New York State Energy Research and Development Authority

Application of Sea-Level Affecting Marshes Model (SLAMM) to Long Island, NY and New York City

Final Report

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Application of Sea-Level Affecting Marshes Model (SLAMM) to Long Island, NY and New York City

Final Report

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Notice

Abstract

Accelerating Sea-Level Rise (SLR) threatens coastal wetlands and infrastructure. Although the extent of SLR in the coming century remains uncertain, there is a need to understand what changes may occur and where they are most likely. To further preparedness in New York State, NYSERDA has funded the application of the Sea-Level Affecting Marshes Model (SLAMM) to the coast of New York. This application of SLAMM incorporated the most up-to-date wetland layers and LiDAR-derived elevation data with an extensive tide range database and dynamic marsh accretion feedbacks based on mechanistic models of marsh and water quality characteristics. Simulations were run under four New York-specific scenarios of future SLR ranging from 0.72 to 1.72 meters of sea level increase by 2100. Model results indicate the effects of SLR will be spatially variable across the entire study area. Considerable marsh losses are predicted to occur in microtidal regimes behind the barrier islands of Long Island, while the barrier islands themselves are subject to dry land losses. Under moderate rates of SLR, high marshes are predicted to be replaced by low (regularly flooded) marshes, while in higher SLR scenarios, the regularly flooded marshes also converted to tidal flats. Stochastic uncertainty analyses were completed; these provide confidence intervals for projections, spatial maps showing likelihood of land conversions, and statistical indicators to characterize possible future outcomes, thus better assisting decision making.

Keywords

New York State, Sea-Level Rise, Coastal Wetlands, Accretion, Sea-Level Affecting Marshes Model, SLAMM

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Acronyms and Abbreviations List

cm	centimeter
DEM	Digital Elevation Map
ft	Feet
GCM	General Climate Model
GIS	Geographic Information Systems
GT	Great Diurnal Tide Range
HREP	Hudson River Estuary Program
HTU	Half-Tide Units (highest tide each day minus the mean tide level)
LiDAR	Light Detection and Ranging– method to produce elevation data
MEM	Marsh Equilibrium Model
MHHW	Mean Higher High Water (average highest tide each day)
m	meter
mm	millimeter
MLLW	Mean Lower Low Water (average lowest tide each day)
MTL	Mean Tide Level
NAVD88	North American Vertical Datum of 1988
NOAA	United States National Oceanic and Atmospheric Administration
NPS	National Parks Service
NWI	National Wetlands Inventory
NYC	New York City
NYS	New York State
NYSDEC	New York State Department of Environmental Conservation
NYSERDA	New York State Energy Research and Development Authority
PSU	Practical Salinity Units
RIM	Rapid Ice Melt
RMSE	Root Mean Standard Error
SD	Standard Deviation
SLAMM	Sea-level Affecting Marshes Model
SLR	Sea-Level Rise
TSS	Total Suspended Solids
USFWS	United States Fish and Wildlife Service
UVM	University of Vermont
VDATUM	NOAA Product for converting vertical datums
WPC	Warren Pinnacle Consulting, Inc.

Executive Summary

In 2012, the New York State Energy Research and Development Authority (NYSERDA) funded an application of the Sea-Level Affecting Marshes Model (SLAMM) in order to understand the potential effects of accelerated sea-level rise (SLR) on the New York Coast. In this work, SLAMM was applied to 1.43 million acres of coastal New York State, including the Hudson River Estuary south of the Tappan Zee Bridge. Model application incorporated the most up-to-date wetland layers available and LiDAR-derived elevation data that was 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. Model runs were produced in two modes:

- "Deterministic" simulations in which model parameters are represented with their best estimate to reflect the most-likely effect of SLR. Separate deterministic model runs were produced for each of four SLR scenarios.
- "Uncertainty analysis" simulations in which parameters and driving variables (such as SLR scenarios) are represented as distributions reflecting the range of uncertainty in model parameters and measured data. Hundreds of model runs were produced for each study area randomly sampling from these distributions.

Deterministic simulations were produced under four scenarios of future SLR corresponding to the General Climate Model Maximum, 1 meter by 2100, the Rapid Ice Melt (RIM) minimum, and RIM maximum scenarios described in the NY ClimAID Report (ranging from increases of 28.3 to 67.8 inches by 2100; http://www.nyserda.ny.gov/climaid). The model results indicate that the effects of SLR will vary widely across the study area. Serious marsh losses are predicted to occur in microtidal regimes behind the barrier islands of Long Island, while the barrier islands themselves are subject to dry land losses. Under moderate rates of SLR, high (irregularly flooded) marshes are predicted to be replaced by low (regularly flooded) marshes, while in higher SLR scenarios, regularly flooded marshes will begin to be converted to tidal flats. Results indicate that 10% of developed lands and up to 11% of undeveloped lands in the entire study area are subject to regular flooding under the SLR scenarios examined.

In the Hudson study area, the Piermont Marsh is threatened by all but the most conservative SLR scenario examined. Results for Jamaica Bay suggest that its marshes will remain somewhat resilient to the effects of SLR alone, even at the highest SLR scenarios. On the other hand, the developed lands surrounding Jamaica Bay may be subject to significant losses due to inundation. In Nassau County, the acreage of irregularly flooded marsh, the predominant marsh type in the county, is predicted to be reduced by a minimum of 49% by 2100 under the GCM Max scenario and may be lost altogether under the RIM Max scenario. Predictions for Gilgo Beach in western

Suffolk County show significant marsh and dry land conversion by 2100, and under the RIM Max scenario open water is predicted to entirely cover the areas currently covered by marshes. In the eastern portion of Suffolk County, islands and spits appear subject to considerable dry-land conversion. Results from the area around Orient, NY, show significant marsh and dry land vulnerability, with some regions converting to open water under the RIM Max scenario.

A Monte Carlo uncertainty analysis was performed to account for various sources of model uncertainties such as observed-data variability and errors in input data. Uncertainty analyses incorporated the spatial uncertainty of the elevation data and the relationship between vertical datums and water levels. Probability distributions for input parameters such as SLR and erosion were derived for the entire study area, while great diurnal tide range and 30-day inundation height probabilities were derived for subsites within the five study areas. Uncertainty in the derived mechanistic accretion models was also carefully accounted for.

Uncertainty analysis results have provided confidence intervals on model projections, worst and best case scenarios, maps showing likelihood of wetland conversions, and histograms of land-cover categories. Confidence intervals of model results, when plotted against deterministic results, suggest that uncertainty in SLR scenarios is the largest driver in overall model uncertainty.

1 Background

Tidal marshes are dynamic ecosystems that provide significant ecological and economic value. Given that tidal marshes are located at the interface between land and water, they can be among the most susceptible ecosystems to climate change, especially accelerated sea-level rise (SLR). Factors such as elevation of marshes relative to the tides, frequency of inundation, salinity, marsh biomass, subsidence, marsh substrate, and the settling of suspended sediment into the marshes can all affect marsh responses to changing water levels. Because of these factors, a simple calculation of current marsh elevations as compared to future projections of sea level does not provide an adequate estimation of marsh fate.

The Sea-Level Affecting Marshes Model (SLAMM) is widely recognized as an effective model to study and predict wetland response to long-term sea-level rise[1]. The model simulates the dominant processes that affect shoreline modifications during long-term sea-level rise and has been applied in every coastal US state.[2] SLAMM predicts when currently-existing marshes are likely to be vulnerable to SLR as well as predicting locations where marshes will migrate upland in response to changes in water levels. SLAMM provides numerical and spatial outputs; its relative simplicity and modest data requirements allow application at a reasonable cost. Mcleod and coworkers[3] wrote 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."

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1 R. A. Park et al., "Using Remote Sensing for Modeling the Impacts of Sea-level rise.," *World Resources Review* 3 (1991): 184–220.

2 J. G Titus et al., "Greenhouse Effect and Sea-level rise: The Cost of Holding Back the Sea," *Coastal Management* 19, no. 2 (1991): 171–204; R.A. Park, J.K. Lee, and D.J. Canning, "Potential Effects of Sea-Level Rise on Puget Sound Wetlands," *Geocarto International* 8, no. 4 (1993): 99, doi:10.1080/10106049309354433; H. Galbraith et al., "Global Climate Change and Sea-level rise: Potential Losses of Intertidal Habitat for Shorebirds," *Waterbirds* 25, no. 2 (2002): 173, doi:10.1675/1524-4695(2002)025[0173:GCCASL]2.0.CO;2; National Wildlife Federation and Florida Wildlife Federation, *An Unfavorable Tide: Global Warming, Coastal Habitats and Sportfishing in Florida*, 2006; P. Glick, J. Clough, and B. Nunley, *Sea-Level Rise and Coastal Habitats in the Pacific Northwest: An Analysis for Puget Sound, Southwestern Washington, and Northwestern Oregon* (National Wildlife Federation, 2007), http://www.nwf.org/sealevelrise/pdfs/PacificNWSeaLevelRise.pdf; C. Craft et al., "Forecasting the Effects of Accelerated Sea-Level Rise on Tidal Marsh Ecosystem Services," *Frontiers in Ecology and the Environment* 7, no. 2 (March 2009): 73–78, doi:10.1890/070219; P Glick et al., *Sea-Level Rise and Coastal Habitats in Southeastern Louisiana: An Application of the Sea Level Affecting Marshes (SLAMM) Model. Draft Technical Report.* (National Wildlife Federation, July 2011).

3 Elizabeth Mcleod et al., "Sea-Level Rise Impact Models and Environmental Conservation: A Review of Models and Their Applications," *Ocean & Coastal Management* 53, no. 9 (September 2010): 507–17, doi:10.1016/j.ocecoaman.2010.06.009.

The SLAMM model was one of the first landscape-scale models to incorporate the effects of vertical marsh accretion rates on predictions of marsh fates, incorporating this process since the mid-1980s.[4] Marsh accretion is the process of wetland elevations changing due to the accumulation of organic and inorganic matter. Since 2010, SLAMM has incorporated dynamic relationships between marsh types, marsh elevations, tide ranges, and predicted accretion rates. The SLAMM application presented here is one of the first applications in which a mechanistic accretion model has been used to define relationships between tide ranges, water levels, and marsh accretion rates.[5]

Other processes that are accounted for within this SLAMM simulation include dry-land inundation, coastal-wetland erosion, and connectivity of wetland habitats. SLAMM is a relatively simple, nonhydrodynamic model that relies on land elevation and tidal range to predict the future of wetland habitats given projected future SLR. The model is also capable of including spatial maps of uplift or subsidence. A detailed description of model processes, underlying assumptions, and equations can be found in the SLAMM 6.2 Technical Documentation (available at http://warrenpinnacle.com/prof/SLAMM).

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4 R. A. Park et al., "The Effects of Sea-level rise on U.S. Coastal Wetlands," in *The Potential Effects of Global Climate Change on the United States: Appendix B - Sea-level rise* (Washington, DC: U.S. Environmental Protection Agency, 1989), 1–1 to 1–55.

5 J. T Morris et al., "Responses of Coastal Wetlands to Rising Sea Level," *Ecology* 83, no. 10 (2002): 2869–77; Jim Morris, "Marsh Equilibrium Model–Version 3.4," August 2013, https://dcerpstaging.rti.org/Portals/0/ModelFS/MEM3v4.pdf.

2 Methods

2.1 Study Area

The project study area was divided into 5 individual SLAMM projects (Figure 1):

- Hudson.
- New York City.
- Nassau County.
- Western Suffolk County.
- Eastern Suffolk County.

Figure 1. Project study area as broken into five individual SLAMM projects

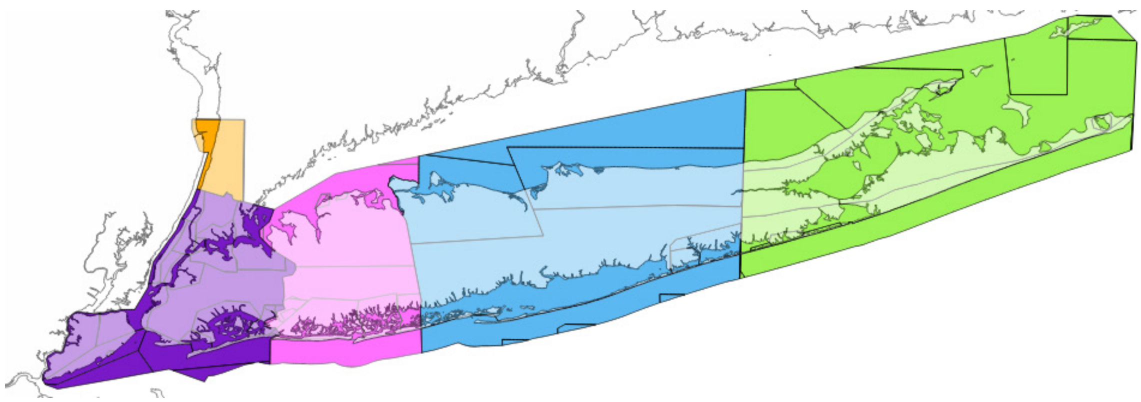


Table 1 breaks down the current land coverage for the entire study area, including over 29,000 acres of marsh lands and over 9,000 acres of beaches. As described in the following section, wetland data sources varied by study area but are heavily representative of the National Wetlands Inventory (NWI) and data provided by the New York State Department of Environmental Conservation (NYSDEC). Land-cover totals presented here do not include some high-elevation dry land in central Long Island (blank regions in Figure 14, Figure 15, and Figure 19) as there were no LiDAR data available for these regions, and they are irrelevant to this SLR-effects study.

Table 1. Land-cover categories for entire New York study area

Land cover type		Area (acres)	Percentage (%)
	Estuarine Open Water	480,207	33
	Open Ocean	379,229	26
	Undeveloped Dry Land	314,383	22
	Developed Dry Land	205,259	14
	Irreg.-Flooded Marsh	22,534	2
	Swamp	8,564	1
	Inland Open Water	7,109	< 1
	Ocean Beach	4,638	< 1
	Estuarine Beach	4,616	< 1
	Regularly flooded Marsh	3,976	< 1
	Tidal Flat	3,444	< 1
	Inland-Fresh Marsh	1,579	< 1
	Trans. Salt Marsh	1,038	< 1
	Tidal Swamp	828	< 1
	Tidal-Fresh Marsh	193	< 1
	Inland Shore	87	< 1
	Rocky Intertidal	63	< 1
	Riverine Tidal	14	< 1
	Ocean Flat	1	< 1
	Total (including water)	1,437,763	100

2.2 Input Raster Preparation

SLAMM is a raster-based model, meaning that input cells are equally sized squares arranged in a grid, like graph paper or a computer-based image. Cells measuring 5 meters by 5 meters were used in this simulation, and each cell contains elevation data, wetland coverage information, and other characteristics such as the presence of dikes or seawalls. This section presents the data sources used in this project and the manipulation steps to create SLAMM input rasters.

2.2.1 Elevation Data

High vertical-resolution elevation data may be the most important SLAMM data requirement. Elevation data demarcate where salt water is predicted to penetrate and, when combined with tidal data, the frequency of inundation for wetlands and marshes.

Hydrologic enforcement. Hydrologic enforcement is the process of defining water-flow pathways to determine where bridges and culverts contained in the digital elevation map (DEM) may be blocking hydrologic flow. Hydrologically enforced DEMs were derived from several sources:

- The elevation layer covering the area of New York City (NYC) was obtained by combining 2010 LiDAR data covering New York City and 2012 U.S. Army Corps of Engineers (USACE) Post-Sandy LiDAR covering the coastlines.
- For Long Island and Hudson regions, elevations were from 2011-2012 New York LiDAR data.

Multiple steps were used to produce a hydro-enforced DEM for the full Hudson/NYC/Long Island project area.

- **Project Boundary Derivation**: For the Long Island and Hudson study areas, LiDAR data were reprocessed for locations at or below 5.5 meters above mean tide level to limit the scope of data processed. (For New York City, the entire LiDAR data set was used.)
- **Data Preparation**: Data were re-projected to project specifications and re-sampled to the 5-meter cell size used in all model runs.
- **Creation of "Breaklines" for Hydrologic Enforcement:** Water-flow pathways were defined to determine where bridges and culverts included in the digital elevation map may be blocking hydrologic flow in the model. Road centerlines were intersected with water flow lines to determine locations to examine. Culverts and bridges were identified using NYS orthoimagery.
- **DEM Hydrologic Enforcement**: Water flow pathways were enforced and written into the project DEMs.

The full set of technical details regarding this geographic information system (GIS) processing can be found in Appendix A.

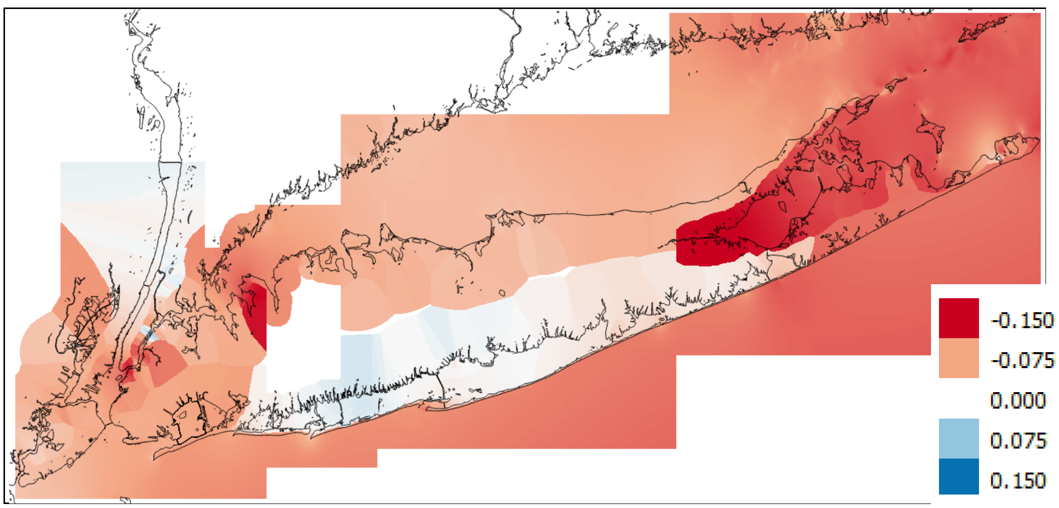
SLAMM Simulation. When the previously described procedures were complete, a preliminary inundation and connectivity analysis was run for the study area using SLAMM. This type of analysis illustrates the frequency of tidal inundation for coastal habitats. This analysis, along with correspondence with NYS stakeholders, allowed us to identify areas that were either inundated too frequently or not frequently enough. When water pathways were inadequately represented, the combined DEMs were further edited by Warren Pinnacle Consulting. In some cases, additional areas were designated as "diked" to capture the effects of natural or man-made impoundments that were not included in our original data set. In other cases, additional culverts and bridges were manually removed where water flows had been impeded based on DEM elevations.

Slope. The slope in degrees of each cell is a SLAMM model input and is used to calculate partial cell conversions. Slope rasters were derived from the hydro-enforced DEMs created above using the "slope tool" in Esri's spatial analyst.

2.2.2 Elevation Correction

Elevation data is commonly provided in a vertical datum (NAVD88) that needs to be adjusted to a tidal basis to predict locations of marsh habitat. NOAA's VDATUM modeling product version 3.2[6] was used to convert elevation data from the NAVD88 vertical datum to a Mean Tide Level (MTL) basis, which is used as the vertical datum in SLAMM. Conversion of wetland elevations to a tidal basis is required as coastal wetlands generally inhabit elevations relative to tide ranges.[7] VDATUM does not provide conversions over dry land; dry-land elevations were corrected using the VDATUM correction from the nearest open water cell. Corrections in the study areas ranged from approximately -0.15 m to 0.1 m. A spatial map of corrections is shown in Figure 2.

Figure 2. VDATUM-derived correction values (meters)



For the Hudson study area, an alternative datum correction analyses carried out by the Stevens Institute of Technology was considered. However, for the southern portion of the Hudson River, represented by our study area, the difference between the VDATUM product and the data from the Stevens Institute was about 1 cm, well within the limits of uncertainty of the LiDAR data. Therefore, the NOAA VDATUM product was used throughout the study area.

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6 U.S. Department of Commerce / NOAA / NOS, "VDatum: NOAA/NOS/Vertical Datum Transformation," accessed November 25, 2013, http://vdatum.noaa.gov/.

7 Karen McKee and Patrick, "The Relationship of Smooth Cordgrass (Spartina Alterniflora) to Tidal Datums: A Review," *Estuaries* 11, no. 3 (1988): 143–51.

2.2.3 Sources of Wetland Layers and Relationship to SLAMM Categories

Several data sources were used to characterize wetland land cover. A detailed presentation for the different study areas is presented in the following section.

The preparation for all wetland layers required several steps, including overlaying all data layers in order of their priorities and conversion to raster maps with 5-m cell resolution. A full accounting of the GIS steps undertaken in this process may be found in Appendix A.

Translating National Wetland Inventory (NWI) data to SLAMM categories was accomplished using Table 4 of the SLAMM Technical Documentation as produced with assistance from Bill Wilen of the National Wetlands Inventory.[8] Specific steps taken for site-specific wetlands data are detailed in the following section.

2.2.3.1 New York City – Staten Island, Queens, and The Bronx

Several sources of wetland data were combined to create the wetland layer used in the New York City study area. The primary wetland layer was provided by the New York State Department of Environmental Conservation (NYSDEC) and dated 1999. The classification of these tidal wetlands has been translated to SLAMM wetland categories according to Table 2.

Within Table 2, the “SM” NYSDEC class includes coastal shoals, bars, and mudflats that are exposed at low tide, but also includes areas that are permanently covered by water (to a maximum depth of approximately one foot at low tide). These areas were initially categorized as SLAMM Tidal Flats and the model converted these regions to open water in locations where they are permanently below low tide.

The secondary source of wetland data was provided by the NWI with photo dates ranging between 1994/1995 for Staten Island, 1985/1995/2004 for The Bronx, and 2004 for Queens. For the New York City study area, this layer was used to classify areas identified as “AA,” “DS,” and “DA” in the NYSDEC 1999 layer, and also to define locations of freshwater (noncoastal) wetlands.

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8 Jonathan Clough et al., “SLAMM 6.2 Technical Documentation,” December 7, 2012, http://warrenpinnacle.com/prof/SLAMM6/SLAMM6.2_Technical_Documentation.pdf.

Table 2. Translation of wetland categories from NYSDEC to SLAMM

NYSDEC 1999		SLAMM	
Symbol	**Class Short Description**	**Category**	**Description**
SM	Coastal Shoals, Bars and Mudflats	11	Tidal Flat
LZ	Littoral Zone	17	Estuarine Water
FC	Formerly Connected	5	Regular Flooded Marsh
SV	Vegetated Coastal Shoals, Bars and Mudflats	25	Vegetated Tidal Flat
BV	Broad-Leaf Vegetation	6	Tidal Fresh Marsh
IM	Intertidal Marsh	8	Regular Flooded Marsh
FM	Fresh Marsh	6	Tidal Fresh Marsh
GV	Graminoid Vegetation	6	Tidal Fresh Marsh
HM	High Marsh	20	Irregular Flooded Marsh
SS	Swamp Shrub	23	Tidal Swamp
ST	Swamp Tree	23	Tidal Swamp
FR	Fern Marsh	6	Tidal Fresh Marsh
TRD	Dead Tree Area	7	Transitional
AA	Adjacent Area	For these three categories a secondary source of wetland data (the NWI data) was used to define the SLAMM category.	
DS	Dredged Spoil		
DA	Default Area		

In addition to the two wetland layers described above, a third layer developed by Eymund Diegel, formerly of the Department of Parks and Recreation, New York City, has been used to remove wetlands that have since been destroyed or have disappeared. (This 2013 data layer only indicated which wetlands have been lost and could not be used as a primary data layer.)

Finally, as the boundary between regularly and irregularly flooded marsh was not well defined in the above datasets, this boundary was partially defined based on wetland elevations relative to tide ranges. Areas initially identified as regularly flooded marsh but whose elevation was high in the tidal frame (height greater than 120% of Mean Higher High Water [average highest tide each day; MHHW]), were converted to irregularly flooded marsh. Conversely, irregularly flooded marshes with initial elevations below 50% of MHHW were converted to regularly flooded marshes. The resulting layer was reviewed and corrected by the staff at the NYC Department of Parks and Recreation to better reflect current marsh to dry-land boundaries, to identify as transitional marsh areas that also receive fresh water, and to identify missing tidal-flat areas.

2.2.3.2 New York City – Jamaica Bay

For Jamaica Bay and the surrounding shorelines (Figure 3), the wetland information and procedures used to create the wetland layer are described in the following section.

The primary wetland layer is a 2008 wetland raster provided by Mark Christiano, GIS specialist of the National Park Service (NPS) - Gateway National Recreation Area. The initial raster has a 0.6 m resolution that has been re-sampled at 5 m for this study. The classification of these tidal wetlands has been translated to SLAMM wetland categories according to Table 3.

Figure 3. Satellite image of Jamaica Bay, NY

Table 3. Translation of wetland categories from NPS layer of Jamaica Bay to SLAMM

NPS 2008		SLAMM	
Code	**Description**	**Code**	**Name**
1	Open water	17	Estuarine Open Water
2	Mudflat	11	Tidal Flat
3	Spartina <50%	8	Regularly flooded Marsh
4	Spartina >50%	8	Regularly flooded Marsh
5	High Marsh	20	Irregularly flooded Marsh

As previously described, the NYSDEC layer was used to fill areas not classified by the primary layer (Table 2). NWI data (2004) was used to classify “AA,” “DS,” and “DA” codes from the NYSDEC layer. In the Jamaica Bay region, the “SM” category of the NYSDEC layer was also reclassified using NWI information. In the primary layer (Christiano) most of these “SM” areas are categorized as open water. The layer developed by Eymund Diegel does not affect this area.

2.2.3.3 Long Island – Nassau and Suffolk County, North and South Shores

For this study area, the 2004 NWI layer was used to describe tidal and fresh water wetlands.

2.2.3.4 Hudson River – Up to Tappan Zee bridge

The wetland layer describing wetlands on the shore of the Hudson River was constructed as follows:
The primary tidal wetland layer was from the NYSDEC Hudson River Estuary Program (HREP) dated 2007.
The relationship between these wetland categories and SLAMM wetland categories is shown in Table 4.

Table 4. Translation of wetland categories from NYSDEC HREP 2007 to SLAMM categories

NYSDEC HREP 20007		SLAMM	
Symbol	**Vegetation Class Description**	**Category**	**Description**
UP	Upland/Non-Wetland, Railroad	2	Undeveloped Dry Land
OW	Open Water, Panne	17	Estuarine Water
UF	Unvegetated Flats	11	Tidal Flat
LI	Vegetated Lower Intertidal, *Scirpus pungens*, *Acorus calamus*/mix, *Polygonum* sp.	6	Tidal Fresh Marsh
TA	*Typha angustifolia*	20	Irregularly flooded Marsh
UI	*Lythrum salicaria* /mix, *Scirpus* sp., *Acorus calamus* /mix, *Polygonum* sp.	20	Irregularly flooded Marsh
PA	*Phragmites australis*	20	Irregularly flooded Marsh
SM	Salt Meadow	8	Regular Flooded Marsh
WS	Wooded Swamp	23	Tidal Swamp
SS	Scrub/Shrub	7	Transitional Marsh
TN	*Trapa natans*	17	Estuarine Water
SV	Submerged Aquatic Vegetation	17	Estuarine Water
SA	*Spartina alterniflora*	8	Regularly flooded Marsh

The "UP" category (upland) was initially categorized as "Undeveloped Dry Land," although it may also contain "Developed Dry Land" (e.g., railroad). The impervious layer information, which is an input grid in SLAMM, was used to distinguish developed versus undeveloped dry land. The "UF" category (unvegetated flats) has been assigned to "Tidal Flats," although it may also include areas that in other wetland layers (e.g., National Estuarine Research Reserve) are categorized as Salt Panne, which is somewhat vegetated. The secondary wetland layer used was a 1995 wetland layer from NWI. Its primary function was to identify freshwater wetlands and inland water bodies within the Hudson River study area.

2.2.4 Dikes and Impoundments

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. However, no additional diked areas in the study area were found when examining the U.S. Army Corps of Engineers National Levee Database.[9]

La Guardia Airport was assumed to be permanently protected by existing and future seawalls (SLAMM simulations will not predict inundation within this area). At time-zero, initial-condition elevation data were allowing regular inundation from the east side of the airport. While La Guardia Airport has occasionally been flooded in the past, currently existing seawalls were not effectively represented in the initial-condition data set. In addition, there is an ongoing engineering project to improve airport protection against inundation.[10]

When dikes or seawalls are missing from the SLAMM data layers, immediate inundation of lands behind the missing levees is usually predicted. This predicted flooding often helps to identify locally managed dikes or levees missing from initial data layers. However, careful examination of initial results did not discover any additional locations with dikes or seawalls within the study area (other than La Guardia Airport as previously discussed).

2.2.5 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).

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9 "US Army Corps of Engineers National Levee Database.," 2014, http://nld.usace.army.mil.

10 Jonathan Allen, "New York to Spend $37.5 Million on LaGuardia Airport Flood Defenses," *Reuters*, November 17, 2013, http://www.reuters.com/article/2013/11/17/us-usa-newyork-laguardia-idUSBRE9AG0FN20131117.

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.

The NYC Land Cover data was created earlier by UVM under a separately funded project as a raster with 3-foot cell resolution. This raster was re-projected from the State Plane Coordinate System with units in feet to UTM projection with units in meters. The raster values were then reclassified to define non-impervious and impervious regions. A similar process as above, creating larger percent-impervious cells based on 25 smaller cells, was then completed. Because the original cells were not in metric resolution, the new metric raster had a cell size of 4.57 m (a 5×5 equivalent of the 3-ft resolution original raster). The final raster was therefore re-sampled to a 5-m cell size for consistency with the remaining model input data sets.

Creation of high-horizontal-resolution percent impervious data was only completed for regions below 5 m above mean-tide level. This process should capture all developed areas potentially vulnerable to SLR by the year 2100.

2.3 Model Timesteps

SLAMM simulations were run from the date of the initial wetland cover layer to 2100 with model-solution time steps of 2025, 2040, 2055, 2070, 2085, and 2100. Maps and numerical data were output for the years 2025, 2055, 2085, and 2100.

2.4 Sea-level Rise Scenarios

The sea-level rise (SLR) scenarios used in this analysis were developed in conjunction with the project's advisory committee. Scenarios correspond to the maximum of the central range of the general climate model (GCM) ensemble and the minimum and maximum of the central range of the rapid ice melt (RIM) estimates as described in the ClimAID report,[11] as well as the intermediate scenario of 1 meter of SLR by 2100 (39.4 inches). The base year for these scenarios is 2002. The "rapid ice-melt scenarios" are based on the potential acceleration of ice-melt rates in the Greenland and West Antarctic ice sheets as well as paleoclimatological studies. Table 5 and Figure 4 show details of SLR relative to the base year of 2002 used in the four scenarios examined.

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[11] Rosenzweig, C., W. Solecki, A. DeGaetano, M. O'Grady, S. Hassol, P. Grabhorn (Eds.). 2011. *Responding to Climate Change in New York State: The ClimAID Integrated Assessment for Effective Climate Change Adaptation. Technical Report.* New York State Energy Research and Development Authority (NYSERDA), Albany, NY..

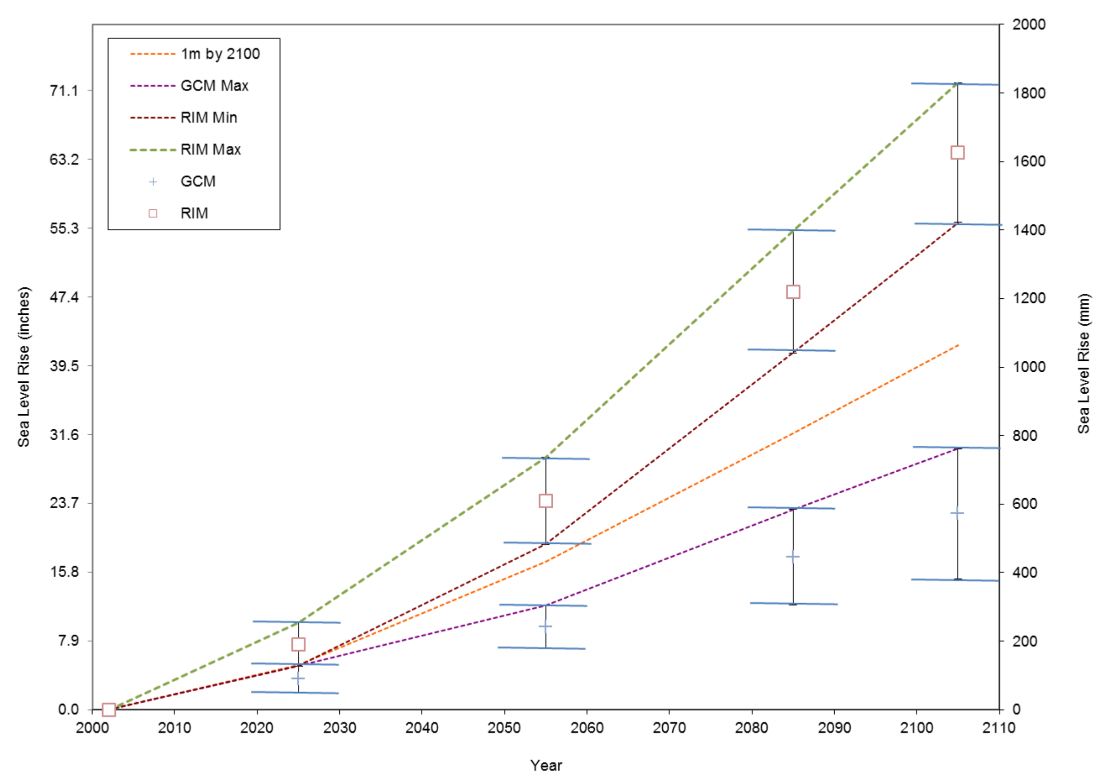
Note that toward the end of this project, NYSERDA and the ClimAID researchers released refined and updated projections for sea level rise. Although too late to be incorporated into this project, the projections are similar enough that significant changes in model results would not be expected..

Table 5. Sea-level rise projections used in SLAMM modeling (in inches)

Scenario	2025	2055	2085	2100
General Climate Model Maximum	5	12	23	28.3
1 m by 2100	5.1	17	31.8	39.4
Rapid Ice Melt Minimum	5	19	41	52.3
Rapid Ice Melt Maximum	10	29	55	67.8

Figure 4. Sea-level rise scenarios simulated using SLAMM compared to the General Climate Model and Rapid Ice Melt model predictions

Horizontal lines on error bars represent the decadal timescale over which predicted SLR may occur..



2.5 Historic Sea-Level Rise Rates

The SLR scenarios shown in Table 5 and Figure 4 are "relative" sea-level rise estimates. This means that SLAMM scenarios do not need to be corrected for differentials between local (or relative) SLR and global (or eustatic) SLR trends. For this reason, within the model, the historic SLR was set to zero in order to model relative sea-level rise rather than eustatic SLR.

According to the National Oceanic and Atmospheric Administration (NOAA), historic sea-level rise trends along the New York coast range from 2.35 mm/yr at Kings Point to 2.78 mm/yr in Montauk. Therefore, each of the four scenarios simulated represents a significant acceleration of SLR from the historical trend.

2.6 Tide Ranges

Tide range data were collected from NOAA tidal datums and tide prediction tables for 2011 within the study area and from the Long Island Shore historical tide database (http://www.lishore.org/). SLAMM requires the great diurnal tide range (GT) as a direct input, along with mean tide range and other tidal datum information provided by the NOAA tidal datums. NOAA's tide prediction tables provide the mean tide range, which was converted to GT by multiplying by the average ratio between mean tide range and great diurnal tide range derived from the NOAA tidal datums.

Data from the LIShore database were available as water levels, and the GT was calculated by determining the maximum and minimum water level for each day for the entire range of available data (0.5 to 8.5 years). The 95^{th} and 5^{th} percentiles were determined, and the GT was calculated as the average within this range to exclude outliers. The GT values in the project area varied from a maximum of 2.5 m at the Bayville Bridge in Oyster Bay, Nassau County, to 0.2 m in Great South Bay, Western Suffolk County. Maps of GT data are provided in Appendix B.

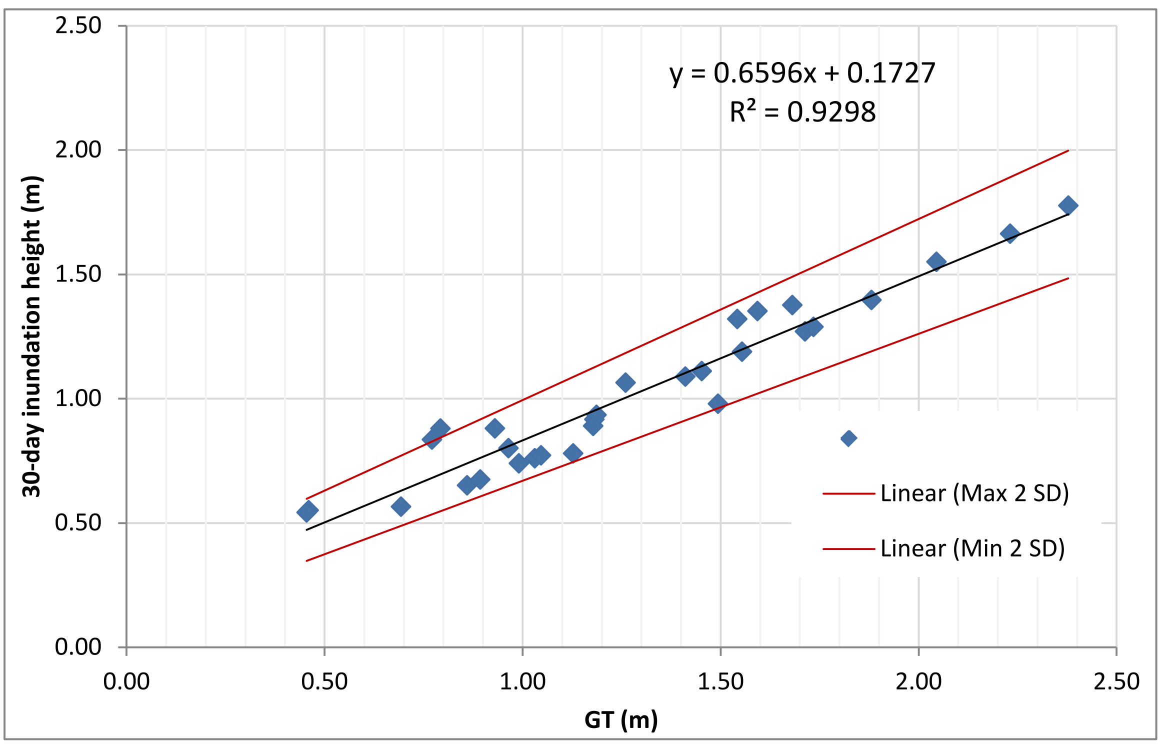
2.7 Salt Elevation

The salt-elevation parameter in SLAMM defines the boundary between coastal wetlands and dry lands (or fresh-water wetlands). This elevation, relative to mean-tide level, is determined through analysis of "higher high" water levels in NOAA tide records. In practice, we have 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 multiple locations in the study area from NOAA verified water-level data as well as the data available from Long Island Shore records. The length of time analyzed varied from 6 months to more than 8 years depending on the available data at each location. All the NOAA data records were 5 years in length (except Mattituck Inlet, where only 2 years of data were available). Regression analysis of the calculated salt elevations versus the great diurnal tide ranges for the entire study area showed a clear correlation between the two variables ($R^2 = 0.93$). This relationship was used to derive site-specific salt elevations based on the great diurnal tide range applied.

In addition, the uncertainty on the regression line was determined and used to guide model calibration (Figure 5). During the initial model runs, if too much dry-land conversion immediately was predicted to occur, the salt-elevation parameter was sometimes reduced as part of model calibration. However, this calibration was kept within two standard deviations of the mean (i.e., 95% confidence interval of the mean).

Figure 5. Great Diurnal Tide Range to 30-Day Inundation Height/Salt Elevation relationship derived from NOAA and Long Island Shore data



2.8 Accretion Rates

Wetland accretion is the upward movement of marshes due to the sequestration of inorganic sediments and biogenic production. Because of this process, coastal marshes and wetlands do not maintain a static elevation but rather tend to move vertically as a function of how frequently they are flooded. To a certain extent, this causes marshes to be less vulnerable to SLR than they would be if their platform elevations were fixed. In this project, mechanistic modeling was used to estimate the response of regularly flooded marsh elevations to different sea-levels. The effects of uncertainty in this relationship were also explored in the uncertainty analysis.

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[12] suggest this value to be appropriate based on Pb-210 measurements. Tidal Fresh Marsh accretion was set to 5 mm/yr based on data presented by Neubauer.[13] 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.[14]

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.

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12 Sean A. Graham et al., "Forms and Accumulation of Soil P in Natural and Recently Restored peatlands—Upper Klamath Lake, Oregon, USA," *Wetlands* 25, no. 3 (2005): 594–606; Christopher B. Craft and William P. Casey, "Sediment and Nutrient Accumulation in Floodplain and Depressional Freshwater Wetlands of Georgia, USA," *Wetlands* 20, no. 2 (2000): 323–32.

13 S.C. Neubauer et al., "Sediment Deposition and Accretion in a Mid-Atlantic (U.S.A.) Tidal Freshwater Marsh," *Estuarine, Coastal and Shelf Science* 54, no. 4 (April 2002): 713–27, doi:10.1006/ecss.2001.0854; Scott C. Neubauer, "Contributions of Mineral and Organic Components to Tidal Freshwater Marsh Accretion," *Estuarine, Coastal and Shelf Science* 78, no. 1 (2008): 78–88.

14 Christopher Craft, personal communication, "Tidal Swamp Accretion," January 30, 2008; Christopher Craft, personal communication, May 9, 2012.

2.9 Tidal Salt Marsh

The current SLAMM application accounts for the important feedbacks between tidal marsh accretion rates and SLR. As Kirwan et al.,[15] described:

> "Coastal ecosystems are known to be highly dynamic environments that have significant capacity to adjust to changes in rates of SLR through non-linear feedback mechanisms. In tidal marshes and mangroves, for example, increasing inundation leads to higher rates of sediment deposition, which helps tidal wetlands keep up with SLR.[16] In salt marshes, vegetation growth is typically more rapid at low elevations and in years of anomalously high sea level.[17] potentially enhancing sediment trapping and organic matter accretion, and limiting erosion.[18] These types of ecogeomorphic feedbacks likely explain the persistence of wetlands within the intertidal zone over thousands of years in the stratigraphic record[19], and observations of accretion rates that are highest in regions with historically high rates of SLR."[20]

In this project, 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.

2.9.1.1 Irregularly Flooded Marsh

The locations of measured accretion data that have been identified as irregularly flooded marsh are summarized in Table 6.

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15 Matthew L. Kirwan et al., "Limits on the Adaptability of Coastal Marshes to Rising Sea Level," *Geophysical Research Letters* 37, no. 23 (2010), http://www.agu.org/journals/gl/gl1023/2010GL045489/2010gl045489-txts01.doc.

16 Denise J Reed, "The Response of Coastal Marshes to Sea-level Rise: Survival or Submergence?" *Earth Surface Processes and Landforms* 20, no. 1 (February 1, 1995): 39–48, doi:10.1002/esp.3290200105.

17 Morris et al., "Responses of Coastal Wetlands to Rising Sea Level."

18 Sergio Fagherazzi, Marco Marani, and Linda K. Blum, *The Ecogeomorphology of Tidal Marshes* (American Geophysical Union, 2004).

19 Alfred C. Redfield, "Development of a New England Salt Marsh," *Ecological Monographs* 42, no. 2 (April 1, 1972): 201–37, doi:10.2307/1942263.

20 Donald R. Cahoon et al., "Coastal Wetland Vulnerability to Relative Sea-Level Rise: Wetland Elevation Trends and Process Controls," in *Wetlands and Natural Resource Management* (Springer, 2006), 271–92, http://link.springer.com/chapter/10.1007/978-3-540-33187-2_12.

Table 6. Irregularly flooded marsh accretion data

Location	Study area	Accretion or Elevation change (red) (mm/yr)	Accretion or Elevation change (red) Standard Deviation (mm/yr)	Elevation (m, NAVD88 from LiDAR)	Great Diurnal Tidal Range - GT (m)	Method	Source
Hubbard- A	Bays	2.30	0.20	0.50	0.96	210 Pb	Kolker (2005)[21]
Hubbard- G	Bays	3.00	0.30	0.50	0.96	210 Pb	Kolker (2005)
Alley Pond (Queens, NY)	North	3.50	1.30	1.40	2.47	210 Pb	Cochran et al. (1998)
Flax Pond, (LI, NY)	North	2.10	0.40	0.93	2.36	210 Pb	Cochran et al. (1998)
Flax Pond, (LI, NY)	North	5.50	not reported	0.93	2.36	210 Pb	Armentano and Woodwell 1975
Flax Pond, (LI, NY)	North	3.60	not reported	0.93	2.36	historical record	Flessa et at. 1977
JB- JoCo Marsh	South	4.40	0.30	0.97	1.83	210 Pb	Kolker (2005)
CR- A	South	3.30	0.30	0.37	0.41	210 Pb	Kolker (2005)
Indian Island	Bays	2.92	0.62	0.50	0.96	SET	Maher TNC
Accobonac	Bays	3.72	0.70	0.33	0.86	SET	Maher TNC
Indian Island	Bays	6.20	0.78	0.50	0.96	SET	Maher TNC
Pine Neck	South	2.51	0.95	0.25	0.90	SET	Maher TNC
Pine Neck	South	7.94	0.84	0.26	0.90	SET	Maher TNC
Smith Point	South	7.19	0.42	0.28	0.41	SET	Maher TNC
Wellington-Wertheim	South	4.41	0.11	0.30	0.41	SET	Maher TNC

Data 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 6. The linear estimate used in modeling is slightly over 4 mm/year of accretion with a very slight increase at lower marsh elevations.

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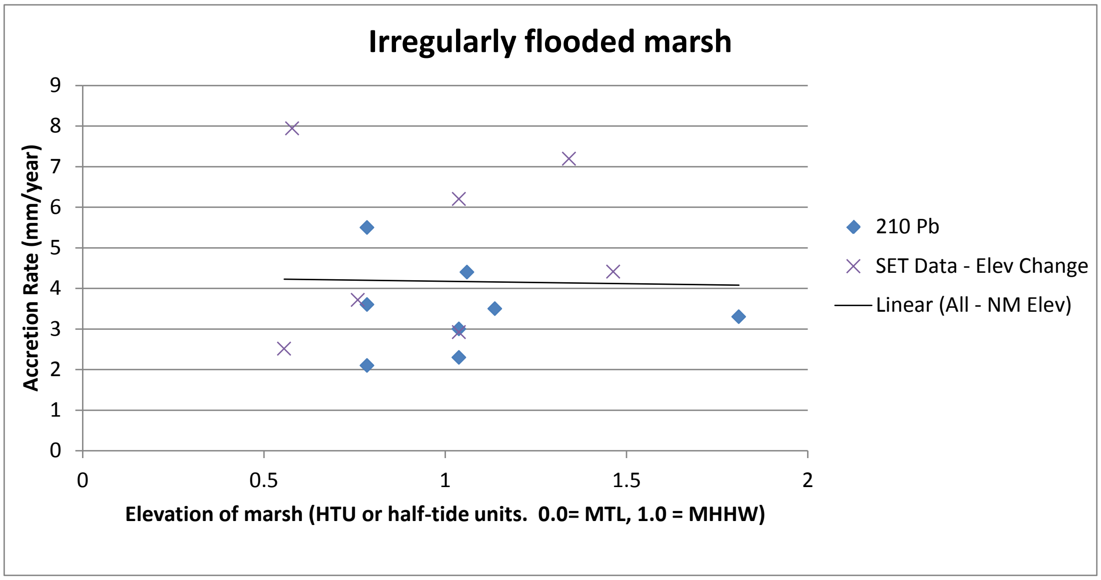
[21] Alexander Samuel Kolker, "The Impacts of Climate Variability and Anthropogenic Activities on Salt Marsh Accretion and Loss on Long Island," 2005.

Figure 6. Irregularly flooded marsh accretion model used for all sites



2.9.1.2 Regularly Flooded Marsh

For this type of marsh, 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[22] to site-specific data. The use of MEM is attractive for several reasons:

- MEM describes feedbacks in marsh accretion rates, is backed up by existing data, and accounts for physical and biological processes that cause these feedbacks. Alternatively, available accretion data could be fit with a simple mathematical function. However, these data are often not available. Furthermore, using a mechanistic model such as MEM helps explain the causes for feedbacks between accretion and elevation and therefore tells a more compelling story.
- MEM can be extrapolated to alternative geographic areas. For example, the model can provide predictions in locations where there are no accretion data available, but other physical/biological parameters are available. These parameters can include suspended sediment concentrations or different tidal regimes.
- Perhaps most importantly, MEM can be extrapolated to elevations in the tidal frame where marshes do not currently exist and therefore accretion data are not available. For example, marshes do not tend to occupy elevations low in the tidal frame (near MTL) unless they have been subject to increased rates of SLR. Therefore a mechanistic model may be required to predict rates of marsh accretion under high-SLR scenarios.

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22 Morris et al., "Responses of Coastal Wetlands to Rising Sea Level"; James T. Morris et al., "Assessment of Carbon Sequestration Potential in Coastal Wetlands," in *Recarbonization of the Biosphere* (Springer, 2012), 517–31, http://link.springer.com/chapter/10.1007/978-94-007-4159-1_24; Morris, "Marsh Equilibrium Model–Version 3.4."

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.

Elevations relative to accretion rates were derived by comparing the location provided in the citations to the corresponding project area DEM (Table 7). As previously noted, there is significant uncertainty in terms of assigning elevations to these marsh platforms.

Table 7. Regularly flooded marsh accretion data

Location	Accretion or Elevation change (red) (mm/yr)	Accretion or Elevation change (red) Standard Deviation (mm/yr)	Elevation (m, NAVD88 from LiDAR)	Great Diurnal Tidal Range - GT (m)	Method	Source	Where applied
Shelter Island (LI, NY)	3	2.7	0.48	0.95	210 Pb	Cochran et al. (1998)	Bays
Bass Creek	5.0	0.3	0.30	0.85	SET	Maher TNC	Bays
Cedar Beach	4.4	0.9	0.35	0.80	SET	Maher TNC	Bays
Hubbard Creek	4.3	0.5	0.45	0.96	SET	Maher TNC	Bays
Mashomack Point	7.0	0.7	0.15	0.85	SET	Maher TNC	Bays
Caumsett Park (LI, NY)	4.1	3.3	-0.14	2.50	210 Pb	Cochran et al. (1998)	North LI
Nissequogue- B	4	0.3	0.15	2.36	210 Pb	Kolker (2005)	North LI
JB- Big Egg	3.8	0.3	0.04	1.73	210 Pb	Kolker (2005)	South LI
HB- Smith D	1.4	0.1	0.67	1.30	210 Pb	Kolker (2005)	South LI
HB- Smith B	3.3	0.4	0.61	1.30	210 Pb	Kolker (2005)	South LI
HB- Hewlett	5	1.2	-0.15	1.45	210 Pb	Kolker (2005)	South LI
JB- East High	2.8	0.4	0.40	1.83	210 Pb	Kolker (2005)	South LI
CR- B	2.7	0.3	0.47	0.41	210 Pb	Kolker (2005)	South LI

2.9.2 Suspended Sediment

Suspended sediment data (in the form of total suspended solids or TSS) were collected from the U.S. EPA STORET Data Warehouse,[23] the New York-New Jersey Harbor & Estuary Program,[24] and the Peconic Estuary Program.[25] The average measurement of 20 milligram per liter (mg/L) for the Hudson study area is relatively high compared to other portions of the study area (shown in Figure 7). However, it is at the low end of the 20-40 mg/L range for the majority of the Hudson River Estuary described by Woodruff and coworkers.[26] Table 8 presents the averages obtained when the TSS data was analyzed by region.

Table 8. Average TSS by study area

Area	Average TSS (mg/L)	Standard Deviation (mg/L)	n
Long Island Sound (North LI)	11.0	8.3	85
Peconic Bay System	11.9	4.6	36
South Shore LI	13.7	5.8	54
NY Harbor/ Staten Island	8.2	4.4	20
Hudson River (to Tappan Zee Bridge)	20.1	17.1	23

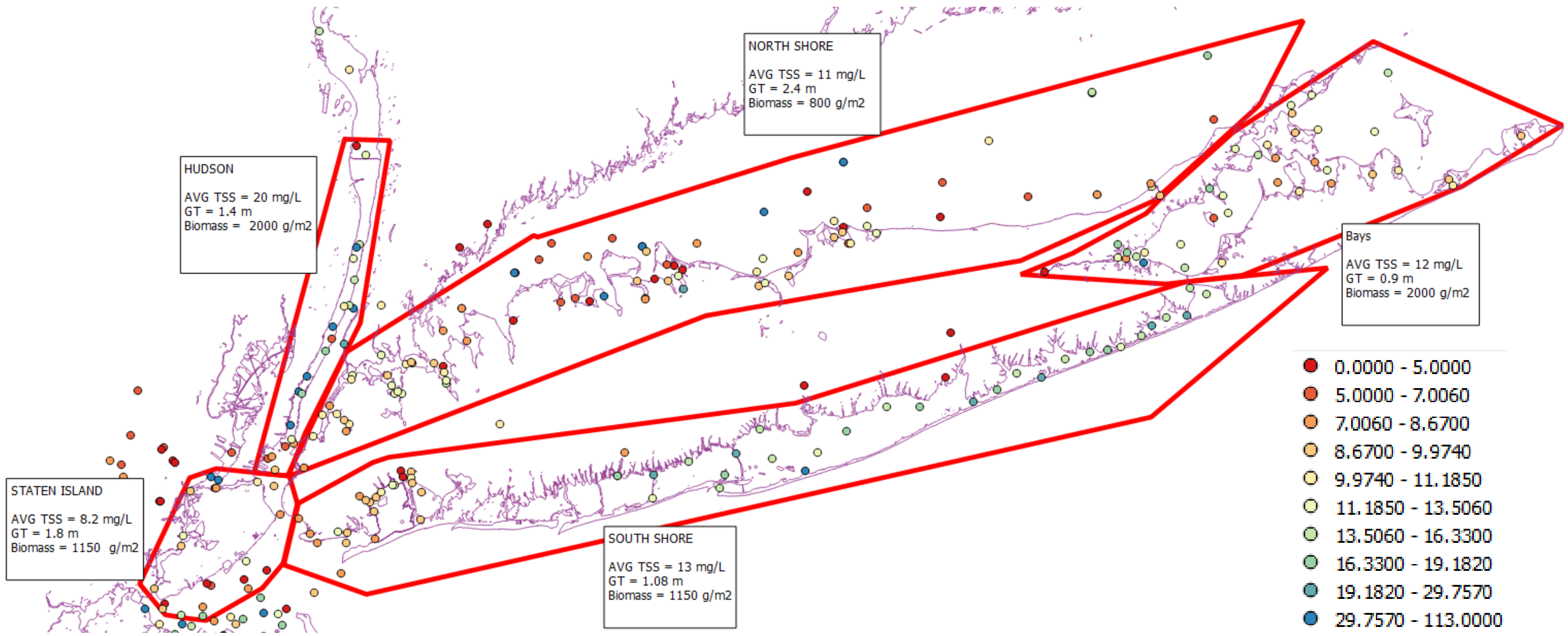
23 http://cfpub.epa.gov/surf/state.cfm?statepostal=NY

24 http://www.harborestuary.org

25 https://gisportal.suffolkcountyny.gov/home/item.html?id=58cb2a1108ff4ccea11716cec9175f65

26 Jonathan D. Woodruff et al., "Seasonal Variation of Sediment Deposition in the Hudson River Estuary," *Marine Geology* 179, no. 1 (2001): 105–19.

Figure 7. Map of Suspended Sediment data used (mg/L) for each accretion area along with GT and Biomass assignments



2.9.3 Marsh Biomass

Relatively few studies on marsh biomass are available within the study area. On the North Shore of Long Island Sound, Anisfeld and Hill measured a maximum "net aboveground primary production" in a *Spartina alterniflora* marsh in Guilford, CT, of 250 grams of carbon per square meter per year.[27] This value can be converted into a biomass basis given that aboveground organic carbon content of *Spartina alterniflora* is generally between 39 and 44%.[28] Assuming that this ratio is 39.2% (Middleburg et al.[29]), the peak biomass for the Guilford Marsh can be estimated at 625 g/m^2. Similarly, values between 700 and 1000 g/m^2 have been measured at Hoadley, Jarvis, and Sherwood marshes in Connecticut.[30] Based on these observations, the North Shore of Long Island was calibrated using an optimal peak biomass of 800 g/m^2.

Hartig et al. measured biomass of *Spartina alterniflora* ranging from 700 to 1450 g/m^2 in Jamaica Bay.[31] The value of 1150 g/m^2 was used as optimal peak biomass for the MEM describing accretion rates in the South Shore of Long Island.

For the Peconic Bay system, the highest measured accretion rates were observed. To match these rates within the MEM model, a higher biomass of 2,000 g/m^2 was used in this region. As discussed in the following section, it is presumed that higher marsh biomass in this region is due to lower observed salinity. Recent studies on low salinity marshes[32] measured average peak biomass ranging from 1,600 to 2,400 g/m^2.

27 Shimon C. Anisfeld and Troy D. Hill, "Fertilization Effects on Elevation Change and Belowground Carbon Balance in a Long Island Sound Tidal Marsh," *Estuaries and Coasts* 35, no. 1 (January 1, 2012): 201–11, doi:10.1007/s12237-011-9440-4.

28 J. J. Middelburg et al., "Organic Carbon Isotope Systematics of Coastal Marshes," *Estuarine, Coastal and Shelf Science* 45, no. 5 (1997): 681–87; Tyler, C, "Geomorphological and Hydrological Controls on Patterns and Process in a Developing Barrier Island Salt Marsh." (Masters, University of Virginia, 1997); Clark Alexander and Michael Robinson, "Quantifying The Ecological Significance Of Marsh Shading: The Impact Of Private Recreational Docks In Coastal Georgia," 2006, http://www.skio.usg.edu/publications/downloads/pdfs/technical/dockshading_on_biomass2006.pdf; John L. Gallagher, "Effect of an Ammonium Nitrate Pulse on the Growth and Elemental Composition of Natural Stands of Spartina Alterniflora and Juncus Roemerianus," *American Journal of Botany*, 1975, 644–48; David T. Osgood and Joseph C. Zieman, "Factors Controlling Aboveground Spartina Alterniflora (smooth Cordgrass) Tissue Element Composition and Production in Different-Age Barrier Island Marshes," *Estuaries* 16, no. 4 (1993): 815–26.

29 Middelburg et al., "Organic Carbon Isotope Systematics of Coastal Marshes."

30 Shimon Anisfeld, "Accretion Rates in Connecticut," personal communication, 2014.

31 Ellen Kracauer Hartig et al., "Anthropogenic and Climate-Change Impacts on Salt Marshes of Jamaica Bay, New York City," *Wetlands* 22, no. 1 (March 2002): 71–89, doi:10.1672/0277-5212(2002)022[0071:AACCIO]2.0.CO;2.

32 Lisa M. Schile et al., "Modeling Tidal Marsh Distribution with Sea-Level Rise: Evaluating the Role of Vegetation, Sediment, and Upland Habitat in Marsh Resiliency," *PloS One* 9, no. 2 (2014): e88760.

For the study area of Staten Island, where no accretion-rate data were available, a MEM accretion rate curve was obtained by using the South Shore of Long Island model, while adjusting for the local measured TSS and tidal data. For the Hudson River, the Peconic Bay parameter set was used, as these are the two lowest-salinity regions within the project.

Salinity. Several studies have indicated that the aboveground growth rate of *Spartina alterniflora* is reduced as salinity increases,[33] and it has been shown that the total biomass decreases as a function of increasing salinity.[34] Analysis of the salinity data from the Suffolk County Department of Health Services shows the Peconic Bay has a much lower average salinity than the north and south shores of Long Island (Table 9). Because no biomass data were available for the Peconic Bay System a higher biomass value was applied to the "Bay" area, as previously discussed.

Table 9. Salinity data for Suffolk County

Area	Average Practical Salinity Units	Standard Deviation	n
Long Island Sound (North LI)	26.5	2.1	709
Peconic Bay System	15.8	8.0	200
South Shore LI	28.0	3.0	12566

MEM Calibration Results. The final set of regularly flooded marsh accretion models plotted against data is shown in Figure 8. The relationship between accretion rates and marsh elevations shown in the data is well captured by the MEM model runs.

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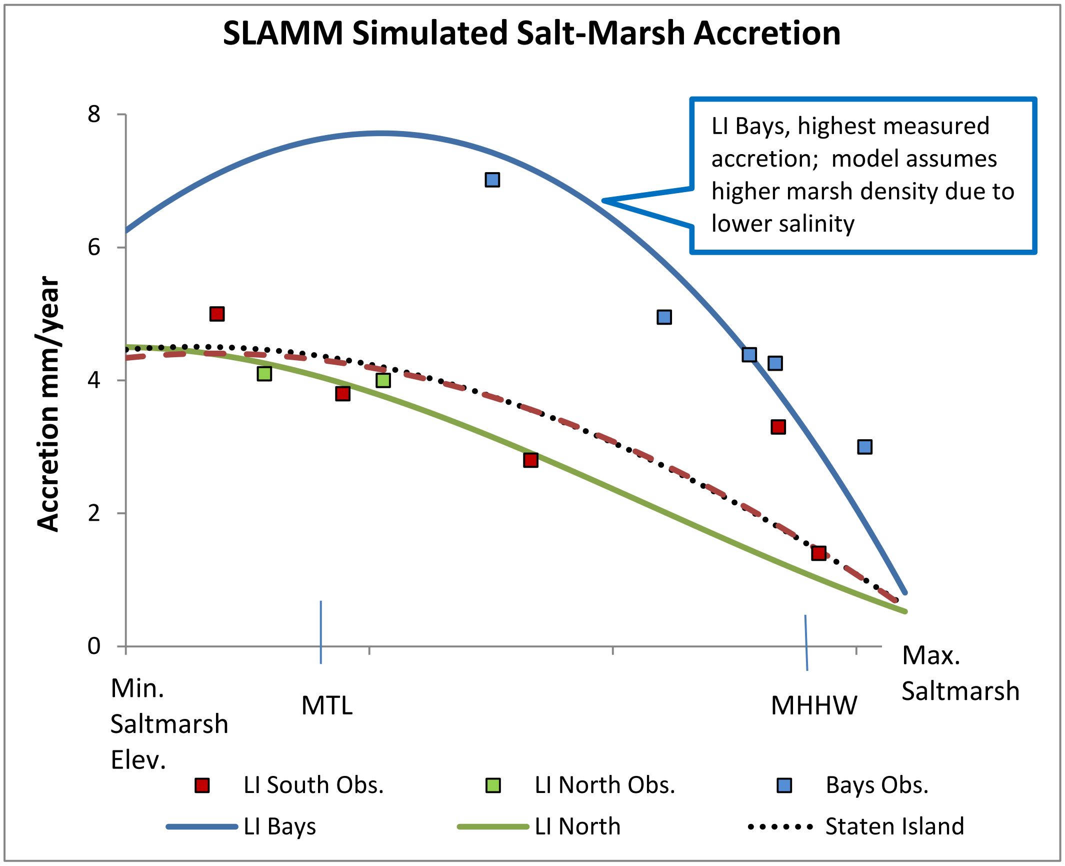
33 Irving A. Mendelssohn and Kenneth L. Marcellus, "Angiosperm Production of Three Virginia Marshes in Various Salinity and Soil Nutrient Regimes," *Chesapeake Science* 17, no. 1 (1976): 15–23; Joy B. Zedler, "Algal Mat Productivity: Comparisons in a Salt Marsh," *Estuaries* 3, no. 2 (1980): 122–31; Rick A. Linthurst and Ernest D. Seneca, "Aeration, Nitrogen and Salinity as Determinants of Spartina Alterniflora Loisel. Growth Response," *Estuaries* 4, no. 1 (1981): 53–63; Rick A. Linthurst and Udo Blum, "Growth Modifications Of *Spartina Alterniflora* Loisel. by the Interaction of pH and Salinity under Controlled Conditions," *Journal of Experimental Marine Biology and Ecology* 55, no. 2 (1981): 207–18; R. F. Dame and P. D. Kenny, "Variability of Spartina Alterniflora Primary Production in the Euhaline North Inlet Estuary," *Marine Ecology Progress Series* 32 (1986): 71–80; B. L. Haines and El L. Dunn, "Growth and Resource Allocation Responses of Spartina Alterniflora Loisel. to Three Levels of NH4-N, Fe, and NaCl in Solution Culture," *Botanical Gazette*, 1976, 224–30.

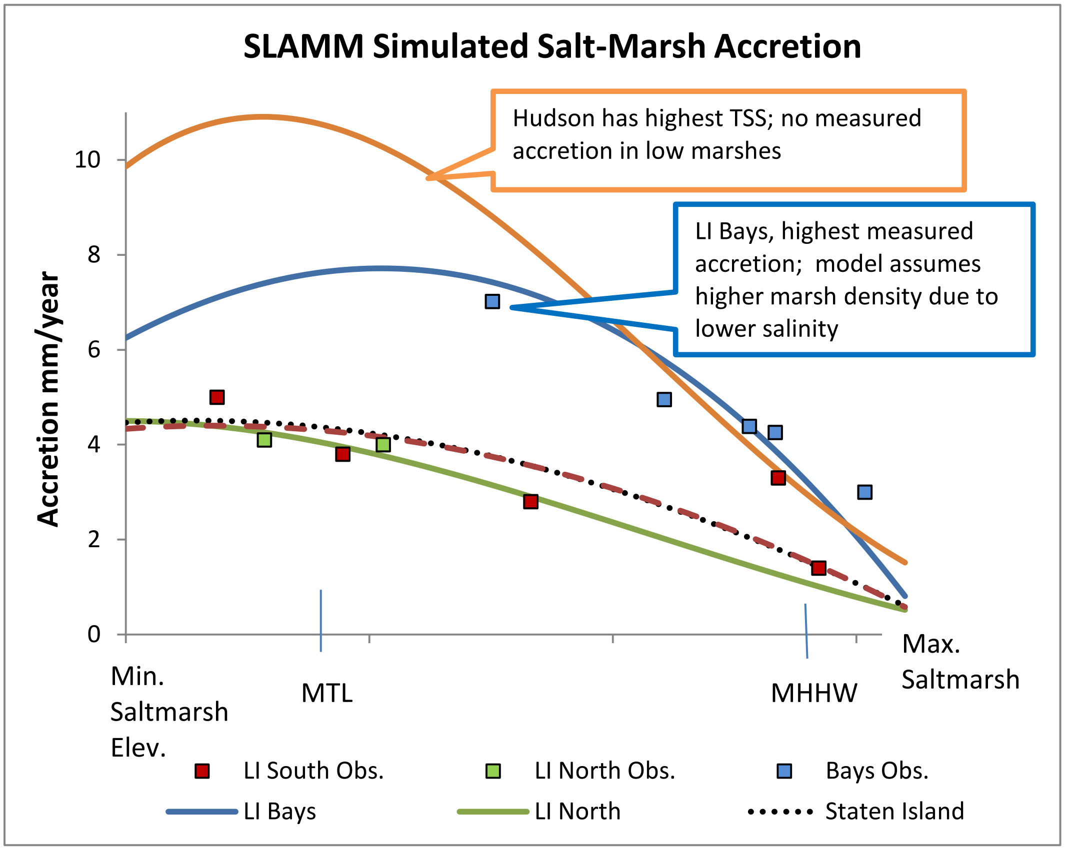
34 Edward A. Vasquez et al., "Salt Tolerance and Osmotic Adjustment of Spartina Alterniflora (Poaceae) and the Invasive M Haplotype of Phragmites Australis (Poaceae) along a Salinity Gradient," *American Journal of Botany* 93, no. 12 (2006): 1784–90.

Figure 8. Regularly flooded marsh accretion models plotted against available data



Note that Figure 8 does not include the Hudson study area for several reasons. First, there are no data for regularly flooded marshes in the Hudson study area to plot against the model runs. Second, there is very little regularly flooded marsh in the Hudson study area (7.5 acres total as an initial condition). Because of the high TSS in the river, the predictions for regularly flooded marsh are higher than the other study areas (Figure 9). However, this model is of limited practical relevance to the study area due to the low initial-condition occurrence in these marshes. The most prominent marsh in the Hudson study area (the Piermont Marsh) is not predicted to convert to regularly flooded marsh until 2085 under the highest SLR scenario used.

Figure 9. Regularly flooded marsh accretion models for all study areas



2.10 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[35] is possible. SLAMM models erosion as additive to inundation and is considered the effect of wave action.

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

2.10.1 Marsh Erosion

Marsh erosion is, in general, much slower than marsh expansion,[36] and SLAMM has been shown to be less sensitive to the marsh erosion parameters than accretion parameters.[37] In this project, 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.[38]

2.10.2 Swamp Erosion

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 predicted 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.

2.10.3 Beach Erosion

Beach erosion rates are difficult to determine due to the ephemeral nature of erosion. In any location, a beach can erode or aggrade by 100 feet in a single month, making determining long-term recession rates nearly impossible.[39] The regular practice of beach nourishment along the coast of New York complicates this issue further. Beach erosion experts suggest any erosion rate derived for New York will be a snapshot and not completely representative of the actual amount of erosion occurring, even if nourishment is considered.[40] However, Leatherman and coworkers 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. [41] Therefore, beach and tidal flat erosion was set to 0.44 m/yr, and the standard deviation was incorporated in the uncertainty analysis (see Section 2.14.6).

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36 Sergio Fagherazzi, "The Ephemeral Life of a Salt Marsh," *Geology* 41, no. 8 (August 1, 2013): 943–44, doi:10.1130/focus082013.1.

37 M. L. Chu-Agor et al., "Global Sensitivity and Uncertainty Analysis of SLAMM for the Purpose of Habitat Vulnerability Assessment and Decision Making," 2010.

38 Fagherazzi, "The Ephemeral Life of a Salt Marsh."

39 Henry Bokuniewicz, "Personal Communication: New York Beach Erosion Information," July 19, 2013.

40 Andy Coburn, "New York Beach Erosion Information," July 23, 2013; Bokuniewicz, "Personal Communication: New York Beach Erosion Information."

41 Stephen P. Leatherman, Keqi Zhang, and Bruce C. Douglas, "Sea-level rise Shown to Drive Coastal Erosion," *Eos, Transactions American Geophysical Union* 81,no. 6 (February 8, 2000): 55–57.

2.11 Model Calibration

Initially, SLAMM simulates a “time zero” step, in which the conceptual model validates the consistency between the existing, “initial condition” wetland maps, elevation data, connectivity, and a spatial accounting of tide ranges. Due to local factors, DEM and NWI uncertainty, and simplifications within the SLAMM conceptual model, some cells inevitably can fall below their lowest allowable elevation category and are immediately converted by the model to a different land-cover category. For example, an area categorized in the wetland layer as fresh-water swamp but in which water is subject to regular saline tides (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. Generally, a threshold tolerance of up to 5% change is allowed for in major land-cover categories in SLAMM analyses.

The wetland data used in this study were derived primarily from the National Wetland Inventory (NWI) maps reflecting land coverage in 2004 (except for New York City where many layers were used; see Section 2.2.3.1 for more detail), making the input data approximately 10 years old at the time of this study. Although the time zero analysis indicated many areas were well represented by these data, in some areas valid changes were noted. In some cases, the high horizontal resolution of the elevation data allowed for a more refined wetland map than the original NWI-generated shapefiles. In other cases, changes in wetlands over the last decade may have occurred ether due to sea-level rise, storms, or anthropogenic activities; these were reflected in the contemporary elevation data, but not the older wetlands data.

The standard mapping protocol for the NWI maps used in this project is to include wetlands with an area of 0.5 acres (2,023 m^2). In addition, “long, narrow rectangles …, such as those following drainage-ways and stream corridors…may or may not be mapped, depending on project objectives.”[42] With a 5-m cell-size, SLAMM is able to discern wetlands of 25 m^2. Therefore, the time zero maps sometimes provide a refinement to the initial wetland layers, as shown in Figure 10.

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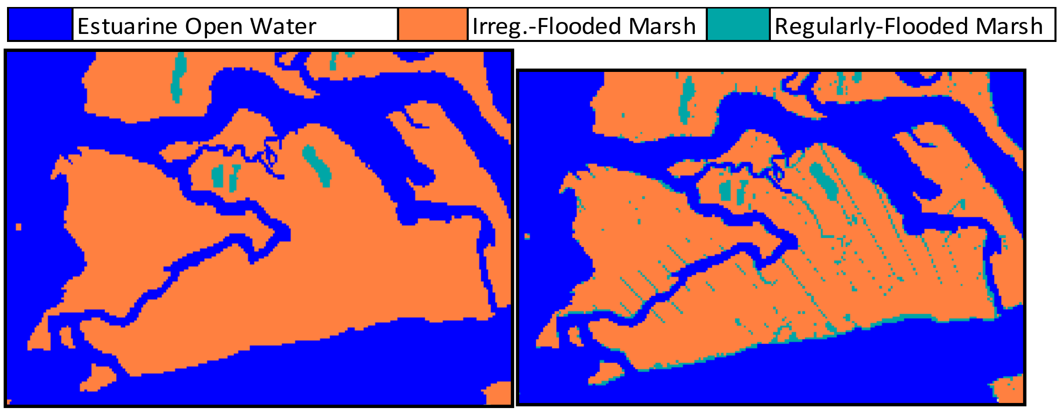
42 Federal Geographic Data Committee,, *Wetlands Mapping Standard* (Reston, VA, July 2009), http://www.fws.gov/wetlands/Documents/FGDC-Wetlands-Mapping-Standard.pdf.

Another issue encountered during model calibration was the immediate flooding of some developed lands. Most often these areas were bridges and piers, which are areas that are represented as development in the wetland layer but whose elevations are not included in the bare-earth elevation layer. Occasionally SLAMM predicts low-lying residential areas to be flooded at least once every 30 days based on tide data. These occurrences were investigated on a case-by-case basis by examining the NY Preliminary Coastal Hazards Inundation Risk Assessment,[43] viewing satellite imagery from Google Earth and Bing Maps, performing Web searches for public records of flooding issues, and contacting local and regional experts.

Figure 10. Unnamed island near Gilgo Beach



Initial wetland layer **Time-zero predicted wetland layer**

Aerial photograph

[43] http://www.arcgis.com/home/webmap/viewer.html?webmap=82a2fa929168434dabb6a3970e1d38e0

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.[44] Table 10 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 10. 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	HTU[45]
Tidal-Fresh Marsh	0.5	HTU[38]
Estuarine Beach	-1	HTU
Rocky Intertidal	-1	HTU
Inland Shore	-1	HTU
Ocean Flat	-1	HTU

44 "The Relationship of Smooth Cordgrass (Spartina Alterniflora) to Tidal Datums: A Review."

45 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.

In addition to the minor adjustments to minimum wetland elevation previously discussed, changes were made to the input parameters on a subsite basis when warranted. Such changes included reducing tide range, or adjusting salt elevation if too much dry-land conversion was observed. As discussed, any reductions to salt elevations were based on the standard error in the relationship between the tide range and the 30-day inundation height shown in Figure 5.

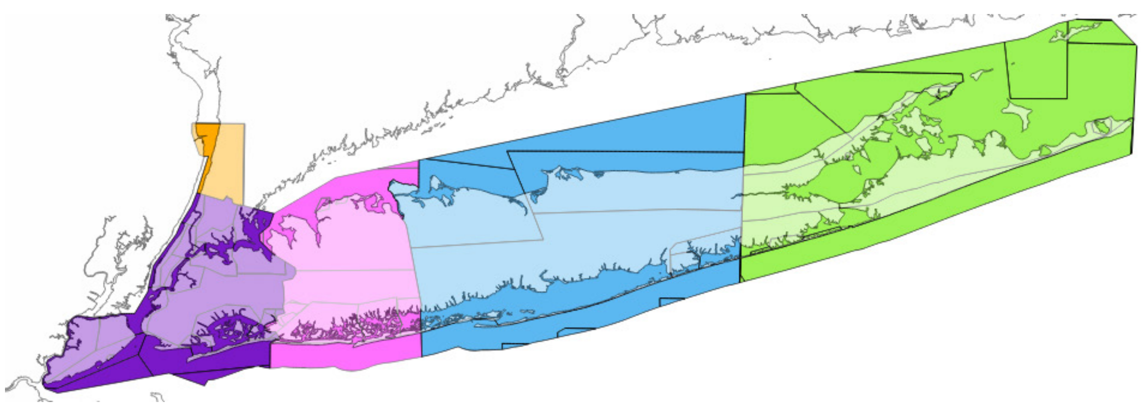
As inundated developed land is unlikely to immediately convert to a coastal wetland, a new land-cover category was included in SLAMM: Flooded Developed Dry Land. This category occurs when developed dry land is inundated by salt water at least once every 30 days and flooded developed land is not subject to more land-cover conversions.

Time-zero maps were compared to the initial-condition maps using GIS software and annotated where large conversions of wetland were observed. Any calibrations or allowable time-zero changes were quality assured by an independent team member. Model projections are reported from time zero forward so that the effect of SLR is accounted for independently of any remaining time-zero changes.

2.12 Model Setup

As noted, the study area was divided into five individual SLAMM projects as shown in Figure 11.

Figure 11. SLAMM project areas from west to east: New York City, Hudson, Nassau County, West Suffolk County and East Suffolk County



Each of these projects was then subdivided into subsites based on tide range and accretion parameters, as described in the following individual site sections.

2.12.1 Hudson

2.12.1.1 Hudson Site Description

The Hudson study area is the smallest of the five projects, extending from the northern boundary of the New York project area and ending at the Tappan Zee Bridge in the North (Figure 12). This study area does not contain extensive marshes, and the largest is the Piermont Marsh adjacent to Tallman Mountain State Park. As shown in Table 11, the most prominent wetland types in the Hudson study area are swamp (103 acres) and irregularly flooded marsh (252 acres). Other types of wetlands combined comprise less than 0.5% of the study area.

As the most prominent wetland in the southern Hudson River, the Piermont marsh has been studied extensively.[46] Analysis of sediment cores indicate the Piermont marsh is approximately 5,700 years old and has had an average rate of deposition of 2.6 mm/yr over its lifetime.[47] Since European settlement in the area in 1697, the sedimentation rate for the Piermont marsh has been measured as 2.9 mm/yr. [48] According to Pederson et al, it "appears that the system [at Piermont Marsh] is in approximate equilibrium with sea-level rise at this time."[49]

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46 Jennifer K. Wong and Dorothy Peteet, "Environmental History of Piermont Marsh, Hudson River, NY," *METHODS* 3 (1998): 12; Dorothy M. Peteet et al., "Hudson River Paleoecology from Marshes: Environmental Change and Its Implications for Fisheries," in *AMERICAN FISHERIES SOCIETY SYMPOSIUM*, vol. 51 (AMERICAN FISHERIES SOCIETY, 2006), 113, http://www.fisheriessociety.org/proofs/hr/peteet.pdf; Franco A. Montalto, Tammo S. Steenhuis, and J. Parlange, "The Hydrology of Piermont Marsh, a Reference for Tidal Marsh Restoration in the Hudson River Estuary, New York," *Journal of Hydrology* 316, no. 1 (2006): 108–28; Han G. Winogrond and Erik Kiviat, "Invasion of Phragmites Australis in the Tidal Marshes of the Hudson River," *Annandale-on-Hudson, New York: Bard College, Master's Thesis*, 1997, http://www.hudsonriver.org/ls/reports/Polgar_Winogrond_TP_06_96_final.pdf.

47 Wong and Peteet, "Environmental History of Piermont Marsh, Hudson River, NY"; Peteet et al., "Hudson River Paleoecology from Marshes."

48 Dee Cabaniss Pederson et al., "Medieval Warming, Little Ice Age, and European Impact on the Environment during the Last Millennium in the Lower Hudson Valley, New York, USA," *Quaternary Research* 63, no. 3 (2005): 238–49.

49 W. Rockwell Geyer, Jonathan D. Woodruff, and Peter Traykovski, "Sediment Transport and Trapping in the Hudson River Estuary," *Estuaries* 24, no. 5 (2001): 670–79; Sasha Spector, Conference call, March 25, 2014.

Table 11. Initial wetland coverage for the Hudson Study Area

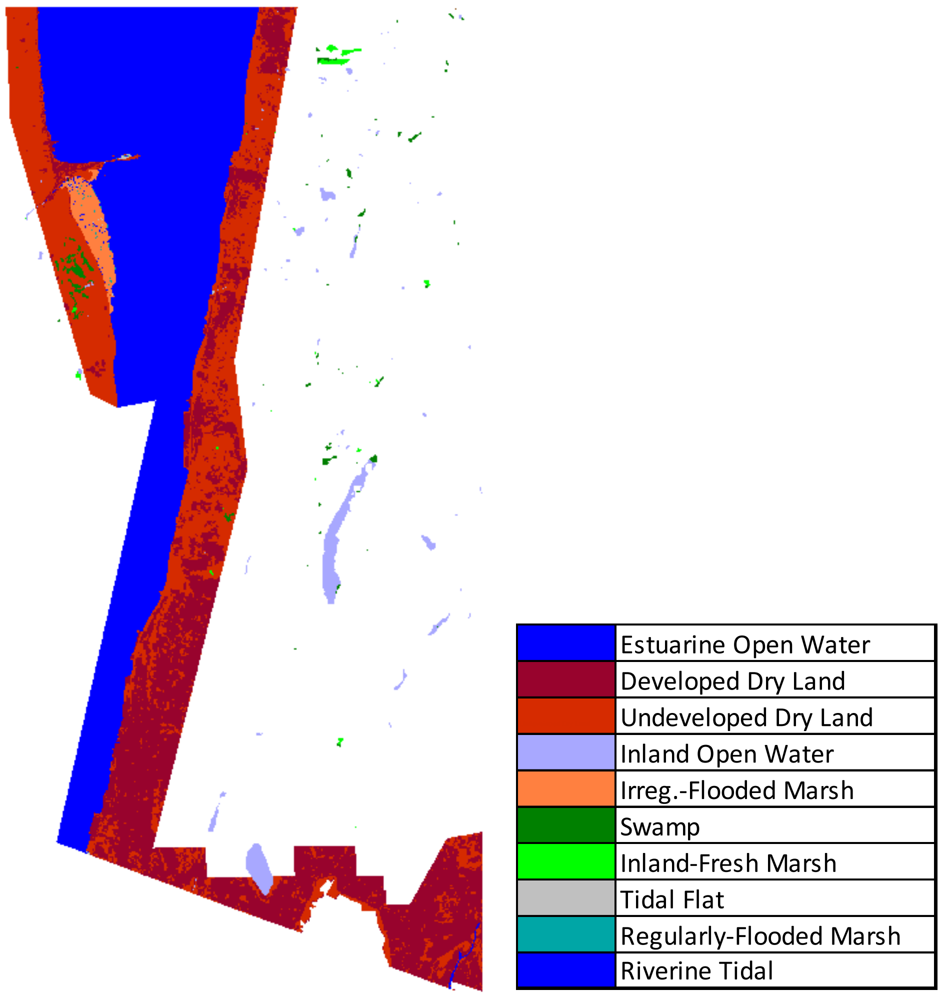
Land cover type		Area (acres)	Percentage
	Estuarine Open Water	7,586	46.3%
	Developed Dry Land	4,165	25.4%
	Undeveloped Dry Land	3,872	23.6%
	Inland Open Water	356	2.2%
	Irreg.-Flooded Marsh	252	1.5%
	Swamp	103	0.6%
	Inland-Fresh Marsh	43	0.3%
	Tidal Flat	8	< 0.1%
	Regularly flooded Marsh	7	< 0.1%
	Riverine Tidal	1	< 0.1%
	Total (including water)	**16,393**	**100.0%**

2.12.1.2 Hudson Site Parameters

A single set of tidal parameters was considered relevant to the entire Hudson study area. The GT was set to 1.1 m throughout the study area based on local tidal data (Figure B-1 in Appendix B).

