) and it is also served via a web-based map viewer, which allows the end-user to identify the criteria incorporated in the generation of each modeled output.

2.2.1. *Model input*

The line feature representing the shoreline is the basis for the SMM, digitized by matching the land-water interface at a scale of 1:1000 using the latest high-resolution digital imagery as a background from the Virginia Base Map Program (VBMP) (source: Virginia Geographic Information Network (VGIN) Aerial Imagery). The file format of the shoreline is a shapefile (common format for storing geometric location and attribute information of geographic features). The shoreline was checked and edited in ArcGIS v10.6.1 to ensure a clean, continuous line. The QA/QC process for revising the shoreline involves running topology rules to ensure that the arc has no overlapping segments or dangles (Rudnicky and Berman, 2020). All required model inputs (criteria) were transferred onto this linear base shoreline by using the Identity Tool in ArcGIS v.10.6.1.

An existing comprehensive inventory of shoreline conditions for tidal localities in Virginia, known as the Comprehensive Coastal Inventory (CCI), developed by the CCRM/ VIMS, provided critical data input for the model. The inventory uses state of the art Global Positioning Systems (GPS) and Geographic Information Systems (GIS) to collect, analyze, and display shoreline conditions. The protocols and techniques have been developed over several years, with adaptations to incorporate recommendation and data needs conveyed by state and local government professionals. The inventory data for each coastal locality was digitized from the latest available high-resolution imagery from the Virginia Base Mapping Program (VBMP) using on-screen, digitizing techniques in ArcGIS. All mapping was accomplished at a scale of 1:1000. The data developed for the Shoreline Inventory was based on a three-zone assessment approach, which generated a collection of descriptive measurements: 1) the immediate riparian zone, evaluated for land use, and tree fringe; 2) the bank, evaluated for height, stability, cover, and

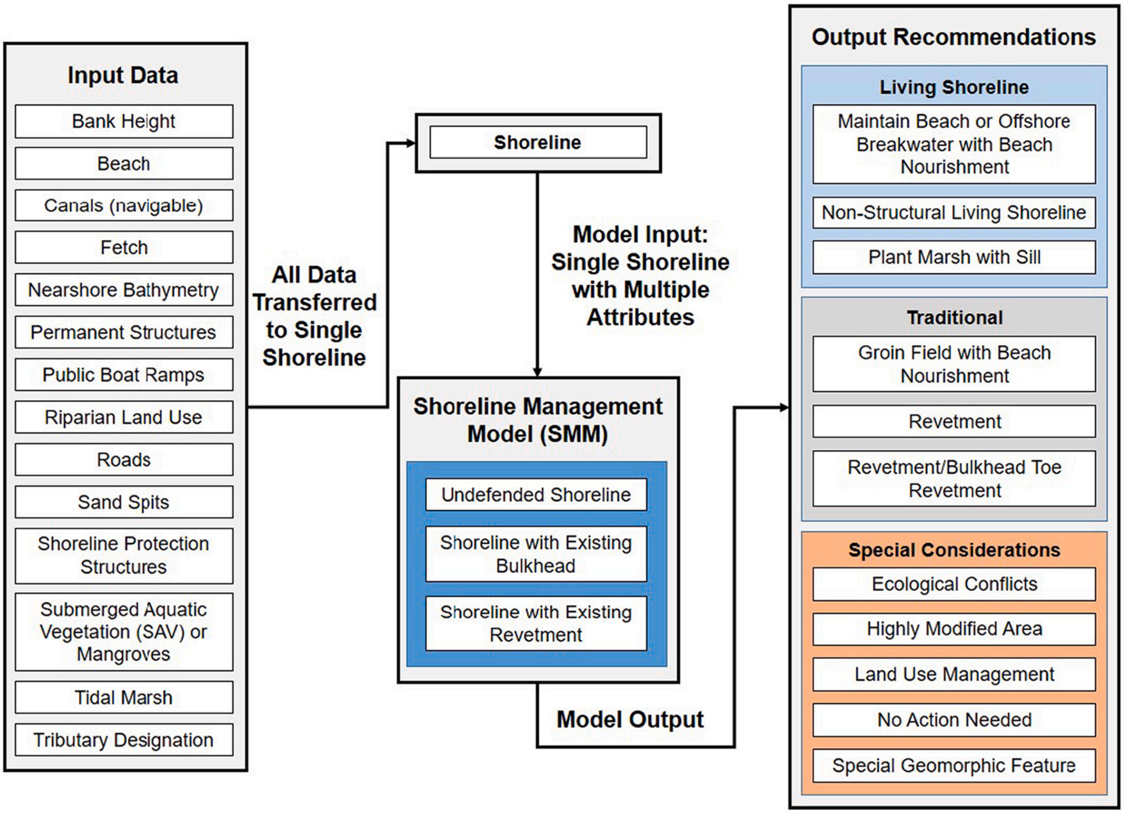

Fig. 2. Conceptual diagram representing input data, major components of the SMM, and the different output recommendations.

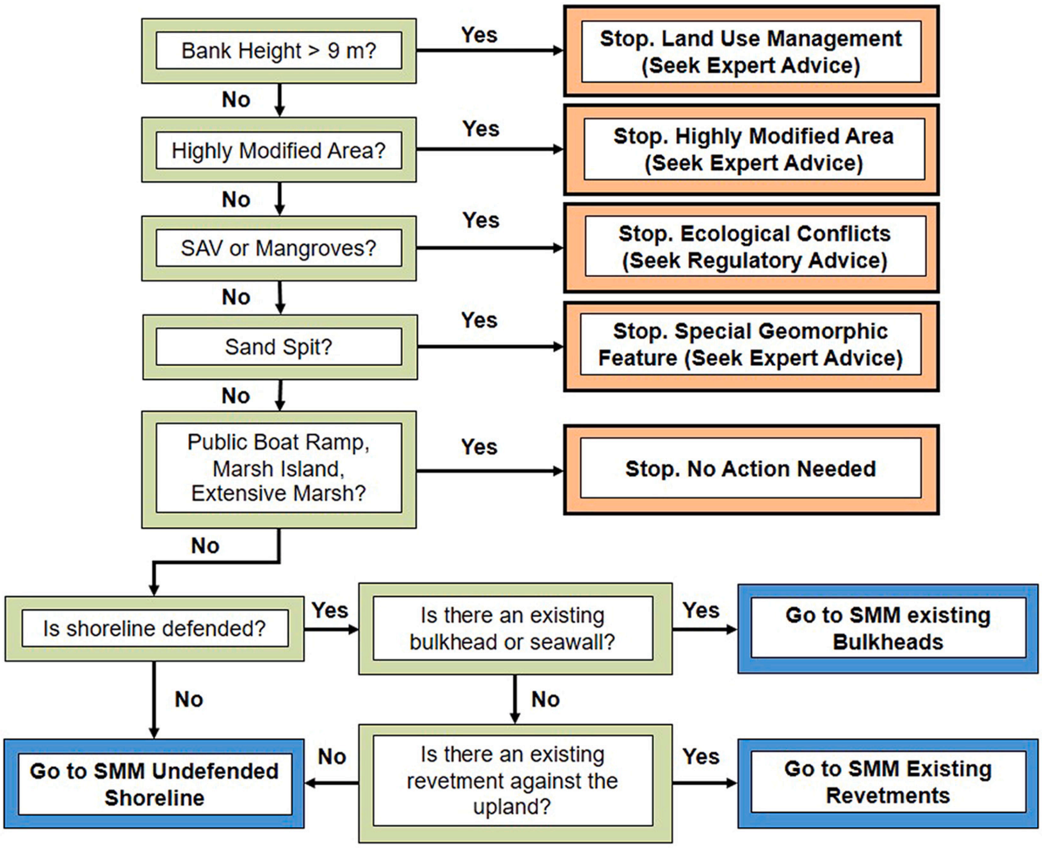

Fig. 3. Shoreline Management Model (SMM) Flow Chart.

natural protection; and 3) the shoreline, describing the presence of shoreline structures for shore protection and recreational uses. Definitions of each of the shoreline features are provided in Appendix E.

