Application of the Sea-Level Affecting Marshes Model (SLAMM 5.1) to Blackwater 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

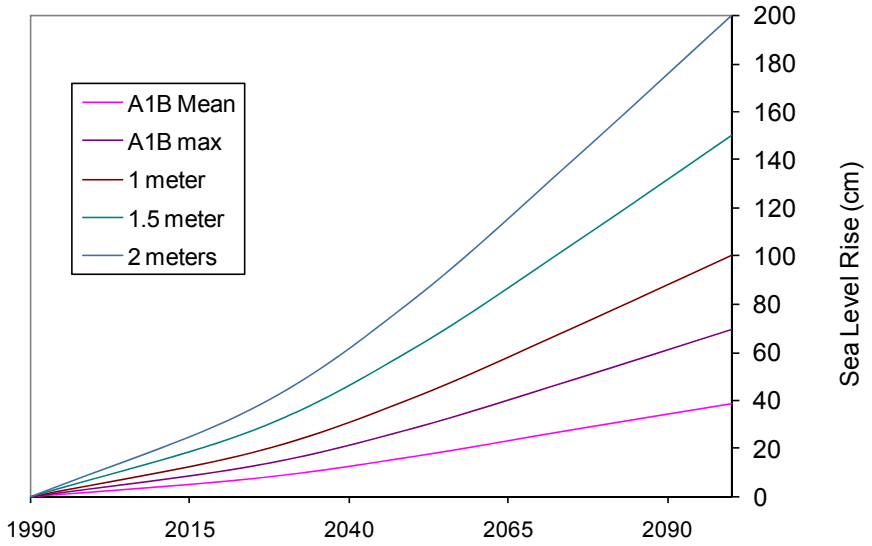
SLAMM 5 was run using scenario A1B from the Special Report on Emissions Scenarios (SRES) – mean and maximum estimates. The A1 scenario assumes that the future world includes very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of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

For the model simulation of Blackwater NWR a combination of 1 arc second NED LiDAR from the USGS and lower resolution, non-LiDAR NED data were used. The LiDAR data has a flight date of 2003 and the non-LiDAR data has a date of 1999.

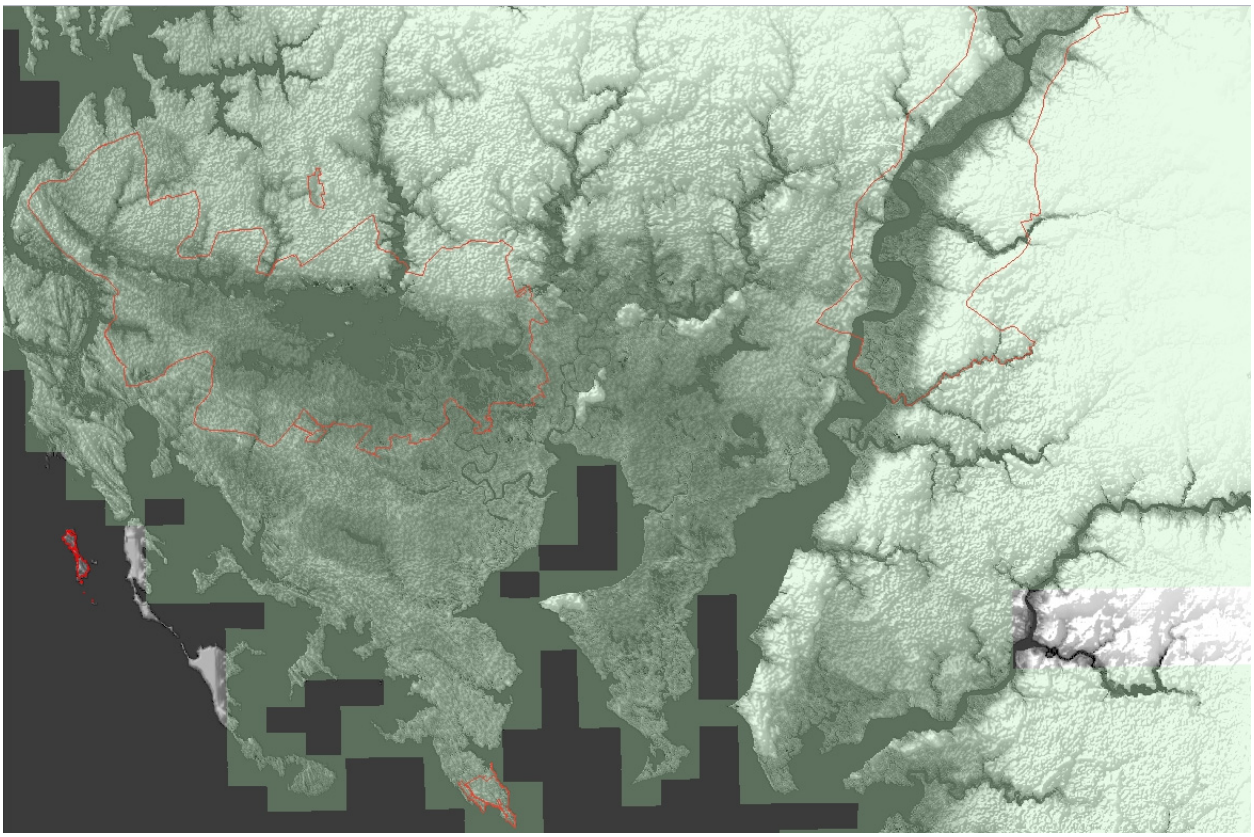


Figure 1: LiDAR coverage in green, non-LiDAR is black. NWR boundaries in red.

The National Wetlands Inventory for Blackwater is based on photo dates of 1982 and 1998.

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

Dry Land	27.3%
Swamp	19.3%
Saltmarsh	13.7%
Estuarine Open Water	12.9%
Irregularly Flooded Marsh	8.6%
Trans. Salt Marsh	8.2%
Tidal Swamp	7.8%

There are several diked wetlands within the Blackwater NWR according to the National Wetlands Inventory (Figure 2). These areas are assumed to be protected from up to 2 meters of local sea level rise.

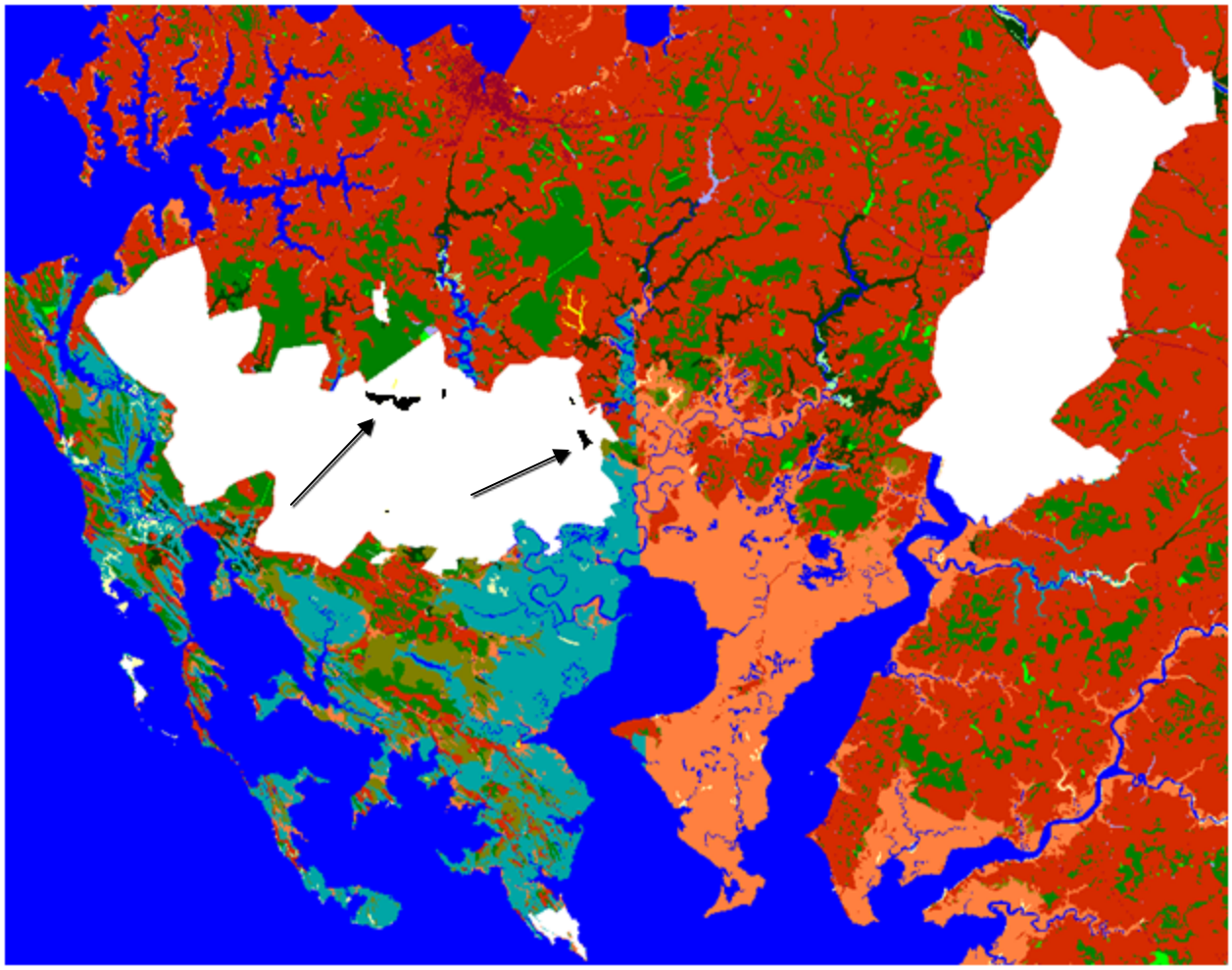


Figure 2: Diked areas in black.

The historic trend for sea level rise was estimated at 3.48 mm/year using long-term data from NOAA gage (8571892, Cambridge, MD). The rate of sea level rise for this refuge is roughly twice the global average for the last 100 years (approximately 1.7 mm/year). Projections of eustatic sea level rise were adjusted for this local difference.

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 3). This study suggests that sea level rise in Chesapeake Bay will increase faster than eustatic trends due to regional heating, freshwater effects, or mass adjustments. Based on this analysis 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.)

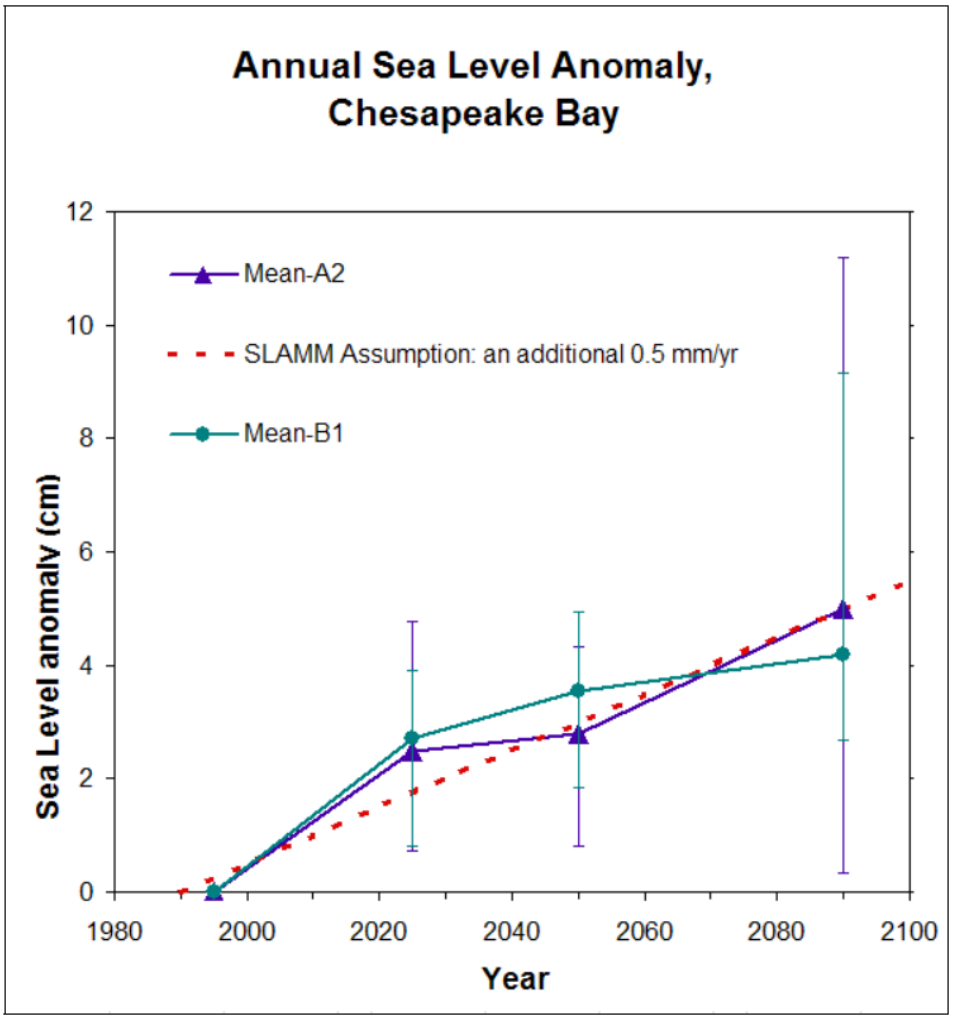


Figure 3: Adjustment of Eustatic SLR in SLAMM shown as red line. Source of model results, Dr. Victoria Coles Research Web Page, 11/15/2009, **http://hpl.umces.edu/vcoles/cbayclim-sl.htm.**

Marsh and tidal flat erosion values – which were set to 1.8 meters per year and 6 meters per year, for the southern portion of the refuge – were decreased to 0.9144 meters per year for sub-site 16 and 1.3716 meters per year for sub-site 17 (Figure 4 and Figure 5). Erosion data were derived using shoreline change data available from Towson University (Coastal Atlas v1.1).

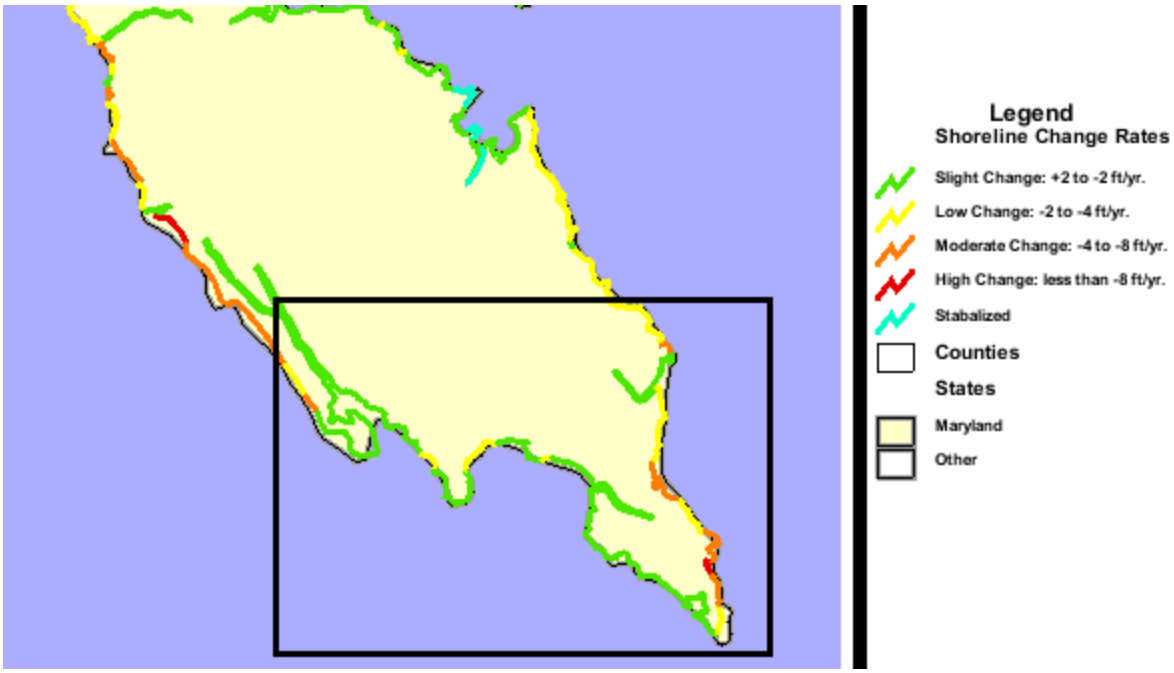


Figure 4: Erosion values used for Blackwater in rectangle. Source of erosion values are Towson University, Coastal Atlas v1.1, Center for GIS at Towson University, http://cgis.towson.edu.

The tidal range for Blackwater NWR is spatially variable within the study area (Figure 5). For Blackwater sub-site 1, the tidal range was determined to be 0.483 meters using a NOAA gage (8571702, Beaverdam Creek, MD). For Blackwater sub-site 2, the tidal range was determined to be 0.472 meters using an alternative gage (8571579, Barren Island, MD). For Blackwater sub-site 3, the tidal range was determined to be 0.745 meters based on a gage in Vienna, MD 8571773. For Blackwater sub-site 4, the tidal range was determined to be 0.62 meters using gage 8572955 (Love Point Pier, MD).

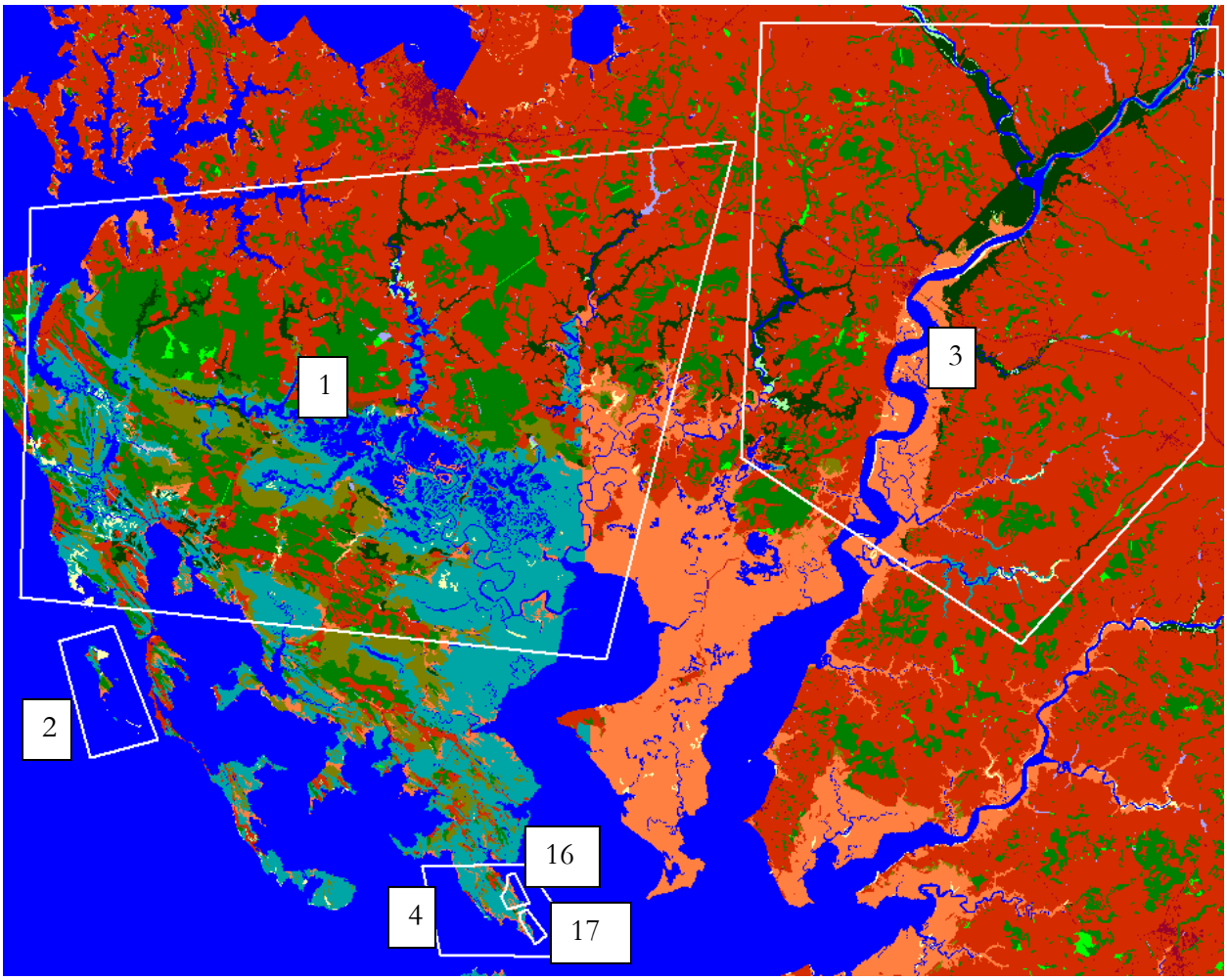


Figure 5: The 4 major input sub-sites for Blackwater NWR.
The two smaller polygons within sub-site 4 were utilized for applying spatially variable erosion rates.

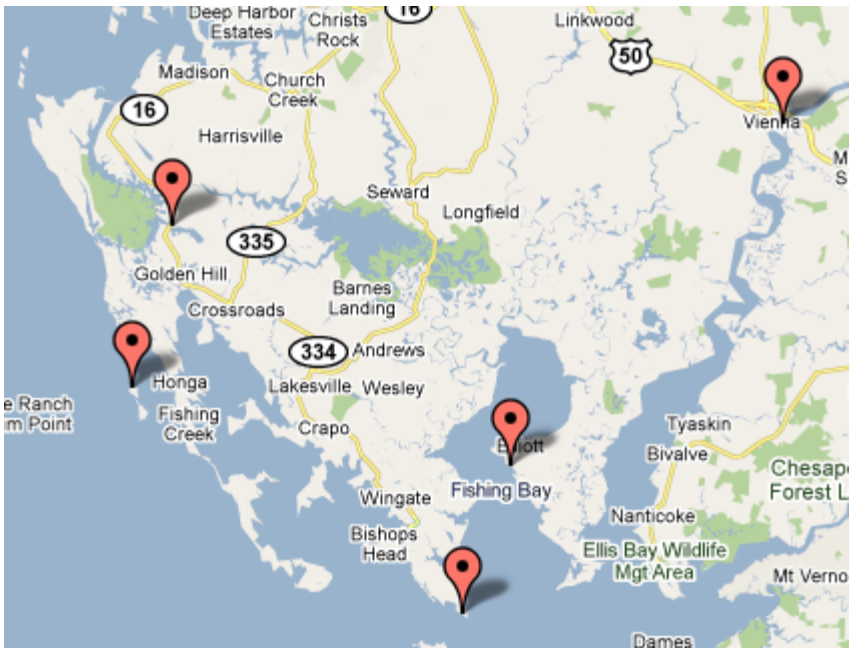


Figure 6: NOAA Gages Relevant to the Study Area.

Accretion rates in regularly flooded marshes were set to 2.65 mm/year based on an accretion study locared within the Blackwater NWR (Stevenson, 1985). Rates for irregularly flooded marshes were set to 5.3 mm/year based on three studies: two from Monie Bay and one from Nanticoke River Estuary (Kearney, 1986; Kearney et al., 1991; Ward et al., 1998). Rates for tidal fresh marshes were set to 7.2 mm/year based on the means of numerous studies within Maryland (n=5, Reed et al., 2008). However, for sub-site 3 the accretion value for irregularly flooded marsh was set to 4.6 mm/year based on results directly measured within Nanticoke River estuary (Kearney, 1986).

The MTL to NAVD correction was derived using the NOAA VDATUM modeling product and also varies spatially. For sub-site 1 the correction was determined to be -0.04 meters. For sub-site 2 the correction was determined to be -0.043 meters. For sub-site 3 the correction was determined to be -0.07 meters. For sub-site 4 the correction was determined to be -0.0469 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. Additionally, the SLAMM model tracks partial conversion of cells based on elevation and slope.

SUMMARY OF SLAMM INPUT PARAMETERS FOR BLACKWATER NWR

Parameter	Global	Sub-site 3	Sub-site 4	Sub-site 5
Description	Chessy North	Blackwater1	Blackwater2	Blackwater3
NWI Photo Date (YYYY)	2000	1998	1998	1982
DEM Date (YYYY)	2000	2003	1999	2003
Direction Offshore [n,s,e,w]	East	South	West	South
Historic Trend (mm/yr)	4.8	3.98	3.98	3.98
MTL-NAVD88 (m)	-0.05	-0.04	-0.043	-0.07
GT Great Diurnal Tide Range (m)	0.58	0.483	0.472	0.745
Salt Elev. (m above MTL)	0.385	0.321	0.314	0.495
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	2.65	2.65	2.65
Irreg. Flood Marsh Accr (mm/yr)	4.8	5.33	5.33	4.6
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	FALSE	TRUE	FALSE

Parameter	Sub-site 6	Sub-site 16	Sub-site 17
Description	Blackwater4	Sub-site 16	Sub-site 17
NWI Photo Date (YYYY)	1982	1982	1982
DEM Date (YYYY)	2003	2003	2003
Direction Offshore [n,s,e,w]	South	East	East
Historic Trend (mm/yr)	3.98	3.98	3.98
MTL-NAVD88 (m)	-0.0469	-0.0469	-0.0469
GT Great Diurnal Tide Range (m)	0.62	0.62	0.62
Salt Elev. (m above MTL)	0.412	0.412	0.412
Marsh Erosion (horz. m /yr)	1.8	0.9144	1.3716
Swamp Erosion (horz. m /yr)	1	1	1
T.Flat Erosion (horz. m /yr)	6	0.9144	1.3716
Reg. Flood Marsh Accr (mm/yr)	2.65	2.65	2.65
Irreg. Flood Marsh Accr (mm/yr)	5.33	5.33	5.33
Tidal Fresh Marsh Accr (mm/yr)	7.2	7.2	7.2
Beach Sed. Rate (mm/yr)	0.5	0.5	0.5
Freq. Overwash (years)	25	25	25
Use Elev Pre-processor [True,False]	FALSE	FALSE	FALSE

Results

SLAMM predicts significant vulnerabilities for Blackwater NWR as a result of sea level rise. Dry land, which comprises roughly one third of the refuge, is lost at a rate of 37% to 60% across all scenarios. Swamp, which comprises roughly one fifth of the refuge, is predicted to lose between 33% and 80% across all scenarios. Regularly flooded marsh (saltmarsh) is predicted to lose between 1% and 48% across all scenarios; irregularly flooded marsh loses between 32% and 97%.