Figure 12. Current land coverage distribution for the Hudson Study Area

SLAMM output maps show current or predicted land-cover conditions at low tide (MLLW).



2.12.1.3 Hudson Calibration

Three rounds of calibration were run on the Hudson study area. These iterations focused on refining the time zero results for the area southwest of Piermont (Ferry Rd), where the initial site parameters led to flooding. An inundation-height analysis was conducted on tide data from 2013 collected by the Lamont-Doherty Earth Observatory and accessed through the XTide Tide Prediction Server for the Piermont Pier tide gauge (41.04° N, 73.88° W).[50] Data indicated a 30-day inundation height of 0.65 m for this area, which provided a suitable time-zero model result (Table 12).

Table 12. Hudson Study Area Time-Zero Results (acres)

	Land cover type	Initial Coverage (acres)	Time Zero - 2004 (acres)	Change (acres)	% Change
	Estuarine Open Water	7,586	7,587	1.5	0%
	Developed Dry Land	4,165	4,162	-3.2	0%
	Undeveloped Dry Land	3,872	3,826	-45.4	-1%
	Inland Open Water	356	356	0.0	0%
	Irreg.-Flooded Marsh	252	245	-6.5	-3%
	Swamp	103	103	0.0	0%
	Inland-Fresh Marsh	43	43	0.0	0%
	Tidal Flat	8.0	8.2	0.3	4%
	Regularly flooded Marsh	7.5	12.2	4.7	63%
	Riverine Tidal	0.8	0.8	0.0	0%
	Tidal Swamp	0.5	0.5	0.0	-5%
	Inland Shore	0.2	0.2	0.0	0%
	Trans. Salt Marsh	0.2	45.6	45.4	25351%

2.12.2 New York City

2.12.2.1 NYC Site Description

The New York City study area includes the marshes on the south shore of The Bronx, Staten Island, Jamaica Bay, and the north shores of Queens. Manhattan and Brooklyn do not contain significant tidal marsh. However, for completeness in Table 13, the current land coverage of all NYC neighborhoods is reported. More than 60% of the

50 Lamont-Doherty Earth Observatory, *Division of Ocean and Climate Physics (OCP) and XTide Server: The XTide Tide Prediction Server Master Index*, n.d., http://xtide.ldeo.columbia.edu:8080/index.html.

area is dry land, mostly developed, and open water covers 36% of the area. The remaining 3% of the NYC area is characterized as follows: 42% is occupied by coastal saline marshes (equivalent to 1.24% of the entire NYC area), 35% is occupied by low-tidal non-vegetated land cover (such as beaches and tidal flats), and the remaining land cover is occupied by inland-open water, tidal-fresh marshes, and inland-fresh marshes.

Table 13. Current land coverage distribution in New York City neighborhoods

Land cover type		Area (acres)	Percentage (%)
	Developed Dry Land	123,973	41.2
	Estuarine Open Water	74,529	24.8
	Undeveloped Dry Land	60,499	20.1
	Open Ocean	32,650	10.9
	Irreg.-Flooded Marsh	2,073	0.7
	Tidal Flat	1,883	0.6
	Regularly flooded Marsh	1,567	0.5
	Inland Open Water	1,014	0.3
	Ocean Beach	738	0.2
	Swamp	549	0.2
	Estuarine Beach	463	0.2
	Inland Fresh Marsh	421	0.1
	Tidal Swamp	76	<0.1
	Trans. Salt Marsh	75	<0.1
	Tidal Fresh Marsh	31	<0.1
	Riverine Tidal	13	<0.1
	Inland Shore	2	<0.1
	Total (including water)	**300,556**	**100**

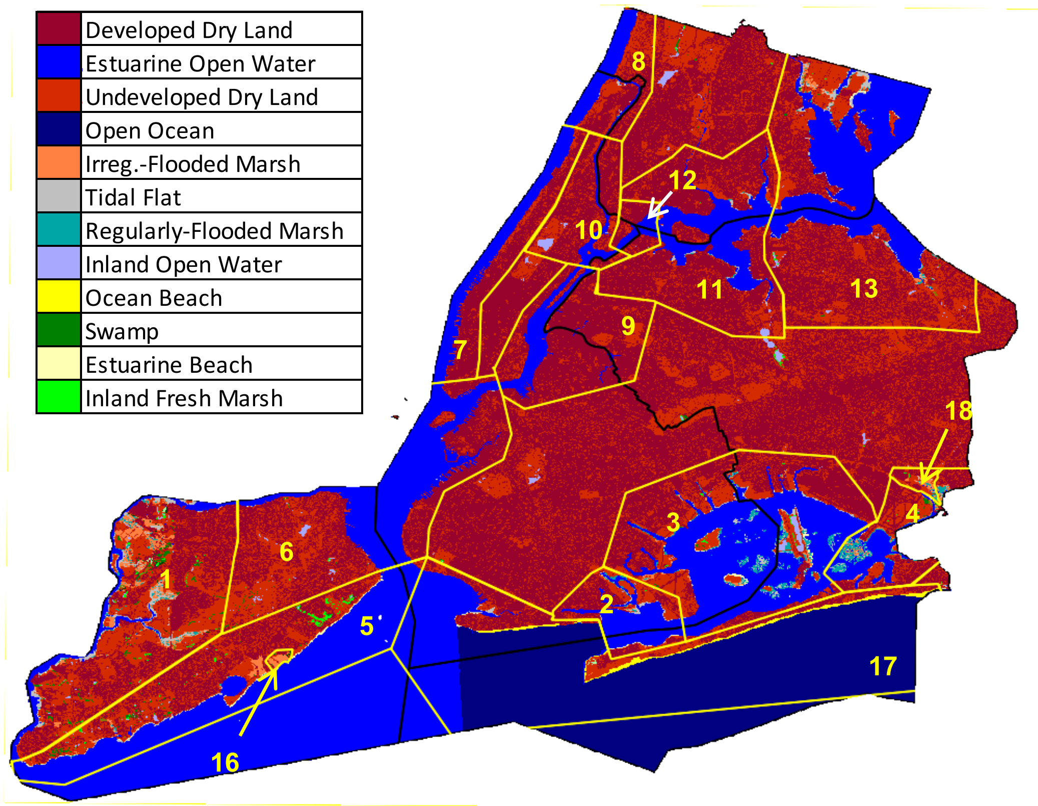
2.12.2.2 NYC Site Parameters

The NYC study area was divided into 16 different subsite areas in order to accommodate spatial tidal variations. Initially, the tidal information used was from the NOAA and LI Shore data as discussed in Sections 2.6 and 2.7. However, some GT and "salt-elevation" parameters were further calibrated after a preliminary inundation-analysis step. Based on model results and feedback from local experts, some tide ranges were reduced to reflect muted tides when going upstream in certain areas and to reduce regular inundation of developed dry lands. These tidal adjustments were always made within the 95% confidence interval of the inundation graph shown in Figure 5 to maintain consistency with the available tidal data. The final tidal parameters were assigned to corresponding subsite boundaries are shown in Table 14 and Figure 13.

Table 14. Tidal ranges and salt elevations for different SLAMM subsites in NYC

Subsite Number and Name	Great Diurnal Tide Range - GT (m)	Salt Elevation (m above MTL)
1 - Staten Island West	1.77	1.23
2 - Entrance Jamaica Bay	1.72	1.31
3 - Jamaica Bay	1.79	1.12
4 - Head of Bay	1.86	1.14
5 - Lower Bay	1.64	1.26
6 - Upper Bay	1.58	1.22
7- Lower Hudson	1.49	1.14
8 - Upper Hudson	1.32	1.04
9 - Lower East River	1.47	1.14
10 - Upper East River	1.6	1.23
11 - La Guardia	2.34	1.72
12 - Hell Gate	2.11	1.56
13 - Little Neck Bay	2.45	1.79
14-15 N / A: Outside study area		
16 - Kissam Avenue	1.5	1.06
17 - LI South	1.64	1.26
18 - Idlewild Reserve	1.1	0.88

Figure 13. NYC land coverage and SLAMM analysis subsites in yellow



2.12.2.3 NYC Calibration

Calibration of the New York City study area was carefully completed in close cooperation with the New York City Department of Parks and Recreation (NYC DPR). More than 15 time-zero runs were produced with various small adjustments until our team was satisfied that our parameter set properly reflected the interplay between tide ranges, elevations, and coastal habitat maps in the initial conditions. Inundation-frequency maps were produced and compared against regularly and irregularly flooded marshes. This procedure was also used to define wetland boundaries (see Section 2.2.3.1). Inundation-frequency maps were also used to identify areas that needed further hydro-enforcement. Consequently, the DEM was modified, for example by removing a bridge or adding a culvert to correct water flows. Post-Sandy LiDAR data was initially preferentially used for this region as the best reflection of current conditions. Post-Sandy LiDAR and pre-Sandy LiDAR are generally equivalent in terms of data error. (Root-mean-square errors [RMSEs] are 12.5 cm and 9.5 cm, respectively). However, comparison of inundation frequencies when using the different elevation sources showed that in some coastal zones the pre-Sandy data better described the landscape and water flows. After consultation with NYC DPR, the DEM was modified by substituting elevations with pre-Sandy data for these areas.

Table 15. New York City Time-Zero Results (acres)

Land cover type		Initial Coverage (acres)	Time Zero - 2008 (acres)	Change (acres)	% Change
	Developed Dry Land	123,973	123,823	-150	-0.1
	Estuarine Open Water	74,529	74,579	50	0.1
	Undeveloped Dry Land	60,499	59,908	-591	-1.0
	Open Ocean	32,650	32,658	8	<0.1
	Irregularly Flooded Marsh	2,073	2,019	-54	-2.6
	Tidal Flat	1,883	1,944	61	3.3
	Regularly flooded Marsh	1,567	1,526	-41	-2.6
	Inland Open Water	1,014	1,010	-4	-0.4
	Ocean Beach	738	732	-6	-0.9
	Transitional Salt Marsh	75	660	585	779.1
	Swamp	549	547	-2	-0.4
	Estuarine Beach	463	463	<1	-0.1
	Inland Fresh Marsh	421	421	0	0.0
	Flooded Developed Dry Land	0	150	150	NA
	Tidal Swamp	76	73	-3	-3.8
	Tidal Fresh Marsh	31	29	-2	-5.3
	Riverine Tidal	13	11	-2	-16.5
	Inland Shore	2	2	<1	-0.3
	Total (including water)	**300,556**	**300,556**		

2.12.3 Nassau County

2.12.3.1 Nassau Site Description

The Nassau County study area includes nearly 180,000 acres. As shown in Table 16, the most dominant wetland type in the county is irregularly flooded marsh (or "intermediate to high marsh") which covers 7,821 acres, or 4% of the study area. These marshes are dominant in the bays in the southern part of the county and are several times more prevalent than other types of marsh found in the Nassau County study area.

Table 16. 2004 Land Coverage for Nassau County

Land cover type		Area (acres)	Percentage (%)
	Estuarine Open Water	61,477	34
	Open Ocean	40,363	23
	Undeveloped Dry Land	36,198	20
	Developed Dry Land	27,581	15
	Irregularly Flooded Marsh	7,821	4
	Inland Open Water	1,261	1
	Tidal Flat	987	1
	Swamp	900	1
	Ocean Beach	854	< 1
	Estuarine Beach	714	< 1
	Regularly flooded Marsh	713	< 1
	Inland-Fresh Marsh	224	< 1
	Transitional Salt Marsh	221	< 1
	Inland Shore	36	< 1
	Tidal-Fresh Marsh	22	< 1
	Tidal Swamp	12	< 1
	Total (including water)	**179,386**	**100**

2.12.3.2 Nassau Site Parameters

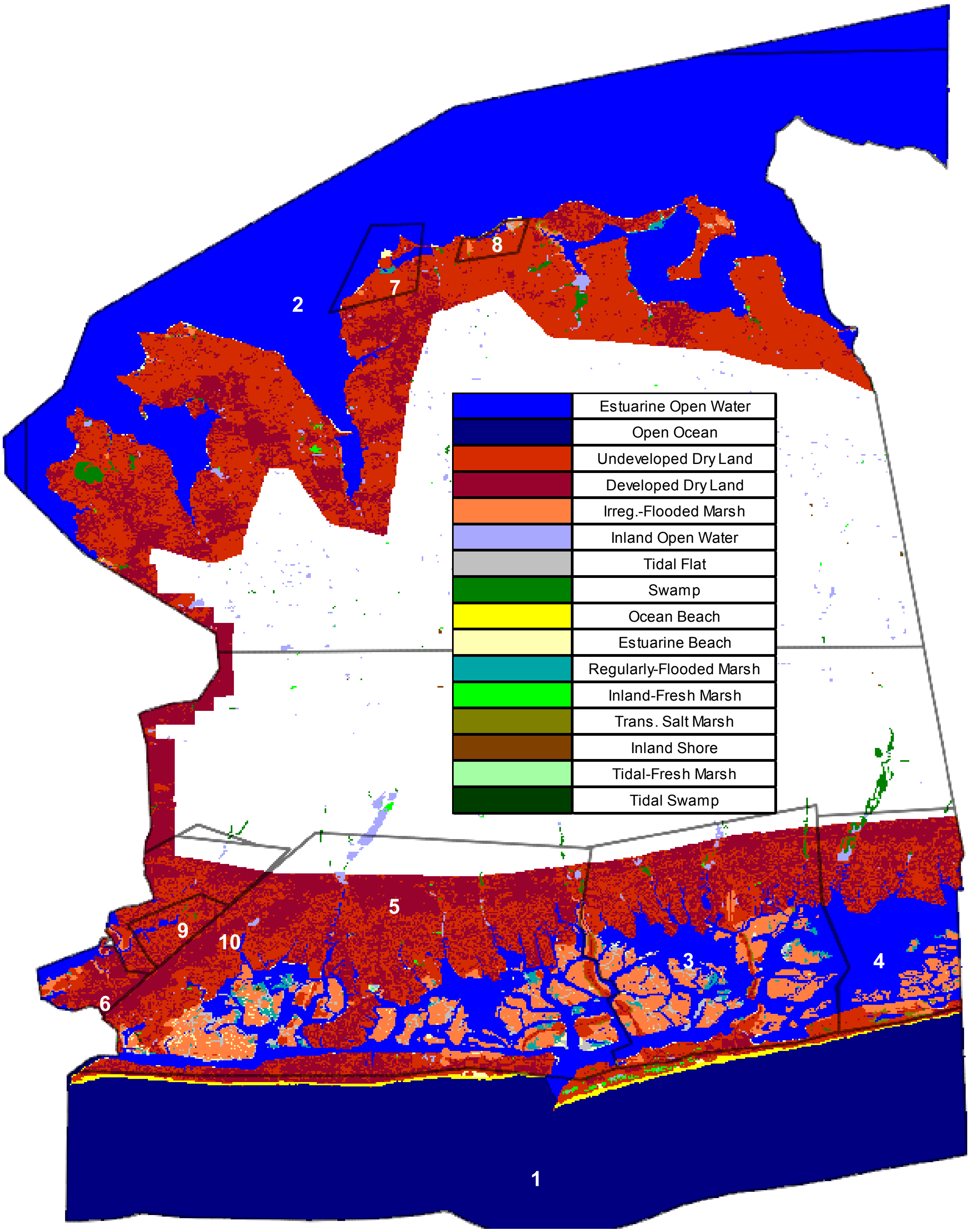
Subsites were assigned based on great diurnal tide range and 30-day inundation height (salt elevation). The minimum elevations of tidal swamp and tidal-fresh marsh were set to 1.0 HTU (MHHW) and 0.7 HTU respectively, based on elevation data for these wetlands within the Nassau study area. The final tidal parameters assigned and corresponding subsite boundaries are shown in Table 17 and Figure 14, respectively.

Table 17. Tide ranges and salt elevations applied to Nassau County

Subsite Number and Name	GT Great Diurnal Tide Range (m)	Salt Elevation (m above MTL)
1 - South	1.41	1.103
2 - North Nassau	2.47	1.54
3 - East Bay	0.86	0.66
4 - Oyster Bay	0.45	0.47
5- Hewlett/Baldwin	1.34	0.85
6 - Grass Hassock	1.87	1.18
7 - North Nassau 84 NWI	2.47	1.54
8 - Frost Creek	1.1	0.89
9 - SVS Woodmere	0.87	0.75
10 - Woodmere behind tidegate	0.1	0.13

Figure 14. Nassau County wetlands and subsites

Numbers correspond to the descriptions in Table 17.



In order to calibrate the Nassau county study area, several iterations of the model were assessed. The changes between the iterations were primarily reductions in the salt elevation to reduce the amount of dry lands being flooded. The Woodmere input subsite was refined during the calibration process using the elevation histogram of swamp elevations in this area to define the 30-day inundation height rather than the relationship shown in Figure 5. This was done due to a lack of subsite-specific tide data to refine the salt elevation in the Woodmere area. The Woodmere subsite was subsequently divided into two separate subsites when it was determined a tide gate was present, restricting tidal flows for a portion of the study area. The area behind the tide gate was assigned a muted tide range (GT = 0.1m) and a low 30-day inundation height (0.13m, based on the point 2 standard errors below the trend line in Figure 5). Our time-zero simulation suggests that the tide gate structure currently prevents regular flooding of dry lands behind it. In model projections, however, the model assumed that the mean tide level behind the tide gate would rise at the same rate as waters outside the tide gate.

Table 18 presents a comparison between the initial observed and time-zero wetland layers for Nassau County. Losses in undeveloped dry land lead to gains in transitional marsh, while losses in irregularly flooded marsh resulted in increases in regularly flooded marsh. As discussed in the Model Calibration section, these changes were accepted based on the age of the input wetland layer and changes that have occurred in the wetland over the last 10 years as confirmed by satellite imagery. The 63 acres of flooded developed land predicted at time zero are in areas that are designated as developed dry land in the wetland layer but do not appear in the bare-earth elevation data layer (piers, docks, and the amphitheater at Jones Beach) or roads and parking lots that have been confirmed to flood via satellite imagery.

Table 18. Nassau Time Zero Results (acres)

		Initial	Time Zero (2004)	Change	% Change
	Estuarine Open Water	61,477	61,791	313.1	1%
	Open Ocean	40,363	40,387	24.1	0%
	Undeveloped Dry Land	36,198	35,914	-283.9	-1%
	Developed Dry Land	2,7581	27,518	-63.4	0%
	Irregularly Flooded Marsh	7,821	6,952	-868.7	-11%
	Inland Open Water	1,261	1,204	-56.9	-5%
	Tidal Flat	987	860	-127.1	-13%
	Swamp	900	893	-6.3	-1%
	Ocean Beach	854	841	-13.1	-2%
	Estuarine Beach	714	679	-34.6	-5%
	Regularly flooded Marsh	713	1508	794.3	111%
	Inland-Fresh Marsh	224	212	-12.3	-6%
	Trans. Salt Marsh	221	494	273.1	124%
	Inland Shore	36	36	0.0	0%
	Tidal-Fresh Marsh	22	21	-0.9	-4%
	Tidal Swamp	12	12	-0.7	-6%
	Flooded Developed Dry Land	0	63	63.4	NA
	Total (including water)	**179,386**	**179,386**	0.0	0%

2.12.4 Western Suffolk County

2.12.4.1 Western Suffolk County Site Description

Due to its size, Suffolk County was divided into eastern and western study areas. The Western Suffolk study area is the smaller of the two areas and extends from the Nassau county border to a longitude of -72.70 degrees west, just east of Eastport and Moriches Bay. The nearly 350,000 acre site is mainly water and dry land with the predominant wetlands being irregularly flooded marsh and swamp. Table 19 shows the initial wetland coverage for this study area.

Table 19. Initial Wetland Coverage for the Western Suffolk Study Area

Land cover type		Area (acres)	Percentage (%)
	Estuarine Open Water	156,973	45
	Open Ocean	76,977	22
	Undeveloped Dry Land	70,394	20
	Developed Dry Land	24,394	7
	Irregularly Flooded Marsh	7,540	2
	Swamp	4,648	1
	Inland Open Water	2,490	1
	Estuarine Beach	1,608	< 1
	Regularly flooded Marsh	1,493	< 1
	Ocean Beach	1,071	< 1
	Trans. Salt Marsh	461	< 1
	Inland-Fresh Marsh	435	< 1
	Tidal Swamp	432	< 1
	Tidal Flat	385	< 1
	Inland Shore	48	< 1
	Tidal-Fresh Marsh	41	< 1
	Rocky Intertidal	1	< 1
	Total (including water)	**349,392**	**100**

2.12.4.2 Western Suffolk County Site Parameters

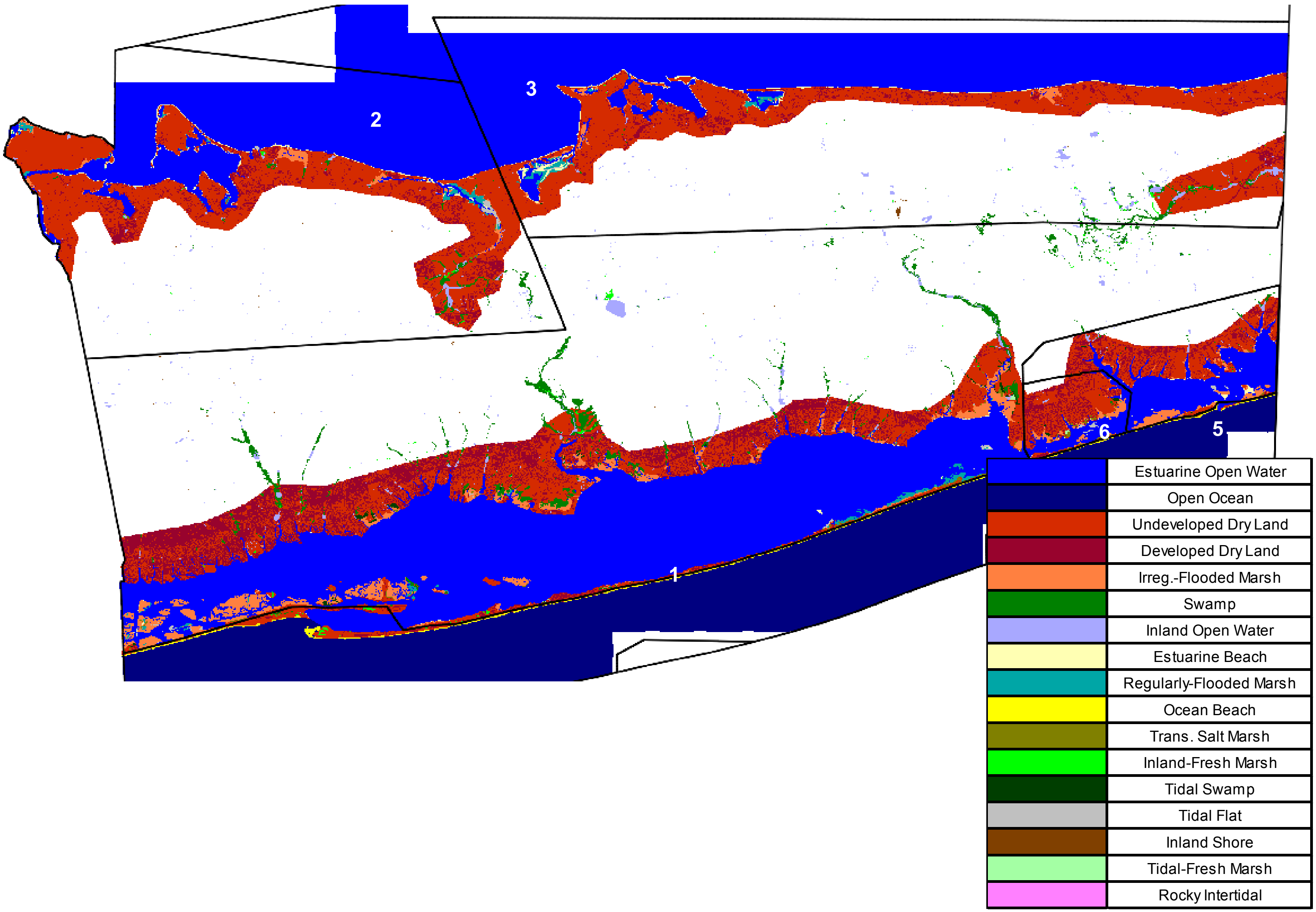
As shown in Table 20 and Figure 15, the site was divided into six input subsites. The designation of subsites was driven by differences in the tide range (GT) and salt elevation parameters.

Table 20. Tide Ranges and Salt Elevations Applied to Suffolk West

Subsite Number and Name	GT Great Diurnal Tide Range (m)	Salt Elevation (m above MTL)
1 - Great South Bay	0.32	0.27
2 - North West	2.42	1.51
3 - North East	2.2	1.38
4 - Open Ocean	0.8	0.7
5 - Moriches	0.77	0.61
6 - Narrow Bay	0.43	0.46

Figure 15. Input subsites applied to Western Suffolk County

Numbers correspond to subsite descriptions in Table 20.



2.12.4.3 Western Suffolk County Calibration

Eight iterations of the western Suffolk study area were run in order to calibrate the SLAMM model. The salt elevations for subsites were reduced to decrease the amount of flooded developed land, and additional subsites were added to refine tide ranges. Results for the final time-zero map are presented in Table 21. The majority of flooded developed dry land predicted at time zero occurs in Mastic Beach. According to local residents, in Mastic Beach the peninsula formed by Sheepen Creek (at 40.745°N -72.853°W) floods at least 5 days per month with new and full moons.[51] In SLAMM, this flooding leads to Riviera Drive being converted to flooded developed land in the Time Zero analysis. The model time zero predictions and representative photos of this area are shown in Figure 16, Figure 17, and Figure 18.

Table 21. Suffolk West Time Zero Results

		Initial	**2004**	**change in Acres**	**% change**
	Estuarine Open Water	156973	157016	43.4	0%
	Open Ocean	76977	77101	123.6	0%
	Undeveloped Dry Land	70394	69956	-437.5	-1%
	Developed Dry Land	24394	24348	-45.2	0%
	Irregularly Flooded Marsh	7540	7041	-499.0	-7%
	Swamp	4648	4638	-10.2	0%
	Inland Open Water	2490	2480	-9.6	0%
	Estuarine Beach	1608	1578	-30.5	-2%
	Regularly flooded Marsh	1493	1860	366.2	25%
	Ocean Beach	1071	996	-74.8	-7%
	Trans. Salt Marsh	461	833	372.1	81%
	Inland-Fresh Marsh	435	435	-0.5	0%
	Tidal Swamp	432	420	-11.9	-3%
	Tidal Flat	385	554	168.8	44%
	Inland Shore	48	48	0.0	0%
	Tidal-Fresh Marsh	41	40	-0.2	0%
	Rocky Intertidal	1	1	0.0	0%
	Flooded Developed Dry Land	0	45	45.2	NA
	Total (including water)	**349392**	**349392**	0.0	0%

[51] Nicole P. Maher, The Nature Conservancy, "Mastic Beach photos," October 1, 2013.

Figure 16. Initial Condition (top) and Time Zero (bottom) Results for Mastic Beach

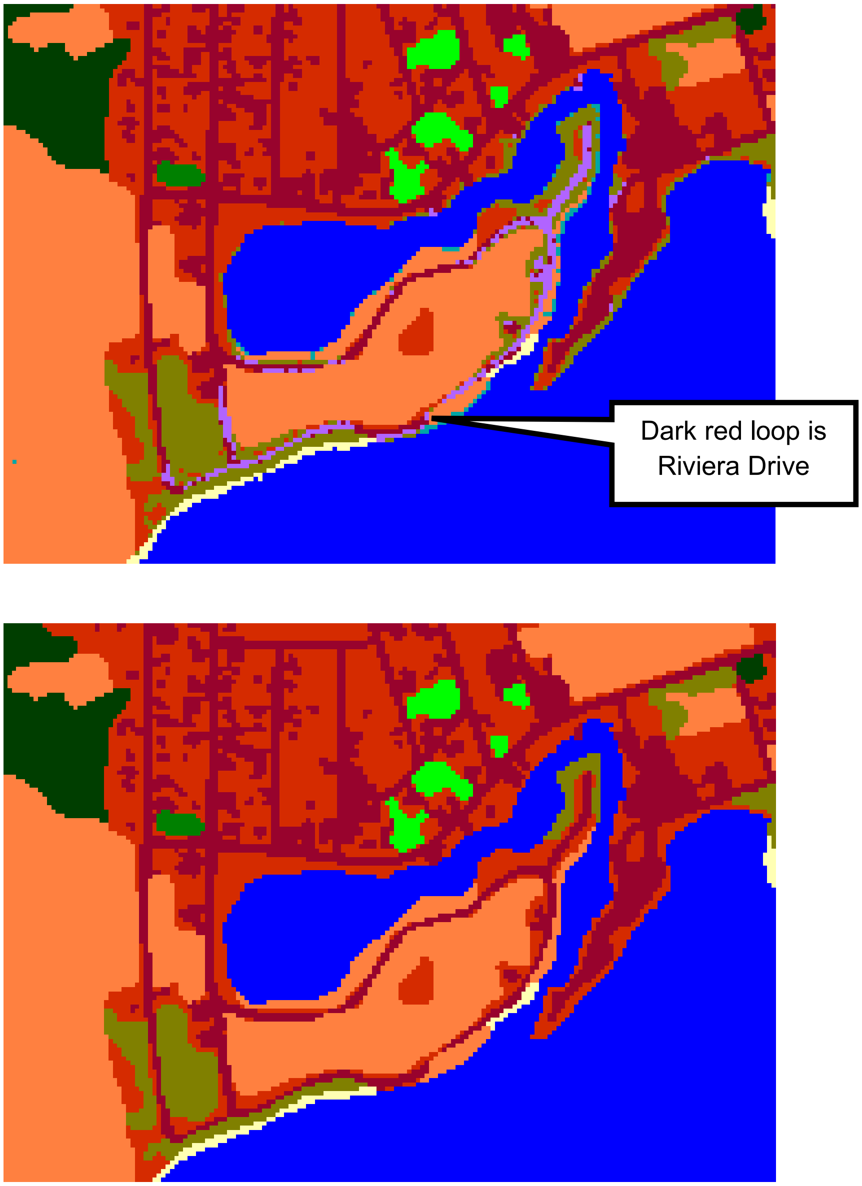


Figure 17. Riviera Drive in Mastic Beach, NY

Printed with permission of Nicole Maher, The Nature Conservancy.

Figure 18. Riviera Drive in Mastic Beach, NY (alternative view)

Printed with permission of Nicole Maher, The Nature Conservancy.

2.12.5 Eastern Suffolk County

2.12.5.1 Eastern Suffolk County Site Description

The Suffolk East project area has nearly 600,000 acres in modeled area, and is the largest of all five study areas. This project area extends from the boundary with western Suffolk county (in the west) to Fishers Island in the east. Like Nassau County and the western portion of Suffolk County, the predominant wetland in Eastern Suffolk County is irregularly flooded (high) marsh.

Table 22. Initial wetland coverage for Eastern Suffolk County

Land cover type		Area (acres)	Percentage (%)
	Open Ocean	229,238	39
	Estuarine Open Water	179,642	30
	Undeveloped Dry Land	143,421	24
	Developed Dry Land	25,146	4
	Irreg.-Flooded Marsh	4,848	1
	Swamp	2,365	< 1
	Inland Open Water	1,988	< 1
	Ocean Beach	1,975	< 1
	Estuarine Beach	1,831	< 1
	Inland-Fresh Marsh	456	< 1
	Tidal Swamp	307	< 1
	Trans. Salt Marsh	281	< 1
	Regularly flooded Marsh	194	< 1
	Tidal Flat	181	< 1
	Tidal-Fresh Marsh	100	< 1
	Rocky Intertidal	62	< 1
	Inland Shore	1	< 1
	Ocean Flat	1	< 1
	Total (incl. water)	592,036	100

2.12.5.2 Eastern Suffolk County Site Parameters

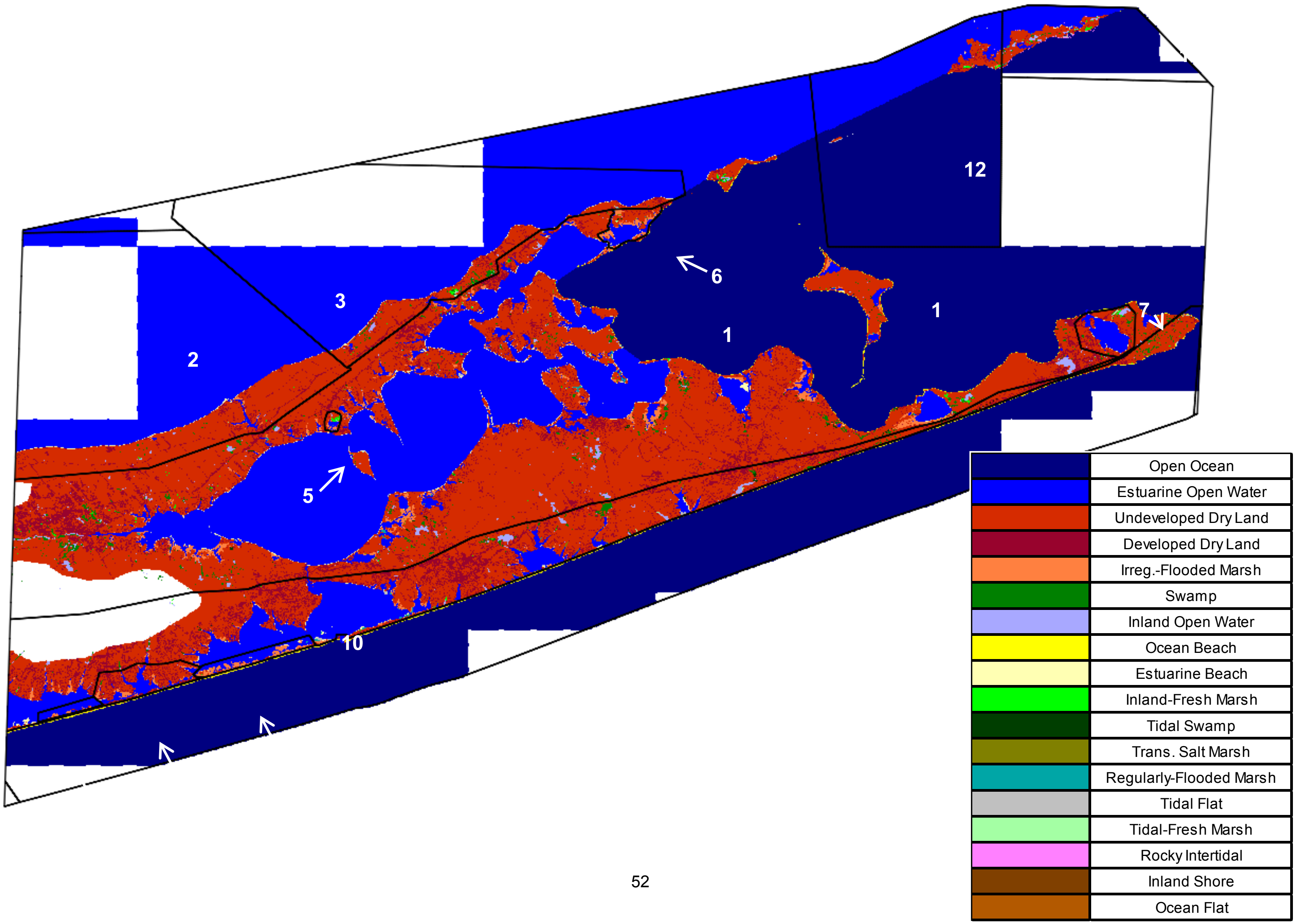
Based on the current elevation data in this site, the minimum elevation for tidal fresh marsh was set to 0.73 HTU, while the minimum elevation for tidal swamp was set to 1.46 HTU. Input subsites were added based on tide range and salt elevation along with two Fishers Island sites. As shown in Table 23, many subsites were added where the tide range was not adjusted but the salt elevation was reduced in order to calibrate the model and reduce initial flooding of dry lands.

Table 23. Tide Ranges and Salt Elevations Applied to Suffolk East

Subsite Number and Name	GT Great Diurnal Tide Range (m)	Salt Elevation (m above MTL)
1 - Global	0.87	0.75
2 - Northwest	1.79	1.35
3 - Northeast	1.45	1.13
4 - Open Ocean	1.17	0.94
5 - New Suffolk	0.44	0.46
6 - Orient Point inside	0.72	0.65
7 - Lake Montauk	0.7	0.63
8 - Hampton Bays	0.87	0.64
9 - Westhampton Beach	0.8	0.55
10 - South	0.87	0.75
11 - Quogue	0.87	0.6
12,13 - Fishers Island	0.87	0.75

Figure 19. Input subsites applied to Eastern Suffolk County

Numbers correspond to subsite descriptions in Table 23.



2.12.5.3 Eastern Suffolk County Calibration

The extensive shoreline of Eastern Suffolk County led to several iterations of model calibration. Several of these subsites were focused on small embayments and water bodies, including Lake Montauk, the inner portion of Orient Point, and an estuary to the west of the town of New Suffolk. In the case of inner Orient Point, the salt elevation was reduced to the 5^{th} percentile of the elevation of swamps in the area, while in the New Suffolk area the salt elevation was determined based on the 5^{th} percentile of the observed elevations of undeveloped dry land within that subsite. The elevations of wetland types were used due to a lack of subsite-specific tide data to use for tidal elevation refinement. Some subsites, like those in Hampton Bay, Westhampton Beach, and Quogue, were added to reduce the amount of developed dry land converting to flooded development at time zero.

During the calibration process, WPC noted some horizontal offset between elevation and wetland data in the southern part of the county. Time-zero results suggested a systematic shift between the wetland and elevation layers, as evidenced by conversions around five meters in width on all eastern-facing shorelines. These conversions primarily occurred on the western side of the Shinnecock Canal.[52] This offset was considered minimal (seemingly limited to one elevation layer input tile) and not investigated further.

Like the peninsula in Mastic Beach (in the Suffolk West study area), there were locations in the Suffolk East area with predicted flooding at time-zero that were verified to be flooding on a regular basis. For example, Creek and Dune Roads were predicted to flood, locations that are already prone to flooding as verified by a local news reports.[53] These supporting examples suggest that some areas of developed land should be allowed to flood during the initial calibration of Suffolk East.

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52 Latitude 40.889589°, Longitude -72.501631°

53 Creek Road (40.964972° -72.861344°) resident Edwin Safford submitted a petition signed by 46 Creek Road residents asking the town to address drainage issues and flooding on the narrow shoreline roadway that terminates at the town's Wading River boat ramp (http://www.riverheadlocal.com/town-hall-notebook/town-board-wrap-up-sept-21#sthash.1WJFsKLf.dpuf). Dune Road between East Quogue and the Shinnecock West Inlet floods with such regularity that residents assert flooding is a constant problem (http://westhampton-hamptonbays.patch.com/groups/police-and-fire/p/town-commits-100-000-to-dune-road-study) .

Table 24. Suffolk East Time Zero Results

		Initial	2010	Change in Acres	% change
	Open Ocean	229238	229342	103.1	0%
	Estuarine Open Water	179642	179810	168.0	0%
	Undeveloped Dry Land	143421	142712	-708.9	0%
	Developed Dry Land	25146	25103	-43.1	0%
	Irregularly Flooded Marsh	4848	4500	-347.8	-7%
	Swamp	2365	2359	-6.0	0%
	Inland Open Water	1988	1979	-8.7	0%
	Ocean Beach	1975	1977	2.7	0%
	Estuarine Beach	1831	1720	-110.7	-6%
	Inland-Fresh Marsh	456	442	-14.7	-3%
	Tidal Swamp	307	294	-13.7	-4%
	Trans. Salt Marsh	281	901	619.9	221%
	Regularly flooded Marsh	194	570	375.7	194%
	Tidal Flat	181	147	-33.3	-18%
	Tidal-Fresh Marsh	100	96	-4.0	-4%
	Rocky Intertidal	62	40	-21.7	-35%
	Inland Shore	1	1	0.0	0%
	Ocean Flat	1	1	0.0	-1%
	Flooded Developed Dry Land	0	43	43.1	NA
	Total (including. water)	**592036**	**592036**	**0.0**	**0%**

2.13 Parameter Summary

A comprehensive listing of the parameters used in this analysis is in Appendix C. The locations of specific subsites can be found in Figure 13, Figure 14, Figure 15, and Figure 19.

2.13.1 SLAMM Conceptual Model (Wetland Elevation to Tide Range relationship)

Table 25 lists the lower-bound elevations for the majority of SLAMM land covers. For the categories in this table, the same conceptual model was used throughout the study area. Whenever land falls below the elevation listed, conversion to a lower-elevation habitat is assumed to occur. Elevations are expressed with a basis of mean-tide level (0=MTL).

Table 25. SLAMM conceptual model used

SLAMM Category	Elevation	Units	Notes
Developed Dry Land	1	Salt Elevation	Dry land is assumed to remain dry until inundated at least once each 30 days.
Undeveloped Dry Land	1	Salt Elevation	Dry land is assumed to remain dry until inundated at least once each 30 days.
Inland Open Water	1	Salt Elevation	Saline influence assumed once flooding occurs once each 30 days.
Inland-Fresh Marsh	1	Salt Elevation	Saline influence assumed once flooding occurs once each 30 days.
Swamp	1	Salt Elevation	Saline influence assumed once flooding occurs once each 30 days.
Trans. Salt Marsh	1	HTU	This scrub-shrub or recently flooded dry-land category is predicted to become emergent vegetation once flooding occurs daily.
Irregularly Flooded Marsh	0.5	HTU	The line between high and low marsh has been set based on analysis of LiDAR data.
Regularly Flooded Marsh	-0.4	HTU	This value is based on McKee and Patrick (1988)[54] and verified with site-specific LiDAR data.
Estuarine Beach	-1	HTU	SLAMM tracks land categories down to MLLW (mean lower low water).
Inland Shore	-1	HTU	SLAMM tracks land categories down to MLLW.
Ocean Beach	-1	HTU	SLAMM tracks land categories down to MLLW.
Ocean Flat	-1	HTU	SLAMM tracks land categories down to MLLW.
Rocky Intertidal	-1	HTU	SLAMM tracks land categories down to MLLW.
Tidal Flat	-1	HTU	SLAMM tracks land categories down to MLLW.

Conversion of tidal-fresh marshes and tidal swamps occurs primarily as a function of salinity rather than elevation. Therefore, lower elevation boundaries can be quite variable from site to site. For this reason, the low-elevation boundary for these categories was allowed to vary across study areas based on site-specific LiDAR data (Table 26). Tidal swamps tend to be more sensitive to salinity and are therefore often located higher in the tidal frame.

54 McKee and Patrick, "The Relationship of Smooth Cordgrass (Spartina Alterniflora) to Tidal Datums: A Review."

Table 26. Lower-elevation boundaries for tidal swamp and tidal-fresh marsh

	Suffolk East		Suffolk West		Nassau		NYC		Hudson	
	Min Elev.	**Min Unit**	**Min Elev.**	**Min Unit**	**Min Elev.**	**Min Unit**	**Min Elev.**	**Min Unit**	**Min Elev.**	**Min Unit**
Tidal Swamp	1.46	HTU	1	HTU	1	HTU	1.3	HTU	1	HTU
Tidal-Fresh Marsh	0.73	HTU	1	HTU	0.7	HTU	1.27	HTU	0.75	HTU

2.14 Uncertainty Analysis Setup

Although the base analyses consider a range of different possible SLR scenarios, the effects of various sources of uncertainties such as input parameters and driving data were not accounted for in the deterministic runs. For example, uncertainties arise when literature parameters are used rather than site-specific data. In addition, the strength of feedbacks between marsh vertical accretion rates and SLR can significantly vary from one site to another. SLAMM includes an uncertainty-analysis module that employs Monte-Carlo simulations to study the effects of uncertainties and produce predictions of wetland coverage as distributions. This module can enhance the value of the results by providing confidence intervals, worst and best case scenarios, likelihood of wetland conversion, and other statistical indicators useful to better characterize possible future outcomes and assist decision making.

All of the site-specific data required by SLAMM, such as the spatial distribution of elevations, wetland coverages, tidal ranges, accretion and erosion rates, local sea-level rise and subsidence rates, may be affected by uncertainties that can propagate into the predicted outputs. The propagation of input-parameter uncertainty into model predictions cannot be derived analytically due to the non-linear spatiotemporal relationships that govern wetland conversion. The Monte Carlo uncertainty analysis module within SLAMM uses efficient Latin-Hypercube sampling of the input parameters [55]. This module generates hundreds of prediction results that are then assembled into probability distributions of estimated wetland coverages.

For each of the model input parameters, an uncertainty distribution was derived based on available site-specific data. Moreover, mechanistic considerations regarding the proper distributional family and the feasible bounds of the variable were considered. Distributions were derived reflecting the potential for measurement errors, uncertainty within measured central tendencies, and professional judgment.[56]

[55] M. D McKay, R. J Beckman, and W. J. Conover, “A Comparison of Three Methods for Selecting Values of Input Variables in the Analysis of Output from a Computer Code,” *Technometrics*, 1979, 239–45.

[56] M. Firestone et al., “Guiding Principles for Monte Carlo Analysis,” 1997.

Because SLAMM calculates equilibrium effects of SLR based on relatively large time-steps, long-term erosion rates, accretion rates, and SLR rates were used to drive model predictions. Therefore, the uncertainty distributions described in the following section are based on long-term measurements rather than incorporating short-term variability within measurements. Cell-by-cell spatial variability has been considered for elevation data, but the majority of the input parameters have uncertainty distributions that vary on a subsite basis.

One important limitation that has to be considered when interpreting these results is that the uncertainties of the general conceptual model in describing system behaviors (model framework uncertainty)[57] are not taken into account. Within this uncertainty analysis, the flow chart of marsh succession is fixed. For example, low marshes must initially pass through a tidal flat category before becoming open water rather than directly converting to open water under any circumstance.

The next sections discuss each of the model's input parameters that are affected by uncertainties, and how they were handled within the uncertainty analysis for this project.

2.14.1 SLR by 2100

The extent of future sea-level rise by 2100 is a key model input parameter and possibly the most uncertain. The drivers of climate change used by scientists to derive potential SLR rates include future levels of economic activity, dominant fuel type (e.g., fossil or renewable, etc.), fuel consumption, and resulting greenhouse gas emissions. Because future values of these driving variables are uncertain, the exact extent of future sea-level rise is also therefore uncertain. Therefore, it is necessary to use a range of potential sea-level-rise scenarios in SLAMM analysis, to present a range of possibilities.

As described in Section 2.4, the deterministic SLR scenarios used in this SLAMM application correspond to the maximum of the General Climate Model (GCM), the Minimum and Maximum of the Rapid Ice Melt (RIM) estimates as described in the ClimAID report,[58] and the intermediate scenario of 1 meter (39.4 inches) of SLR by 2100. The base year for these scenarios is 2002. In the uncertainty analysis, sea-level rise scenarios were drawn from the triangular probability distribution shown in Figure 20. The deterministic SLR scenarios are also presented in order to illustrate their relationship to the possible simulated SLR scenarios. Figure 20 shows that, under the probability distribution of SLR applied, 1m by 2100 is the "most likely" scenario of those simulated by the deterministic model runs.

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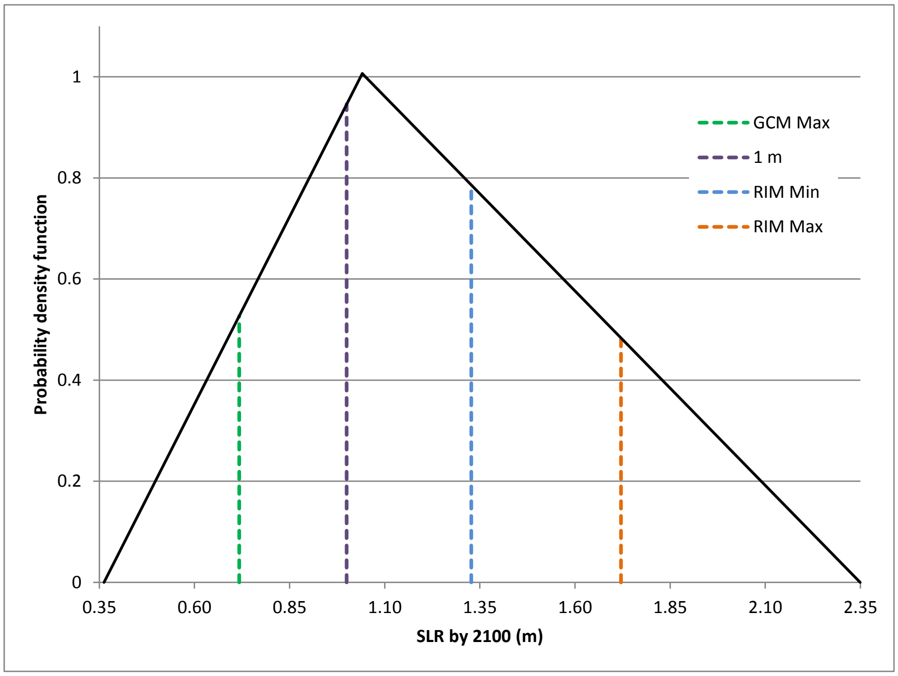
57 Noha Gaber et al., *Guidance on the Development, Evaluation, and Application of Environmental Models* (US Environmental Protection Agency, Office of Research and Development, 2008).

58 *Responding to Climate Change in New York State: The ClimAID Integrated Assessment for Effective Climate Change Adaptation in New York State*.

Figure 20. SLR probability distribution



In order to derive the probability distribution in Figure 20, information from the recent NYC Panel on Climate Change (NPCC2) report[59] was used in addition to the ClimAID report[60]. The NPCC2 study estimates that by the 2020s the sea-level rise (with respect to 2000-2004 baseline level) at the Battery in NYC has a 10% probability to be 5.08 cm or less and a 90% probability to be less than or equal to 27.94 cm. By the 2050s, the 10th percentile SLR is estimated to be 17.78 cm while the 90th percentile is equal to 78.74 cm, as presented in Table 27.

Table 27. Baseline and SLR Projections (Source NPCC2)

Sea-level rise baseline (2000-2004) 0 inches	Low-estimate (10th percentile)	Middle range (25th to 75th percentile)	High-estimate (90th percentile)
2020s	5.1 cm (2 in)	10.2 to 20.3 cm (4 to 8 in)	27.9 cm (11 in)
2050s	17.8 cm (7 in)	27.9 to 61.0 cm (11 to 24 in)	78.7 cm (31 in)

59 C. Rosenzweig and W. Solecki (Editors), NPCC2, *New York City Panel on Climate Change, 2013: Climate Risk Information 2013: Observations, Climate Change Projections, and Maps. Prepared for Use by the City of New York Special Initiative on Rebuilding and Resiliency, New York, New York.*, accessed June 19, 2014, http://www.nyc.gov/html/planyc2030/downloads/pdf/npcc_climate_risk_information_2013_report.pdf.

60 *Responding to Climate Change in New York State: The ClimAID Integrated Assessment for Effective Climate Change Adaptation in New York State..*

The sea-level rise estimates shown in Table 27 closely correspond to the GCM Min and RIM Max SLR scenarios. To incorporate these estimates and percentages the SLR predictions were extrapolated to 2100: the 10th percentile SLR projection was set to 36.2 cm (14.3 in), while the 90th percentile set to 1.84 m (72.4 in) by 2100. Assuming a symmetrical, triangular probability distribution, the most likely SLR scenario was estimated equal to 1.04 m (41 in) SLR by 2100. However, the historic SLR rate at the Battery (2.77 mm/yr) is already higher than the estimated current SLR rate of the 10th percentile SLR projection (2.2 mm/yr). It was deemed unlikely that future SLR rates will be lower than the historic recorded data during the past century. For this reason, the more conservative estimate was set to as the minimum possible SLR scenario rather than the 10th percentile, while 1.04-m and 1.84-m SLR by 2100 were kept as the most likely and the 90th percentile SLR scenarios, respectively. The highest possible SLR rate scenario was set to 2.35 m (92.5 in) by 2100.

2.14.2 Digital Elevation Map Uncertainty

LiDAR elevation data is subject to measurement errors due to equipment limitations. In addition, in marsh areas, the laser pulse used to measure elevations does not always reach the bare earth, causing additional errors and uncertainty[61]. In this SLAMM application, elevation-data uncertainty was evaluated by randomly applying elevation-data error statistics and creating a series of equally likely elevation maps. Maps were created adding a spatially autocorrelated error field to the existing digital elevation map[62]. Heuvelink's method has been widely recommended as an approach for assessing the effects of elevation data uncertainty[63]. This approach uses the normal distribution as specified by the Root Mean Squared Error (RMSE) for the LiDAR-derived dataset and applies it randomly over the entire study area, with spatial autocorrelation included,[64] as shown in Figure 21. A stochastic analysis is then executed (implementing the model with one of these elevation maps) to assess the overall effects of elevation uncertainty. In this analysis, it was assumed that elevation errors were strongly spatially autocorrelated, using a p-value of 0.2495. The declared vertical accuracy for the each LiDAR data layer applied was examined and the RMSE applied for the Hudson, Nassau, and Suffolk Counties (East and West) study areas was 0.09 m, while the New York City area had a higher RMSE of 0.125 m applied.

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61 Keil A. Schmid, Brian C. Hadley, and Nishanthi Wijekoon, "Vertical Accuracy and Use of Topographic LIDAR Data in Coastal Marshes," *Journal of Coastal Research* 27, no. 6A (2011): 116–32.

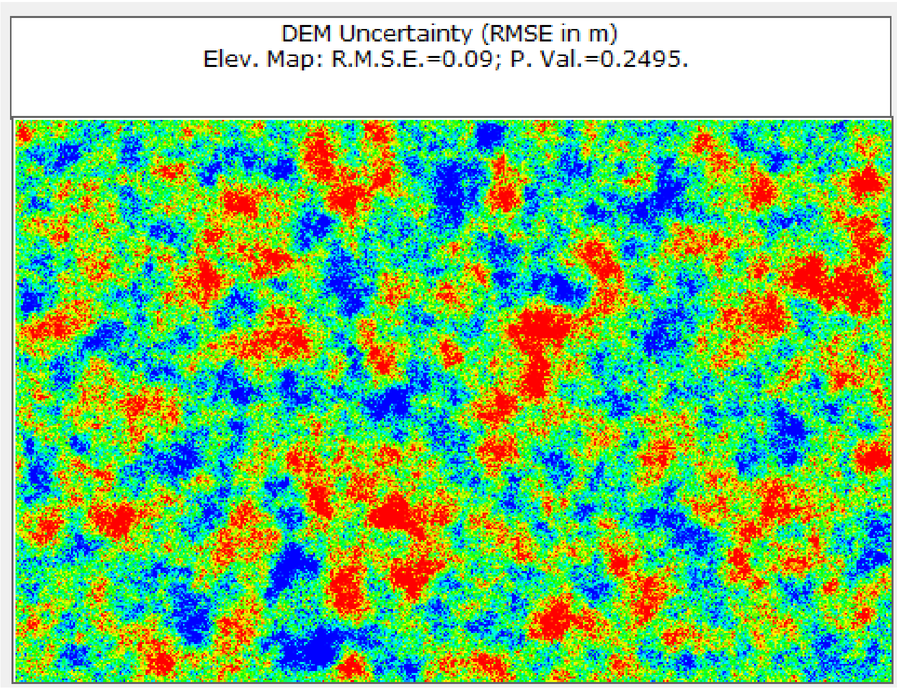
62 G. B. M. Heuvelink, *Error Propagation in Environmental Modelling with GIS* (CRC Press, 1998).

63 Amii R. Darnell, Nicholas J. Tate, and Chris Brunsdon, "Improving User Assessment of Error Implications in Digital Elevation Models," *Computers, Environment and Urban Systems* 32, no. 4 (July 2008): 268–77, doi:10.1016/j.compenvurbsys.2008.02.003; G. J Hunter and M. F Goodchild, "Modeling the Uncertainty of Slope and Aspect Estimates Derived from Spatial Databases," *Geographical Analysis* 29, no. 1 (1997): 35–49.

64 Hunter and Goodchild, "Modeling the Uncertainty of Slope and Aspect Estimates Derived from Spatial Databases."

Figure 21. Example of a DEM uncertainty map

Min (blue) = -0.135 m, Max (red) = 0.135.



2.14.3 Vertical Datum Correction

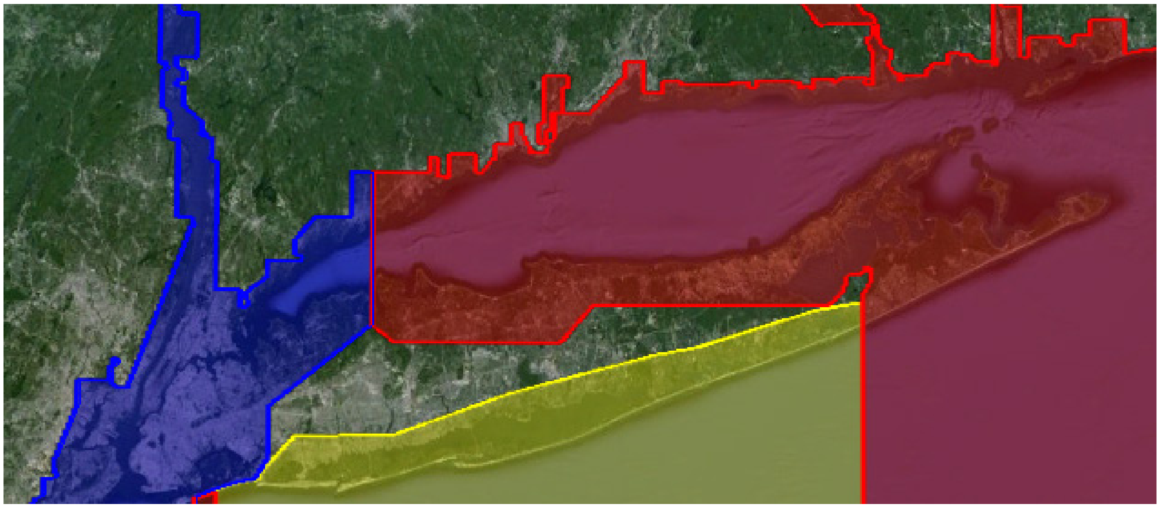
Correction of elevation data to a tidal basis using the NOAA VDATUM product is also subject to uncertainty due to measurement errors and VDATUM model errors. NOAA characterizes the "maximum cumulative uncertainty" for each location in the documentation of the model[65]. Like the DEM uncertainty, the vertical-datum-correction uncertainty was also applied via spatially variable autocorrelated maps. Three MTL to NAVD88 correction grids were used in the datum transformation for this study: the NY/NJ harbor, NY Great Bay, and the RI/CT (Figure 22). Each one has a slightly different "maximum cumulative uncertainty:" NY/NJ harbor = 9.3 cm, NY Great South Bay= 11.4 cm, and the outer NY Bight, RI/CT = 10.2 cm. Because of the complicated boundaries of these data sets as compared to the study project boundaries and the similar maximum cumulative uncertainties of the data sets, the RMSE for the datum correction was set to 10 cm for the entire study area. Like the DEM uncertainty the assumption of strong spatial autocorrelation was maintained and a p-value of 0.2495 was applied.

[65] National Oceanic and Atmospheric Association, "VDatum: Estimation of Vertical Uncertainties in VDatum - Last Revised: July 2009," *Vertical Datum Transformation: Integrating America's Elevation Data*, 2010, http://roadwaytocollege.com/go/page.pl/000000A/http/vdatum.noaa.gov/docs/est_uncertainties.html.

Figure 22. VDATUM transformation grid coverage areas for the NY Coast

Image from Google Earth, NOAA.

Blue area = NY/NJ Harbor, Yellow area = NY Great South Bay, Red area = outer NY Bight RI/CT

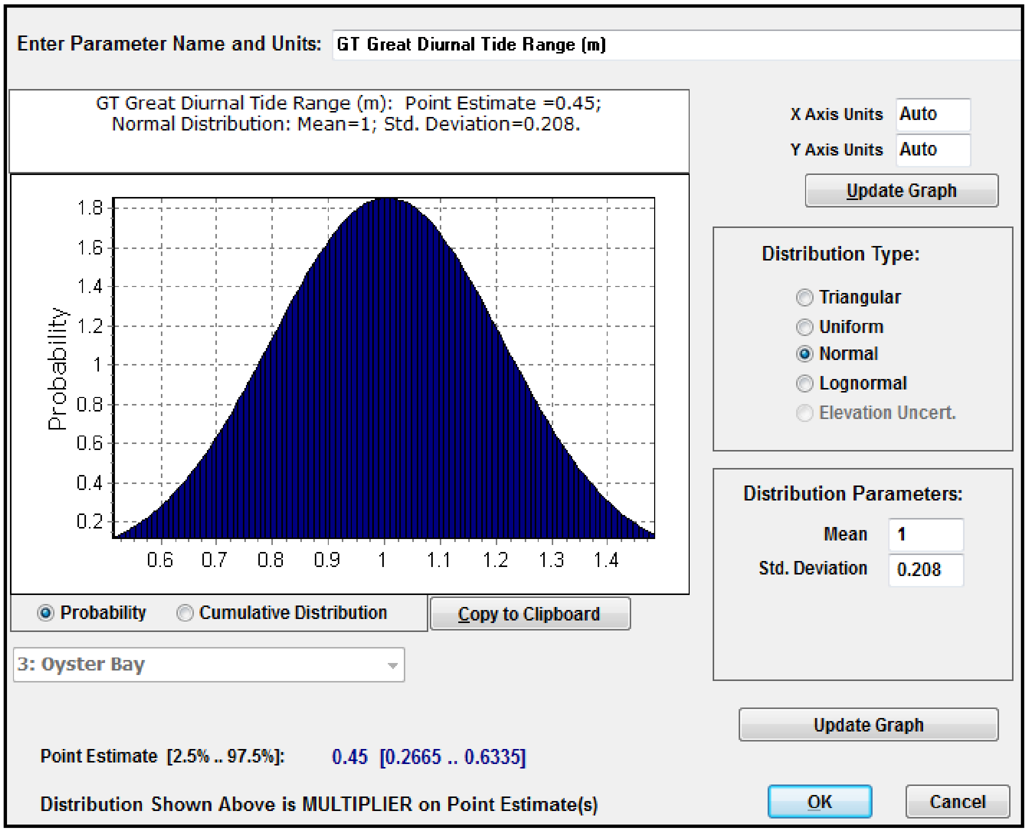


2.14.4 Great Diurnal Tide Range

Tide ranges are not measured at each cell, and therefore there is spatial uncertainty associated with the tide range assigned. The error associated with the tide ranges applied was considered on an input subsite basis. The GT of each input subsite was represented by a unique probability distribution based on the data used to derive the tide range estimate. These distributions represent multipliers on point estimates, rather than the distribution of the tide range itself. (This approach allows SLAMM to remain flexible when using one probability distribution for many input subsites with varying tide range). An example of the SLAMM interface showing the uncertainty of the Oyster Bay subsite in Nassau County is shown in Figure 23.

In order to calculate the standard deviation multiplier applied for each subsite, the standard deviation of the tide data considered for each subsite was calculated. When less than four tide range values were used to determine the GT for an input subsite, the difference between the GT applied and the maximum GT observed was calculated, as was the difference between the GT applied and the minimum GT observed, and the greater of these two values was applied as the standard deviation. When subsites were added to represent muted tide ranges (behind a tide gate or upriver) where tide data were not available, the standard deviation of nearby subsites were applied.

Figure 23. Example Input Distribution for Great Diurnal Tide Range Uncertainty



2.14.5 Salt Elevation

The elevation of the coastal wetland to dry land boundary is also subject to uncertainty due to tide range uncertainty and spatial interpolation. The distribution of uncertainties affecting the salt elevation were estimated by calculating the variability of the measured 30-day elevation data with respect to the best fit linear relationship between great diurnal tide ranges and 30-day inundation elevations identified in Section 2.7. The standard deviation of the measured data with respect to the model is approximately 9 cm. Uncertainty distributions of all salt elevations are thus modeled as Gaussian distributions with expected values equal to salt elevations calculated by the linear relationship for a given GT and with a standard deviation equal to 9 cm.

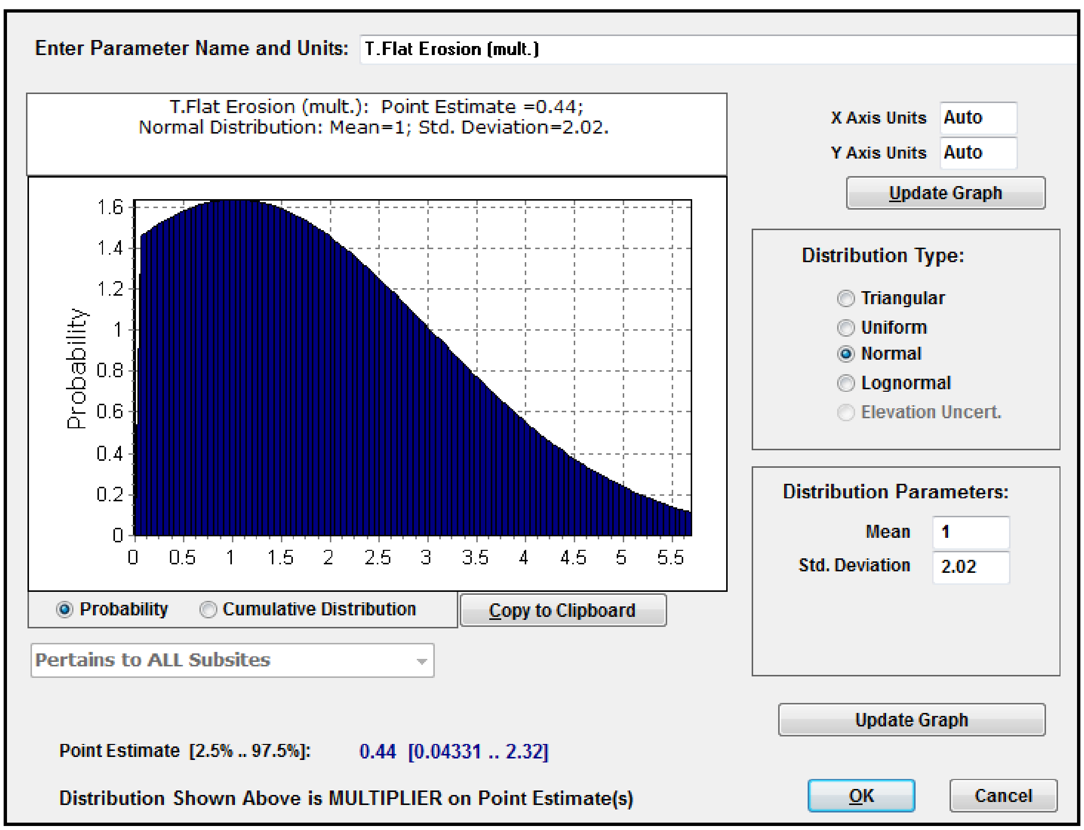
Since the GTs applied are also uncertain variables, the sampling of the salt elevation for each model realization was carried out by first sampling the GT from its uncertainty distribution. Once a GT is sampled for the next model realization, the *mean* salt elevation is calculated using the linear relationship presented in Figure 5. Finally a multiplier on the salt elevation is sampled from its Gaussian uncertainty distribution and applied to the model iteration.

2.14.6 Erosion

Historical erosion rates can be quite variable in both space and time, and the projection of future erosion rates involves a combination of data and professional judgment. Uncertainty parameters associated with marsh, swamp, and tidal flat erosion parameters were applied uniformly across the study area. The marsh erosion rate applies to all marshes in the study area subject to erosion (adjacent to open water with 9 km fetch). Marsh erosion was assigned a uniform distribution with multipliers ranging from 0 to 2, allowing an equally likely value from 0 m/yr to 2m/yr to be selected, based on data reported by Fagherazzi.[66] Uncertainty in swamp erosion was estimated using a normally distributed probability range with a standard deviation of 0.4 based on professional judgment, as no site-specific data were available. The tidal flat erosion rate applies to beaches and tidal flats. Tidal flat erosion was assigned a normal distribution with a multiplier standard deviation of 2.02 based on the work of Leatherman.[67] This distribution is presented in Figure 24 and shows that the allowable range of tidal flat erosion was extremely wide, ranging from

0 to more than 2 m per year. This range incorporates the uncertainty of the effects of large storms and, to some extent, beach nourishment that may occur.

Figure 24. Tidal Flat/Beach Erosion



66 Fagherazzi, "The Ephemeral Life of a Salt Marsh."

67 Leatherman, Zhang, and Douglas, "Sea-level rise Shown to Drive Coastal Erosion."

2.14.7 Accretion

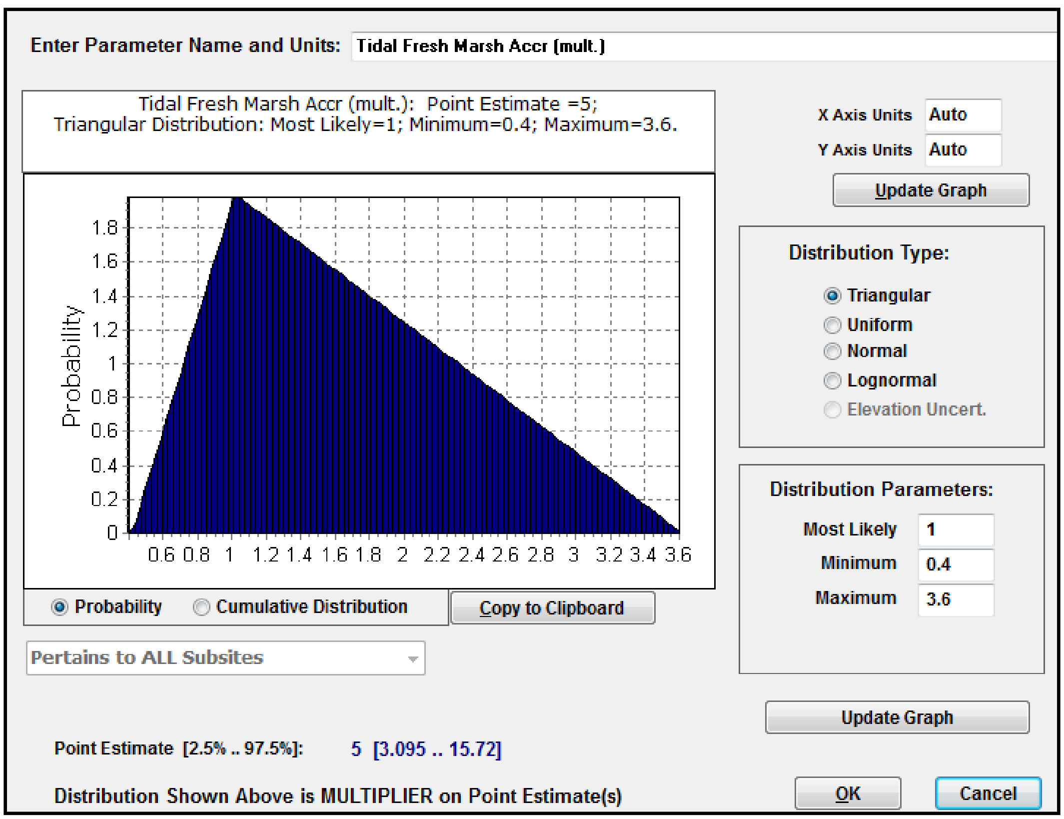
2.14.7.1 Accretion Point Estimate Uncertainty

Due to a lack of spatially variable site-specific data, uncertainty distributions for the following categories were applied uniformly throughout the entire study area:

- Accretion rates for freshwater marshes (inland and tidal).
- Swamp and tidal swamp accretion rates.
- Beach sedimentation rates.

Tidal fresh marsh accretion was applied as a triangular distribution with a minimum of 2 mm/yr and a maximum of 18 mm/yr, with a most likely value of 5 mm/yr (corresponding to multipliers of 0.4, 3.6, and 1, respectively). The minimum for this distribution was derived from work by Neubauer in the Hudson River[68] while the maximum was derived from studies of tidal-fresh marshes along the mid-Atlantic coast[69]. The distribution applied is presented in Figure 25.

Figure 25. Tidal fresh marsh accretion distribution assigned for uncertainty analysis



68 Neubauer, "Contributions of Mineral and Organic Components to Tidal Freshwater Marsh Accretion."

69 Neubauer et al., "Sediment Deposition and Accretion in a Mid-Atlantic (U.S.A.) Tidal Freshwater Marsh."

Inland fresh marsh accretion uncertainty was applied a normal distribution with a multiplier standard deviation of 0.153, which was determined from data presented by Craft and coworkers.[70] This assignment resulted in a relatively narrow range of possible values with 2.5th and 97.5th percentile values of 0.7 and 1.3 mm/yr, respectively.

Tidal swamp accretion was applied a uniform probability distribution. Based on data from Craft[71] collected in Georgia tidal swamps, a maximum of 2.8 mm/yr and a minimum of 0.6 mm/yr were applied. Accretion observations by Craft were also used to inform the probability distribution for swamps. Based on unpublished data from the Altamaha River in Georgia[72], a uniform distribution with a minimum on 0.2 mm/yr and maximum 3.4 mm/yr was applied.

Beach sedimentation rate uncertainty was applied as a uniform distribution from 0.1 to 2 mm/yr. Beach sedimentation rates tend to be spatially variable, and are often lower than marsh accretion rates due to the lack of vegetation to trap sediments. This range is fairly wide, since there is a considerable amount of uncertainty in beach sedimentation due to nourishment activities, which are not included in this study.

2.14.7.2 Mechanistic Accretion Model Uncertainty

The accretion models and measured accretion data variability described in Section 2.8 were used to estimate the uncertainty distributions attributed to tidal marsh accretion rates.

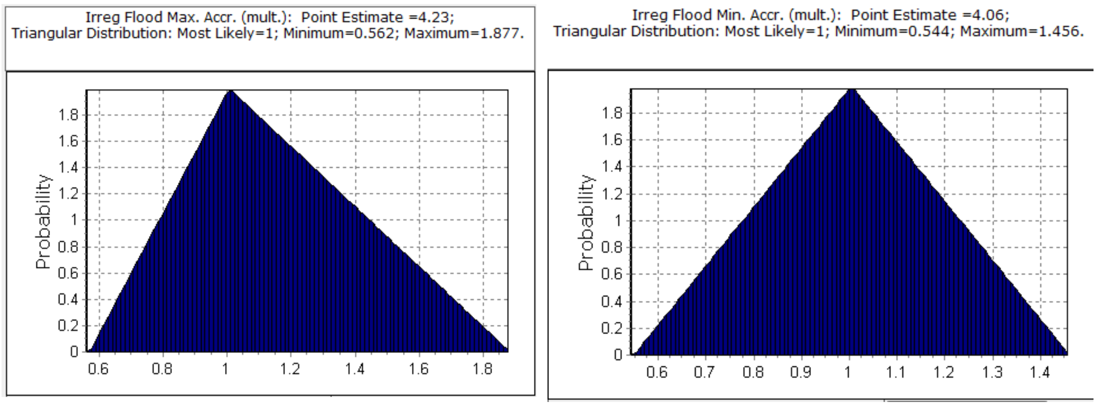
Irregularly flooded marsh. The general *linear* accretion-elevation relationship used in the deterministic model runs is also maintained in the uncertainty analysis (see Section 2.8.1.1). However, the maximum and minimum accretion rates assigned at the boundaries of the marsh elevation range (0.5 HTU to 1 Salt Elevation) are drawn from probability distributions. These probability distributions were derived using the variability of the available measured accretion rates with respect to the best fit linear model (see Figure 6) calculated to be 1.85 mm/yr. The goal was to determine the ensemble of linear accretion models that would fit the available data within their confidence intervals. A triangular distribution was then assigned both for the minimum (observed at 1 SE elevation) and maximum (observed at 0.5 HTU) accretion values as shown in Figure 26.

70 C. B. Craft and C. J. Richardson, "Recent and Long-Term Organic Soil Accretion and Nutrient Accumulation in the Everglades," *Soil Science Society of America Journal* 62, no. 3 (1998): 834–43; Craft and Casey, "Sediment and Nutrient Accumulation in Floodplain and Depressional Freshwater Wetlands of Georgia, USA."

71 Christopher B. Craft, "Tidal Freshwater Forest Accretion Does Not Keep Pace with Sea-level rise," *Global Change Biology* 18, no. 12 (December 2012): 3615–23, doi:10.1111/gcb.12009.

72 Craft, Christopher, personal communication, February 27, 2014.

Figure 26. Uncertainty distributions for maximum and minimum accretion rates for irregularly flooded marsh

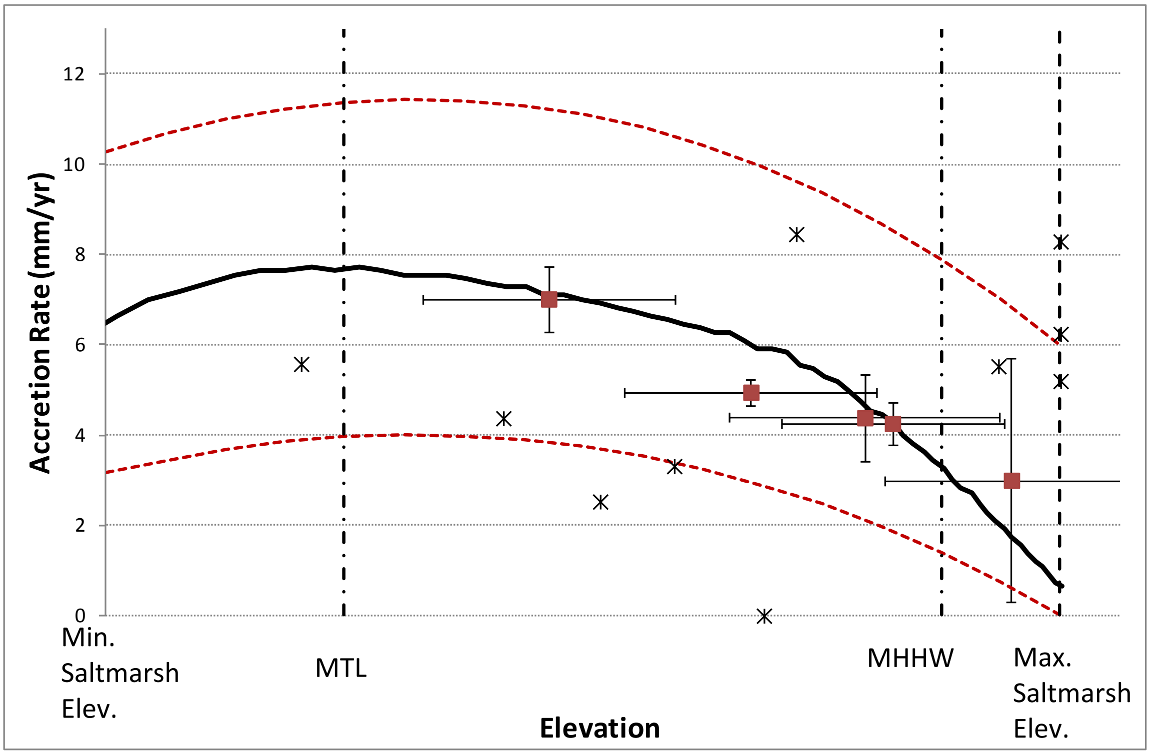


The triangular distributions in Figure 26 were determined by assigning the most likely probability at the maximum and minimum values used in the deterministic runs, 4.23 mm/yr and 4.06 mm/yr , respectively. The range for these triangular distributions was estimated by adding or subtracting to the most likely value one or two standard deviations of the observed accretion rate data. For the maximum accretion rate, the possible range was set to [2.38, 7.94] mm/yr, and for the minimum accretion rate [2.21, 5.91] mm/yr. With these probability distributions applied, most of the model realizations have a highest accretion rate at lower elevations, when the marsh is inundated more frequently, reflecting a capability of the marsh to respond to SLR increase by increasing accretion. However, model realizations where accretion is higher at higher elevations are also possible, perhaps due to higher productivity in less-saline conditions. Furthermore, higher accretion rates at higher elevations cannot be ruled out from the available accretion data, as shown in Figure 6.

Regularly flooded marsh. For low tidal marsh, uncertainty in accretion-feedback curves was estimated by considering the uncertainty and variability within available accretion data. Accretion measurement uncertainty and associated elevation-data uncertainty were either provided or estimated (e.g. by considering the elevation variability around the sampling location). We then investigated how the uncertainty of these data could propagate into a calibrated MEM model. As MEM contains several parameters that can be varied to calibrate the model, for simplicity (and consistency with our approach for irregularly flooded marsh), only maximum and minimum accretion rates were considered as uncertainty variables. Given this choice, the calibrated MEM model identified for the deterministic runs (see Figure 9) can be varied by these two rescaling factors. An example is shown in Figure 27, where the uncertainty for marsh accretion rate in the Peconic Bay area is investigated.

