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Engineering With Nature® Program

Swan Island Resilience Model Development

Phase I: Conceptual Model

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and Jeffrey K. King

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Abstract

This report documents the development of an integrated hydrodynamic and ecological model to test assumptions about island resilience. Swan Island, a 25-acre island in Chesapeake Bay, Maryland, was used as a case study. An interagency, interdisciplinary team of scientists and engineers came together in a series of workshops to develop a simplified resilience model to examine the ability of islands to reduce waves and erosion and the impacts to nearby habitats and shorelines. This report describes the model development process and the results from this first key step: model conceptualization. The final conceptual model identifies four main components: vegetative biomass, island elevation, waves/currents, and sediment supply. These components interact to form and support specific habitat types occurring on the island: coastal dunes, high marsh, low marsh, and submerged aquatic vegetation. The pre-and post-construction field data, coupled with hydrodynamic ecological models, will provide predictive capabilities of island resilience and evaluations of accrued benefits for future island creation and restoration projects. The process and methods described can be applied to island projects in a variety of regions and geographic scales.

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Contents

Abstract.....	ii
Figures and Tables.....	iv
Preface	v
1 Introduction	1
1.1 Background	1
1.2 Objective	1
1.3 Approach	2
2 Model Purpose	3
3 Model Development Approach	4
4 Conceptual Model Development.....	5
5 Description and Importance of Model Components and Relationships.....	8
5.1 Overall effect of wind, waves, and water levels (hydrodynamics).....	8
5.1.1 <i>Advanced CIRCulation (ADCIRC) (Storm Surge)</i>	9
5.1.2 <i>STeady-state WAVE (STWAVE) (Radiation Stress)</i>	10
5.2 Importance of model components to Swan Island habitat types.....	10
5.2.1 <i>Coastal dunes</i>	11
5.2.2 <i>High marsh</i>	13
5.2.3 <i>Low marsh</i>	17
5.2.4 <i>Submerged aquatic vegetation (SAV)</i>	20
6 Model Development Considerations	26
7 Future Model Development Steps	27
7.1 Quantification	27
7.2 Evaluation	27
7.3 Application	27
8 Summary	28
References.....	29
Report Documentation Page	

Figures and Tables

Figures

Figure 1. Aerial view of Swan Island in 2019, one year post placement.	2
Figure 2. Conceptual model including both measured and non-measured parameters. Blue boxes are measured parameters, blue lines are processes estimated based on measured quantities, literature values, or expert opinion. Yellow circles and arrows are external forcing factors not directly measured by the project team. Green indicates benefits not quantified through project monitoring.....	6
Figure 3. Simplified model including primary components deemed essential for understanding island performance (i.e., resilience) over time.	7
Figure 4. Coastal storm modeling framework for computing hydrodynamic storm conditions based on storm forcing parameters.	9
Figure 5. Aerial photograph taken pre-placement with the shaded polygons depicting the habitat locations. Note, SAV beds occur in areas adjacent to island in figure.....	11
Figure 6. Relationship between storm frequency and dune elevation. Based on Duran and Moore (2013) and Brantley et al. (2014). Elevation reflective of tidal amplitude, mean sea level and wave energy.....	12
Figure 7. Relationship of vegetation and dune elevation. Based on Lalimi et al. (2017). LAI – Leaf Area Index.....	13
Figure 8. Biomass elevation curve adapted from Watson et al. (2016) (Figure 4b) equation was derived from the data using a polynomial function in excel. MHW – Mean High Water.	15
Figure 9. Data plotted and equation is based on Kirwan and Guntenspergen (2012), $P < 0.001$	16
Figure 10. Relationship between <i>S. alterniflora</i> biomass and elevation at Swan Island – preplacement.....	19
Figure 11. SAV percent (%) cover by elevation (M NAVD88) at Swan Island (MD DNR unpublished data).	22

Tables

Table 1. Description and importance of preliminary model components.	25
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Preface

This report is part of a larger study to examine the benefits of the Swan Island Restoration. The project was funded in part by the US Engineering Research and Development Center (ERDC), Dredging Operations and Environmental Research (DOER) program and the Engineering With Nature® (EWN®) Program. Dr. Todd Bridges was the DOER program manager and Director of the EWN Program.

This study was conducted for the DOER and EWN programs under Project 33143, “Swan Island Restoration” The technical monitor was Dr. Jeff K. King.

At the time of publication, Ms. Patty Tolley was Chief, Wetlands and Coastal Ecology EEW Branch; and Mr. Mark D. Farr was the Division Chief, Ecosystem Evaluation and Engineering Division (EE) branch. The Director of ERDC-EL was Dr. Edmund Russo. Ms. Tiffany Burroughs was Headquarters USACE Navigation Business Line Manager, and Mr. Charles E. Wiggins, ERDC Coastal and Hydraulics Laboratory, was the ERDC Technical Director for Civil Works and Navigation, Research, Development, and Technology Transfer portfolio.

COL Christian Patterson was Commander of ERDC, and Dr. David W. Pittman was the Director.

1 Introduction

1.1 Background

Swan Island, located in the Chesapeake Bay (Figure 1), serves as a case study for the beneficial use of dredged sediments and the application of Engineering with Nature® (EWN®) principles. In fall 2018, the US Army Corps of Engineers (USACE) Baltimore District began maintenance dredging of the Big Thorofare federal navigation channel located at Smith Island, Maryland. After dredging activities were concluded in April 2019, approximately 61,000 cubic yards (CY) of sediment were beneficially placed as part of the overall island restoration effort. Other restoration efforts included the establishment of additional natural and nature-based features (NNBF) such as planting of high and low marsh and dune vegetation on the island (primary NNBF), which was completed in July 2019. The result was a transformation of the 11-acre (ac) placement area from a low-elevation fragmented marsh to one with a wider range of habitats sitting higher in the tidal frame offering a lot in terms of increased resilience to wind-driven waves and Sea Level Rise (SLR) of the surrounding area and ecological benefits. However, evaluation of these perceived benefits, especially resilience benefits, are needed to address the uncertainties surrounding island performance over time. Performance in this context refers to the ability of the island to reduce wave action, resist erosion, and provide intended ecological benefits. For the next three years, the USACE-Baltimore District, US Army Engineer Research and Development Center (ERDC), National Oceanic and Atmospheric Administration (NOAA), US Fish and Wildlife Service (USFWS), and the Maryland Department of Natural Resources (MD DNR) have committed to study the island to better understand its ecological and engineering performance. The pre-and post-construction field data, coupled with hydrodynamic ecological models, will provide predictive capabilities of island resilience and evaluations of accrued benefits for future island creation and restoration projects.

1.2 Objective

The purpose of this report is to document the development of an integrated hydrodynamic and ecological model that will assist in testing

assumptions about island resiliency, decisions on adaptive management actions, and evaluating the performance of EWN features.

1.3 Approach

The integrated model is being developed with an interagency, interdisciplinary team of scientists and engineers, listed above, in a group mediated process. The report will describe the model development process and results in the first key step of model development: model conceptualization.

Figure 1. Aerial view of Swan Island in 2019, one year post placement.



2 Model Purpose

The development of an integrated hydrodynamic and ecological model will address some uncertainties by quantifying island coastal resilience characteristics as the island changes and matures. For this work, resilience is defined as the ability to bounce back from storm events or from chronic stressors such as the ability to maintain flood reduction and ecological function in the face of SLR, erosion, subsidence, etc. Resilience over time has a direct bearing on the protective capacity of the island to reduce waves and erosion to surrounding habitats and nearby communities. This modeling approach can be applied to other NNBF projects to support their implementation by addressing data gaps related to project performance.

Quantifying resilience in this context requires evaluation of the linkages between the ecological, hydrodynamic, and topographic parameters of the island, to examine questions such as:

1. How resilient is the island and its habitats against rising sea level and periodic storm events?
2. What is the protective capacity of Swan Island for example, in terms of reduction in wave height for the Town of Ewell? Alternatively, how many waves and current energy can the island withstand and remain intact?
3. How will SLR inundation scenarios change as biomass increases?
4. How often would maintenance activities be needed to maintain island physical (elevation) and functional (biomass) characteristics? Can the model be used to determine or test adaptive management alternatives to make informed decisions?

