Application of the Sea-Level Affecting Marshes Model (SLAMM 5.1) to Rappahannock 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 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 5 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 (Irregularly Flooded) Marsh," and "Tidal Swamp."
- *Optional.* In a defined estuary, salt marsh, Irregularly Flooded 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

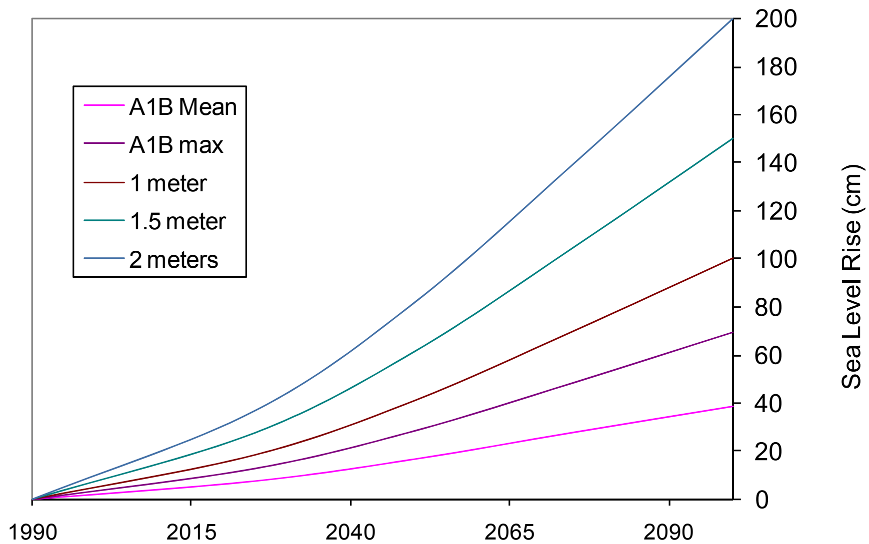
SLAMM 5 was run using scenario A1B from the Special Report on Emissions Scenarios (SRES) – mean and maximum estimates. The A1 scenario assumes that the future world includes very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of 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

The digital elevation map (DEM) used in this model simulation was derived from the National Elevation Dataset (NED). NED metadata indicate that these data were derived from USGS maps dated 1968 and 1987, with 10 foot contour intervals (Figure 1). No high vertical resolution elevation data (e.g. LiDAR data) were available for this refuge simulation.

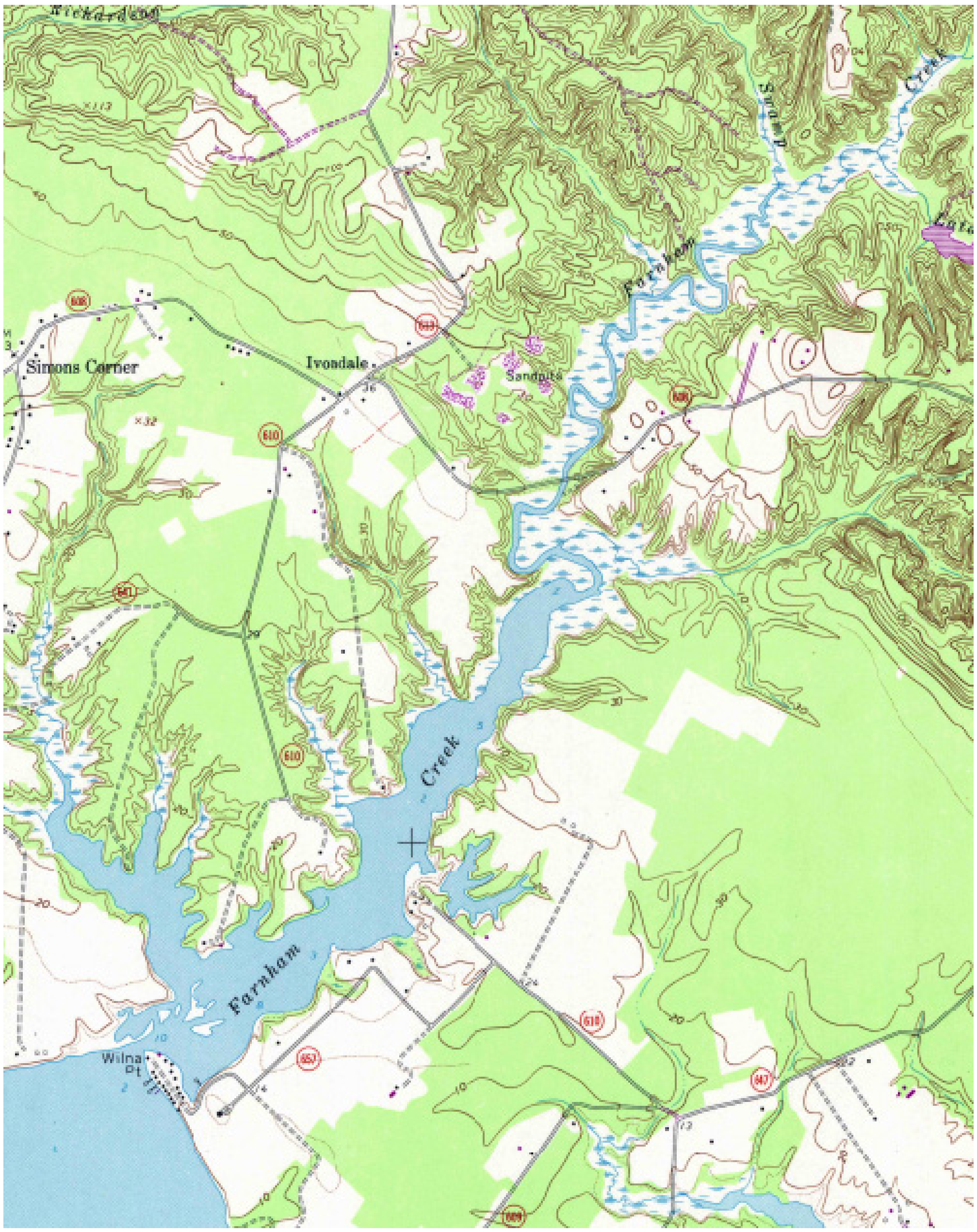


Figure 1: USGS contour map for portion of Rappahannock NWR.

The National Wetlands Inventory for Rappahannock is based on photo dates of 1981, 1988 and 1990.

Converting the NWI survey into 30 meter cells indicates that the approximately two hundred eighty five thousand acre refuge (approved acquisition boundary including water) is composed of the categories as shown below:

Dry Land	71.6%
Estuarine Open Water	12.2%
Swamp	5.2%
Riverine Tidal	3.4%
Irregularly Flooded Marsh	2.7%
Tidal Swamp	2.2%

There are many diked or impounded wetlands in the Rappanock NWR according to the National Wetlands Inventory.

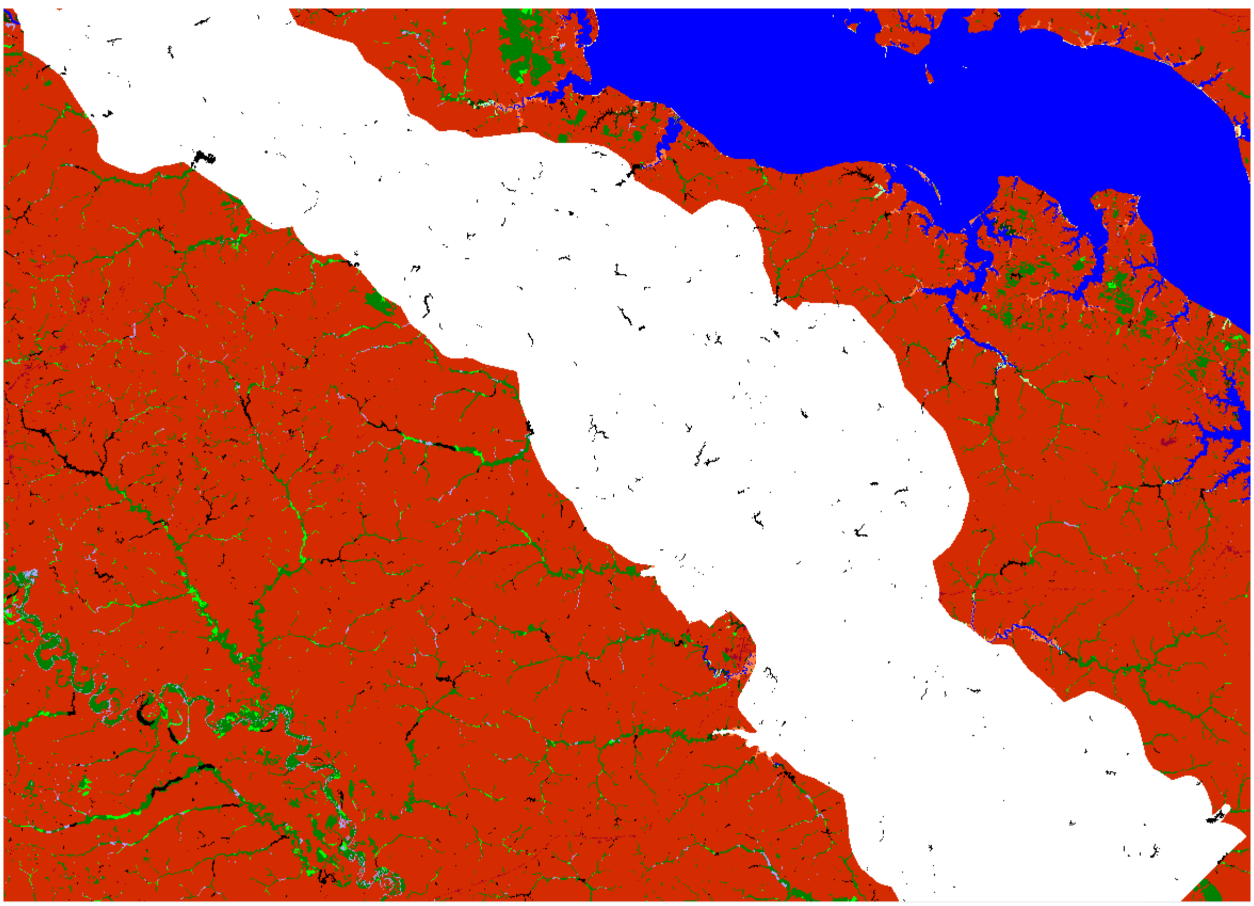


Figure 2: Diked areas in black.

The historic trend for sea level rise was estimated 4.39 mm/year using the average of two NOAA gages (8637624, Gloucestor Point, VA; 8635750, Lewisetta, VA). The rate of sea level rise for this refuge is more than twice the global average for the last 100 years (approximately 1.7 mm/year).

Eustatic projections of future sea level rise were further increased by 0.5 mm/year as a result of a study performed by Dr. Victoria Coles of University of Maryland (Figure 2). This study suggests that sea level rise in Chesapeake Bay will increase faster than eustatic trends due to regional heating, freshwater effects, and/or mass adjustments. Based on this analysis an additional 0.5 mm/year were added to eustatic sea level rise trends. (This adjustment was performed by adding 0.5 mm/year to the historic SLR trend parameter.)

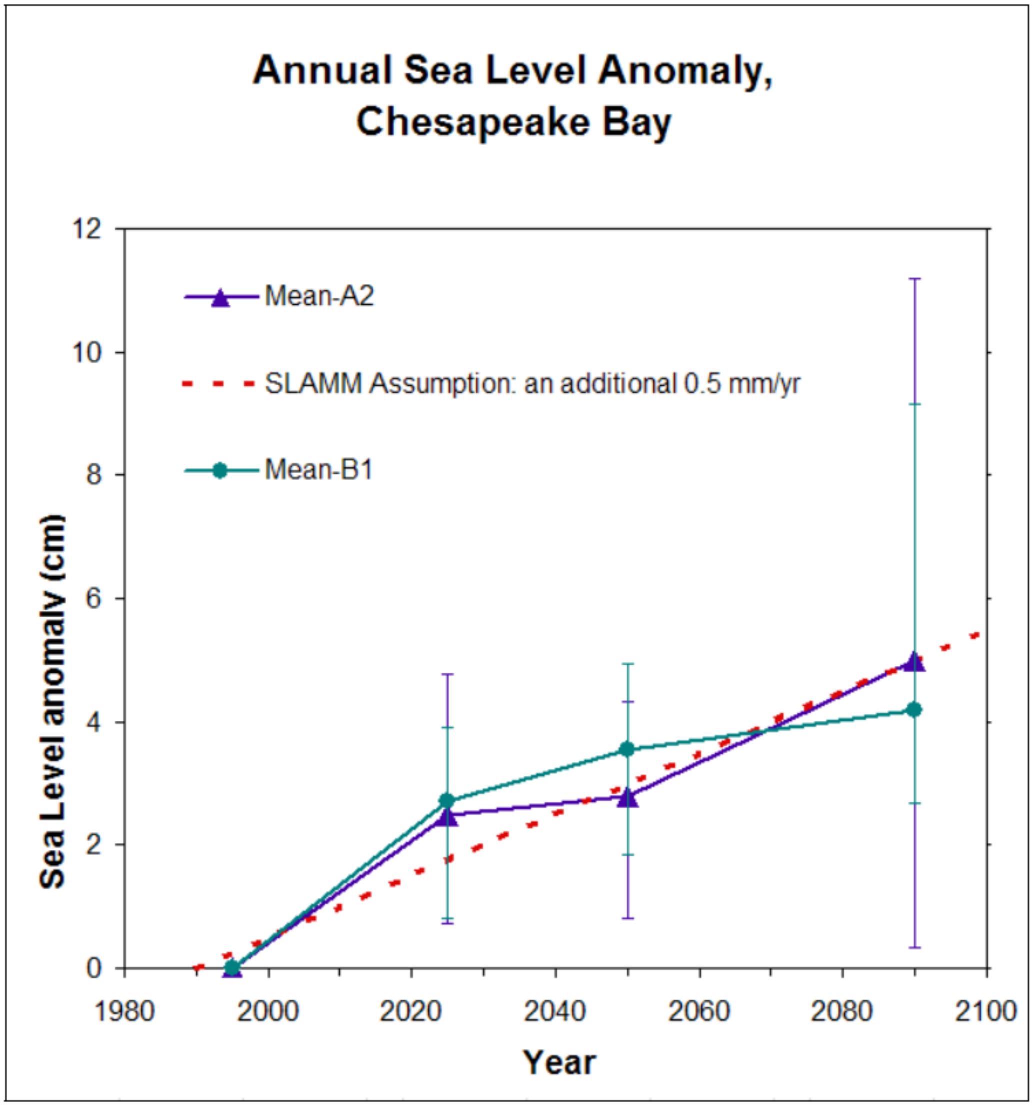


Figure 3: Adjustment of Eustatic SLR in SLAMM illustrated as red line. Source of model results, Dr. Victoria Coles Research Web Page, 11/15/2009, **http://hpl.umces.edu/vcoles/cbayclim-sl.htm**.

The tidal range for the Rappahannock NWR was specified to vary spatially (Figure 4) using three NOAA tide gages (8636580, Windmill Point, VA; 8635985, Wares Wharf, VA; 8635257, Rappahannock Bend, VA) (Figure 5).

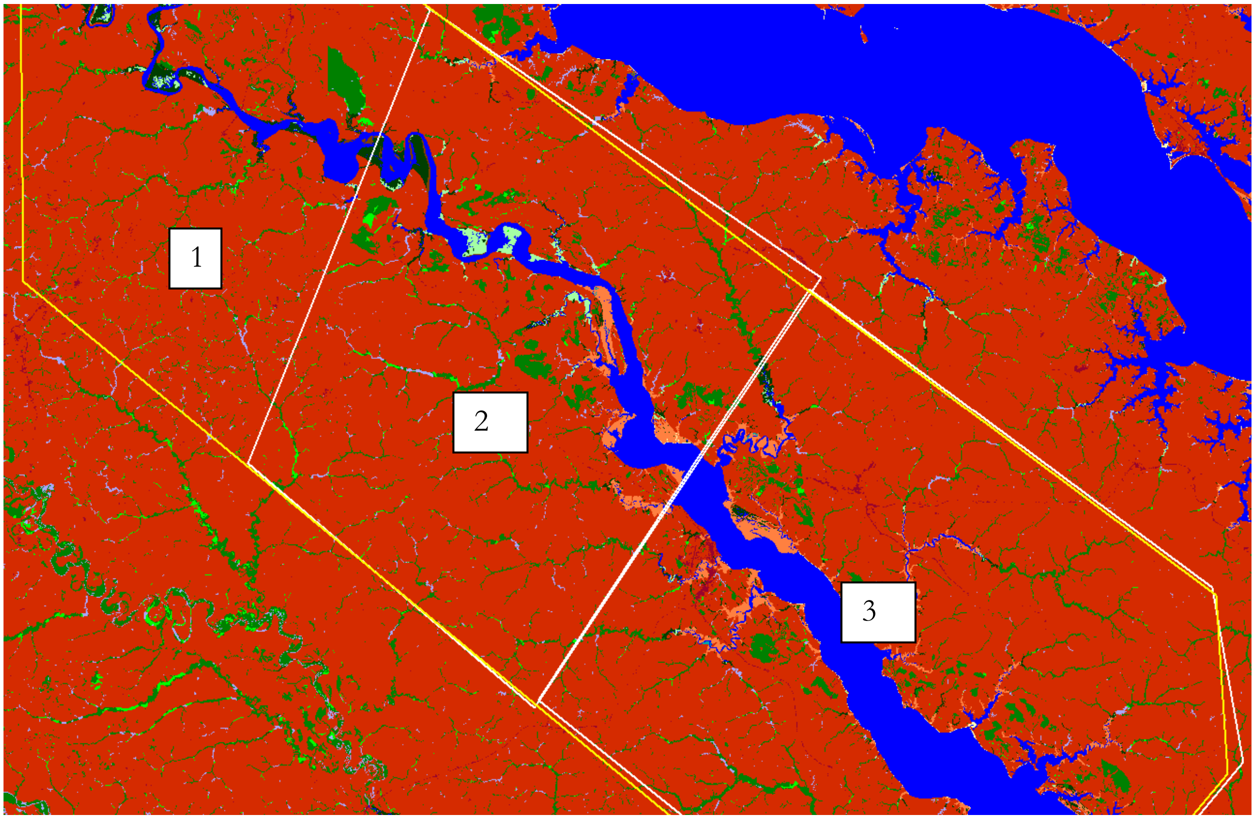


Figure 4: Input sub-sites.

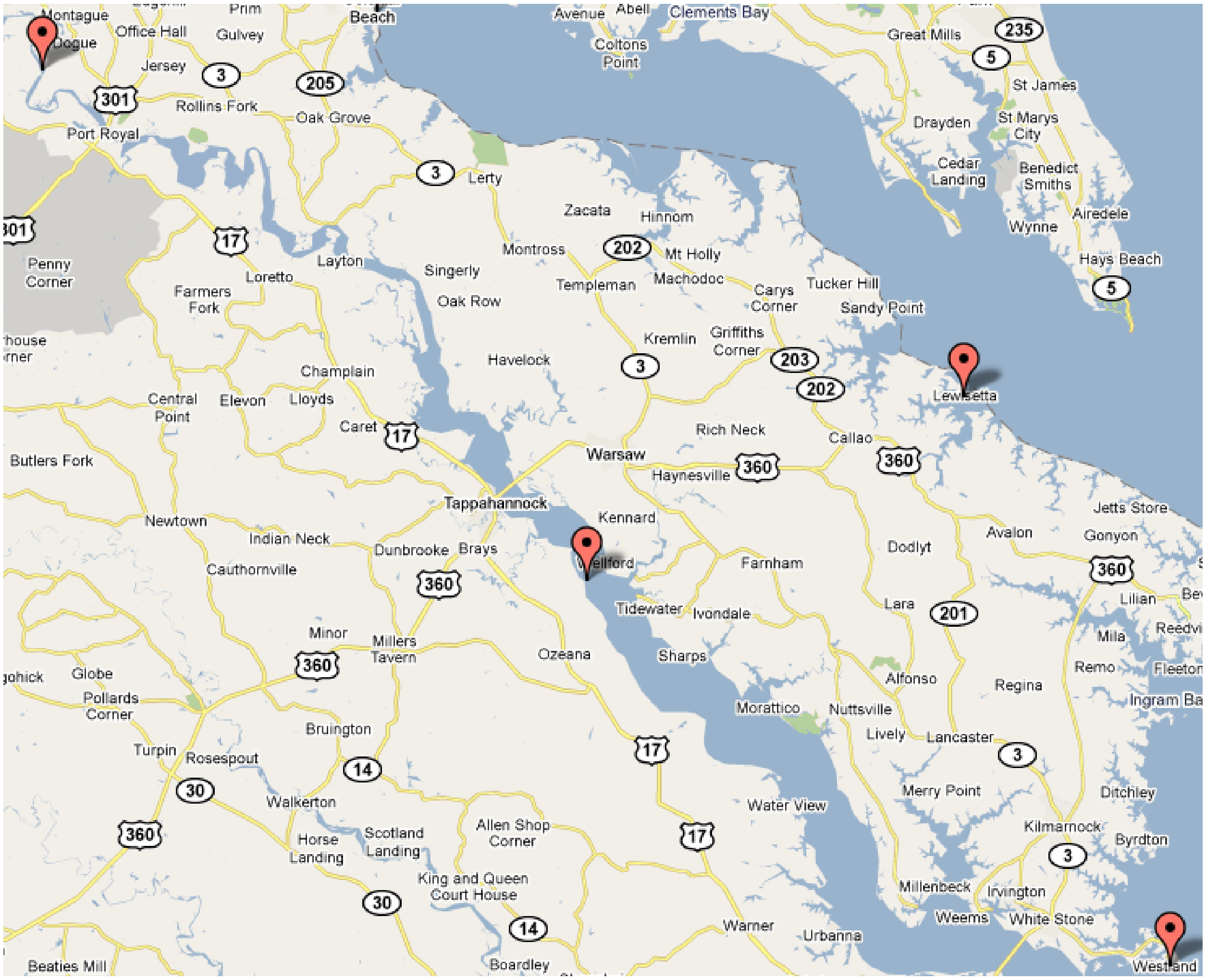


Figure 5: NOAA Gage Relevant to the Study Area.

No site-specific marsh accretion data were located for this refuge. Accretion rates in regularly flooded marshes were set to 6 mm/year (n=2), irregularly flooded marshes to 4.8 mm/year (n=5) and tidal fresh to 7.2 mm/year (n=5) using the means of numerous studies of marsh accretion within Maryland (Reed et al., 2008).

The MTL to NAVD88 correction was derived using the NOAA VDATUM modeling product. The correction varies by sub-site, and was determined to range from -0.04 to -0.05 meters.

Modeled U.S. Fish and Wildlife Service refuge boundaries for Virginia 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. Additionally, the SLAMM model will track partial conversion of cells based on elevation and slope.

The refuge manager of the Eastern Virginia Rivers NWR Complex, Joseph F. McCauley, indicated the existence of LiDAR for the refuge around Fort A.P. Hill (Figure 6). This data was not pursued since it barely covers the refuge itself.

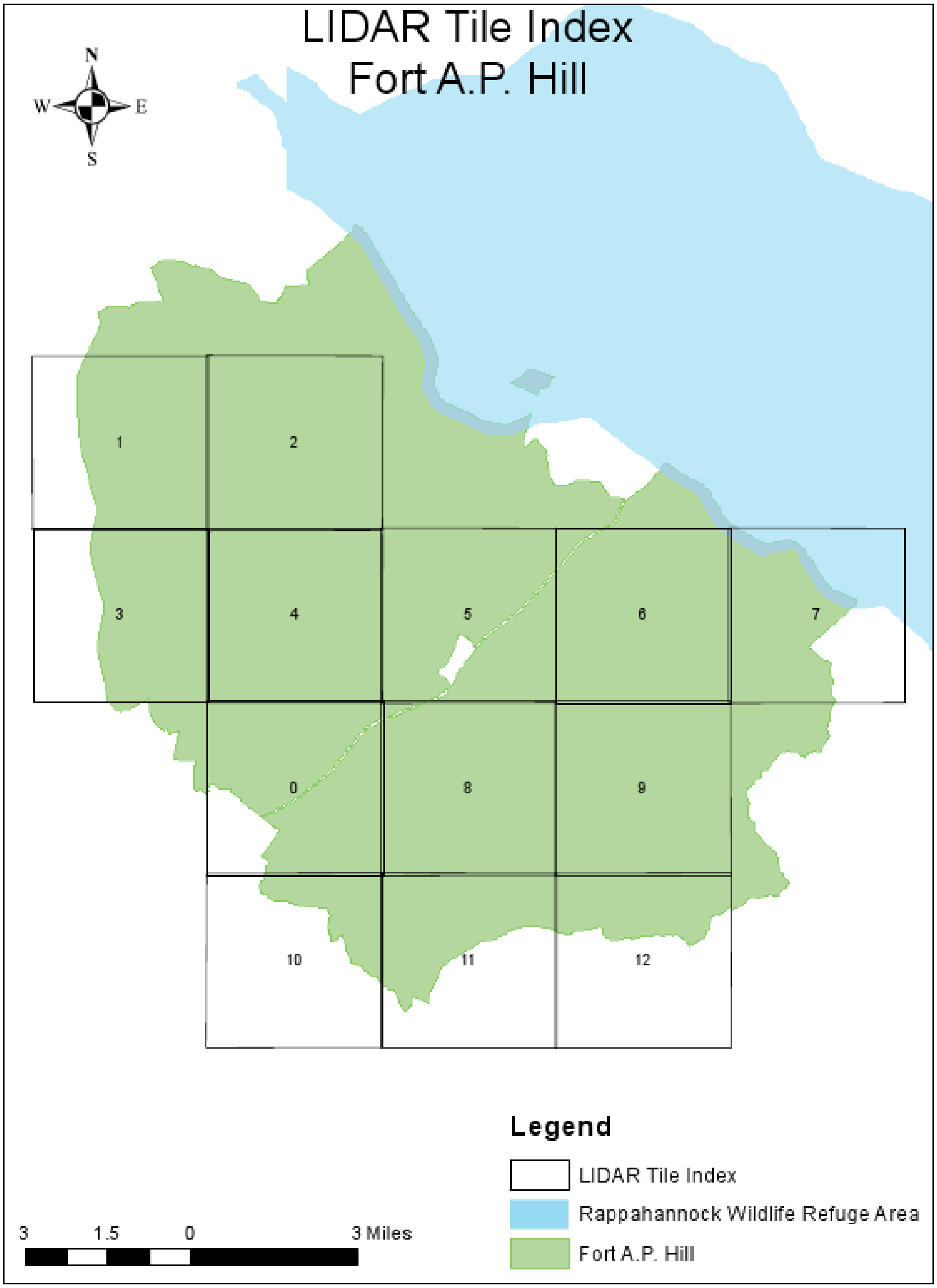


Figure 6: Fort A.P. Hill LiDAR coverage

SUMMARY OF SLAMM INPUT PARAMETERS FOR RAPPAHANNOCK NWR

Parameter	Global	Sub-site 1	Sub-site 7	Sub-site 8
Description	Chessy North	Rappahannock Upper	Rappahannock Lower	Rappahannock Mid
NWI Photo Date (YYYY)	2000	2000	2000	2000
DEM Date (YYYY)	1968	1968	1968	1968
Direction Offshore [n,s,e,w]	East	East	East	East
Historic Trend (mm/yr)	4.8	4.89	4.89	4.89
MTL-NAVD88 (m)	-0.05	-0.04	-0.05	-0.04
GT Great Diurnal Tide Range (m)	0.58	0.755	0.629	0.692
Salt Elev. (m above MTL)	0.385	0.502	0.418	0.46
Marsh Erosion (horz. m /yr)	1.8	1.8	1.8	1.8
Swamp Erosion (horz. m /yr)	1	1	1	1
T.Flat Erosion (horz. m /yr)	6	6	6	6
Reg. Flood Marsh Accr (mm/yr)	6	6	6	6
Irreg. Flood Marsh Accr (mm/yr)	4.8	4.8	4.8	4.8
Tidal Fresh Marsh Accr (mm/yr)	7.2	7.2	7.2	7.2
Beach Sed. Rate (mm/yr)	0.5	0.5	0.5	0.5
Freq. Overwash (years)	25	25	25	25
Use Elev Pre-processor [True,False]	TRUE	TRUE	TRUE	TRUE

Results

SLAMM predicts that Rappahannock NWR will show some effects of sea level rise. Up to four percent of dry land, which makes up the majority of the refuge, is predicted to be lost. Of the nearly eight thousand acres of irregularly flooded marsh (often brackish marsh), between one third and two thirds is predicted to be lost (converted to regularly flooded salt marsh or open water.)