SLR by 2100 (m)	0.39	0.69	1	1.5	2
Dry Land	37%	43%	49%	56%	60%
Swamp	33%	49%	57%	70%	80%
Saltmarsh	1%	22%	42%	48%	48%
Irregularly Flooded Marsh	32%	82%	93%	96%	97%
Trans. Salt Marsh	-5%	46%	49%	42%	46%
Tidal Swamp	75%	89%	93%	96%	97%
Estuarine Beach	77%	94%	97%	98%	99%
Inland Fresh Marsh	-10%	-10%	11%	63%	85%
Dev. Dry Land	27%	31%	34%	38%	45%
Riverine Tidal	89%	90%	91%	92%	92%

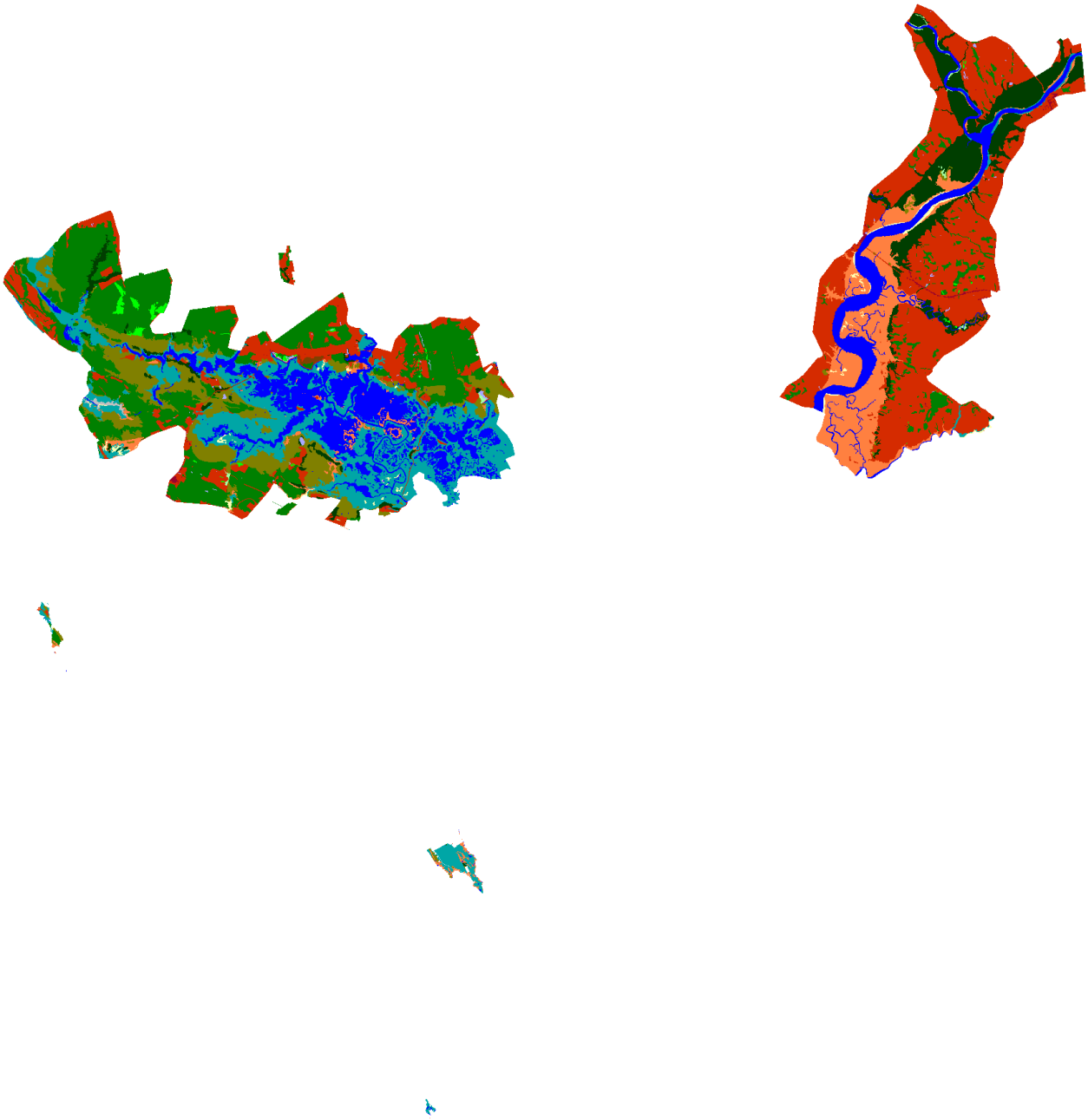
Predicted Loss Rates of Land Categories by 2100 Given Simulated Scenarios of Eustatic Sea Level Rise

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

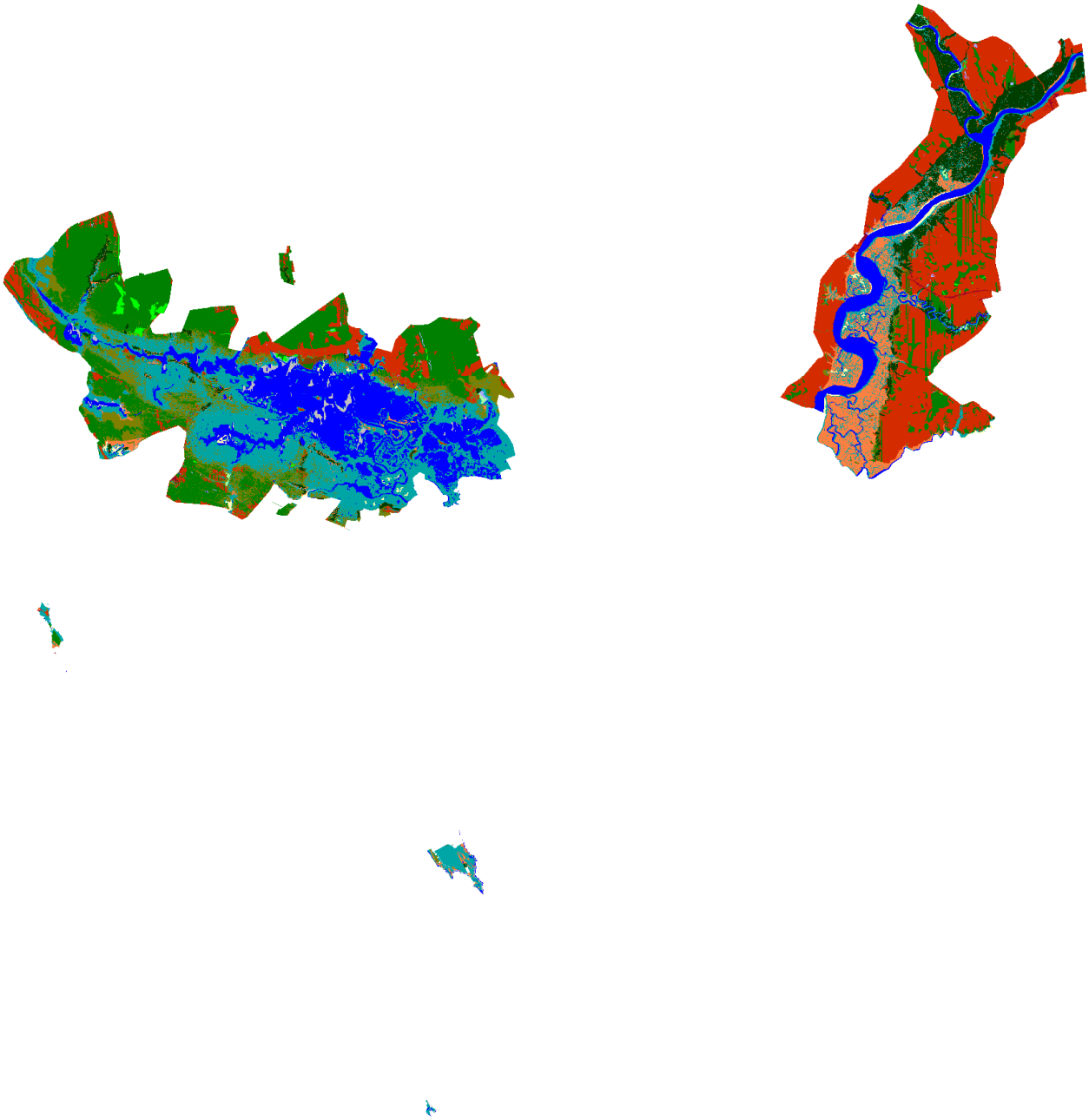
Blackwater Raster
IPCC Scenario A1B-Mean, 0.39 M SLR Eustatic by 2100

Results in Acres

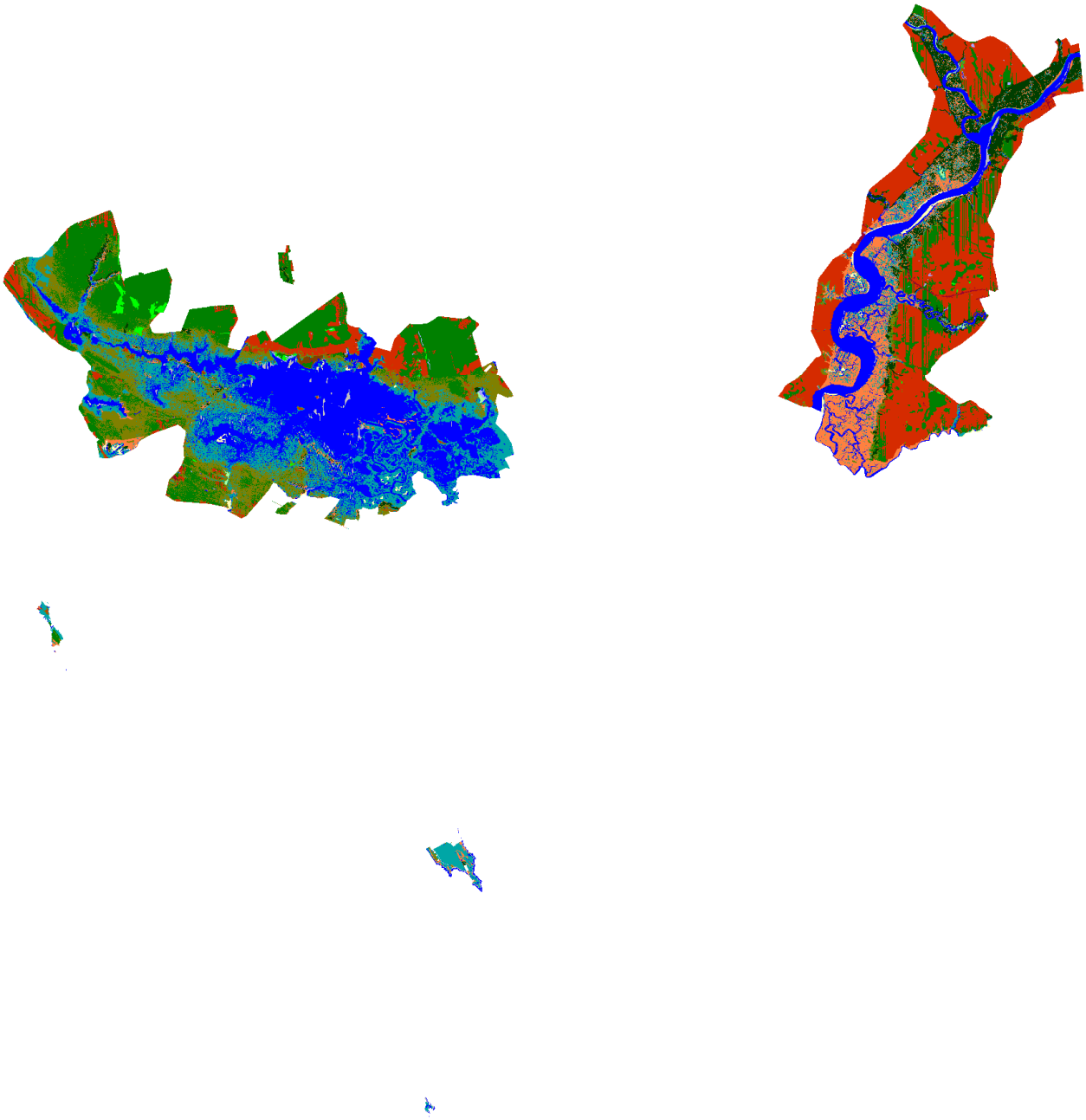
	Initial	2025	2050	2075	2100
Undev. Dry Land	20607.2	16753.7	15167.9	13925.8	13069.0
Swamp	14575.3	14257.2	13072.9	11317.2	9740.4
Saltmarsh	10355.8	15527.8	11663.0	9508.1	10280.5
Estuarine Open Water	9757.1	12286.9	16791.5	23523.9	28902.2
Irregularly Flooded Marsh	6447.9	4656.8	5426.1	5323.1	4358.2
Trans. Salt Marsh	6161.0	5291.5	7887.9	7883.1	6493.2
Tidal Swamp	5874.3	4884.1	3774.9	2434.9	1494.8
Estuarine Beach	388.3	387.1	383.4	283.2	87.6
Inland Fresh Marsh	331.8	319.7	321.9	337.9	366.6
Dev. Dry Land	211.9	178.8	169.0	160.8	154.4
Riverine Tidal	211.7	61.2	55.8	32.7	23.8
Inland Open Water	156.3	119.2	110.8	105.4	102.3
Tidal Fresh Marsh	110.1	98.0	98.0	98.0	98.0
Inland Shore	95.9	90.3	86.2	50.8	23.7
Tidal Flat	74.7	447.2	350.1	374.5	164.5
Total (incl. water)	**75359.3**	**75359.3**	**75359.3**	**75359.3**	**75359.3**



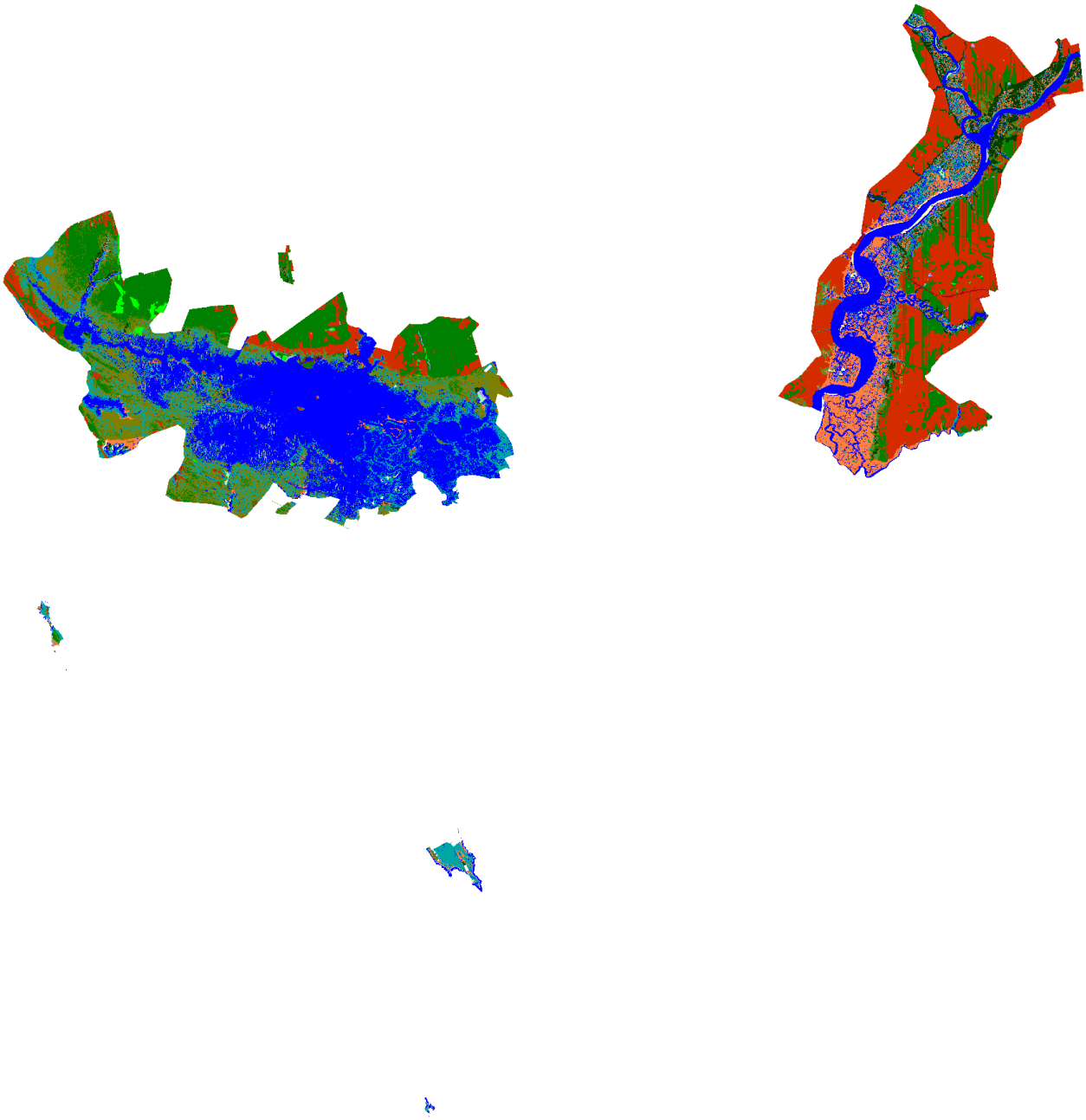
Blackwater NWR, Initial Condition



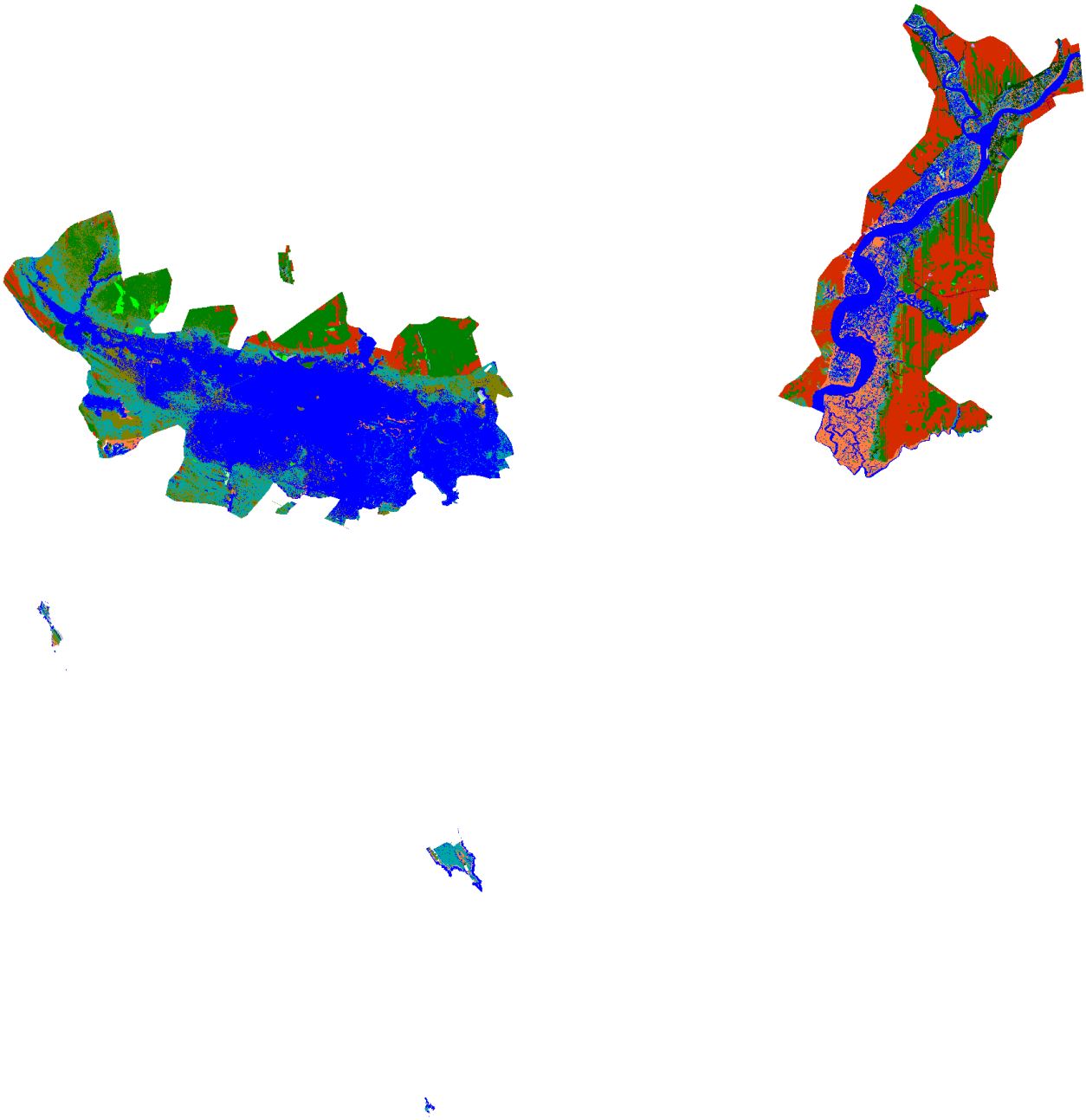
Blackwater NWR, 2025, Scenario A1B Mean



Blackwater NWR, 2050, Scenario A1B Mean



Blackwater NWR, 2075, Scenario A1B Mean

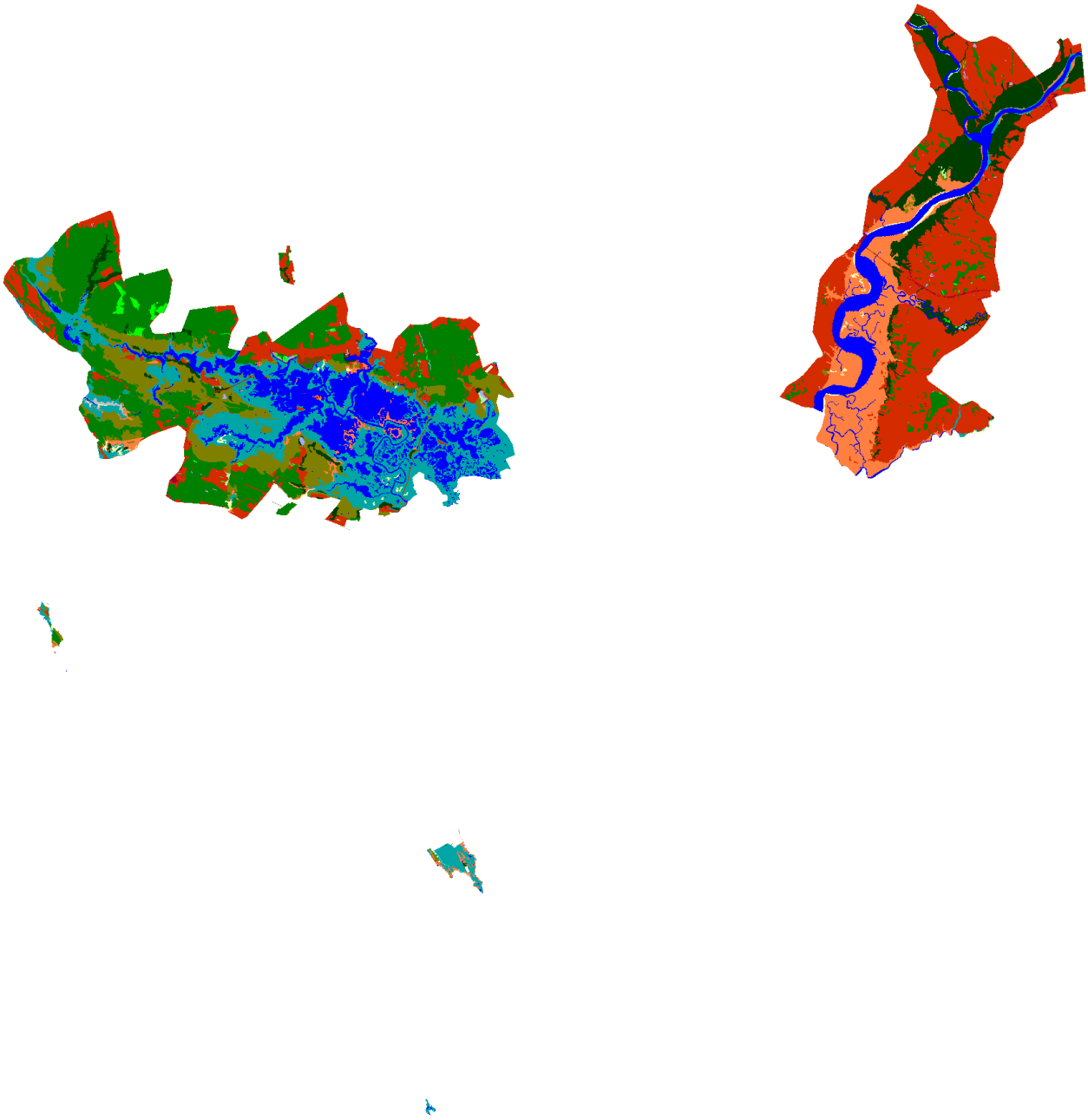


Blackwater NWR, 2100, Scenario A1B Mean

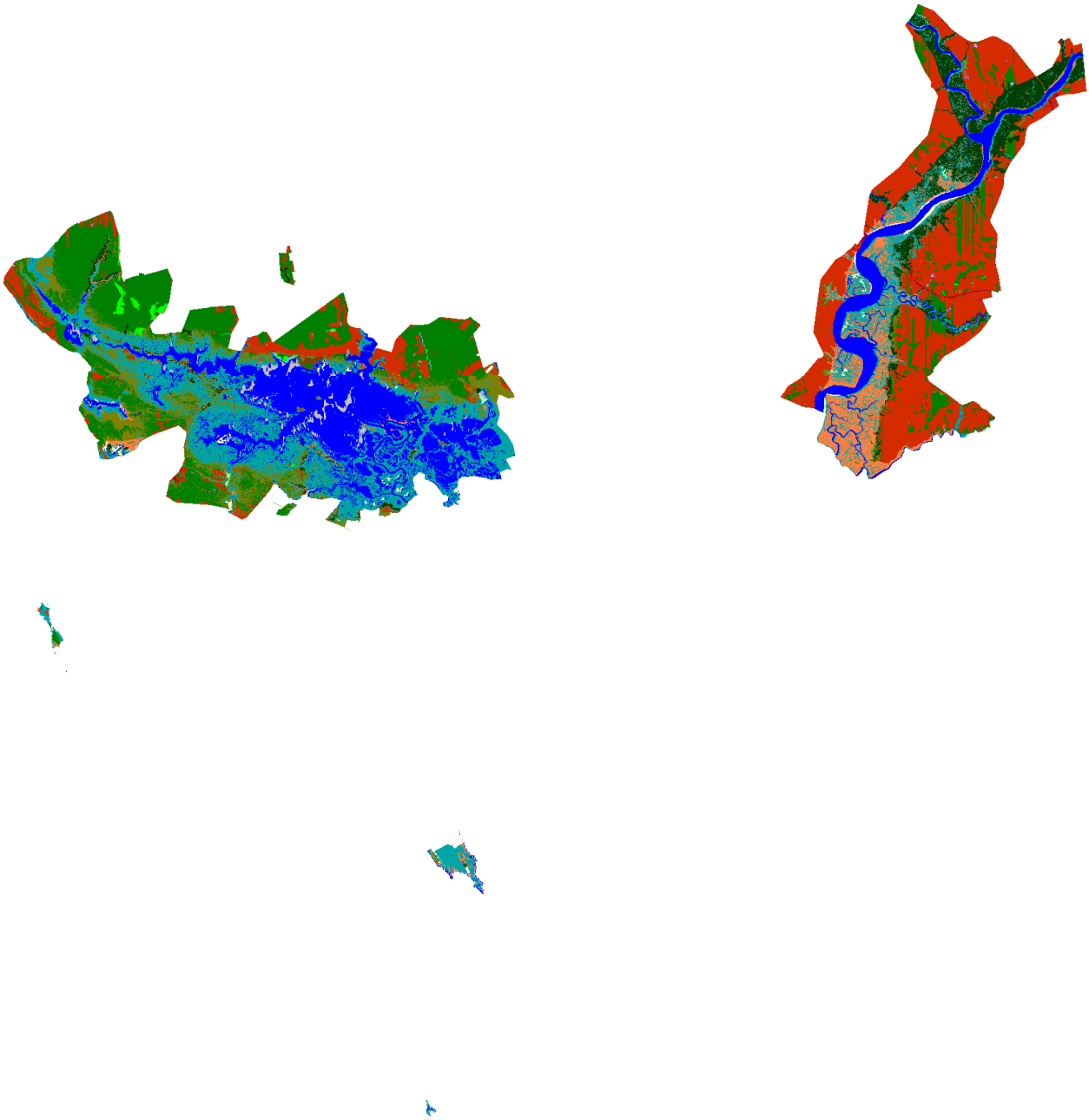
Blackwater Raster
IPCC Scenario A1B-Max, 0.69 M SLR Eustatic by 2100