3 Model Development Approach

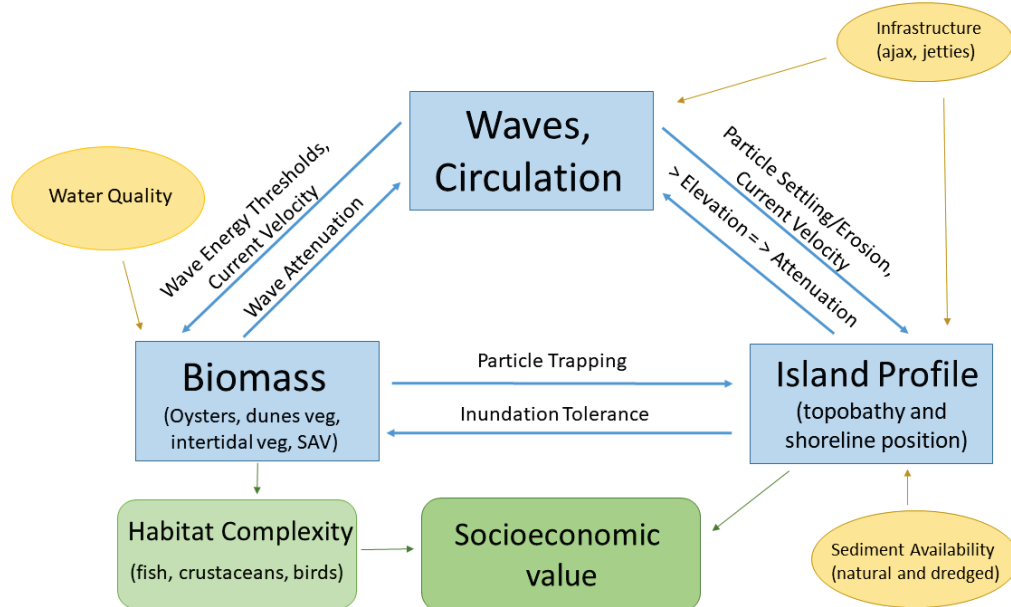
A model is a simplification or abstraction of a process or system that helps answer questions related to its behavior and response to future scenarios. Developing a model typically involves a series of steps completed in an iterative manner: conceptualization, quantification, testing/evaluation, application, and communication. The Swan Island Resilience Model is being developed with the Group Mediated Model Development approach, which explicitly involves model stakeholders in each model development step through interactive workshops (Herman et al. 2020). The Group Mediated Model Development approach is a good fit for the broader Swan Island Restoration project since the project requires adaptive management decisions to be made with consensus from multiple study partners. Through two interactive workshops, participants determined the primary project objectives and identified the important ecosystem components to be monitored (Herman et al. 2020; Appendix A). This formed the basis for the development of model objectives and conceptualization.

The first workshop was held April 11-12, 2019, at the Blackwater National Wildlife Refuge, Cambridge, MD. The 22 participants at this workshop included the core project team and additional stakeholders with a vested interest in coastal resilience, ecosystem restoration monitoring, and research within the Chesapeake Bay region (Herman et al. 2020). Collectively, they identified the important components of Swan Island's ecosystem and prioritized them according to their importance in understanding the consequences and benefits of island restoration. An initial conceptual ecological model, draft Monitoring, and Adaptive Management Plan, and a published workshop proceedings document resulted from the workshop (Herman et al. 2020). The second workshop held Feb 25-26, 2020 in Vicksburg, MS included the core project team that are directly involved in the implementation, management, and monitoring of Swan Island: USACE Baltimore District, USACE ERDC-Environmental and Coastal and Hydraulics Laboratory, NOAA-National Centers for Coastal Ocean Science, and Maryland Department of Natural Resources. The overarching goal was to review the conceptual model components and relationships among the components to determine data gaps and next steps for model development.

4 Conceptual Model Development

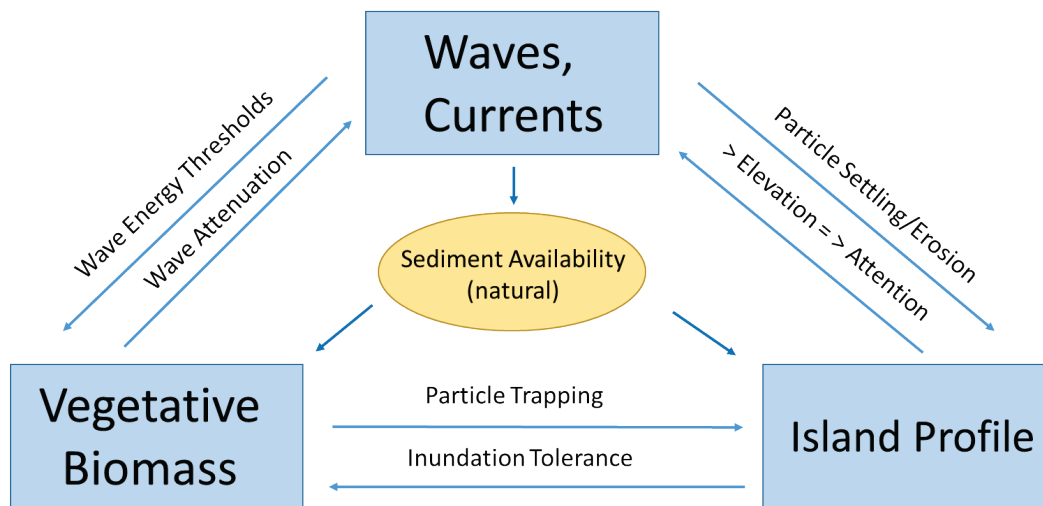
The conceptual model is the culmination of various decisions made by group consensus through the iterative model development approach. It represents the most important system components for addressing the primary project objective of assessing island performance (e.g., wave height reduction effectiveness) over time. At the island level, there were eight different components (Figure 2) identified that represent indicators of system-level processes that build, support, influence, or impact Swan Island. Three were considered primary components that directly related to project objectives and are being directly measured through on-going monitoring efforts: 1) Waves/Currents, 2) Island Profile (topography/elevations), and 3) Biomass (oysters, coastal dune, intertidal (high and low marsh) and submerged aquatic vegetation [SAV]) (Figure 2, shown in blue boxes). Two other components, habitat complexity and socioeconomic value (e.g., recreational), were identified as benefits, but were outside the scope of model development objectives (Figure 2, green boxes). Therefore, these are not included in the next phase of model development at this time. Finally, three external drivers were identified as components that are not being directly measured but must be considered. These include infrastructure, water quality, and sediment availability (dredged/natural sources). During the second workshop, there was general agreement amongst the participants of the importance of sediment availability from natural sources, especially its influence on both biomass and the island profile. Therefore, sediment availability will be retained within the model and will be part of the next model development steps.

Figure 2. Conceptual model including both measured and non-measured parameters. Blue boxes are measured parameters, blue lines are processes estimated based on measured quantities, literature values, or expert opinion. Yellow circles and arrows are external forcing factors not directly measured by the project team. Green indicates benefits not quantified through project monitoring.



The conceptual model was further refined to represent only the measured or estimated components included in Phase I of model development (Figure 3). Circulation was changed to currents in the top component, biomass was changed to vegetative biomass, and the group dropped oysters as part of that component. This simplification was made because focusing on capturing changes in vegetation biomass was of primary importance. Other components may be included as needed following model quantification and evaluation.

Figure 3. Simplified model including primary components deemed essential for understanding island performance (i.e., resilience) over time.