SMM inputs included a large array of shoreline characteristics ($n = 14$) from CCI and other sources. Below is a description of each of the model inputs:

2.2.1.1. Bank height. Bank height is the vertical distance measured from the base (or the toe) to the top of the bank. It can be estimated from imagery, field inspection, videography, topographic maps, LIDAR, or from a combination of these sources. We used bank height data derived from the CCI. Bank height categories (i.e., 0–1.5, 1.5–9.0, and > 9.0 m) were used to determine if bank grading to a 3:1 bank slope is feasible without impacting permanent structures (e.g., roads, houses). To that end, we buffered the shoreline based on the bank height using the maximum height (maxHgt) for each bank height category. The buffer was calculated using the following formula: ((3 x maxHgt) + 6), where (3 x maxHgt) gives the preferred 3 to 1 bank slope, and 6 adds an extra six meters of horizontal distance from top of the modeled slope for margin of safety. The modeled buffer was used to assist with the creation of the roads and permanent structures layer described further below. Additionally, the bank height was used by the SMM to search for low bank height (0–1.5 m) and high bank height (>9.0 m) when determining recommendations.

2.2.1.2. Beach/wide beach. Beach information was populated into the base shoreline by scanning the shoreline for beaches using the latest high-resolution imagery from VBMP, as well as utilizing a pre-existing beach dataset (CCI). Beaches were coded as linear features to portray their spatial location only. The land water interface for beach environments was delineated between the dry beach and wet beach (if present) or the dry beach and the shallow water (if wet beach was not present). These parameters were delineated based on color signature; color explicit in the infra-red imagery where: dry beach is represented by "stark white," and wet beach by "gray white." Wide beaches have at least three meters of dry sand persistently visible above high tides (Hardaway et al., 2006). The model only considers the width of a beach when it occurs with a groin field, otherwise it is processed as a regular beach. This process is detailed in Appendix C.

2.2.1.3. Canals, public boat ramps, & sand spits. These land features, (created as one layer in ArcGIS using high-resolution imagery) represent complex conditions or navigational interests and/or constraints necessitating additional review outside of the model to determine preferred erosion control options if any, and for which a recommendation is not provided. For these special conditions, the model, based on remote sensed data, may not provide an appropriate or feasible recommendation. For canals and ramps, space limitations and navigation interests must be considered. For small sand spits, the need for erosion control may not be warranted given the ephemeral nature and persistence under sea level rise questions. Model output flags these areas and provides the user additional guidance for next steps.

2.2.1.4. Fetch. Fetch was determined as the longest distance over water to the nearest shoreline based on 16 directions radiating from a point on the shoreline. Fetch is used as a substitution for wave energy. This data was created using the Fetch Model developed at CCRM/VIMS to calculate the average maximum fetch based on the values within four quadrants (NE, SE, SW, and NW). The final fetch input layer had information about the maximum single line fetch, and the maximum average quadrant fetch classification (a mean derived from all compass points within a 90-degree angle), with values of "Low", "Moderate", or "High", where: Low = 0–0.8 Km, Moderate = 0.8–3.2 Km, High ≥3.2 Km. The longest fetch vector and the average of the fetch vectors by quadrant computed at a given point determine the fetch class for that point. The information coded in the points is then transferred to the paired shoreline segments.

2.2.1.5. Nearshore bathymetry. Nearshore water depth is an important consideration in determining the type of erosion control structures that are feasible. Shallow nearshores are suitable for the application of on-bottom structures, where allowed, that rise above or nearly above the high-water level including breakwaters and sills. If the nearshore is too deep, or the substrate gradient is too steep, strategies such as planting marshes, and constructing breakwaters or sills may not be practical. Since detailed shallow water bathymetry is rarely available, and to make the model application more universal, the SMM calculates a distance from the shoreline to the one-meter water depth contour as an indicator of the nearshore water depths. The further the one-meter bathymetric contour is from the shore, the more gradual the slope and the shallower the water. To determine this parameter, we used the NOAA topobathy (Danielson and Tyler, 2016) contour layer. The distance of the one-meter bathymetric contour to the shoreline was used to determine if the nearshore is suitable for shallow water management strategies. When the one-meter bathymetric contour is greater than 10 m offshore, nearshore depth is considered "Shallow," otherwise it is coded as "Deep".

2.2.1.6. Roads and permanent structures. TIGER/line shapefiles from the US Census Bureau (https://www.census.gov/geographies/mapping-files/time-series/geo/tiger-line-file.html) were used as model inputs for roads. Building footprint data (Virginia Geographic Information Network (VGIN)) was verified by visual inspection to improve the accuracy of permanent structures coding on the baseline shoreline. Please note permanent structures are visible upland structures (i.e., houses or swimming pools), not shoreline structures (e.g., bulkhead, riprap, etc.) or septic fields or wells.

2.2.1.7. Shoreline protection structures. We employed the high-resolution inventory of shoreline structures generated by CCRM/VIMS to spatially assign shoreline protection structures to the base shoreline. This line feature dataset was coded for erosion control structures that are located on or off the shoreline, such as bulkhead, riprap (revetment), marina, and wharf (definitions in Appendix C). Marina was included in the model because they often have hardened shorelines. Breakwater, groin, and marsh toe (marsh sill) were coded as offshore structures, whereas bulkheads and most revetments are coded as onshore.

2.2.1.8. Submerged Aquatic Vegetation (SAV). Environmental regulation and policy may prohibit the building of certain shoreline protection structures where protected habitats, such as submerged aquatic vegetation (SAV) exist. For the Virginia model, we used SAV data from the SAV Monitoring & Restoration Program at VIMS. We searched for SAV within nine meters of the shoreline, using a composite of the most recent five years of SAV data (presence/absence), to address the ephemeral nature of SAV in response to varying climate conditions and species. For model application in other settings, end users may opt to incorporate special habitat data: 1) utilize existing sources for geospatial SAV data, 2) develop the delineation by using high-resolution imagery (preferred), or 3) use best professional judgment of sites of known occurrence.

2.2.1.9. Tidal Marsh. An existing spatial marsh dataset could be used as model input, or a layer of tidal marshes can be generated by digitizing the marsh polygons using high-resolution imagery. We used the Tidal Marsh Inventory (CCRM/VIMS) as marsh data input. Marshes were digitized (1:1000 scale) using high resolution, geo-referenced natural color imagery collected by the Virginia Base Mapping Program (VBMP). Marsh boundaries were field checked, primarily using Global Positioning System instrumentation from as shallow-draft vessel, navigating at slow speeds parallel to the shoreline. Additionally, site visits where conducted when possible. The marsh polygon layer was transferred to the base shoreline using the Identity Tool in ArcGIS v.10.6.1. The value of "Marsh present," "Marsh Island," or "No" are incorporated into the SMM. Marsh islands are isolated vegetated wetlands surrounded by water (see the definition in Appendix E) and are generally not part of the base shoreline. Inclusion of marsh islands in the model is optional.

