Application of the Sea-Level Affecting Marshes Model (SLAMM 6) to Elizabeth A. Morton NWR

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Introduction

Tidal marshes are among the most susceptible ecosystems to climate change, especially accelerated sea level rise (SLR). The Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) suggested that global sea level will increase by approximately 30 cm to 100 cm by 2100 (IPCC 2001). Rahmstorf (2007) suggests that this range may be too conservative and that the feasible range by 2100 is 50 to 140 cm. Rising sea levels may result in tidal marsh submergence (Moorhead and Brinson 1995) and habitat "migration" as salt marshes transgress landward and replace tidal freshwater and irregularly-flooded marsh (Park et al. 1991).

In an effort to plan for and potentially mitigate the effects of sea-level rise on the U.S. National Wildlife Refuge System (Refuge System), the U. S. Fish and Wildlife Service (FWS) uses a variety of analytical approaches, most notably the SLAMM model. FWS conducts some SLAMM analysis in-house and, more commonly, contracts the application of the SLAMM model. In most cases Refuge System SLAMM analyses are designed to assist in the development of comprehensive conservation plans (CCPs), land acquisition plans, habitat management plans, and other land and resource management plans.

This is the second application of SLAMM to Elizabeth A. Morton (henceforth referred to as Morton) NWR. The first application of SLAMM to the refuge, carried out in 2008, did not include LiDAR-derived elevation data instead the digital elevation map (DEM) was derived from a 1956 survey. The wetland layer used for the previous project was from the National Wetlands Inventory from 1994. The cell size for that project was 30 meters.

To improve the SLAMM projections for the Morton NWR, data from the refuge was parsed from a larger study of the New York coast, funded by the New York State Energy Research and Development Authority. This application of SLAMM incorporated the most up-to-date wetland layers and LiDAR-derived elevation data layers that were hydrologically enforced to ensure accurate water paths through culverts and under bridges. An extensive tide-range database and mechanistic models of marsh accretion were used. Across the study area, the SLAMM model was spatially calibrated with regard to tidal parameters and inundation heights. The SLAMM application report prepared for NYSERDA is available at http://www.nyserda.ny.gov/-/media/Files/Publications/Research/Environmental/SLAMM%20report.pdf

The NYSERDA study area was divided into five individual SLAMM projects, as shown in Figure 1. Morton NWR is located in the Suffolk East project.

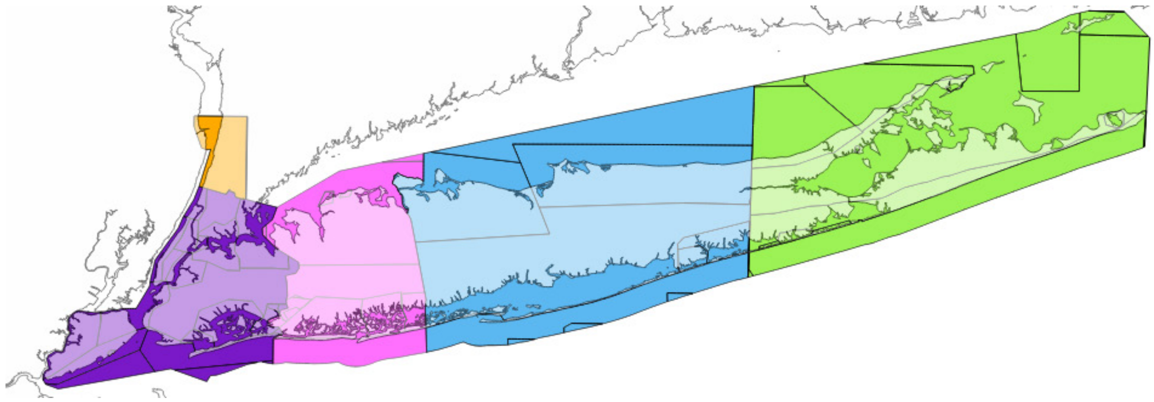


Figure 1. Project study area as broken into five individual SLAMM projects. Orange = Hudson, purple = NYC, pink = Nassau, blue = Suffolk West, green = Suffolk East.

Model Summary

Changes in tidal marsh area and habitat type in response to sea-level rise were modeled using the Sea Level Affecting Marshes Model (SLAMM 6) that accounts for the dominant processes involved in wetland conversion and shoreline modifications during long-term sea level rise (Park et al. 1989; www.warrenpinnacle.com/prof/SLAMM).

Successive versions of the model have been used to estimate the impacts of sea level rise on the coasts of the U.S. (Titus et al. 1991; Lee et al. 1992; Park et al. 1993; Galbraith et al. 2002; National Wildlife Federation & Florida Wildlife Federation 2006; Glick et al. 2007; Craft et al. 2009).

Within SLAMM, there are five primary processes that affect wetland fate under different scenarios of sea-level rise:

- **Inundation:** The rise of water levels and the salt boundary are tracked by reducing elevations of each cell as sea levels rise, thus keeping mean tide level (MTL) constant at zero. The effects on each cell are calculated based on the minimum elevation and slope of that cell.
- **Erosion:** Erosion is triggered based on a threshold of maximum fetch and the proximity of the marsh to estuarine water or open ocean. When these conditions are met, horizontal erosion occurs at a rate based on site- specific data.
- **Overwash:** Barrier islands of under 500 meters (m) width are assumed to undergo overwash during each specified interval for large storms. Beach migration and transport of sediments are calculated. Overwash due to large storms was included in this model application.
- **Saturation:** Coastal swamps and fresh marshes can migrate onto adjacent uplands as a response of the fresh water table to rising sea level close to the coast. Soil saturation was not included in these simulations.

- **Accretion:** Sea level rise is offset by sedimentation and vertical accretion using average or site-specific values for each wetland category. Accretion rates may be spatially variable within a given model domain and can be specified to respond to feedbacks such as frequency of flooding.

SLAMM Version 6.0 was developed in 2008/2009 and is based on SLAMM 5. SLAMM 6.0 provides backwards compatibility to SLAMM 5, that is, SLAMM 5 results can be replicated in SLAMM 6. However, SLAMM 6 also provides several optional capabilities.

- Accretion Feedback Component: Feedbacks based on wetland elevation, distance to channel, and salinity may be specified. This feedback is used where adequate data exist for parameterization.
- Salinity Model: Multiple time-variable freshwater flows may be specified. Salinity is estimated and mapped at MLLW, MHHW, and MTL. Habitat switching may be specified as a function of salinity. This optional sub-model is not utilized in USFWS simulations.
- Integrated Elevation Analysis: SLAMM will summarize site-specific categorized elevation ranges for wetlands as derived from LiDAR data or other high-resolution data sets. This functionality is used in USFWS simulations to test the SLAMM conceptual model at each site. The causes of any discrepancies are then tracked down and reported on within the model application report.
- Flexible Elevation Ranges for land categories: If site-specific data indicate that wetland elevation ranges are outside of SLAMM defaults, a different range may be specified within the interface. In USFWS simulations, the use of values outside of SLAMM defaults is rarely utilized. If such a change is made, the change and the reason for it are fully documented within the model application reports.
- Many other graphic user interface and memory management improvements are also part of the new version including an updated *Technical Documentation*, and context sensitive help files.

For a thorough accounting of SLAMM model processes and the underlying assumptions and equations, please see the SLAMM 6.0 *Technical Documentation* (Clough et al. 2010). This document is available at http://warrenpinnacle.com/prof/SLAMM

All model results are subject to uncertainty due to limitations in input data, incomplete knowledge about factors that control the behavior of the system being modeled, and simplifications of the system (Council for Regulatory Environmental Modeling 2008). Site-specific factors that increase or decrease model uncertainty may be covered in the *Discussion* section of this report.

Sea Level Rise Scenarios

Some SLAMM 6 predictions are obtained using SLR estimates from the Special Report on Emissions Scenarios (SRES) published by the Intergovernmental Panel on Climate Change (IPCC). All IPCC scenarios describe futures that are generally more affluent than today and span a wide range of future levels of economic activity, with gross world product rising to 10 times today's values by 2100 in the lowest, to 26-fold in the highest scenarios (IPCC 2007). Among the IPCC families of scenarios, two approaches were used, one that made harmonized assumptions about global population, economic growth, and final energy use, and those with an alternative approach to quantification. This is important to keep in mind as not all of the IPCC scenarios share common assumptions regarding the driving forces of climate change.

In this model application, the A1B scenario mean and maximum predictions are applied. Important assumptions were made in this scenario: reduction in the dispersion of income levels across economies (i.e. economic convergence), capacity building, increased cultural and social interactions among nations, and a substantial reduction in regional differences in per capita income, primarily from the economic growth of nations with increasing income (Nakicenovic et al. 2000). In addition, the A1 family of scenarios assumes that the future world includes rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Given today's global economic and political climate, as well as environmental and ecological constraints, these may not be feasible assumptions for the future.

In particular, the A1B scenario assumes that energy sources will be balanced across all sources, with an increase in use of renewable energy sources coupled with a reduced reliance on fossil fuels (Nakicenovic et al. 2000). Given this A1B scenario, the IPCC WGI Fourth Assessment Report (IPCC 2007) suggests a likely range of 0.21 m to 0.48 m of SLR by 2090-2099 "excluding future rapid dynamical changes in ice flow." The IPCC-produced A1B-mean scenario that was run as a part of this project falls near the middle of this estimated range, predicting 0.39 m of global SLR by 2100. A1B-maximum predicts 0.69 m of global SLR by 2100. However, other scientists using the same set of economic growth scenarios have produced much higher estimates of SLR as discussed below.

Recent literature (Chen et al. 2006; Monaghan et al. 2006) indicates that eustatic sea level rise is progressing more rapidly than was previously assumed. This underestimation may be due to the dynamic changes in ice flow omitted within the IPCC report's calculations, and a consequence of overestimating the possibilities for future reductions in greenhouse gas emissions while concurrently striving for economic growth.

A recent paper in the journal *Science* (Rahmstorf 2007) suggests that, taking into account possible model error, a feasible range of 50 to 140 cm by 2100. This work was recently updated and the ranges were increased to 75 to 190 cm (Vermeer and Rahmstorf 2009). Pfeffer et al. (2008) suggests that 2 m by 2100 is at the upper end of plausible scenarios due to physical limitations on glaciological conditions. A recent US intergovernmental report states "Although no ice-sheet model is currently capable of capturing the glacier speedups in Antarctica or Greenland that have been observed over the last decade, including these processes in models will very likely show that IPCC AR4 projected SLRs for the end of the 21st century are too low" (Clark 2009). A recent paper by

Grinsted et al. (2009) states that "sea level 2090-2099 is projected to be 0.9 to 1.3 m for the A1B scenario…" Grinsted also states that there is a "low probability" that SLR will match the lower IPCC estimates.

The variability of SLR predictions presented in the scientific literature illustrates the significant amount of uncertainty in estimating future SLR. Much of the uncertainty may be due to the unknown future of the drivers climate change, such as fossil fuel consumption and the scale of human enterprise. In order to account for these uncertainties, and to better reflect these uncertainties as well as recently published peer-reviewed measurements and projections of SLR as noted above, SLAMM was run not only assuming A1B-mean and A1B-maximum SLR scenarios, but also for 1 m, 1.5 m, and 2 m of eustatic SLR by the year 2100 as shown in Figure 2.

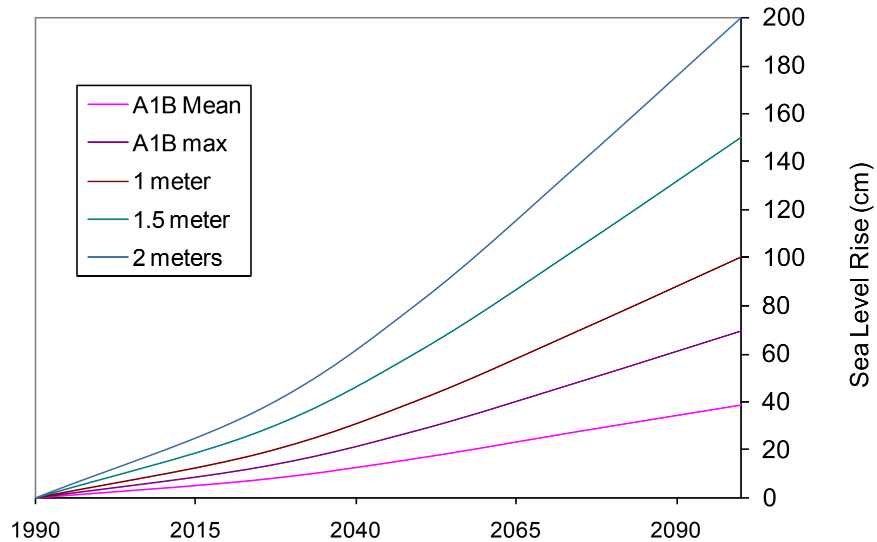


Figure 2. Summary of SLR scenarios utilized.

Data Sources and Methods

This section describes the set-up of the SLAMM model for Morton NWR, which was carried out for a project funded by NYSERDA for the entirety of the Long Island coast. Further details regarding that project and the methods summarized here can be found in the SLAMM application report prepared for NYSERDA: http://www.nyserda.ny.gov/-/media/Files/Publications/Research/Environmental/SLAMM%20report.pdf

Wetland layer.

Table 1 shows the most recent available wetland layer derived from National Wetland Inventory (NWI) survey dated 2004. Converting the surveys into 5 m x 5 m cells indicated that the approximately 178 acre refuge (approved acquisition boundary including water) is composed of the following categories:

Table 1. Land Cover in Study Area

Land cover type		Area (acres)	Percentage
	Undeveloped Dry Land	113.3	63.8%
	Estuarine Beach	31.5	17.8%
	Irreg.-Flooded Marsh	18.3	10.3%
	Estuarine Open Water	13.1	7.4%
	Inland Open Water	0.6	0.4%
	Inland-Fresh Marsh	0.5	0.3%
	Swamp	0.1	0.1%
	Total (incl. water)	**178**	**100.0%**

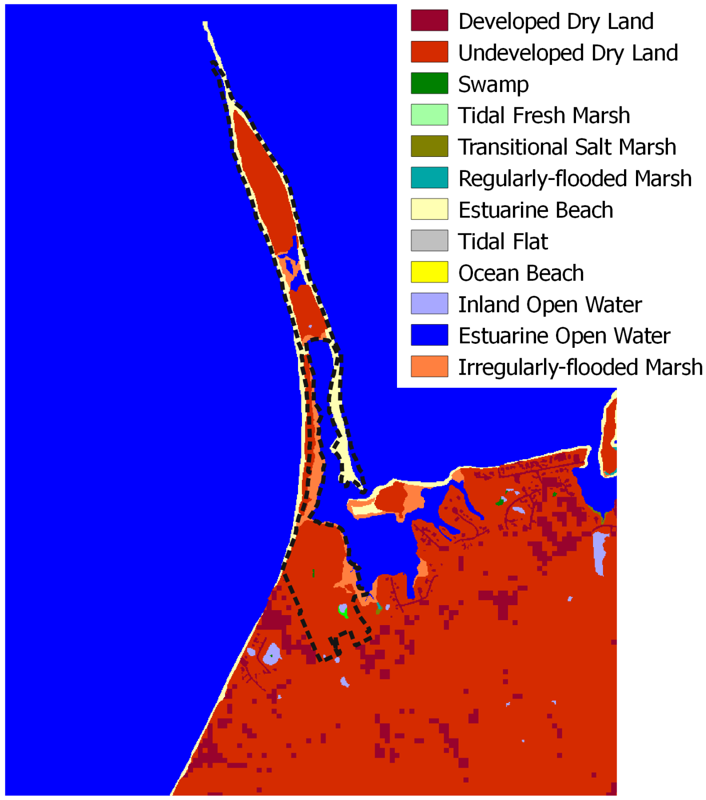


Figure 3. Morton NWR Approved Acquisition Boundary.

Percent Impervious. Impervious surface data describe artificial surfaces and structures through which water cannot penetrate. As such, they are representative of developed lands. In SLAMM, if a dry-land cell is more than 25% covered by artificial impervious surfaces it is assumed to be developed-dry land. Percent impervious rasters were derived from two separate impervious-surface vector layers created by the University of Vermont Spatial Analysis Lab (UVM).
For the Long Island and Hudson regions, the impervious data received from UVM was initially a vector layer of areas mapped as either pervious or impervious. The vector data was converted to a raster with 1 m cell resolution and then re-sampled to a 5 m cell size. The areas of the twenty five 1 m cells within each new 5 m cell were summed to calculate percent impervious for the 5 m cell size.

Elevation Data. The elevation layer covering the study area is based on 2011-2012 New York LiDAR data. These elevation data were hydrologically enforced to define water-flow pathways to determine where bridges and culverts contained in the digital elevation map (DEM) may be blocking hydrologic flow.

Dikes and Impoundments. According to the National Wetland Inventory, no dikes or impoundments are present in the Morton approved acquisition boundary or its environs. The connectivity algorithm was also used in this simulation to capture the effects of any natural or man-made impoundments that may not have been marked as diked in the NWI wetland layer. The connectivity module of

SLAMM ensures that dry land only converts to wetland if there is an unimpeded path from open water to the dry land in question.

