Application of the Sea-Level Affecting Marshes Model (SLAMM 5.1) to Eastern Neck NWR

Prepared For: Dr. Brian Czech, Conservation Biologist

U. S. Fish and Wildlife Service
National Wildlife Refuge System
Division of Natural Resources and Conservation Planning
Conservation Biology Program
4401 N. Fairfax Drive - MS 670
Arlington, VA 22203

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Jonathan S. Clough & Evan C. Larson, Warren Pinnacle Consulting, Inc.
PO Box 253, Warren VT, 05674
(802)-496-3476

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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 Irregularly Flooded 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 8 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 in this model application.

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

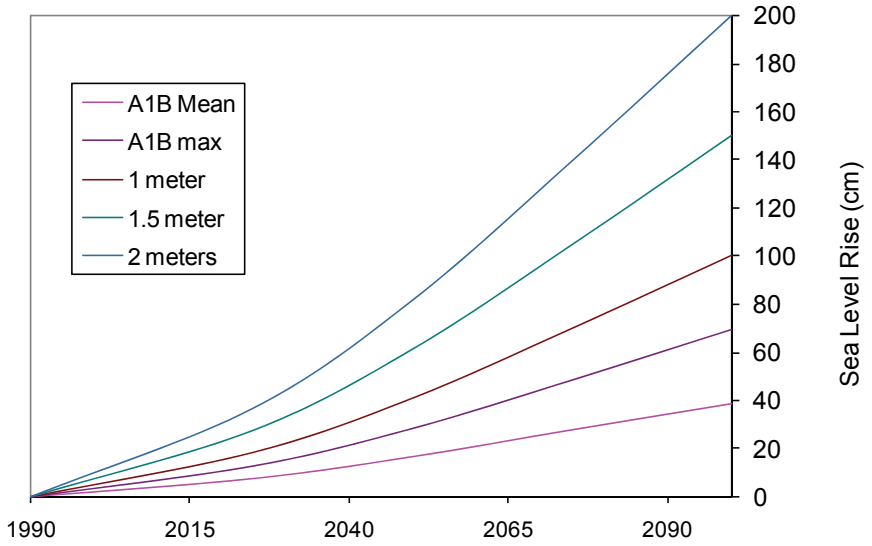
SLAMM 5 was run using scenario A1B from the Special Report on Emissions Scenarios (SRES) – mean and maximum estimates. The A1 scenario assumes that the future world includes very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. In particular, the A1B scenario assumes that energy sources will be balanced across all sources. Under the A1B scenario, the IPCC WGI Fourth Assessment Report (IPC, 2007) suggests a likely range of 0.21 to 0.48 meters of sea level rise by 2090-2099 "excluding future rapid dynamical changes in ice flow." The A1B-mean scenario that was run as a part of this project falls near the middle of this estimated range, predicting 0.40 meters of global sea level rise by 2100.

The latest 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 the 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. Pfeffer et al. (2008) suggests that 2 meters by 2100 is at the upper end of plausible scenarios due to physical limitations on glaciological conditions. A recent US intergovernmental report states "Although no ice-sheet model is currently capable of capturing the glacier speedups in Antarctica or Greenland that have been observed over the last decade, including these processes in models will very likely show that IPCC AR4 projected sea level rises for the end of the 21st century are too low." (US Climate Change Science Program, 2008) A recent paper by

Grinsted et. al. (2009) states that "sea level 2090-2099 is projected to be 0.9 to 1.3 m for the A1B scenario, with low probability of the rise being within Intergovernmental Panel on Climate Change (IPCC) confidence limits."

To allow for flexibility when interpreting the results, SLAMM was also run assuming 1 meter, 1½ meters, and 2 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



Additional information on the development of the SLAMM model is available in the technical documentation, which may be downloaded from the SLAMM website (Clough and Park, 2008).

Methods and Data Sources

For the model simulation of Eastern Neck NWR LiDAR with a flight data of 2003 were used to define cell elevations.

The National Wetlands Inventory for Eastern Neck is based on a photo date of 1982. Converting this NWI survey into 30 meter cells indicates that the approximately two thousand acre refuge (approved acquisition boundary including water) is composed of the categories as shown below:

Dry Land	62.7%
Irregularly Flooded Marsh	28.0%
Estuarine Open Water	4.8%
Swamp	2.1%

There are no diked wetlands in the Eastern Neck NWR according to the National Wetlands Inventory. However, the northwestern shore of the refuge is protected by onshore and offshore breakwaters (Figure 2 & Figure 3). According to the Comprehensive Conservation Plan there are 8,700 linear feet of exiting refuge shoreline protection on the west side of the island (USFWS 2009).

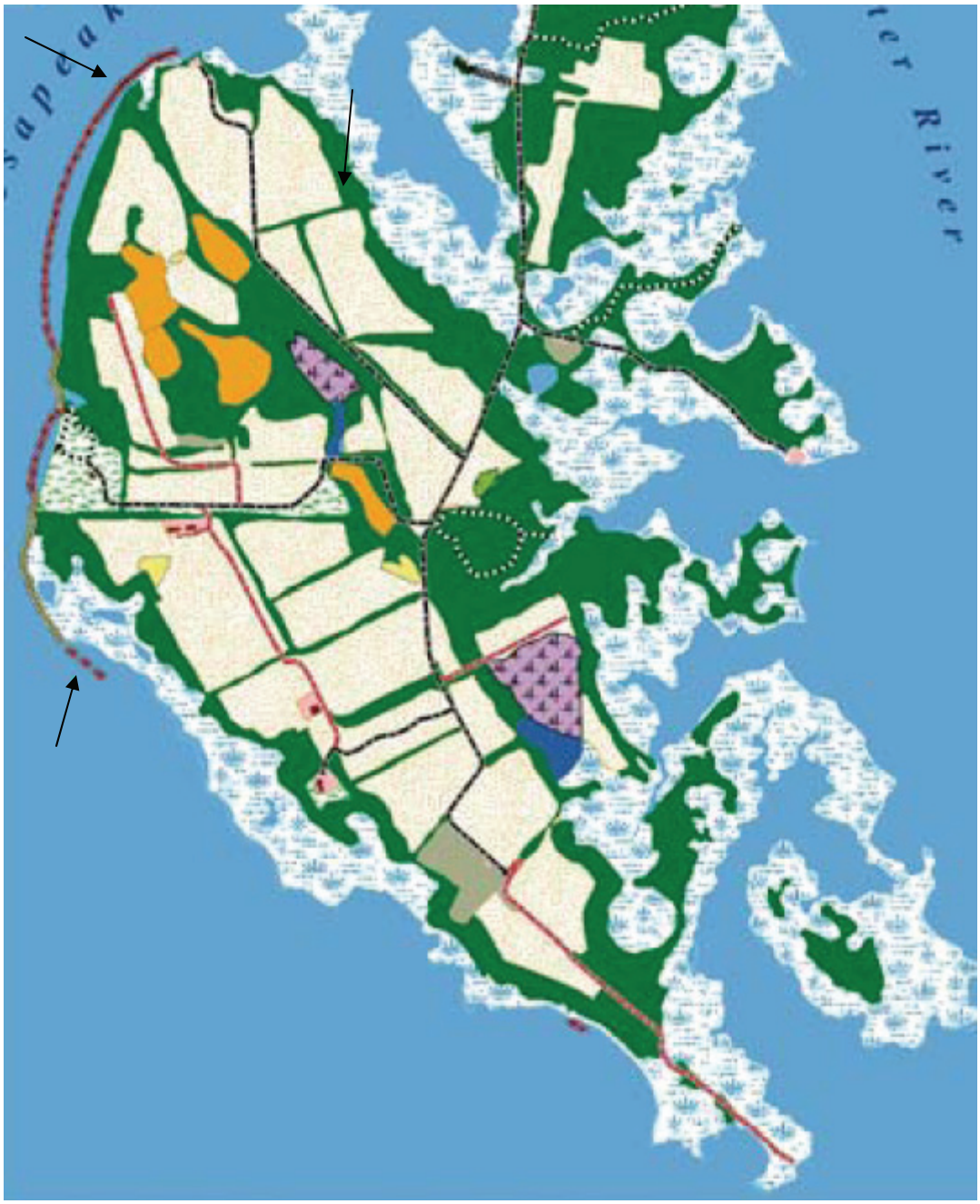


Figure 2: Breakwaters on the shore of the refuge.

Figure 3: Satellite Imagery of Offshore Breakwater in Northwestern Eastern Neck NWR.

A discrepancy of about 70 meters, or slightly more than two cells, was discovered in the NWI coding of beaches in the southwest (Figure 4). This indicates that significant shoreline change has already occurred since the NWI photo of 1982. However, much of the area that has been lost is now located outside of the newly defined refuge boundary. Additional model uncertainty does remain due to the age of the NWI data and potential shifts in wetland boundaries in the interim.

Figure 4: Difference of about 70 meters.

The historic trend for sea level rise was estimated 3.44 mm/year (8536110, Eastern Neck). The rate of sea level rise for this refuge is roughly twice the global average for the last 100 years (approximately 1.5-2.0 mm/year).

As a simplification, erosion values for the northwestern areas behind the breakwaters were set to zero meters/year (Figure 5). Marsh and dry land loss for this portion of the refuge are therefore solely due to inundation effects. This assumption is probably somewhat conservative as no breakwater can be assumed to be 100% efficient in preventing erosion from wave action.

The tidal range for the Eastern Neck NWR was determined to be 0.514 meters (8572955, Love Point Pier, MD) (Figure 6).

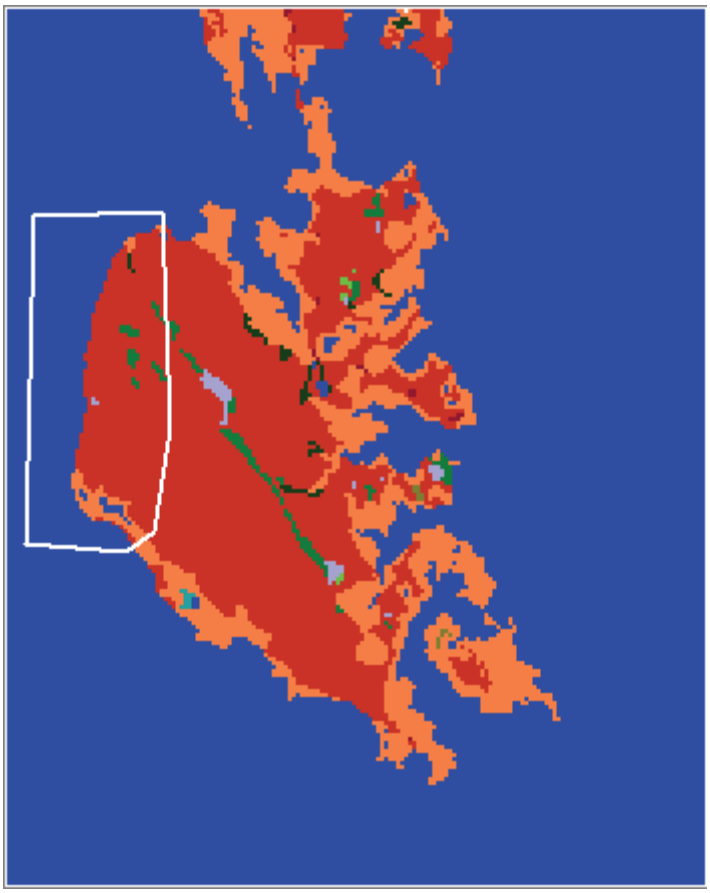


Figure 5: Model "subsite 1" used for area protected by breakwaters.

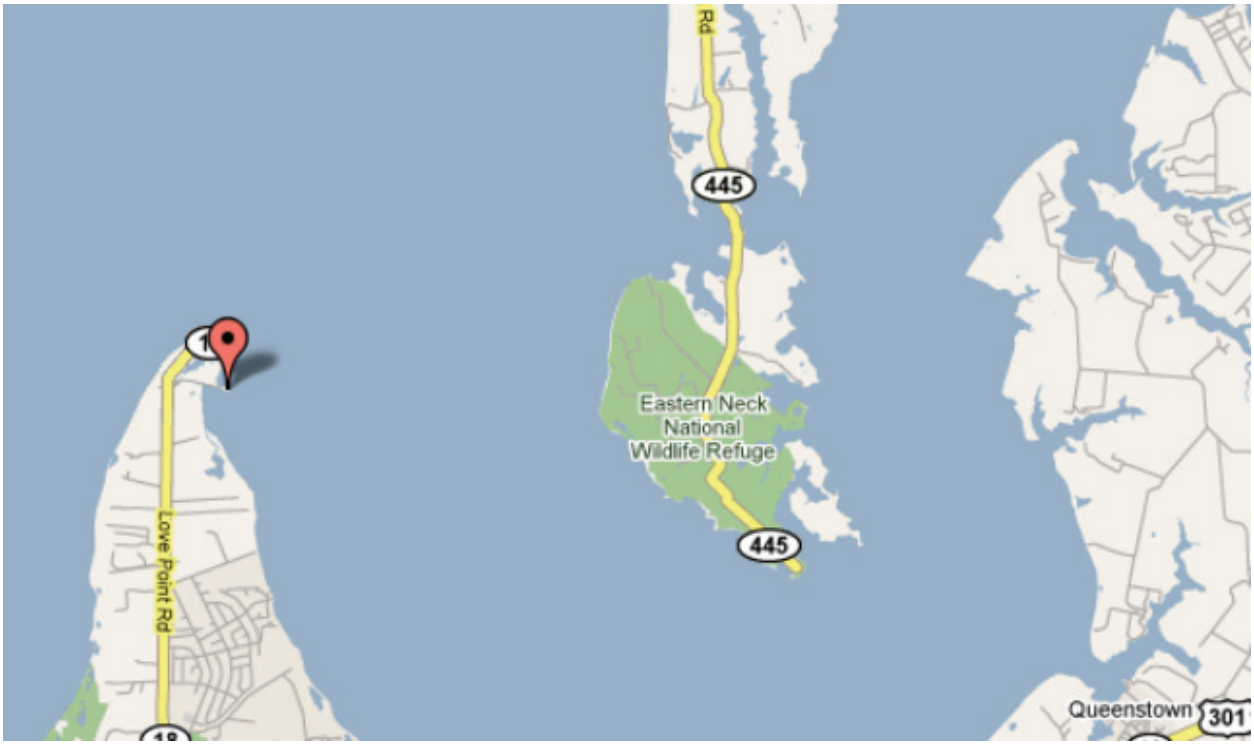


Figure 6: NOAA Gage Relevant to the Study Area.