Note that while the entirety of Swan Island is a key part of providing protective services to surrounding areas (e.g., Smith Island), there are separable habitat types on the island that provide unique environmental benefits and services that are also restoration targets of the project. These include the coastal dune, high marsh, low marsh, and SAV habitats. These habitats support unique assemblages of species that depend upon similar environmental drivers, such as sediment erosion/accretion, and hydrologic regimes (tides, currents, waves). The model should capture the response of these habitat types along with the entirety of Swan Island itself, requiring the development of an integrated hydrodynamic/ecological model to be composed of multiple modules representing unique habitats of the Swan Island system. Dune, high marsh, low marsh, and SAV habitat modules will be coupled together to project the long-term dynamics of the entire island system.

5 Description and Importance of Model Components and Relationships

The following sections are intended to describe the importance of model components and their complex interactions that form Swan Island and the island's impact on the surrounding hydrodynamic processes. These descriptions are also meant to illustrate how these model components will help meet model objectives and answer research questions.

5.1 Overall effect of wind, waves, and water levels (hydrodynamics)

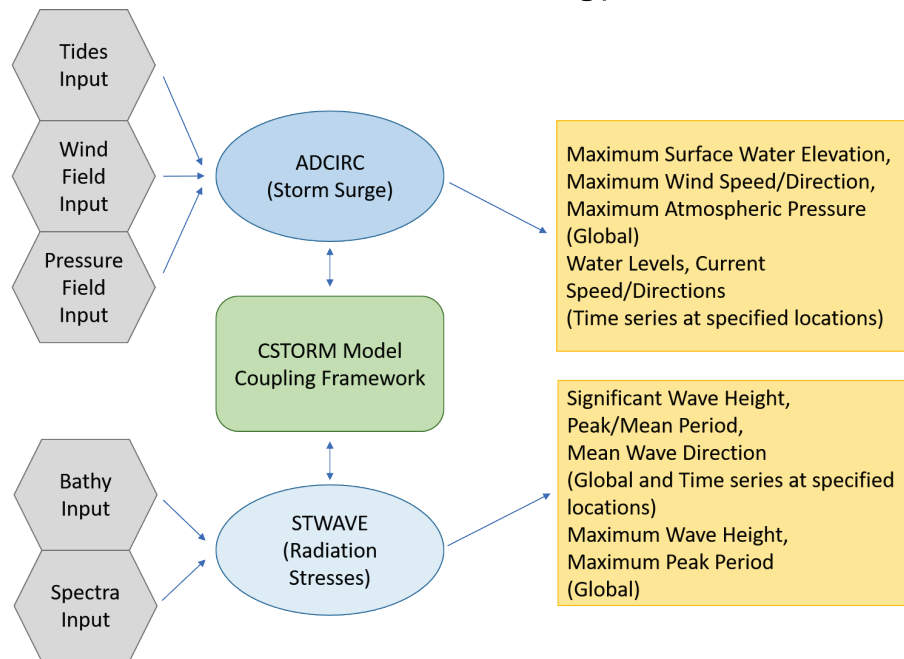
Swan Island attenuates waves during everyday conditions and storm events. A numerical, spatially explicit wave action model will be used to quantify how much wave attenuation is occurring in the surrounding area due to varying wind energy conditions, from speeds of 2.5 m/s to 50 m/s at angles of 0 degrees to 360 degrees facing Swan Island. Similarly, a storm surge model, coupled with this wave action model, will be used to estimate water level and current velocities during historical tropical storm events. These models will be run over two domains: one including Swan Island and another that will not. The outputs will be combined with the habitat modules described in the following sections.

This computational approach to model the effect of wind, waves, circulation, and currents around Swan Island will use the Coastal STORM Modeling System (CSTORM-MS) two way coupling framework (Massey et al. 2011b) (Figure 4). The CSTORM-MS framework efficiently communicates between the radiation stress and storm surge time-dependent models (STWAVE and ADCIRC) as they run in parallel. Figure 4 shows the communication from each storm parameter input, into the wave and current models, and the following two sections describe the models. To effectively model hydrodynamic storm conditions, the output from each model will be shared through time through the coupler.

The results from these hydrodynamic models will be used to estimate the protection benefit Swan Island might have on the surrounding area (i.e., how much does it slow the flow during storm events – protecting the surrounding area from erosion?). Results from the wave attenuation analysis can be paired with observed winds to better understand the wave action that occurs with and without Swan Island in this region. This can

help ecological teams predict the performance of planted vegetation and coastal protection features (dunes, marsh) on the island, and the surrounding area. These models can also inform on the coastal resiliency benefit provided by Swan Island, as well as help design a monitoring plan for the yearly maintenance needed to keep Swan Island thriving.

Figure 4. Coastal storm modeling framework for computing hydrodynamic storm conditions based on storm forcing parameters.



5.1.1 Advanced CIRCulation (ADCIRC) (Storm Surge)

Advanced CIRCulation (ADCIRC) is a finite-element-based hydrodynamic model (Westerink et al. 1994; Luetlich et al. 1992). ADCIRC is both a hydrodynamic and computational model that solves for the depth-integrated equations of mass and momentum conservation using highly flexible, unstructured grids. The grids are composed of nodes, which have an x, y, and z value, and elements that are essentially triangle shapes communicating the hydrostatic pressure differential between the nodes. ADCIRC applies wind speed, atmospheric pressure, tidal boundary conditions, and wave conditions from STWAVE as forcings at each time step during the model run. Then, it solves for the equations mentioned above to find the current speed and water height at each node within the mesh at every time step during the model's run time. The model assumes water is compressible, and that hydrostatic pressure conditions exist.

5.1.2 Steady-state WAVE (STWAVE) (Radiation Stress)

STeady-state WAVE (STWAVE) is a phase-averaged spectral wave model for nearshore wave generation, propagation, transformation, and dissipation (Smith et al. 2001; Smith 2007; Massey et al. 2011). STWAVE numerically solves the steady-state conservation of spectral wave action along with backward-traced wave rays. During the model simulations, recording nodes specified by the user, referred to as stations, are recording the significant wave height, mean wave period, mean wave direction, peak wave period, wind magnitude, wind direction, and water elevation for each time step. These station locations will also record the water level, wind speed, and mean-sea-level pressures through time calculated by ADCIRC at those locations.

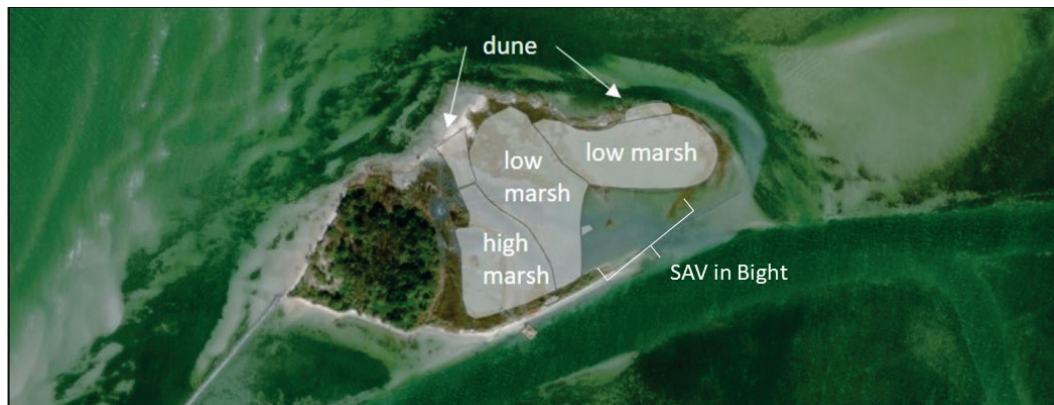
A spatially-explicit mesh will be developed to account for changes in topography for model runs with and without Swan Island. For runs without the island, the area in the mesh where Swan Island was will reflect the bathymetry of the surrounding area. Model runs with and without the island will be done to compare differences in hydrodynamics (e.g., waves). The results from these runs can then be compared to better understand the island's effect on the surrounding area.

5.2 Importance of model components to Swan Island habitat types

The following sections will provide a description of how physical and environmental processes interact to form and support the island's habitat types and the feedback loop between the biological response and physical processes (Figure 3).

