Appendix I

Erin Victory/TCI

Refuge beaches

SLAMM (Sea Level Affecting Marshes Model) Analysis

Application of the Sea-Level Affecting Marshes Model (SLAMM 5.0) to Nomans Land Island NWR

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Introduction

Tidal marshes are among the most susceptible ecosystems to climate change, especially accelerated sea level rise (SLR). The International Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) suggested that global sea level will increase by approximately 30 cm to 100 cm by 2100 (IPCC 2001). Rahmstorf (2007) suggests that this range may be too conservative and that the feasible range by 2100 could be 50 to 140 cm. Pfeffer et al. (2008) suggests that 200 cm by 2100 is at the upper end of plausible scenarios due to physical limitations on glaciological conditions. Rising sea level may result in tidal marsh submergence (Moorhead and Brinson 1995) and habitat migration as salt marshes transgress landward and replace tidal freshwater and brackish marsh (Park et al. 1991).

In an effort to address the potential effects of sea level rise on United States national wildlife refuges, the U. S. Fish and Wildlife Service contracted the application of the SLAMM model for most Region 4 refuges. This analysis is designed to assist in the production of comprehensive conservation plans (CCPs) for each refuge along with other long-term management plans.

Model Summary

Changes in tidal marsh area and habitat type in response to sea-level rise were modeled using the Sea Level Affecting Marshes Model (SLAMM 5.0) that accounts for the dominant processes involved in wetland conversion and shoreline modifications during long-term sea level rise (Park et al. 1989; www.warrenpinnacle.com/prof/SLAMM).

Successive versions of the model have been used to estimate the impacts of sea level rise on the coasts of the U.S. (Titus et al., 1991; Lee, J.K., R.A. Park, and P.W. Mausel. 1992; Park, R.A., J.K. Lee, and D. Canning 1993; Galbraith, H., R. Jones, R.A. Park, J.S. Clough, S. Herrod-Julius, B. Harrington, and G. Page. 2002; National Wildlife Federation et al., 2006; Glick, Clough, et al. 2007; Craft et al., 2009.

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

- **Inundation:** The rise of water levels and the salt boundary are tracked by reducing elevations of each cell as sea levels rise, thus keeping mean tide level (MTL) constant at zero. The effects on each cell are calculated based on the minimum elevation and slope of that cell.
- **Erosion:** Erosion is triggered based on a threshold of maximum fetch and the proximity of the marsh to estuarine water or open ocean. When these conditions are met, horizontal erosion occurs at a rate based on site-specific data.
- **Overwash:** Barrier islands of under 500 meters width are assumed to undergo overwash during each 25-year time-step due to storms. Beach migration and transport of sediments are calculated.
- **Saturation:** Coastal swamps and fresh marshes can migrate onto adjacent uplands as a response of the fresh water table to rising sea level close to the coast.

- **Accretion:** Sea level rise is offset by sedimentation and vertical accretion using average or site-specific values for each wetland category. Accretion rates may be spatially variable within a given model domain.

SLAMM Version 5.0 is the latest version of the SLAMM Model, developed in 2006/2007 and based on SLAMM 4.0. SLAMM 5.0 provides the following refinements:

- The capability to simulate fixed levels of sea-level rise by 2100 in case IPCC estimates of sea-level rise prove to be too conservative;
- Additional model categories such as "Inland Shore," "Irregularly Flooded (Brackish) Marsh," and "Tidal Swamp."
- *Optional.* In a defined estuary, salt marsh, brackish marsh, and tidal fresh marsh can migrate based on changes in salinity, using a simple though geographically-realistic salt wedge model. This optional model was not used when creating results for Nomans Land Island NWR.

Model results presented in this report were produced using SLAMM version 5.0.1 which was released in early 2008 based on only minor refinements to the original SLAMM 5.0 model. Specifically, the accretion rates for swamps were modified based on additional literature review. For a thorough accounting of SLAMM model processes and the underlying assumptions and equations, please see the SLAMM 5.0.1 technical documentation (Clough and Park, 2008). This document is available at http://warrenpinnacle.com/prof/SLAMM

All model results are subject to uncertainty due to limitations in input data, incomplete knowledge about factors that control the behavior of the system being modeled, and simplifications of the system (CREM 2008).