Historic sea level rise rates. The applied historic trend for local sea level rise was 2.78 mm/yr based on mean sea-level trend data recorded at Montauk, NY (NOAA gauge # 8510560). This rate is somewhat higher than the global (eustatic) SLR for the last 100 years (set to 1.7 mm/yr), potentially indicating minor subsidence in the region or some other factor causing local SLR to be higher than the global average. This subsidence rate, 1.08 mm/yr, was kept constant for all scenarios and time duration.

Tide Ranges. The value of great diurnal range (GT) was applied using the information from NOAA gauge stations in the surrounding area. The Global subsite (of the larger Suffolk County East project completed for NYSERDA), which covers the entire refuge, was given a tide range of 0.87m.

Salt elevation. This parameter within SLAMM designates the boundary between wet and dry lands or saline wetlands and fresh water wetlands. Based on regional data for and model calibration in the Time Zero timestep, the salt elevation was set to 0.75m.

Accretion rates. As part of the NYSERDA project, a full literature search was conducted to collect relevant accretion rates. In addition, unpublished data from members of the project advisory committee were used to determine the accretion rates for the study area.

The Inland Fresh Marsh accretion rate was set to 1 mm/yr. Studies of fens and freshwater marshes in Michigan and Georgia suggest this value to be appropriate based on Pb-210 measurements (Craft and Casey 2000; Graham et al. 2005). Tidal Fresh Marsh accretion was set to 5 mm/yr based on data presented by Neubauer (Neubauer 2008; Neubauer et al. 2002). Tidal-fresh marsh accounts for only one half of one percent of coastal wetlands in the study area. Accretion feedbacks were not used for tidal-fresh marshes due to a lack of site-specific data. Lacking site-specific data, values of 1.6 mm/yr and 1.1 mm/yr were assigned for swamp and tidal swamp accretion, respectively, which were measured in Georgia by Dr. Christopher Craft (Craft 2008, 2012).

Beach sedimentation was set to 0.5 mm/yr, a commonly used value in SLAMM applications. Average beach sedimentation rates are assumed to be lower than marsh-accretion rates due to the lack of vegetation to trap suspended sediment, though it is known to be highly spatially variable. In addition, it is worth noting that beach nourishment, predominant throughout the study area, is not accounted for in these SLAMM simulations.

The current SLAMM application accounts for the important feedbacks between tidal marsh accretion rates and SLR. Feedback relationships were investigated using observed accretion rates and platform elevations and a model-based approach. Elevations relative to accretion rates were derived by comparing the location provided in the citations to the corresponding project area DEM. There is significant uncertainty in terms of assigning elevations to these marsh platforms, especially when core data were used to derive accretion rates. (The requisite assumption would need to be that the marsh has maintained an equilibrium elevation relative to tide levels for the historical period in question.) Locations were also compared to the input wetland layer to differentiate between low and high marsh.

Irregularly-flooded marsh. Data for Irregularly-flooded marshes have been analyzed to determine if they exhibit spatial trends or underlying feedback relationships with elevations. However, elevation trends are difficult to discern as shown in Figure 4. The linear estimate used in modeling is slightly over 4 mm/year of accretion with a very slight increase at lower marsh elevations.

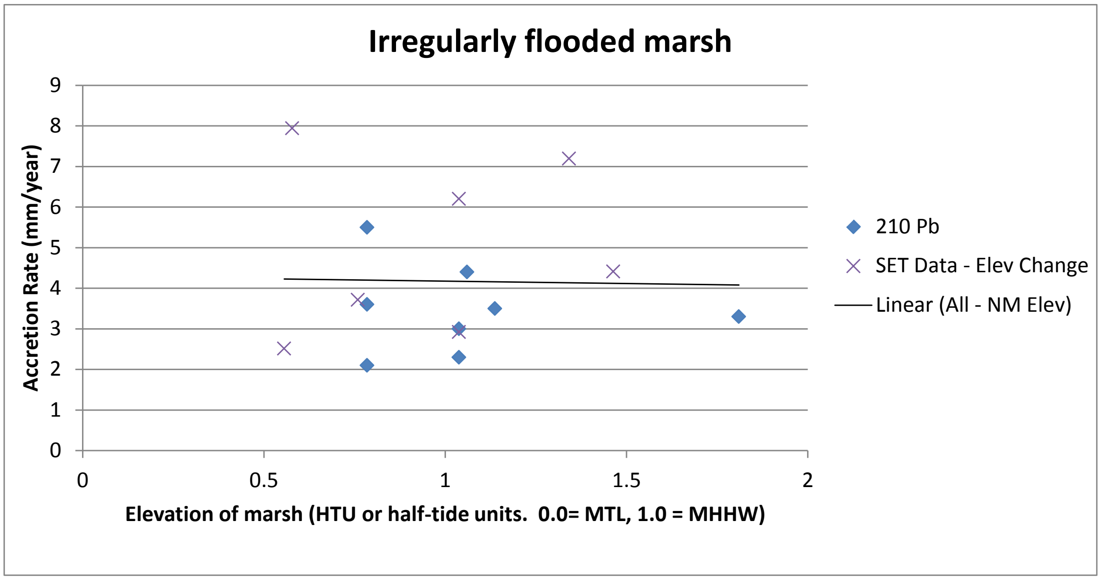


Figure 4. Irregularly flooded marsh accretion model used for all sites

Regularly-flooded marsh. For regularly—flooded marshes accretion rates and their relationship with elevation were derived by calibrating the Marsh Equilibrium Model (MEM) developed by Morris and coworkers at the University of South Carolina to site-specific data (Morris 2013; Morris et al. 2002, 2012).

The key physical input parameters of the MEM model are tide ranges, suspended sediment concentrations, initial sea-level and marsh platform elevations, and the elevations defining the domain of marsh existence within the tidal frame. Biological input parameters are the peak concentration density of standing biomass at the optimum elevation, organic matter decay rates, and parameters determining the contribution to accretion from belowground biomass. However, several input parameters are not always known (e.g. partitioning between organic and inorganic components of accretion, peak biomass, settling velocities, trapping coefficients, organic matter decay rate, belowground turnover rate and others). The approach followed was to define estimated MEM input parameters based on observations when available and fit the unknown model parameters using observed accretion rates.

Accretion feedback models for regularly flooded marsh were derived for 5 geographic regions within the study area: Long Island Sound, the Peconic Bay System, South Shore Long Island, Staten Island/NY Harbor, and the lower Hudson River. Morton NWR is located within the Long Island Bays accretion region, shown in the blue line and observed points in Figure 5.

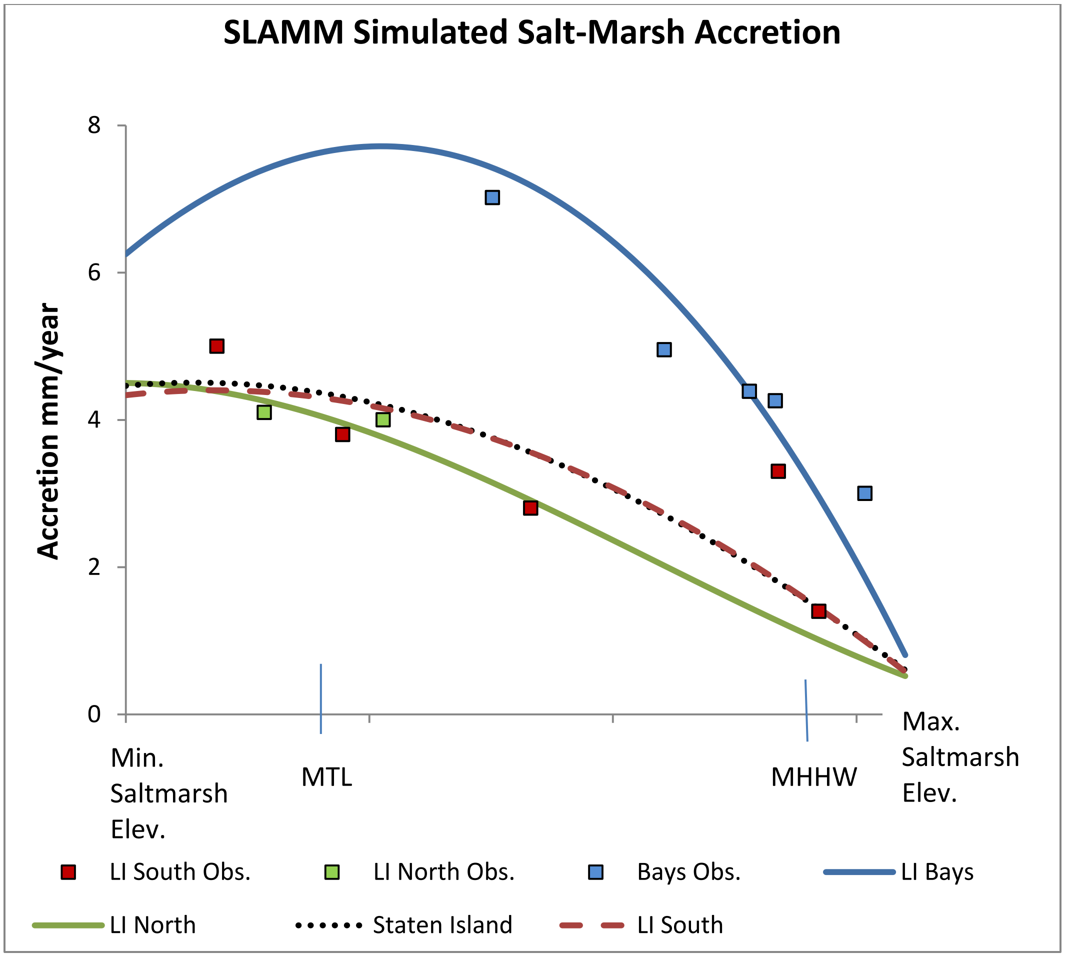


Figure 5. Regularly flooded marsh accretion models plotted against available data

Erosion rates. In SLAMM, average erosion rates are entered for marshes, swamps, and beaches. Horizontal erosion is only applied when the wetland type in question is exposed to open water and where a 9-km fetch[1] is possible. SLAMM models erosion as additive to inundation and is considered the effect of wave action. Marsh erosion was set to 1 meter per year, suggested by Fagherazzi to be at the higher end of erosion rates observed of a marsh boundary by wave action (Fagherazzi 2013). Swamp erosion was set to 1 m/yr, a rate commonly used in SLAMM when site-specific data are unavailable. Beach erosion was set based on the work of Leatherman and coworkers who examined 134 km of shoreline in Southern Long Island and determined an erosion rate of 0.44 mm/yr with a standard deviation of 0.89 m/yr (Leatherman et al. 2000).

Elevation correction. MTL to NAVD88 correction was applied using a spatially varying raster.

Model Timesteps. Model forecast data is output for years 2025, 2050, 2075 and 2100 with the initial condition date set to 2010, the most recent wetland data available in the Suffolk East study area.

[1] "Fetch" is the distance traveled by waves over open water, calculated by the model based on current land-cover predictions.

Refuge boundaries. Modeled USFWS refuge boundaries for Morton are based on Approved Acquisition Boundaries as published on the USFWS Geospatial Services website (http://www.fws.gov/GIS/Data/CadastralDB/). The cell-size used for this analysis is 5 m x 5 m.

Input subsites and parameter summary.

Table 2 summarizes all SLAMM input parameters for the study area. Values for parameters with no specific local information were kept at the model default value.

Table 2. Summary of SLAMM input parameters for Morton NWR.

Parameter	Value Applied
NYSERDA Study area	Suffolk East
Subsite Name	Global
NWI Photo Date (YYYY)	2004
DEM Date (YYYY)	2012
Historic SLR (eustatic)	1.7
Historic SLR (local)	2.78
Direction Offshore [n,s,e,w]	South
GT Great Diurnal Tide Range (m)	0.87
Salt Elev. (m above MTL)	0.7
Marsh Erosion (horz. m /yr)	1
Swamp Erosion (horz. m /yr)	1
T.Flat Erosion (horz. m /yr)	0.44
Tidal-Fresh Marsh Accr (mm/yr)	5
Inland-Fresh Marsh Accr (mm/yr)	1
Tidal Swamp Accr (mm/yr)	1.1
Swamp Accretion (mm/yr)	1.6
Beach Sed. Rate (mm/yr)	0.5
Reg Flood Max. Accr. (mm/year)	7.7165
Reg Flood Min. Accr. (mm/year)	0.8065
Reg Flood Elev a (mm/(year HTU^3))	-0.4078
Reg Flood Elev b (mm/(year HTU^2))	-5.3847
Reg Flood Elev c (mm/(year*HTU))	1.3613
Reg Flood Elev d (mm/year)	7.6316
Irreg Flood Max. Accr. (mm/year)	4.23
Irreg Flood Min. Accr. (mm/year)	4.06
Irreg Flood Elev c (mm/(year*HTU))	-0.12
Irreg Flood Elev d (mm/year)	4.29

Changes to the SLAMM conceptual model. In order for SLAMM to initially reproduce a similar land cover to the available wetland survey, the minimum elevations for some wetland categories were set to the values based on site-specific LiDAR data. These adjustments to the conceptual model were necessary to prevent SLAMM from predicting immediate inundation of these areas and reflect local dynamic wetland regimes in riverine environments. Within SLAMM, Tidal Swamp and Tidal Fresh Marsh lower-boundary elevations are assumed to be highly dependent on freshwater flow and therefore are generally set based on site-specific data. The minimum elevation of regularly flooded marsh was set to -0.4 half tide units (HTU) based on observations for Long Island by McKee and Patrick (McKee and Patrick 1988). Table 3 presents the minimum elevations applied for the entire study area; site-specific changes made to the SLAMM conceptual model for Tidal Swamp and Tidal Fresh Marsh are described in the individual site sections.

Table 3. Default minimum wetland elevations in SLAMM conceptual model

HTU = Half-tide unit

SLAMM Category	Minimum Elevation	Minimum Elevation Unit
Undeveloped Dry Land	1	Salt Elevation
Developed Dry Land	1	Salt Elevation
Swamp	1	Salt Elevation
Ocean Beach	-1	HTU
Inland-Fresh Marsh	1	Salt Elevation
Tidal Flat	-1	HTU
Regularly flooded Marsh	-0.4	HTU
Riverine Tidal	1	Salt Elevation
Irreg.-Flooded Marsh	0.5	HTU
Inland Open Water	1	Salt Elevation
Trans. Salt Marsh	1	HTU
Tidal Swamp	1.46	HTU
Tidal-Fresh Marsh	0.73	HTU
Estuarine Beach	-1	HTU
Rocky Intertidal	-1	HTU
Inland Shore	-1	HTU
Ocean Flat	-1	HTU

Calibration of the initial conditions

Initially, SLAMM simulates a "time zero" step, in which the consistency of model assumptions for wetland elevations is validated with respect to available wetland coverage information, elevation data and tidal frames. Due to simplifications within the SLAMM conceptual model, DEM and wetland layer uncertainty, or other local factors, some cells may fall below their lowest allowable elevation category and would be immediately converted by the model to a different land cover category. For example, an area categorized in the wetland layer as swamp that would be regularly inundated by tidal water according to its elevation and tidal information will be converted to a tidal marsh. These cells represent outliers on the distribution of elevations for a given land-cover type. SLAMM predictions suggest that <1 acre of dry land is currently inundated frequently enough to start transitioning to salt marsh as shown in the dry-land and transitional-salt-marsh categories(presented in Table 4 below). Similarly, just under 3 acres of irregularly-flooded marsh are at a low enough elevation in the initial condition LiDAR layer to be converted to regularly-flooded marsh.

Because of these differences, predicted gains and losses of wetland categories are made with respect to the initial coverage predicted by SLAMM at time zero. These results are summarized in the following table as "2010."

Table 4. SLAMM Time zero results

		Initial	2010	Change in Acres	% Change (- is loss)
	Undeveloped Dry Land	113.3	112.5	-0.7	-1%
	Estuarine Beach	31.5	31.5	0.0	0%
	Irreg.-Flooded Marsh	18.3	15.4	-2.9	-16%
	Estuarine Open Water	13.1	13.1	0.0	0%
	Inland Open Water	0.6	0.6	0.0	0%
	Inland-Fresh Marsh	0.5	0.5	0.0	0%
	Swamp	0.1	0.1	0.0	0%
	Regularly-Flooded Marsh	0.0	2.9	2.9	na
	Trans. Salt Marsh	0.0	0.7	0.7	na

Results

Percentage losses by 2100 for each land-cover type given different SLR scenarios are presented in Table 5. As discussed above, land-cover losses are calculated in comparison to the "time zero" or "2010" wetland coverage.