2.2.1.10. Tributary designation. Small tidal creeks and tributaries with little average wave exposure occasionally may have a single fetch vector that can run a considerable distance, depending on sinuosity of the shoreline. This could cause an erroneous designation of the shoreline segment as "High" or "Moderate" fetch when the actual average condition is moderate or low energy. The modeled output would reflect the imprecise higher energy designation and recommend a strategy which would be over engineered for the actual site (e.g., revetment or a breakwater). To address this issue, we created an attribution of "Tidal Creek" to classify these low energy settings regardless of the presence of one or two isolated vectors (of 16 analyzed) longer than three kilometers. This classification was used only in the SMM for undefended shorelines. The tributary attribute and values were transferred onto the base shoreline using different geoprocessing tools in ArcGIS.

2.2.2. Model setup

Below is a brief description of the steps to set up the SMM. For further details refer to the Shoreline Management Model Manual (Rudnicky and Berman, 2020).

2.2.2.1. Model main branch. There are several operations required prior to running the SMM. These steps involve coding and transferring all necessary data into a single shoreline, and classifying the shoreline as 'Defended" (shoreline structures present) or "Undefended." In addition, the main model branch uses the added attributes in the single shoreline to identify areas of special consideration (i.e., canals, marinas, commercial or industrial land use with hardened shoreline [i.e., bulkhead, riprap, wharf], areas where riparian [immediately landward of the shoreline] land use is paved [e.g., large parking lots], and roads that have been identified as being close to the shoreline) (Fig. 3). Shoreline classified as "defended" is input into one of the two defended shoreline branches in the model: a) Existing Bulkhead or b) Existing Revetment. All shoreline segments not coded for structure are passed to the Undefended branch of the model. The results from the three branches are merged back into one final output (i.e., line feature portraying the shoreline management recommendations). The three branches of the SMM are explained in more detail below.

2.2.2.2. Existing bulkhead model branch. All defended shorelines are input into this branch. The model selects the structures equal to bulkhead or seawall. The selected records are processed using a series of selections and reselections to find various conditions based on fetch (exposure), nearshore depth (bathymetry), wide beaches, groins (offshore structure), and roads/permanent structures next to a low bank (Appendix A). The results of this model are transferred back into the model main branch of the SMM.

2.2.2.3. Existing revetment model branch. This model branch selects from all the structures coded as riprap. The branch continues in the same way that the Existing Bulkhead model branch does with selections and reselections to find various conditions based on fetch (exposure), nearshore depth (bathymetry), wide beaches, groins (offshore structures), and roads/permanent structures next to a low bank (Appendix B). The results of this model are transferred back into the model main branch of the SMM.

2.2.2.4. Undefended model branch. The input to this branch is undefended shorelines and any defended shoreline not captured by the two defended sub-models. The branch presents a series of sub-selections of various conditions (beach, marsh, fetch, bathymetry, offshore structures, structures associated with low height bank, and tributaries) to determine the shoreline recommendation (Appendix C). The results of this model are transferred back into the main branch of the SMM.

2.2.3. Evaluation of the model performance

The evaluation of the SMM performance was conducted as a direct comparison of model outputs against field observation and on-site recommendations. We used field data from the VIMS Advisory Database to extract shoreline management recommendations made by scientists based on on-site observations during shoreline evaluation visits. The on-site field recommendations from 40 shoreline sites (sites were sorted by waterway to ensure sites with a variety of wave climate settings) were compared with the output of the SMM to assess agreement.

An error matrix (or covariance matrix) was employed to statistically quantify the degree of agreement between on-site recommendations and SMM outputs. The matrix allowed the overall model accuracy evaluation and calculation of the Kappa statistic, a robust statistic, and the most commonly reported measure in assessing model agreement using categorical variables with multiple levels (McHugh, 2012; Tang et al. 2015). Errors in the GIS environment can be divided into positional errors (observed element is no longer there, new element has been added, or the location is not accurate), classification errors (based on observations or modeled classification incorrect assignment), and error propagation. Classification errors are reported as omission, commission, and overall error. Moreover, as suggested by Viera and Garrett (2005), the Kappa statistic was calculated to express how much better (or worse) the classification is relative to chance alone.

3. Results - model output

3.1. Recommended best management practices

Based on the site conditions, the SMM generated a spatial linear feature with recommended preferred shoreline best management practices for defended and undefended shoreline. The new line feature class provided eleven possible recommendations: three living shoreline options: 1) non-structural living shoreline, 2) maintain beach or offshore breakwater with beach nourishment, 3) plant marsh with sill), and three conventional management approaches: 1) revetment, 2) bulkhead with toe revetment, 3) groin field with beach nourishment, and five areas of special consideration. Areas of special consideration (i.e., land use management, highly modified area, ecological conflict, special geomorphic feature, no action needed) were assigned based on site-specific features, such as presence of submerged aquatic vegetation, shorelines with steep banks, and highly developed upland, among others (Table 1). See Appendix D for the definition of each.

Table 1
SMM recommendations for Virginia Shoreline: length (km) and percent (%).

SMM Recommendation	Shoreline length (km)	Percent (%)
Plant Marsh with Sill	*991*	*7*
Maintain Beach or Offshore Breakwater with Beach Nourishment	*639*	*5*
Non-Structural Living Shoreline	*9078*	*66*
Groin Field with Beach Nourishment	30	<1
Revetment	212	2
Revetment/Bulkhead Toe Revetment	5	<1
Land Use Management	41	<1
Highly Modified Area	688	5
Ecological Conflicts	1113	8
Special Geomorphic Feature	25	<1
No Action Needed	958	7
Total	**13,779**	**100**

Along the shoreline, we found that 350 km (61%) of existing bulkhead and 523 km (69%) of revetment are suitable for replacement with a living shoreline treatment (Table 2). Most of the remaining conventional hardening is in a setting where expert advice is recommended due to a highly modified landscape or presence of an ecological conflict. These results suggest that conversion of this shoreline to marsh and beach, possibly including vegetated riparian buffers, can offset some of the historic resource losses and serve as a conservation strategy (Bilkovic et al., 2016), count toward restoration goals, and provide other co-benefits such as natural vistas, flood benefits, recreation, and more.

Examples of SMM spatial outputs are displayed in Fig. 4. The top panel represents a low energy area, mostly with residential and commercial land uses with SMM recommendations of: “Non-Structural Living Shoreline”, “Revetment,” and “Revetment/Bulkhead Toe Revetment.” The bottom panel represents a combination of physical setting (high and low energy systems), where “Non-Structural Living Shorelines” are mostly recommended in the sheltered shorelines, and sections of shorelines with higher exposure were identified as “Ecological Conflict” due to the presence of submerged aquatic vegetation (SAV).

3.2. *Evaluation of model performance*

The forty locations with reported on-site field recommendations employed to generate the error matrix for the model validation are displayed in Fig. 5.

The error matrix (Table 3) summarizes the relationship between model outputs and the field data and on-site recommendations. The bold numbers in the diagonal indicate the agreement between the SMM and the field evidence at each category. The commission error is analogous to a Type II error or a false positive. The omission error is analogous to a Type I error or a false negative. Appendix F shows a commonly cited scale to interpret the value of the Kappa statistic (Landis and Koch, 1977; Viera and Garrett, 2005). The model results are largely consistent with field recommendations. The SMM performed with an overall accuracy of 82.5% and with a Kappa statistic of 0.72, which can be translated as “substantial agreement” (Appendix F) (Viera and Garrett, 2005).