Results in Acres

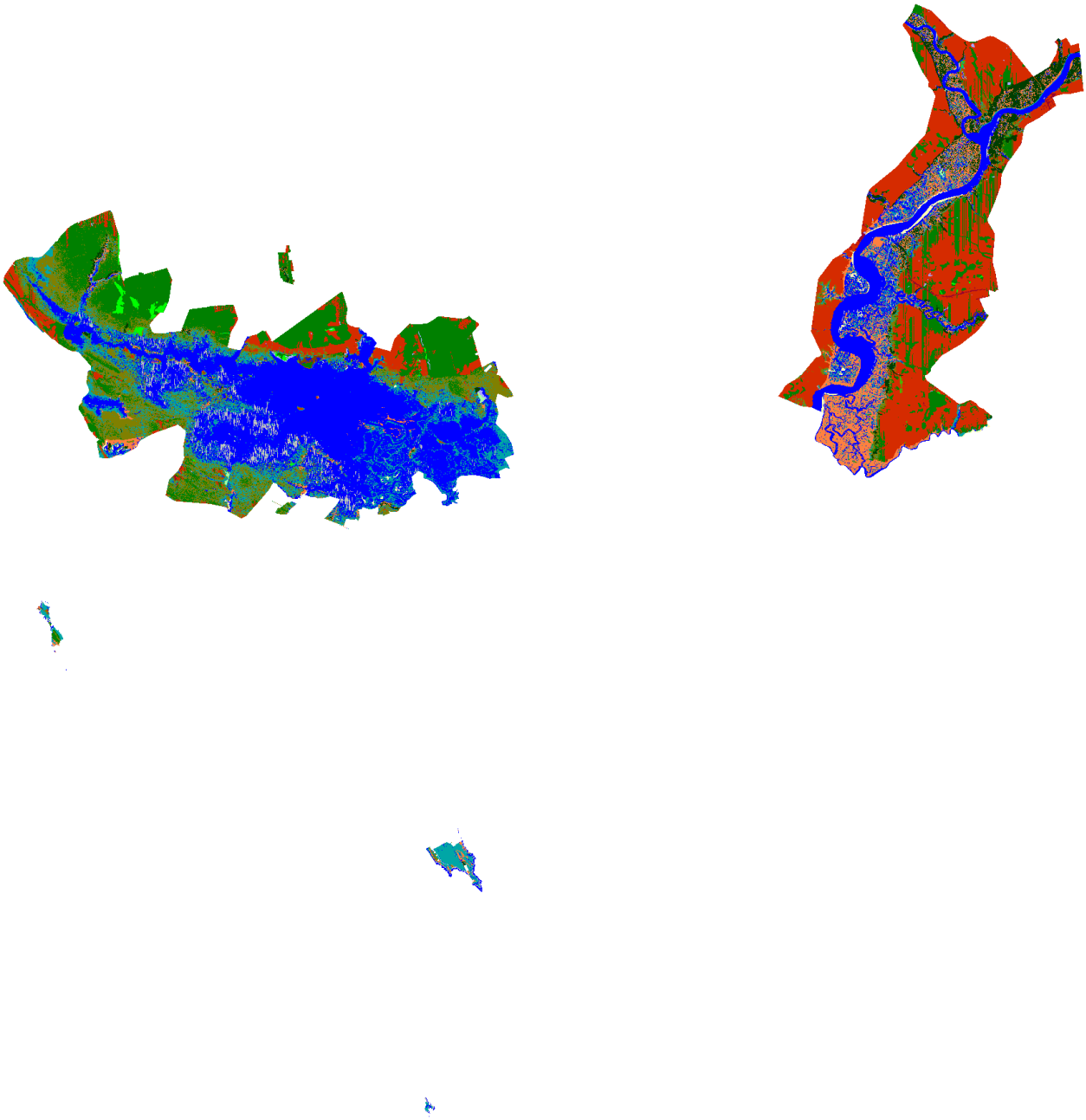
	Initial	2025	2050	2075	2100
Undev. Dry Land	20607.2	16574.2	14748.5	13108.2	11786.5
Swamp	14575.3	13655.7	11454.3	9189.7	7468.7
Saltmarsh	10355.8	15260.9	9210.3	11963.4	8074.1
Estuarine Open Water	9757.1	14180.7	22922.2	30886.9	40363.3
Irregularly Flooded Marsh	6447.9	4148.9	5049.5	3097.3	1148.0
Trans. Salt Marsh	6161.0	5193.4	7009.5	4817.0	3345.4
Tidal Swamp	5874.3	4454.6	2656.2	1196.5	628.5
Estuarine Beach	388.3	386.6	307.0	67.6	22.0
Inland Fresh Marsh	331.8	321.5	332.5	370.9	364.2
Dev. Dry Land	211.9	175.7	163.4	153.0	146.5
Riverine Tidal	211.7	53.6	44.7	24.2	20.9
Inland Open Water	156.3	115.9	108.3	101.6	95.0
Tidal Fresh Marsh	110.1	74.3	74.3	74.3	61.0
Inland Shore	95.9	89.8	69.8	20.9	8.8
Tidal Flat	74.7	673.5	1208.7	287.6	1826.4
Total (incl. water)	**75359.3**	**75359.3**	**75359.3**	**75359.3**	**75359.3**



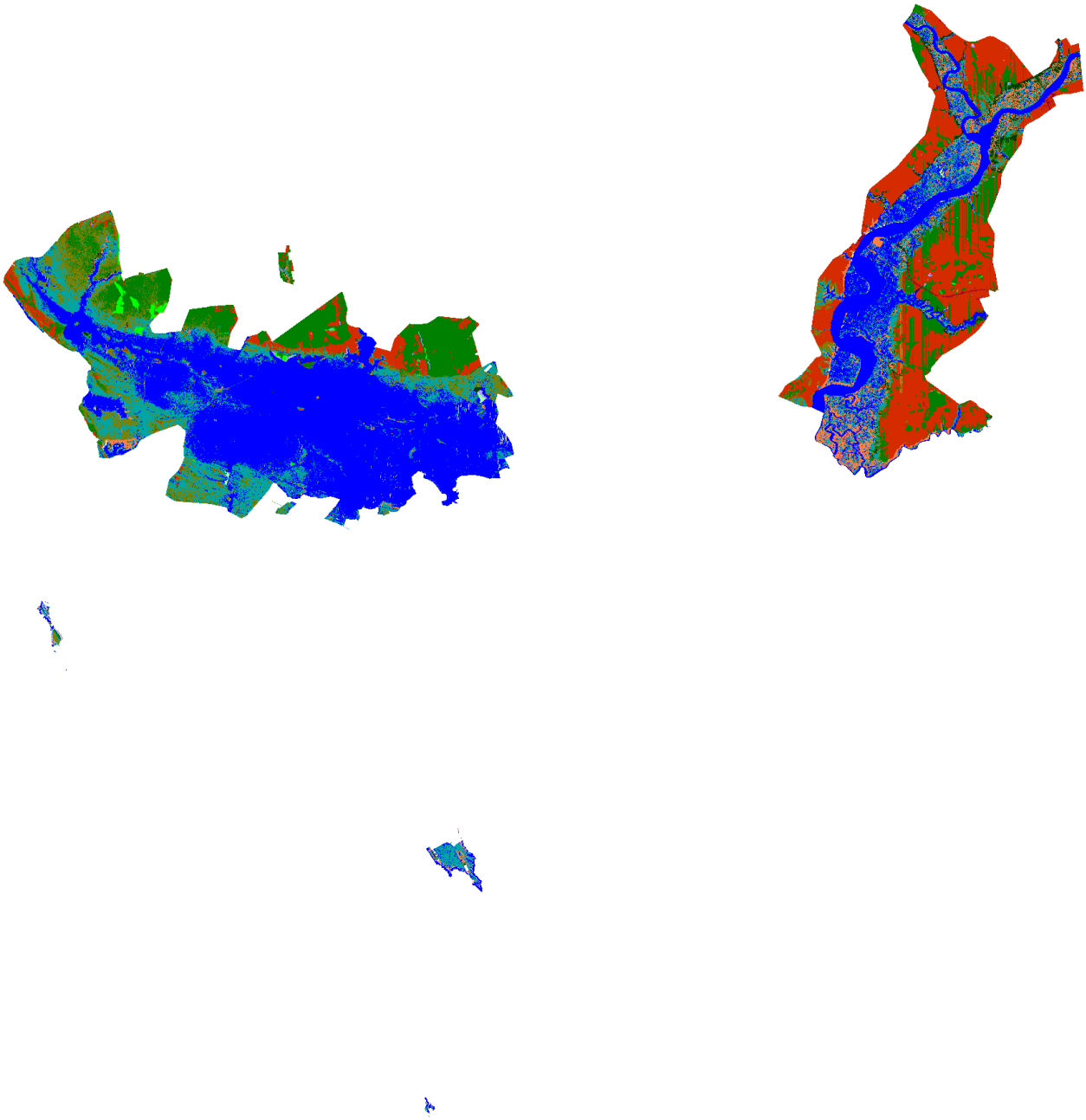
Blackwater NWR, Initial Condition



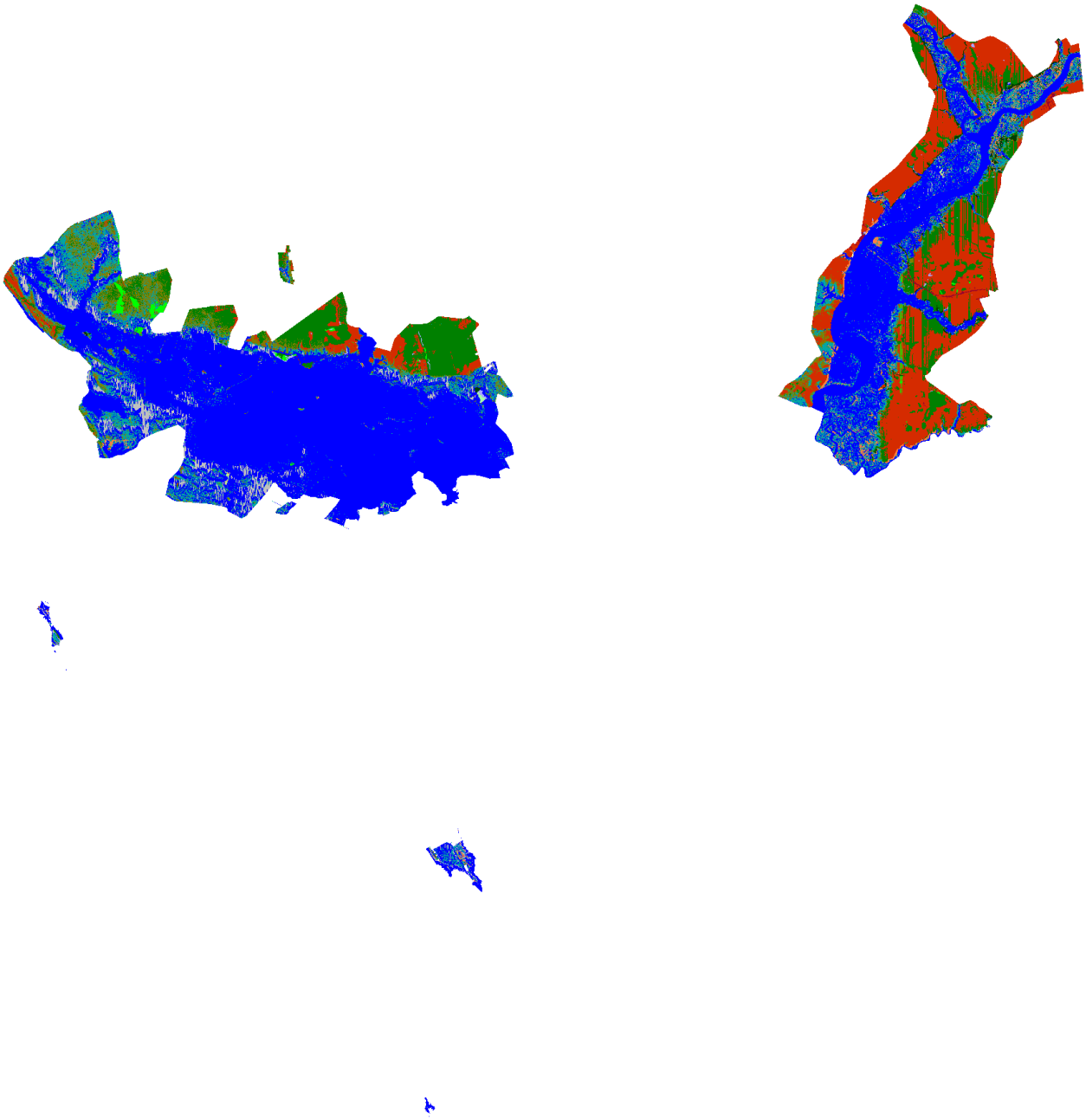
Blackwater NWR, 2025, Scenario A1B Maximum



Blackwater NWR, 2050, Scenario A1B Maximum



Blackwater NWR, 2075, Scenario A1B Maximum

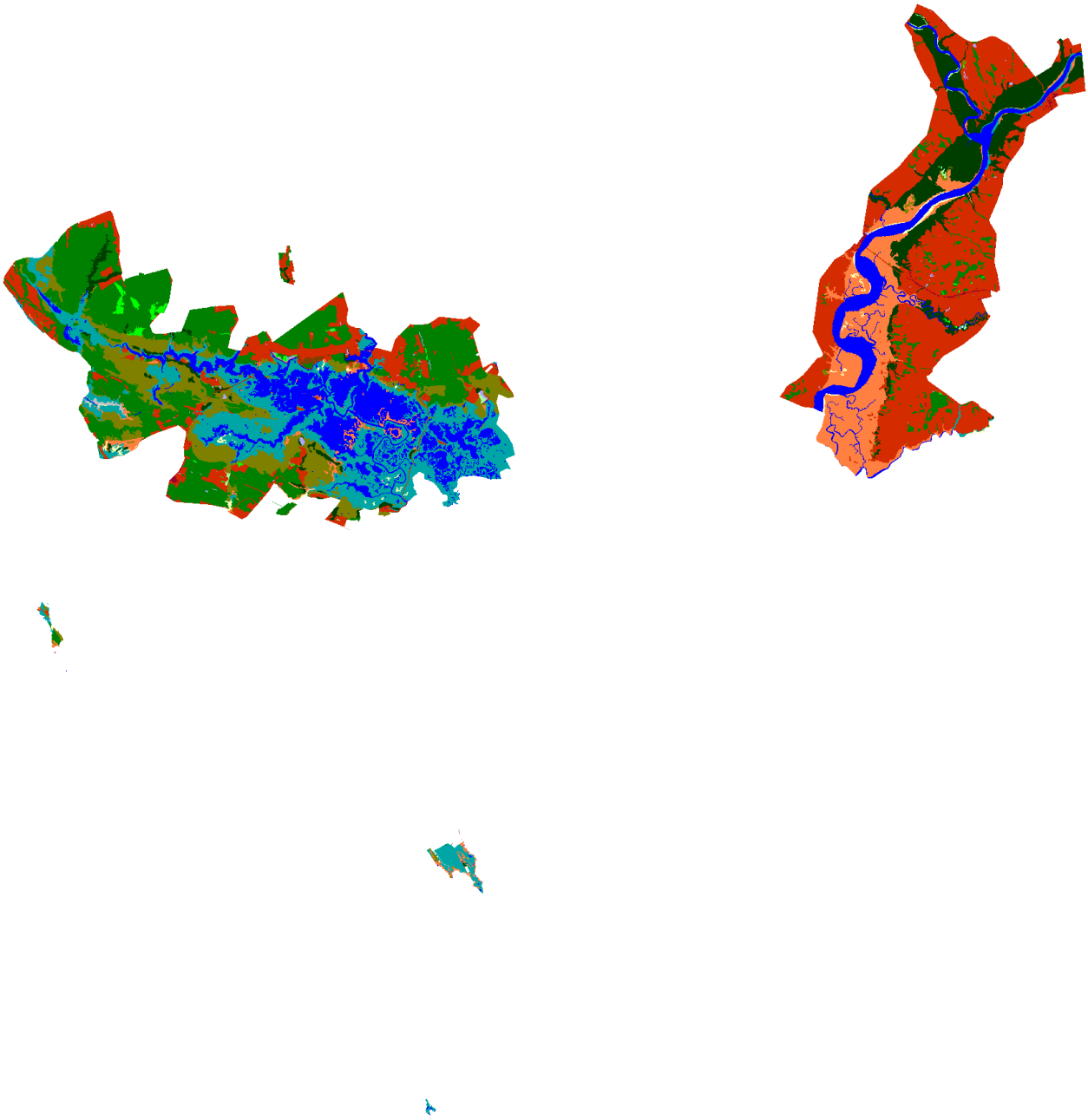


Blackwater NWR, 2100, Scenario A1B Maximum

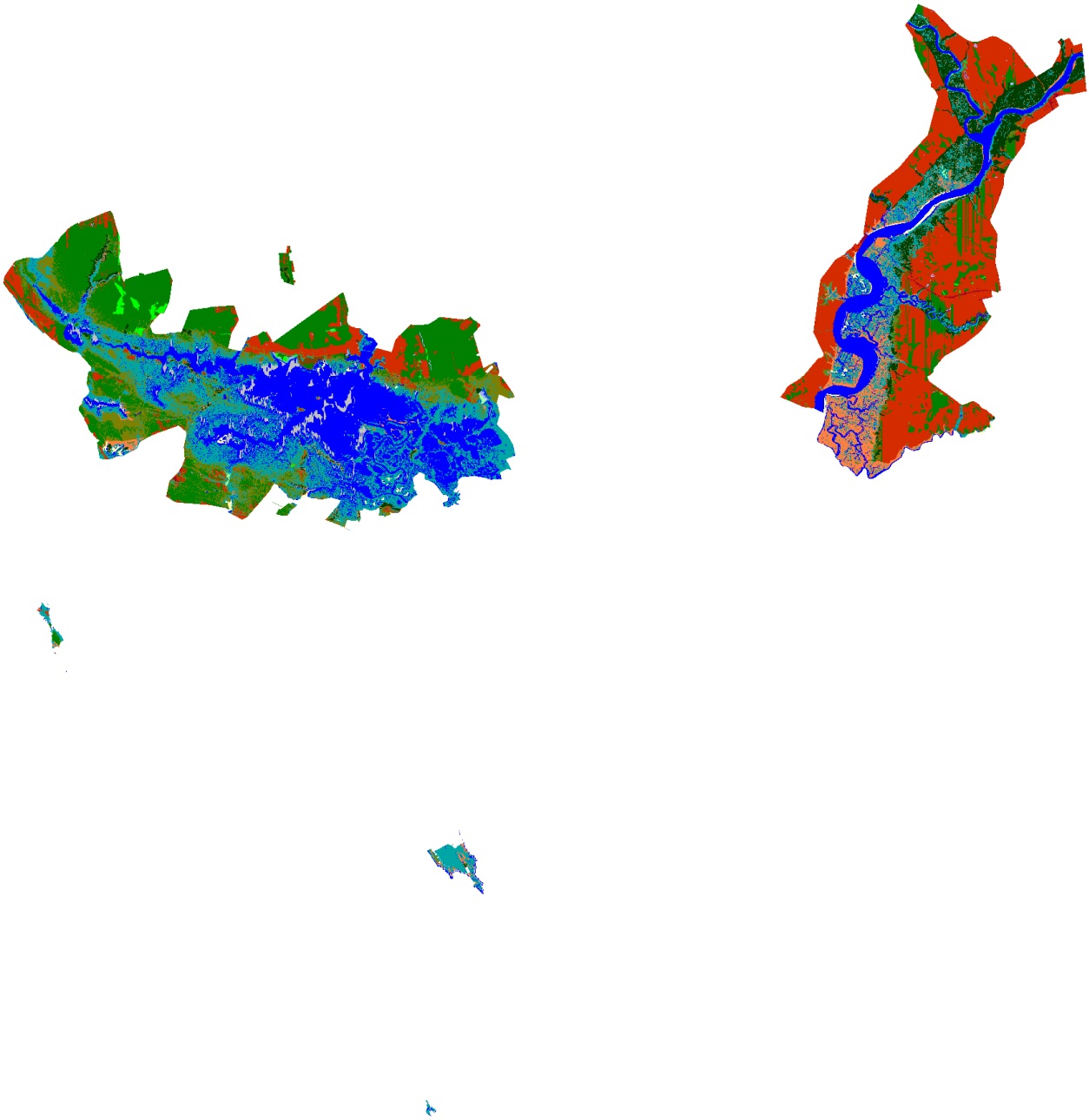
Blackwater Raster
1 Meter Eustatic SLR by 2100

Results in Acres

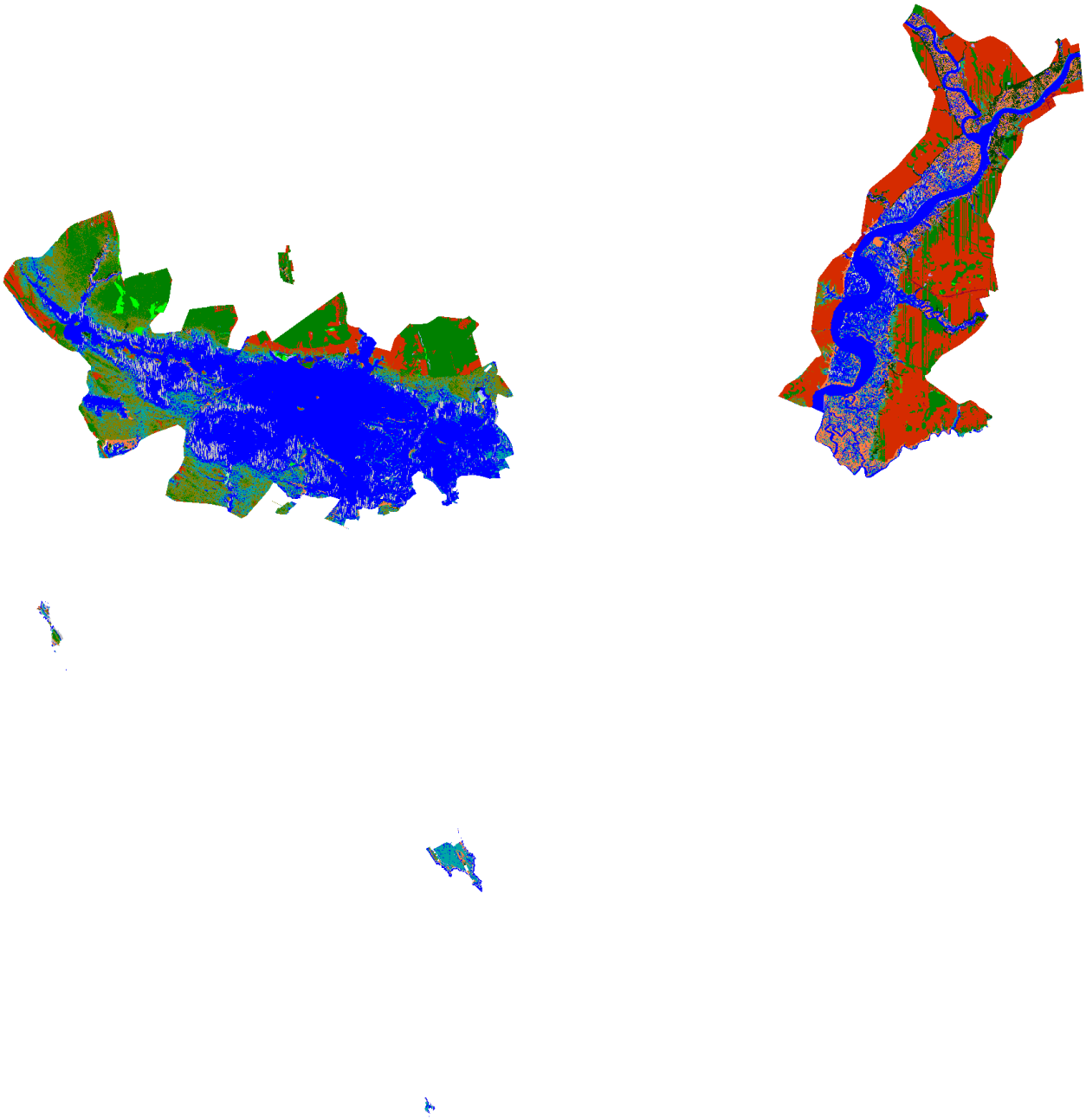
	Initial	2025	2050	2075	2100
Undev. Dry Land	20607.2	16355.8	14219.1	12183.6	10572.4
Swamp	14575.3	13005.2	10099.8	7654.4	6218.6
Saltmarsh	10355.8	15044.0	7818.8	10088.1	5962.1
Estuarine Open Water	9757.1	16169.6	28141.6	37502.0	46746.4
Irregularly Flooded Marsh	6447.9	3522.5	4029.4	1467.2	452.8
Trans. Salt Marsh	6161.0	5112.4	6142.4	4631.9	3111.8
Tidal Swamp	5874.3	3937.3	1721.1	663.6	402.4
Estuarine Beach	388.3	385.7	130.3	25.9	12.1
Inland Fresh Marsh	331.8	315.3	322.5	330.0	296.5
Dev. Dry Land	211.9	172.1	158.3	147.9	139.8
Riverine Tidal	211.7	39.8	35.4	20.9	19.8
Inland Open Water	156.3	113.4	105.0	96.5	91.6
Tidal Fresh Marsh	110.1	65.0	65.0	41.7	26.7
Inland Shore	95.9	88.7	40.0	10.5	5.2
Tidal Flat	74.7	1032.5	2330.5	495.0	1301.1
Total (incl. water)	**75359.3**	**75359.3**	**75359.3**	**75359.3**	**75359.3**