Sea-Level Rise Scenarios

The primary set of eustatic (global) sea level rise scenarios used within SLAMM was derived from the work of the Intergovernmental Panel on Climate Change (IPCC 2001). SLAMM 5 was run using the following IPCC and fixed-rate scenarios:

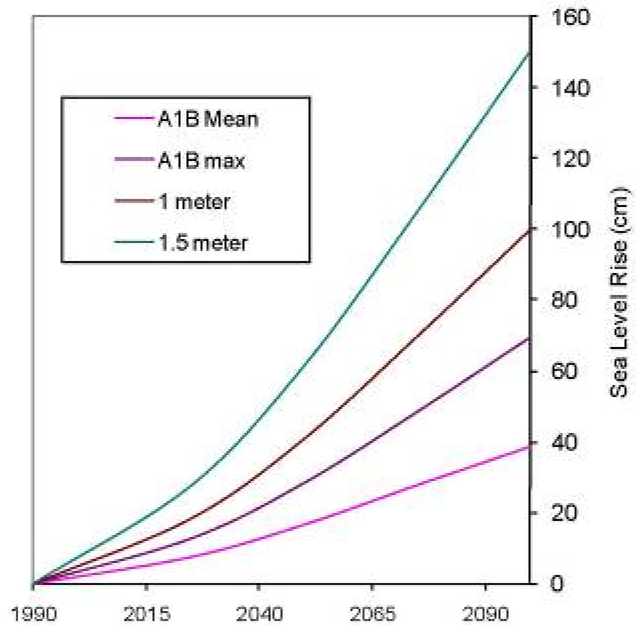
Scenario	Eustatic SLR by 2025 (cm)	Eustatic SLR by 2050 (cm)	Eustatic SLR by 2075 (cm)	Eustatic SLR by 2100 (cm)
A1B Mean	8	17	28	39
A1B Max	14	30	49	69
1 meter	13	28	48	100
1.5 meter	18	41	70	150

Recent literature (Chen et al., 2006, Monaghan et al., 2006) indicates that the eustatic rise in sea levels is progressing more rapidly than was previously assumed, perhaps due to dynamic changes in ice flow omitted within the IPCC report's calculations. A recent paper in the journal *Science* (Rahmstorf, 2007) suggests that, taking into account possible model error, a feasible range by 2100 might be 50 to 140 cm. A recent US intergovernmental report states "Although no ice-sheet model is currently capable of capturing the glacier speedups in Antarctica or Greenland that have been observed over the last decade, including these processes in models will very likely show that IPCC

AR4 projected sea level rises for the end of the 21st century are too low." (US Climate Change Science Program, 2008)

To allow for flexibility when interpreting the results, SLAMM was also run assuming 1 meter, 1½ meters of eustatic sea-level rise by the year 2100. The A1B- maximum scenario was scaled up to produce these bounding scenarios (Figure 1).

Figure 1: Summary of SLR Scenarios Utilized



Methods and Data Sources

LIDAR elevation data are unavailable for this National Wildlife Refuge (NWR). Elevation data used are based on National Elevation Data (NED). An examination of the NED metadata indicates that this digital elevation map (DEM) was derived from a 1942 survey (Fig. 2). The contour interval used to derive the DEM was ten feet.