Accretion rates in regularly flooded marshes were set to 2.5 mm/year, irregularly flooded marshes to 3 mm/year and tidal fresh to 3.8 mm/year. Some of the lowest rates of accretion in Maryland have been measured in the east coast of Chesapeake Bay: (2.65 mm/yr at Blackwater, 3.33 mm/yr at Muddy Creek, 1.8 mm/yr at Nanticoke River Estuary, Reed et. al, 2008). Wetlands have been declining in this region for many years, the postulated driving force being rising water levels (Kearney et. all, 1988).

The MTL to NAVD correction was derived using the NOAA VDATUM modeling product. The correction was determined to be -0.027 meters.

Modeled U.S. Fish and Wildlife Service refuge boundaries for Maryland are based on Approved Acquisition Boundaries as published on the FWS National Wildlife Refuge Data and Metadata website. 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.

The refuge manager, Michele Whitbeck, noted the presence of additional LiDAR data through Les Vilchek at Blackwater NWR. Since high quality LiDAR was already available for the study site, this contact was not pursued. The refuge manager did not indicate the presence of other local studies containing model parameters.

SUMMARY OF SLAMM INPUT PARAMETERS FOR EASTERN NECK NWR

Parameter	Global	SubSite 1
Description	Eastern Neck	Barriers
NWI Photo Date (YYYY)	1982	1982
DEM Date (YYYY)	2003	2003
Direction Offshore [n,s,e,w]	West	West
Historic Trend (mm/yr)	3.44	3.44
MTL-NAVD88 (m)	-0.027	-0.027
GT Great Diurnal Tide Range (m)	0.514	0.514
Salt Elev. (m above MTL)	0.34181	0.34181
Marsh Erosion (horz. m /yr)	1.8	0
Swamp Erosion (horz. m /yr)	1	0
T.Flat Erosion (horz. m /yr)	6	0
Reg. Flood Marsh Accr (mm/yr)	2.5	2.5
Irreg. Flood Marsh Accr (mm/yr)	3	3
Tidal Fresh Marsh Accr (mm/yr)	3.8	3.8
Beach Sed. Rate (mm/yr)	0.5	0.5
Freq. Overwash (years)	25	25
Use Elev Pre-processor [True,False]	FALSE	FALSE

Results

SLAMM predicts that Eastern Neck NWR will be vulnerable to the effects of sea level rise. Dry land, which comprises a majority of the refuge, is expected to decline from 14% to 41% across all scenarios. Losses for swamp, which comprises roughly 2% of the refuge, are predicted to be roughly parallel to those of dry land. Irregularly flooded marsh, which makes up roughly one third if the refuge, is predicted to decline between 7% and 99% across all scenarios. Irregularly flooded marshes losses are quite severe in scenarios of 0.69 meters (eustatic) and above.

SLR by 2100 (m)	0.39	0.69	1	1.5	2
Dry Land	14%	23%	28%	36%	41%
Irreg. Flooded Marsh	7%	59%	93%	98%	99%
Swamp	9%	20%	26%	33%	46%

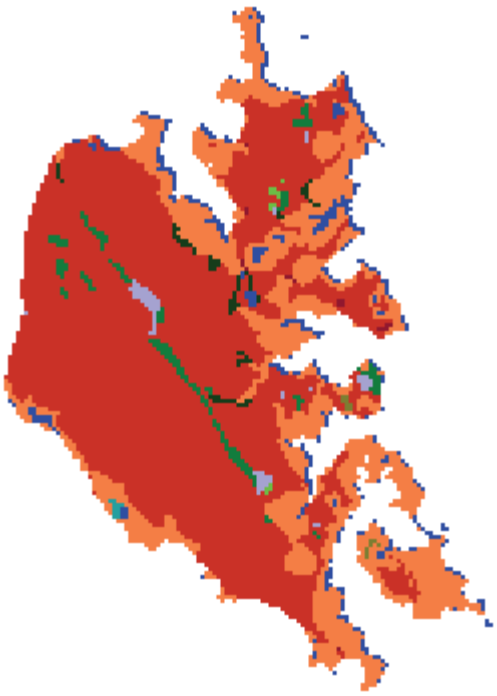
Predicted Loss Rates of Land Categories by 2100 Given Simulated Scenarios of Eustatic Sea Level Rise

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

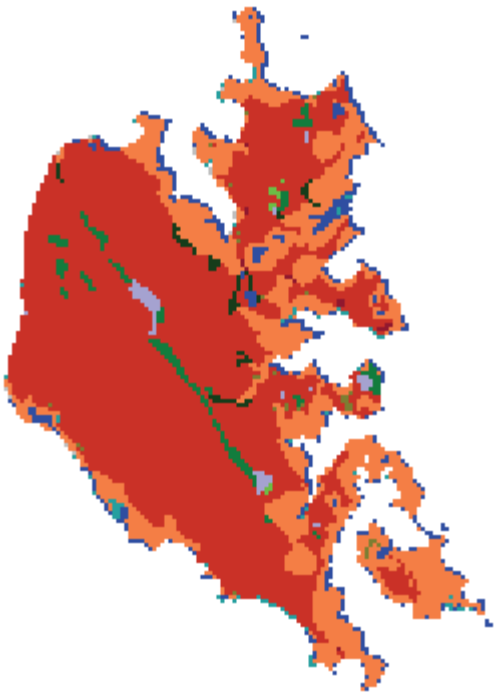
Eastern Neck Raster
IPCC Scenario A1B-Mean, 0.39 M SLR Eustatic by 2100

Results in Acres

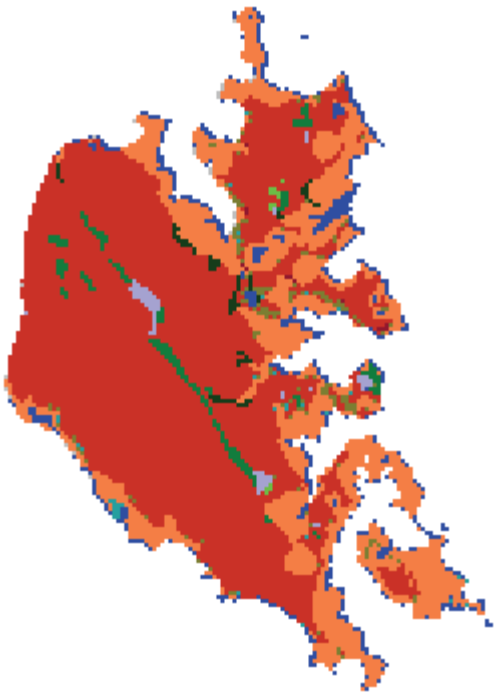
	Initial	2025	2050	2075	2100
Dry Land	1311.7	1296.9	1263.0	1198.1	1128.7
Irregularly Flooded Marsh	585.3	557.3	552.1	550.6	546.6
Estuarine Open Water	101.0	113.3	129.0	137.0	147.2
Swamp	44.7	44.1	43.8	43.1	40.7
Tidal Swamp	18.7	18.7	18.3	16.9	15.2
Inland Open Water	17.3	17.3	17.1	16.2	13.6
Dev. Dry Land	4.2	4.2	2.9	0.7	0.1
Trans. Salt Marsh	3.3	11.9	41.4	74.6	80.9
Inland Fresh Marsh	3.1	3.1	3.1	3.1	3.1
Regularly Flooded Marsh	2.4	23.6	18.3	49.8	115.6
Tidal Flat	0.0	1.4	2.9	1.7	0.1
Total (incl. water)	**2091.8**	**2091.8**	**2091.8**	**2091.8**	**2091.8**



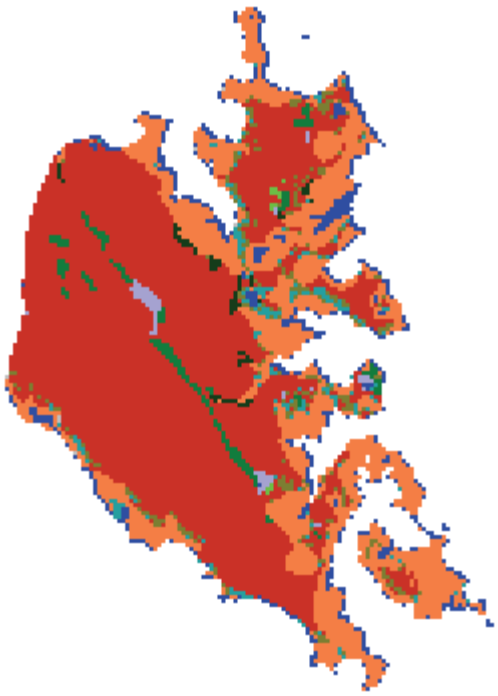
Eastern Neck NWR, Initial Condition



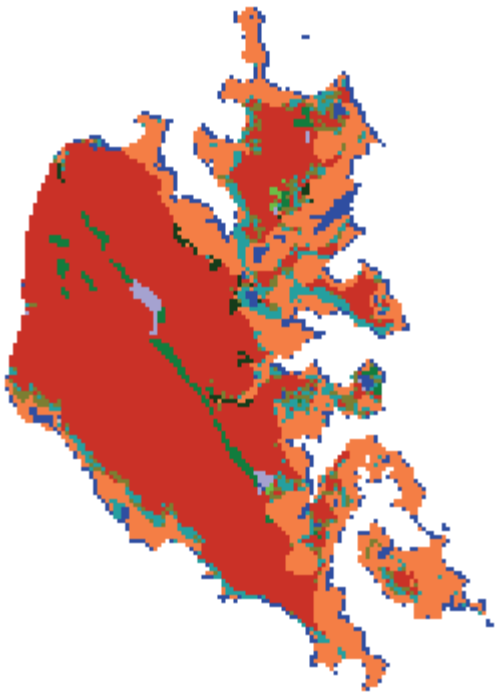
Eastern Neck NWR, 2025, Scenario A1B Mean



Eastern Neck NWR, 2050, Scenario A1B Mean



Eastern Neck NWR, 2075, Scenario A1B Mean

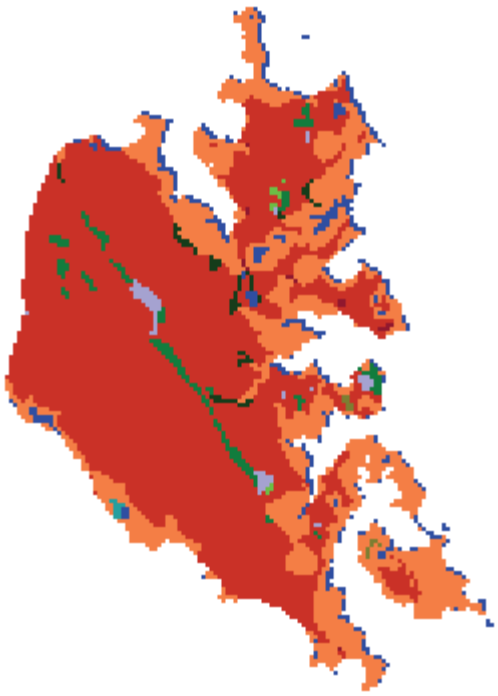


Eastern Neck NWR, 2100, Scenario A1B Mean

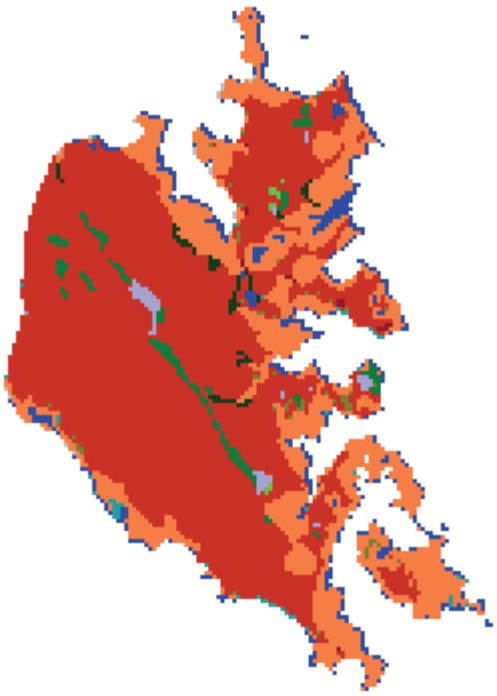
Eastern Neck Raster
IPCC Scenario A1B-Max, 0.69 M SLR Eustatic by 2100