The predominant land-cover types in the refuge at present are undeveloped dry land, estuarine beach, and irregularly-flooded marsh. Each of these land-cover categories are predicted to suffer losses under each accelerated SLR scenario examined. Estuarine beach and irregularly-flooded marsh appear to be quite vulnerable to accelerated SLR, particularly under the higher rates of SLR examined. The loss of irregularly-flooded marsh is compensated in part by the establishment of transitional-flooded marsh as low-lying dry lands become inundate more often, and by the conversion to regularly flooded marsh. Increases in regularly-flooded marsh are predicted up to a certain extent, with a maximum increase occurring under the 1 m SLR by 2100 scenario. However, for higher SLR scenarios also these low marshes are predicted to not be able to keep up with the rate of SLR.

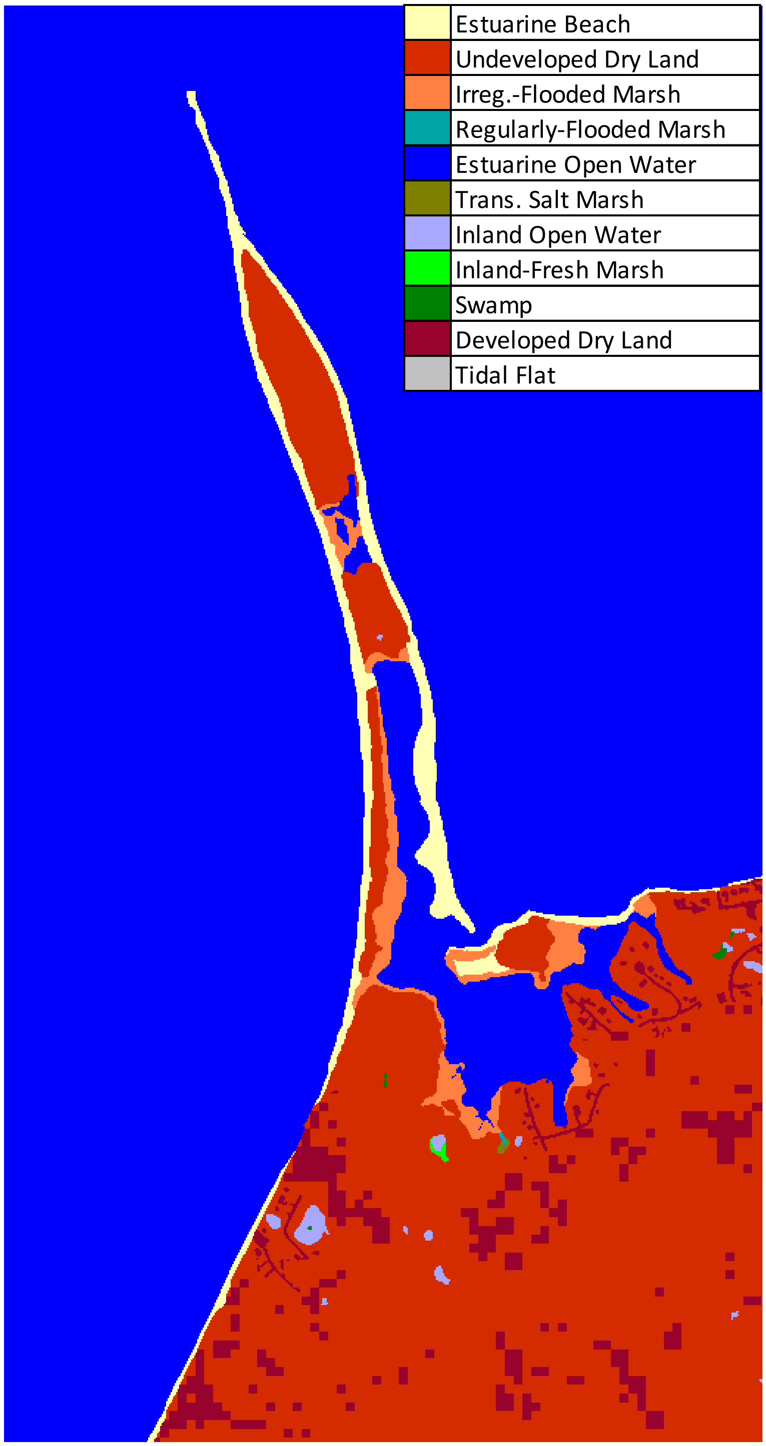
Table 5. Predicted loss rates of land categories by 2100 given simulated scenarios of eustatic SLR at Morton NWR.

Land cover category	Acres in 2010	Percentage Land cover change from 2010 to 2100 for different SLR scenarios				
		Mean	Maximum	1 meter	1.5 meter	2 meter
Undeveloped Dry Land	112.6	-2%	-9%	-13%	-17%	-21%
Estuarine Beach	31.5	-6%	-22%	-37%	-62%	-81%
Irreg.-Flooded Marsh	15.5	-3%	-30%	-66%	-88%	-96%
Regularly-Flooded Marsh	13.1	8%	216%	564%	507%	202%
Trans. Salt Marsh	2.8	333%	1028%	719%	279%	299%

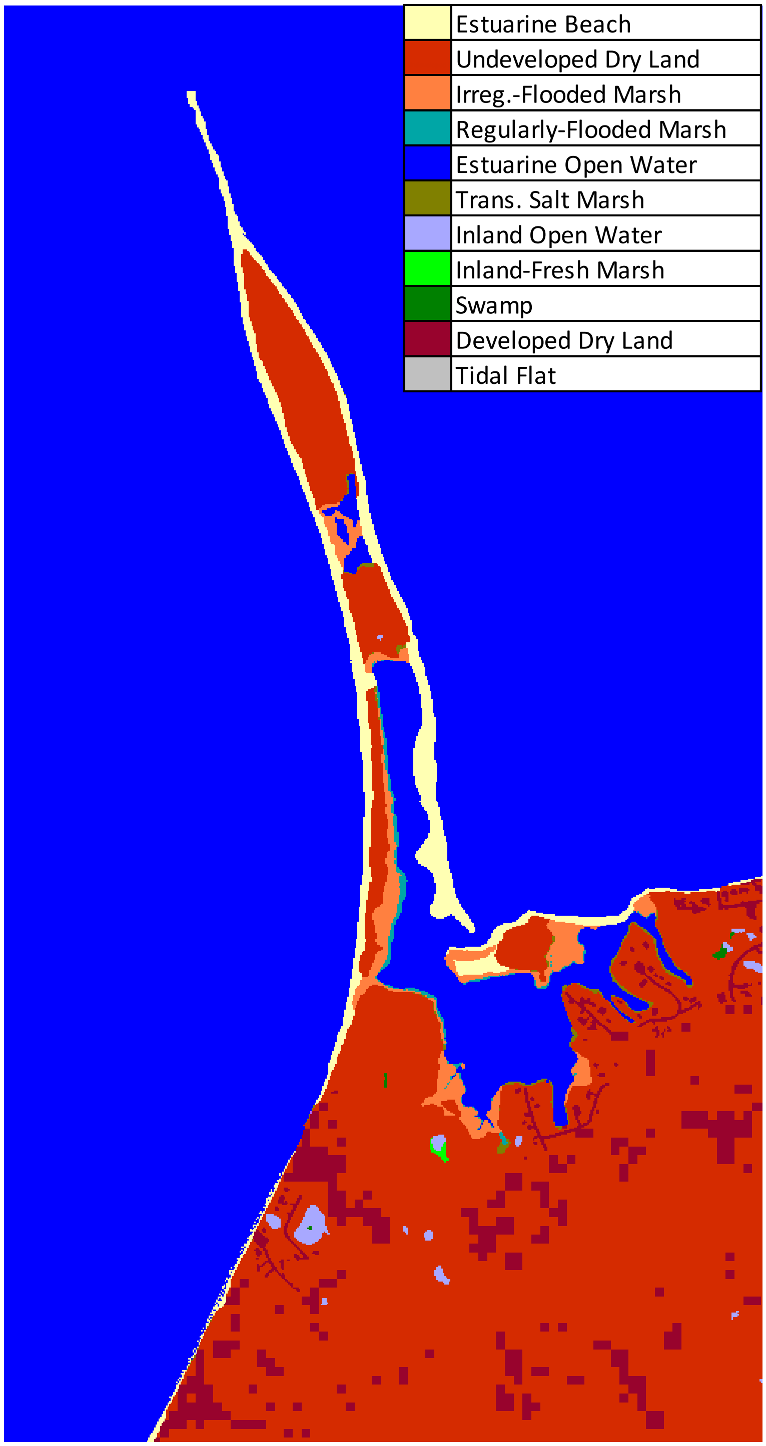
IPCC A1B Mean

Results in Acres

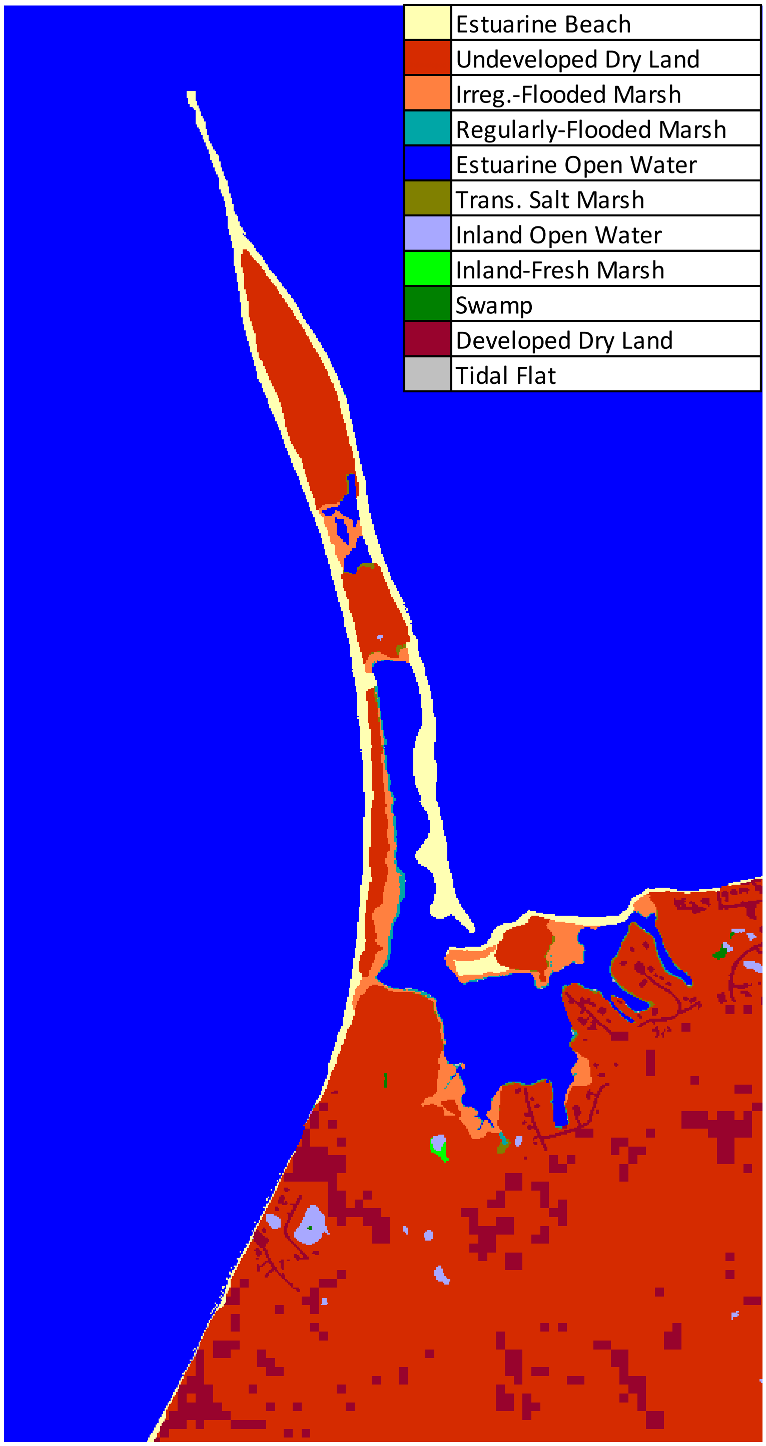
		Initial	2025	2050	2075	2100
	Estuarine Beach	31.5	31.5	31.4	31.1	29.5
	Undeveloped Dry Land	112.6	112.5	112.1	111.7	109.9
	Irreg.-Flooded Marsh	15.5	15.5	15.5	15.3	15.1
	Regularly-Flooded Marsh	2.8	2.3	2.4	2.7	3.0
	Estuarine Open Water	13.1	13.7	13.9	14.2	15.8
	Trans. Salt Marsh	0.7	0.6	0.9	1.3	3.0
	Inland Open Water	0.6	0.6	0.6	0.6	0.6
	Inland-Fresh Marsh	0.5	0.5	0.5	0.5	0.5
	Swamp	0.1	0.1	0.1	0.1	0.1
	Total (incl. water)	**178**	**178**	**178**	**178**	**178**



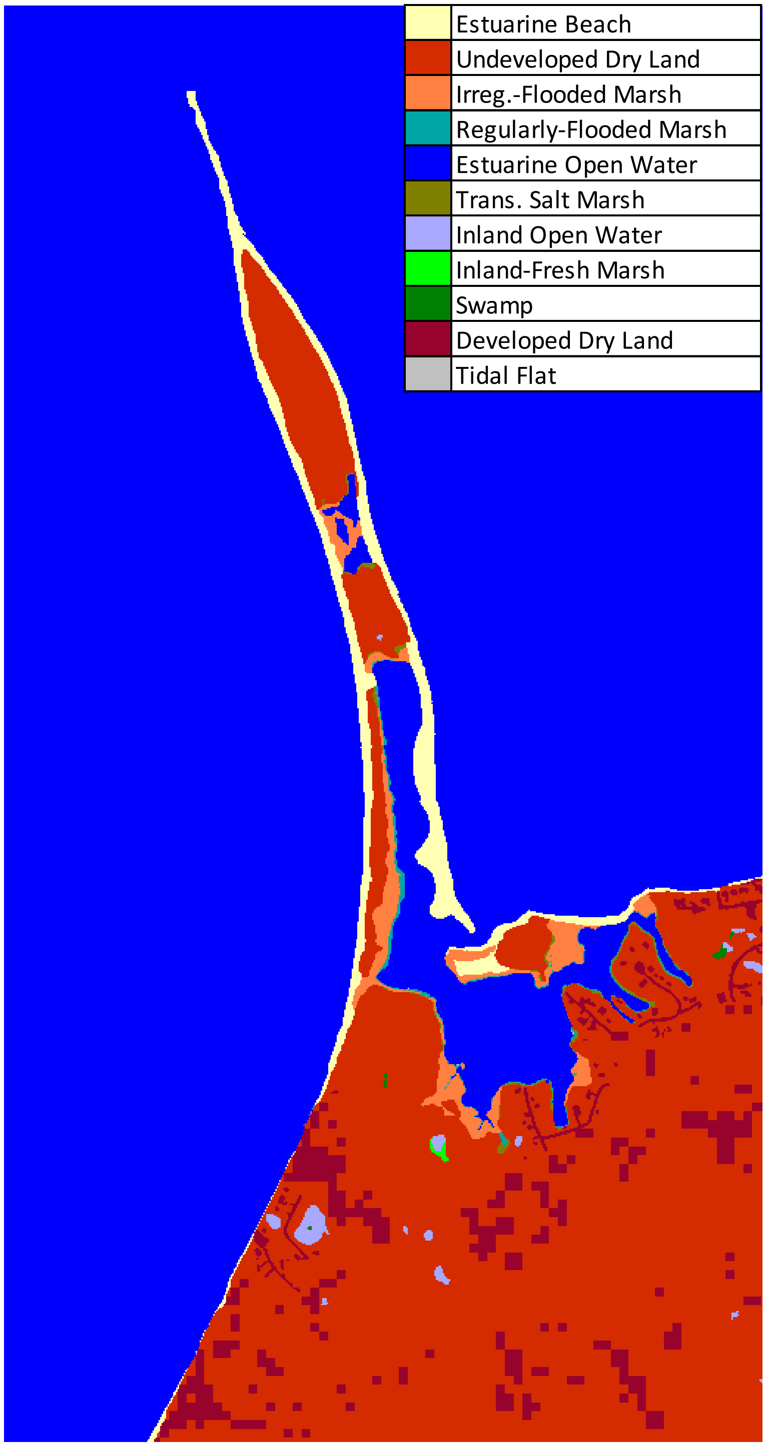
Morton NWR, Initial Condition.



