



Considerations for Integrating Ecological and Hydrogeomorphic Models

Developing a Comprehensive Marsh Vegetation Model

by Emily R. Russ, Taylor S. Cagle, and Todd M. Swannack

PURPOSE: Predictive models for salt marsh management require a systems perspective that recognizes the dynamic interactions between physical and ecological processes. It is critical to link physical process and landscape evolution models to quantify hydro-eco-geomorphic feedbacks in marsh environments. A framework that explicitly defines how to integrate these disparate models is a necessary step towards developing a comprehensive marsh model. This technical note (TN) proposes an approach to integrate existing hydrodynamic and geomorphic models with a mechanistic vegetation model into a coupled framework to better simulate salt marsh evolution.

BACKGROUND: Salt marshes are among the most valuable coastal habitats. They provide a suite of ecosystem services such as flood risk reduction, carbon sequestration, and habitat for a variety of species (Costanza et al. 1997). However, salt marshes are disappearing at an alarming rate due to increased sea level rise, reduced sediment input, and increased coastal development prompting conservation, restoration, and maintenance actions that optimize ecosystem services.

Marsh restoration is an active area of applied research that can involve restoring hydrologic connectivity to passively increase sediment availability, nourishing areas with direct (e.g., thin layer placement [TLP]) and indirect sediment using dredged material (e.g., nearshore placement), and preventing erosion with methods such as creating living shorelines. With the many restoration approaches available, a comprehensive understanding of the physical and biological processes acting in marsh systems is necessary to determine the most effective strategy that maximizes project benefits.

Numerical modeling is a powerful tool that can provide insight into the complex processes occurring in marsh systems. These models can be utilized to evaluate long-term resilience of salt marshes within the context of climate change (i.e., sea level rise, sediment supply) or short-term impacts due to storm events (i.e., flood risk management capacity). Within the US Army Corps of Engineers (USACE), numerical models are used as planning and forecasting tools that aid in decision making, including those regarding risks, benefits, and overall performance of salt marsh restoration projects. Although there are both physical process models and landscape evolution, specifically vegetation change, models that can be applied to answer specific questions regarding the impact of potential management alternatives (e.g., how TLP impacts water levels and current velocities or how increased elevations impact vegetation habitat suitability), the individual models are operated separately or transfer information in only one direction (e.g., the change in water

surface elevation forces the change in plant growth, but the effect of plant growth on water surface elevation is not included). The lack of integration between these models limits their ability to represent these dynamic hydro-eco-geomorphic feedbacks, which reduces their overall efficacy towards restoration project planning. As greater focus is placed on understanding the whole system, there is a need to integrate formerly disparate models, including improved model process descriptions for smoother linkage, to improve overall prediction fidelity and enable management alternative comparisons. Further, understanding the mechanisms driving marsh dynamics will enable more realistic climate change applications than using historical observations.

Salt marsh systems are dynamic environments that are shaped through feedbacks between hydrodynamic, morphological, and ecological processes (Figure 1). Hydrodynamics has a significant impact on sediment transport, which directly affects morphology, water levels, flow velocities, and water properties such as temperature and salinity. These factors in turn affect plant establishment, growth, and mortality. Water levels are largely controlled by elevation, which is strongly linked to biomass (Morris et al. 2002). Dense stands of vegetation attenuate wave and current energy by increasing drag, which can facilitate sediment deposition and reduce shear stresses on the bed. Aboveground biomass (i.e., stems and leaves) can directly intercept suspended sediment while belowground biomass (i.e., roots and rhizomes) stabilizes the bed. Vegetation directly increases elevation through organic accretion and root growth (Kirwan and Guntenspergen 2012). These interactions also create feedback loops that reinforce vegetation absence by concentrating flow in unvegetated areas, which elevates bed shear stresses and prevents vegetation growth and establishment.