Figure 27. MEM uncertainty investigation based on uncertainty in observed data

Observed data (red squares) are shown with one standard-deviation error bars; asterisks represent observed data with two standard deviations; the black line represents the best MEM fit used in deterministic runs; and dashed red lines represent the uncertainty model boundaries.



The data points in Figure 27 are presented with one standard deviation error bar. The red dashed lines are upper and lower accretion boundaries that include the measured data within two standard deviations of their uncertainty. In this example, the uncertainty distribution for the maximum accretion rate was chosen as a Gaussian curve with the most likely value equal to the maximum accretion rate determined for the deterministic runs, 7.7 mm/yr, and standard deviation equal to 1.9 mm/yr, which defines a 95% interval equal to [4, 11.4] mm/yr. The minimum accretion rate has been also selected as a Gaussian distribution with a most likely rate equal to 0.8 mm/yr and a nominal standard deviation equal to 2.7 mm/yr. However, this distribution was truncated at 0 to avoid negative accretion values.

When interpreting Figure 27, in essence, any accretion feedback curve drawn between these two red lines with the same general parabolic shape could be produced by one of the uncertainty model's iterations. A low minimum accretion rate could be paired with a high maximum accretion rate for example, providing a very strong feedback. Given uncertainty about future suspended-sediment concentrations, spatial variability within marsh accretion rates, and relatively high uncertainty in our data sets, the intent was to be as conservative as possible and to sample from a wide range of feasible relationships between accretion rates and marsh elevation.

A similar procedure was employed for all MEM models applied to this project.[73] The identified uncertainty distributions are summarized in Table 28. The last two columns provide the range of 95% of the accretion sample values drawn from these distributions.

Table 28. Summary of uncertainty accretion rate distribution

MAX Reg Flood Accretion (mm/year)	Distribution type	Most Likely (mm/yr)	Min-Max or Standard Deviation (mm/yr) *	2.5th percentile (mm/yr)	97.5th percentile (mm/yr)
LI North Shore	Triangular	4.5	1.2-8.9	2.0	8.0
LI South Shore	Triangular	4.4	1.2-8.9	2.0	8.0
LI Bays	Normal	7.7	1.9	4.0	11.4
Staten Island	Triangular	4.5	1.2-8.9	2.0	8.0
Hudson	Normal	10.9	1.9	7.2	14.6

MIN Reg Flood Accretion (mm/year)	Distribution type	Most Likely (mm/yr)	Min-Max or Standard Deviation (mm/yr) *	2.5th percentile (mm/yr)	97.5th percentile (mm/yr)
LI North Shore	Triangular	0.5	0-3.9	0.15	3.5
LI South Shore	Triangular	0.6	0-4.2	0.18	3.5
LI Bays	Normal**	0.8	1.9	0.10	7.1
Staten Island	Triangular	0.6	0-4.1	0.18	3.5
Hudson	Normal**	1.5	1.9	0.10	6.9

* Max-Min accretion rate for triangular distribution and standard deviation for normal distribution.

** Distribution is truncated at zero so that negative accretion rates are not possible.

[73] When the original accretion rate curve was derived from another area with more data, e.g., Hudson from LI Bays model, uncertainty distributions were produced by rescaling uncertainty intervals derived from the original location.

3 Deterministic Model Results and Discussion

In the following subsections, deterministic model results (non-uncertainty analysis results) are presented individually for each of the five modeled study areas, as well as the entire study area. Tables of land-cover acreage at each time step for each SLR scenario simulated are included, as well as summary tables showing the percentage loss and acreage gain for selected land-cover types. It is important to note that changes presented in the summary tables are compared to the 2004 or 2010 time-zero result and therefore represent projected land-cover changes as a result of sea-level rise excluding any predicted changes that occur when the model is applied to initial-condition data.

3.1 Entire Study Area

Results of SLR are presented in Table 29, but SLR effects are spatially variable across the entire study area. Heavy marsh losses are predicted to occur in vulnerable microtidal regimes behind southern barrier islands, and these southern barrier islands themselves are especially subject to dry land losses.

Table 29. Predicted percentage change in land covers from 2004 to 2100 for the entire study area

Land-cover category	Acres in 2004	Percentage Land cover change from 2004 to 2100 for different SLR scenarios			
		GCM Max	1m	RIM Min	RIM Max
Estuarine Open Water	480,824	1.4	2.8	4.3	6.6
Open Ocean	379,488	0.4	0.5	0.7	0.9
Undeveloped Dry Land	312,317	-3.0	-5.1	-7.8	-11.0
Developed Dry Land	204,954	-1.8	-3.8	-6.6	-10.4
Irregularly Flooded Marsh	20,759	-41	-81	-93	-96
Swamp	8,540	-6	-11	-16	-21
Inland Open Water	7,030	-6	-11	-14	-17
Regularly Flooded Marsh	5,475	189	314	320	274
Ocean Beach	4,547	-14	-7	-2	4
Estuarine Beach	4,440	-40	-50	-58	-69
Tidal Flat	3,472	-9	38	123	166
Trans. Salt Marsh	2,933	110	141	170	181
Inland-Fresh Marsh	1,551	-13	-27	-34	-47
Tidal Swamp	799	-41	-64	-80	-88
Flooded Developed Dry Land	305	1213	2522	4464	6672
Tidal-Fresh Marsh	187	-13	-37	-57	-70
Inland Shore	87	0.0	0.0	0.0	0.0
Rocky Intertidal	41	-71	-85	-91	-94
Riverine Tidal	12	-47	-48	-50	-53
Ocean Flat	1	-9	-31	-54	-77

Figure 28. Marsh and Tidal-Flat fate as a function of SLR by 2100

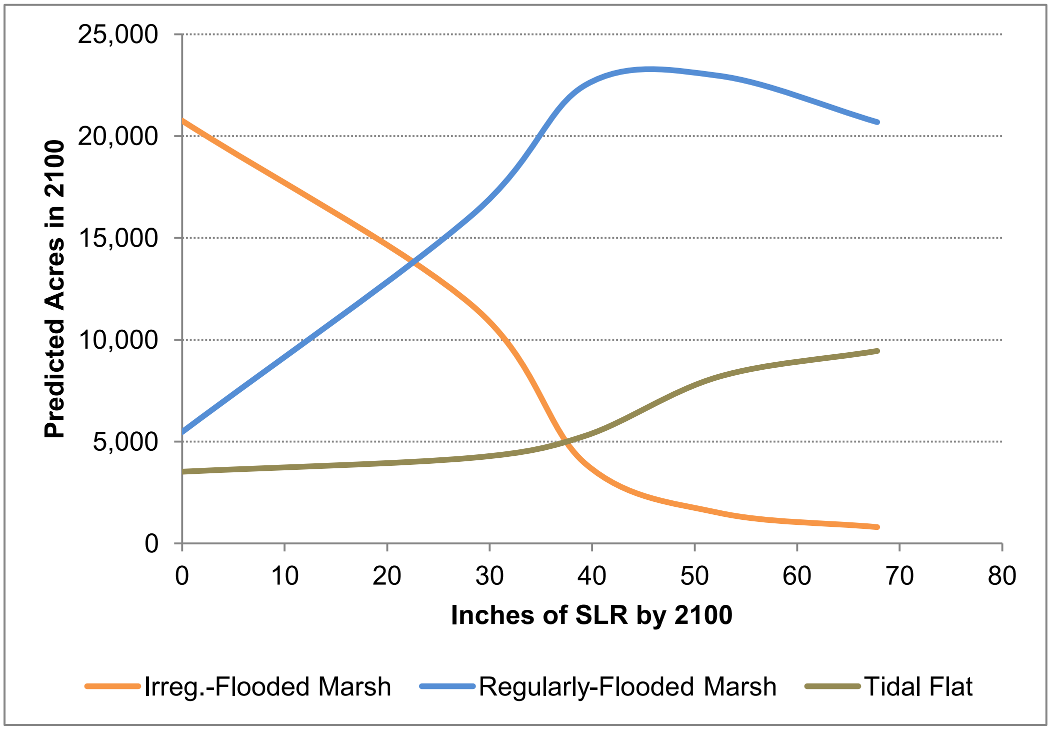
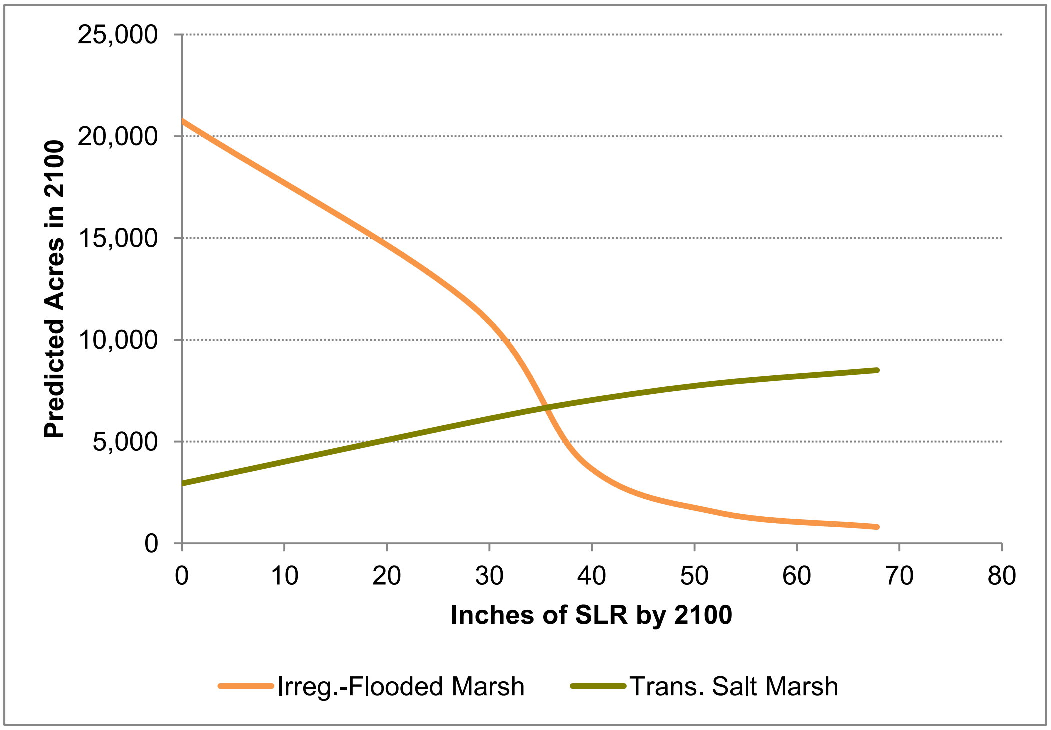


Figure 28 illustrates the effect that different SLR scenarios will have on irregularly flooded marshes, regularly flooded marshes, and tidal flats by 2100. Under moderate rates of SLR, high marshes begin to be lost and replaced by low (regularly flooded) marshes. Under higher scenarios, the regularly flooded marshes also begin to be lost, converting to tidal flats.

It is important to note that there is some uncertainty regarding the capability of high marshes (irregularly flooded marshes) to migrate onto dry lands. When dry lands fall below the 30-day inundation level and are assumed to convert to a coastal wetland, SLAMM generally converts these lands to the "transitional salt marsh" category as opposed to irregularly flooded marshes. The transitional salt marsh category contains recently flooded dry lands and also scrub-shrub intertidal habitats. If some of these transitional salt marsh categories become viable emergent high marshes (irregularly flooded marshes), then some degree of high-marsh loss may be overstated by the model. However, as shown in Figure 29, the potential increase of 5,000 acres of transitional salt marsh would not be sufficient to overcome the predicted losses of approximately 20,000 acres of irregularly flooded marshes.

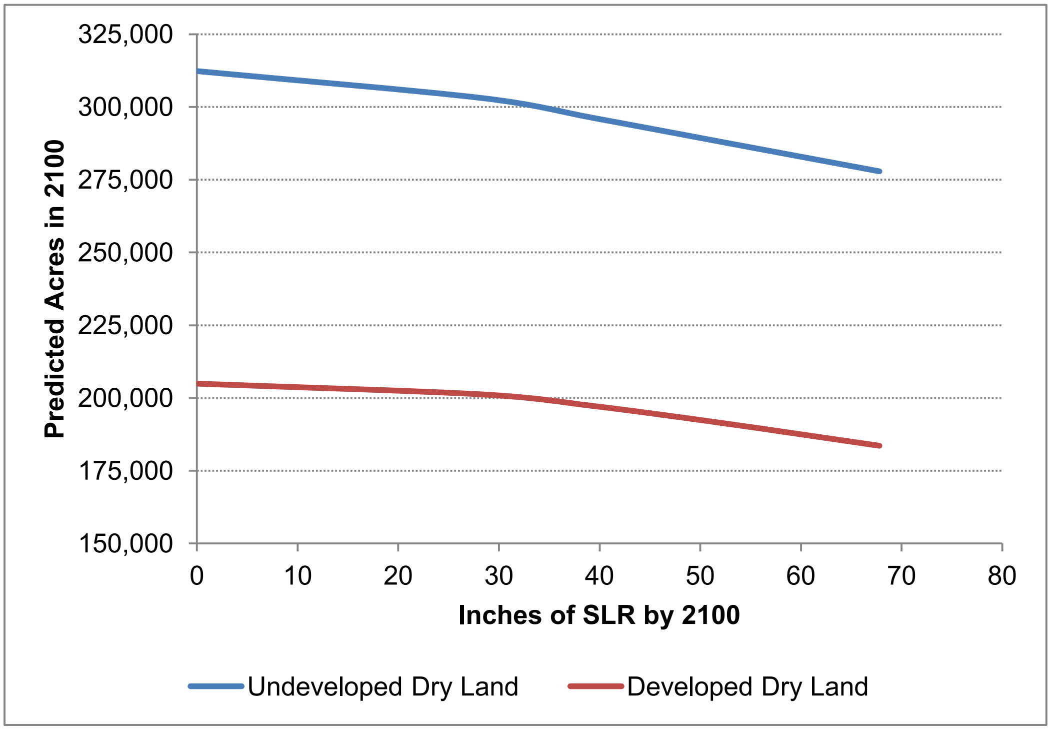
Figure 29. Relationship between High Marshes and Transitional Salt Marshes



Another observation about predicted marsh losses under accelerated SLR is that even when marsh loss is not predicted, accelerated SLR will make all marshes more vulnerable to future SLR and storms. When SLR occurs, even though marsh accretion rates can increase, marsh platforms will become lower in elevation relative to tide levels. In some cases marshes may be predicted by the model to persist but would only require a small additional push of water levels to convert to tidal flats or open water.

Up to 10% of developed lands and up to 11% of undeveloped lands are also vulnerable under the SLR scenarios examined (Figure 30).

Figure 30. Dry-land fate as a function of SLR by 2100



Presenting results maps for the entire study area, which was mapped at 5 meters cell size, is not practical for this type of report. However, the sections below will discuss results for each of the five individual study areas and will present some maps of interest. Maps presented herein are only a tiny portion of available mapped output, however. As part of this project, GIS maps of the entire study area are being made publicly available for every scenario and time-step simulated along with numerous maps derived from uncertainty analyses. These data are available at http://warrenpinnacle.com/prof/SLAMM/NYSERDA/.

3.2 Hudson

The SLAMM model predicts that the Piermont Marsh will be fairly resilient to the effects of accelerated SLR under the GCM Max scenario (Table 30). However, by 2085 this marsh is predicted to convert from irregularly flooded (high) marsh to regularly flooded marsh and potentially tidal flats under the higher SLR scenarios examined (Figure 31). LiDAR data combined with the VDATUM correction suggest that the marsh is currently 28 to 31 inches above mean-tide level. Over 80 years, SLAMM predicts an additional 12 inches of elevation gain due to irregularly flooded marsh accretion. Assuming that the marsh converts to a viable low marsh, the high sediment concentrations in the Hudson River may enable additional sediment trapping and higher accretion rates. However, by 2100 under the RIM-Max scenario, the majority of marsh at this site is predicted to be lost. In addition, if there is local subsidence occurring on the marsh platform, conversion could occur at an earlier date. Table 31 through Table 34 show land-cover predictions for the Hudson River study area under the lowest through the highest SLR scenarios examined.

Table 30. Hudson Land cover Change Summary

Positive indicates a gain, whereas negative indicates a loss.

Land-cover category	Acres in 2004	Percentage Land cover change from 2004 to 2100 for different SLR scenarios			
		GCM Max	1m	RIM Min	RIM Max
Estuarine Open Water	7,587	0.6	0.6	0.7	1.0
Developed Dry Land	4,162	-0.3	-0.6	-1.4	-3.0
Undeveloped Dry Land	3,826	-0.8	-1.3	-1.8	-2.7
Inland Open Water	356	0.0	0.0	0.0	-0.1
Irregularly Flooded Marsh	245	-4.4	-62.2	-98.8	-99.7
Swamp	103	0.0	0.0	0.0	-0.1
Trans. Salt Marsh	46	-80	-72	-64	-32
Inland-Fresh Marsh	43	0.0	0.0	0.0	0.0
Regularly flooded Marsh	12	347	1587	2364	995
Tidal Flat	8	-74.1	-71.0	-27.8	1968.9
Flooded Developed Dry Land	3	382	830	1814	3957
Riverine Tidal	1	-45.7	-49.6	-55.8	-57.4
Tidal Swamp	0	-71	-98	-100	-100
Inland Shore	0	0.0	0.0	0.0	0.0

Figure 31. SLAMM predictions for Piermont Marsh in 2085 and 2100 compared to initial conditions

SLAMM output maps show current or predicted land-cover conditions at low tide (MLLW).

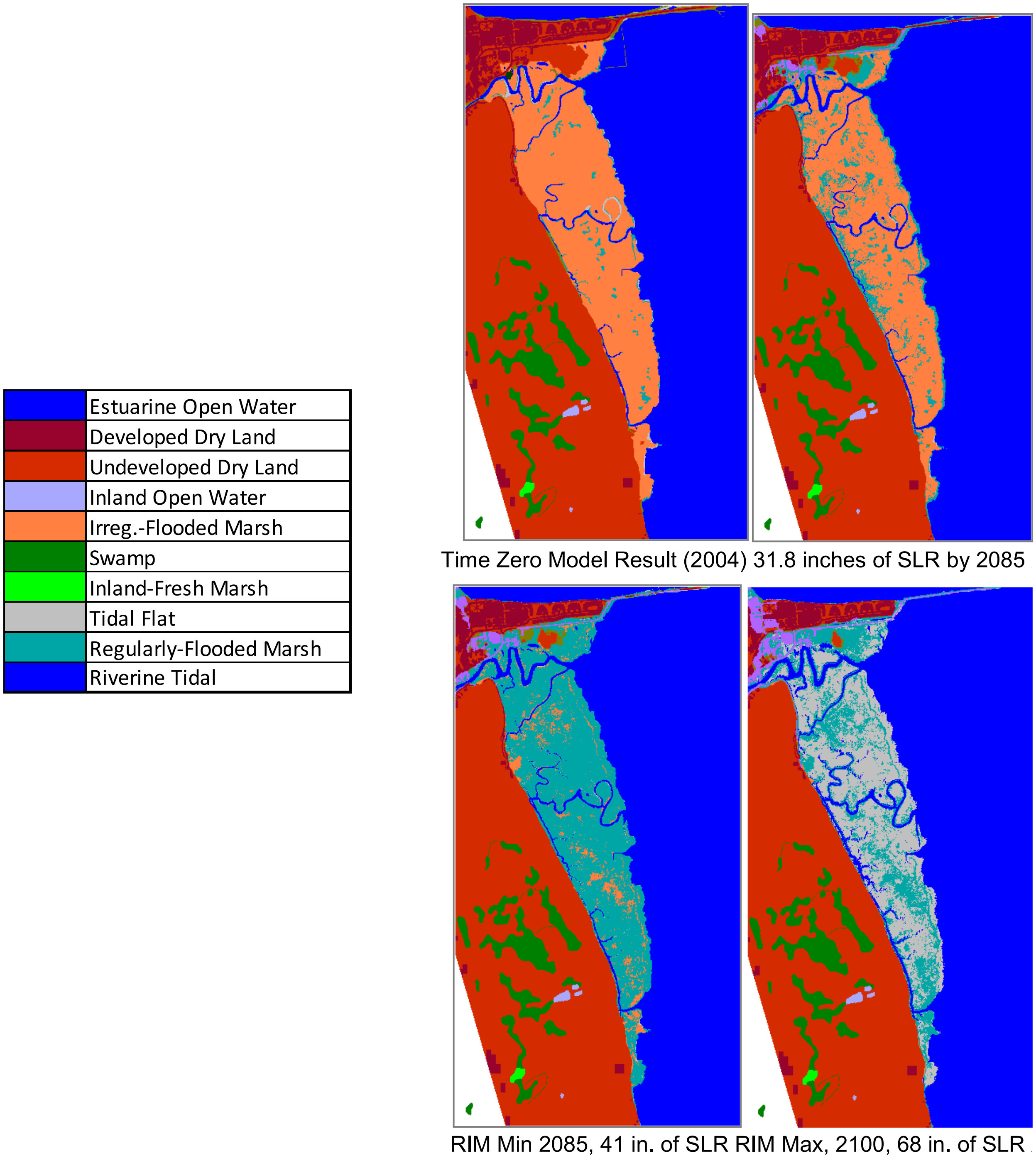


Table 31. Hudson GCM Max (acres)

		Initial	2004	2025	2055	2085	2100
	Estuarine Open Water	7,586	7,587	7,592	7,620	7,628	7,629
	Developed Dry Land	4,165	4,162	4,161	4,160	4,155	4,150
	Undeveloped Dry Land	3,872	3,826	3,824	3,819	3,803	3,796
	Inland Open Water	356	356	356	356	356	356
	Irregularly Flooded Marsh	252	245	245	244	238	234
	Swamp	103	103	103	103	103	103
	Inland-Fresh Marsh	43	43	43	43	43	43
	Tidal Flat	8	8	7	11	3	2
	Regularly flooded Marsh	7	12	54	27	43	55
	Riverine Tidal	1	1	1	1	1	0
	Tidal Swamp	0	0	0	0	0	0
	Inland Shore	0	0	0	0	0	0
	Trans. Salt Marsh	0	46	3	4	10	9
	Flooded Developed Dry Land	-	3	4	5	10	15
	Total (including water)	**16,393**	**16,393**	**16,393**	**16,393**	**16,393**	**16,393**

Table 32. Hudson 1m (acres)

		Initial	2004	2025	2055	2085	2100
	Estuarine Open Water	7,586	7,587	7,592	7,625	7,632	7,634
	Developed Dry Land	4,165	4,162	4,161	4,158	4,146	4,135
	Undeveloped Dry Land	3,872	3,826	3,824	3,812	3,791	3,778
	Inland Open Water	356	356	356	356	356	356
	Irregularly Flooded Marsh	252	245	245	239	208	93
	Swamp	103	103	103	103	103	103
	Inland-Fresh Marsh	43	43	43	43	43	43
	Tidal Flat	8	8	7	7	3	2
	Regularly flooded Marsh	7	12	54	34	81	206
	Riverine Tidal	1	1	1	1	0	0
	Tidal Swamp	0	0	0	0	0	0
	Inland Shore	0	0	0	0	0	0
	Trans. Salt Marsh	0	46	3	8	11	13
	Flooded Developed Dry Land	-	3	4	7	19	30
	Total (including water)	**16,393**	**16,393**	**16,393**	**16,393**	**16,393**	**16,393**

Table 33. Hudson RIM MIN (acres)

		Initial	2004	2025	2055	2085	2100
	Estuarine Open Water	7,586	7,587	7,592	7,627	7,637	7,642
	Developed Dry Land	4,165	4,162	4,161	4,157	4,132	4,104
	Undeveloped Dry Land	3,872	3,826	3,824	3,809	3,775	3,758
	Inland Open Water	356	356	356	356	356	356
	Irregularly Flooded Marsh	252	245	245	237	28	3
	Swamp	103	103	103	103	103	103
	Inland-Fresh Marsh	43	43	43	43	43	43
	Tidal Flat	8	8	7	7	5	6
	Regularly flooded Marsh	7	12	54	35	263	300
	Riverine Tidal	1	1	1	1	0	0
	Tidal Swamp	0	0	0	0	-	-
	Inland Shore	0	0	0	0	0	0
	Trans. Salt Marsh	0	46	3	10	18	16
	Flooded Developed Dry Land	-	3	4	8	33	61
	Total (including water)	**16,393**	**16,393**	**16,393**	**16,393**	**16,393**	**16,393**

Table 34. Hudson RIM MAX (acres)

		Initial	2004	2025	2055	2085	2100
	Estuarine Open Water	7,586	7,587	7,593	7,634	7,648	7,666
	Developed Dry Land	4,165	4,162	4,161	4,149	4,089	4,035
	Undeveloped Dry Land	3,872	3,826	3,820	3,795	3,755	3,724
	Inland Open Water	356	356	356	356	356	356
	Irregularly Flooded Marsh	252	245	242	181	2	1
	Swamp	103	103	103	103	103	103
	Inland-Fresh Marsh	43	43	43	43	43	43
	Tidal Flat	8	8	7	6	13	171
	Regularly flooded Marsh	7	12	57	95	289	133
	Riverine Tidal	1	1	1	0	0	0
	Tidal Swamp	0	0	0	0	-	-
	Inland Shore	0	0	0	0	0	0
	Trans. Salt Marsh	0	46	6	14	19	31
	Flooded Developed Dry Land	-	3	4	16	76	130
	Total (including water)	**16,393**	**16,393**	**16,393**	**16,393**	**16,393**	**16,393**

3.3 New York City

In the New York City study area, the most vulnerable habitat types to SLR are high marshes (irregularly flooded) followed by estuarine beaches. The model assumes that some of these high marshes and dry lands will be colonized by low marshes (regularly flooded) and, indeed, regularly flooded marshes are predicted to fare well under all scenarios examined (Table 35, Table 36).

Table 35. NYC land cover change summary

Positive indicates a gain, and negative indicates a loss.

Land-cover category	Initial coverage - 2008 (acres)	Percentage land cover change from 2008 to 2100 for different SLR scenarios			
		GCM Max	1 m	RIM Min	RIM Max
Developed Dry Land	123,823	-1	-2	-4	-7
Undeveloped Dry Land	59,908	-2	-4	-6	-10
Irreg.-Flooded Marsh	2,019	-5	-35	-69	-82
Tidal Flat	1,944	-38	-53	-55	-15
Regularly flooded Marsh	1,526	47	120	209	225
Ocean Beach	732	-3	5	21	36
Trans. Salt Marsh	660	62	102	127	188
Swamp	547	-4	-8	-12	-24
Estuarine Beach	463	-39	-47	-54	-60
Inland Fresh Marsh	421	-5	-11	-21	-50
Flooded Dev. Dry Land	150	651	1,579	3,176	5,279
Tidal Swamp	73	-20	-39	-59	-74
Tidal Fresh Marsh	29	-28	-42	-48	-59
Inland Shore	2	0	0	0	0
Open Water	108,259	1	2	2	3

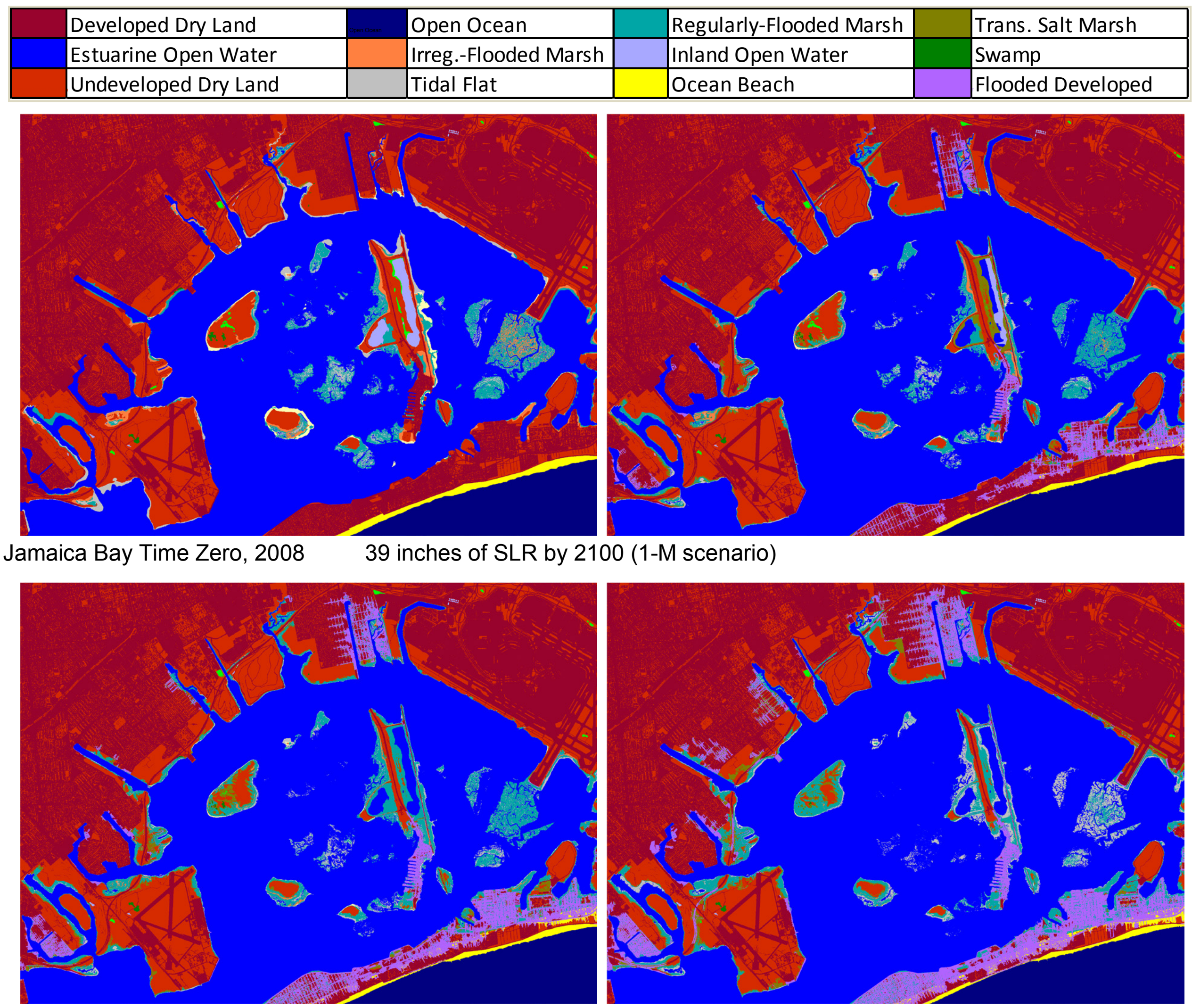
Similar to the overall projections for NYC, results for Jamaica Bay suggest that its marshes will remain somewhat resilient to the effects of SLR, even at the highest SLR scenarios examined (Figure 32). On the other hand, extensive flooded developed-dry lands are predicted. Resilient marsh is predicted on the basis of relatively high initial-condition marsh elevations and moderate rates of marsh elevation gain due to accretion. In addition, marshes are predicted to expand into some undeveloped dry land regions. Predicted marsh resilience may seem surprising given that Jamaica Bay marshes are already retreating.[74] However, the results presented here look exclusively at the effects of SLR on marshes, while anthropogenic stresses such as excess nitrogen from wastewater, water pollution,

[74] Jamaica Bay Watershed Protection Plan Advisory Committee, *An Update on the Disappearing Salt Marshes of Jamaica Bay, New York* (Gateway National Recreation Area, National Park Service, U.S. Department of the Interior, August 2, 2007).

dredging, and boat traffic, have been identified as the probable causes of current marsh dieback in Jamaica Bay.[75] SLAMM results may therefore be seen as optimistic results, assuming that causes of current marsh losses have been successfully mitigated. Results are less optimistic with regard to developed land on the barrier islands south of the bay, however, due to their low land elevations. Table 37 through Table 40 show land-cover predictions for the New York City study area under the GCM Max through the RIM Max SLR scenarios.

Figure 32. SLAMM predictions for Jamaica Bay Marsh in 2100 compared to initial conditions

SLAMM output maps show current or predicted land-cover conditions at low tide (MLLW).



Jamaica Bay Time Zero, 2008 — 39 inches of SLR by 2100 (1-M scenario)

RIM Minimum in 2100 (52.3 inches of SLR) — RIM Maximum in 2100 (67.8 inches)

75 Hartig et al., "Anthropogenic and Climate-Change Impacts on Salt Marshes of Jamaica Bay, New York City."; Jamaica Bay Watershed Protection Plan Advisory Committee, *An Update on the Disappearing Salt Marshes of Jamaica Bay, New York.*

Table 36. NYC land cover change summary in acres

Positive indicates a gain, and negative indicates a loss..

Land-cover category	Initial coverage - 2008 (acres)	Land cover change from 2008 to 2100 for different SLR scenarios (acres)			
		GCM Max	1 m	RIM Min	RIM Max
Developed Dry Land	123,823	-975	-2,370	-4,757	-8,450
Undeveloped Dry Land	59,908	-1,440	-2,434	-3,795	-5,748
Irregularly Flooded Marsh	2,019	-97	-709	-1,385	-1,646
Tidal Flat	1,944	-736	-1,031	-1,066	-288
Regularly flooded Marsh	1,526	718	1,836	3,184	3,460
Ocean Beach	732	-19	39	149	264
Trans. Salt Marsh	660	409	670	829	1,362
Swamp	547	-23	-43	-63	-130
Estuarine Beach	463	-179	-215	-247	-276
Inland Fresh Marsh	421	-20	-47	-89	-210
Flooded Dev. Dry Land	150	975	2,370	4,757	8,450
Tidal Swamp	73	-15	-28	-43	-53
Tidal Fresh Marsh	29	-8	-12	-14	-17
Inland Shore	2	0	0	0	0
Open Water	108,259	1,411	1,973	2,539	3,282

Table 37. NYC GCM Max (acres)

		Initial	2008	2025	2055	2085	2100
	Developed Dry Land	123,973	123,823	123,799	123,726	123,349	122,849
	Estuarine Open Water	74,529	74,579	74,712	75,029	75,813	76,019
	Undeveloped Dry Land	60,499	59,908	59,753	59,534	58,833	58,468
	Open Ocean	32,650	32,658	32,664	32,704	32,768	32,778
	Irregularly Flooded Marsh	2,073	2,019	2,010	2,002	1,960	1,922
	Tidal Flat	1,883	1,944	1,832	1,813	1,360	1,208
	Regularly flooded Marsh	1,567	1,526	1,974	1,784	2,050	2,245
	Inland Open Water	1,014	1,010	1,010	1,012	871	867
	Ocean Beach	738	732	727	691	680	713
	Trans. Salt Marsh	75	660	364	507	922	1,069
	Swamp	549	547	546	541	531	524
	Estuarine Beach	463	463	462	441	299	283
	Inland Fresh Marsh	421	421	421	420	403	400
	Flooded Dev. Dry Land	0	150	175	247	625	1,124
	Tidal Swamp	76	73	71	69	62	58
	Tidal Fresh Marsh	31	29	29	29	23	21
	Riverine Tidal	13	11	6	6	6	6
	Inland Shore	2	2	2	2	2	2
	Total (including water)	**300,556**	**300,556**	**300,556**	**300,556**	**300,556**	**300,556**

Table 38. NYC 1 m SLR by 2100 (acres)

		Initial	2008	2025	2055	2085	2100
	Developed Dry Land	123,973	123,823	123,798	123,590	122,474	121,453
	Estuarine Open Water	74,529	74,585	74,734	75,253	76,113	76,660
	Undeveloped Dry Land	60,499	59,907	59,751	59,185	58,208	57,474
	Open Ocean	32,650	32,671	32,695	32,755	32,799	32,821
	Irregularly Flooded Marsh	2,073	2,019	2,009	1,969	1,722	1,310
	Tidal Flat	1,883	1,949	1,833	1,701	1,235	919
	Regularly flooded Marsh	1,567	1,526	1,968	1,890	2,612	3,362
	Inland Open Water	1,014	1,011	1,011	1,011	865	764
	Ocean Beach	738	720	697	659	720	758
	Trans. Salt Marsh	75	654	365	750	1,044	1,324
	Swamp	549	547	546	535	518	504
	Estuarine Beach	463	458	446	370	270	244
	Inland Fresh Marsh	421	421	421	406	397	374
	Flooded Dev. Dry Land	0	150	175	383	1,499	2,520
	Tidal Swamp	76	73	71	65	53	45
	Tidal Fresh Marsh	31	29	29	24	18	17
	Riverine Tidal	13	11	6	6	6	6
	Inland Shore	2	2	2	2	2	2
	Total (including water)	**300,556**	**300,556**	**300,556**	**300,556**	**300,556**	**300,556**

Table 39. NYC RIM Min (acres)

		Initial	2008	2025	2055	2085	2100
	Developed Dry Land	123,973	123,823	123,799	123,529	121,199	119,066
	Estuarine Open Water	74,529	74,585	74,734	75,498	76,819	77,240
	Undeveloped Dry Land	60,499	59,908	59,753	59,081	57,317	56,113
	Open Ocean	32,650	32,671	32,695	32,773	32,835	32,881
	Irregularly Flooded Marsh	2,073	2,019	2,010	1,947	1,011	634
	Tidal Flat	1,883	1,949	1,833	1,546	873	883
	Regularly flooded Marsh	1,567	1,526	1,967	1,961	3,705	4,710
	Inland Open Water	1,014	1,011	1,011	1,008	764	691
	Ocean Beach	738	720	697	653	761	868
	Trans. Salt Marsh	75	654	363	778	1,318	1,483
	Swamp	549	547	546	532	500	484
	Estuarine Beach	463	458	446	308	242	212
	Inland Fresh Marsh	421	421	421	405	372	331
	Flooded Dev. Dry Land	0	150	175	445	2,774	4,907
	Tidal Swamp	76	73	71	64	42	30
	Tidal Fresh Marsh	31	29	29	21	16	15
	Riverine Tidal	13	11	6	6	6	6
	Inland Shore	2	2	2	2	2	2
	Total (including water)	**300,556**	**300,556**	**300,556**	**300,556**	**300,556**	**300,556**

Table 40. NYC RIM Max (acres)

		Initial	2008	2025	2055	2085	2100
	Developed Dry Land	123,973	123,813	123,755	122,786	118,586	115,363
	Estuarine Open Water	74,529	74,583	74,760	75,993	77,366	77,939
	Undeveloped Dry Land	60,499	59,841	59,623	58,420	55,829	54,093
	Open Ocean	32,650	32,660	32,675	32,762	32,869	32,921
	Irreg.-Flooded Marsh	2,073	2,008	1,985	1,573	515	362
	Tidal Flat	1,883	1,946	1,810	1,357	995	1,659
	Regularly flooded Marsh	1,567	1,536	2,071	2,650	4,769	4,996
	Inland Open Water	1,014	1,008	1,009	864	689	679
	Ocean Beach	738	730	719	732	913	994
	Trans. Salt Marsh	75	726	409	939	1,597	2,088
	Swamp	549	547	542	519	453	416
	Estuarine Beach	463	463	459	294	217	187
	Inland Fresh Marsh	421	421	421	399	321	211
	Flooded Dev. Dry Land	0	160	218	1,187	5,387	8,610
	Tidal Swamp	76	72	69	55	27	19
	Tidal Fresh Marsh	31	29	25	17	14	12
	Riverine Tidal	13	11	6	6	6	5
	Inland Shore	2	2	2	2	2	2
	Total (including water)	**300,556**	**300,556**	**300,556**	**300,556**	**300,556**	**300,556**

3.4 Nassau

Deterministic model simulations suggest Nassau County will lose significant amounts of marsh habitat under the accelerated sea-level rise scenarios examined. Table 41 presents a summary of the land cover changes predicted in each SLR scenario simulated. The acreage of irregularly flooded marsh, the predominant marsh type in this study area, is predicted to be reduced by a minimum of 49% by 2100 under the GCM Max scenario. Under the RIM Max scenario, irregularly flooded marsh is predicted to be reduced to 1% of its current area by 2100. Tidal swamp is also predicted to sustain serious losses by 2100 under all SLR scenarios examined, while inland-fresh marsh is slightly more resilient under the GCM Max scenario and begins to sustain important losses under the 1m by 2100 scenario. Dry lands are predicted to be affected, with nearly 10% of developed and undeveloped dry land predicted to be inundated at 2100 under the 1m SLR by 2100 scenario. Losses are balanced by gains in regularly flooded marsh, transitional marsh, and tidal flat.

Table 41. Nassau land cover change summary

Positive indicates a gain, and negative indicates a loss.

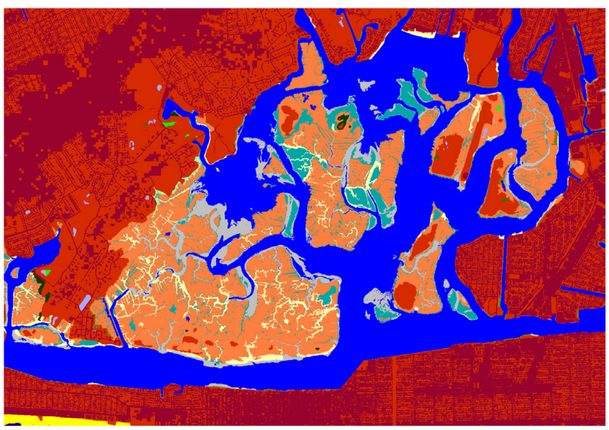
Land-cover category	Acres in 2004	Percentage Land cover change from 2004 to 2100 for different SLR scenarios			
		GCM Max	1m	RIM Min	RIM Max
Estuarine Open Water	61,791	3	5	9	14
Open Ocean	40,387	0	1	1	1
Undeveloped Dry Land	35,914	-5	-9	-14	-21
Developed Dry Land	27,518	-4	-8	-15	-23
Irreg.-Flooded Marsh	6,952	-49	-92	-98	-99
Regularly flooded Marsh	1,508	236	406	268	215
Inland Open Water	1,204	-8	-10	-11	-14
Swamp	893	-5	-8	-12	-14
Tidal Flat	860	-63	32	205	143
Ocean Beach	841	-11	-1	12	29
Estuarine Beach	679	-48	-56	-65	-72
Trans. Salt Marsh	494	147	183	243	294
Inland-Fresh Marsh	212	-16	-52	-56	-59
Inland Shore	36	0	0	0	0
Tidal-Fresh Marsh	21	-7	-22	-33	-62
Tidal Swamp	12	-53	-75	-90	-97

SLAMM simulations suggest Hewlett Bay will be significantly affected by accelerated SLR. Marshes that are currently classified as irregularly flooded are predicted to become regularly flooded and begin to disappear to tidal flat and open water with increasing sea level. Flooding of dry land is predicted to be widespread, with 50% of developed and 51% of undeveloped dry land lost by 2100 under the RIM maximum scenario. While marsh losses are predicted to occur evenly throughout the area, flooding of developed dry land is most notable on the southern and eastern shores of the bay, as shown in Figure 33. Table 42 through Table 45 show land-cover predictions in each output timestep for the Nassau study area under all SLR scenarios examined..

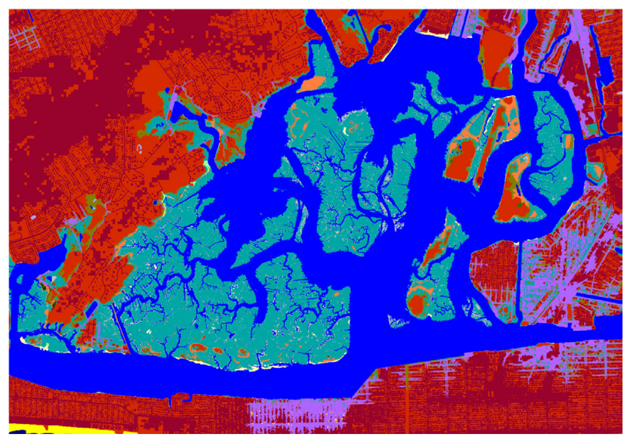
Figure 33. SLAMM predictions for Hewlett Bay Marsh in 2100 compared to initial conditions

SLAMM output maps show current or predicted land-cover conditions at low tide (MLLW).

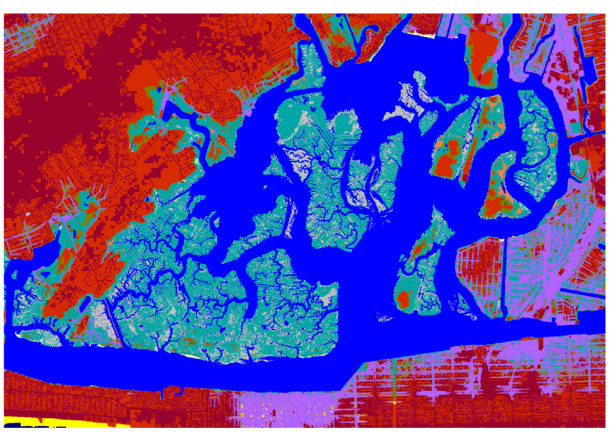
Developed Dry Land	Open Ocean	Regularly-Flooded Marsh	Trans. Salt Marsh
Estuarine Open Water	Irreg.-Flooded Marsh	Inland Open Water	Swamp
Undeveloped Dry Land	Tidal Flat	Ocean Beach	Flooded Developed



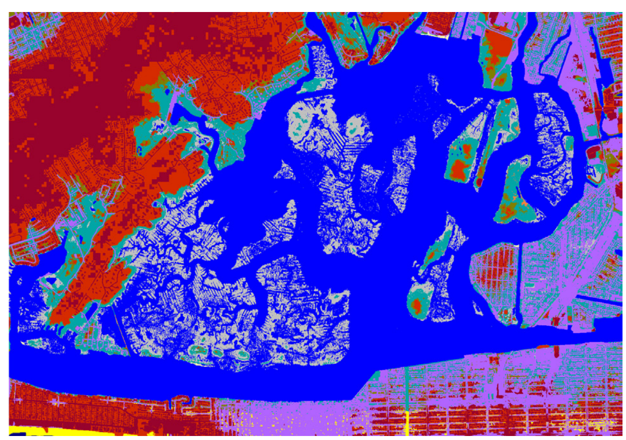
Hewlett Bay Time Zero, 2004



39 inches of SLR by 2100 (1-M scenario)



RIM Minimum in 2100 (52.3 inches of SLR)



RIM Maximum in 2100 (67.8 inches)

Table 42. Nassau GCM Max (acres)

		Initial	2004	2025	2055	2085	2100
	Estuarine Open Water	61,477	61,791	62,200	62,769	63,387	63,614
	Open Ocean	40,363	40,387	40,423	40,484	40,544	40,574
	Undeveloped Dry Land	36,198	35,914	35,829	35,617	34,742	34,170
	Developed Dry Land	27,581	27,518	27,505	27,417	26,853	26,409
	Irregularly Flooded Marsh	7,821	6,952	6,888	6,736	5,322	3,541
	Inland Open Water	1,261	1,204	1,170	1,165	1,139	1,108
	Tidal Flat	987	860	849	531	323	318
	Swamp	900	893	890	884	866	853
	Ocean Beach	854	841	809	757	755	748
	Estuarine Beach	714	679	631	530	394	353
	Regularly flooded Marsh	713	1,508	1,471	1,532	3,046	5,069
	Inland-Fresh Marsh	224	212	208	195	185	178
	Trans. Salt Marsh	221	494	367	536	1,040	1,218
	Inland Shore	36	36	36	36	36	36
	Tidal-Fresh Marsh	22	21	21	21	20	20
	Tidal Swamp	12	12	11	11	7	5
	Flooded Developed Dry Land	-	63	76	164	728	1,172
	Total (including water)	**179,386**	**179,386**	**179,386**	**179,386**	**179,386**	**179,386**

Table 43. Nassau 1m (acres)

		Initial	2004	2025	2055	2085	2100
	Estuarine Open Water	61,477	61,791	62,205	63,111	63,898	64,594
	Open Ocean	40,363	40,387	40,423	40,493	40,562	40,601
	Undeveloped Dry Land	36,198	35,914	35,827	35,322	33,769	32,723
	Developed Dry Land	27,581	27,518	27,502	27,214	26,088	25,272
	Irregularly Flooded Marsh	7,821	6,952	6,882	5,823	975	536
	Inland Open Water	1,261	1,204	1,170	1,157	1,103	1,083
	Tidal Flat	987	860	848	463	707	1,136
	Swamp	900	893	890	875	840	825
	Ocean Beach	854	841	809	773	775	829
	Estuarine Beach	714	679	630	463	337	296
	Regularly flooded Marsh	713	1,508	1,474	2,401	7,402	7,624
	Inland-Fresh Marsh	224	212	208	191	174	102
	Trans. Salt Marsh	221	494	368	668	1,204	1,399
	Inland Shore	36	36	36	36	36	36
	Tidal-Fresh Marsh	22	21	21	20	18	16
	Tidal Swamp	12	12	11	8	4	3
	Flooded Developed Dry Land	-	63	79	367	1,493	2,309
	Total (including water)	**179,386**	**179,386**	**179,386**	**179,386**	**179,386**	**179,386**

Table 44. Nassau RIM Min (acres)

		Initial	2004	2025	2055	2085	2100
	Estuarine Open Water	61,477	61,791	62,200	63,219	64,839	67,158
	Open Ocean	40,363	40,387	40,423	40,497	40,586	40,658
	Undeveloped Dry Land	36,198	35,914	35,829	35,129	32,500	30,781
	Developed Dry Land	27,581	27,518	27,505	27,101	25,065	23,490
	Irregularly Flooded Marsh	7,821	6,952	6,888	4,757	358	162
	Inland Open Water	1,261	1,204	1,170	1,153	1,079	1,066
	Tidal Flat	987	860	849	474	2,152	2,621
	Swamp	900	893	890	872	818	791
	Ocean Beach	854	841	809	782	861	940
	Estuarine Beach	714	679	631	443	294	238
	Regularly flooded Marsh	713	1,508	1,471	3,462	6,615	5,552
	Inland-Fresh Marsh	224	212	208	190	101	94
	Trans. Salt Marsh	221	494	367	764	1,547	1,692
	Inland Shore	36	36	36	36	36	36
	Tidal-Fresh Marsh	22	21	21	20	16	14
	Tidal Swamp	12	12	11	8	2	1
	Flooded Developed Dry Land	-	63	76	480	2,516	4,091
	Total (including water)	**179,386**	**179,386**	**179,386**	**179,386**	**179,386**	**179,386**

Table 45. Nassau RIM Max (acres)

		Initial	2004	2025	2055	2085	2100
	Estuarine Open Water	61,477	61,791	62,404	63,840	67,999	70,693
	Open Ocean	40,363	40,387	40,433	40,520	40,649	40,725
	Undeveloped Dry Land	36,198	35,914	35,716	34,112	30,407	28,345
	Developed Dry Land	27,581	27,518	27,463	26,381	23,131	21,272
	Irregularly Flooded Marsh	7,821	6,952	6,431	762	109	51
	Inland Open Water	1,261	1,204	1,169	1,112	1,060	1,031
	Tidal Flat	987	860	851	1,054	3,391	2,093
	Swamp	900	893	884	844	785	767
	Ocean Beach	854	841	804	804	978	1,087
	Estuarine Beach	714	679	589	370	232	191
	Regularly flooded Marsh	713	1,508	1,817	6,974	4,129	4,747
	Inland-Fresh Marsh	224	212	205	177	93	87
	Trans. Salt Marsh	221	494	433	1,178	1,924	1,944
	Inland Shore	36	36	36	36	36	36
	Tidal-Fresh Marsh	22	21	21	17	12	8
	Tidal Swamp	12	12	11	5	1	0
	Flooded Developed Dry Land	-	63	118	1,200	4,450	6,309
	Total (including water)	**179,386**	**179,386**	**179,386**	**179,386**	**179,386**	**179,386**

3.5 Suffolk West

Under all SLR scenarios examined, the western portion of Suffolk County is predicted to suffer serious losses of irregularly flooded marsh. These loses are balanced by gains in regularly flooded marsh, as presented in Table 46. Tidal swamps and tidal fresh marshes are also predicted to be vulnerable in this study area.

Table 46. Suffolk West Land cover Change Summary

Positive indicates a gain, and negative indicates a loss.

Land-cover category	Acres in 2004	Percentage Land cover change from 2004 to 2100 for different SLR scenarios			
		GCM Max	1m	RIM Min	RIM Max
Estuarine Open Water	157058	1	4	6	8
Open Ocean	77101	1	1	1	2
Undeveloped Dry Land	69956	-4	-7	-10	-14
Developed Dry Land	24348	-4	-8	-13	-17
Irregularly Flooded Marsh	7041	-55	-86	-95	-98
Swamp	4638	-7	-11	-16	-20
Inland Open Water	2480	-2	-4	-7	-9
Regularly flooded Marsh	1860	165	123	134	133
Estuarine Beach	1578	-31	-40	-45	-56
Ocean Beach	996	-9	3	3	-1
Trans. Salt Marsh	834	96	101	148	132
Tidal Flat	512	206	363	366	410
Inland-Fresh Marsh	435	-9	-18	-24	-29
Tidal Swamp	420	-45	-68	-84	-90
Inland Shore	48	0	0	0	0
Flooded Developed Dry Land	45	2398	4494	6957	9311
Tidal-Fresh Marsh	40	-2	-28	-46	-47
Rocky Intertidal	1	-20	-28	-36	-48

Effects of SLR for Suffolk West appear to be especially pronounced in southern marshes, behind barrier islands where low tide ranges make these marshes more vulnerable. Additionally, islands and spits at the western portion of the study area are subject to considerable dry-land conversion. For example, in Gilgo Beach, predictions show significant marsh and dry land conversion by 2100 even under the most conservative SLR scenarios considered

(Figure 34). Under these lower scenarios, irregularly flooded marshes are predicted to be converted to regularly flooded marsh and tidal flat by 2100. Under the highest SLR scenario, RIM Max, open water is predicted to entirely cover the areas currently covered by marshes (Figure 35). Table 47 to Table 50 show changes in acreage predictions over time for each modeled land-cover type and for each SLR scenario run for the Suffolk West study area.

Figure 34. Gilgo Beach, NY (top) Time Zero, 2004 and (bottom) GCM Max, 2100

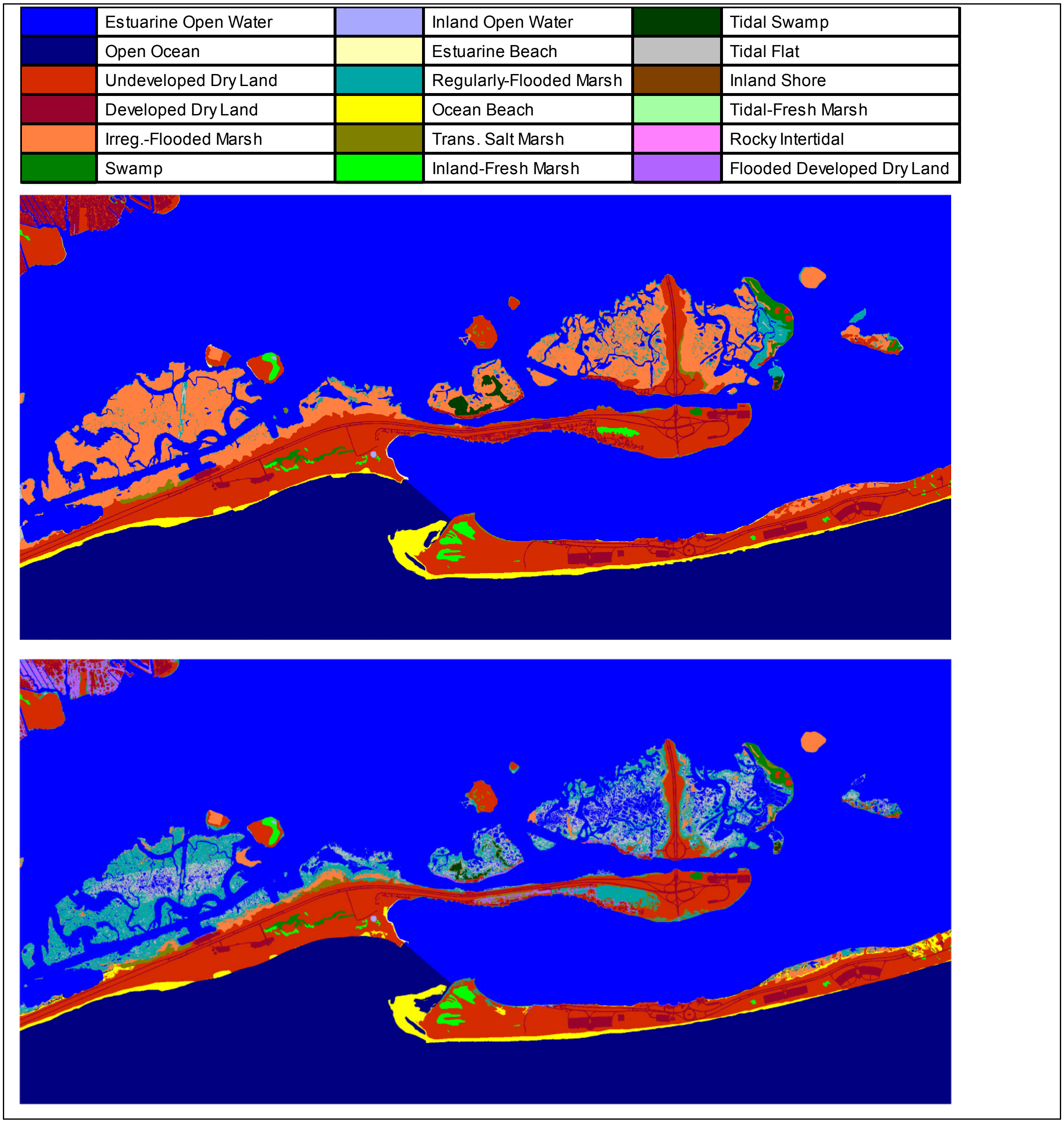


Figure 35. Gilgo Beach, NY (top) 1 m SLR, 2100 and (bottom) RIM Max, 2100

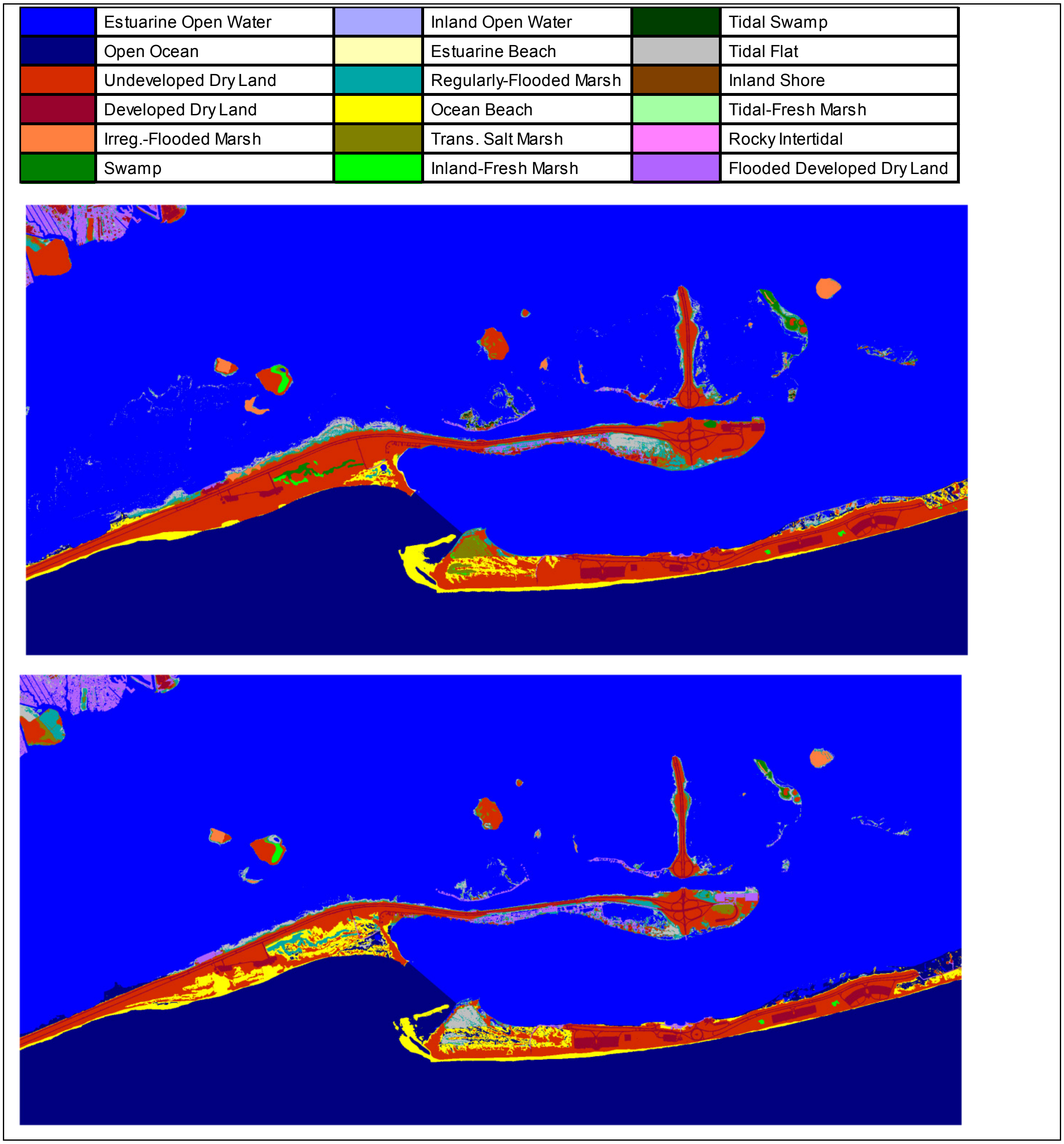


Table 47. Suffolk West GCM Max (acres)

		Initial	2004	2025	2055	2085	2100
	Estuarine Open Water	156,973	157,058	157,287	157,766	158,382	159,386
	Open Ocean	76,977	77,101	77,197	77,323	77,437	77,506
	Undeveloped Dry Land	70,394	69,956	69,839	69,534	68,273	67,396
	Developed Dry Land	24,394	24,348	24,327	24,237	23,666	23,264
	Irregularly Flooded Marsh	7,540	7,041	6,937	6,652	4,272	3,140
	Swamp	4,648	4,638	4,631	4,579	4,398	4,304
	Inland Open Water	2,490	2,480	2,477	2,474	2,454	2,426
	Estuarine Beach	1,608	1,578	1,522	1,398	1,244	1,090
	Regularly flooded Marsh	1,493	1,860	2,005	2,176	4,357	4,921
	Ocean Beach	1,071	996	911	815	854	904
	Trans. Salt Marsh	461	834	647	874	1,531	1,638
	Inland-Fresh Marsh	435	435	434	431	405	397
	Tidal Swamp	432	420	412	386	286	233
	Tidal Flat	385	512	610	500	1,020	1,570
	Inland Shore	48	48	48	48	48	48
	Tidal-Fresh Marsh	41	40	40	40	40	40
	Rocky Intertidal	1	1	1	1	1	1
	Flooded Developed Dry Land	-	45	66	157	728	1,129
	Total (including water)	**349,392**	**349,392**	**349,392**	**349,392**	**349,392**	**349,392**

Table 48. Suffolk West 1m by 2100 (acres)

		Initial	2004	2025	2055	2085	2100
	Estuarine Open Water	156,973	157,058	157,289	158,026	161,250	163,730
	Open Ocean	76,977	77,101	77,197	77,342	77,545	77,716
	Undeveloped Dry Land	70,394	69,956	69,836	69,080	66,720	65,310
	Developed Dry Land	24,394	24,348	24,326	24,047	22,965	22,317
	Irregularly Flooded Marsh	7,540	7,041	6,929	4,792	1,671	993
	Swamp	4,648	4,638	4,631	4,490	4,224	4,114
	Inland Open Water	2,490	2,480	2,477	2,463	2,413	2,392
	Estuarine Beach	1,608	1,578	1,522	1,353	1,016	950
	Regularly flooded Marsh	1,493	1,860	2,010	3,783	4,370	4,149
	Ocean Beach	1,071	996	910	850	976	1,030
	Trans. Salt Marsh	461	834	649	1,106	1,667	1,672
	Inland-Fresh Marsh	435	435	434	424	391	358
	Tidal Swamp	432	420	412	341	192	133
	Tidal Flat	385	512	614	861	2,479	2,373
	Inland Shore	48	48	48	48	48	48
	Tidal-Fresh Marsh	41	40	40	40	36	29
	Rocky Intertidal	1	1	1	1	1	1
	Flooded Developed Dry Land	-	45	67	346	1,429	2,077
	Total (including water)	**349,392**	**349,392**	**349,392**	**349,392**	**349,392**	**349,392**

Table 49. Suffolk West RIM Min (acres)

		Initial	2004	2025	2055	2085	2100
	Estuarine Open Water	156,973	157,058	157,287	158,178	162,989	166,308
	Open Ocean	76,977	77,101	77,197	77,350	77,723	78,050
	Undeveloped Dry Land	70,394	69,956	69,839	68,819	64,997	62,941
	Developed Dry Land	24,394	24,348	24,327	23,929	22,176	21,203
	Irregularly Flooded Marsh	7,540	7,041	6,937	3,912	673	335
	Swamp	4,648	4,638	4,631	4,448	4,059	3,887
	Inland Open Water	2,490	2,480	2,477	2,458	2,385	2,311
	Estuarine Beach	1,608	1,578	1,522	1,329	957	875
	Regularly flooded Marsh	1,493	1,860	2,005	4,236	4,303	4,345
	Ocean Beach	1,071	996	911	879	1,061	1,023
	Trans. Salt Marsh	461	834	647	1,236	2,111	2,066
	Inland-Fresh Marsh	435	435	434	421	349	331
	Tidal Swamp	432	420	412	317	117	69
	Tidal Flat	385	512	610	1,324	3,202	2,386
	Inland Shore	48	48	48	48	48	48
	Tidal-Fresh Marsh	41	40	40	40	24	22
	Rocky Intertidal	1	1	1	1	1	0
	Flooded Developed Dry Land	-	45	66	465	2,218	3,190
	Total (including water)	**349,392**	**349,392**	**349,392**	**349,392**	**349,392**	**349,392**

Table 50. Suffolk West RIM Max (acres)

		Initial	2004	2025	2055	2085	2100
	Estuarine Open Water	156,973	157,058	157,391	160,026	166,589	168,923
	Open Ocean	76,977	77,101	77,218	77,439	78,079	78,439
	Undeveloped Dry Land	70,394	69,956	69,654	67,307	62,558	60,497
	Developed Dry Land	24,394	24,348	24,275	23,235	21,024	20,139
	Irregularly Flooded Marsh	7,540	7,041	5,875	1,456	269	165
	Swamp	4,648	4,638	4,587	4,249	3,853	3,733
	Inland Open Water	2,490	2,480	2,473	2,430	2,310	2,252
	Estuarine Beach	1,608	1,578	1,477	1,104	872	700
	Regularly flooded Marsh	1,493	1,860	2,876	4,019	4,549	4,338
	Ocean Beach	1,071	996	908	995	1,037	982
	Trans. Salt Marsh	461	834	786	1,762	2,263	1,936
	Inland-Fresh Marsh	435	435	432	396	329	308
	Tidal Swamp	432	420	393	210	61	42
	Tidal Flat	385	512	837	3,525	2,159	2,613
	Inland Shore	48	48	48	48	48	48
	Tidal-Fresh Marsh	41	40	40	32	21	21
	Rocky Intertidal	1	1	1	1	0	0
	Flooded Developed Dry Land	-	45	119	1,158	3,369	4,255
	Total (including water)	**349,392**	**349,392**	**349,392**	**349,392**	**349,392**	**349,392**

3.6 Suffolk East

The Suffolk East study area is predicted to have some fairly significant vulnerabilities to sea-level rise. From 6% to 9% of undeveloped and developed dry land will be subject to regular flooding by 2100 if the rapid-ice-melt scenarios occur, and from 91% to 96% of high marshes. Based on initial elevations and SLR scenarios, the majority of inland fresh marshes, tidal swamps, estuarine beaches, and tidal-fresh marshes could also be lost by 2100 (Table 51).

Table 51. Suffolk East Land cover Change Summary

Positive indicates a gain, and negative indicates a loss.

Land-cover category	Acres in 2010	Percentage Land cover change from 2004 to 2100 for different SLR scenarios			
		GCM Max	1m	RIM Min	RIM Max
Open Ocean	229,341	0	0	1	1
Estuarine Open Water	179,809	1	1	2	4
Undeveloped Dry Land	142,713	-2	-4	-6	-8
Developed Dry Land	25,103	-2	-4	-6	-9
Irregularly Flooded Marsh	4,501	-25	-76	-91	-96
Swamp	2,359	-5	-12	-18	-25
Inland Open Water	1,979	-6	-16	-19	-25
Ocean Beach	1,977	-21	-19	-18	-17
Estuarine Beach	1,720	-45	-57	-70	-82
Transitional Salt Marsh	900	146	195	193	170
Regularly flooded Marsh	569	522	1188	1324	935
Inland-Fresh Marsh	442	-24	-44	-49	-60
Tidal Swamp	294	-40	-62	-79	-88
Tidal Flat	147	-51	145	1166	1750
Tidal-Fresh Marsh	96	-14	-43	-69	-85
Flooded Developed Dry Land	43	1,195	2,360	3,744	4,814
Rocky Intertidal	40	-72	-86	-93	-95
Inland Shore	1	0	0	0	0
Ocean Flat	1	-9	-31	-54	-77

Effects of SLR for Suffolk East appear to be especially pronounced in southern marshes behind barrier islands that are predicted to be vulnerable due to their current low tide ranges. Additionally, islands and spits at the eastern portion of the study area are subject to considerable dry-land conversion. For example, results from the area around Orient, NY, are highlighted in Figure 36 and Figure 37. Results show significant marsh and dry land vulnerability, with some regions converting to open water. Table 52 through Table 55 show land-cover predictions over time for the Suffolk East study area under the GCM Max through the RIM Max SLR scenarios.

Figure 36. Orient, NY area predictions in 2010 and 2085 given 32 inches of SLR

SLAMM output maps show current or predicted land-cover conditions at low tide (MLLW)

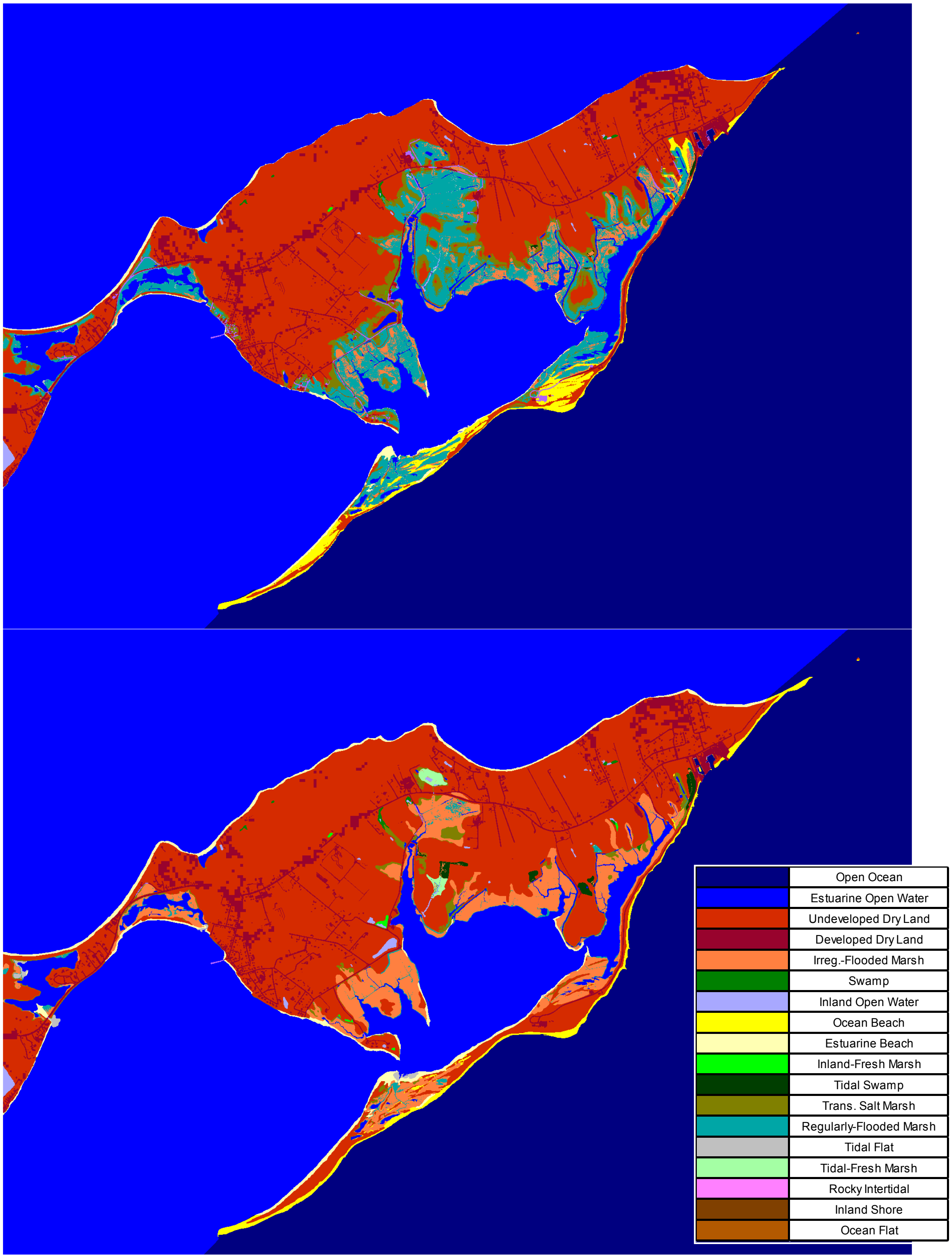


Figure 37. Orient, NY area predictions in 2085 under Rapid Ice-Melt Scenarios

Top figure shows 41 inches of SLR and bottom shows 55 inches of SLR by 2085.

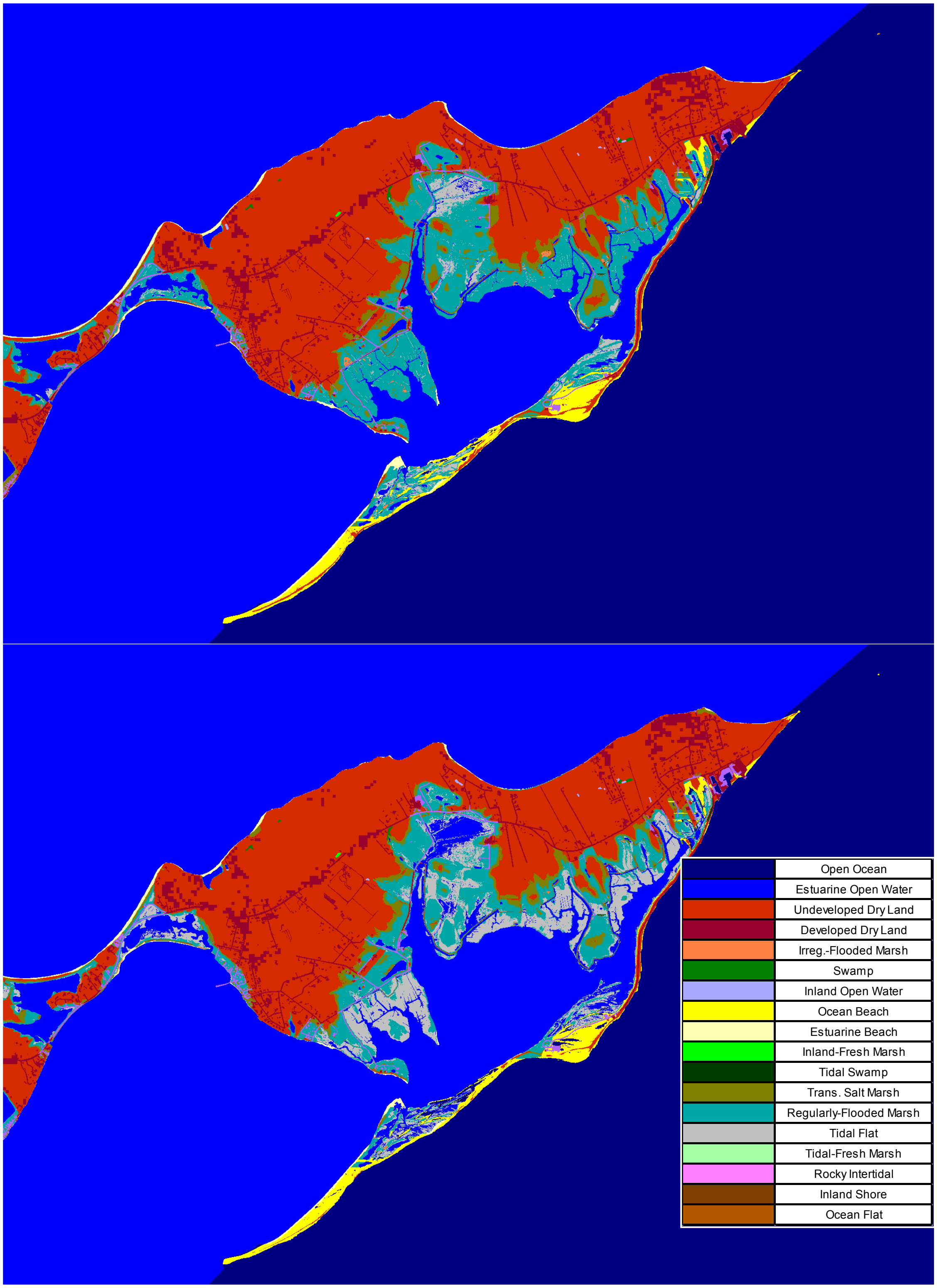


Table 52. Suffolk East GCM Max (acres)

		Initial	2010	2025	2055	2085	2100
	Open Ocean	229,238	229,341	229,468	229,768	230,056	230,191
	Estuarine Open Water	179,642	179,809	179,973	180,337	180,747	181,084
	Undeveloped Dry Land	143,421	142,714	142,509	141,881	140,268	139,283
	Developed Dry Land	25,146	25,103	25,088	25,026	24,777	24,590
	Irregularly Flooded Marsh	4,848	4,496	4,466	4,376	3,754	3,322
	Swamp	2,365	2,359	2,356	2,340	2,282	2,245
	Inland Open Water	1,988	1,979	1,968	1,957	1,948	1,852
	Ocean Beach	1,975	1,977	1,875	1,658	1,545	1,563
	Estuarine Beach	1,831	1,720	1,617	1,384	1,114	946
	Inland-Fresh Marsh	456	442	412	396	368	337
	Tidal Swamp	307	294	289	266	212	177
	Trans. Salt Marsh	281	899	804	1,261	2,192	2,477
	Regularly flooded Marsh	194	572	844	1,002	2,201	3,229
	Tidal Flat	181	148	176	139	99	88
	Tidal-Fresh Marsh	100	96	96	95	87	83
	Rocky Intertidal	62	40	36	28	16	11
	Inland Shore	1	1	1	1	1	1
	Ocean Flat	1	1	1	1	1	1
	Flooded Developed Dry Land	-	43	59	120	369	556
	Total (including water)	**592,036**	**592,036**	**592,036**	**592,036**	**592,036**	**592,036**

Table 53. Suffolk East 1m by 2100 (acres)

		Initial	2010	2025	2055	2085	2100
	Open Ocean	229,238	229,342	229,469	229,816	230,174	230,346
	Estuarine Open Water	179,642	179,810	179,974	180,517	181,271	181,772
	Undeveloped Dry Land	143,421	142,713	142,502	141,250	138,612	136,963
	Developed Dry Land	25,146	25,103	25,087	24,934	24,436	24,087
	Irregularly Flooded Marsh	4,848	4,495	4,462	3,891	1,966	1,179
	Swamp	2,365	2,359	2,356	2,320	2,197	2,071
	Inland Open Water	1,988	1,979	1,968	1,946	1,839	1,670
	Ocean Beach	1,975	1,977	1,875	1,684	1,641	1,602
	Estuarine Beach	1,831	1,720	1,616	1,313	899	736
	Inland-Fresh Marsh	456	442	412	392	327	248
	Tidal Swamp	307	294	288	241	147	110
	Trans. Salt Marsh	281	900	809	1,519	2,382	2,844
	Regularly flooded Marsh	194	573	849	1,753	5,161	6,864
	Tidal Flat	181	148	176	138	199	423
	Tidal-Fresh Marsh	100	96	96	87	65	54
	Rocky Intertidal	62	40	36	22	9	6
	Inland Shore	1	1	1	1	1	1
	Ocean Flat	1	1	1	1	1	1
	Flooded Developed Dry Land	-	43	59	212	711	1,060
	Total (including water)	**592,036**	**592,036**	**592,036**	**592,036**	**592,036**	**592,036**

Table 54. Suffolk East RIM MIN (acres)

		Initial	2010	2025	2055	2085	2100
	Open Ocean	229,238	229,341	229,468	229,837	230,303	230,577
	Estuarine Open Water	179,642	179,809	179,973	180,592	181,903	183,436
	Undeveloped Dry Land	143,421	142,714	142,509	140,892	136,648	134,314
	Developed Dry Land	25,146	25,103	25,088	24,880	24,017	23,493
	Irregularly Flooded Marsh	4,848	4,496	4,466	3,590	886	482
	Swamp	2,365	2,359	2,356	2,291	2,055	1,934
	Inland Open Water	1,988	1,979	1,968	1,943	1,749	1,602
	Ocean Beach	1,975	1,977	1,875	1,693	1,670	1,630
	Estuarine Beach	1,831	1,720	1,617	1,277	732	519
	Inland-Fresh Marsh	456	442	412	383	240	225
	Tidal Swamp	307	294	289	230	100	63
	Trans. Salt Marsh	281	899	804	1,709	2,857	2,719
	Regularly flooded Marsh	194	572	844	2,196	6,720	7,015
	Tidal Flat	181	148	176	151	979	2,339
	Tidal-Fresh Marsh	100	96	96	83	42	30
	Rocky Intertidal	62	40	36	20	5	3
	Inland Shore	1	1	1	1	1	1
	Ocean Flat	1	1	1	1	1	0
	Flooded Developed Dry Land	-	43	59	267	1,130	1,653
	Total (including water)	**592,036**	**592,036**	**592,036**	**592,036**	**592,036**	**592,036**

Table 55. Suffolk East RIM MAX (acres)

		Initial	2010	2025	2055	2085	2100
	Open Ocean	229,238	229,349	229,520	229,972	230,581	230,996
	Estuarine Open Water	179,642	179,850	180,100	181,195	184,073	187,669
	Undeveloped Dry Land	143,421	142,635	142,104	139,200	133,705	131,126
	Developed Dry Land	25,146	25,098	25,052	24,578	23,378	22,789
	Irregularly Flooded Marsh	4,848	4,439	4,157	1,616	353	191
	Swamp	2,365	2,357	2,343	2,227	1,888	1,764
	Inland Open Water	1,988	1,977	1,962	1,841	1,587	1,491
	Ocean Beach	1,975	1,977	1,875	1,785	1,788	1,641
	Estuarine Beach	1,831	1,685	1,527	1,041	505	304
	Inland-Fresh Marsh	456	415	401	336	224	165
	Tidal Swamp	307	291	271	158	56	36
	Trans. Salt Marsh	281	990	1,004	2,140	2,867	2,745
	Regularly flooded Marsh	194	639	1,293	4,995	6,057	6,046
	Tidal Flat	181	147	209	311	3,179	2,696
	Tidal-Fresh Marsh	100	95	91	59	24	14
	Rocky Intertidal	62	40	32	12	3	2
	Inland Shore	1	1	1	1	1	1
	Ocean Flat	1	1	1	1	0	0
	Flooded Developed Dry Land	-	48	95	569	1,768	2,357
	Total (including water)	**592,036**	**592,036**	**592,036**	**592,036**	**592,036**	**592,036**

4 Uncertainty Analysis Results and Discussion

4.1 Overview

For uncertainty simulations, the number of model realizations ranged from 100 to 300, depending on the study area (Table 56) resulting in approximately 42,000 hours of CPU time. The fewest runs were produced for Suffolk East as it had the longest CPU time per iteration. Extra runs were produced for the New York City study area to add precision to confidence intervals and to assess the effect of added iterations on uncertainty-map predictions as discussed in this section.