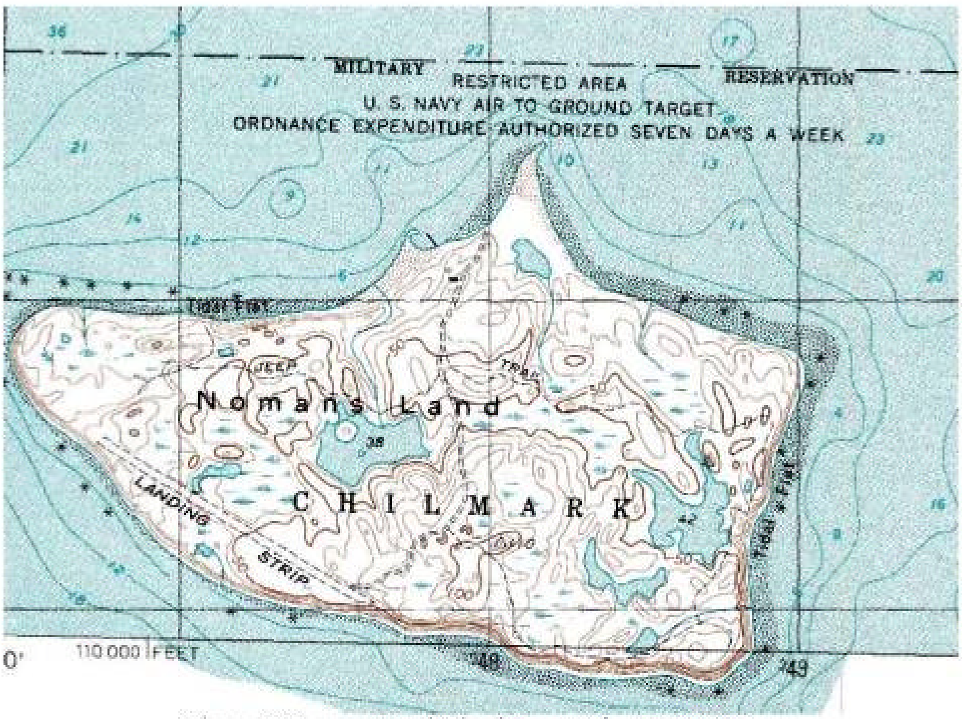


Figure 2: Nomans Land Island Excerpt from USGS Map.

The National Wetlands Inventory for Nomans Land Island is based on a photo date of 2005. The digitized NWI map and the digital elevation map match closely but there is a minor offset evident at the southern portion of the site (Figure 3).

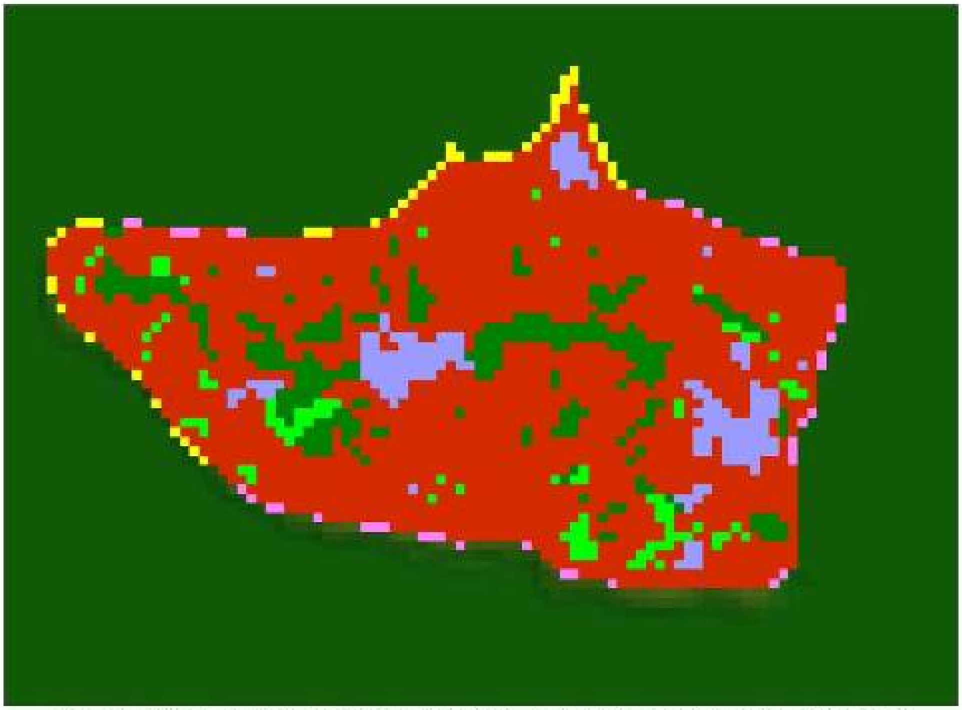


Figure 3: NWI Layer over DEM layer (green). Minor Discrepancy at Southern End.

Converting the NWI survey into 30 meter cells indicates that the approximately six hundred acre refuge (approved acquisition boundary) is primarily composed of the categories as shown below:

Dry Land	71.9%
Swamp	10.5%
Open Ocean	6.0%
Inland Open Water	5.9%
Inland Fresh Marsh	3.6%
Rocky Intertidal	1.2%
Ocean Beach	1.0%

Based on the NWI coverage, there are no dikes or impounded wetlands within the Nomans Land Island NWR.