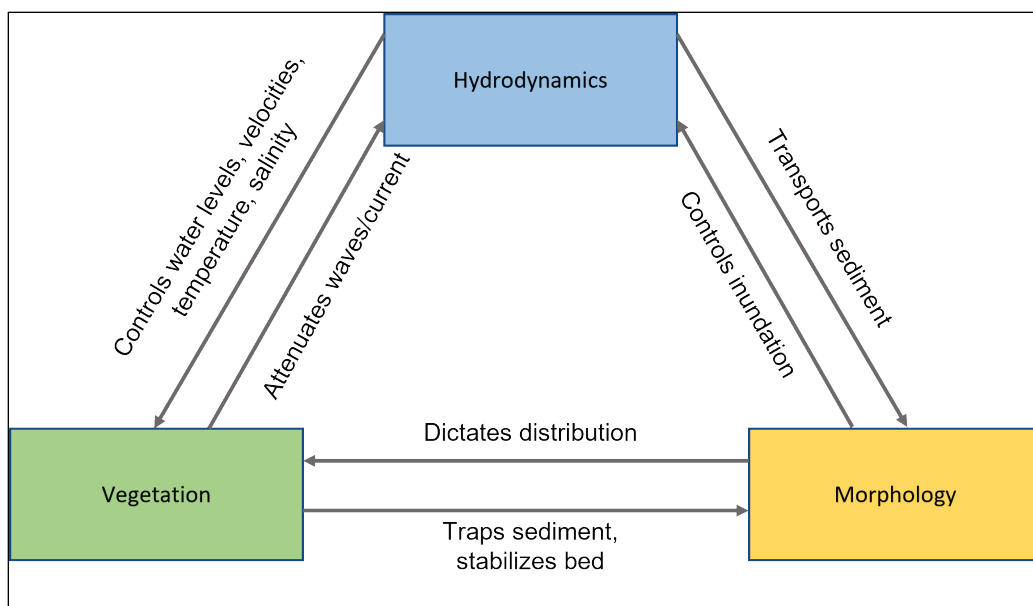


Figure 1. Conceptual diagram demonstrating the feedbacks between hydrodynamics (waves and tides), morphology, and vegetation (above and belowground biomass) on a salt marsh.

There are many stand-alone models that have been developed to simulate some of these components (e.g., hydrodynamic models, vegetation dynamics models). However, a strategy for coupling existing models together to form one single integrated model is essential for accurately

representing marsh system evolution. This document serves as (1) a brief summary of existing ecogeomorphic salt marsh models and (2) a conceptual framework for the strategy that will be applied to couple a mechanistic vegetation model with existing hydrodynamic and geomorphic models in salt marsh systems.

EXISTING ECOGEOMORPHIC SALT MARSH MODELS: Many stand-alone salt marsh models have been developed to represent feedbacks between hydrodynamics, morphology, and vegetation production. Most of these models use inundation (duration and frequency) as a proxy to estimate vegetation biomass production of a single species, in which biomass is limited by oxygen stress and salinity stress at lower and upper limits in the tidal frame (Morris et al. 2002; Mudd et al. 2004; Mariotti and Fagherazzi 2010). Multiple salt marsh models have adapted this approach across varying spatial scales (point-based to 3D landscapes) while incorporating additional physical drivers (e.g., waves, erosion) to simulate both vertical and lateral processes (Piercy et al. 2023; Fagherazzi et al. 2020). Although these models provide important information on marsh system feedbacks, they rely on statistical relationships to predict maximum biomass which neglects plant- and community-scale processes and limits model transferability rather than applying process-based growth and mortality equations.

The Delft3D modeling suite has been used to integrate hydrogeomorphic models with plant dynamics models that explicitly simulate growth, mortality, and dispersal (e.g., Temmerman et al. 2007; Best et al. 2018; Baustian et al. 2018; Brückner et al. 2019). The existing macrophyte module VEGMOD, within the D-Water Quality Processes library of Delft3D, has mainly been applied in reservoirs and focuses on water quality effects on plant growth (Deltares 2022); however, VEGMOD requires significant modifications for application in marsh systems (e.g., Baustian et al. 2018). Better representation of marsh vegetation dynamics has been achieved by integrating hydromorphodynamic modules with a population dynamics approach that considers both biotic and abiotic controls (Temmerman et al. 2007; Best et al. 2018; Baustian et al. 2018; Brückner et al. 2019).

Generally, vegetation dynamics models quantify biomass as the sum of vegetation gain from establishment, growth, dispersal, and loss due to mortality (Best et al. 2018). The plant biomass output is then used to update roughness (e.g., drag coefficient, Manning's coefficient) in the hydrodynamic model (Baptist et al. 2007) which is used in sediment transport and bed morphology model components. Adjusted bed levels, water levels, current velocities, and shear stresses from the hydrodynamic and geomorphic models are inputs to the vegetation model. Table 1 summarizes the plant processes modeled, vegetation metrics, and feedbacks into the hydrogeomorphic models of existing coupled models.