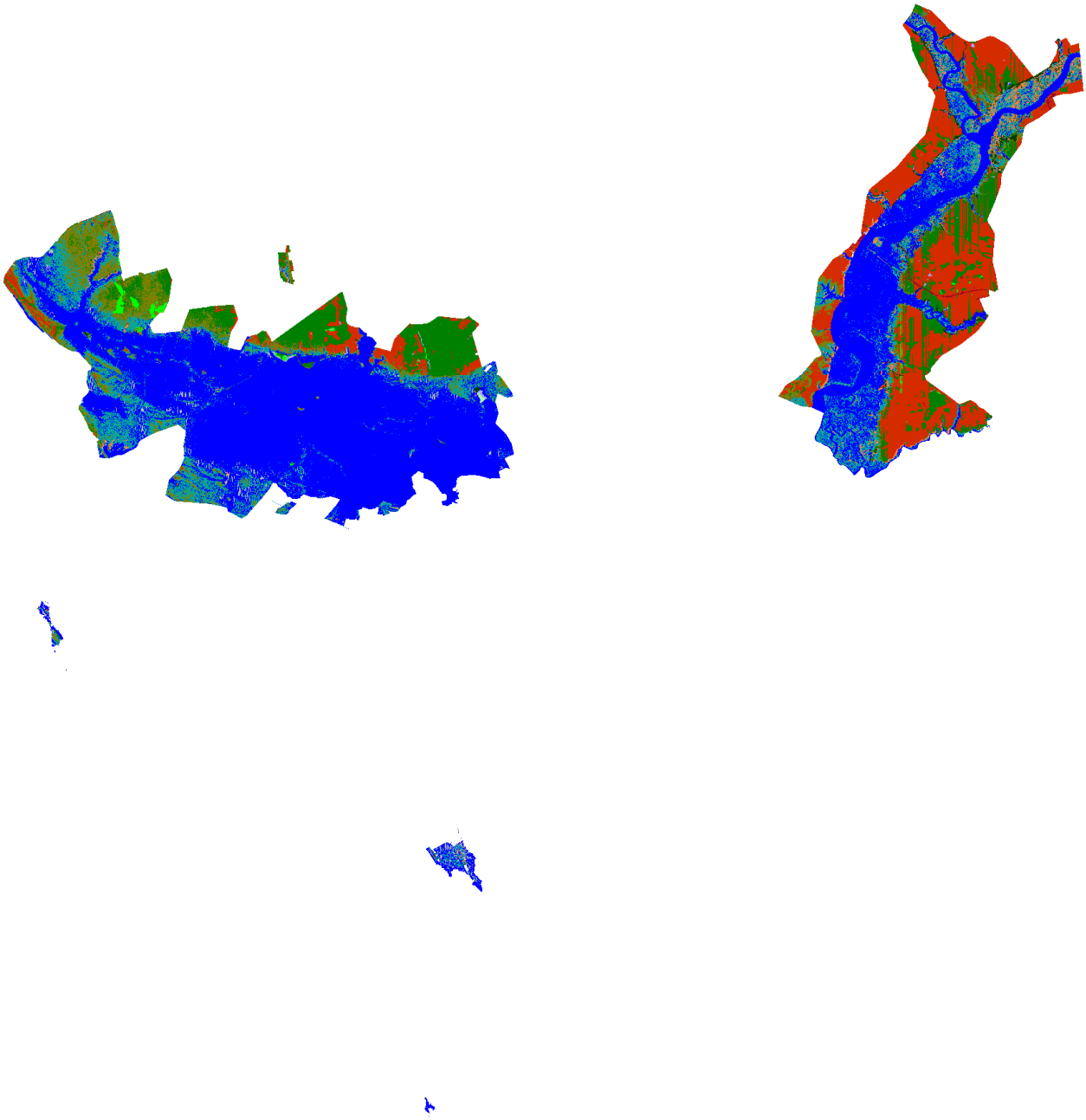
Blackwater NWR, Initial Condition



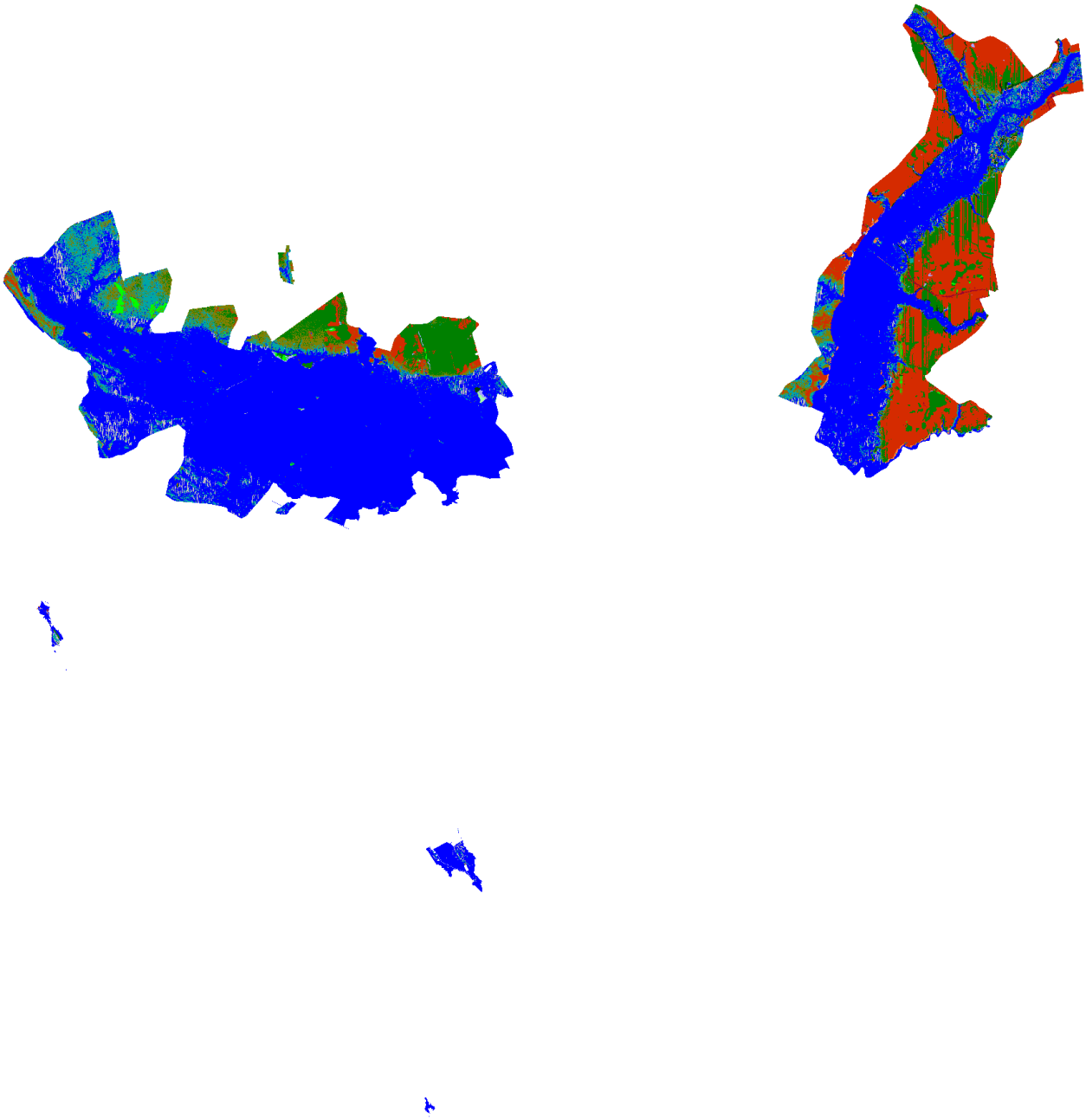
Blackwater NWR, 2025, 1 meter



Blackwater NWR, 2050, 1 meter



Blackwater NWR, 2075, 1 meter

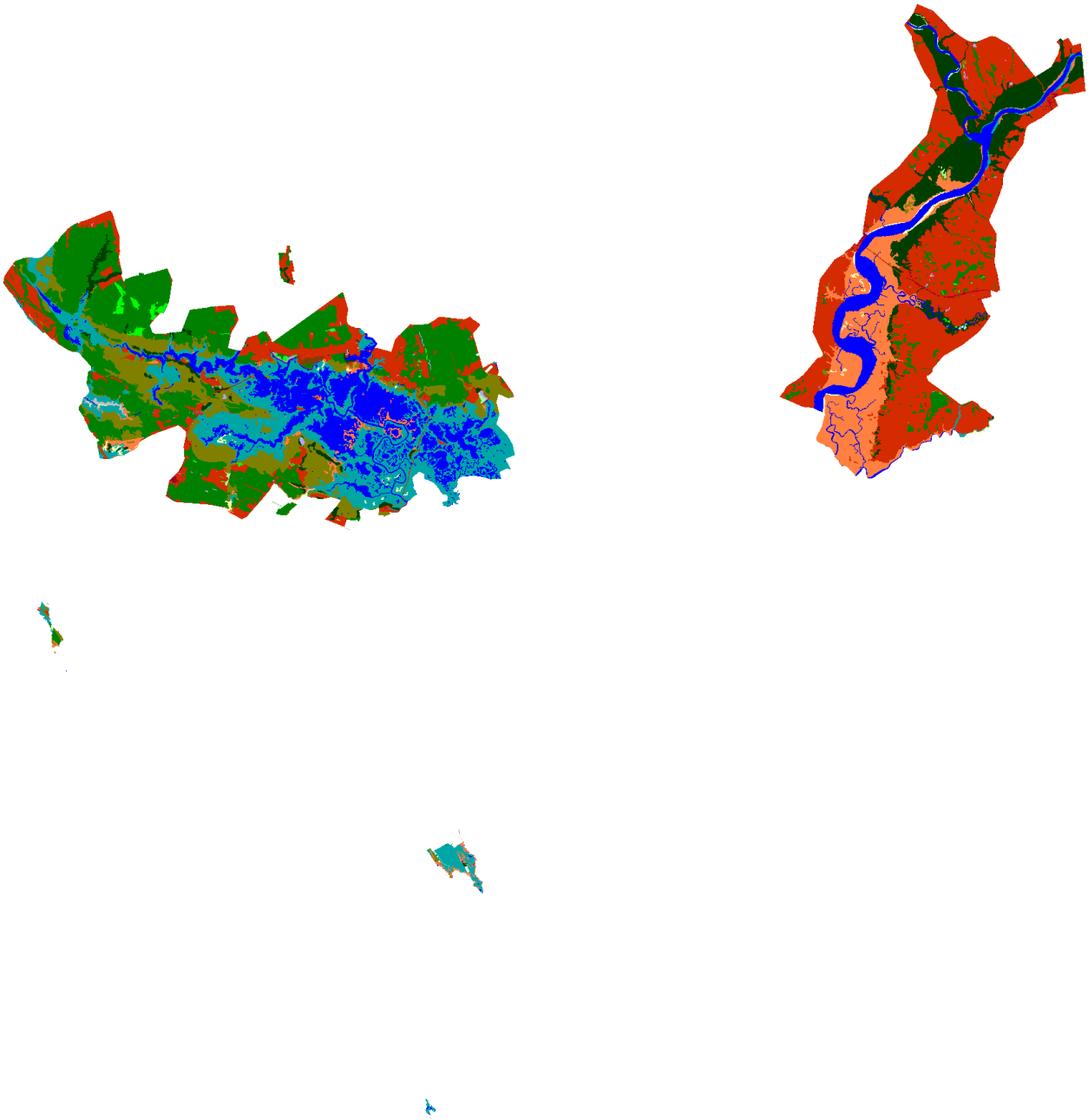


Blackwater NWR, 2100, 1 meter

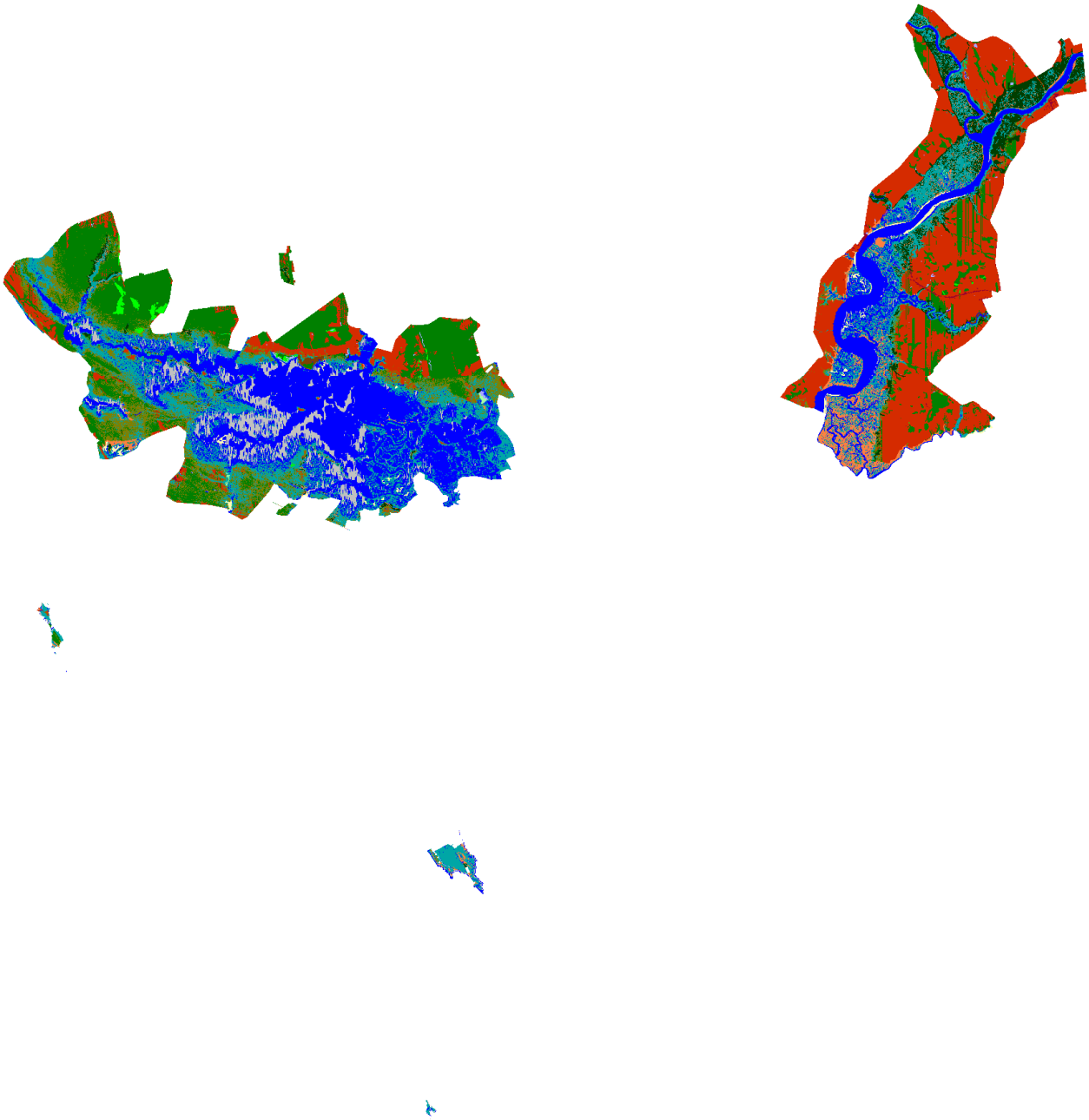
Blackwater Raster
1.5 Meters Eustatic SLR by 2100

Results in Acres

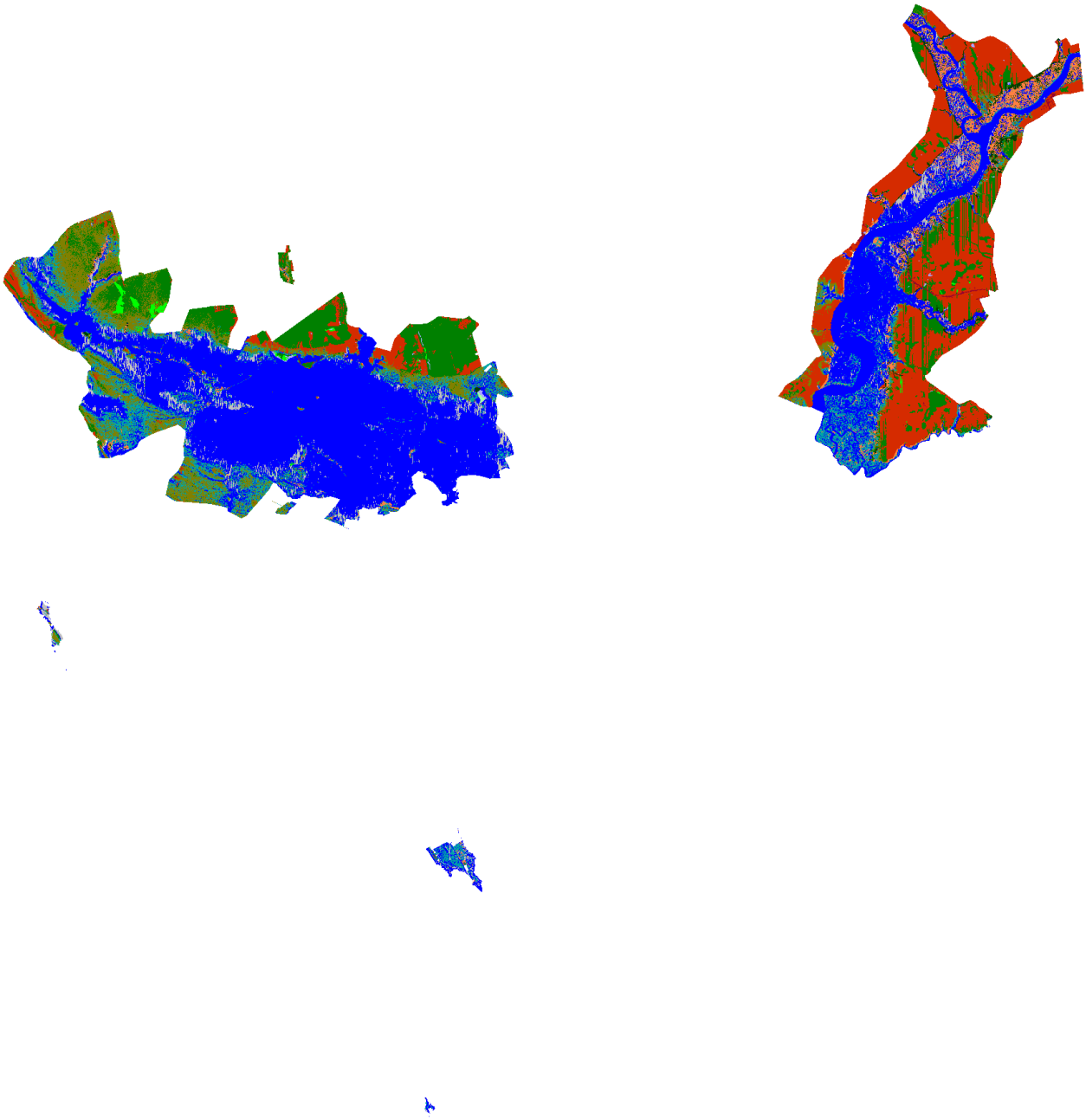
	Initial	2025	2050	2075	2100
Undev. Dry Land	20607.2	16008.7	13369.7	10869.1	9090.5
Swamp	14575.3	11878.4	8288.1	6085.4	4401.3
Saltmarsh	10355.8	14357.9	7316.3	8948.6	5346.8
Estuarine Open Water	9757.1	18394.9	33408.5	42520.0	50394.7
Irregularly Flooded Marsh	6447.9	2462.1	2622.4	665.0	254.8
Trans. Salt Marsh	6161.0	5006.3	6455.1	4780.5	3589.9
Tidal Swamp	5874.3	3049.5	889.0	394.2	247.4
Estuarine Beach	388.3	380.2	46.2	12.1	8.7
Inland Fresh Marsh	331.8	302.0	291.3	240.8	124.0
Dev. Dry Land	211.9	168.4	151.6	140.0	131.7
Riverine Tidal	211.7	30.0	24.2	20.0	16.9
Inland Open Water	156.3	109.6	100.7	92.1	78.9
Tidal Fresh Marsh	110.1	50.0	38.2	21.4	19.6
Inland Shore	95.9	85.3	17.6	5.4	2.9
Tidal Flat	74.7	3076.0	2340.5	564.8	1651.2
Total (incl. water)	**75359.3**	**75359.3**	**75359.3**	**75359.3**	**75359.3**



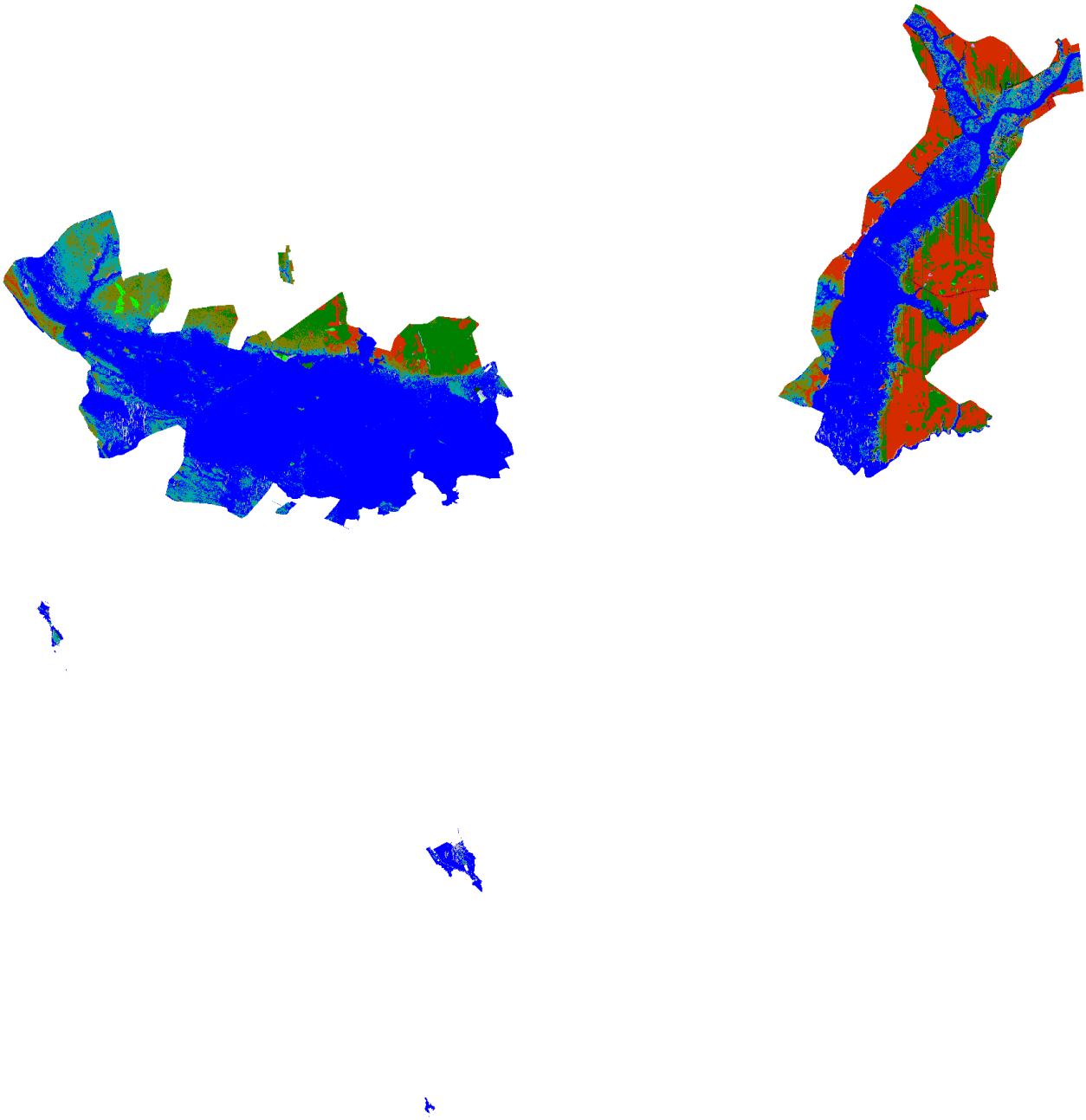
Blackwater NWR, Initial Condition



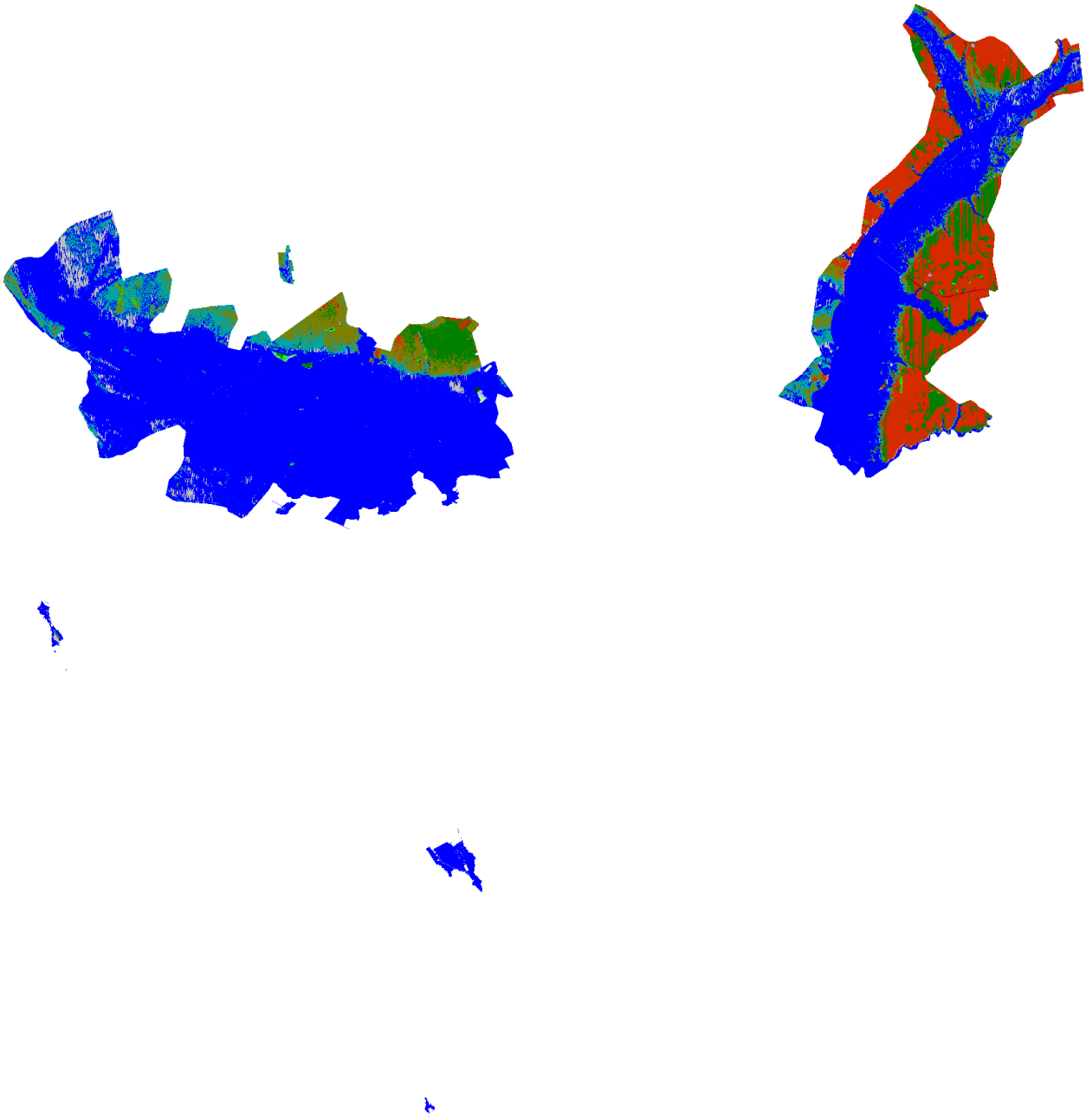
Blackwater NWR, 2025, 1.5 meter



Blackwater NWR, 2050, 1.5 meter



Blackwater NWR, 2075, 1.5 meter

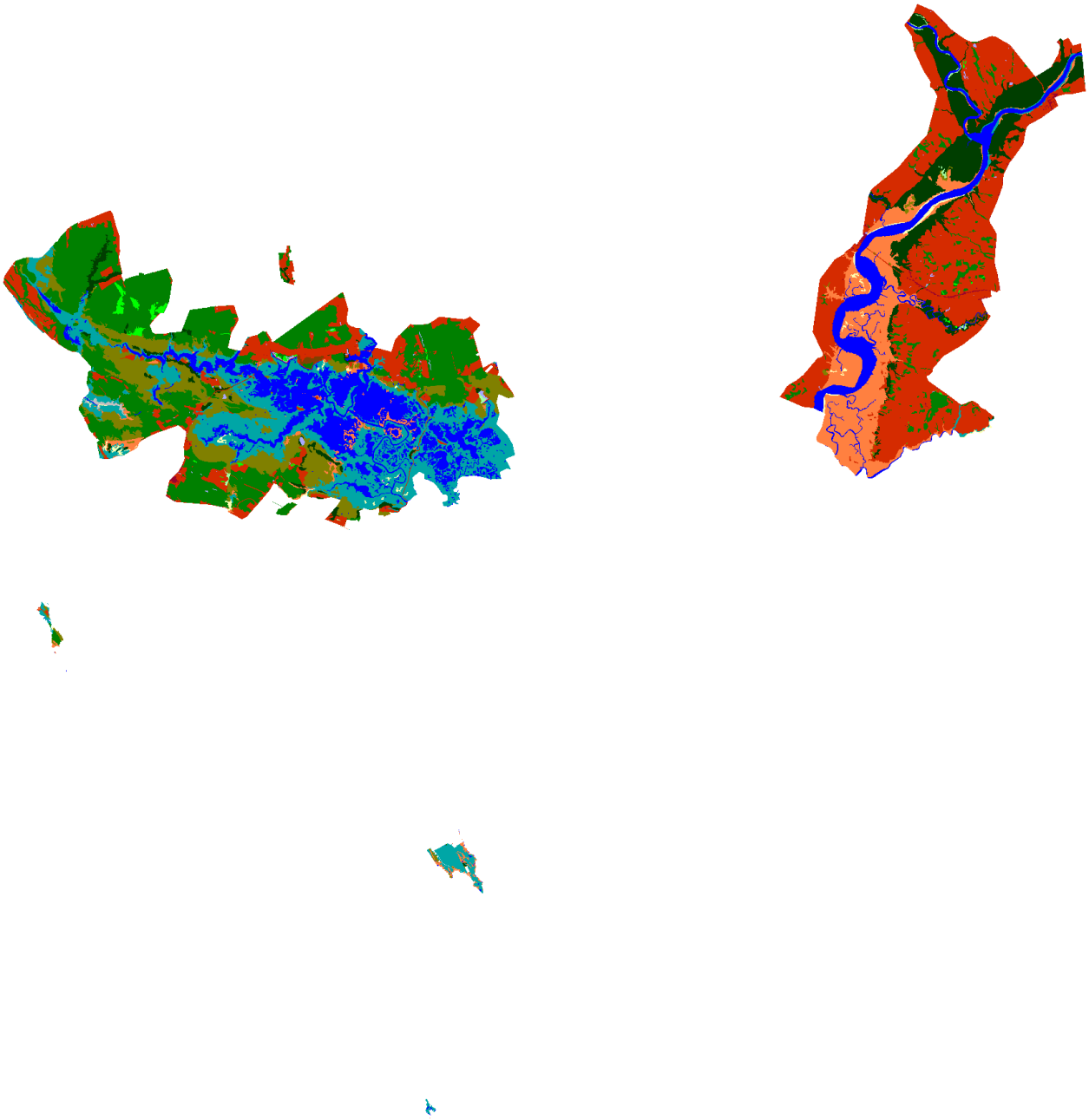


Blackwater NWR, 2100, 1.5 meter

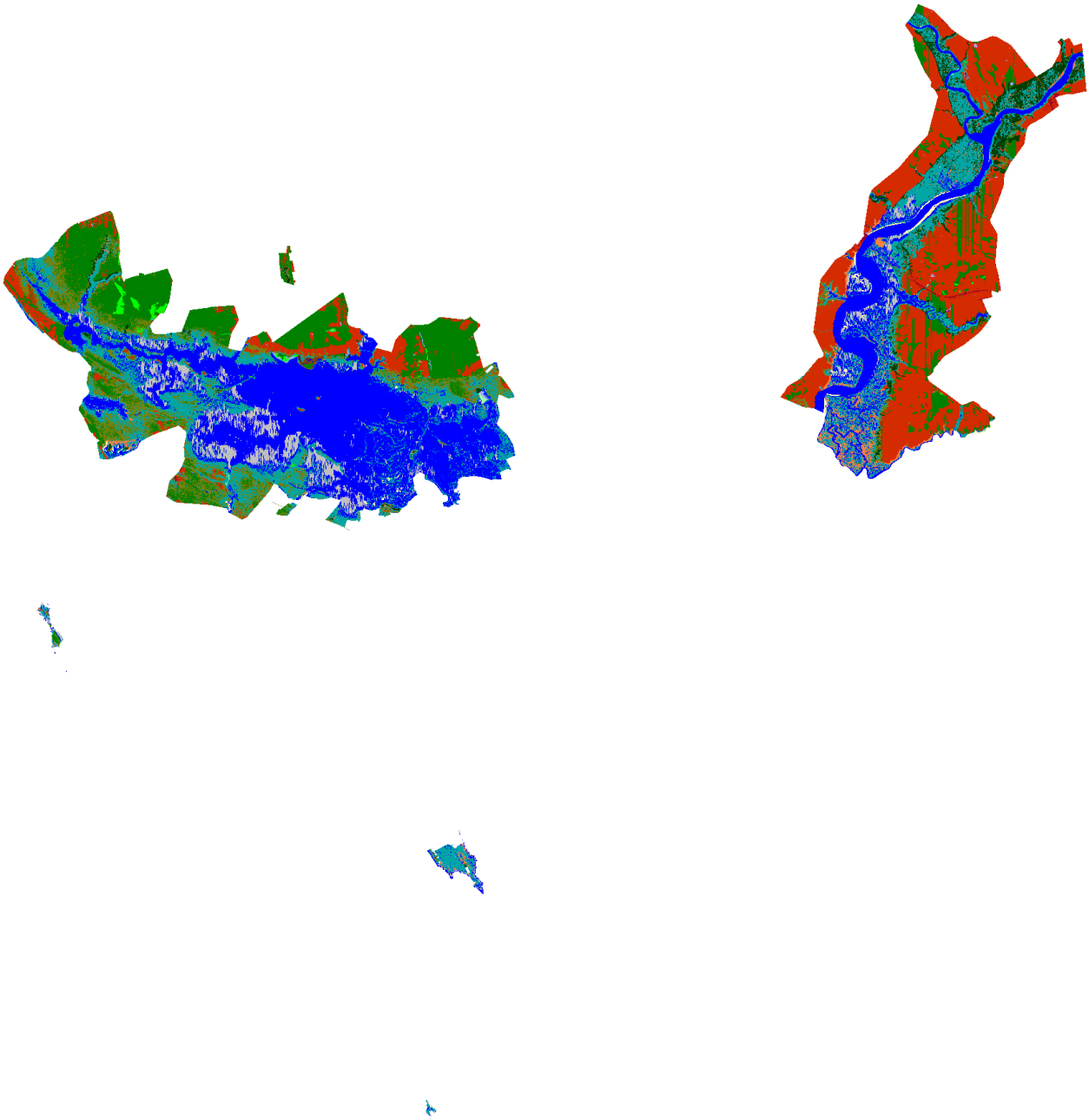
Blackwater Raster
2 Meters Eustatic SLR by 2100