Table 56. Uncertainty Iterations by Study Area

Study Area	Suffolk East	Suffolk West	Nassau	NYC	Hudson
Iterations Run	100	150	200	300	200

As the number of Monte Carlo simulations increases, the confidence of statistical estimates, such as mean, moments, and percentiles, also increases. However, given the 5-meter cell size and large study area for this application, it was not possible to expend additional CPU time and complete this project on schedule. Therefore, the calculation of land-cover confidence intervals takes into account the number of iterations run and widens these confidence intervals based on this number. Using non-parametric statistical methods, without requiring assumptions regarding the underlying statistical distribution, the confidence interval of each percentile can be calculated using the properties of binomial distributions.[76] With 100 iterations, the 90% confidence intervals for the 5th and 95th percentile estimates are already reasonably narrow (Figure 38). With 300 iterations, it narrows further (Figure 39). To be conservative, in the graphs presented herein the 5th percentile curve is reported by its lowest 5% confidence boundary, while the 95th percentile curve by its highest 95% confidence boundary (these are the widest intervals, illustrated in Figure 38 and Figure 39 as solid black lines).

In summary, the number of uncertainty iterations performed in this analysis was relatively small due to CPU-time restrictions. However, this limitation was accounted for by conservatively widening confidence intervals in year-to-year maps and tables of output. Additionally, we assessed differences in derived maps based on the number of iterations performed and concluded that these errors are unlikely to have an impact on map interpretation.

[76] J E Walsh, *Handbook of Nonparametric Statistics* (New York: Van Nostrand Reinhold, 1962).

Figure 38. NYC Uncertainty Analysis (300 iterations) with Confidence Intervals of Percentiles

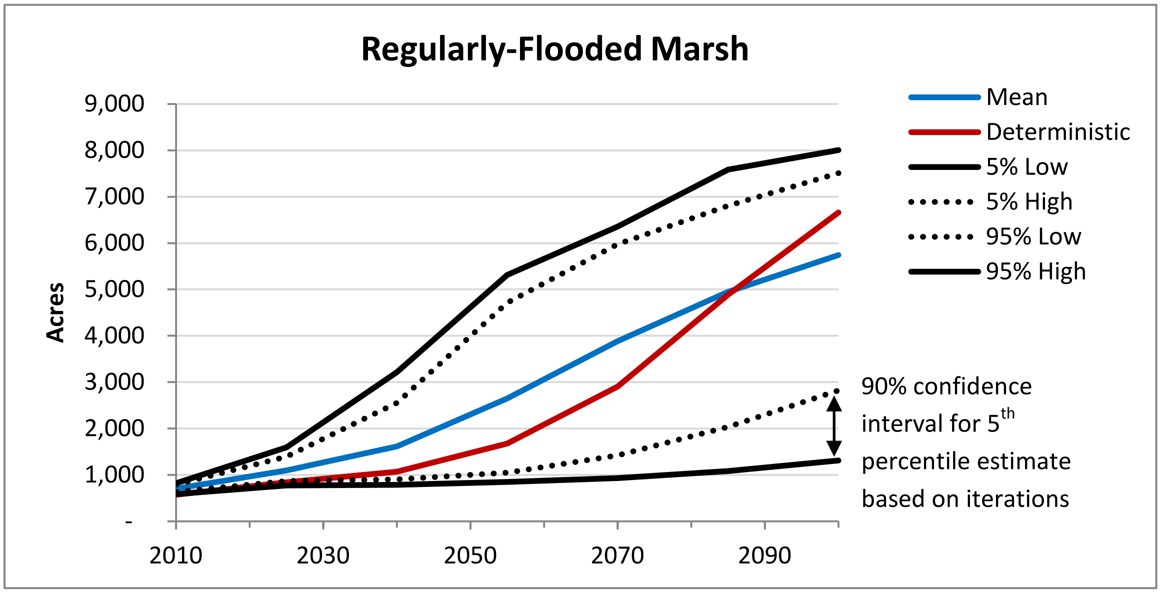
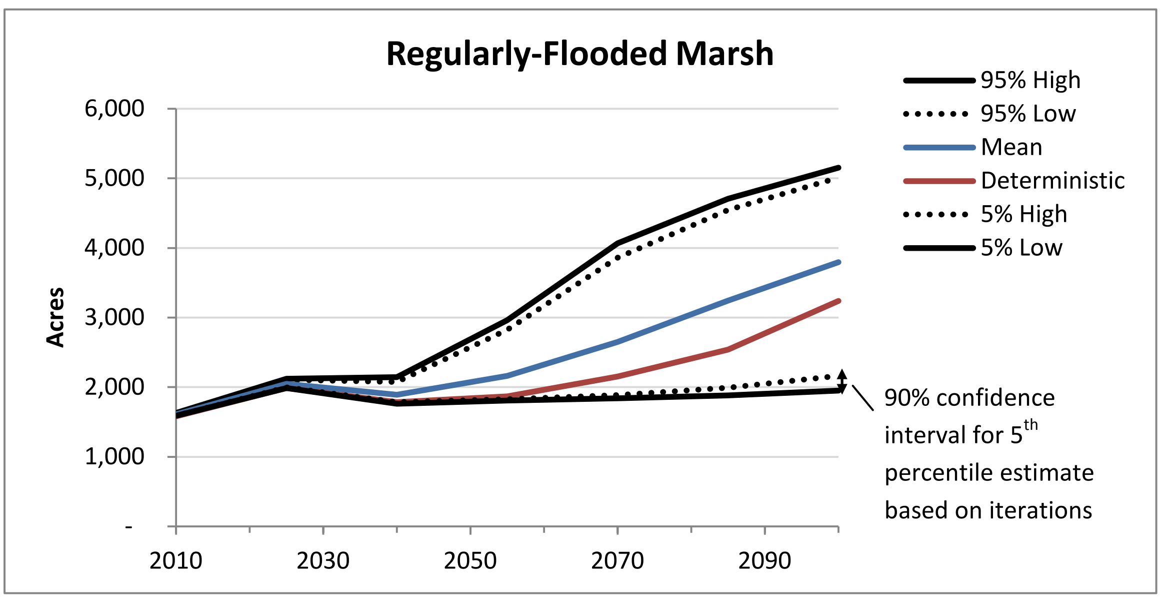
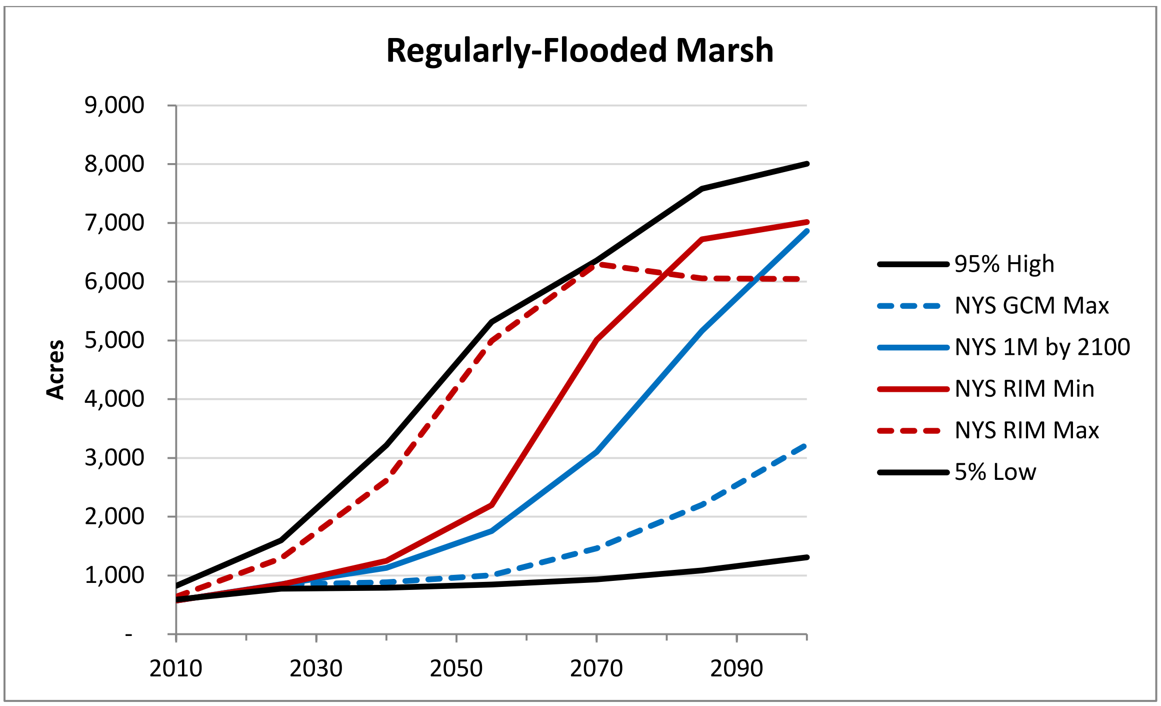


Figure 39. Suffolk East Uncertainty Analysis (100 iterations) with Confidence Intervals of Percentiles



It is worth noting that the results presented above represent uncertainty in all model parameters and driving variables including sea-level rise. While the model is sensitive to many parameters (especially accretion rates)[77], sea-level rise is often the most important driver of model uncertainty. When presenting time series of confidence intervals in this report, we also plot deterministic results for each of the four SLR scenarios. These four deterministic results help to add context of how much the overall uncertainty interval is driven by future SLR as opposed to other parameter choices. For example, Figure 40 shows that considering *all* of the parametric and SLR uncertainty in the model can cause regularly flooded marsh predictions to vary from 1300 to 8000 acres. This same figure shows that using point-estimate deterministic parameters and allowing SLR to vary, this range extends from 3300 to 7000 acres (an area 55% as wide). Therefore the majority of model uncertainty for this land-cover category is driven by the uncertainty in SLR predictions themselves.

Figure 40. Uncertainty predictions for Suffolk East with Four Deterministic Scenarios for Context

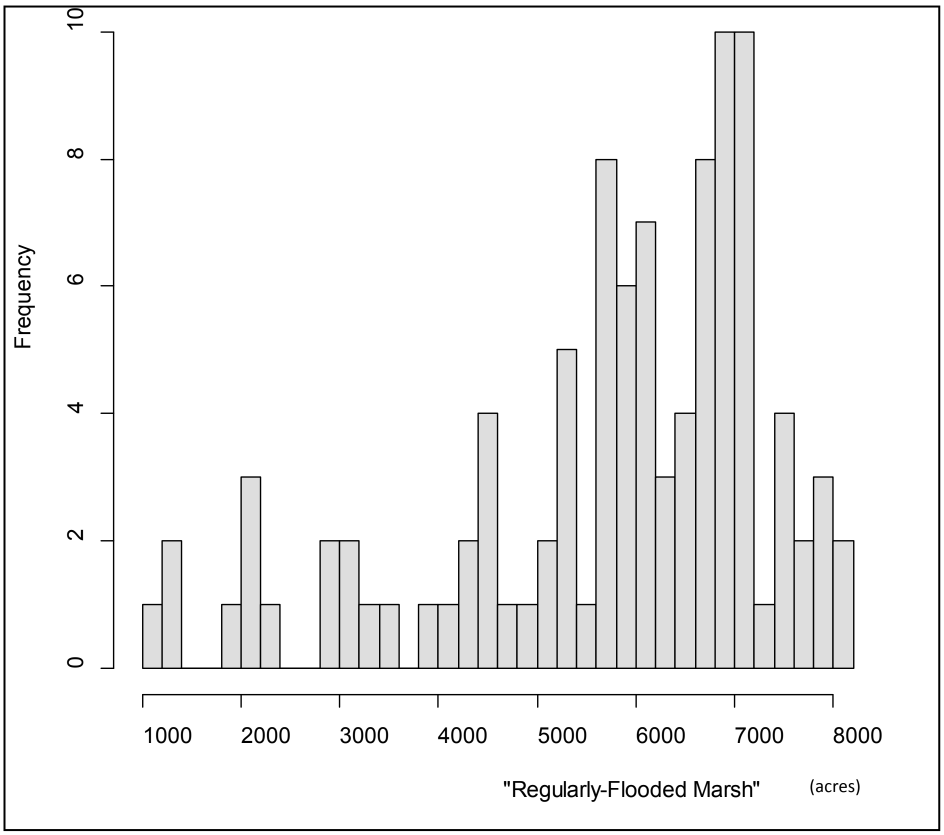


In addition to presenting confidence intervals on model predictions, SLAMM uncertainty results can be presented as histograms of wetland acreages at a given year. This presentation can provide additional information about the fate of each category. For example Figure 41 (which corresponds with Figure 40 above) shows that the majority of simulations predict that low marshes will inhabit more than 4000 acres by 2100, though the 5th percent confidence

77 Chu-Agor et al., "Global Sensitivity and Uncertainty Analysis of SLAMM for the Purpose of Habitat Vulnerability Assessment and Decision Making."

interval is as low as 1300 acres. In other words, even though the confidence interval may range from 1300 to 8000 acres, the histogram shows us that a result over the midpoint (of 4650 acres) is much more likely than a result under the midpoint of the confidence interval. Numerous example histograms of SLAMM model results are presented in Appendix F, and histograms for all SLAMM categories in 2100 are available at the project website: http://warrenpinnacle.com/prof/SLAMM/NYSERDA/.

Figure 41. Histogram of regularly flooded marsh predictions in Suffolk East in 2100

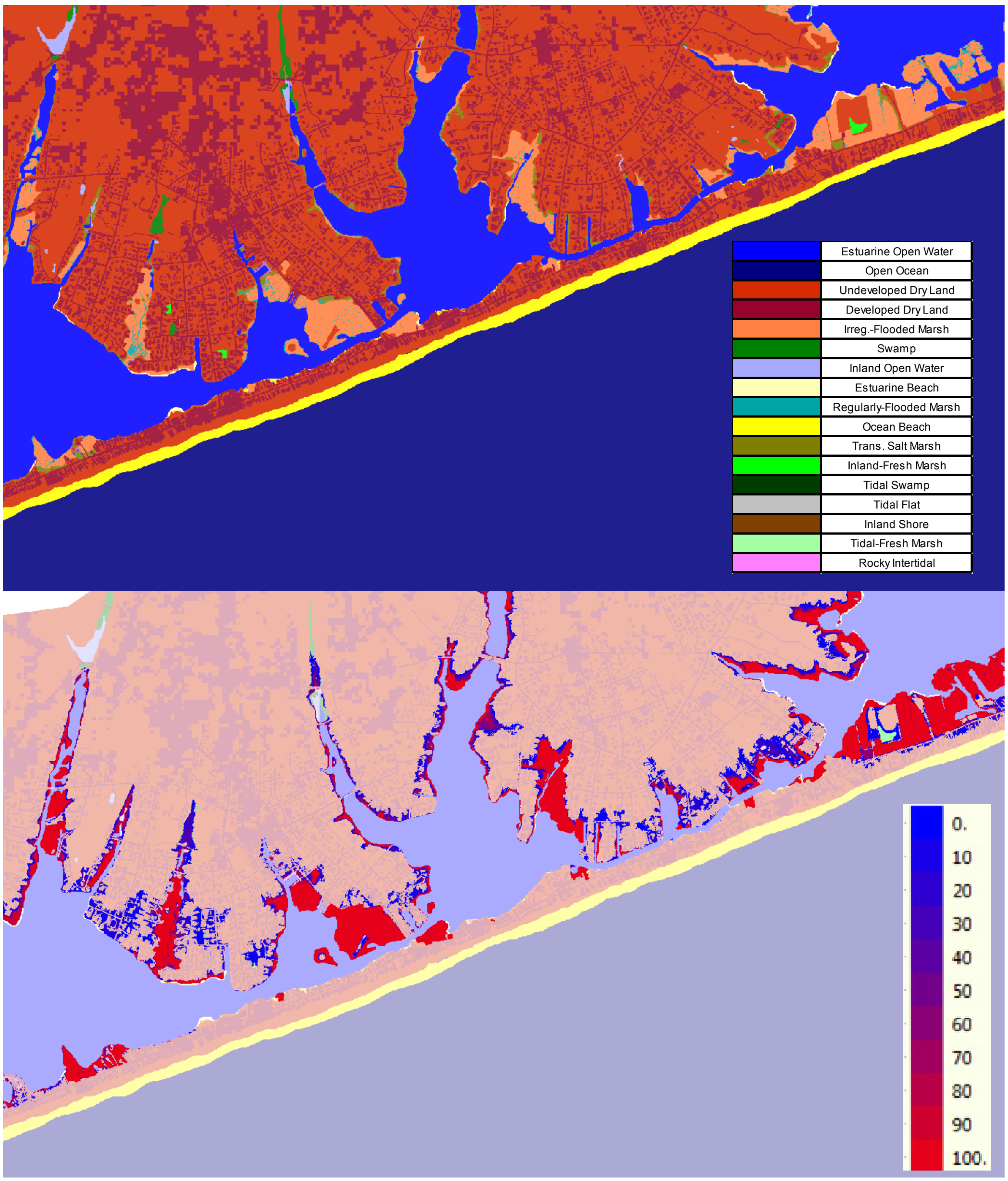


Finally, uncertainty-analysis results can be presented as a series of GIS maps in which uncertainty results are broken down on a cell-by-cell basis. The four maps that were specifically derived for this project are:

- **Percent Likelihood of Habitat Change:** For each cell in the study area, the percent likelihood that this cell has changed category since the start of the simulation.
- **Probability that the cell is a coastal marsh:** This map can assist in identifying potential locations for "marsh migration." A coastal marsh is defined as a cell that is flooded by tidal waters including low marsh (regularly flooded marsh), high marsh (irregularly flooded marsh), dry land recently converted to marsh (transitional marsh), and tidal-fresh marshes.
- **Probability that the cell contains flooded-developed land:** Likelihood a developed cell in initial layers will be regularly flooded at the map date.
- **Probability that a land category has converted to open water:** Likelihood a cell that is not water at low tide (MLLW) will become open water at that tide at the map date.

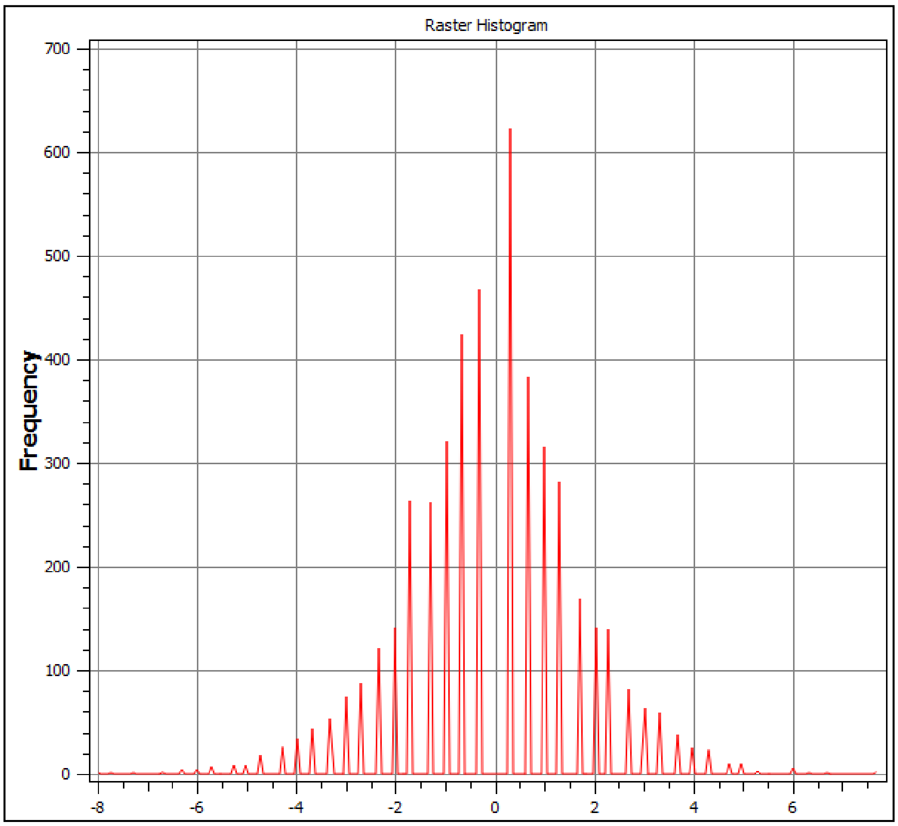
Within this report, these uncertainty maps are illustrated over faded land-cover maps for context as illustrated in Figure 42. All uncertainty map GIS outputs are also available at the project website: http://warrenpinnacle.com/prof/SLAMM/NYSERDA/

Figure 42. Example "Percent Likelihood of Coastal Marsh" Plot for 2025 (bottom) compared to Initial Condition Map (top)



To examine the sensitivity of output maps to the number of iterations run at each site, output maps for New York City were derived after 100 and 300 iterations and the two output layers were compared. The analysis suggested that the maximum "error" due to smaller iteration size was less than an 8% difference in a given cell and that over 99% of cell-specific "errors" were within 5% (Figure 43). The magnitude of these differences suggests that map interpretation will not significantly change on the basis of the number of iterations performed.

Figure 43. Histogram showing cell-by-cell differences between 300 and 100 iterations



Uncertainty-analysis results presented by study area may be found in Section 4.2.

4.2 Hudson Uncertainty Analysis Results

Uncertainty-analysis results for the Hudson study area suggest that coastal marsh results are the most uncertain categories overall. Table 57 presents statistics of results for 2055 and Table 58 shows the uncertainty intervals widening by 2100.

Table 57. Uncertainty Results for Hudson Study Area by Land-cover category (2055)

Land cover Type	Min	5th Percentile (Low)	Mean	95th Percentile (High)	Max	Std. Dev.
Estuarine Open Water	7,600	7,606	7,625	7,638	7,640	8
Developed Dry Land	4,124	4,138	4,154	4,162	4,162	7
Undeveloped Dry Land	3,770	3,780	3,807	3,826	3,828	13
Inland Open Water	356	356	356	356	356	0
Swamp	103	103	103	103	103	0
Irregularly Flooded Marsh	49	96	211	246	246	43
Inland-Fresh Marsh	43	43	43	43	43	-
Regularly flooded Marsh	12	19	63	185	243	47
Flooded Dev. Dry Land	3	3	11	27	41	7
Tidal Flat	3	4	9	21	24	4
Trans. Salt Marsh	2	3	10	21	27	5

Table 58. Uncertainty Results for Hudson Study Area by Land-cover category (2100)

Land cover Type	Min	5th Percentile (Low)	Mean	95th Percentile (High)	Max	Std. Dev.
Estuarine Open Water	7,615	7,624	7,651	7,824	7,876	45
Developed Dry Land	3,949	3,989	4,104	4,159	4,161	50
Undeveloped Dry Land	3,643	3,682	3,764	3,815	3,822	34
Inland Open Water	356	356	356	356	356	0
Swamp	103	103	103	103	103	0
Inland-Fresh Marsh	43	43	43	43	43	-
Regularly flooded Marsh	21	28	179	319	325	96
Flooded Dev. Dry Land	4	6	61	176	216	50
Trans. Salt Marsh	3	7	18	51	57	11
Tidal Flat	2	2	27	166	184	48
Irregularly Flooded Marsh	0	1	86	243	246	90

The histograms in Figure 44 show that by 2100, low acreages of irregularly-flooded marsh are most likely for the study area, while regularly-flooded marsh acreage probabilities do not vary widely in the range from 25 to 325 acres.

Figure 44. Histograms for Irregularly- and Regularly flooded Marsh, Hudson 2100

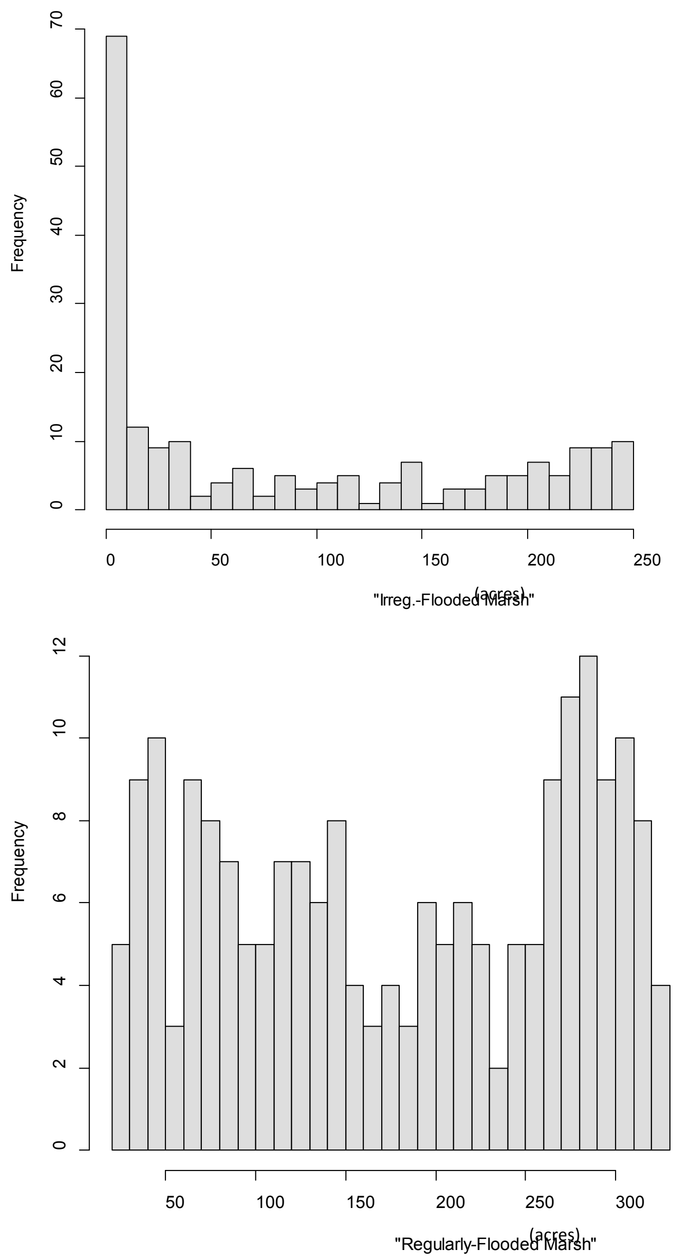


Figure 45 to Figure 47 suggest that, up until 2025, the current land coverage of the area is quite robust with minimal predicted changes. Following 2025, irregularly flooded marsh will start to be increasingly inundated and converted to regularly flooded marsh.

Figure 45. Time series for irregularly flooded marsh area coverage, Hudson

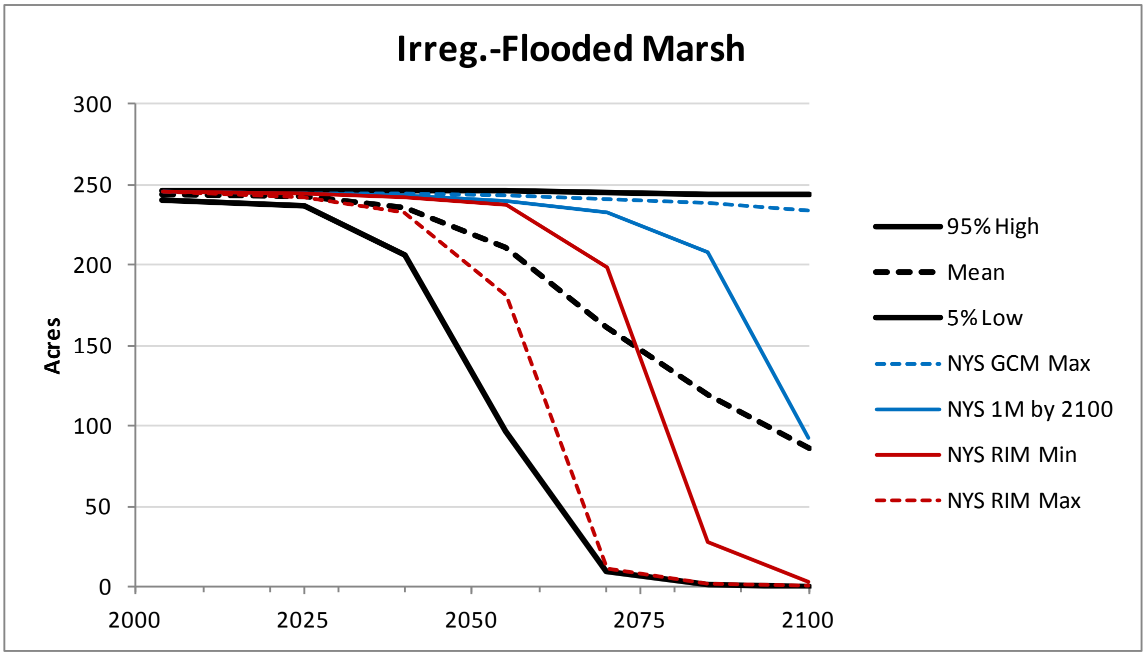


Figure 46. Time series for regularly flooded marsh area coverage, Hudson

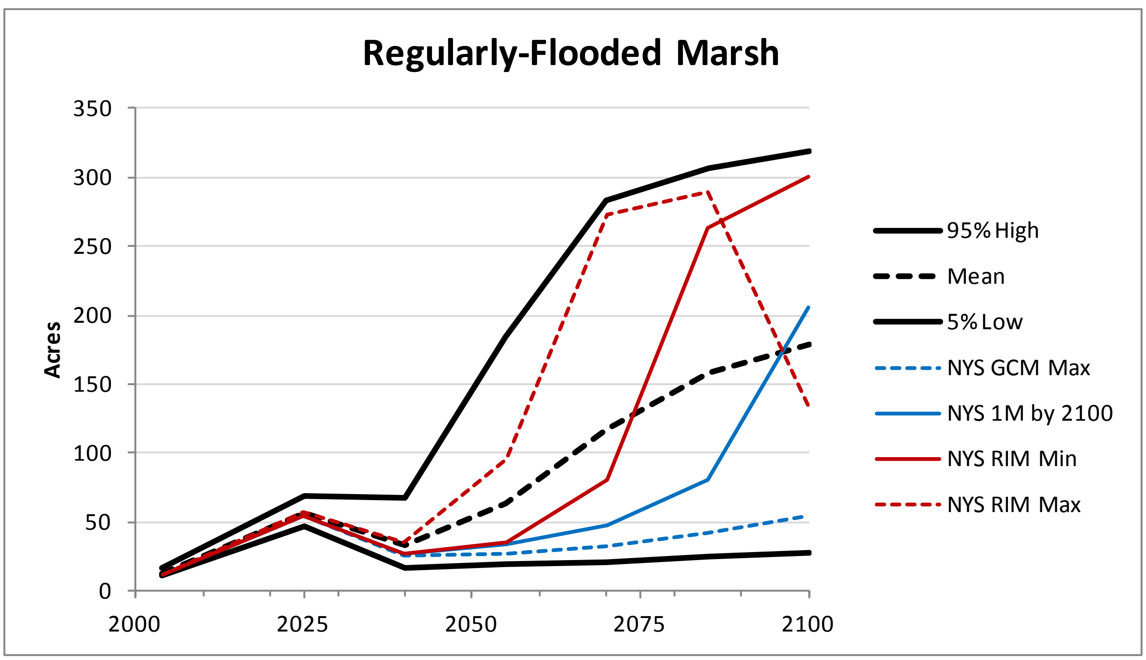
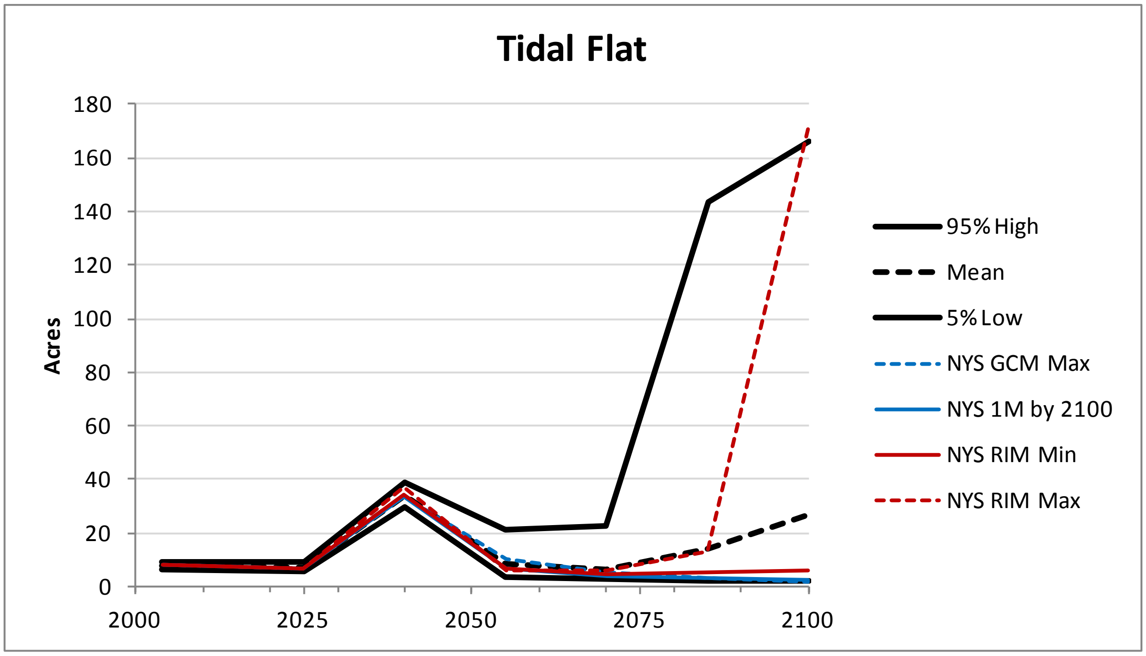


Figure 47. Time series for tidal flat area coverage, Hudson



The maps in Figure 48 and Figure 49 show that there is a low percent likelihood of habitat change in the Hudson study area in the short term, but a high percent likelihood of habitat change in the long term. While the model predicts a high probability that the Piermont Marsh habitat will change in the coming century, it is somewhat unlikely that the marsh will become open water (Figure 50). However, this result does not take into account any model structural uncertainty: The SLAMM habitat-succession flow chart suggests that high marshes must pass through low marshes and then tidal flats before becoming open water; direct conversion to open water due to substrate collapse is not considered.

As shown in Figure 50, the areas most likely to become open water occur near streams and outlets and along marsh edges. Other parts of the pier, as well as the Ferry Road corridor, are likely to become marsh (Figure 51). Appendix D presents additional maps in the time series for the Hudson study area, illustrating the increasing likelihood of habitat change and persistence of coastal marsh from 2025 to 2085.

Figure 48. Hudson River/ Piermont Marsh percent likelihood of habitat change by 2025

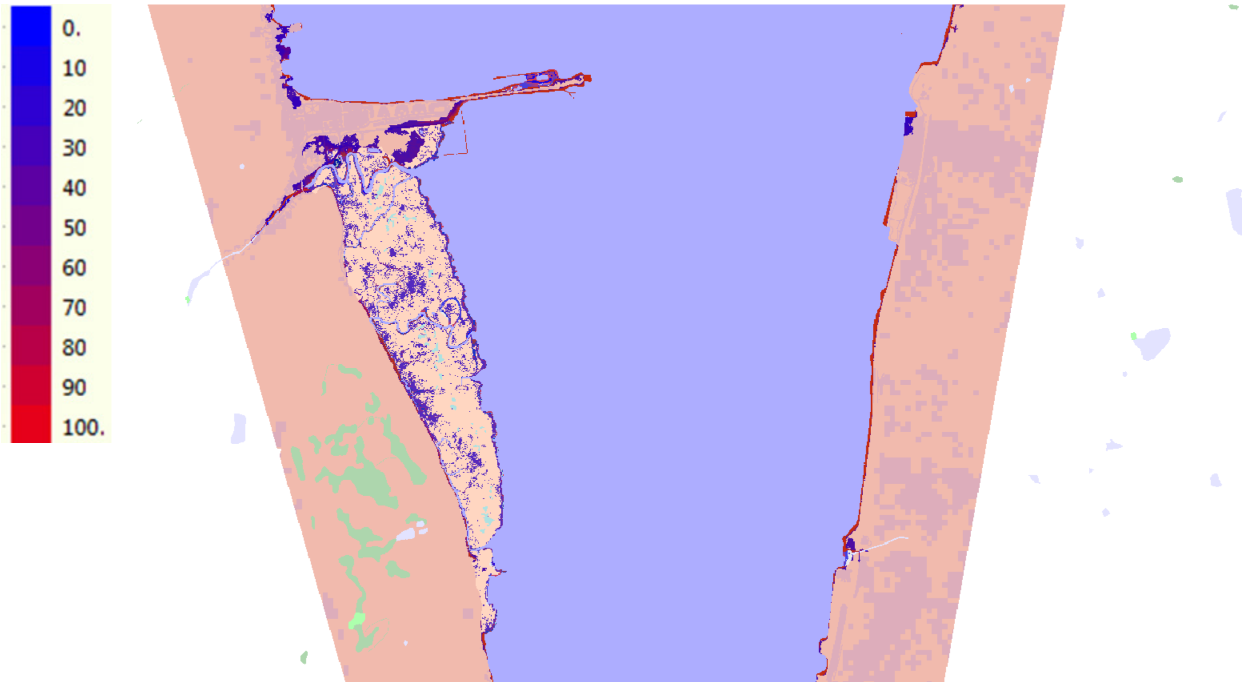


Figure 49. Hudson River/ Piermont Marsh percent likelihood of habitat change by 2100

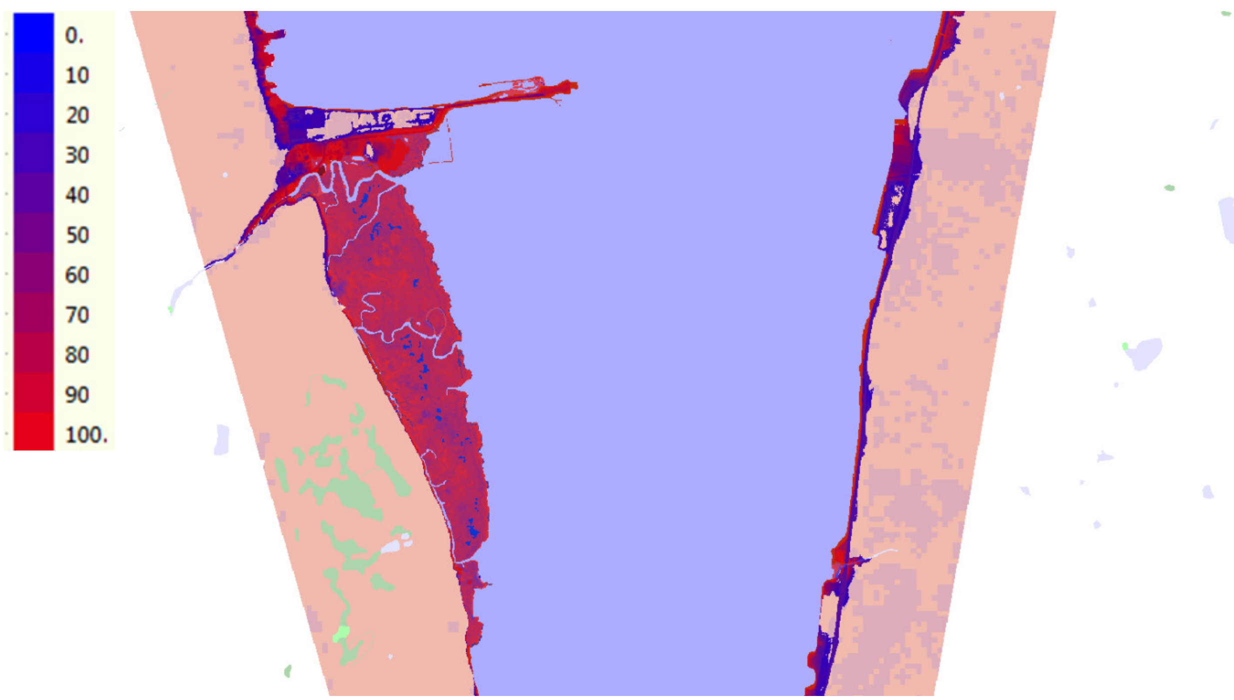


Figure 50. Hudson River/ Piermont Marsh percent likelihood of becoming open water by 2100

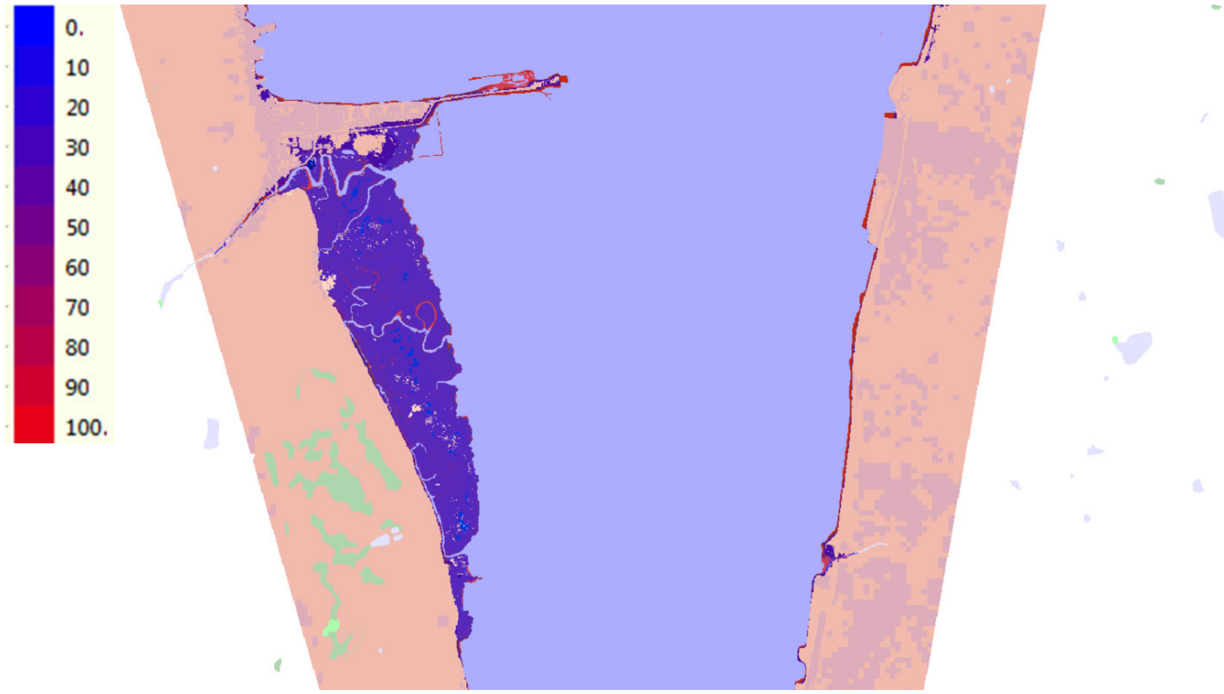
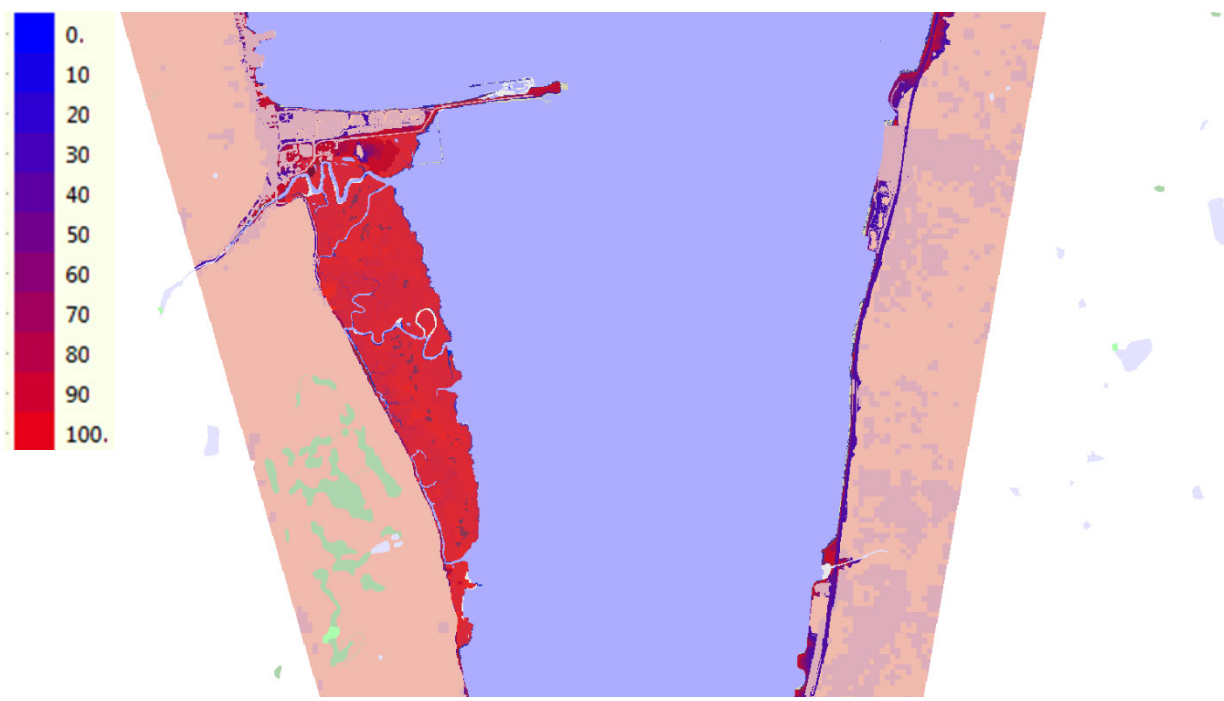


Figure 51. Hudson River/ Piermont Marsh percent likelihood of being coastal marsh in 2100



4.3 NYC Uncertainty Analysis Results

Uncertainty-analysis results for the New York City study area are presented in Table 59 (year 2055) and Table 60 (year 2100). The widest uncertainty intervals for this site are for dry lands and for regularly flooded marshes.

Table 59. Uncertainty results for NYC study area by land-cover category (2055)

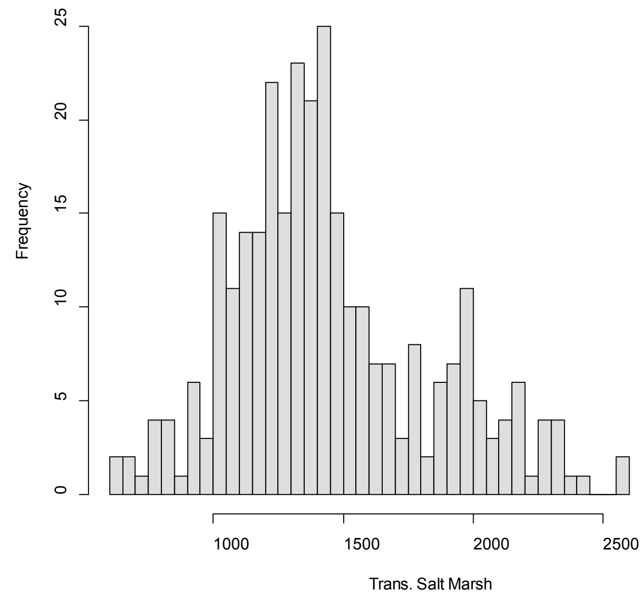
Land cover Type	Min	5th Percentile (Low)	Mean	95th Percentile (High)	Max	Std. Dev.
Developed Dry Land	121,905	122,423	123,351	123,757	123,794	392
Estuarine Open Water	74,773	75,029	75,528	76,263	76,554	341
Undeveloped Dry Land	57,777	58,081	59,005	59,688	59,884	436
Open Ocean	32,679	32,717	32,780	32,814	32,824	26
Regularly flooded Marsh	1,752	1,809	2,161	2,963	3,212	335
Tidal Flat	1,146	1,227	1,551	1,877	2,087	171
Irregularly Flooded Marsh	1,048	1,258	1,799	2,006	2,016	208
Inland Open Water	766	814	974	1,017	1,020	67
Ocean Beach	584	598	657	738	841	43
Swamp	509	513	531	546	547	9
Inland-Fresh Marsh	373	380	409	421	421	13
Estuarine Beach	254	267	338	408	425	40
Trans. Salt Marsh	228	384	755	1,147	1,293	209
Flooded Developed Dry Land	180	216	622	1,550	2,068	392
Tidal Swamp	45	52	63	71	72	5
Tidal-Fresh Marsh	16	17	25	30	31	4
Riverine Tidal	6	6	6	6	6	0
Inland Shore	2	2	2	2	2	0

Table 60. Uncertainty results for NYC study area by land-cover category (2100)

Land cover Type	Min	5th Percentile (Low)	Mean	95th Percentile (High)	Max	Std. Dev.
Developed Dry Land	109,753	113,237	119,835	123,439	123,701	2,902
Estuarine Open Water	75,347	75,619	76,933	78,591	79,534	784
Undeveloped Dry Land	51,628	53,031	56,617	59,072	59,396	1,653
Open Ocean	32,746	32,790	32,887	32,975	33,007	46
Regularly flooded Marsh	1,823	1,949	3,795	5,154	5,312	1,020
Tidal Flat	815	853	1,200	2,030	2,231	312
Inland Open Water	623	659	742	1,015	1,021	92
Trans. Salt Marsh	613	789	1,446	2,288	2,597	385
Ocean Beach	523	550	790	1,042	1,147	144
Swamp	386	401	486	541	544	38
Flooded Developed Dry Land	273	535	4,139	10,736	14,220	2,902
Irregularly Flooded Marsh	237	290	1,065	1,982	2,011	551
Inland-Fresh Marsh	177	192	332	413	420	66
Estuarine Beach	138	157	222	308	352	41
Tidal Swamp	12	16	41	66	70	15
Riverine Tidal	5	5	6	6	6	0
Tidal-Fresh Marsh	4	11	21	30	31	6
Inland Shore	2	2	2	2	2	0

The histograms in Figure 52 show that the highest likelihood for transitional saltmarsh is between 1000 and 1500 acres by 2100. While up to 15,000 acres of developed land could be flooded, it is more likely that this number will be between 500 and 5,000 acres.

Figure 52. Histograms for Transitional Salt Marsh and Flooded Developed Land for New York City Study Area in 2100 (acres)



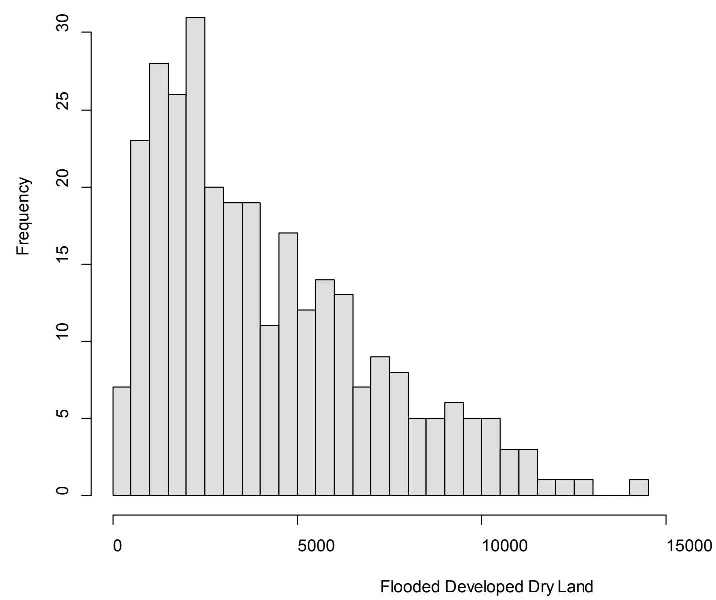


Figure 53 to Figure 55 provide times series of predicted changes of dry land and their 90% confidence interval. Similar patterns of dry-land losses are observed for all study areas. In NYC, developed dry land starts having inundation problems in 2050 under all scenarios considered. By 2100, a maximum of 14,000 acres could be regularly flooded.

Figure 53. Time series for developed dry land area coverage in New York City

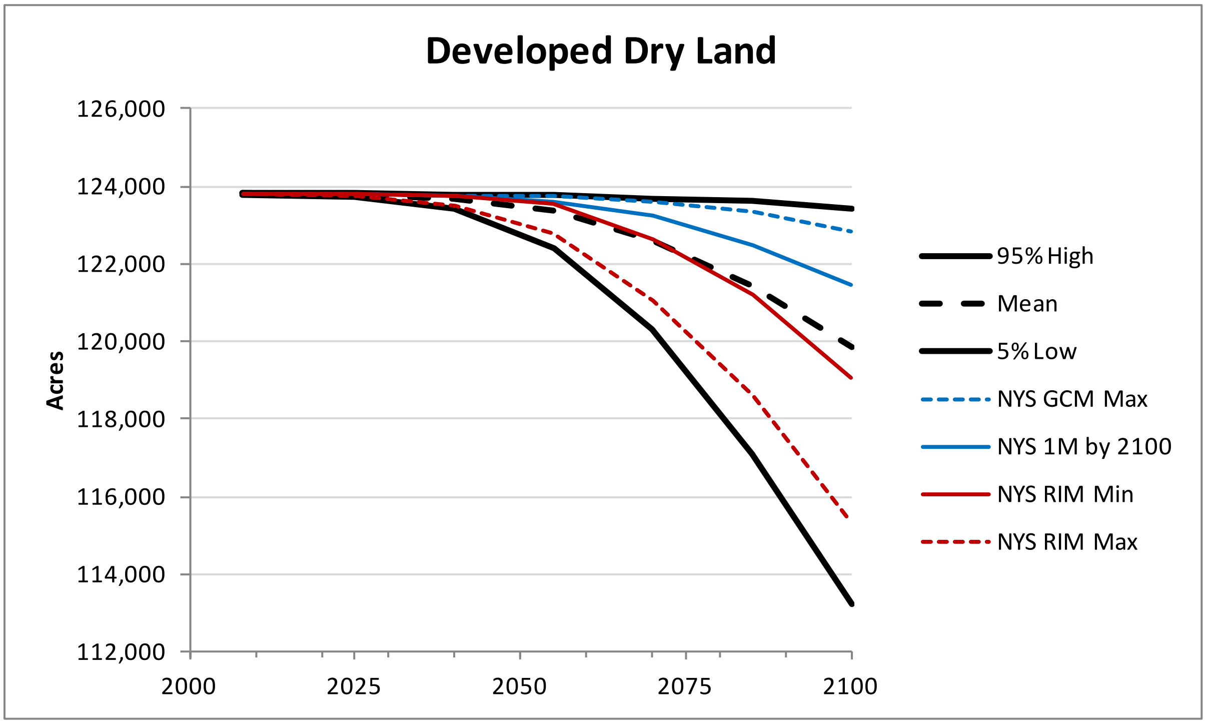


Figure 54. Time series for undeveloped dry land area coverage in New York City

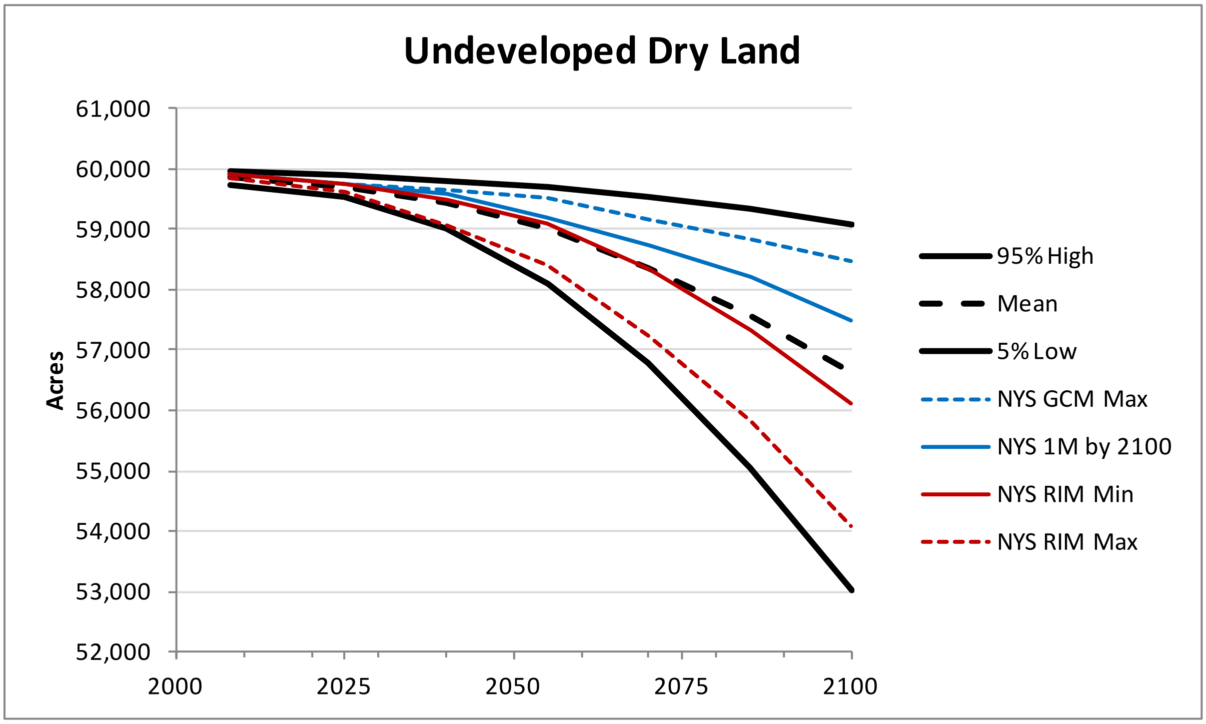


Figure 55. Time series for flooded developed dry land area coverage in New York City

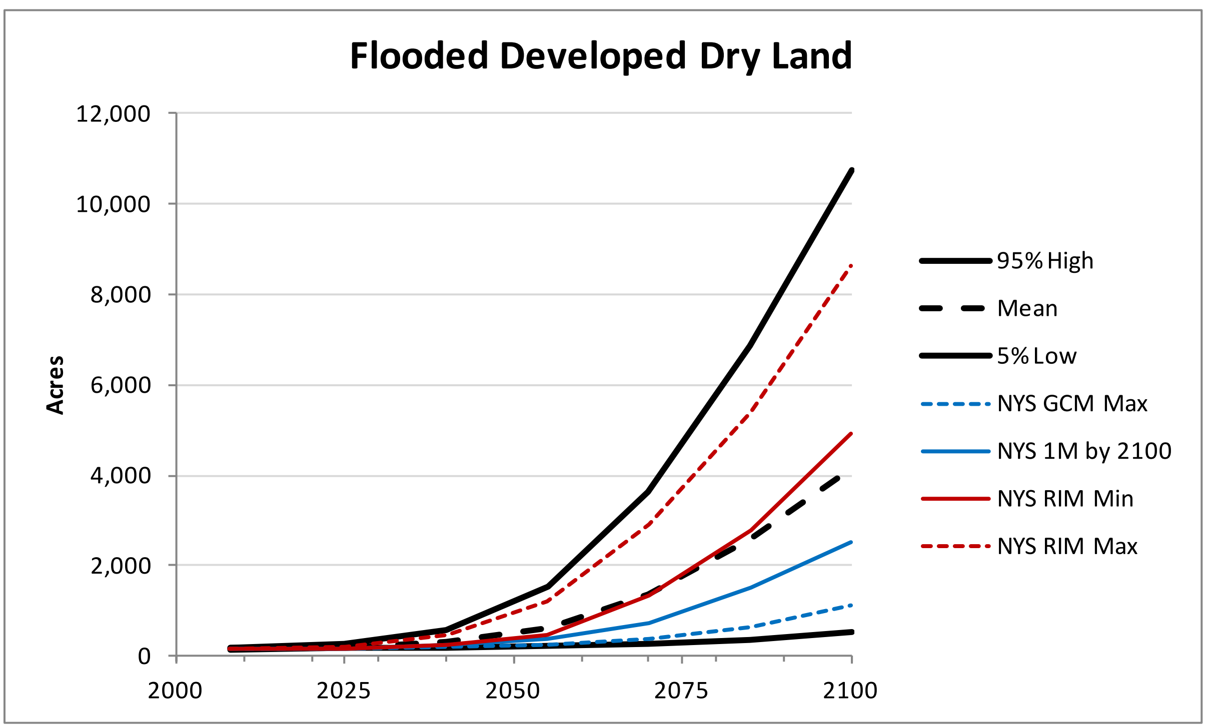


Figure 56. Time series for irregularly flooded marsh area coverage in New York City

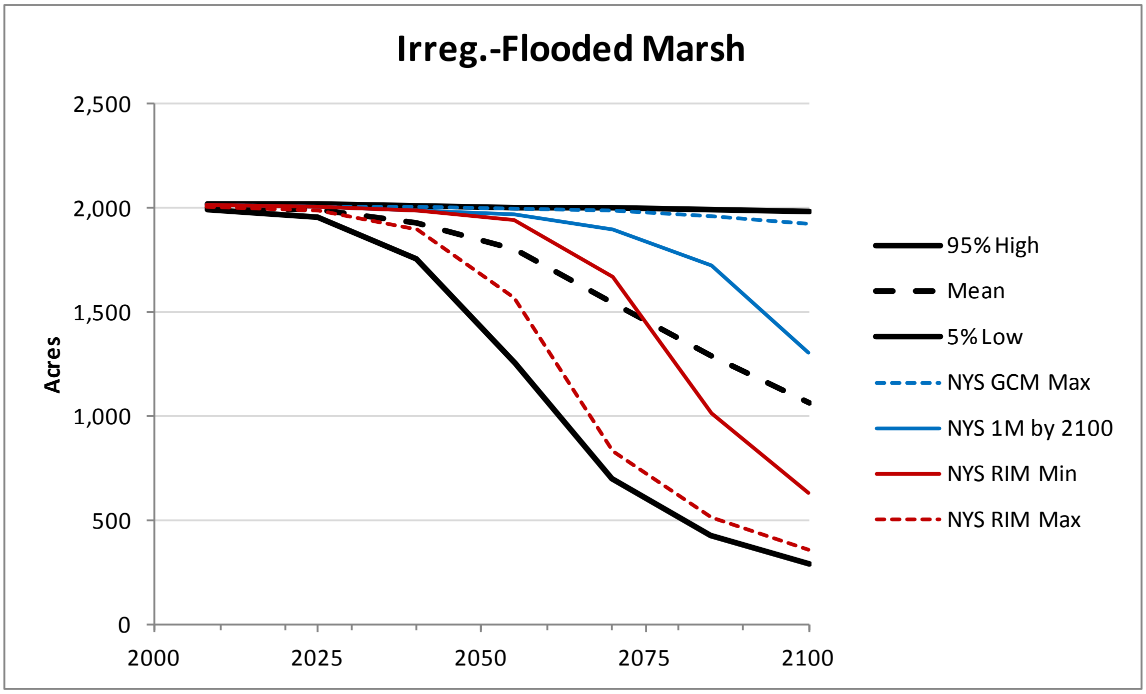


Figure 57. Time series for regularly flooded marsh area coverage in New York City

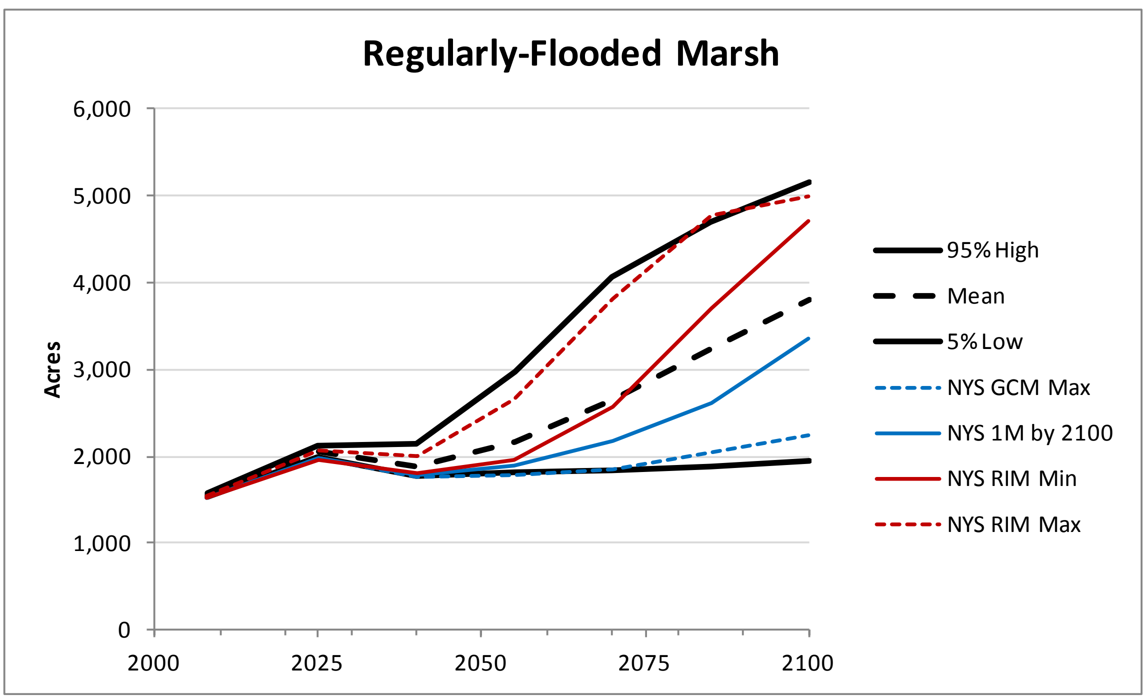
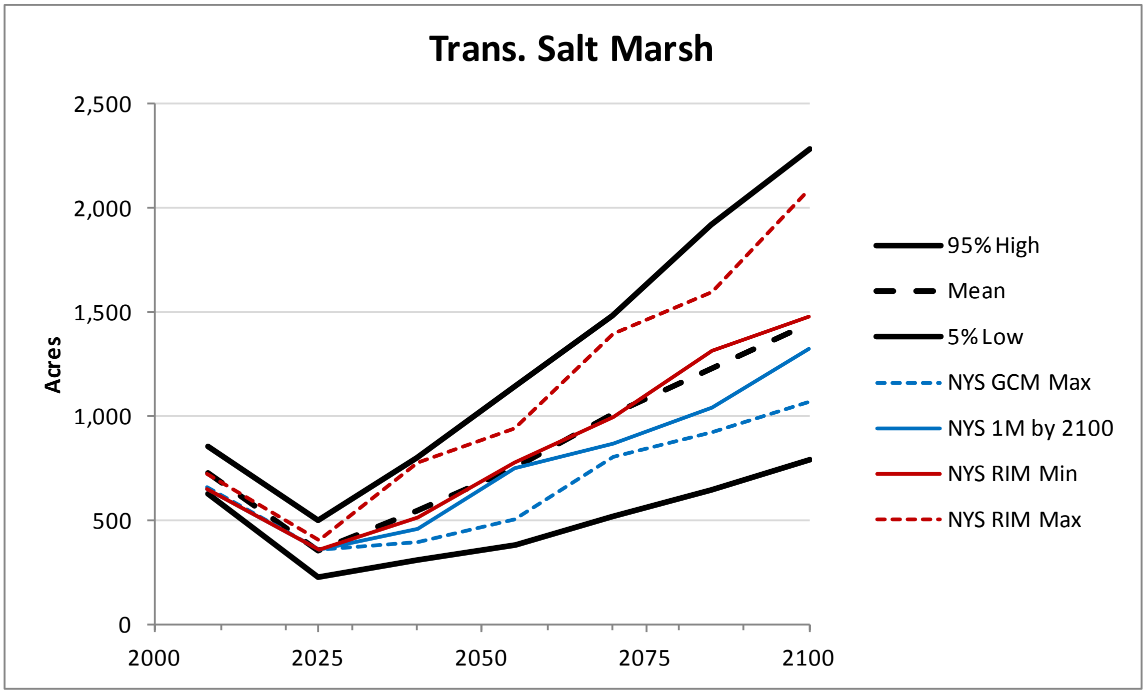


Figure 58. Time series for transitional salt marsh area coverage in New York City



In the New York City study area, the greatest likelihood of habitat change is predicted in Northwest Staten Island (Fresh Kills), Flushing Meadows, Coney Island, Jamaica Bay, and the Rockaway Peninsula, as shown in Figure 59. Figure 60 illustrates that predicted changes may result in extensive flooding of developed land, particularly in Coney Island, the Rockaways, and Broad Channel. In lower Manhattan and surrounding boroughs, some low-lying infrastructure, including FDR Drive, is very likely to be flooded by 2085, as presented in Figure 61. The maps in Appendix D show the timeseries of the likelihood of flooded developed land in NYC at different times over the coming century. Although serious flooding of developed land is likely within the area, results indicate it is most likely to occur later in the century.

Portions of the NYC study area are exceedingly likely to become wetlands in the coming century. Most notably Fresh Kills Park and surrounding areas are highly likely to become wetlands (Figure 62).The results presented in Figure 63 show that many of the larger wetland islands in Jamaica Bay are likely to remain wetlands through the century. However, it is important to consider that these results do not include the effects of water quality on marsh viability.

Figure 59. NYC Percent Likelihood of habitat change by 2100

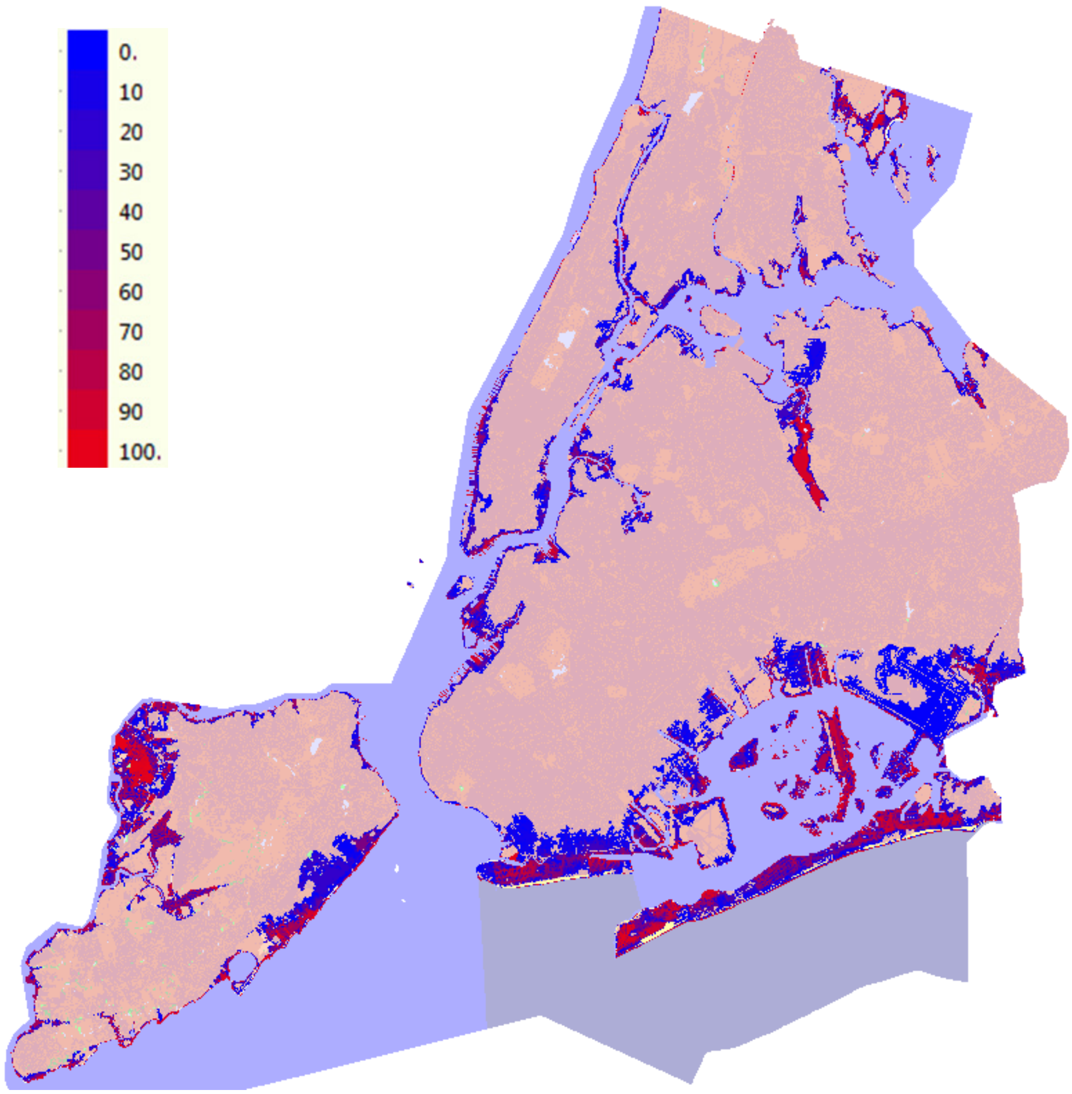


Figure 60. NYC percent likelihood of flooded developed land by 2100

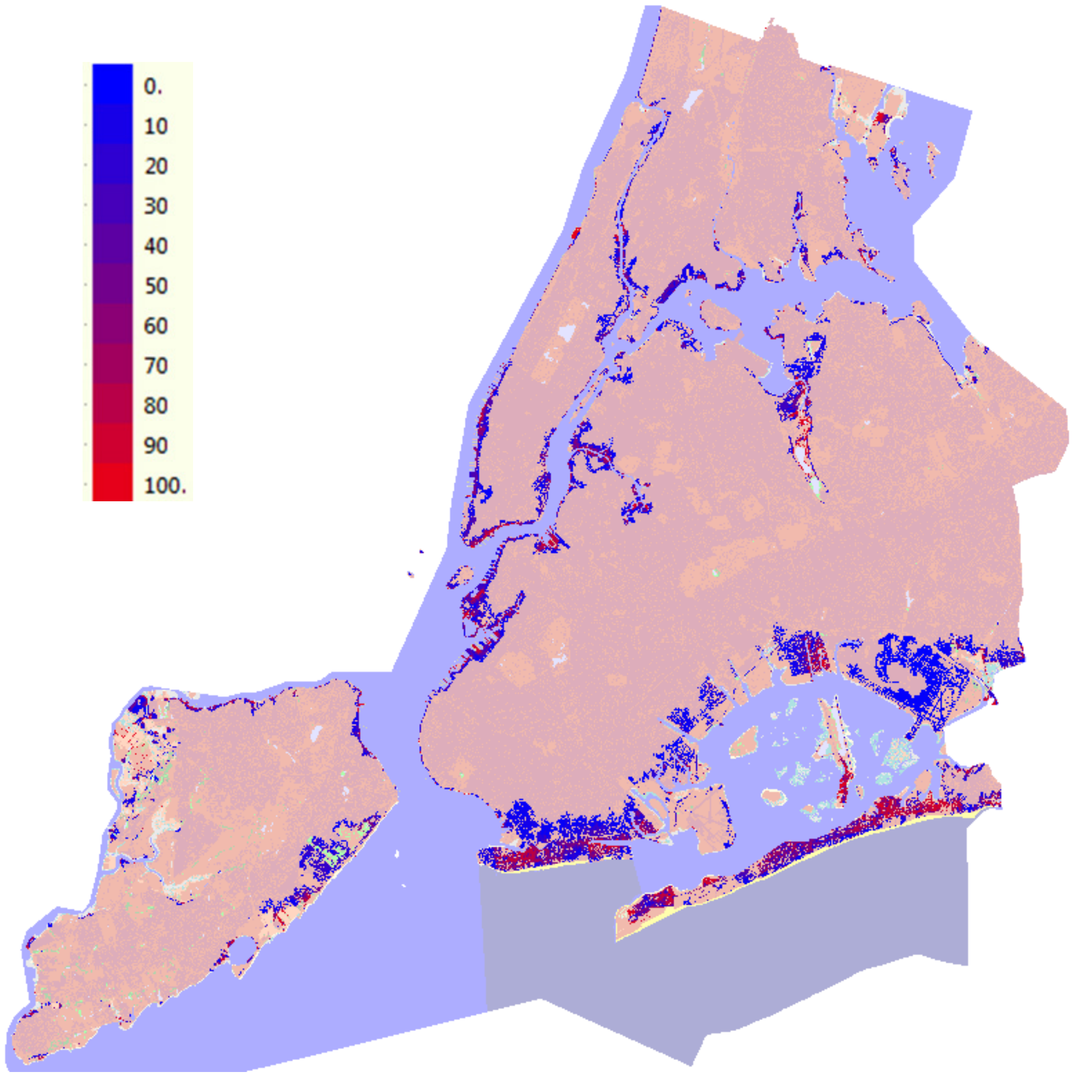


Figure 61. Lower Manhattan percent likelihood of flooded developed land by 2085

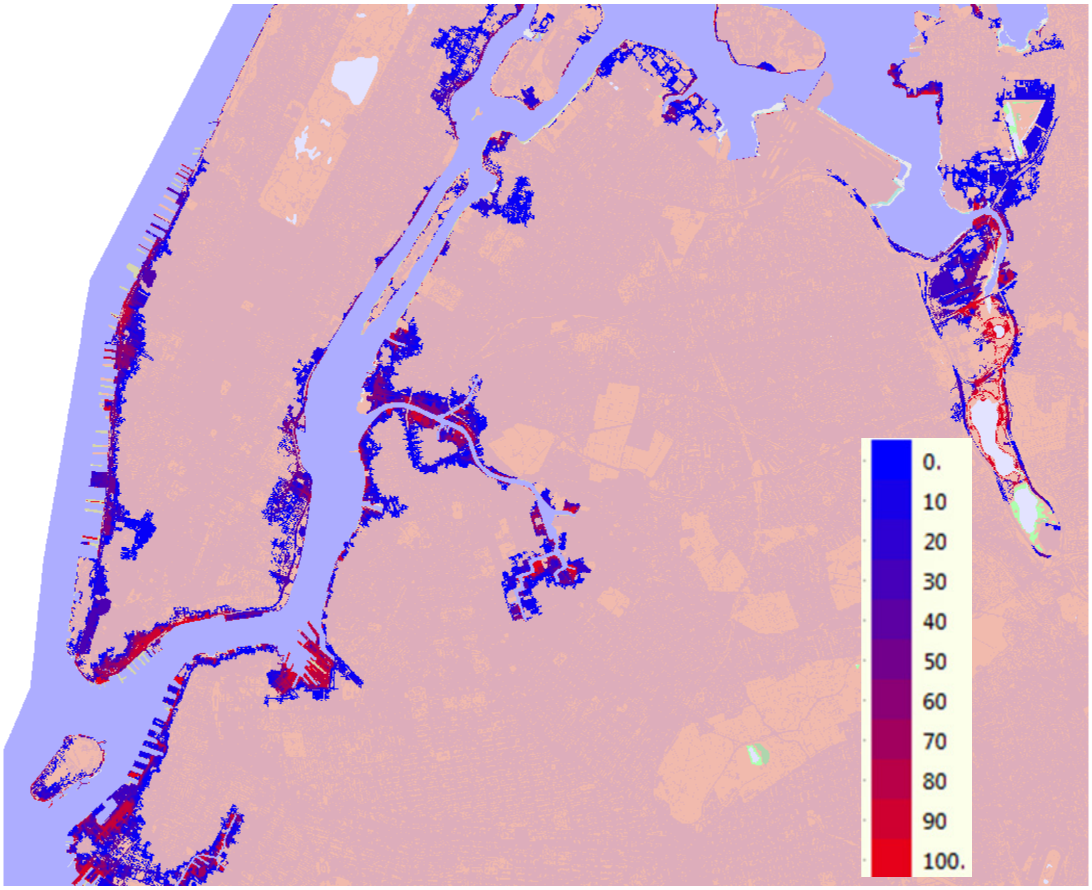


Figure 62. NYC percent likelihood of coastal wetland by 2100

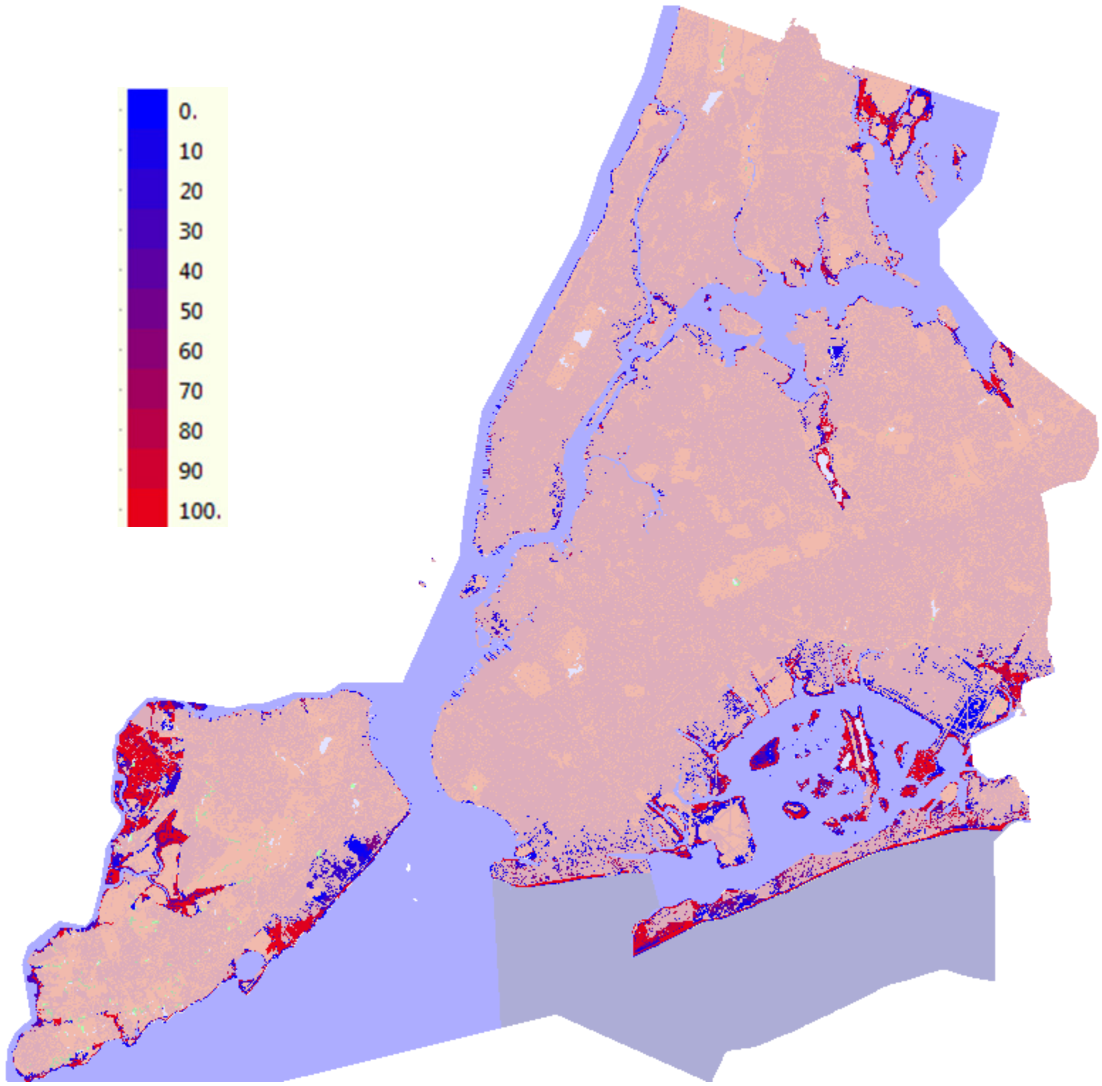
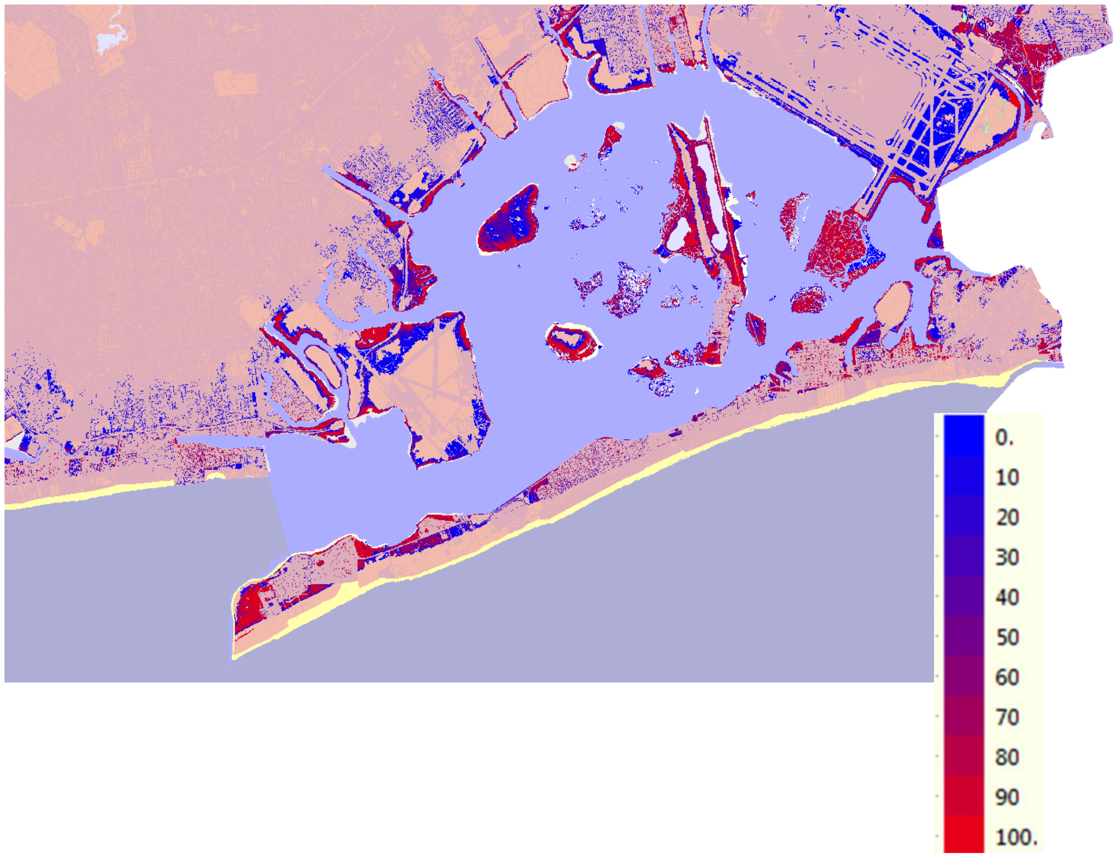


Figure 63. Jamaica Bay percent likelihood of coastal wetland by 2100



4.4 Nassau Uncertainty Analysis Results

Uncertainty-analysis results for the Nassau study area indicate that coastal marsh results have the widest confidence intervals. Table 61 presents statistics of results for 2055 and Table 62 shows the uncertainty intervals widening by 2100 as generally occurs in all study areas.