Table 1. Examples of existing marsh models and their plant processes, vegetation metrics, and feedbacks. M represents mortality.			
Source	Plant Processes Modeled	Vegetation Metric(s)	Feedbacks
Temmerman et al. 2007	-Establishment -Growth (carrying capacity) -Dispersal -Inundation stress (M) -Flow stress (M)	-Stem density	-Updated drag -Updated roughness
Best et al. 2018	-Establishment -Growth (carrying capacity) -Dispersal -Inundation stress (M) -Flow stress (M)	-Stem density	-Updated drag -Updated roughness -Bed level change
Baustian et al. 2018	-Growth (temperature dependent + nutrient limitation) -Biomass allocation (above/belowground)- Inundation stress (M) -Grazing (M) -Senescence (M) -Species distribution	-Vegetation biomass (above and belowground)	-Updated drag -Updated roughness -Bed level change -Nutrient release
Brückner et al. 2019	-Colonization -Growth (seasonal differences in rate) -Inundation stress (M) -Flow stress (M) -Erosion/burial (M)	-Plant height -Stem diameter -Stem density -Root length	-Updated drag -Updated roughness -Bed level change

FRAMEWORK FOR MODELING SALT MARSH DYNAMICS: We propose a coupled modeling framework that integrates mechanistic hydrodynamic, morphologic, and vegetation dynamics models to better capture feedbacks in marsh systems and increase prediction accuracy. Using mechanistic models within this framework, rather than relying on statistical relationships, predicts interactions between physical and biological processes from ecological first principles and ensures transferability to other locations and/or species.

The Delft3D integrated models (Table 1) provide a template for conceptualizing an integrated marsh model framework. Several mechanistic hydrodynamic and morphologic models already exist and use well-established equations (i.e., Navier-Stokes equations), while most existing vegetation models have been developed from statistical relationships. Figure 2 conceptualizes a general mechanistic, photosynthesis-based vegetation model that can be modified for a specific habitat with user-defined vegetation community characteristics (i.e., growth, mortality, dispersal).