The unique habitats on Swan Island are represented by distinct plant communities or vegetation types based on their locations within the tidal frame, reflected in their elevation/bathymetry (Figure 5). Coastal dunes are rarely inundated except during overwash events. High marsh grasses occur lower in elevation than dunes and are inundated at infrequent intervals. Low marsh is inundated on every high tide and exposed on low tides. SAV occurs at sub-tidal water depths, usually not greater than 2 m deep in this region and does not tolerate being frequently exposed at low tides. Initially, oyster biomass was considered in Phase I model development but given the low abundance of oysters currently at the site, this module will not be included in this phase of model development.

Figure 5. Aerial photograph taken pre-placement with the shaded polygons depicting the habitat locations. Note, SAV beds occur in areas adjacent to island in figure.



5.2.1 Coastal dunes

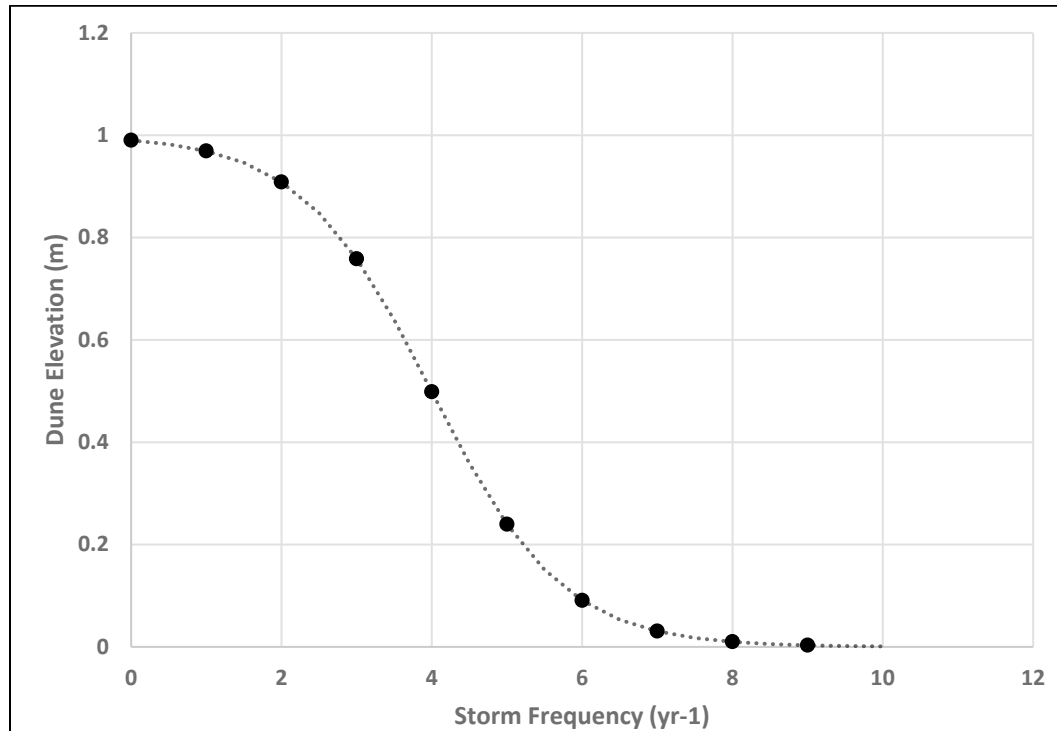
The main drivers of coastal dune formation and persistence identified were sediment supply/transport, vegetation, and storm impacts. Hydrodynamic processes that influence sediment supply and accretion/erosion include wave height, circulation, current velocity, tidal inundation, and storms (Duran and Moore 2013).

5.2.1.1 Biomass – Island profile

Duran and Moore (2013) report that foredune height is primarily driven by the location of the vegetation in relation to the shoreline coupled with wave height. Beaches with high wave height have higher foredunes than beaches with low wave height. Dunes may accrete sediment during normal conditions when waves stir up sediments from the beach and wind deposits them inland, particularly if vegetation is present to reduce wind speeds (Walker et al. 2013). On the other hand, waves become higher and break further inland during storm events, which may erode sediments from dunes and damage vegetation (Mull and Ruggiero 2014). Storms may also cause storm surges, allowing the stormwater to overtop dunes and inundate dune vegetation. For the purposes of this report, storms are defined as an event that has increased wind speed, periods of precipitation, and elevated hydrodynamic levels (e.g., wave height, velocity). As the frequency of storms increase, there is less time for dunes to recover and dunes with frequent overtopping events are typically lower and are dominated by more tolerant vegetation (*Spartina patens*) (Brantley et al. 2014). Figure 6 depicts a relationship between the relative frequencies of storms (damage) and dune elevation based on reports from Duran and Moore (2013) and Brantley et al. (2014). Note that the

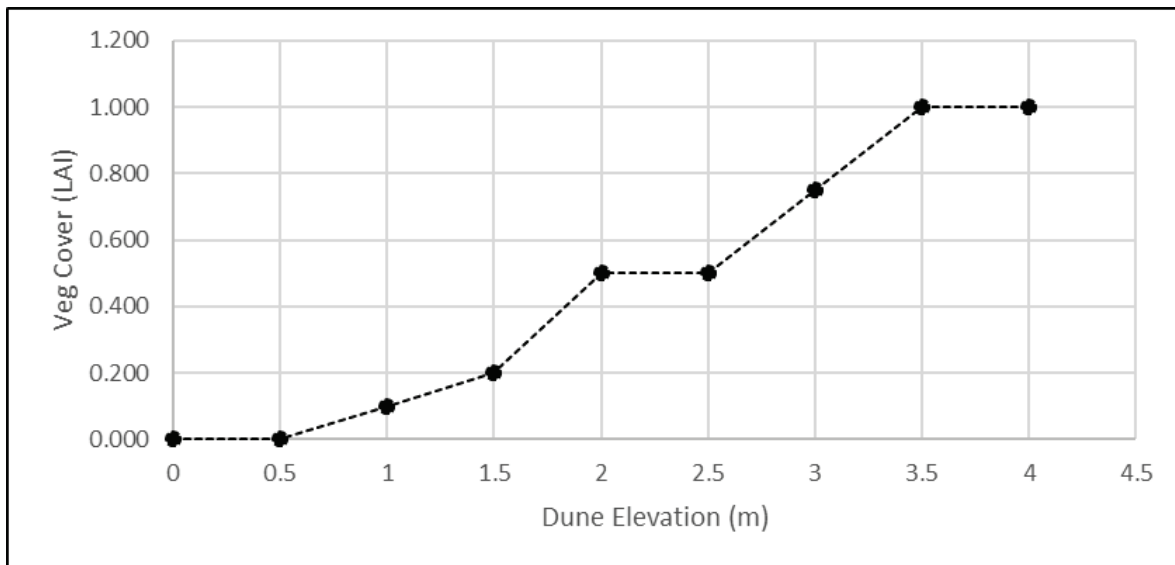
relationship in this context does not consider severity of storm, which may also influence ability of dune system to recover.

Figure 6. Relationship between storm frequency and dune elevation. Based on Duran and Moore (2013) and Brantley et al. (2014). Elevation reflective of tidal amplitude, mean sea level and wave energy.



Swan Island does not have a very wide beach nor an extensive dune system, which makes it vulnerable to storm damage and overwash events. However, as part of the restoration activities, sediment was placed (+4.5 ft MLLW; 1.05 m NAVD88 and +3 ft MLLW 0.59 m NAVD88) to increase dune elevation and to provide greater storm damage protection. Dune elevation has a strong influence on the type and distribution of vegetative biomass that can survive in a location due to the inundation tolerance of individual species (Hester et al. 2005). Moreover, Lalimi et al. (2017) found there was a relationship between vegetation cover and dune elevation (Figure 7) at Hog Island, Virginia. As aboveground biomass increases within a dune system, more sediment can be captured and deposited, resulting in increased elevation. However, there are constraints on how much sediment can accumulate before plant physiological burial tolerances are reached (Dech and Maun 2005) in addition to sediment supply constraints (Houser et al. 2008).