Results in Acres

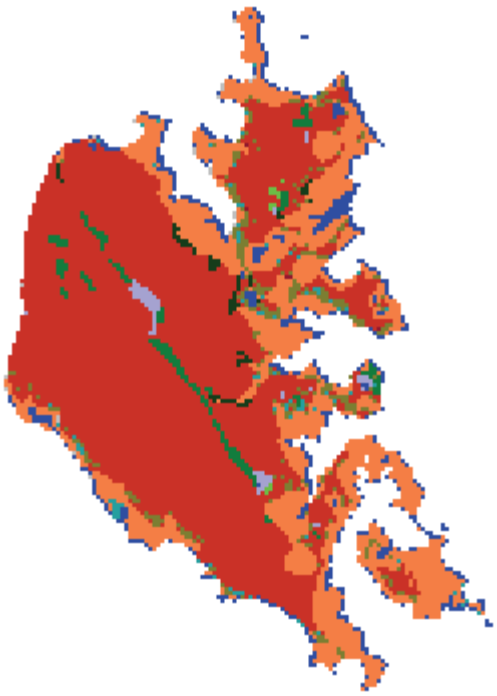
	Initial	2025	2050	2075	2100
Dry Land	1311.7	1288.7	1214.8	1105.6	1016.3
Irregularly Flooded Marsh	585.3	552.5	548.5	502.6	251.9
Estuarine Open Water	101.0	120.2	137.9	159.7	286.2
Swamp	44.7	43.9	43.3	39.6	36.0
Tidal Swamp	18.7	18.7	17.0	13.9	8.2
Inland Open Water	17.3	17.3	16.5	13.6	9.6
Dev. Dry Land	4.2	4.1	1.3	0.0	0.0
Trans. Salt Marsh	3.3	19.6	80.4	117.1	94.0
Inland Fresh Marsh	3.1	3.1	3.1	3.1	3.1
Regularly Flooded Marsh	2.4	21.5	26.3	136.3	375.6
Tidal Flat	0.0	2.2	2.7	0.4	10.9
Total (incl. water)	**2091.8**	**2091.8**	**2091.8**	**2091.8**	**2091.8**



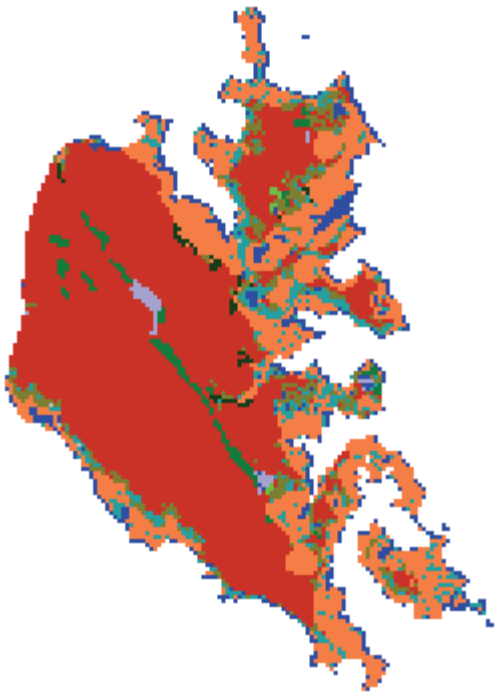
Eastern Neck NWR, Initial Condition



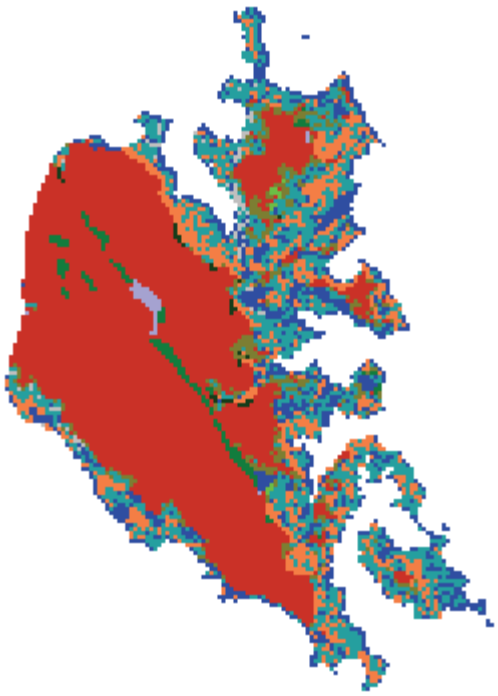
Eastern Neck NWR, 2025, Scenario A1B Maximum



Eastern Neck NWR, 2050, Scenario A1B Maximum



Eastern Neck NWR, 2075, Scenario A1B Maximum

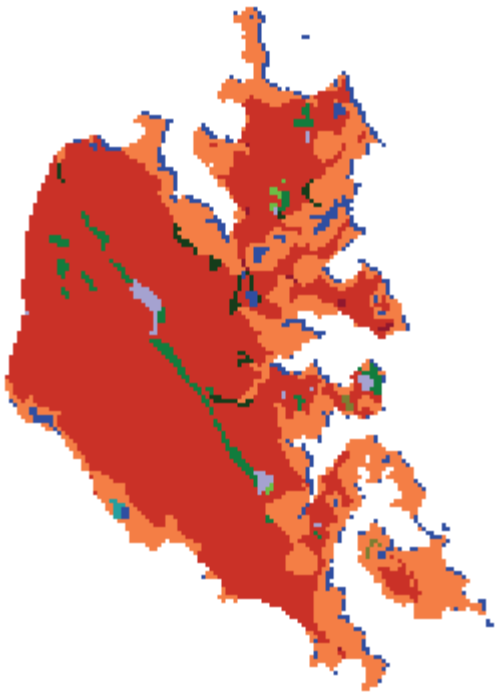


Eastern Neck NWR, 2100, Scenario A1B Maximum

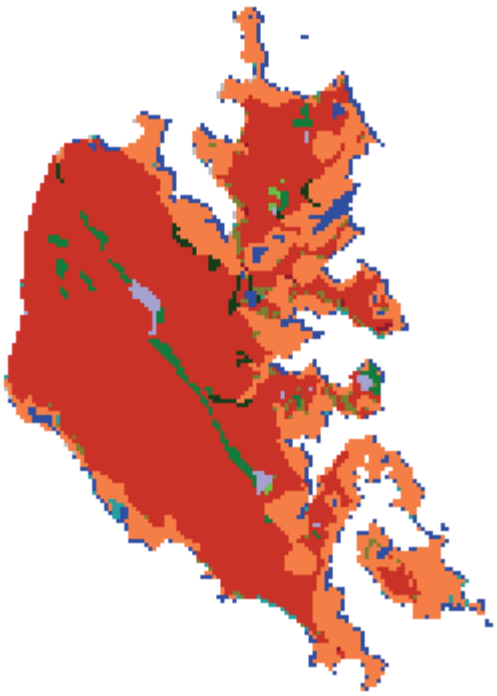
Eastern Neck Raster
1 Meter Eustatic SLR by 2100

Results in Acres

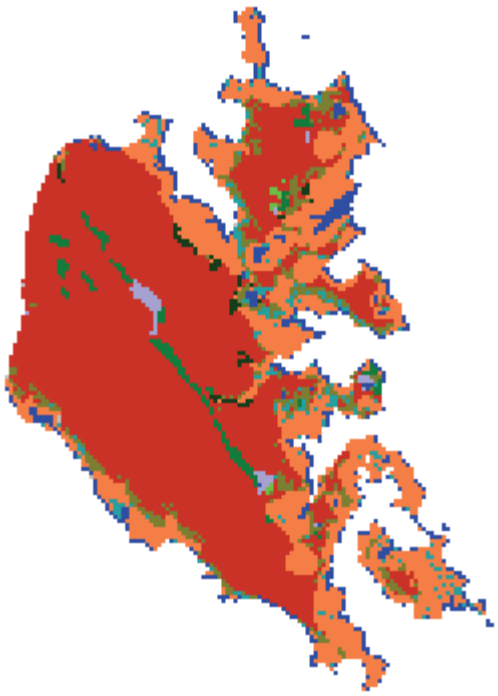
	Initial	2025	2050	2075	2100
Dry Land	1311.7	1272.8	1158.4	1029.2	940.5
Irregularly Flooded Marsh	585.3	550.3	525.8	201.3	44.0
Estuarine Open Water	101.0	122.4	143.9	209.3	586.1
Swamp	44.7	43.8	41.6	36.4	33.1
Tidal Swamp	18.7	18.3	15.4	8.4	5.5
Inland Open Water	17.3	17.3	15.3	9.6	9.1
Dev. Dry Land	4.2	3.5	0.1	0.0	0.0
Trans. Salt Marsh	3.3	36.3	122.8	135.3	93.5
Inland Fresh Marsh	3.1	3.1	3.1	2.9	1.6
Regularly Flooded Marsh	2.4	21.5	63.6	454.9	295.4
Tidal Flat	0.0	2.4	1.7	4.6	83.0
Total (incl. water)	**2091.8**	**2091.8**	**2091.8**	**2091.8**	**2091.8**



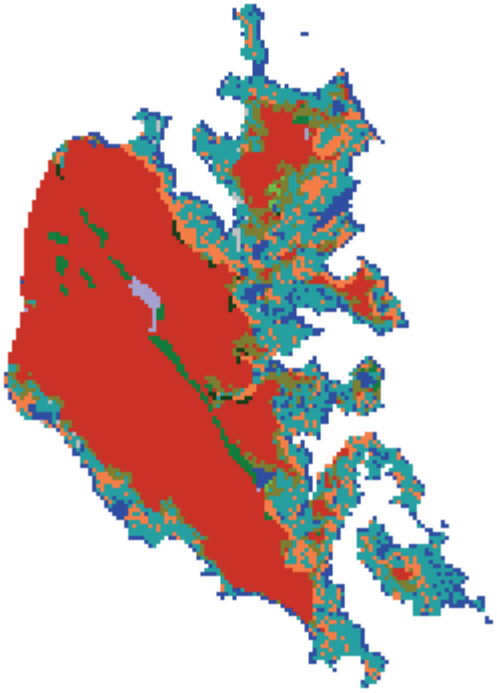
Eastern Neck NWR, Initial Condition



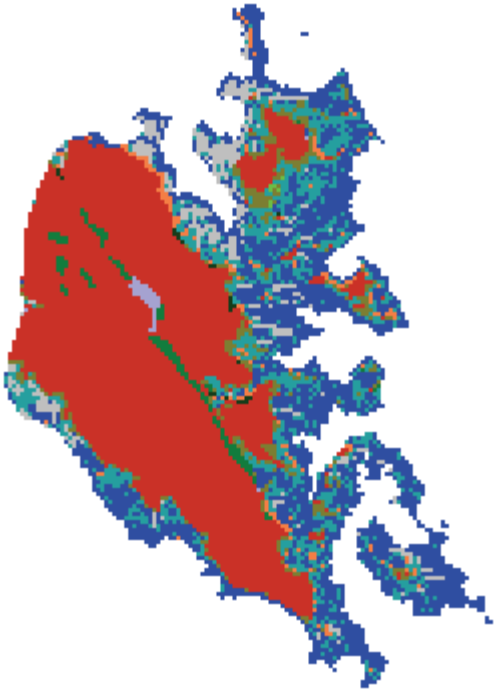
Eastern Neck NWR, 2025, 1 meter



Eastern Neck NWR, 2050, 1 meter



Eastern Neck NWR, 2075, 1 meter

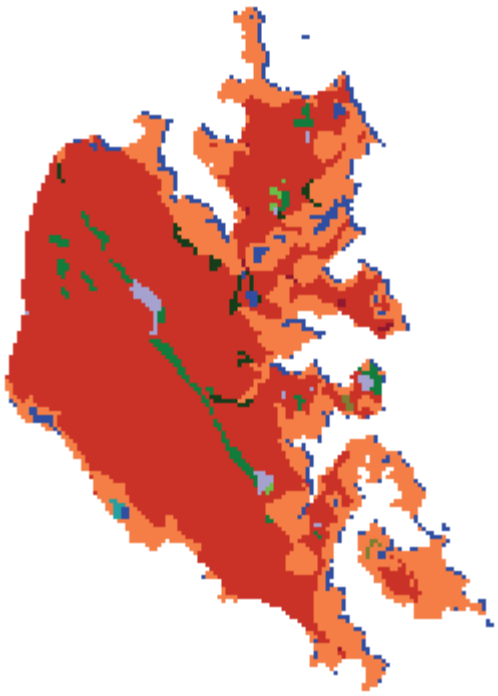


Eastern Neck NWR, 2100, 1 meter

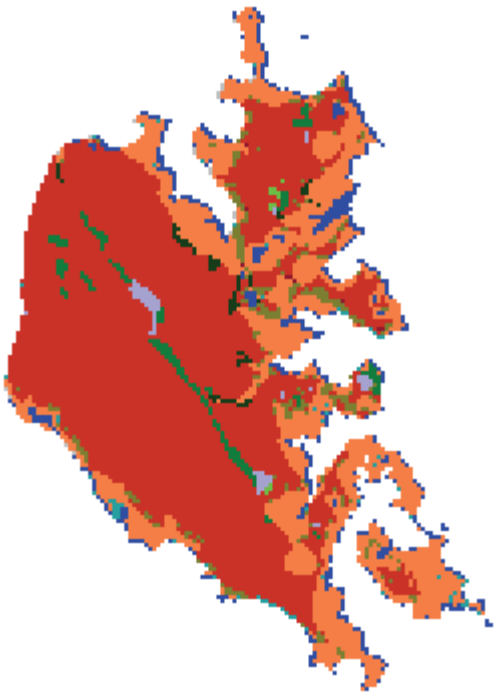
Eastern Neck Raster
1.5 Meters Eustatic SLR by 2100