Results in Acres

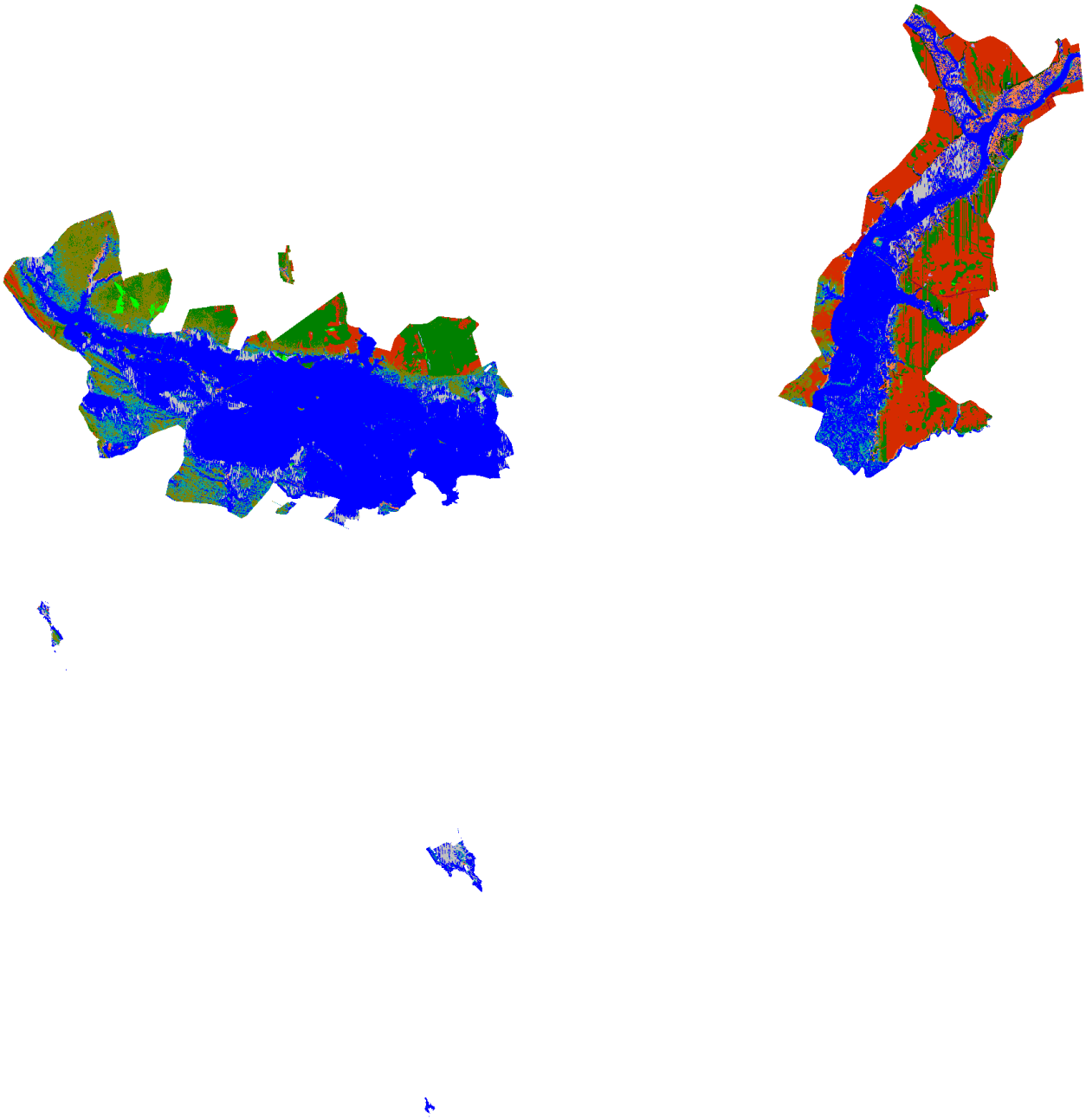
	Initial	2025	2050	2075	2100
Undev. Dry Land	20607.2	15650.9	12502.0	9708.0	8337.0
Swamp	14575.3	10833.6	6976.8	4840.5	2923.4
Saltmarsh	10355.8	14101.3	6105.6	8901.0	5417.9
Estuarine Open Water	9757.1	22081.7	36561.1	45307.6	52295.9
Irregularly Flooded Marsh	6447.9	1523.1	1897.6	400.9	186.5
Trans. Salt Marsh	6161.0	4720.7	7098.4	5083.7	3337.6
Tidal Swamp	5874.3	2243.9	563.7	277.4	156.3
Estuarine Beach	388.3	297.2	21.3	9.4	5.2
Inland Fresh Marsh	331.8	285.7	251.7	112.0	51.4
Dev. Dry Land	211.9	164.7	146.7	134.4	116.8
Riverine Tidal	211.7	24.9	22.7	18.2	16.2
Inland Open Water	156.3	107.4	97.2	87.4	68.5
Tidal Fresh Marsh	110.1	39.3	24.0	19.6	5.5
Inland Shore	95.9	69.4	9.7	3.4	2.3
Tidal Flat	74.7	3215.6	3080.8	455.8	2438.8
Total (incl. water)	**75359.3**	**75359.3**	**75359.3**	**75359.3**	**75359.3**



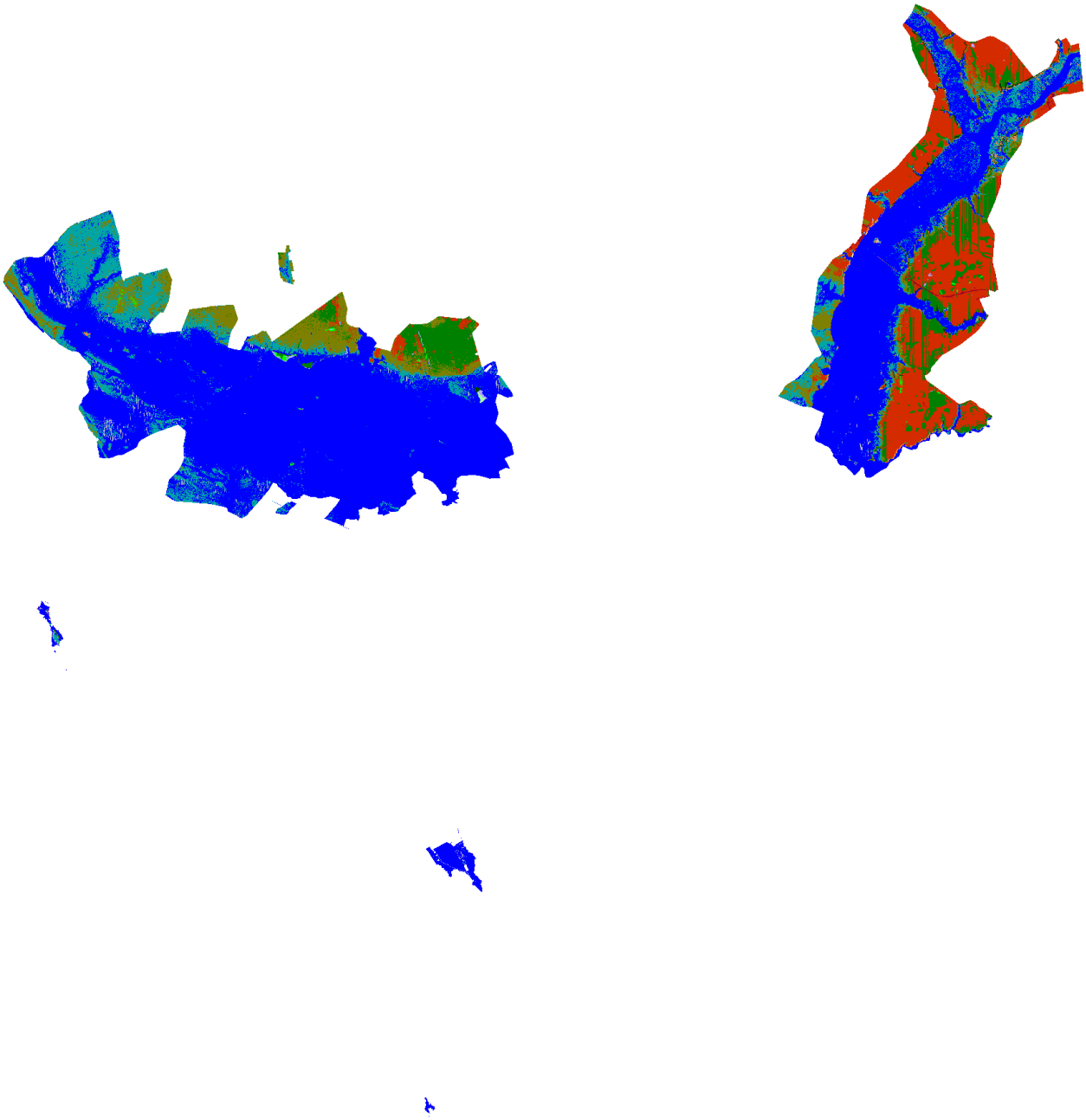
Blackwater NWR, Initial Condition



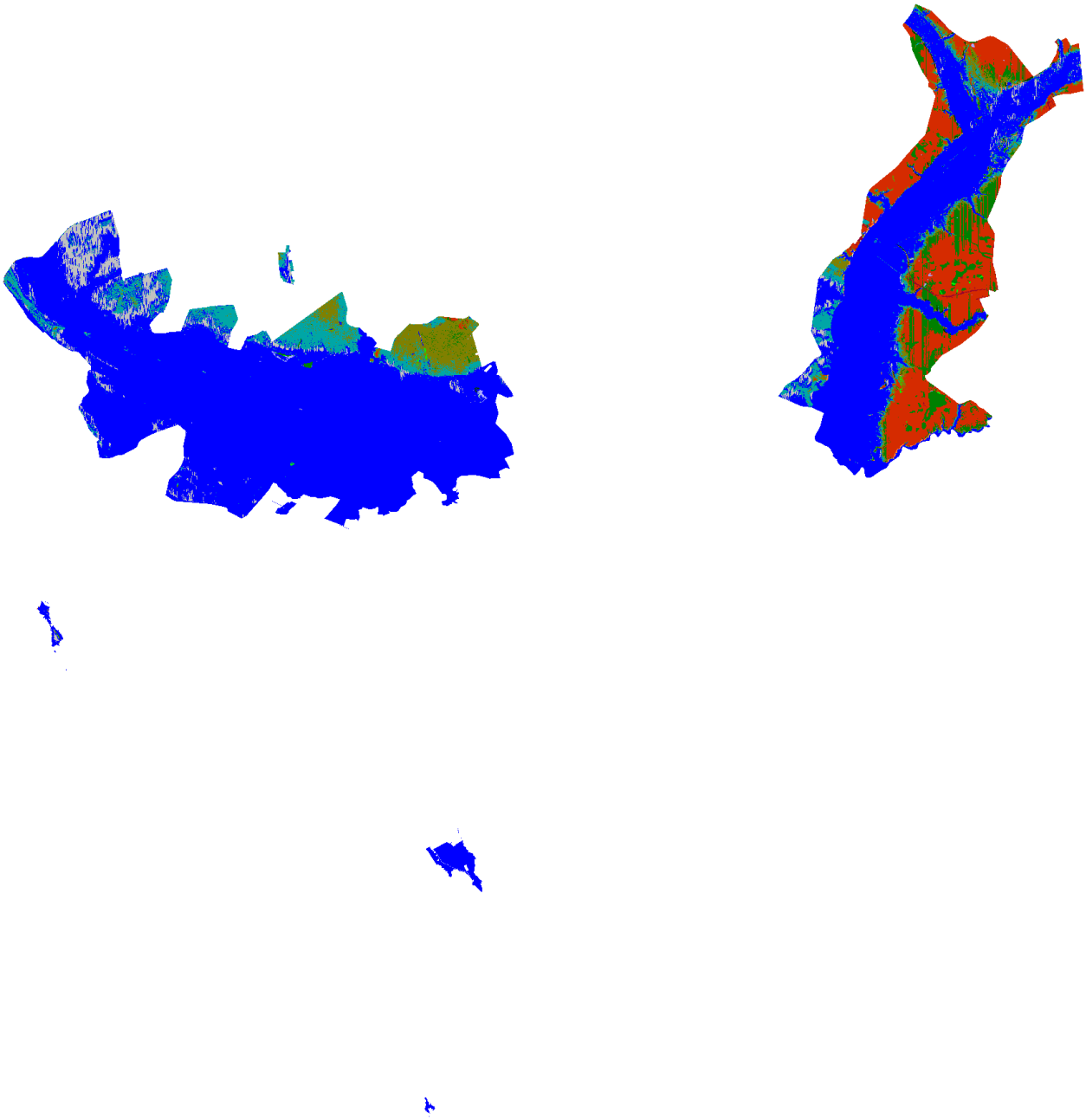
Blackwater NWR, 2025, 2 meters



Blackwater NWR, 2050, 2 meters



Blackwater NWR, 2075, 2 meters



Blackwater NWR, 2100, 2 meters

Discussion

SLAMM simulations suggest that Blackwater NWR is particularly vulnerable to the effects of sea level rise due to the site's combination of low-elevation wetlands, low tidal range and relatively low measured marsh accretion values. Predicted marsh vulnerability at Blackwater is not without precedent; saltwater intrusion has already resulted in the loss of thousands of marshland acres over the past 70 years (USFWS 2006).

SLAMM additionally predicts some low-lying dry land will convert to swamp due to soil saturation. Coastal swamps and fresh marshes can migrate 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.

Model results for this site are somewhat less uncertain than many other sites due to high vertical-resolution LiDAR data which covers the vast majority of the site. Additionally, there are many accretion studies within Maryland, Chesapeake Bay, and some within the refuge itself.

Some remaining sources of model uncertainty are the application of a spatially and temporally constant accretion rate to individual marshes within the refuge. Local factors may result in spatial variation in marsh accretion. In addition, vertical marsh accretion rates may react to an increase in sea level rise due to more frequent inundation and higher sediment concentrations within water. This could potentially lead to some additional marsh resilience.

On the other hand, the SLAMM model does not take into account the potential for additional land subsidence (beyond what has been captured by the long-term Cambridge MD NOAA Gage) which could result in more severe effects.

- Some scientists attribute dramatic losses of marshes at Blackwater to more rapid subsidence due to groundwater withdrawals to support the surrounding agriculture. (Scientific Review of the Prescribed Fire Program at Blackwater National Wildlife Refuge, 2005)
- Stevenson, Rooth, Sundberg, and Kearney (2002) have the following observation: "Analysis using digitized photography has revealed that marshes are being lost more rapidly in the northern than southern sections of Blackwater. The former is closest to the center of a large cone of depression in the most important underlying aquifer in the region. The groundwater withdrawals at Cambridge correspond to a rapid rise in sea level which appears to be two to three times the present global rate of 1 to 2 mm yr."
- Some papers in the literature suggest a historical sea-level rise of 9 mm/year in Cambridge, MD (Nerem & Schenewerk, 1997) (Boesch, D.R., Greer, J., Eds., 2003, p 33)
- Based on a short time-period, GPS readings at Cambridge MD have suggested a land subsidence of 5.2 mm/year (Nerem & Schenewerk, 1997). This would be additive to the eustatic sea level trend to get an overall historic rate of sea-level rise in Cambridge.

Even without taking into account the potential for additional subsidence, SLAMM predicts that open water at this site will increase by a factor of five under scenarios of one meter of eustatic SLR or greater, resulting in a refuge that is over 60% comprised of open water.

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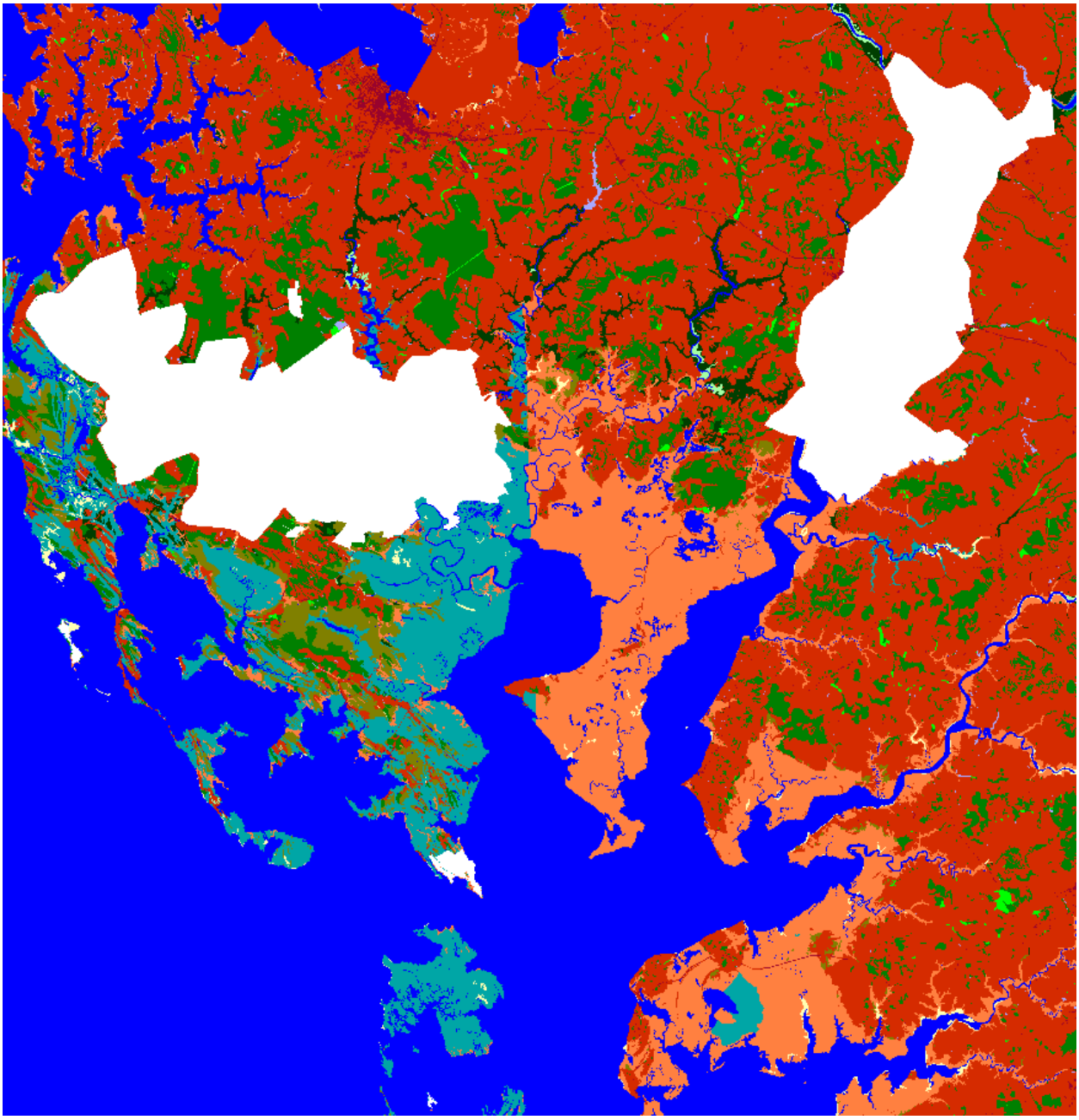
Appendix A: Contextual Results

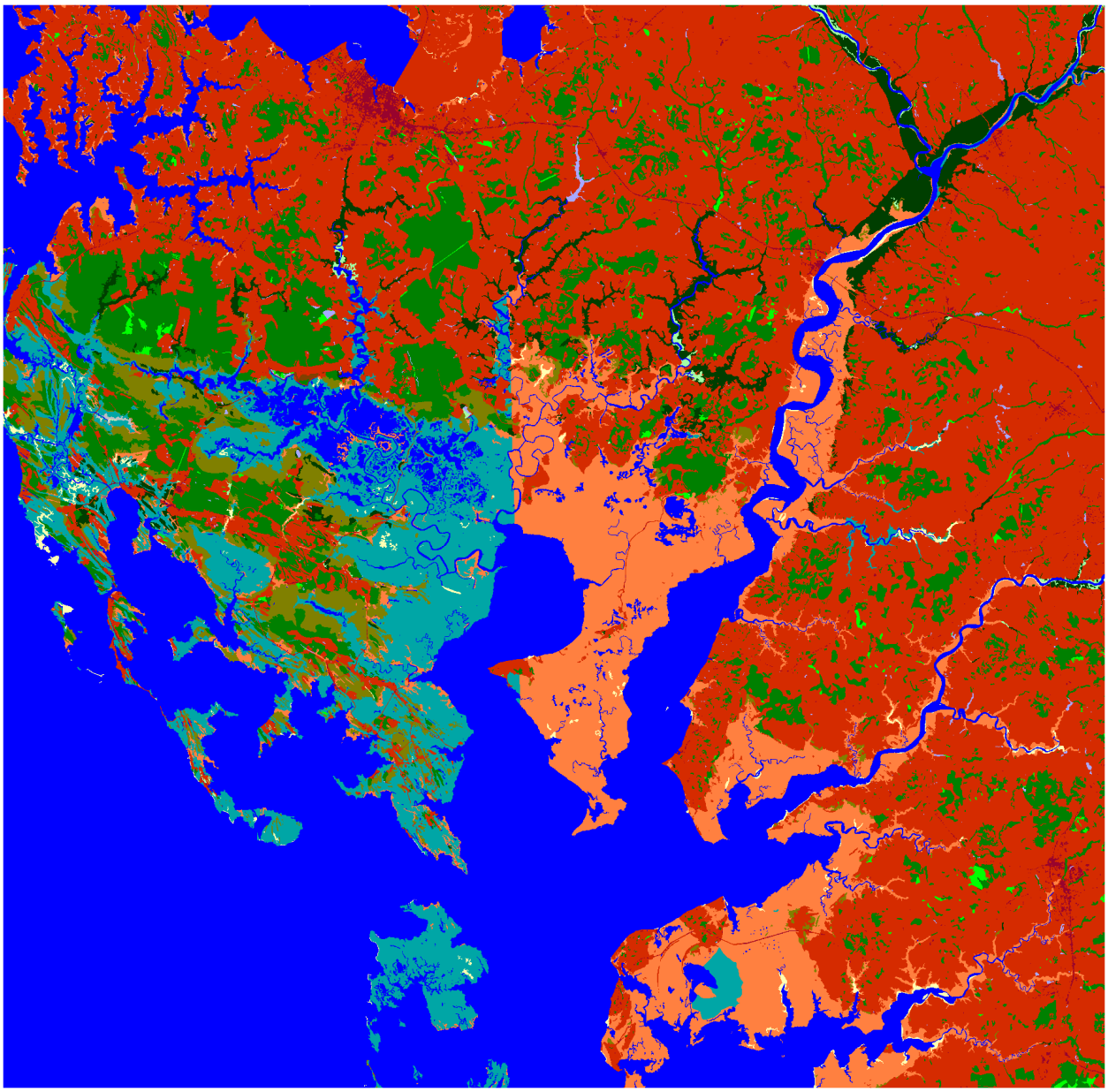
The SLAMM model does take into account the context of the surrounding lands or open water when calculating effects. For example, erosion rates are calculated based on the maximum fetch (wave action) which is estimated by assessing contiguous open water to a given marsh cell. Another example is that inundated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

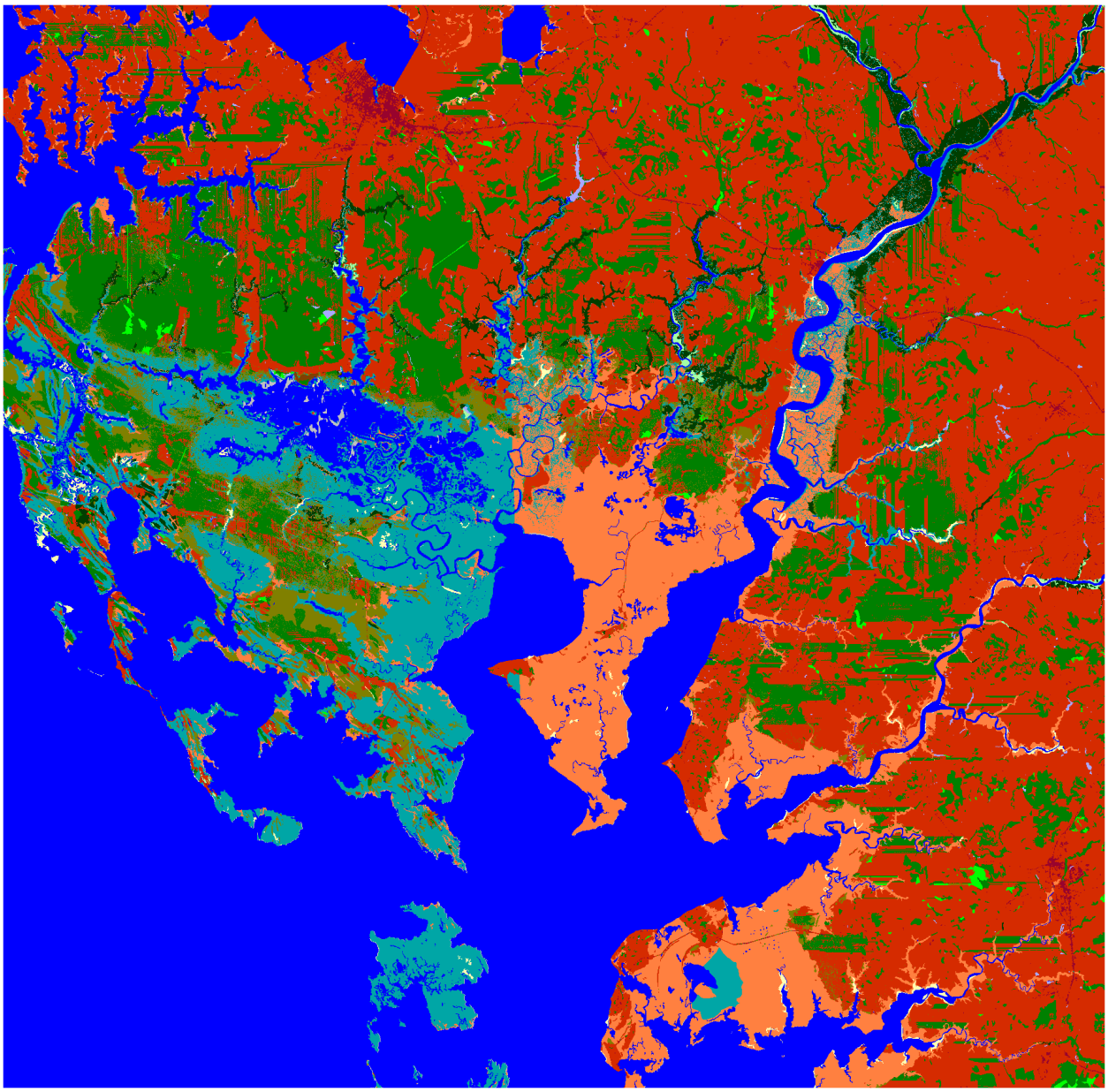
- Results were closely examined (quality assurance) within USFWS refuges but not closely examined for the larger region.
- Site-specific parameters for the model were derived for USFWS refuges whenever possible and may not be regionally applicable.
- Especially in areas where dikes are present, an effort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



