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# Application of the Sea-Level Affecting Marshes Model (SLAMM) to the Lower Delaware Bay, with a Focus on Salt Marsh Habitat

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Washington, DC 20460

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# DISCLAIMER

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# ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| DE | Delaware |
| GIS | Geographic Information System |
| DEM | Digital Elevation Model |
| GMSL | Global mean sea level |
| GT | Great Diurnal Tide Range |
| HTU | Half-tide Units |
| IFM | Irregularly-Flooded Marsh |
| LiDAR | Light Detection and Ranging |
| NAVD88 | North American Vertical Datum of 1988 |
| NJ | New Jersey |
| NWI | National Wetlands Inventory |
| MHHW | Mean Higher High Water |
| MLLW | Mean Lower Low Water |
| MTL | Mean Tidal Level |
| NJ | New Jersey |
| NOAA | National Oceanic and Atmospheric Administration |
| PDE | Partnership for the Delaware Estuary |
| RFM | Regularly-Flooded Marsh |
| SET | Surface Elevation Table |
| SLAMM | Sea-Level Affecting Marshes Model |
| SLR | Sea level rise |
| SSIM | Site-Specific Intensive Monitoring |
| USEPA | U.S. Environmental Protection Agency |
| USGS | U.S. Geological Survey |
| VDATUM | Vertical Datum Transformation Tool |
| VLM | Vertical land movement |

# PREFACE

This report was prepared by the U.S. Environmental Protection Agency (USEPA) Office of Research and Development, as part of the Air and Energy (A-E) research program, with support from Tetra Tech, Inc., and in collaboration with the Partnership for the Delaware Estuary (PDE). The A-E research program provides scientific information and tools to support USEPA's commitment to clean air, clean water and sustainable natural resources, even as environmental conditions change. A key component of this is the development of sound science to support adaptation. Adaptation involves preparing for and adjusting to the effects of expected future environmental changes. Because these effects are diverse, interactive, and difficult to predict, adapting management of natural resources in this context can be very challenging.

In the case of coastal salt marshes--which provide valued ecosystem services such as flood control, water purification and critical habitat--sea level rise (SLR) is interacting with physical and biological attributes of the system to induce complex changes in different salt marsh habitats. In this report, projected changes for seven salt marsh areas of the Delaware Bay are examined using the Sea Level Affecting Marshes Model (SLAMM, v. 6.7). These areas were chosen because they are of key management concern to PDE and its partners. SLAMM simulates the dominant processes involved in determining distributions of wetlands across space and time under conditions of accelerated SLR. This report uses SLAMM to generate and interpret critical information for assessing the relative vulnerabilities of different salt marshes to SLR. Besides fulfilling the immediate information needs of PDE and its partners, these projections also serve an additional purpose; namely, as inputs to a larger study on how to interpret and use this type of vulnerability information for robust analysis and design of effective adaptation practices for protecting, restoring and/or enabling migration of valued salt marsh ecosystems.

## AUTHORS, CONTRIBUTORS, AND REVIEWERS

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## AUTHORS


Jenifer Stamp, Tetra Tech, Inc.

Anna Hamilton, Tetra Tech, Inc.

Marissa Liang, ORISE Fellow at U.S. EPA

Jonathan Clough, Warren Pinnacle Consulting, Inc.

Marco Propato, Warren Pinnacle Consulting, Inc.

LeeAnn Haaf, Partnership for Delaware Estuary, Inc.

Jordan M. West, U.S. EPA, Office of Research and Development


## INTERNAL REVIEWERS

Thomas Johnson, U.S. EPA, Office of Research and Development

Regina Poeske, U.S. EPA, Region 3

Matthew Konfirst, U.S. EPA, Region 3

## EXTERNAL REVIEWERS

Patty Glick, National Wildlife Federation

David M. Kidwell, National Oceanic and Atmospheric Administration

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# APPENDICES

# EXECUTIVE SUMMARY

This report presents results from the Sea-Level Affecting Marshes Model (SLAMM, v. 6.7), which was used to generate spatially explicit projections for sea level rise (SLR)-induced changes in acreage for seven salt marshes in the Lower Delaware Bay. Four of the marshes are located in New Jersey (Dividing, Lower Maurice, Dennis, Reeds Beach) and three are located in Delaware (Broadkill, Mispillion, Lower St. Jones). SLAMM is widely recognized as an effective model to study and predict wetland response to long-term SLR (Park et al. 1991) and has been applied in every coastal U.S. state. Prior SLAMM work has been performed in the Delaware Bay (Kassakian et al. 2017), but our methods differ in that we derive results for specific marsh areas and utilize more recent, higher resolution elevation data, the most recent SLR projections, and site-specific accretion data. These SLAMM simulations were performed as part of a larger project by the USEPA on frameworks and methods for characterizing relative wetland vulnerabilities in order to inform adaptation of management programs and practices (Wardrop et al. 2019).

We ran SLAMM simulations for early to late century time periods under three SLR scenarios (low, intermediate and high), based on projections in Sweet et al. (2017). We also generated results for three different model protection scenarios, ranging from no protection (where all cells are subject to inundation) to protection of all dry land (where all cells designated as dry land are protected from inundation). In addition, we ran a sensitivity analysis to better understand the influence of each input variable on the projected changes in salt marsh acreage.

Results are reported in three sections:

1. ***Projected changes in all SLAMM land cover categories***, with specific attention given to the three SLAMM land cover categories that are considered to be salt marsh habitat: regularly-flooded marsh, irregularly-flooded marsh and transitional salt marsh (Warren Pinnacle Consulting 2016). Outputs include tables and maps typically found in other SLAMM reports.
2. ***Projected changes in high, low and total salt marsh acreage***. High marsh was defined as the aggregation of irregularly-flooded marsh and transitional salt marsh, low marsh was defined as regularly-flooded marsh and total marsh was the aggregation of all three salt marsh habitats. Outputs diverge from traditional SLAMM outputs and include: scatterplots of response (mean percent change in acreage) versus exposure (mean relative SLR); and site-specific gain/loss maps that highlight areas where changes are projected to occur. The intent was to explore new ways of visualizing patterns across salt marsh habitats and to compare results across specific sites and time periods, which could help inform management actions.
3. ***Sensitivity analysis*** to assess the relative effect on model outputs of key input variables: Great Diurnal Tide Range (GT), salt elevation, marsh erosion, and accretion rates.

The SLAMM simulations projected that all sites will experience loss of high marsh acreage by late century and gains in low marsh and total salt marsh acreage. Rates of change varied across sites, time periods and SLR scenarios. The Broadkill and Mispillion sites in Delaware were projected to experience higher percent loss of high marsh sooner (early to mid-century). By late century, particularly under the high SLR scenario, the New Jersey sites (which have higher rates of vertical land movement and subsidence) were projected to experience large losses in high marsh habitat. By late century, areas initially categorized as low marsh were also projected to be lost at many sites (via conversion to tidal flats or open water). The conversion/loss of low marsh is projected to occur at a slower rate than conversion of high marsh; low marshes are assumed to have higher accretion rates since they are inundated more frequently and collect more sediment. In the sensitivity analysis, the tide range (GT) was the most dominant factor driving the gain and loss of regularly- and irregularly-flooded marshes, and salt elevation had the greatest impact on transitional salt marsh. The marsh erosion and accretion variables had much smaller effects (<1%).

SLAMM is a useful tool for projecting SLR-induced changes in salt marsh acreage; however, factors such as marsh condition, stressors (e.g., hydrologic alteration, nutrient enrichment) and impacts from large storms are not taken into account and need to be considered in concert with the SLAMM results to best inform decisions. There are also uncertainties associated with the input data (e.g., limited tide range data and variable Surface Elevation Table data). Despite these limitations, the SLAMM results have both immediate and longer-term applications for informing wetlands and land-management decisions in coastal areas, such as where to prioritize conservation or restoration efforts, where to plan for change, and where to set up long-term monitoring sites to detect whether changes are occurring as projected.

# 1 BACKGROUND

This report presents model simulations of projected sea level rise (SLR)-induced changes in acreage of seven salt marsh areas in the Lower Delaware Bay, with a particular focus on changes in high (irregularly inundated) versus low (regularly inundated) marsh. The projections were generated using the Sea Level Affecting Marshes Model (SLAMM, v. 6.7), which is widely recognized as an effective tool to study and predict wetland response to long-term SLR (Park et al. 1991) and has been applied in every coastal U.S. state (Craft et al. 2009; Galbraith et al. 2002; Glick et al. 2007, 2013; Glick and Clough 2006; Park et al. 1993; Titus et al. 1991, Warren Pinnacle Consulting, Inc. 2015). While there have been prior SLAMM efforts in the Delaware Bay (Kassakian et al. 2017[1]), our results differ in that we focus on seven specific marsh areas and utilize more recent, higher resolution elevation data, the most recent SLR projections, and site-specific accretion data. These SLAMM simulations were designed to be of interest not only in their own right, but also as a component of a larger U.S. Environmental Protection Agency (USEPA) project that is developing frameworks and methods for characterizing relative wetland vulnerabilities and assessing implications for wetlands management activities (Wardrop et al. 2019).

## 1.1 Coastal Wetlands of the Delaware Estuary

The vulnerability[2] of coastal wetlands to SLR is evidenced by their loss due to more frequent inundation. Coastal wetlands of the Delaware (DE) Estuary are considered especially vulnerable to SLR (Kreeger et al. 2010, Callahan et al. 2017); recent studies indicate that rates of SLR along the U.S. mid-Atlantic coast have accelerated in recent decades faster than the global mean (Sallenger et al. 2012). SLR is one of many factors contributing to the loss and degradation of coastal wetlands in the DE Estuary. Other factors include conversion of wetlands to agricultural or other land uses, land subsidence due to groundwater withdrawal, mosquito control ditching, incremental filling, hydrological alterations such as dredging, nutrient enrichment and spread of invasive species (Sun et al. 1999, Haaf et al. 2015, USEPA 2015, Haaf et al. 2017). From 1996-2010, the acreage of estuarine wetlands declined across the Delaware Estuary (-1.77%; -194 acres; -79 hectares per year), with the largest losses occurring in the lower New Jersey Bayshore (-3.08%; -1,915 acres; -775 hectares per year) (Haaf et al. 2017).

While SLAMM simulations provide outputs for all wetland types, our primary focus in this report is on salt marshes. Salt marshes are, by definition, inundated periodically by the tides. They are typically divided into high and low zones. The low salt marsh is normally inundated by tidal water at least once per day and in the Mid-Atlantic is predominantly covered by the tall form of Smooth Cordgrass (*Spartina*

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[1]In an earlier study, Industrial Economics generated SLAMM results for the Delaware Estuary (IE 2010), which were later used in the Kassakian et al. 2017 article. These earlier results were generated with an older version of SLAMM, coarser-resolution elevation data, one SLR scenario (a 1 m increase by 2100) and different output subsites (they generated results for 27 subsites/rectangular blocks that cover the tidal portion of the Delaware Bay).

[2]Vulnerability is the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change (including sea level rise) with accompanying variability and extremes. It is a function of the character, magnitude and rate of variation to which a system is exposed, its sensitivity, and its adaptive capacity. (Adapted from Climate Change Science Program 2008)

*alterniflora*). The high salt marsh is covered by water only sporadically (once per day or less). There are two SLAMM land cover categories that are flooded at this frequency: irregularly-flooded marsh and transitional salt marsh. Irregularly-flooded marsh, which generally borders low marsh habitat, is characterized by the short form of Smooth Cordgrass, Spike Grass (*Distichlis spicata*), and Saltmeadow Rush (*Juncus gerardii*), while transitional salt marsh is located at the landward edge and has more woody vegetation such as scrub-shrub habitat. For our purposes, we considered both irregularly-flooded marsh and transitional salt marsh to be high marsh habitat. For some managers, it is important to distinguish between high and low marsh habitat because there are some differences in the types of ecosystem services each provide. For example, low marsh provides habitat for mussels and crabs (Able et al. 2007); high marsh provides critical habitat for species of conservation concern, such as the salt marsh sparrow (Gjerdrum et al. 2005) and the American black duck; and total marsh (high and low combined) provides protection from coastal flooding and erosion.

Survival of salt marshes in rising waters will depend on their natural ability to maintain surface elevations relative to sea level, which is governed by whether net vertical accretion of the marsh surface occurs at a rate at least equal to that of relative SLR (Reed 1995). Net vertical accretion is influenced by sediment deposition, which when combined with vegetation processes, results in accumulation of organic and inorganic matter. Relative SLR is generally considered to be the net combination of eustatic (global) SLR, local oceanic currents, and land subsidence. Although salt marshes can adapt to these changes, there is a threshold of SLR at which a marsh can no longer sustain natural feedbacks (D'Alpaos et al. 2011). When this threshold is reached, death of marsh vegetation occurs (Raposa et al. 2015, Watson et al. 2015, 2016, 2017). In addition, the combination of greater inundation with wave action can lead to increased shoreline erosion (Ashton et al. 2008), as well as greater susceptibility to storm surge that causes interior wetland erosion and breakup (Raposa et al. 2015, Wigand et al. 2017). The degree to which a particular coastal wetland may be impacted by these related factors can vary due to differences in coastal geology and the wave climate (the distribution of wave characteristics averaged over a period of time for a particular location) (Ashton et al. 2008, Leonardi et al. 2018).

The loss of coastal wetlands poses a very serious problem in the DE Estuary because of the ecosystem services they provide. These services are wetland functions that are economically valuable and important for human health and well-being, such as: protecting inland areas from tidal and storm damage; providing water storage; protecting against flooding; providing important habitat for a wide variety of wildlife, including waterfowl; filtering contaminants and helping to sustain water quality; capturing and sequestering carbon; providing spawning and nursery habitat for commercial fisheries; supporting recreation; and providing aesthetic value (Kreeger et al. 2015, Partnership for the Delaware Estuary 2017). Therefore, SLAMM-generated information on potential changes in wetland area and habitat types can have important implications for decision making regarding land use and wetland management priorities, strategies and techniques.

## 1.2 Model Summary

SLAMM (see Box 1 for specifications) projects when and where marshes are likely to experience a change in inundation due to SLR based on SLR rates, elevation data, accretion/sedimentation rates, tidal data, and erosion rates. SLAMM also identifies locations where marshes may migrate upland in response to changes in water levels, based on the relationship between marsh types and their frequency of inundation. The model simulates the dominant natural processes that affect shoreline modifications during long-term SLR and uses a complex decision tree incorporating geometric and qualitative relationships to predict changes in coastal land cover classes.

SLAMM is not a hydrodynamic model. Rather, SLAMM projects long term shoreline and habitat class changes based upon a succession of equilibrium states with sea level. Model outputs include mapped distributions of wetlands at different time steps in response to sea level changes as well as tabular and graphical data. Mcleod et al. (2010) state in their review of sea-level rise impact models that "... the SLAMM model provides useful, high-resolution insights regarding how sea-level rise may impact coastal habitats".

**Box 1.** SLAMM software is free and has modest data requirements (Appendix A). It is helpful if the user has prior experience working with Geographic Information System (GIS) software (such as ArcGIS or QGIS) and high resolution elevation data like Light Detection and Ranging (LiDAR). Prior to running SLAMM, all spatial data must be converted into raster inputs with identical cell sizes and dimensions. SLAMM also requires a certain amount of computer processing power. As a general rule, a minimum of 4GB RAM is recommended, as well as a 64-bit version of Windows OS. Exact requirements vary depending the resolution of the input data files as well as the size of the study area.

SLAMM assumes that wetlands occupy a range of vertical elevations that are a function of the tide range. Because of this, rather than expressing marsh elevation in absolute values (e.g., meters, feet, etc.), SLAMM computes units relative to the local tide datum for each cell at each time step (section 2.2.5.1). SLAMM can also calculate relative SLR as a function of global SLR scenarios offset by local factors such as subsidence and isostatic adjustment (section 2.2.4). SLR is offset by marsh accretion and other factors affecting marsh surface elevation.

When the model is applied, each study site is divided into cells of equal area (5 m x 5 m for these simulations) that are treated individually. The conversion from one land cover class to another is computed by considering the new cell elevation at a given time step with respect to the class in that cell and its inundation frequency. Default wetland elevation ranges are available as a function of tidal ranges, or ranges may be entered by the user if site-specific data are available. The connectivity module determines salt-water flow pathways under normal tidal conditions using the method of Poulter and Halpin (2008). In general, when a cell's elevation falls below the minimum elevation of the current land cover class and is connected to open water (or an adjacent connected cell), then the land cover is converted to a new class according to a decision tree.

Accretion, or the accumulation of organic and inorganic matter, is one of the most important processes affecting marsh capability to respond to SLR. The SLAMM model was one of the first landscape-scale models to incorporate the effects of vertical marsh accretion rates on projections of marsh fates, having done so since the mid-1980s (Park et. al.1989). Since 2010, SLAMM has incorporated dynamic relationships among marsh types, wetland elevations, tide ranges, and predicted rates of change in wetland elevations. The SLAMM application presented here utilizes feedbacks among marsh elevations, water level, and elevation-change rates derived from local data to parameterize rates of accretion and shallow subsidence or compaction. This feedback is also supported by similar results from mechanistic accretion and shallow-subsidence models (e.g., Morris et al. 2002, Morris 2013).

As with any numerical model, SLAMM has limitations. Since SLAMM is not a hydrodynamic model, cell-by-cell water flows are not projected as a function of topography and hydrological processes (e.g., water diffusion and advection). Furthermore, it does not capture known/potential feedback mechanisms between hydrodynamic and ecological systems. Suspended sediments in water are not accounted for via mass balance, which may affect accretion (e.g., local bank sloughing does not affect nearby sedimentation rates). The erosion model is also very simple and does not capture more complicated processes such as new channel development. SLAMM has the capability to apply a salt-wedge model in an estuary and an overwash model for barrier islands to account for second order effects that may occur due to changes in the spatial relationships among the coastal elements; each of these model processes is rather simple and has not been applied in these simulations. A more detailed description of model processes, underlying assumptions, and equations can be found in the SLAMM Technical Documentation (Warren Pinnacle Consulting, Inc. 2016: http://warrenpinnacle.com/prof/SLAMM/).

## 1.3 Case Study Scope

For this case study, we ran SLAMM simulations for four sites in New Jersey (NJ) (Dividing, Lower Maurice, Dennis, Reeds Beach) and three in Delaware (DE) (Broadkill, Mispillion, Lower St. Jones). We used four early- to late-century time periods (2025, 2050, 2075, 2100) and three SLR scenarios (low, intermediate and high). We also generated results for three different model protection scenarios: no protection (where all cells are subject to inundation); protection of developed dry land (where cells designated as dry land with development are managed to prevent changes in inundation); and protection of all dry land (where all cells designated as dry land are managed to prevent changes in inundation). Because of the large volume of results, in the main report we only present results from: the intermediate SLR scenario (1 m global mean sea level (GMSL) rise by 2100), which is considered “very likely” (>90% probability) under future simulations of moderate rates of ocean warming (Sweet et al. 2017); along with the “protect developed dry land” scenario (which seems most likely, based on feedback from local practitioners). The full set of results for all scenarios are included in the appendices. In addition, we ran a sensitivity analysis to evaluate how much influence each input variable has on the projected changes in salt marsh acreage.

The sections that follow explain our methods for site delineation, input parameters and data, and model setup and calibration. These are followed by results presented in three sections: 1) projected changes for all SLAMM land cover categories (standard SLAMM outputs); 2) projected changes in high, low and total marsh (new ways of visualizing patterns); and 3) sensitivity analysis on key input variables (GT, salt elevation, marsh erosion, accretion rate).

# 2 METHODS

## 2.1 Study Area and Site Delineation

The study areas include four sites in NJ (Dividing, Lower Maurice, Dennis, Reeds Beach) and three in DE (Broadkill, Mispillion, Lower St. Jones) (Figure 1). Marsh areas were delineated with assistance from the Partnership for the Delaware Estuary (PDE) based on:

- Locations of salt marshes: polyhaline areas were targeted to reduce complexities associated with freshwater inputs (mean salinity values ranged from approximately 14 to 26 ppt)
- Monitoring and management units (as per PDE's convention)
- Watershed basins
- Locations of Mid-Atlantic Coastal Wetland Assessment (MAWCA) sites; this includes Tidal Rapid Assessment Method (TRAM) data and Site-Specific Intensive Monitoring (SSIM) data (Kreeger and Padeletti 2013).