Results in Acres

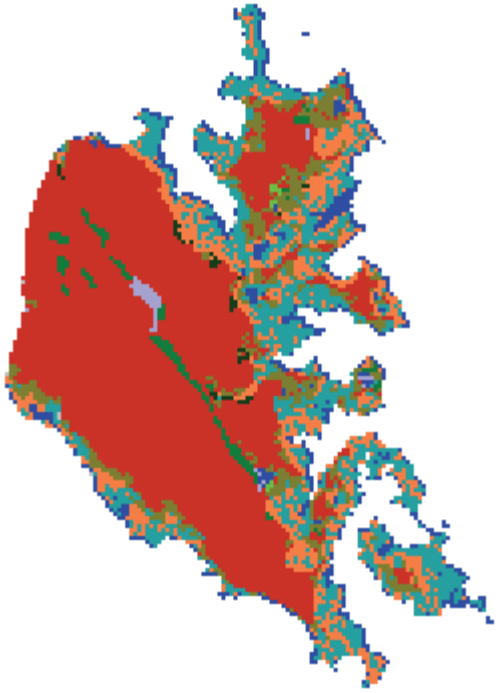
	Initial	2025	2050	2075	2100
Dry Land	1311.7	1236.0	1072.0	939.9	846.3
Irregularly Flooded Marsh	585.3	546.3	277.9	36.4	12.3
Estuarine Open Water	101.0	122.5	153.7	445.8	860.4
Swamp	44.7	43.5	38.1	33.0	29.9
Tidal Swamp	18.7	17.2	11.0	5.4	2.6
Inland Open Water	17.3	17.3	11.6	9.1	8.7
Dev. Dry Land	4.2	2.1	0.0	0.0	0.0
Trans. Salt Marsh	3.3	74.6	173.0	139.6	97.4
Inland Fresh Marsh	3.1	3.1	3.0	0.8	0.1
Regularly Flooded Marsh	2.4	26.7	349.4	420.3	166.6
Tidal Flat	0.0	2.4	2.0	61.6	67.5
Total (incl. water)	**2091.8**	**2091.8**	**2091.8**	**2091.8**	**2091.8**



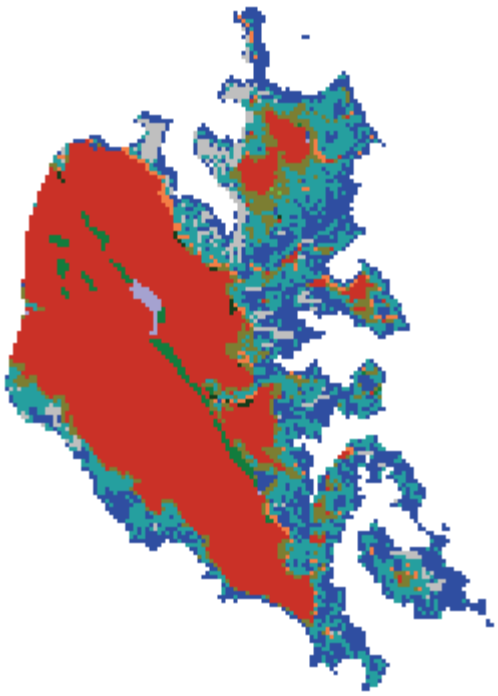
Eastern Neck NWR, Initial Condition



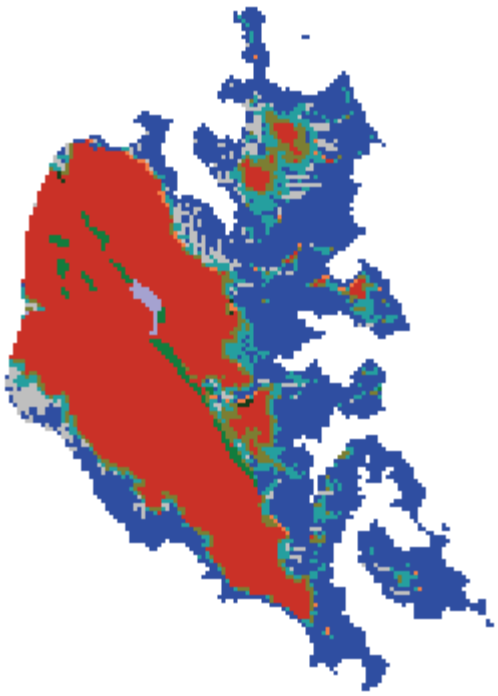
Eastern Neck NWR, 2025, 1.5 meter



Eastern Neck NWR, 2050, 1.5 meter



Eastern Neck NWR, 2075, 1.5 meter

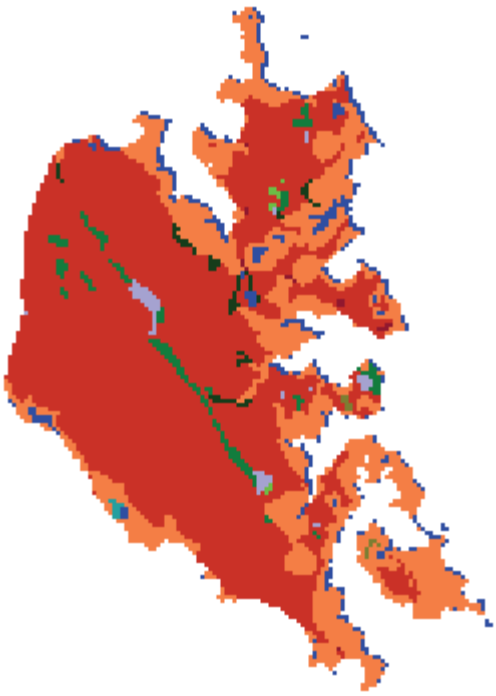


Eastern Neck NWR, 2100, 1.5 meter

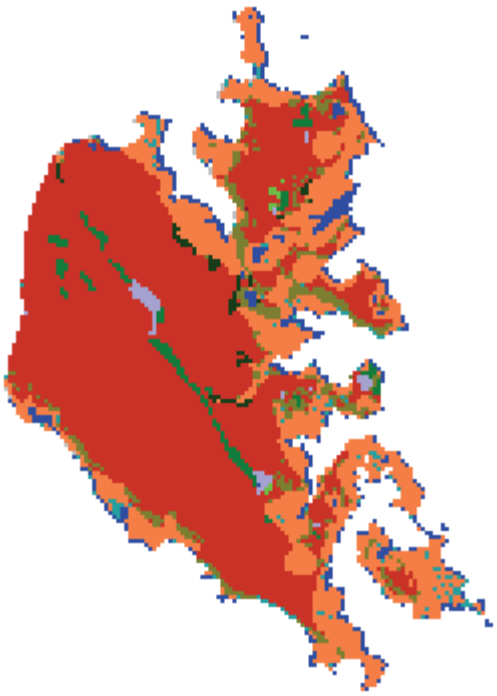
Eastern Neck Raster
2 Meters Eustatic SLR by 2100

Results in Acres

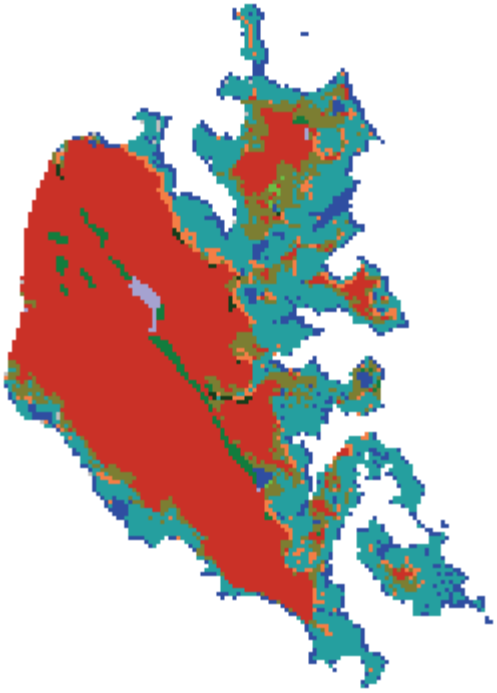
	Initial	2025	2050	2075	2100
Dry Land	1311.7	1196.5	1005.3	873.0	774.9
Irregularly Flooded Marsh	585.3	528.8	80.7	15.7	5.3
Estuarine Open Water	101.0	122.8	173.9	577.0	978.5
Swamp	44.7	42.9	35.4	30.9	24.4
Tidal Swamp	18.7	16.4	7.0	3.2	1.3
Inland Open Water	17.3	17.1	9.6	8.7	8.7
Dev. Dry Land	4.2	0.7	0.0	0.0	0.0
Trans. Salt Marsh	3.3	115.8	200.3	139.1	105.0
Inland Fresh Marsh	3.1	3.1	2.5	0.1	0.0
Regularly Flooded Marsh	2.4	45.4	573.4	269.1	151.4
Tidal Flat	0.0	2.4	3.9	175.0	42.5
Total (incl. water)	**2091.8**	**2091.8**	**2091.8**	**2091.8**	**2091.8**



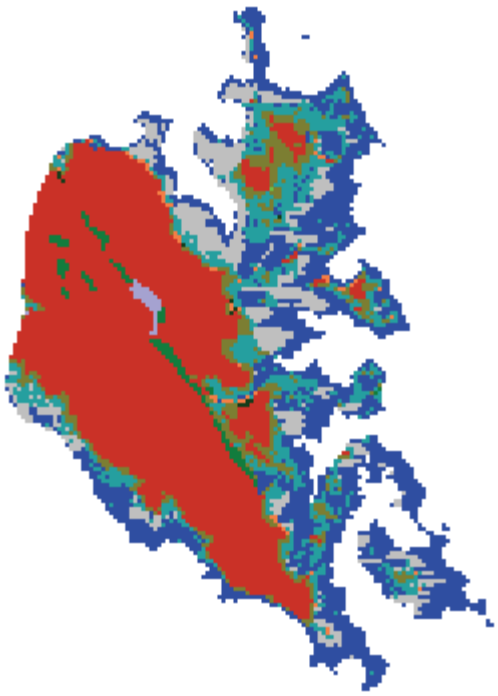
Eastern Neck NWR, Initial Condition



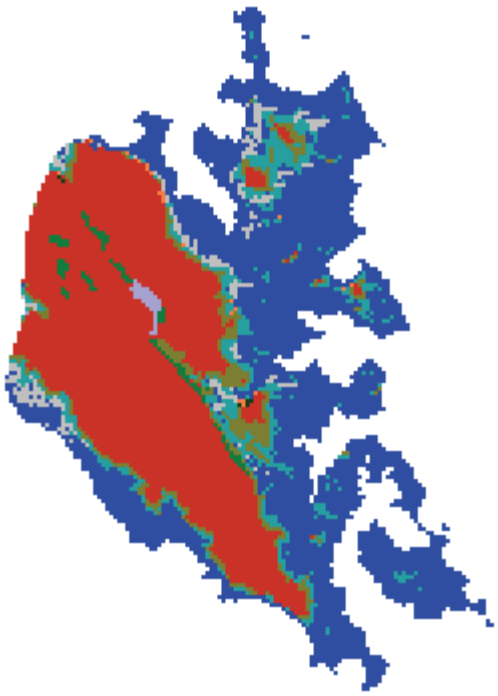
Eastern Neck NWR, 2025, 2 meters



Eastern Neck NWR, 2050, 2 meters



Eastern Neck NWR, 2075, 2 meters



Eastern Neck NWR, 2100, 2 meters

Discussion

These model results suggest that Eastern Neck National Wildlife Refuge will be impacted by the effects of sea level rise. Dry land, irregularly flooded marshes, and swamps are predicted lost at varying degrees and mostly on the eastern shore of the refuge. When local sea level rise rates exceed estimated marsh accretion, low-lying marshes are predictably inundated. When sea level rise reaches and exceeds one meter by 2100, nearly all marshlands at this location are predicted to convert to open water.

If erosion rates are effectively minimized by the breakwater on the northwestern shore, the SLAMM model predicts that inundation of dry land will be relatively minimal in those locations.

The 27-year-old NWI data combined with a rapidly changing shoreline adds a layer of uncertainty to model predictions (Figure 4). Future modeling efforts would benefit from more updated NWI.