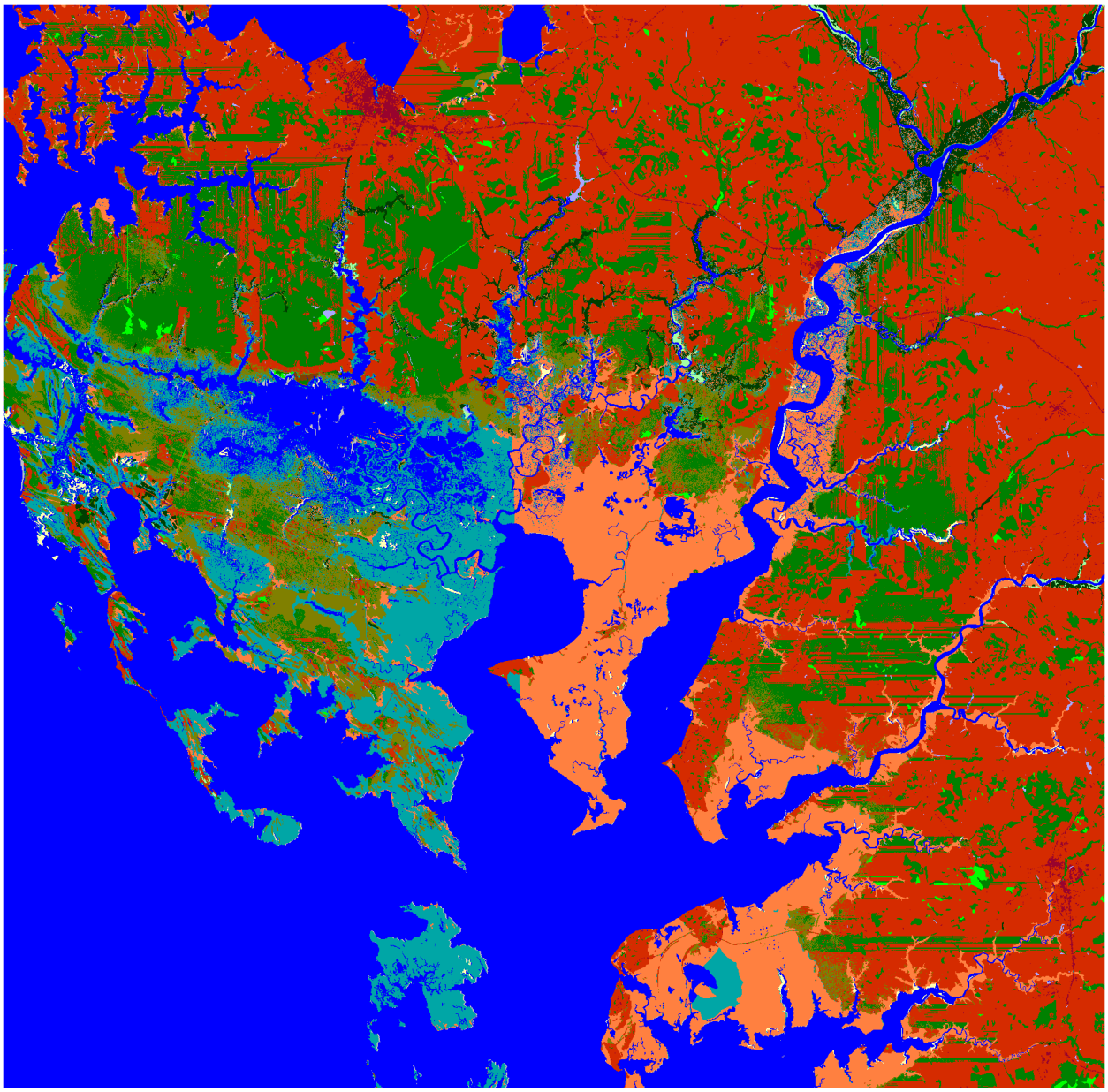
Location of Blackwater National Wildlife Refuge (white area) within simulation context



Blackwater NWR, Initial Condition



Blackwater NWR, 2025, Scenario A1B Mean



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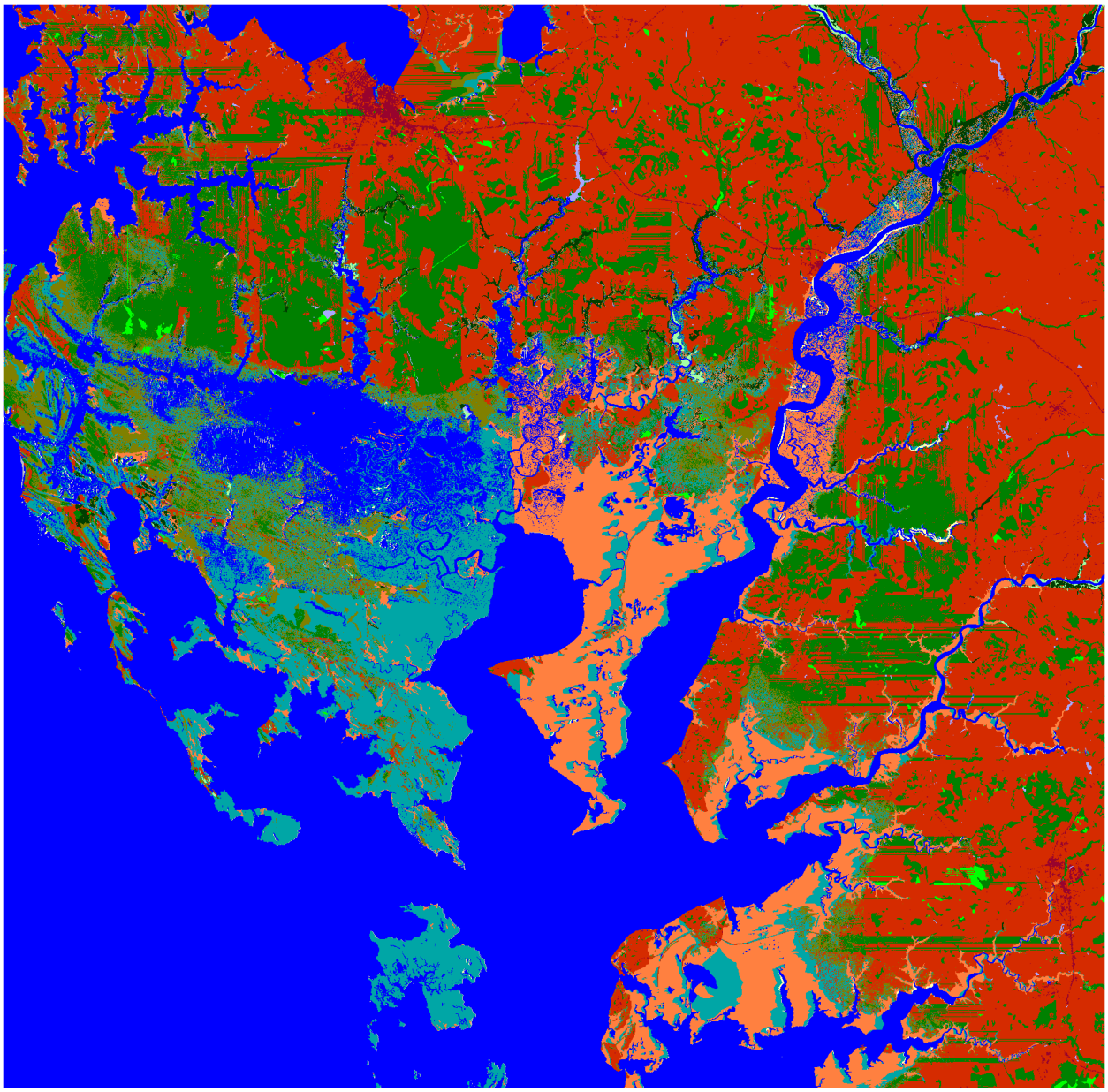
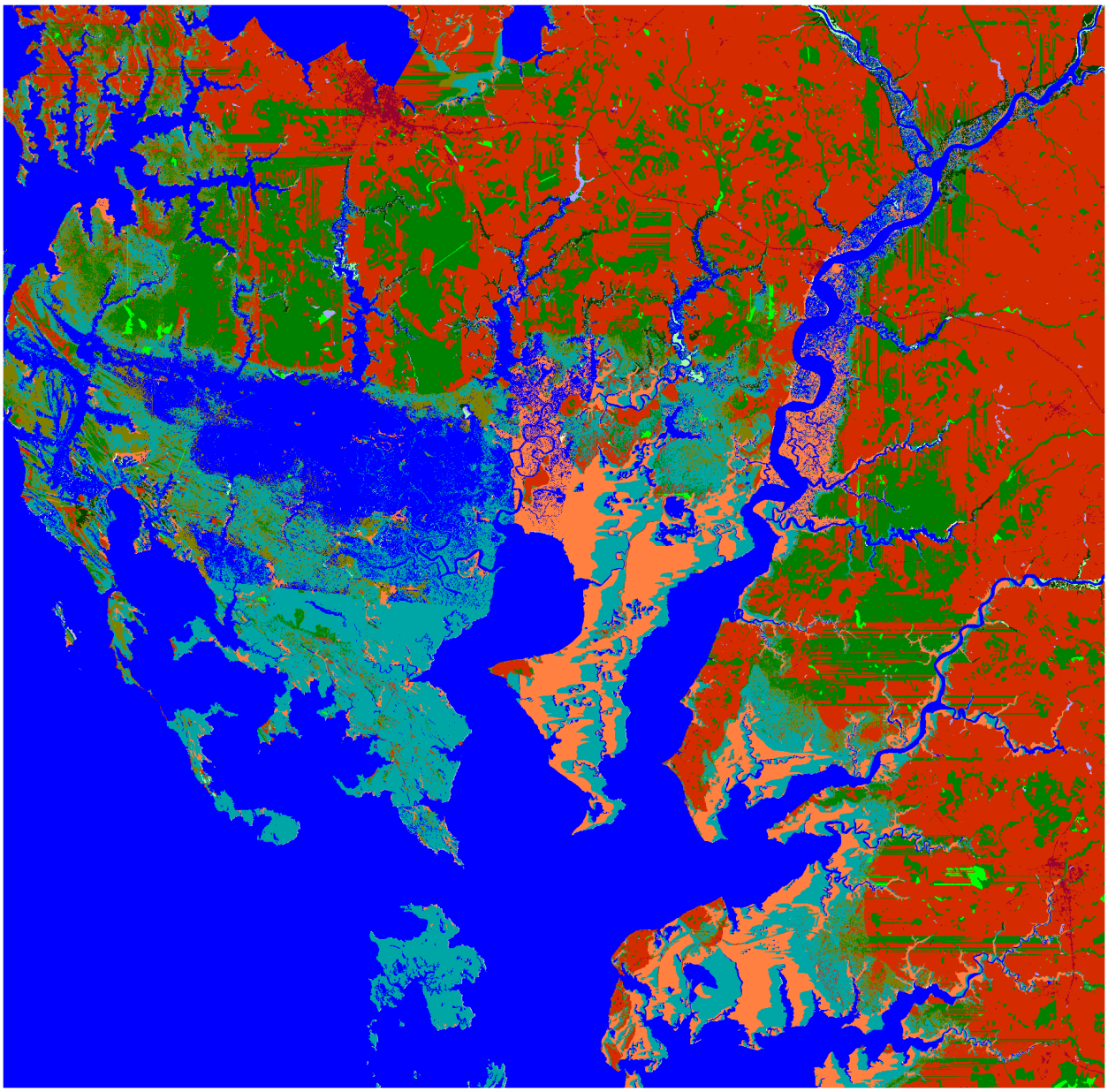
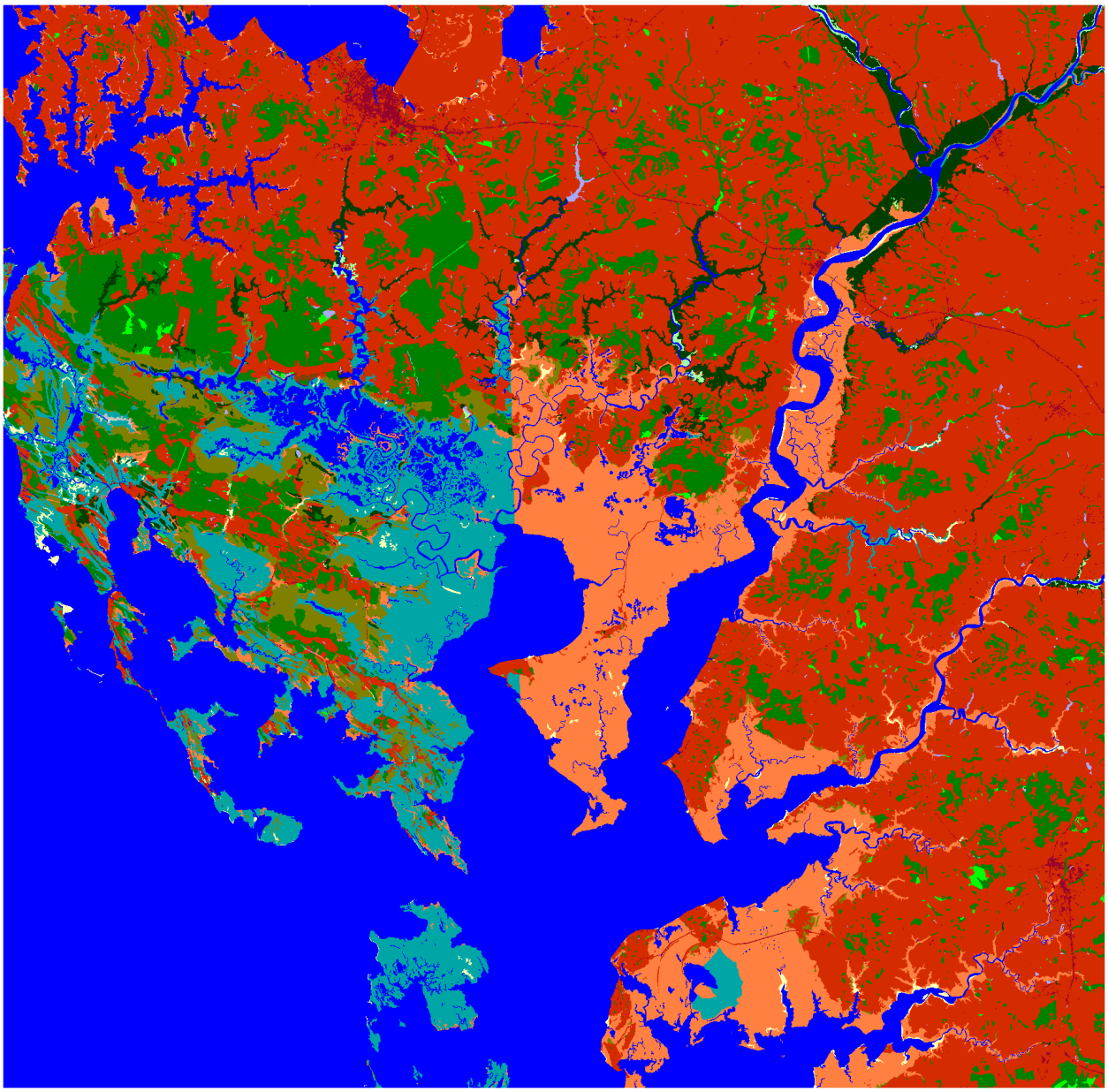


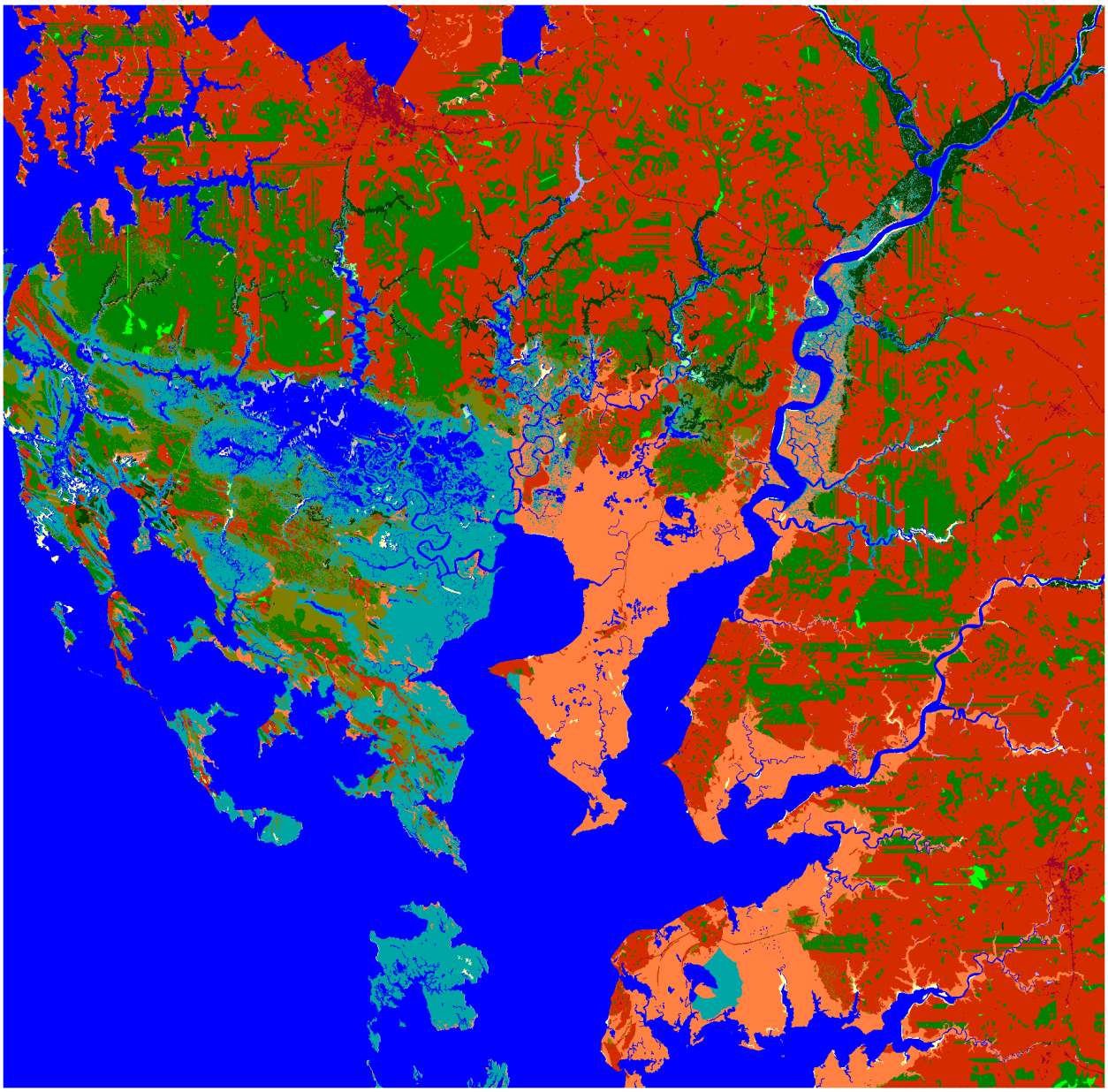
Blackwater NWR, 2075, Scenario A1B Mean



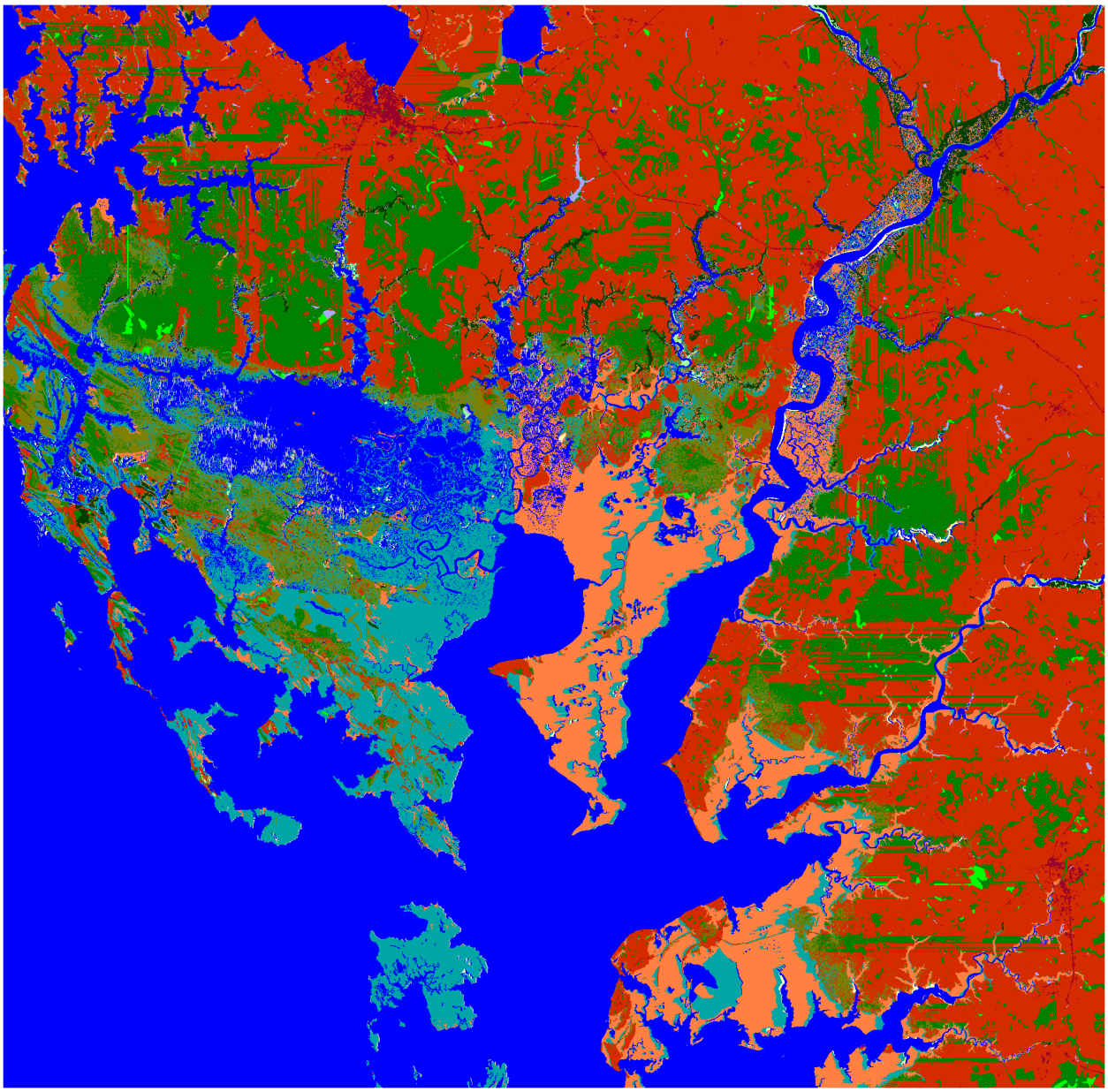
Blackwater NWR, 2100, Scenario A1B Mean



Blackwater NWR, Initial Condition



Blackwater NWR, 2025, Scenario A1B Maximum



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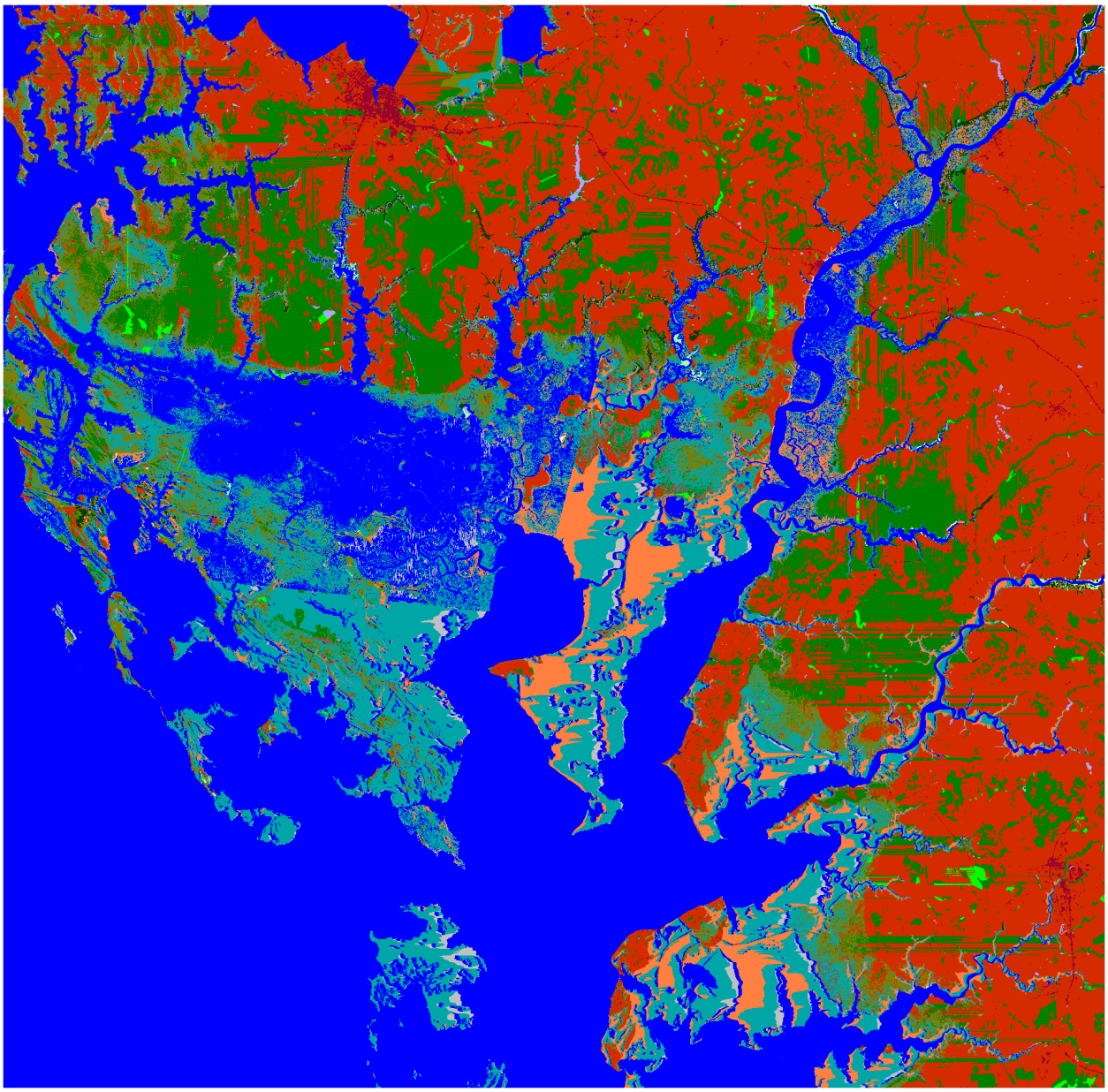
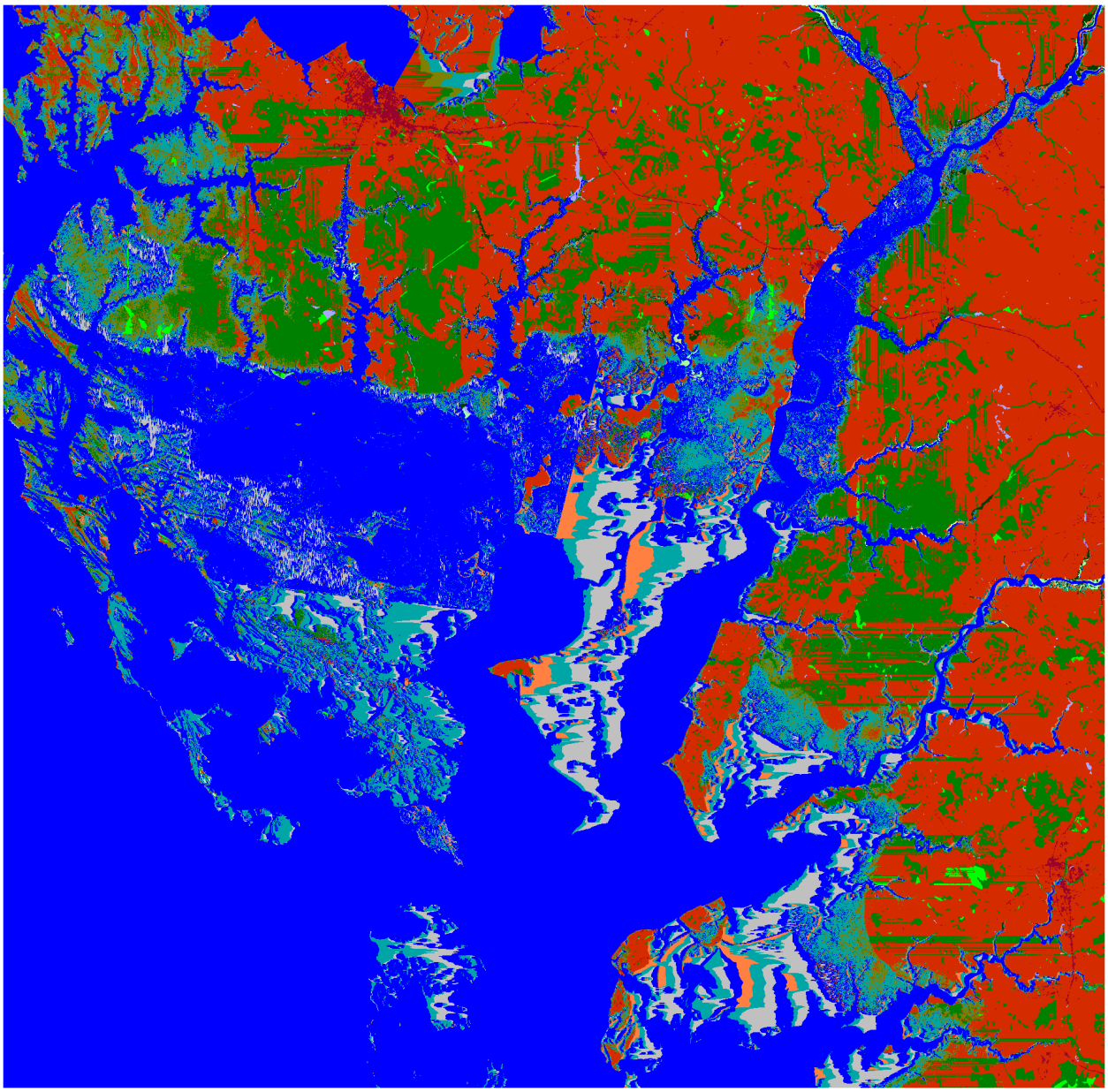
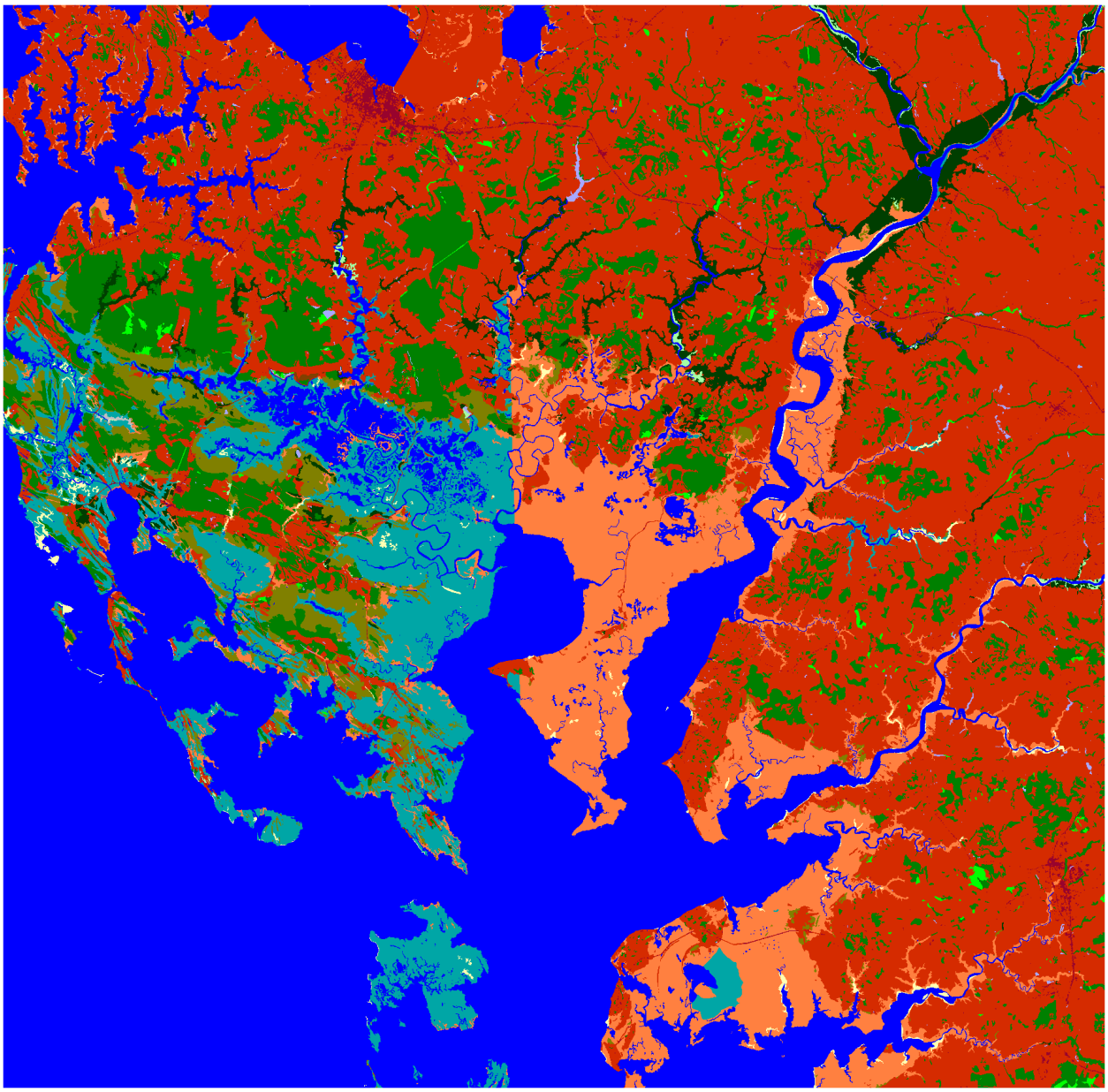