4. Discussion and applications

We have presented a novel geospatial model to inform, assist, enhance, and streamline regulatory decisions by identifying best management practices for tidal shoreline erosion control. The spatial visualization of the SMM output provides a unique tool to answer specific coastal management questions (e.g., Beck et al., 2017; Bilkovic and Mitchell, 2017; Berman et al., 2018; *Phase One,* 2021); particularly at a locality or regional scale, where site-specific observation may not account for the length of the shoreline or adjacent bio-physical variables. Some advantages of the SMM compared with other living shoreline models and coastal management decision support tools (e.g., Sharp et al., 2020; Bezore et al., 2020; *Phase One,* 2021; *Phase One,* 2021) are: 1) the parcel scale, spatially explicit inventory of shoreline conditions are input to the model, 2) fourteen variables are considered, 3) it produces eleven recommendations for all shoreline- undefended and defended- including living shoreline retrofits where suitable, 4) outputs have undergone a rigorous validation process based on over 10 years of permitting decisions, 5) the model was developed and updated based on formal and informal feedback from end-users at workshops and through other communications, and 6) the model is exportable; the SMM can be modified to determine living shoreline suitability that reflects local policy and regulations.

Table 2
SMM recommendations for shoreline with existing conventional hardening, bulkhead and riprap shoreline.

SMM Recommendation	Existing Bulkhead (Km)	Existing Riprap (Km)
Plant Marsh with Sill	46	64
Maintain Beach or Offshore Breakwater with Beach Nourishment	67	175
Non-Structural Living Shoreline	237	284
Groin Field with Beach Nourishment	4	3
Revetment	32	24
Revetment/Bulkhead Toe Revetment	5	0
Land Use Management	1	2
Highly Modified Area	139	100
Ecological Conflicts	46	104
Special Geomorphic Feature	<1	<1
No Action Needed	<1	<1
Total	**578**	**755**

The SMM outputs show a substantial agreement with the on-site recommendations provided by coastal scientists. Most of the modeled Virginia shoreline (73%) is suitable for a living shoreline (non-structural and marsh with sill), which is the expected result given the sheltered nature of most of the tributary shoreline (Hobbs et al., 2015). Along the Bayshore and river mouths, shore reaches of higher energy dominated by sandy beaches, 5% of the shoreline is suitable for breakwaters with beach nourishment. A small percentage of shoreline (3%) is recommended for revetment or bulkhead toe revetment; a smaller number than expected based on the observed revetted Virginia shoreline (Center for Coastal Resources Management (CCRM), 2019). When the model recommendation for revetment/ bulkhead toe revetment are compared to the existing revetment and bulkhead percentage (9%) (Center for Coastal Resources Management (CCRM), 2019) it appears unlikely that the prevalence of existing structures is based on the true erosion conditions, but on considerations such as perceived risk, bank stability concerns not related to tidal erosion, overland runoff or landscaping (Stafford and Guthrie, 2020). In addition, there are certain tidal reaches with well-established and sustaining SAV that are identified as possible ecological conflicts (example Fig. 4). These areas may be suitable for LS implementation, but proper design might encroach into SAV which is generally not permissible.

4.1. *Model limitations*

It is important to state that the SMM recommendations are made without consideration of certain physical and socio-economic parameters, such as shoreline length, ownership, or property value. Recommendations are based on best available geospatial physical and ecological data, which may not reflect the actual conditions present on the shoreline. We note that the implementation of SMM recommendations requires a site-specific assessment. The SMM performed with an accuracy of 82.5%. The model accuracy is dependent upon the availability, currency, and precision of the data and the interpretation of the remotely sensed imagery. For the present study, the SMM land use data range from 2008 to 2017. This means that anthropogenic or natural changes may have occurred in the landscape post data collection, particularly for those localities with older data. As both development and naturally occurring chronic and stochastic changes affect infrastructure and natural features extent and distribution, recommendations based on consideration of those criteria may no longer be suitable. However, with a Virginia regulatory program that restricts the placement of buildings within 30 m of the shoreline, no longer suitable recommendations are less likely to be attributed to new infrastructure and more likely due to changes in natural features. Regardless, at locality scales wherein cumulative shoreline may be hundreds of kilometers, anthropogenic changes or natural changes at parcel scale will not impact the overall relevance of the recommendation to the locality.

There are site-specific conditions that can limit the implementation of any recommended practice such as nearshore substrate, nearshore water depths, below surface infrastructure including wells and septic systems, and others (Davis, 2017; Miller et al., 2015). Remotely sensed data may not be available or lack adequate precision to properly reflect

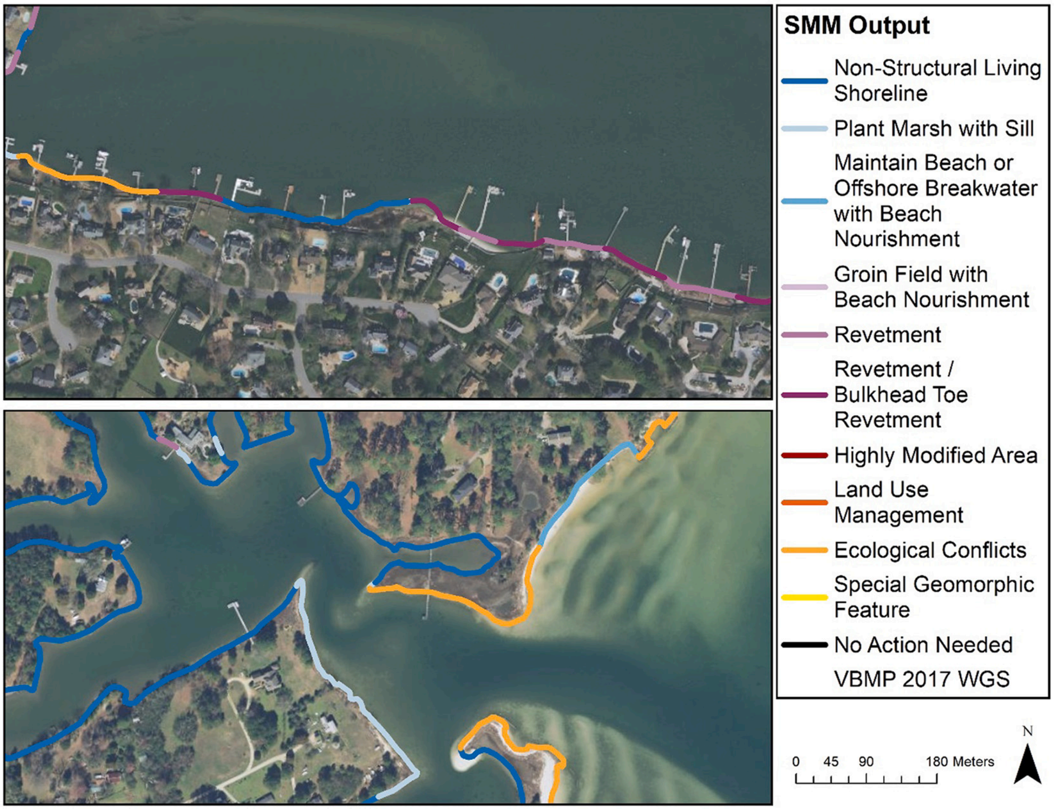

Fig. 4. Sections of the shoreline of City of Virginia Beach (top) and Gloucester County (bottom), Virginia, displaying the SMM outputs. Background image: VBMP2017/VBMP2017_WGS—Virginia Geographic Information Network (VGIN).

site-specific conditions. For example, construction of a living shoreline marsh with sill requires a substrate material that will support the weight of the sill material, commonly granite. Lacking detailed data on subaqueous bottom geology may result in a living shoreline recommendation where it is not suitable. The reliance on fetch distance as a surrogate for energy and erosion condition does not incorporate boat-wake caused erosion; a concern particularly in small creeks (Bilkovic et al., 2019).