Additionally, accretion rates are held constant at rates measured in nearby locations. If there is a positive feedback between marsh accretion and sea level rise due to more frequent inundation and higher sediment concentrations, marshlands may be somewhat more resilient at this site. Site-specific accretion measurements would also reduce uncertainty. However extensive dry-land inundation is also predicted at this site; a prediction that is not subject to uncertainties regarding marsh accretion rates.

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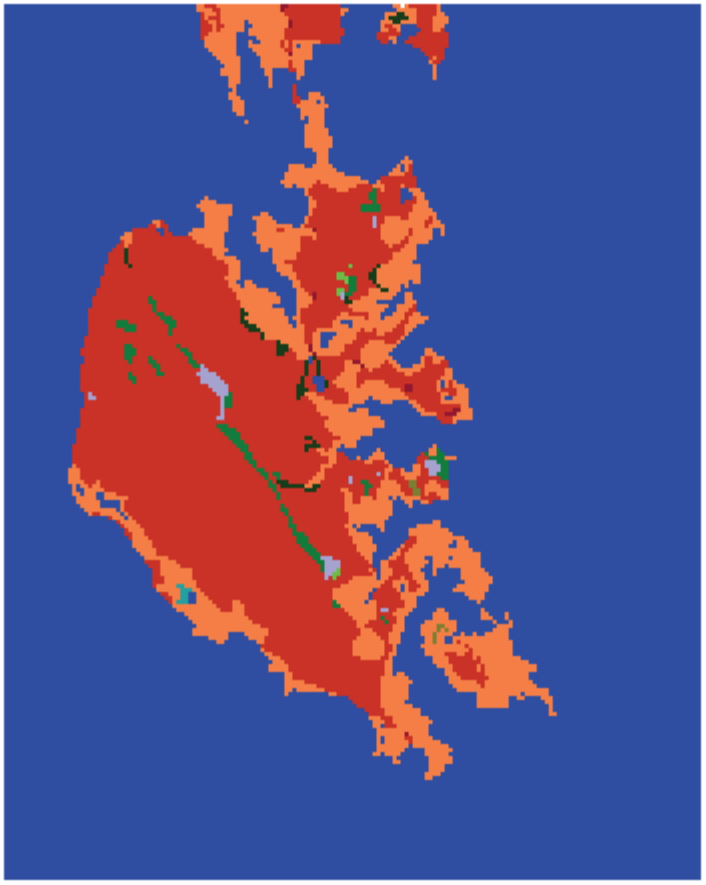
Appendix A: Contextual Results

The SLAMM model does take into account the context of the surrounding lands or open water when calculating effects. For example, erosion rates are calculated based on the maximum fetch (wave action) which is estimated by assessing contiguous open water to a given marsh cell. Another example is that inundated dry lands will convert to marshes or ocean beach depending on their proximity to open ocean.

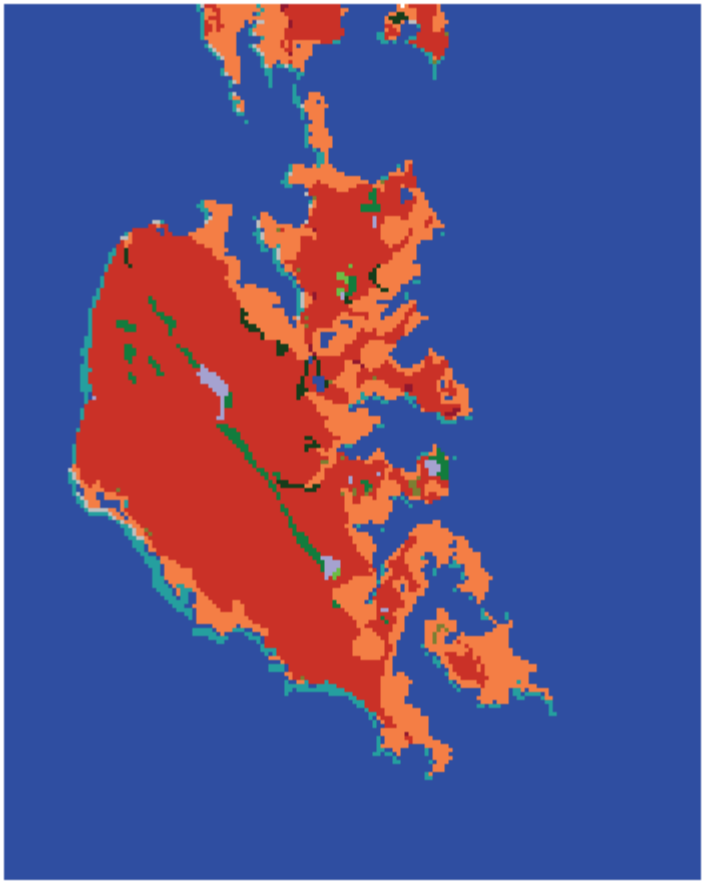
For this reason, an area larger than the boundaries of the USFWS refuge was modeled. These results maps are presented here with the following caveats:

- Results were closely examined (quality assurance) within USFWS refuges but not closely examined for the larger region.
- Site-specific parameters for the model were derived for USFWS refuges whenever possible and may not be regionally applicable.
- Especially in areas where dikes are present, an effort was made to assess the probable location and effects of dikes for USFWS refuges, but this effort was not made for surrounding areas.

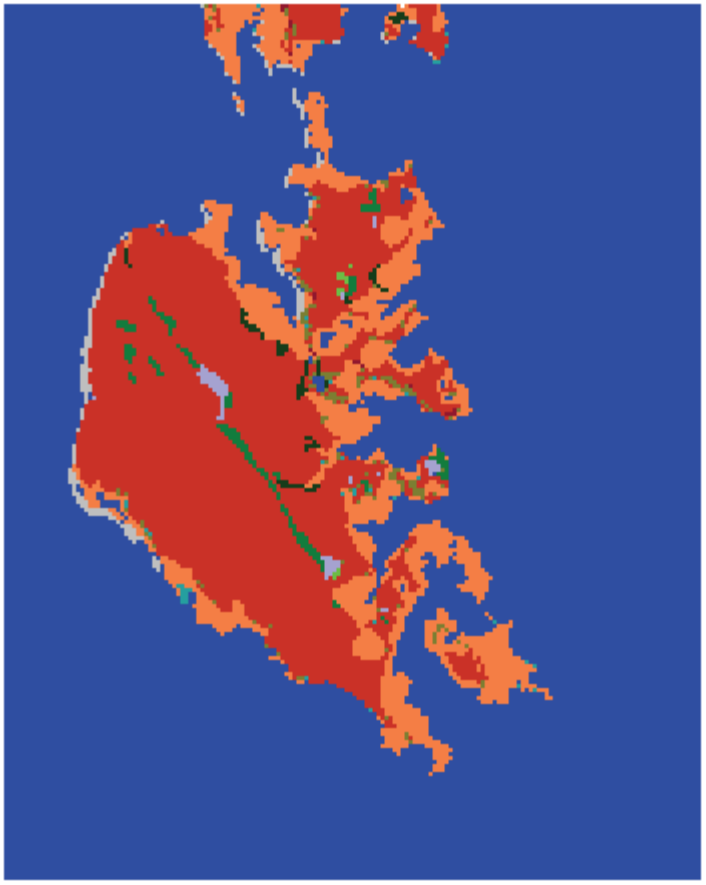
Location of Eastern Neck National Wildlife Refuge (white area) within simulation context



Eastern Neck NWR, Initial Condition



Eastern Neck NWR, 2025, Scenario A1B Mean



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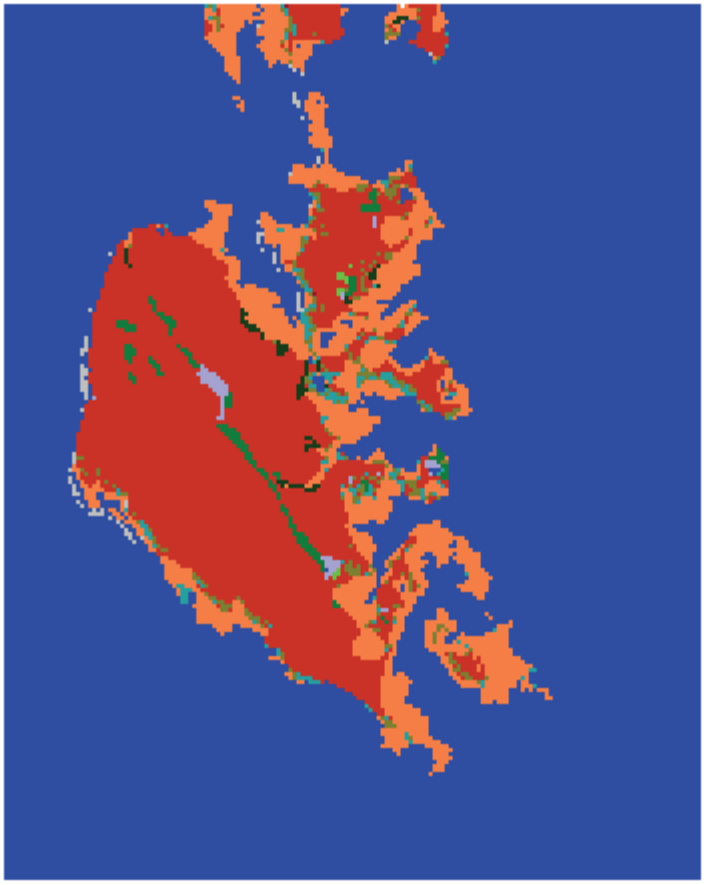
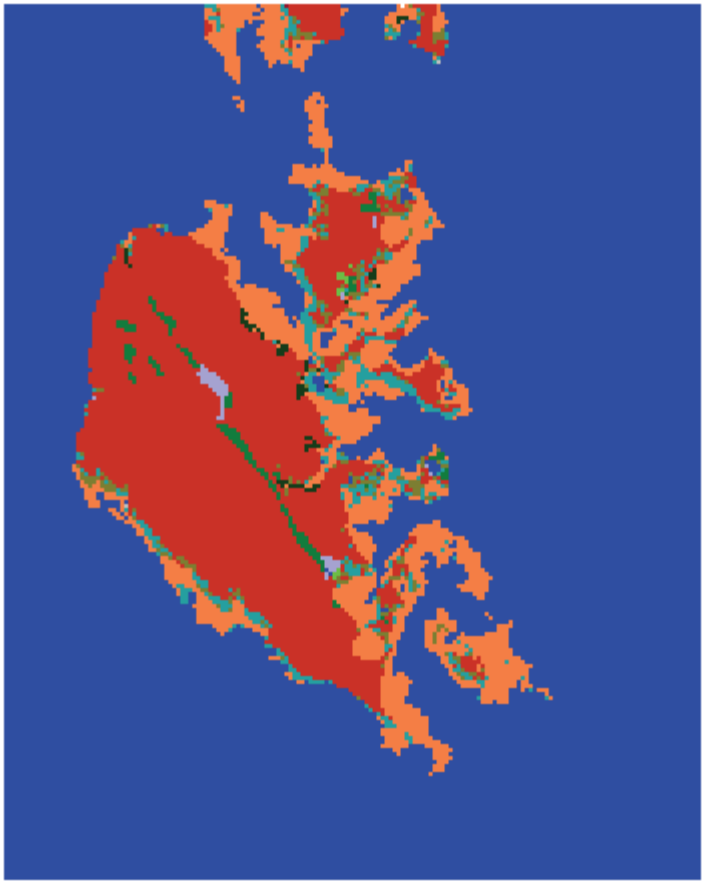
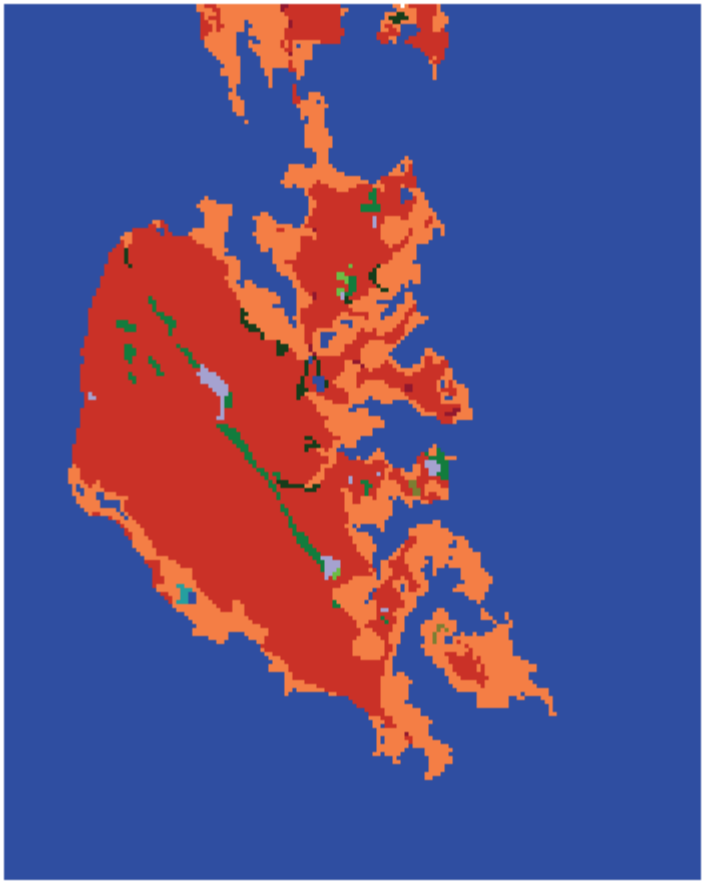