Figure 7. Relationship of vegetation and dune elevation. Based on Lalimi et al. (2017). LAI – Leaf Area Index.



5.2.1.2 Waves/currents (hydrodynamics) – Island profile/biomass

Dunes act as a line of protection, mitigating the impact of storms and providing some protection for the island behind them (Jackson et al. 2019). They also may provide part of the sediment supply for the adjacent high marsh area, although this has yet to be determined. There is some question of how persistent Swan Island dunes will be over time considering the potential impact of SLR coupled with more frequently occurring intense storms because of climate change. However, there is hope that planting dune building plant species may increase the resiliency of the dunes through aboveground and below ground biomass growth (Jackson et al. 2019). Plant roots facilitate soil formation that acts to bind loose sediments, making it harder to break apart under wave actions (Sigren et al. 2014). The presence of vegetation on dunes can reduce erosion and frequency of overwash events (Silva et al. 2016) and dunes with remnant vegetation seem to recover more quickly from storm damage (Corbella and Stretch 2012).

5.2.2 High marsh

Spartina patens is a high marsh species occurring near and slightly above Mean High Water (MHW), transitioning to the low marsh species *Spartina alterniflora* below this tidal zone. Unlike *S. alterniflora*, *S. patens* does not tolerate frequent inundation. Research in *S. patens* marshes in Chesapeake Bay and New England indicate there are

biogeomorphic feedbacks with increased tidal inundation that lead to lower rates of organic matter production, peat formation, and thus greater rates of marsh submergence. In contrast, at higher elevations there is increased organic production that may lead to a sustainable marsh system (Kirwan and Guntenspergen 2012; Watson et al. 2016).

Declines in high marsh systems have been documented in New England where increased tidal inundation sets in motion the biogeomorphic feedbacks that lead to conversion to low marsh. The decline of *S. patens* at more frequent tidal inundation are attributed to the following: *S. patens* utilizes a C-4 photosynthesis pathway which is common among drought-tolerant plants in arid regions, *S. patens* cannot tolerate anoxic soils common for low marsh (Bertness 1991) and their roots are associated with facultative fungal symbionts that fix atmospheric nitrogen, but these fungi are intolerant of saturation (Burke et al. 2002; Cooke et al 1993). For these reasons, *S. patens* is adapted to well-drained soils and loses productivity in saturated conditions with elevated porewater sulfide (Watson et al. 2016). Precipitation was found to have little to no effect on *S. patens* growth (Watson et al. 2016).

In the northeast, *S. patens* marshes occur at elevations equivalent to 0.05-0.10 m above MHW, which receives partial tidal inundation. Therefore, the plants do not experience total inundation on a regular basis (Watson et al. 2016).

5.2.2.1 Biomass – Island profile interactions

On Swan Island, the elevation range over which *S. patens* occurs is 0.38 to 0.70 NAVD 88.¹ Since *S. patens* does not tolerate regular tidal inundation, the biogeomorphic feedbacks that build elevation are less dependent on sediment processes as compared to low marsh and more dependent on organic accretion (Kirwan and Guntenspergen 2012).

Figures 8 and 9 show biomass/elevation curves from two papers for *S. patens*. The first, from Watson et al. (2016), is the result of experimental work in a New England estuary. The second is the result of marsh experiments in Blackwater National Wildlife Refuge (BWNWR) (Kirwan and Guntenspergen 2012). It is important to note that the elevation range

¹ Davis, J. Unpublished. *Swan Field Data Collection*.

of the experimental work in BWNWR did not extend to as high an elevation as the work by Watson et al. (2016); however, research sites were found within similar relative positions with their respective tidal frames. After the Swan Island high marsh becomes established the biomass/elevation data will be collected, and their curves derived. Until these data become available, model development will proceed using the parabolic elevation curves derived from Kirwan and Guntenspergen (2012) and Watson et al. (2016). In addition, the stem height and density relationship derived by Watson et al. (2016) may be used to convert the existing *S. patens* density and stem heights to biomass ($y = 6.61 \times 10^{-5}x^2 + 2.16 \times 10^{-4}x$ where y is stem weight and x is height; $R^2 = 0.793$).

Figure 8. Biomass elevation curve adapted from Watson et al. (2016) (Figure 4b) equation was derived from the data using a polynomial function in excel. MHW – Mean High Water.

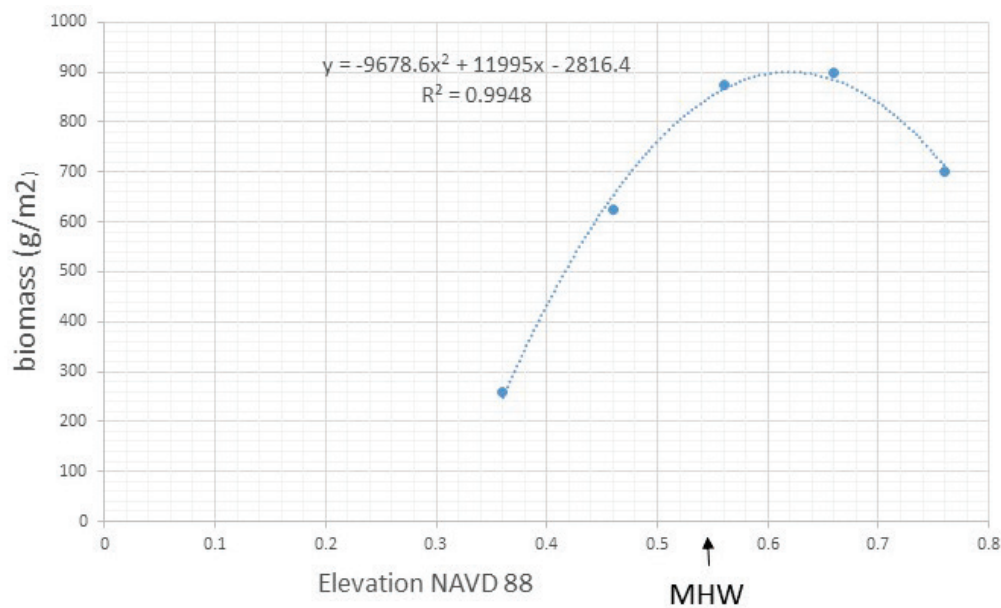
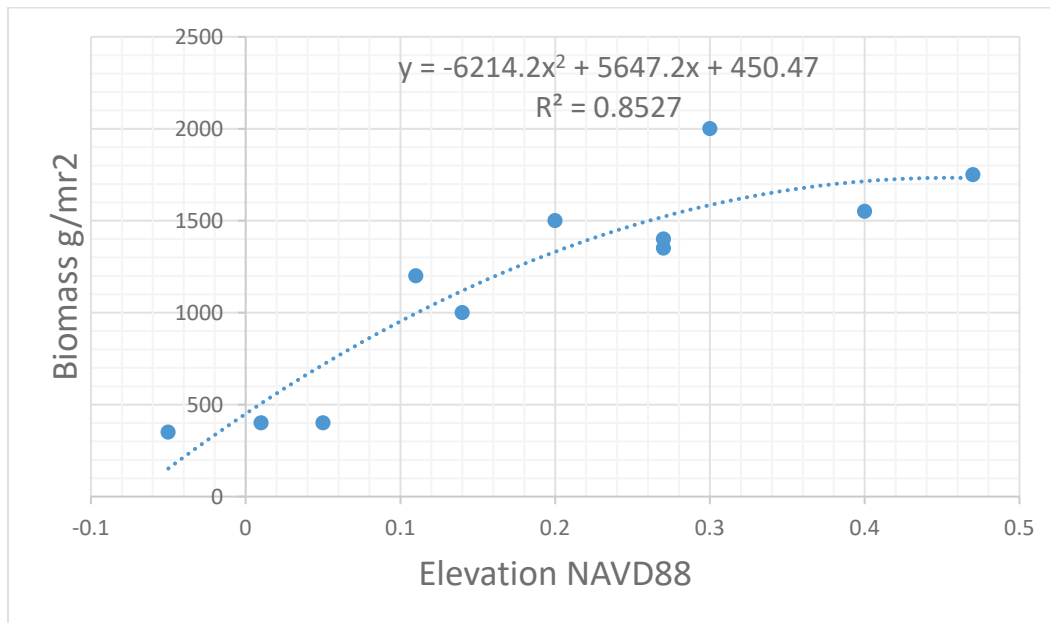


Figure 9. Data plotted and equation is based on Kirwan and Guntenspergen (2012), $P < 0.001$.