SLR by 2100 (m)	0.39	0.69	1	1.5	2
Dry Land	2%	2%	3%	3%	4%
Irregularly Flooded Marsh	33%	77%	93%	78%	66%
Tidal Swamp	3%	9%	13%	37%	57%

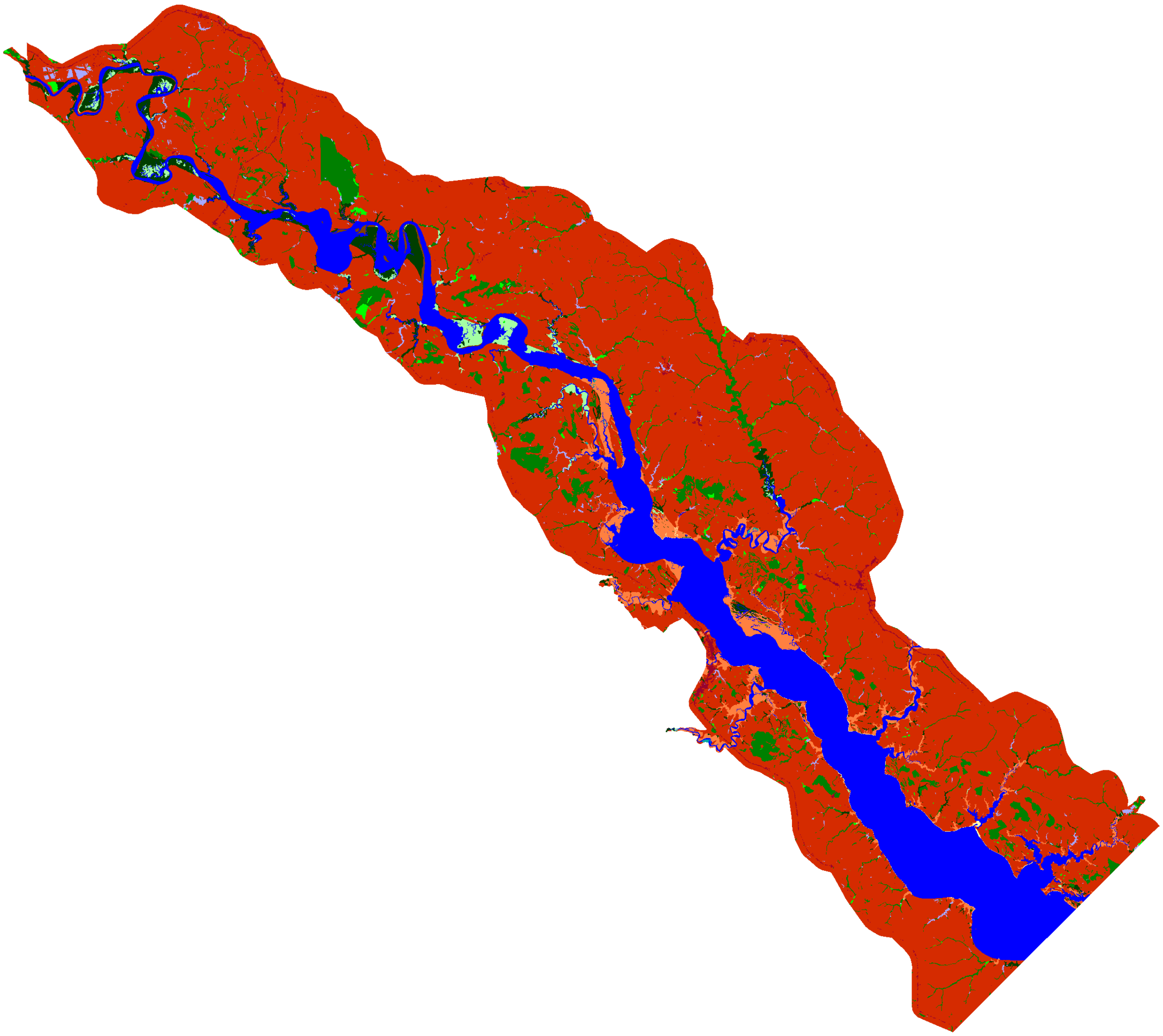
Predicted Loss Rates of Land Categories by 2100 Given Simulated Scenarios of Eustatic Sea Level Rise

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

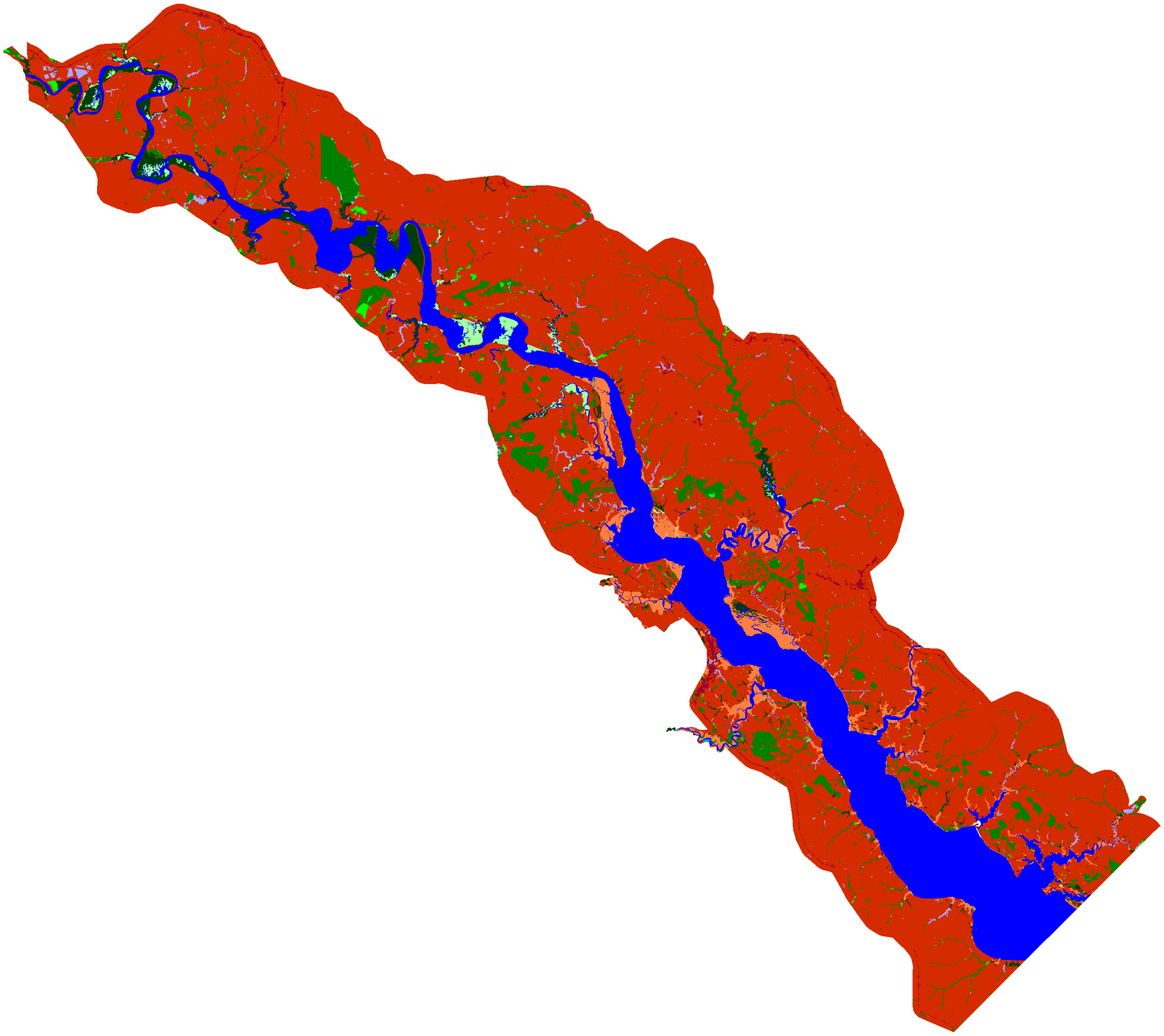
Rappahannock Raster
IPCC Scenario A1B-Mean, 0.39 M SLR Eustatic by 2100

Results in Acres

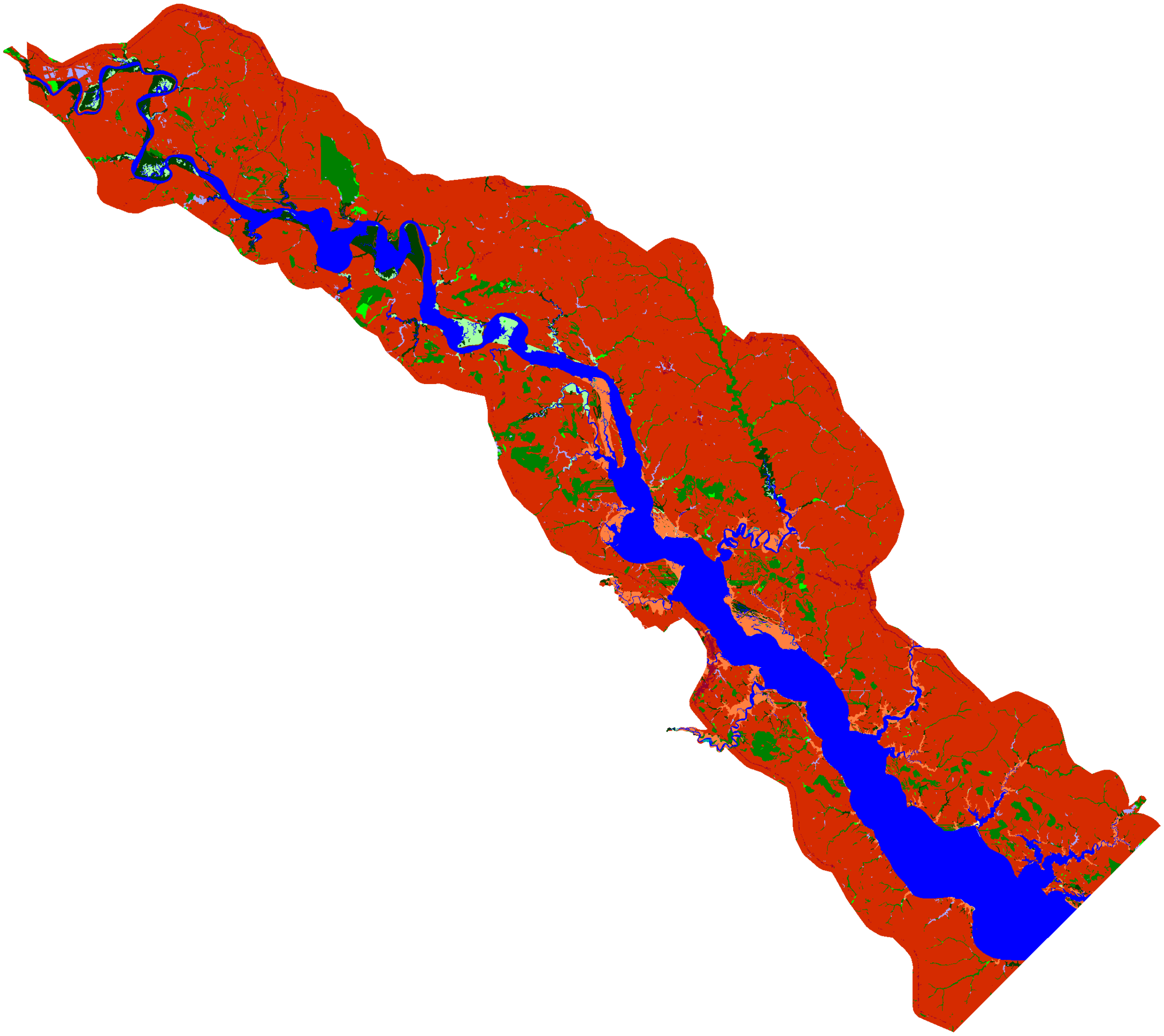
	Initial	2025	2050	2075	2100
Undev. Dry Land	203776.0	202867.8	202310.2	201068.9	200049.2
Estuarine Open Water	34606.7	34880.3	35265.3	36254.0	36904.0
Swamp	14710.2	15557.1	15825.7	16451.8	17003.3
Riverine Tidal	9621.0	9617.9	9386.9	8597.8	8099.8
Irregularly Flooded Marsh	7820.7	7778.1	7631.5	6459.6	5204.1
Tidal Swamp	6223.9	6215.8	6195.0	6161.2	6058.9
Tidal Fresh Marsh	2178.1	2179.2	2180.2	2186.3	2189.1
Inland Open Water	1903.2	1920.1	1918.9	1908.4	1889.4
Dev. Dry Land	1758.7	1748.1	1744.3	1735.9	1734.5
Inland Fresh Marsh	1381.7	1381.7	1381.7	1387.8	1389.2
Inland Shore	367.2	185.2	172.8	148.4	137.9
Estuarine Beach	235.1	146.5	81.6	29.7	14.4
Saltmarsh	56.9	63.5	196.8	1577.3	3372.6
Trans. Salt Marsh	38.5	80.6	334.1	664.9	582.6
Tidal Flat	0.0	56.0	52.9	46.2	49.0
Total (incl. water)	**284678.1**	**284678.1**	**284678.1**	**284678.1**	**284678.1**



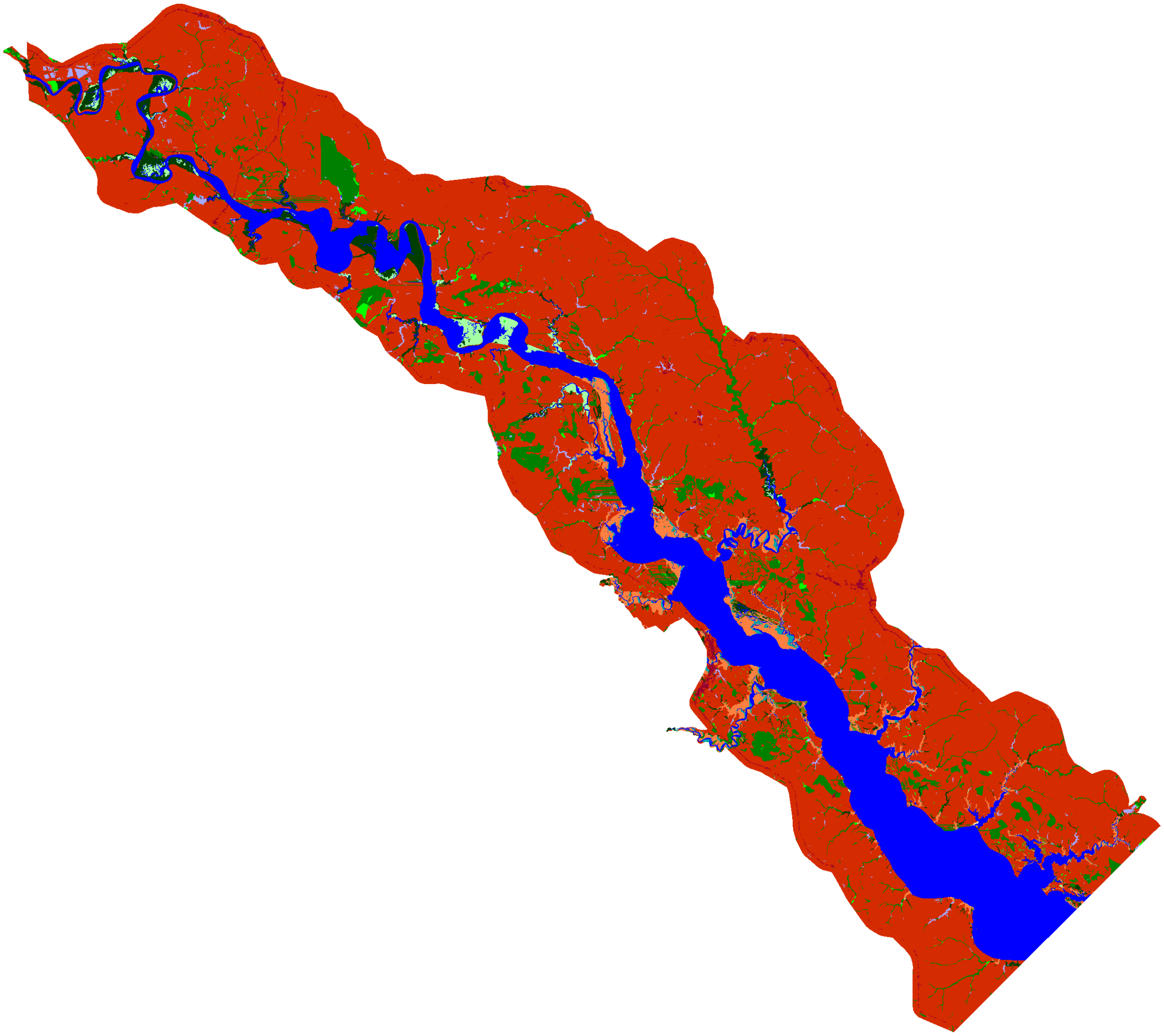
Rappahannock NWR, Initial Condition



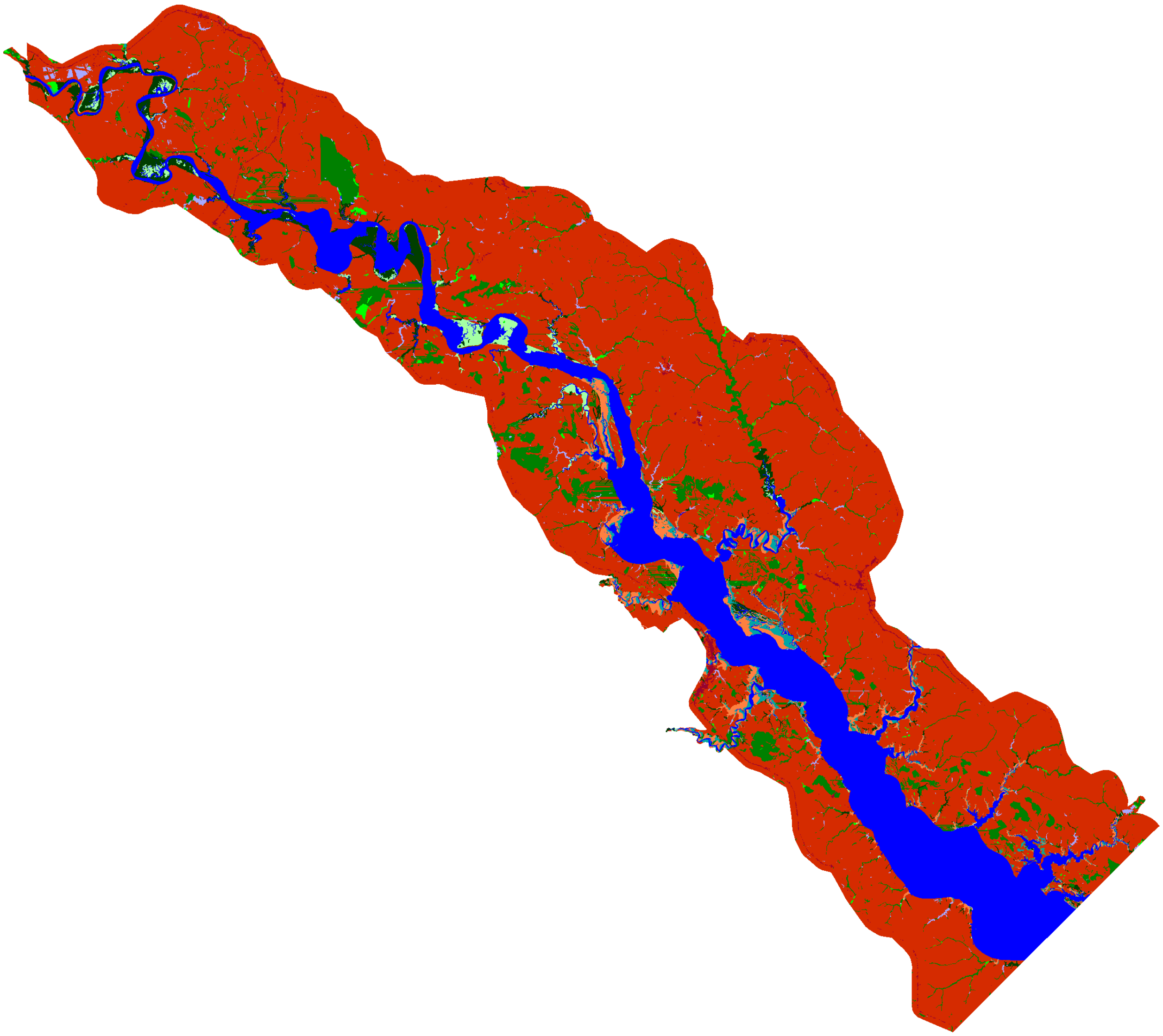
Rappahannock NWR, 2025, Scenario A1B Mean



Rappahannock NWR, 2050, Scenario A1B Mean



Rappahannock NWR, 2075, Scenario A1B Mean

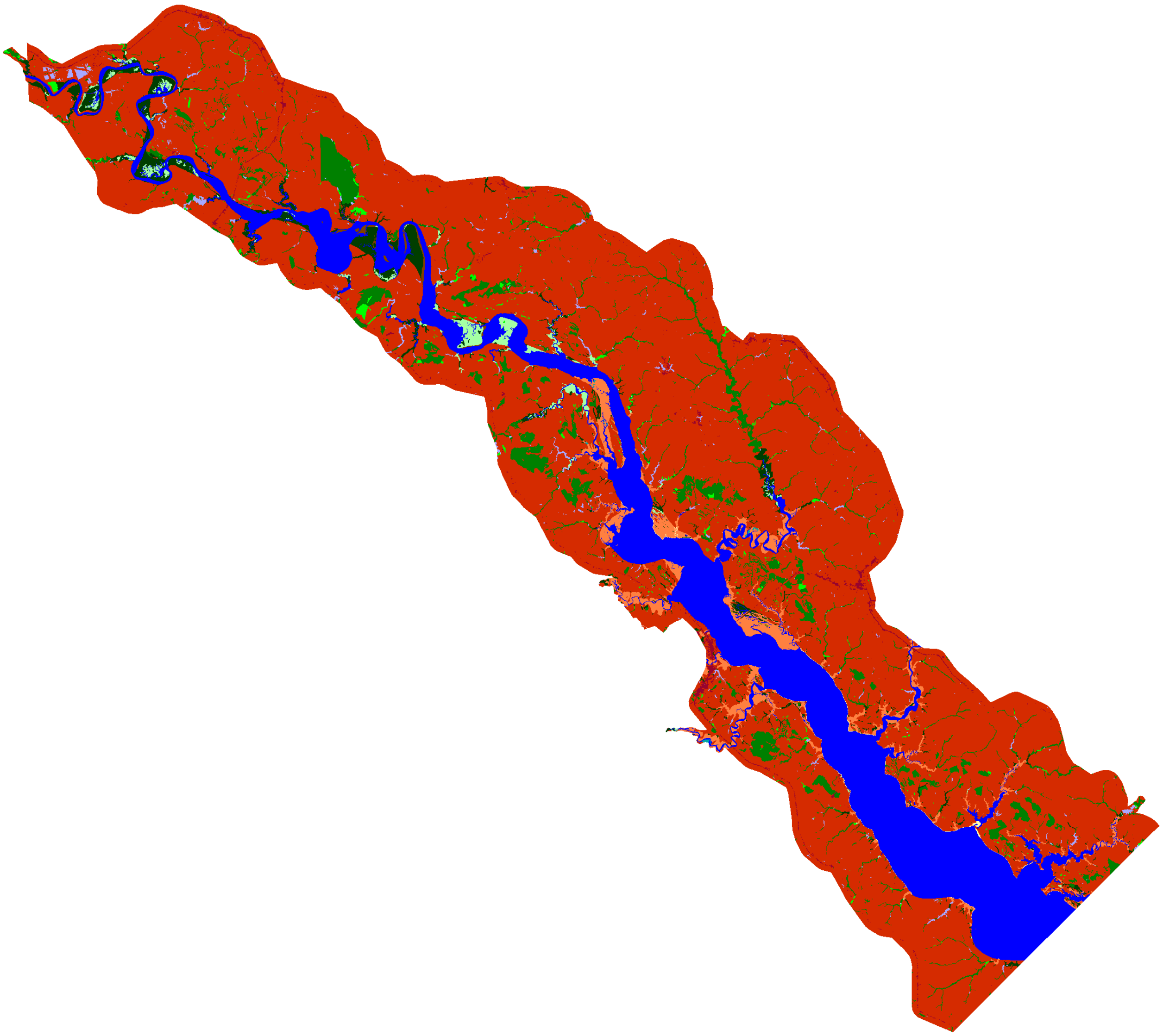


Rappahannock NWR, 2100, Scenario A1B Mean

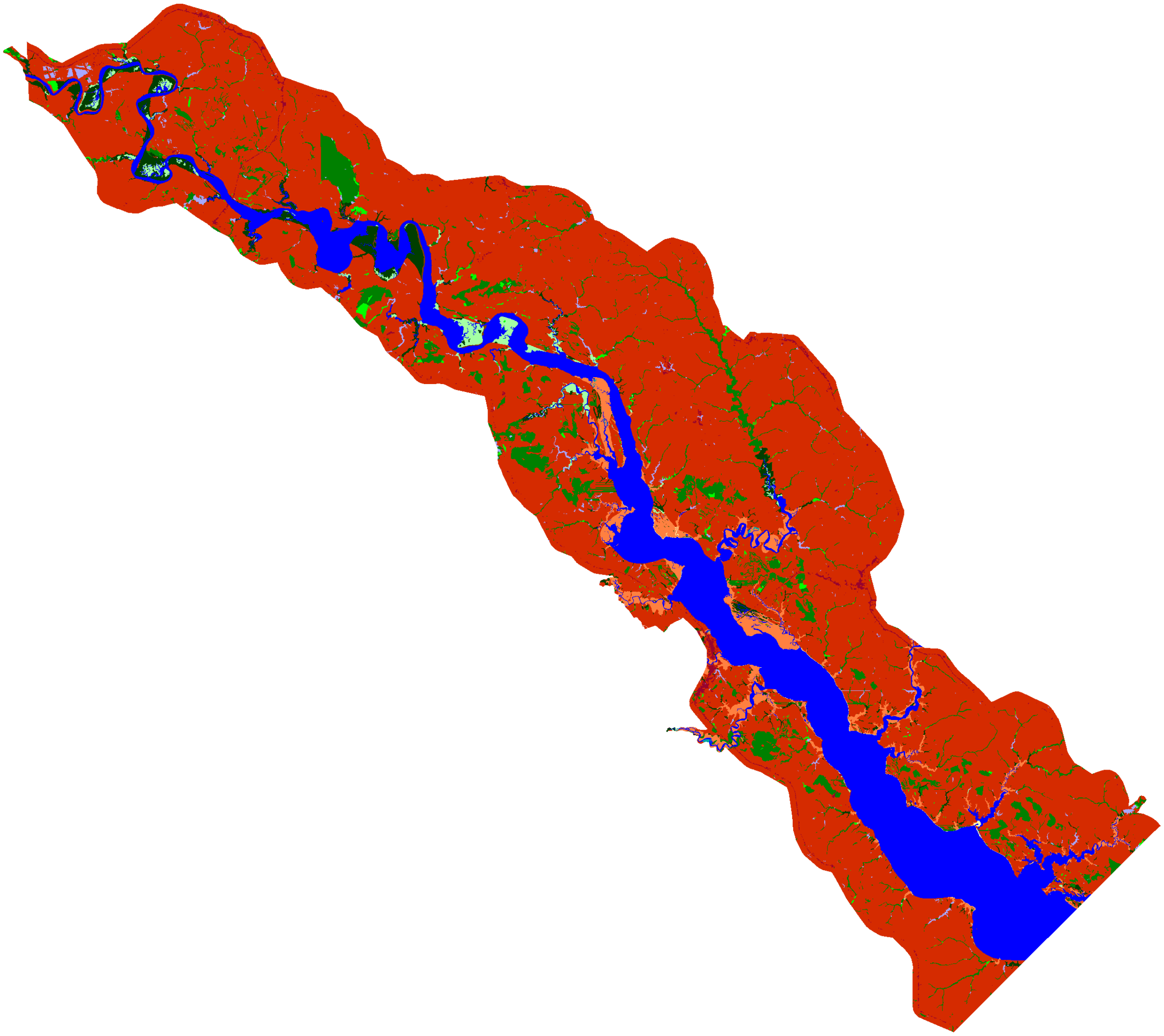
Rappahannock Raster
IPCC Scenario A1B-Max, 0.69 M SLR Eustatic by 2100