Eastern Neck NWR, 2075, Scenario A1B Mean



Eastern Neck NWR, 2100, Scenario A1B Mean



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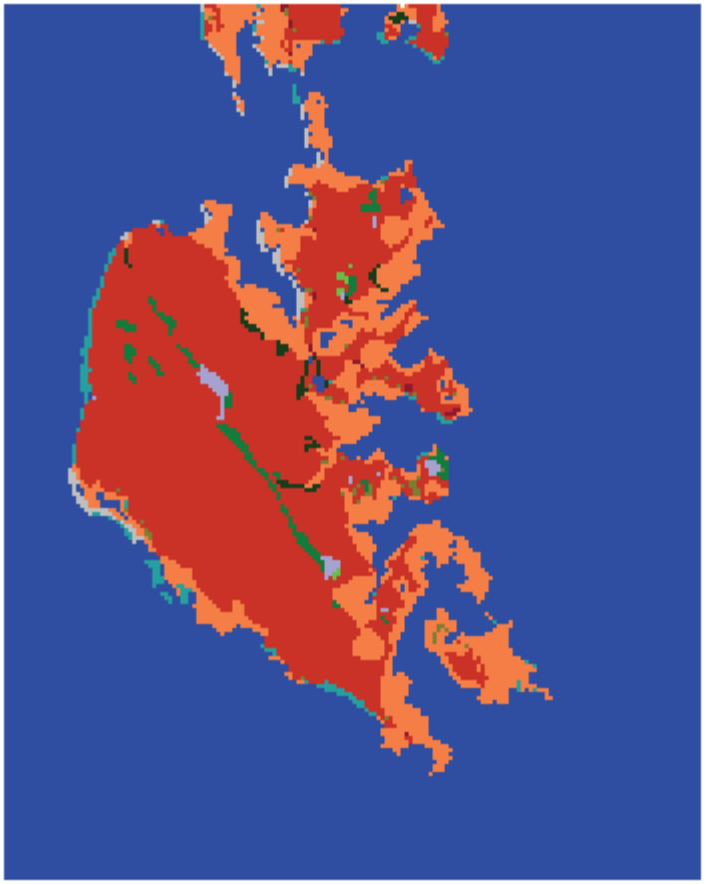
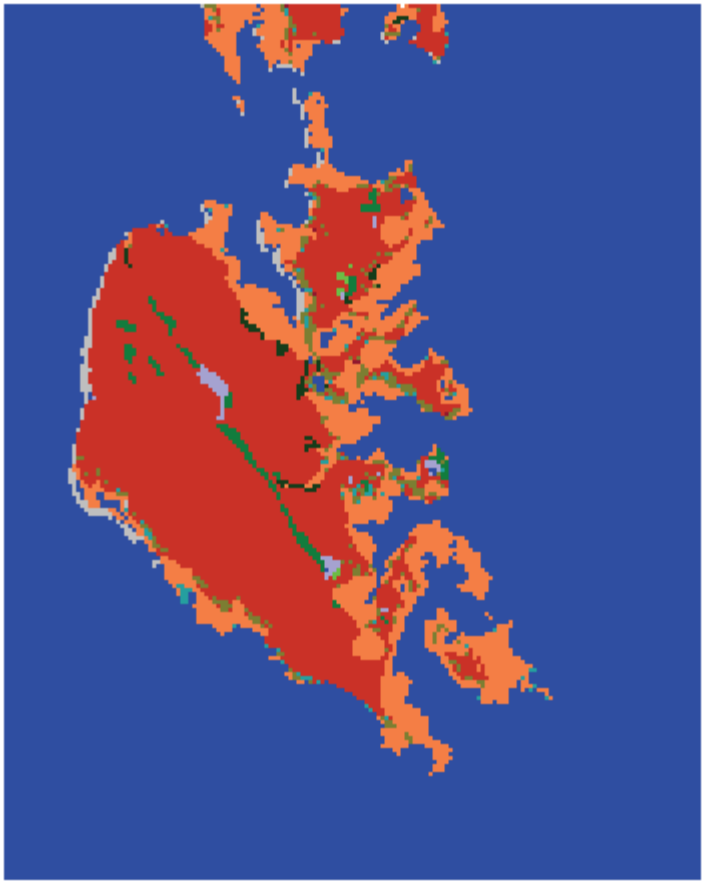


Eastern Neck NWR, 2025, Scenario A1B Maximum



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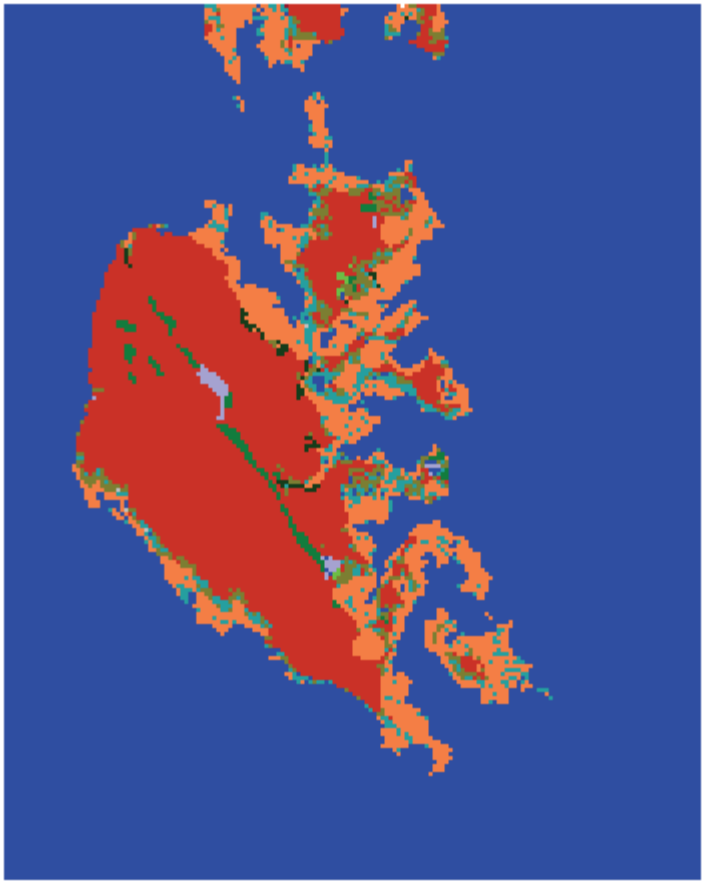

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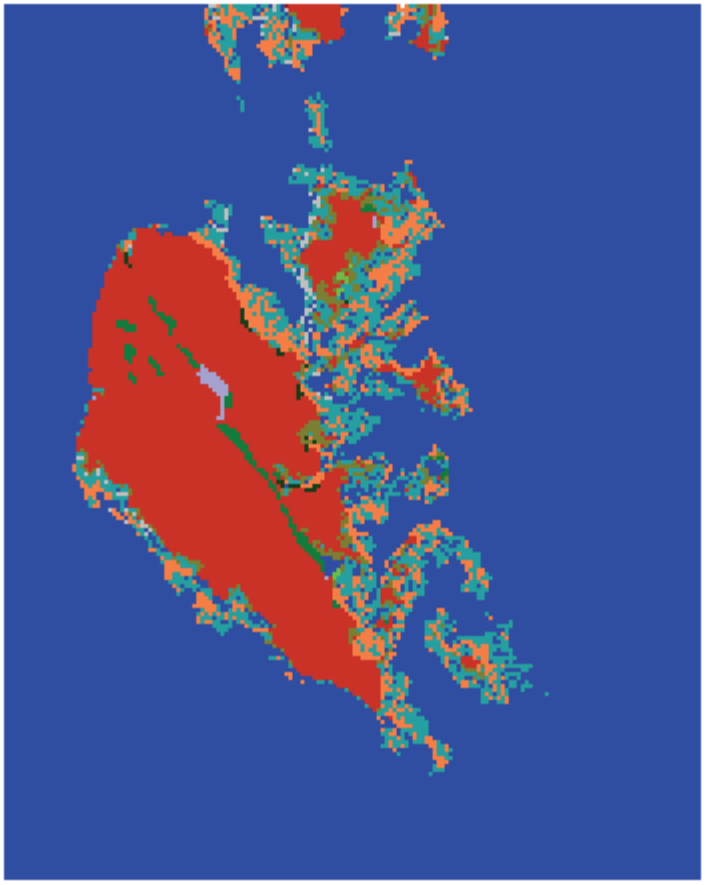

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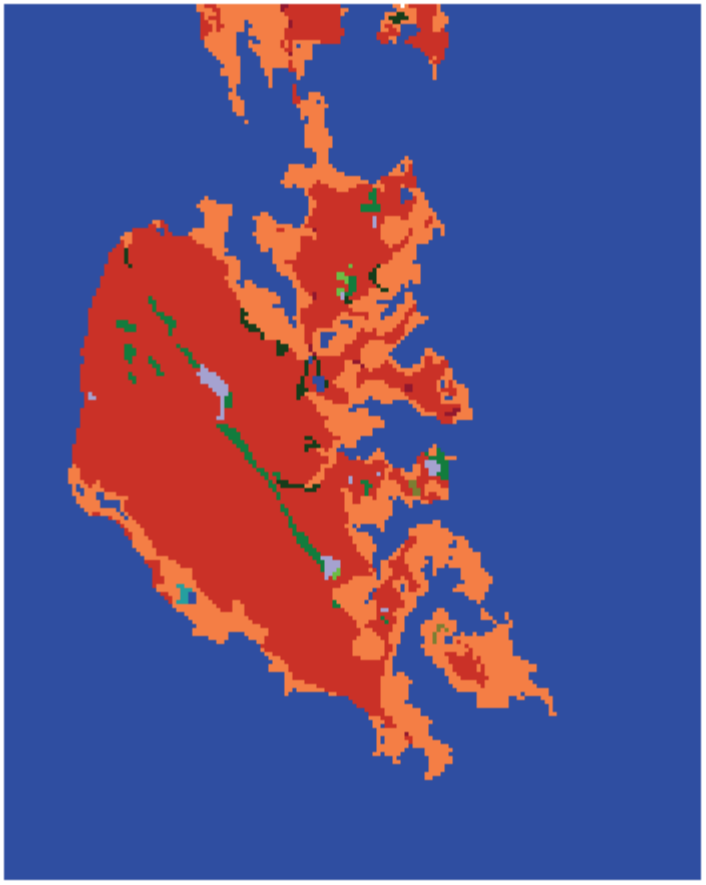

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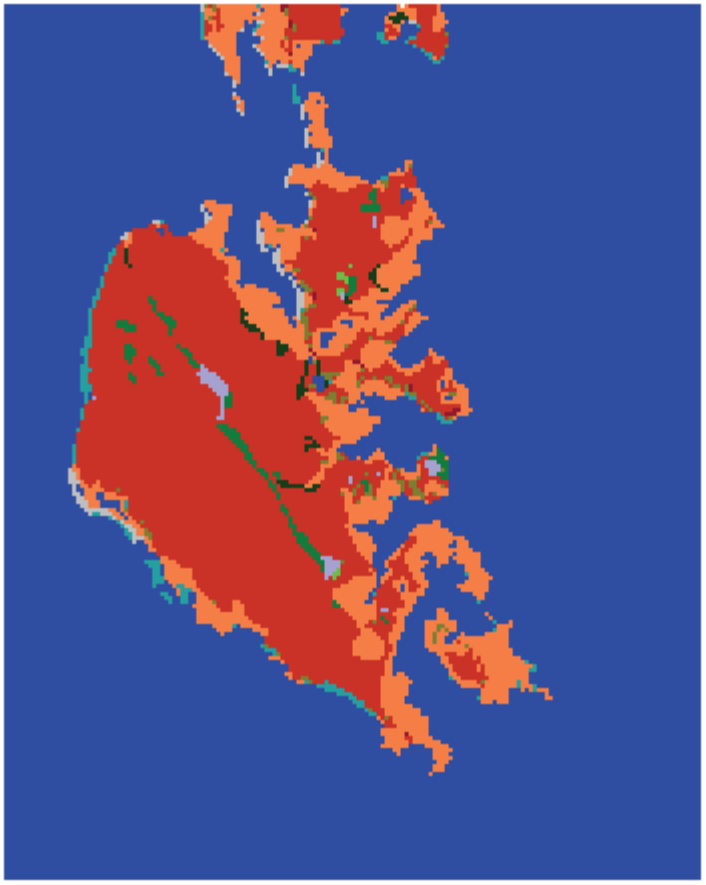
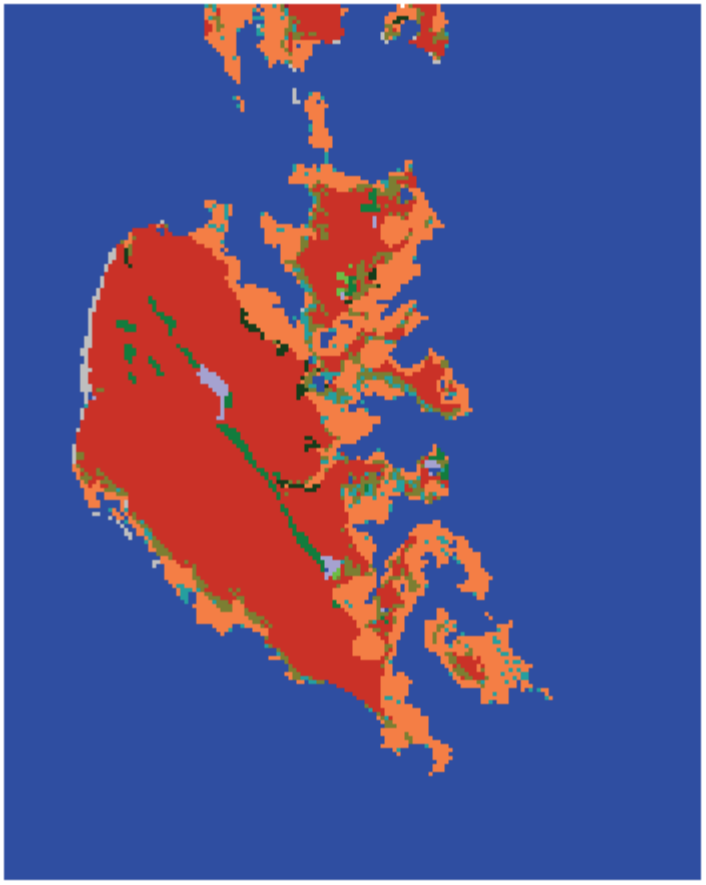