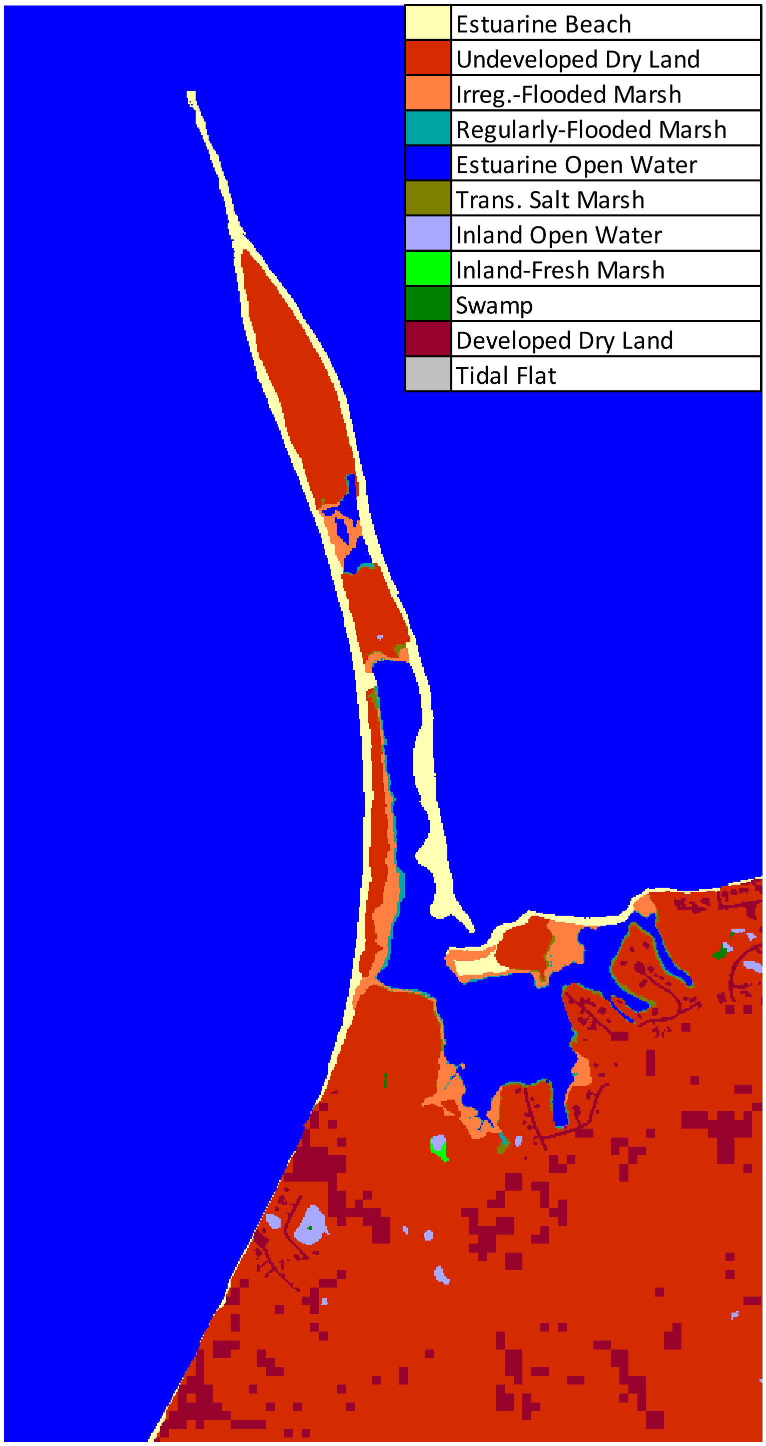
Morton NWR, SLAMM 2010.



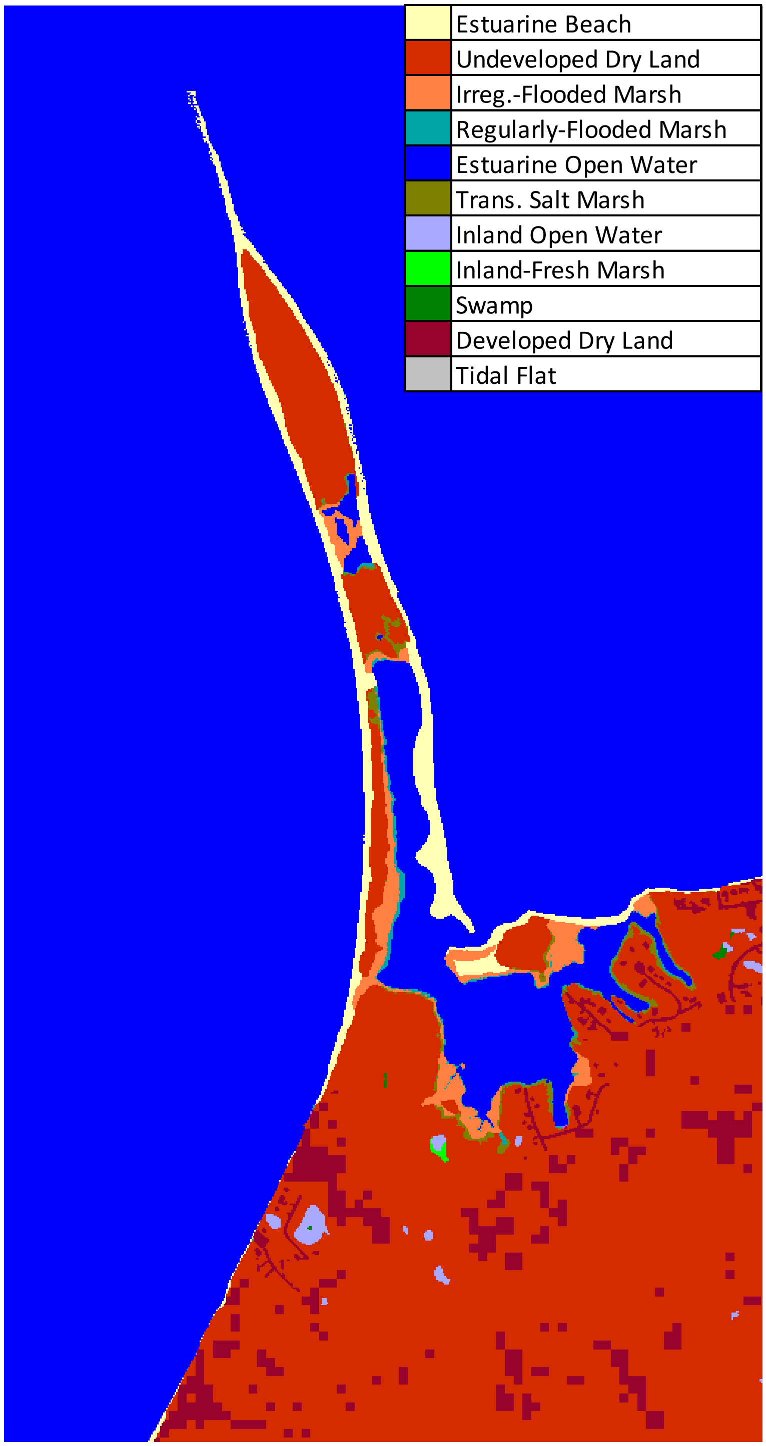
Morton NWR, 2025, Scenario A1B Mean, 0.39 m SLR



Morton NWR, 2050, Scenario A1B Mean, 0.39 m SLR by 2100.



Morton NWR, 2075, Scenario A1B Mean, 0.39 m SLR by 2100.

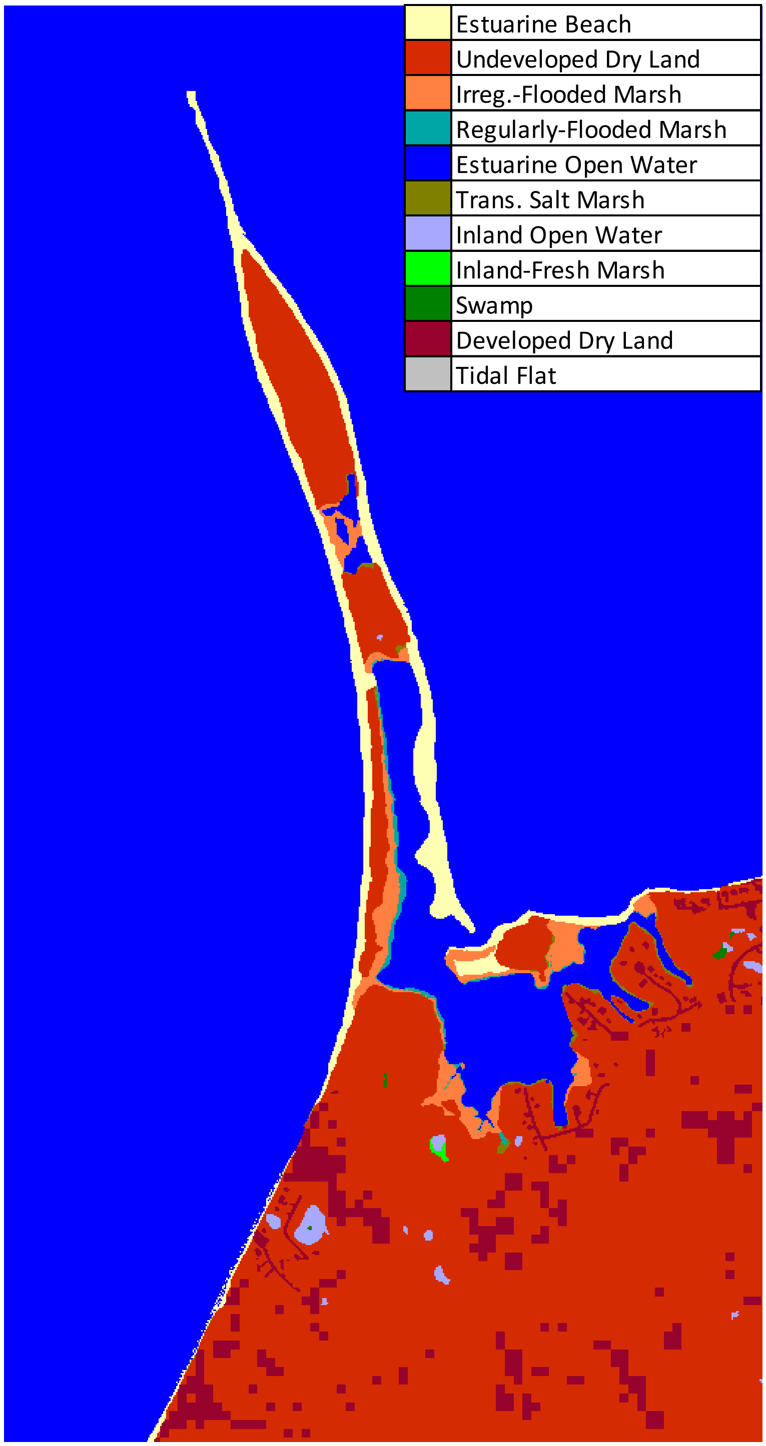


Morton NWR, 2100, Scenario A1B Mean, 0.39 m SLR by 2100.

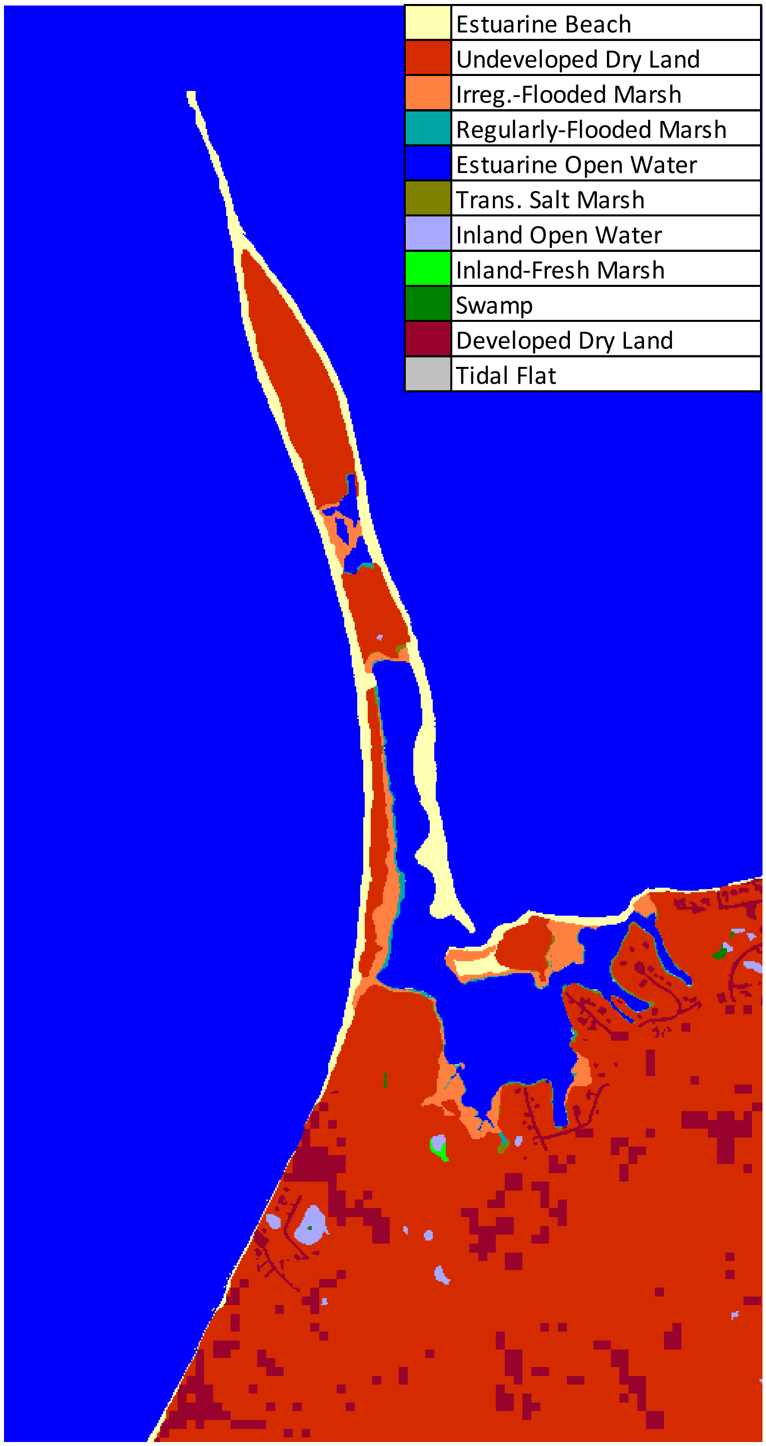
IPCC A1B Maximum

Results in Acres

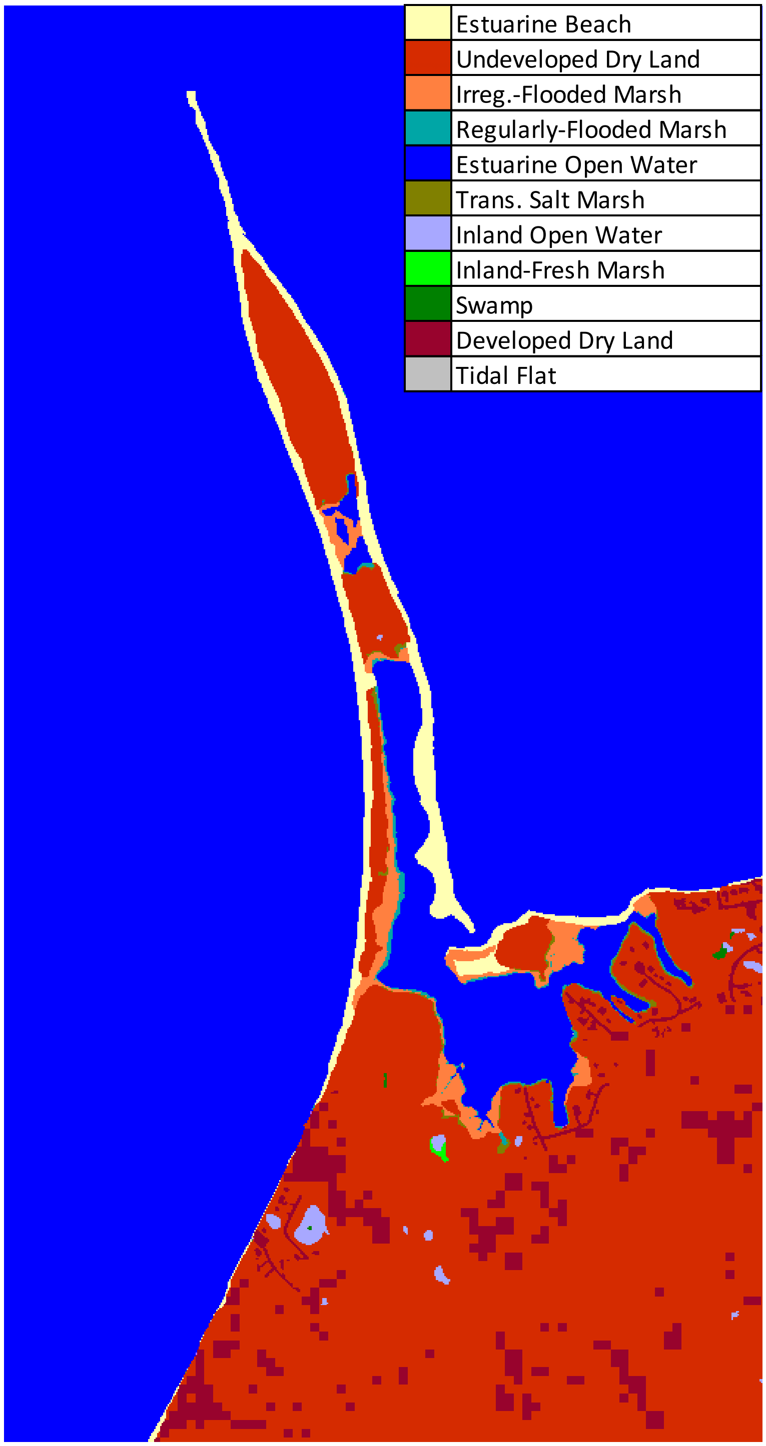
		Initial	2025	2050	2075	2100
	Estuarine Beach	31.5	31.5	31.2	27.9	24.5
	Undeveloped Dry Land	112.6	112.4	111.6	107.9	102.4
	Irreg.-Flooded Marsh	15.5	15.4	14.9	13.8	10.9
	Regularly-Flooded Marsh	2.9	2.5	3.2	4.6	9.1
	Estuarine Open Water	13.1	13.8	14.2	17.8	21.5
	Trans. Salt Marsh	0.7	0.6	1.3	4.4	8.0
	Inland Open Water	0.6	0.6	0.6	0.6	0.6
	Inland-Fresh Marsh	0.5	0.5	0.5	0.5	0.5
	Swamp	0.1	0.1	0.1	0.1	0.1
	Total (incl. water)	**178**	**178**	**178**	**178**	**178**