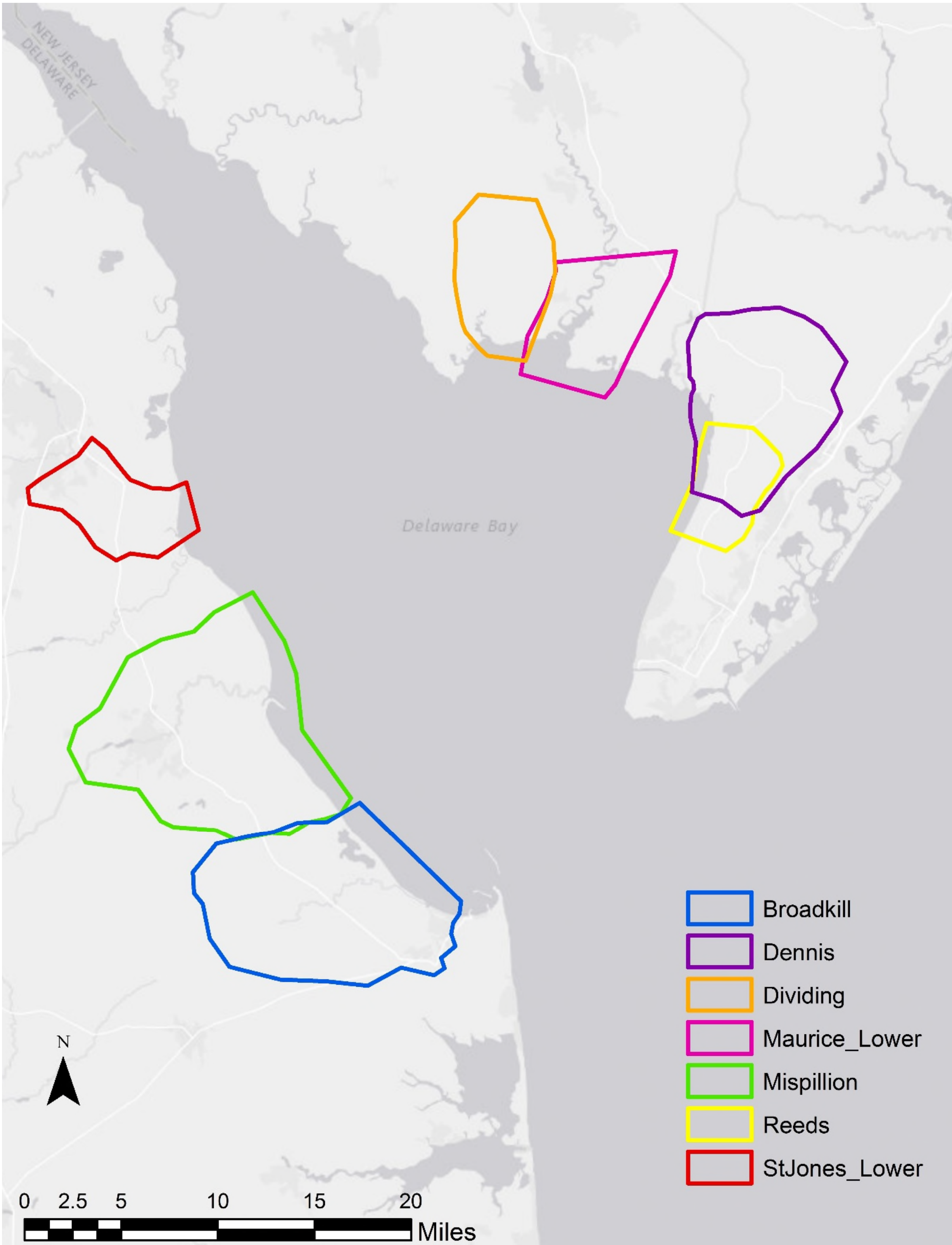

*Figure 1. Map of the seven sites in the Lower Delaware Bay. Note that the partially-overlapping Dennis and Reeds sites were modeled separately as per PDE's convention to view them as different units for monitoring and management.*

## 2.2 Input Parameters and Data Preparation

### 2.2.1 Raster Data Preparation

SLAMM is a raster-based model that utilizes input cells that are equally-sized squares arranged in a grid. This section describes the sources and steps used to process the raster data for use in SLAMM. Data types reviewed in this section include elevation, wetland land cover, dikes and impoundments, and impervious land cover.

#### *2.2.1.1 Elevation Data*

High vertical-resolution elevation data may be the most important SLAMM data requirement. SLAMM uses elevation data to demarcate where salt water is projected to penetrate, and then combines this information with tidal data to determine the extent and frequency of saltwater inundation.

Elevation data for the Lower Delaware Bay were downloaded from the National Oceanic and Atmospheric Administration (NOAA) Digital Coast Data Viewer (https://coast.noaa.gov/dataviewer/#/lidar/search/). We used the 2015 U.S. Geological Survey (USGS) Coastal National Elevation Database Topobathymetric Digital Elevation Model (DEM): NJ and DE dataset, which is a composite of the best available high-resolution elevation data through 2014 (based on the North American Vertical Datum of 1988 (NAVD88). The DE data and coastal NJ data are based on 2014 (Post-Hurricane Sandy) surveys, while data for the inland areas in the Dividing and Maurice watersheds are derived from a 2008 statewide survey. The dataset is a mix of light detection and ranging (LiDAR) and bathymetric data, which were compiled into a common database and aligned both vertically and horizontally to a common reference system. The data have a vertical accuracy of 20 cm and were tested to meet vertical root mean square error in open terrain. It should be noted, however, that LiDAR has limited penetration ability in marsh areas with dense vegetation, which reduces the accuracy of LiDAR to estimate bare surface elevations in those areas (Medeiros et al. 2015, Buffington et al. 2016). To reduce file sizes and GIS processing times, elevation data were split into four separate blocks prior to analysis (Appendix A, Figure A1).

#### *2.2.1.2 Vertical Elevation Transformation*

NOAA's Vertical Datum Transformation Tool (VDATUM, version 3.2; NOAA 2013) was utilized to convert elevation data from the NAVD88 vertical datum to Mean Tide Level (MTL), which is the vertical datum used in SLAMM. This is required as coastal wetlands occupy elevation ranges related to tide ranges as opposed to geodetic datums (where elevations are computed in relation to a specific zero point; e.g., NAVD88 is referenced to a point in Quebec, Canada) (McKee and Patrick 1988). VDATUM does not provide vertical corrections over dry land; dry-land elevations were corrected using the VDATUM correction from the nearest open water. Corrections in the study areas ranged from –0.135 m to -0.003 m. A spatial map of corrections is shown in Figure 2.

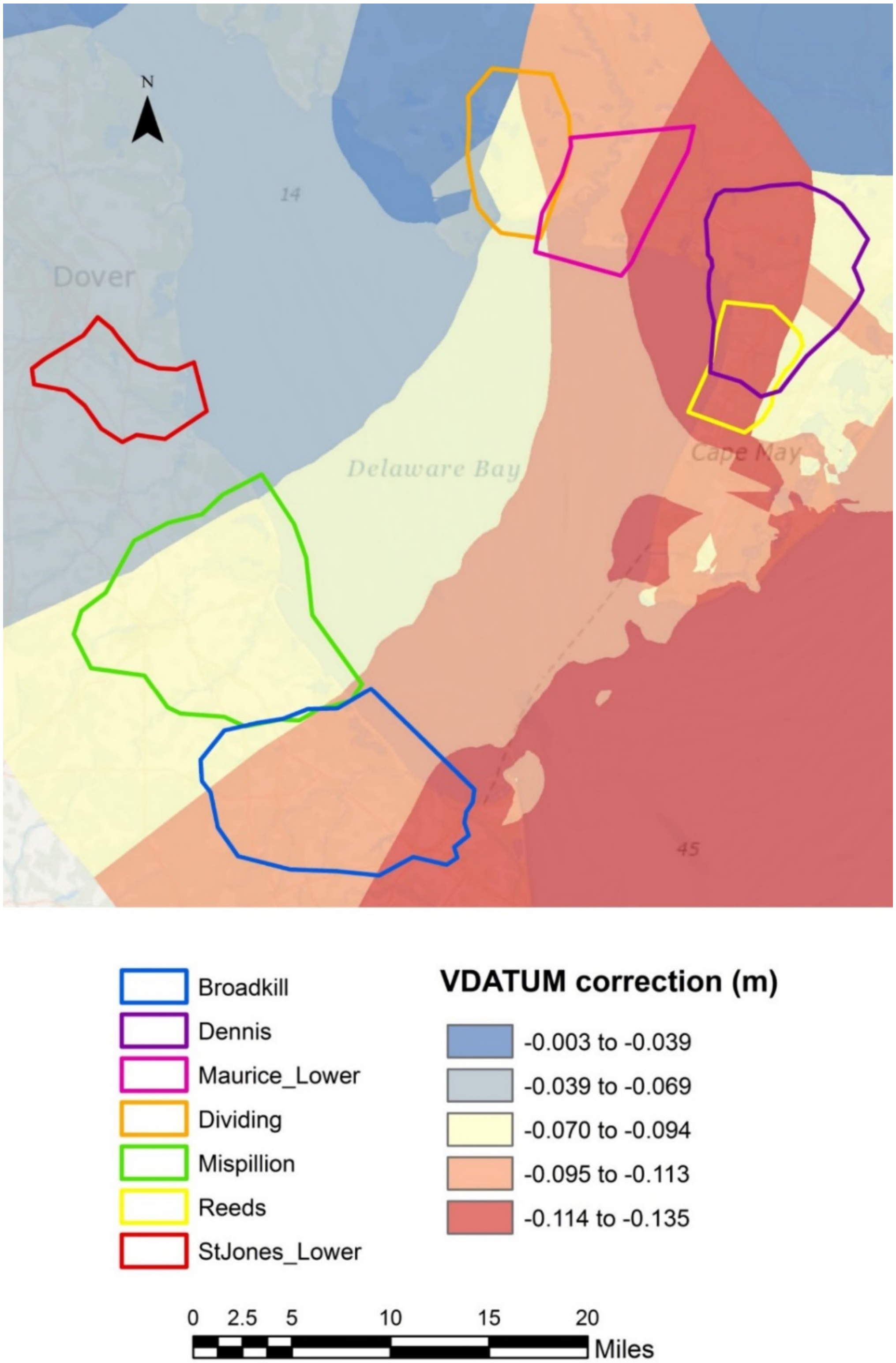


*Figure 2. VDATUM-derived correction values. Note that the partially-overlapping Dennis and Reeds sites were modeled separately as per PDE's convention to view them as different units for monitoring and management.*

#### *2.2.1.3 Slope*

Accurate slopes (elevation gradients) of the marsh surface are used in the calculation of the fraction of a cell that is lost (transferred to another class). In this study, the slope raster was derived from the DEM elevation data layer described in Section 2.2.1.1 using QGIS software (QGIS Development Team 2016). The same analysis can also be conducted by using the surface slope tool of ArcGIS (a license-based geographic information system).

#### *2.2.1.4 Wetland Land Cover Data and Translation to SLAMM*

Wetland raster layers were created from National Wetlands Inventory (NWI) GIS shapefiles for DE and NJ (https://www.fws.gov/wetlands/Data/Data-Download.html). The NWI maps are based on photo interpretation. Image dates for the study area range from 1995-2009 (Figure 3).

NWI land coverage codes were translated into SLAMM codes per the translation table in Appendix B (which was produced by Warren Pinnacle (Clough et al. 2016) with assistance from Bill Wilen of the NWI). Since dry land (developed or undeveloped) is not classified by NWI, SLAMM classifies cells as dry land if they are initially blank (in the wetland inventory) but have an assigned elevation (above mean-tide level). It should be noted that there is some uncertainty in land-cover inputs[3]. For example, the input photography is not tidally-coordinated, so the boundary lines between "tidal swamp" and fresh water "swamp" categories can be arbitrary (which in turn makes cells in these areas more prone to misclassification). Thus, it is important to ground truth local areas where management activities are being planned and to use the SLAMM model as a tool for looking at overall trends in an area (versus focusing on individual cells).

After the translation was performed, the resulting raster was checked visually to ensure the projection information was correct, the number of rows and columns was consistent with the other rasters in the project area, and to ensure that the data looked complete based on the source data. The resulting land cover for the area is shown in Figure 4.

Initial land cover areas for the seven sites are summarized in Table 1. Study areas range from 70,748.1 acres (Mispillion) to 14,917.7 acres (Reeds Beach). On average, undeveloped dry land comprised the largest percentage of study area (43%) followed by estuarine open water (16%). Other land use categories (listed in descending order, based on percent of total acreage averaged across sites) include irregularly-flooded marsh (13%), swamp (12.5%), regularly-flooded marsh (7%), developed dry land (4%), tidal swamp (2%), inland open water (1.5%), transitional salt marsh (1%), inland fresh marsh (0.4%), tidal fresh marsh (0.2%), estuarine beach (0.1%), inland shore (0.1%), riverine tidal (0.1%), tidal flat (0.03%), flooded developed dry land (0.02%) and ocean beach (<0.01%).

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[3]There are several sources of uncertainty with NWI maps. For example, maps are not tidally coordinated, so there is uncertainty at the water to beach/wetland interface; and it is often difficult to discern where forested swamps end and forested upland habitats begin based on photo interpretation. Based on the NWI source data accuracy file, there is 98% feature accuracy distinguishing wetland versus upland (meaning 2% may be upland instead of wetland or vice-versa); there is 85% classification accuracy (meaning 15% of the classified wetlands may have an incorrect attribution , e.g., high marsh instead of low marsh; and the NWI does not classify marsh systems that are less than 0.2 hectares (https://www.fws.gov/wetlands/Documents/FGDC-Wetlands-Mapping-Standard.pdf).

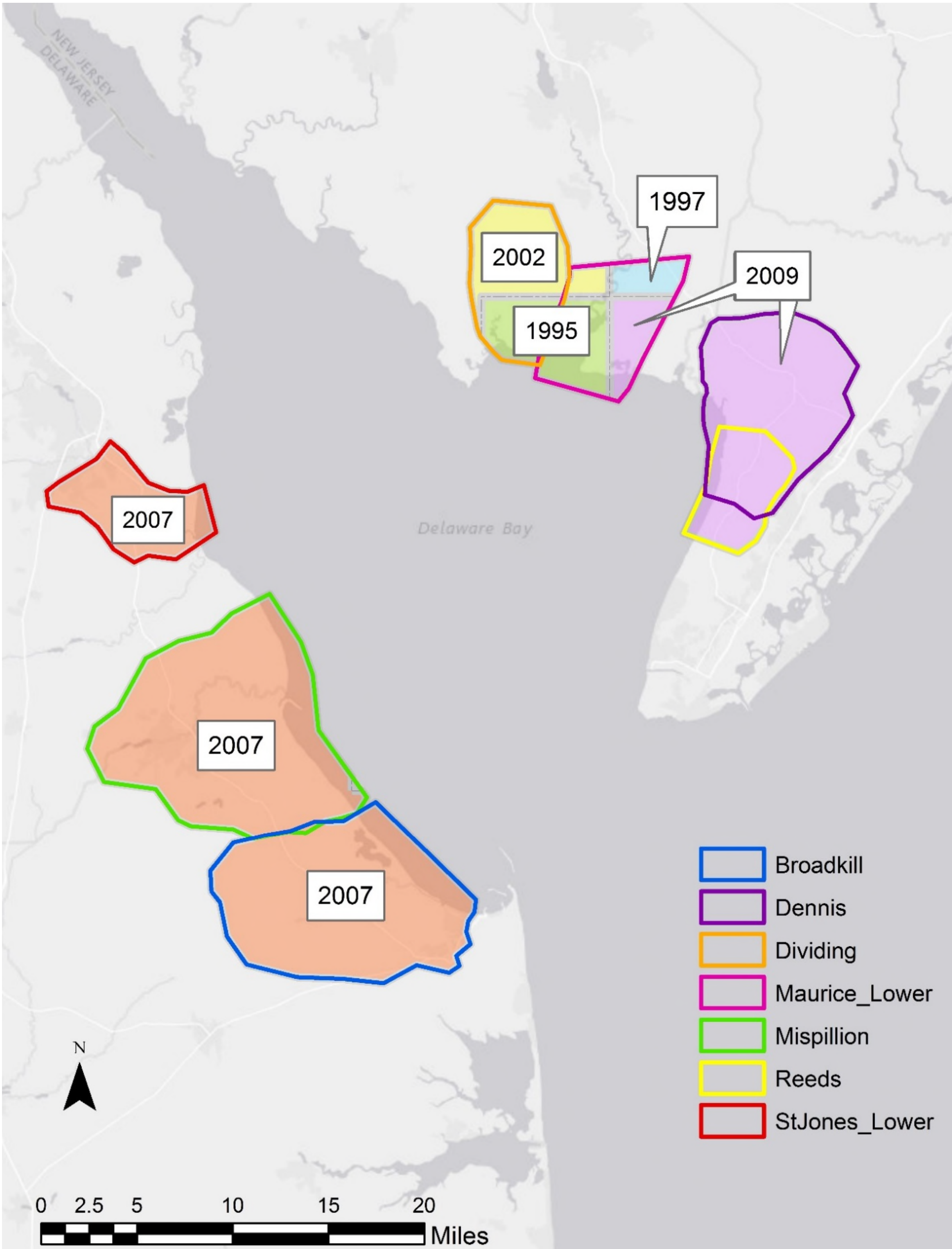



*Figure 3. The NWI date and corresponding boundary of the study sites. Note that the partially-overlapping Dennis and Reeds sites were modeled separately as per PDE's convention to view them as different units for monitoring and management.*

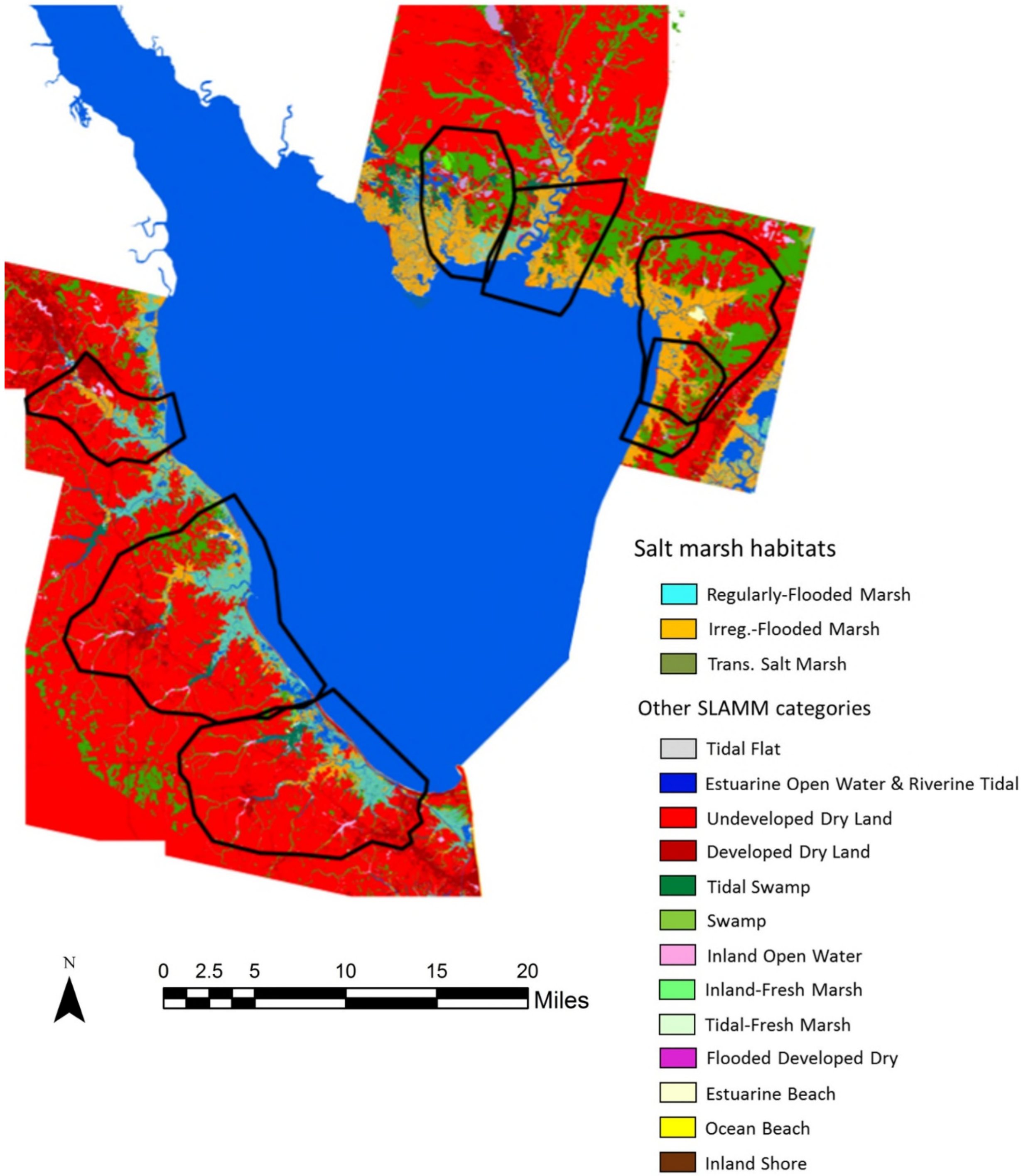



*Figure 4. Initial land cover. The study sites are outlined in black. Note that the partially-overlapping Dennis and Reeds sites were modeled separately as per PDE's convention to view them as different units for monitoring and management.*