Eastern Neck NWR, 2025, 1 meter



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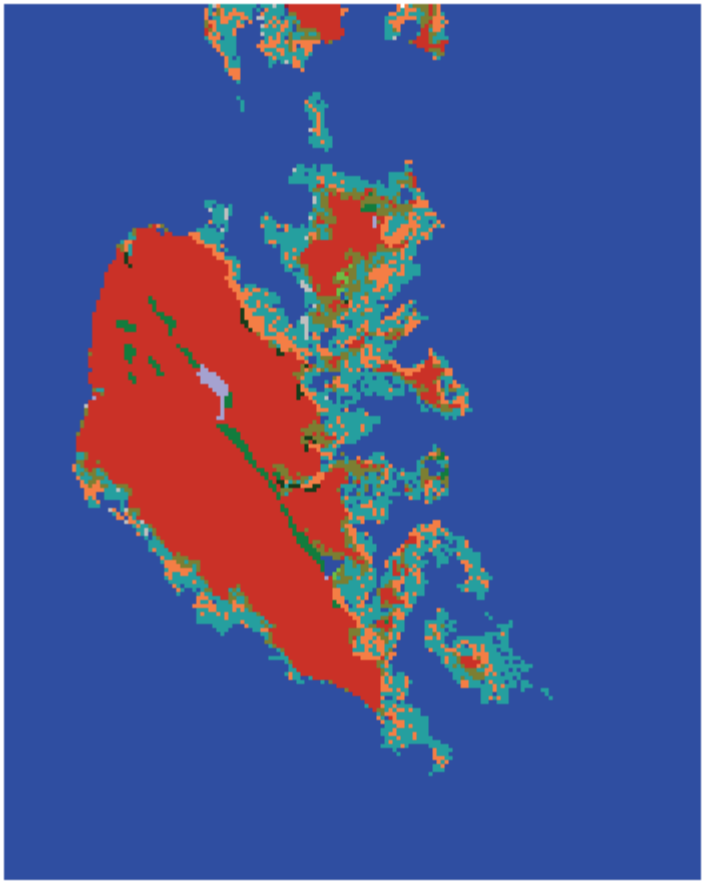

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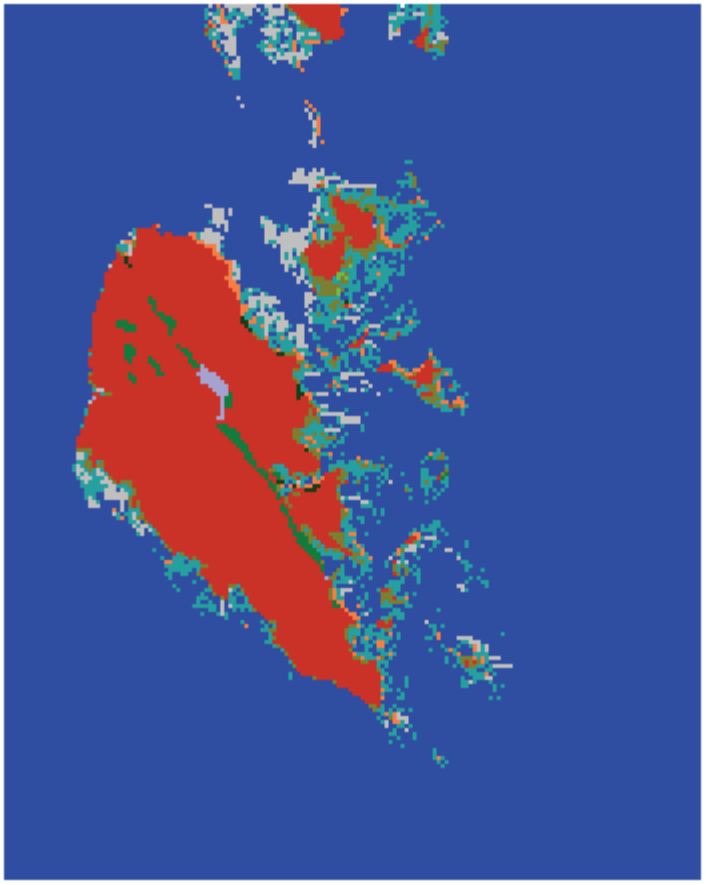
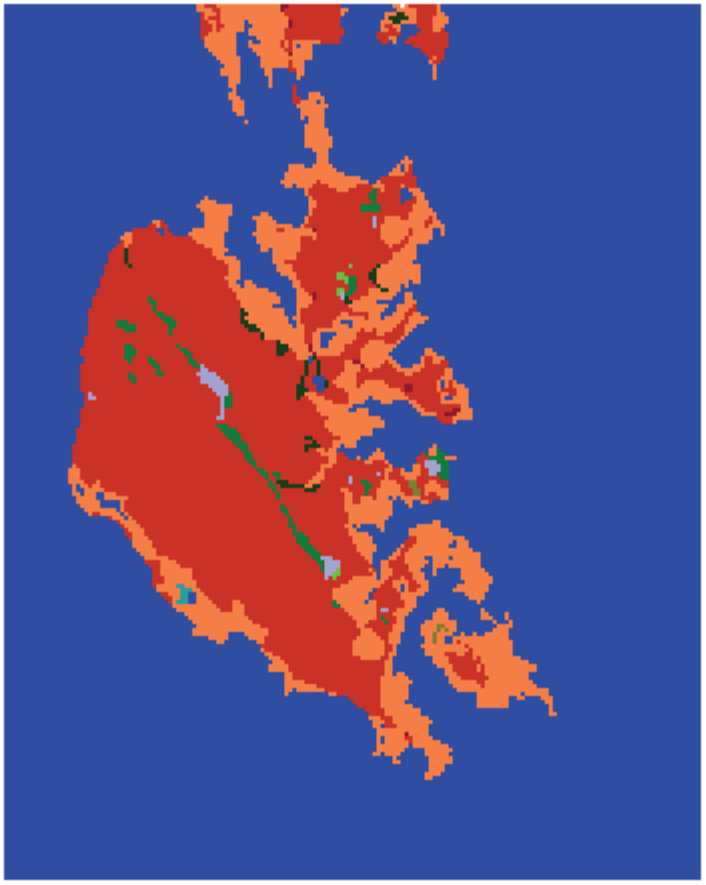
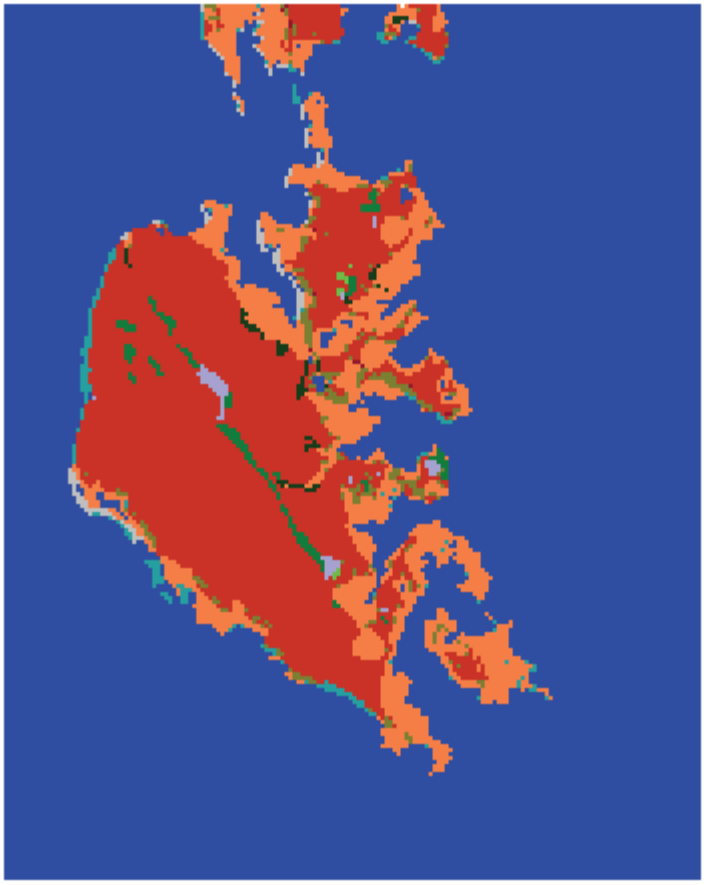