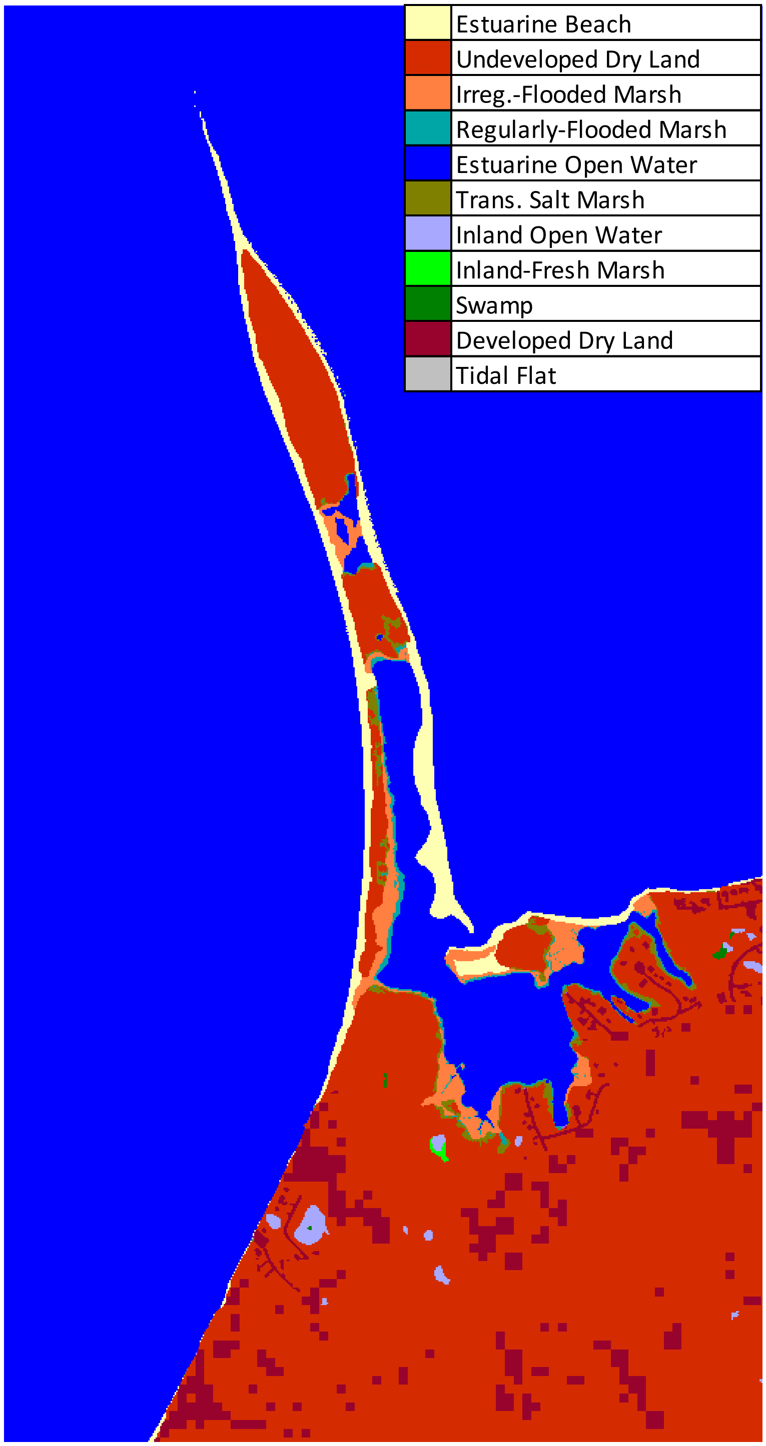
Morton NWR, SLAMM 2010.



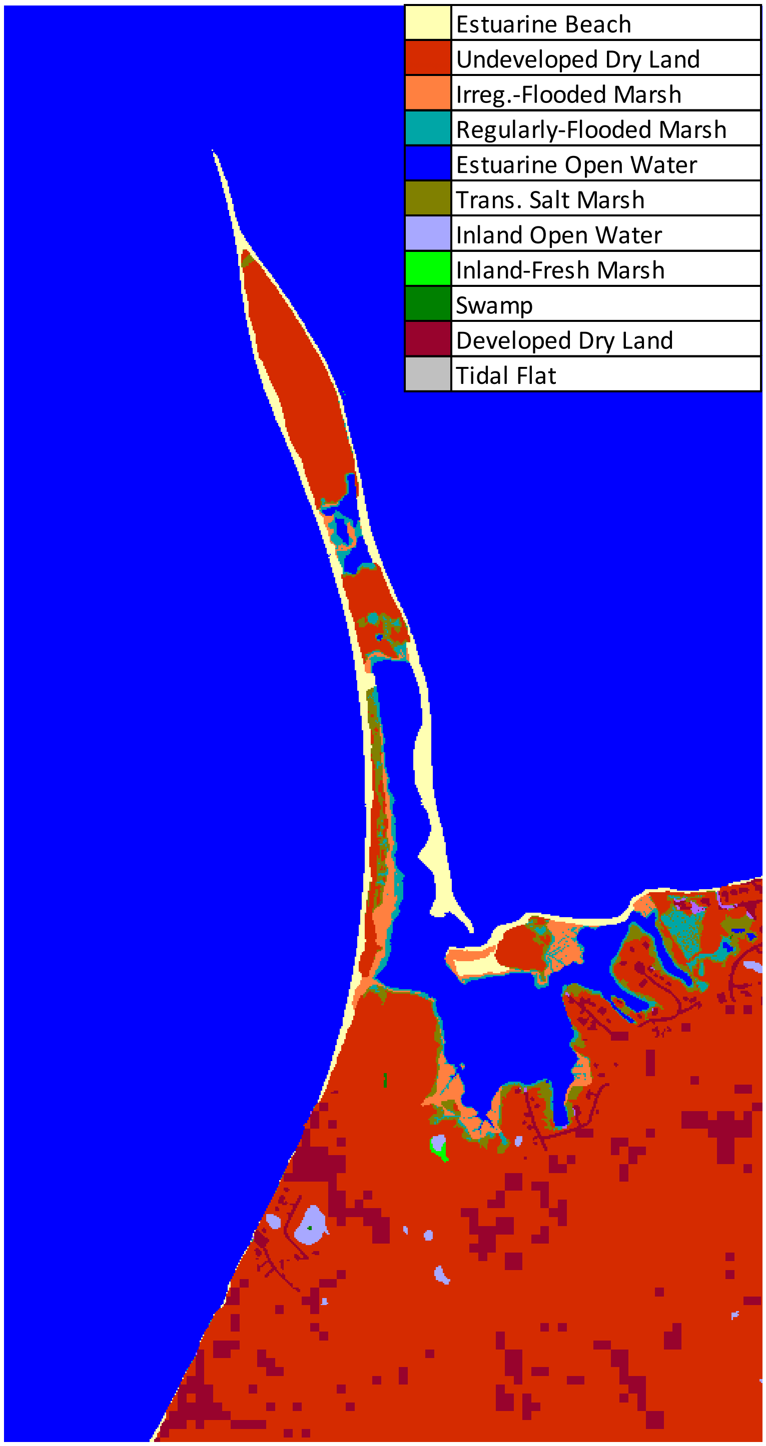
Morton NWR, 2025, Scenario A1B Maximum, 0.69 m SLR by 2100.



Morton NWR, 2050, Scenario A1B Maximum, 0.69 m SLR by 2100.



Morton NWR, 2075, Scenario A1B Maximum, 0.69 m SLR by 2100.

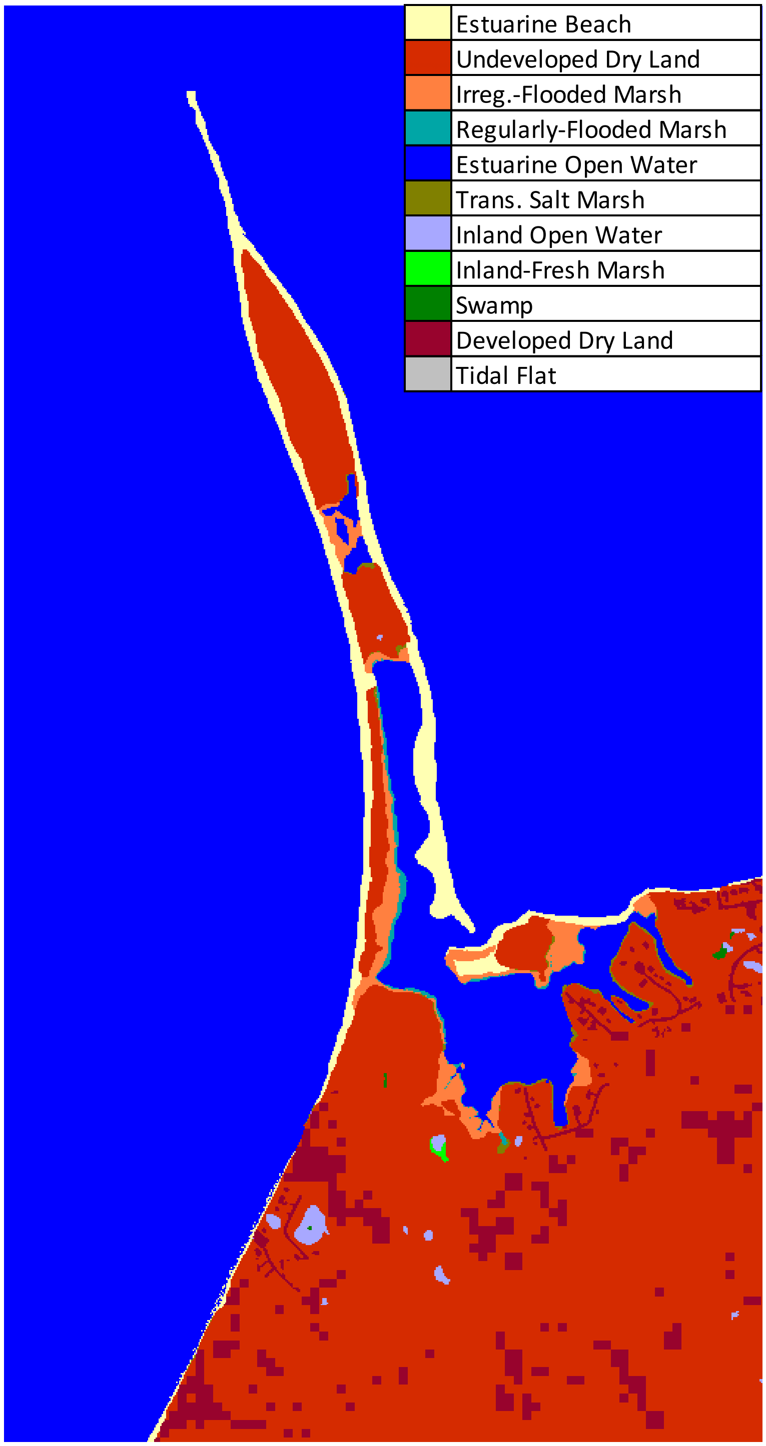


Morton NWR, 2100, Scenario A1B Maximum, 0.69 m SLR by 2100.