*Table 1. Acreage (and percentage of total acreage) of initial land cover categories across the seven sites.*

| SLAMM Category | Acreage (% of total) | | | | | | |
|---|---|---|---|---|---|---|---|
| | **Broadkill (DE)** | **Mispillion (DE)** | **St. Jones Lower (DE)** | **Dividing (NJ)** | **Maurice Lower (NJ)** | **Dennis (NJ)*** | **Reeds (NJ)*** |
| Developed Dry Land | 3232.2 (5.5%) | 2827.5 (4%) | 1973.8 (10.6%) | 128.6 (0.6%) | 394.8 (1.6%) | 747.8 (1.8%) | 257.6 (1.7%) |
| Undeveloped Dry Land | 36833.4 (62.2%) | 40211.5 (56.8%) | 9876.2 (53.1%) | 5857.3 (25.4%) | 5431.5 (22.4%) | 15648.3 (37.3%) | 4553.4 (30.5%) |
| Swamp | 2348.6 (4%) | 4683.6 (6.6%) | 732.2 (3.9%) | 4599.5 (20%) | 3288 (13.5%) | 11409.2 (27.2%) | 3515.5 (23.6%) |
| Inland-Fresh Marsh | 167.2 (0.3%) | 162.2 (0.2%) | 42.8 (0.2%) | 316.4 (1.4%) | 80.3 (0.3%) | 53.6 (0.1%) | 34.1 (0.2%) |
| Tidal-Fresh Marsh | 164.3 (0.3%) | 40.3 (0.1%) | 48.3 (0.3%) | 54.1 (0.2%) | 17.6 (0.1%) | 39.3 (0.1%) | 3.9 (0%) |
| Trans. Salt Marsh | 69.8 (0.1%) | 369.3 (0.5%) | 2.5 (0%) | 399.3 (1.7%) | 440.2 (1.8%) | 838.9 (2%) | 263 (1.8%) |
| Regularly-Flooded Marsh | 3284.3 (5.5%) | 6440 (9.1%) | 1859.6 (10%) | 1977.7 (8.6%) | 1550.8 (6.4%) | 400.8 (1%) | 213.1 (1.4%) |
| Estuarine Beach | 148.9 (0.3%) | 165.1 (0.2%) | 36.2 (0.2%) | 0 (0%) | 25.4 (0.1%) | 1.9 (0%) | 5 (0%) |
| Tidal Flat | 0 (0%) | 93.5 (0.1%) | 10.1 (0.1%) | 4.4 (0%) | 11.5 (0%) | 11.4 (0%) | 0 (0%) |
| Ocean Beach | 0 (0%) | 0 (0%) | 0 (0%) | 0 (0%) | 0 (0%) | 13.3 (0%) | 19.6 (0.1%) |
| Inland Open Water | 897.7 (1.5%) | 668.2 (0.9%) | 349.1 (1.9%) | 880.2 (3.8%) | 32.2 (0.1%) | 320.6 (0.8%) | 72.8 (0.5%) |
| Riverine Tidal | 208.9 (0.4%) | 137.1 (0.2%) | 2.6 (0%) | 7.2 (0%) | 6 (0%) | 0.9 (0%) | 0 (0%) |
| Estuarine Open Water | 8106.8 (13.7%) | 11159.9 (15.8%) | 2194 (11.8%) | 2827.7 (12.3%) | 7543.7 (31%) | 4127 (9.8%) | 2657.3 (17.8%) |
| Irreg.-Flooded Marsh | 2261.9 (3.8%) | 2622.4 (3.7%) | 1357.3 (7.3%) | 4788.7 (20.8%) | 4854.1 (20%) | 8348.4 (19.9%) | 3290.7 (22.1%) |
| Inland Shore | 37 (0.1%) | 40 (0.1%) | 8.6 (0%) | 100.6 (0.4%) | 3.8 (0%) | 8.3 (0%) | 1.8 (0%) |
| Tidal Swamp | 1463.1 (2.5%) | 1127.6 (1.6%) | 101 (0.5%) | 1082.6 (4.7%) | 584.6 (2.4%) | 17.8 (0%) | 17.1 (0.1%) |
| Flooded Developed Dry Land | 0 (0%) | 0 (0%) | 0 (0%) | 8.1 (0%) | 35.9 (0.1%) | 9.6 (0%) | 12.8 (0.1%) |
| ***Total acres*** | ***59223.8*** | ***70748.1*** | ***18594.4*** | ***23032.4*** | ***24300.4*** | ***41997*** | ***14917.7*** |

**Due to the partial overlap in the Dennis and Reeds monitoring and management units, they are not fully independent (9,850 total acres overlap).*

#### 2.2.1.5 Dikes and Impoundments

Dikes, levees and other barriers to inundation were taken into account so that water flow could be simulated more realistically. Dike rasters were created using NWI data. All NWI wetland polygons with the “diked or impounded” attribute “h” were selected from the original NWI data layer, and these lands were assumed to be permanently protected from flooding. This procedure has the potential to miss dry lands that are protected by dikes and seawalls, as contemporary NWI data contains wetlands data only.

#### 2.2.1.6 Impervious Land Cover

Impervious land cover data describe artificial surfaces and structures through which water cannot penetrate. In SLAMM, dry land is categorized as developed or undeveloped. If a dry-land cell is covered by more than 25% impervious surfaces, it is assumed to be “developed” dry land. In this study, percent impervious rasters were derived from the 2011 National Land Cover Dataset (Xian et al. 2011). The cell size was resampled from the original 30 m resolution to a 5 m resolution in order to match the cell resolution of the other rasters in the project.

## 2.2.2 Model Timesteps

SLAMM simulations were run from either 2007 or 2014 (depending on years of the initial wetland cover layers, which varied depending on the NWI photo dates and DEM dates; see Appendix A) to 2100 with model-solution time steps at 2025, 2050, 2075 and 2100. Although equal time intervals may be desirable for management and planning purposes, under higher SLR scenarios, significant changes will likely occur over shorter time steps. Thus, a shorter time interval may be needed to capture rapid changes. This may be particularly important in the U.S. mid-Atlantic region, where rates of SLR have been occurring at an accelerated rate compared to the global mean (Sallenger et al. 2012).

## 2.2.3 Sea Level Rise Scenarios

The SLR scenarios used in this analysis are based on the most recent global SLR projections published by NOAA (Sweet et al. 2017), which came from a joint effort of the Sea Level Rise and Coastal Flood Hazard Scenarios and Tools Interagency Task Force. These projections incorporate the most up-to-date science (specifically the improved understanding of complex behaviors of the large, land-based ice sheets of Greenland and Antarctica), and utilize the most up-to-date methodologies for making regional adjustments to global mean SLR scenarios. The projections include six scenarios ranging from low (0.3 m by 2100) to extreme (2.5 m by 2100). Table 2 shows details of SLR relative to the base year of 2000. For this case study, we generated SLAMM results for three SLR scenarios: low, intermediate and high, each of which is considered to be “very likely” (>90% probability) under future simulations of low, moderate and high rates of warming, respectively (Sweet et al. 2017). These encompass the SLR scenarios recommended by the DE SLR Technical Committee[4] (Callahan et al. 2017). Recent studies

[4] For planning purposes, the DE SLR Technical Committee has decided to use SLR scenarios of 0.52 m, 0.99 m, and 1.53 m by 2100, relative to year 2000. These three scenarios closely correspond to the intermediate-low, intermediate and intermediate-high scenarios from the Sweet et al. 2017 report (Table 2).

suggest that the "extreme" rate (2.5 m GMSL rise by 2100) is possible, although the probability of this extreme outcome cannot currently be assessed (Sweet et al. 2017).

*Table 2. Global mean SLR projections by scenario (Sweet et al. 2017). Base year is 2000. For this case study, we generated results for the low, intermediate and high SLR scenarios (highlighted in green).*

| Scenario | Global mean sea level (m) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 2010 | 2020 | 2030 | 2040 | 2050 | 2060 | 2070 | 2080 | 2090 | 2100 |
| Low | 0.03 | 0.06 | 0.09 | 0.13 | 0.16 | 0.19 | 0.22 | 0.25 | 0.28 | 0.30 |
| Intermediate-Low | 0.04 | 0.08 | 0.13 | 0.18 | 0.24 | 0.29 | 0.35 | 0.40 | 0.45 | 0.50 |
| Intermediate | 0.04 | 0.10 | 0.16 | 0.25 | 0.34 | 0.45 | 0.57 | 0.71 | 0.85 | 1.00 |
| Intermediate-high | 0.05 | 0.10 | 0.19 | 0.3 | 0.44 | 0.60 | 0.79 | 1.00 | 1.20 | 1.50 |
| High | 0.05 | 0.11 | 0.21 | 0.36 | 0.54 | 0.77 | 1.00 | 1.30 | 1.70 | 2.00 |
| Extreme | 0.05 | 0.11 | 0.24 | 0.41 | 0.63 | 0.90 | 1.20 | 1.60 | 2.00 | 2.50 |

### 2.2.4 Vertical Land Movement

The relative SLR at the local scale can differ significantly from the global mean SLR. Vertical land movement (VLM), or subsidence, is an important factor that contributes to this discrepancy. For our case study, we utilized data from Zervas et al. (2013) to adjust for VLM. Their rates are based on an oceanographic analysis of long-term (30-60 year) NOAA tide gauge station measurements along the coasts of DE and NJ. Zervas et al. (2013) found greater subsidence rates in NJ than in DE (2.1mm/yr versus 1.7mm/yr, respectively) likely due to artificial groundwater withdrawal over decades (Sun et al. 1999). Within SLAMM, we added these VLM rates to the historic eustatic trend (1.7 mm/yr) to get historic relative SLR trend inputs of 3.4 mm/yr at the DE sites and 3.8 mm/yr at the NJ sites, and assumed that the VLM rate would remain the same through the end of this century.

### 2.2.5 Tide Ranges

SLAMM requires Great Diurnal Tide Range (GT)[5] as an input. Tide range data were collected from the NOAA Tides and Currents website (www.tidesandcurrent.noaa.gov) and were based on the present National Tidal Datum Epoch (1983-2001). GT values across the seven study sites ranged from 1.42 m at Lewes to 1.96 m at Fortescue (Table 3, Figure 5).

[5]GT is the difference between mean higher high water (MHHW) and mean lower low water (MLLW) levels.

*Table 3. Great diurnal tide range (GT) inputs for the seven sites.*

| State | Site | Great Diurnal Tide Range (m) | NOAA station ID |
|---|---|---|---|
| NJ | Dividing Creek | 1.96 | 8536931, Fortescue |
| NJ | Maurice River | 1.96 | 8536931, Fortescue |
| NJ | Dennis Creek | 1.92 | 8536581, Bidwell Creek |
| NJ | Reeds Beach | 1.92 | 8536581, Bidwell Creek |
| DE | Broadkill | 1.42 | 8557390, Lewes |
| DE | Mispillion | 1.81 | 8554399, Port Mahon |
| DE | St. Jones | 1.81 | 8554399, Port Mahon |

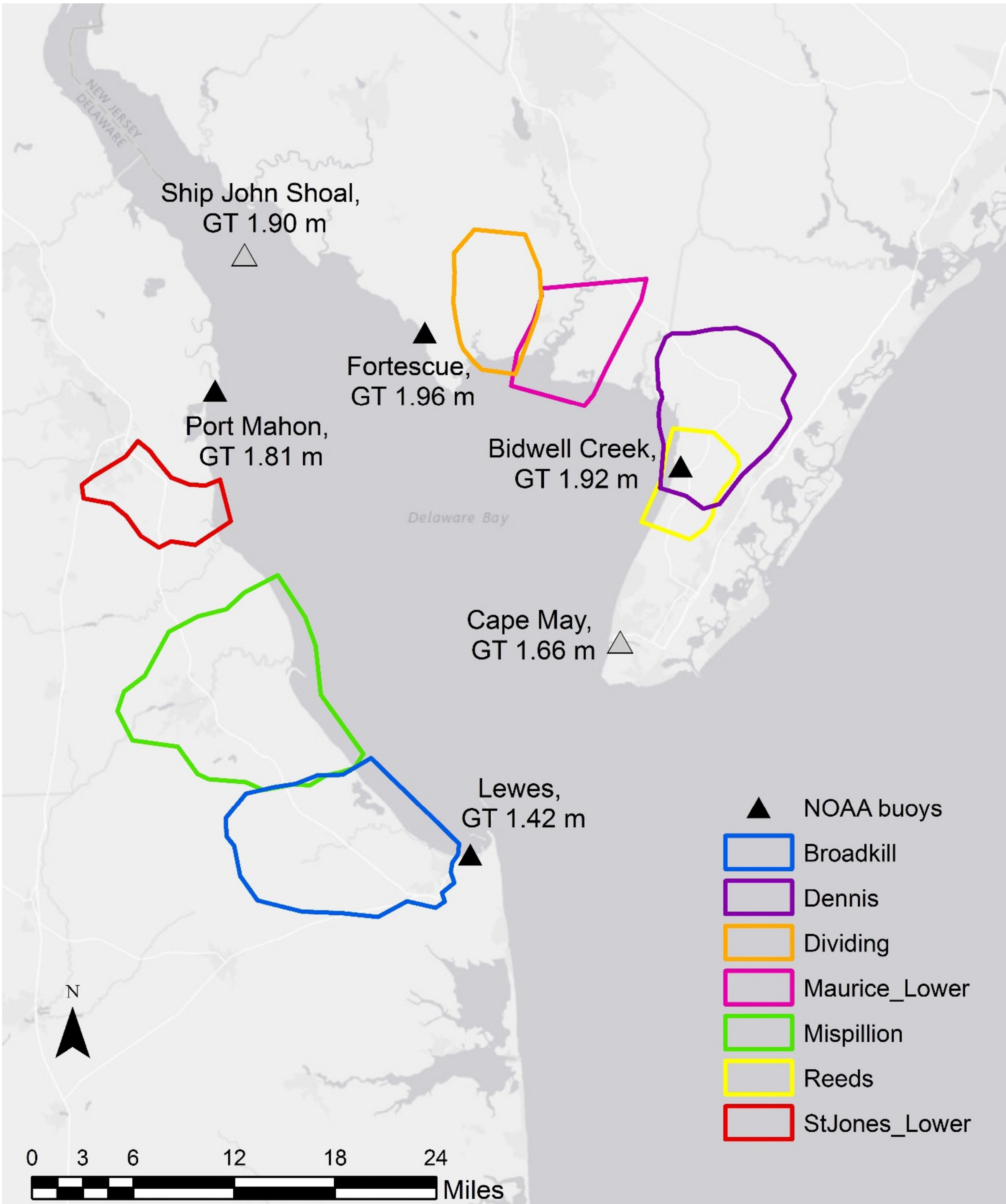



*Figure 5. GT data were derived from the NOAA buoys shown as black triangles in this map. Two additional NOAA buoys (Cape May and Ship John Shoal; shown as gray triangles) were used to generate salt elevation. Note that the partially-overlapping Dennis and Reeds sites were modeled separately as per PDE's convention to view them as different units for monitoring and management.*

### *2.2.5.1 Elevations expressed in half tide units (HTU)*

In general, wetlands occupy a range of vertical elevations that is a function of the tide range (Titus and Wang 2008); one conceptual example of this is shown in Figure 6. Because of this, rather than expressing marsh elevation in absolute values (e.g., meters, feet, cm, etc.), SLAMM uses units relative to the local tide range or “half-tide units”. A half-tide unit (HTU) is defined as half of the great diurnal tide range (GT/2). A numerical example follows:

- If a marsh elevation is X meters above MTL, its elevation in HTU is given by X/(GT/2).
- For example, consider a marsh with an elevation 1 m above MTL, with a GT of 1.5 m. The height of the marsh in HTU is equal to 1/(1.5/2)=1.33 HTU.
- This set of units is straightforward to understand if you consider that MTL is defined as 0.0 HTU, MHHW is defined as 1.0 HTU, and MLLW is defined as -1.0 HTU. A marsh with an elevation above 1.0 HTU falls above the high tide line regardless of the absolute value of the tide.

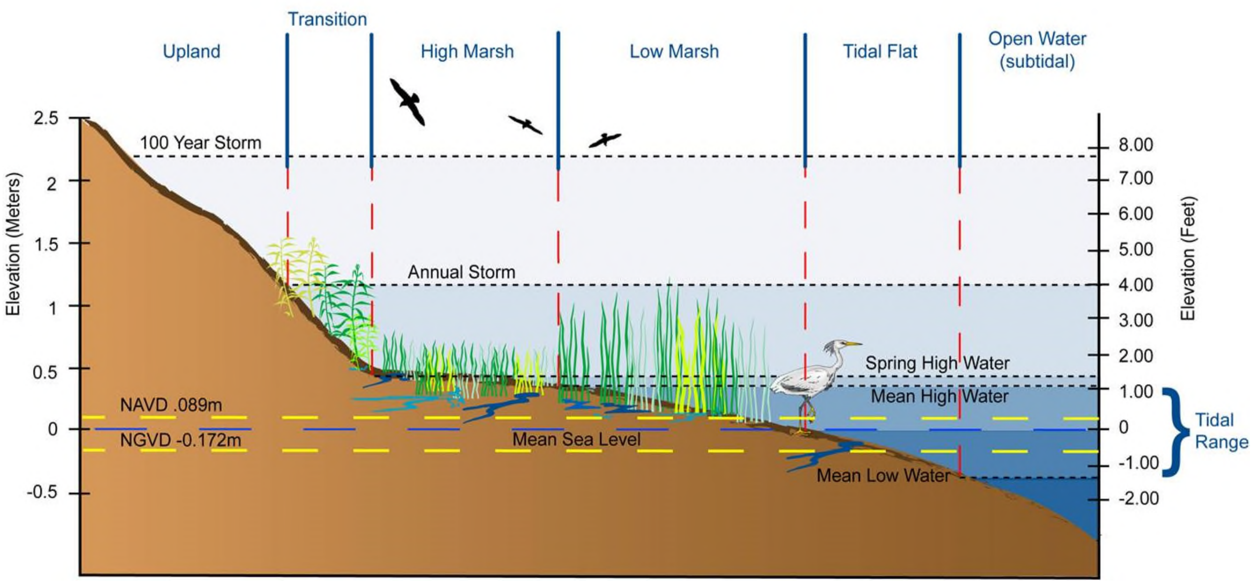



*Figure 6. Relationship between tides, wetlands, and reference elevations for an example estuarine shore profile. Source: Titus and Wang 2008.*

## 2.2.6 SLAMM Salt Elevation Parameter

The salt-elevation parameter in SLAMM defines the boundary between coastal wetlands and dry lands (or fresh-water wetlands). This elevation, relative to MTL, is determined through analysis of “higher high” water levels in NOAA tide records. Warren Pinnacle, the consulting firm that has been developing SLAMM software since 1998, has found that the elevation that differentiates coastal wetlands and dry lands is approximately the height that is inundated once every 30 days.

Therefore, the 30-day inundation level was determined for the most proximate buoys in the study area that had NOAA-verified water-level data, which were: Lewes, Cape May and Ship John Shoal (Table 4;

Figure 5). We downloaded hourly water level data from these three buoys from 2012-2016 and calculated: 1) the monthly maximum water level; 2) the minimum of the monthly maximum water levels in each year; and 3) the mean value across years (Table 4). We then obtained the GT for the three buoys from the NOAA Tides and Currents website (as described in Section 2.2.5) and calculated the (HTUs (= GT/2). We plotted the HTUs against the mean salt elevations for the three buoys and did a linear regression analysis (Figure 7). We then used the formula from the regression analysis to calculate salt elevations for each of the seven sites (Table 5).

*Table 4. Salt elevation calculations were based on data from three NOAA buoys.*

| Tide Gauge Station | Mean salt elevation (m above MTL) | | | | | | GTU (m) | HTU (GT/2) (m) |
|---|---|---|---|---|---|---|---|---|
| | 2016 | 2015 | 2014 | 2013 | 2012 | Overall (2012-2016) | | |
| Lewes, DE (8557380) | 1.076 | 1.070 | 0.981 | 1.051 | 1.015 | 1.039 | 1.418 | 0.709 |
| Cape May, NJ (8536110) | 1.204 | 1.185 | 1.117 | 1.209 | 1.130 | 1.169 | 1.659 | 0.830 |
| Ship John Shoal, NJ (8537121) | 1.262 | 1.142 | 1.177 | 1.209 | 1.130 | 1.184 | 1.899 | 0.950 |

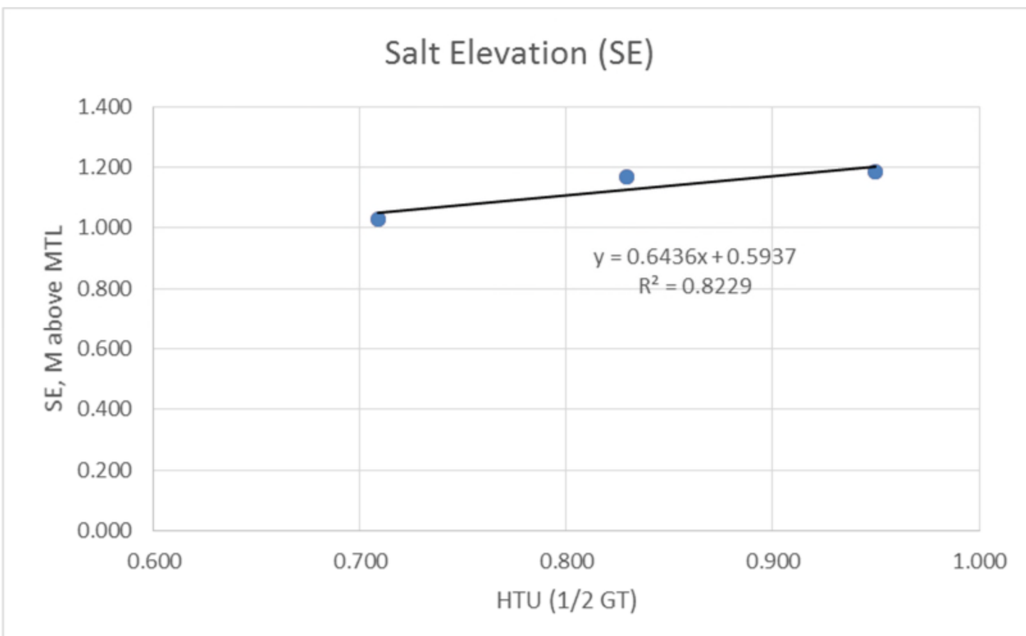



*Figure 7. HTUs were plotted against the mean salt elevations for the three buoys to derive the linear regression formula that was used to calculate salt elevations for the seven sites.*

*Table 5. Salt elevations for the seven sites.*

| Site | GT (m) | HTU (GT/2) | Salt elevation (m above MTL)[1] |
|---|---|---|---|
| Broadkill | 1.42 | 0.71 | 1.05[2] |
| Mispillion | 1.81 | 0.91 | 1.18[2] |
| StJones | 1.81 | 0.91 | 1.18 |
| Reeds | 1.92 | 0.96 | 1.21 |
| Dennis | 1.92 | 0.96 | 1.21 |
| Dividing | 1.96 | 0.98 | 1.22 |
| Maurice | 1.96 | 0.98 | 1.22 |

[1]Salt elevations were derived from the following equation: 0.6436*HTU+0.5937 (based on Figure 8)
[2]During model calibration, salt elevations for the Broadkill and Mispillion were reduced to 1.04 and 1.10, respectively, to account for moderating effects of barriers and dunes (Appendix A).