5.2.2.2 Biomass – SLR, storm, wave, current interactions

Numerous studies have found that high marsh vegetation such as *S. patens* is particularly vulnerable to SLR. The reason being that sediment trapping processes central to the persistence of low marsh species are less important in high marsh, and any increases in tidal inundation from SLR will further increase water levels during storm events. Therefore, continued SLR is expected to further stress these plants leading to their ultimate replacement with a low marsh species, unless there is space for migration (Watson et al. 2016; Bigalbal et al. 2018).

On Swan Island, the high marsh is buffered to the north and south by low dunes colonized by native plants, while the west side is protected by an 8-ac forested heron rookery (Figure 5). Therefore, it is mainly on the east side, at or near the MHW boundary, where high marsh plants may experience inundation from tides (Figure 5). The south side of Swan Island experiences regular boat wakes from the channel located parallel to the island, but the wave energy is dissipated on the beach and does not impact the high marsh on a regular basis. However, overwash events from storms, especially along the north side, may cause erosion and/or plant damage but could also result in a sediment deposition event. It is worth noting that islands in Tangier Sound, Virginia experienced an average 21% loss in area within 13 yr, mostly due to erosion from overwash events that resulted in

the loss of small dunes, vegetation, and forest cover, suggesting more frequent storm and tidal inundation on these islands (Erwin et al. 2011).

Local SLR projections based on historic rates for the Chesapeake Bay and three emissions scenarios from the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Church et al. 2013) are 0.49 m, 0.98 m, 1.68 m, and 2.32 m. This would result in a marsh migration rate of 0.61, 0.92, 1.53 and 1.83 m, respectively (Mitchell et al. 2013; NOAA 2017). Storm impacts would increase the inundation extent predicted by these SLR scenarios and influence maximum water levels and wave heights (Bigalbal et al. 2018) with higher intensity storms having a greater impact.

On Swan Island, there is limited space for marsh migration except for the forested heron rookery to the west. This is the only upland area for marsh migration. Marsh migration would occur if tidal inundation regimes increased causing a forest dieback scenario (Fagherazzi et al. 2019), which has not yet been observed on the island. Adaptive management such as further placement of sediment to optimal high marsh elevations and planting, would allow high marsh to persist despite SLR. With no action, the area that is now colonized by high marsh is anticipated over time to convert to low marsh and ultimately open water (Watson et al. 2016).

5.2.3 Low marsh

Low Marsh is the portion of the vegetated intertidal zone inundated on most high tides (falls below MHW). The dynamics of this zone are dominated by biogeomorphic feedbacks among plant biomass, sediments, and water movement (Kirwan and Guntenspergen 2012) that influence both the elevation of the marsh platform and stability of the vegetated shoreline.

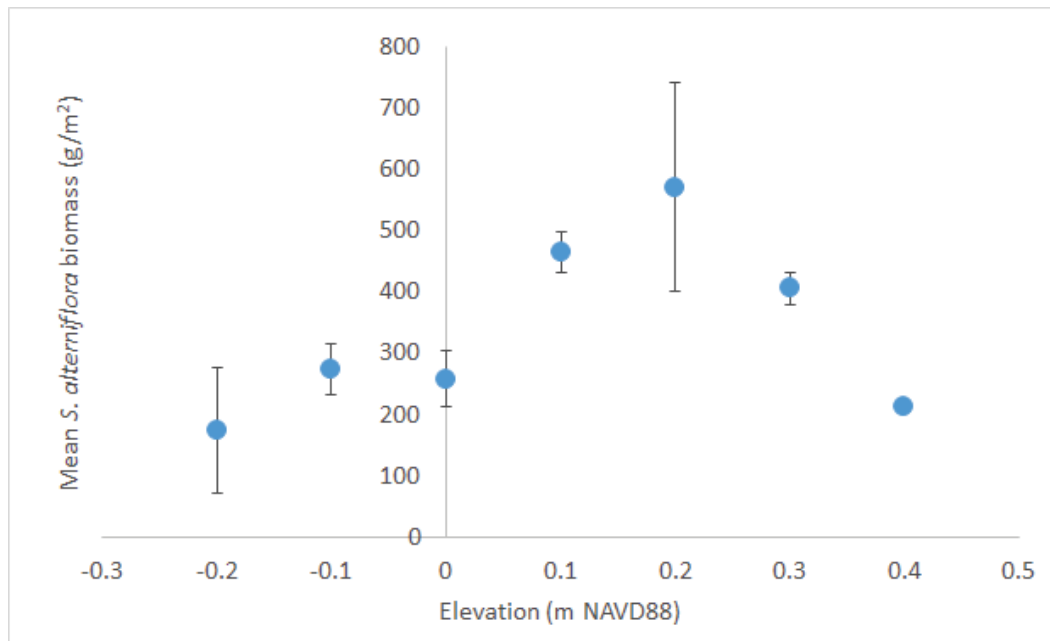
5.2.3.1 Biomass – Island profile interactions

The leaves and stems of plants attenuate waves and slow the movement of water, reducing both velocity and turbulence and, as a result, causing suspended particles carried in the water to be deposited on the marsh surface (Leonard and Croft 2006; Mudd et al. 2009). This capacity to influence water movements confers protection against wave-induced erosion, within the range of wave conditions that plants can tolerate. Over time, the resulting sediment deposition contributes to marsh platform

elevation. Plants further influence elevation through the production of belowground roots and rhizomes which contribute to soil volume (Nyman et al. 1993; Turner et al. 2004). Previous studies have demonstrated that: 1) greater vegetative biomass results in greater rates of sediment deposition (Morris et al. 2002; Davis et al. 2017) if sediment is not limiting, and 2) the longer a marsh is flooded, the more sediment it accumulates (French and Spencer 1993; Leonard 1997). As a result, marshes that sit deeper in the tidal frame experience greater rates of sediment deposition than those higher. At the same time, inundation limits where low marsh vegetation grows and thrives. There is often a parabolic relationship between low-marsh biomass and elevation that is driven by inundation tolerance (Morris et al. 2002; Voss et al. 2013). At higher elevations with less frequent inundation, plant biomass is limited by high porewater salinity and sulfide concentrations, at very low elevations, biomass is limited by inundation time. Between these end points is the zone of maximum biomass which represents the optimal conditions for growth at that site. This zone usually occurs around the elevation of mean sea level. The feedbacks among inundation, biomass, and suspended sediments allow marshes to adjust their position in the tidal frame in response to changing sea levels and provide the foundation for how the Swan Island model will capture low marsh elevation dynamics.

Before the Swan Island restoration project began, the relationship between *S. alterniflora* biomass and elevation on the Island was documented (Figure 10). While site-specific data on suspended sediment concentrations is not in hand, data from the Chesapeake Bay Program's data hub will be used (<http://data.chesapeakebay.net/WaterQuality>) as a starting point for estimating suspended sediment concentrations at the site. Similarly, the data necessary to determine site-specific tidal datums are currently being collected – until those data are available, published datums from the nearest NOAA NWLON station will be used (Bishop's Head MD, #8571421).

Figure 10. Relationship between *S. alterniflora* biomass and elevation at Swan Island – preplacement.