The historic trend for sea level rise was estimated at 2.665 mm/year using the average value of the two closest stations (8449130, Nantucket Island, MA; 8447930, Woods Hole, Buzzards Bay, MA). This measured rate is somewhat higher than the global average for the last 100 years (approximately 1.5-2.0 mm/year). Any effects of isostatic rebound that have affected this region for the last 100 years are assumed to be captured within that historic trend and that same rate of isostatic rebound is projected forward into the next 100 years.

The tide range at this site was estimated at 1.05 meters using the average value from the two closest NOAA oceanic gages (8448376, Cuttyhunk, MA; 8448725, Menemsha Harbor, MA). The NAVD88 correction source was determined from average values of the four closest gages with NAVD data (8447930, Woods Hole, Buzzards Bay, MA; 8447505, Chatham, Stage Harbor, MA; 8447435, Chatham, Lydia Cove, MA; 8447495, Saquatucket Harbor, MA).

Figure 4: NOAA Gages Relevant to the Study Area.

Accretion rates in salt and brackish marshes are not relevant to this site as no marshes appear in the initial condition, nor in future predictions.

Modeled U.S. Fish and Wildlife Service refuge boundaries are based on Approved Acquisition Boundaries as published on the FWS "National Wildlife Refuge Data and Metadata" website. The modeling team was in contact with Eastern Massachusetts National Wildlife Refuge Complex biologist Stephanie Koch to ensure model parameters were consistent with local knowledge.

The cell-size used for this analysis was 30 meter by 30 meter cells. However, the SLAMM model does track partial conversion of cells based on elevation and slope.

SUMMARY OF SLAMM INPUT PARAMETERS FOR NOMANS LAND

Description	Nomans Land Island
DEM Source Date (yyyy)	1942
NWI_photo_date (yyyy)	2005
Direction_OffShore (N|S|E|W)	S
Historic_trend (mm/yr)	2.865
NAVD88_correction (MTL-NAVD88 in meters)	-0.092
Water Depth (m below MLW- N/A)	2
TideRangeOcean (meters: MHHW-MLLW)	1.05
TideRangeInland (meters)	1.05
Mean High Water Spring (m above MTL)	0.698
MHSW Inland (m above MTL)	0.698
Marsh Erosion (horz meters/year)	1.8
Swamp Erosion (horz meters/year)	1
TFlat Erosion (horz meters/year) [from 0.5]	0.5
Salt marsh vertical accretion (mm/yr) Final	3.78
Brackish March vert. accretion (mm/yr) Final	3.78
Tidal Fresh vertical accretion (mm/yr) Final	5.9
Beach/T.Flat Sedimentation Rate (mm/yr)	0.5
Frequency of Large Storms (yr/washover)	50
Use Elevation Preprocessor for Wetlands	TRUE

Results

Nomans Land Island National Wildlife Refuge is predicted to show some effects from sea level rise. The refuge is predicted to lose more than half of its ocean beach in the most conservative scenario. Swamp and dry land loss is predicted to be less severe.

SLR by 2100 (m)	0.39	0.69	1	1.5
Dry Land	3%	4%	4%	5%
Swamp	1%	1%	2%	2%
Ocean Beach	56%	62%	98%	98%

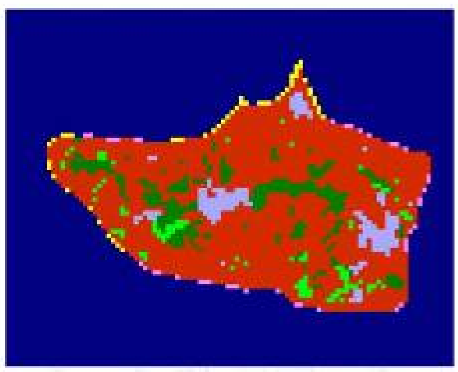
Predicted Loss Rates of Land Categories by 2100 Given Simulated Scenarios of Eustatic Sea Level Rise

Maps of SLAMM input and output to follow will use the following legend:

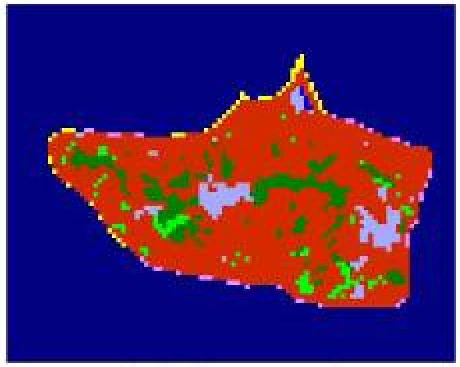
Nomans Land Island NWR
IPCC Scenario A1B-Mean, 0.39 M SLR Eustatic by 2100

Results in Acres

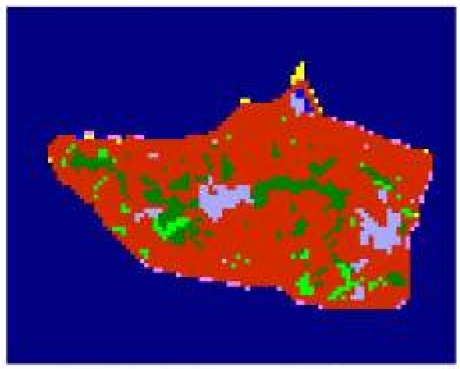
	Initial	2025	2050	2075	2100
Open Ocean	1106.9	1110.0	1117.1	1123.7	1128.7
Dry Land	449.0	447.8	444.2	439.5	435.6
Swamp	64.9	64.5	64.3	64.3	64.3
Inland Open Water	36.5	35.1	34.7	34.5	34.5
Inland Fresh Marsh	22.0	22.0	22.0	22.0	22.0
Ocean Beach	11.1	9.6	6.9	5.3	4.9
Rocky Intertidal	9.6	9.1	8.1	7.0	5.9
Estuarine Open Water	0.0	1.3	2.2	2.9	3.1
Tidal Flat	0.0	0.4	0.4	0.1	0.0
Estuarine Beach	0.0	0.0	0.1	0.8	1.0
Total (incl. water)	**1700.0**	**1700.0**	**1700.0**	**1700.0**	**1700.0**



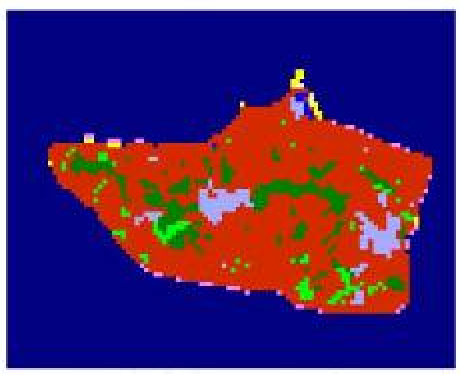
Nomans Land Island, Initial Condition



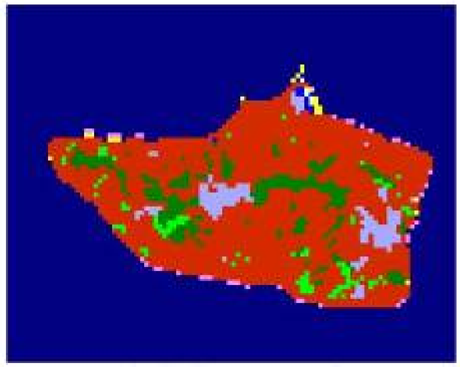
Nomans Land Island, 2025, Scenario A1B Mean