## 2.2.7 Wetland Elevation-Change Rate

We performed a literature search to collect relevant data on accretion rates and wetland-elevation change rates. In addition, where appropriate, Surface Elevation Tables (SET) data from Site Specific Intensive Monitoring (SSIM) sites[6] were used to determine models of wetland elevation-change rates for the study area. SETs are portable lightweight mechanical leveling devices with movable fiberglass or metal pins that are lowered to the ground. They are used to measure millimeter-scale changes in wetland surface elevation relative to a fixed benchmark. Repeated measurements of the same patch of sediment surface are taken through time (Lynch et al. 2015). Changes in vertical elevation at the soil surface can be highly variable over space and time. The changes occur due to a combination of surface and subsurface processes such as accretion, erosion, soil organic matter accumulation, decomposition, compaction, and groundwater flux. Having localized SET data enhances studies like ours and is important for regional coastal wetland vulnerability assessments and predictive ecological models (Osland et al. 2017).

### *2.2.7.1 Tidal Salt Marsh*

The current SLAMM application attempts to account for what are potentially critical feedbacks between tidal-marsh surface elevation change rates and SLR (Kirwan et al. 2010). In tidal marshes, increasing inundation can lead to additional deposition of inorganic sediment that can help tidal wetlands keep pace with rising sea levels (Reed 1995). In addition, salt marshes will often grow more rapidly at lower elevations allowing for further inorganic sediment trapping (Morris et al. 2002). The extent to which such feedbacks can offset SLR is subject to limits, however, based on habitat condition as well as on the quantity of suspended sediments and the rate of SLR (Kirwan 2010).

[6] The following organizations run the SSIM stations: (1) Delaware Department of Natural Resources and Environmental Control (DNREC) Wetland Management and Assessment Program and PDE run the Broadkill; (2) Delaware National Estuarine Research Reserve (DNERR) (also part of DNREC) funds/runs the St. Jones; and (3) PDE, Barnegat Bay Partnership and the Academy of Natural Sciences run the stations at Dividing, Maurice, and Dennis.

There are two primary coastal marsh types within our modeling area that are subject to these feedbacks:

- **Regularly-Flooded Marsh (RFM)** includes low to mid elevation marshes. Roughly speaking, these are marshes that are inundated by tidal water at least once per day.

- **Irregularly-Flooded Marsh (IFM)** includes high elevation marshes. These marshes are inundated by tidal water once per day or less.

The persistence and conversion dynamics of RFM and IFM in SLAMM are summarized as follows:
– SLAMM assumes that wetlands will occupy a range of vertical elevations that is a function of the tide range and the mean-tide level (Titus and Wang 2008) (Figure 6).
– When the IFM platform falls below the modeled minimum elevation, the land cover is converted to RFM.
– When the RFM falls below the modeled minimum elevation, generally below mean-tide level, then the land cover is converted to non-vegetated tidal flats.
– The elevation intervals of existence (relative to tide ranges) can be adjusted by the user to reflect local conditions.

Note: The upper elevation boundaries are not critical to the model; SLAMM does not project any conversion to IFM or dry-land production above these elevations. However, examining these boundaries is important to validate the consistency of model assumptions with regard to observed wetland coverage, elevations, and tide data.

SET data were available for five of the seven sites (Table 6, Figures 8-9). We used these data to determine models of elevation change in RFM and IFM in the study area (Figure 10). Due to the limited amount of SET data, data from all sites were grouped together, and the following steps were performed to derive accretion rate formulas (the same formulas were applied at all seven sites):

- We calculated a linear relationship between marsh elevation-change rates and marsh platform elevations, to derive the slope of this relationship (-1.634 mm/year per meter of elevation) (Attachment 1, Excel worksheet).
- As the majority of stations are within the IFM elevation range, this linear relationship is used for IFM (Attachment 1).
- We estimated a parabolic relationship for RFM using SLAMM accretion parameters and knowledge of mechanistic modeling curves and the type of curves derived for other sites (e.g., Virginia's Eastern Shore (Warren Pinnacle Consulting, Inc. 2015), New York City (Clough et al. 2014)). Elevation-change rates are extremely limited for elevations below MHHW so best professional judgment was used (Figure 10).
- Parabolic curves for RFM were added to all model applications and tested within the model interface.
- In the absence of site-specific data, values for tidal fresh marsh accretion (the approximate average of IFM rate in the absence of specific data) and inland fresh marsh (1 mm/yr) and swamp accretion (3 mm/yr) were added based on model defaults and professional judgment.

We compared the curves to those used at other sites and found reasonable correspondence. Elevation change tables and plots for each site with SET data can be found in Appendix C.

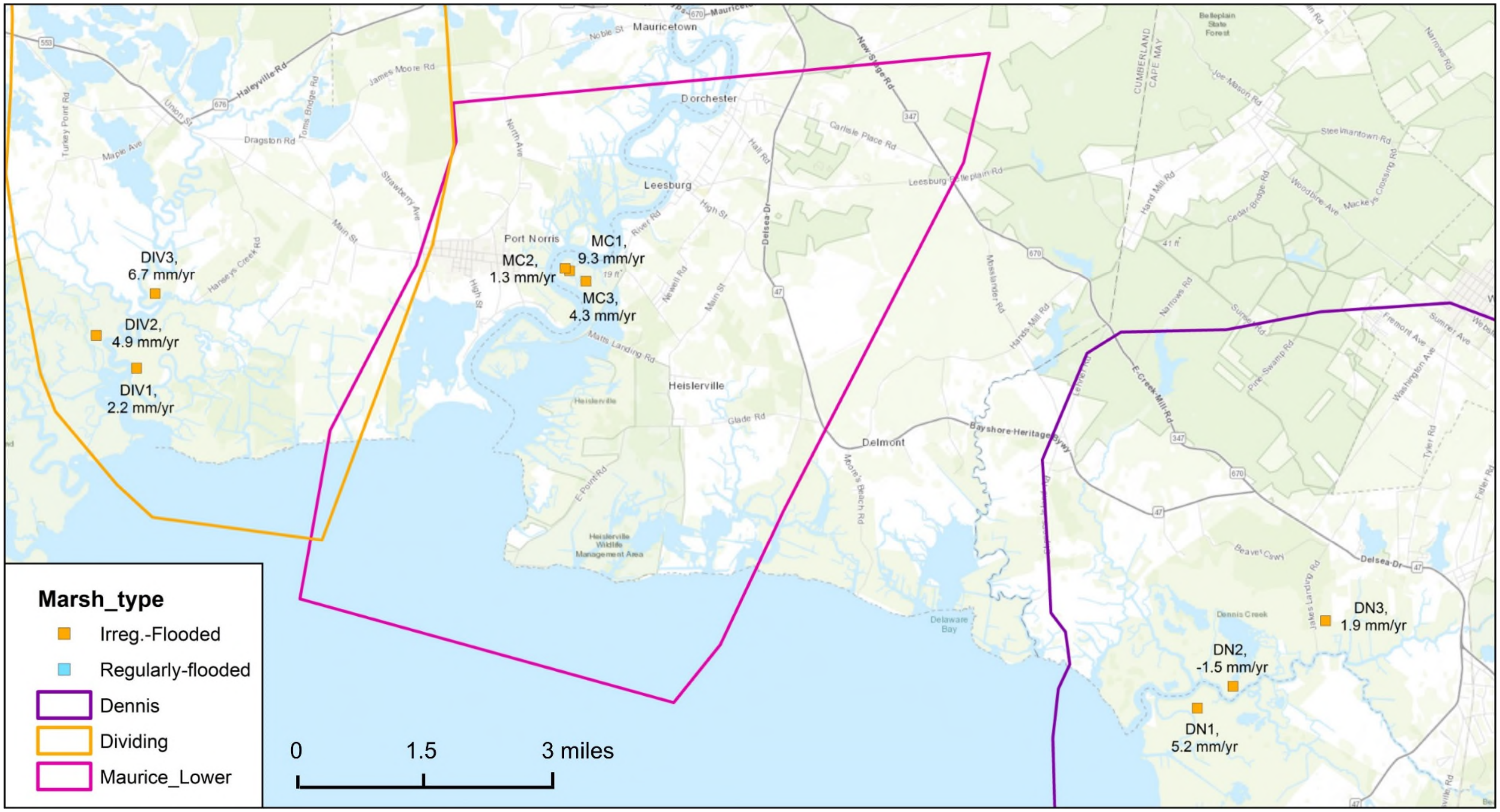
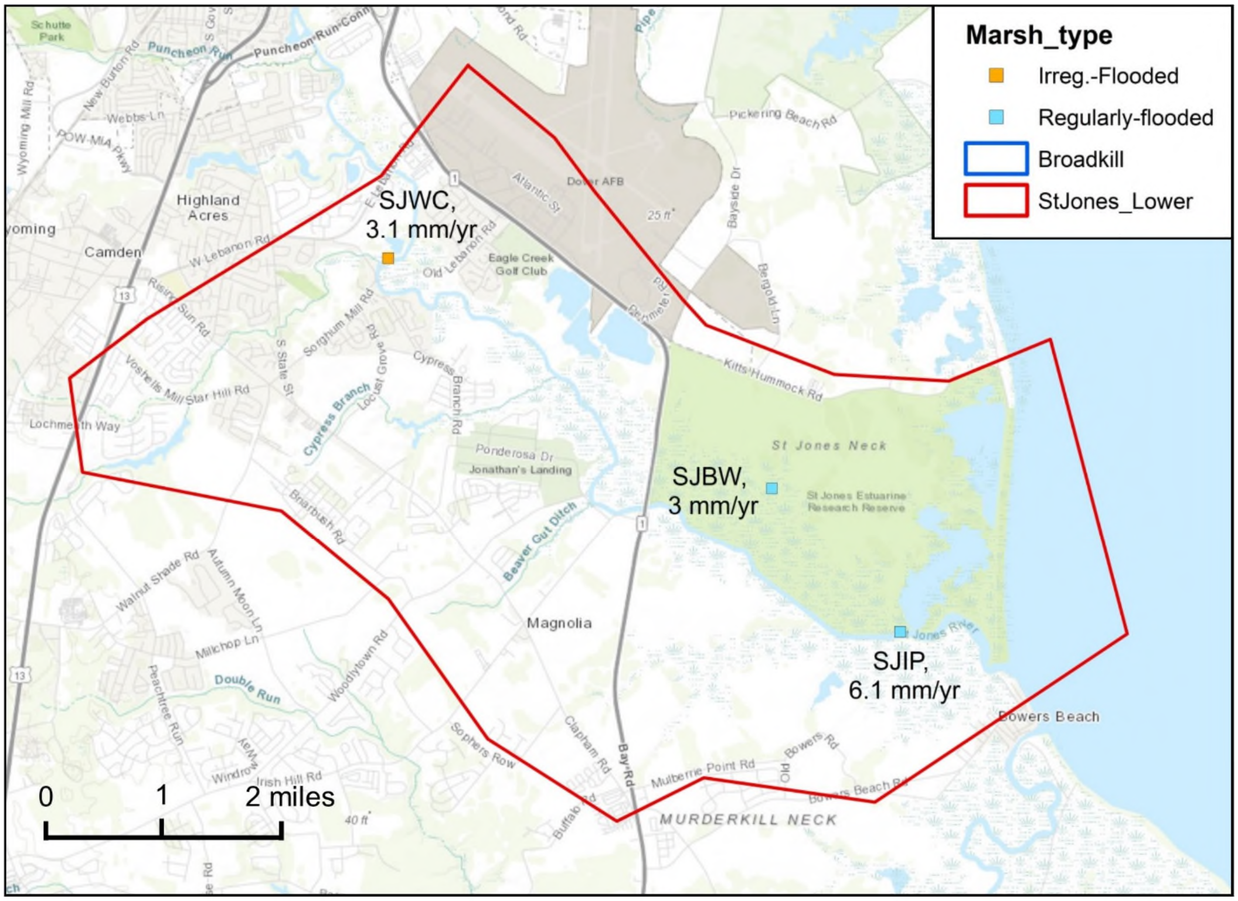



*Figure 8. Locations of SET sites in the New Jersey marshes (Dividing (DIV), Maurice (MC) and Dennis (DN)). Values equal elevation change (mm/yr) averaged across the period of record. All are located in irregularly-flooded marsh.*



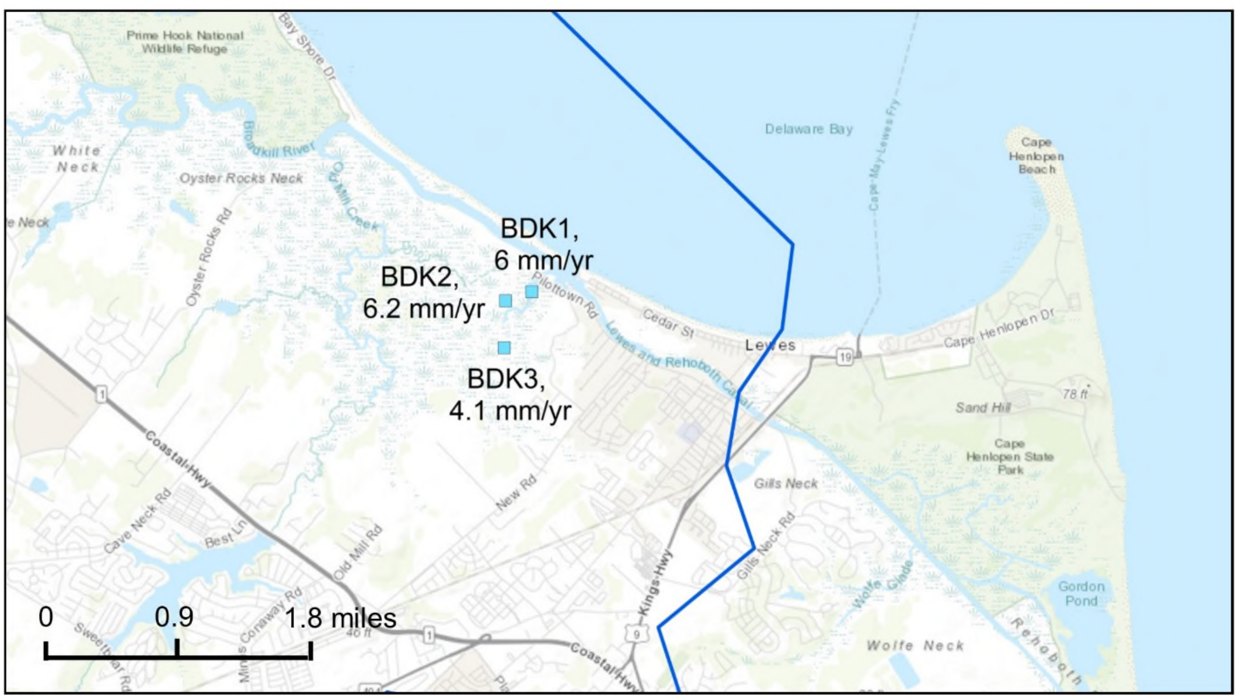




*Figure 9. Locations of SET sites in the Delaware marshes (St. Jones (upper map) and Broadkill (lower map). Values equal elevation change (mm/yr) averaged across the period of record.*

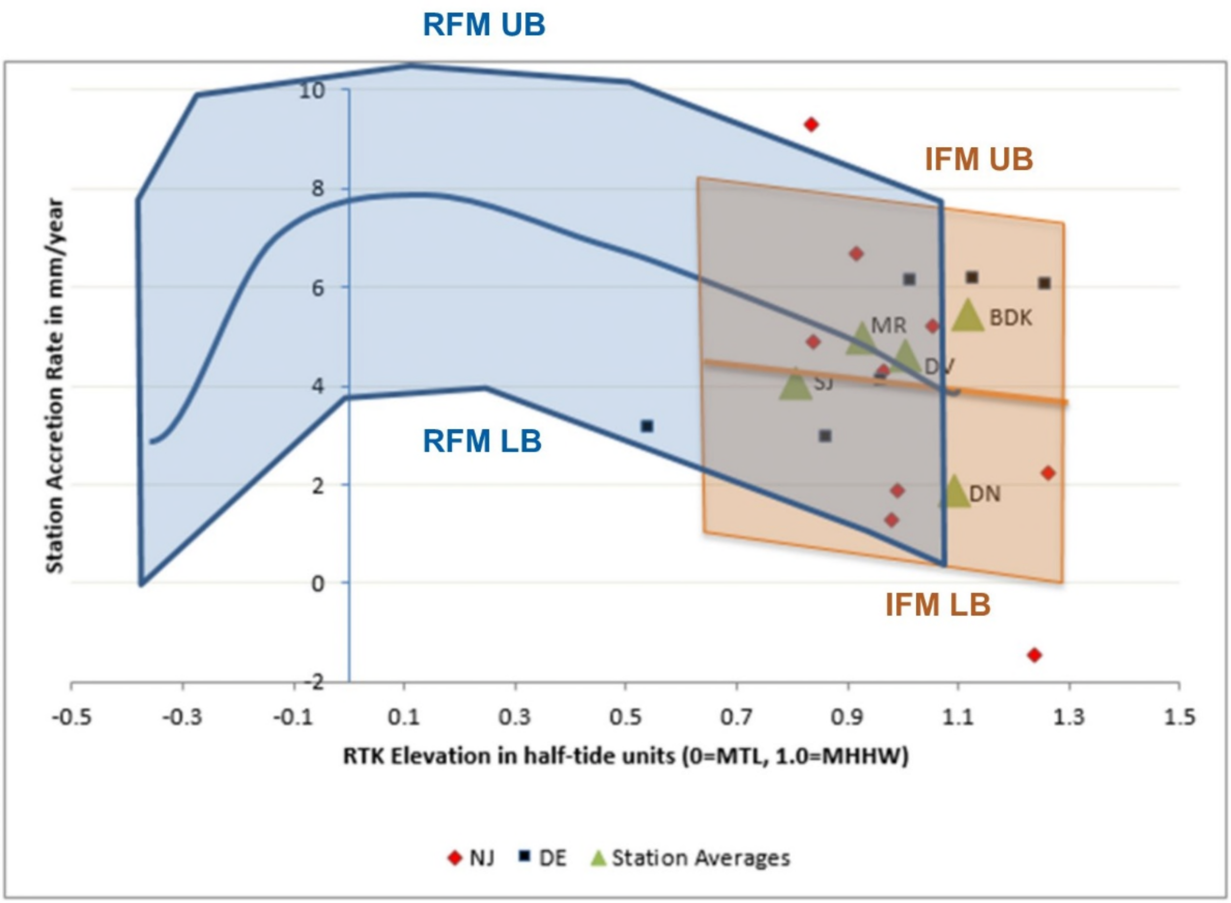



*Figure 10. RFM and IFM SLAMM Elevation-Change Models. The blue shaded area defines the RFM boundaries (LB = lower bound, UB = upper bound) while the IFM boundaries are shown in orange. The dots represent SET data from the five sites listed in Table 6. Measured elevation-change rates regularly exceeded 5 mm/year and extended up to 9.3 mm/year while taken at elevations near MHHW. For this reason, assuming a potential increase in mean accretion rates to 8 mm/year as flooding frequency increases provides a reasonable estimate.*

*Table 6. Locations of the SET stations, elevation change rate (averaged across the period of record) and first and last SET measurement dates (dates cover the period of record available at the time of the analysis; more data may now be available).*

| Site | State | Longitude | Latitude | SET Station ID | Marsh type (SLAMM category) | Mean elevation change (mm/yr) | First date | Last date |
|---|---|---|---|---|---|---|---|---|
| Broadkill | DE | -75.1660 | 38.7873 | BDK1 | Regularly-flooded | 6.0 | 2014-05-28 | 2016-08-24 |
| | | -75.1698 | 38.7863 | BDK2 | Regularly-flooded | 6.2 | | |
| | | -75.1699 | 38.7811 | BDK3 | Regularly-flooded | 4.1 | | |
| St. Jones | DE | -75.4174 | 39.0707 | SJIP (Impoundment) | Regularly-flooded | 6.1 | 2007-06-07 | 2015-03-19 |
| | | -75.4375 | 39.0881 | SJBW (Boardwalk) | Regularly-flooded | 3.0 | 2004-06-22 | 2015-09-01 |
| | | -75.4975 | 39.1158 | SJWC (Wildcat) | Irreg.-Flooded | 3.1 | 2007-06-18 | 2015-03-18 |
| Dennis | NJ | -74.8775 | 39.1697 | DN1 | Irreg.-Flooded | 5.2 | 2011-05-13 | 2015-09-11 |
| | | -74.8698 | 39.1734 | DN2 | Irreg.-Flooded | -1.5 | | |
| | | -74.8496 | 39.1845 | DN3 | Irreg.-Flooded | 1.9 | | |
| Dividing | NJ | -75.1080 | 39.2273 | DIV1 | Irreg.-Flooded | 2.2 | 2012-05-31 | 2015-10-21 |
| | | -75.1168 | 39.2328 | DIV2 | Irreg.-Flooded | 4.9 | | |
| | | -75.1040 | 39.2398 | DIV3 | Irreg.-Flooded | 6.7 | | |
| Maurice | NJ | -75.0148 | 39.2442 | MC1 | Irreg.-Flooded | 9.3 | 2011-04-18 | 2015-10-06 |
| | | -75.0139 | 39.2438 | MC2 | Irreg.-Flooded | 1.3 | | |
| | | -75.0103 | 39.2420 | MC3 | Irreg.-Flooded | 4.3 | | |

#### *2.2.7.2 Other Wetland Types*

We lacked information on accretion rates and wetland-elevation change rates specific to the Lower Delaware Bay for the other wetland habitat types. As a default, we used the values shown in Table 7 for all sites. Table 7 cites the sources that the default values are based on. Average beach sedimentation rates are assumed to be lower than marsh-accretion rates due to the lack of vegetation to trap suspended sediment, though they are known to be highly spatially variable. In addition, it is worth noting that future beach nourishment, should it occur within the study area, is not accounted for in these SLAMM simulations.

