Tidal Marsh Vulnerability to Sea-Level Rise: Significance of High-Resolution Models

Karinna Nunez,
Joseph Zhang, Julie Herman, William Reay, Carl Hershner

Chesapeake Community
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VIMS | William & Mary
Virginia Institute of Marine Science

BACKGROUND - Importance of Tidal Marshes

Provide habitat for fish, invertebrates, and waterfowl among many others

Offer upland erosion protection

Filter and remove several pollutants

Provide long-term carbon storage

Tidal Marshes & Sea Level Rise (SLR)

The **Chesapeake Bay** region is one of the most vulnerable areas in the U.S., with mean relative SLR rate in the order of **5 mm yr^{-1}** and accelerating.
(Ezer and Atkinson 2015; Boon et al. 2018)

Tidal Marshes & Sea Level Rise (SLR)

(ian.umces.edu/symbols)

<u>To keep pace with SLR:</u>

- **Marshes accrete vertically** (organic accumulation & inorganic sediment deposition)
- **Marshes migrate horizontally**

Marsh Vertical Accretion & SLR

Marshes possess a
theoretical maximum vertical accretion rate of 5 mm yr^{-1}
(*Morris et al. 2016*)

This rate is commensurate with the mean relative SLR in the Chesapeake Bay
(~ 5 mm yr^{-1})

Based on **accelerated projections of SLR**, it is expected that marshes will rely considerably on **inorganic sediment** supplies to offset changes in water level

Factors Affecting Vertical Accretion & Horizontal Migration

topography/land use

slope (near shore topography)

shoreline structures

Current Marsh Models

Large-scale landscape models

(e.g. SLAMM)

Site-specific models

(e.g. MEM)

Current Marsh Models

Large-scale landscape models

(e.g. SLAMM)

- Structured grids
- Fixed rates in the simulations
- Simulate general trends over large areas, but typically with a very coarse resolution
- <u>MAIN LIMITATION</u>: down scale model results to local levels

Current Marsh Models

- Mechanistic approach
- Simulate marsh responses for a specific site with a particular set of conditions and settings
- MAIN LIMITATION: Scaling issues - Using results from an individual marsh to make long-term projections at larger spatial extents is challenging due to the broad range of geomorphic settings across landscapes

Site-specific models
(e.g. MEM)

Current Marsh Models

Large-scale landscape models

(e.g. SLAMM)

Site-specific models

(e.g. MEM)

A Multi-scale Approach for Simulating Tidal Marsh Evolution

Nunez K, Zhang Y, Herman J, Reay W, Hershner C *(in press)*. A Multi-scale Approach for Simulating Tidal Marsh Evolution. Ocean Dynamics

Advanced modeling framework
that integrates the
physical and human components
needed to simulate and assess the evolution
and persistence of tidal marshes under
different sea-level rise scenarios

Dynamic high-resolution model to evaluate marsh evolution:

TIDAL MARSH MODEL (TMM)

Unique Model Features

TIDAL MARSH MODEL (TMM)

cross-scale model

Process at one temporal (e.g. day, year) or spatial (e.g. creek, ocean) scale can interact with processes at another scale.

dynamic rates

varying rates in space and time

barriers to marsh migration

Shoreline erosion control structures (e.g. bulkhead)

SCHISM
(Semi-implicit Cross-scale Hydroscience Integrated System Model)

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Major Characteristics of SCHISM

- Open-source community-supported modeling system
- Unstructured grids
- Finite element/volume formulation
- Higher-order Eulerian-Lagrangian treatment of momentum advection
- Semi-implicit time stepping (no mode splitting)

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Study Areas

TMM

EXPORTABLE

Tidal Marsh {TMM}

Model Development

Formulations & Parameterization	Formatting Spatial Data	Grid Generation	Run Model / Export Outputs to GIS Environment	Evaluation of Model Performance
System and boundaries Resolution Forcing & mechanistic functions State variables Governing equations	Spatial dataset for assisting grid generation Generation of DEMs (elevation surfaces)	Unstructured Grid Combination of different cell shapes Connectivity list Iterative process	SCHISM framework Fortran and Matlab Scripts to Export TMM outputs	Calibration Skill Assessment