4.2. Model applications

The code of the SMM is exportable for application along tidal shorelines. Recommendations and definitions may be customized to reflect regional terminology and guidance for shoreline erosion control strategies, particularly living shorelines suitability modeling. In collaboration with communities in Galveston Bay, Texas; Tampa Bay, Florida; Mobile Bay, Alabama; Lake Pontchartrain, Louisiana; and Maryland, the SMM has been adapted to reflect local conditions and meet local management needs. Modifications have incorporated inclusion of habitats such as mangroves, and variable shoreline management recommendations (e.g., Boland and O'Keife, 2018). These locales have applied the model to their settings and developed a calibration and validation process based on their use. For instance, in the case of Mobile Bay, Alabama, the SMM performed with 84% of accuracy; SMM outputs and on-site recommendations agreed in 97 sites out of 116 sites surveyed *(S. Jones, personal communication, July 7, 2020)*.

Possible applications of the SMM to management questions could include decision-making for habitat restoration, flood benefits relatives to climate resilience, implementation of natural and nature-based features, water quality, best management practices or any combination of those. For example, Berman et al. (2020) applied the SMM to calculate the potential pollutant load reduction that could be achieved via implementation of living shorelines where suitable in Virginia. Implementation of best management practices to address non-point source pollution is a critical component of pollution load reduction. Using the SMM for both, defended and undefended shorelines, allowed for calculation of load reductions (using values from Chesapeake Bay Program, 2019) for new shoreline treatments, and where conventional structures were retrofitted with a living shoreline. Another example of the SMM application is the identification of restoration project recommendations for coastal flood benefits in conjunction with water quality and Federal Emergency Management Administration (FEMA), National Flood Insurance Program (NFIP) co-benefits for coastal Virginia. A NOAA funded project (#NA17NOS4730142) identified all coastal buildings, at elevations below three meters, which lack any coastal natural or nature-based features (NNBF) between tidal waters and the building location. Where these locations intercept the shoreline, they were identified as targets for creation/ restoration of NNBF(s) to provide flooding, water quality and possible NFIP benefits. As tidal marsh is one such feature, and the SMM identifies where they are suitable as an element of a living shoreline; the model recommendations can inform planning and implementation of living shoreline projects to achieve multiple benefits.

5. Conclusions

The application of the SMM provides a novel approach to identify best management practices to address erosion along tidal shorelines. The evaluation of the model performance showed a substantial agreement when compared with on-site recommendations, with some limitations as described above. Nevertheless, the broad scale need and uses for such a tool counterbalance the limitations. The SMM was used to produce recommendations for Virginia with living shorelines modeled as suitable for 73% of the shoreline. One of the major advantages of implementing these recommendations is that natural components, such as marsh

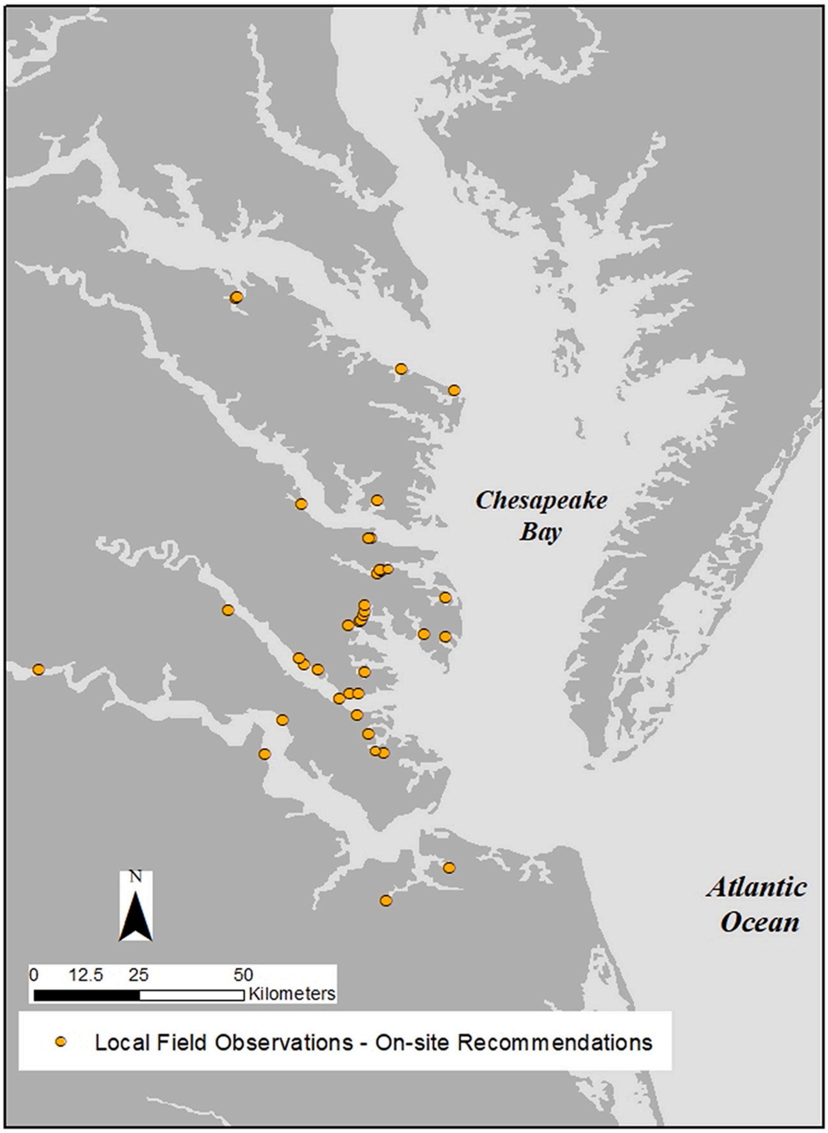

Fig. 5. Points used to generate the error matrix (40 points) along Virginia's Chesapeake Bay shoreline. These locations represent the field recommendations used to validate model outputs.

Table 3
SMM recommendations.

		Non-Structural Living Shoreline	Plant Marsh with Sill	Maintain Beach or Offshore Breakwater	[a]Traditional Management Approach	[b]Maintain Existing Treatment	Total	Omission Error
On-site Recomm-endations	Non-Structural Living Shoreline	**21**	1	0	0	0	22	0.05
	Plant Marsh with Sill	1	**6**	2	0	0	9	0.33
	Maintain Beach or Offshore Breakwater	0	0	**5**	0	0	5	0.00
	[a]Traditional Management Approach	0	0	0	**0**	0	0	0.00
	[b]Maintain Existing Treatment	0	0	3	0	**1**	4	0.75
	Total	22	7	10	0	1	**40**	
	Commission Error	0.05	0.14	0.50	0.00	0.00		0.82

[a] Traditional Management Approach = revetment, bulkhead with toe revetment, groin field with beach nourishment.

[b] Maintain Existing Treatment = riprap, bulkhead.

vegetation, are self-sustaining and can expand or migrate given the right conditions (Gittman et al., 2014; Leo et al., 2019; *Phase One,* 2021. In this way, the SMM enables and supports decision-making consistent with public policy promoting the use of nature-based solutions (*Phase One,* 2021), or natural and nature-based features, for shoreline management. While developed to support tidal shoreline permit decision-making, the output is accessible to a wide range of audiences, from coastal planners and scientists (e.g., *Phase One,* 2021) to private property owners and private businesses (e.g., Boland and O'Keife, 2018). The SMM can be an important management tool, incorporated into shoreline management plans, situation reports, and guidance documents.