*Table 7. Accretion rate inputs that were used for the other marsh types (at all sites).*

| Parameter | Input | Source |
|---|---|---|
| Tidal-Fresh Marsh Accr (mm/yr) | 5 | Neubauer et al. 2002, Neubauer 2008 |
| Inland-Fresh Marsh Accr (mm/yr) | 1 | Craft and Casey 2000, Graham et al. 2005 |
| Tidal Swamp Accr (mm/yr) | 1.1 | Warren Pinnacle Consulting, Inc. 2015 (based on personal communications with Dr. Christopher Craft) |
| Swamp Accretion (mm/yr) | 1.6 | |
| Beach Sed. Rate (mm/yr) | 0.5 | Warren Pinnacle Consulting, Inc. 2015 |

### 2.2.8 Erosion Rates

Average marsh erosion rates were calculated for each study site based on aerial photography using the USGS ArcGIS tool Digital Shoreline Assessment System (Thieler et al. 2009). The calculations were performed on shorelines that had fetch exposure greater than 30 m. Table 8 lists the erosion rates for each site, which were provided by PDE.

SLAMM simulates erosion as additive to inundation. Horizontal wetland erosion is assumed to be the effect of wave action, and marsh or swamp erosion is assumed to only occur when the wetland type in question is directly exposed to open water with sufficient "fetch" (i.e., the open-water region over which waves can set up). The SLAMM model default only triggers erosion in cells that have greater than a 9-km fetch. In this case study, the 9-km default would have underestimated erosion because SLAMM would have only applied erosion in the few areas that have a 9-km fetch across the open bay (compared to a more common 30 m fetch within tidal creeks). To better match the shoreline erosion calculations (that were based on data with a 30 m fetch), we reduced the fetch requirement to 0.1 km (100 m). We used 0.1 km instead of 30 m due to uncertainty in our input wetland-layer rasters and concerns about overestimating erosion in small rivers.

Swamp erosion was set to 1 m/yr, a rate commonly used in SLAMM when site-specific data are unavailable. Within SLAMM, swamp erosion is only projected at a swamp to open water interface. As swamps are rarely exposed to open wave action in this study area, this parameter is of limited significance here.

*Table 8. Average marsh erosion rates for each site (Demberger et al. 2017).*

| State | Site | Erosion rates (m/yr) |
|---|---|---|
| NJ | Dividing Creek | -0.430 |
| NJ | Maurice River | -0.340 |
| NJ | Dennis Creek | -0.240 |
| NJ | Reeds Beach | -0.240 |
| DE | St. Jones | -0.309 |
| DE | Broadkill | -0.116 |
| DE | Mispillion | -0.564 |

## 2.3 SLAMM Model Setup and Calibration

The study area was divided into four blocks to reduce computer processing time: Dividing and Maurice (NJ); Dennis and Reeds Beach (NJ); Broadkill and Mispillion (DE); and St. Jones (DE) (Appendix A, Figure A1). Within several of the marsh areas, we had to create input subsites to account for differences in NWI photo dates, DEM dates, tide range, salt elevation and marsh erosion rates. Maps of the input subsites are included in Appendix A.

Before running the future SLR simulations, we performed “time zero” SLAMM runs in each block to identify any initial problems with key SLAMM modeling inputs, such as NWI land cover, elevations, modeled tidal ranges and hydraulic connectivity. In these “time zero” runs, the tides are applied to the study area, but no SLR, accretion or erosion inputs are considered. Differences will arise between the original NWI land cover layer and the SLAMM “time zero” land cover layer if cells are below the lowest allowable elevation land cover categories (based on the SLAMM settings), which causes them to be converted to a different land cover category (Table 9).

Where differences occurred, we generally found that the land cover re-categorization by SLAMM better described the current coverage in these areas, which was not surprising given that some NWI images date back to the 1990s. In some cases, the reason for initial land cover conversions of dry land is due to differences in the horizontal resolutions of the input datasets. The native resolution of the impervious cover layer (which is used to identify developed areas) is 30 m x 30 m, versus the higher horizontal resolution elevation data (which, in this study, is 5 m x 5 m). The higher resolution elevation data allow SLAMM to better define the wet to dry land interface at time zero.

For calibration, we checked the accuracy of the “time zero” SLAMM land cover layers by using GIS software to overlay aerial photographs and GIS inundation files over the land cover layer (with particular focus in areas where large conversions of wetlands were observed). In addition, two practitioners with local knowledge reviewed the “time zero” maps. Appendix A contains results from the “time zero” SLAMM runs and descriptions of corrections that were made to the land cover layers prior to running the future simulations.

*Table 9. Inundation models for "Traditional SLAMM" Categories (when cells fall below their lower elevation boundaries, these are generally what they convert to).*

| SLAMM category | General conversions (exceptions may occur) |
|---|---|
| Irreg.-Flooded Marsh | Regularly-Flooded Marsh |
| Trans. Salt Marsh | Regularly-Flooded Marsh |
| Regularly-Flooded Marsh | Tidal Flat |
| Tidal-Fresh Marsh | Tidal Flat |
| Tidal Flat | Estuarine Open Water |
| Developed Dry Land | Trans. Salt Marsh or Flooded Developed Dry Land (depending on model settings) |
| Undeveloped Dry Land | Trans. Salt Marsh |
| Inland-Fresh Marsh | Trans. Salt Marsh |
| Swamp | Trans. Salt Marsh |
| Tidal Swamp | Irreg.-Flooded Marsh |
| Inland Open Water | Estuarine Open Water |
| Estuarine Beach | Estuarine Open Water |
| Riverine Tidal | Estuarine Open Water |
| Inland Shore | Estuarine Open Water |
| Ocean Beach | Open Ocean |

### 2.3.1 Model Protection Scenarios

Human responses to losses of dry land in the face of SLR are uncertain. In cases for which land values are high, land owners are likely to continue to erect dikes and seawalls to prevent increasing inundation. In other locations, only developed land will be protected, or landowners will abandon property, thereby allowing wetland conversion. To test the impacts of these responses, SLAMM has the capability to model three different simplified protection scenarios:

- "Protect None," where all cells are subject to inundation and can be converted to other habitat types in the simulations
- "Protect Developed Dry Land," where cells designated as developed dry land are protected from inundation and cannot be converted to other habitat types in the simulations
- "Protect All Dry Land," where cells designated as dry land (developed and undeveloped) are protected from inundation and cannot be converted to other habitat types in the simulations.

Comparing these results can also help to assess wetland migration potential. For example, subtracting results of the "Protect Developed Dry Land" scenario from the "Protect None" scenario quantifies the potential marsh encroachment into developed dry land. Another option is to subtract results from the "Protect All Dry Land" scenario from the "Protect Developed Dry Land" scenario, which allows for assessment of possible marsh colonization in undeveloped dry land. For our study, we generated results for all three protection scenarios.

## 2.4 Sensitivity Analysis

We ran sensitivity analyses[7] to better understand the influence of each input variable on the projected changes in salt marsh acreage. SLAMM sensitivity analysis examines one variable at a time. We ran analyses on the following parameters: GT, salt elevation, marsh erosion, and min/max accretion rates for regularly- and irregularly-flooded marsh. Input parameters were varied by 15% (as per professional judgment based on potential measurement error and uncertainty in model inputs). The analyses were performed using the intermediate SLR scenario (1 m GMSL rise by 2100) (Sweet et al. 2017).

# 3 RESULTS

In this section, we present projected changes in habitat for the seven sites. Model projections are reported from time zero forward so that the projected land cover changes are only due to SLR and not due to initial model calibration. To bracket the most plausible range of sea level change projections (given what we know at this time), we ran SLAMM model simulations for three SLR scenarios (low, intermediate, and high per Sweet et al. 2017; Table 2)[8]. Along with the three model protection scenarios (see Section 2.3.1), this resulted in a total of nine combinations of outputs. Due to the large quantity of simulation and analysis results, here we only present results from the intermediate SLR scenario (1 m GMSL rise by 2100), which is considered “very likely” (>90% probability) under future simulations of moderate rates of warming (Sweet et al. 2017). For the model protection scenario, we limited the results to the “Protect Developed Dry Land” scenario, which our work group felt was most likely. The full set of results for each site (covering all nine combinations of outputs) are available in Appendices D-J.

While reporting the intermediate SLR scenario suits our purposes for this report, recent studies suggest an even higher rate of SLR is possible (Sweet et al. 2017). This may be particularly important to consider in the U.S. mid-Atlantic region, where rates of SLR have occurred at an accelerated rate compared to the global mean (Sallenger et al. 2012, Callahan et al. 2017). Because upper end/low probability events carry a disproportionate level of risk (with higher-consequence changes), it may be prudent for some managers to focus on results from a higher risk (albeit less likely) scenario.

Results are divided into three sections. Section 3.1 describes general patterns across sites and includes maps with projected changes in all SLAMM land cover categories, as well as a table showing percent change at one example site. The full set of SLAMM outputs for each site can be found in Appendices D-J. We have kept Section 3.1 short as our primary focus is on Section 3.2, which contains the cross-site comparisons of high, low and total salt marsh habitats. These outputs diverge from traditional SLAMM outputs to include scatterplots of response (mean percent change in acreage) versus exposure (mean SLR) and site-specific gain/loss maps that highlight where vulnerabilities to changes in high and low

[7]SLAMM 6.7 includes a built-in nominal range sensitivity analysis based on Frey and Patil (2001).

[8] The SLR scenario chosen has a large effect on projected changes in high and low marsh acreage, especially by 2100. This is due to differences in conversion rates. For example, at Dennis, under the low SLR scenario, large tracts of high marsh remain by 2100; under the intermediate SLR scenario, these areas have converted from high marsh to low marsh; under the high SLR scenario, these areas have converted from low marsh to tidal flat.

marsh are projected to occur. Finally, Section 3.3 summarizes results from the sensitivity analysis (with the full set of results available in Appendix K).

## 3.1 Projected changes in all SLAMM land cover categories

At time zero, undeveloped dry land, regularly and irregularly-flooded marsh, swamp, tidal swamp and estuarine open water habitats generally comprise the largest areas. For salt marsh habitats specifically, on average, at time zero, the irregularly-flooded marsh habitat (shown in orange in the maps) comprises a higher percentage of acreage at the NJ sites than the DE sites (21% versus 4.2%, respectively). The mean percent acreage of regularly-flooded marsh (shown in light blue in the maps) at time zero is higher at the DE sites compared to the NJ sites (9% versus 4%, respectively). Sites in both states have similar mean percentages of transitional salt marsh (2%). Table 10 is an example of one of the types of tables typically found in SLAMM reports. It shows projected changes in acreage of SLAMM land use categories from time zero to 2100. Figures 11-12 show the spatial distributions of the SLAMM land cover categories across the DE and NJ sites, respectively, over three time periods (time zero, 2050 and 2100). Percent change tables for each site and each SLAMM land cover category can be found in Appendices D-J.

While patterns of change vary across sites and time periods, some general themes are evident. For example, the regularly-flooded marsh habitats are projected to gain acreage through late century at all sites, primarily due to gains from inundation/conversion of irregularly-flooded marsh. By 2100, some areas initially categorized as regularly-flooded marsh are lost. More specifically, two of the DE sites (Broadkill and Mispillion) lose large areas of regularly-flooded marsh along the bay (through conversion to tidal flat and estuarine open water) (Figure 11). Some areas in Dividing and Lower Maurice undergo a similar transition (Figure 12). By 2100, all sites are projected to lose large percentages of irregularly-flooded marsh acreage (on average 88%) due to inundation and conversion to regularly-flooded marsh. The large-scale loss of irregularly-flooded marsh is particularly noticeable at Dennis, Reeds Beach and the Lower St. Jones in the mid versus late-century maps (Figures 11-12). These are just a few of the many interesting patterns in the SLAMM outputs. Detailed information on projected land cover changes at each site can be found in Appendices D-J.

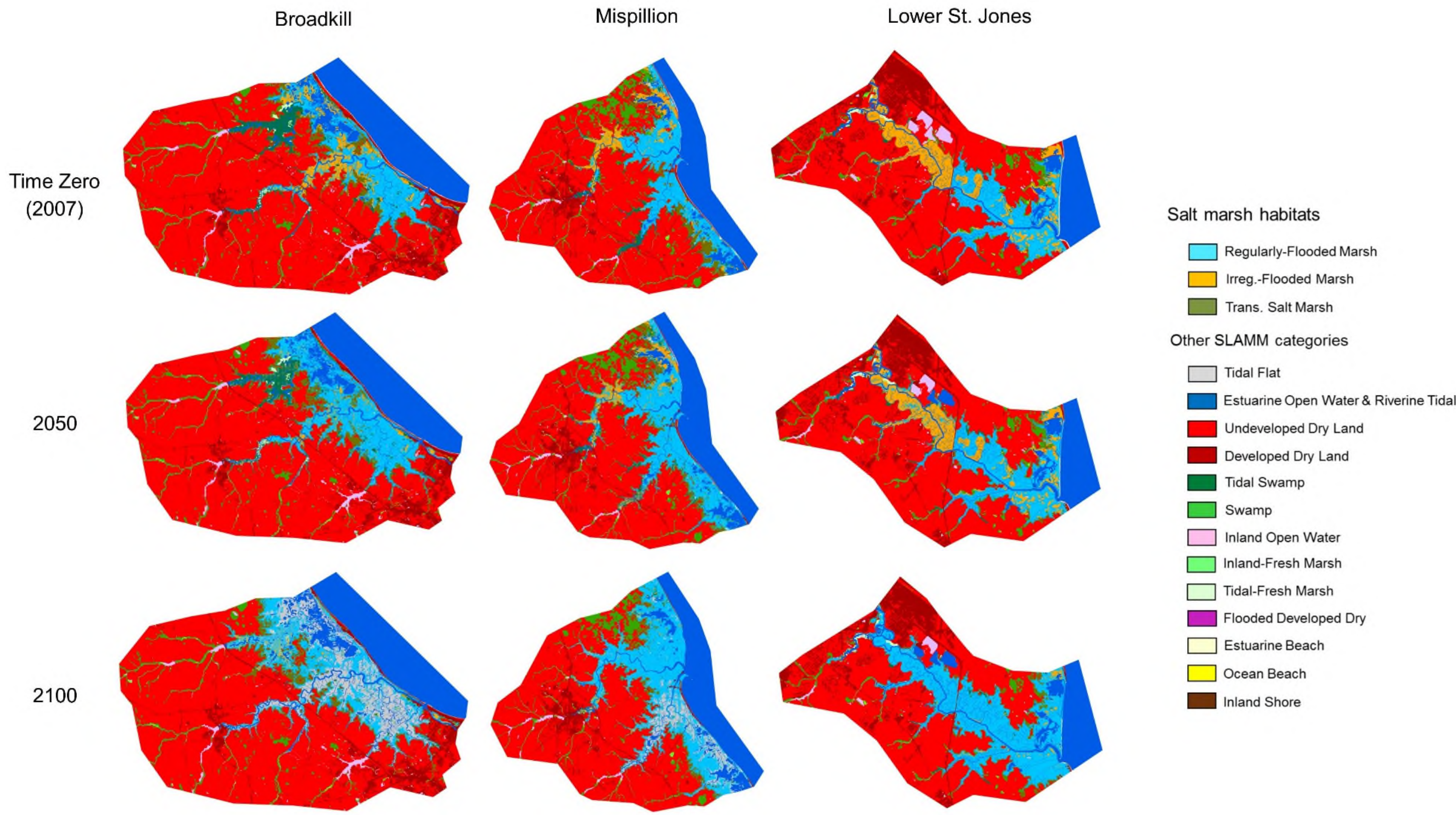



*Figure 11. SLAMM land use categories from early- to late-century for the Delaware sites (Broadkill, Mispillion and Lower St. Jones) under the intermediate SLR scenario (based on Sweet et al. 2017) and "protect dry developed land" modeling scenario. Note that these maps have been magnified to similar sizes for ease of pattern comparisons and are thus not to scale with each other; for relative scales please see Figure 1.*

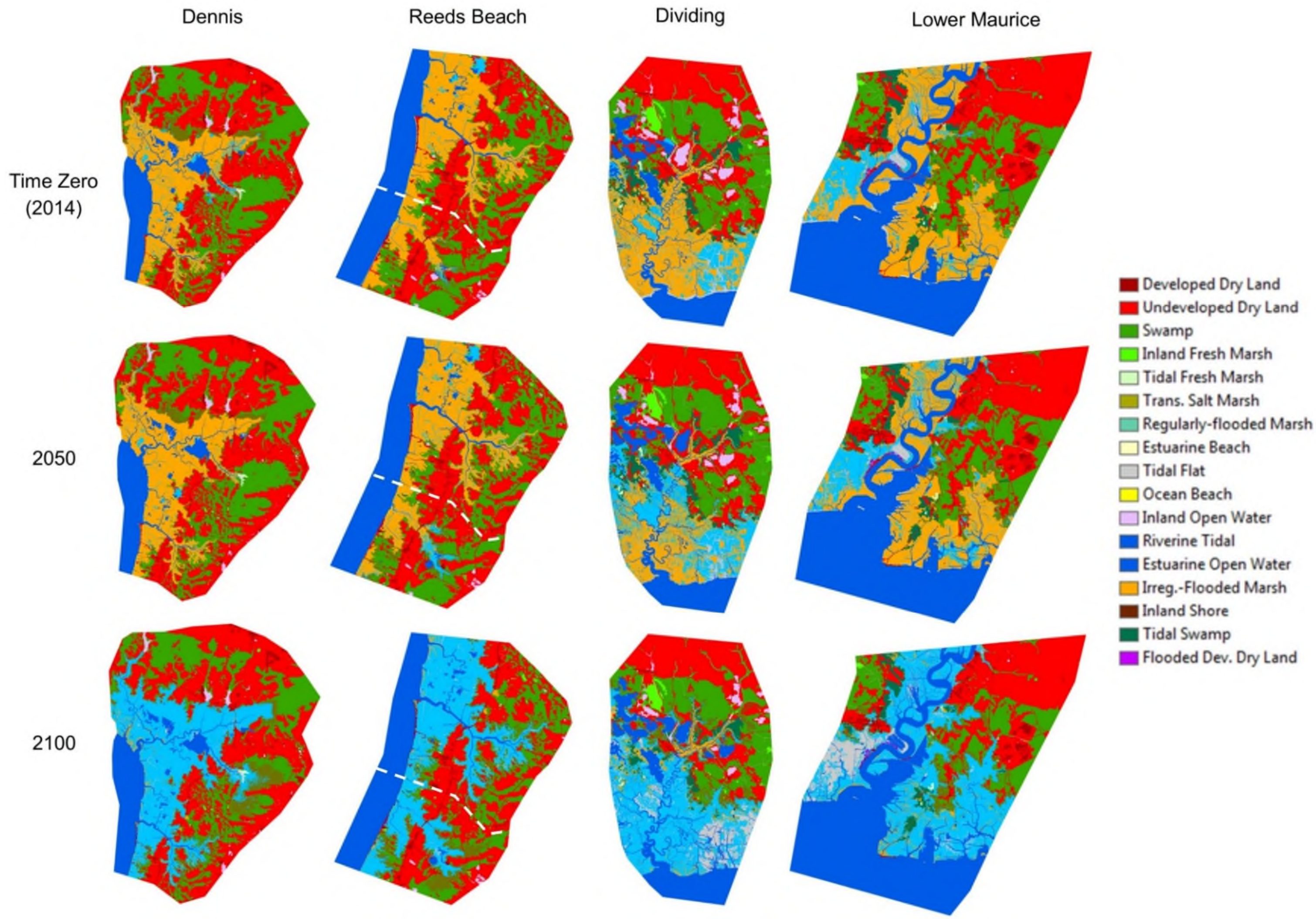



*Figure 12. SLAMM land use categories from early- to late-century for the New Jersey sites (Dennis, Reeds Beach, Dividing and Lower Maurice) under the intermediate SLR scenario (based on Sweet et al. 2017) and "protect dry developed land" modeling scenario. For Reeds Beach, the area above the white dotted line is the area of overlap with Dennis. Note that these maps have been magnified to similar sizes for ease of pattern comparisons and are thus not to scale with each other; for relative scales please see Figure 1.*

*Table 10. Example of a percent change table typically found in SLAMM reports. This table, which is based on data from the Broadkill (DE) site, shows projected changes in acreage of SLAMM land use categories from time zero to 2100. Salt marsh habitats are in bold print because they are the focus of our larger project case study. Percent change calculations are based on change in acreage relative to time zero. The % change cells are color-coded based on direction of change (loss in light red; gains in green). Results are based on the intermediate SLR scenario (Sweet et al. 2017) and "protect dry developed land" modeling scenario (which prevents the developed dry land categories from changing, thus the hashes).*

| SLAMM category | Acres | | | | | % Change | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 2007 | 2025 | 2050 | 2075 | 2100 | 2025 | 2050 | 2075 | 2100 |
| **Irreg.-Flooded Marsh** | **1613.0** | **1301.0** | **547.8** | **832.2** | **348.4** | **-19.3** | **-66.0** | **-48.4** | **-78.4** |
| **Trans. Salt Marsh** | **1626.7** | **1583.3** | **1974.1** | **2220.6** | **1813.1** | **-2.7** | **21.4** | **36.5** | **11.5** |
| **Regularly-Flooded Marsh** | **3955.8** | **4678.8** | **5907.4** | **6931.7** | **5036.7** | **18.3** | **49.3** | **75.2** | **27.3** |
| Tidal Flat | 38.3 | 54.1 | 113.6 | 462.7 | 4458.9 | 41.4 | 196.8 | 1108.4 | 11545.8 |
| Estuarine Open Water | 8415.7 | 8509.8 | 8630.6 | 8804.5 | 9264.4 | 1.1 | 2.6 | 4.6 | 10.1 |
| Undeveloped Dry Land | 35813.8 | 35472.2 | 34774.4 | 33708.7 | 32557.3 | -1.0 | -2.9 | -5.9 | -9.1 |
| Swamp | 1802.6 | 1752.8 | 1669.4 | 1599.8 | 1531.2 | -2.8 | -7.4 | -11.2 | -15.1 |
| Tidal Swamp | 1445.9 | 1428.2 | 1254.8 | 426.4 | 107.2 | -1.2 | -13.2 | -70.5 | -92.6 |
| Inland Open Water | 727.1 | 718.3 | 708.7 | 698.4 | 682.5 | -1.2 | -2.5 | -3.9 | -6.1 |
| Tidal-Fresh Marsh | 159.3 | 157.3 | 147.2 | 108.4 | 20.3 | -1.2 | -7.6 | -32.0 | -87.3 |
| Inland-Fresh Marsh | 131.7 | 128.5 | 123.3 | 113.2 | 105.9 | -2.5 | -6.4 | -14.0 | -19.6 |
| Estuarine Beach | 114.0 | 92.7 | 67.3 | 43.5 | 28.3 | -18.6 | -41.0 | -61.8 | -75.2 |
| Riverine Tidal | 105.7 | 72.5 | 33.1 | 3.9 | 0.9 | -31.4 | -68.7 | -96.4 | -99.2 |
| Inland Shore | 37.0 | 37.0 | 37.0 | 37.0 | 36.7 | 0.0 | 0.0 | 0.0 | -0.7 |
| Ocean Beach | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | -- | -- | -- | -- |
| Open Ocean | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | -- | -- | -- | -- |
| Developed Dry Land | 3232.2 | -- | -- | -- | -- | -- | -- | -- | -- |
| Flooded Developed Dry Land | 0.0 | -- | -- | -- | -- | -- | -- | -- | -- |

## 3.2 Projected changes in high, low and total marsh acreage

In this section we present results from analyses in which we aggregated the salt marsh SLAMM land use categories into two marsh types:

- **High marsh**: irregularly-flooded marsh and transitional salt marsh[9].
- **Low marsh**: regularly-flooded marsh.