Results in Acres

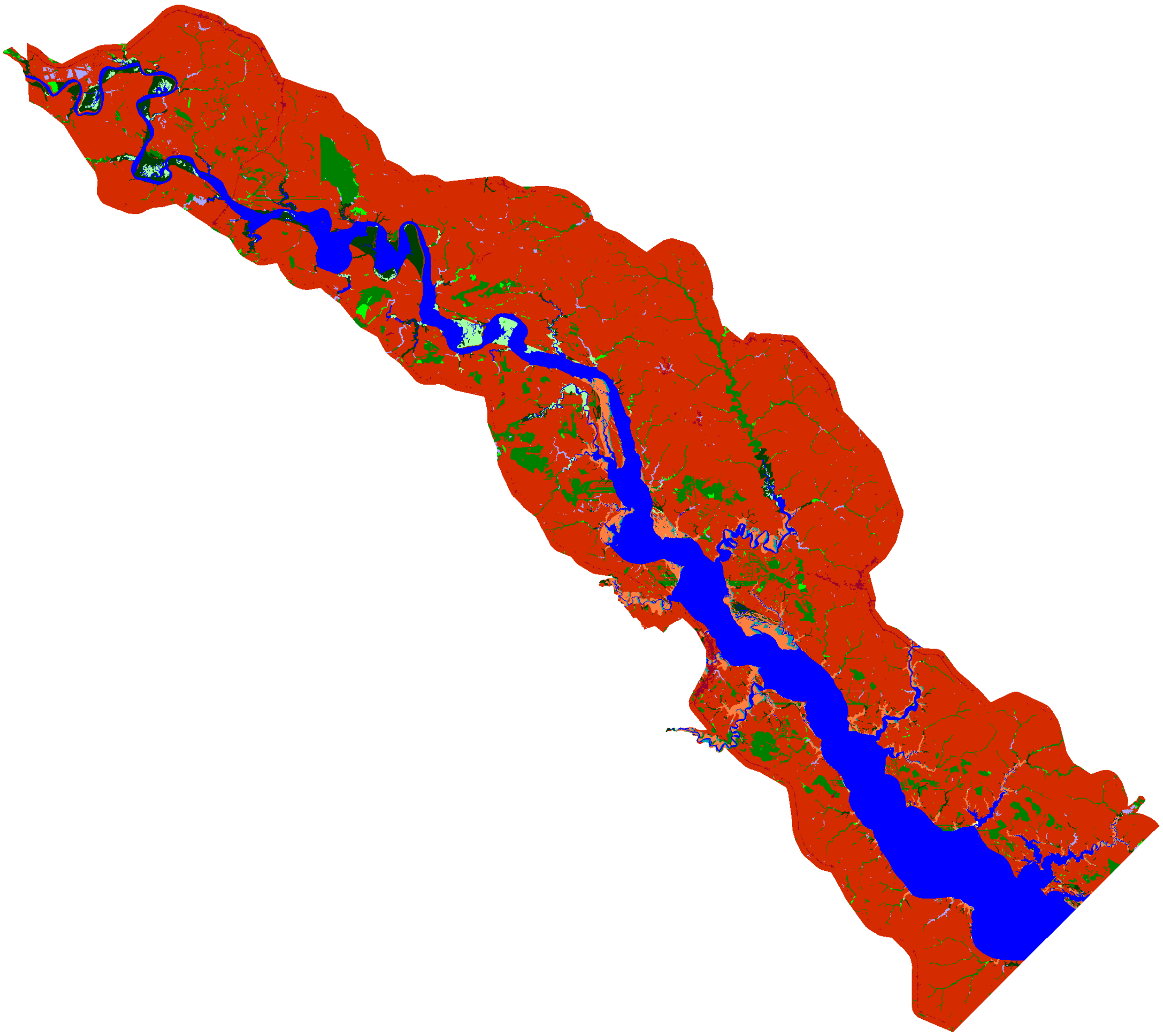
	Initial	2025	2050	2075	2100
Undev. Dry Land	203776.0	202867.8	202053.3	200563.1	199157.8
Estuarine Open Water	34606.7	34880.3	35303.7	37116.7	40757.6
Swamp	14710.2	15557.1	15813.2	16603.1	17091.3
Riverine Tidal	9621.0	9617.9	9384.1	8405.3	7584.5
Irregularly Flooded Marsh	7820.7	7778.1	6595.0	3598.2	1792.1
Tidal Swamp	6223.9	6215.8	6183.6	6067.3	5640.6
Tidal Fresh Marsh	2178.1	2179.2	2180.3	2183.0	2182.1
Inland Open Water	1903.2	1920.1	1918.2	1893.5	1873.4
Dev. Dry Land	1758.7	1748.1	1738.5	1734.7	1732.3
Inland Fresh Marsh	1381.7	1381.7	1381.7	1388.0	1387.2
Inland Shore	367.2	185.2	161.3	139.5	131.4
Estuarine Beach	235.1	146.5	58.7	16.3	0.2
Saltmarsh	56.9	63.5	1298.8	4300.9	3851.1
Trans. Salt Marsh	38.5	80.6	548.6	609.6	865.9
Tidal Flat	0.0	56.0	58.9	58.8	630.4
Total (incl. water)	**284678.1**	**284678.1**	**284678.1**	**284678.1**	**284678.1**



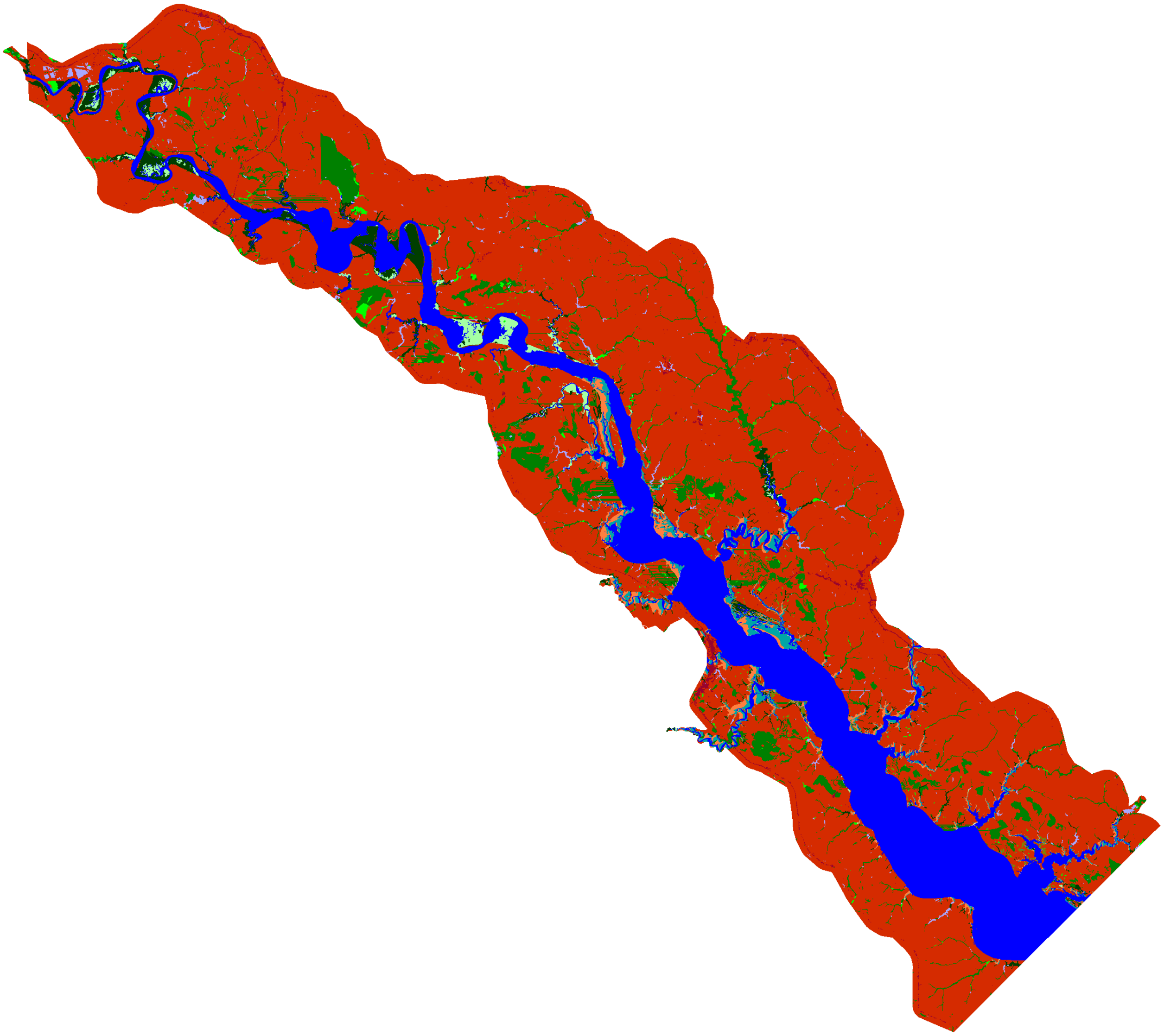
Rappahannock NWR, Initial Condition



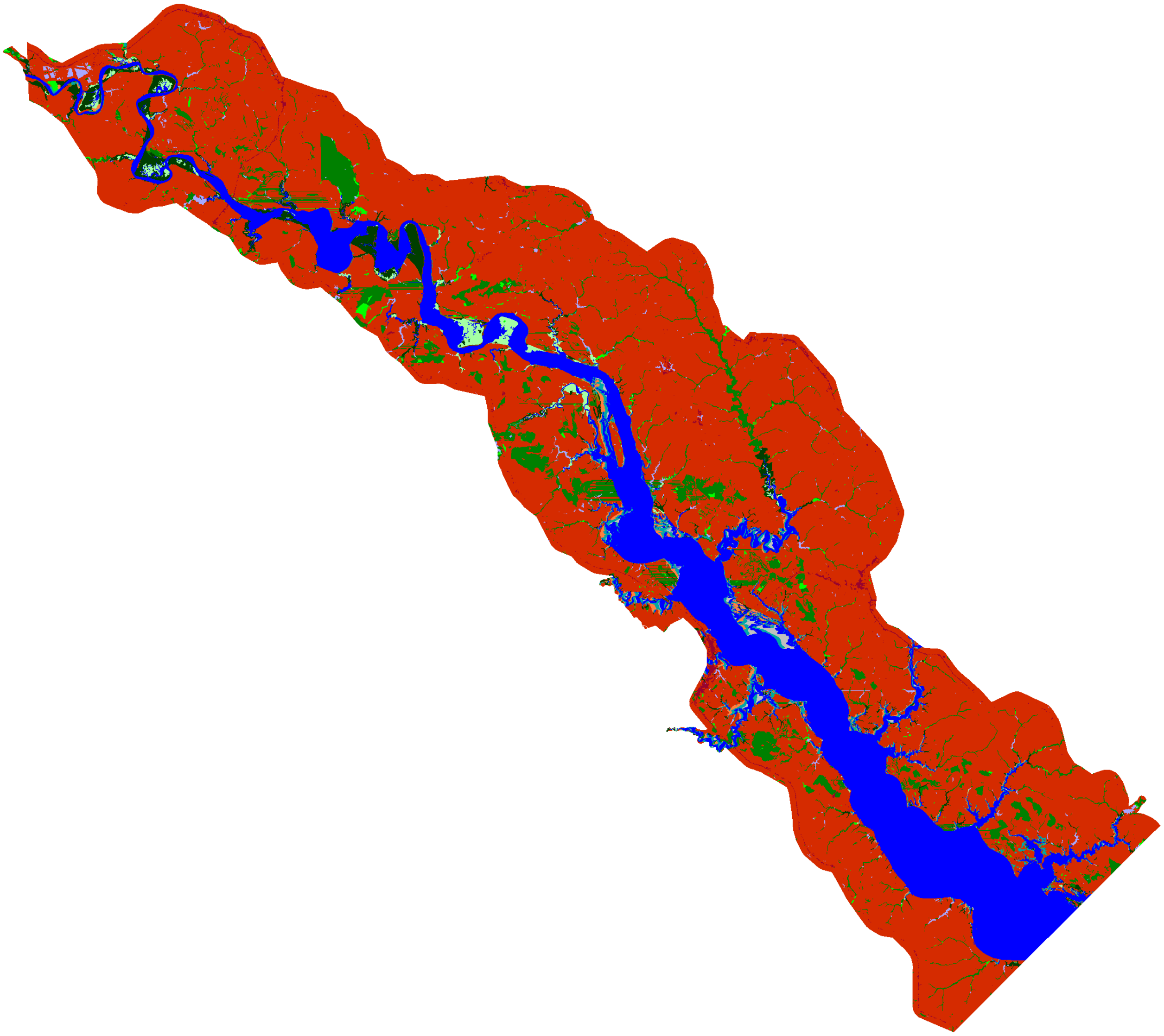
Rappahannock NWR, 2025, Scenario A1B Maximum



Rappahannock NWR, 2050, Scenario A1B Maximum



Rappahannock NWR, 2075, Scenario A1B Maximum

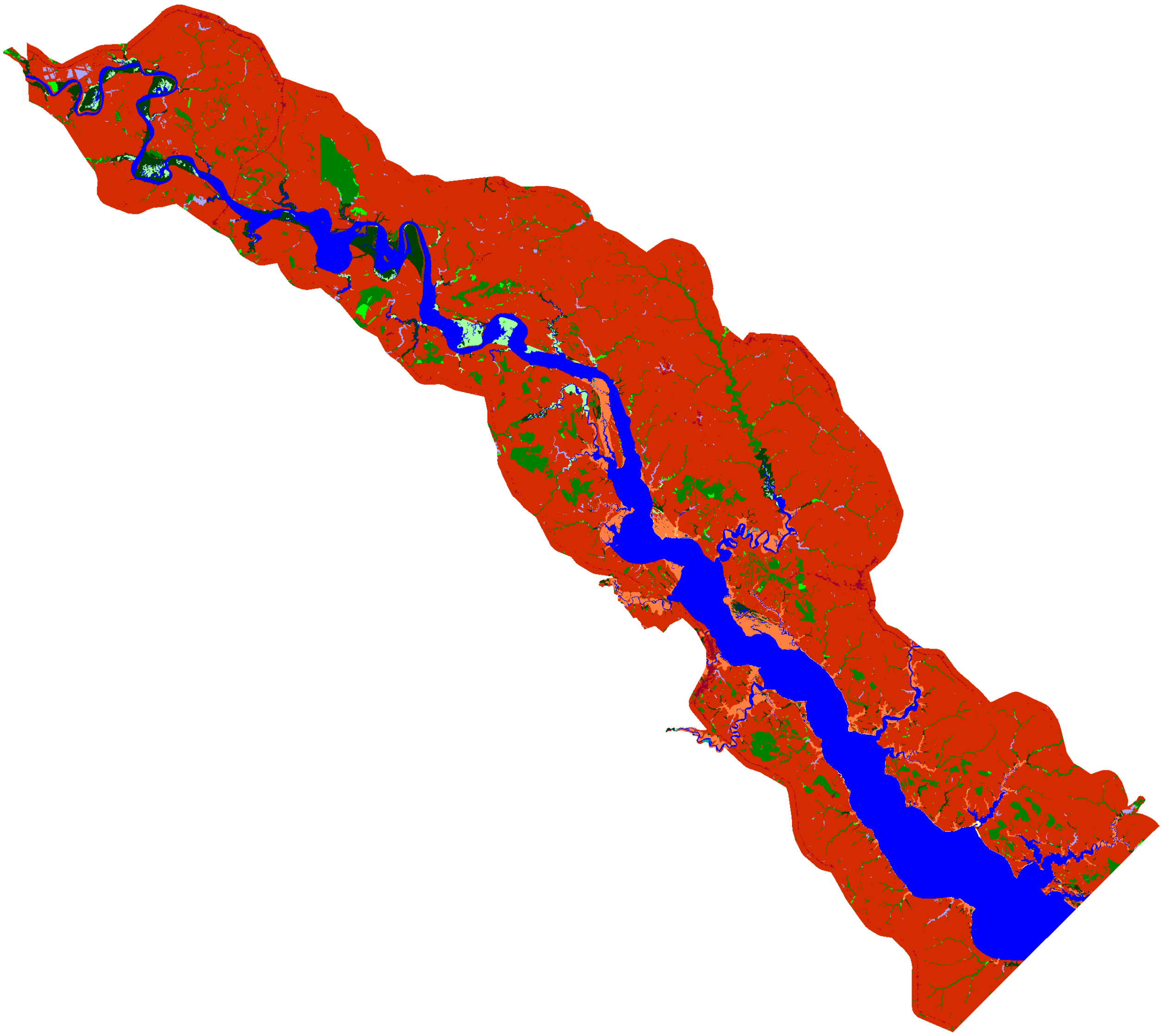


Rappahannock NWR, 2100, Scenario A1B Maximum

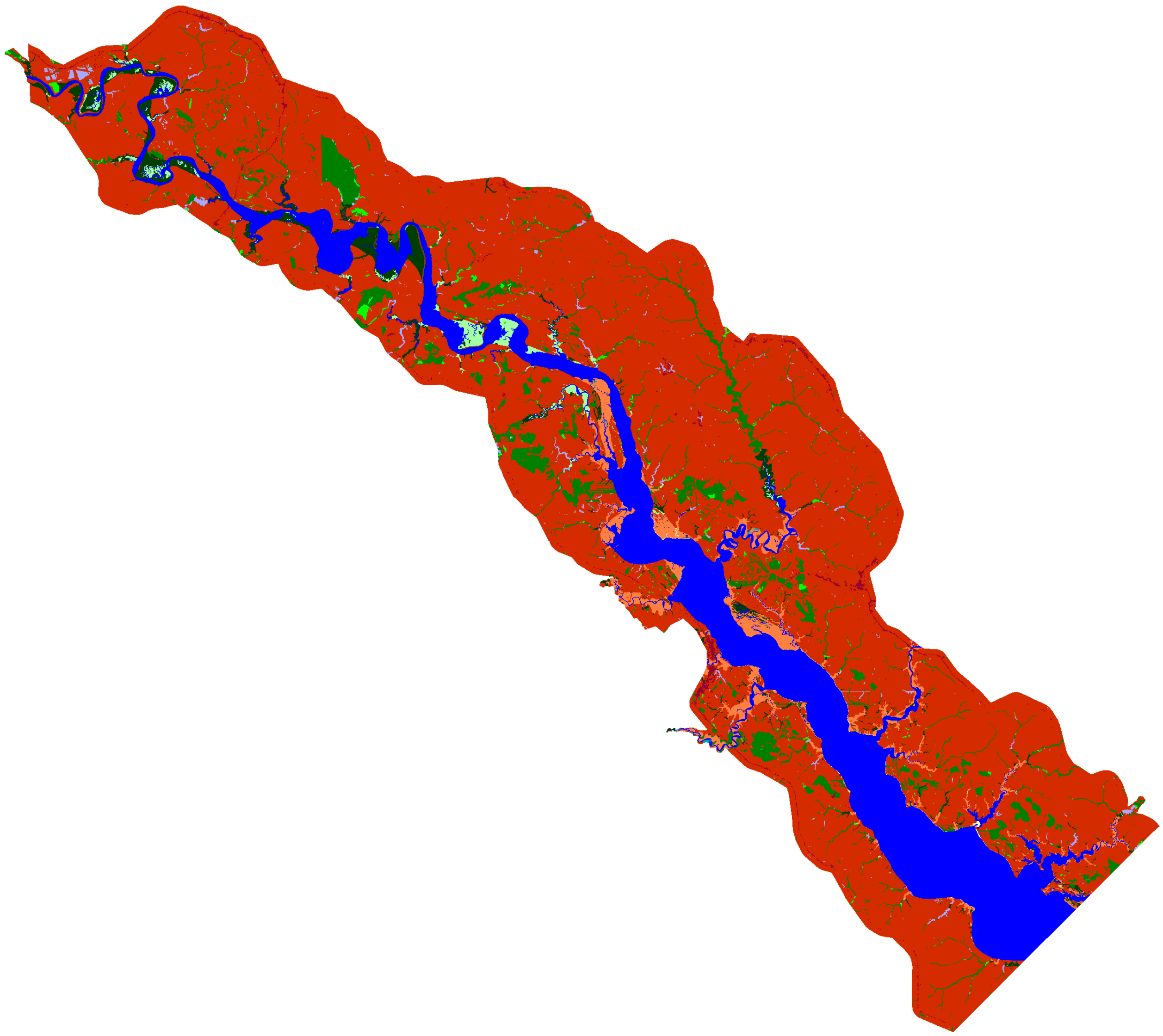
Rappahannock Raster
1 Meter Eustatic SLR by 2100

Results in Acres

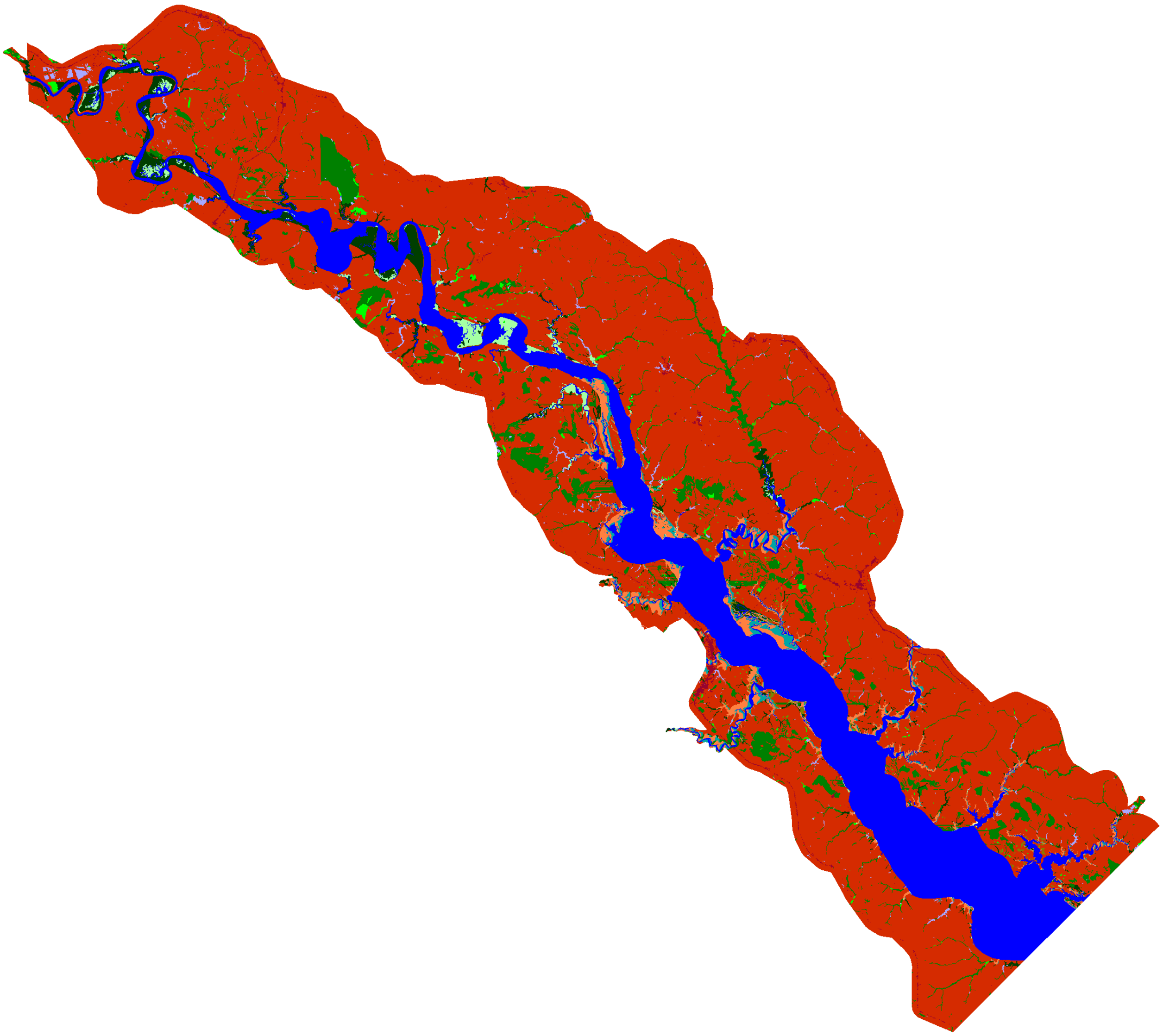
	Initial	2025	2050	2075	2100
Undev. Dry Land	203776.0	202920.3	201979.8	200223.5	198488.2
Estuarine Open Water	34606.7	34876.7	35291.2	38852.2	43972.4
Swamp	14710.2	15508.5	15823.2	16615.3	17142.7
Riverine Tidal	9621.0	9617.9	9419.7	8240.9	7250.0
Irregularly Flooded Marsh	7820.7	7777.4	5305.4	1711.6	574.3
Tidal Swamp	6223.9	6216.5	6177.3	5929.8	5403.1
Tidal Fresh Marsh	2178.1	2179.5	2179.2	2173.2	2159.3
Inland Open Water	1903.2	1920.4	1918.7	1891.2	1866.1
Dev. Dry Land	1758.7	1749.2	1739.3	1734.3	1730.2
Inland Fresh Marsh	1381.7	1381.7	1381.6	1384.7	1375.0
Inland Shore	367.2	188.9	166.0	136.8	129.1
Estuarine Beach	235.1	146.5	36.3	3.6	0.0
Saltmarsh	56.9	62.7	2594.2	4508.4	2569.6
Trans. Salt Marsh	38.5	75.9	605.3	881.6	1231.0
Tidal Flat	0.0	56.0	60.7	391.0	787.1
Total (incl. water)	**284678.1**	**284678.1**	**284678.1**	**284678.1**	**284678.1**