Code availability

Model tutorials, code, and outputs can be accessed at: https://www.vims.edu/ccrm/ccrmp/bmp/smm/

Credit author statement

Dr. Karinna Nunez: Conceptualization, Methodology, Software, Investigation, Validation, Formal Analysis, Writing, Supervision, and Project Administration - (model development, calibration, and validation; spatial and statistical analyses; coastal resiliency and adaptations; living shorelines; manuscript preparation).

M.S. Tamia Rudnicky: Conceptualization, Methodology, Software, Dara Curation, Visualization – (data generation, model development, web applications, manuscript preparation).

M.A. Pamela Mason: Conceptualization, Resources, Writing, Funding Acquisition – (living shorelines, coastal management, policy and regulations; formulation of decision trees, manuscript preparation).

M.S. Christine Tombleson: Conceptualization, Validation, Data Curation, and Writing – (living shorelines, model calibration and validation; formulation of decision trees; manuscript preparation).

M.S. Marcia Berman: Conceptualization, Writing, Funding Acquisition – (model development, formulation of decision trees, coastal management, manuscript preparation).

We confirm that this work is original and has not been published elsewhere, nor is it currently under consideration for publication elsewhere.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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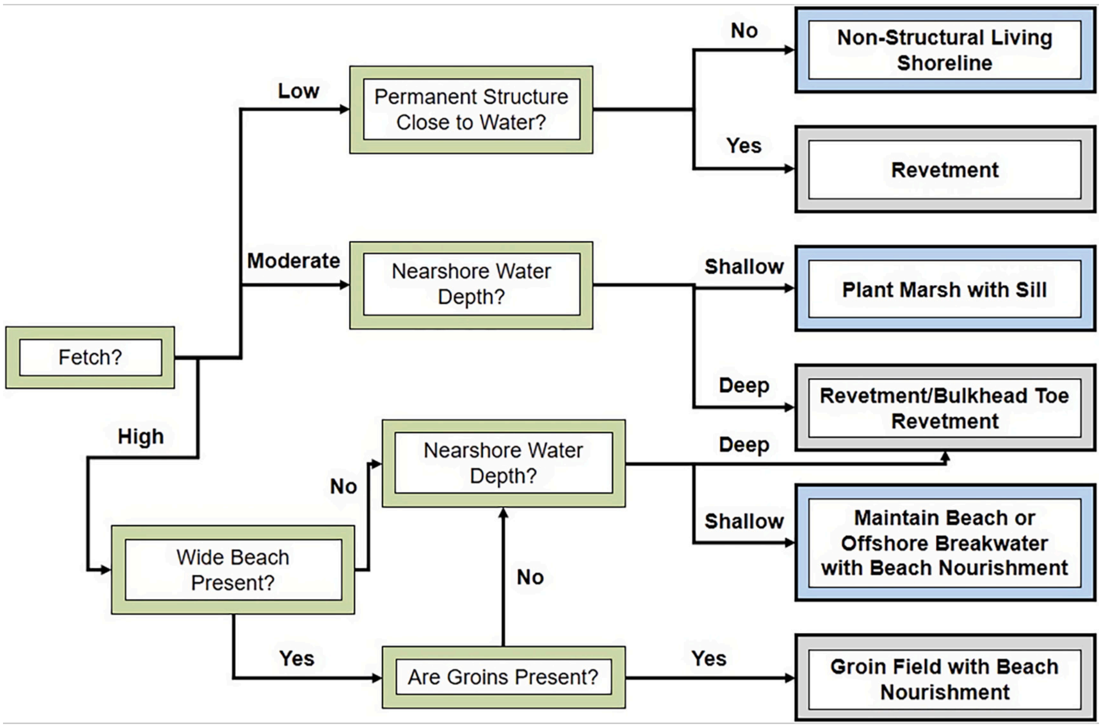
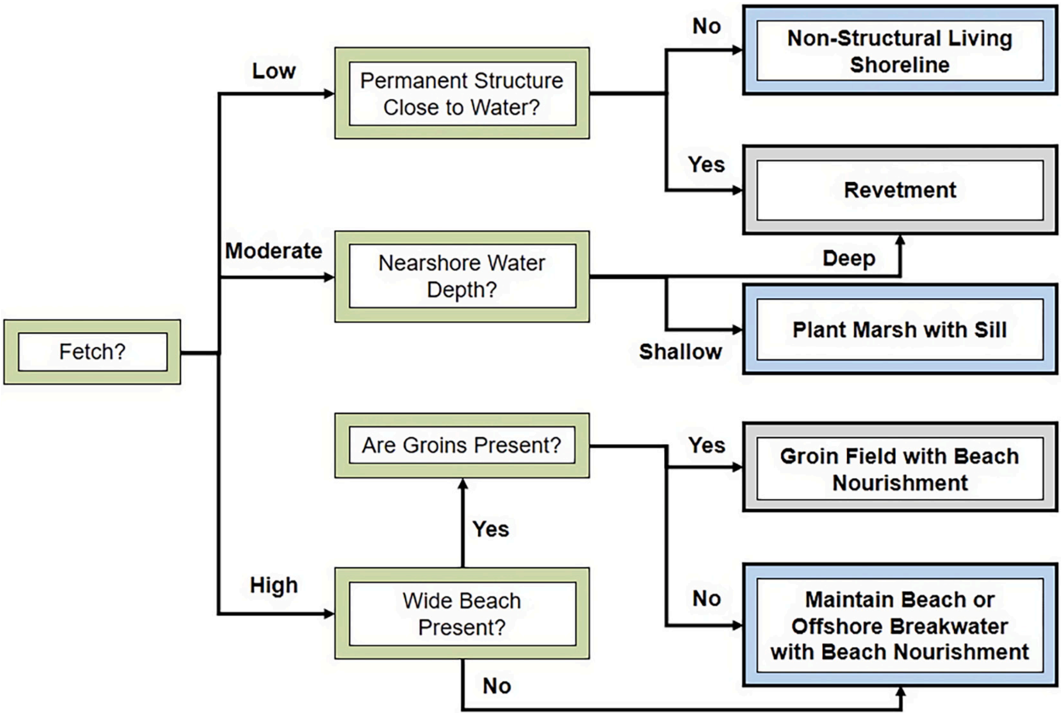
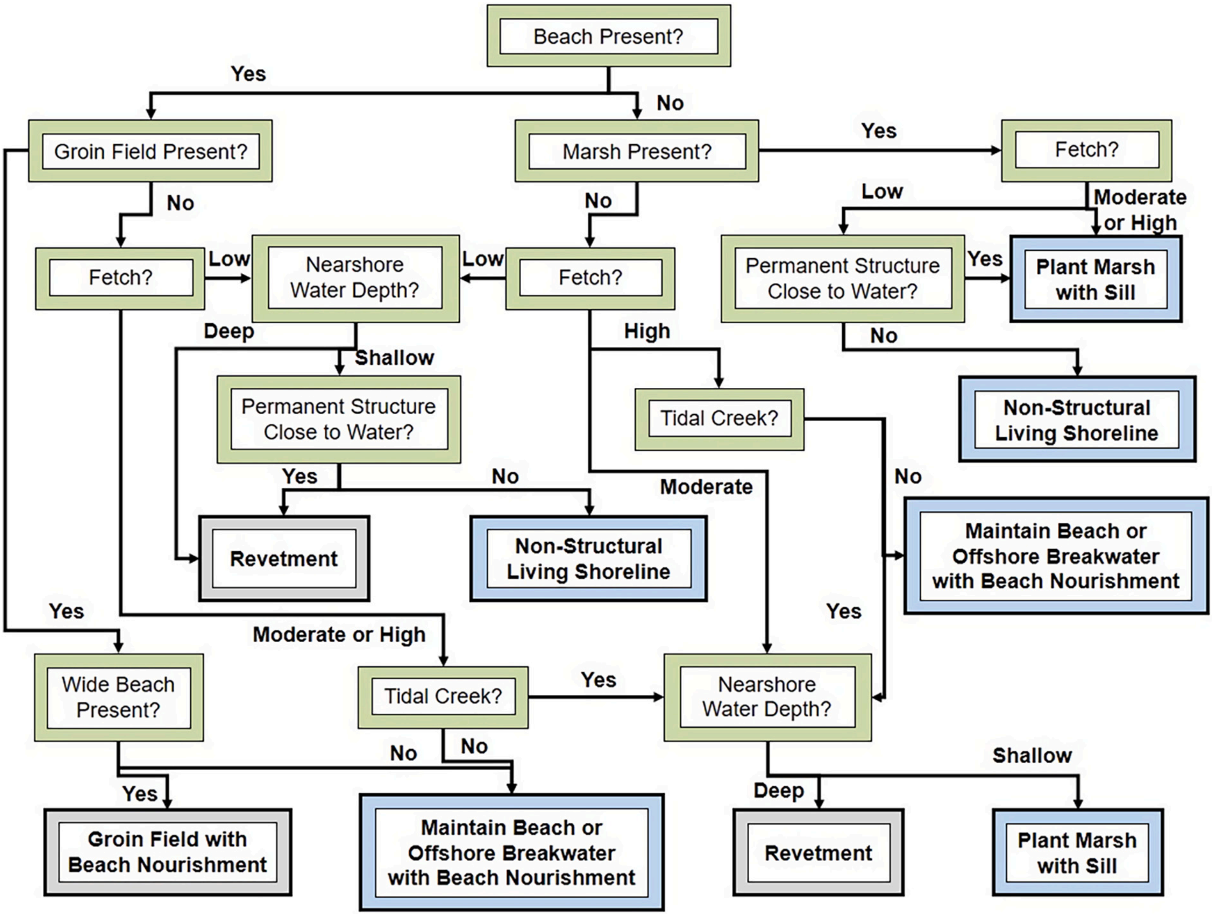
Appendix A. Flow Chart for Existing Bulkhead Sub-Model