5.2.3.2 Biomass – Waves/circulation

S. alterniflora-dominated shorelines are common in low to moderate wave energy settings, but do not occur on shorelines that regularly experience waves of 0.3 m or greater (Shafer et al. 2003; Roland and Douglas 2005). These findings provide the threshold values for marsh existence. Within the range of standard energy conditions where *S. alterniflora* does occur, rates of shoreline erosion are linearly correlated with wave energy according to the relationship:

$$E = 0.67P$$

where E = erosion rate and P = wave power (Leonardi et al. 2016). Wave power is computed as

$$P = \frac{\rho g^2}{64\pi} H_{mo}^2 T$$

Where P=wave energy flux per unit of wave-crest length, H_{mo} =the significant wave height, T= wave period, ρ =water density, g=acceleration by gravity. Thus, measured wave energy conditions can be used to predict changes in shoreline position. As waves travel beyond the immediate shoreline and into the marsh, interactions with both the marsh substrate

and vegetation dissipate wave energy thus protecting areas further inland. This function is maximized at the marsh edge; the majority of incoming wave energy is dissipated within the first 30-80 m of marsh (Knutson 1982; Yang et al. 2012). Wave energy reduction increases with increased stem density and canopy height (Leonard and Croft 2006; Möller 2006; Yang et al. 2012) and is maximized when the water level is no higher than the marsh canopy (Gedan et al. 2011). As a result, the extent to which vegetation reduces incoming wave energy will vary seasonally in response to annual cycles of vegetative growth and senescence and during high water events. Both wave energy reduction and sediment deposition rates are positively correlated with stem density, as a result, both are likely to vary with seasonal fluctuations in standing biomass and across the spatial gradient of a marsh.

The impact of extreme weather events on low marsh habitat are strongly controlled by shoreline topography and tidal stage. Shorelines with scarped edges are more susceptible to wave erosion than shorelines characterized by a gradual slope across the intertidal (Theurkauf et al. 2015). During high wave events, scarped shorelines may experience significant erosion when water levels are such that the waves directly impact the shoreline; when water levels are higher than the shoreline edge, direct impacts on the shoreline are minimized (Tonelli et al. 2010). As a result, hurricanes, nor'easters, and other storm events that hit during high tide often have minimal impacts on shorelines and low marsh habitat. The primary exception is that these events often result in a measurable deposition of sediments on the marsh surface. Such events have been hypothesized to be an important contributor to the ability of coastal marshes to build (McKee and Cherry 2009).

5.2.4 Submerged aquatic vegetation (SAV)

Submerged aquatic vegetation (SAV) beds are prevalent in the shallow waters surrounding Swan Island, with dense beds on the west and north sides of the island, some fringing beds on the south side, and sparse beds in the “bight” (area along southeast shoreline) (Figure 5). *Ruppia maritima* is the dominant species of SAV surrounding Swan Island. Other SAV species, including *Zostera marina* and *Zannichellia palustris*, are present but less abundant.

SAV are exposed to tides, currents (wind-driven and wave-driven), and waves (Koch 2001). A feedback mechanism appears to develop between

SAV and their fluid environment (Koch et al. 2006). See Batiuk et al. (2000), Koch (2001), and Koch et al. (2006) for a review of these feedback mechanisms.

5.2.4.1 Biomass – Depth, tides, and waves

Minimum SAV depth distribution is limited to mean low water level since SAV cannot tolerate desiccation or high light, particularly UV radiation, of the intertidal environment. Tides and waves play a role in the minimum SAV depth distribution. Chambers (1987) suggests the minimum depth of distribution ($Z_{\min}$) is dependent on tidal amplitude (A) and wave mixing depth:

$$Z_{\min} = (A/2) + ((gT^2)/2\pi)/2$$

where g is acceleration of gravity (9.805 m/s²). The wave period (T) for these waves can be predicted according to the following equation:

$$T = [0.46W/g][gF/W^2]^{0.28}$$

where W is the wind velocity (m/s) and F is the fetch (m).

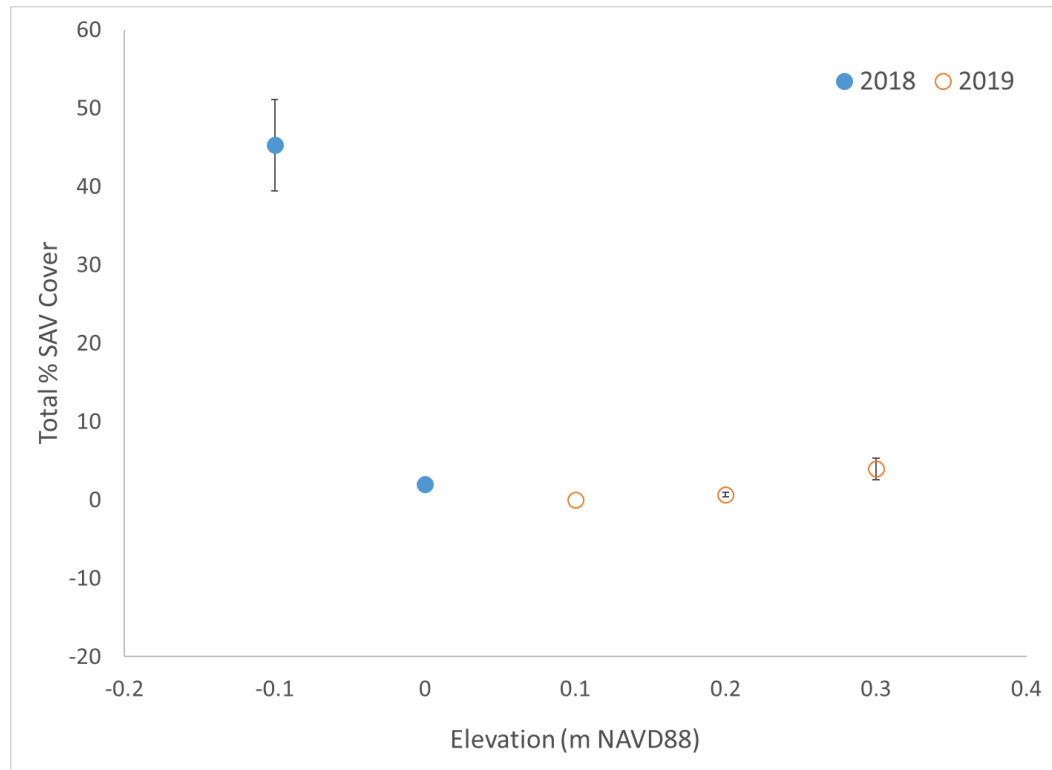
SAV can occur in more exposed areas characterized by wind-driven waves, as well as in shallow coastal areas such as the Chesapeake Bay, where ripples are more typical (Batiuk et al. 2000). These differences in wave conditions can impact the depth of wave mixing and the minimum depth of SAV distribution.

While the minimum depth of SAV is influenced by tides and waves, maximum depth distribution is generally dependent on light availability (Batiuk et al. 1992). SAV beds surrounding Swan Island occur from approximately 30 cm below mean low water to 170 cm below mean low water.¹ Orth and Moore (1988) observed *Ruppia maritima* beds on the eastern shore of Maryland between +20 cm to -100 cm mean low water. SAV within the Swan Island “bight” was present at depths ranging from -16 to -33 cm (-0.1682 to -0.0861 m NAVD88) prior to sediment placement

¹ Maryland Department of Natural Resources. 2019. Submersed Aquatic Vegetation Field Data Collection at Swan Island. Unpublished.

and from 0 to -7 cm (0.0967 to 0.3063 m NAVD88) after sediment placement (Figure 12).

Figure 11. SAV percent (%) cover by elevation (M NAVD88) at Swan Island (MD DNR unpublished data).



High wave action, such as during storms, can have direct negative impacts (e.g., uprooting, breakage) or indirect impacts (e.g., sediment resuspension and/or transport, changes in sediment grain size) that may bury existing SAV or prevent seed establishment. As a result, exposed areas tend to have patchy seagrasses or are unvegetated (Fonseca and Bell 1998; Hovel et al. 2002; Krause-Jensen et al. 2003), which in turn impacts wave attenuation.