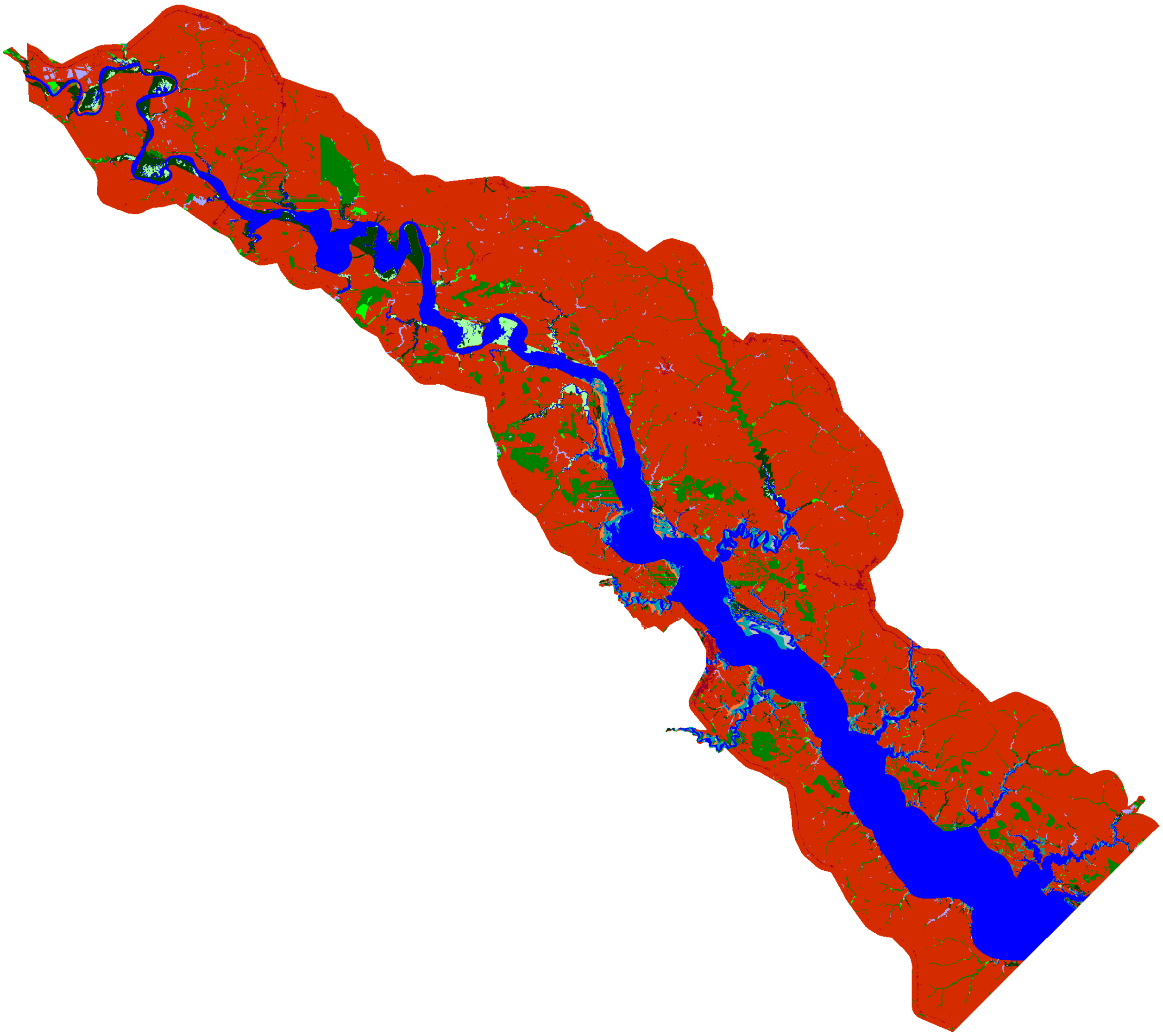
Rappahannock NWR, Initial Condition



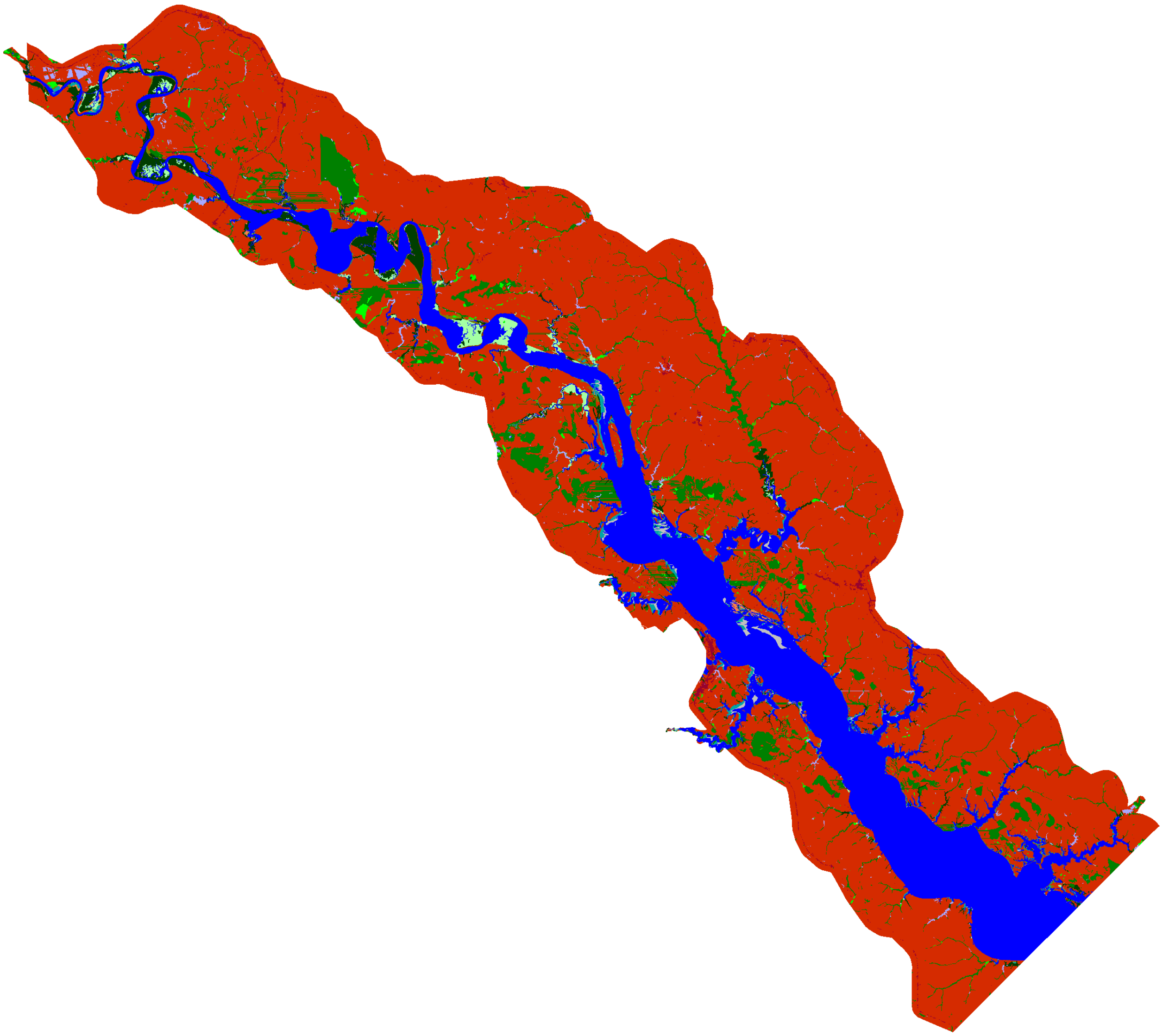
Rappahannock NWR, 2025, 1 meter



Rappahannock NWR, 2050, 1 meter



Rappahannock NWR, 2075, 1 meter

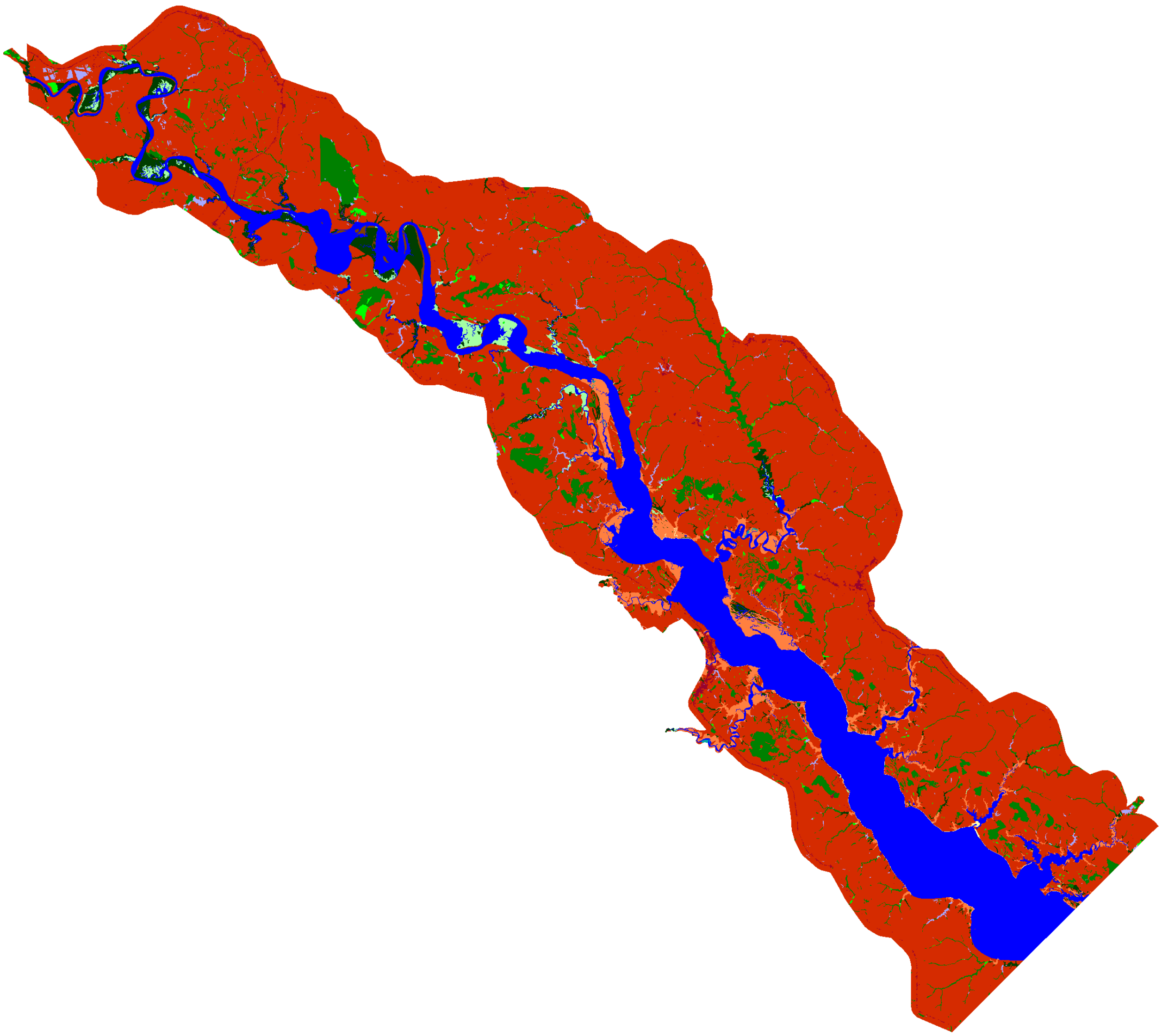


Rappahannock NWR, 2100, 1 meter

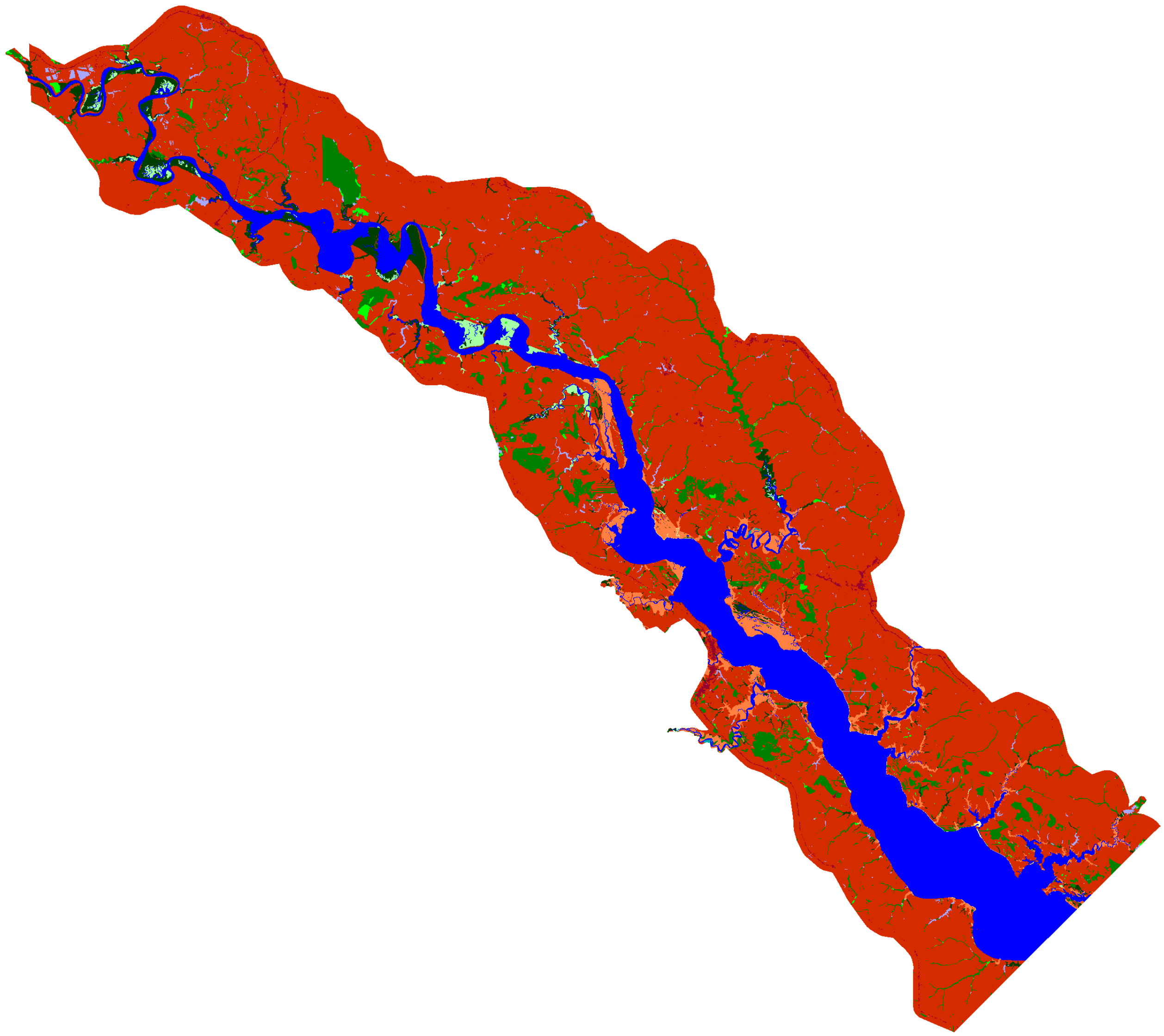
Rappahannock Raster
1.5 Meters Eustatic SLR by 2100

Results in Acres

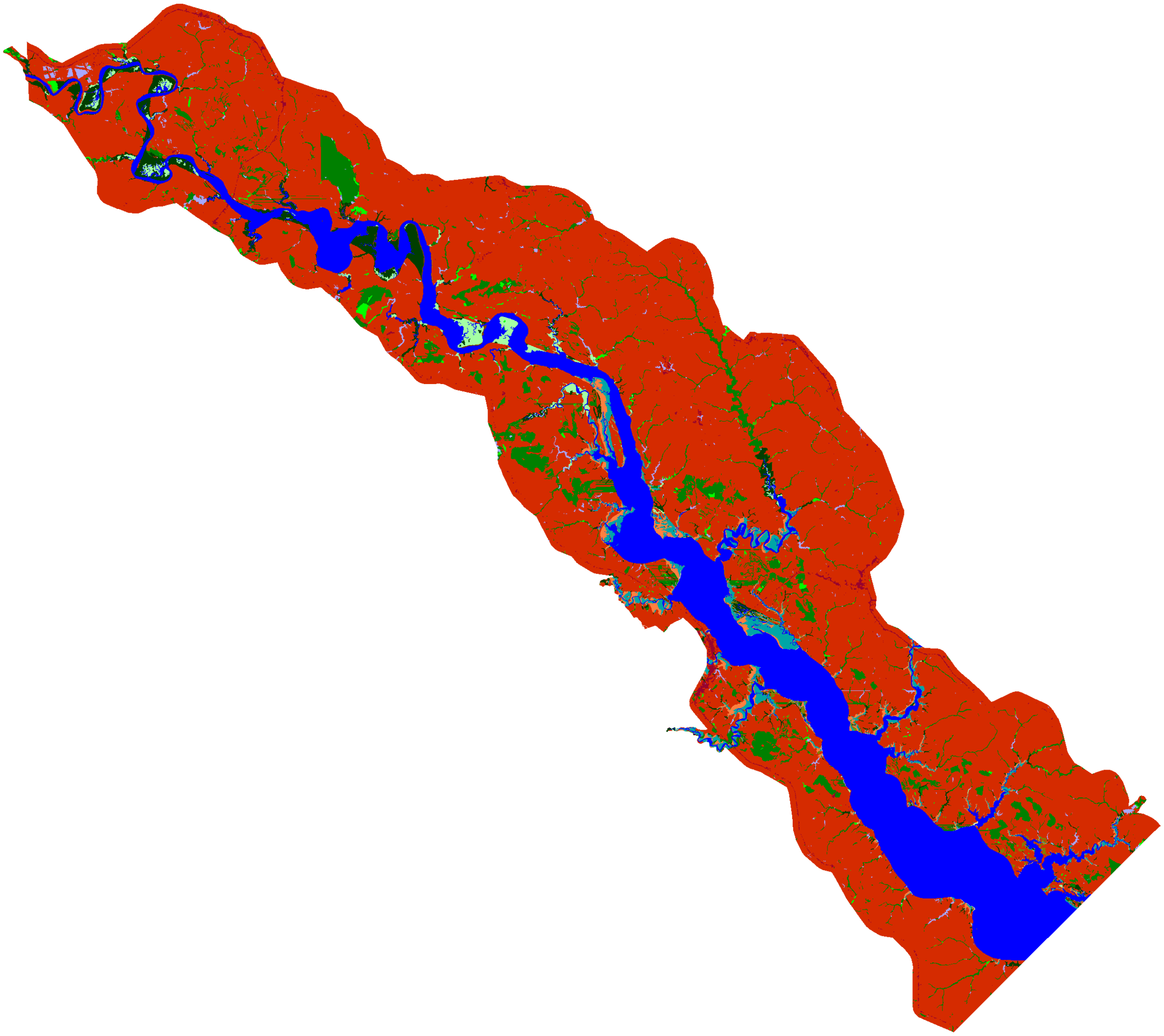
	Initial	2025	2050	2075	2100
Undev. Dry Land	203776.0	202920.3	201684.6	199332.7	196991.9
Estuarine Open Water	34606.7	34876.7	35333.7	40558.4	46408.1
Swamp	14710.2	15508.5	15852.2	16708.2	17287.0
Riverine Tidal	9621.0	9617.9	9415.5	7794.9	6687.2
Irregularly Flooded Marsh	7820.7	7777.4	3167.4	669.8	1744.8
Tidal Swamp	6223.9	6216.5	6144.2	5529.3	3923.3
Tidal Fresh Marsh	2178.1	2179.5	2172.4	2145.2	2024.9
Inland Open Water	1903.2	1920.4	1918.6	1885.4	1858.0
Dev. Dry Land	1758.7	1749.2	1736.4	1731.9	1718.8
Inland Fresh Marsh	1381.7	1381.7	1380.0	1358.1	1350.7
Inland Shore	367.2	188.9	151.5	130.9	120.3
Estuarine Beach	235.1	146.5	23.9	0.1	0.0
Saltmarsh	56.9	62.7	4760.8	4011.2	2114.7
Trans. Salt Marsh	38.5	75.9	873.7	1451.6	1782.3
Tidal Flat	0.0	56.0	63.2	1370.5	666.1
Total (incl. water)	**284678.1**	**284678.1**	**284678.1**	**284678.1**	**284678.1**



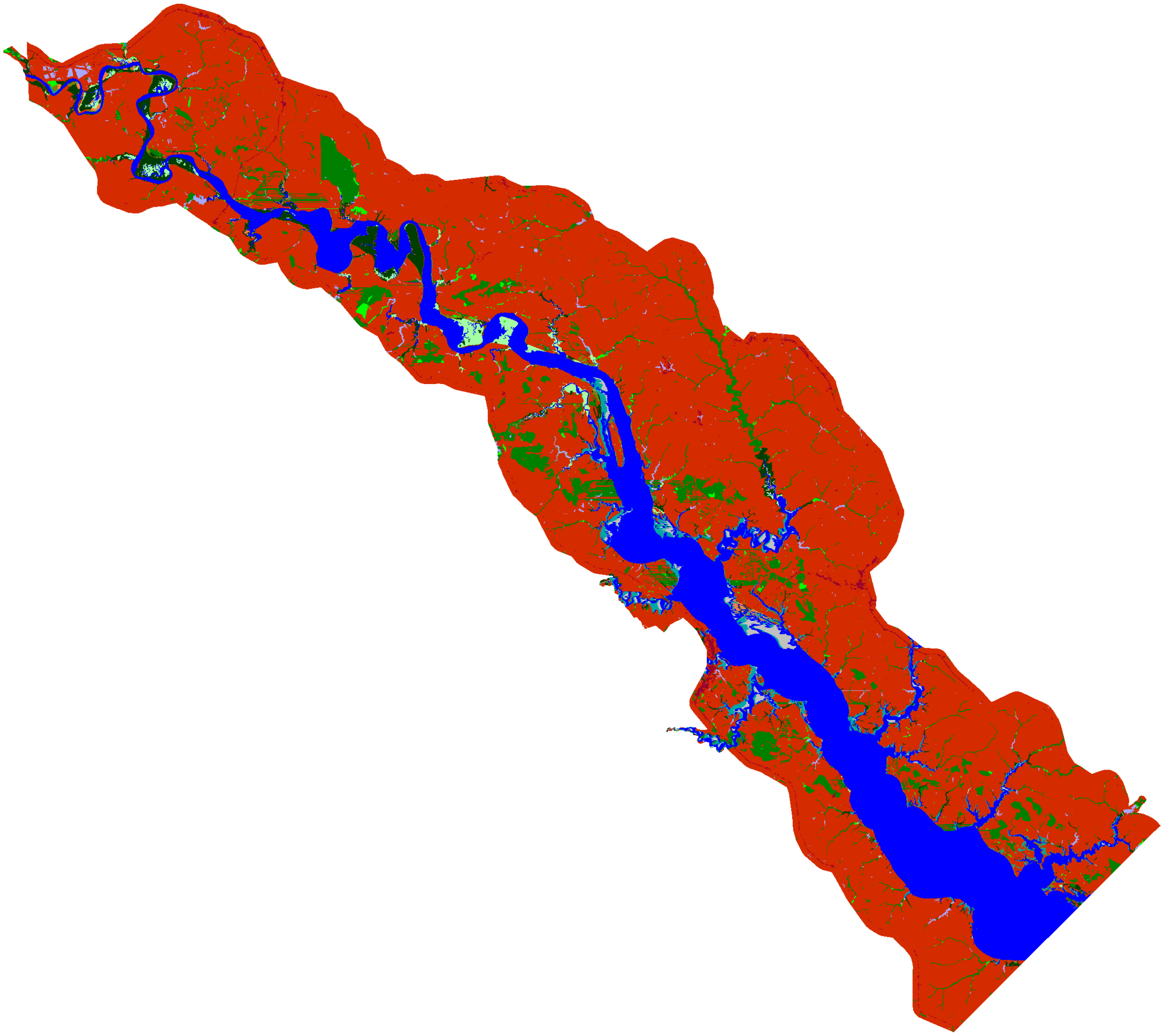
Rappahannock NWR, Initial Condition



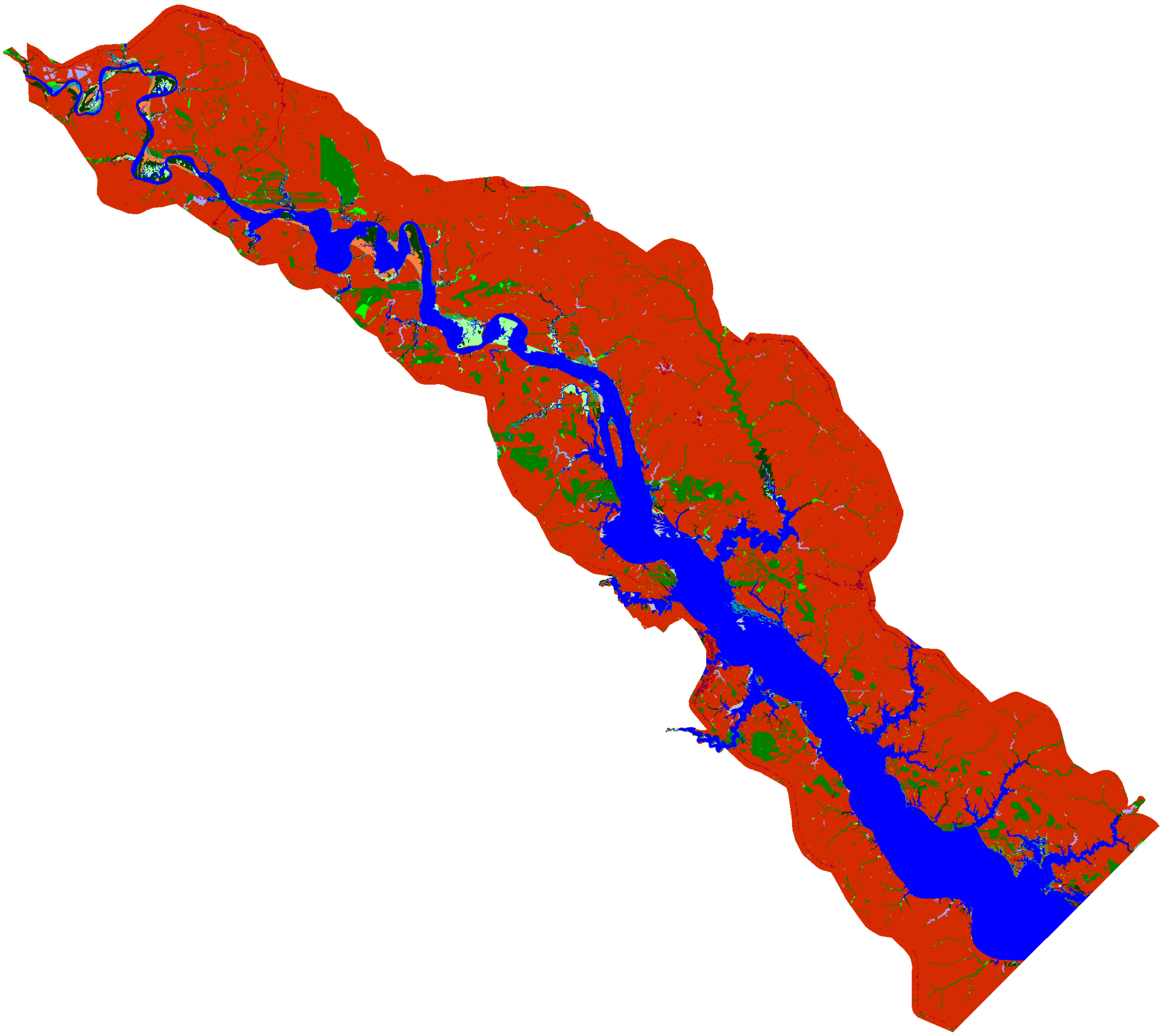
Rappahannock NWR, 2025, 1.5 meter



Rappahannock NWR, 2050, 1.5 meter



Rappahannock NWR, 2075, 1.5 meter

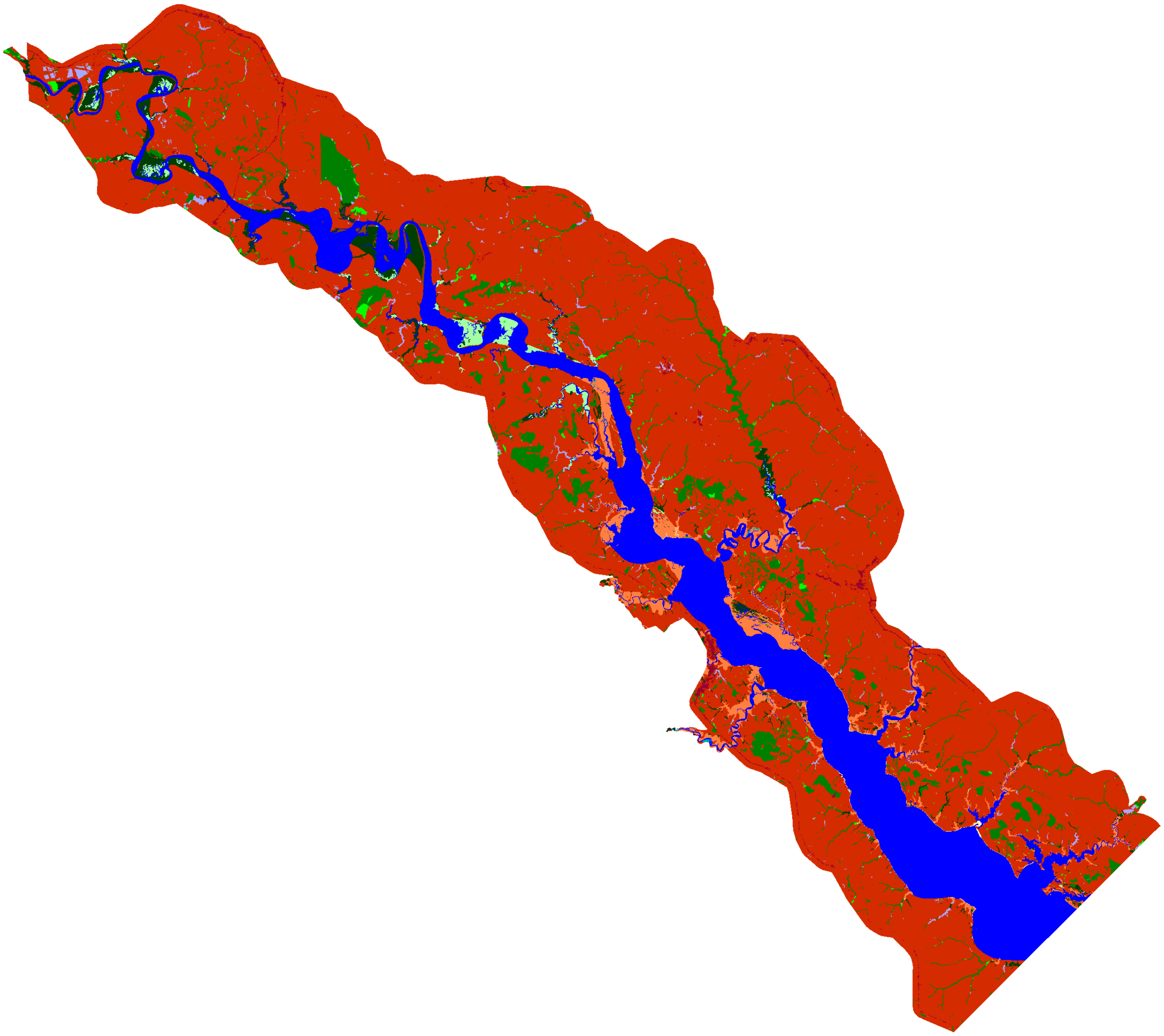


Rappahannock NWR, 2100, 1.5 meter

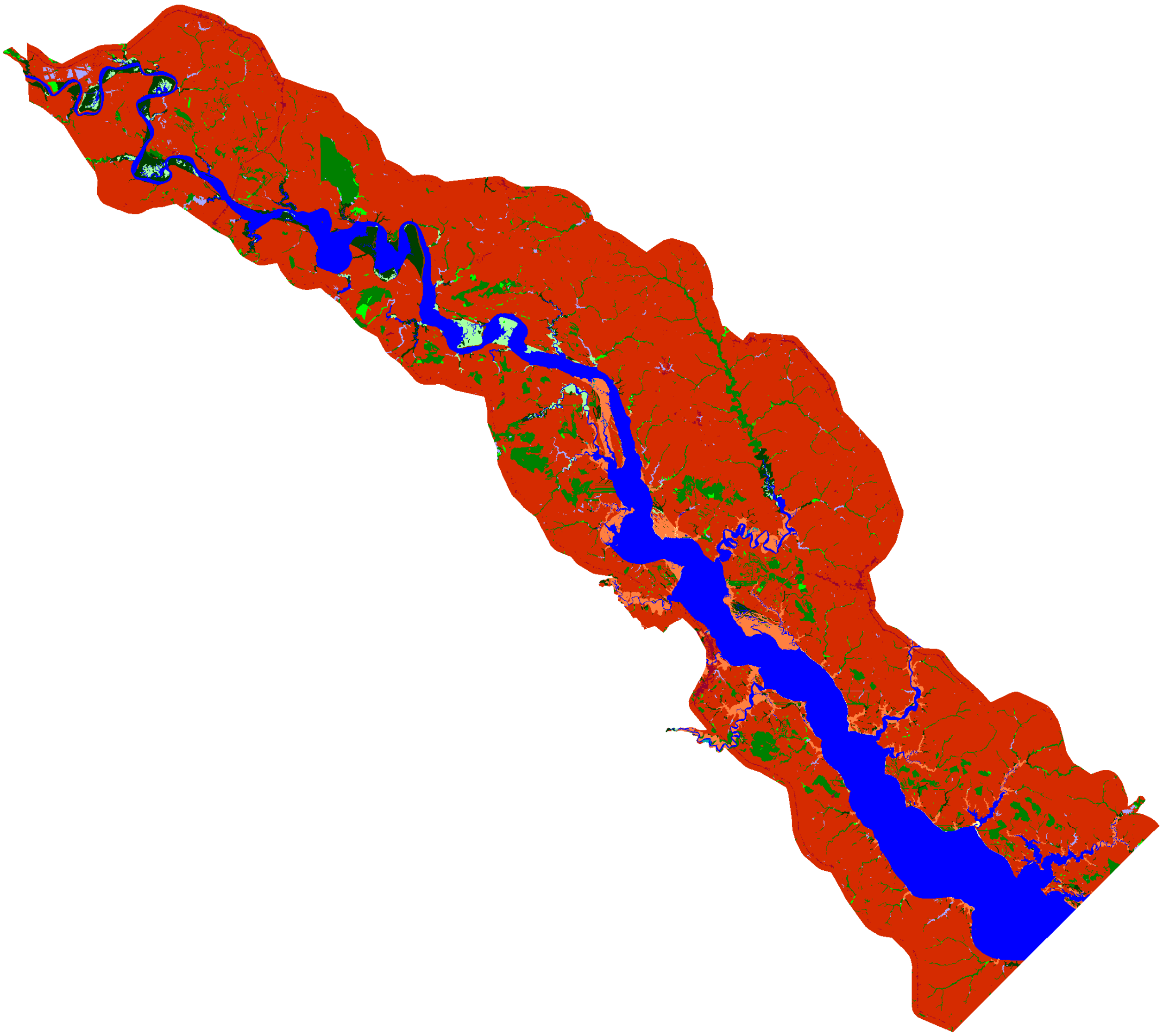
Rappahannock Raster
2 Meters Eustatic SLR by 2100