Primary input datasets used for the TMM and supporting models

Dataset	Source
Historic Tidal Marshes (1:24,000) Current Tidal Marshes (Scale: 1:1,000)	Tidal Marsh Inventories – CCRM, VIMS
Shoreline Structures	Shoreline Inventory Program – CCRM, VIMS
Riparian Land use (distance: 100 ft.)	Shoreline Inventory Program – CCRM, VIMS
LIDAR data	United States Geological Survey (USGS)
Bathymetry	NOAA and CBNERR, VIMS
Bottom Type (grain sizes)	VIMS, Maryland Geological Survey (MGS), and field samples
River Input (average daily values)	United States Geological Survey (USGS)
Total Suspended Solids	Chesapeake Bay Program
Atmospheric Forcing	North American Regional Reanalysis (NARR)
Tides	US East Coast Tidal Database

Grid Generation

One of the strengths of this model approach is that it uses an **unstructured grid** for the simulation

Grid generation software: SMS (Surface-water Modelling System) by Aquaveo .com

Grid Generation

This type of grid allows multiple resolutions over the domain, and higher resolution where fine scales are important

Marsh areas were resolved at **1 m** cross-shore and **5-10 m** along-shore for fringe marshes

Marsh cells are defined in the grid by an **increased bottom roughness factor (RF)** (Ye et al. 2013)

Kilometers
0 0.1 0.2 0.4

Unstructured Grid - Carter Creek

TMM Code Specifications

TMM simulates marsh migration under the joint influence from tides, wind waves, sediment transport, precipitation, and SLR

<u>TMM accounts for:</u>

- shoreline bank erosion (water-marsh interphase)
- upland erosion inputs at the upland-marsh edge
- marsh vertical accretion through mineral sediment deposition
- marsh landward migration under changing sea levels with constraints from physical barriers (e.g. ripraps, bulkheads, etc.)

TMM – Evaluation of Model Performance

Hindcast (past 40 years)

Field Observations

TMM Evaluation – 1) Marsh Boundary Evolution

Historic Tidal Marsh Inventory
(70s - initial conditions)

Hindcast: past 40 years

Tidal Marsh Model (TMM) output

Current Tidal Marsh Inventory
(2010 Inventory)

Center for Coastal Resources Management
Virginia Institute of Marine Science

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TMM Evaluation – 1) Marsh Boundary Evolution

Hindcast outputs (past 40 years)

1) Marsh Boundary Evolution - Error Matrix & Kappa Statistic

Direct comparison between TMM output and the Current Tidal Marsh Inventory

Evaluation: 100 random points (generated in ArcGIS) located on the marshes in each study site

1) Marsh Boundary Evolution – Error Matrix & Kappa Statistic

TASKINAS CREEK	Current Tidal Marsh Inventory					
Tidal Marsh Model (TMM)		No Change	Marsh Gain	Marsh Loss	TOTAL	Commission Error
	No Change	48	5	6	59	0.19
	Marsh Gain	3	16	0	19	0.16
	Marsh Loss	8	0	14	22	0.36
	TOTAL	59	21	20	100	
	Omission Error	0.19	0.24	0.30		**0.22**

Overall Accuracy = 78%

Kappa Statistic = 0.613

CARTER CREEK	Current Tidal Marsh Inventory					
Tidal Marsh Model (TMM)		No Change	Marsh Gain	Marsh Loss	TOTAL	Commission Error
	No Change	45	2	7	54	0.17
	Marsh Gain	2	8	0	10	0.20
	Marsh Loss	8	0	28	36	0.22
	TOTAL	55	10	35	100	
	Omission Error	0.18	0.20	0.20		**0.19**

Overall Accuracy = 81%

Kappa Statistic = 0.630

Computation of K_{hat} Coefficient of Agreement

$$\hat{K} = \frac{N\sum_{i=1}^{k} x_{ii} - \sum_{i=1}^{k}(x_{i+} \times x_{+i})}{N^2 - \sum_{i=1}^{k}(x_{i+} \times x_{+i})}$$