Table 61. Uncertainty results for Nassau study area by land-cover category (2055)

Land cover Type	Min	5th Percentile (Low)	Mean	95th Percentile (High)	Max	Std. Dev.
Estuarine Open Water	62,384	62,463	63,270	64,342	64,638	466
Open Ocean	40,402	40,431	40,501	40,544	40,549	24
Undeveloped Dry Land	32,671	33,438	34,896	35,732	35,839	657
Developed Dry Land	25,179	25,764	26,921	27,464	27,498	481
Regularly flooded Marsh	1,318	1,542	4,023	6,751	7,196	1,653
Inland Open Water	1,088	1,100	1,144	1,178	1,186	22
Swamp	825	831	868	890	893	16
Ocean Beach	704	710	789	900	960	47
Tidal Flat	388	414	742	1,598	2,170	326
Irregularly Flooded Marsh	369	590	3,991	6,760	6,950	1,913
Trans. Salt Marsh	349	397	872	1,543	1,618	331
Estuarine Beach	341	350	465	588	611	63
Inland-Fresh Marsh	99	105	182	218	219	29
Flooded Developed Dry Land	83	117	660	1,817	2,402	481
Inland Shore	36	36	36	36	36	-
Tidal-Fresh Marsh	14	16	20	21	21	1
Tidal Swamp	3	4	8	11	11	2

Table 62. Uncertainty results for Nassau study area by land-cover category (2100)

Land cover Type	Min	5th Percentile (Low)	Mean	95th Percentile (High)	Max	Std. Dev.
Estuarine Open Water	62,852	63,031	66,376	72,106	72,672	2,676
Open Ocean	40,450	40,496	40,637	40,816	40,835	73
Undeveloped Dry Land	25,725	26,716	31,641	35,098	35,388	2,280
Developed Dry Land	19,053	19,841	24,241	27,096	27,238	2,009
Regularly flooded Marsh	1,686	1,975	5,547	7,611	8,076	1,337
Inland Open Water	1,014	1,018	1,076	1,151	1,161	34
Swamp	728	747	813	872	885	35
Ocean Beach	683	698	903	1,225	1,395	150
Trans. Salt Marsh	644	889	1,540	2,142	2,225	364
Flooded Developed Dry Land	343	485	3,340	7,740	8,529	2,009
Tidal Flat	193	294	1,583	3,126	3,316	859
Estuarine Beach	165	170	293	465	510	74
Inland-Fresh Marsh	84	86	121	197	204	39
Inland Shore	36	36	36	36	36	-
Irregularly Flooded Marsh	18	28	1,218	6,332	6,689	1,712
Tidal-Fresh Marsh	2	5	17	21	21	4
Tidal Swamp	0	0	3	9	10	3

Figure 64 shows that both the undeveloped dry land and low marsh probabilities are slightly skewed to the right within their confidence intervals (higher acreages by 2100 are more likely than lower acreages).

Figure 64. Histograms for Undeveloped Dry Land and Low Marsh for Nassau Study Area in 2100

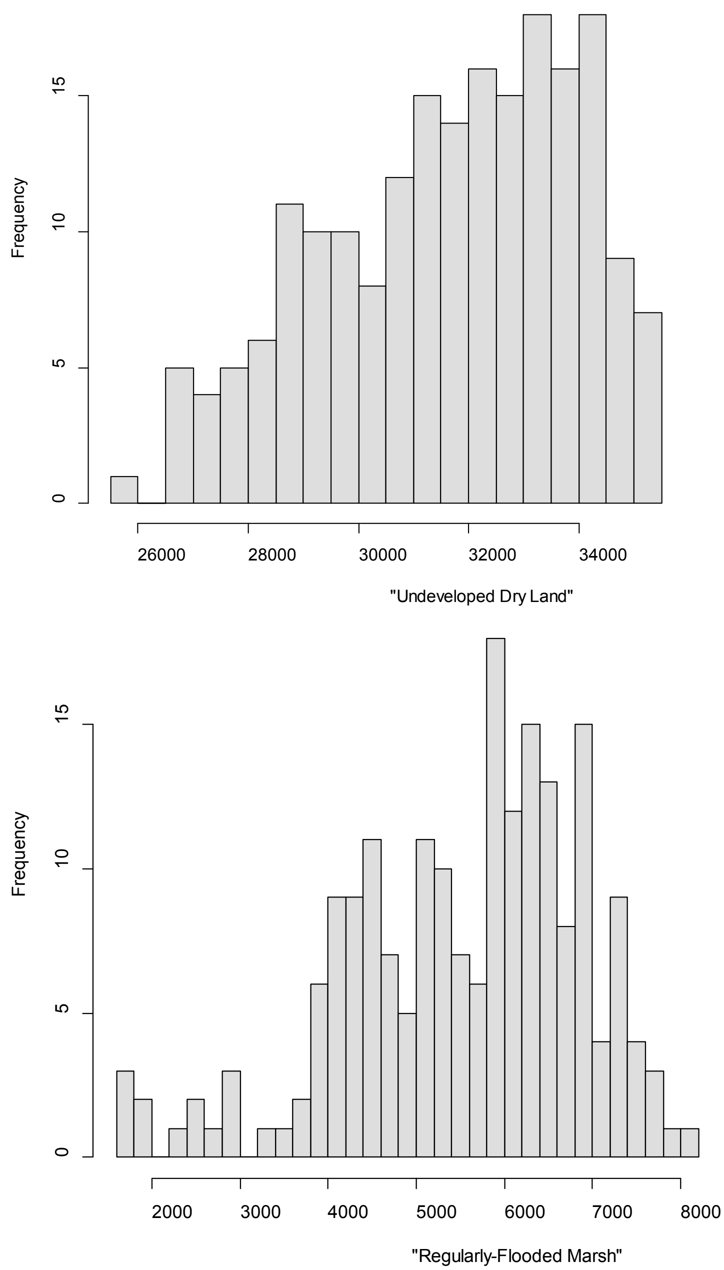


Figure 65. Time series for irregularly flooded marsh area coverage, Nassau

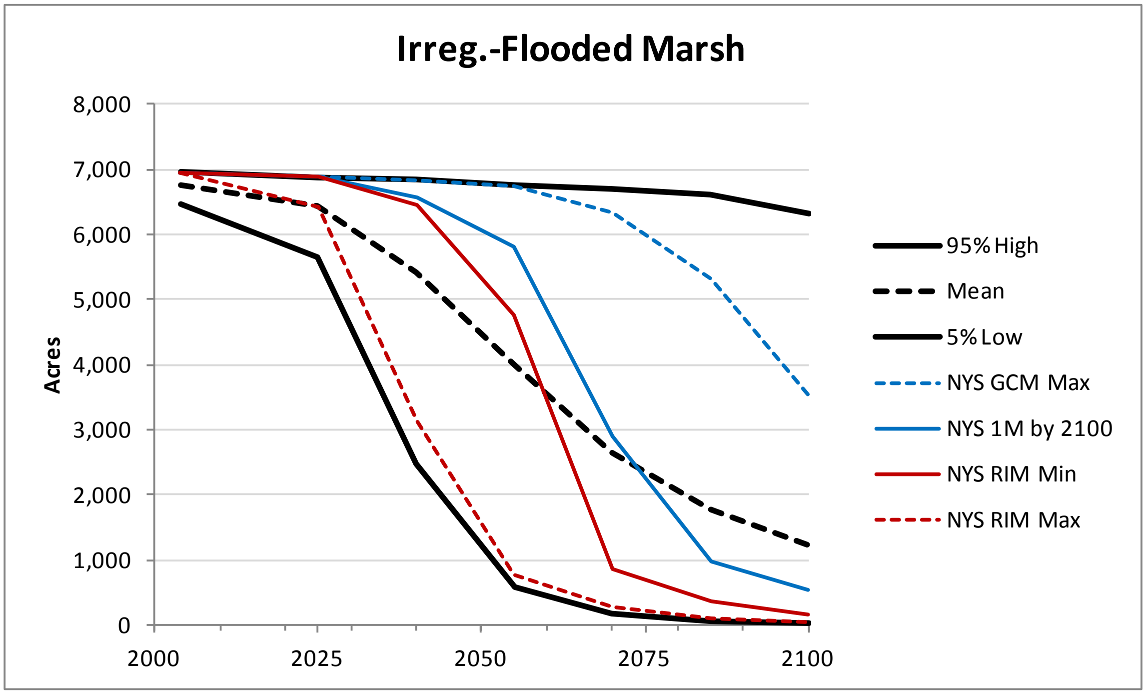


Figure 66. Time series for irregularly flooded marsh area coverage, Nassau

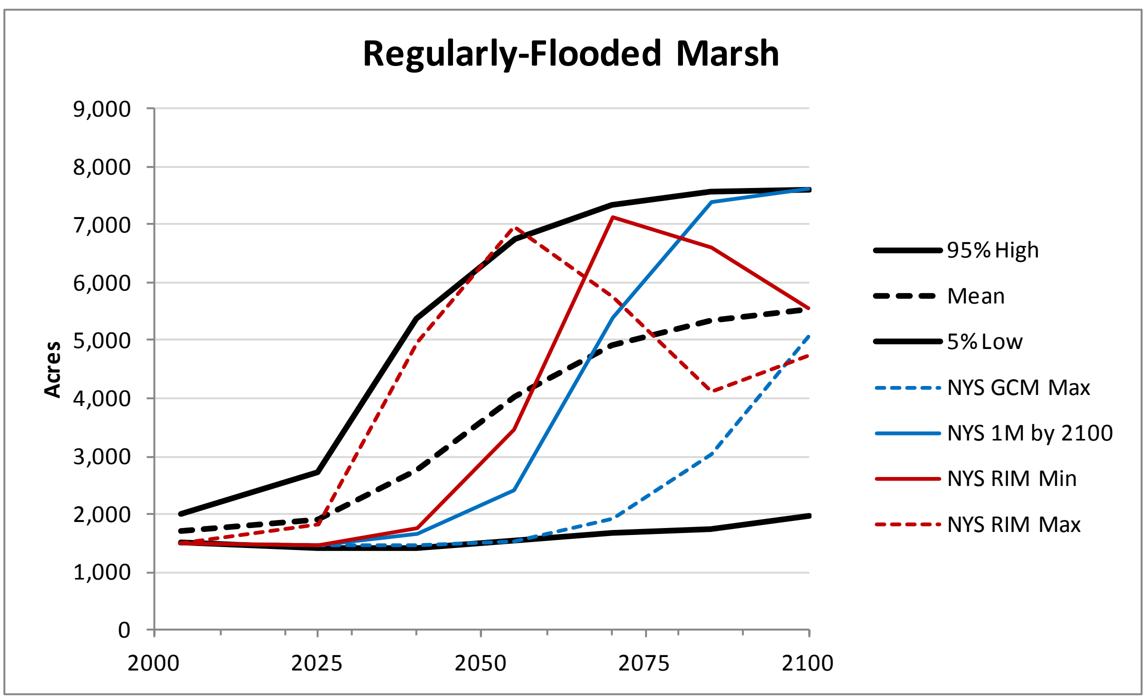
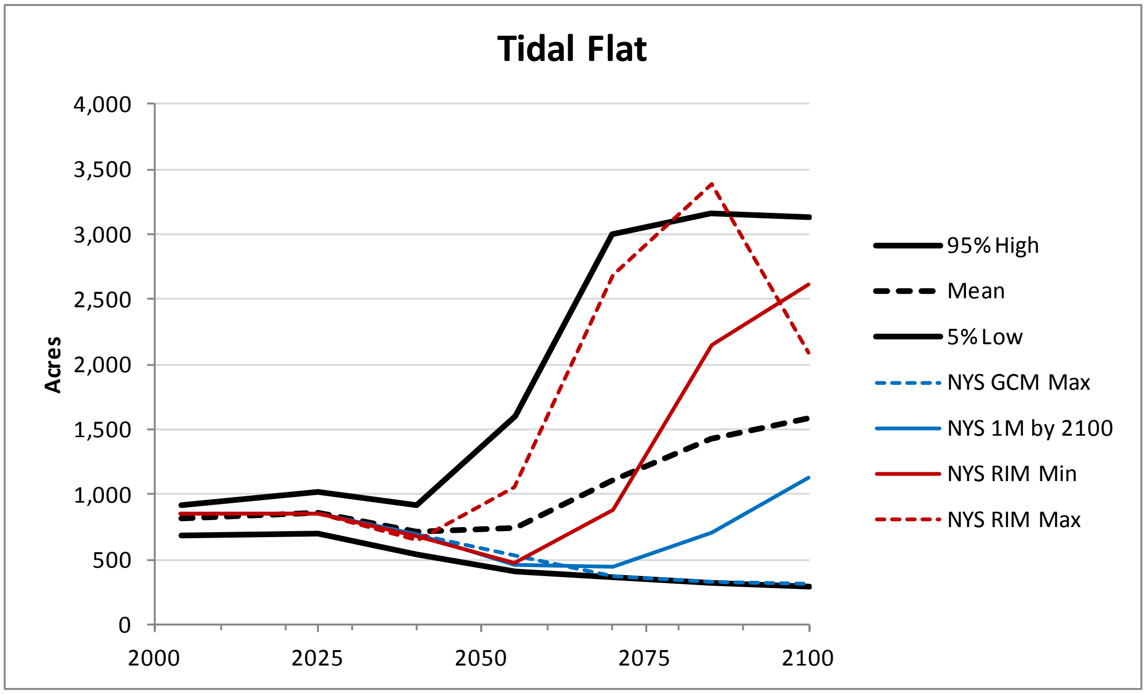


Figure 67. Time series for tidal flat area coverage, Nassau



Similar to what was observed in NYC and Hudson, irregularly flooded marsh coverage is predicted to decline starting in 2025 while regularly flooded marsh acreage increases. Tidal flats may actually increase under higher SLR scenarios, but this increase is at the expense of vegetated marshes and even dry lands.

In Nassau County there is a low to mid-range likelihood that habitats will change based on sea-level rise in the short term (Figure 68). However, in the long term, it is very likely that there will be extensive changes in habitat (Figure 69). In particular, the southern shores of the county are extremely likely to be affected by sea-level rise by the end of the century. It appears most likely that marshes in the southwest of the county will remain marsh but in the southeast are more likely to become open water by 2100 (Figure 70). On the north shore of the county, it appears much more likely that converted land will be marsh rather than open water (Figure 71). As shown in Figure 72, extensive flooding of developed lands in Nassau County is likely by 2100. The coastal communities of Long Beach, Island Park, Baldwin Harbor, Merrick, Massapequa, and East Massapequa are highly likely to be affected by sea-level rise within this century.

The time series presented in Appendix D illustrate the likelihood of land loss in Nassau County within the century.

Figure 68. Nassau Percent Likelihood of habitat change by 2025

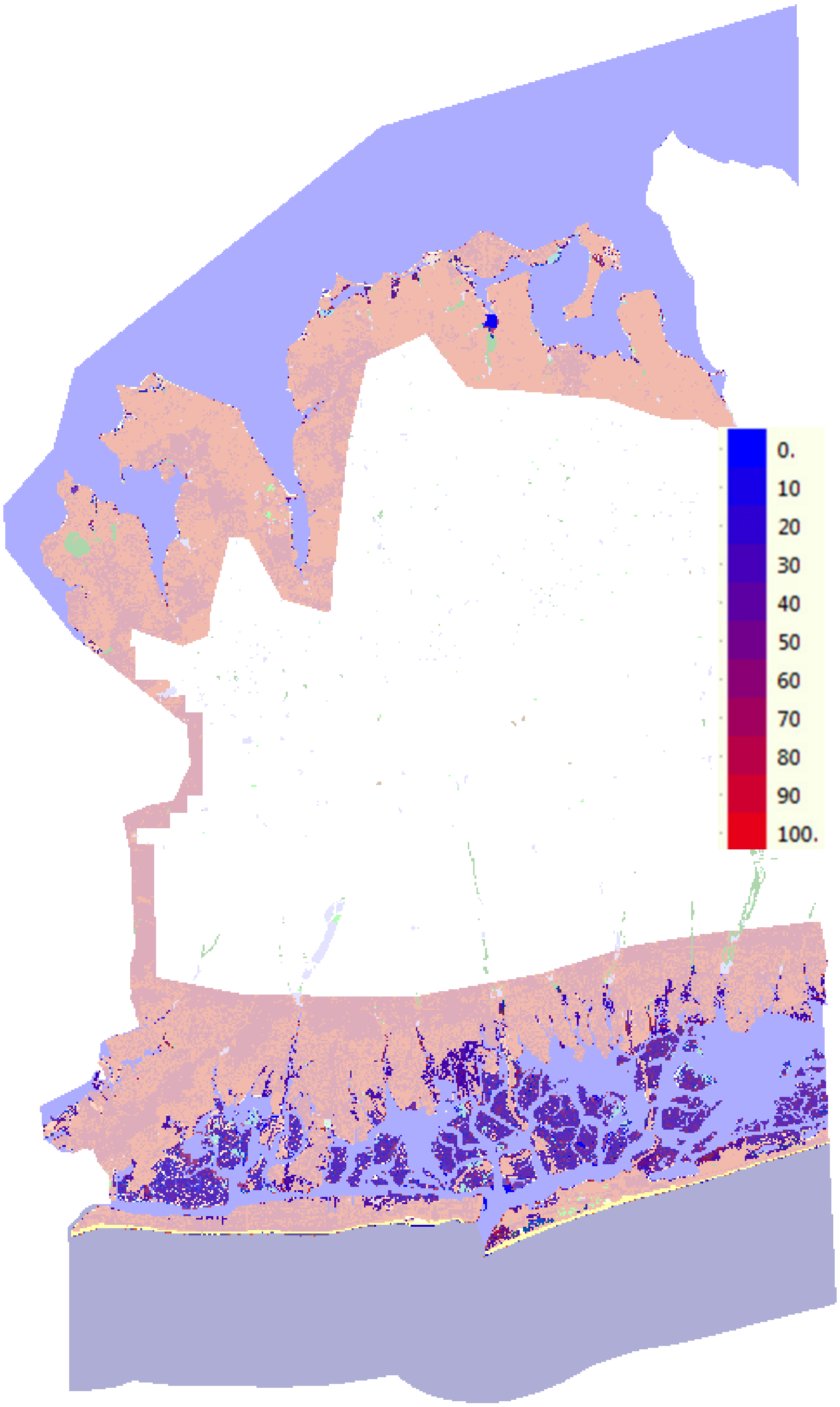


Figure 69. Nassau Percent Likelihood of habitat change by 2100

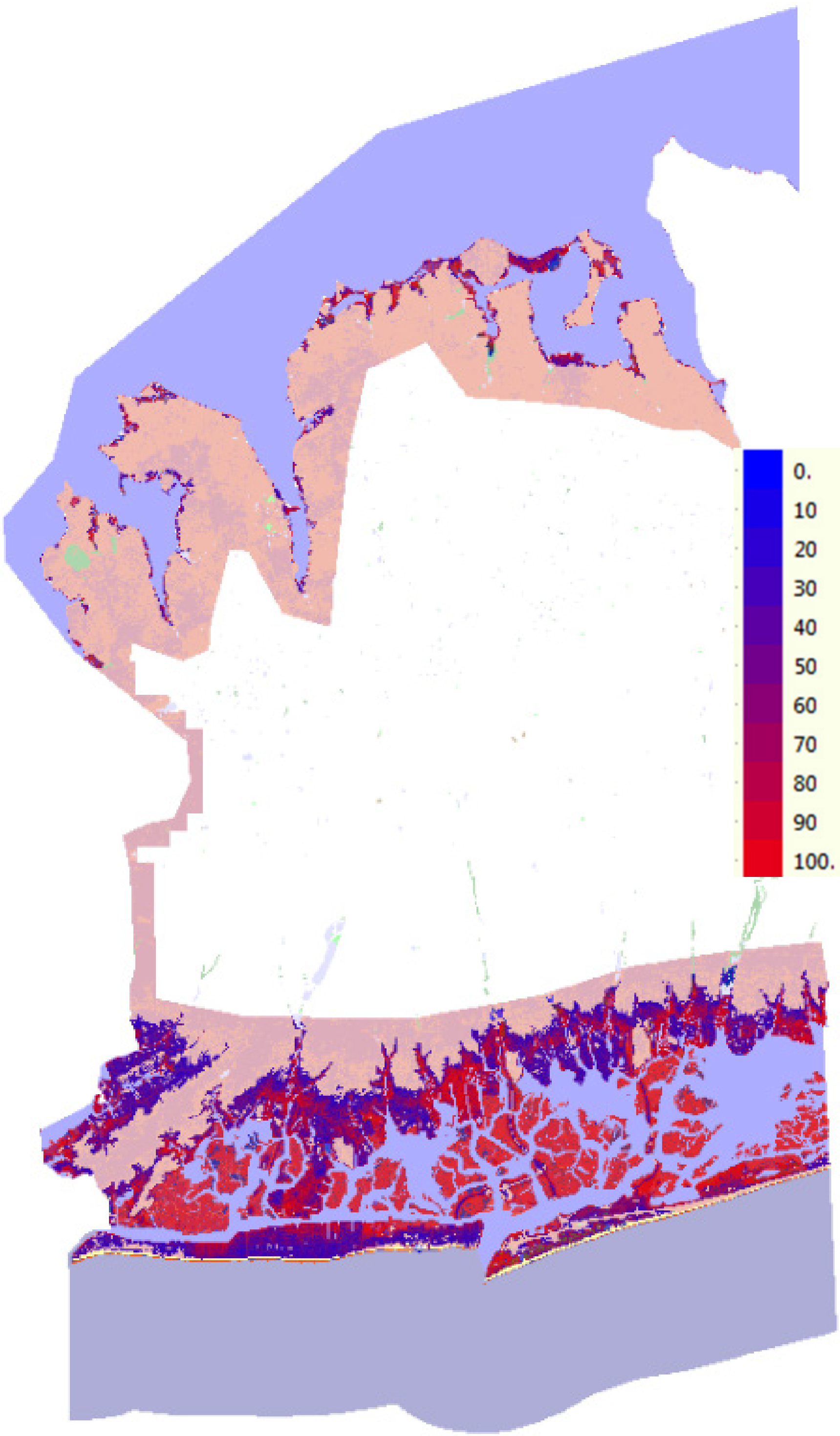


Figure 70. Nassau percent likelihood of land to open water by 2100

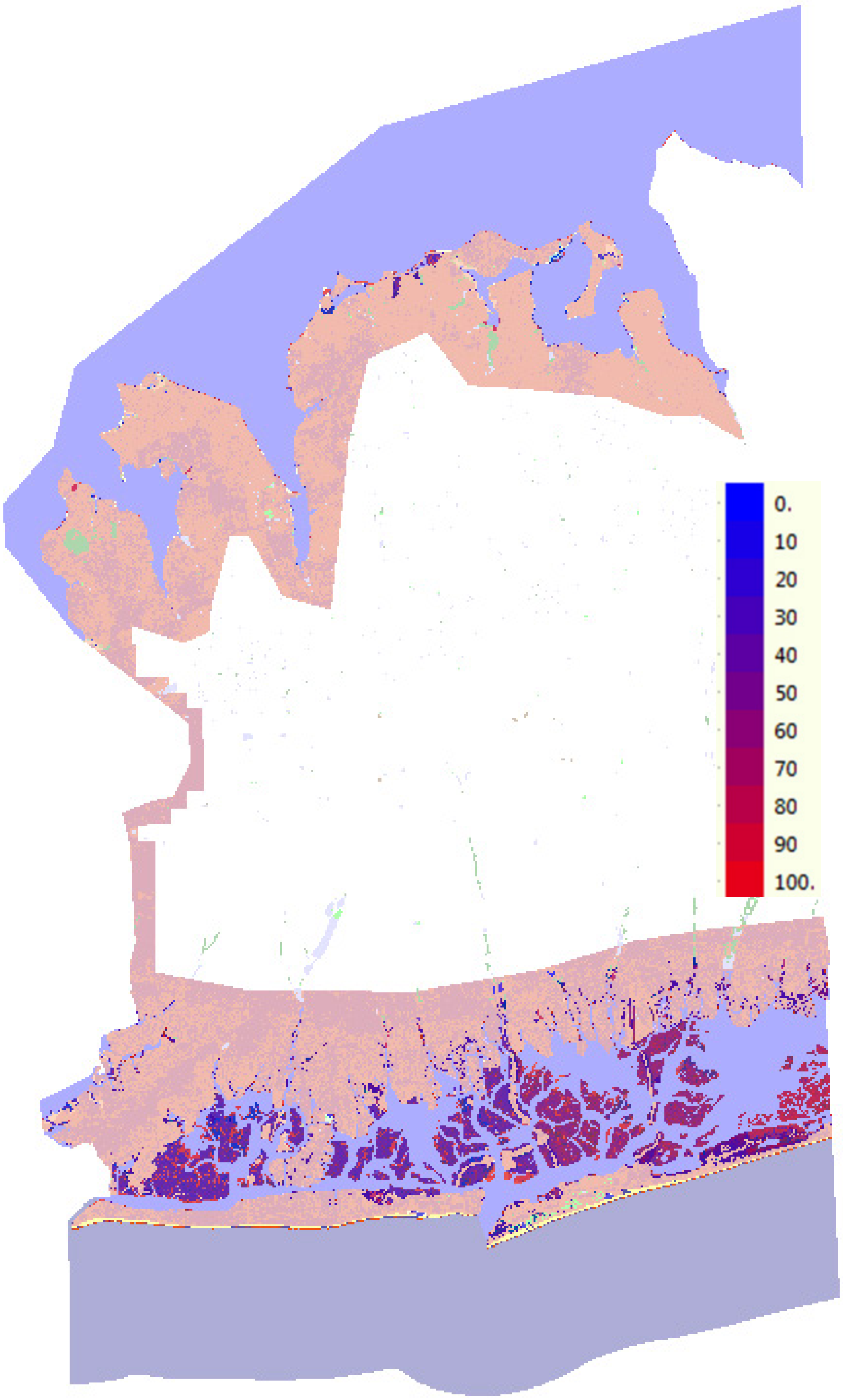


Figure 71. Nassau percent likelihood of coastal marsh by 2100

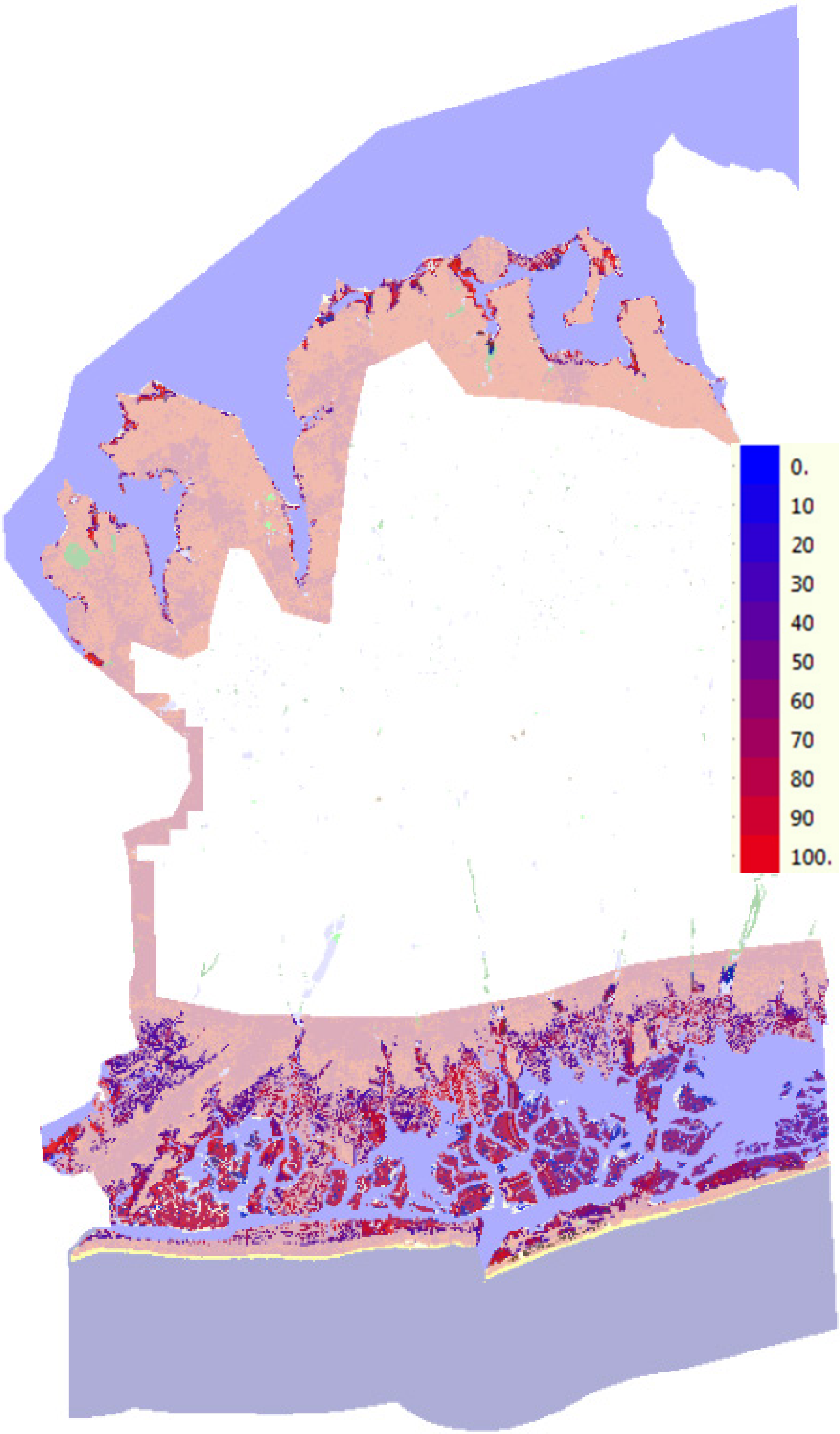
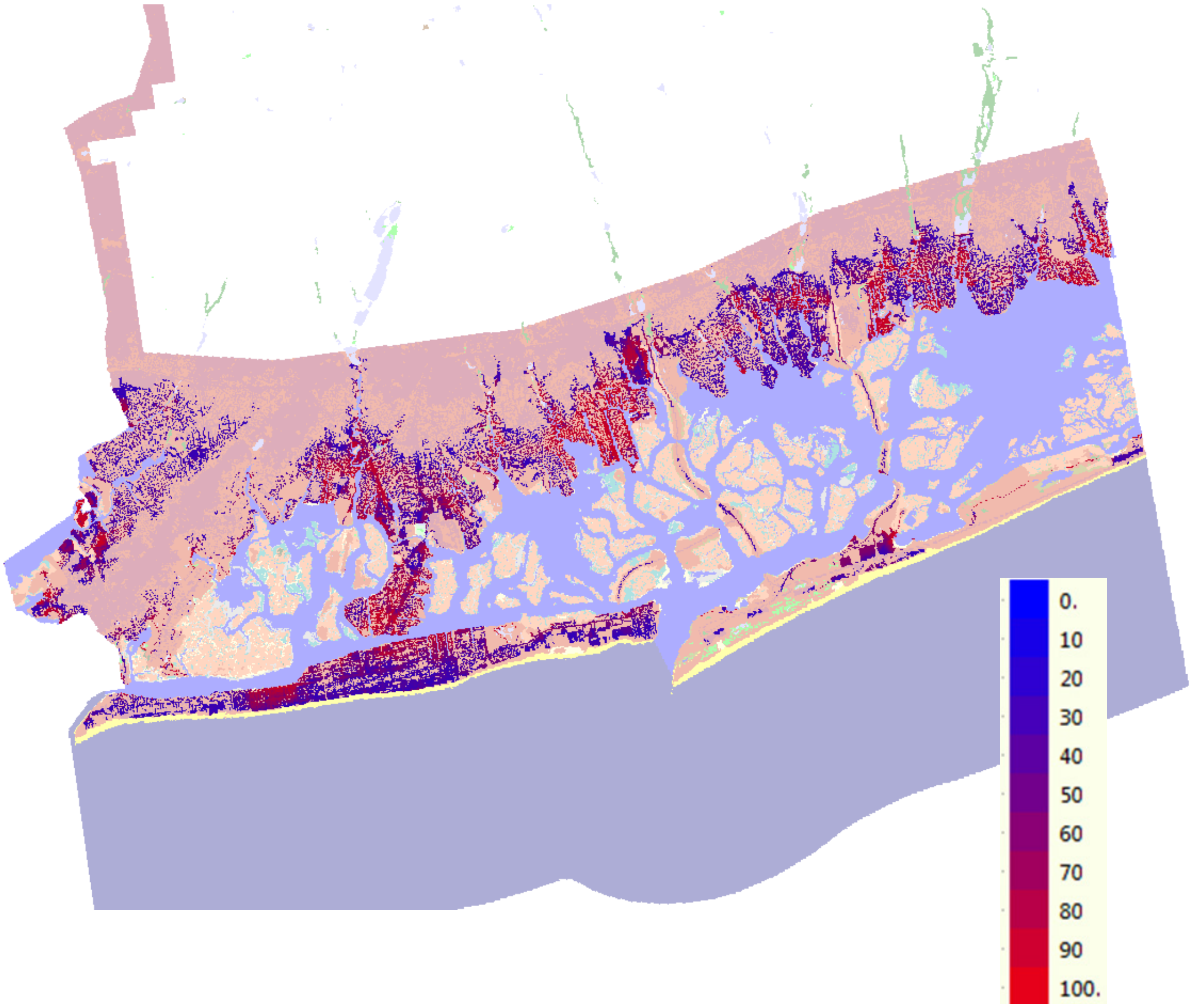


Figure 72. Southern Nassau percent likelihood of flooded developed by 2100



4.5 Suffolk West Uncertainty Analysis Results

Uncertainty-analysis results for the Suffolk West study area are presented in Table 63 (year 2055) and Table 64 (year 2100). Examining the standard deviations, high marsh has the most acreage uncertainty by 2055 and undeveloped dry land is most uncertain by 2100 (excluding open-water categories).

Table 63. Uncertainty results for Suffolk West study area by land-cover category (2055)

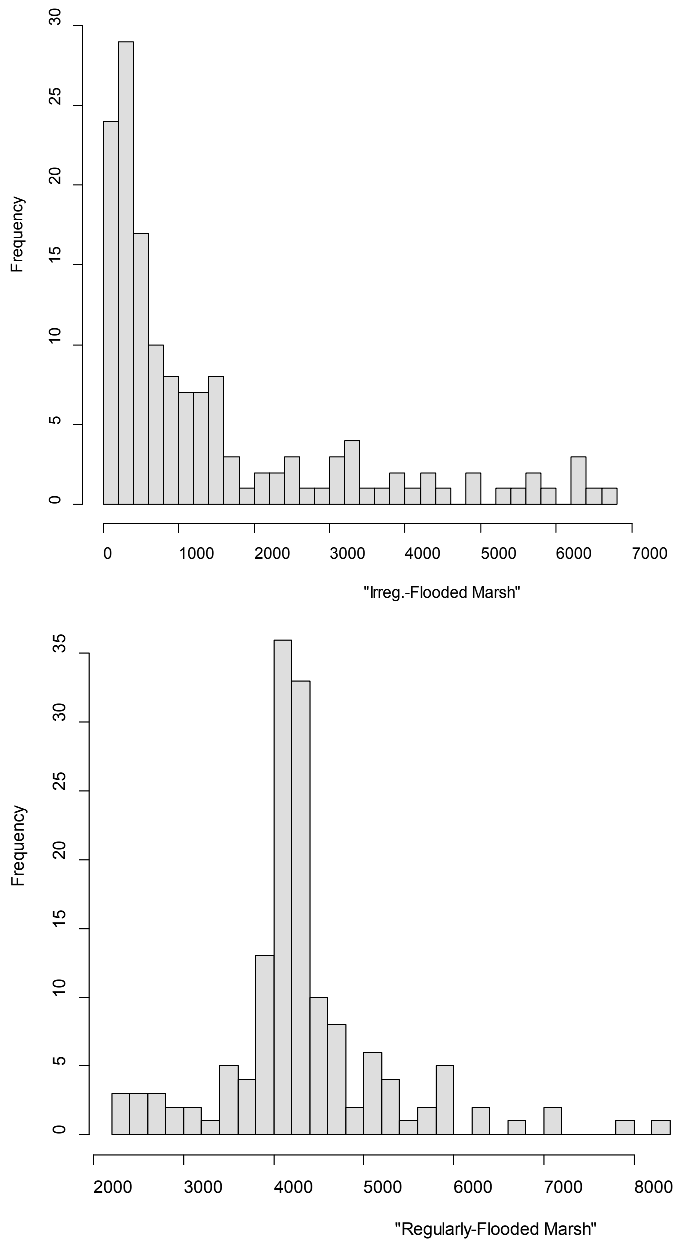
Land cover Type	Min	5th Percentile (Low)	Mean	95th Percentile (High)	Max	Std. Dev.
Estuarine Open Water	157,519	157,555	158,718	161,252	161,415	966
Open Ocean	77,170	77,193	77,364	77,508	77,529	62
Undeveloped Dry Land	65,263	65,812	68,362	69,752	69,796	1,062
Developed Dry Land	22,242	22,485	23,703	24,308	24,314	498
Swamp	4,053	4,097	4,413	4,639	4,639	161
Inland Open Water	2,368	2,398	2,450	2,486	2,491	23
Regularly flooded Marsh	1,848	1,891	3,710	5,714	6,075	1,026
Estuarine Beach	1,051	1,059	1,311	1,474	1,518	106
Irregularly Flooded Marsh	853	997	3,928	6,959	7,036	1,799
Ocean Beach	783	784	934	1,193	1,229	117
Trans. Salt Marsh	658	675	1,393	2,380	2,504	471
Tidal Flat	434	450	1,611	3,480	3,832	933
Inland-Fresh Marsh	358	375	412	434	435	16
Tidal Swamp	141	149	307	410	416	71
Flooded Developed Dry Land	80	86	690	1,909	2,152	498
Inland Shore	48	48	48	48	48	-
Tidal-Fresh Marsh	24	26	38	40	40	3
Rocky Intertidal	1	1	1	1	1	0

Table 64. Uncertainty results for Suffolk West study area by land-cover category (2100)

Land cover Type	Min	5th Percentile (Low)	Mean	95th Percentile (High)	Max	Std. Dev.
Estuarine Open Water	157,830	157,964	164,416	170,753	171,142	3,702
Open Ocean	77,270	77,334	77,879	78,682	78,755	372
Undeveloped Dry Land	57,935	58,532	64,090	69,015	69,148	2,840
Developed Dry Land	19,021	19,317	21,758	24,030	24,097	1,305
Swamp	3,583	3,630	4,041	4,589	4,624	258
Regularly flooded Marsh	2,280	2,383	4,339	7,088	8,209	940
Inland Open Water	2,148	2,171	2,344	2,473	2,479	80
Trans. Salt Marsh	1,033	1,105	1,849	2,515	3,293	300
Ocean Beach	746	765	1,019	1,344	1,469	148
Estuarine Beach	541	580	954	1,319	1,423	179
Tidal Flat	386	453	2,048	3,136	3,389	589
Flooded Developed Dry Land	297	364	2,635	5,077	5,372	1,305
Inland-Fresh Marsh	297	302	354	426	430	37
Irregularly Flooded Marsh	111	120	1,446	6,379	6,720	1,693
Inland Shore	48	48	48	48	48	-
Tidal Swamp	30	32	141	376	390	94
Tidal-Fresh Marsh	21	21	32	40	40	8
Rocky Intertidal	0	0	1	1	1	0

Figure 73 suggests that while high and low marshes have fairly wide confidence intervals by 2100, the majority of predictions for these categories fall within a more narrow range (from 0 to 1500 acres for irregularly-flooded marshes and from 3500 to 4750 acres for regularly-flooded marshes).

Figure 73. Histograms for High and Low Marsh for Suffolk West Study Area in 2100



In Suffolk West it is interesting to note that initial conditions for marsh areas (2004 results) have higher uncertainty, as shown in Figure 74 and Figure 75. This is mostly due to the initial-condition elevations in this region: many high-marsh cells have elevations that are close to their low boundary. Therefore addition of an elevation error field has a good chance of moving the cell below this boundary and converting these cells to regularly flooded marshes. For other land-cover types this is not the case, as shown in Figure 76. Figure 75 also suggests that predicted changes over time of regularly flooded marsh are less sensitive to the different SLR scenarios and are instead dependent on other uncertain input variables.

Results maps indicate that the western half of Suffolk County is likely to be transformed by sea-level rise in the coming century. In the short term (by 2025), changes are less likely and those that are probable appear limited to marshes and coastal fringes (Figure 77). However, by 2100 the entire southern coast of western Suffolk County will undergo some type of habitat shift (including the marsh islands of Great South Bay, coastal areas of East Islip, East Mastic Beach, and the Carmans River Delta, Figure 78). As illustrated in Figure 79, changes on the south coast are likely to be losses of marsh to open water. On the north shore of this portion of the county, it is also likely that the habitat changes will result in marshes, as presented in Figure 80. Finally, there is a high likelihood that developed lands will be flooded by 2100, particularly on Fire Island (Figure 81). Appendix D presents additional uncertainty maps for western Suffolk County.

Figure 74. Time series for irregularly flooded marsh in Suffolk West

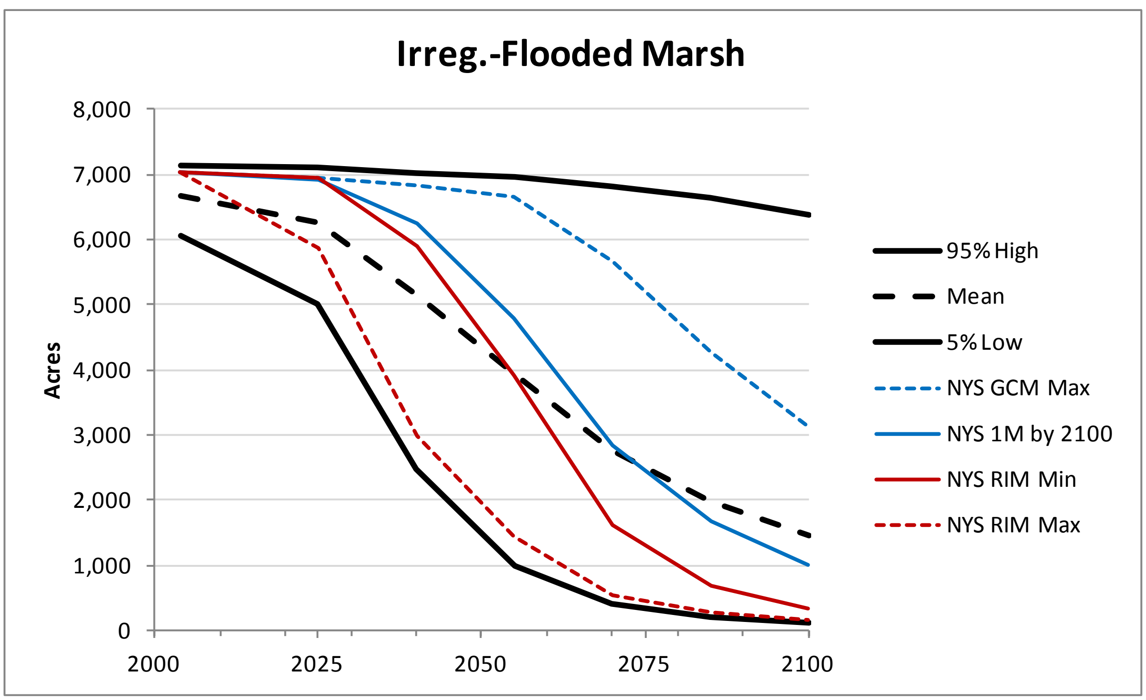


Figure 75. Time series for regularly flooded marsh in Suffolk West

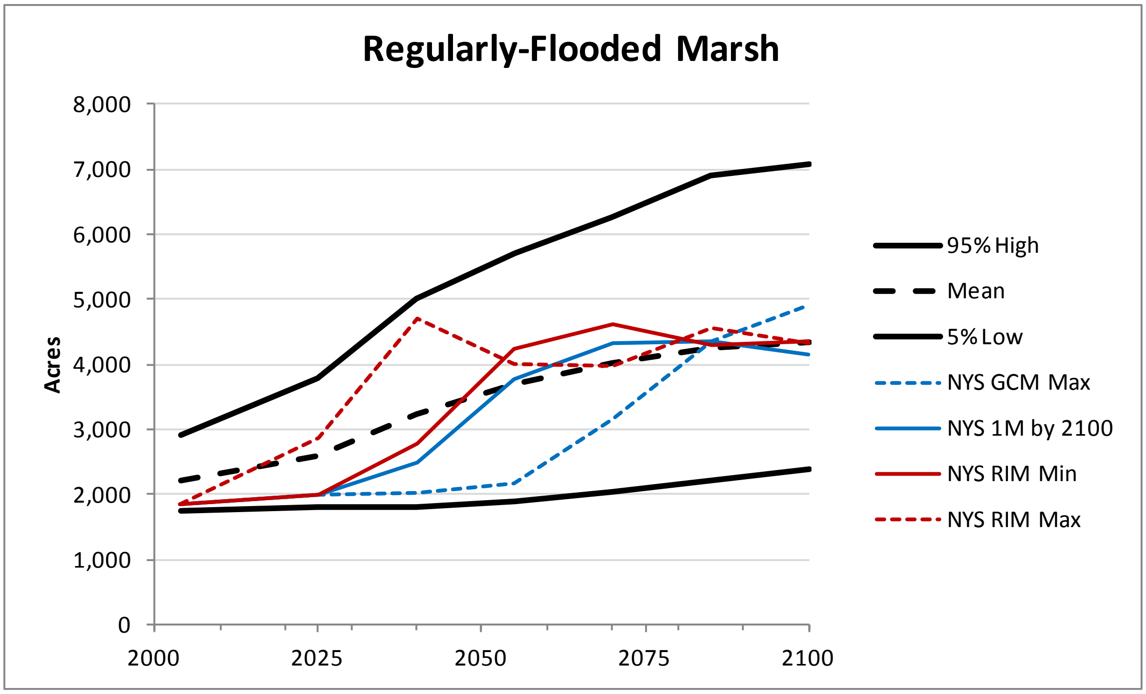


Figure 76. Time series for estuarine beach in Suffolk West

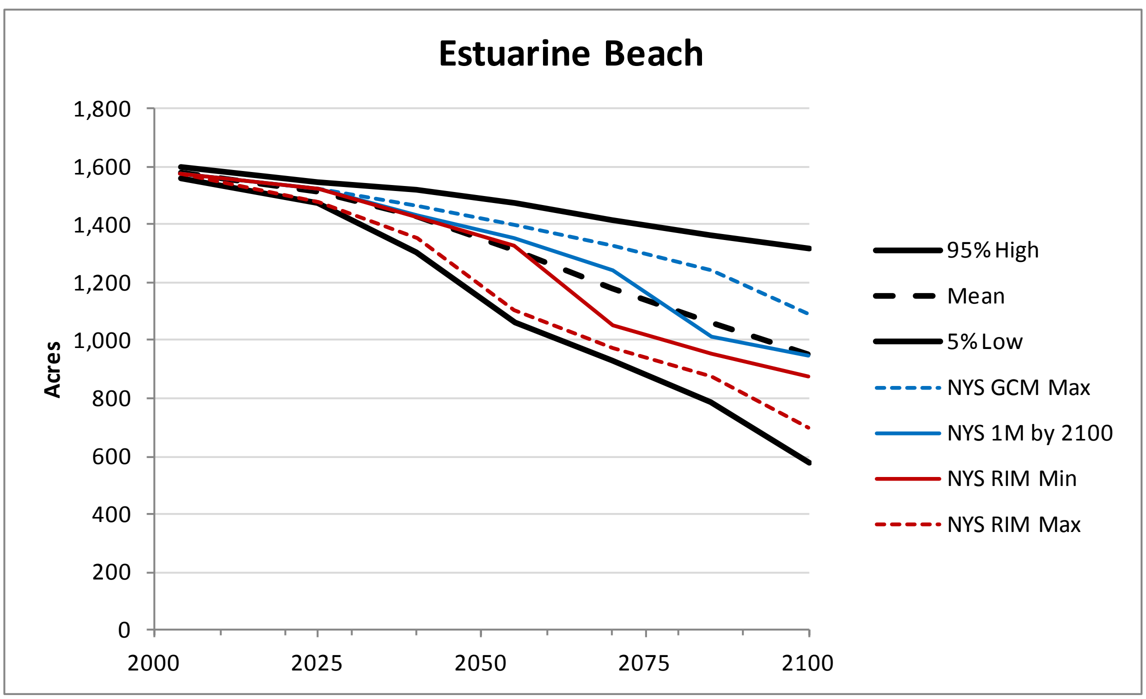


Figure 77. Suffolk West percent likelihood of habitat change by 2025

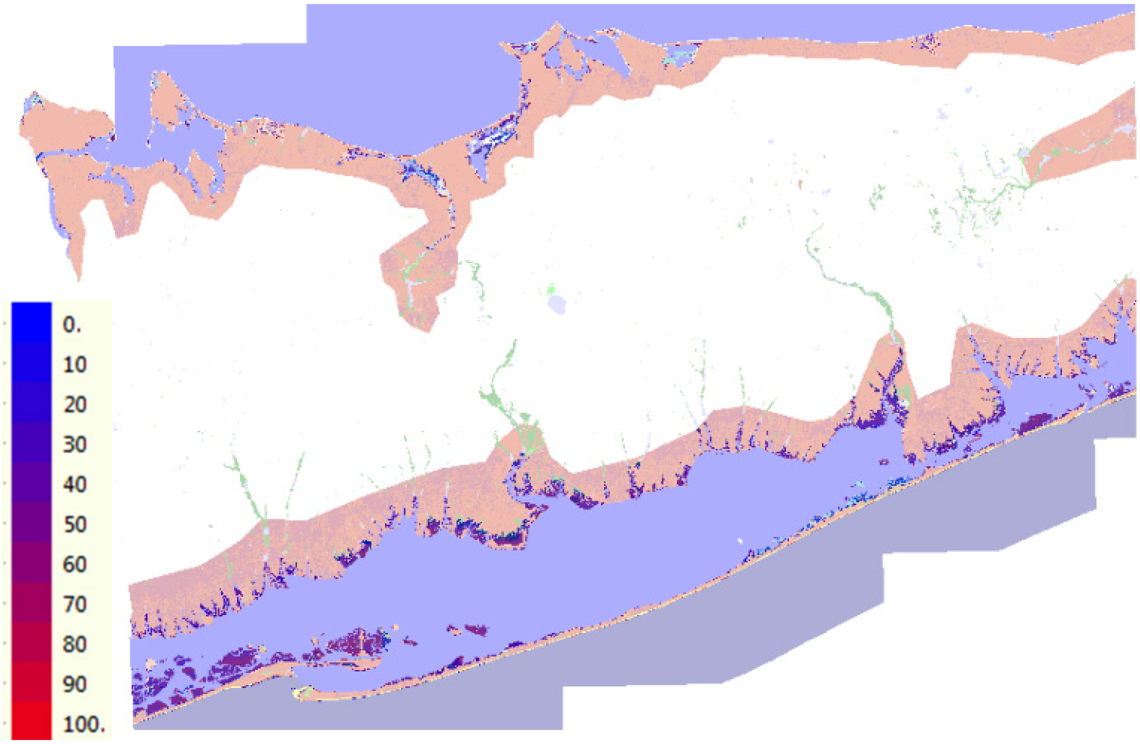


Figure 78. Suffolk West percent likelihood of habitat change by 2100

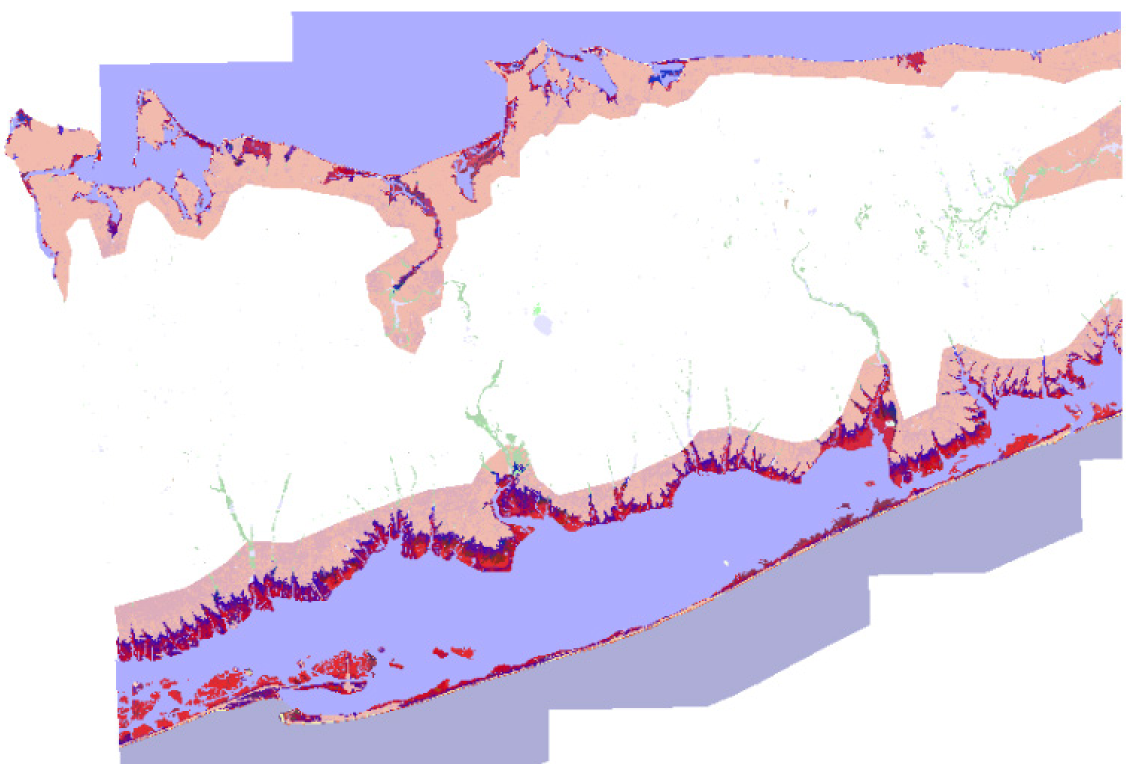


Figure 79. Suffolk West percent likelihood of land to open water by 2100

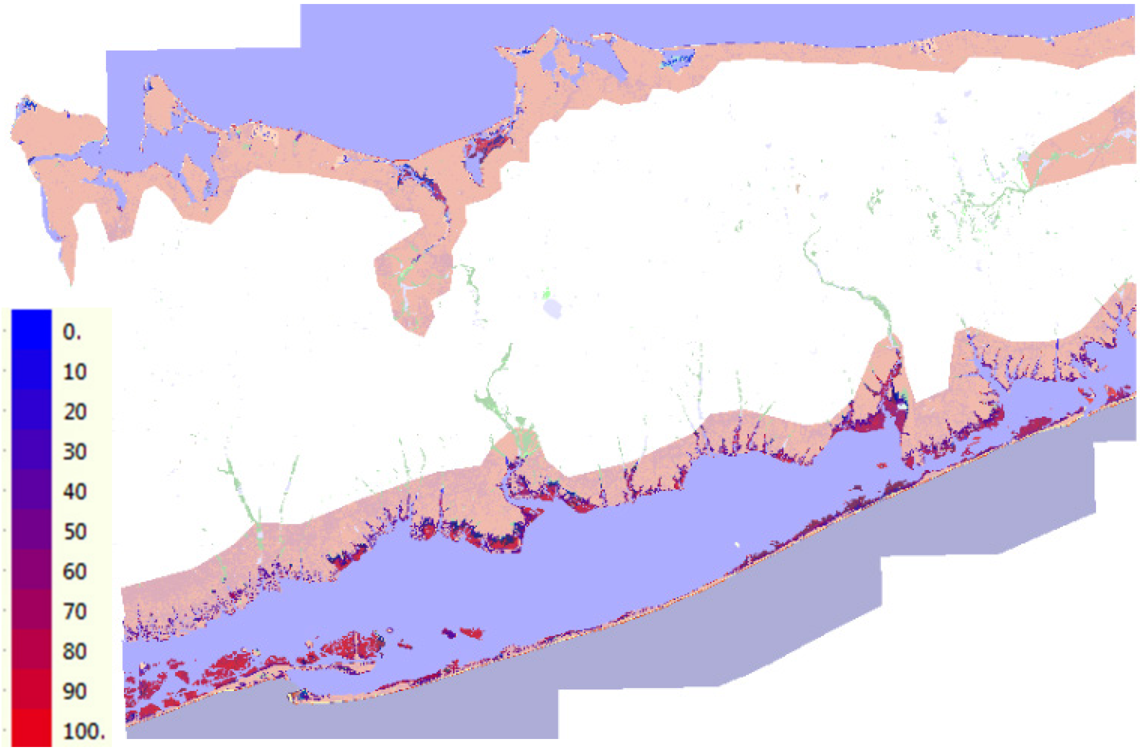


Figure 80. Suffolk West percent likelihood of coastal wetland by 2100

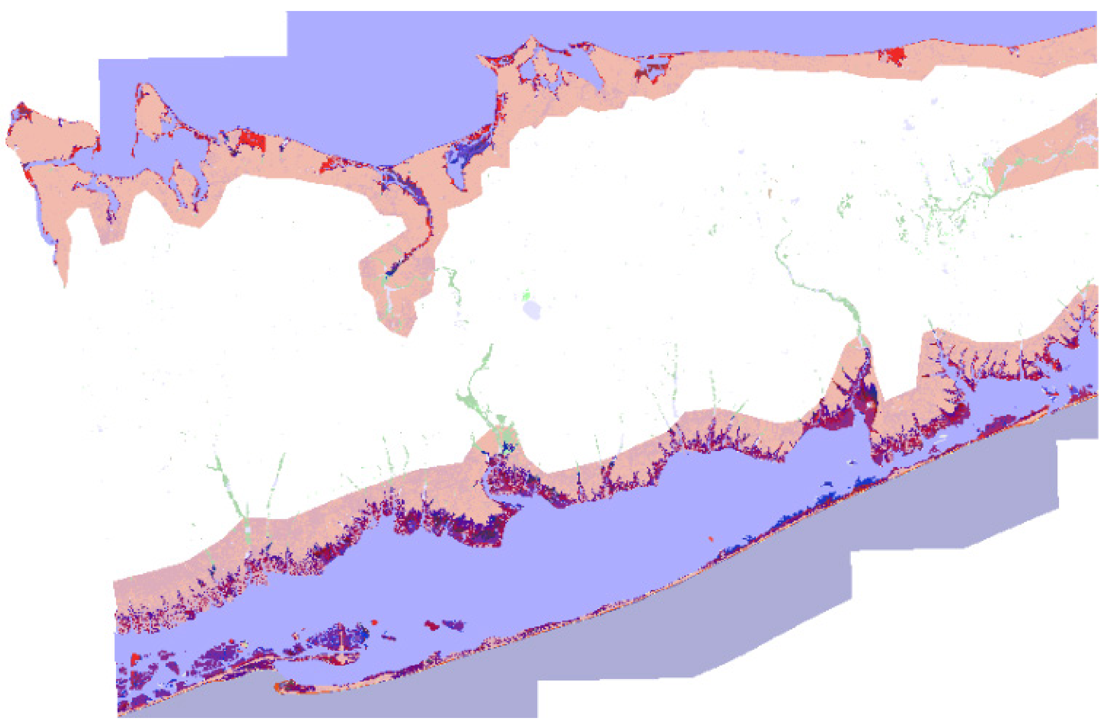
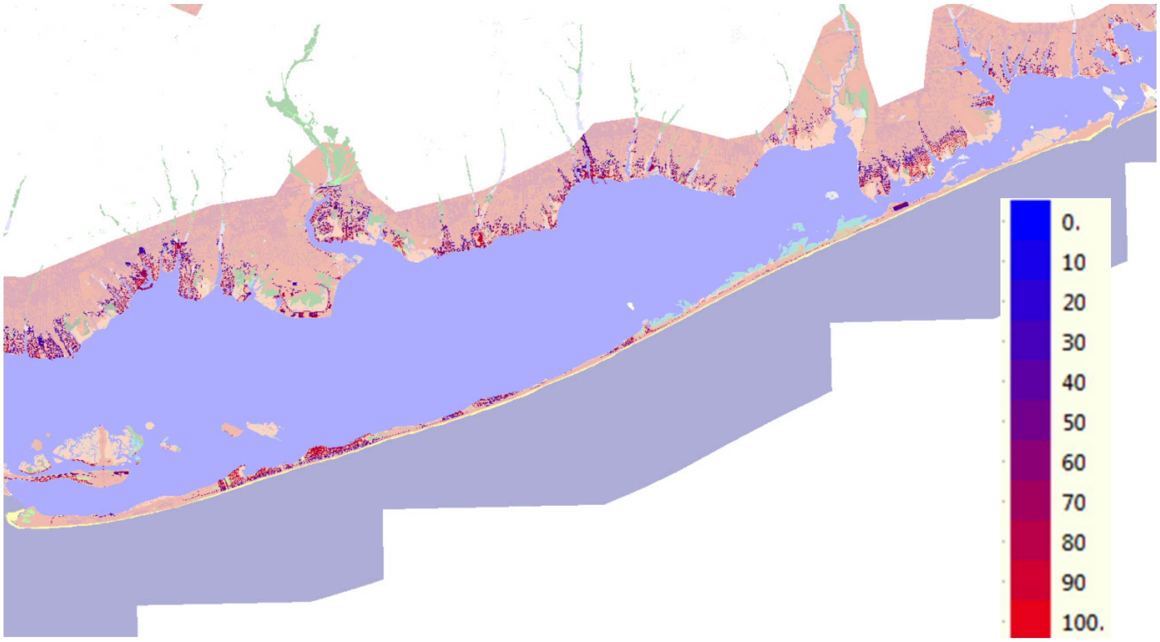


Figure 81. Suffolk West detail: Fire Island percent likelihood of flooded developed land by 2100



4.6 Suffolk East Uncertainty Analysis Results

Table 65 presents the confidence intervals for each land-cover category for Suffolk East by 2055. Dry land and high and low marshes have the widest confidence intervals in this location. Table 66 presents wider confidence intervals by 2100 and tidal-flats join the list of most-uncertain land-cover categories.

Table 65. Uncertainty results for Suffolk East study area by land-cover category (2055)

Land cover Type	Min	5th Percentile (Low)	Mean	95th Percentile (High)	Max	Std. Dev.
Open Ocean	229,386	229,481	229,899	230,154	230,166	155
Estuarine Open Water	180,037	180,113	180,698	181,467	181,527	327
Undeveloped Dry Land	137,734	137,928	140,641	142,287	142,287	1,130
Developed Dry Land	24,277	24,308	24,814	25,054	25,068	190
Swamp	2,135	2,140	2,287	2,354	2,357	55
Inland Open Water	1,764	1,774	1,926	1,978	1,984	47
Ocean Beach	1,462	1,463	1,672	2,033	2,046	145
Irregularly Flooded Marsh	1,042	1,210	3,190	4,443	4,448	921
Trans. Salt Marsh	925	950	1,741	3,017	3,404	536
Estuarine Beach	917	929	1,248	1,549	1,611	138
Regularly flooded Marsh	816	846	2,648	5,316	5,538	1,283
Inland-Fresh Marsh	274	313	372	419	433	30
Tidal Swamp	120	132	223	284	285	40
Tidal Flat	95	104	238	928	1,046	171
Flooded Developed Dry Land	78	92	333	838	869	190
Tidal-Fresh Marsh	53	55	86	97	97	11
Rocky Intertidal	8	9	20	32	34	6
Inland Shore	1	1	1	1	1	0
Ocean Flat	1	1	1	1	1	0

Table 66. Uncertainty results for Suffolk East study area by land-cover category (2100)

Land cover Type	Min	5th Percentile (Low)	Mean	95th Percentile (High)	Max	Std. Dev.
Open Ocean	229,580	229,773	230,507	231,400	231,408	348
Estuarine Open Water	180,440	180,454	183,325	190,139	190,310	2,554
Undeveloped Dry Land	128,050	129,209	135,597	141,072	141,195	3,193
Developed Dry Land	22,028	22,305	23,769	24,902	24,910	698
Trans. Salt Marsh	1,806	1,830	2,688	3,850	3,995	465
Swamp	1,488	1,564	2,010	2,327	2,327	196
Inland Open Water	1,423	1,441	1,666	1,955	1,959	145
Ocean Beach	1,362	1,374	1,632	2,047	2,063	164
Regularly flooded Marsh	1,059	1,308	5,739	8,006	8,034	1,680
Flooded Developed Dry Land	236	244	1,377	2,842	3,119	698
Estuarine Beach	212	220	692	1,322	1,388	266
Irregularly Flooded Marsh	111	128	1,346	4,251	4,392	1,198
Inland-Fresh Marsh	107	113	252	393	395	69
Tidal Flat	59	59	1,255	3,252	3,484	1,073
Tidal Swamp	19	24	111	261	265	64
Tidal-Fresh Marsh	13	13	64	97	97	28
Rocky Intertidal	2	2	6	19	22	5
Inland Shore	1	1	1	1	1	0
Ocean Flat	0	0	1	1	1	0

Figure 82 shows the wide range in predictions for low marshes in the Suffolk East study area. Below the RIM MAX SLR scenario, regularly flooded marsh acreages increase over time when high marshes and dry lands are converted to low marshes. Under the RIM Max SLR scenario, regularly flooded marsh predictions start to decline again as they become inundated and convert to tidal flats and open water. Figure 83 shows that for the transitional salt-marsh category in 2100, SLR is not the most important variable driving model uncertainty (all of the deterministic model results are quite similar and in the center of the confidence interval). For this category, accretion-rate and elevation-data uncertainty are likely driving the 2100 confidence interval rather than SLR.

Figure 82. Time series of regularly flooded marsh area coverage in Suffolk East

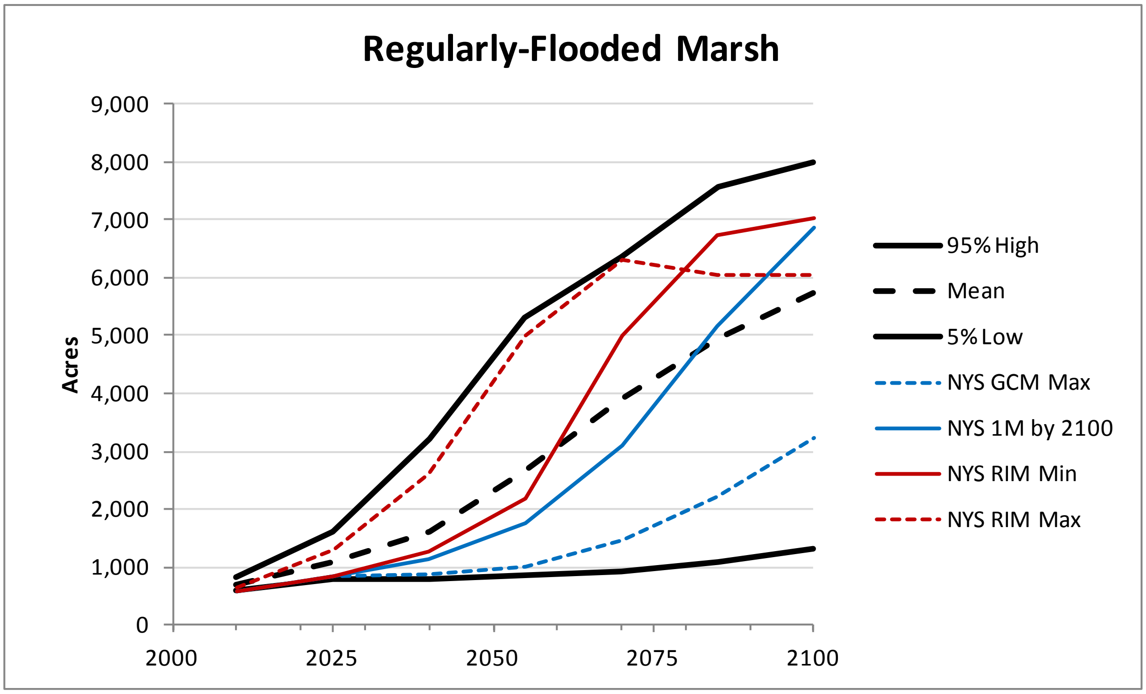
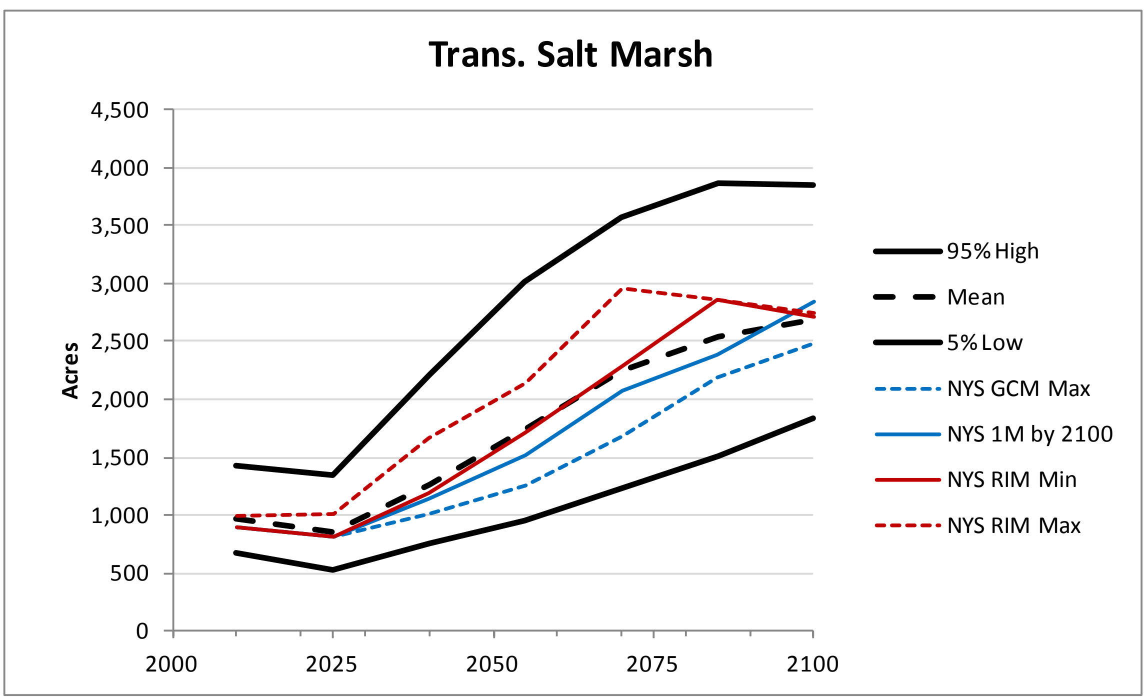


Figure 83. Time series of transitional salt marsh area coverage in Suffolk East



The maps presented in Figure 84 through Figure 88 illustrate that it is very likely that accelerated sea-level rise will affect the landscape in Eastern Suffolk County in the coming century. Although there is generally a low probability of habitat change between now and 2025, it is nearly certain that widespread habitat change will occur by 2100. Results of uncertainty analyses indicate it is more likely that there will be a shift to coastal wetlands (a category that includes beaches) rather than to open water. Of particular interest are that areas of Napeague, Greenport, and Long Beach Bay, shown in Figure 88, where it very likely that habitat shifts will occur. Appendix D presents the timeseries of percent likelihood of coastal marshes in eastern Suffolk County in the coming century.