Results in Acres

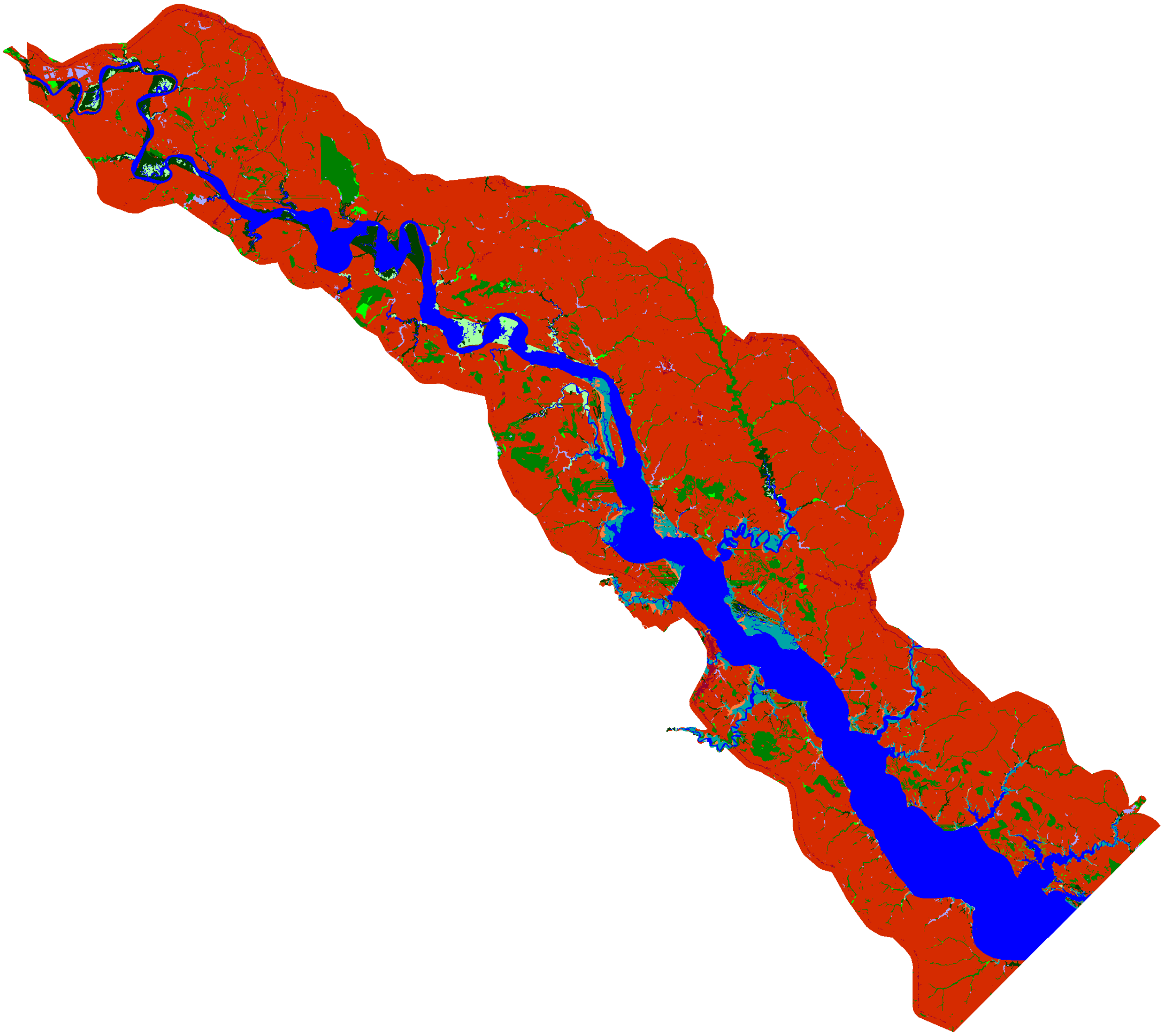
	Initial	2025	2050	2075	2100
Undev. Dry Land	203776.0	202920.3	201423.5	198500.6	195710.0
Estuarine Open Water	34606.7	34876.7	35362.5	41605.5	47602.0
Swamp	14710.2	15508.5	15846.0	16777.1	17470.1
Riverine Tidal	9621.0	9617.9	9412.9	7417.3	6228.2
Irregularly Flooded Marsh	7820.7	7777.4	1809.6	1123.9	2647.9
Tidal Swamp	6223.9	6216.5	6074.8	5067.6	2691.5
Tidal Fresh Marsh	2178.1	2179.5	2164.7	2054.5	1808.9
Inland Open Water	1903.2	1920.4	1918.4	1871.3	1850.9
Dev. Dry Land	1758.7	1749.2	1735.3	1728.0	1711.9
Inland Fresh Marsh	1381.7	1381.7	1358.8	1345.0	1324.5
Inland Shore	367.2	188.9	143.9	127.2	88.1
Estuarine Beach	235.1	146.5	14.3	0.0	0.0
Saltmarsh	56.9	62.7	6183.3	2959.8	3054.2
Trans. Salt Marsh	38.5	75.9	1162.0	1942.9	2136.7
Tidal Flat	0.0	56.0	68.3	2157.3	353.2
Total (incl. water)	**284678.1**	**284678.1**	**284678.1**	**284678.1**	**284678.1**



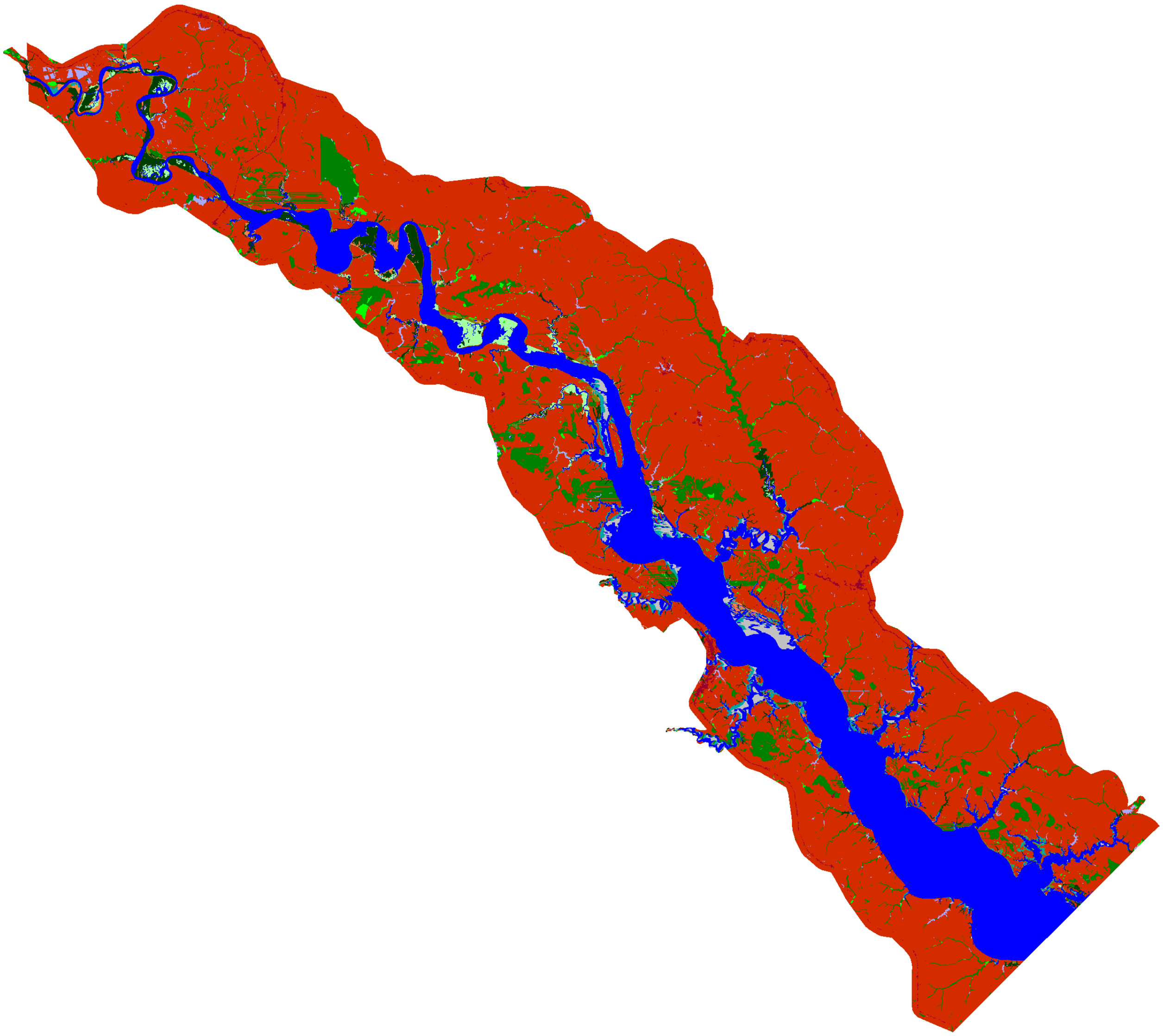
Rappahannock NWR, Initial Condition



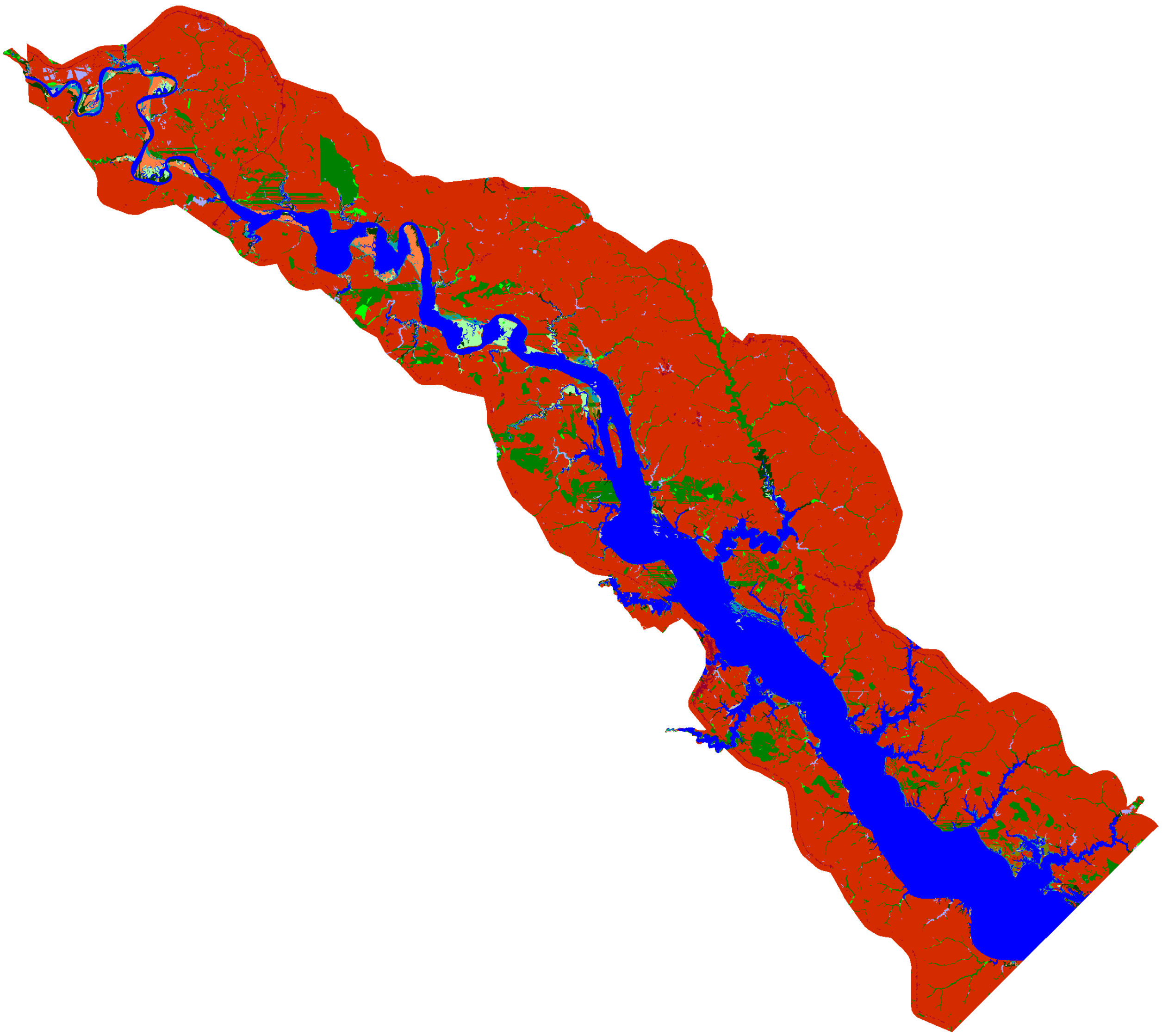
Rappahannock NWR, 2025, 2 meters



Rappahannock NWR, 2050, 2 meters



Rappahannock NWR, 2075, 2 meters



Rappahannock NWR, 2100, 2 meters

Discussion

The two most significant SLAMM predictions for Rappahannock NWR are the losses of irregularly flooded marsh and soil saturation effects.

Irregularly flooded marsh is modeled with a vertical accretion rate of 4.8 mm/year based on regional averages. This means that irregularly flooded marsh should be able to keep up with *local* sea level rises of up to 0.5 meters per century. When the combination of eustatic sea level rise and local factors are predicted to produce higher local sea level rises, irregularly flooded marshes start to convert to regularly flooded marshes (possibly salt marshes depending on water salinity). In the more aggressive SLR scenarios, large swaths of irregularly flooded marshes are converted to open water.

Soil saturation is also predicted to occur in all model simulations. This is the process of coastal swamps and fresh marshes migrating onto adjacent uplands as the near-shore fresh-water table responds to rising sea levels. When the predicted fresh water table rises above dry land elevations then soil saturation and dry-land conversion is predicted to occur. There is some model uncertainty when estimating the local fresh water table, however.

The best available elevation data for this site are based on ten foot contour maps which means that wetland elevations are quite uncertain. Additionally site-specific accretion data would provide information about local sediment supply and how effectively marshes will be able to keep up with accelerated sea level rise. Accretion data were derived based on regional averages which is a source of model uncertainty.

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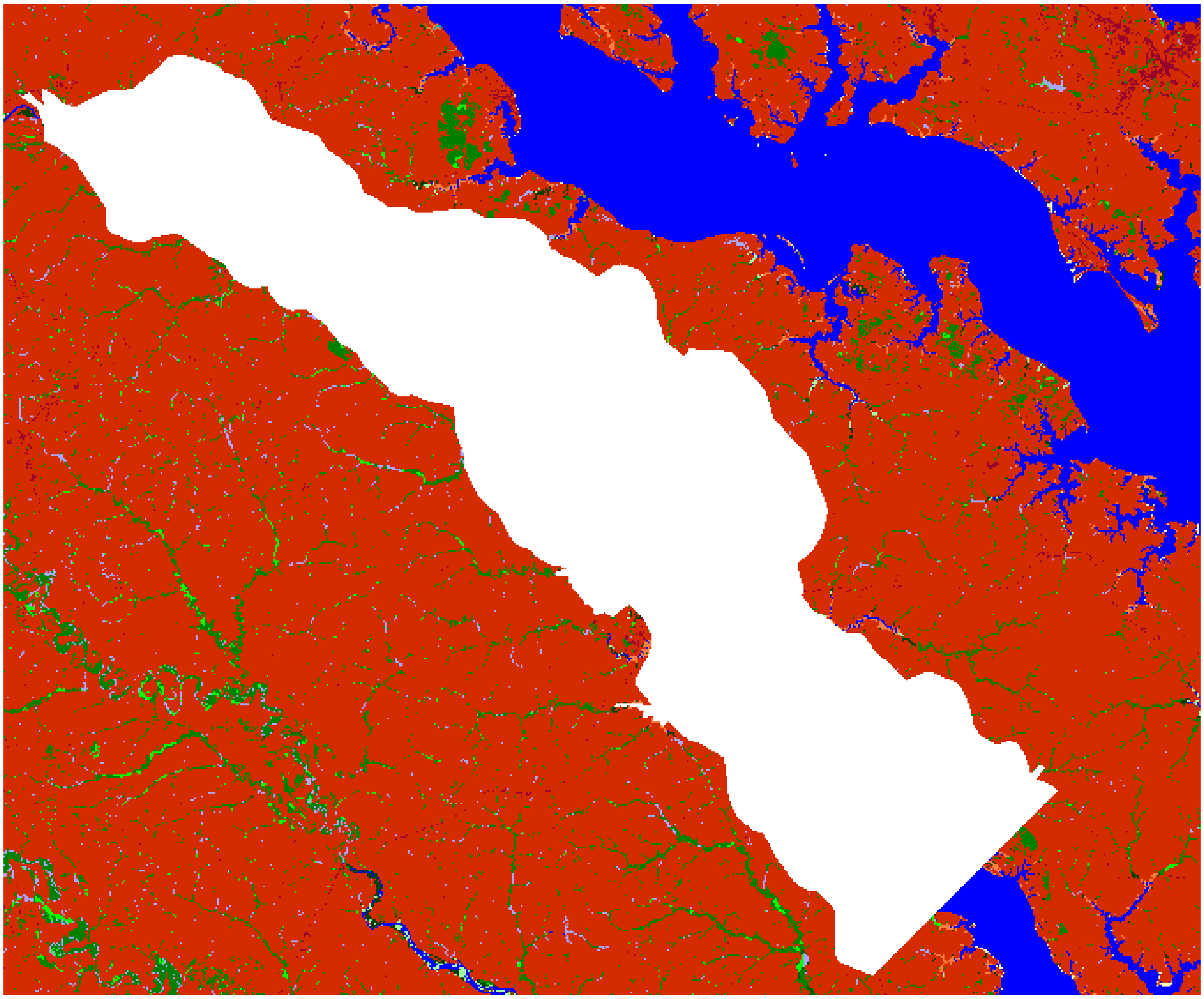
Appendix A: Contextual Results

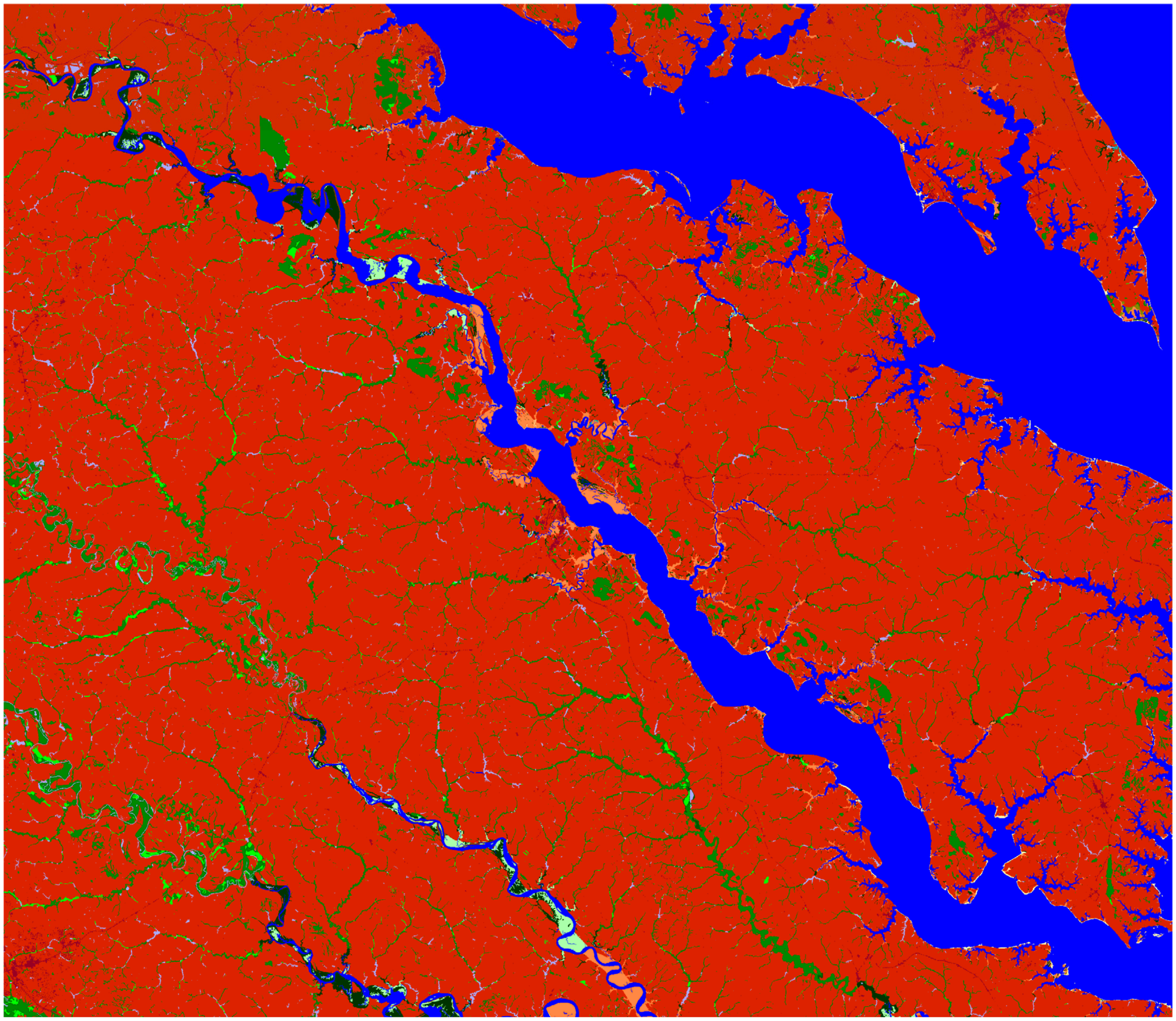
The SLAMM model does take into account the context of the surrounding lands or open water when calculating effects. For example, erosion rates are calculated based on the maximum fetch (wave action) which is estimated by assessing contiguous open water to a given marsh cell. Another example is that inundated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

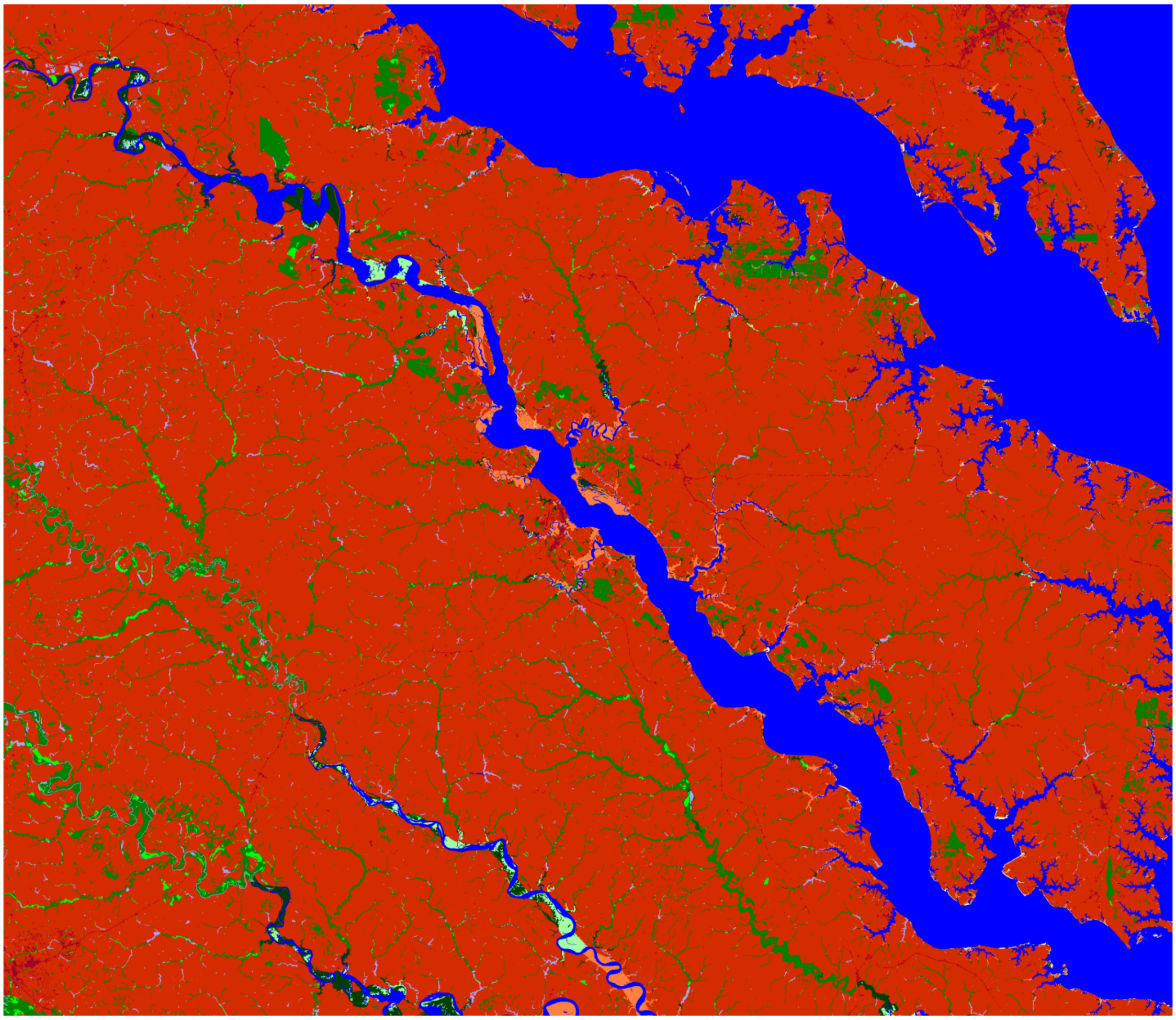
- Results were closely examined (quality assurance) within USFWS refuges but not closely examined for the larger region.
- Site-specific parameters for the model were derived for USFWS refuges whenever possible and may not be regionally applicable.
- Especially in areas where dikes are present, an effort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