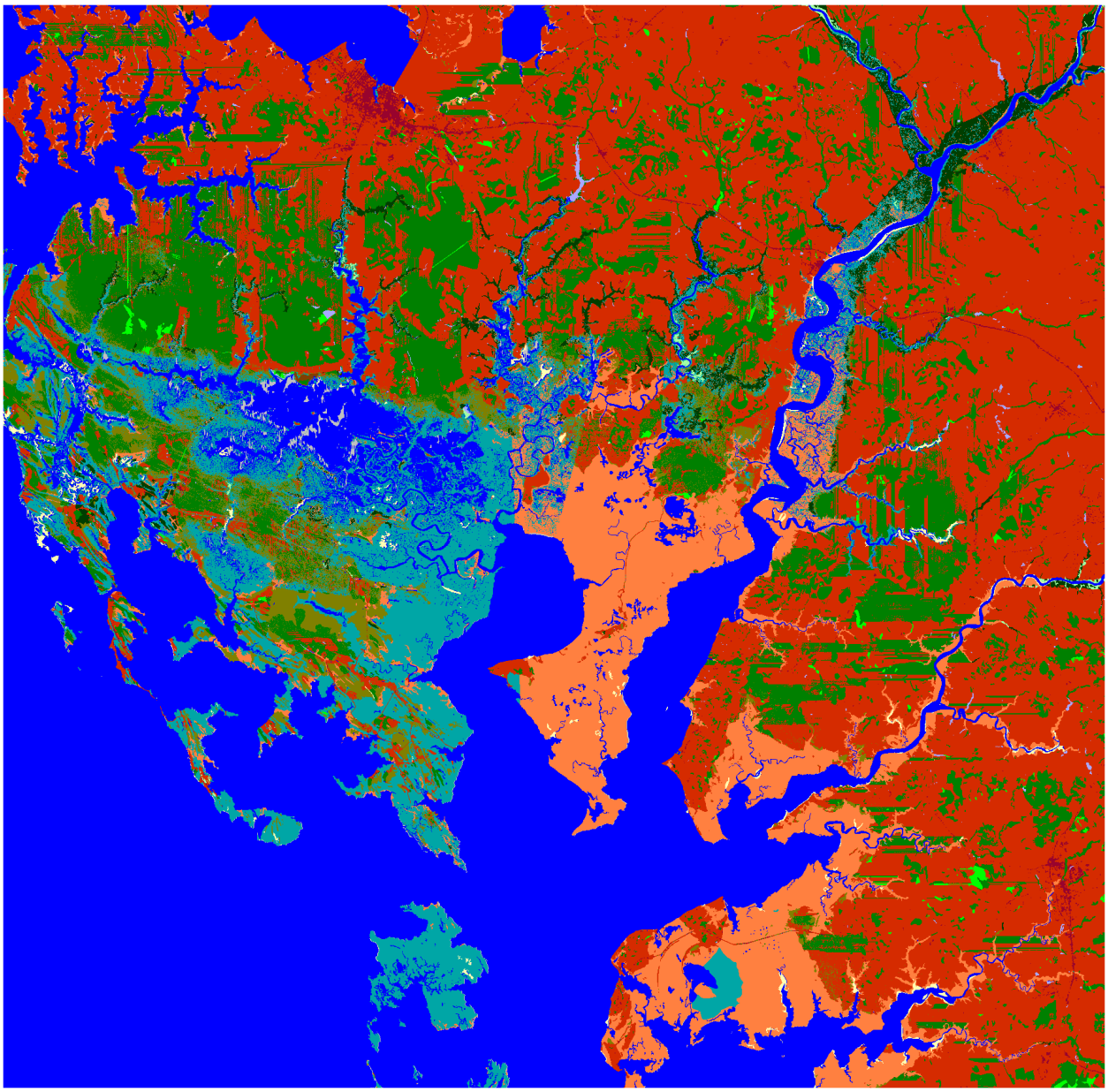
Blackwater NWR, 2075, Scenario A1B Maximum



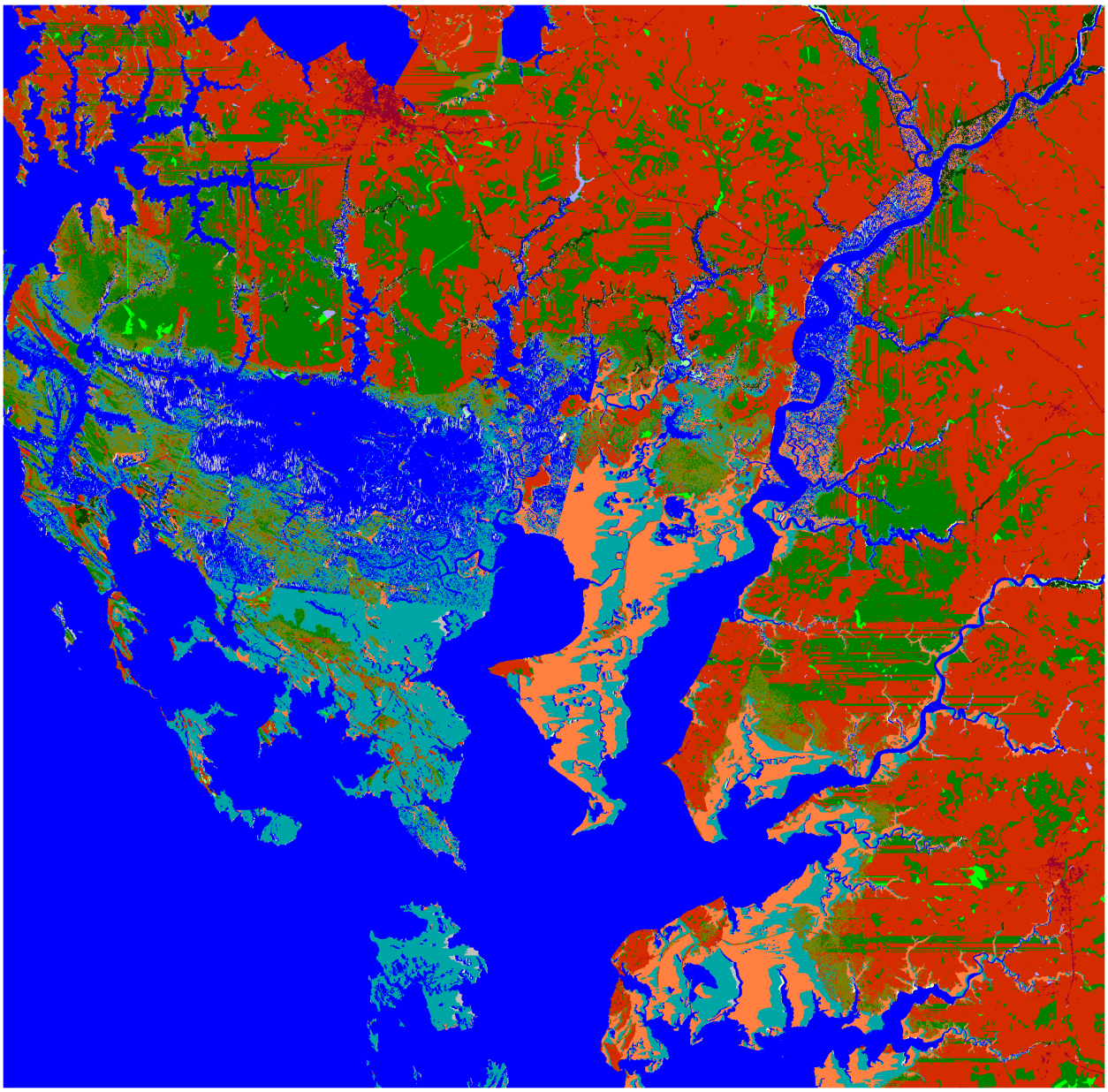
Blackwater NWR, 2100, Scenario A1B Maximum