Figure 84. Suffolk East percent likelihood of habitat change by 2025

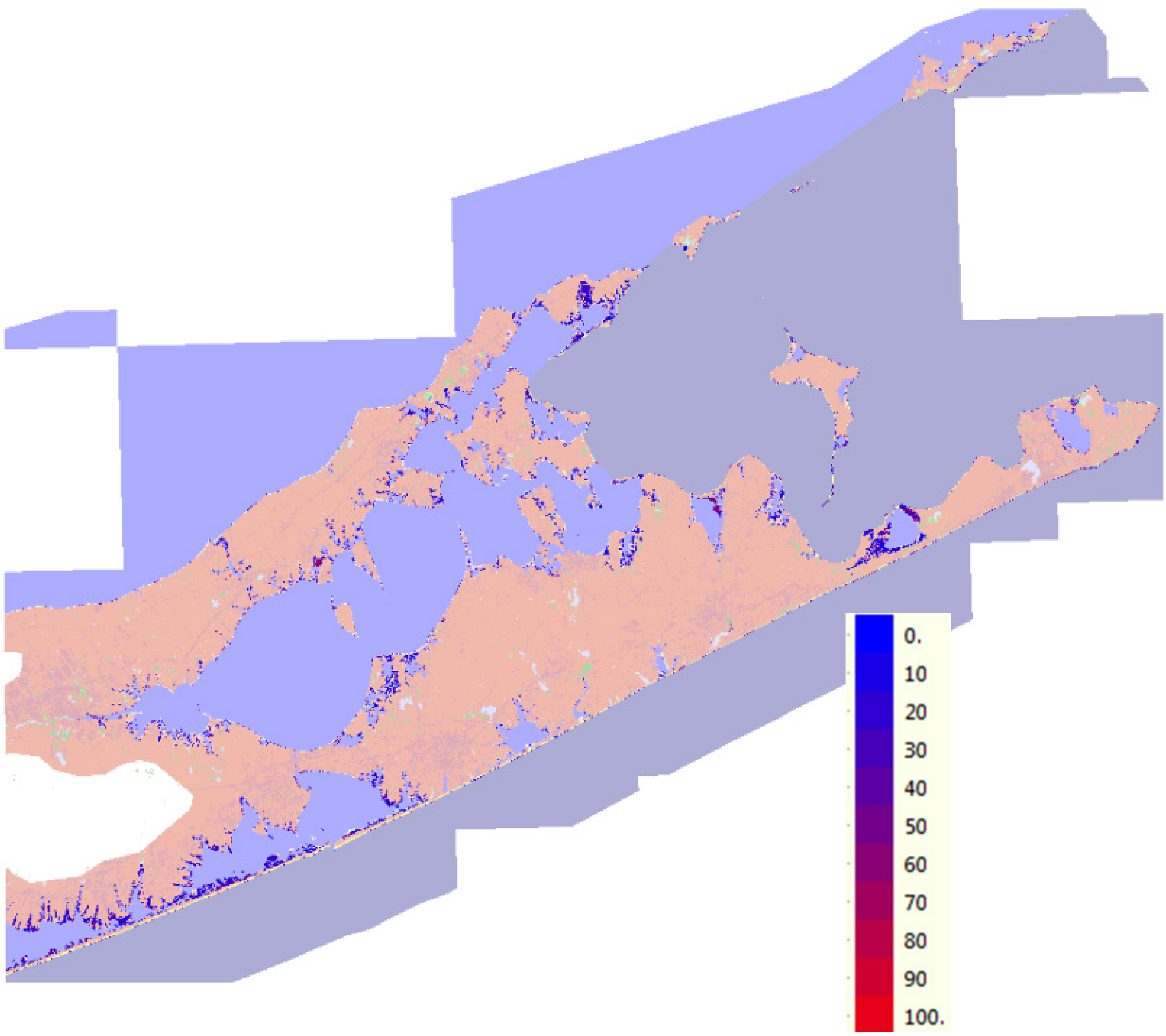


Figure 85. Suffolk East percent likelihood of habitat change by 2100

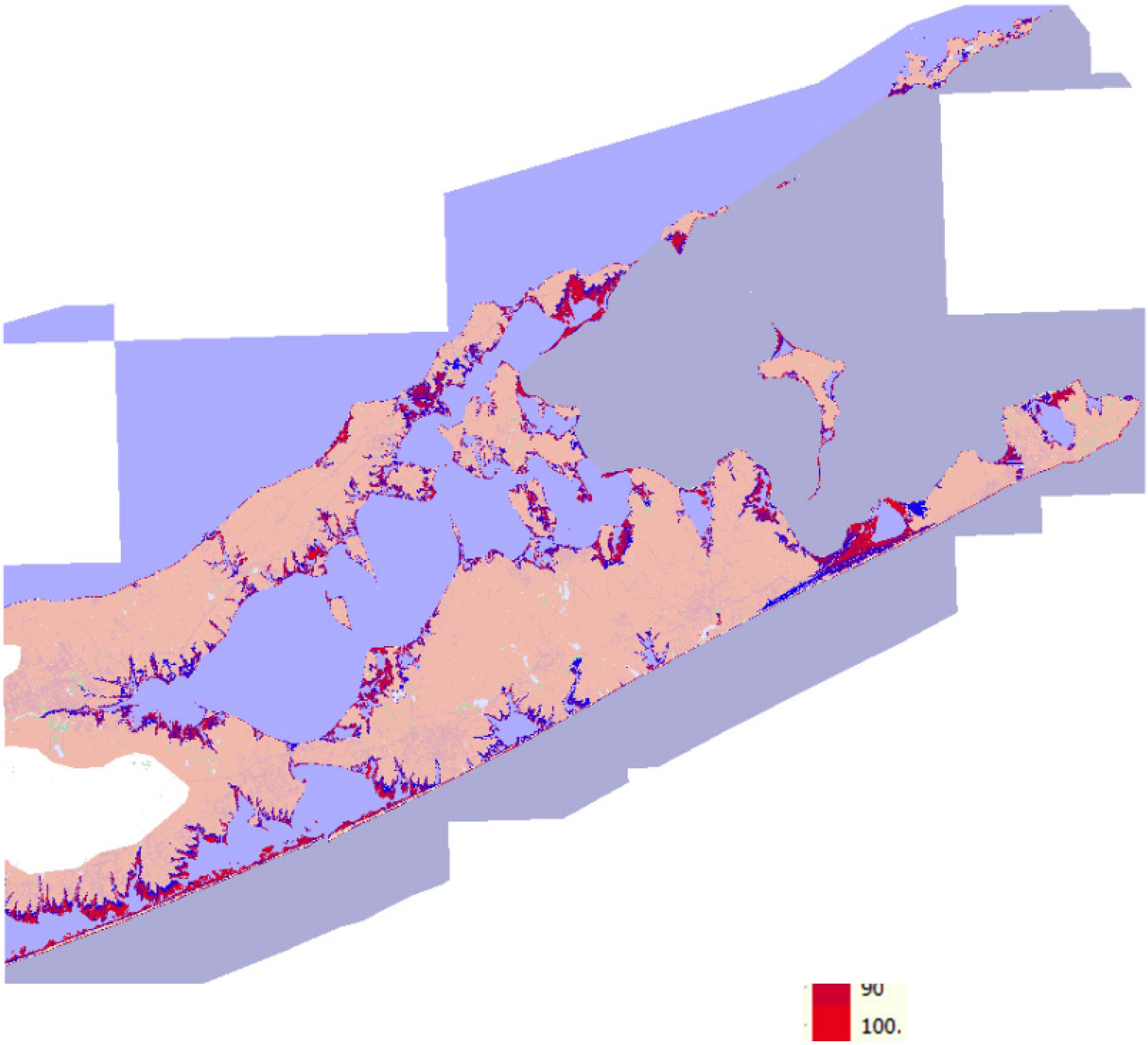


Figure 86. Suffolk East percent likelihood of land to open water by 2100

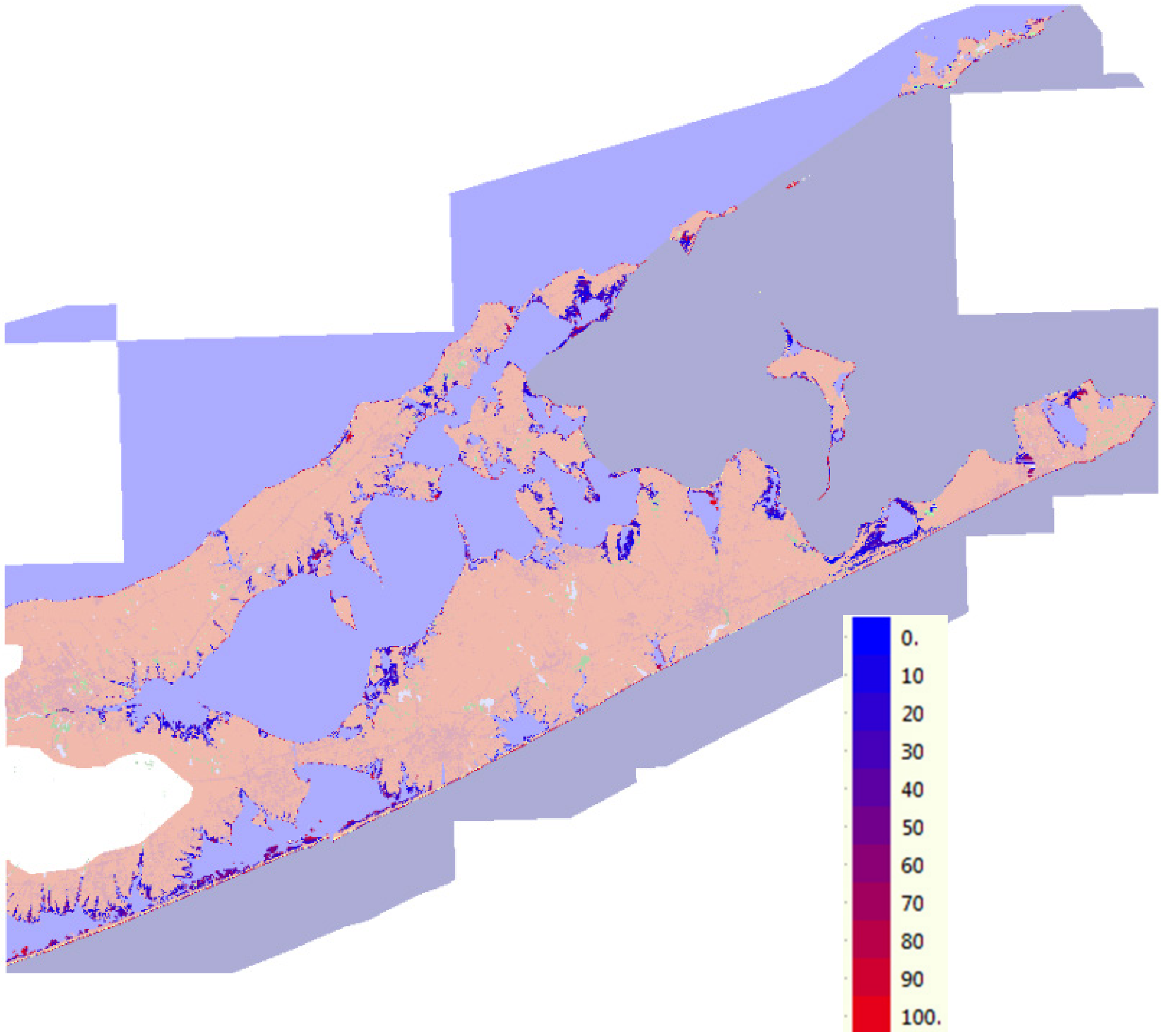


Figure 87. Suffolk East percent likelihood of coastal marsh by 2100

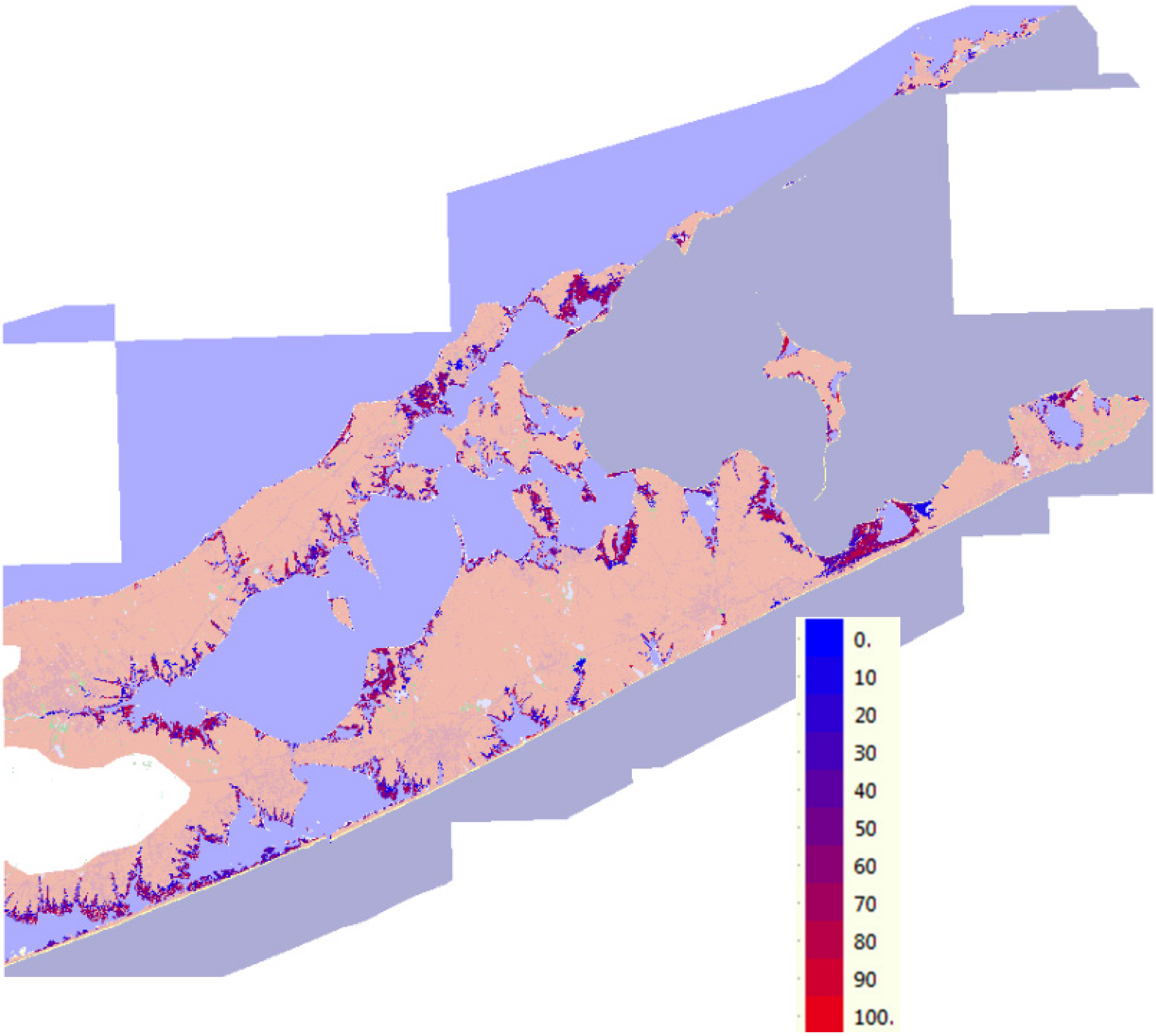
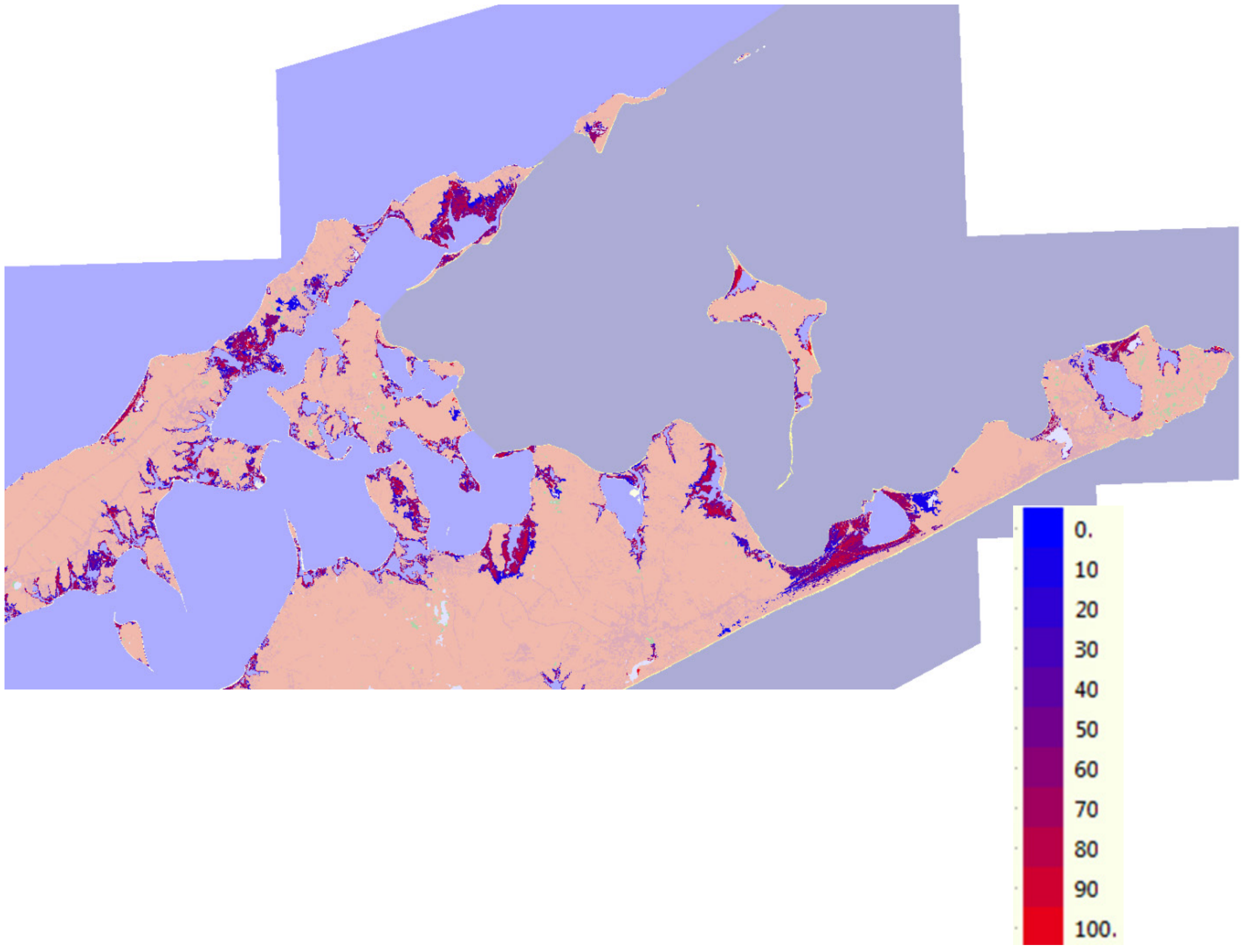


Figure 88. Suffolk East (detail) percent likelihood of coastal marsh by 2100



Appendix A: GIS Processing Details

A.1 Hydrologic Enforcement

"Hydrologic enforcement" is the process of defining water-flow pathways to determine where bridges and culverts contained in the DEM may be blocking hydrologic flow. Multiple steps were used to produce a hydro-enforced DEM for the full Hudson/NYC/Long Island project area. Technical details about this process follow here.

A.1.1 Project Boundary Derivation

For the Long Island and Hudson study areas, LiDAR data were reprocessed for locations at or below 5.5 m above mean tide level to limit the scope of data processed. (For New York City, the entire LiDAR data set was used.) A 25-ft cell resolution raster was downloaded from NOAA and used to derive the 5.5m above mean tide level project boundary line in Long Island. NOAA coastal files were downloaded, extracted, and re-projected from geographic to UTM coordinates.

A.1.2 Data Preparation

For the New York City study area, the NYC 1-ft DEM raster file was re-projected from NAD 1983 State Plane New York Long Island FIPS 3104 Feet to NAD83 UTM Zone 18N. The data were re-sampled from their native 1m to the project-specific 5m cell size using mean value. For the Long Island and Hudson study areas, NOAA coastal 1 m DEM raster files were downloaded, extracted, and merged to create a mosaic of raster tiles. The data were then re-sampled from 1-m to 5-m cell size, also using mean value. A combined 5-m mosaic of the NOAA and NYC rasters was created to cover the entire project area.

A.1.3 Creation of Breaklines for Hydrologic Enforcement

An overview of the breakline creation process is as follows:

1. Determine locations where additional breaklines are needed.
2. Create polygons across culverts and bridges left in the elevation data.
3. Create a downstream flow surface from each polygon.

The New York State Accident Location Information System (ALIS) road centerline file and the National Hydrography Dataset (NHD) were intersected together to create a point feature class of all possible culvert/bridge locations, resulting in approximately 975 locations identified in the full project area. Each of these intersection locations was visually checked using the LiDAR data and NYS orthoimagery as reference to see if a bridge or culvert existed in the area. If a bridge/culvert did exist, a polygon at least 5m wide (one cell size in the raster) was digitized where the bridge/culvert crossed the water feature.

An artificial flow path (GIS line feature) was drawn through the polygon in a downstream direction. The endpoints of the artificial path were snapped to any lakes/ponds or tidal water polygon breaklines already created from the NOAA data. The elevation values for the NOAA breakline data were conflated to the end points of artificial path. Where no NOAA breaklines existed, elevation values were conflated to the artificial path end points from the DEMs. Using a custom scripted tool in ArcGIS, downstream flow was enforced, ensuring the start point of each artificial path is the same elevation or higher than the endpoint. Vertices were edited as needed to ensure downstream flow direction.

With the end points of the artificial path conforming to the downstream constraint, elevation values were interpolated along the path length and then conflated to the orthogonal edge of the breakline polygon. First the vertices of all polygons and of each artificial path were densified to 5m. Then the elevation values for the interior vertices for each artificial path were computed using a linear algorithm using the start point and end point elevations. If the start point and end point have the same elevation value, then all interior vertices will have the same elevation value. Using the LP360 Flatten River Polygon tool, the elevation values of each artificial path were conflated to each vertex of the polygons that were digitized at each bridge/culvert location, resulting in 3D polygon breaklines that cut through every culvert/bridge location in the study area.

A.1.4 DEM Hydrologic Enforcement

The DEM 5-m mosaic raster was converted to a multipoint feature class. Using the multipoint feature class and breaklines previously described, an ESRI terrain dataset was created enforcing the breaklines in the terrain. The terrain dataset was then converted to a raster DEM with a 5-m cell resolution. The breakline polygon areas were reviewed in a final quality control step to ensure they were represented in the final DEM.

A.2 Wetland Layer Processing

The preparation for all wetland layers required the following steps:

- The projection for each data source was checked and converted to NAD83 UTM Zone 18 north if required.
- ESRI's ArcGIS Union tool was used to join each wetland data layer in order of priority.
- The attributes for the priority layer were updated with each subsequent joining operation.
- This process was repeated until all the data sources were combined in the order of priority.
- ESRI's Dissolve tool was used to merge adjacent polygons with the same attribute.
- The wetland polygons for individual project areas were merged together into one single data set representing the full extent of the project using ESRI's Merge tool.
- ESRI's Conversion tool was used to convert the polygon data to raster format with 5-m cell resolution.
- Each project area was then extracted from the full extent raster using ESRI's Spatial Analyst tool "Extract by Mask."

Appendix B: Tide Range Maps

Figure B-1. Tide Range Data for Hudson Study Area (GT or Great Diurnal Ranges Shown)

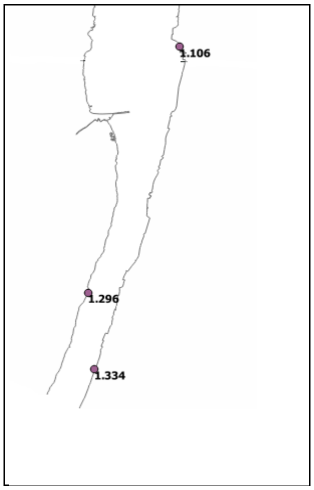


Figure B-2. Tide Range Data (GTs) for New York City and Staten Island Study Area

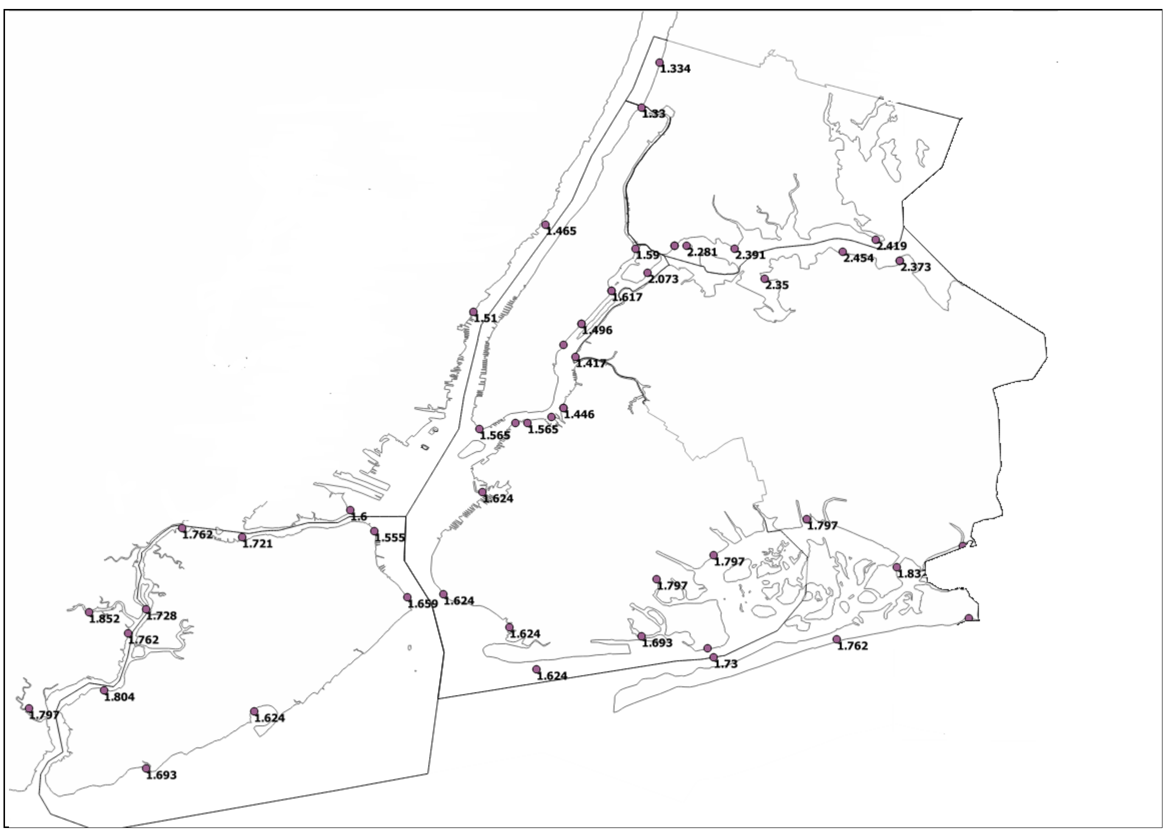


Figure B-3. Tide Range Data (GTs) for Nassau Area

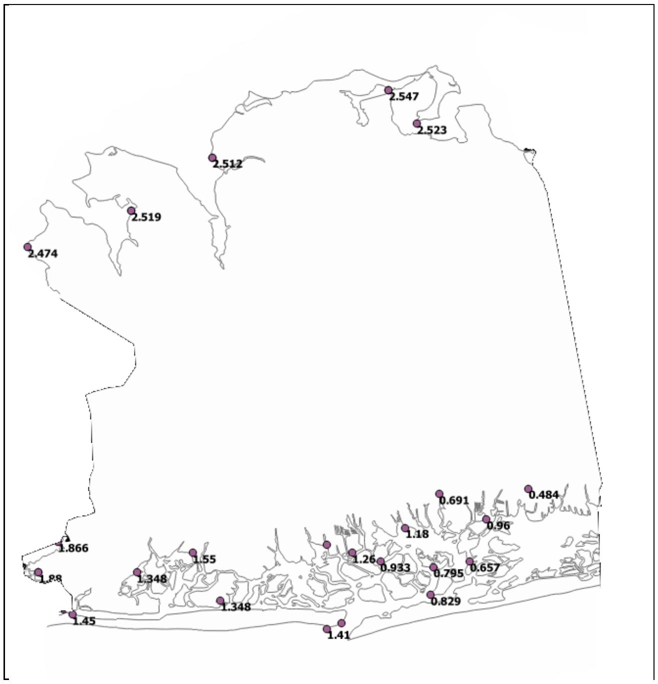


Figure B-4. Tide Range Data (GTs) for Suffolk West Study Area

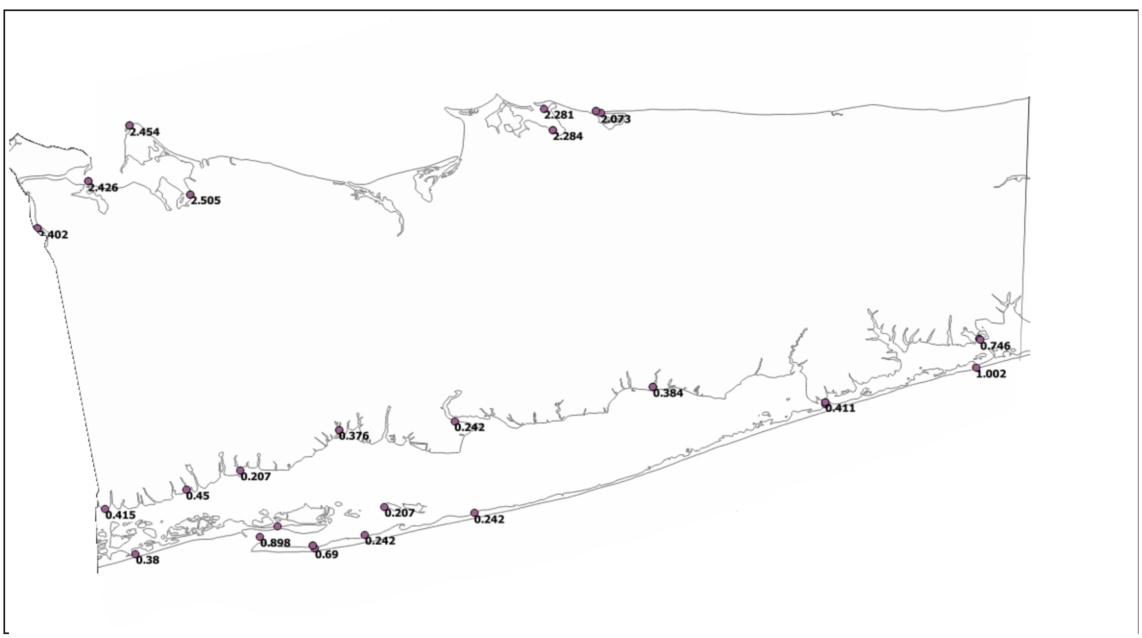
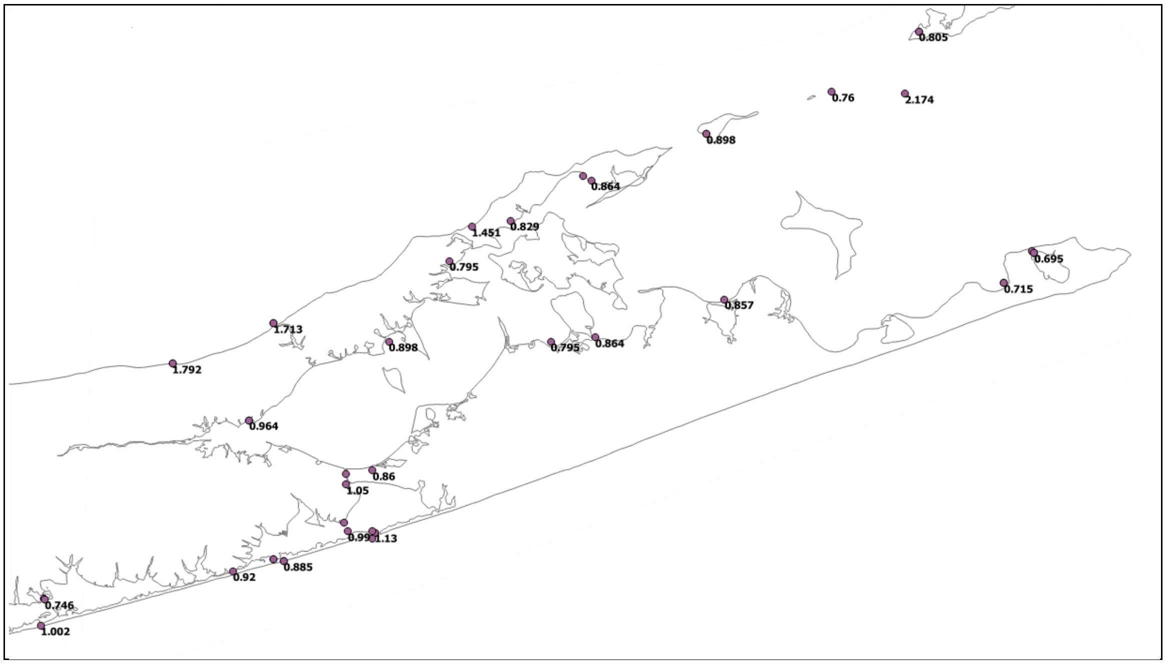


Figure B-5. Tide Range Data (GTs) for Suffolk East Study Area



Appendix C: Comprehensive Tables of Input Parameters

Study Area	**Suffolk E**	**Suffolk E**	**Suffolk E**	**Suffolk E**	**Suffolk E**	**Suffolk E**	**Suffolk E**	**Suffolk E**
Subsite Number	Global	SubSite 1	SubSite 2	SubSite 3	SubSite 4	SubSite 5	SubSite 6	SubSite 7
Description		Northwest	Northeast	Open Ocean	New Suffolk	Orient Point inside	Lake Montauk	Hampton Bays
NWI Photo Date (YYYY)	2004	2004	2004	2004	2004	2004	2004	2004
DEM Date (YYYY)	2012	2012	2012	2012	2012	2012	2012	2012
Direction Offshore [n,s,e,w]	East	North	North	South	East	East	East	North
GT Great Diurnal Tide Range (m)	0.87	1.79	1.45	1.17	0.44	0.72	0.7	0.87
Salt Elev. (m above MTL)	0.75	1.35	1.13	0.94	0.46	0.65	0.63	0.64
Marsh Erosion (horz. m /yr)	1	1	1	1	1	1	1	1
Swamp Erosion (horz. m /yr)	1	1	1	1	1	1	1	1
T.Flat Erosion (horz. m /yr)	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44
Tidal-Fresh Marsh Accr (mm/yr)	5	5	5	5	5	5	5	5
Inland-Fresh Marsh Accr (mm/yr)	1	1	1	1	1	1	1	1
Tidal Swamp Accr (mm/yr)	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Swamp Accretion (mm/yr)	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
Beach Sed. Rate (mm/yr)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Reg Flood Max. Accr. (mm/year)	9.79	4.5	4.5	4.4	9.79	9.79	9.79	4.4
Reg Flood Min. Accr. (mm/year)	0.94	0.52	0.52	0.58	0.94	0.94	0.94	0.58
Reg Flood Elev a (mm/(year HTU^3))	-2.7333	0.9119	0.9119	0.1137	-2.7333	-2.7333	-2.7333	0.1137
Reg Flood Elev b (mm/(year HTU^2))	-3.4678	-1.8639	-1.8639	-1.9795	-3.4678	-3.4678	-3.4678	-1.9795
Reg Flood Elev c (mm/(year*HTU))	0.7482	-2.0182	-2.0182	-0.8914	0.7482	0.7482	0.7482	-0.8914
Reg Flood Elev d (mm/year)	9.7541	4.0515	4.0515	4.3035	9.7541	9.7541	9.7541	4.3035
Irreg Flood Max. Accr. (mm/year)	4.23	4.23	4.23	4.23	4.23	4.23	4.23	4.23
Irreg Flood Min. Accr. (mm/year)	4.06	4.06	4.06	4.06	4.06	4.06	4.06	4.06
Irreg Flood Elev c (mm/(year*HTU))	-0.12	-0.12	-0.12	-0.12	-0.12	-0.12	-0.12	-0.12
Irreg Flood Elev d (mm/year)	4.29	4.29	4.29	4.29	4.29	4.29	4.29	4.29

Study Area	Suffolk E	Suffolk E	Suffolk E	Suffolk E	Suffolk E	Suffolk W	Suffolk W	Suffolk W
Subsite Number	SubSite 8	SubSite 9	Sub.10	SubSite 11	SubSite 12	Global	SubSite 1	SubSite 2
Description	Westhampton Beach	South	Quogue	Fishers Island East	Fishers Island West	Great South Bay	North West	North East
NWI Photo Date (YYYY)	2004	2004	2004	2010	2010	2004	2004	2004
DEM Date (YYYY)	2012	2012	2012	2012	2012	2012	2012	2012
Direction Offshore [n,s,e,w]	North	South	South	East	East	South	North	North
GT Great Diurnal Tide Range (m)	0.8	0.87	0.87	0.87	0.87	0.32	2.42	2.2
Salt Elev. (m above MTL)	0.55	0.75	0.6	0.75	0.75	0.27	1.51	1.38
Marsh Erosion (horz. m /yr)	1	1	1	1	1	1	1	1
Swamp Erosion (horz. m /yr)	1	1	1	1	1	1	1	1
T.Flat Erosion (horz. m /yr)	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44
Tidal-Fresh Marsh Accr (mm/yr)	5	5	5	5	5	5	5	5
Inland-Fresh Marsh Accr (mm/yr)	1	1	1	1	1	1	1	1
Tidal Swamp Accr (mm/yr)	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Swamp Accretion (mm/yr)	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
Beach Sed. Rate (mm/yr)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Reg Flood Max. Accr. (mm/year)	4.4	4.4	9.79	9.79	9.79	4.4	4.5	4.5
Reg Flood Min. Accr. (mm/year)	0.58	0.58	0.94	0.94	0.94	0.58	0.52	0.52
Reg Flood Elev a (mm/(year HTU^3))	0.1137	0.1137	-2.7333	-2.7333	-2.7333	0.1137	0.9119	0.9119
Reg Flood Elev b (mm/(year HTU^2))	-1.9795	-1.9795	-3.4678	-3.4678	-3.4678	-1.9795	-1.8639	-1.8639
Reg Flood Elev c (mm/(year*HTU))	-0.8914	-0.8914	0.7482	0.7482	0.7482	-0.8914	-2.0182	-2.0182
Reg Flood Elev d (mm/year)	4.3035	4.3035	9.7541	9.7541	9.7541	4.3035	4.0515	4.0515
Irreg Flood Max. Accr. (mm/year)	4.23	4.23	4.23	4.23	4.23	4.23	4.23	4.23
Irreg Flood Min. Accr. (mm/year)	4.06	4.06	4.06	4.06	4.06	4.06	4.06	4.06
Irreg Flood Elev c (mm/(year*HTU))	-0.12	-0.12	-0.12	-0.12	-0.12	-0.12	-0.12	-0.12
Irreg Flood Elev d (mm/year)	4.29	4.29	4.29	4.29	4.29	4.29	4.29	4.29

Study Area	Suffolk W	Suffolk W	Suffolk W	Nassau	Nassau	Nassau	Nassau	Nassau
Subsite Number	SubSite 3	SubSite 4	SubSite 5	Global	SubSite 1	SubSite 2	SubSite 3	SubSite 4
Description	Open Ocean	Moriches	Narrow Bay		North Nassau	East Bay	Oyster Bay	Hewlett/Baldwin
NWI Photo Date (YYYY)	2004	2004	2004	2004	2004	2004	2004	2004
DEM Date (YYYY)	2012	2012	2012	2012	2012	2012	2012	2012
Direction Offshore [n,s,e,w]	South	South	South	South	North	South	South	South
GT Great Diurnal Tide Range (m)	0.8	0.77	0.43	1.41	2.47	0.86	0.45	1.34
Salt Elev. (m above MTL)	0.7	0.61	0.46	1.103	1.54	0.66	0.47	0.85
Marsh Erosion (horz. m /yr)	1	1	1	1	1	1	1	1
Swamp Erosion (horz. m /yr)	1	1	1	1	1	1	1	1
T.Flat Erosion (horz. m /yr)	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44
Tidal-Fresh Marsh Accr (mm/yr)	5	5	5	5	5	5	5	5
Inland-Fresh Marsh Accr (mm/yr)	1	1	1	1	1	1	1	1
Tidal Swamp Accr (mm/yr)	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Swamp Accretion (mm/yr)	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
Beach Sed. Rate (mm/yr)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Reg Flood Max. Accr. (mm/year)	4.4	4.4	4.4	4.4	4.5	4.4	4.4	4.4
Reg Flood Min. Accr. (mm/year)	0.58	0.58	0.58	0.58	0.52	0.58	0.58	0.58
Reg Flood Elev a (mm/(year HTU^3))	0.1137	0.1137	0.1137	0.1137	0.9119	0.1137	0.1137	0.1137
Reg Flood Elev b (mm/(year HTU^2))	-1.9795	-1.9795	-1.9795	-1.9795	-1.8639	-1.9795	-1.9795	-1.9795
Reg Flood Elev c (mm/(year*HTU))	-0.8914	-0.8914	-0.8914	-0.8914	-2.0182	-0.8914	-0.8914	-0.8914
Reg Flood Elev d (mm/year)	4.3035	4.3035	4.3035	4.3035	4.0515	4.3035	4.3035	4.3035
Irreg Flood Max. Accr. (mm/year)	4.23	4.23	4.23	4.23	4.23	4.23	4.23	4.23
Irreg Flood Min. Accr. (mm/year)	4.06	4.06	4.06	4.06	4.06	4.06	4.06	4.06
Irreg Flood Elev c (mm/(year*HTU))	-0.12	-0.12	-0.12	-0.12	-0.12	-0.12	-0.12	-0.12
Irreg Flood Elev d (mm/year)	4.29	4.29	4.29	4.29	4.29	4.29	4.29	4.29

Study Area	**Nassau**	**Nassau**	**Nassau**	**Nassau**	**Nassau**	**NY City**	**NY City**	**NY City**
Subsite Number	SubSite 5	SubSite 6	SubS. 7	SubSite 8	SubSite 9	Global	SubSite 1	SubSite 2
Description	Grass Hassock	North Nassau - 84 NWI	Frost Creek	SVS Woodmere	Woodmere behind tidegate		Staten Island West	Entrance Jamaica Bay
NWI Photo Date (YYYY)	2004	1984	2004	2004	2004	2002	2002	2002
DEM Date (YYYY)	2012	2012	2012	2012	2012	2010	2012	2012
Direction Offshore [n,s,e,w]	South	North	North	South	South	East	East	West
GT Great Diurnal Tide Range (m)	1.87	2.47	1.1	0.87	0.1	1.61	1.77	1.72
Salt Elev. (m above MTL)	1.18	1.54	0.89	0.75	0.13	1.2	1.23	1.31
Marsh Erosion (horz. m /yr)	1	1	1	1	1	1	1	1
Swamp Erosion (horz. m /yr)	1	1	1	1	1	1	1	1
T.Flat Erosion (horz. m /yr)	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44
Tidal-Fresh Marsh Accr (mm/yr)	5	5	5	5	5	5	5	5
Inland-Fresh Marsh Accr (mm/yr)	1	1	1	1	1	1	1	1
Tidal Swamp Accr (mm/yr)	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Swamp Accretion (mm/yr)	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
Beach Sed. Rate (mm/yr)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Reg Flood Max. Accr. (mm/year)	4.4	4.5	4.5	4.4	4.4	4.51	4.51	4.4
Reg Flood Min. Accr. (mm/year)	0.58	0.52	0.52	0.58	0.58	0.6	0.6	0.58
Reg Flood Elev a (mm/(year HTU^3))	0.1137	0.9119	0.9119	0.1137	0.1137	0.207	0.207	0.1137
Reg Flood Elev b (mm/(year HTU^2))	-1.9795	-1.8639	-1.8639	-1.9795	-1.9795	-1.9777	-1.9777	-1.9795
Reg Flood Elev c (mm/(year*HTU))	-0.8914	-2.0182	-2.0182	-0.8914	-0.8914	-1.0617	-1.0617	-0.8914
Reg Flood Elev d (mm/year)	4.3035	4.0515	4.0515	4.3035	4.3035	4.3679	4.3679	4.3035
Irreg Flood Max. Accr. (mm/year)	4.23	4.23	4.23	4.23	4.23	4.23	4.23	4.23
Irreg Flood Min. Accr. (mm/year)	4.06	4.06	4.06	4.06	4.06	4.06	4.06	4.06
Irreg Flood Elev c (mm/(year*HTU))	-0.12	-0.12	-0.12	-0.12	-0.12	-0.12	-0.12	-0.12
Irreg Flood Elev d (mm/year)	4.29	4.29	4.29	4.29	4.29	4.29	4.29	4.29

Study Area	NY City	NY City	NY City	NY City	NY City	NY City	NY City
Subsite Number	SubSite 3	SubSite 4	SubSite 5	SubSite 6	SubSite 7	SubSite 8	SubSite 9
Description	Jamaica Bay	Head of Bay	Lower Bay	Upper Bay	Lower Hudson	Upper Hudson	Lower East River
NWI Photo Date (YYYY)	2008	2002	2002	2002	2002	2002	2002
DEM Date (YYYY)	2012	2012	2012	2012	2012	2012	2012
Direction Offshore [n,s,e,w]	West	West	South	South	South	South	South
GT Great Diurnal Tide Range (m)	1.79	1.86	1.64	1.58	1.49	1.32	1.47
Salt Elev. (m above MTL)	1.12	1.14	1.26	1.22	1.14	1.04	1.14
Marsh Erosion (horz. m /yr)	1	1	1	1	1	1	1
Swamp Erosion (horz. m /yr)	1	1	1	1	1	1	1
T.Flat Erosion (horz. m /yr)	0.44	0.44	0.44	0.44	0.44	0.44	0.44
Tidal-Fresh Marsh Accr (mm/yr)	5	5	5	5	5	5	5
Inland-Fresh Marsh Accr (mm/yr)	1	1	1	1	1	1	1
Tidal Swamp Accr (mm/yr)	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Swamp Accretion (mm/yr)	1.6	1.6	1.6	1.6	1.6	1.6	1.6
Beach Sed. Rate (mm/yr)	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Reg Flood Max. Accr. (mm/year)	4.4	4.4	4.51	4.51	10.9082	10.9082	10.9082
Reg Flood Min. Accr. (mm/year)	0.58	0.58	0.6	0.6	1.5153	1.5153	1.5153
Reg Flood Elev a (mm/(year HTU^3))	0.1137	0.1137	0.207	0.207	4.8329	4.8329	4.8329
Reg Flood Elev b (mm/(year HTU^2))	-1.9795	-1.9795	-1.9777	-1.9777	-10.072	-10.072	-10.072
Reg Flood Elev c (mm/(year*HTU))	-0.8914	-0.8914	-1.0617	-1.0617	-2.5711	-2.5711	-2.5711
Reg Flood Elev d (mm/year)	4.3035	4.3035	4.3679	4.3679	10.753	10.753	10.753
Irreg Flood Max. Accr. (mm/year)	4.23	4.23	4.23	4.23	4.26	4.23	4.23
Irreg Flood Min. Accr. (mm/year)	4.06	4.06	4.06	4.06	4.06	4.06	4.06
Irreg Flood Elev c (mm/(year*HTU))	-0.12	-0.12	-0.12	-0.12	-0.12	-0.12	-0.12
Irreg Flood Elev d (mm/year)	4.29	4.29	4.29	4.29	4.29	4.29	4.29

Study Area	NY City	NY City	NY City	NY City	NY City	NY City	NY City	NY City
Subsite Number	Sub. 10	SubSite 11	SubSite 12	SubSite 13	SubSite 14	SubSite 15	SubSite 16	SubSite 17
Description	Upper East River	La Guardia	Hell Gate	Little Neck Bay	East Rockaway Inlet	Mott Creek	Kissam Avenue	LI South
NWI Photo Date (YYYY)	2002	2002	2002	2002	2002	2002	2002	2002
DEM Date (YYYY)	2012	2012	2012	2012	2012	2012	2012	2012
Direction Offshore [n,s,e,w]	North	East	East	North	West	East	East	South
GT Great Diurnal Tide Range (m)	1.6	2.34	2.11	2.45	1.43	0.1	1.5	1.64
Salt Elev. (m above MTL)	1.23	1.72	1.56	1.79	1.12	0.13	1.06	1.26
Marsh Erosion (horz. m /yr)	1	1	1	1	1	1	1	1
Swamp Erosion (horz. m /yr)	1	1	1	1	1	1	1	1
T.Flat Erosion (horz. m /yr)	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44
Tidal-Fresh Marsh Accr (mm/yr)	5	5	5	5	5	5	5	5
Inland-Fresh Marsh Accr (mm/yr)	1	1	1	1	1	1	1	1
Tidal Swamp Accr (mm/yr)	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Swamp Accretion (mm/yr)	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
Beach Sed. Rate (mm/yr)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Reg Flood Max. Accr. (mm/year)	4.5	4.5	4.5	4.5	4.4	4.4	4.51	4.4
Reg Flood Min. Accr. (mm/year)	0.52	0.52	0.52	0.52	0.58	0.58	0.6	0.58
Reg Flood Elev a (mm/(year HTU^3))	0.9119	0.9119	0.9119	0.9119	0.1137	0.1137	0.207	0.1137
Reg Flood Elev b (mm/(year HTU^2))	-1.8639	-1.8639	-1.8639	-1.8639	-1.9795	-1.9795	-1.9777	-1.9795
Reg Flood Elev c (mm/(year*HTU))	-2.0182	-2.0182	-2.0182	-2.0182	-0.8914	-0.8914	-1.0617	-0.8914
Reg Flood Elev d (mm/year)	4.0515	4.0515	4.0515	4.0515	4.3035	4.3035	4.3679	4.3035
Irreg Flood Max. Accr. (mm/year)	4.23	4.23	4.23	4.23	4.23	4.23	4.23	4.23
Irreg Flood Min. Accr. (mm/year)	4.06	4.06	4.06	4.06	4.06	4.06	4.06	4.06
Irreg Flood Elev c (mm/(year*HTU))	-0.12	-0.12	-0.12	-0.12	-0.12	-0.12	-0.12	-0.12
Irreg Flood Elev d (mm/year)	4.29	4.29	4.29	4.29	4.29	4.29	4.29	4.29

Study Area	NY City	Hudson	Hudson
Subsite Number	SubSite 18	H_Global	H_SubSite 1
Description	Idlewild Reserve		SubSite 1
NWI Photo Date (YYYY)	2002	2004	2004
DEM Date (YYYY)	2012	2012	2012
Direction Offshore [n,s,e,w]	East	South	South
GT Great Diurnal Tide Range (m)	1.1	1.5	1.1
Salt Elev. (m above MTL)	0.88	1.16	0.65
Marsh Erosion (horz. m /yr)	1	1	1
Swamp Erosion (horz. m /yr)	1	1	1
T.Flat Erosion (horz. m /yr)	0.44	0.44	0.44
Tidal-Fresh Marsh Accr (mm/yr)	5	5	5
Inland-Fresh Marsh Accr (mm/yr)	1	1	1
Tidal Swamp Accr (mm/yr)	1.1	1.1	1.1
Swamp Accretion (mm/yr)	1.6	1.6	1.6
Beach Sed. Rate (mm/yr)	0.5	0.5	0.5
Reg Flood Max. Accr. (mm/year)	4.4	14.78	14.78
Reg Flood Min. Accr. (mm/year)	0.58	1.69	1.69
Reg Flood Elev a (mm/(year HTU^3))	0.1137	3.3302	3.3302
Reg Flood Elev b (mm/(year HTU^2))	-1.9795	-8.3253	-8.3253
Reg Flood Elev c (mm/(year*HTU))	-0.8914	-5.123	-5.123
Reg Flood Elev d (mm/year)	4.3035	14.072	14.072
Irreg Flood Max. Accr. (mm/year)	4.23	4.23	4.23
Irreg Flood Min. Accr. (mm/year)	4.06	4.06	4.06
Irreg Flood Elev c (mm/(year*HTU))	-0.12	-0.12	-0.12
Irreg Flood Elev d (mm/year)	4.29	4.29	4.29

Appendix D: Uncertainty Maps

D.1 Hudson

Figure D-1. Hudson River/ Piermont Marsh Percent Likelihood of habitat change by 2055

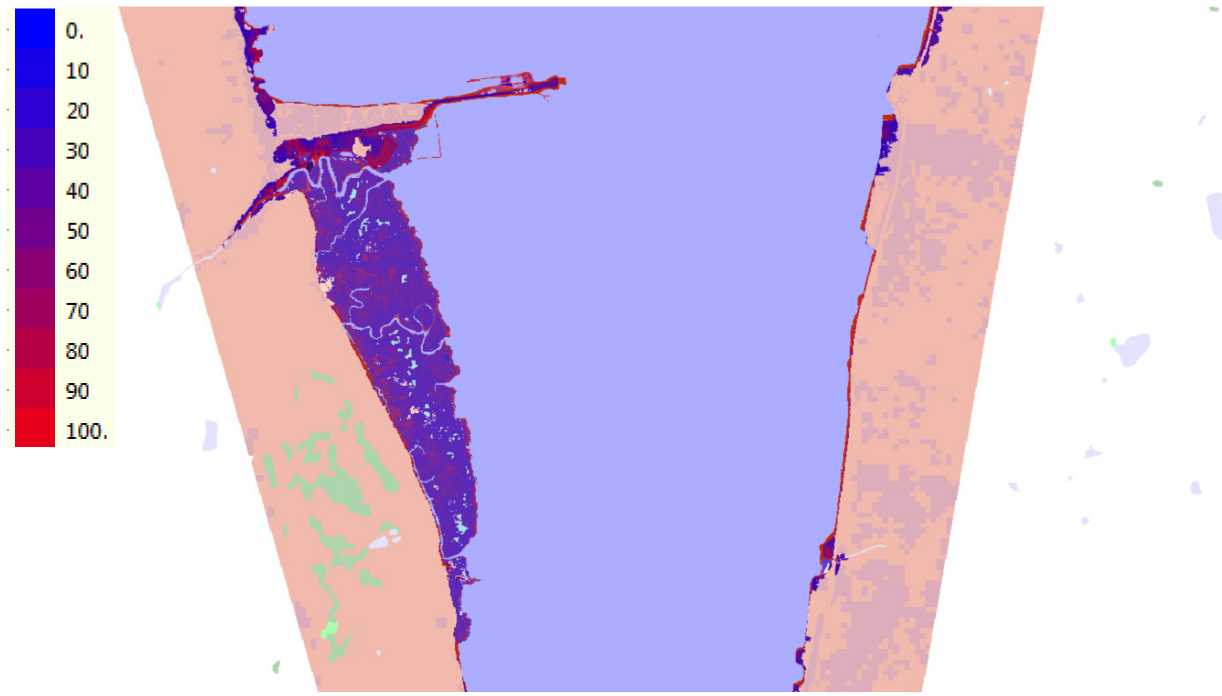


Figure D-2. Hudson River/Piermont Marsh Percent Likelihood of habitat change by 2085

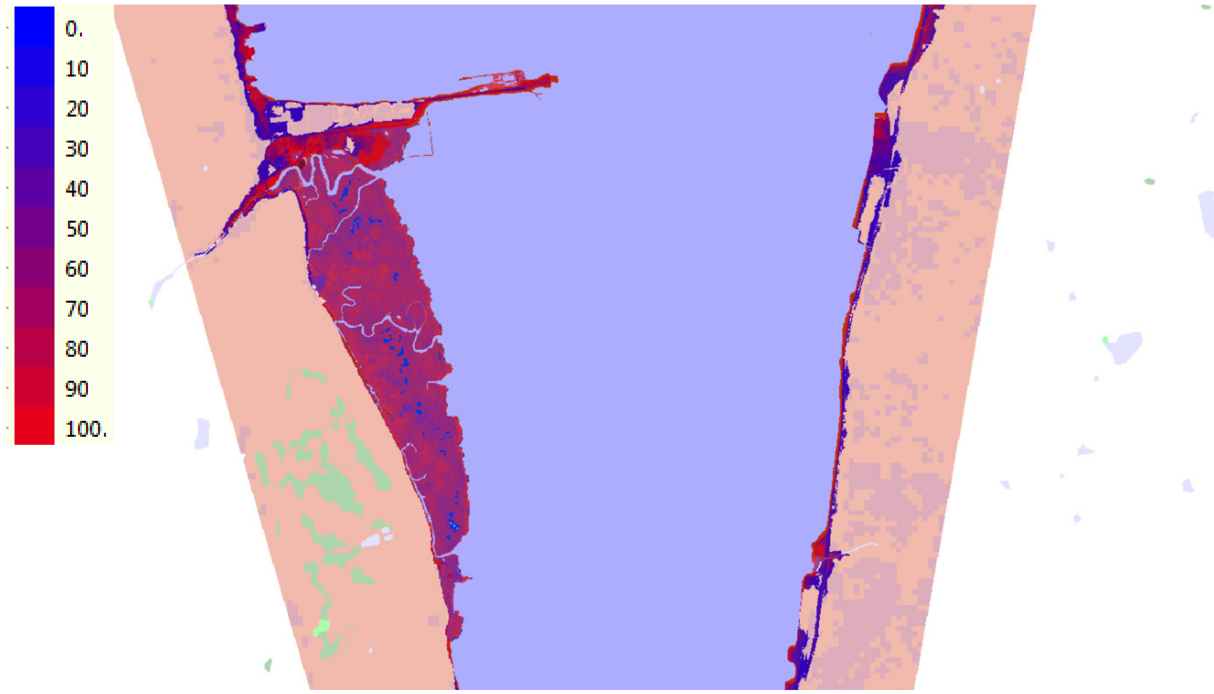


Figure D-3. Hudson River/Piermont Marsh Percent Likelihood of being coastal marsh in 2025

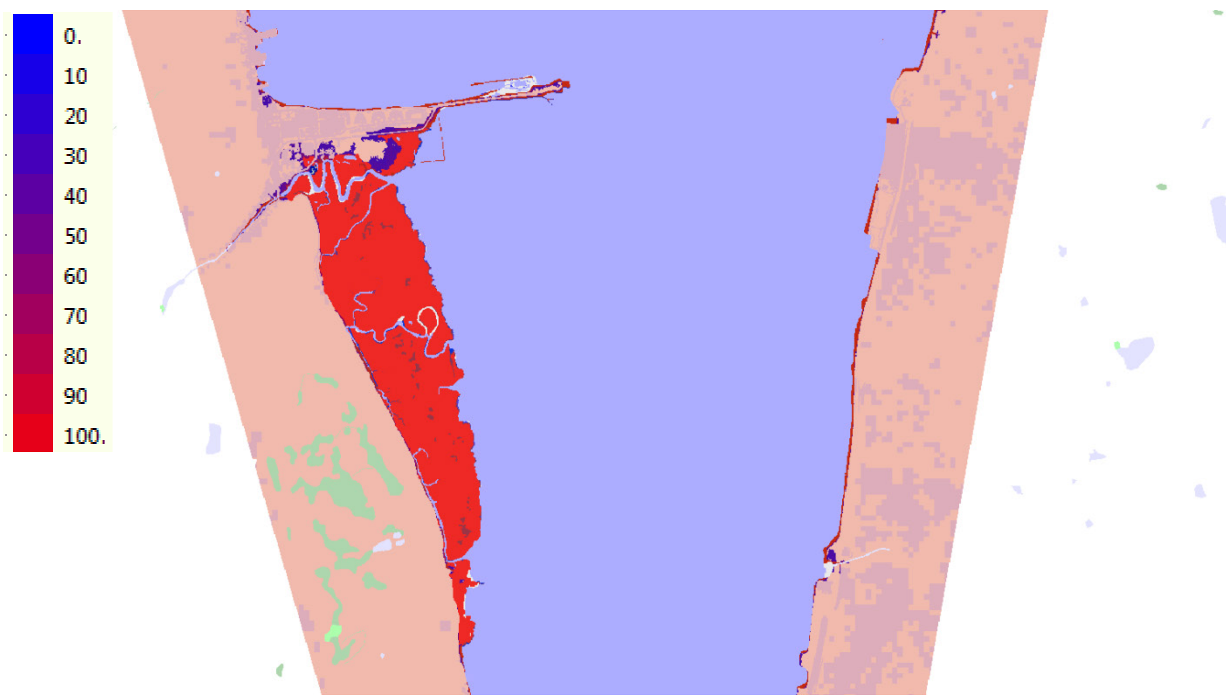


Figure D-4. Hudson River/Piermont Marsh Percent Likelihood of being coastal marsh in 2055

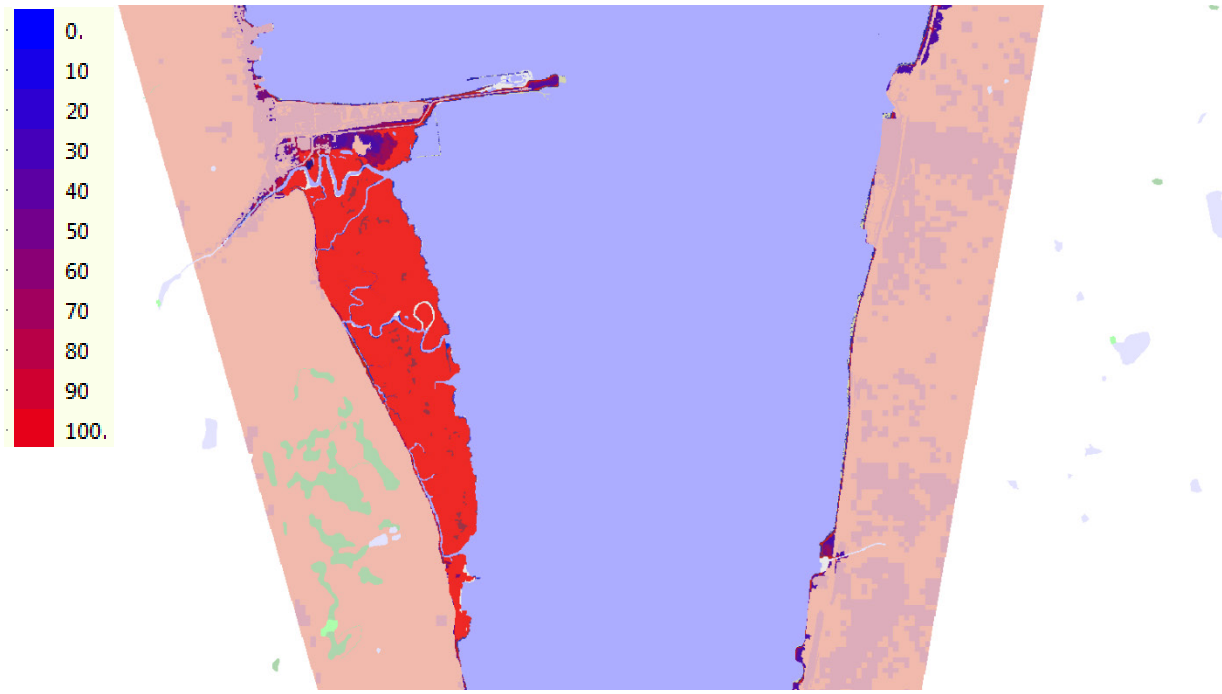
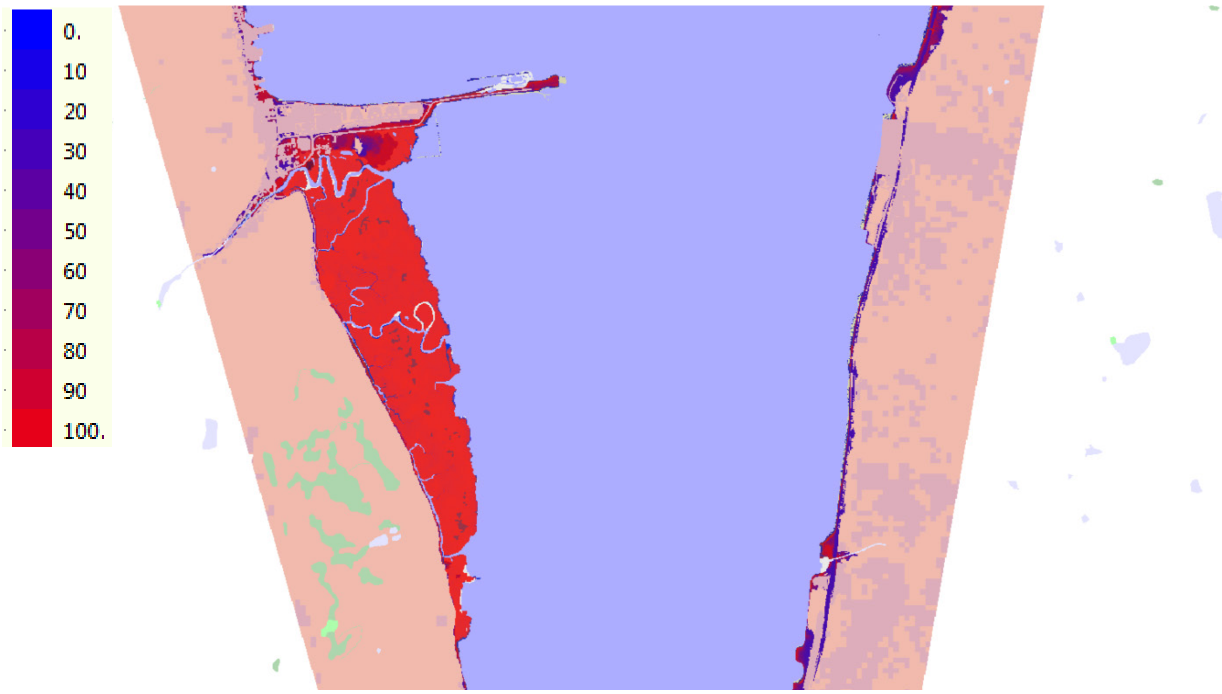


Figure D-5. Hudson River/ Piermont Marsh Percent Likelihood of being coastal marsh in 2085



D.2 New York City

Figure D-6. NYC Percent Likelihood of flooded developed land by 2025

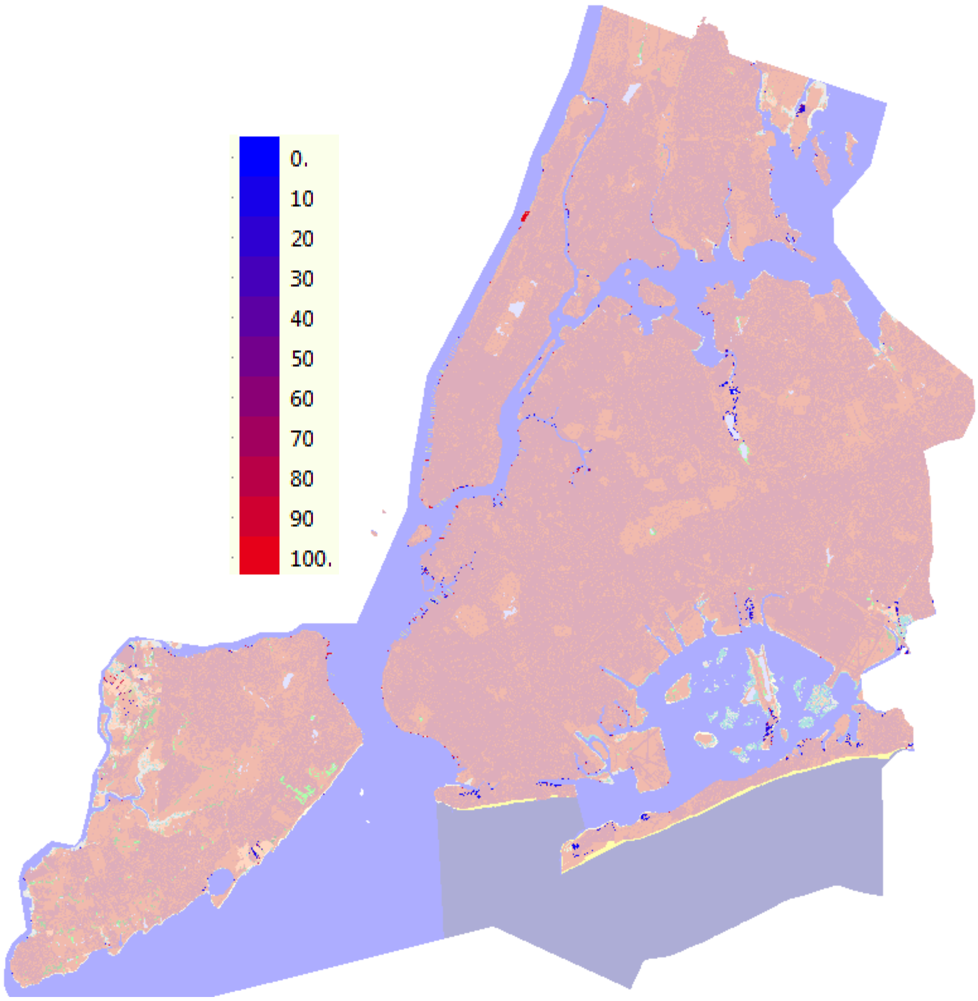


Figure D-7. NYC Percent Likelihood of flooded developed land by 2055

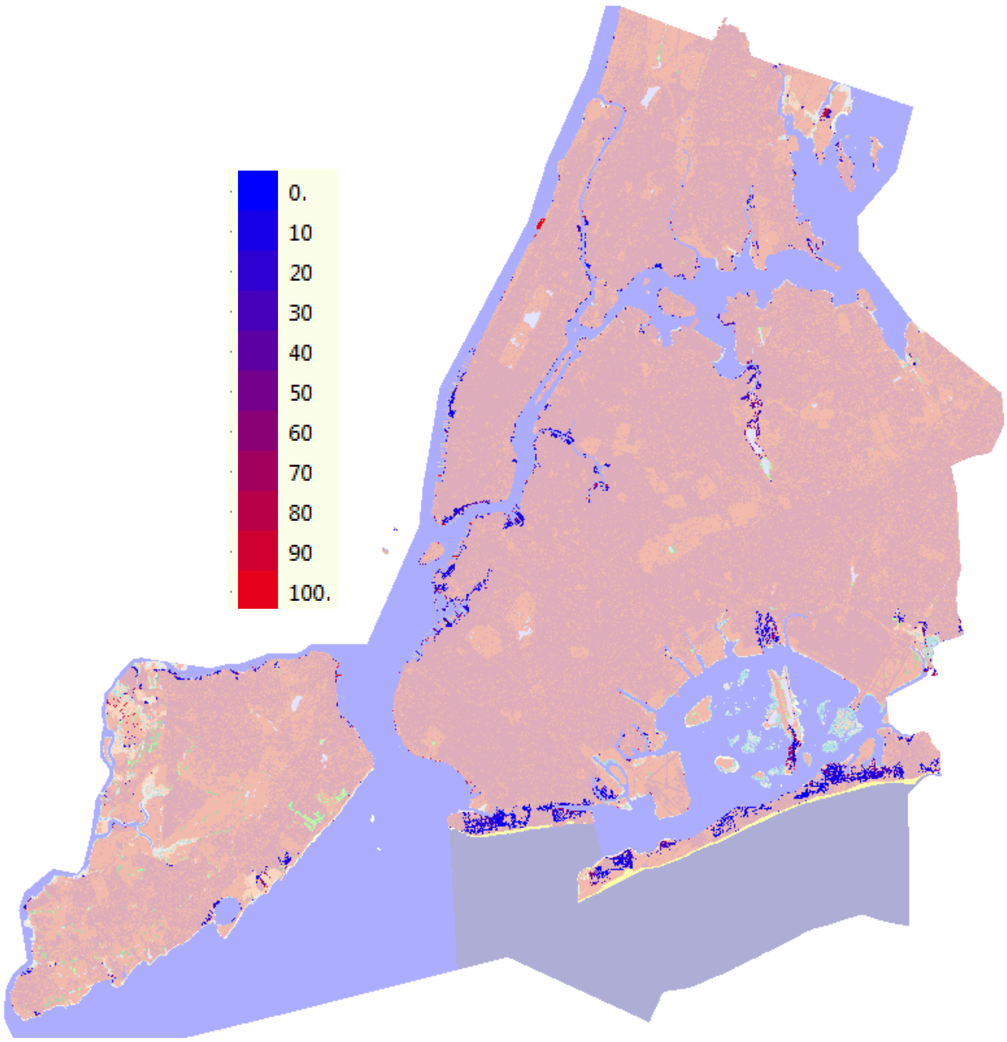


Figure D-8. NYC Percent Likelihood of flooded developed land by 2085

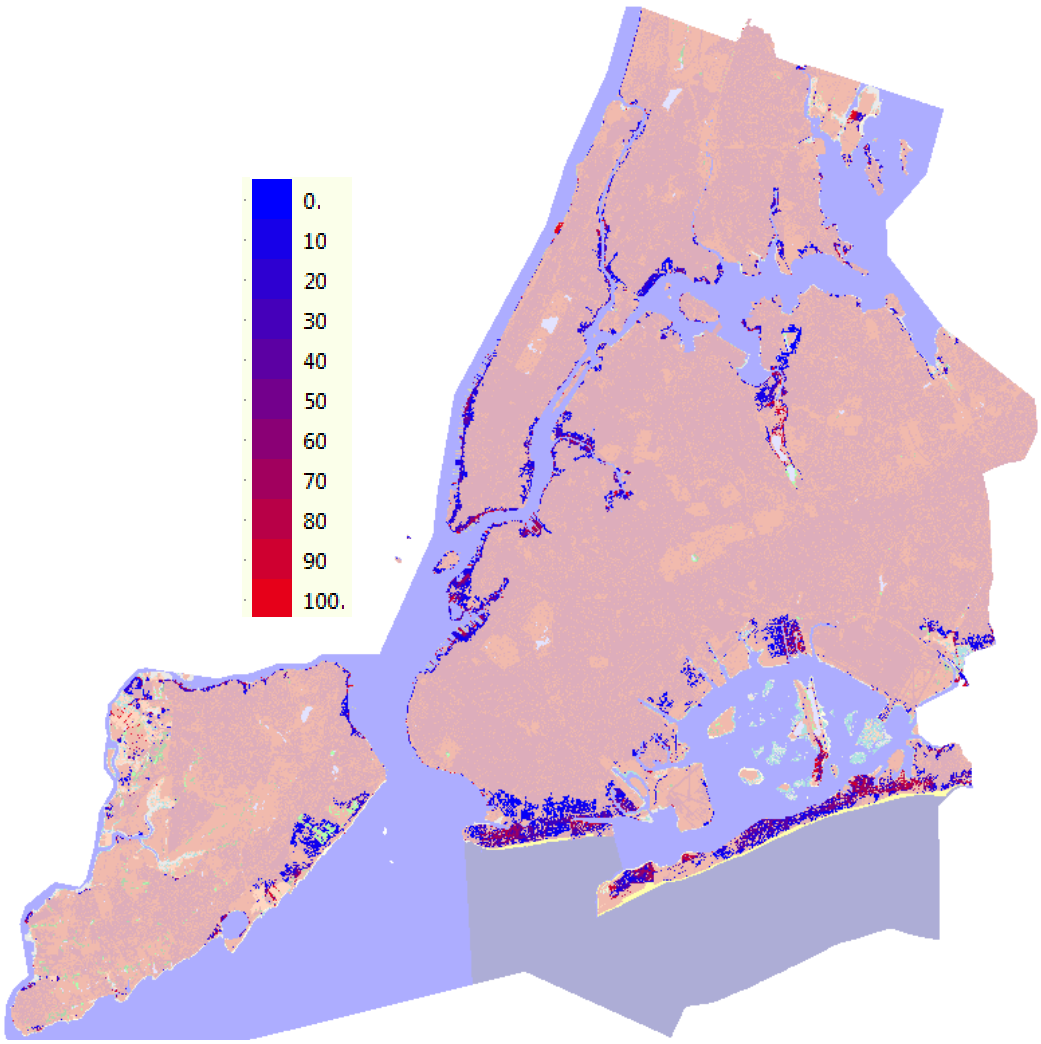


Figure D-9. NYC Percent Likelihood of habitat change by 2025

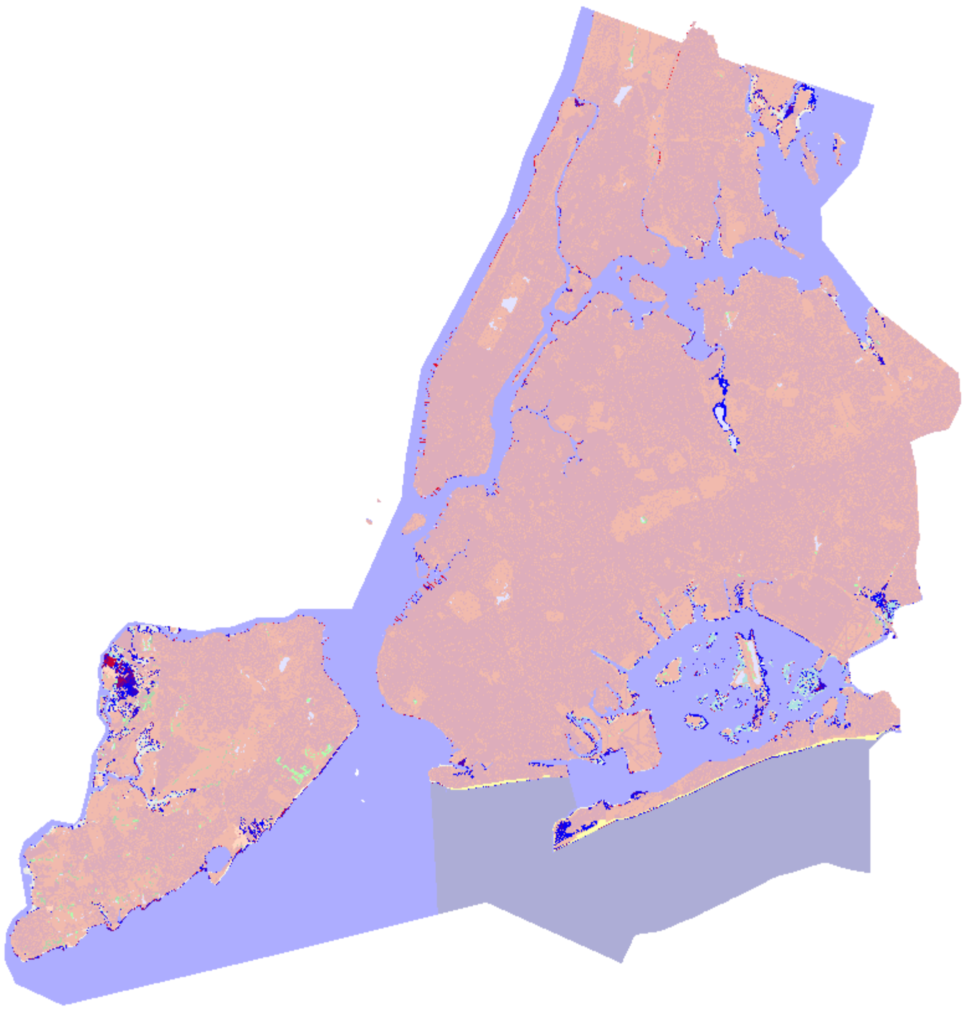


Figure D-10. NYC Percent Likelihood of habitat change by 2055

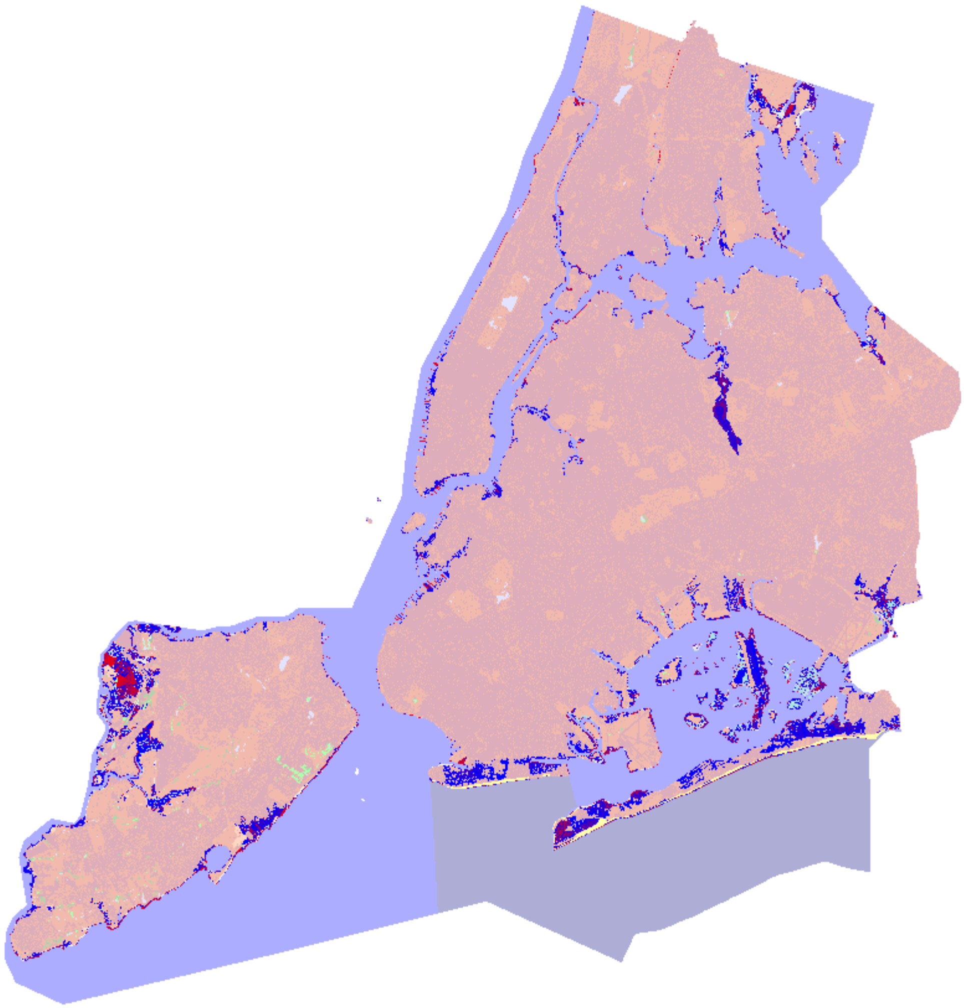
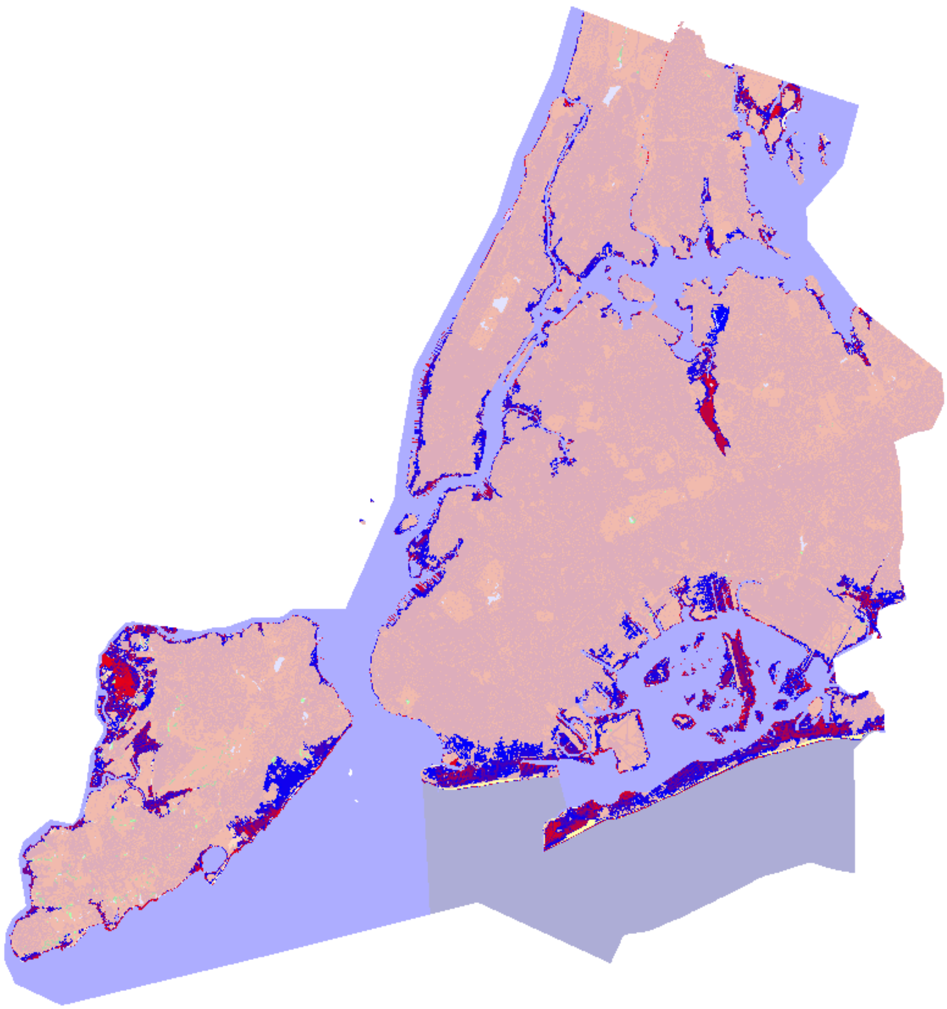