Interpretation of Kappa

	Poor	Slight	Fair	Moderate	Substantial	Almost perfect
Kappa	0.0	.20	.40	.60	.80	1.0

Kappa	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

Viera et al., 2005

TMM – Evaluation of Model Performance

Hindcast (past 40 years)

Field Observations

TMM Evaluation – 2) Distribution of Marsh Sediments

Locations of marsh near surface (upper 8 cm) sediment cores

Samples were analyzed for grain size

TMM Evaluation – 2) Distribution of Marsh Sediments

		Mean Absolute Error (MAE)	Observations Standard Deviation Ratio (RSR)	Nash_Sutcliffe Efficiency (NSE)	Willmott Modified Index of Agreement (dr)
Carter Creek	Sand	0.08	0.43	0.81	0.86
	Mud	0.08	0.43	0.81	0.86
Taskinas Creek	Sand	0.10	0.61	0.62	0.83
	Mud	0.10	0.61	0.62	0.83

Different statistical descriptors were used to evaluate the model's ability to reproduce the distribution of observed marsh sediment fractions

Carter Creek show a **strong agreement** between model outputs and observations

Levels of Agreement						
	Less than chance agreement	Slight agreement	Fair agreement	Moderate agreement	Substantial agreement	Almost perfect agreement
Kappa Statistic [a]	<0	0.01-0.20	0.21-0.40	0.41-0.60	0.61-0.80	0.81-0.99

Levels of Agreement				
	Unsatisfactory	Satisfactory	Good	Very Good
NSE [b]	< 0.50	0.50 < NSE < 0.65	0.65 < NSE < 0.75	0.75 < NSE < 1.0
RSR [c]	> 0.70	0.60 < RSR < 0.70	0.50 < RSR < 0.60	0.00 < RSR < 0.50

Levels of Agreement			
	Possible values	Optimal value	Preferred values
MAE [d]	0 to ∞	0	Low values
Willmott index of agreement [d e]	0 to 1	1	0.5 to 1.0 [f] > 0.8 [g]

Based on: [a]Viera et al. 2005; [b]Moriasi et al. 2007; [c]Singh et al. 2004; [d]Bennett et al. 2013, [e]Willmott et al. 2012; [f]Machiwal and Jha 2015; [g]De Jager 1994

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Taskinas Creek show a **satisfactory agreement** between model outputs and observations

Levels of Agreement						
	Less than chance agreement	Slight agreement	Fair agreement	Moderate agreement	Substantial agreement	Almost perfect agreement
Kappa Statistic [a]	<0	0.01-0.20	0.21-0.40	0.41-0.60	0.61-0.80	0.81-0.99

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Photo Credit: Kory Angstadt

Main Current Model Limitation

- Biological processes have not been incorporated in the simulations

Tidal Marsh
{TMM}

This innovative approach of simulating marsh evolution based on **physical processes and human factors** explained the majority of the variability in the systems studied

- Highly- resolved output will provide coastal managers with a more accurate tool to determine the fate of tidal marshes over large regions
- TMM allows simulations in areas where biological parameters are extremely variable and detailed data on biological processes are limited

Summary

The TMM advances the state of the science by building a better foundation to simulate marsh extent and distribution in large areas, but with the kind of spatially explicit resolution currently only available from site-specific marsh evolution studies

TMM **overcomes some limitations** that the current marsh models present:

Current Models LIMITATIONS		TMM
scaling problems	→	**"cross-scale model" Semi-implicit time stepping**
constant rates	→	capacity for a much more **dynamic simulation** *(i.e. rates vary in space and time as determined by changes in the hydrodynamic conditions of the system)*
exclusion of hardened shoreline structure impacts	→	**highly resolves (~1m) marsh transgression**

Thank you!

Karinna Nunez
karinna@vims.edu

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Study Areas

- CBNERR's reserve (pristine site)
- Embayed marshes
- Adjacent upland: forest and scrub shrubs
- No hardened shoreline structures
- **Mostly: steep slopes and upland bank heights >1.5m**

- Embayed and fringe marshes
- Adjacent upland: forest, agriculture and residential
- hardened shoreline structures / roads
- **Mostly: gradual slopes and upland bank heights < 1.5m**