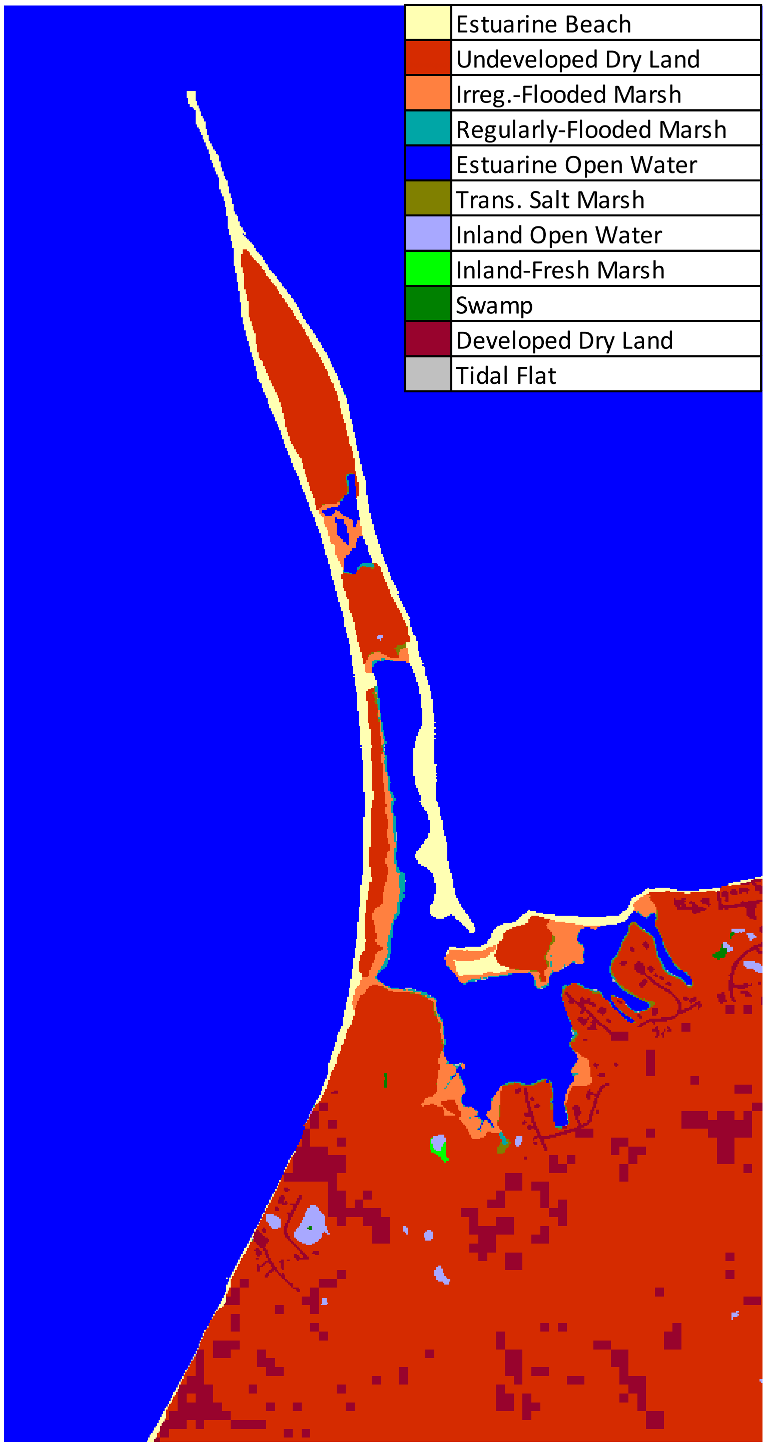
1 meter

Results in Acres

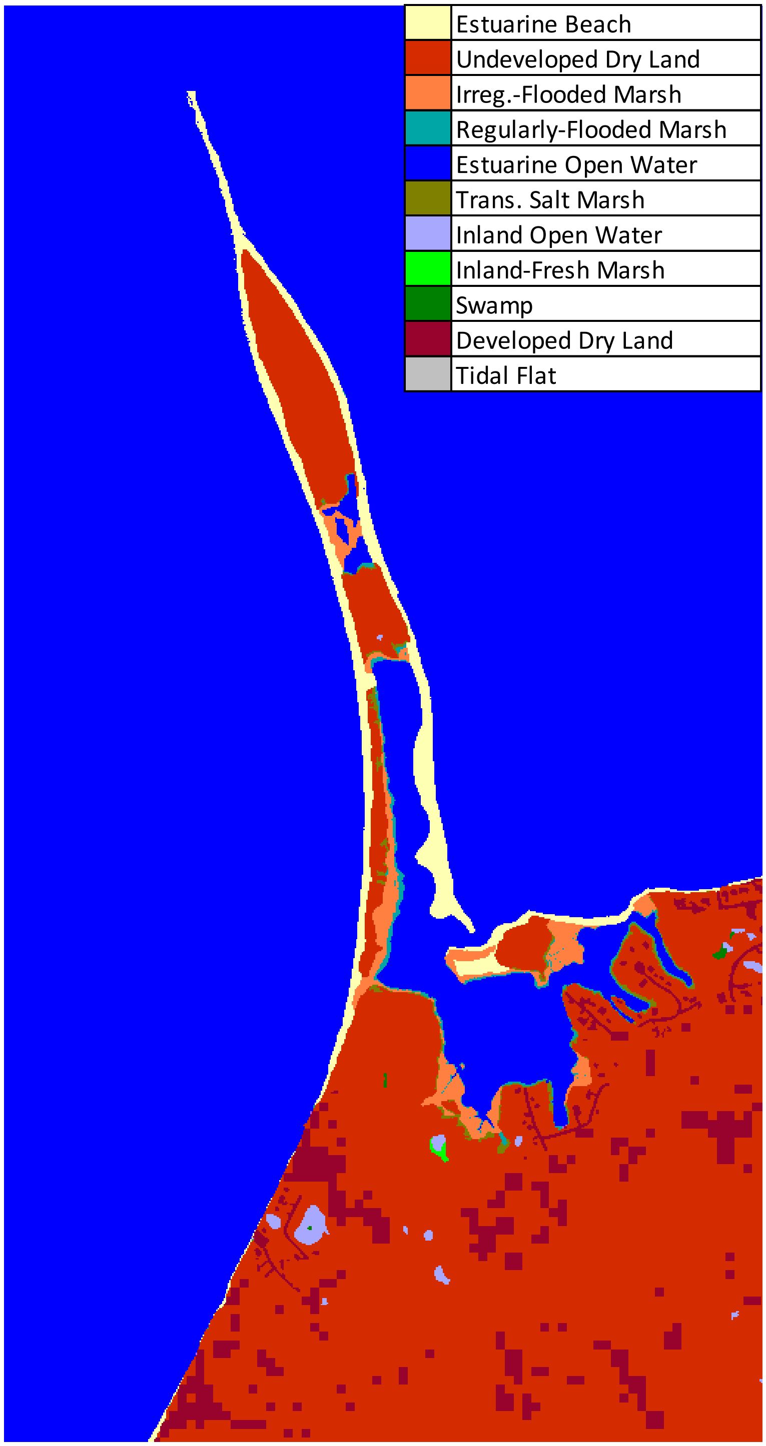
		Initial	2025	2050	2075	2100
	Estuarine Beach	31.5	31.5	30.3	24.9	20.0
	Undeveloped Dry Land	112.5	112.3	110.3	103.6	98.0
	Irreg.-Flooded Marsh	15.4	15.2	14.0	9.9	5.3
	Regularly-Flooded Marsh	2.9	2.7	3.9	9.4	19.6
	Estuarine Open Water	13.1	13.9	15.5	21.5	27.3
	Trans. Salt Marsh	0.7	0.6	2.2	6.9	6.1
	Inland Open Water	0.6	0.6	0.6	0.6	0.6
	Inland-Fresh Marsh	0.5	0.5	0.5	0.5	0.5
	Swamp	0.1	0.1	0.1	0.1	0.1
	Tidal Flat	-	0.1	0.0	0.0	0.1
	Total (incl. water)	**178**	**178**	**178**	**178**	**178**



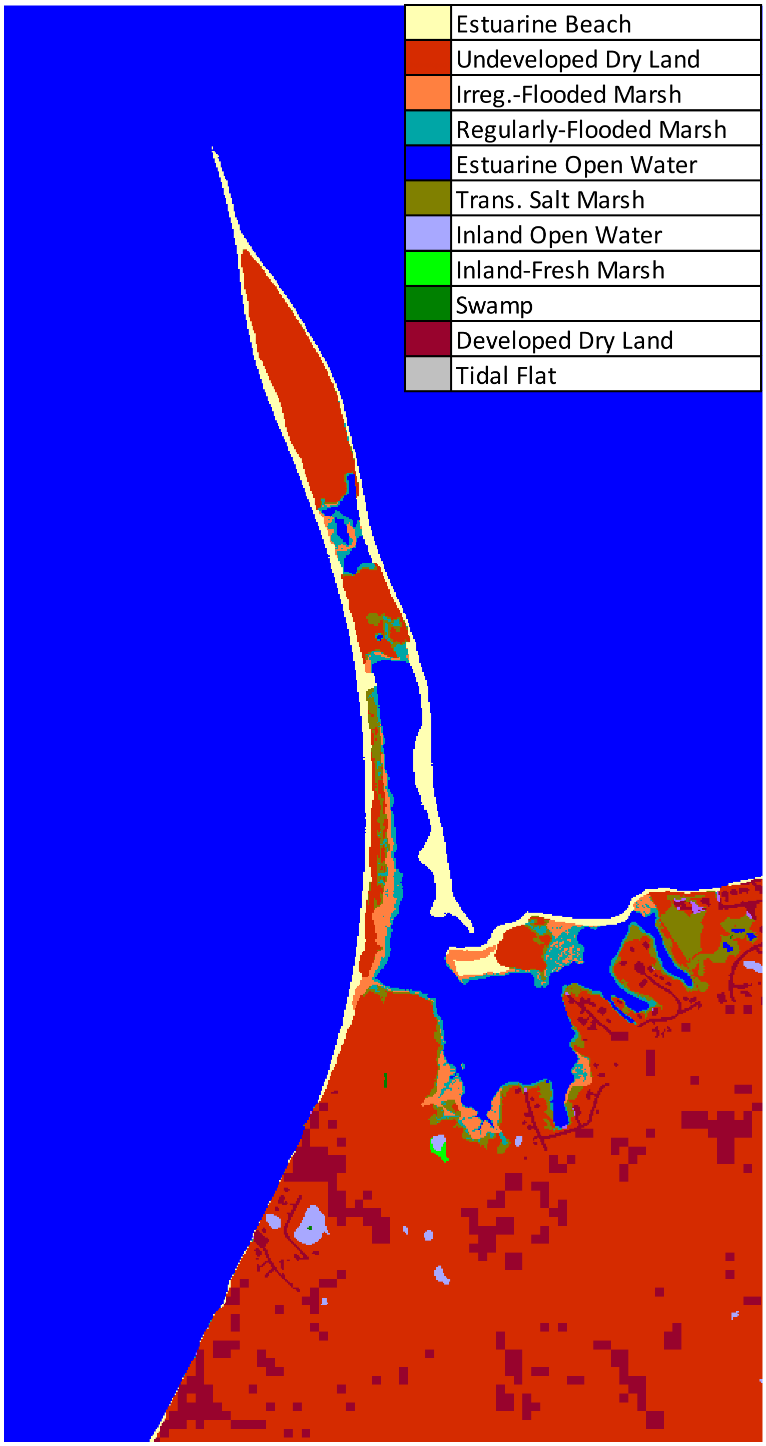
Morton NWR, SLAMM 2010.



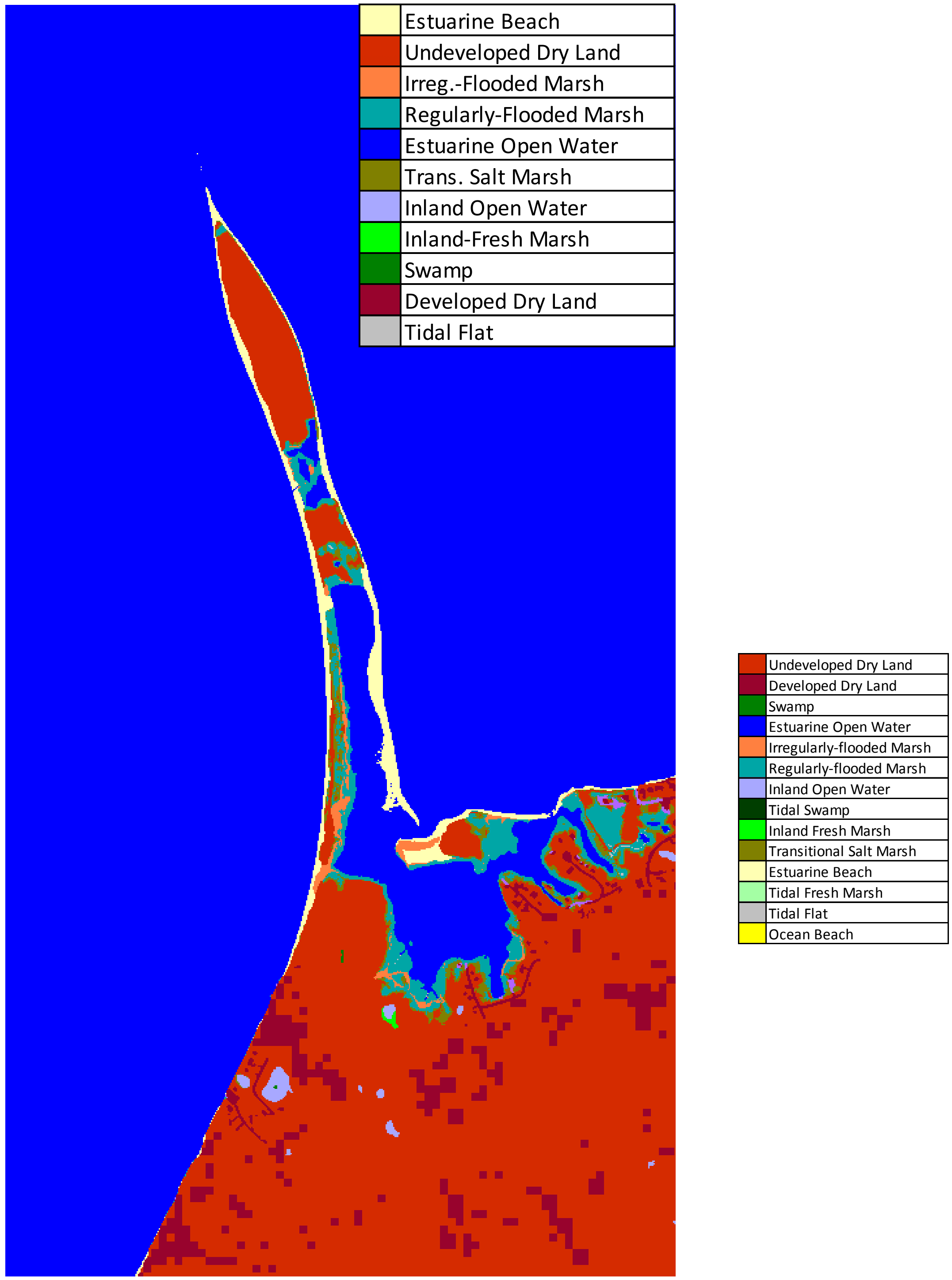
Morton NWR, 2025, 1 m SLR by 2100.



Morton NWR, 2050, 1 m SLR by 2100.



Morton NWR, 2075, 1 m SLR by 2100.

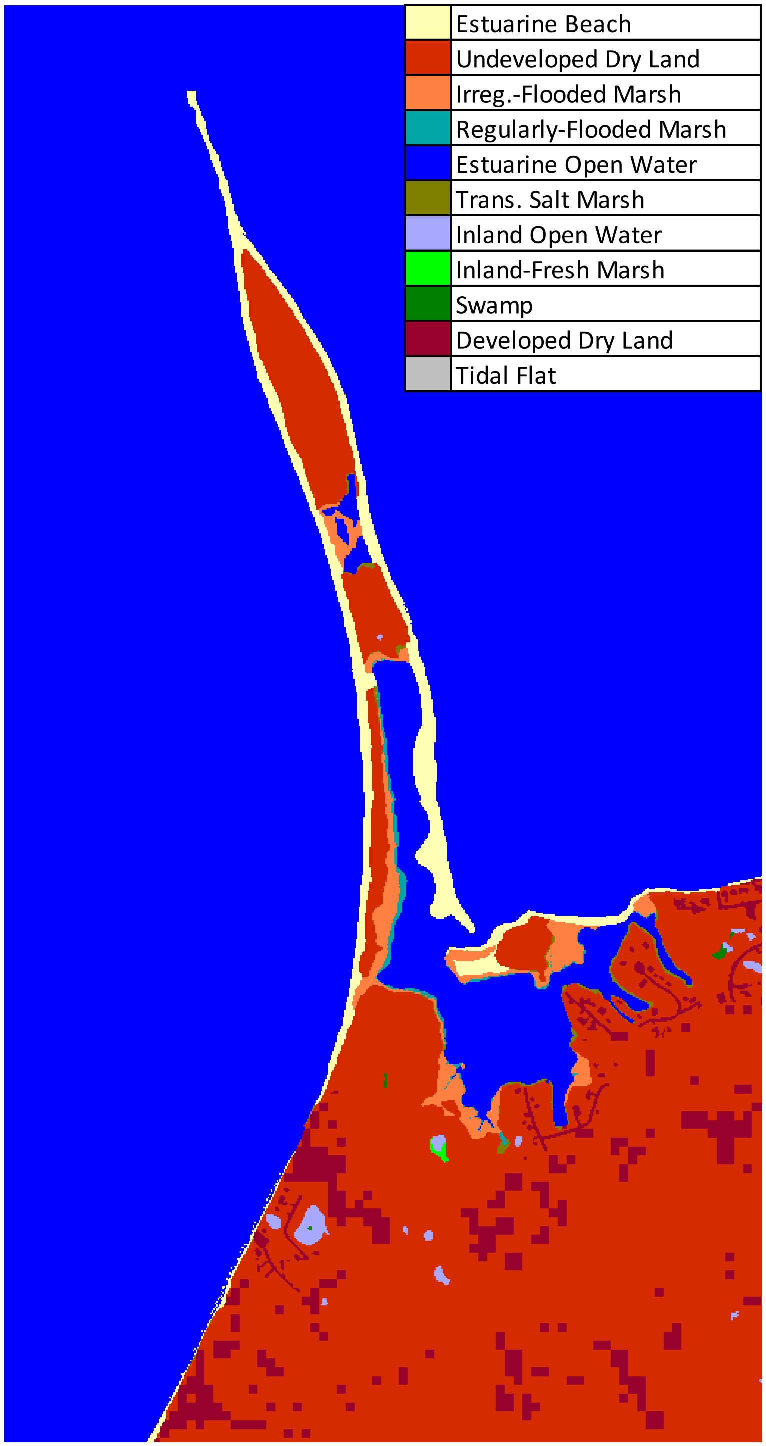


Morton NWR, 2100, 1 m SLR by 2100.