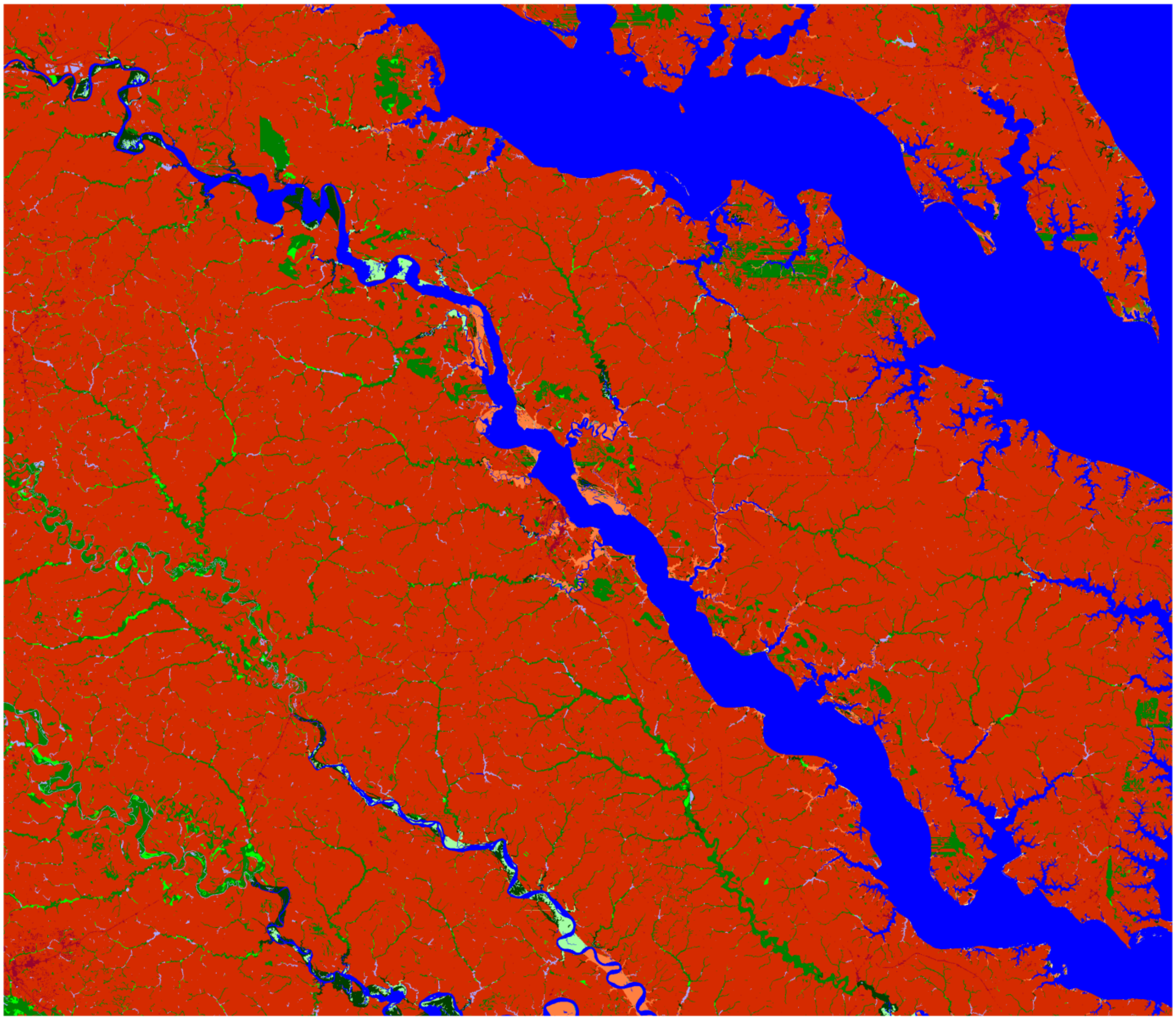
Location of Rappahannock National Wildlife Refuge (white area) within simulation context



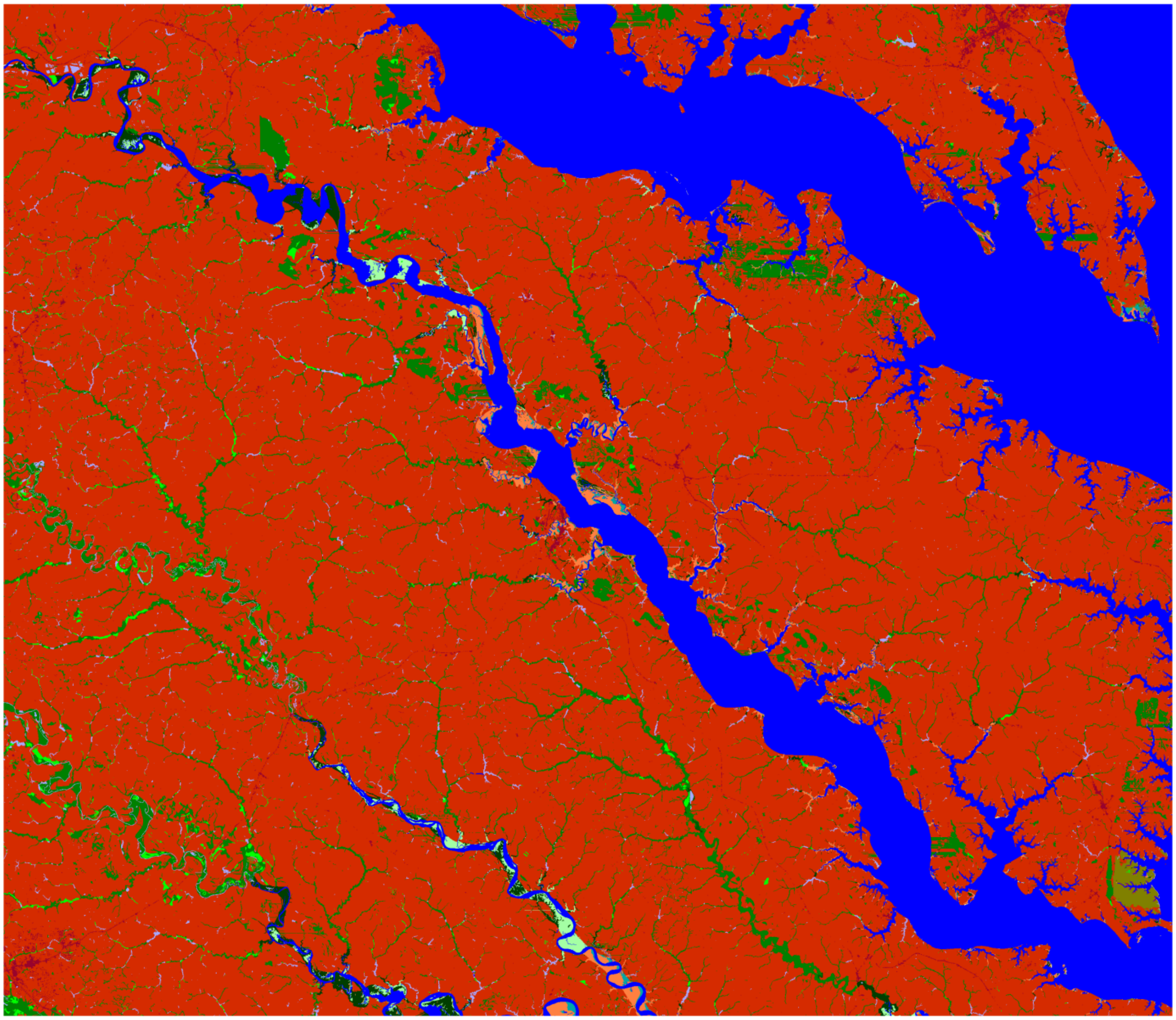
Rappahannock NWR, Initial Condition



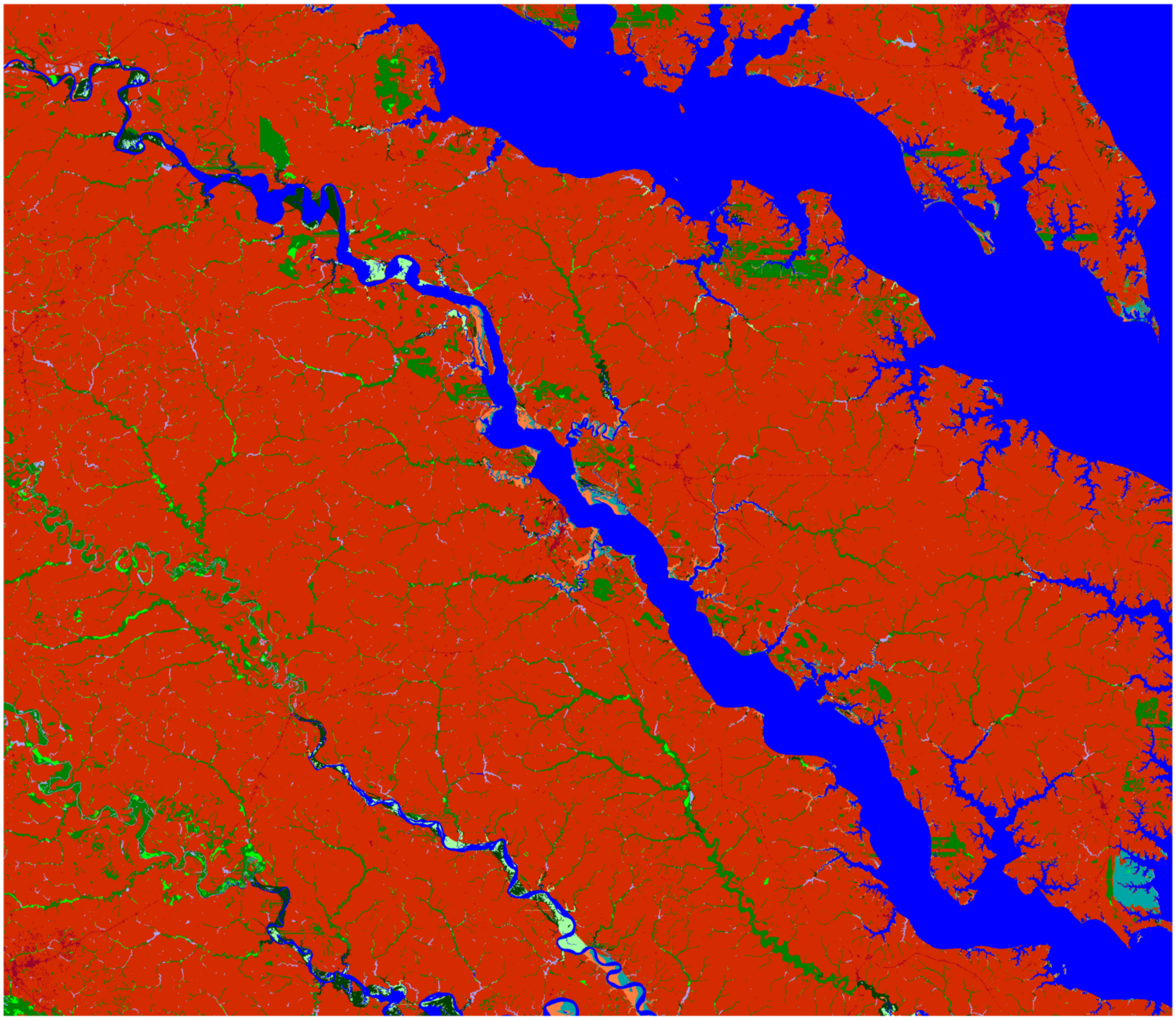
Rappahannock NWR, 2025, Scenario A1B Mean



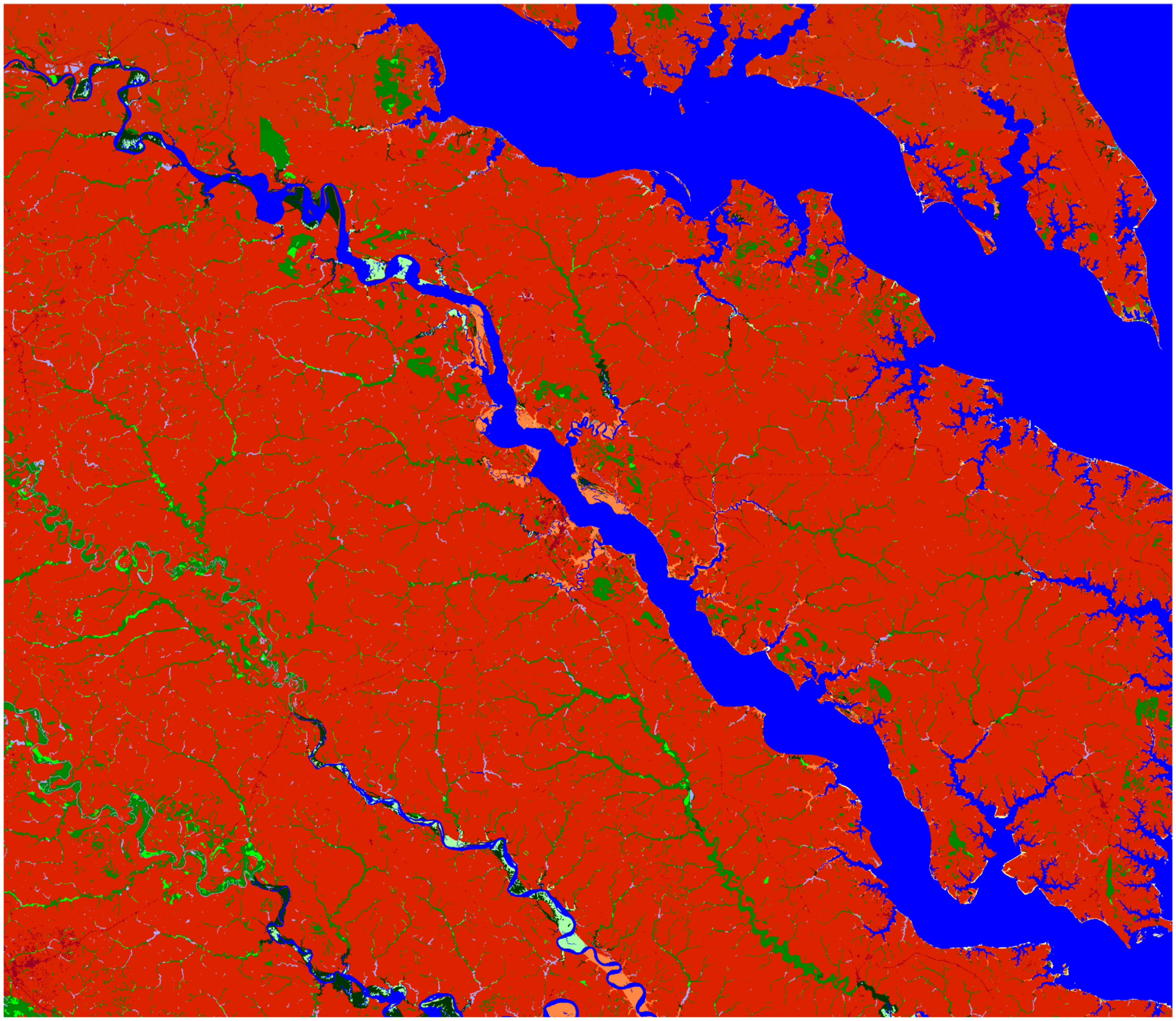
Rappahannock NWR, 2050, Scenario A1B Mean



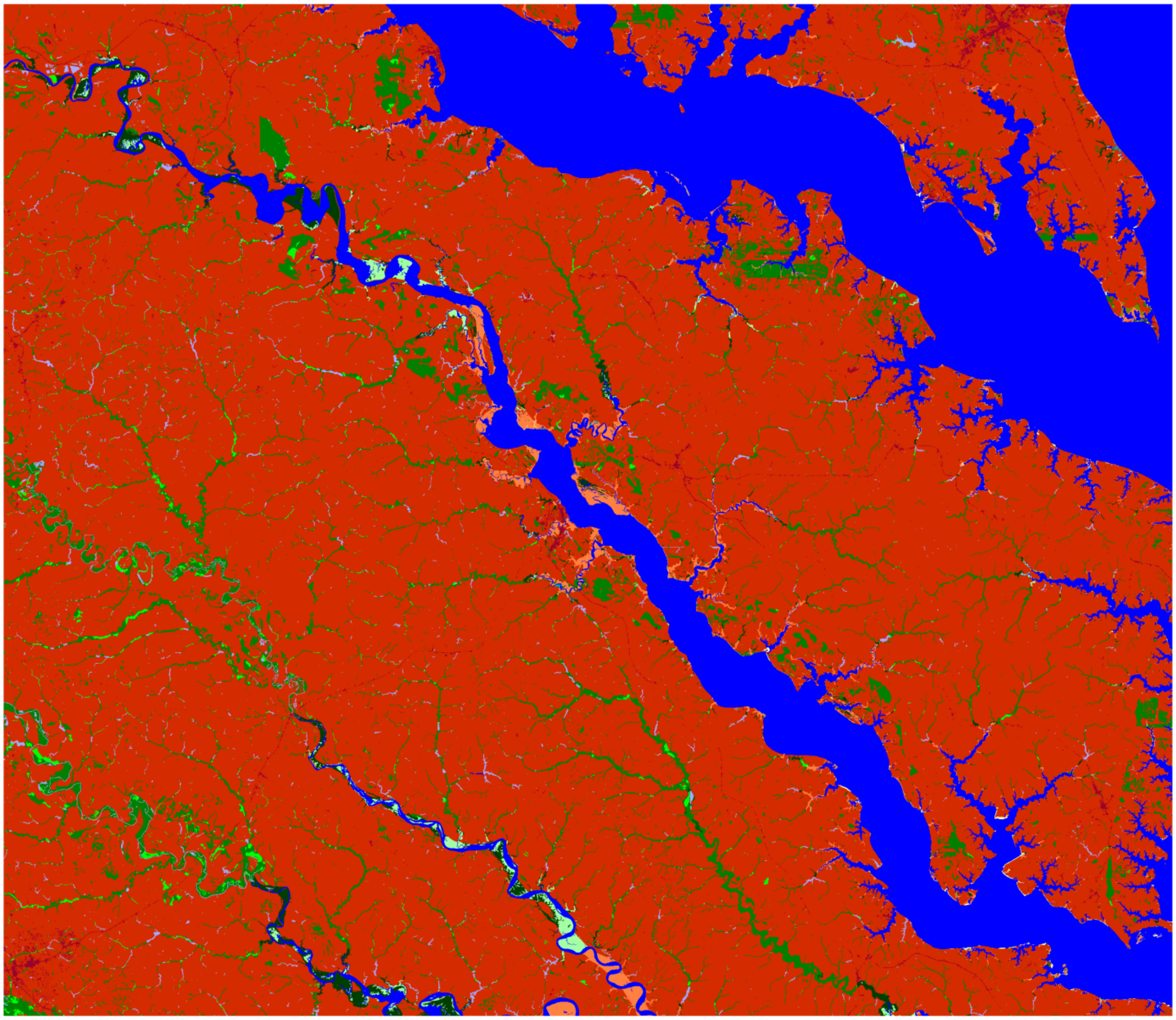
Rappahannock NWR, 2075, Scenario A1B Mean



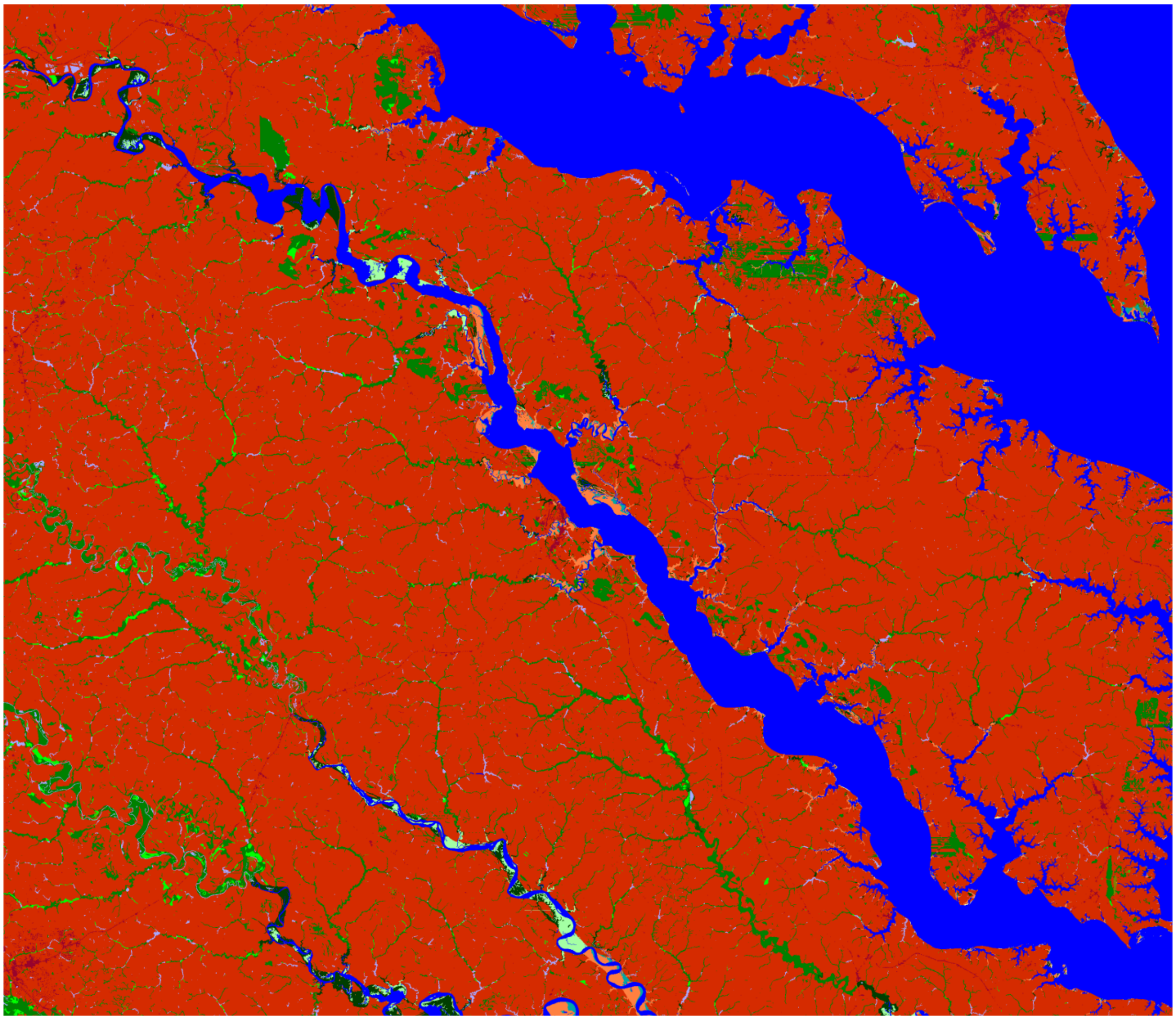
Rappahannock NWR, 2100, Scenario A1B Mean



Rappahannock NWR, Initial Condition



Rappahannock NWR, 2025, Scenario A1B Maximum



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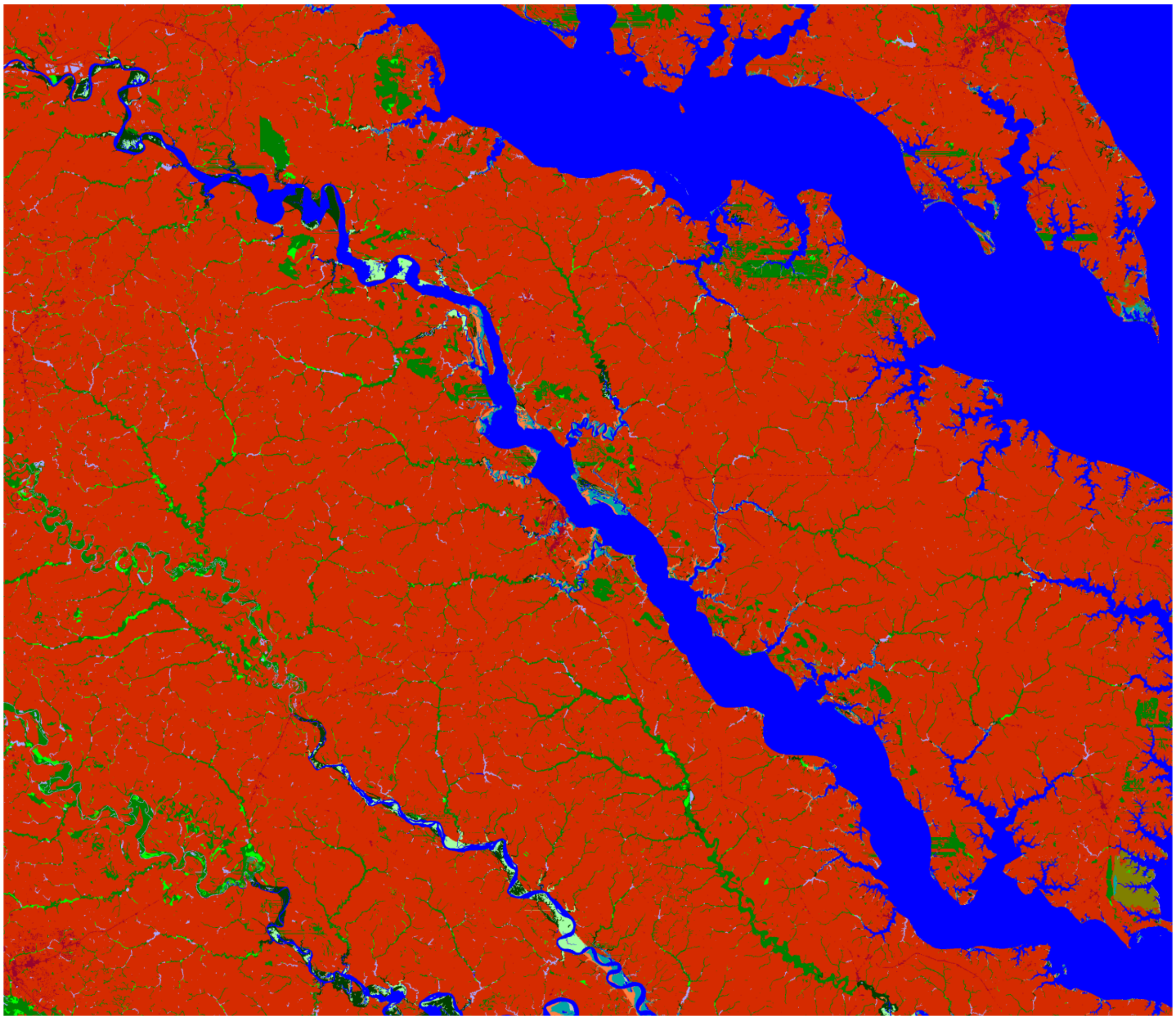

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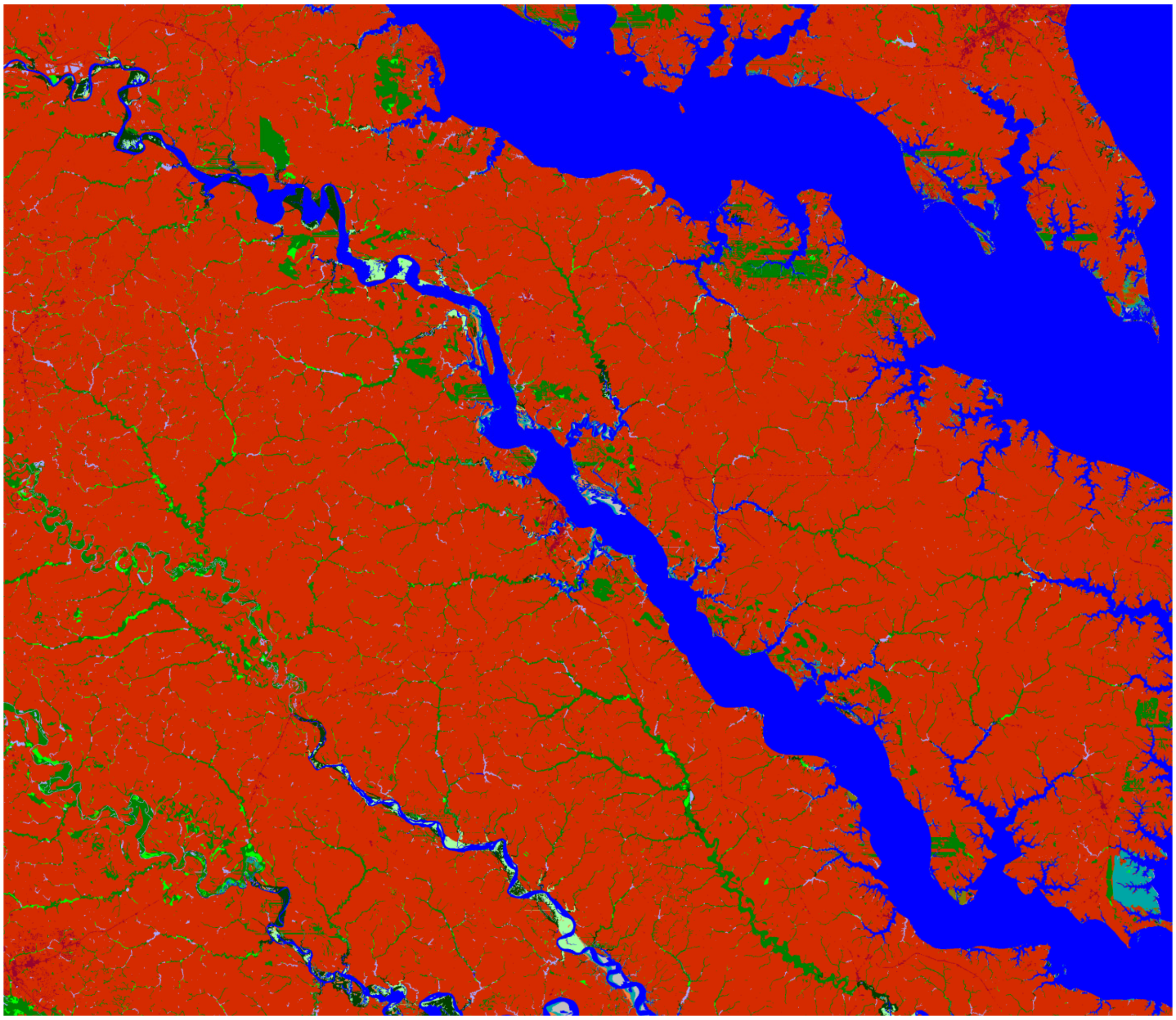