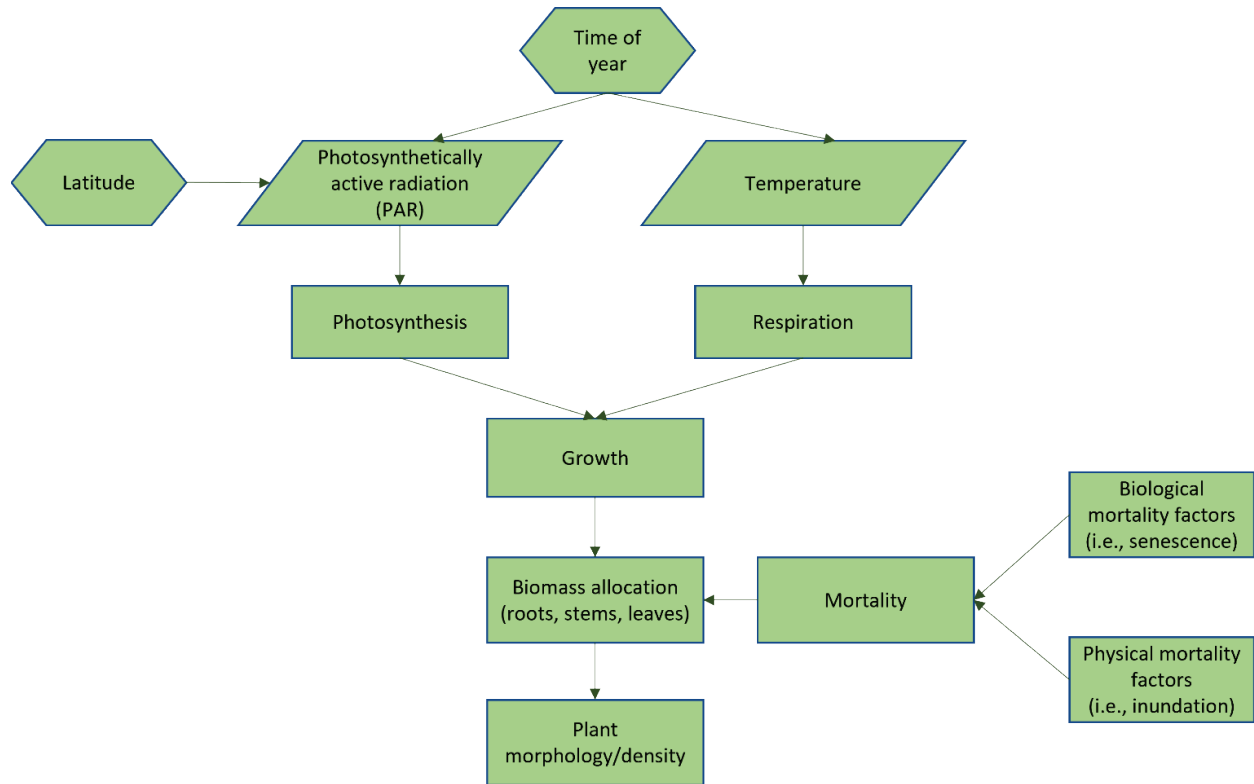


Figure 2. Conceptual diagram of a generalized mechanistic vegetation model illustrating the processes to estimate biomass.

Coupled Model Inputs/Outputs: Integrating disparate hydrodynamic, morphologic, and vegetation dynamics models is a non-trivial endeavor. It will require many considerations such as identifying inputs and outputs of each model and determining the appropriate mechanism to transfer information between models at varying spatial and temporal scales. Figures 3 and 4 depict a potential framework, with and without sediment transport, for this integration.

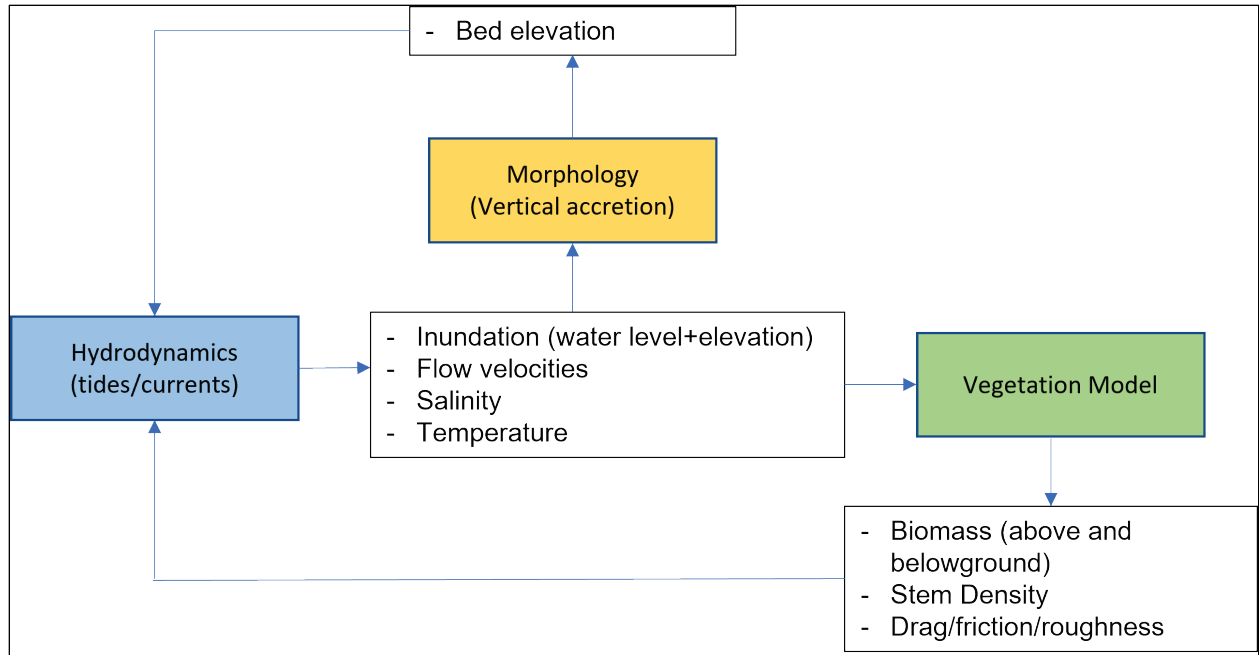


Figure 3. Framework (without sediment transport) for coupling mechanistic vegetation, hydrodynamic, and geomorphic models. *Colored boxes* indicate separate models; *white boxes* with arrows coming out and in represent model output and input, respectively.