As discussed in Section 1.1, the two marsh types differ in that low marsh areas are flooded daily, while high marshes are inundated by tidal water once per day or less. The SLAMM model assumes that low marsh will be lost to inundation from SLR at a slower rate than high marsh due to positive feedbacks between inundation and accretion (Section 2.2.7.1). For some managers, it is important to distinguish between high and low marsh habitat because there are some differences in the types of ecosystem services each provide (e.g., low marsh provides habitat for mussels and crabs, and high marsh provides critical habitat for the salt marsh sparrow, which is a bird species of conservation concern).

The intent of these additional analyses is to:

- Compare results across marsh types (high marsh, low marsh, total marsh [high plus low])
- Compare results across sites
    - o Which sites are most and least vulnerable to long-term SLR rise and why?
    - o Where are changes in marsh type most likely to occur?
- Compare results across time periods
    - o How much do results vary over time?
    - o Are "tipping points" evident?

Results and maps presented in this section are not typically included in SLAMM reports, and so are a novel application of SLAMM outputs. Our intent is to illustrate the response of salt marshes to SLR so that practitioners can detect important patterns across marsh types, sites and time periods.

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[9] Within SLAMM, initial conditions for irregularly-flooded marshes is that they are primarily composed of "irregularly-flooded estuarine intertidal emergent marsh" based on the National Wetlands Inventory, while "transitional marshes/scrub shrub" are primarily composed of "estuarine intertidal scrub-shrub and forested." Because of this, the starting point of a transitional marsh is more of a woody plant than for high marsh. However, these two classes significantly overlap in terms of their frequency of flooding (their elevation range in relation to the tides.) When SLAMM finds dry land falling into this elevation range, there is significant uncertainty as to whether the new wetland habitat will be an emergent marsh or a woody shrub type. SLAMM generally categorizes these new wetlands as "transitional marsh" as this signifies a land category that has recently transitioned, and the presence of an emergent marsh is undetermined.

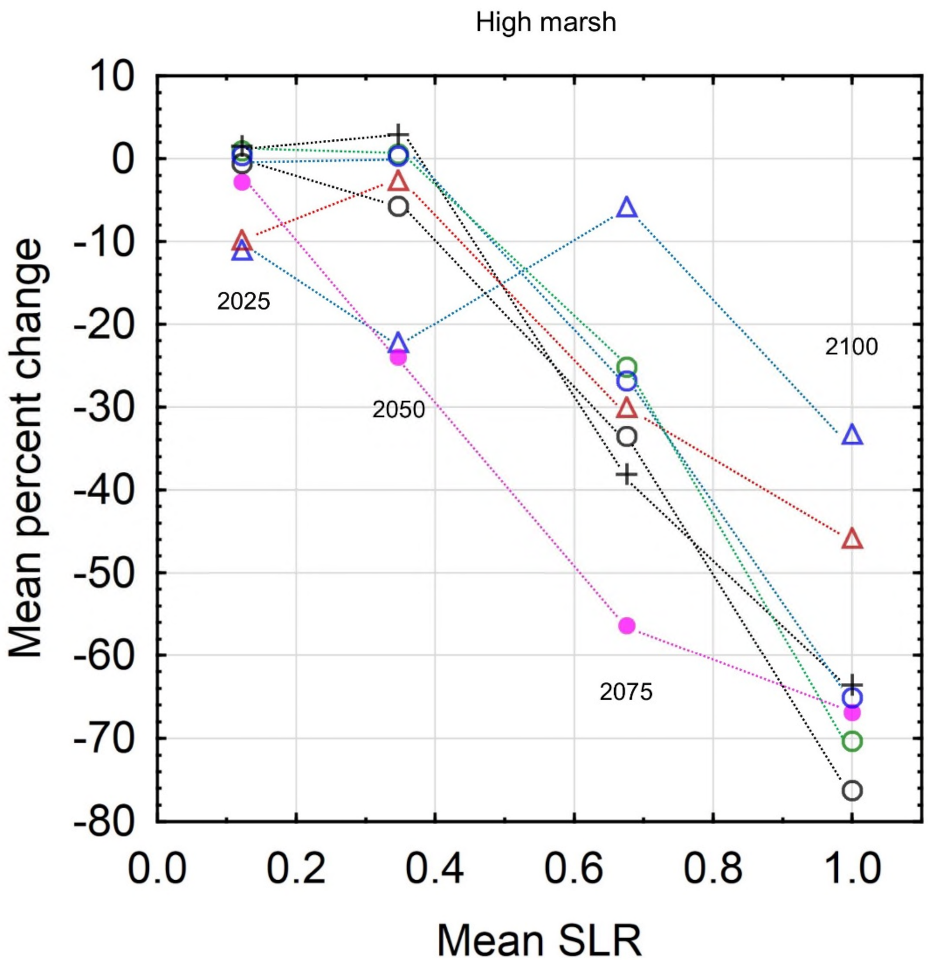
In the sections below, we highlight results for each marsh type. The accompanying scatterplots (Figures 13-15) allow for easy visualization of differences across sites and time periods. The full set of results for each site (including the exact percent gain/loss numbers) can be found in Appendices D-J. This is followed by a section where the results for each marsh type are visualized as gain/loss maps (Figures 16-22), with brief examples of some spatial patterns that could have implications for management decisions.

### 3.2.1 High Marsh

Despite variations in rates among sites and over time, all sites are projected to experience high marsh acreage loss over time (Figure 13). General patterns include:

- 2025 - Broadkill and Mispillion have the highest percent loss (~10%); other sites have < 5%
- 2050 - Dividing and Broadkill have the highest percent loss (20-25%); other sites have < 6%
- 2075 – Dividing has the highest percent loss (56%) and Broadkill has the lowest (6%); the other sites are grouped in-between (25-38%)
- 2100 – Lower Maurice and Dennis overtake Dividing with the highest percent loss (76 and 70% loss, respectively); Dividing, Reeds Beach and St. Jones are close behind (> 60% loss); Broadkill and Mispillion have the lowest percent loss (30-50%).

Note that at all sites but the Broadkill, the percent loss in high marsh acreage increases from 2050 onward. From 2050 to 2075, high marsh acreage is still being lost at the Broadkill, but at a lower rate. This is because the Broadkill has large areas of tidal swamp and low-lying undeveloped dry land that convert to high marsh during this time period. After 2075, these areas of high marsh convert to low marsh, which causes the percent loss of high marsh acreage to increase again.




| Symbol | Site | Acres | | |
|---|---|---|---|---|
| | | Time zero | 2050 | 2100 |
| △ | Broadkill | 3239.7 | 2521.8 | 2161.5 |
| ○ | Dennis | 9152.5 | 9206.5 | 2716.0 |
| ● | Dividing | 5026.6 | 3820.8 | 1665.4 |
| ○ | Maurice | 5225.4 | 4926.7 | 1241.0 |
| △ | Mispillion | 4261.6 | 4152.6 | 2309.7 |
| ○ | Reeds | 3515.5 | 3528.3 | 1226.3 |
| + | St Jones | 1518.8 | 1563.2 | 553.2 |

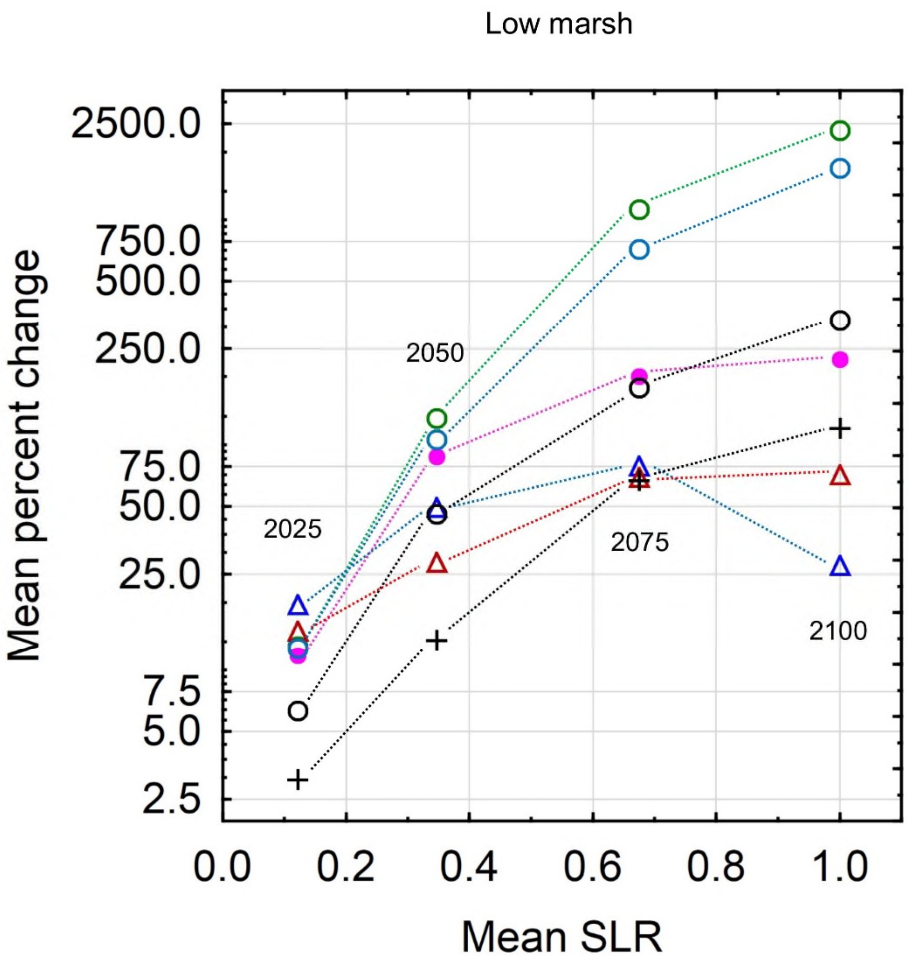
*Figure 13. Scatterplot of mean percent change in high marsh acreage versus mean SLR (across four time steps - 2025, 2050, 2075, 2100), based on the intermediate SLR scenario and "protect dry developed land" modeling scenario. Due to the partial overlap in the Dennis and Reeds monitoring and management units, the acreages for these two sites are not fully independent. For more information about each site, see Appendices D-J.*

### 3.2.2 Low Marsh

Despite variations in rates among sites and over time, all sites are projected to experience low marsh acreage gains over time (Figure 14). General patterns include:

- 2025 - Broadkill has the highest percent gain (18%); St. Jones has the lowest (3%)
- 2050 – Dennis and Reeds Beach have the highest percent increase (123% and 98%, respectively); St. Jones has the lowest (13%)
- 2075 – Dennis and Reeds Beach continue to have the highest percent increase (1042% and 692%, respectively); Broadkill and Mispillion have the lowest (75% and 67%, respectively)
- 2100 – Dennis and Reeds Beach continue to have the highest percent increase (2339% and 1586%, respectively); Broadkill now has the lowest, dropping down to 27%.

Note that at all sites but the Broadkill, the percent gain in low marsh acreage increases over time. From 2075 to 2100, low marsh acreage is still being gained at the Broadkill, but at a lower rate. This is because the Broadkill has large areas of low marsh near the bay that convert to tidal flats.




| Symbol | Site | Acres | | |
|---|---|---|---|---|
| | | Time zero | 2050 | 2100 |
| △ | Broadkill | 3955.8 | 5907.4 | 5036.7 |
| ○ | Dennis | 421.6 | 939.3 | 10282.6 |
| ● | Dividing | 1707.7 | 3121.5 | 5533.0 |
| ○ | Maurice | 1299.5 | 1899.9 | 5638.5 |
| △ | Mispillion | 7165.8 | 9188.7 | 12114.5 |
| ○ | Reeds | 235.0 | 467.0 | 3961.4 |
| + | St Jones | 1865.2 | 2102.1 | 3933.5 |

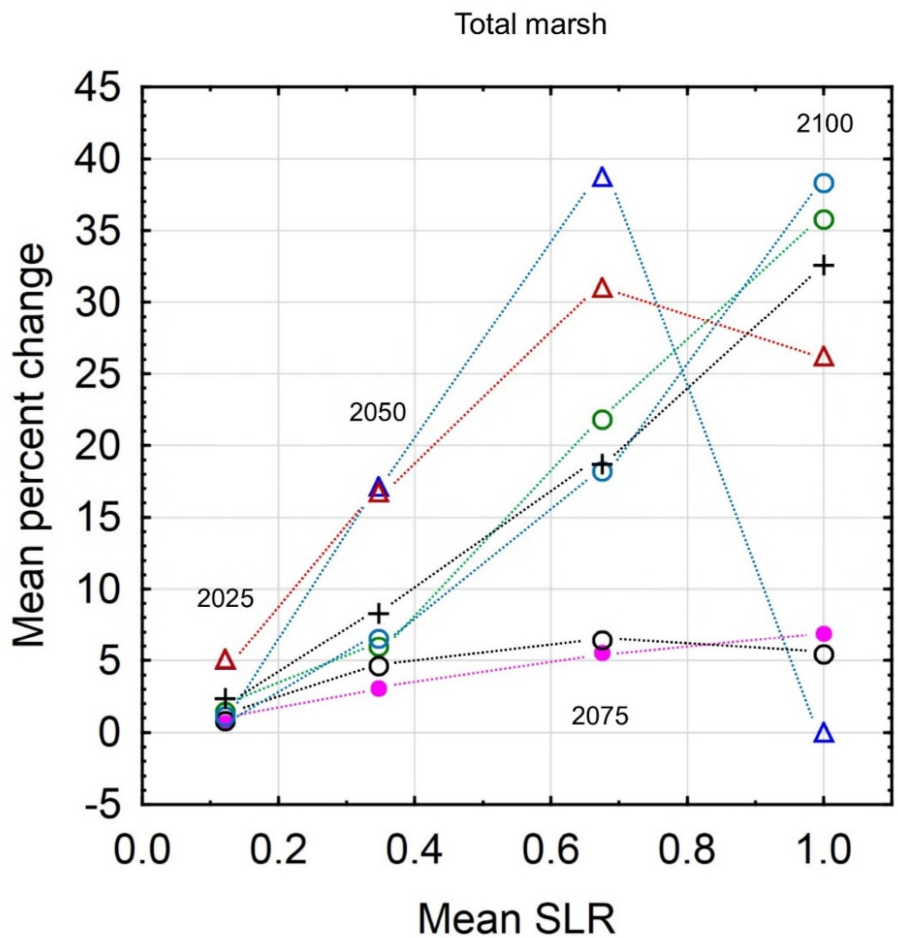
*Figure 14. Scatterplot of mean percent change in low marsh acreage versus mean SLR (across four time steps - 2025, 2050, 2075, 2100), based on the intermediate SLR scenario and "protect dry developed land" modeling scenario. The y-axis has been log-transformed. Due to the partial overlap in the Dennis and Reeds monitoring and management units, the acreages for these two sites are not fully independent. For more information about each site, see Appendices D-J.*

### 3.2.3 Total Marsh

Despite variations in rates among sites and over time, all sites are projected to experience gains in total salt marsh acreage (Figure 15). General patterns include:

- 2025 - Broadkill and Mispillion have the highest percent gain (5%); NJ sites have the lowest percent gain (<2%)
- 2050 – Broadkill and Mispillion continue to have the highest percent gain (17%); NJ sites still have the lowest (<7%)
- 2075 – Broadkill and Mispillion continue to have the highest percent gains (39% and 31%, respectively); Dividing and Lower Maurice have the lowest (<7%)
- 2100 – Broadkill drops to around 0.04%; Dennis, Reeds Beach and Lower St. Jones have the highest percent gains (>30%).

Note that from 2075 to 2100, the Broadkill goes from having the highest percent gains (39%) to the lowest (0.04%; meaning the total marsh acreage at 2100 is about the same as at time zero). The high rate of gains from 2050 to 2075 is driven in part by the conversion of large areas of tidal swamp and undeveloped dry land to high marsh. The drop from 2075 to 2100 is due to the loss of these high marsh areas in combination with the loss of large areas of low marsh near the bay (which convert to tidal flats).




| Symbol | Site | Acres | | |
|---|---|---|---|---|
| | | Time zero | 2050 | 2100 |
| △ | Broadkill | 7195.6 | 8429.2 | 7198.2 |
| ○ | Dennis | 9574.1 | 10145.8 | 12998.6 |
| ● | Dividing | 6734.3 | 6942.3 | 7198.4 |
| ○ | Maurice | 6524.9 | 6826.6 | 6879.5 |
| △ | Mispillion | 11427.5 | 13341.3 | 14424.2 |
| ○ | Reeds | 3750.5 | 3995.3 | 5187.7 |
| + | St Jones | 3384.0 | 3665.2 | 4486.6 |

*Figure 15. Scatterplot of mean percent change in total marsh acreage versus mean SLR (across four time steps - 2025, 2050, 2075, 2100), based on the intermediate SLR scenario and "protect dry developed land" modeling scenario. Due to the partial overlap in the Dennis and Reeds monitoring and management units, the acreages for these two sites are not fully independent. For more information about each site, see Appendices D-J.*

## 3.2.4 Gain/Loss Patterns

Site-specific gain/loss maps (which highlight areas where changes are occurring) are shown in Figures 16-22. Spatial patterns of gains and losses of different marsh types, both within and among sites, could inform management decisions. Such decisions might include where and when to prioritize conservation or restoration efforts, plan for change, or establish long-term monitoring sites to detect whether changes are occurring as projected.

For example, within the Broadkill (DE) site (Figure 16), a noticeable spatial pattern is that significant total marsh losses are projected by 2100 in the southeast portion (due to conversions from low marsh to open water and/or tidal flats); but in the northwest portion, both high and low marsh types are stable or gaining, resulting in an overall increase in total marsh in that area. Depending on the management goal, this pattern may be relevant for decisions about where (or whether) to engage in restoration or conservation activities at different specific locations within the Broadkill site.

Meanwhile, in NJ, the partially overlapping sites of Dennis (Figure 21) and Reeds Beach (Figure 22) show another pattern. They begin as predominantly high marsh at time zero but undergo a dramatic changeover to mostly low marsh by 2100. It may be important to monitor here to determine whether this shift occurs as projected; it is possible that the more frequent inundation of the high marsh habitats will result in peat collapse and direct conversion of high marshes into tidal flats or open water (DeLaune et al. 1994). Either way (successful conversion or not), it would mean major losses of critical habitat for high marsh species. And while total marsh area shows acreage gains, there is some question as to whether flood and erosion control services would be the same with such a different plant community composition.

Finally, at the larger scale, if you compare patterns at the four NJ sites (Figures 19-22) versus the three DE sites (Figures 16-18) (which together encompass a large portion of the Lower Delaware Bay), there are differences that could affect large-scale management of high marsh habitat. In NJ, there is far more high marsh habitat at time zero (20,184 acres) than in DE (9,020 acres) (Figure 13). However, by 2100, losses of high marsh acreage are far more extensive in NJ (loss of 13,982 total acres, down to 6,202 acres) compared to DE (loss of 3,996 total acres, down to 5,025 acres)[10]. If these changes occur as projected, the differential losses of high versus low marsh habitat types between the NJ and DE sides of the bay would change the proportions of critical habitat available for different species, and potentially affect what would be needed to manage target species and services at the regional scale.