Nomans Land Island, 2050, Scenario A1B Mean



Nomans Land Island, 2075, Scenario A1B Mean

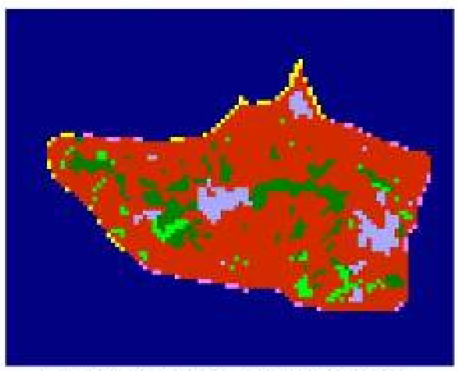


Nomans Land Island, 2100, Scenario A1B Mean

Nomans Land Island NWR
IPCC Scenario A1B-Max, 0.69 M SLR Eustatic by 2100

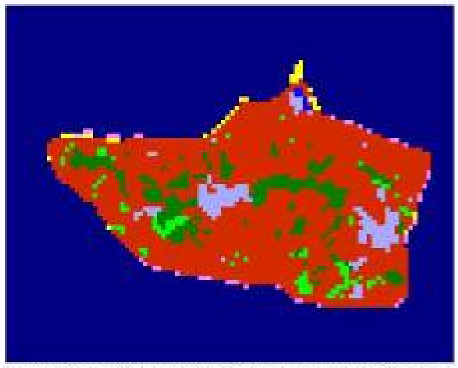
Results in Acres

	Initial	2025	2050	2075	2100
Open Ocean	1106.9	1111.4	1120.8	1129.0	1134.8
Dry Land	449.0	447.3	441.2	434.8	432.4
Swamp	64.9	64.5	64.3	64.3	64.0
Inland Open Water	36.5	35.1	34.7	34.5	34.5
Inland Fresh Marsh	22.0	22.0	22.0	22.0	22.0
Ocean Beach	11.1	9.0	6.5	5.5	4.3
Rocky Intertidal	9.6	8.9	7.4	5.6	3.7
Estuarine Open Water	0.0	1.3	2.3	3.1	3.0
Tidal Flat	0.0	0.4	0.4	0.1	0.3
Estuarine Beach	0.0	0.0	0.4	1.1	1.1
Total (incl. water)	**1700.0**	**1700.0**	**1700.0**	**1700.0**	**1700.0**

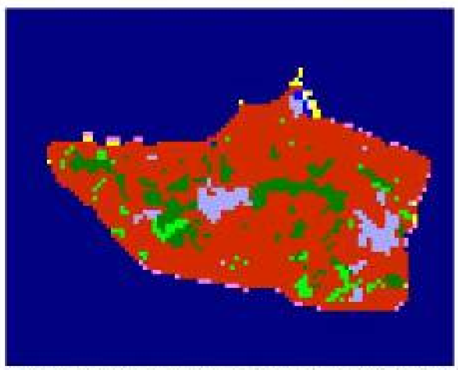


Nomans Land Island, Initial Condition

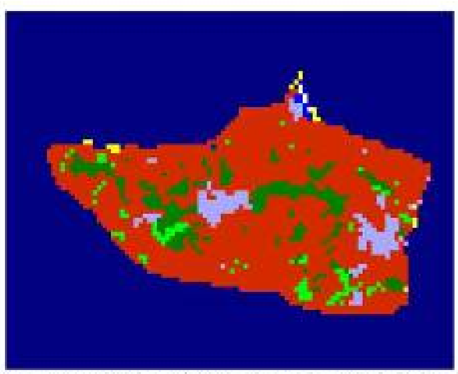
Nomans Land Island, 2025, Scenario A1B Maximum



Nomans Land Island, 2050, Scenario A1B Maximum



Nomans Land Island, 2075, Scenario A1B Maximum

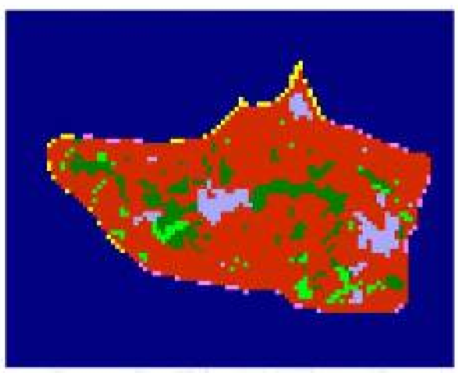


Nomans Land Island, 2100, Scenario A1B Maximum

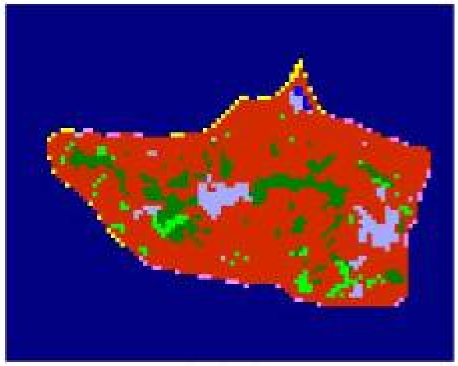
Nomans Land Island NWR
1 Meter Eustatic SLR by 2100