Appendix B. Flow Chart for Existing Revetment Sub-Model



Appendix C. Flow Chart for Undefended Shoreline Sub-Model



Appendix D. SMM recommendations – Definitions

Groin Field with Beach Nourishment - Maintain existing wide beach between groins. Remove unnecessary structures at the backshore (e.g., bulkheads) and stabilize the bank with grading and riparian buffer plants. Repair/replace existing groins, add beach nourishment and plant beach vegetation.

Maintain Beach OR Offshore Breakwaters with Beach Nourishment - If shoreline exceeds 60 m in length, remove existing shoreline structure, add beach nourishment sand, consider offshore breakwaters or another type of wave attenuation device with beach nourishment; consider adding plantings to the nourished areas. When the shoreline length is less than 60 m an offshore breakwater may not be practical. In this case, remove failed shoreline structures and repair or construct a revetment as far landward as possible. Consider shoreline enhancement such as creation of vegetated wetlands and/or riparian buffer and/or sandy beach/dune above and immediately channel-ward of the structure.

Non-Structural Living Shoreline - Remove existing shoreline structure if present; grade bank if necessary, and install a non-structural living shoreline, which may include riparian buffer plantings along the bank, and/or marsh plants, coir logs, or oyster reefs along the shoreline. Best choice for low energy environments.

Plant Marsh with Sill - In moderate energy environments, a sill may be required to establish a living shoreline. Remove any existing shoreline structure if present and grade the bank if possible. Stabilize bank with riparian vegetation and plant a marsh with a sill. If the bank cannot be graded, repair existing shoreline structure with a minimal footprint and consider incorporating a marsh with a sill or some other shoreline enhancement (e.g., oyster reef).

Revetment - Remove existing failing or failed shoreline structure, if present. Construct new revetment as far landward as possible; grade the bank and plant vegetation buffers where possible. If grading is not possible, construct or repair existing revetment in the same alignment. A bulkhead should be considered only if previously present and the site is limited by navigation. Consider shoreline enhancement such as creation of vegetated wetlands and/or riparian buffer and/or sandy beach/dune above and immediately channel-ward of the structure. In high energy settings where shoreline extends more than 60 m see option for Offshore Breakwater with Beach Nourishment.

Revetment / Bulkhead Toe Revetment - If grading is possible, remove the failed bulkhead and replace with a revetment landward of the current bulkhead. When grading not possible, (re)construct bulkhead in the same alignment and/or add a toe revetment. Consider a shoreline enhancement project such as creation of vegetated wetlands and/or riparian buffer and/or sandy beach/dune above and immediately channelward of the structure.

Special Considerations

Ecological Conflicts - Management options for this shoreline may be limited by the presence of Submerged Aquatic Vegetation (SAV) or Mangroves. In the case of Virginia shorelines, users should seek advice from the Virginia Marine Resources Commission Habitat Management Division. For other states, seek advice from your local marine regulatory agency.

Highly Modified Area - Management options for this shoreline may be limited due to the presence of highly developed upland (e.g., commercial wharfs) or infrastructure directly adjacent to the shoreline (e.g., road), and will depend on the need for and limitations posed by navigation access and erosion control. Seek expert advice on the design of your project.

Land Use Management - Shorelines with tall banks greater than nine meters limit possible solutions to address bank erosion. Forces other than tidal erosion, such as over-land runoff, upland development, and vegetation management are likely also having effect on bank conditions. Assessment of all factors and modifications to address causes for bank erosion are recommended. This may include changes to vegetation management, implementation of projects to address storm water, relocating buildings, utilities, and other infrastructure. All new construction should be located 30 m or more from the top of bank. Actions may also include requesting zoning variances for relief from setback and other land use requirements or restrictions that may increase erosion risk. Seek expert advice to inform management options.

No Action Needed - No specific management actions are suitable for shoreline protection (e.g., boat ramps, undeveloped marsh, and barrier islands).

Special Geomorphic Feature - Maintain the natural condition of this shoreline to allow for unimpeded sediment movement and the corresponding response of wetlands, beach and/or dune. If primary structures are present and threatened, seek expert advice on the design of your project.

Appendix E. Glossary of Shoreline Features

Agricultural - Land use defined as agricultural includes farm tracts that are cultivated and crop producing. This designation is not applicable for pastureland, which is coded as Grass.

Bank Height – Bank height is the height of the bank from the base to the top. We estimate height from imagery, field inspection, videography, LIDAR or a combination of all data sources.

Bare - Land use defined as bare includes areas void of any vegetation or obvious land use. Bare areas include those that have been cleared for construction.

Beaches - Beaches are persistent sandy shores that are visible during high tides. These features can be wide or thin lenses of sand. Beaches are coded as linear features at the wet/dry line to portray their location only. If a beach does not have a visible wet/dry line, then the line feature is located at the seaward edge of the beach. 'Wide' beaches have at least 25 ft of dry sand persistently visible above high tides. Beach features coded along tidal marsh shorelines are persistent, sandy features located on the water side of tidal marsh vegetation. Sand washed into tidal marshes is not coded as a beach if the marsh vegetation &/or marsh edge is still clearly visible. This classification of beaches along tidal marsh shorelines can include professional judgment.