Finally, it should be noted that when weighing these or any other potential management considerations, there will be other important decision criteria to consider as well. The type of gain/loss information in this report will need to be analyzed in combination with information on, e.g., the ownership status (private or public) of the marshlands, impacts of projects and marsh loss/migration on property values, and other factors. GIS files with information on land ownership and conservation status are available and can be overlaid onto the SLAMM projections to help inform management decisions.

[10] The Reeds Beach acreage that overlaps with Dennis was excluded from this calculation to avoid double counting.

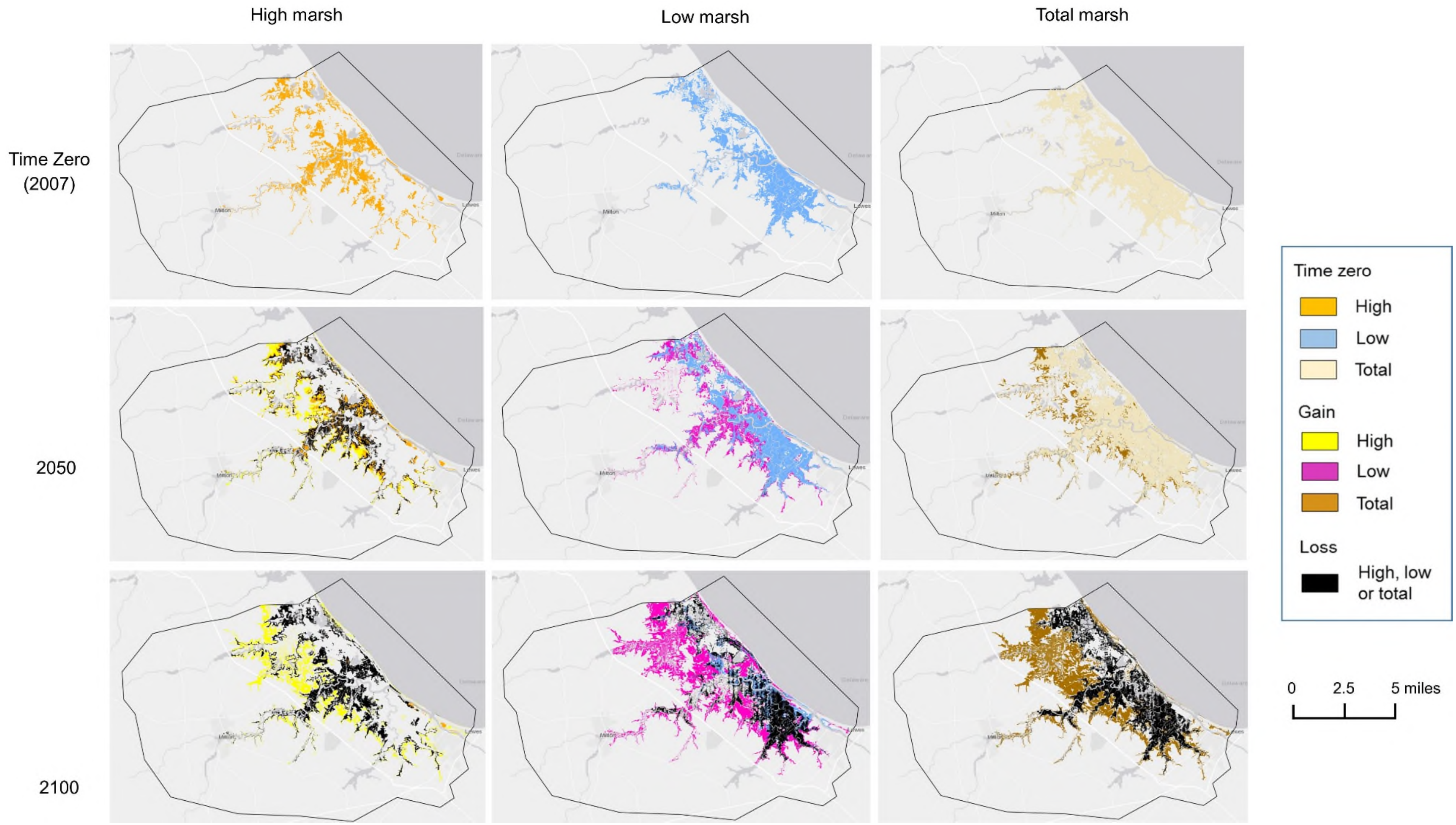


*Figure 16. Gain/loss maps for the Broadkill (DE) site, based on the intermediate SLR scenario and "protect dry developed land" modeling scenario.*

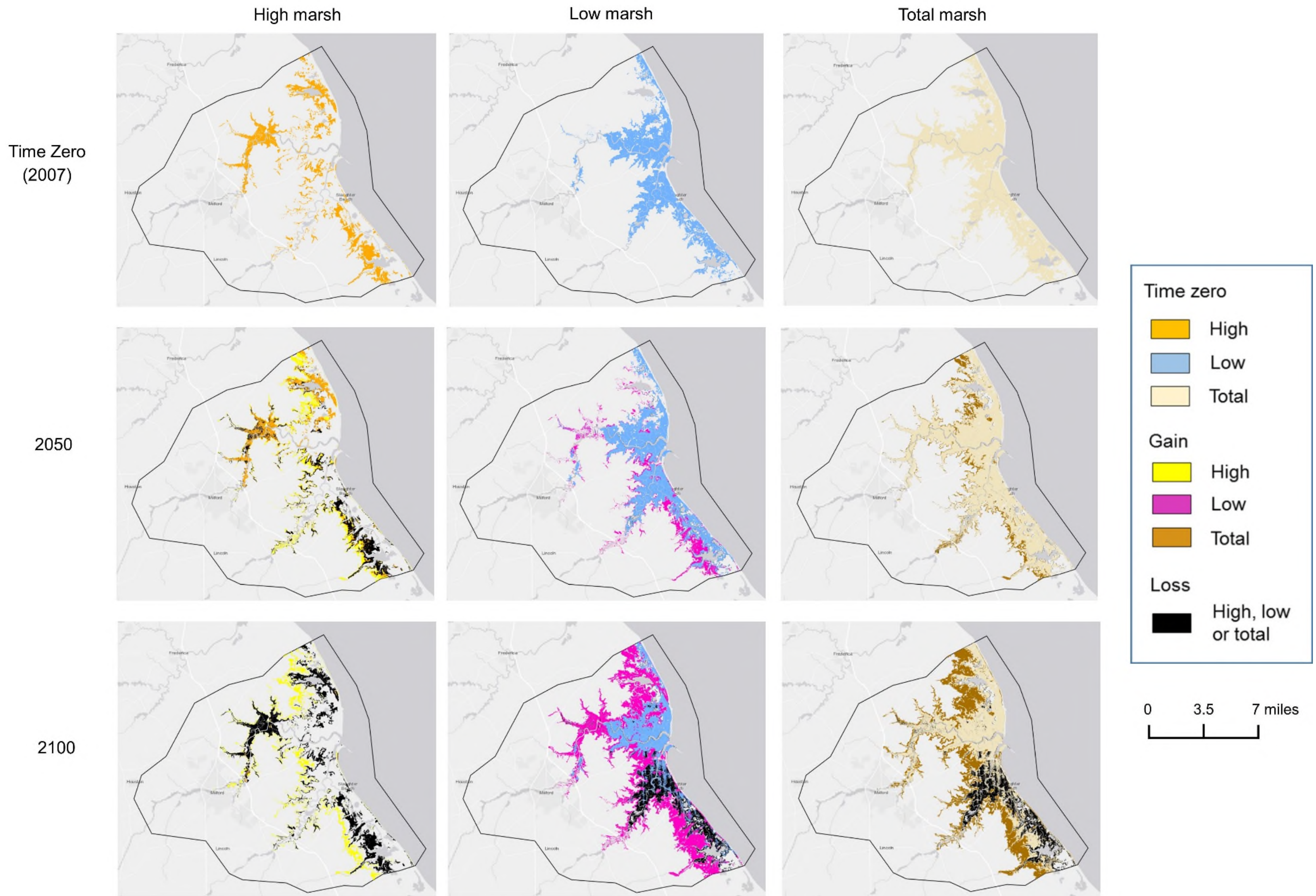



*Figure 17. Gain/loss maps for the Mispillion (DE) site, based on the intermediate SLR scenario and "protect dry developed land" modeling scenario.*

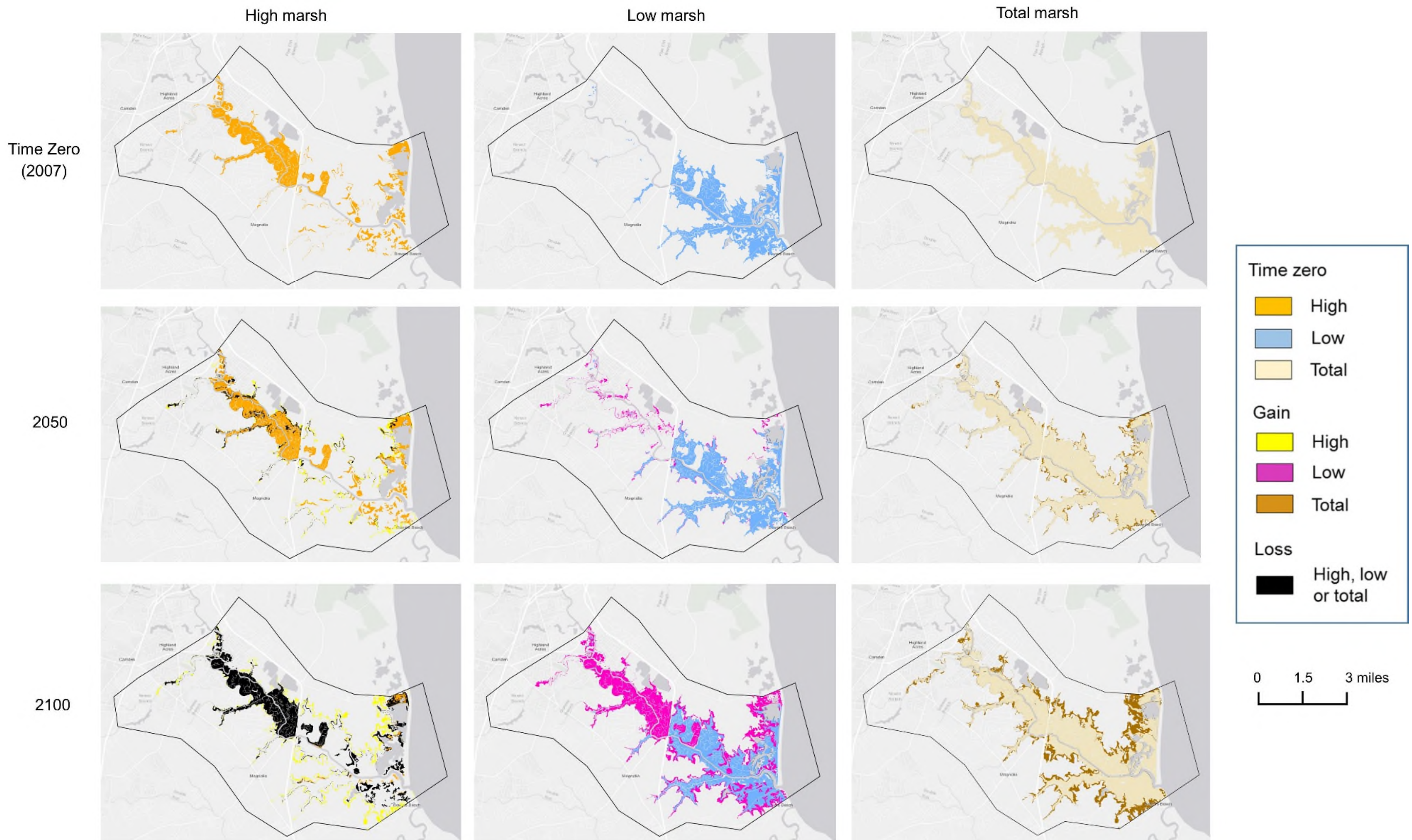



*Figure 18. Gain/loss maps for the Lower St. Jones (DE) site, based on the intermediate SLR scenario and "protect dry developed land" modeling scenario.*

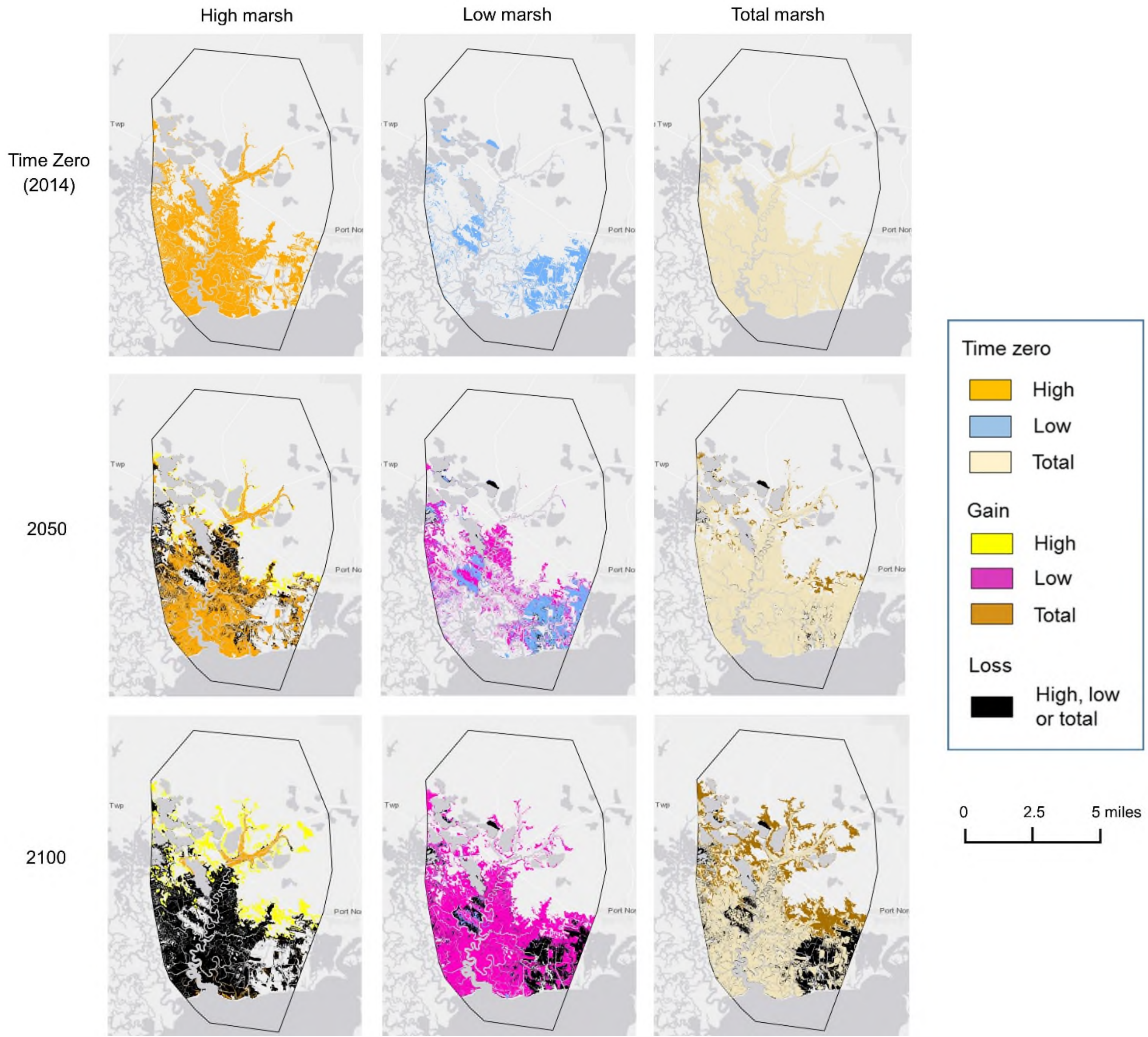



*Figure 19. Gain/loss maps for Dividing (NJ) site, based on the intermediate SLR scenario and "protect dry developed land" modeling scenario.*

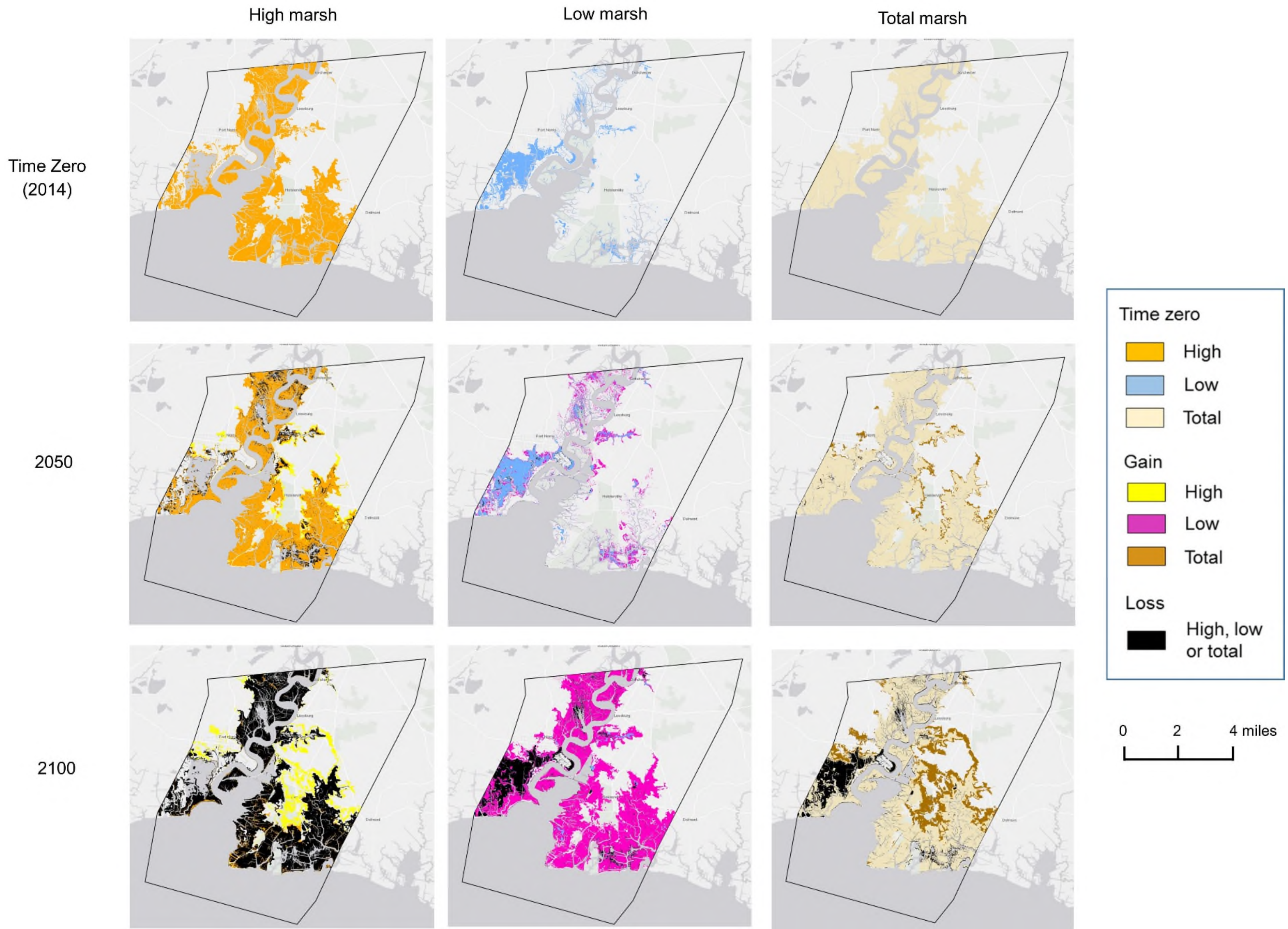


*Figure 20. Gain/loss maps for Lower Maurice (NJ) site, based on the intermediate SLR scenario and "protect dry developed land" modeling scenario.*