Results in Acres

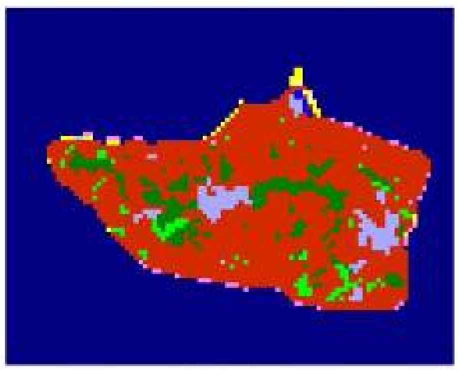
	Initial	2025	2050	2075	2100
Open Ocean	1106.9	1112.9	1123.4	1133.8	1143.1
Dry Land	449.0	446.5	438.4	433.0	430.3
Swamp	64.9	64.5	64.3	64.1	63.8
Inland Open Water	36.5	34.7	34.5	34.5	34.2
Inland Fresh Marsh	22.0	22.0	22.0	22.0	22.0
Ocean Beach	11.1	8.4	7.0	4.0	0.2
Rocky Intertidal	9.6	8.7	6.7	4.1	1.5
Estuarine Open Water	0.0	1.8	2.7	3.2	3.3
Estuarine Beach	0.0	0.0	0.8	1.1	1.1
Tidal Flat	0.0	0.5	0.4	0.3	0.4
Total (incl. water)	**1700.0**	**1700.0**	**1700.0**	**1700.0**	**1700.0**



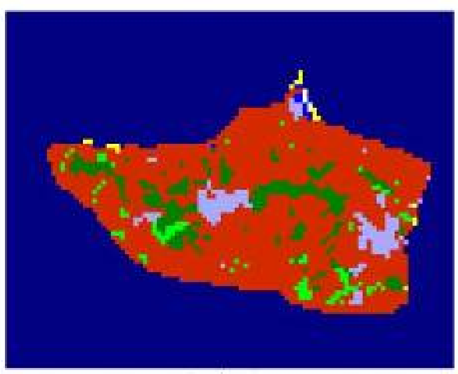
Nomans Land Island, Initial Condition



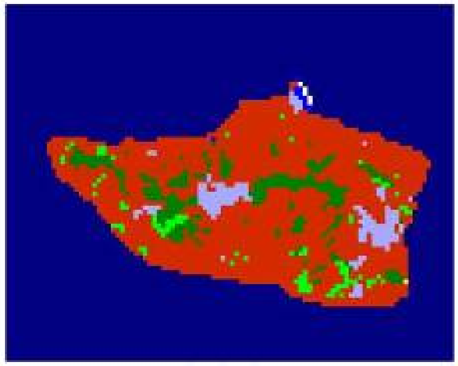
Nomans Land Island, 2025, 1 meter



Nomans Land Island, 2050, 1 meter



Nomans Land Island, 2075, 1 meter

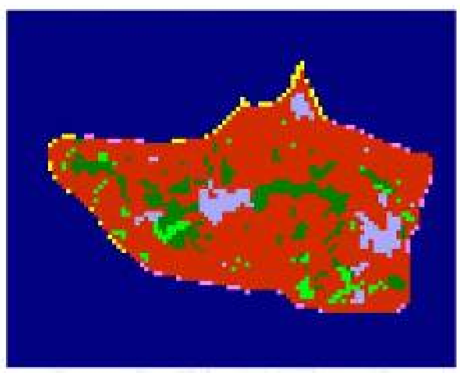


Nomans Land Island, 2100, 1 meter

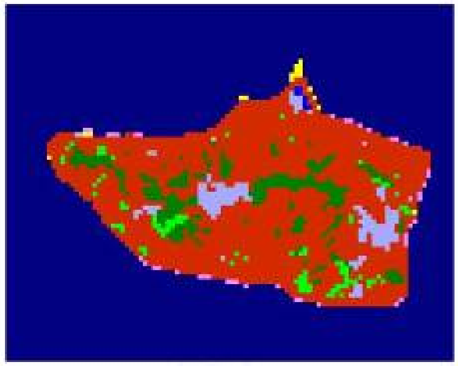
Nomans Land Island NWR
1.5 Meters Eustatic SLR by 2100