Wave attenuation within SAV beds depends on water depth, current velocity, leaf length, and type of vegetation (canopy or meadow). Wave attenuation is strongest in dense SAV beds due to increased drag and in meadows where plant biomass takes up most of the water column (Batiuk et al. 2000). Within the Chesapeake Bay, most SAV species tolerate waves less than 2 m in height, though canopy forming species, such as *Ruppia maritima*, are limited by waves exceeding 1 m.

Wave attenuation values between 20 and 76% were obtained in laboratory studies when the SAV plants were occupying the entire water column (Fonseca and Cahalan 1992) while field studies measured values between 1.6 and 80% (Koch 1996; Prager and Halley 1999; Gruber and Kemp 2010). Koch (1996) observed higher wave attenuation at low tides when plants occupied more of the water column.

5.2.4.2 Biomass – Currents

Currents below 5 cm s⁻¹ have been suggested as limiting to seagrasses due to a reduction in the flux of carbon and nutrients to the leaf surface (Fonseca and Kenworthy 1987; Koch 1994). Intermediate currents (10 – 100 cm s⁻¹) can reduce SAV plant self-shading, increase settlement of suspended particles, lower friction velocities at the sediment surface, increase residence time, increase settlement of larvae, and reduce in epiphytic growth. Currents that promote healthy marine SAV growth fall between 10 and 100 cm s⁻¹, while freshwater SAV species prefer lower currents (<50 cm s⁻¹) (see Table vI-1 in Batiuk et al. 2000). Strong currents (> 100 cm s⁻¹), much like higher wave conditions, can have negative impacts on SAV, such as erosion, plant breakage, or removal.

SAV can reduce current velocities, but the magnitude is dependent on bed density and height, local hydrodynamic conditions, and water depth (Batiuk et al. 2000). Vertical flows are altered when plants occupy a large portion of the water column (when water depth is less than ten times the canopy height) (Nepf and Vivoni 2000). As a result, depending on the species and shoot density, water speeds in the canopy can be 2 to 10 times slower than outside of the bed. Hansen and Reidenbach (2012, 2013) found eelgrass beds reduced near-bottom mean velocities by 70 to 90% compared to an adjacent unvegetated region and velocities were reduced approximately 60 % in the summer and 40 % in the winter. Gurbisz et al. (2017) found that current speed was, on average, 57% less within the bed during high biomass versus low biomass time periods, while river discharge and tidal current speeds in the main channel remained similar.

5.2.4.3 Biomass – Sediment characteristics

Most seagrasses, or mesohaline and polyhaline SAV species in the Chesapeake Bay are constrained to sediments with less than 30% fines (< 64 µm). However, freshwater species of SAV can tolerate sediments with up to 62% fine material. As SAV beds attenuate currents and waves,

fine and organic particles tend to be trapped, which increases the nutrient availability to the plants (Kenworthy et al. 1982). As a result, SAV can grow faster and more robust (Short 1987) with higher nutrient levels. However, over time, sediment accumulation by dense SAV may lead to organic contents so high that they become detrimental. Organic contents higher than five percent have been suggested as detrimental to most seagrasses (Koch 2001; Kemp et al. 2004) and SAV growth is reduced when porewater sulfide concentration exceed 1 m (Batiuk et al. 2000).

Particle accumulation within the SAV bed can be seasonal, with higher rates during the summer/peak plant biomass. Gruber and Kemp (2010) found during the June period of peak plant biomass, suspended solids were reduced by 60% within the plant stand of *Stukenia pectinata*, which was stable and relatively unaffected by periods of high wind speed or water depth. However, resuspension may be greater than deposition during the winter when above-ground biomass is low, and with high wave exposure and currents or major storm events. Gurbisz et al. (2016) found that wind-driven resuspension of sediments, which were deposited within the SAV bed following a major flood event, occurred in the spring when plant biomass was low, but resuspension decreased during the summer when plant biomass increased.

Table 1. Description and importance of preliminary model components.

Model Components	Data sources	Units
Waves/Water levels/Currents	Collected - ADVs on 4 platforms	Wave height per unit time/Max Velocity and Max Water levels
Vegetative Biomass: Dune, high marsh, low marsh, SAV,	Combination of collections, literature and derived from vegetation height and density relationships	Mass/cover per unit area
Island Profile	GPS integrated imagery from drones/RTK GPS	Elevation Shoreline position Bathymetry
Sediment Availability (Natural)	ISCOs or MDDNR data from Tangier Sound	TSS – mass of suspended material per volume of water.

6 Model Development Considerations

Temporal resolution of model components is another complicating factor. For example, sediment transportation will fluctuate tidally (daily inundation (related efficiency of sediment trapping, k), seasonal inundation (spring, fall tides), and (yearly) storm events (erode/ deposit, related to average deposition, q)). The underlying processes do not change, however. Day to day there will be no major change, however, in the longer term (decades), model outputs will be subject to the above considerations of plant biomass and elevation.

For now, it is decided it will be sufficient to model daily sediment accretion as constant, with deposition location influenced by distance of decay. Likewise, seasonality is also assumed constant. Yearly however, we would expect accretion, which will manifest in the model processes (increased elevation). The main exogenous yearly consideration is storms, which calls for integration of pulse events to the model, with large scale events in discrete time scales.

7 Future Model Development Steps

7.1 Quantification

Model quantification is the enumeration of relationships identified in the conceptualization phase. As presented in Section 5, some model quantification was already begun. However, as quantification progresses, the model development team may revisit the model objective or conceptual model to revise or tweak as more information is compiled, reviewed, and synthesized at the group level.

7.2 Evaluation

As model development proceeds, review and revision of the model occur at each step of the process. It is a positive intrinsic mechanism in the group mediated model development process. Model evaluation is a specific step in the development process that requires a concise review of the model to ensure the outputs are reasonable and meeting objectives. This is conducted once testable model outputs are generated.

7.3 Application

Once model evaluation has been conducted and model outputs are deemed reasonable and meet expectations, the model may be applied to the specific questions at hand. For Swan Island, the team will be answering questions related to resilience of certain habitat types, with respect to SLR, wave action, erosion and long-term change, overall island persistence, impact of island persistence to surrounding areas, and future maintenance activities, including need and timing of dredged material.

8 Summary

This report presented the progress of an interagency team developing an integrated hydrodynamic and ecological model that will assist in testing assumptions about Island resiliency, decisions on adaptive management actions, and evaluating performance of EWN features. The interdisciplinary team consists of scientists, project managers, biologists, and engineers. The Group mMediated Model Development approach is being utilized by the team to ensure close coordination of project stakeholders and model end users.

The team has completed the first phase of model development and model conceptualization in an iterative fashion with various revisions based on improved understanding of important ecosystem components that address model questions and objectives. Important components identified are vegetative biomass, island elevation, waves/currents, and sediment supply. The report contains descriptions of how these important components interact to form and support specific habitat types occurring on the island: coastal dunes, high marsh, low marsh, and submerged aquatic vegetation. Future model development steps will include quantification, evaluation, and application.

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14. ABSTRACT This report documents the development of an integrated hydrodynamic and ecological model to test assumptions about island resilience. Swan Island, a 25-acre island in Chesapeake Bay, Maryland, was used as a case study. An interagency, interdisciplinary team of scientists and engineers came together in a series of workshops to develop a simplified resilience model to examine the ability of islands to reduce waves and erosion and the impacts to nearby habitats and shorelines. This report describes the model development process and the results from this first key step: model conceptualization. The final conceptual model identifies four main components: vegetative biomass, island elevation, waves/currents, and sediment supply. These components interact to form and support specific habitat types occurring on the island: coastal dunes, high marsh, low marsh, and submerged aquatic vegetation. The pre-and post-construction field data, coupled with hydrodynamic ecological models, will provide predictive capabilities of island resilience and evaluations of accrued benefits for future island creation and restoration projects. The process and methods described can be applied to island projects in a variety of regions and geographic scales.					
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