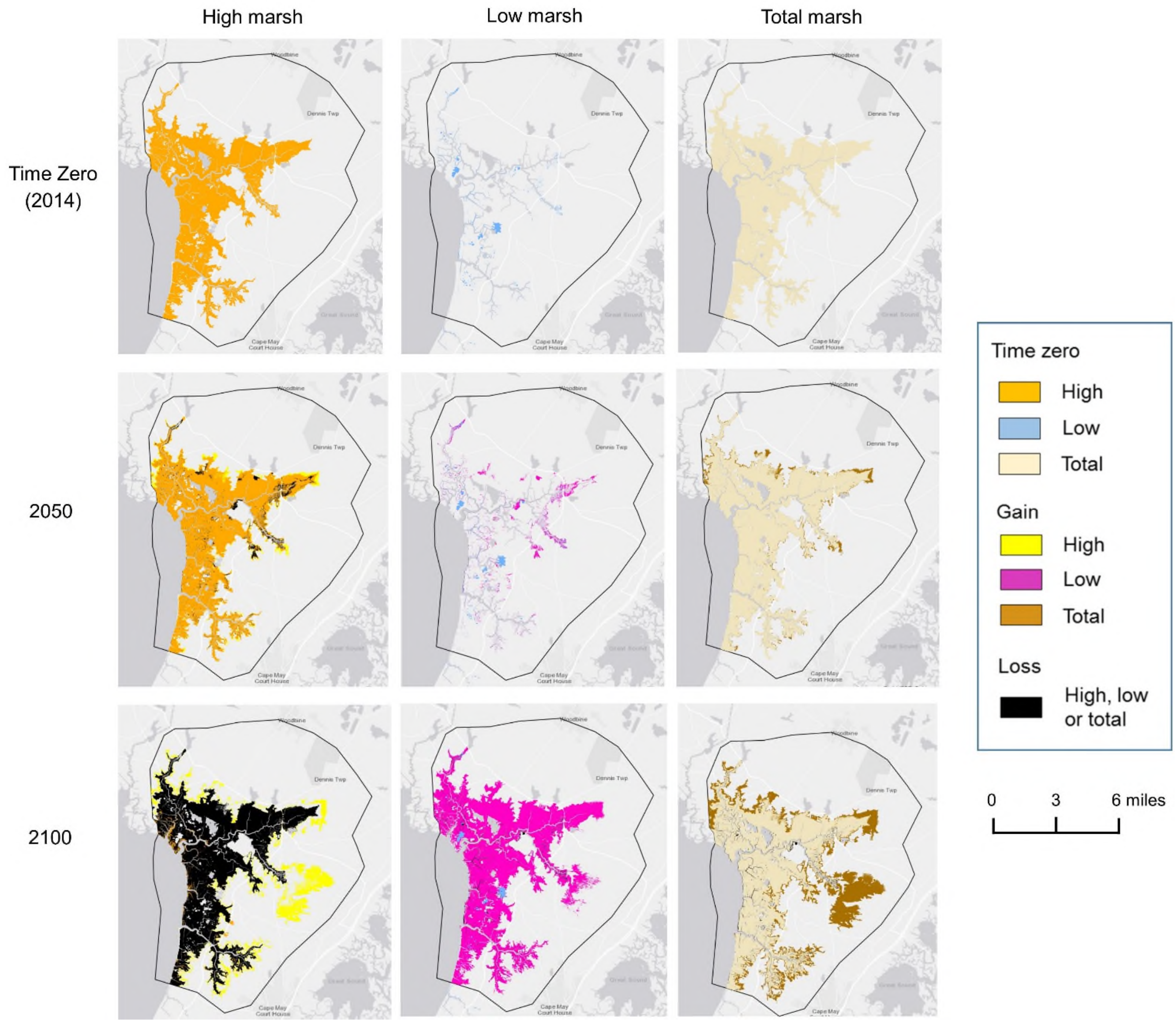


*Figure 21. Gain/loss maps for Dennis (NJ) site, based on the intermediate SLR scenario and "protect dry developed land" modeling scenario.*

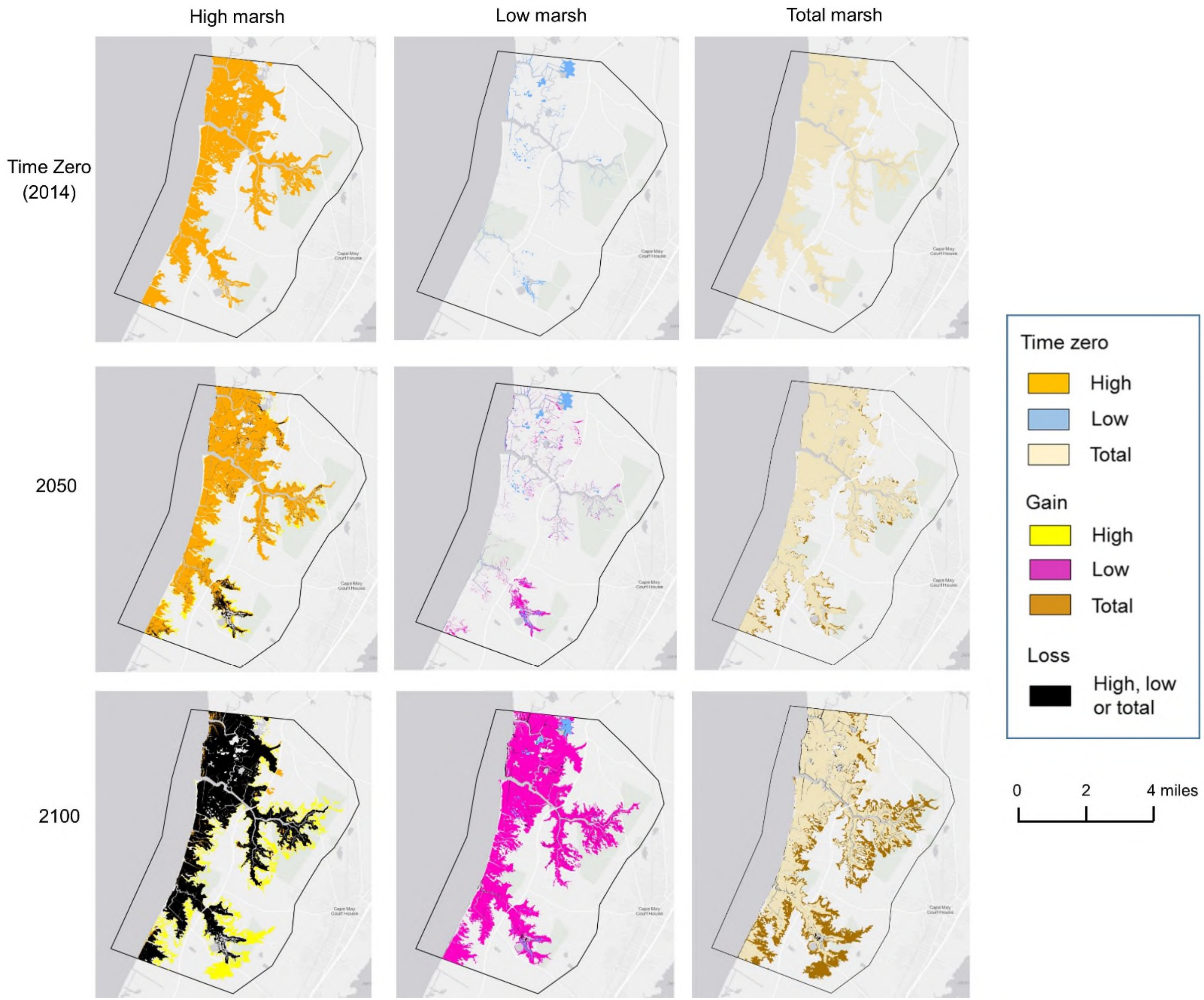



*Figure 22. Gain/loss maps for Reeds Beach (NJ) site, based on the intermediate SLR scenario and "protect dry developed land" modeling scenario.*

## 3.3 Sensitivity Analysis

A sensitivity analysis is "the study of how uncertainty in the output of a model (numerical or otherwise) can be apportioned to different sources of uncertainty in the model input" (Saltelli et al., 2004). Sensitivity analysis therefore clarifies the relationship between model inputs and model outputs to understand the potential impacts of uncertainties in model parameters.

As described in Section 2.5, the sensitivities of high marsh and low marsh to changes in GT, salt elevation, marsh erosion, and regularly- and irregularly-flooded minimum and maximum accretion were evaluated under the intermediate SLR scenario. Table 11 contains a summary of mean, minimum and maximum percent acreage change across sites when each (individual) test variable is increased and decreased by 15% (the mean percent change value represents the average of both directions). Results are presented for three SLAMM land use categories: regularly-flooded marsh (low marsh), irregularly-flooded marsh (high marsh) and transitional salt marsh (high marsh). Appendix K contains more detailed results, including tornado diagrams with visual illustrations of the percentage changes for each site (and each test variable).

Among the tested variables, GT is the dominant factor driving gain and loss of regularly- and irregularly-flooded marshes (which is expected given how the tide range demarcates the boundary between high marsh and low marsh). Salt elevation has greatest impact on transitional salt marsh, followed by GT. The marsh erosion and accretion variables had a much smaller effect (<1%) (Table 11). While this general pattern holds true across sites, the magnitude of change varies (e.g., percent change in acreage of irregularly-flooded marsh driven by GT ranges from 1.4% at Broadkill to 74% at Dennis; Appendix K).

While the results help us better understand the influence of each input variable on the projected changes in salt marsh acreage, they should be interpreted with caution due to limitations associated with the sensitivity analysis, which only considers one variable at a time. In reality, responses are driven by multiple interacting factors. It is also worth noting that, with regard to accretion rates, changing the minimum and maximum accretion rates one at a time does not have a big impact on the generated accretion rate curve (Table 11). The SLAMM model is generally sensitive to accretion rates (Chu-Agor et al. 2011), so if an overall multiplier[11] was available (across the range of accretion rates simulated, versus only the minimum and maximum), this would have had a larger effect on model outputs.

In addition to performing the sensitivity analysis, we also did cross-site comparisons of key variables that are known to affect the vulnerability of sites to SLR. Our intent was to gain a better understanding of reasons behind the differences in projected changes across sites (which could potentially help inform management strategies; for example, living shorelines could potentially be an effective tactic for sites with high erosion rates, thin-layer sediment applications could potentially enhance low elevation sites, etc.). We compared tide range, salt elevation, marsh erosion rate, elevation change rate (based on site-specific SET data) and elevation data. Results suggest that the following characteristics may contribute

[11] Multipliers, which are based on distribution values, may be used to assist with modifying variables that may be spread out over multiple subsites. In other words, if accretion rates are assumed to increase by 10% they increase by 10% over all subsites simultaneously.

to differences in relative vulnerabilities across sites: Dividing – low mean elevation, higher tide range; Broadkill - low mean elevation; Dennis - lowest elevation change rate; Reeds Beach - highest marsh erosion rate; NJ sites – higher subsidence rates (Table 12).

*Table 11. Summary of results from the sensitivity analysis. Values represent the mean, minimum and maximum percent acreage change across sites when each (individual) test variable is increased and decreased by 15%. Accr. = accretion. Rows highlighted in orange have the largest effect (darker = more, lighter = less).*

| Marsh type | Variable | % Acreage change | | |
|---|---|---|---|---|
| | | **Mean** | **Minimum** | **Maximum** |
| Regularly flooded marsh | GT Great Diurnal Tide Range | 8.75 | 3.20 | 14.70 |
| | Salt Elevation | 1.94 | 1.20 | 2.70 |
| | Marsh Erosion | 0.35 | 0.10 | 0.90 |
| | Mean Reg Flood Max. Accr. | 0.54 | 0.20 | 1.30 |
| | Mean Reg Flood Min. Accr. | 0.30 | 0.10 | 0.90 |
| | Mean Irreg Flood Max. Accr. | 0.43 | 0.20 | 1.10 |
| | Mean Irreg Flood Min. Accr. | 0.48 | 0.20 | 1.50 |
| Irregularly flooded marsh | GT Great Diurnal Tide Range | 32.47 | 1.40 | 74.25 |
| | Salt Elevation | 2.96 | 0.20 | 8.81 |
| | Marsh Erosion | 0.33 | 0.10 | 0.70 |
| | Mean Reg Flood Max. Accr. | 0.53 | 0.00 | 0.86 |
| | Mean Reg Flood Min. Accr. | 0.23 | 0.00 | 0.40 |
| | Mean Irreg Flood Max. Accr. | 0.32 | 0.10 | 0.50 |
| | Mean Irreg Flood Min. Accr. | 0.40 | 0.10 | 0.54 |
| Transitional salt marsh | GT Great Diurnal Tide Range | 17.00 | 12.40 | 22.80 |
| | Salt Elevation | 34.62 | 20.00 | 49.39 |
| | Marsh Erosion | 0.06 | 0.00 | 0.10 |
| | Mean Reg Flood Max. Accr. | 0.06 | 0.00 | 0.10 |
| | Mean Reg Flood Min. Accr. | 0.02 | 0.00 | 0.10 |
| | Mean Irreg Flood Max. Accr. | 0.06 | 0.00 | 0.20 |
| | Mean Irreg Flood Min. Accr. | 0.08 | 0.00 | 0.20 |

*Table 12. Principal factors affecting vulnerability to SLR (tide range, salt elevation, erosion, accretion, elevation).*

| Sites | Historic Relative SLR Trend* (mm/yr) | Great Diurnal Tide Range (m) | Salt elevation (m above MTL) | Marsh Erosion (horz. m /yr) | SET elevation change (mm/yr) – mean (min to max) | | Elevation (m) – mean ± st dev | |
|---|---|---|---|---|---|---|---|---|
| | | | | | High marsh | Low marsh | High marsh | Low marsh |
| Broadkill (DE) | 3.4 | 1.42 | 1.04 | 0.12 | -- | 5.42 (4.1 to 6.2) | 0.405 ± 0.26 | 0.244 ± 0.21 |
| Mispillion (DE) | 3.4 | 1.81 | 1.1 | 0.56 | -- | -- | 0.672 ± 0.24 | 0.461 ± 0.27 |
| St. Jones (DE) | 3.4 | 1.81 | 1.18 | 0.31 | 3.13 (NA) | 4.54 (3.0 to 6.1) | 0.805 ± 0.23 | 0.972 ± 0.17 |
| Dennis (NJ) | 3.8 | 1.92 | 1.21 | 0.44 | 1.87 (-1.5 to 5.2) | -- | 0.810 ± 0.17 | 0.337 ± 0.38 |
| Reeds (NJ) | 3.8 | 1.92 | 1.21 | 1.34 | -- | -- | 0.809 ± 0.18 | 0.399 ± 0.40 |
| Dividing (NJ) | 3.8 | 1.96 | 1.22 | 0.43 | 4.61 (2.2 to 6.7) | -- | 0.689 ± 0.20 | 0.033 ± 0.39 |
| Maurice (NJ) | 3.8 | 1.96 | 1.22 | 0.42 | 4.97 (1.3 to 9.3) | -- | 0.833 ± 0.23 | 0.008 ± 0.41 |

*VLM rates were applied to the historic eustatic trend (1.7mm/yr) (Section 2.2.4)

# 4 CONCLUSIONS

SLAMM was used to project potential responses of seven sites in the Lower Delaware Bay to accelerated SLR. This study combined the best available elevation data with tidal data and site-specific accretion and erosion rates. We examined three SLR scenarios (low = 0.3 m by 2100, intermediate = 1 m by 2100, and high = 2 m by 2100) and found the salt marshes to be increasingly vulnerable to the effects of SLR as the rate of SLR was increased, as evidenced by conversion to different habitat types.

The SLAMM simulations projected that all sites will experience loss of high marsh acreage by late century. The high marsh habitats are projected to be lost at a faster rate than low marsh habitats, largely because high marshes are assumed to have lower accretion rates (since they are inundated less and collect less sediment). Additionally, high marsh plants (*Spartina patens, Distichlis spicata*) are less tolerant of changes to inundation frequency compared to the low marsh dominant, *Spartina alterniflora* (Naidoo et al. 1992), which suggests that high marshes will likely be disproportionately impacted by more frequent inundation compared to low marsh habitats. The Broadkill and Mispillion sites in DE are projected to experience the highest percent loss of high marsh acreage by 2025 (around 10%), likely due in part to low elevations (on average, the elevation of high marsh habitats at these two sites is lower than at other sites). By 2075, six of the seven sites are projected to lose over 20% of their high marsh acreage. Projected losses in high marsh are even more extreme under the high SLR scenario. Under this scenario, the large areas of high marsh in NJ (which has higher rates of vertical land movement and subsidence than DE) are projected to convert to low marsh by 2050 or 2075 (and then tidal flats or open water by 2100). Opportunities for landward migration of high marsh will likely be limited due to development and terrain (steep slopes).

Low marsh acreage change shows a contrary pattern to high marsh, with projections of overall gains. SLAMM assumes that low marsh has higher accretion rates than high marsh (and thus a higher likelihood of building elevation and keeping pace with SLR) because low marsh habitats are inundated more frequently and collect more sediment. While these overall gains may seem favorable, certain low marsh areas are projected to be lost as early as mid-century (particularly near the bay and river channels). Although these areas are relatively small compared to the areas of gains, some of these low marshes may be highly valued for crab or mussel habitat, flood protection or recreation. Thus, it is important to consider location and not just overall percent change.

The SLAMM simulations project varying rates of change across sites, time periods and SLR scenarios, which is not unexpected due to the unique characteristics of each site. For example, the Broadkill (DE) site has a large tidal swamp that is projected to convert to high marsh at a time when the other sites are mostly projected to experience high marsh losses. The Broadkill also has a low marsh area along the bay that is at a lower elevation than most other sites, which partly explains why it is projected to convert to tidal flat sooner than low marsh areas at other sites. While patterns may vary in part due to these unique characteristics, the sensitivity analysis shows that similar factors drive the patterns across sites (the two most dominant driving factors being great diurnal tide range and salt elevation).

One of the factors that affects the outcome of the SLAMM simulations is the selection of the model protection scenario (Section 2.3.1). In the main report, we only present results from the "Protect

Developed Dry Land" scenario (which our work group felt was most likely), where cells designated as developed dry land were protected from inundation and could not be converted to salt marsh habitats in the simulations. If protections are extended to include undeveloped dry land as well (the "Protect All Dry Land" scenario), there are substantial reductions in the percent of regularly-flooded and transitional salt marsh acreage at certain sites by late century (Appendix L). The DE sites, which have large areas of low-lying undeveloped dry land bordering the salt marshes, are particularly affected by this change. This type of examination of marsh migration potential shows how management and human activities can affect outcomes. The gain/loss maps in Section 3.2 highlight the areas in the Lower Delaware Bay that are most likely to be affected and can help inform decisions about trade-offs between restricting marsh movement and potential loss of ecosystem services.

It is possible that the projections for the Broadkill (DE) and Mispillion (DE) sites may over-predict flooding frequency in certain areas. These two sites are difficult to accurately model because they are influenced by barriers/dunes along the coast and have also been highly modified. In recent years, a large restoration project has been underway in the Prime Hook National Wildlife Refuge (which covers portions of both sites), where some of the marsh areas behind the barrier/dunes have significantly subsided due to many years of impoundments. There may also be dikes or flow alterations affecting these sites that are not currently accounted for in the GIS layers. All sites in the study area are affected to some degree by anthropogenic landscape alterations, which are contributing to the ongoing loss of coastal wetlands. In the Delaware Estuary, known sources of disturbance include conversion of wetlands to agricultural and other land uses, mosquito control ditching, incremental filling, hydrological alterations such as dredging, nutrient enrichment and spread of invasive species (Haaf et al. 2015, USEPA 2015, Haaf et al. 2017).

In considering these results, it is important to bear in mind some limitations of the study. As discussed earlier in the report, there are limitations with SLAMM itself, as well as with some of the input data. For example, anthropogenic changes such as beach nourishment, shoreline armoring and levee construction are not included in the simulations presented here. Another consideration is that SLAMM projects that high marsh habitat that is regularly flooded will successfully convert into a viable low marsh habitat. In some cases, it is possible that the more frequent inundation of the high marsh habitats will result in peat collapse and direct conversion of high marshes into tidal flats or open water (DeLaune et al. 1994). Given that changes in inundation frequency can be injurious to marsh habitats, the projections from this model application can be considered optimistic.

Our study also exposed some data gaps and research needs. Tide range, salt elevation and wetland elevation-change rates are critical input parameters for SLAMM. While tide range and Surface Elevation Table (SET) data do exist for this project, it would be helpful to have more localized tide range data (as the NOAA buoys were not located at any of the study sites), especially since tide range and salt elevation emerged as very important input variables in the sensitivity analysis. It would also be helpful to have more SET data, particularly in low marsh habitats. Strategically placed SET stations across the region would help improve studies like ours and would also have importance for regional coastal wetland vulnerability assessments and predictive ecological models (Osland et al. 2017).

The SET data that we analyzed in this study showed that accretion/elevation change data are highly variable, sometimes even at the same site. Thus, it is fair to say that there is considerable uncertainty in the precision of the accretion inputs that were used for this project. As a potential follow-up to this project, the confidence of model results could be evaluated and quantified using the built-in SLAMM uncertainty-analysis module. Using Monte-Carlo simulations, the SLAMM model can be run iteratively, with model inputs randomly drawn from distributions representing input uncertainty. Each model realization represents one possible “future” for the studied area. All model realizations are then assembled into probability distributions of wetland coverage reflecting the effect of input data/model uncertainties on prediction results. When uncertainty-analysis is incorporated, the relative simplicity of the SLAMM model becomes a useful compromise that allows for an efficient characterization of uncertainties without excessive computational time. In addition, all model uncertainties can be summarized in a single map such as the “percent likelihood of a coastal marsh” for each modeled cell at a given date. In this manner, a complex uncertainty analysis can actually simplify the presentation of model results.

Even taking these limitations into account, the results of this report have both immediate and longer-term applications. The current modeling provides a set of maps and numerical results for examining which dry lands and wetlands are expected to be most vulnerable to SLR and in what timeframe. As demonstrated in Section 3.2.4, outputs like the gain/loss maps can be used to help facilitate the evaluation of wetlands and land-management decisions given the likely threat of accelerated SLR in this region. Results can also be used to inform monitoring strategies. For example, long-term monitoring sites could be established in areas projected to be “transitional”, which would enable researchers to track whether changes are occurring as projected (e.g., is high marsh converting to low marsh as projected, or is it converting directly to open water, and is high marsh migrating into freshwater swamp areas as projected?). In addition, it will also be important for researchers to track how the changes in high and low marsh dynamics are affecting ecosystem services and the protective capacity of the marsh area. It is our hope that the vulnerabilities to SLR identified by the SLAMM projections in this report, when considered in the context of management objectives for target services, can support robust analysis and design of effective adaptation practices for protecting, restoring and/or enabling migration of valued salt marsh ecosystems.

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