Results in Acres

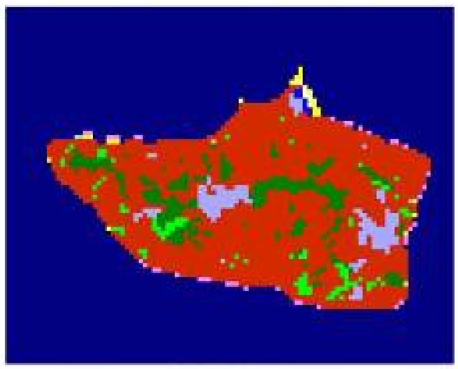
	Initial	2025	2050	2075	2100
Open Ocean	1106.9	1115.8	1130.6	1142.1	1148.4
Dry Land	449.0	445.2	434.6	430.6	426.8
Swamp	64.9	64.4	64.3	64.0	63.7
Inland Open Water	36.5	34.7	34.5	34.2	34.2
Inland Fresh Marsh	22.0	22.0	22.0	22.0	22.0
Rocky Intertidal	9.6	8.3	5.4	1.8	0.0
Ocean Beach	11.1	7.2	4.2	0.4	0.2
Estuarine Open Water	0.0	1.8	2.7	3.2	3.2
Estuarine Beach	0.0	0.0	1.4	1.3	0.9
Tidal Flat	0.0	0.5	0.4	0.4	0.5
Total (incl. water)	**1700.0**	**1700.0**	**1700.0**	**1700.0**	**1700.0**



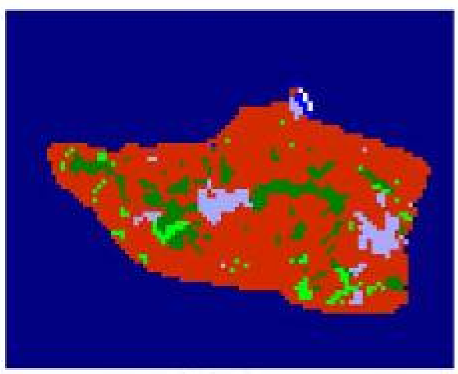
Nomans Land Island, Initial Condition



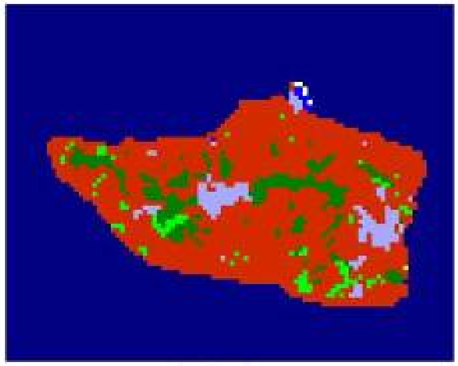
Nomans Land Island, 2025, 1.5 meter



Nomans Land Island, 2050, 1.5 meter



Nomans Land Island, 2075, 1.5 meter



Nomans Land Island, 2100, 1.5 meter

Discussion:

Model results for Nomans Land Island NWR indicate that only the lowest-elevation portions of the island (such as the Cobble Spit to the north of the island) are vulnerable to the effects of sea level rise. Vulnerability of ocean beaches is high relative to other land categories due to its low elevation. Dry land and swamp lie in elevations mostly above sea level rise predictions, so these land categories are expected to remain relatively unchanged.

Model results for this site are subject to some uncertainty. Dry land elevations are poorly characterized by a low-resolution and out-of-date digital elevation model (from 1942). Predicted dry-land loss rates would be refined with a higher vertical resolution and more updated dataset (LiDAR, for instance). Additionally, ocean beach erosion is difficult to precisely characterize with a relatively simple model. In this analysis, ocean beach elevations were estimated as a function of tidal range because elevation data have low vertical resolution.

Despite the uncertainty about what may occur around the edges of the model domain, the higher elevation portions of the island, which comprise the majority of the refuge, may safely be assumed to remain invulnerable to sea level rise.

The SLAMM model does account for the local effects of isostatic rebound by taking into account the historical sea level rise for each site. The historical rate of land movement is predicted to continue through the year 2100 (i.e. the rate of isostatic rebound is assumed to remain constant).

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