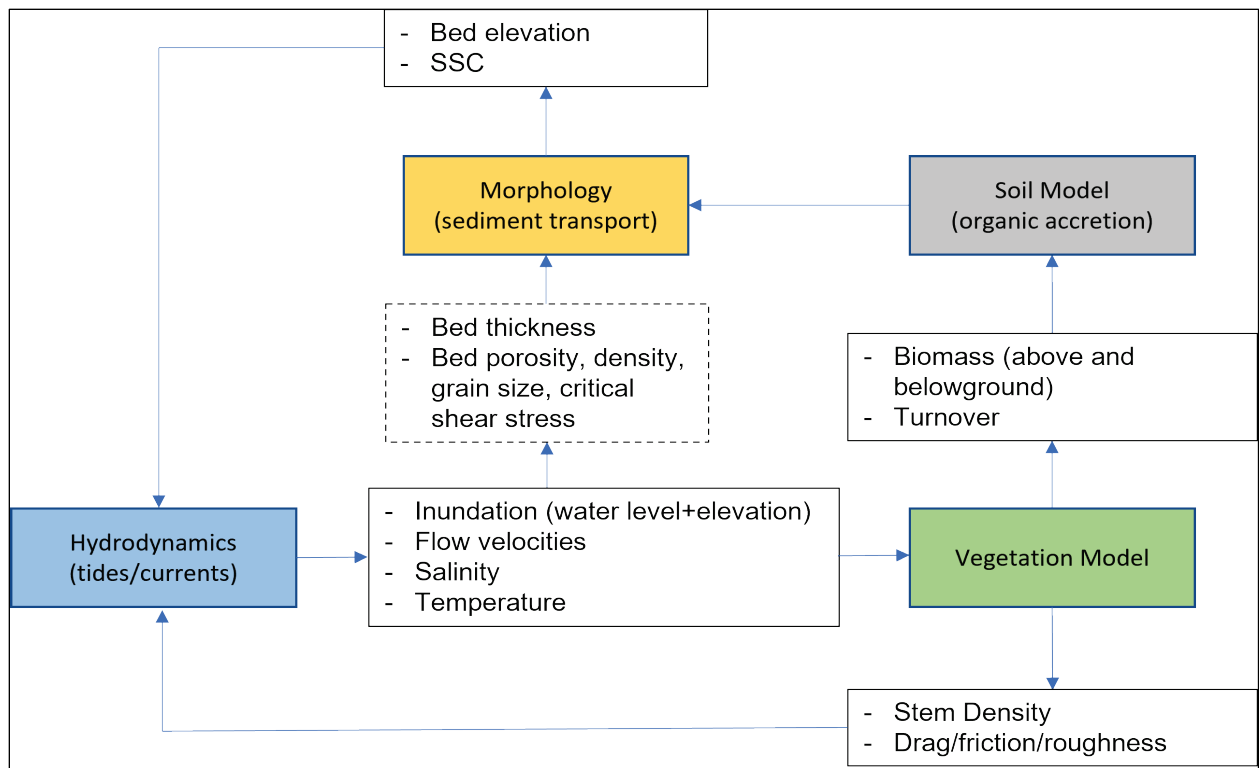


Figure 4. Framework (with sediment transport) for coupling mechanistic vegetation, hydrodynamic, and geomorphic models. *Colored boxes* indicate separate models; *white boxes* with arrows coming out and in represent model output and input, respectively. *Dashed box* represents separate input (i.e., not from other model output).

Initial elevations and vegetation distributions will be defined on a spatial grid. A hydrodynamic model forced by tidal action will be used to predict water levels, current velocities, and salinity/temperature on this grid (waves can also be important in controlling these outputs but are omitted here to simplify this conceptualization). The morphology model can be a simple vertical accretion model in which mineral deposition (a function of inundation depth, frequency, and suspended sediment concentration [SSC]), is added to the elevation. Alternatively, sediment transport can be incorporated into the morphology model using a mass balance approach to quantify advection, diffusion, erosion, and deposition to update elevations and SSCs. Additional sediment characteristics such as bed porosity, thickness, grain size, and critical shear stress are also necessary for this morphology model. Water levels (as a function of elevation), current velocities, salinity, and temperature are used as inputs to the vegetation model. Marsh vegetation dynamics will be controlled by growth, dispersal, and mortality factors (see Table 2). For example, in addition to seasonal growth and senescence (plant aging and seasonal dieback), growth parameters define the water level, current velocities, and salinities that maintain and encourage growth, while mortality parameters will define the thresholds at which plants begin to die off (Table 2). Ideally the vegetation model will predict above and belowground biomass. New growth can be established in cells where vegetation is absent through sexual reproduction, assuming seeds are transported through tidal action, or asexual reproduction, assuming unvegetated cells are adjacent to vegetated cells. It is important to note that marsh morphology is also affected by vegetation. Mineral accumulation will be accounted for in the morphology model through plant-induced velocity changes which facilitate sediment settling. A soils model can be included to simulate organic accretion from vegetation turnover. The hydrodynamics model then uses the updated bed elevation (from the morphology model) and bed roughness (from plant density and morphology) which will impact water levels and current velocities in the next timestep.