Figure D-11. NYC Percent Likelihood of habitat change by 2085



D.3 Nassau

Figure D-12. Nassau Percent Likelihood of land to open water by 2025

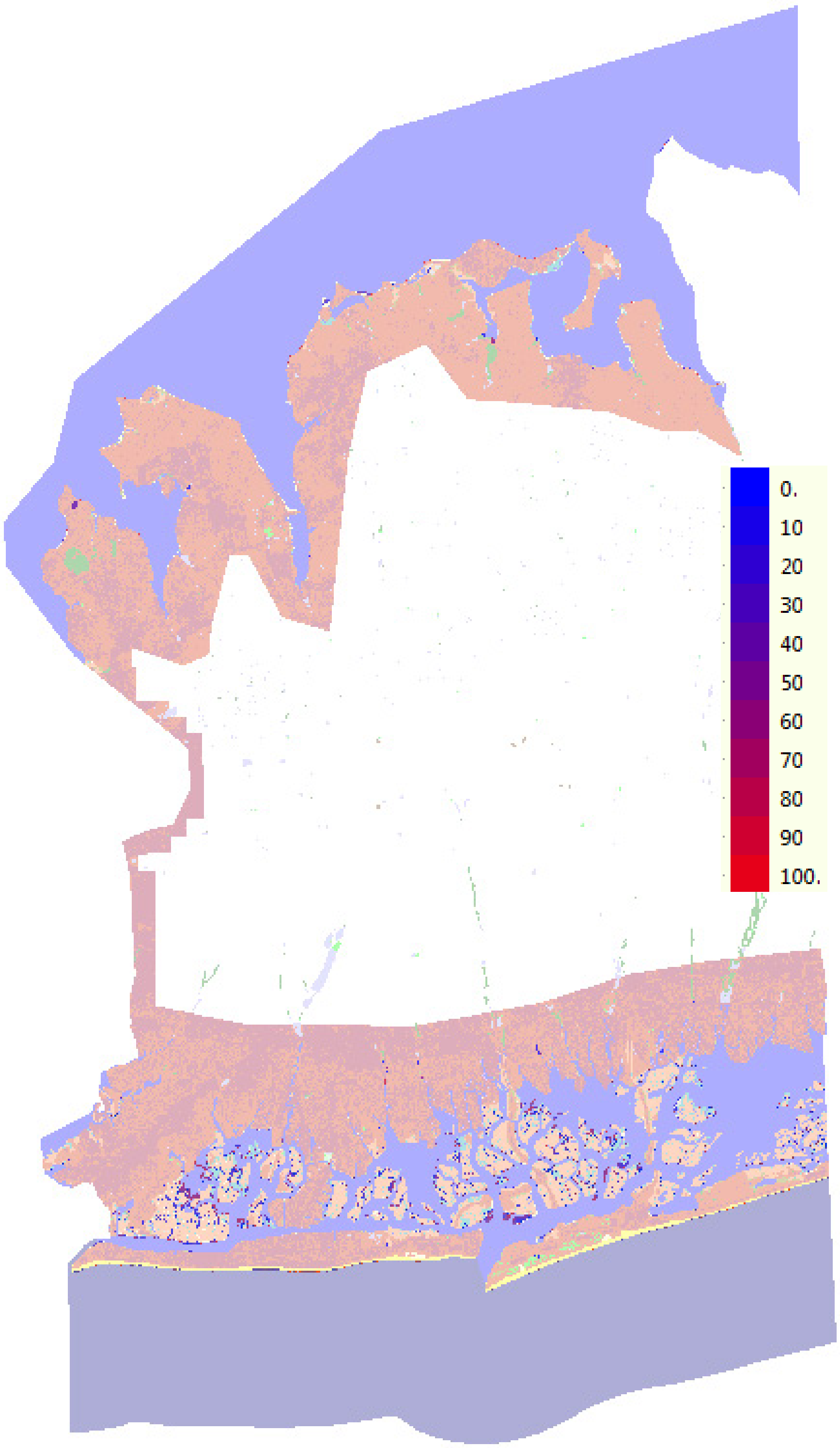


Figure D-13. Nassau Percent Likelihood of land to open water by 2055

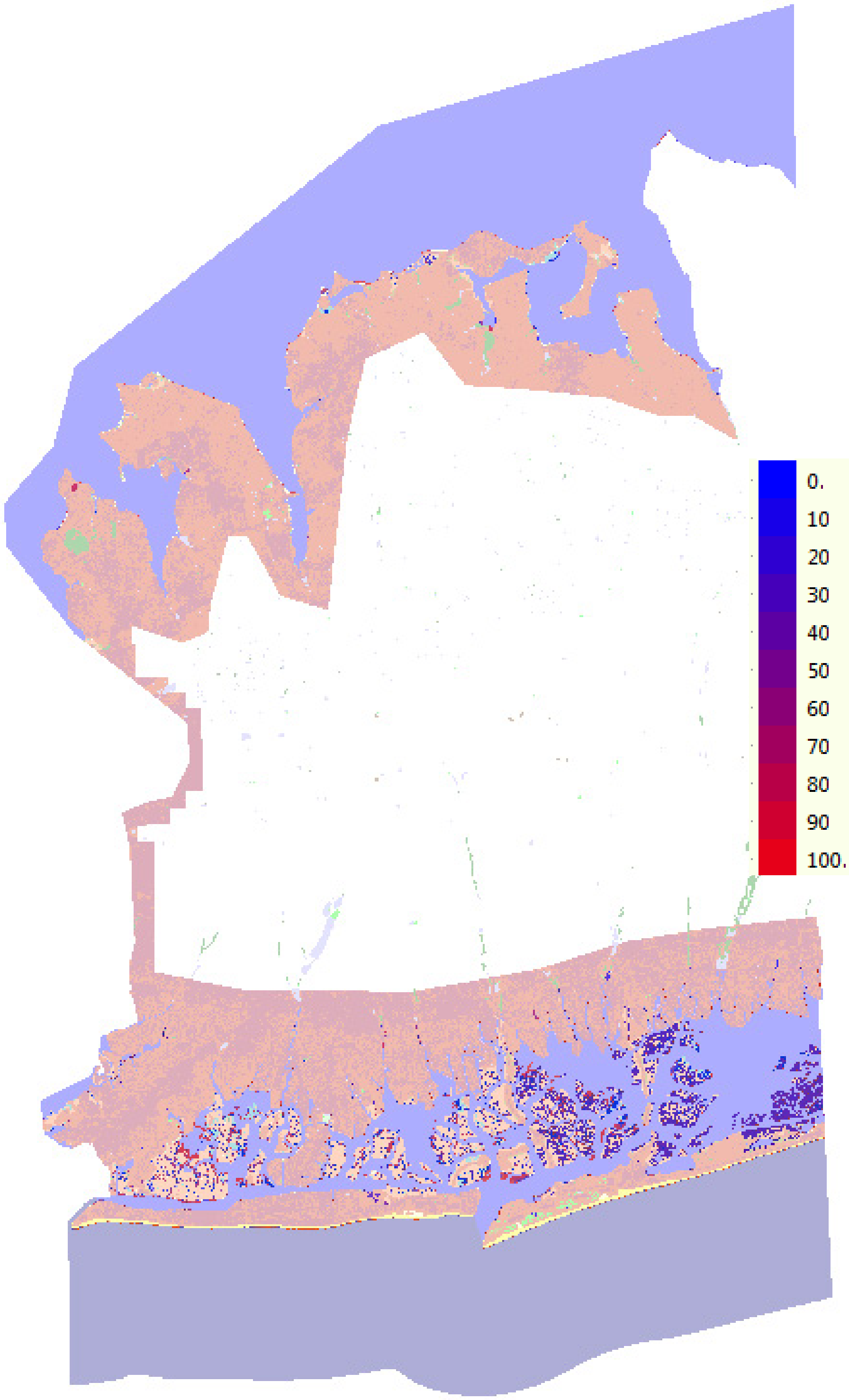
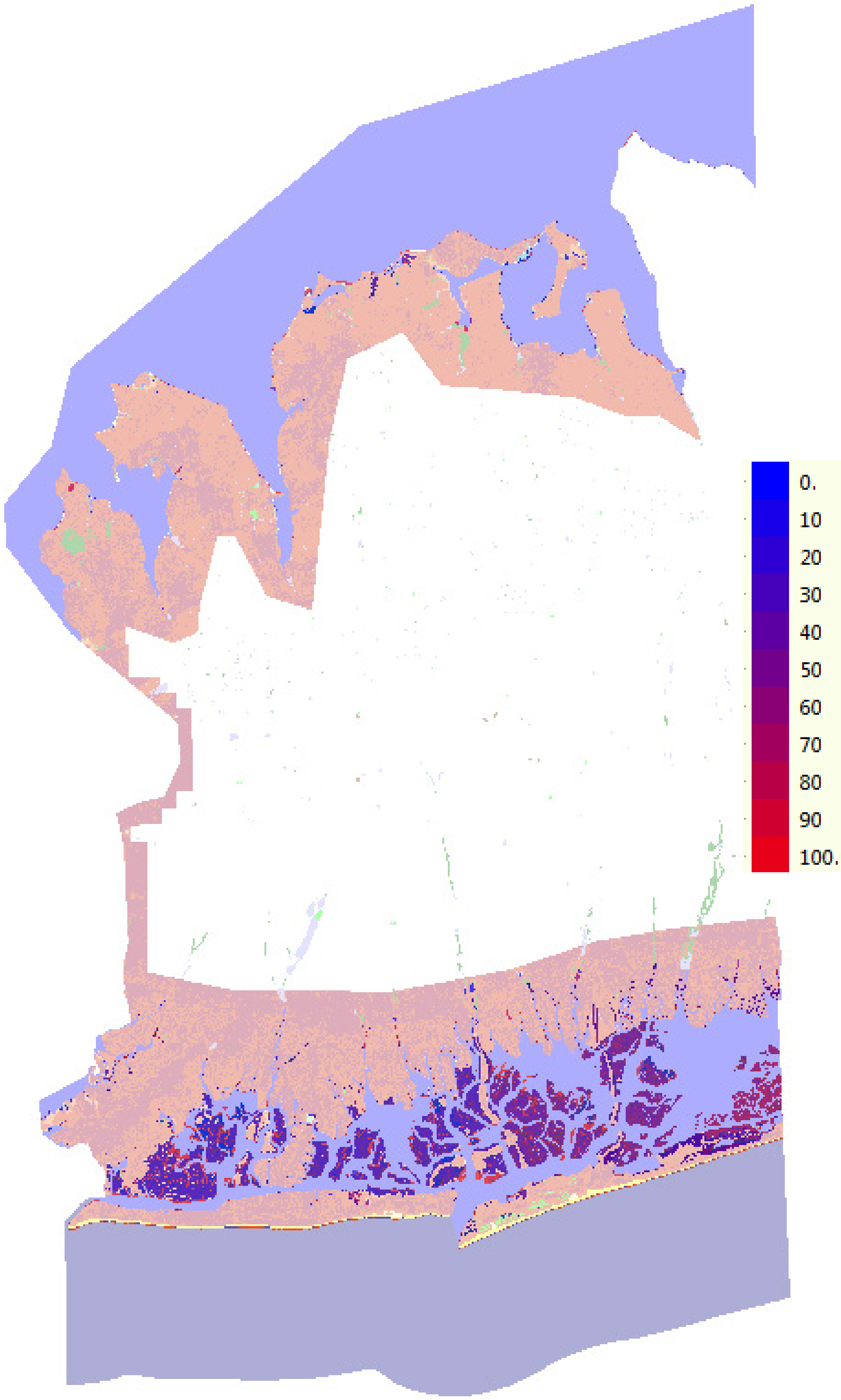


Figure D-14. Nassau Percent Likelihood of land to open water by 2085



D.4 Suffolk West

Figure D-15. Suffolk West Percent Likelihood of habitat change by 2055

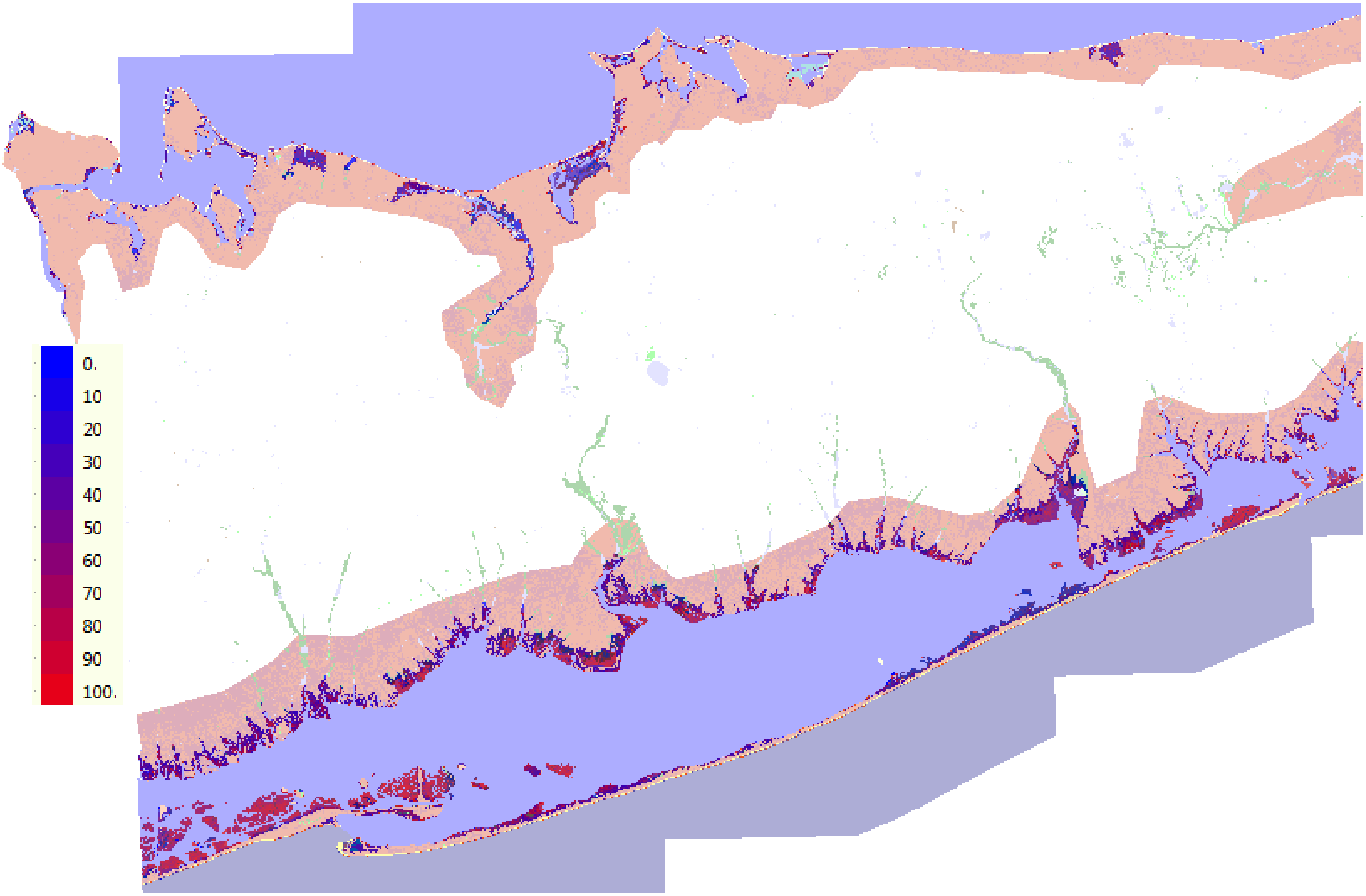


Figure D-16. Suffolk West Percent Likelihood of habitat change by 2085

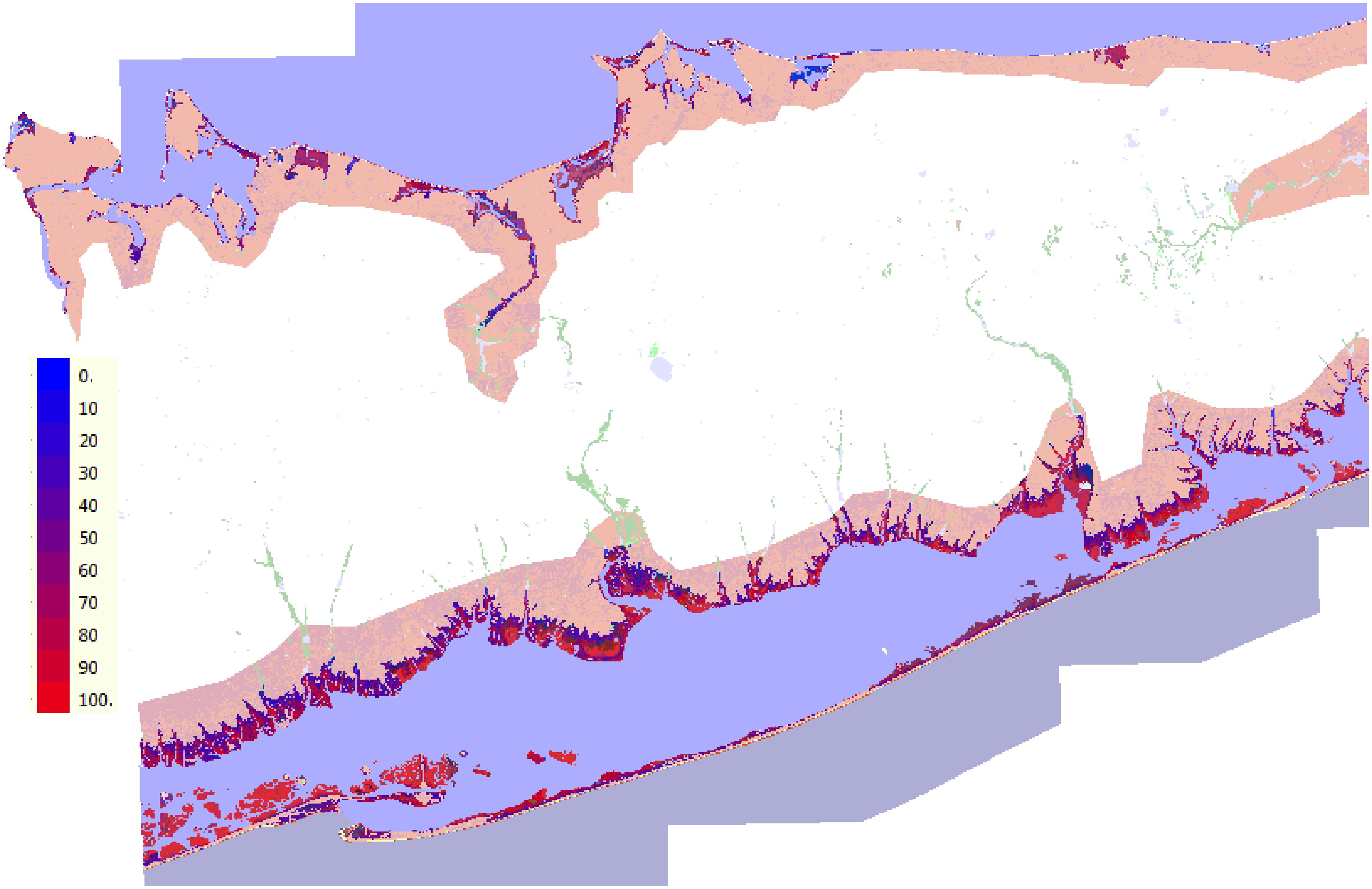


Figure D-17. Suffolk West Percent Likelihood of coastal wetland by 2025

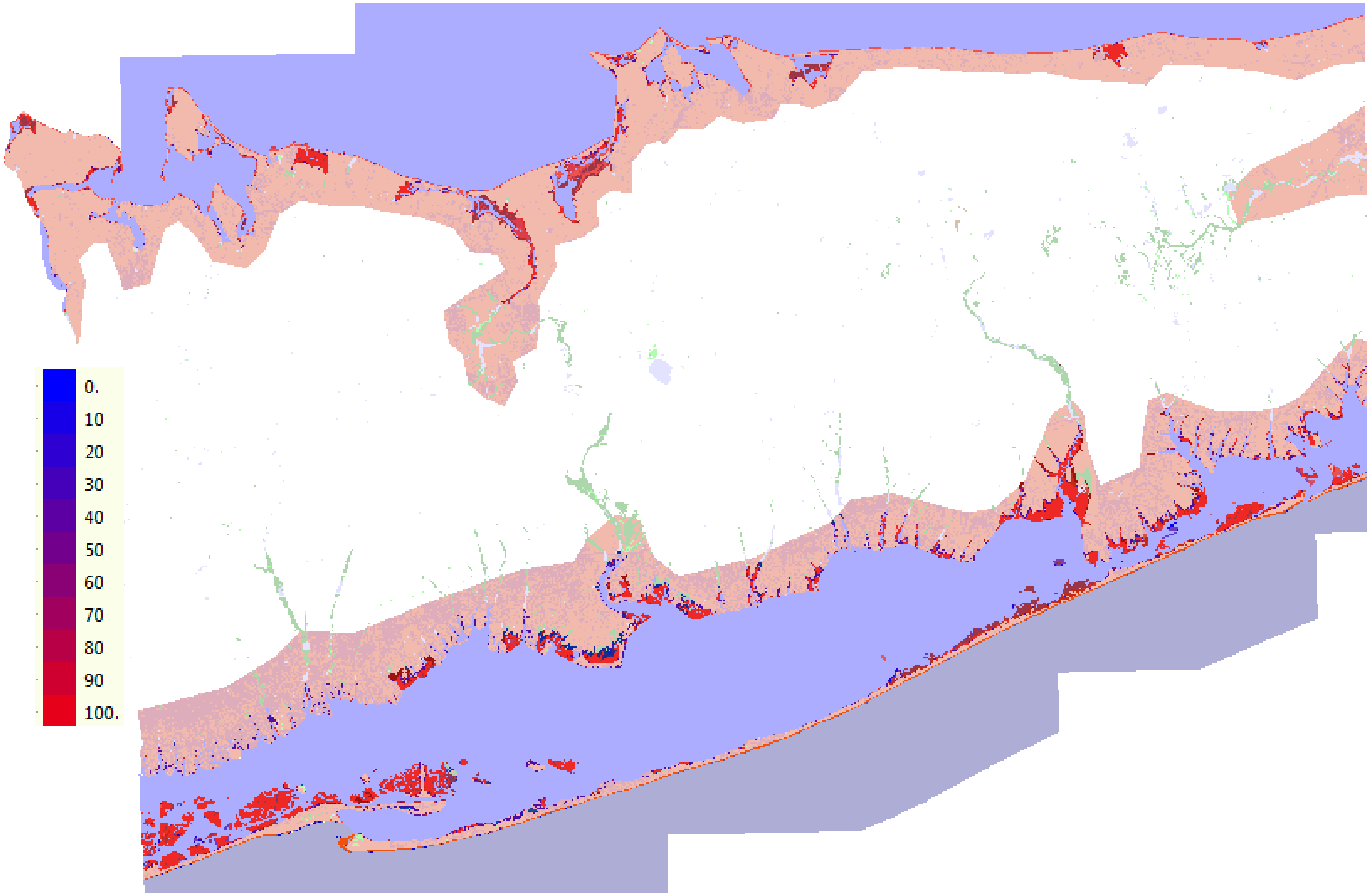


Figure D-18. Suffolk West Percent Likelihood of coastal wetland by 2055

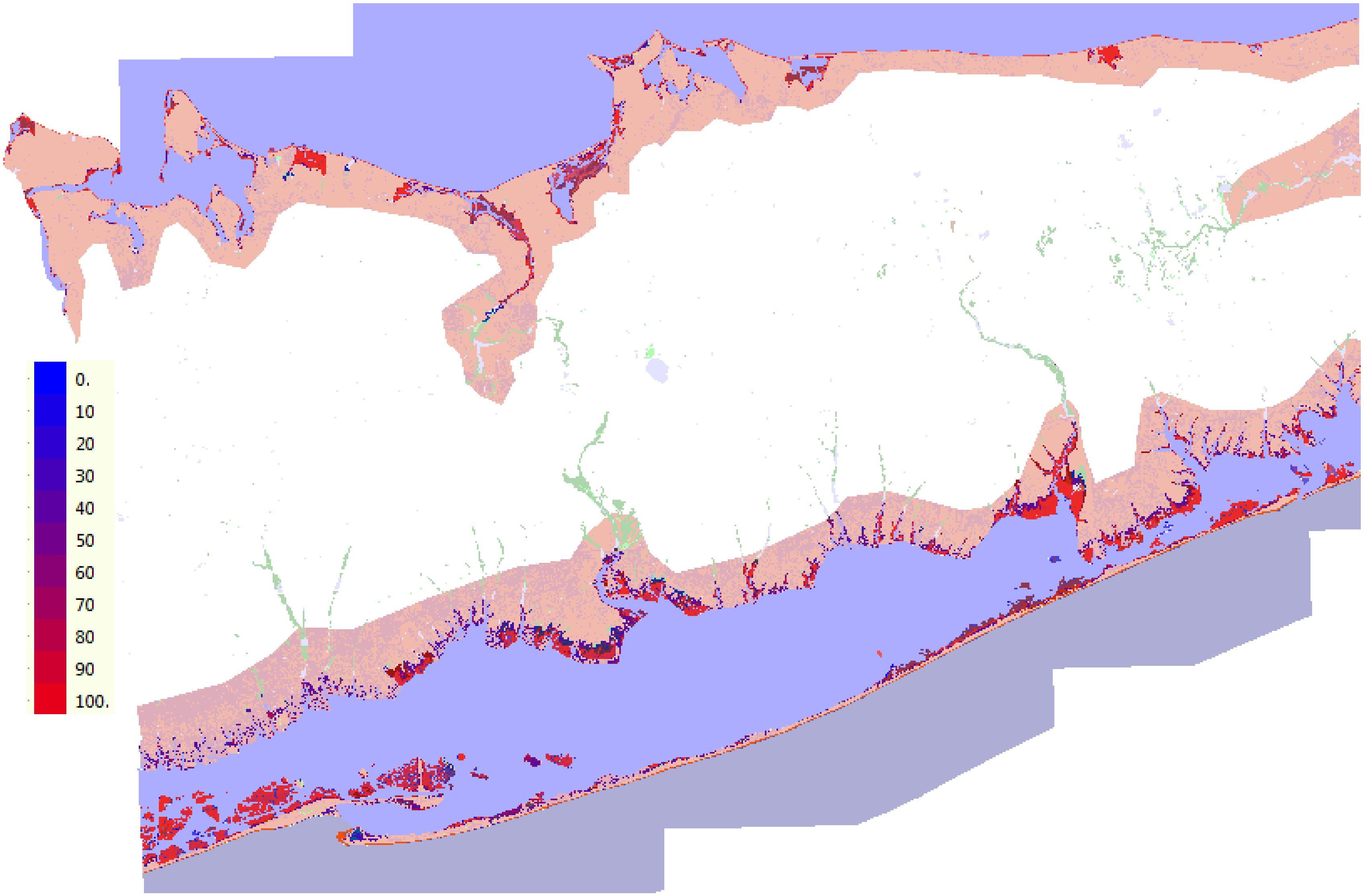
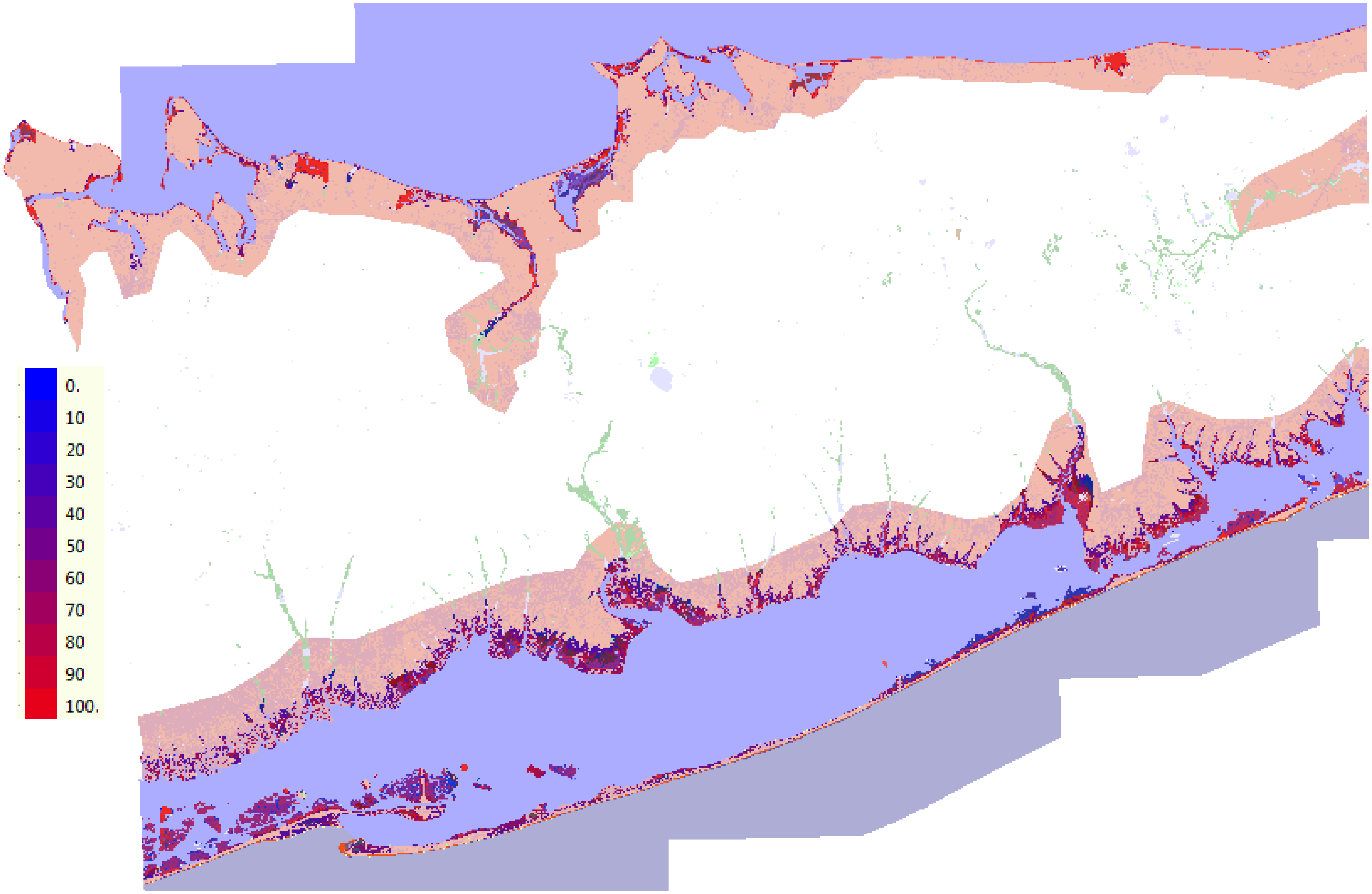


Figure D-19. Suffolk West Percent Likelihood of coastal wetland by 2085



D.5 Suffolk East

Figure D-20. Suffolk East Percent Likelihood of coastal marsh by 2025

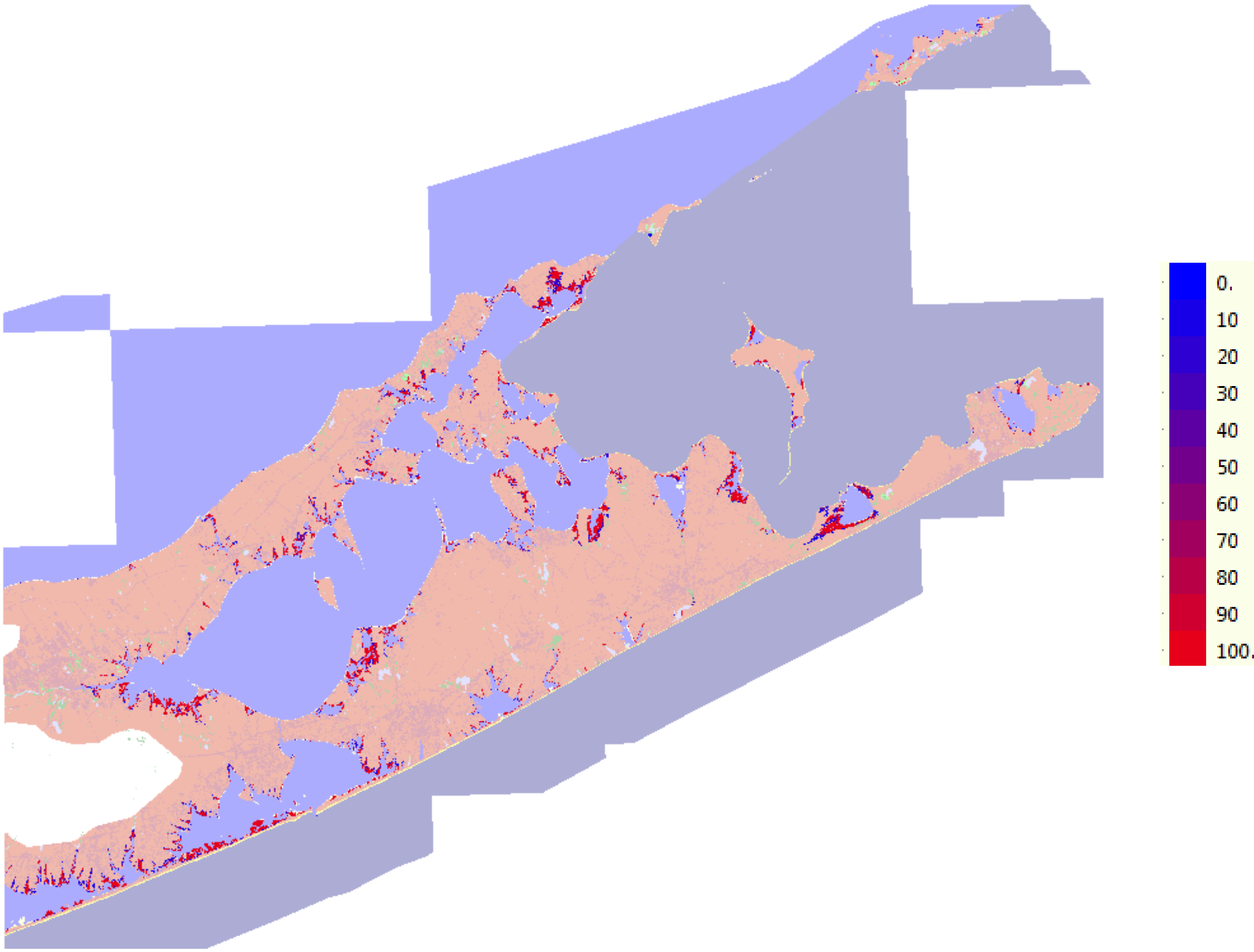


Figure D-21. Suffolk East Percent Likelihood of coastal marsh by 2055

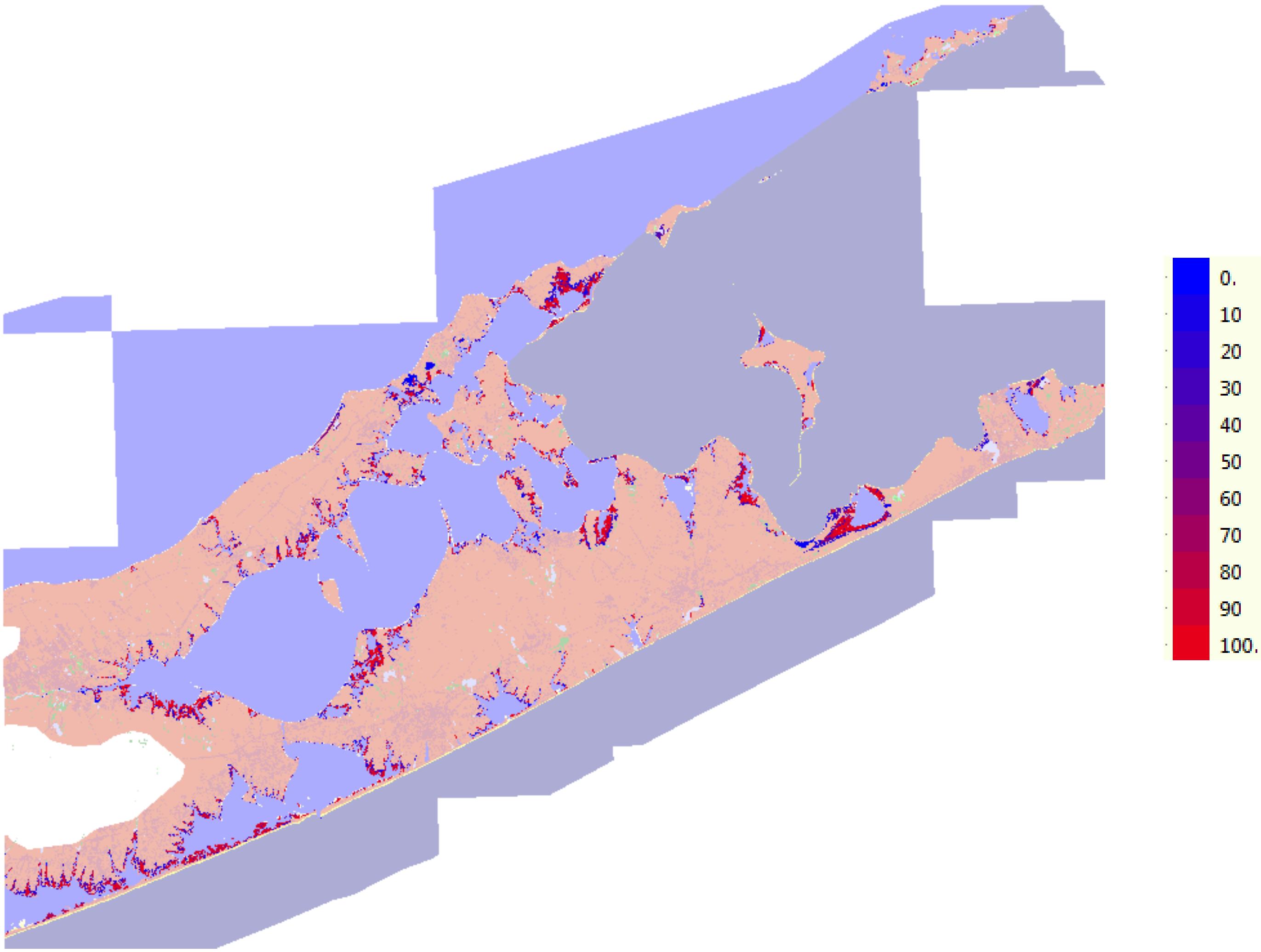
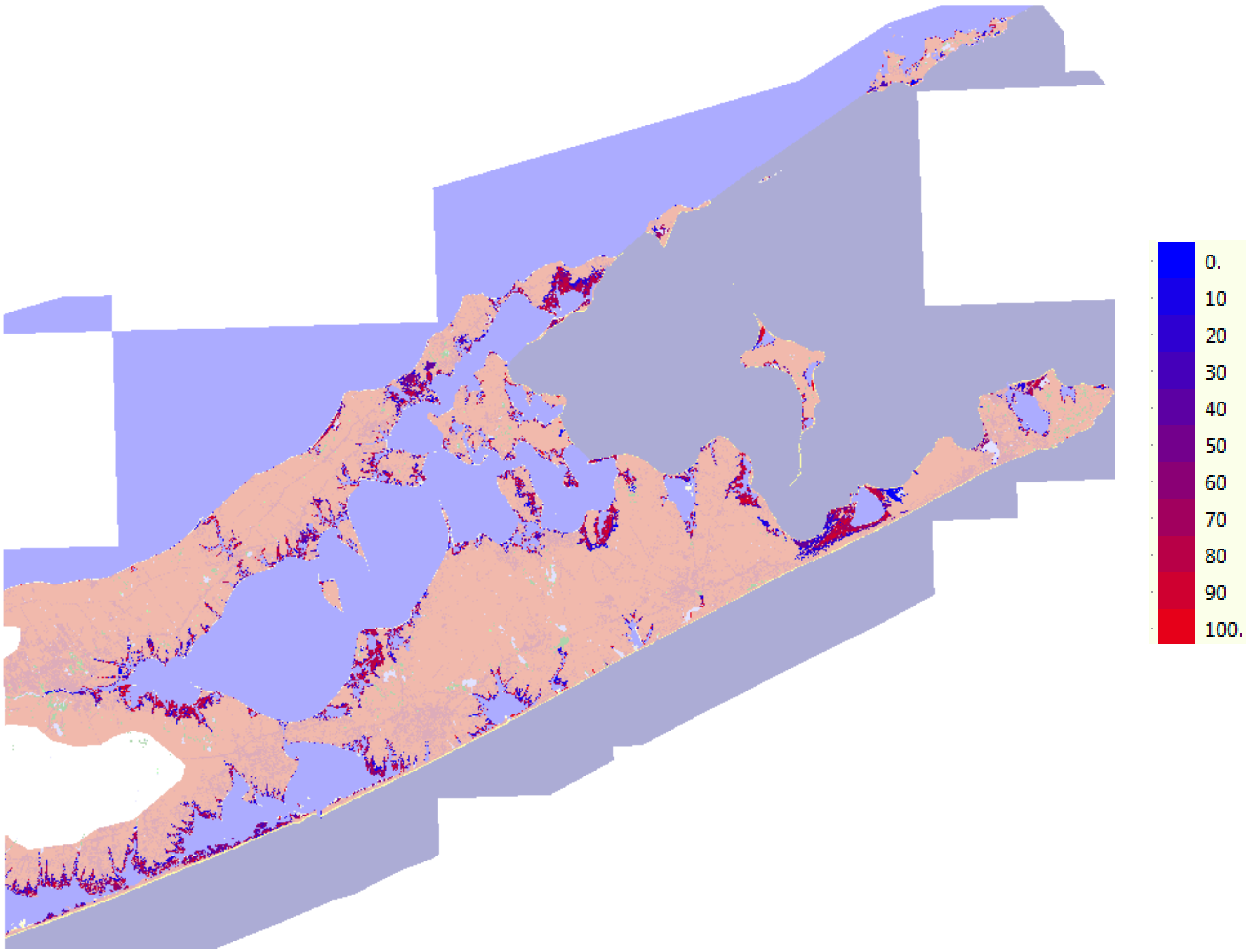


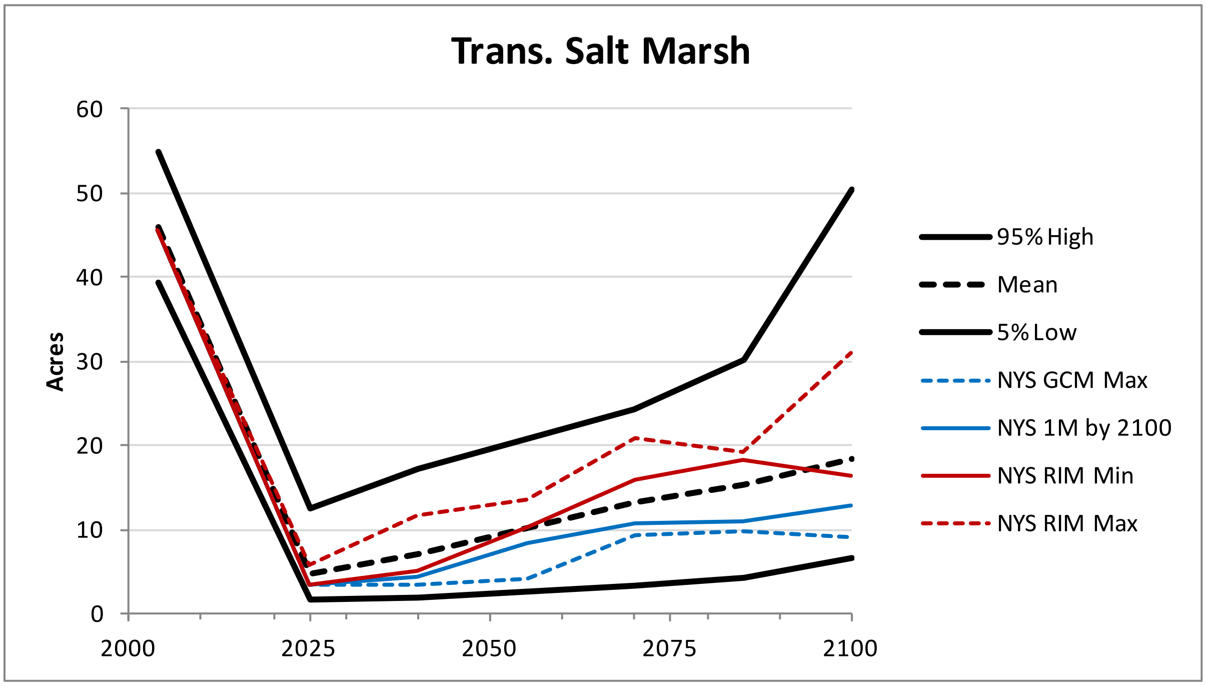
Figure D-22. Suffolk East Percent Likelihood of coastal marsh by 2085



Appendix E: Uncertainty Graphs

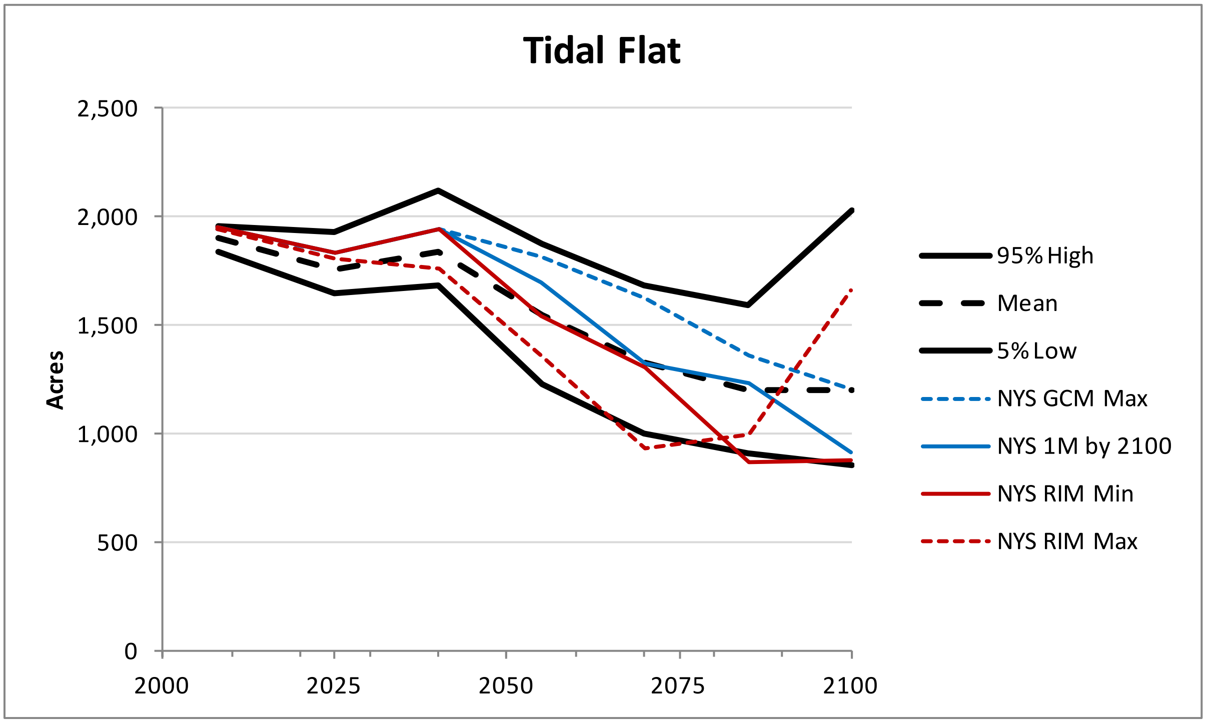
E.1 Hudson

Figure E-1. Uncertainty time series for transitional salt marsh coverage in Hudson River, NY.



E.2 New York City

Figure E-2. Uncertainty time series for tidal flat coverage in New York City



E.3 Nassau

Figure E-3. Uncertainty time series for undeveloped dry land coverage in Nassau County

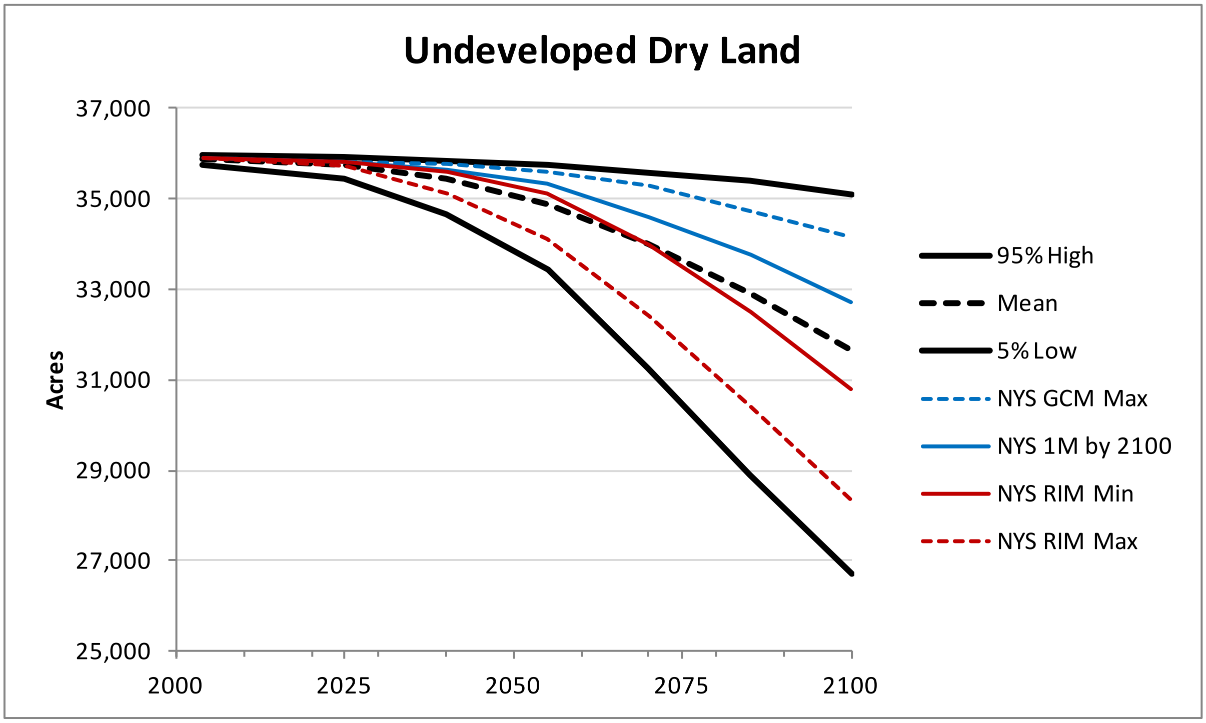


Figure E-4. Uncertainty time series for developed dry land coverage in Nassau County

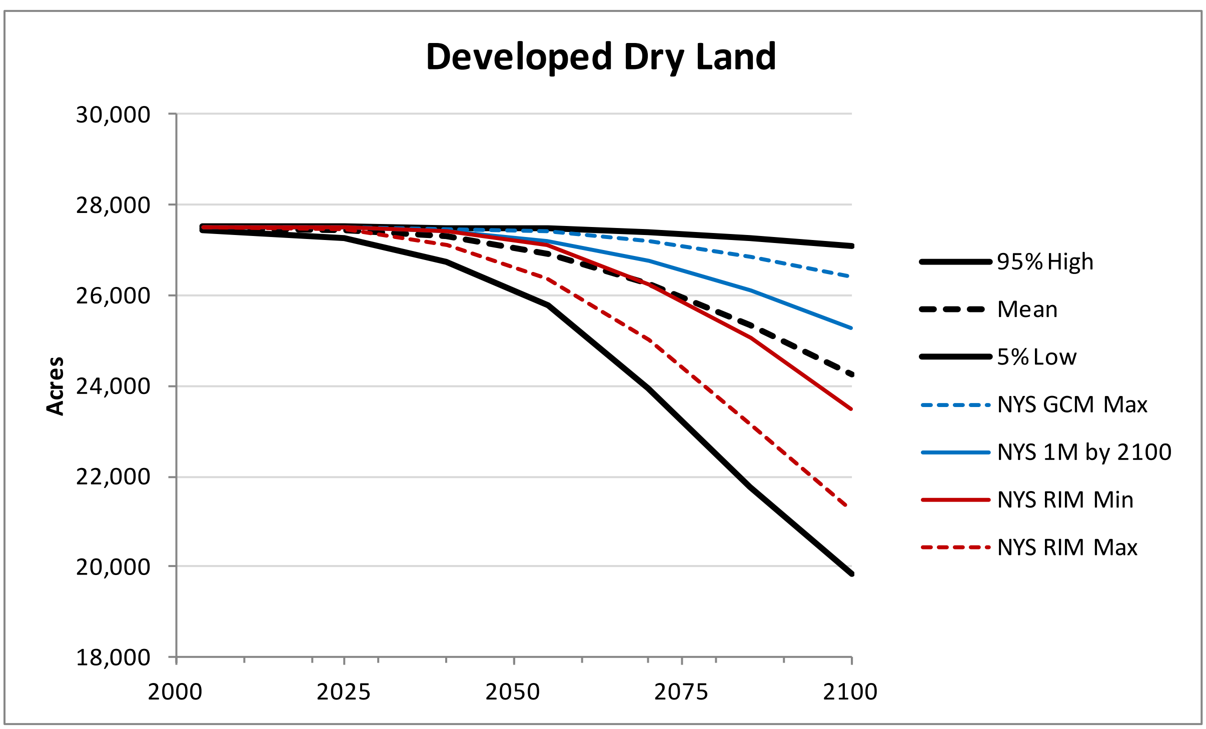


Figure E-5. Uncertainty time series for flooded developed dry land coverage in Nassau County

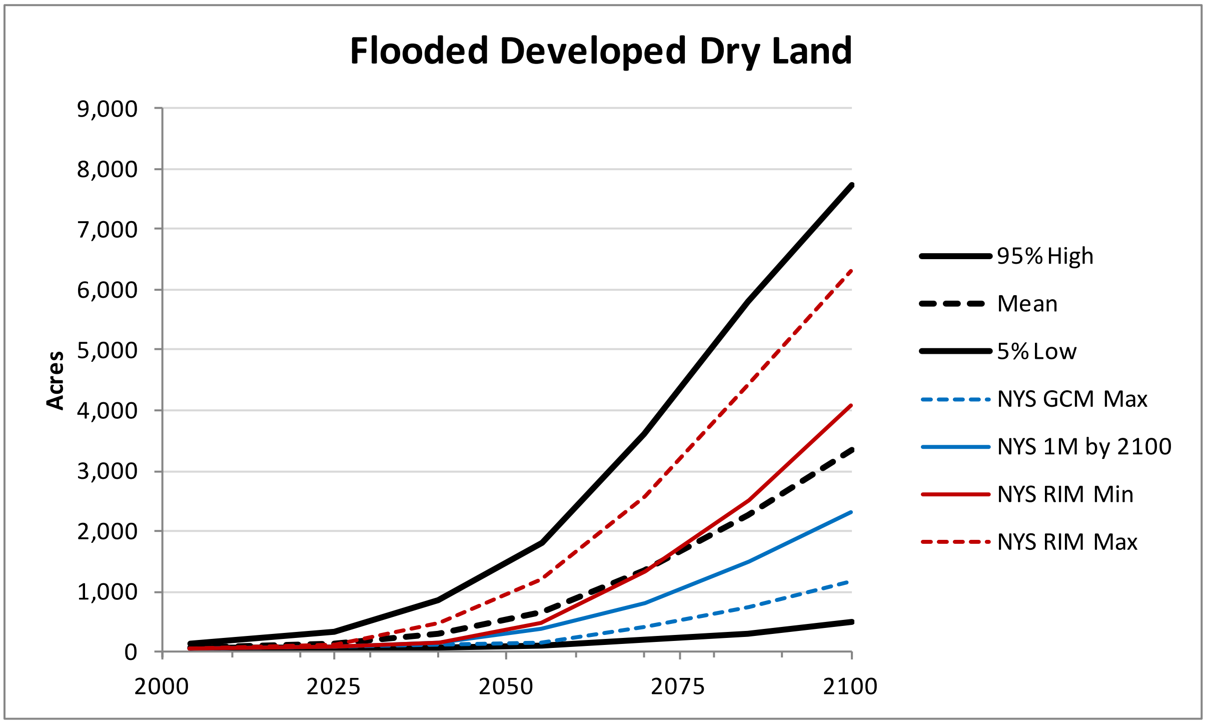


Figure E-6. Uncertainty time series for irregularly flooded marsh coverage in Nassau County

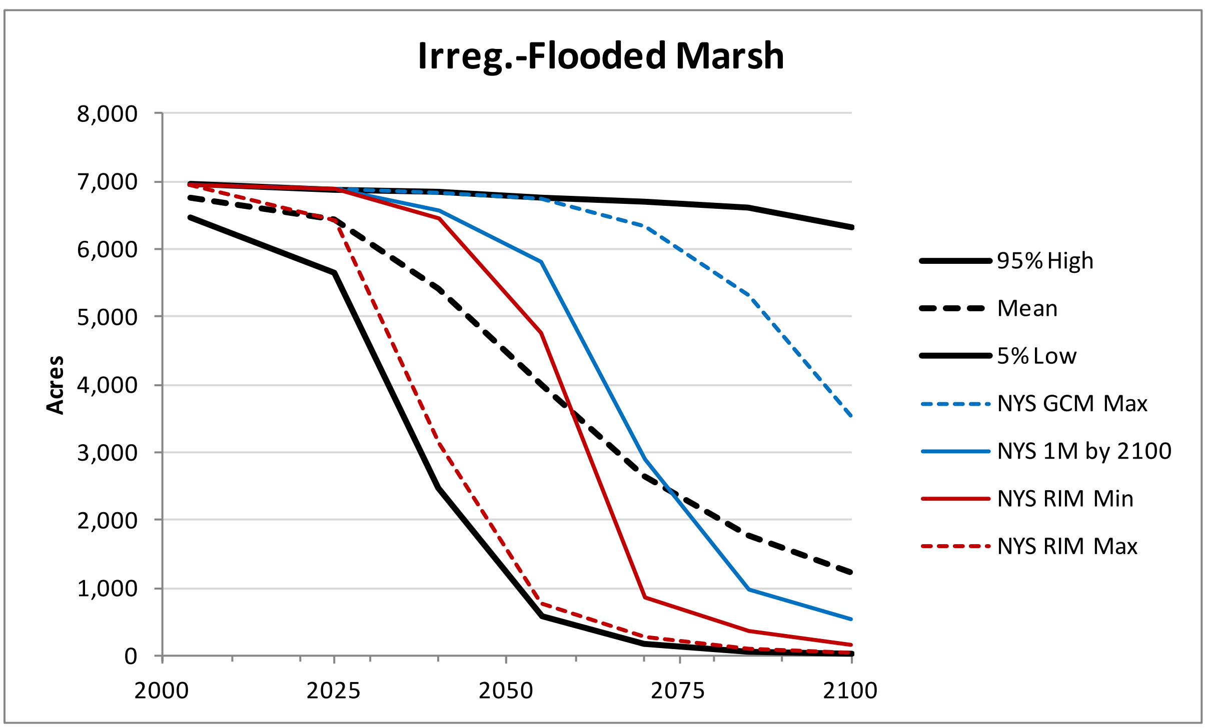


Figure E-7. Uncertainty time series for tidal flat coverage in Nassau County

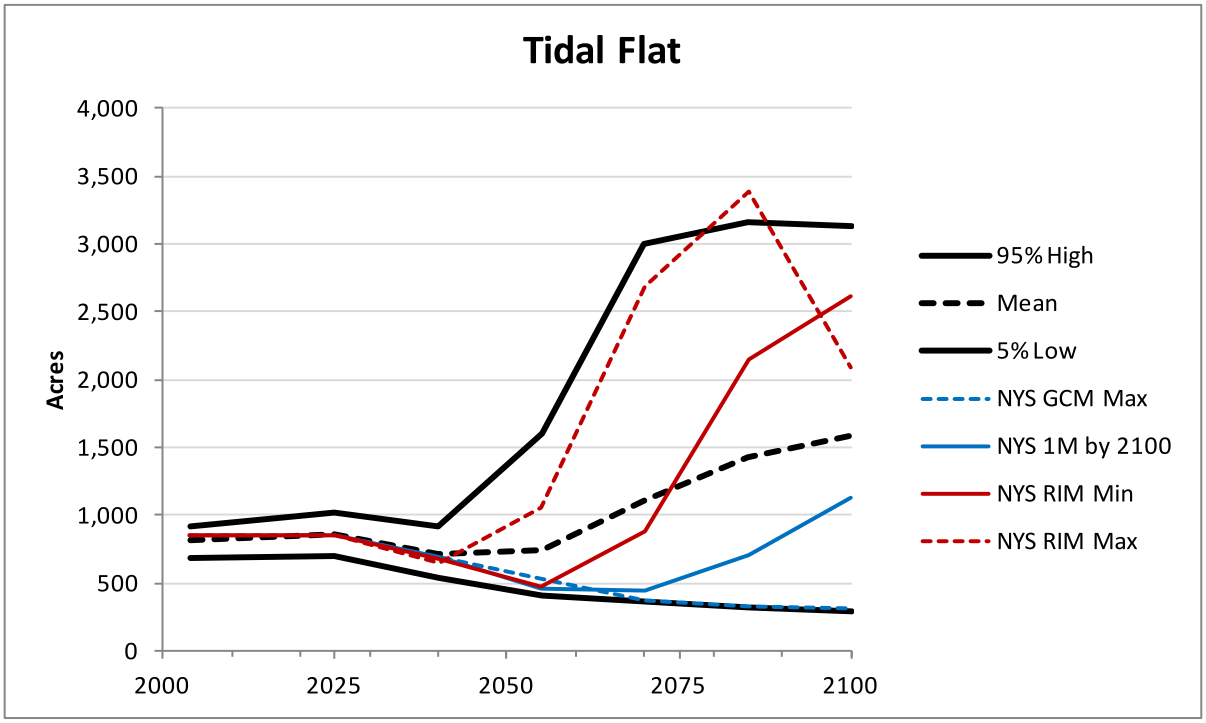


Figure E-8. Uncertainty time series for swamp coverage in Nassau County

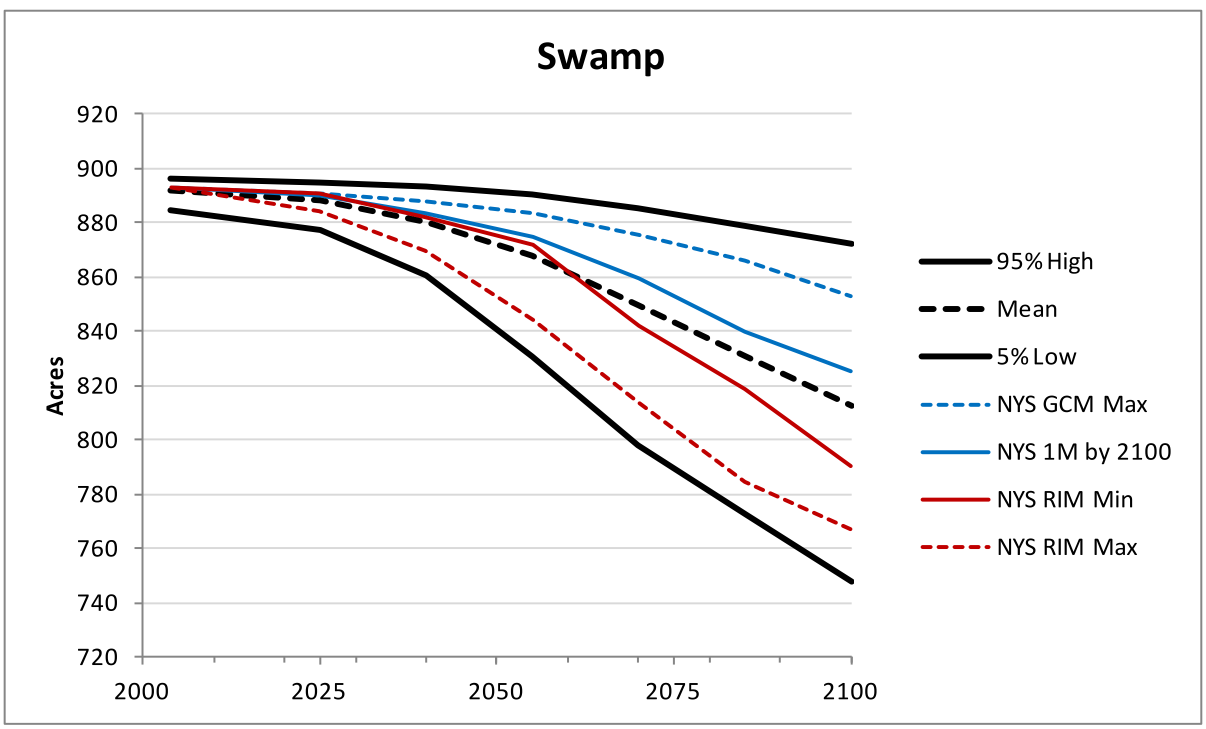


Figure E-9. Uncertainty time series for regularly flooded marsh coverage in Nassau County

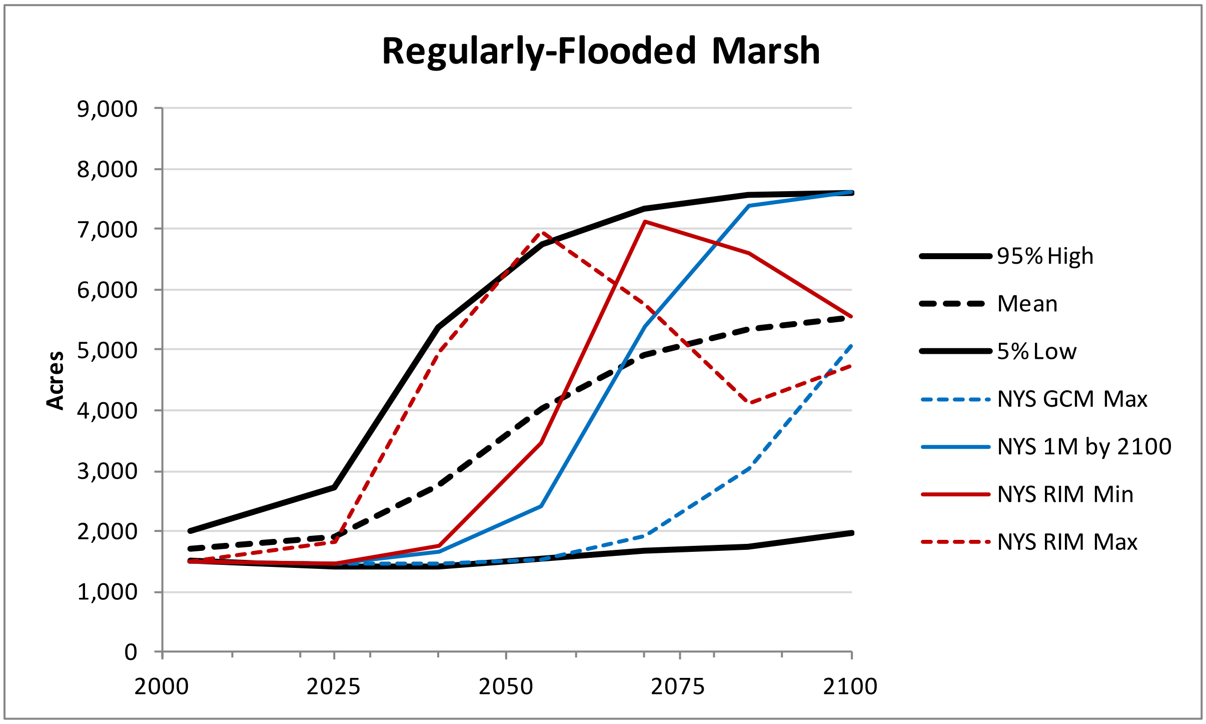
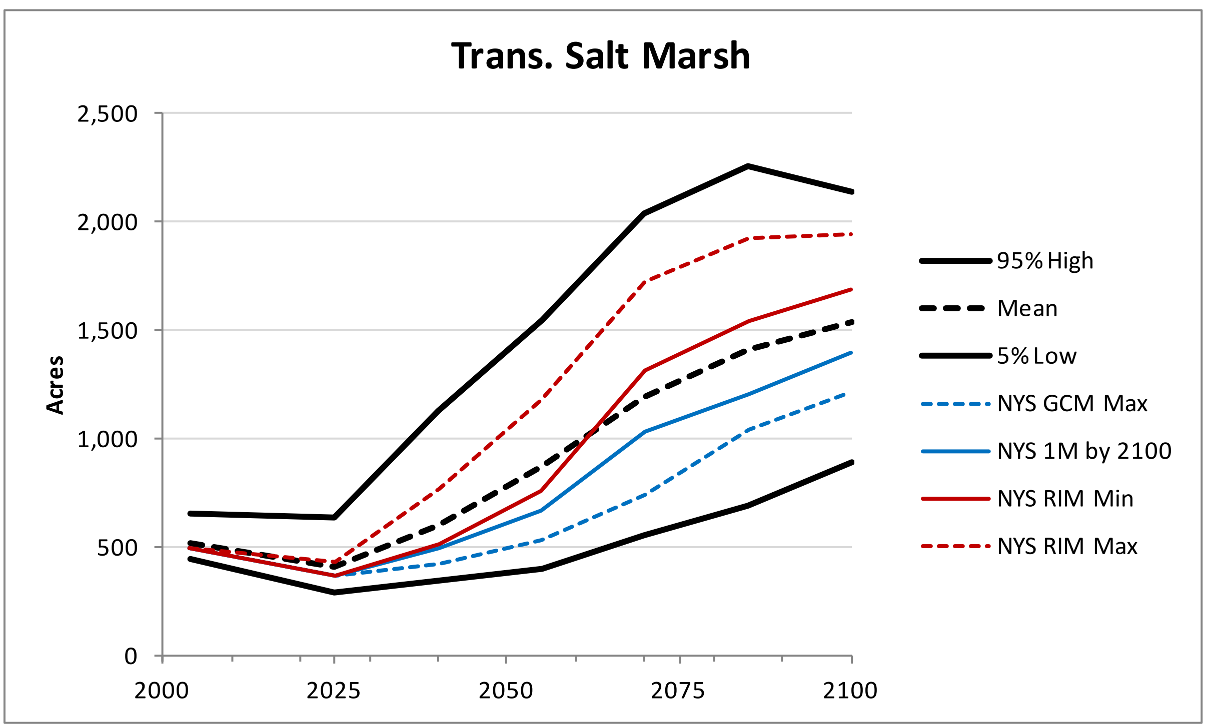


Figure E-10. Uncertainty time series for transitional salt marsh coverage in Nassau County



E.4 Suffolk West

Figure E-11. Uncertainty time series for undeveloped dry land coverage in Suffolk County, west area

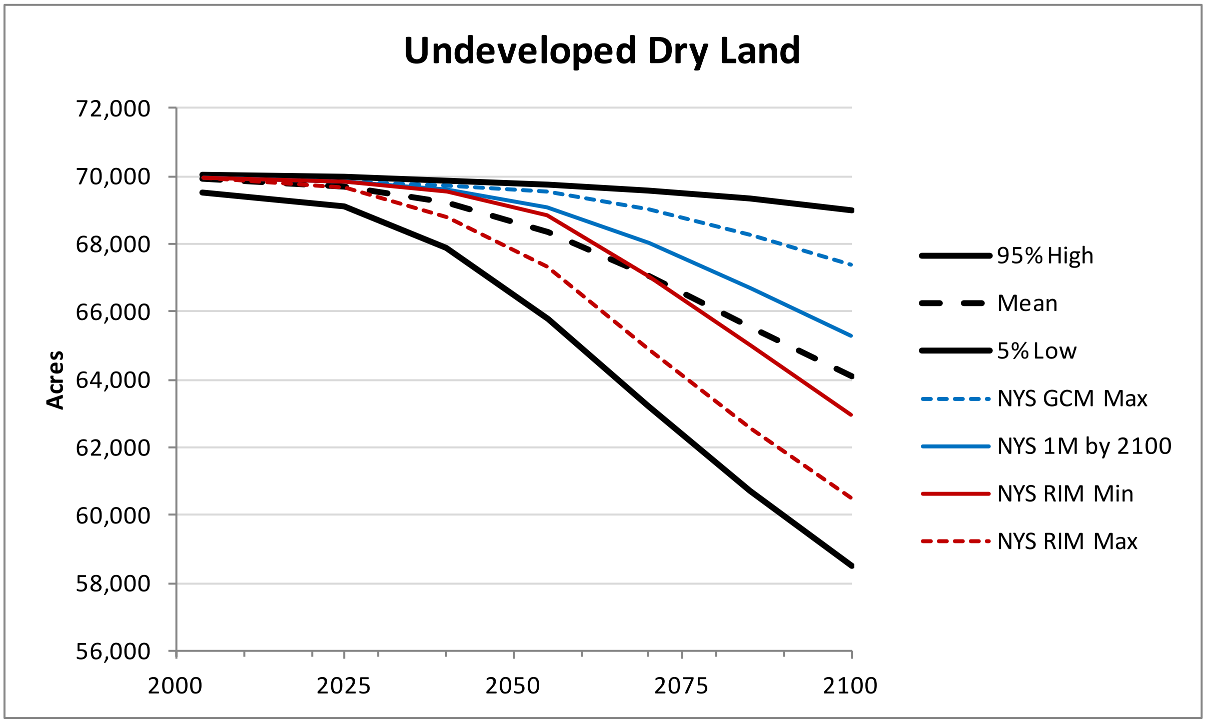


Figure E-12. Uncertainty time series for developed dry land coverage in Suffolk County, west area

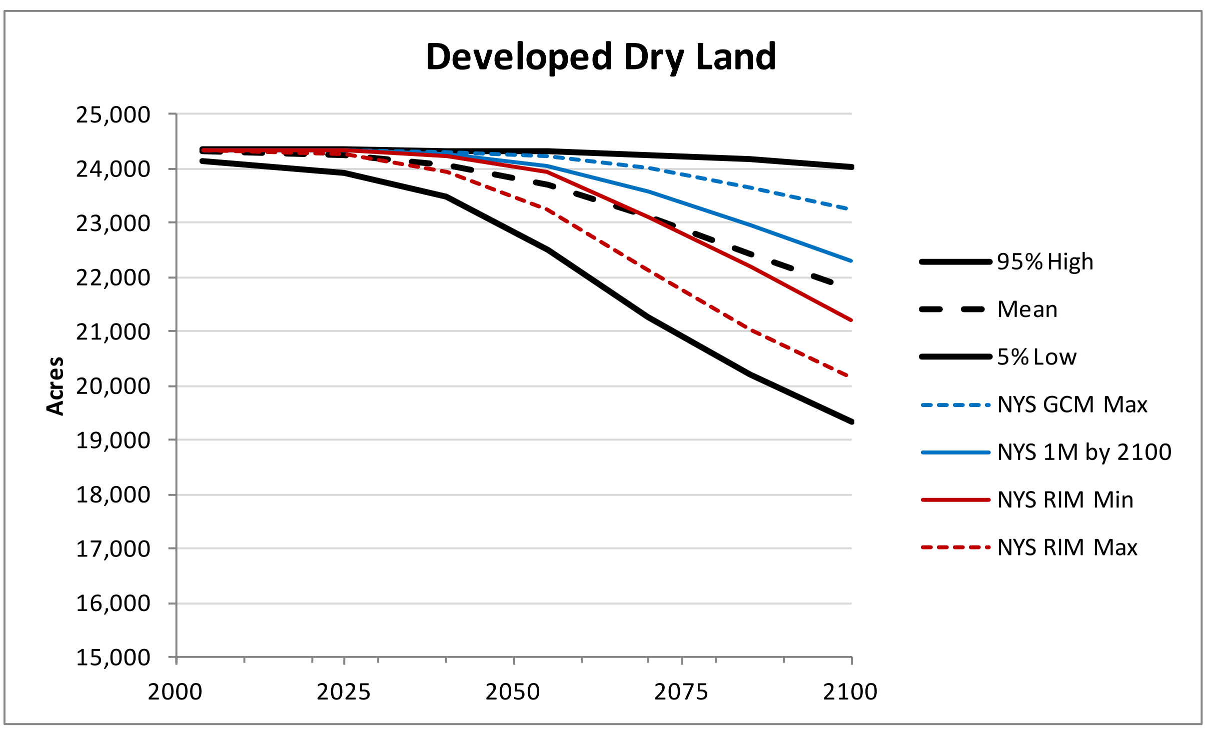


Figure E-13. Uncertainty time series for flooded developed dry land coverage in Suffolk County, west area

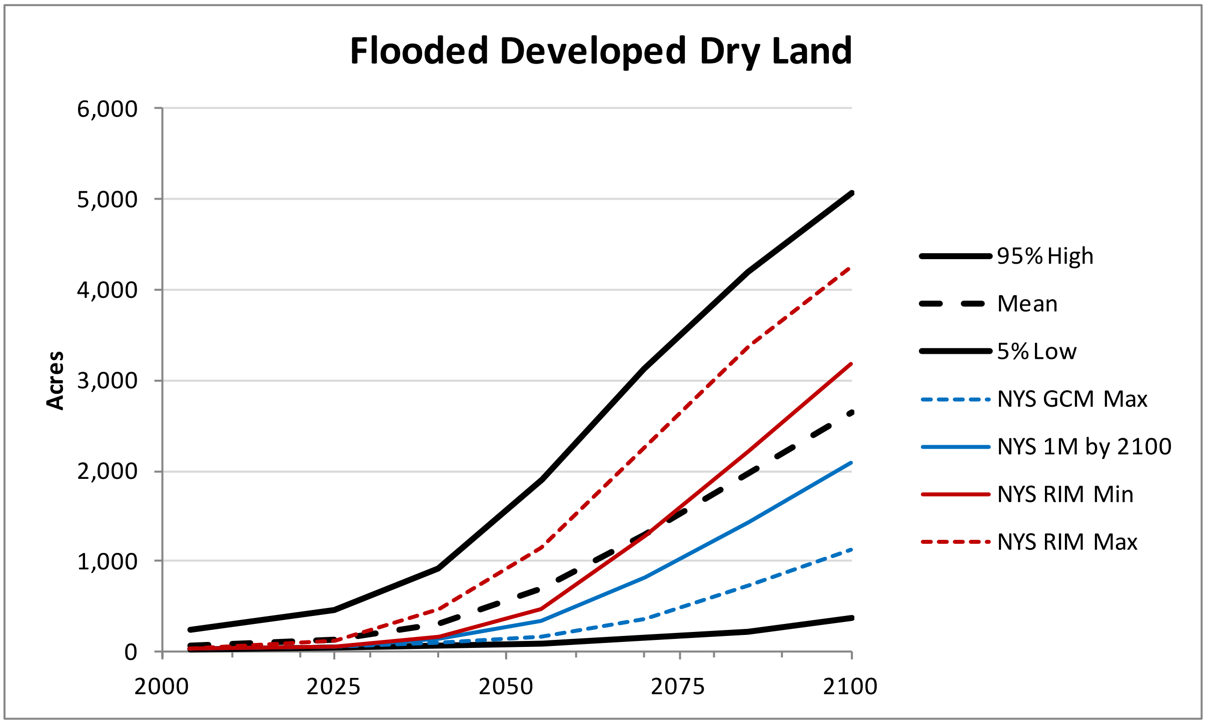


Figure E-14. Uncertainty time series for irregularly flooded marsh coverage in Suffolk County, west area

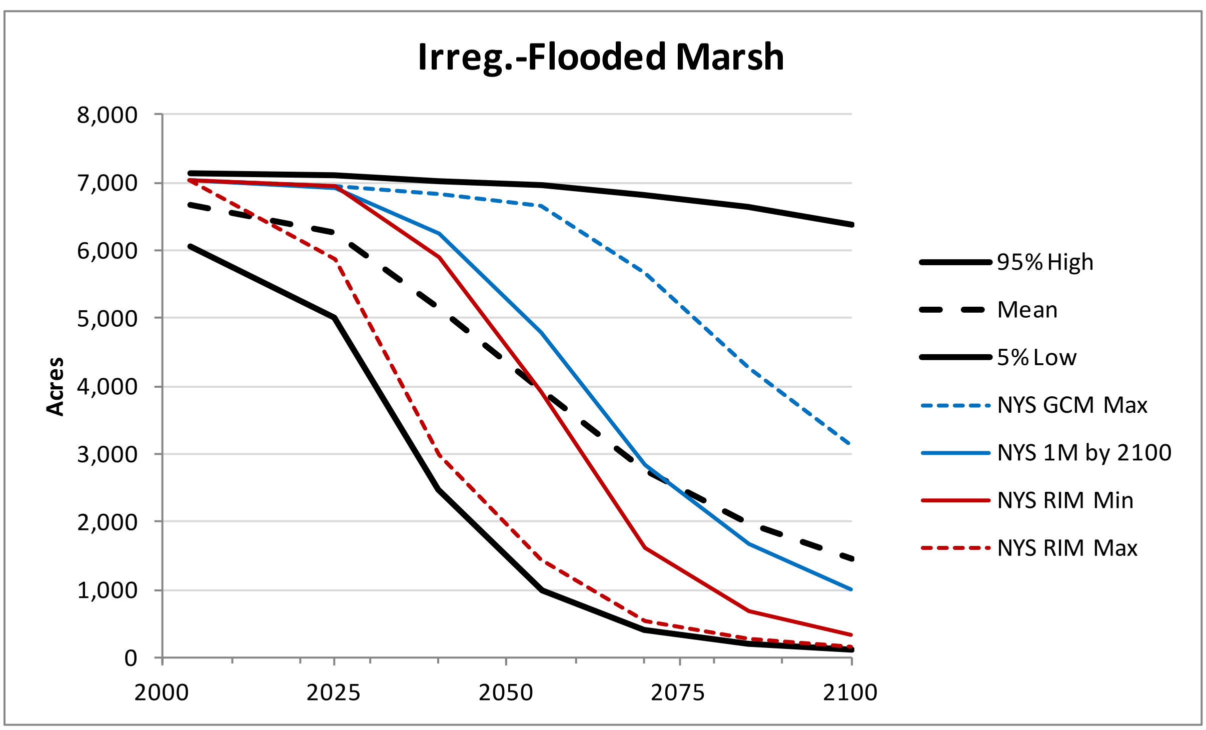


Figure E-15. Uncertainty time series for swamp coverage in Suffolk County, west area

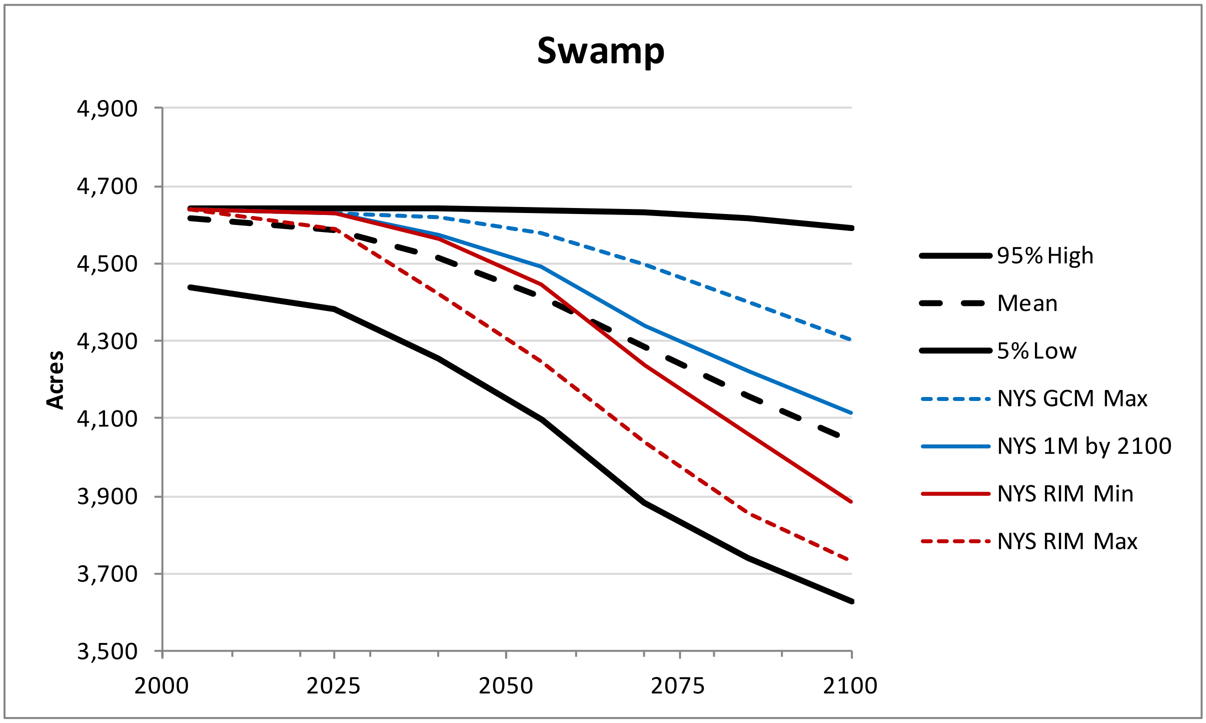


Figure E-16. Uncertainty time series for estuarine beach coverage in Suffolk County, west area