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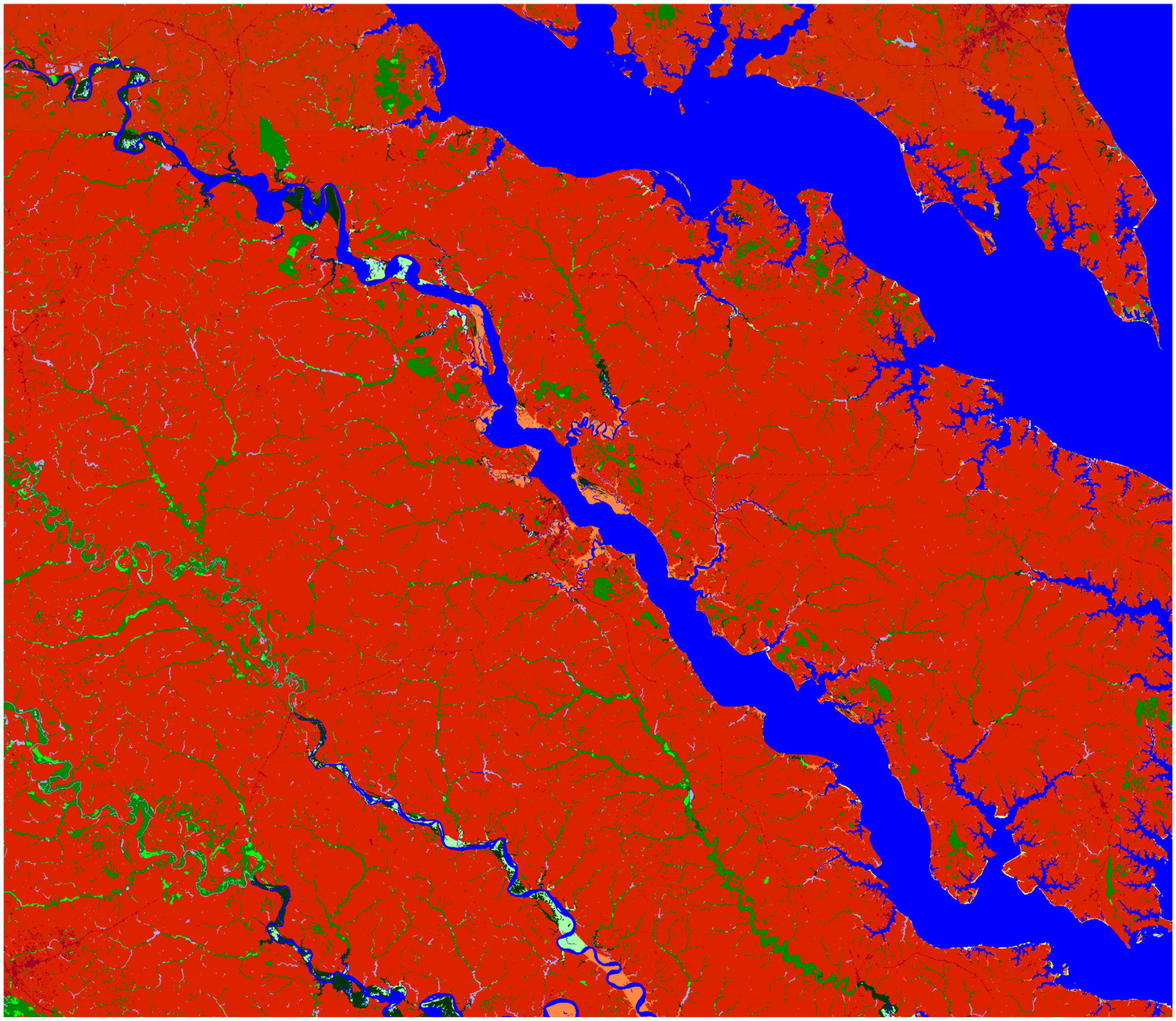
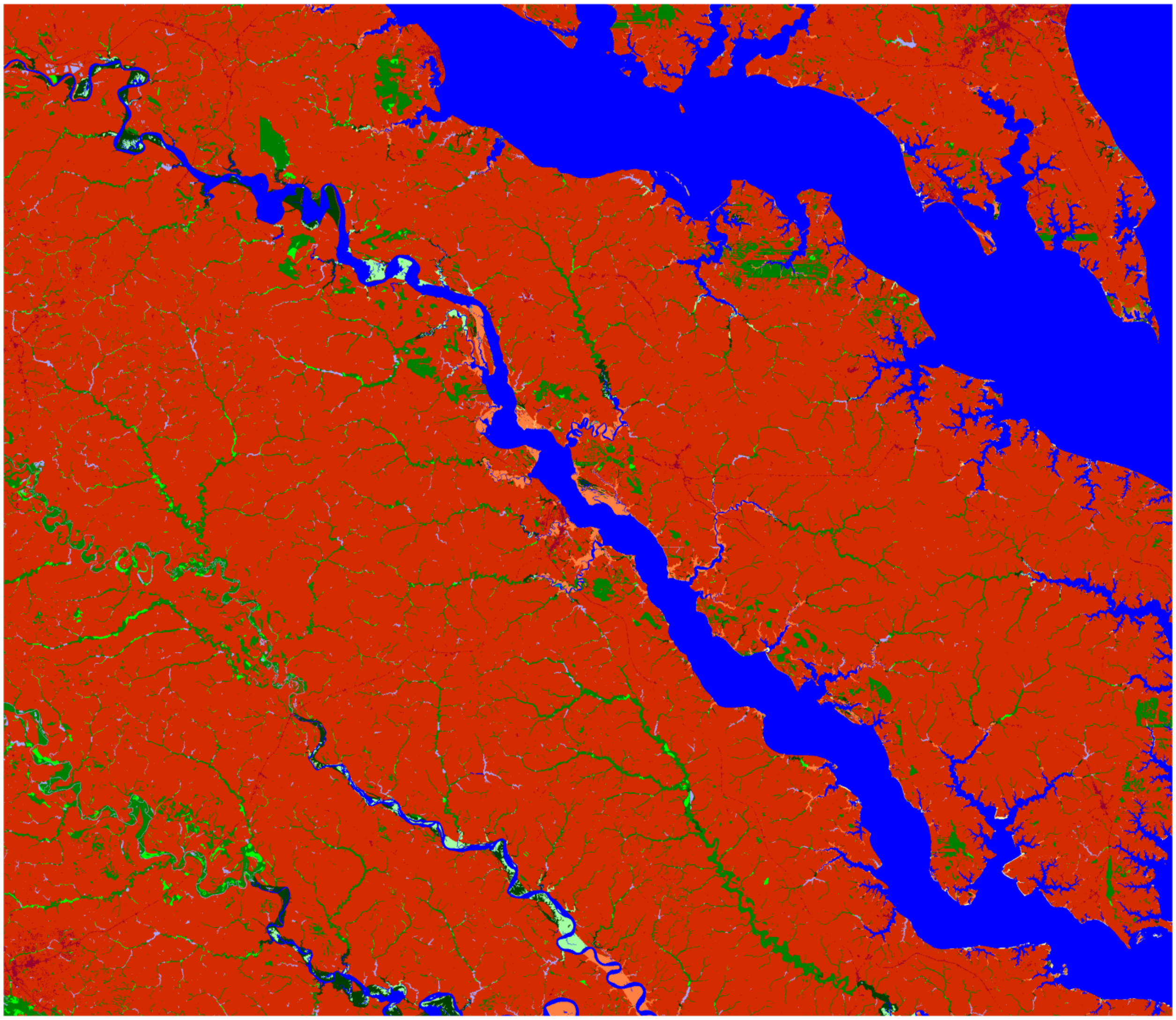
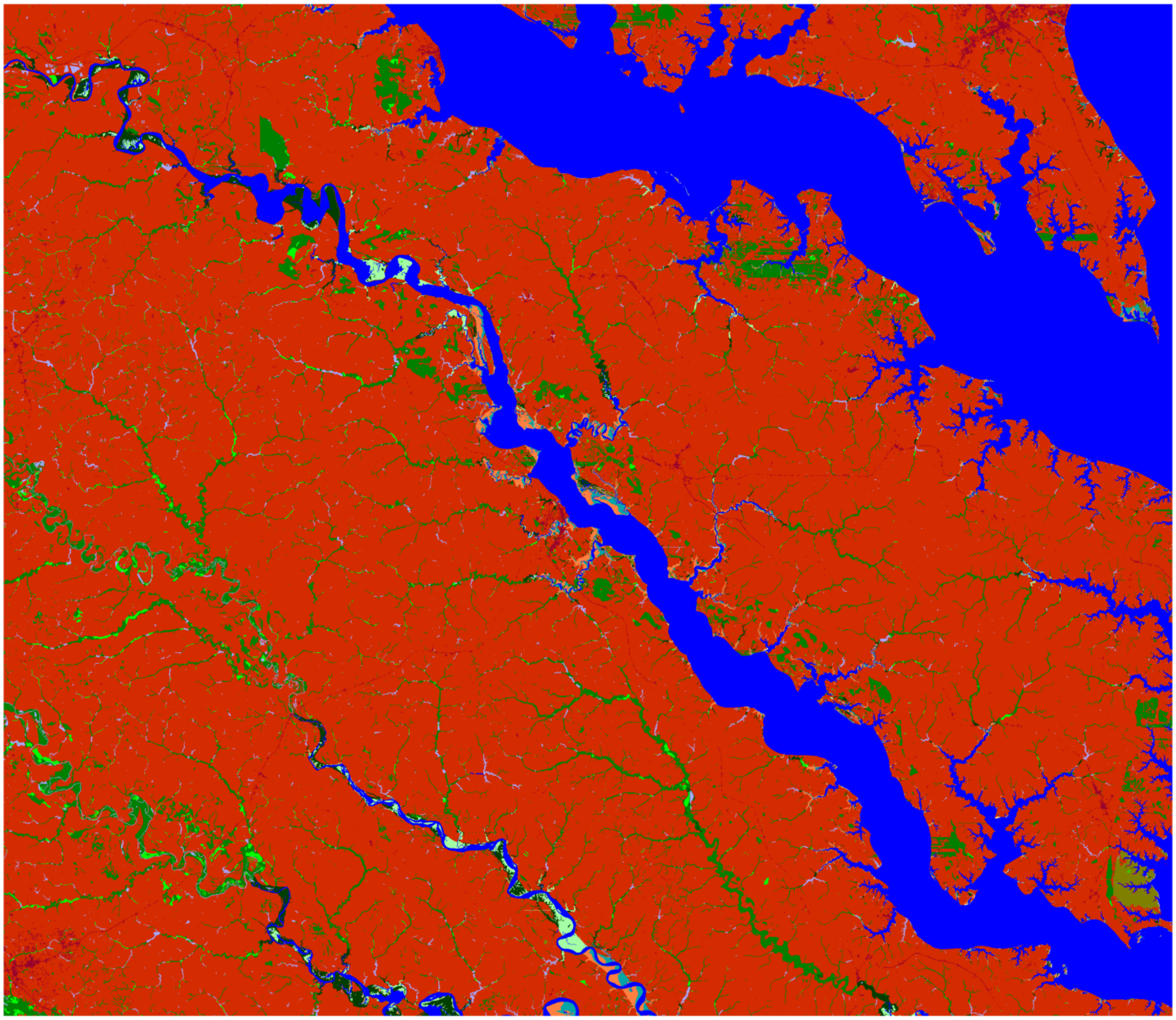


Rappahannock NWR, Initial Condition



Rappahannock NWR, 2025, 1 meter



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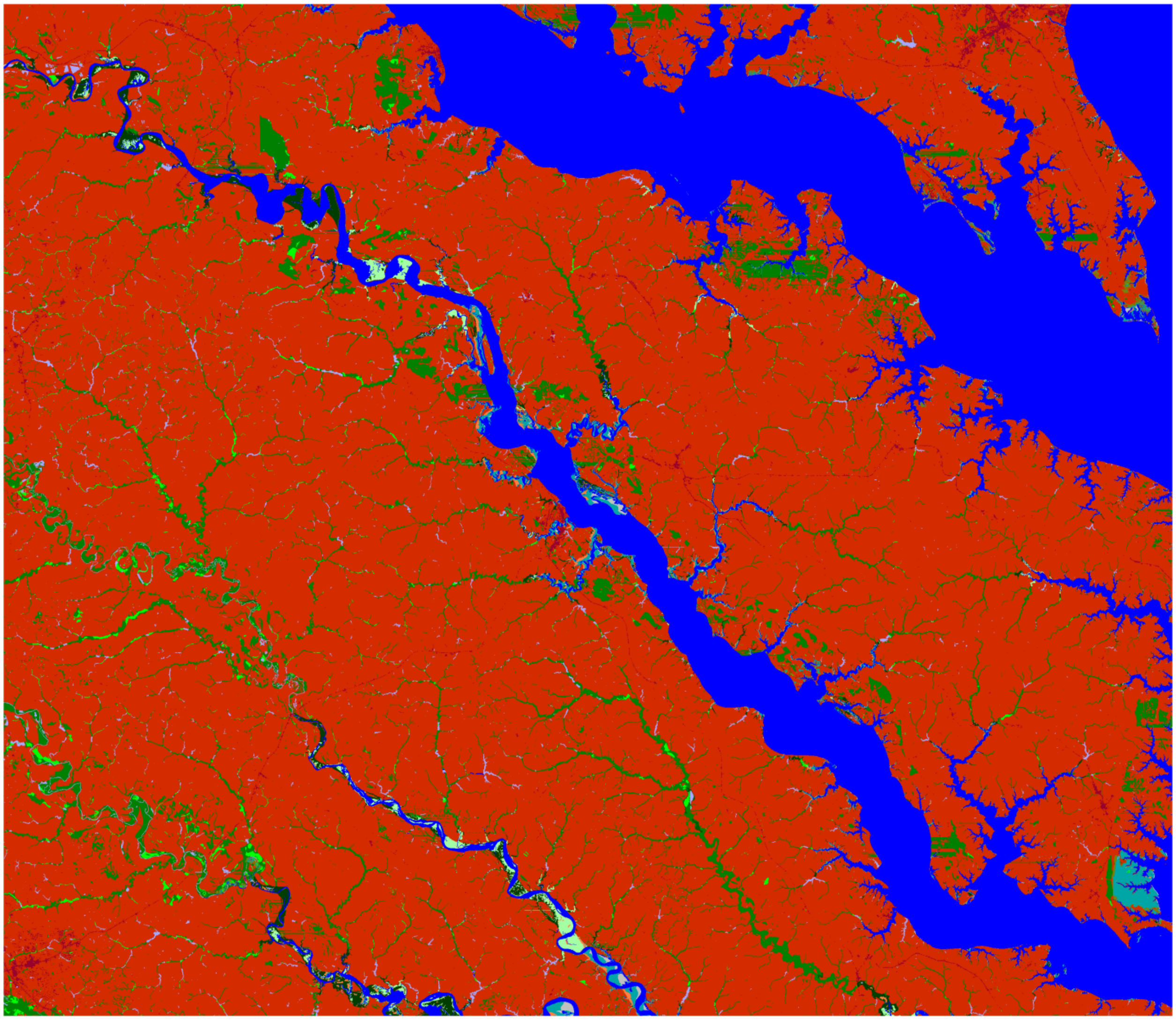

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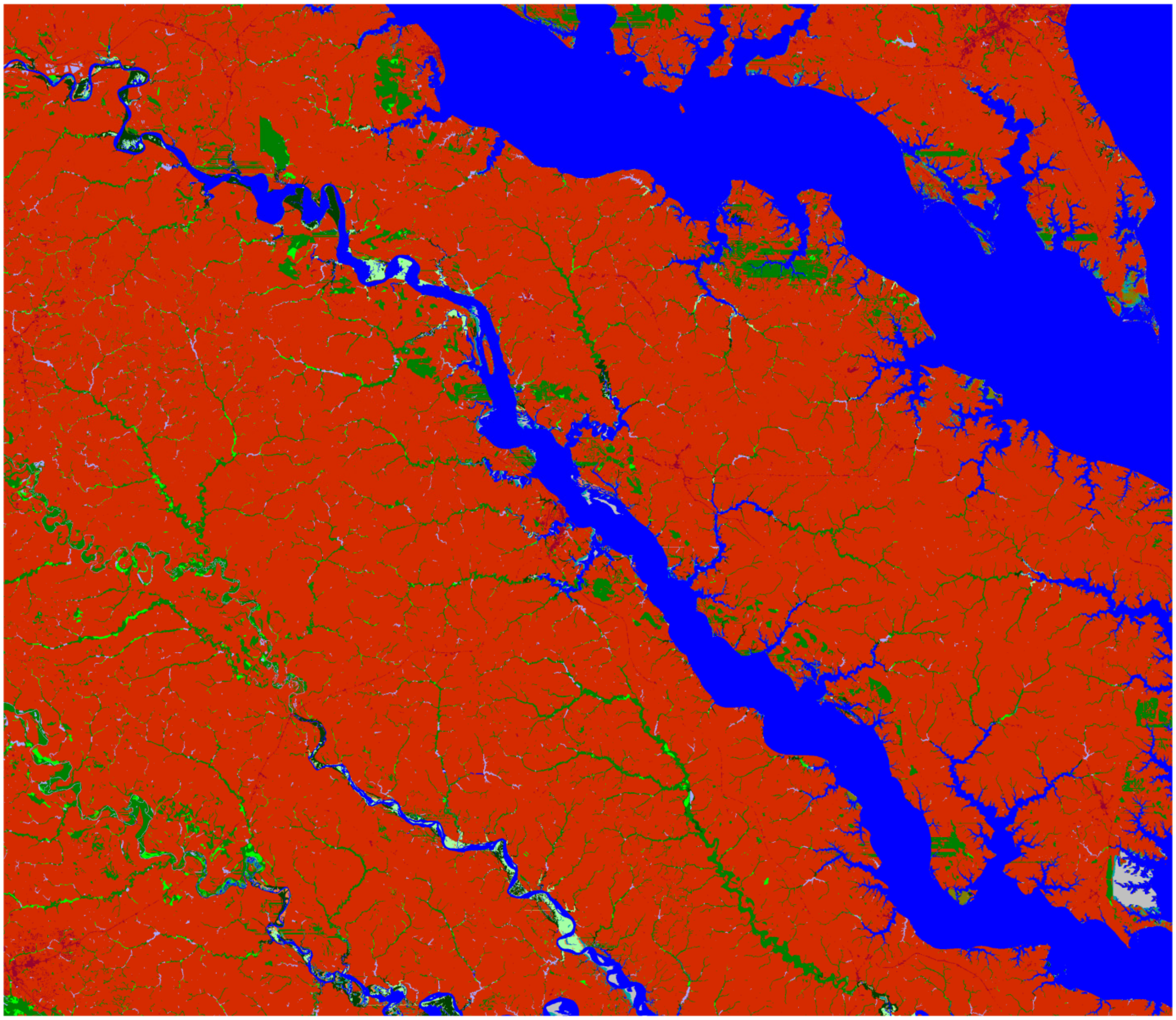
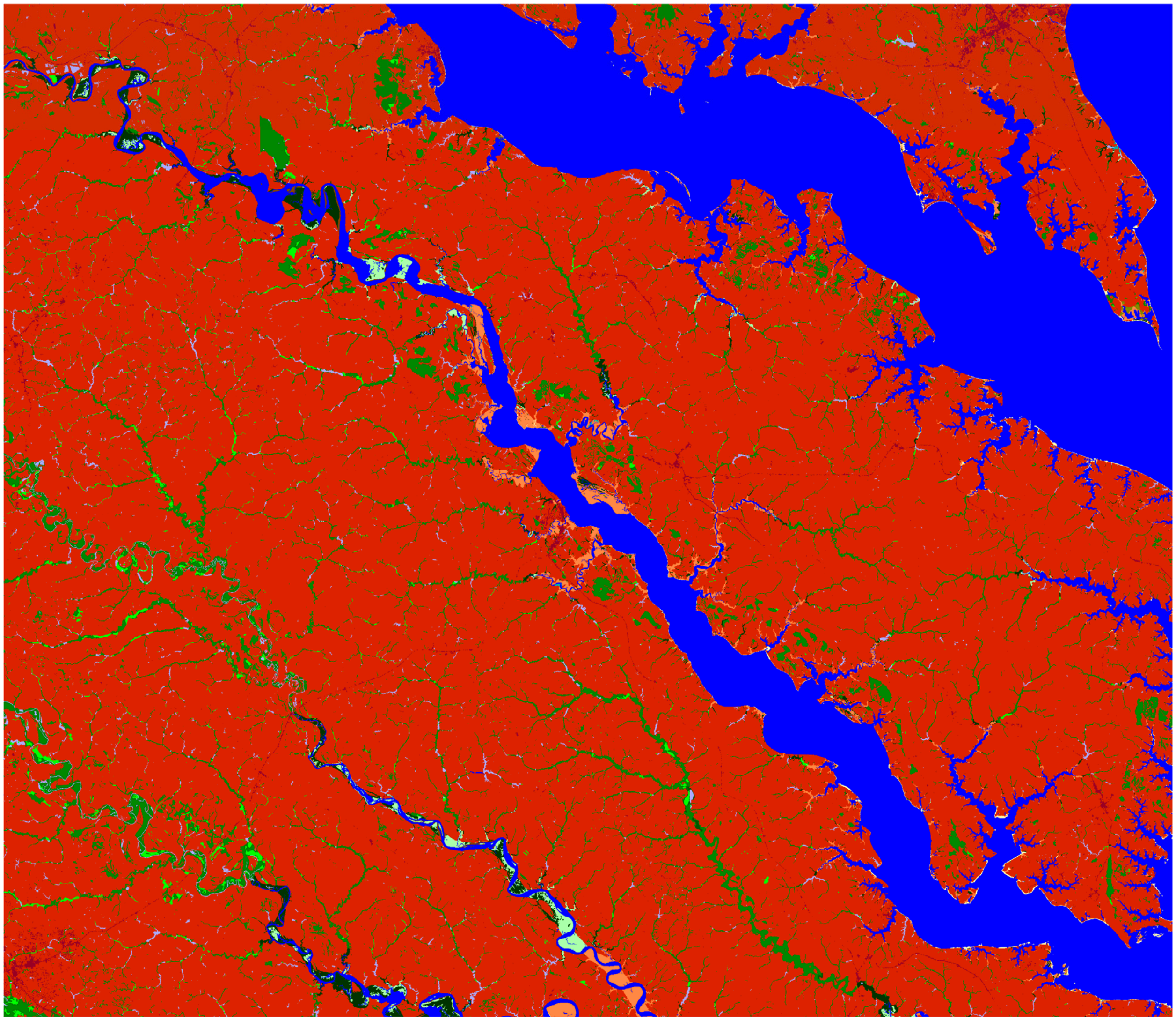
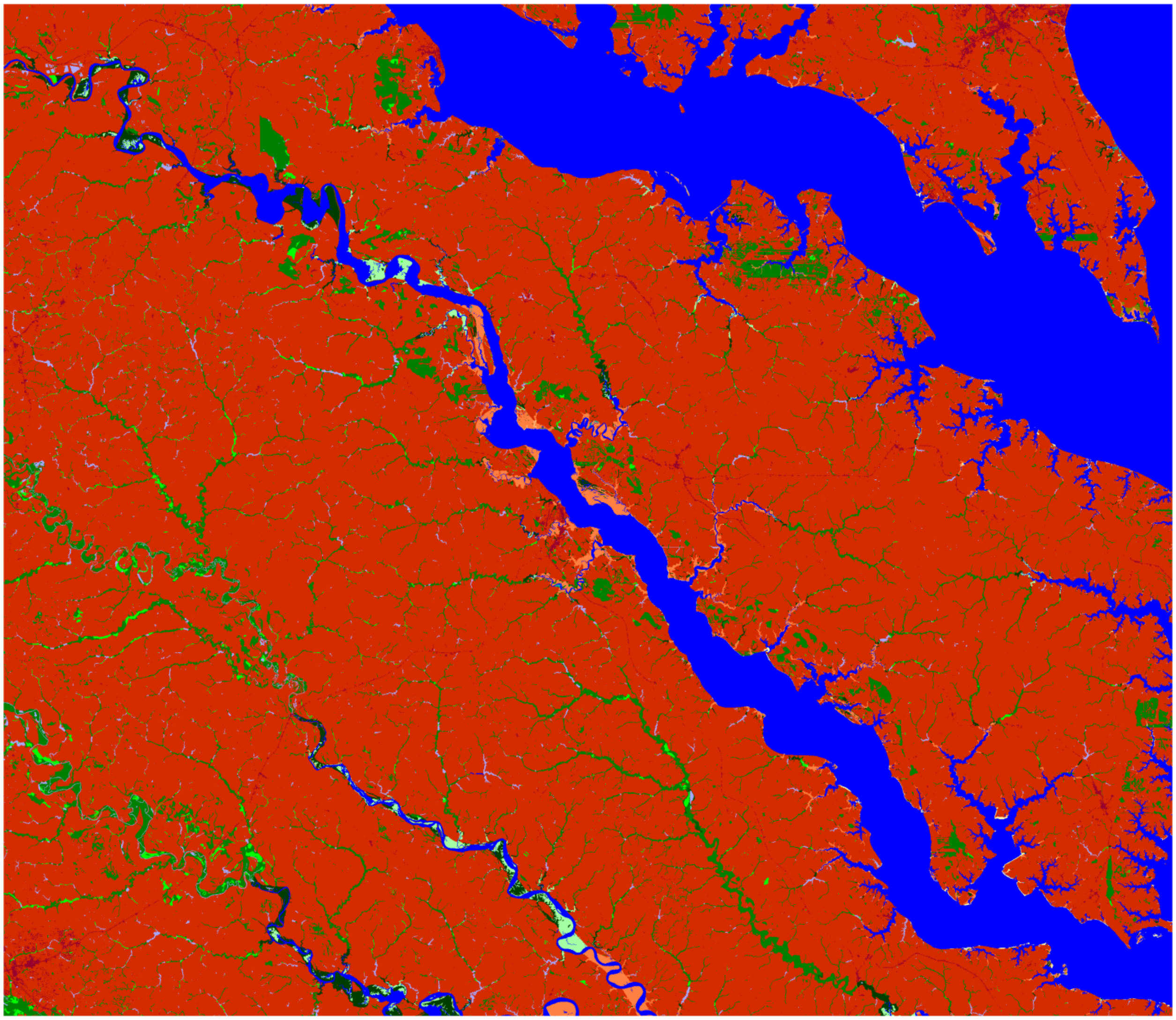