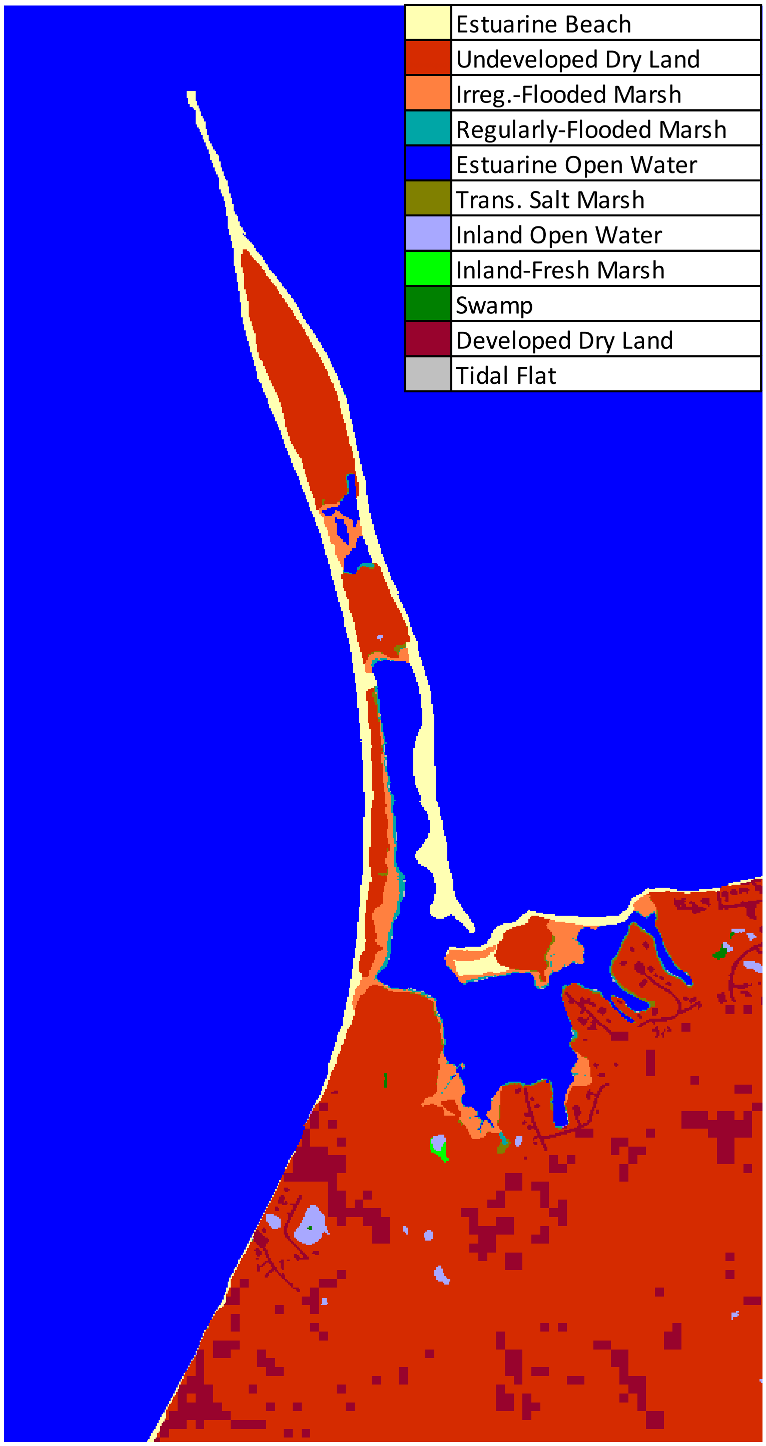
1.5 meters

Results in Acres

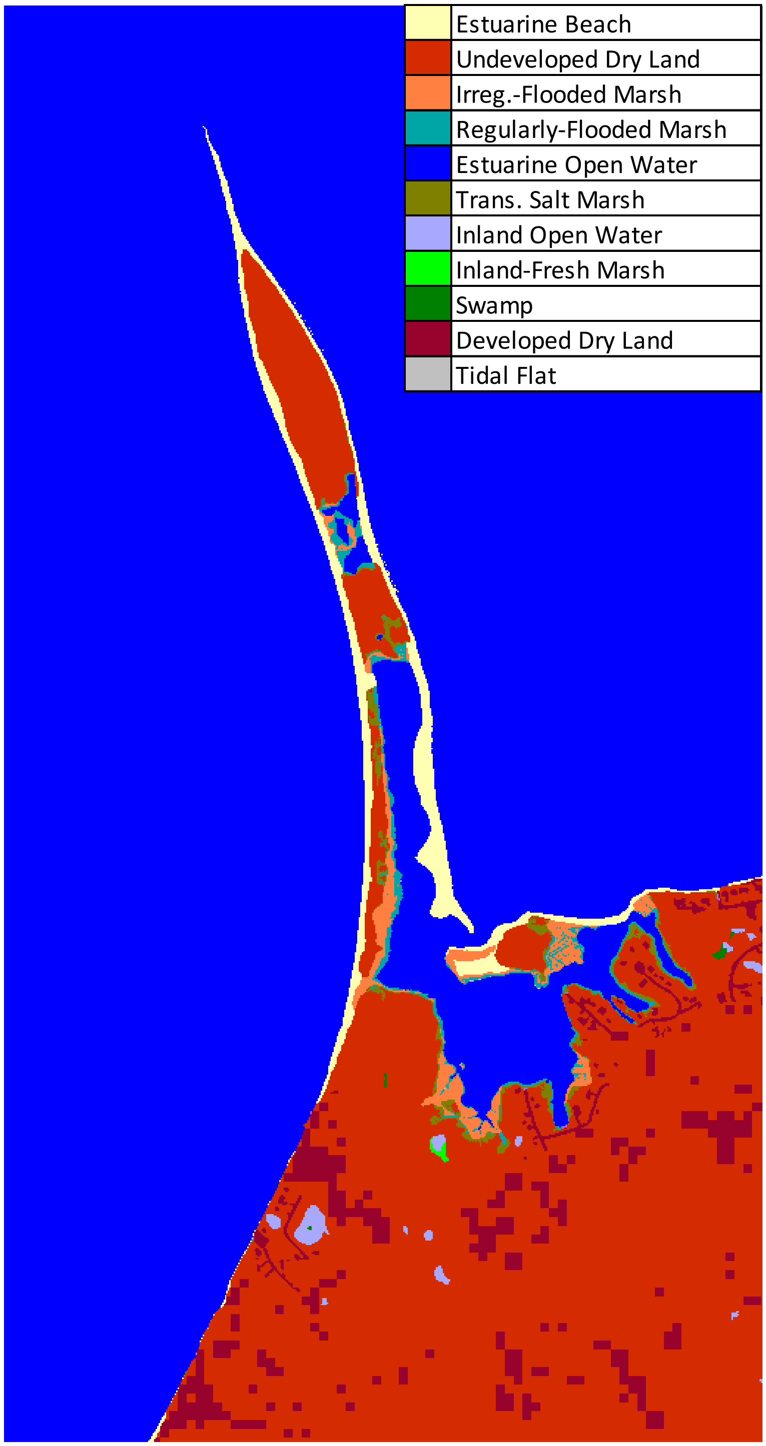
		Initial	2025	2050	2075	2100
	Estuarine Beach	31.5	31.4	26.9	20.1	12.1
	Undeveloped Dry Land	112.5	112.0	106.9	98.2	93.4
	Irreg.-Flooded Marsh	15.3	14.8	10.7	4.4	1.8
	Regularly-Flooded Marsh	3.1	3.0	7.3	19.3	18.6
	Estuarine Open Water	13.1	14.1	19.7	28.5	42.9
	Trans. Salt Marsh	0.8	0.8	4.9	5.4	2.9
	Inland Open Water	0.6	0.6	0.6	0.6	0.6
	Inland-Fresh Marsh	0.5	0.5	0.5	0.5	0.5
	Swamp	0.1	0.1	0.1	0.1	0.1
	Tidal Flat	-	0.1	0.0	0.6	4.6
	Total (incl. water)	**178**	**178**	**178**	**178**	**178**



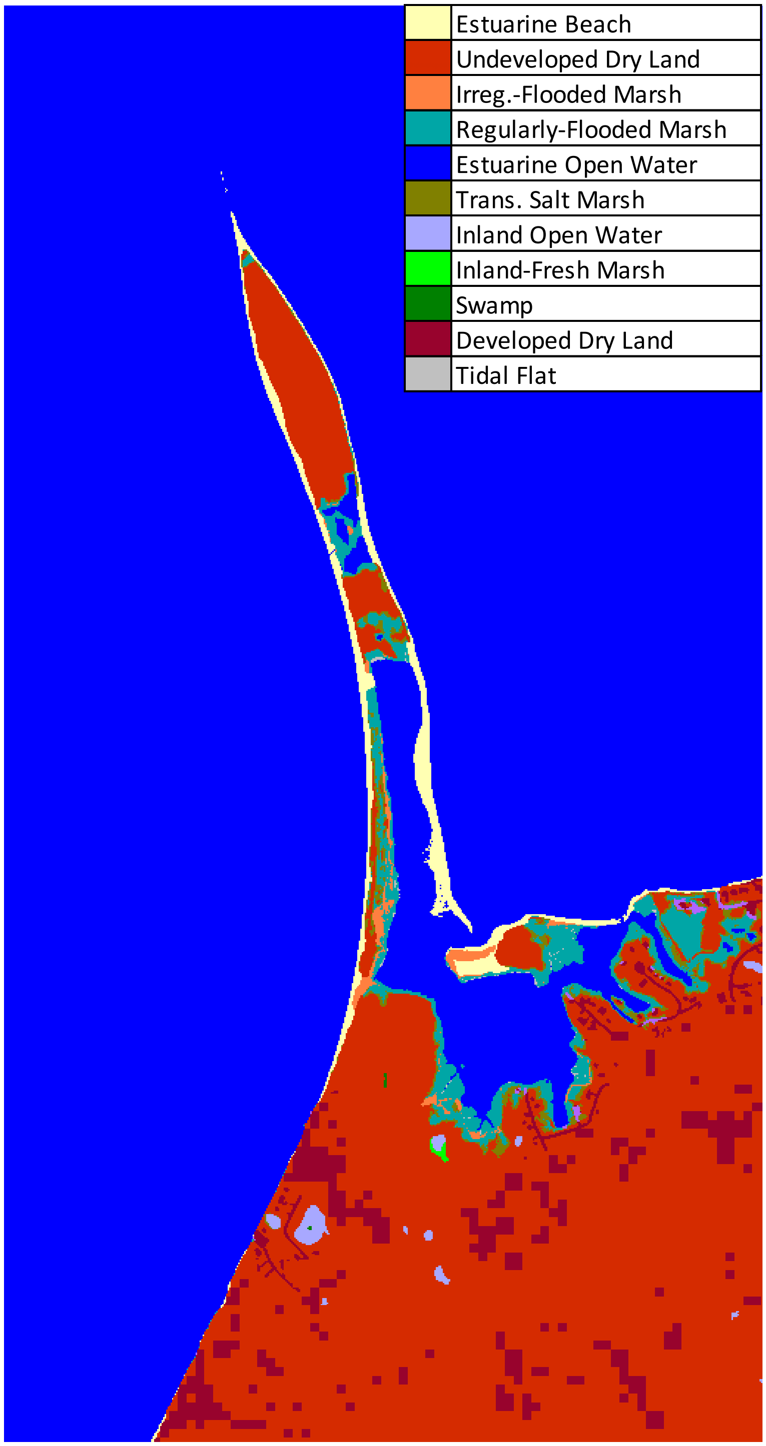
Morton NWR, SLAMM 2010.



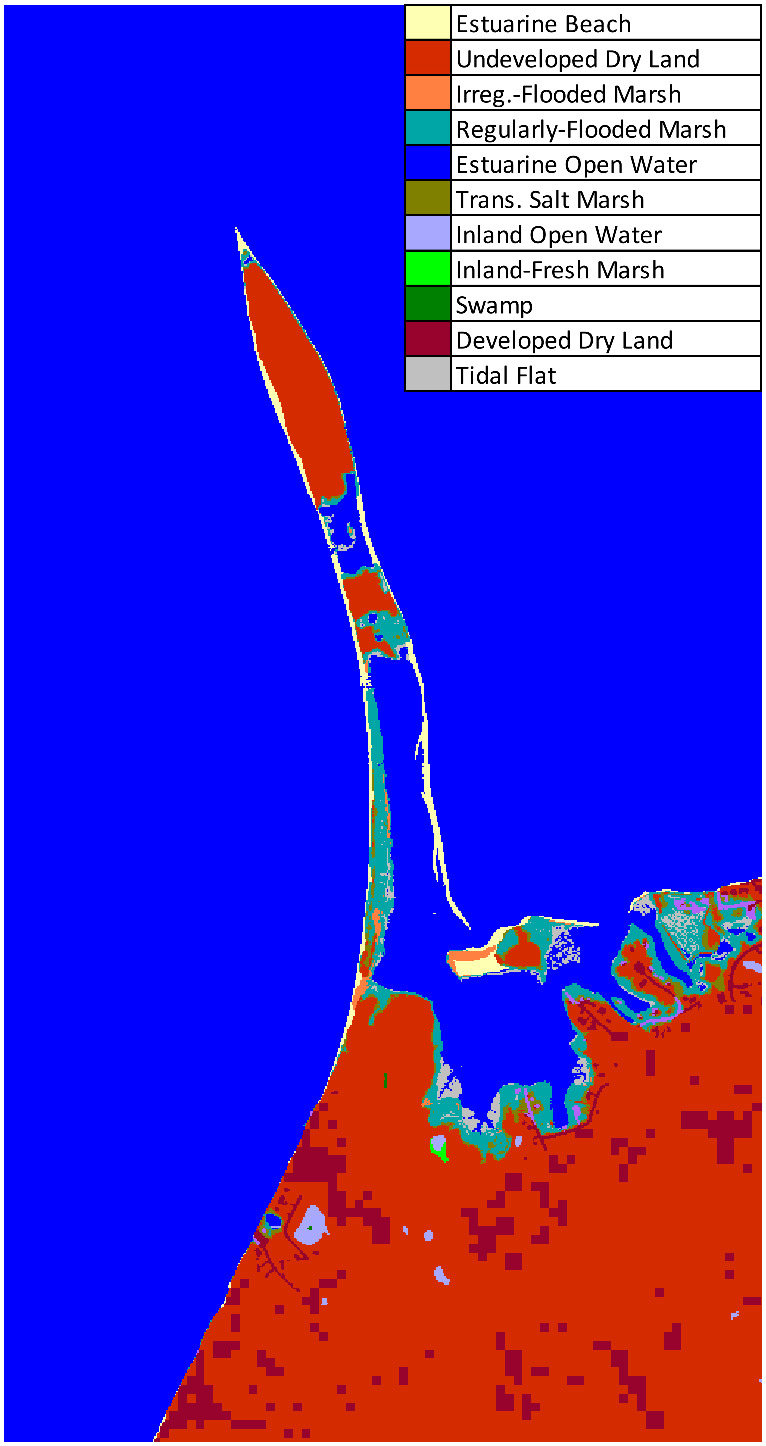
Morton NWR, 2025, 1.5 m SLR by 2100.



Morton NWR, 2050, 1.5 m SLR by 2100.



Morton NWR, 2075, 1.5 m SLR by 2100.

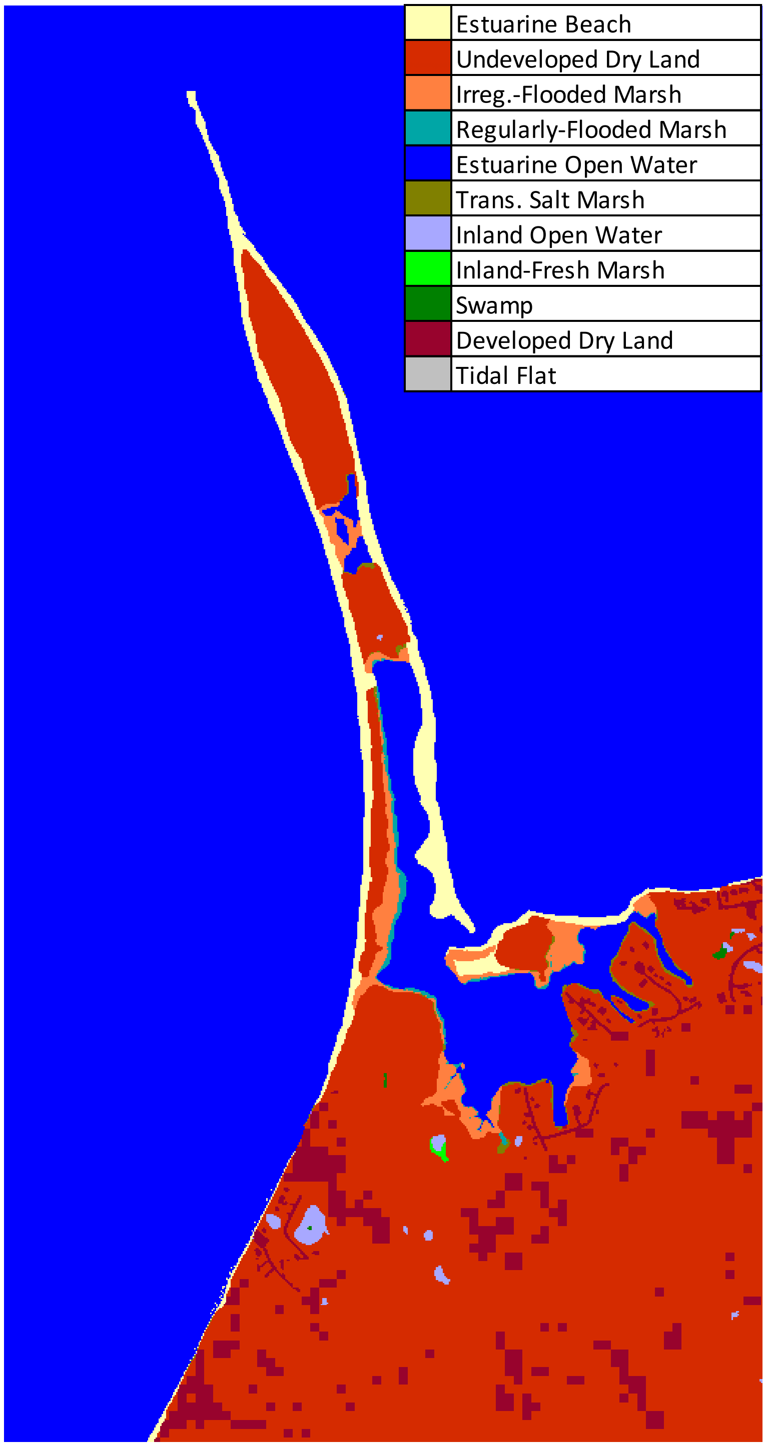


Morton NWR, 2100, 1.5 m SLR by 2100.