Boat Ramp - Boat ramps are used to launch vessels of all types. They are usually constructed of concrete, but wood and gravel ramps are also found. Point identification of boat ramps does not discriminate based on type, size, material, or quality of the launch. This inventory attempts to distinguish, when possible, private versus public ramps. Ramps located in privately owned, commercial marinas and residential communities are classified as private.

Breakwaters - Breakwaters are structures that sit offshore and generally occur in a parallel series along the shore. Some breakwaters are attached to the land and are referred to as headland breakwaters. Their purpose is to attenuate and deflect incoming wave energy, protecting the fastland behind and between the structures. The Shoreline Inventory does not map individual breakwaters. A breakwater "system" is delineated and depicted as a line parallel to the series of breakwaters. Breakwaters are distinguished from marsh toe revetments by the size of the structures and presence of a sand beach instead of a tidal marsh landward from the structures. The classification can include best professional judgment.

Bulkhead - Bulkheads are traditionally treated wood or steel "walls" constructed to offer protection from wave attack. More recently, plastics are being used in the construction. Bulkheads are vertical structures built slightly seaward of the problem area and backfilled with suitable fill material. They function like a retaining wall, as they are designed to retain upland soil, and prevent erosion of the bank from impinging waves. From aerial photography, long stretches of bulkheaded shoreline may be observed as an unnaturally straight or angular coast. They are mapped and illustrated as linear features along the shoreline. In rare cases, the bulkhead may be located well inland from the depicted location because the coding follows a digital shoreline.

Commercial - Commercial is a land use classification denoting small commercial operations such as shops, restaurants, as well as campgrounds. These operations are not necessarily water dependent businesses.

Debris – Debris represents nonconforming materials and rubble dumped along the shoreline in a haphazard manner. Debris can include tires, bricks, broken concrete rubble, and railroad ties as examples. The inventory maps Unconventional instead of Debris when the material is deliberately placed for shoreline protection in a manner similar to riprap, bulkhead, and other shoreline protection structures.

Dilapidated Bulkhead – A bulkhead which has failed due to deterioration from age or storm damage is called a dilapidated bulkhead. In many cases the structure may not be able to perform erosion control functions any longer.

Forest Land Use - Forest cover includes deciduous, evergreen, and mixed forest stands. The land use is classified as Forest if there is a dense cover of trees and no other land use category is apparent close to the shoreline, e.g., residential, commercial, industrial, agriculture, etc.

Grass - Grasslands include large unmanaged fields, managed grasslands adjacent to large estates, agriculture tracts reserved for pasture, and grazing. While a general rule of thumb will classify a tract as "grass" if a home sits behind a large tract of grass, a designation of "residential" may be made if there are similar tracts adjacent to each other. This designation can be determined using best professional judgment.

Groin field - Groins are low profile structures that sit perpendicular to the shore. They can be constructed of rock, timber, or concrete. They are frequently set in a series known as a groin field, which may extend along a stretch of shoreline for some distance. Unless only a single groin can be detected, this inventory does not delineate individual groins in a groin field. The groin field is mapped as one linear feature parallel to the shoreline running along the length of the groin series. When effective, groins will trap sediment moving alongshore.

Industrial - Industrial operations are larger commercial businesses and can include areas where power plants, pulp mills, refineries, etc. are in operation along the coast.

Jetty – A jetty is a structure which is perpendicular to the shoreline and generally located near navigation channels and other places associated with navigation, such as the entrance of tidal creeks and tributaries, boat ramps, or marina boat basins. The function of a jetty is to reduce wave action and prevent sediment transported alongshore from accumulating in navigation areas.

Land Use – Land Use refers to the predominant condition in the immediate riparian area within 100 ft of the adjacent shoreline. While the actual assessment of land use is defined by a distance, the classification can include best professional judgment; particularly when development or other land use activity is setback on the parcel.

Marina - Marinas are denoted as line features in this survey. The infrastructure associated with the marina (e.g., bulkheading, docks, wharfs, etc.) are not digitized individually. However, if a boat ramp is noted it will be surveyed separately and coded as private. Marinas are generally commercial operations. However, smaller scale community docks offering slips and launches for residences are becoming more popular. To distinguish these facilities from commercial marinas, the user could check the riparian land use delineation. If "residential" the marina is most likely a community facility.

Marsh –Tidal marsh at least 20 sq. ft. in area, meeting the definition established in Virginia's Tidal Wetlands Act, and not otherwise considered a marsh island. In all cases, wetland vegetation must be relatively well established, although not necessarily healthy. In previous Tidal Marsh Inventories, marshes were further classified based on morphology and physiographic setting.

Marsh Island – A marsh island is a vegetated wetland that is completely isolated from the mainland and found in open water. A marsh that is surrounded by water due to dissection from small tidal creeks was classified as marsh, not a marsh island.

Marsh toe revetment (aka Marsh sill) –A low revetment placed offshore from an existing marsh or new planted marsh is classified as marsh toe revetment. The structure may include tidal openings to allow for the easy exchange of free-swimming organisms during tidal cycles. Marsh toe revetments are mapped as offshore linear features running along the length of the structure. Marsh toe revetments are distinguished from breakwaters by the linear placement and presence of a tidal marsh instead of a sand beach landward from the structure. The classification can include best professional judgment.

Military – A land use classification of Military marks the location of federal military reservations. This classification is generally reserved for the section of the base where active operations and infrastructure exist. Expansive military property adjacent to these areas which are unmanaged forest areas, for example, may be classified as forest land use.

Paved - Paved areas represent roads which run along the shore and generally are located at the top of the banks. Paved also includes parking areas such as parking at boat landings, or commercial facilities.

Residential – Residential land use includes single and multi-family dwellings located near the shoreline.

Riprap (aka Revetments) - Sloped structures constructed with large, heavy stone or other materials placed against the upland bank for erosion protection are classified as riprap. Riprap is mapped as a linear feature along the shoreline. Riprap is also used next to failing bulkheads (bulkhead toe revetments). The inventory maps only riprap when this type of structure is co-located with bulkheads. A similar structure is used to protect the edge of eroding marshes. This use is mapped as marsh toe revetment, not riprap.

Scrub-shrub - Scrub-shrub is a land use class that includes small trees, shrubs, and bushy plants. This land use is easily distinguished during remote sensing compared to Forest and Grass.

Shoreline – generalized term for the land-water interface.

Sand Spit - A narrow coastal landform tied to the upland shoreline at one end resulting from the deposition of sand moved by tides and currents. Spit features are generally sandy and may be dominated by beach, dune, and/or marsh habitats. For inventory purposes, this definition does not include spit features that are developed or have developable upland.

Unconventional - Unconventional features represent segments along the shore where alternative material has been deliberately placed for shoreline protection. Unconventional features may include unique materials placed in a similar manner as riprap or bulkheads, such as engineered precast concrete products. It may also include unique placement or arrangement of conventional materials like riprap that does not fit other structure definitions. The inventory maps Debris instead of Unconventional when the material is haphazardly scattered and not providing any shoreline protection value.

Wharf – Typically describes a shore parallel structure where boats are tied. In this inventory, Wharf is generally associated with large industrial, public or commercial facilities.

Appendix F. Interpretation of the model performance (Viera and Garrett, 2005)

Kappa value	Agreement
< 0	Less than chance agreement
0.01–0.20	Slight agreement
0.21–0.40	Fair agreement
0.41–0.60	Moderate agreement
0.61–0.80	Substantial agreement
0.81–0.99	Almost perfect agreement

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