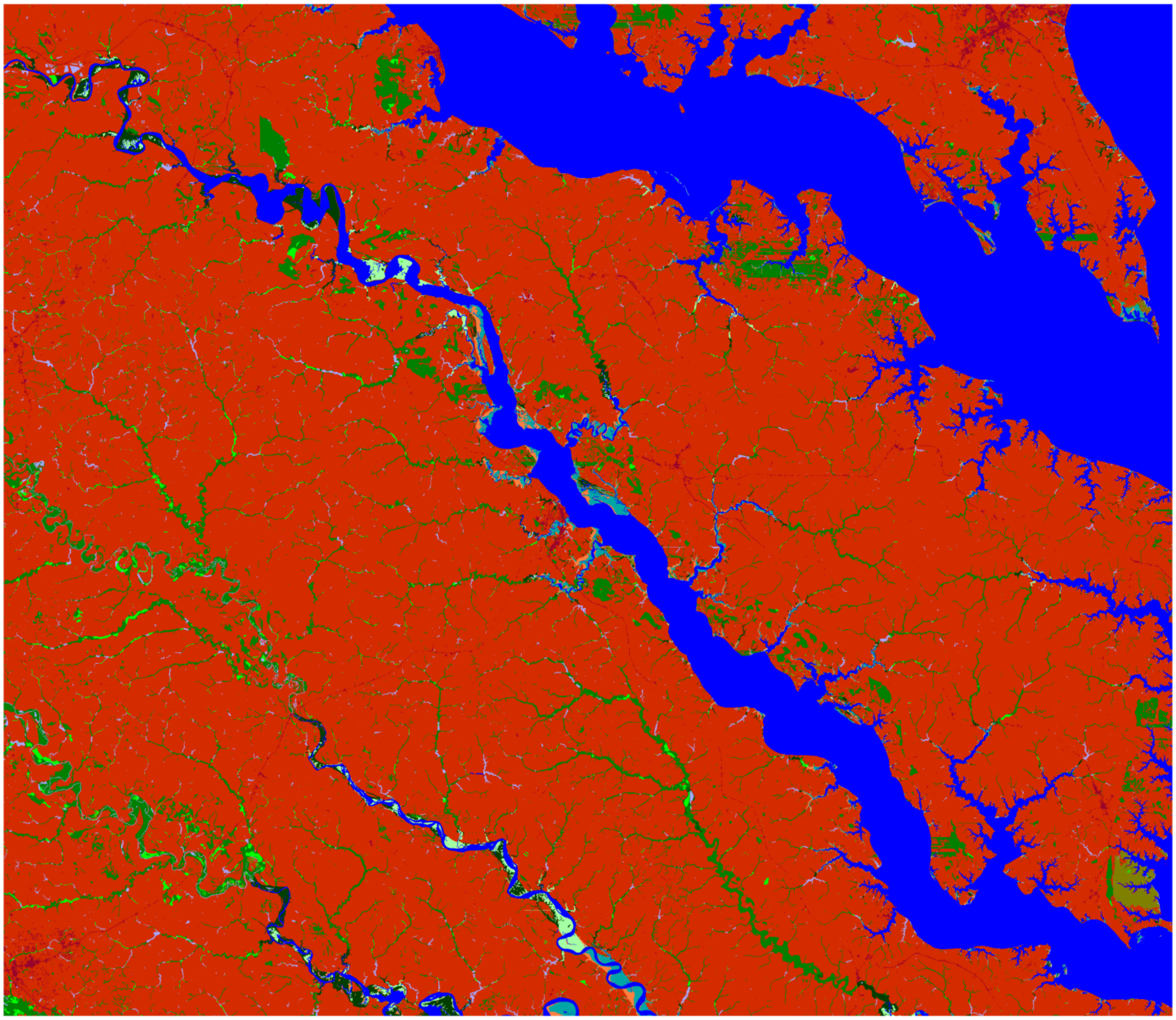
Rappahannock NWR, 2100, 1 meter



Rappahannock NWR, Initial Condition



Rappahannock NWR, 2025, 1.5 meter



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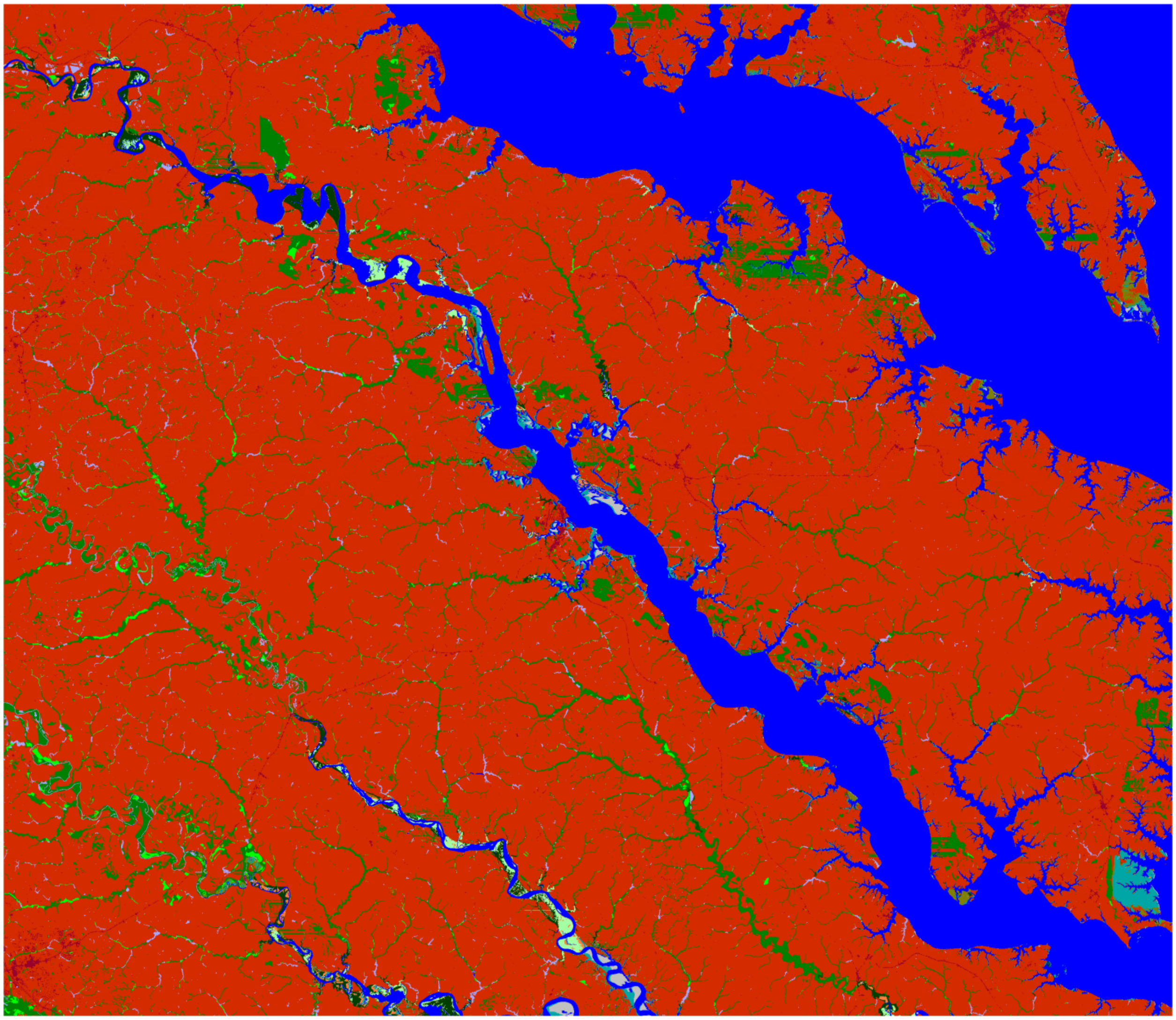
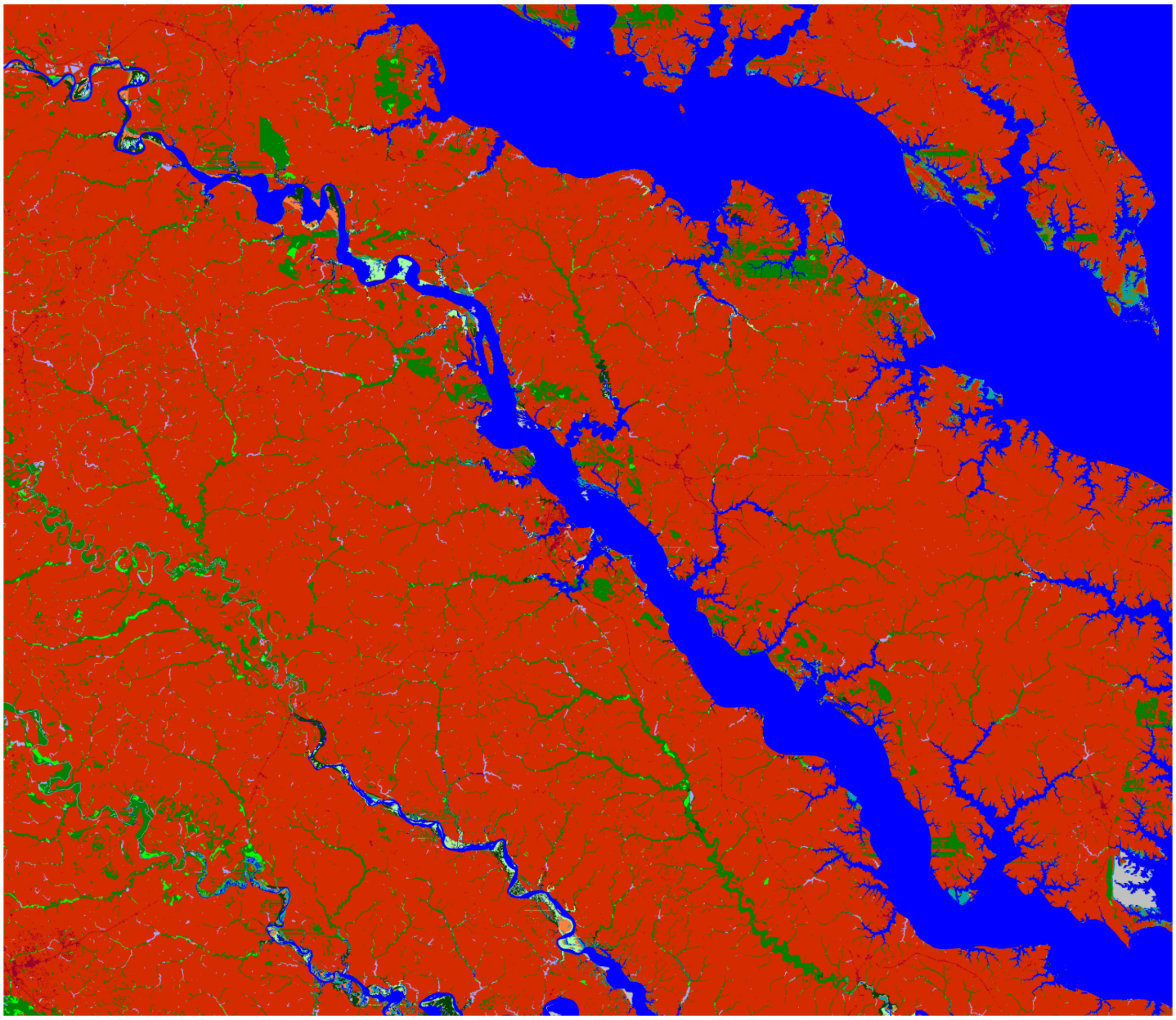
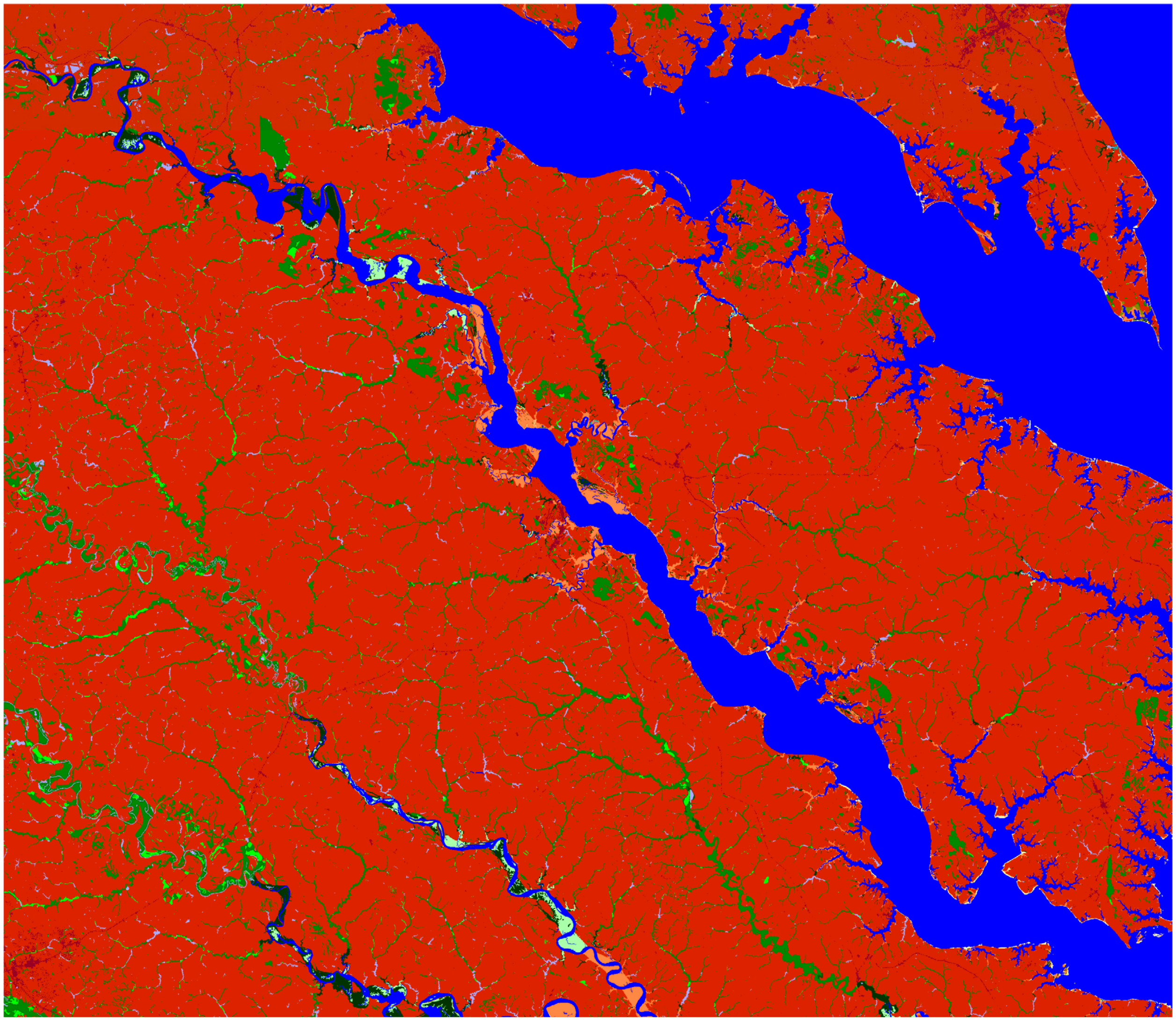


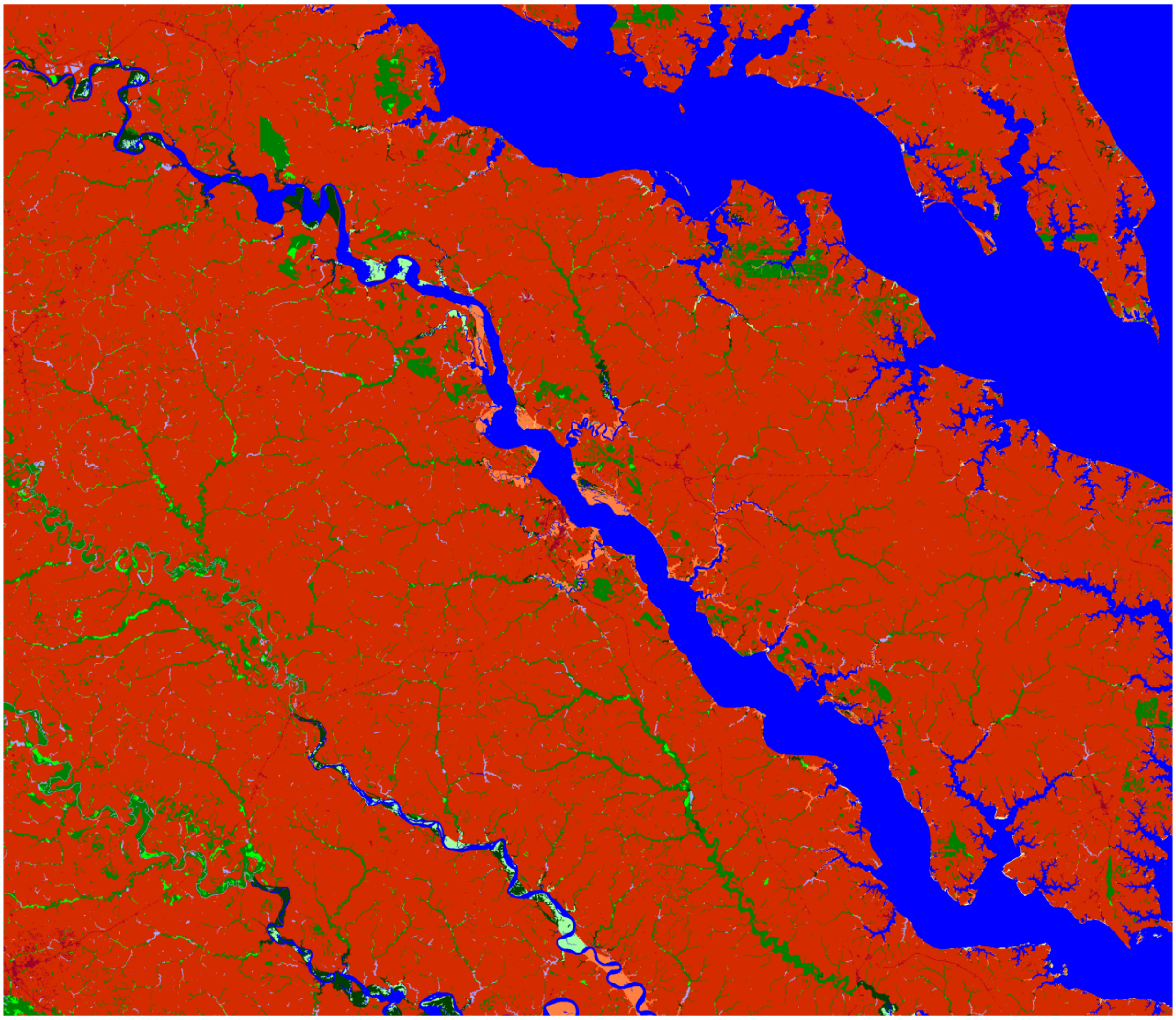
Rappahannock NWR, 2075, 1.5 meter



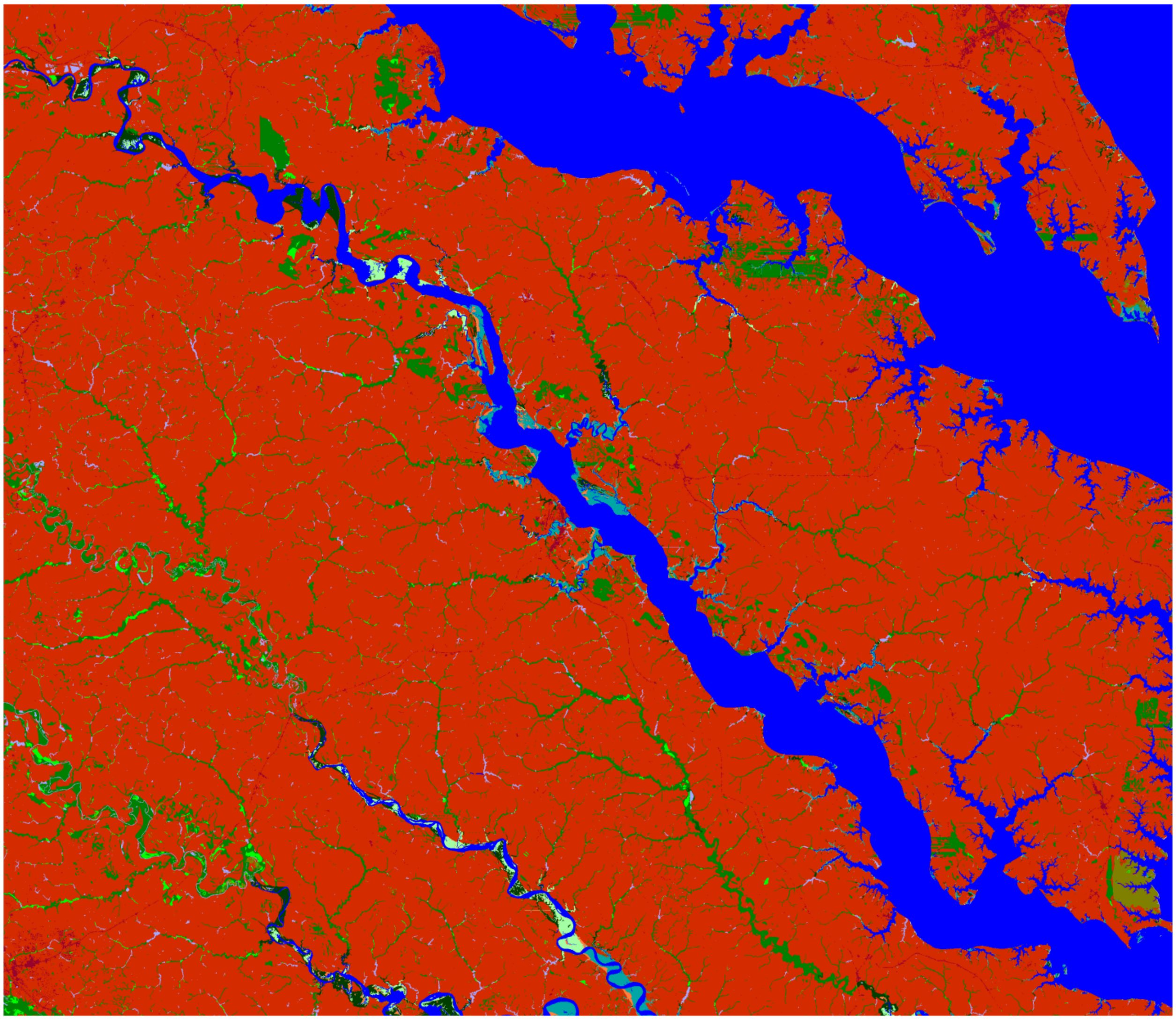
Rappahannock NWR, 2100, 1.5 meter



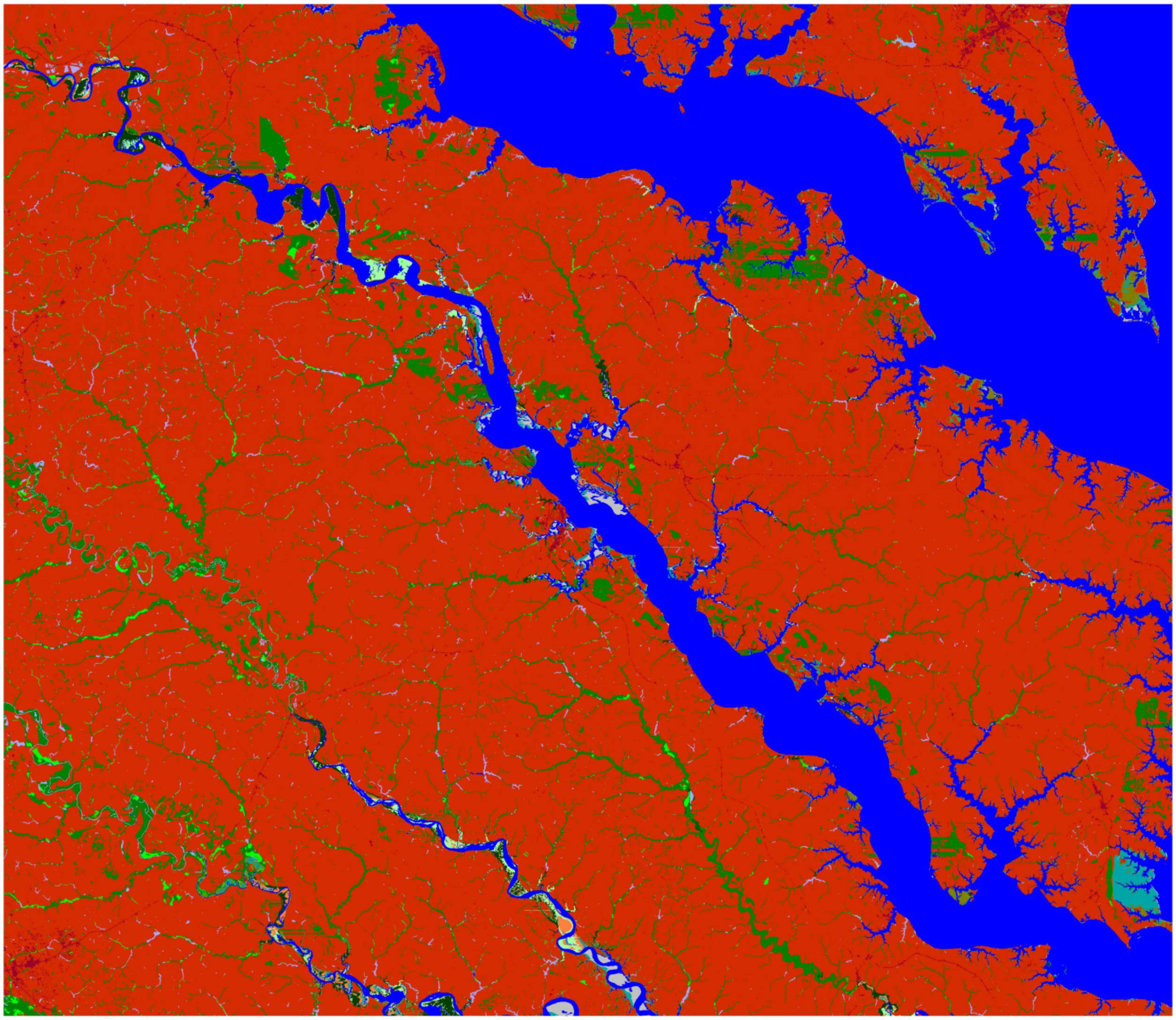
Rappahannock NWR, Initial Condition



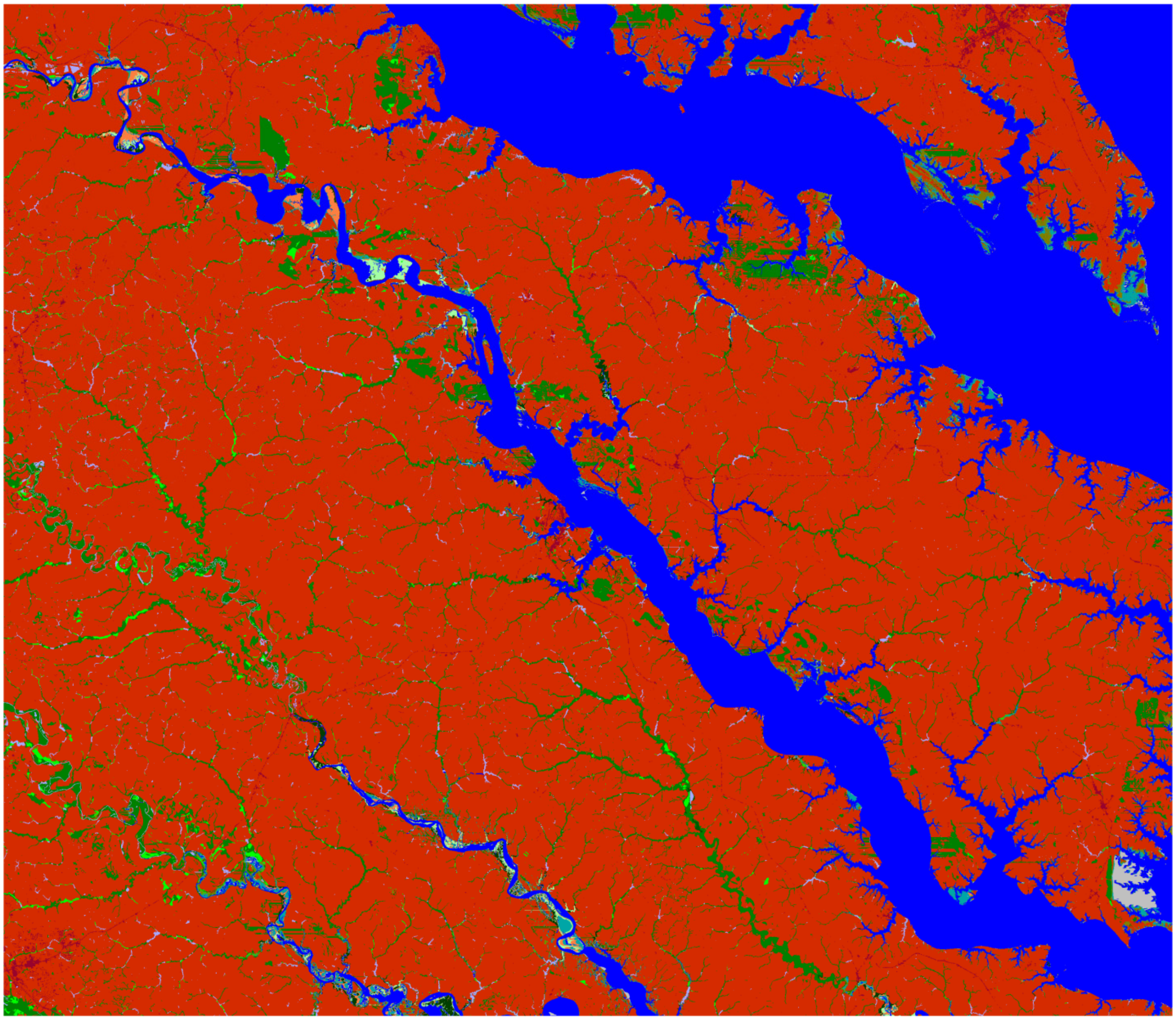
Rappahannock NWR, 2025, 2 meter



Rappahannock NWR, 2050, 2 meter



Rappahannock NWR, 2075, 2 meter



Rappahannock NWR, 2100, 2 meter