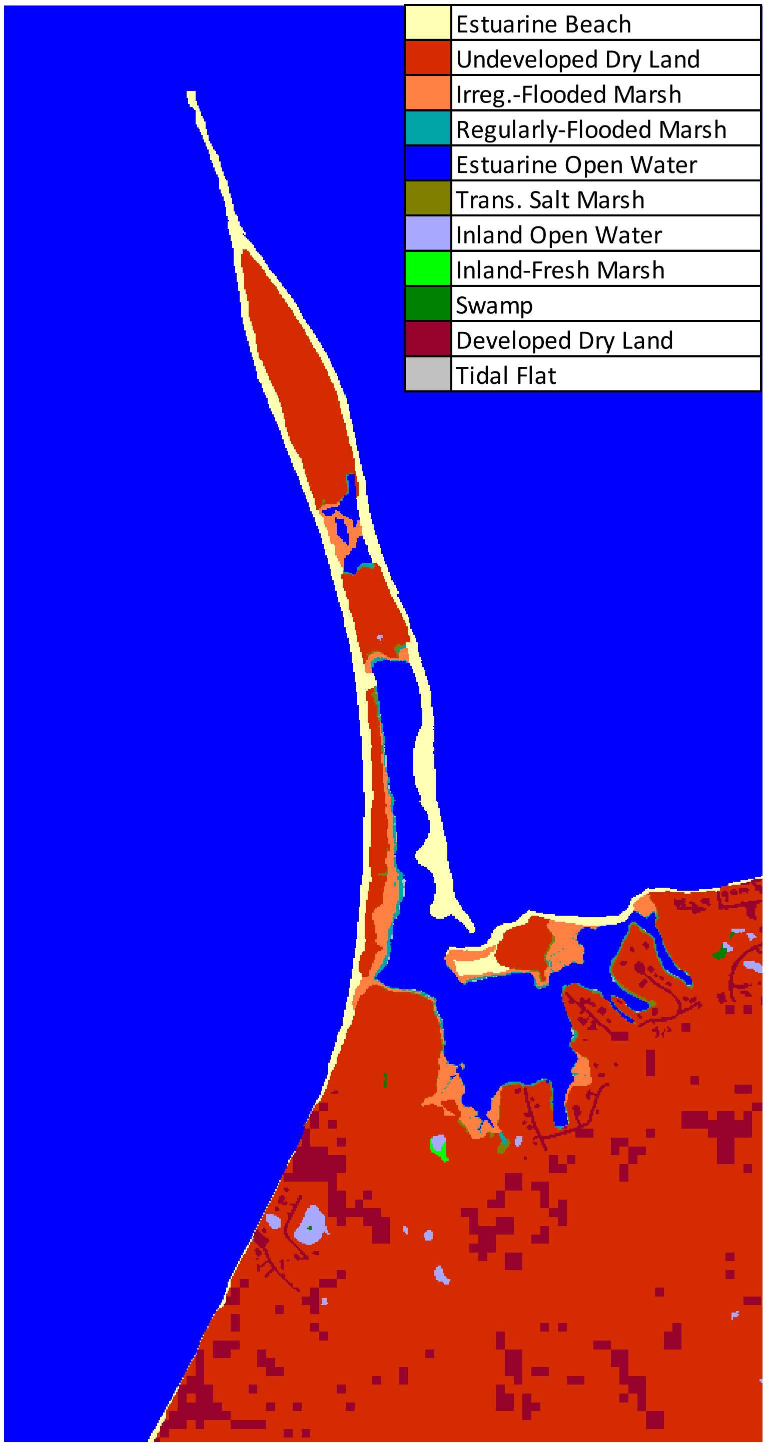
2 meters

Results in Acres

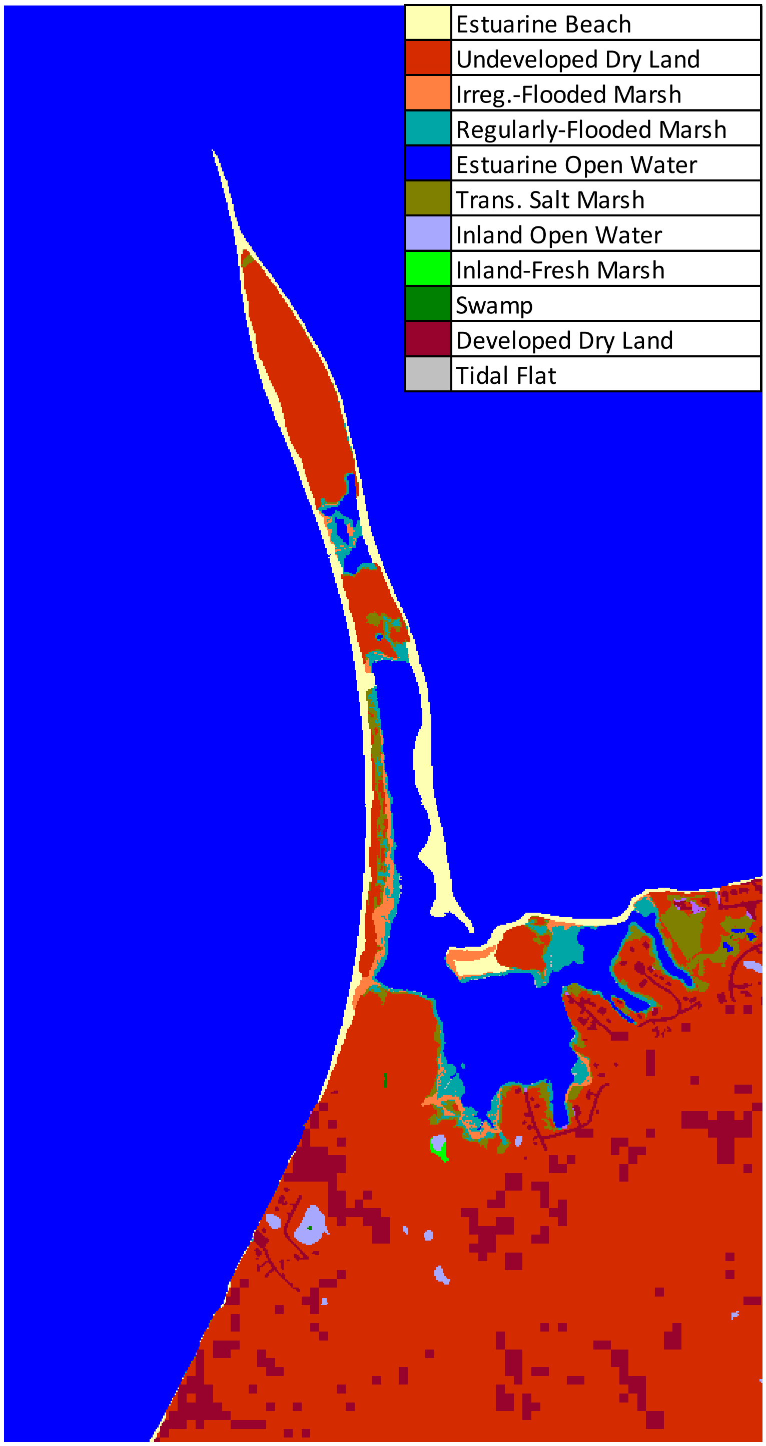
		Initial	2025	2050	2075	2100
	Estuarine Beach	31.5	31.3	24.5	14.4	6.0
	Undeveloped Dry Land	112.5	111.8	103.0	94.8	88.8
	Irreg.-Flooded Marsh	15.2	14.4	6.9	2.1	0.7
	Regularly-Flooded Marsh	3.2	3.3	12.0	17.1	9.6
	Estuarine Open Water	13.1	14.4	23.0	39.2	62.2
	Trans. Salt Marsh	0.8	0.9	6.6	3.6	3.2
	Inland Open Water	0.6	0.6	0.6	0.6	0.6
	Inland-Fresh Marsh	0.5	0.5	0.5	0.5	0.5
	Swamp	0.1	0.1	0.1	0.1	0.1
	Tidal Flat	-	0.3	0.2	5.1	5.8
	Total (incl. water)	**178**	**178**	**178**	**178**	**178**



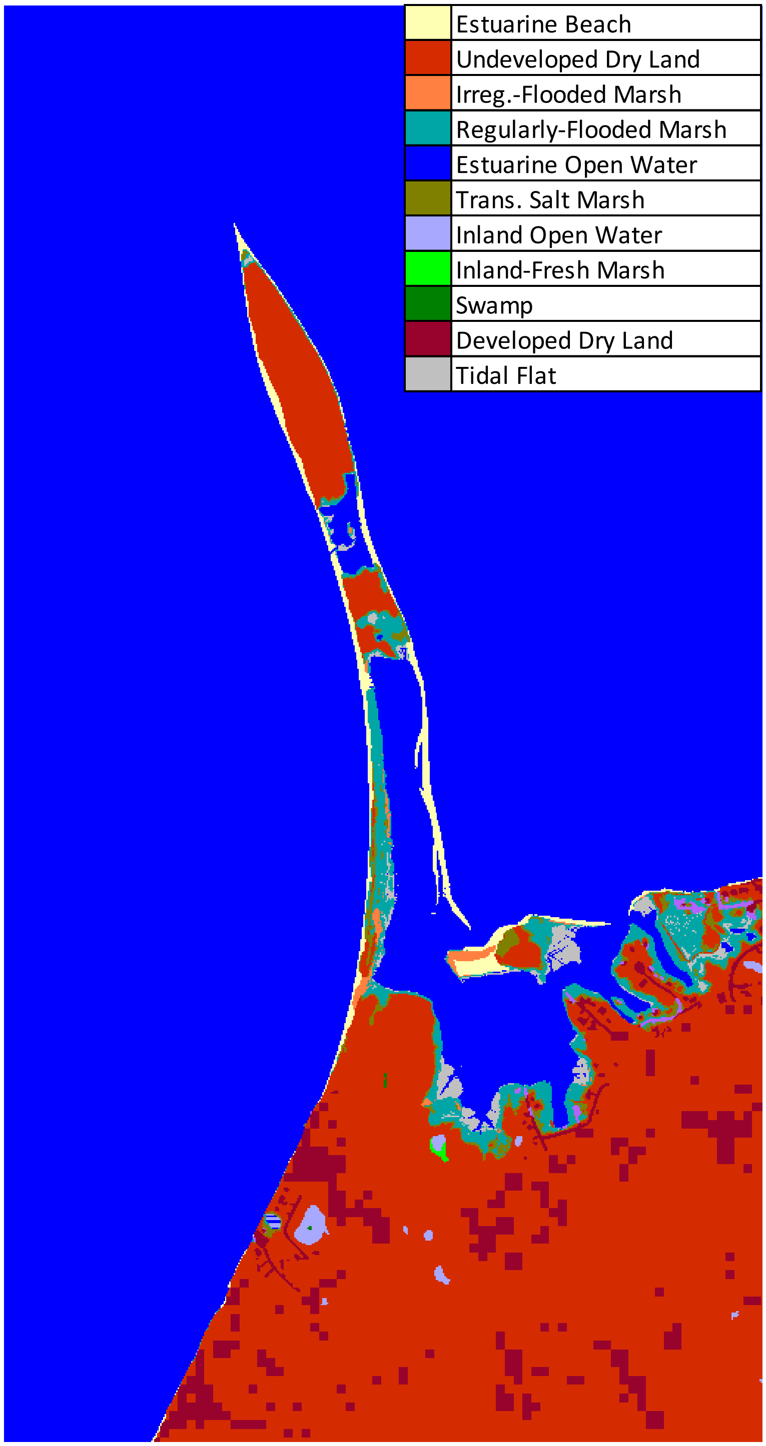
Morton NWR, SLAMM 2010.



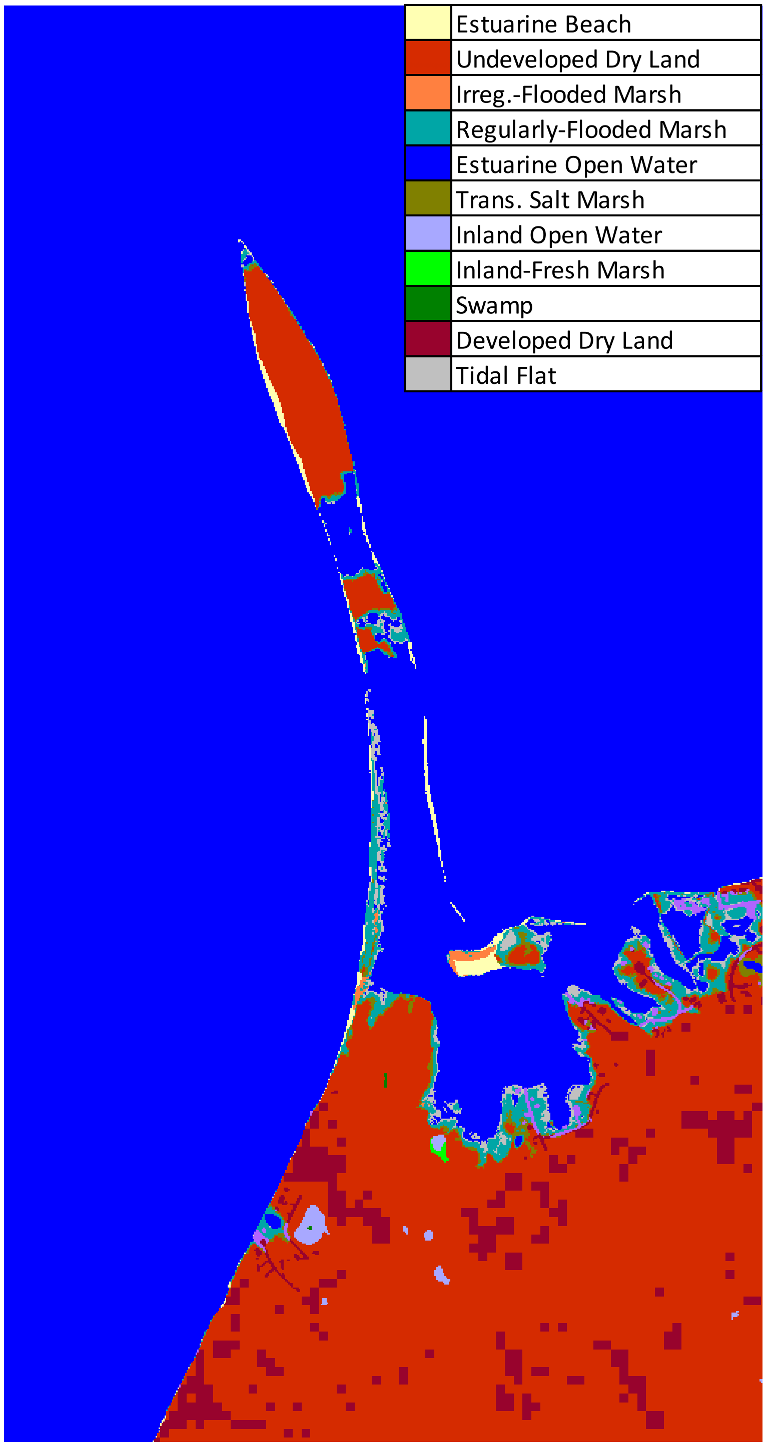
Morton NWR, 2025, 2 m SLR by 2100.



Morton NWR, 2050, 2 m SLR by 2100.



Morton NWR, 2075, 2 m SLR by 2100.



Morton NWR, 2100, 2 m SLR by 2100.

Discussion

SLAMM predictions suggest Elizabeth A. Morton NWR is moderately vulnerable to accelerated SLR. Increases in regularly flooded and transitional marsh are predicted under some accelerated SLR scenarios; these occur due to losses in dry land and irregularly-flooded marsh habitat.

The first application of SLAMM to EA Morton NWR did not include LiDAR-derived elevation data while the current study incorporated Hydro-enforced LiDAR-derived elevation data collected in 2012. In addition, the previous application used a wetland data from the National Wetlands Inventory from 1994, while the current study incorporated data from 2004. Compared to the previous SLAMM analysis of the refuge conducted in 2008, in general, wetlands appear more resilient to accelerated SLR. Whereas 100% of irregularly flooded marsh and estuarine beach were predicted to be lost by 2100 under the IPCC A1B Max scenario in the previous model application, in the current project losses of irregularly flooded marsh and estuarine beach are predicted to be 30% and 22%, respectively. However, near complete loss of irregularly flooded marsh is predicted under the 2m of SLR by 2100 scenario.

While data-layer updates have considerably improved the SLAMM projections reported here, input layers, parameter inputs (as mentioned above), and the conceptual model continue to have uncertainties that should be kept in mind when interpreting these results. Perhaps most importantly, the extent of future sea-level rise is unknown, as are the drivers of climate change used by scientists when projecting SLR rates. Future levels of economic activity, fuel type (e.g., fossil or renewable, etc.), fuel consumption, and greenhouse gas emissions are unknown and estimates of these driving variables are speculative. To account for these uncertainties, results presented here investigated effects for a wide range of possible sea level rise scenarios, from a more conservative rise (0.39 m by 2100) to a more accelerated process (2 m by 2100). To better support managers and decision-makers, the results presented here could be studied as a function of input-data uncertainty to provide a range of possible outcomes and their likelihood.

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