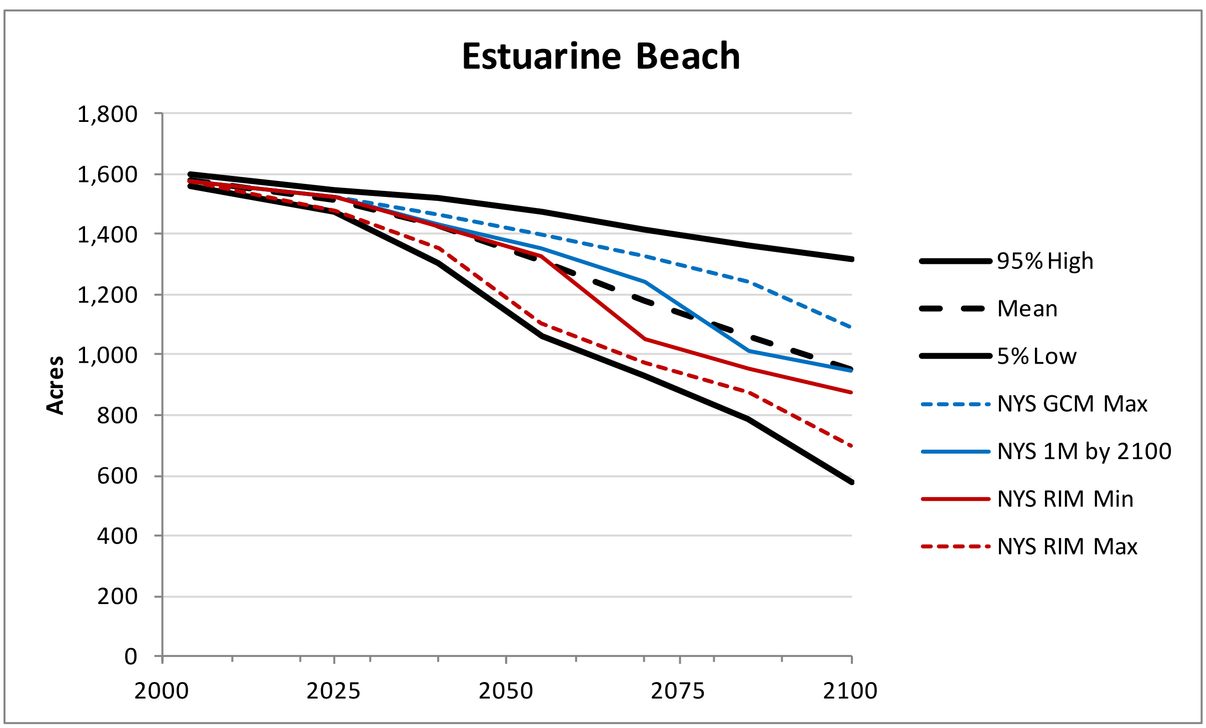


Figure E-17. Uncertainty time series for regularly flooded marsh coverage in Suffolk County, west area

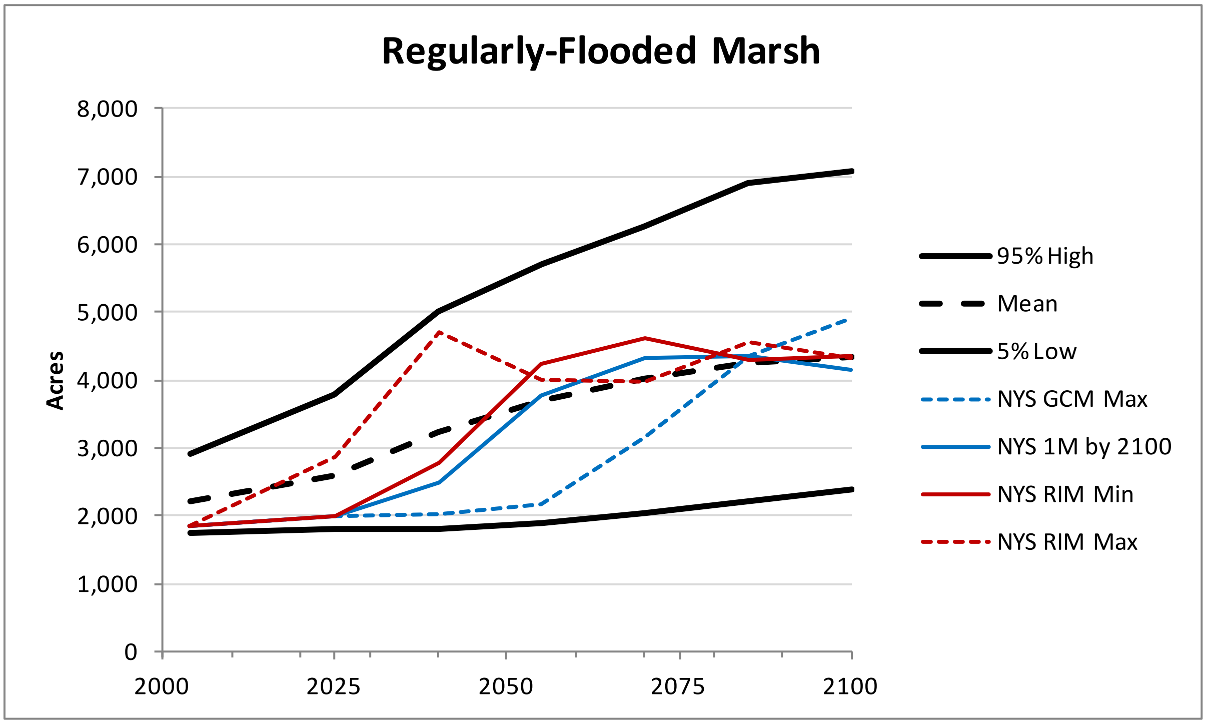
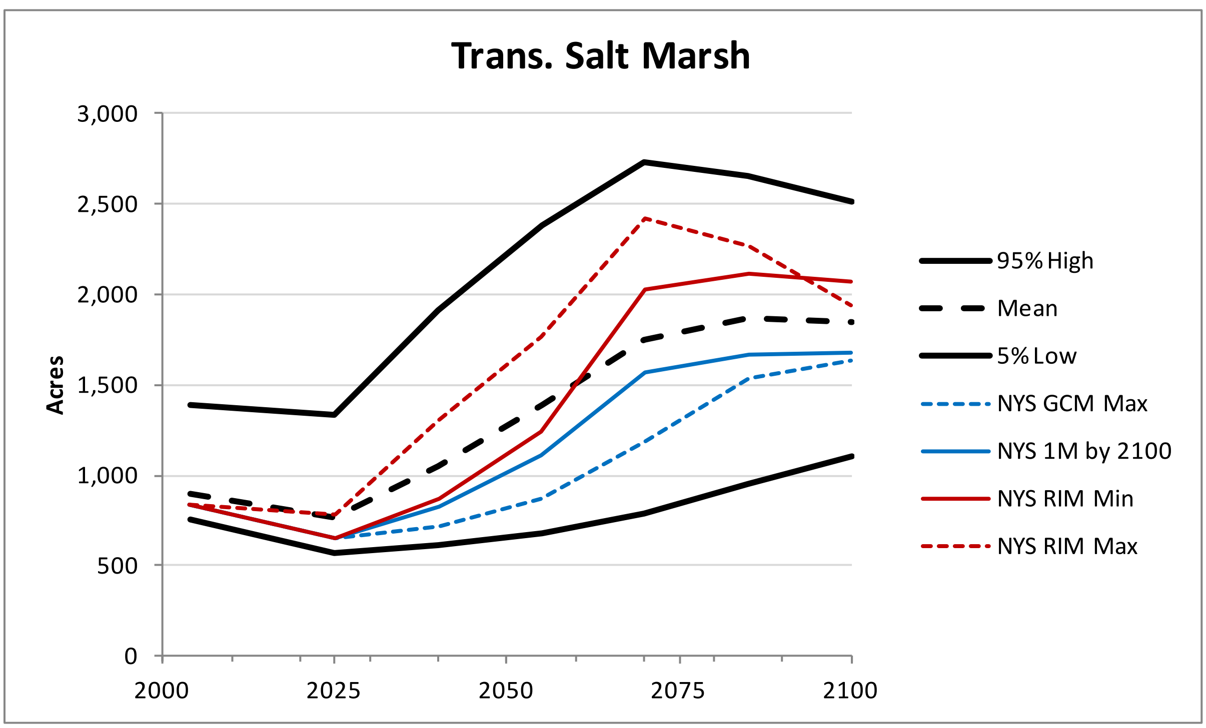


Figure E-18. Uncertainty time series for transitional salt marsh coverage in Suffolk County, west area



E.5 Suffolk East

Figure E-19. Uncertainty time series for undeveloped dry land coverage in Suffolk County, east area

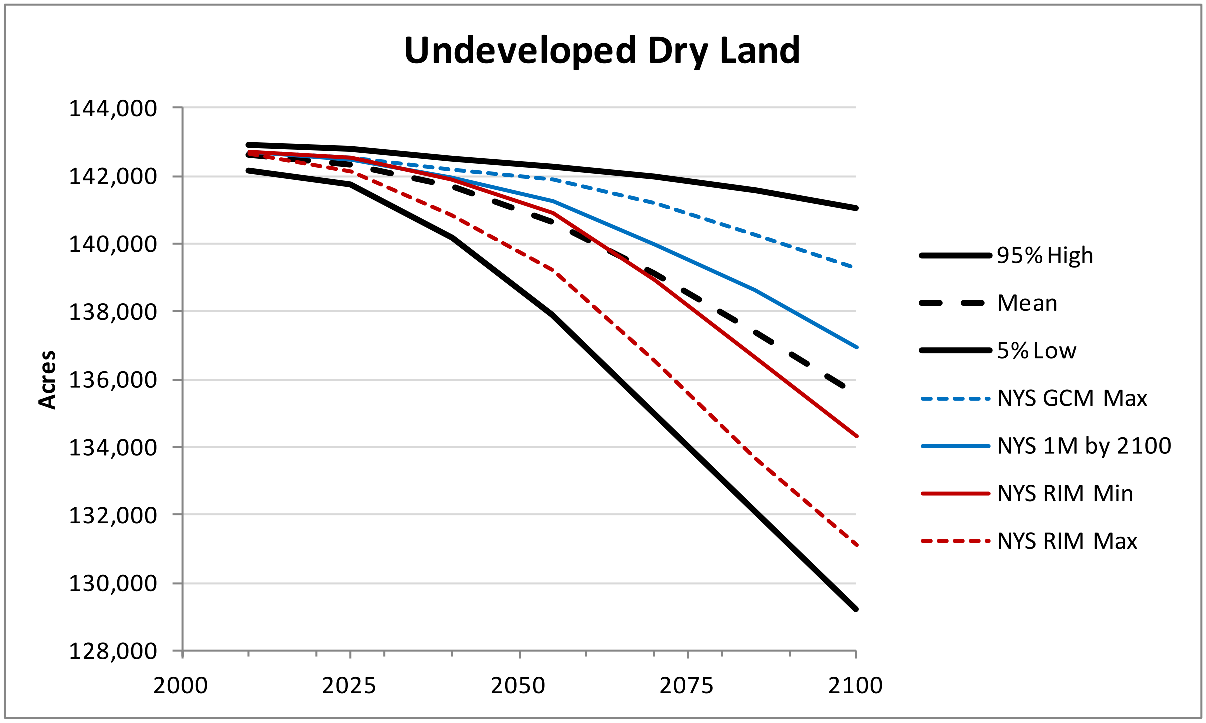


Figure E-20. Uncertainty time series for developed dry land coverage in Suffolk County, east area

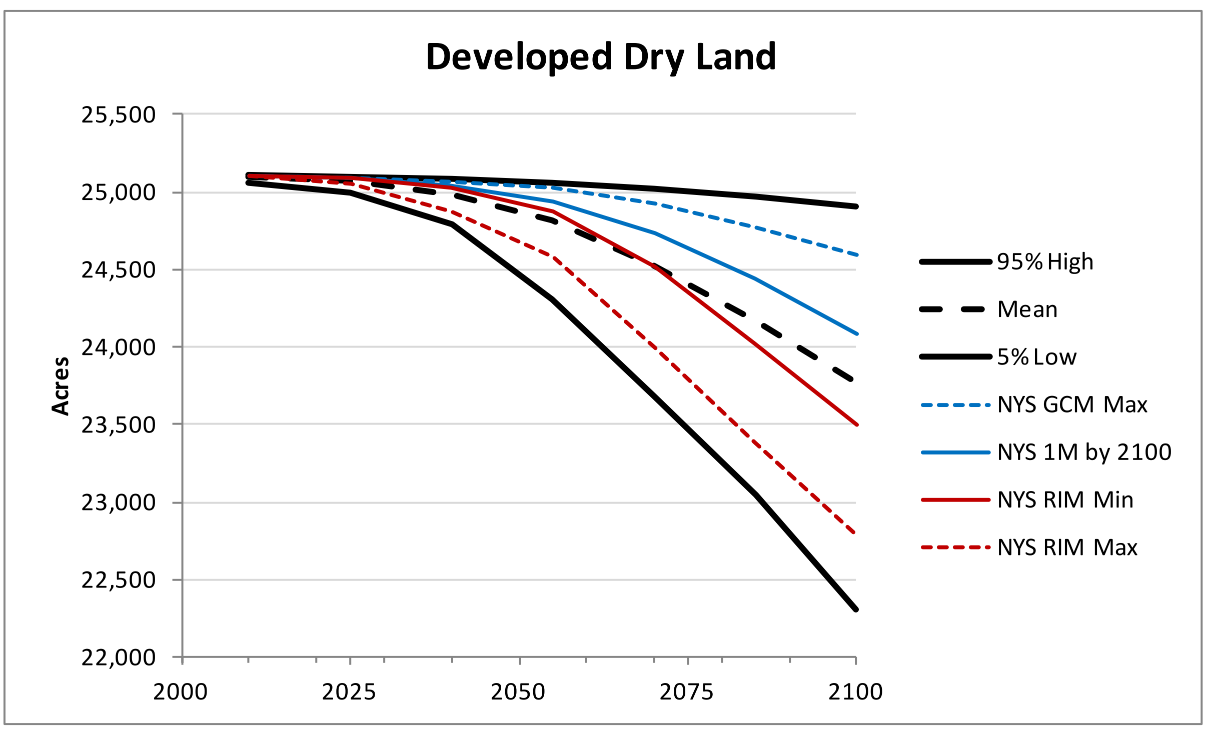


Figure E-21. Uncertainty time series for flooded developed dry land coverage in Suffolk County, east area

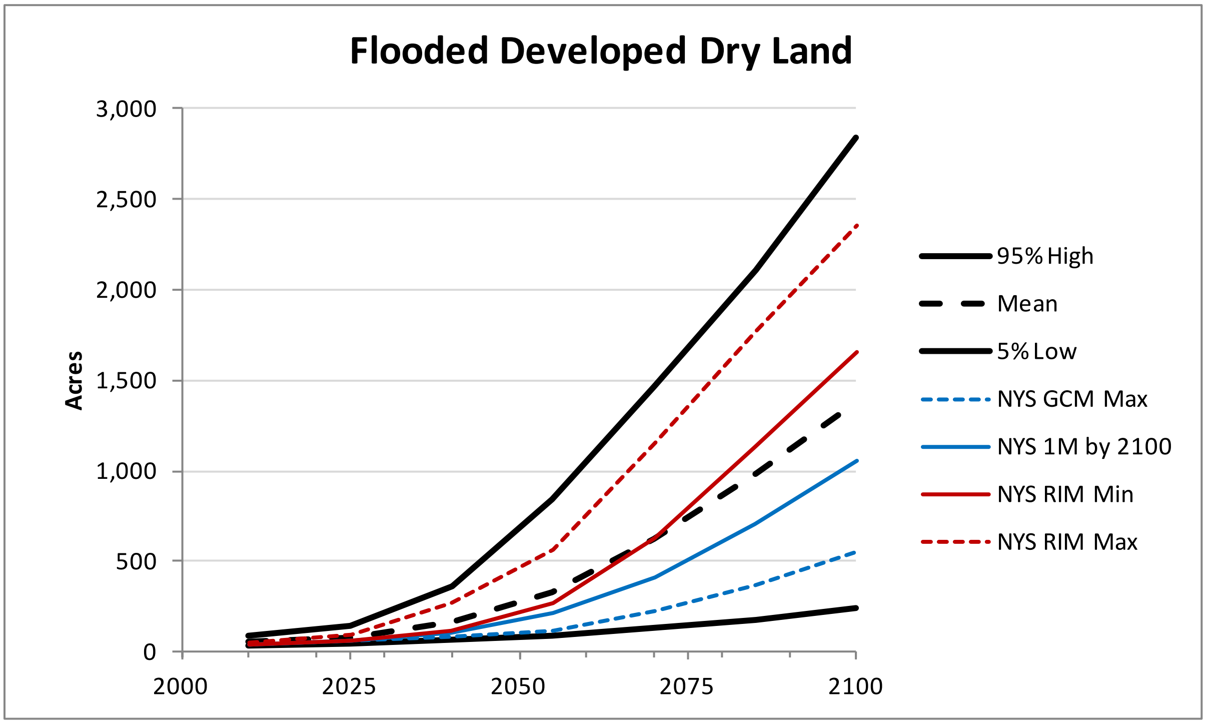


Figure E-22. Uncertainty time series for irregularly flooded marsh coverage in Suffolk County, east area

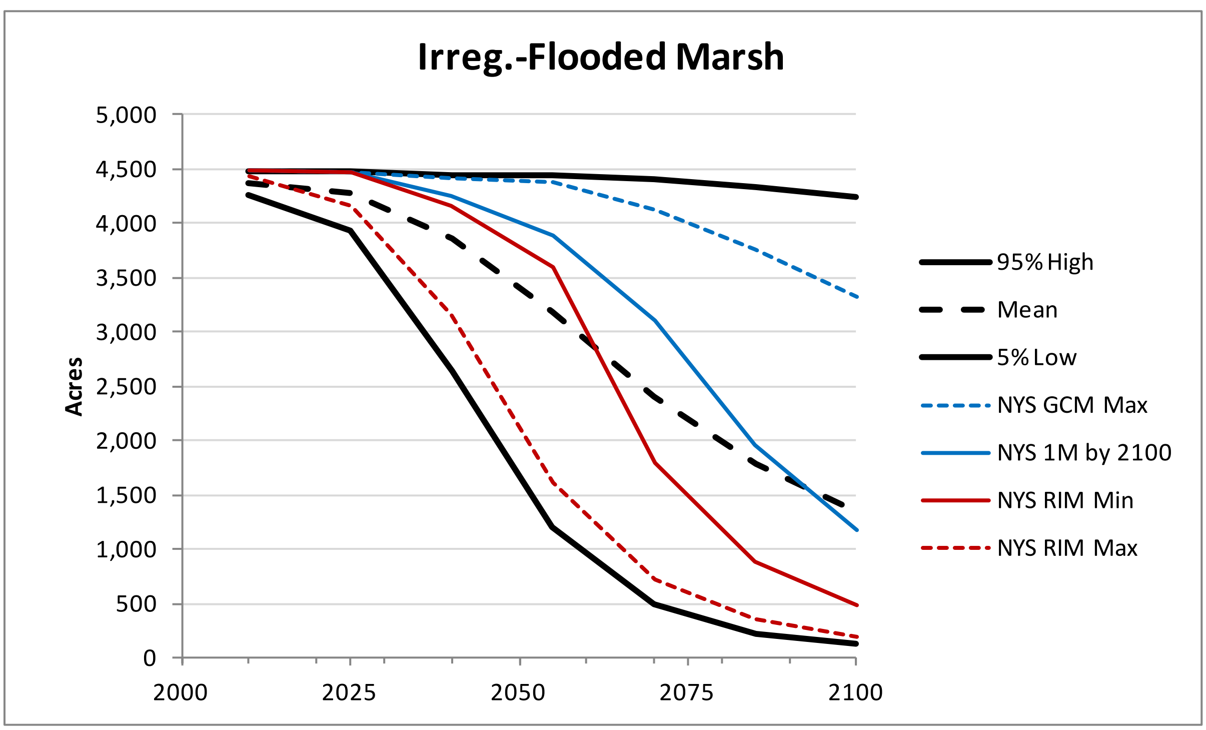


Figure E-23. Uncertainty time series for swamp coverage in Suffolk County, east area

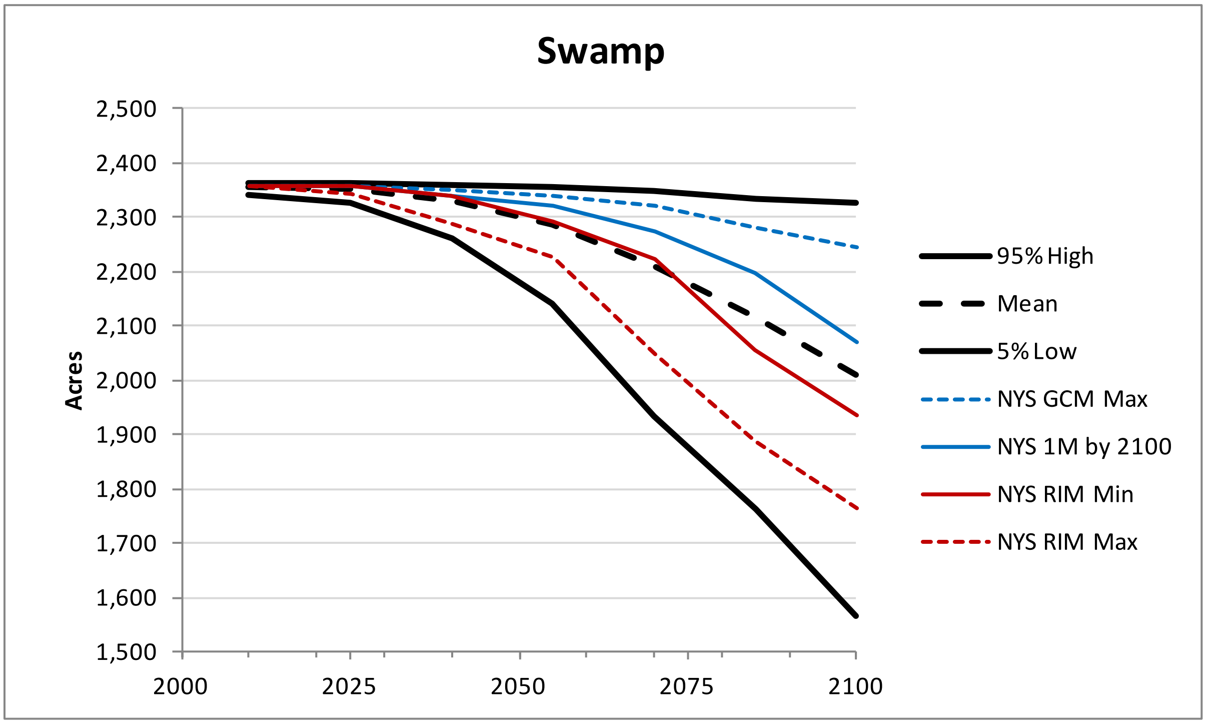


Figure E-24. Uncertainty time series for regularly flooded marsh coverage in Suffolk County, east area

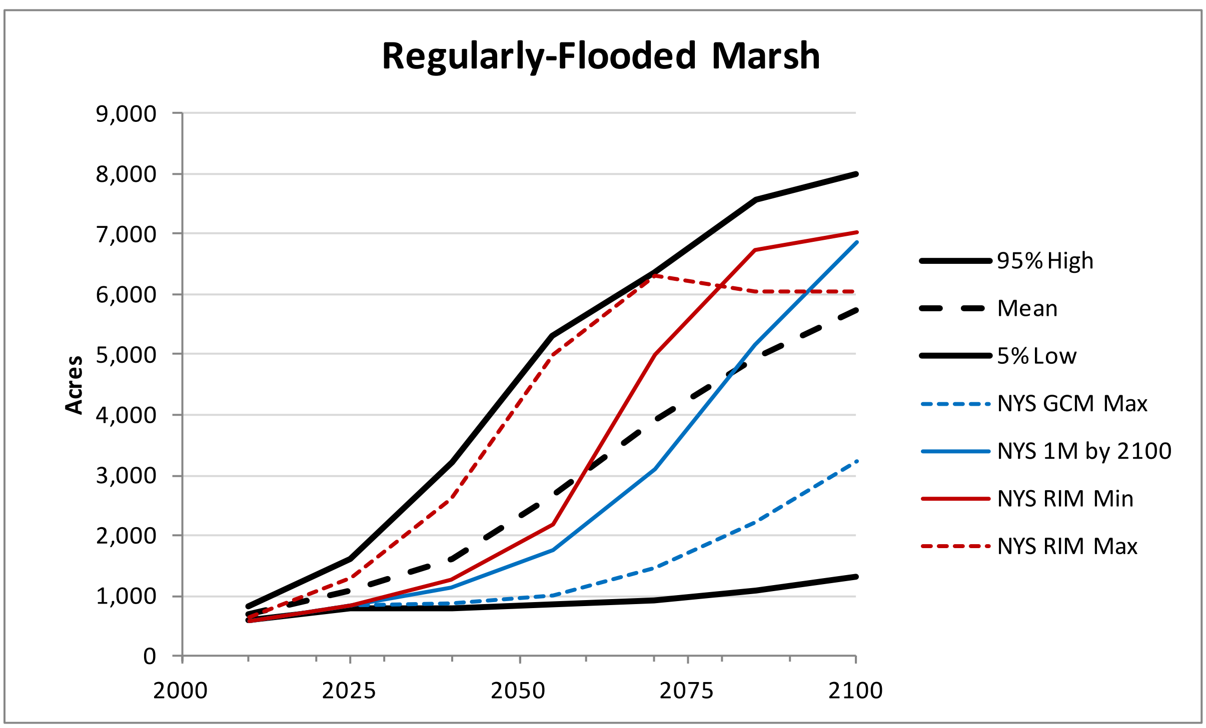
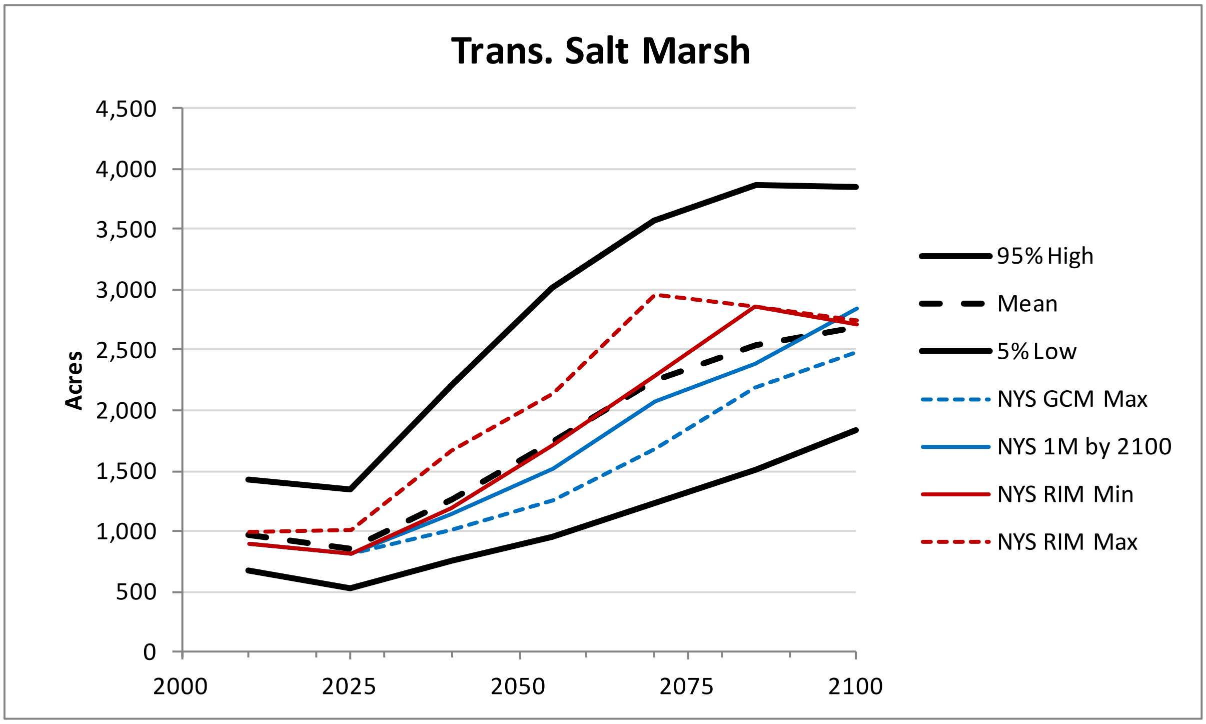


Figure E-25. Uncertainty time series for transitional salt marsh coverage in Suffolk County, east area



Appendix F: Uncertainty Histograms

F.1 Hudson

Figure F-1. Histogram for Tidal Flat for the Hudson Study Area in 2100 (acres)

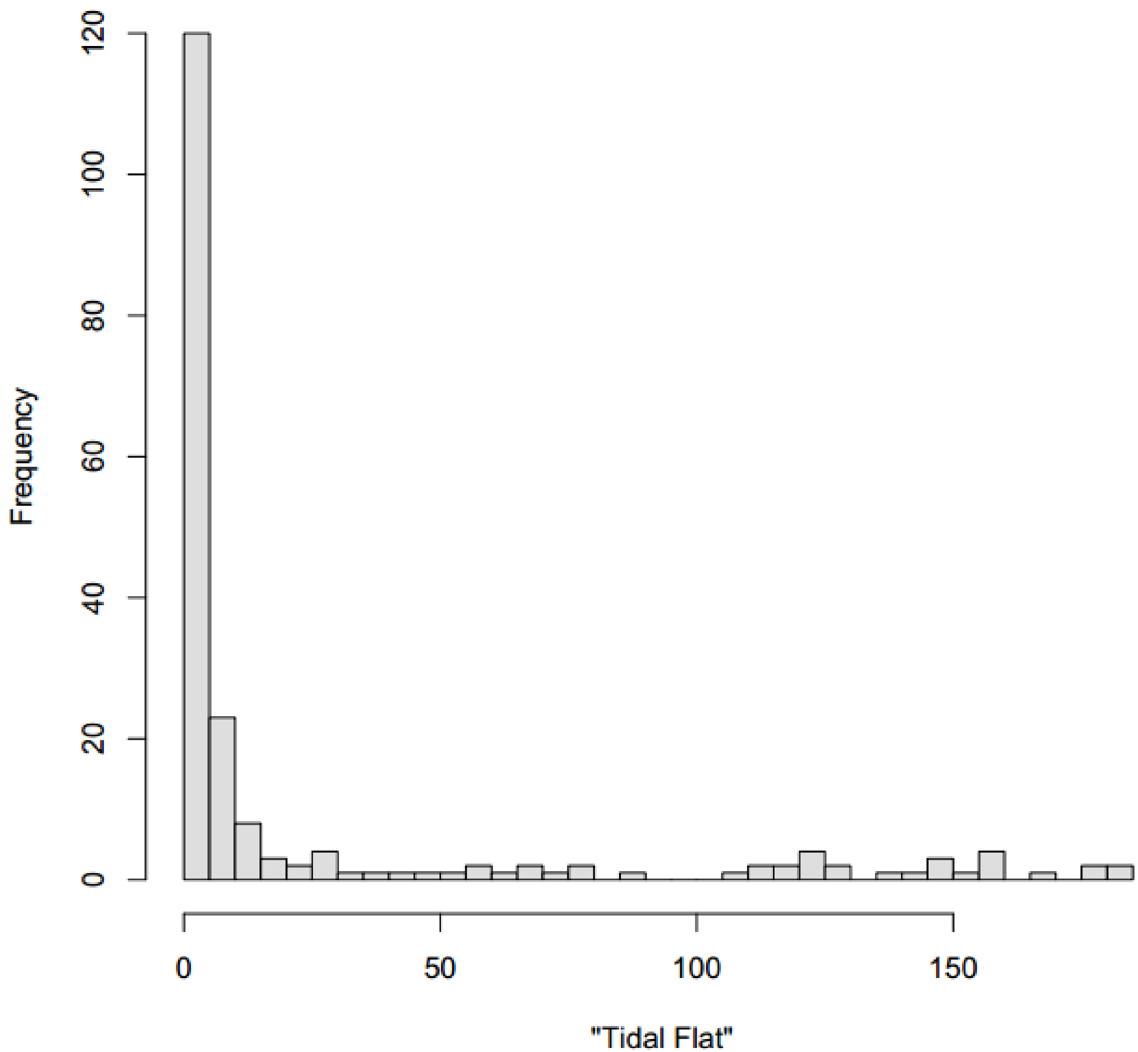


Figure F-2. Histogram for Developed Dry Land for the Hudson Study Area in 2100 (acres)

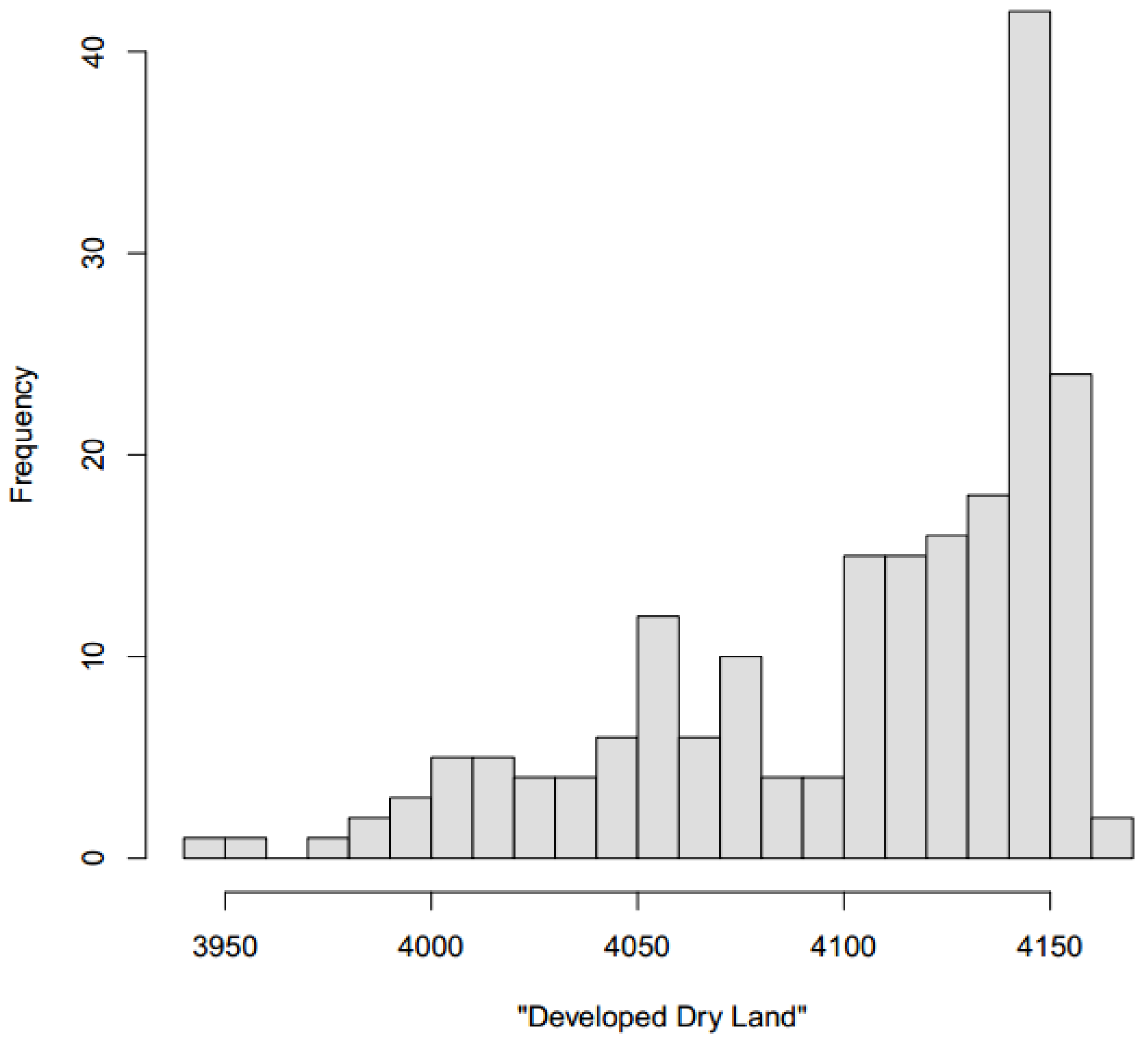
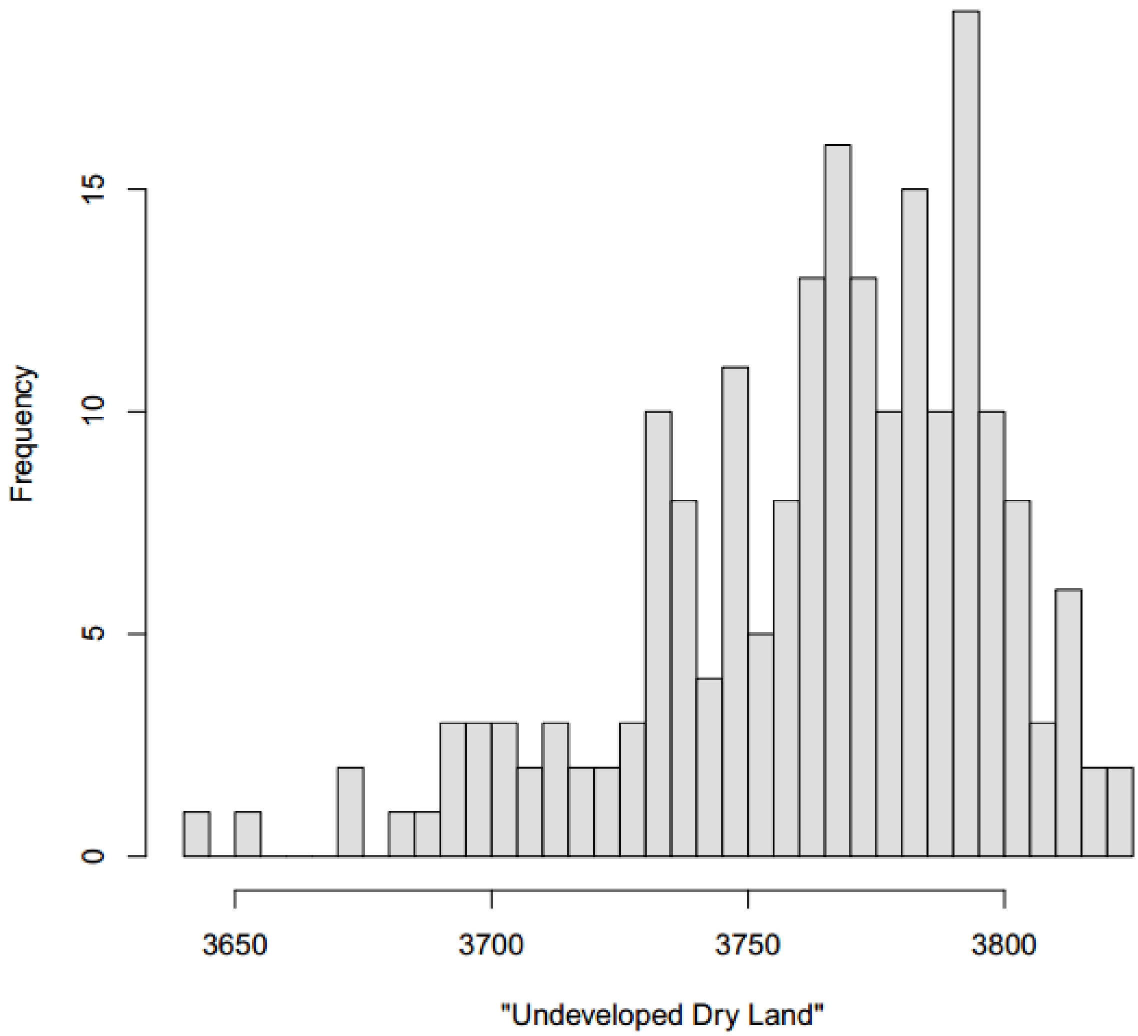


Figure F-3. Histogram for Undeveloped Dry Land for the Hudson Study Area in 2100 (acres)



F.2 New York City

Figure F-4. Histogram for Irregularly Flooded Marsh for the NYC Study Area in 2100 (acres)

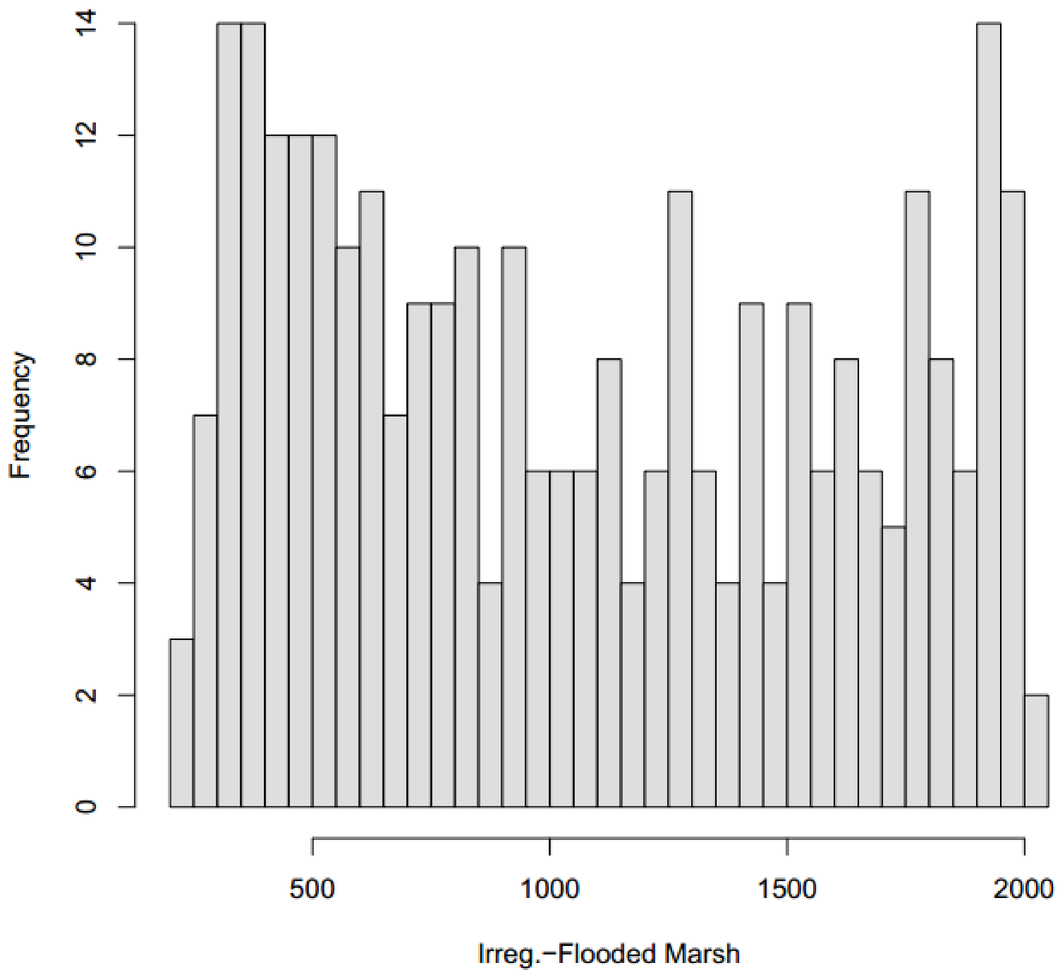
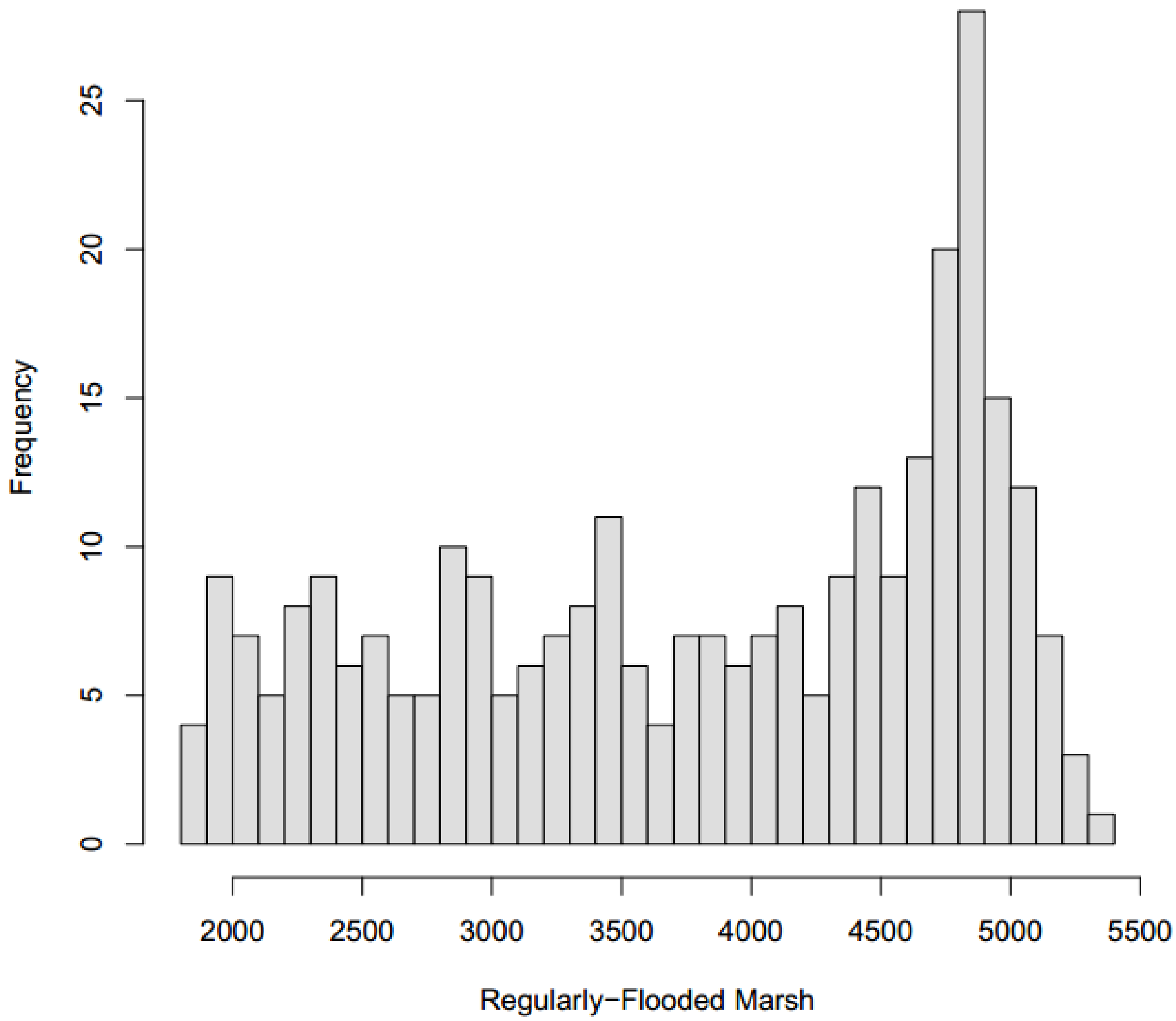


Figure F-5. Histogram for Regularly Flooded Marsh for the NYC Study Area in 2100 (acres)



F.3 Nassau

Figure F-6. Histogram for Developed Dry Land for the Nassau County Study Area in 2100 (acres)

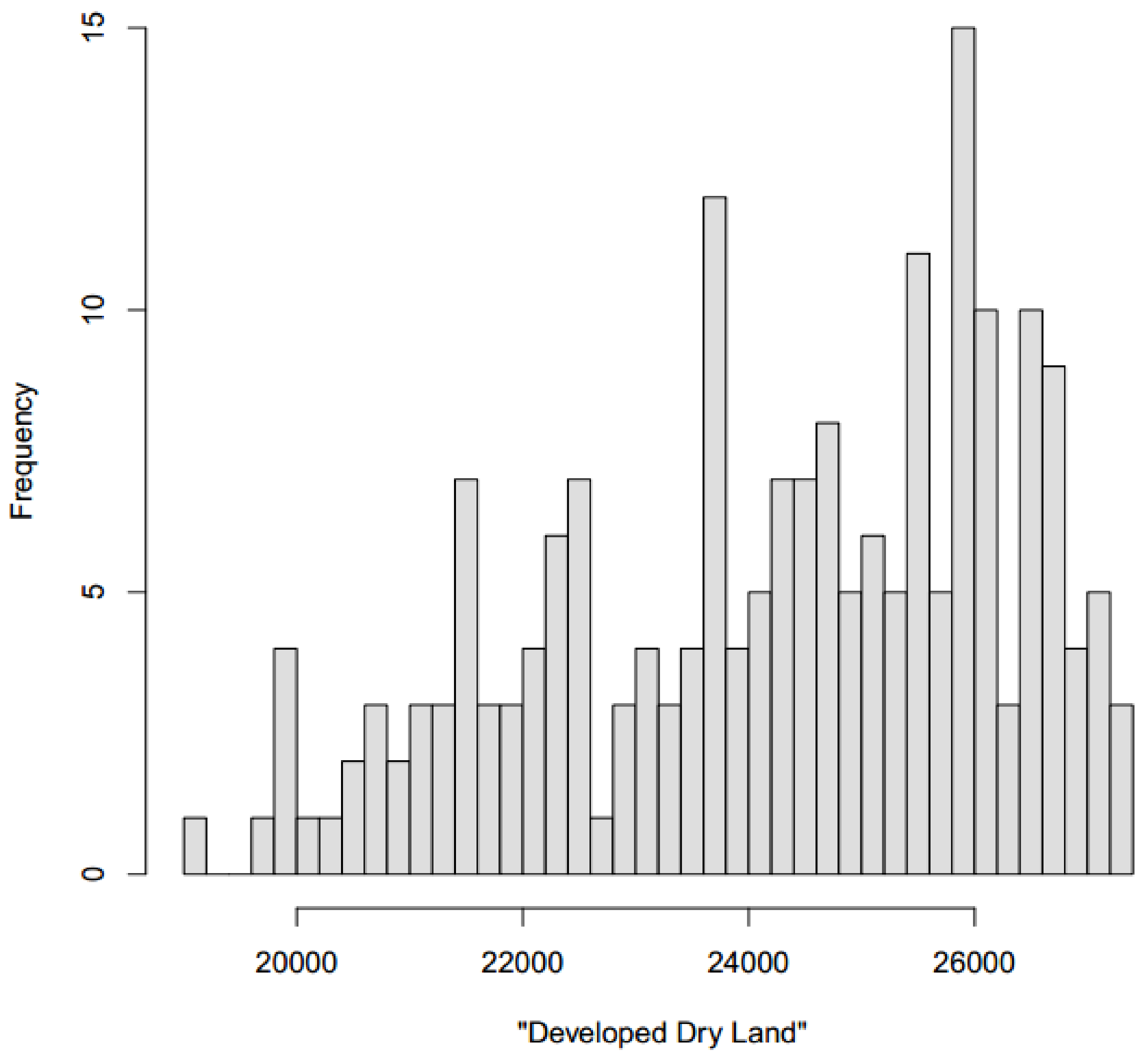


Figure F-7. Histogram for Transitional Marsh for the Nassau County Study Area in 2100 (acres)

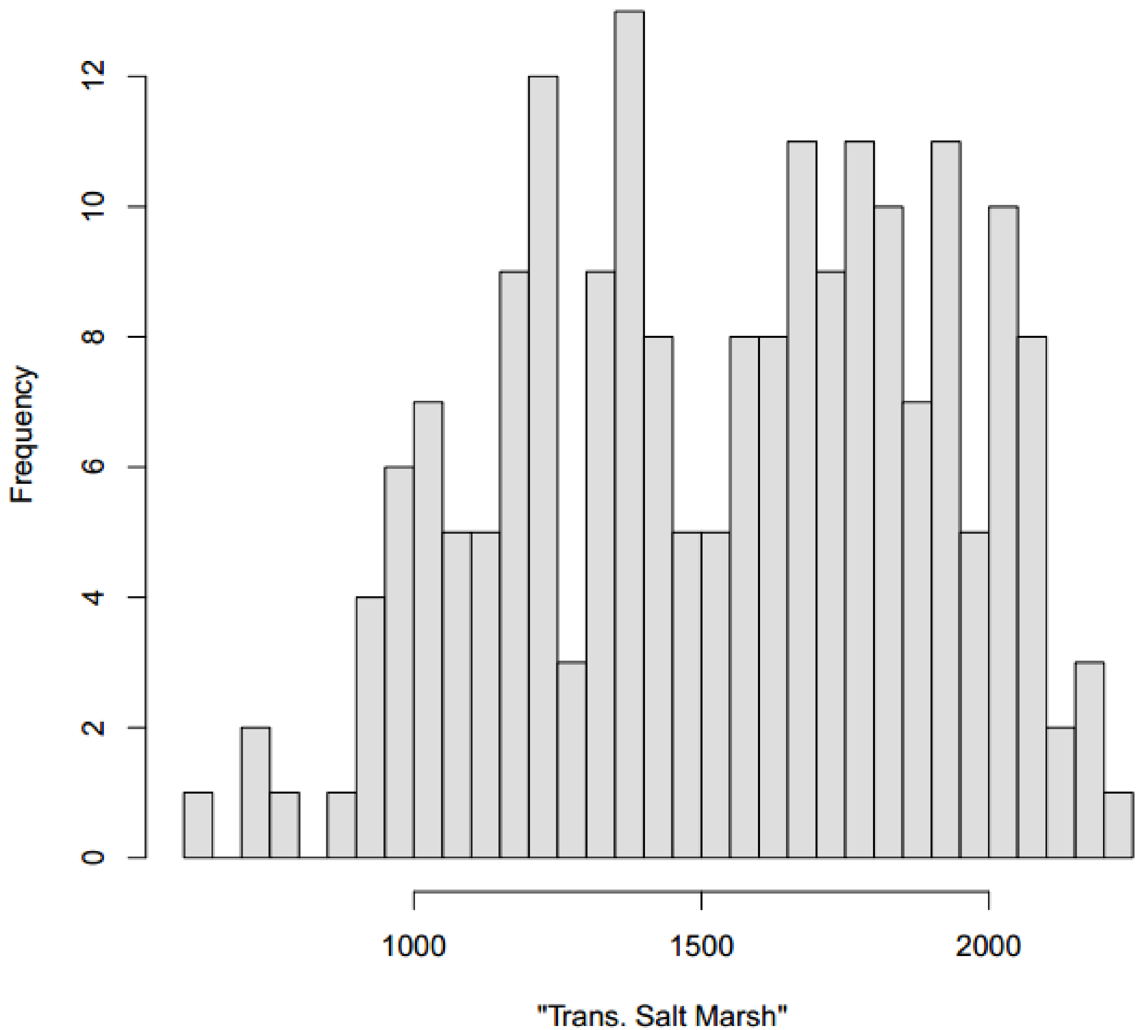
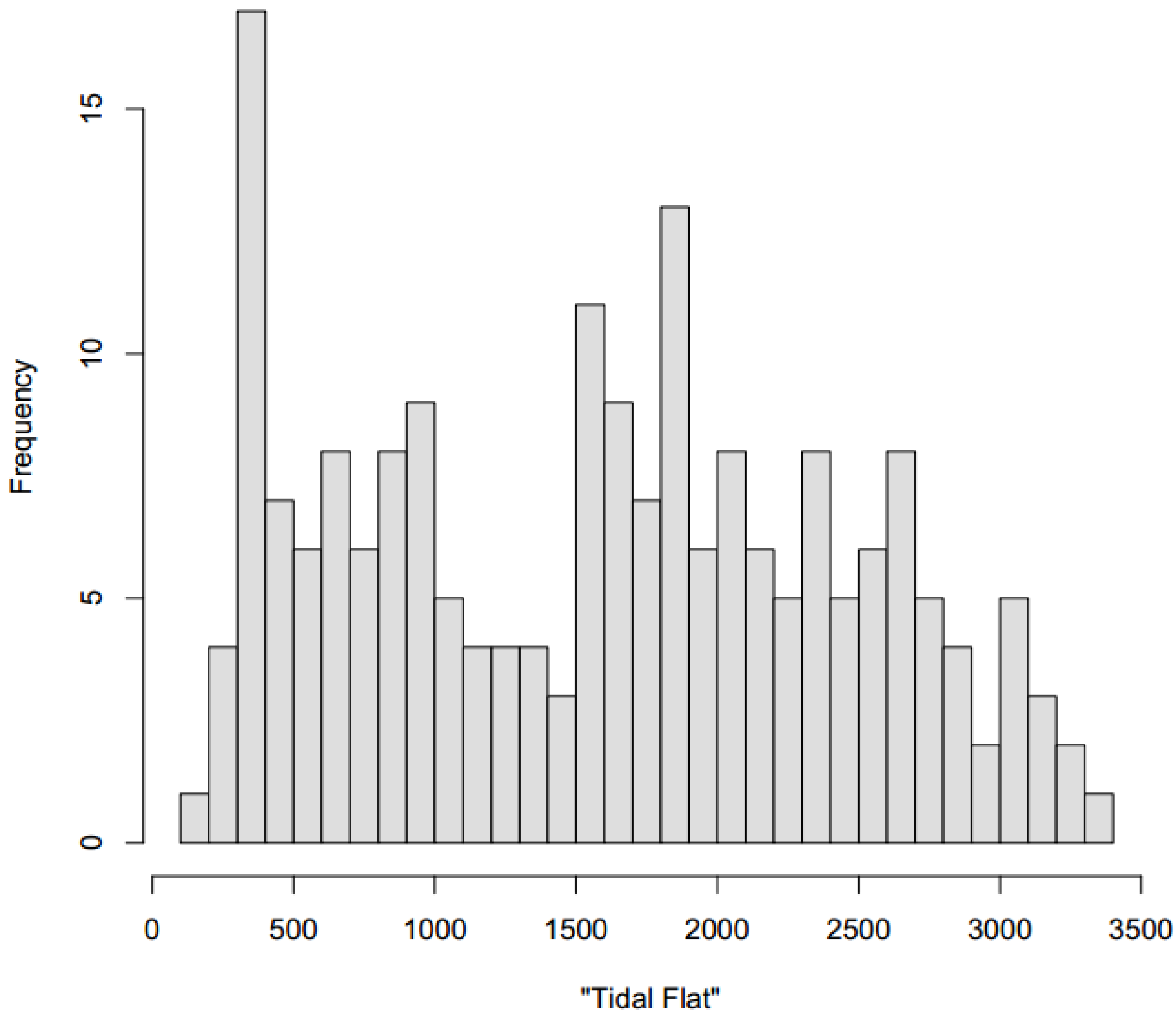


Figure F-8. Histogram Tidal Flat for the Nassau County Study Area in 2100 (acres)



F.4 Suffolk West

Figure F-9. Histogram Developed Dry Land for the Suffolk West Study Area in 2100 (acres)

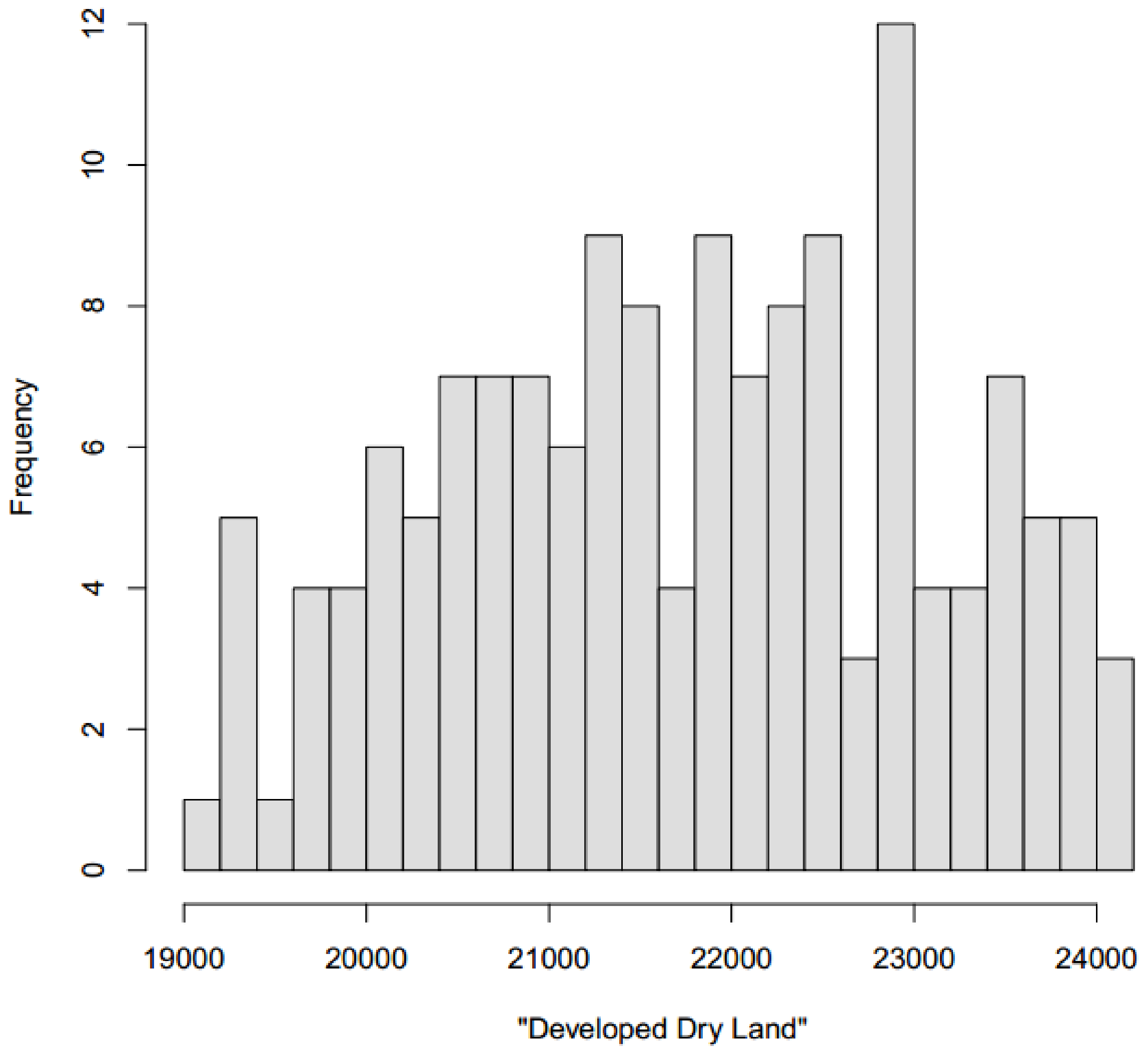


Figure F-10. Histogram Undeveloped Dry Land for the Suffolk West Study Area in 2100 (acres)

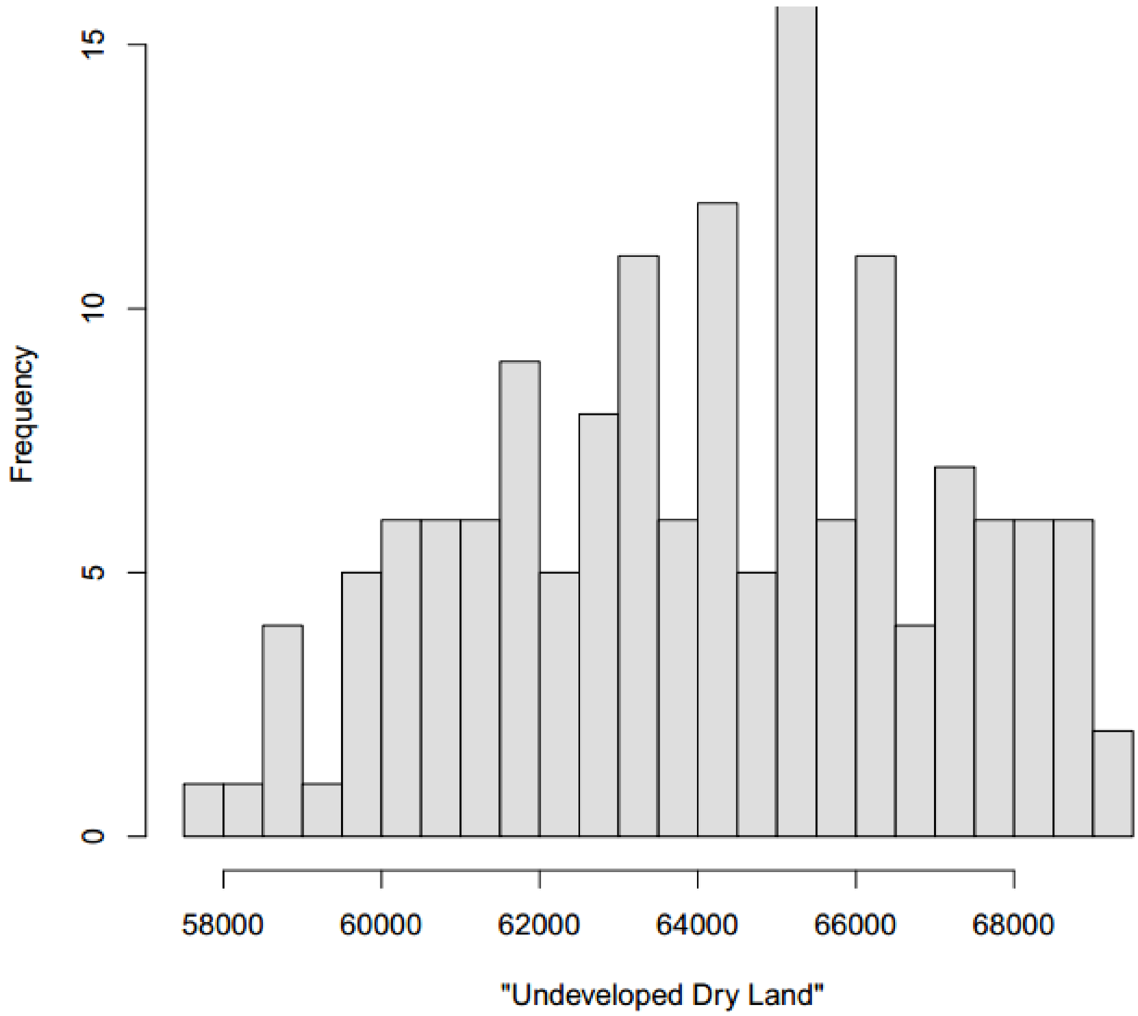
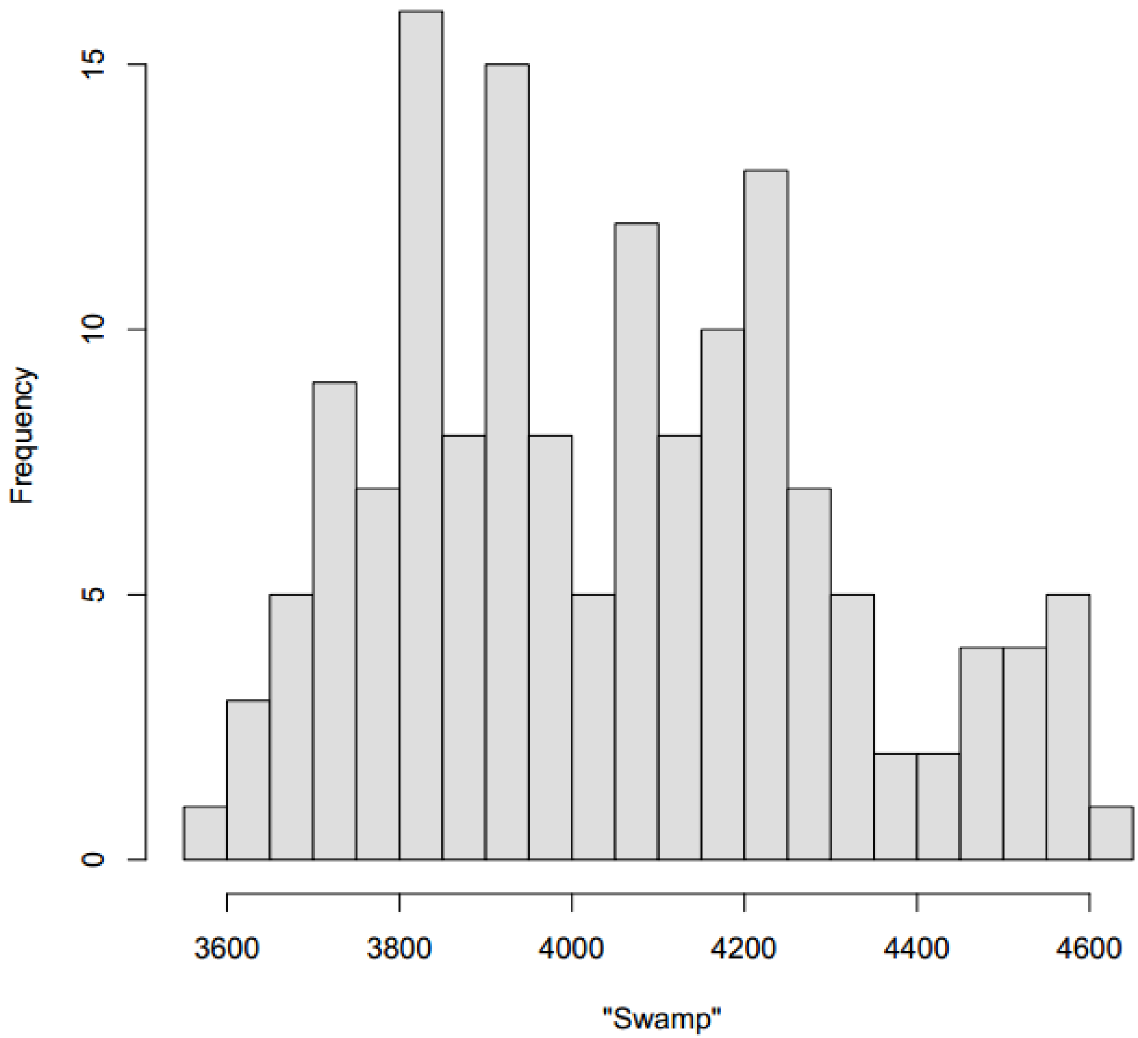


Figure F-11. Histogram Swamp for the Suffolk West Study Area in 2100 (acres)



F.5 Suffolk East

Figure F-12. Histogram for Regularly Flooded Marsh for the Suffolk East Study Area in 2100 (acres)

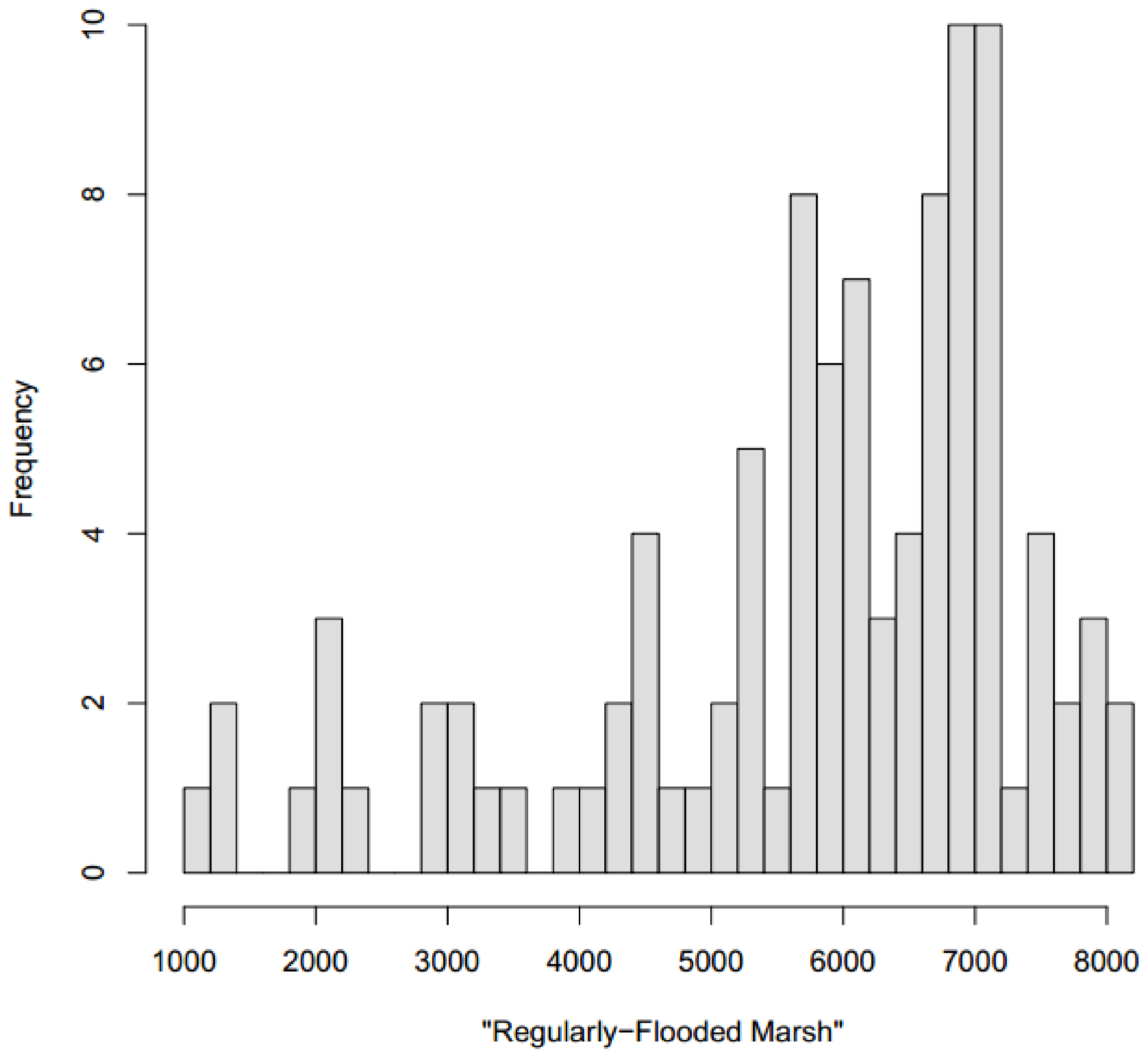


Figure 1.3 Histogram for Irregularly Flooded Marsh for the Suffolk East Study Area in 2100 (acres)

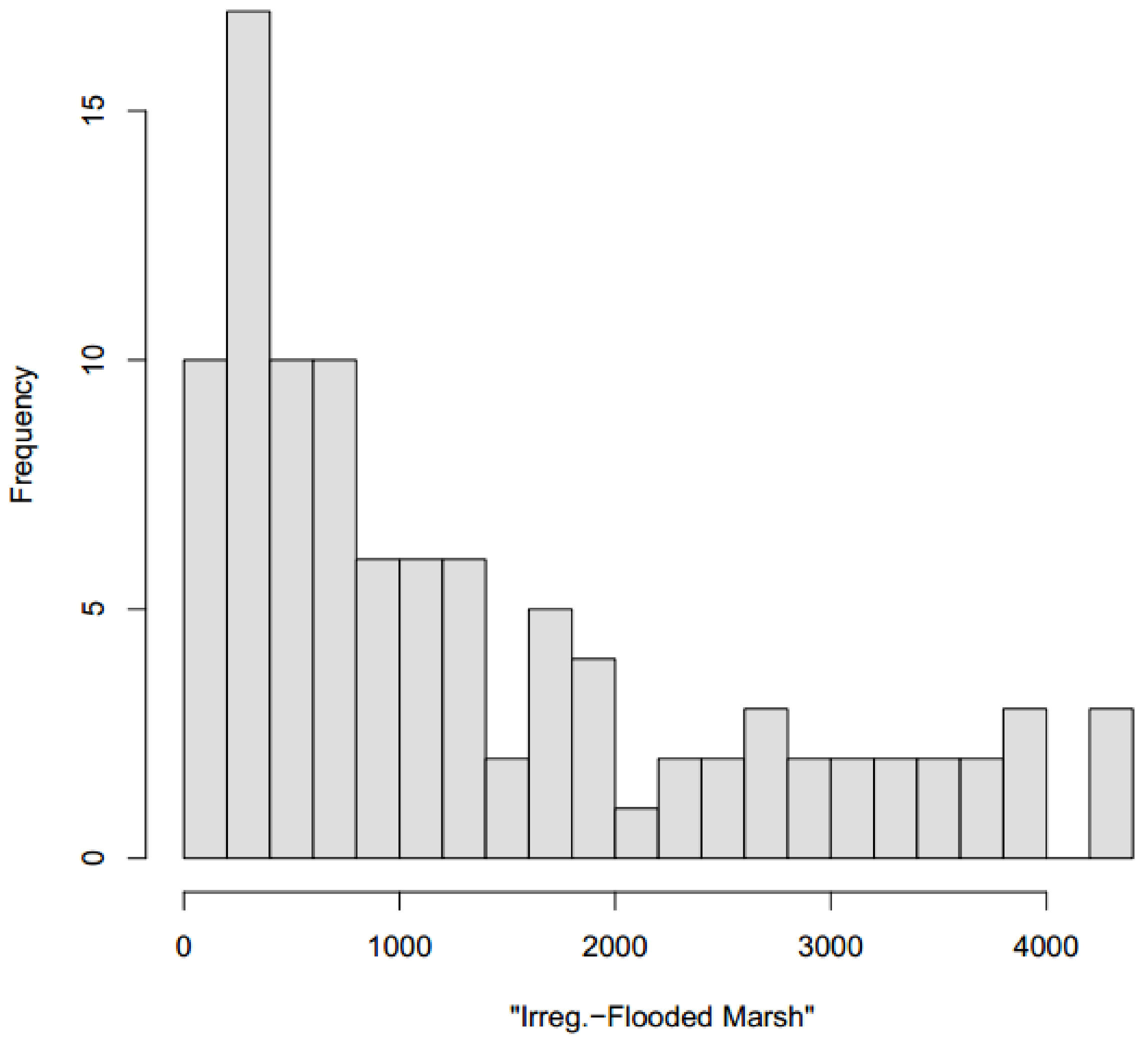
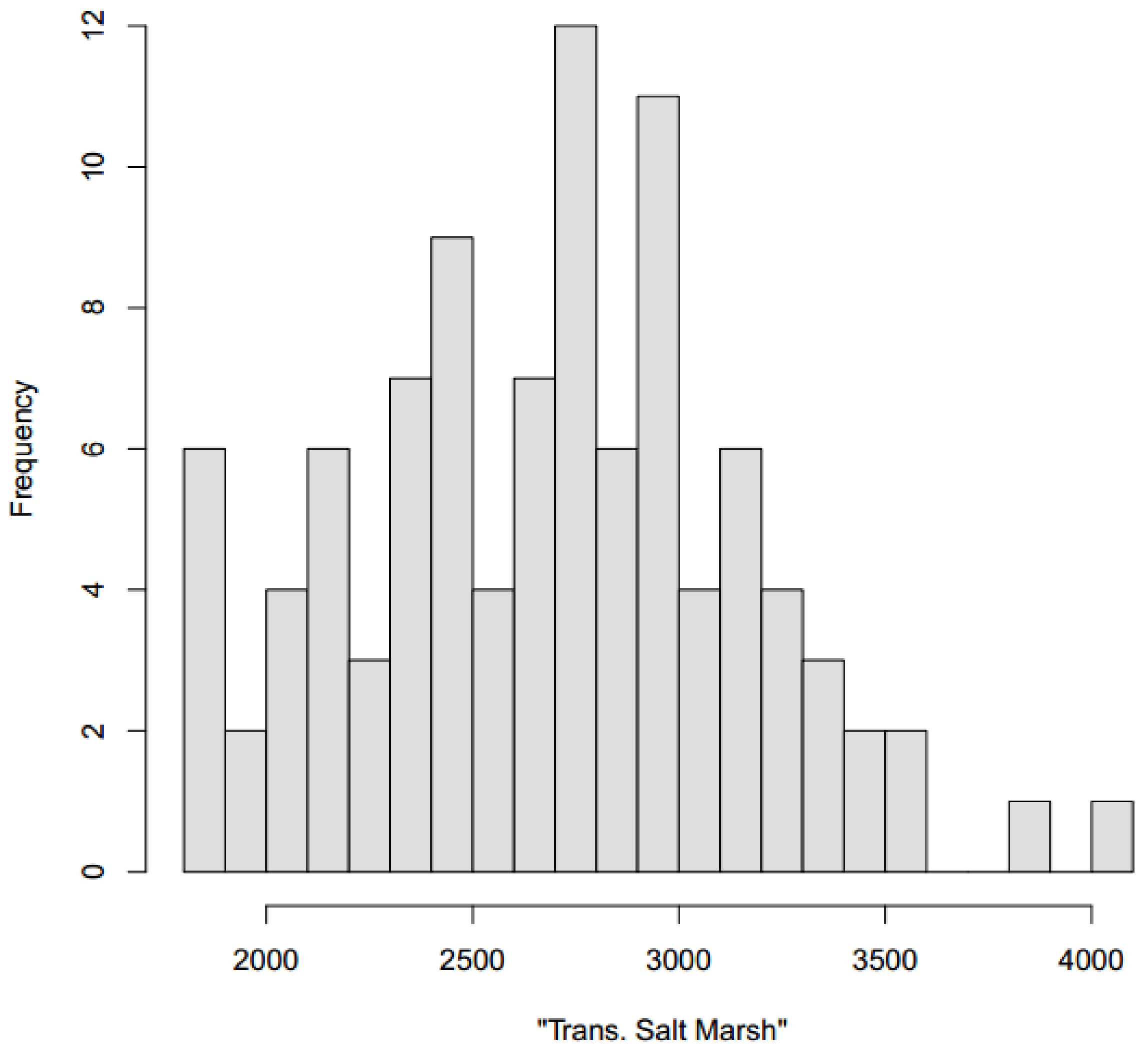


Figure F-14. Histogram for Transitional Salt Marsh for the Suffolk East Study Area in 2100 (acres)



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Application of Sea-Level Affecting Marshes Model (SLAMM) to Long Island, NY and New York City

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State of New York
Andrew M. Cuomo, Governor

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