Table 2 Growth and mortality factors affecting salt marsh vegetation.	
Growth Factors	Mortality Factors
<i>Hydrodynamic</i>	
Optimal water levels (MLW-MHW)	High water/low water
Optimal velocity	High velocities
Optimal temperatures	Too cold/too hot
Optimal salinities	Too fresh/hypersaline
<i>Morphologic</i>	
Optimal Accumulation Rates	High erosion/deposition rates
<i>Other</i>	
	Herbivory
Optimal nutrient availability	Nutrient limited
	Senescence

Temporal Scale: Temporal scale is another important consideration since all the processes in the integrated model do not operate on the same timescale. Assuming a semi-diurnal tidal signal, an hourly timestep may be used to capture tidal cycle dynamics. Whereas an accurate representation of vegetation growth using the proposed vegetation model is achievable with a daily timestep since vegetation growth occurs more gradually. The hydrodynamic model outputs could be aggregated into a daily timestep, such as daily inundation frequency and duration and average current velocities, and then passed to the vegetation model. In contrast to hydrodynamics and vegetation dynamics, morphology changes in models are usually represented over longer time scales, on the

order of months to years. Various approaches have been used to overcome this difference such as applying a morphological factor at each hydrodynamic timestep to scale the morphology change to a longer time period without increasing the simulation time (e.g., Temmerman et al. 2005; Best et al. 2018). Another option is to define a separate coupling timestep (i.e., greater than the individual model time step) to pass information between models such that computational time is reduced without significantly affecting the results (e.g., Alizad et al. 2016). In this framework, it is likely that each model timestep will differ, and thus it is critical to determine an appropriate coupling timestep (i.e., linking hydrodynamics and vegetation dynamics daily, updating bathymetry seasonally) that captures feedbacks while optimizing model performance.

Model Integration: As these models are not natively linked and may have differences in spatial scale, temporal scale, and input/output naming conventions, the use of a model coupling toolkit, such as the Python Modeling Toolkit (PyMT, <https://pymt.readthedocs.io/en/latest/>), can help with model integration. PyMT provides a set of tools that can handle disparate spatial and temporal scales and facilitate data exchange. Another coupling method is to develop or use existing models that are built with the standard methods of the Community Surface Dynamics Modeling System's Basic Modeling Interface (BMI, <https://bmi.readthedocs.io/en/stable/>), which is designed to make models easier to learn, use, and couple.

Integrated Model Applications: The goal of integrating existing hydrogeomorphic models with a mechanistic vegetation model is to represent the dynamic feedbacks occurring more accurately in a salt marsh system, which will result in more realistic model output. This information is critical for coastal planners and managers for forecasting both long- and short-term changes. For example, an integrated approach can demonstrate whether mineral and organic sediment accumulation is sufficient for a vegetated salt marsh to endure sea level rise and other climate change impacts. Further, it can help managers identify when and what maintenance actions are necessary. Over shorter scales, an integrated marsh model can be used to quantify the limits of flood protection and determine if additional measures are necessary.

Next Steps: Once an integrated model is developed, the next steps will be to evaluate the model performance. The Seven Mile Island Innovation Laboratory (SMIIL) is a USACE research site in a salt marsh system in New Jersey where hydrodynamic (water levels, current velocities), morphologic (topography, bathymetry, sediment flux), and vegetation (percent cover, above and below-ground biomass) data are being collected. The multiple datasets from SMIIL are ideal for testing an integrated salt marsh model.

CONCLUSIONS: Salt marsh systems are shaped through dynamic interactions between hydrodynamics, morphology, and vegetation. As salt marshes are increasingly vulnerable to rising sea levels, reduced sediment input, and more frequent storm impacts, marsh management and restoration are critical for their persistence. Due to the strong feedbacks within marsh systems, integrated hydrodynamic, morphologic, and vegetation models are necessary for making short- and long-term predictions related to their survival and for planning appropriate management and restoration actions. Although disparate physical process and ecological evolution models exist, there is currently no framework for integrating these models at USACE. This TN proposes a conceptual framework to integrate these models to better represent salt marsh dynamics.

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