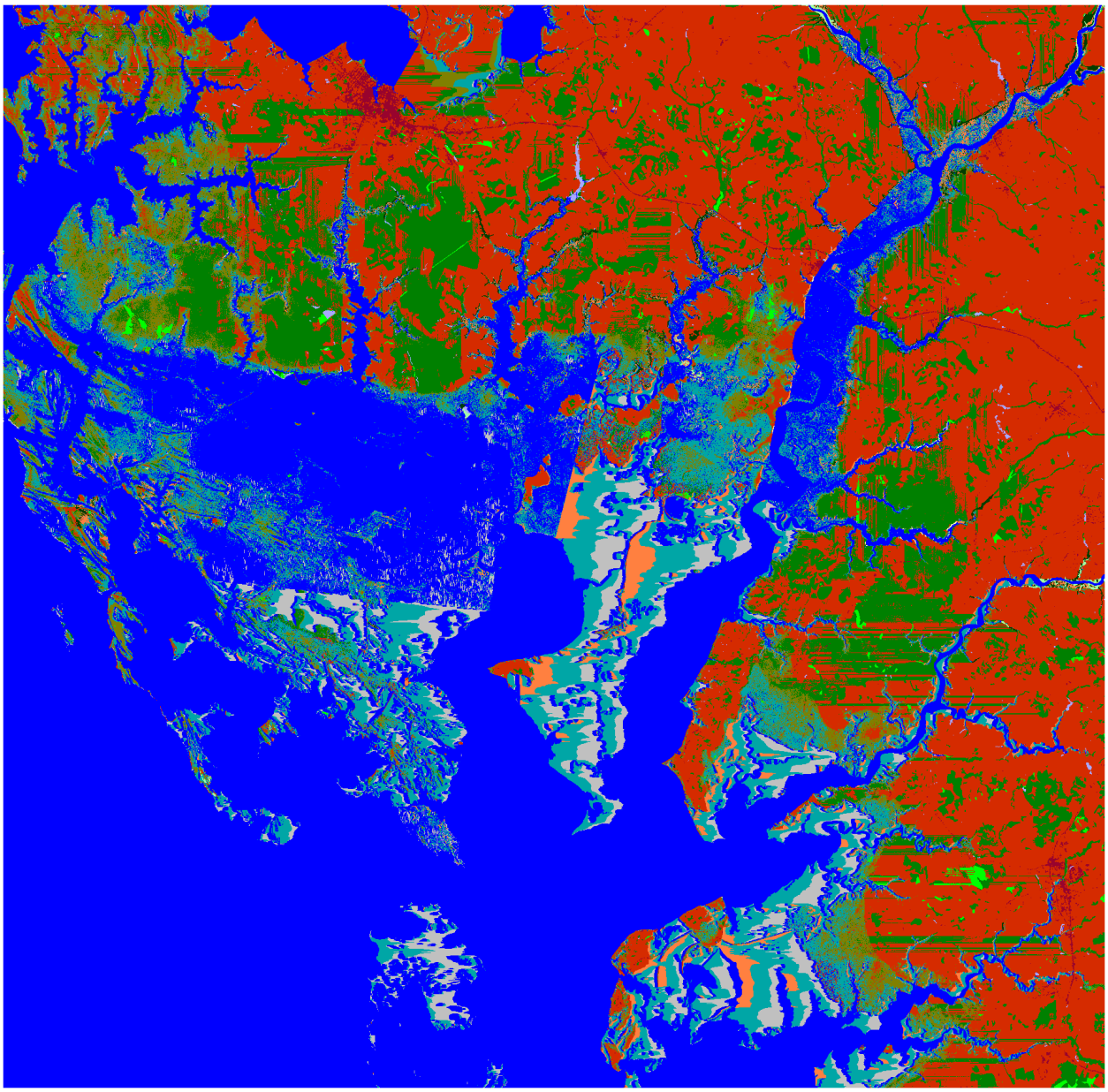
Blackwater NWR, Initial Condition



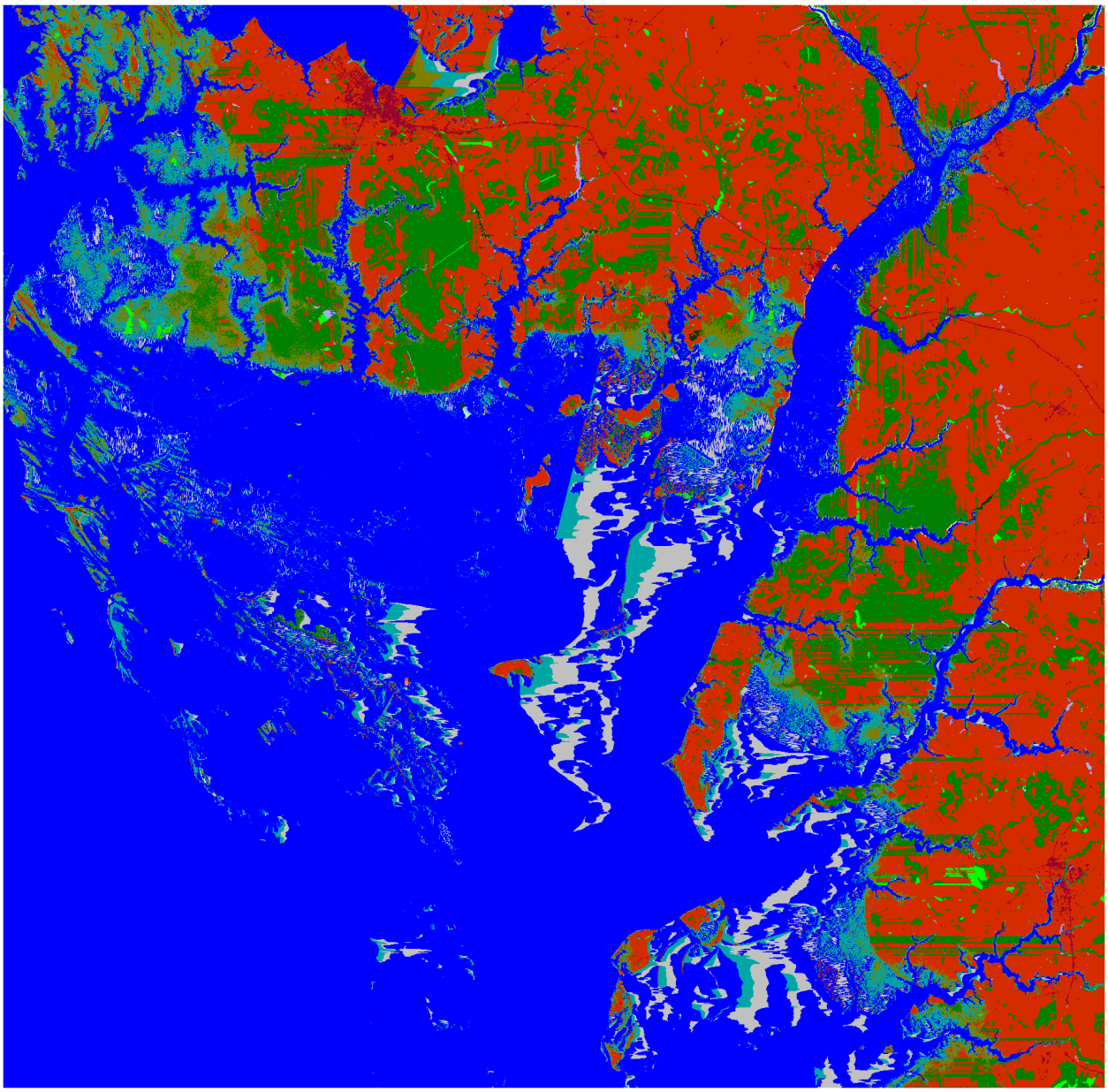
Blackwater NWR, 2025, 1 meter



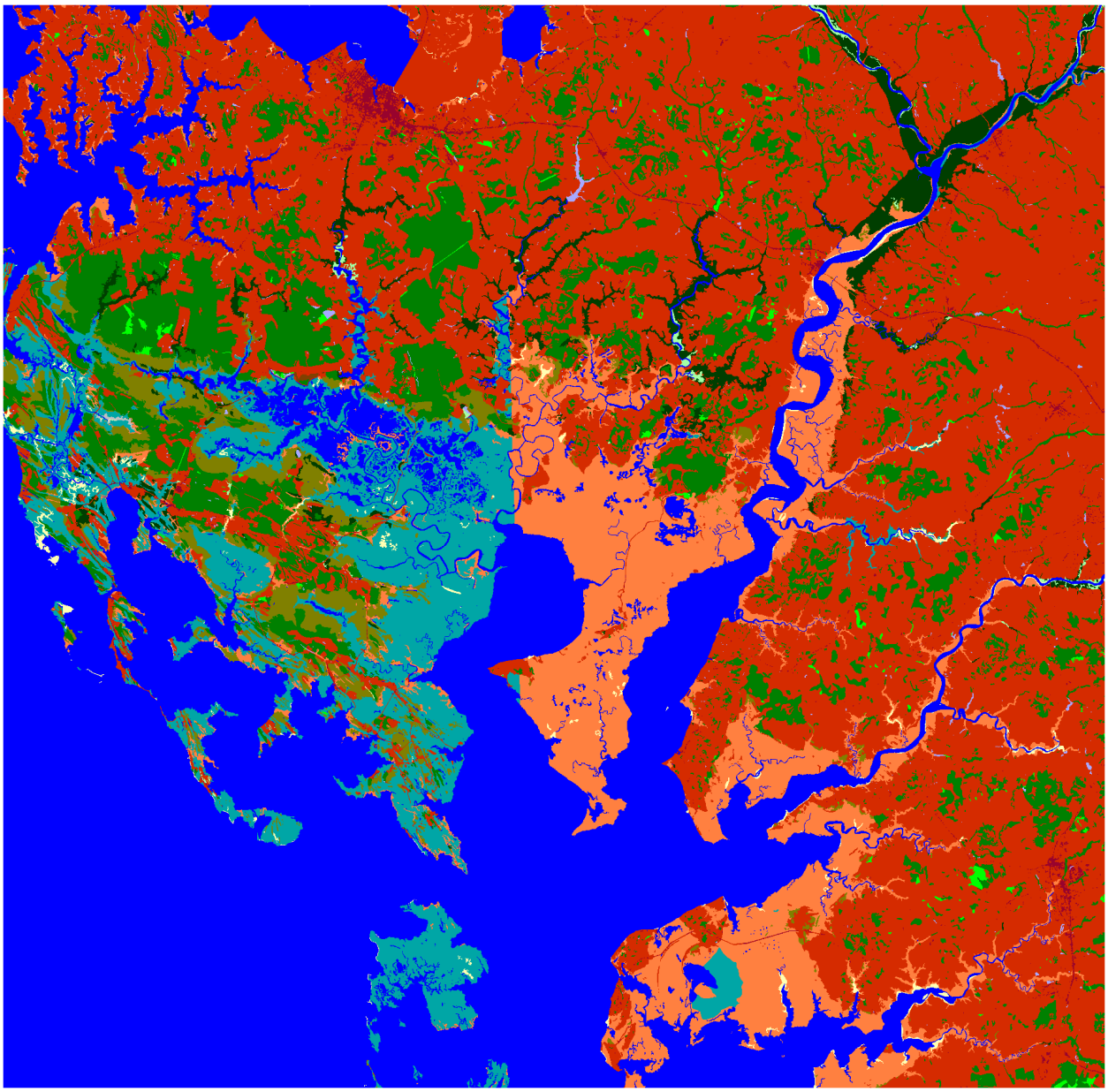
Blackwater NWR, 2050, 1 meter



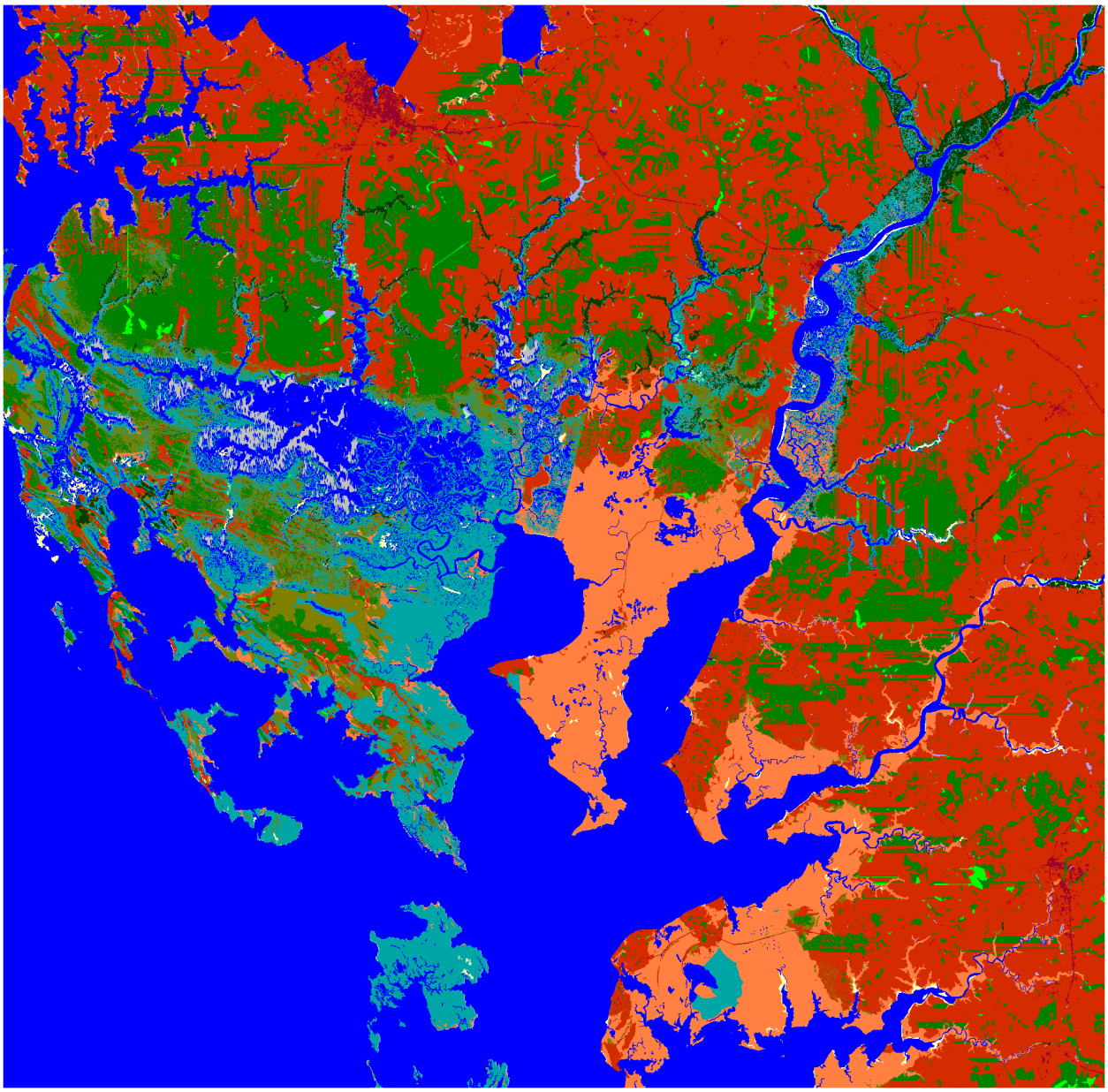
Blackwater NWR, 2075, 1 meter



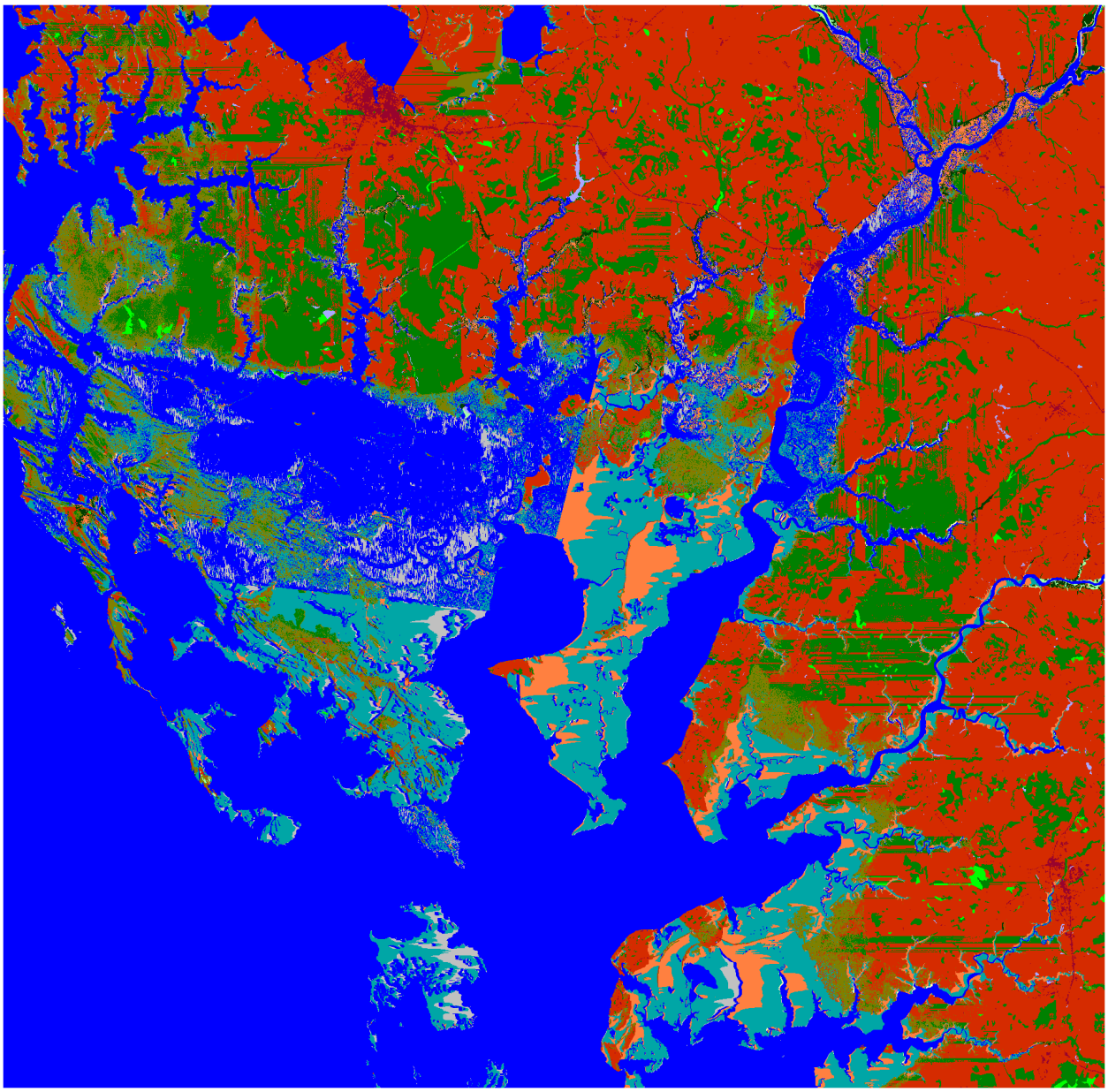
Blackwater NWR, 2100, 1 meter



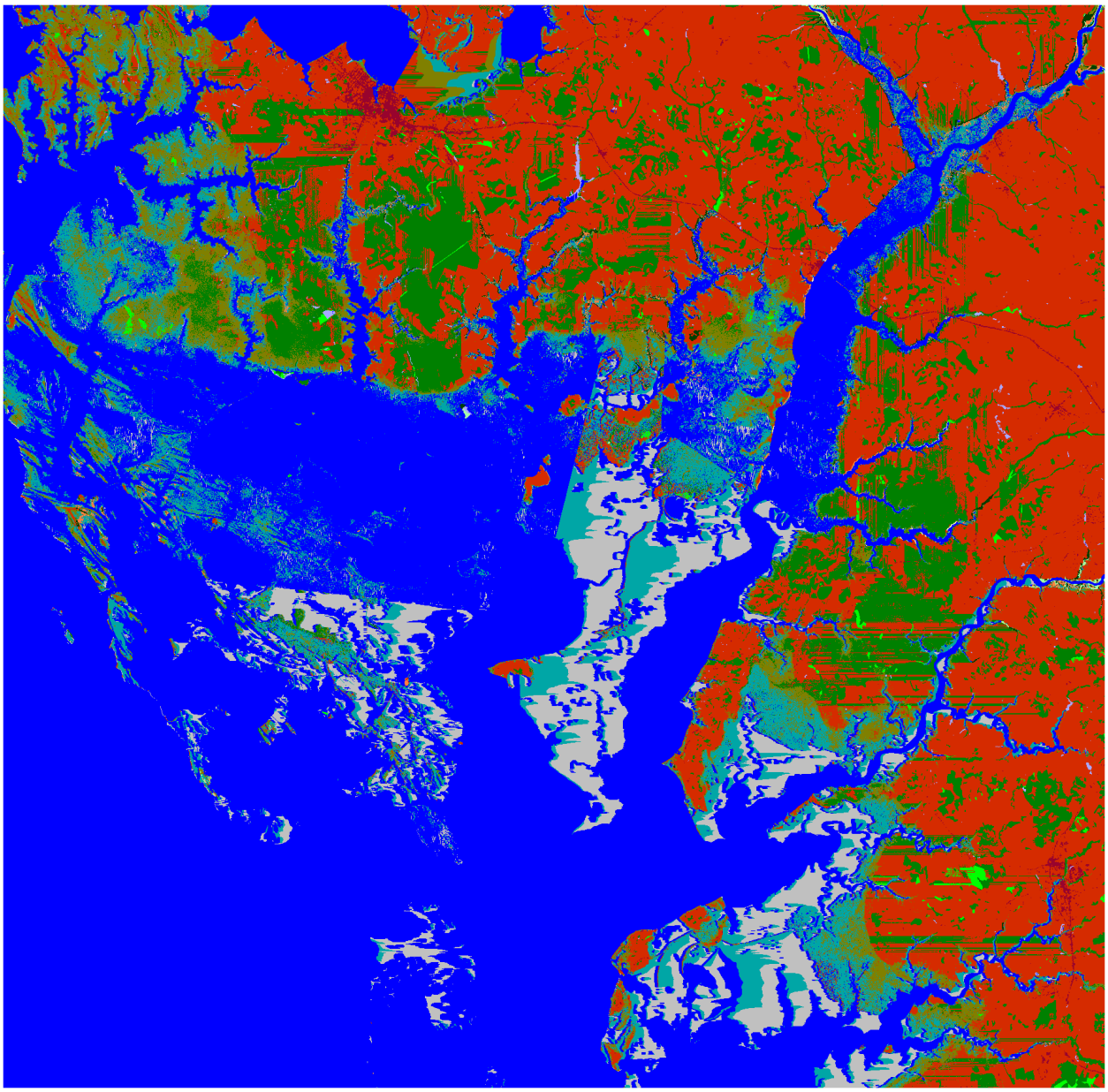
Blackwater NWR, Initial Condition



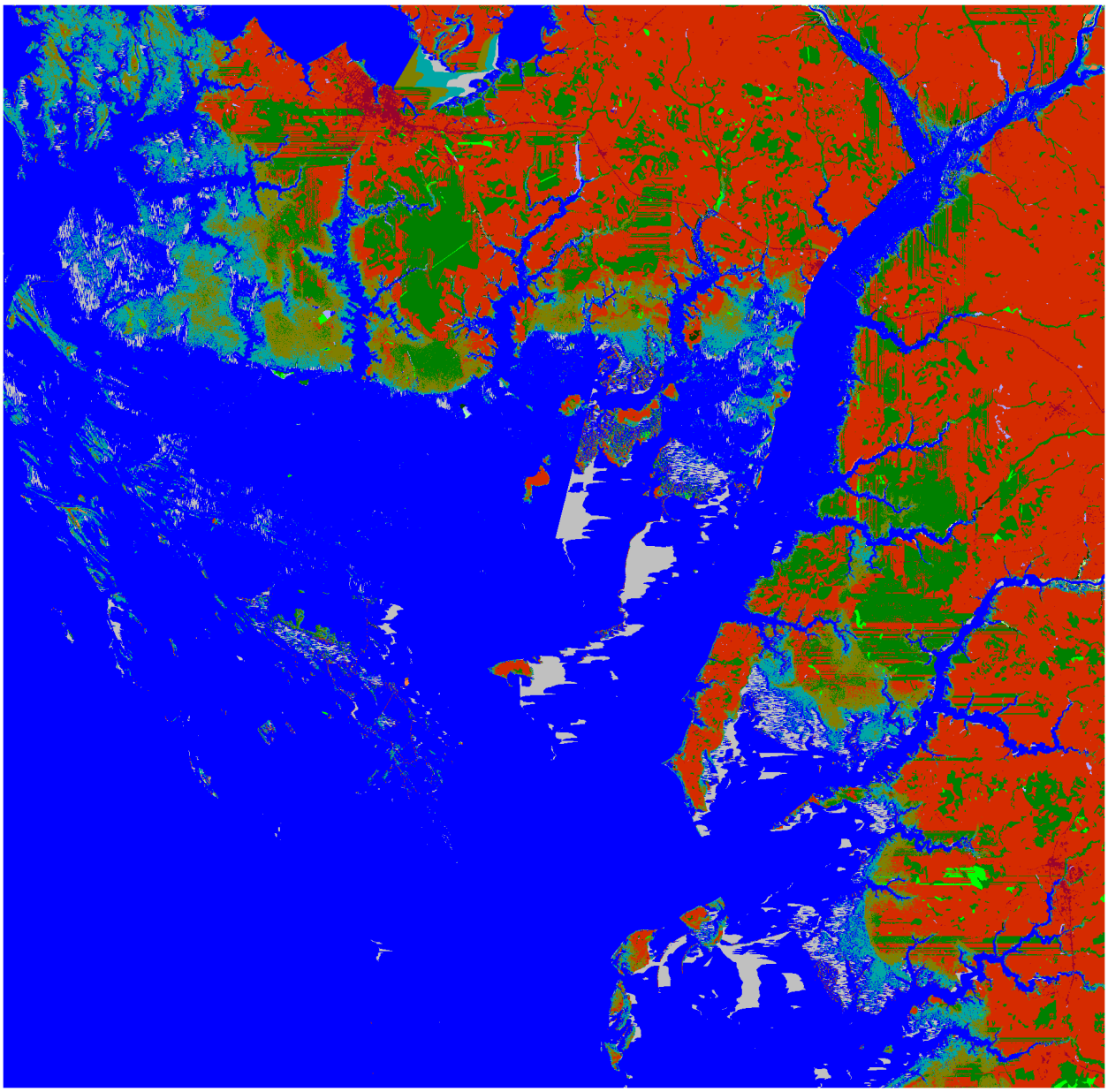
Blackwater NWR, 2025, 1.5 meter



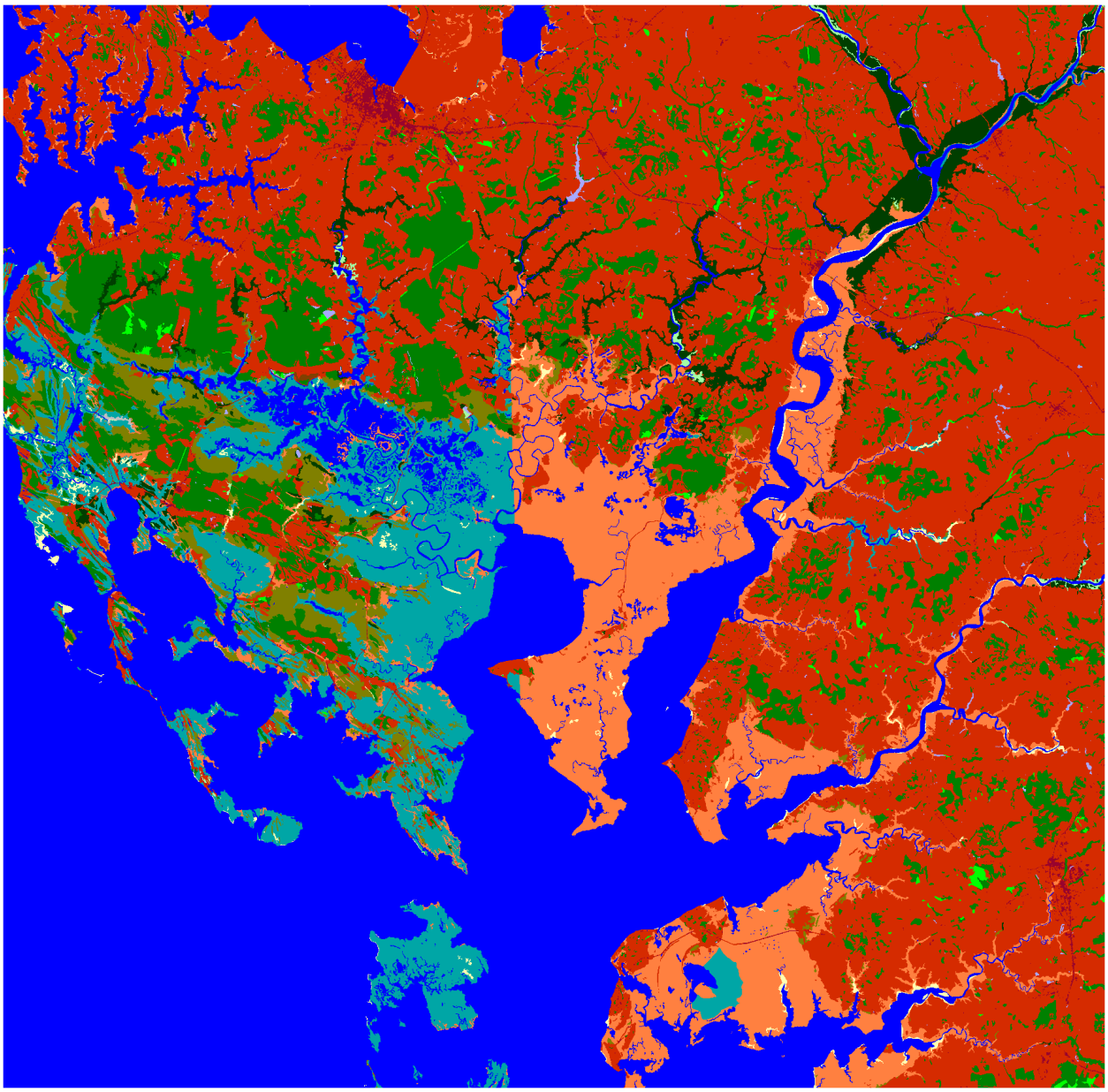
Blackwater NWR, 2050, 1.5 meter



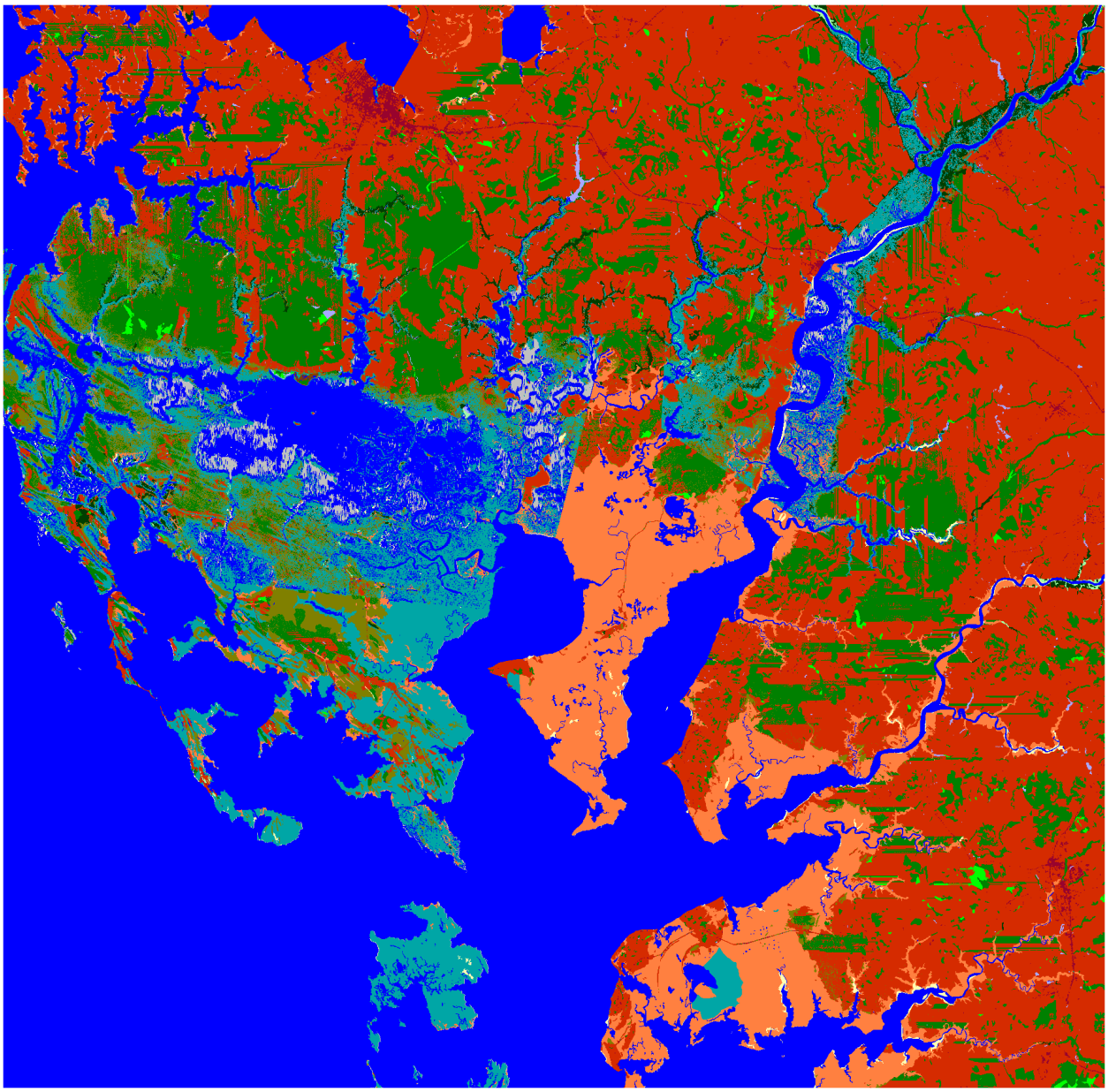
Blackwater NWR, 2075, 1.5 meter



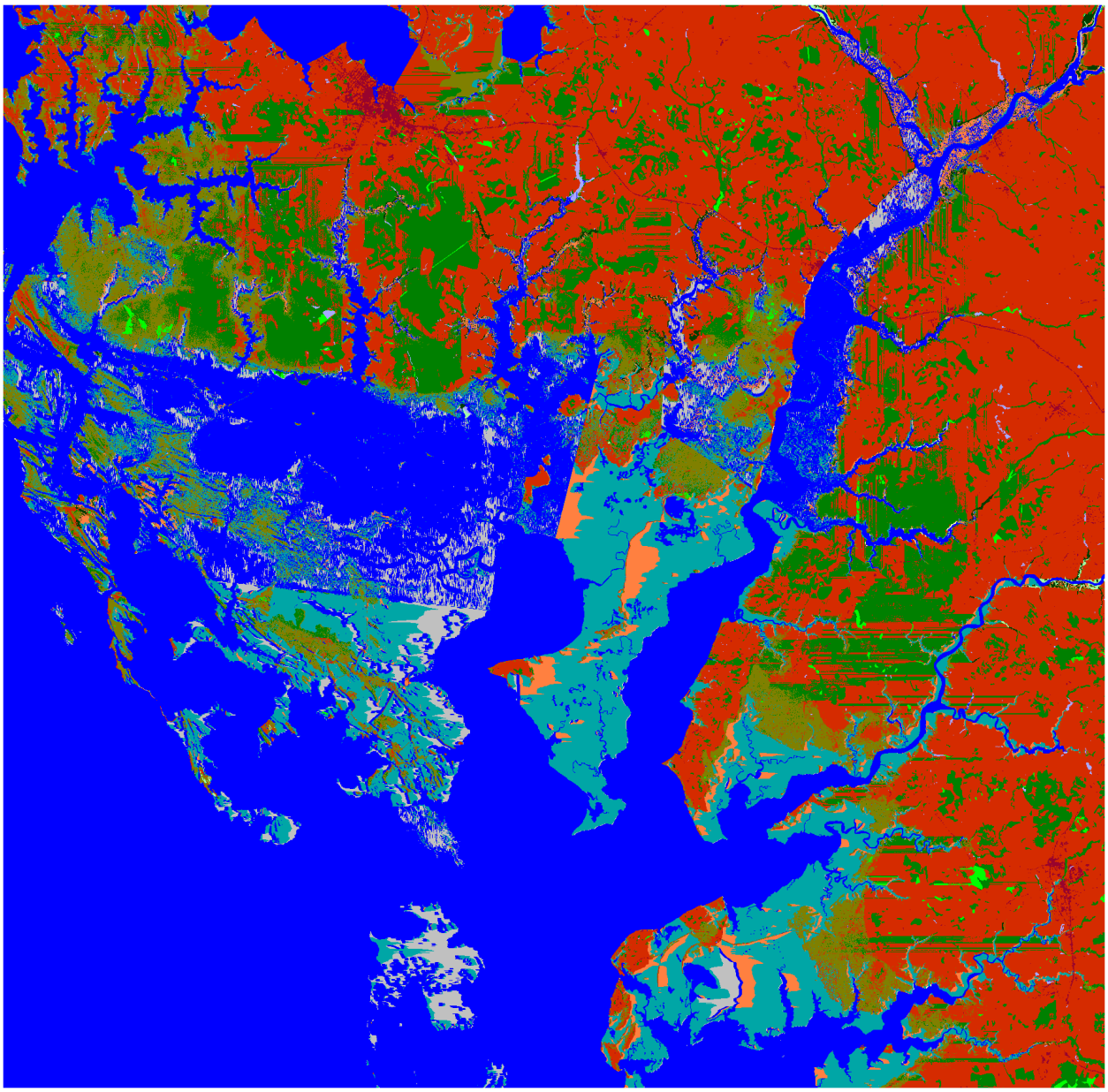
Blackwater NWR, 2100, 1.5 meter



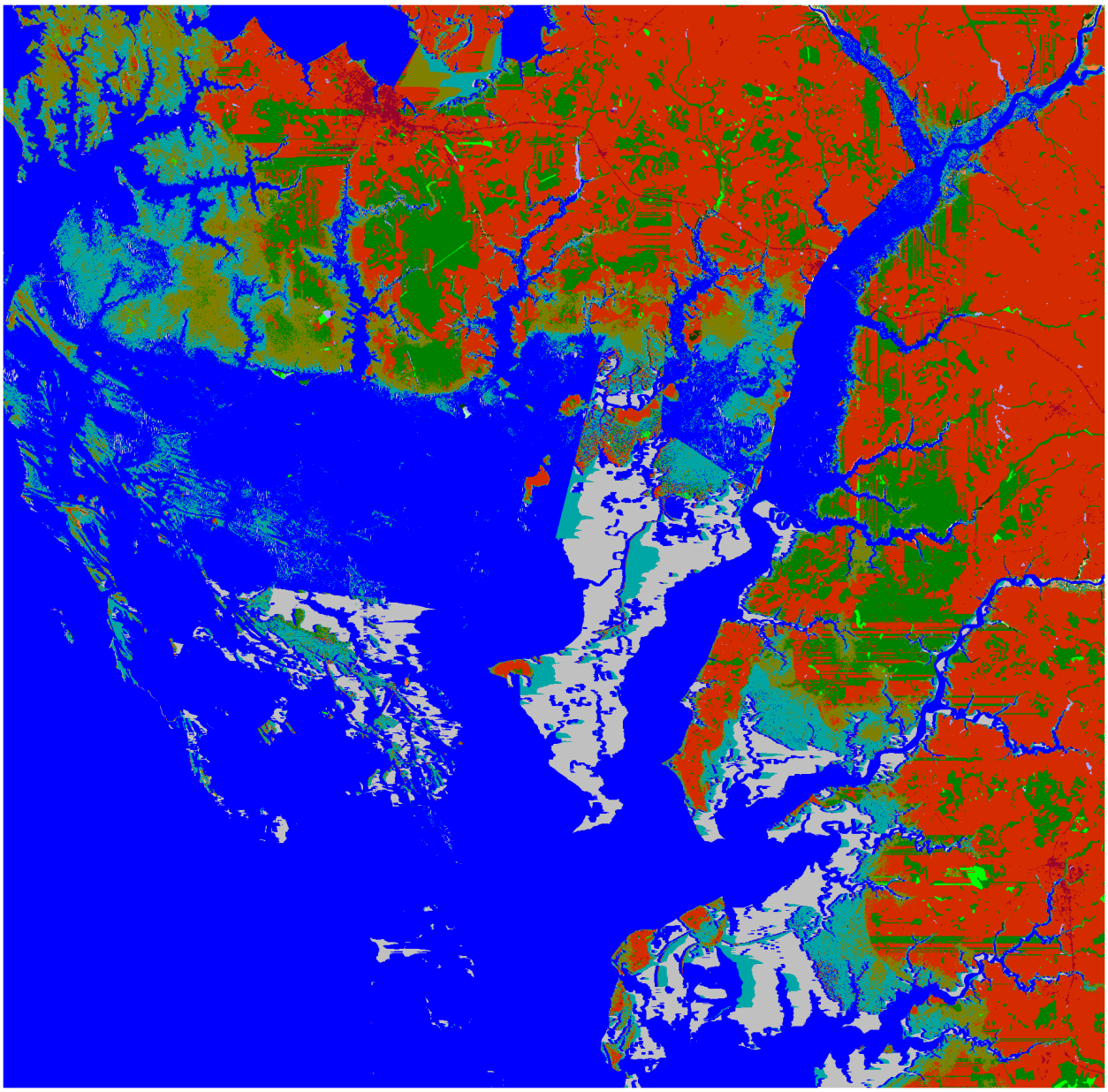
Blackwater NWR, Initial Condition



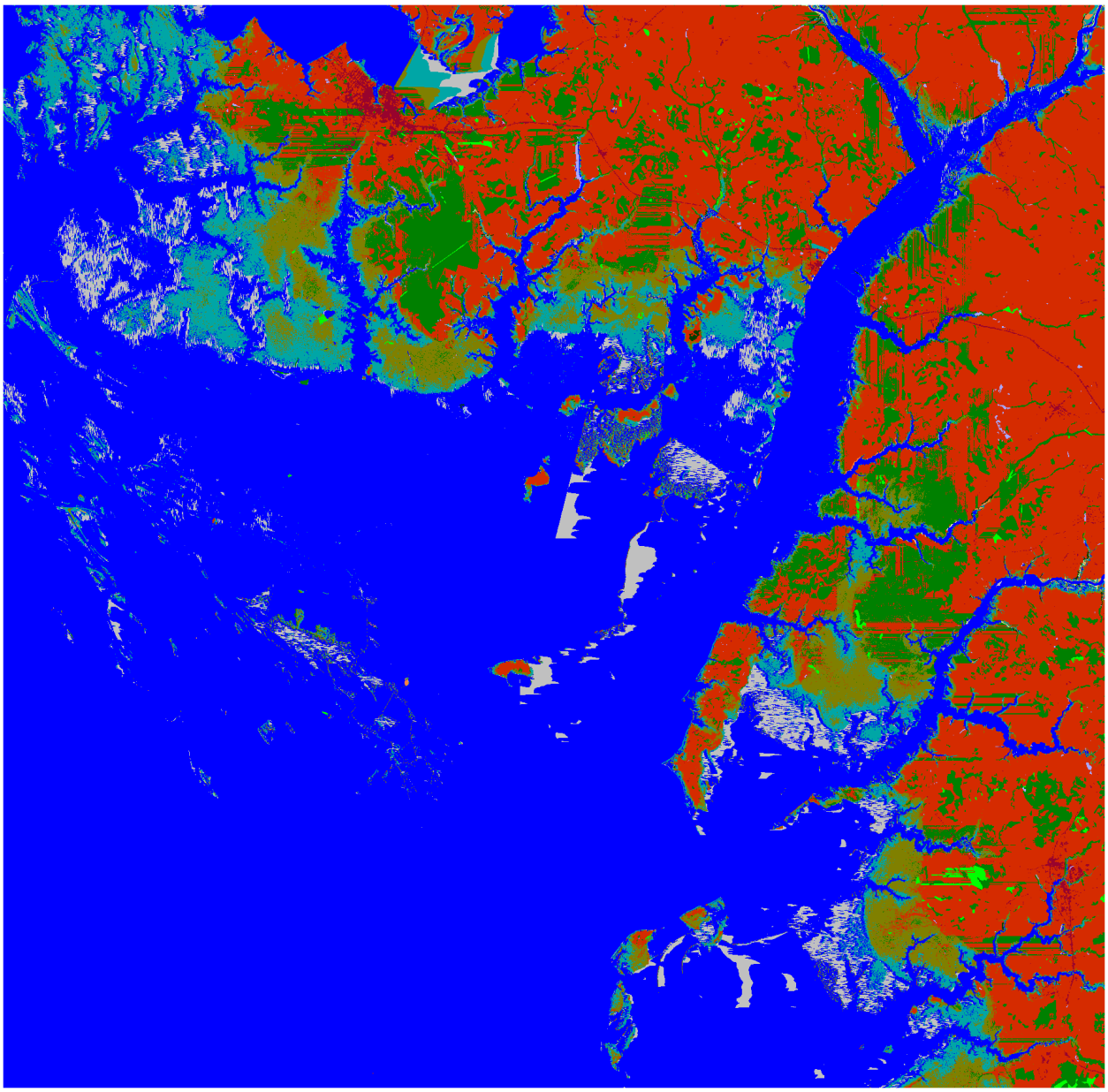
Blackwater NWR, 2025, 2 meter



Blackwater NWR, 2050, 2 meter



Blackwater NWR, 2075, 2 meter



Blackwater NWR, 2100, 2 meter