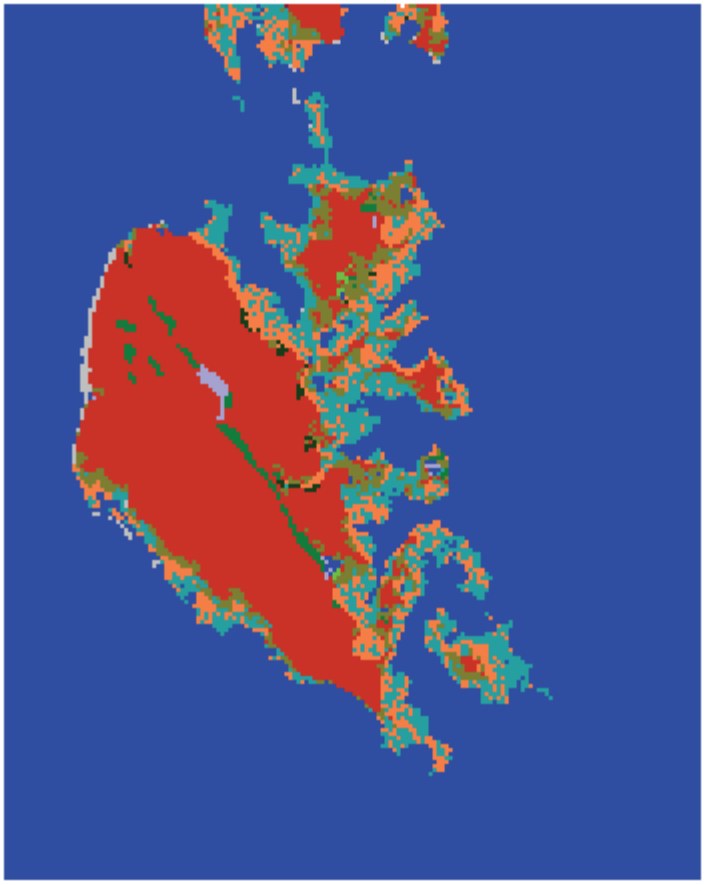
Eastern Neck NWR, 2100, 1 meter



Eastern Neck NWR, Initial Condition



Eastern Neck NWR, 2025, 1.5 meter



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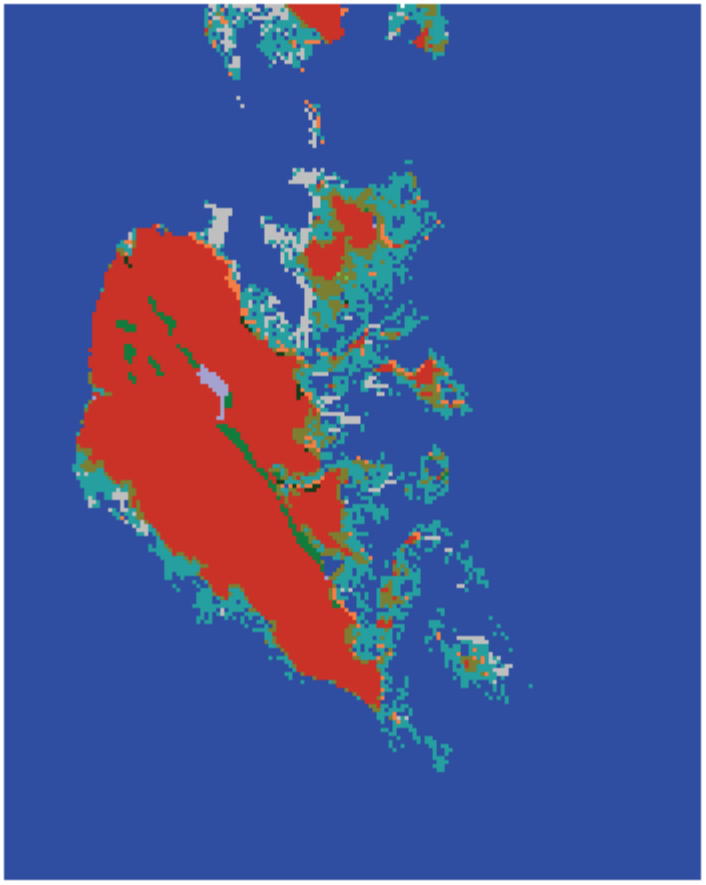
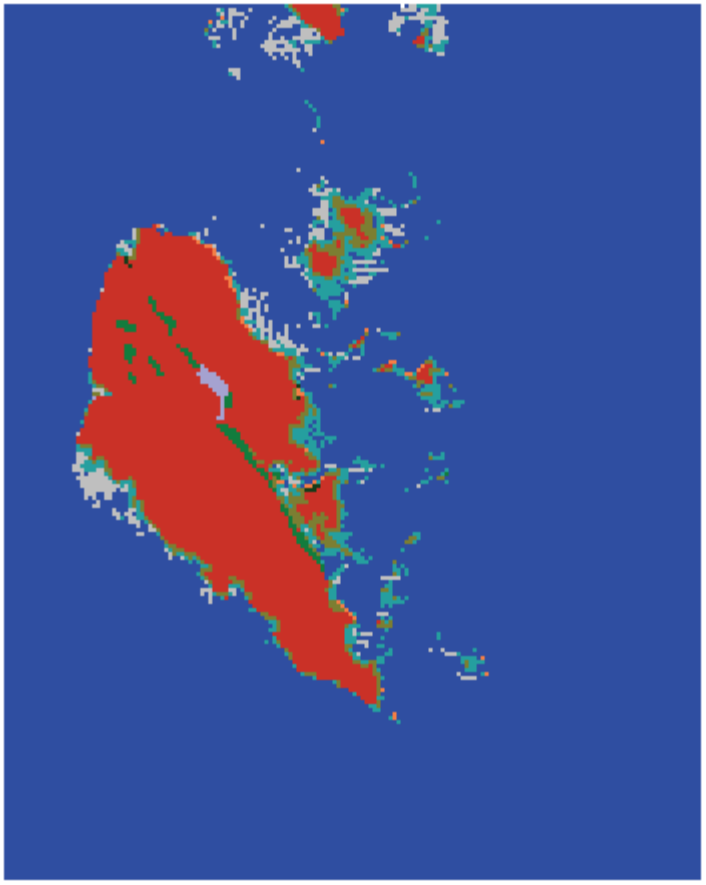
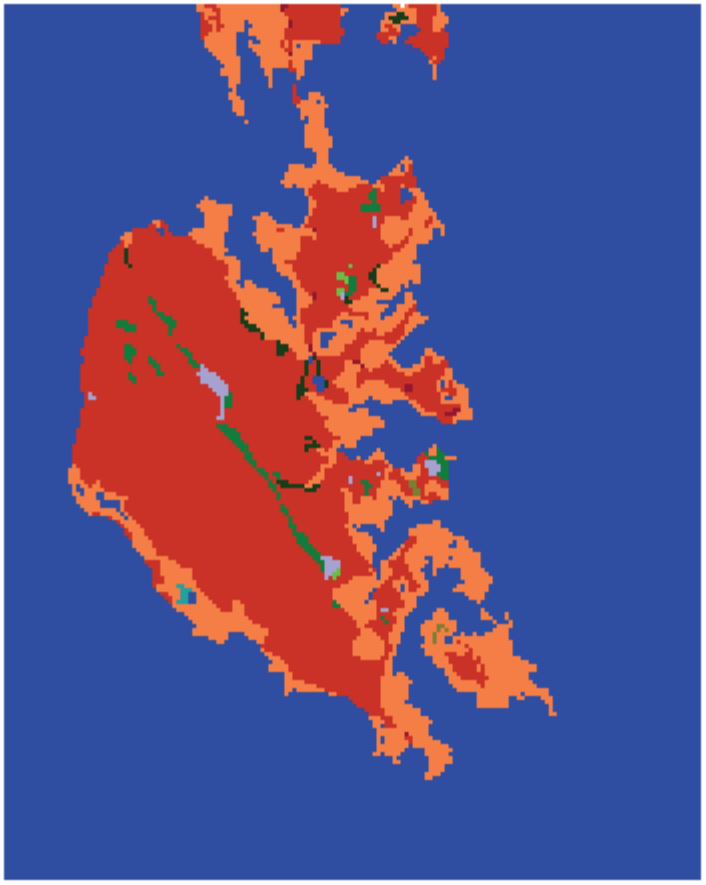


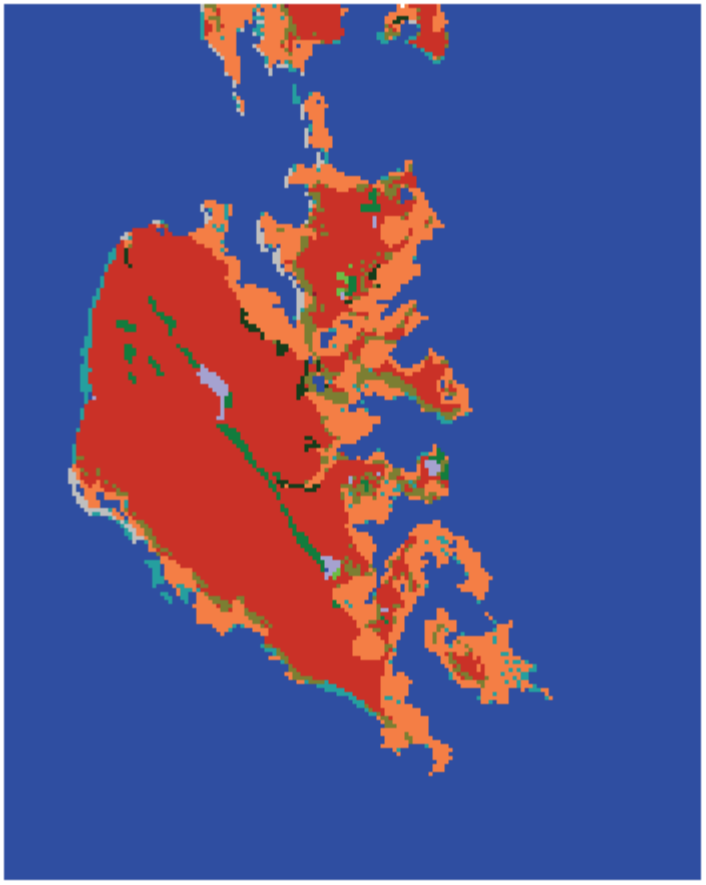
Eastern Neck NWR, 2075, 1.5 meter



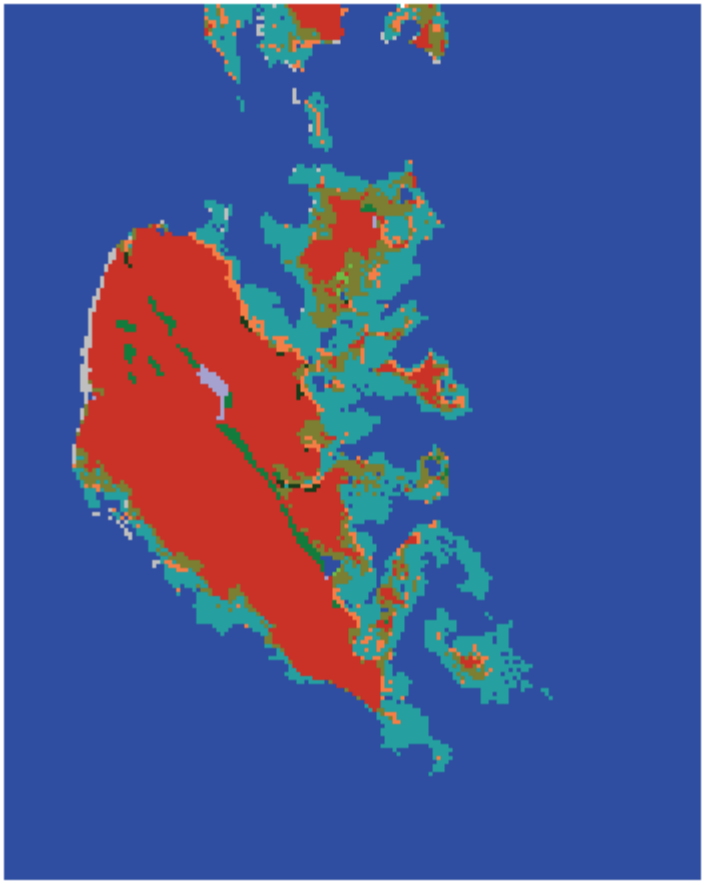
Eastern Neck NWR, 2100, 1.5 meter



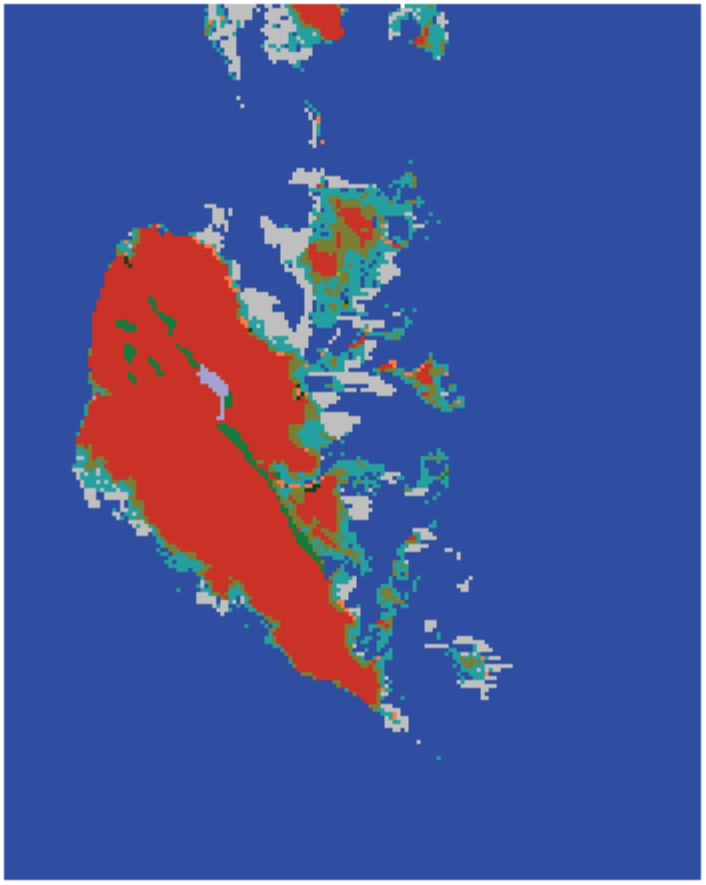
Eastern Neck NWR, Initial Condition



Eastern Neck NWR, 2025, 2 meter



Eastern Neck NWR, 2050, 2 meter



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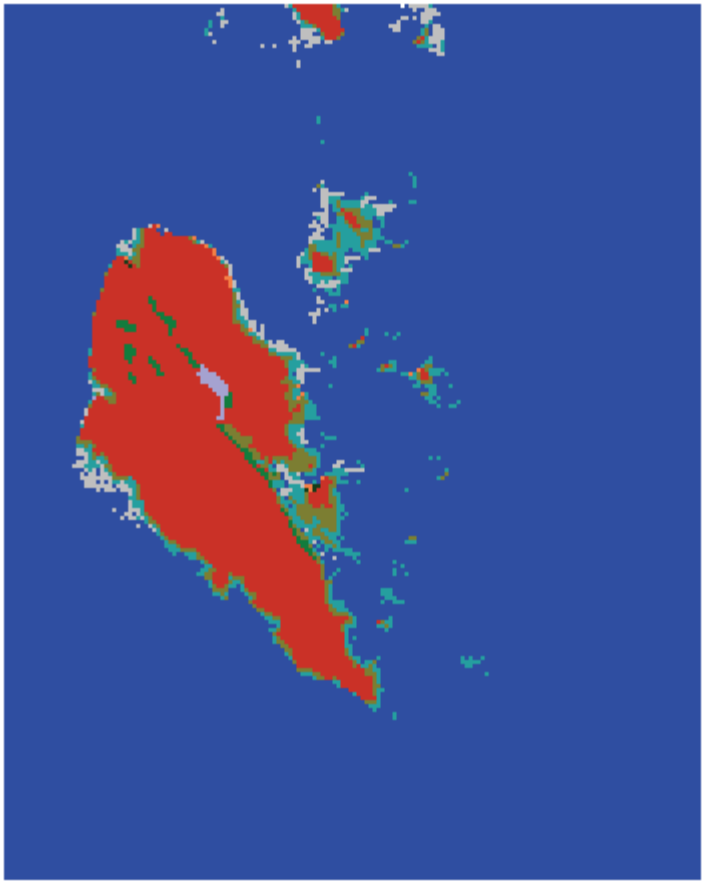

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