Application of the Sea-Level Affecting Marshes Model (SLAMM 6) to Anahuac NWR

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Introduction

Tidal marshes are among the most susceptible ecosystems to climate change, especially accelerated sea-level rise (SLR). The Intergovernmental 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 is 50 to 140 cm. Rising sea levels 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 (R. A. 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 several coastal Region 2 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. As noted above, this analysis is a summary of model runs produced by The Nature Conservancy through grant from the Gulf of Mexico Foundation, Inc., to support the Gulf of Mexico Alliance (Clough et al. 2011).

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 6) 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 et al. 1992; Park et al. 1993; Galbraith et al. 2002; National Wildlife Federation & Florida Wildlife Federation 2006; Glick et al. 2007; Craft et al. 2009). The first phase of this work was completed using SLAMM 5, while the second phase simulations were run with SLAMM 6.

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 m width are assumed to undergo overwash during each specified interval for large 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 or can be specified to respond to feedbacks such as frequency of flooding.

SLAMM Version 6.0 was developed in 2008/2009 and is based on SLAMM 5. SLAMM 6.0 provides backwards compatibility to SLAMM 5, that is, SLAMM 5 results can be replicated in SLAMM 6. However, SLAMM 6 also provides several optional capabilities.

- Accretion Feedback Component: Feedbacks based on wetland elevation, distance to channel, and salinity may be specified. This feedback is used in USFWS simulations where adequate data exist for parameterization.
- Salinity Model: Multiple time-variable freshwater flows may be specified. Salinity is estimated and mapped at MLLW, MHHW, and MTL. Habitat switching may be specified as a function of salinity. This optional sub-model is not utilized in USFWS simulations.
- Integrated Elevation Analysis: SLAMM will summarize site-specific categorized elevation ranges for wetlands as derived from LiDAR data or other high-resolution data sets. This functionality is used in USFWS simulations to test the SLAMM conceptual model at each site. The causes of any discrepancies are then tracked down and reported on within the model application report.
- Flexible Elevation Ranges for land categories: If site-specific data indicate that wetland elevation ranges are outside of SLAMM defaults, a different range may be specified within the interface. In USFWS simulations, the use of values outside of SLAMM defaults is rarely utilized. If such a change is made, the change and the reason for it are fully documented within the model application reports.
- Many other graphic user interface and memory management improvements are also part of the new version including an updated *Technical Documentation*, and context sensitive help files.

For a thorough accounting of SLAMM model processes and the underlying assumptions and equations, please see the SLAMM 6.0 *Technical Documentation* (Clough et al. 2010). 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). Site-specific factors that increase or decrease model uncertainty may be covered in the *Discussion* section of this report.

Sea Level Rise Scenarios

Forecast simulations used scenario A1B from the Special Report on Emissions Scenarios (SRES) – mean and maximum estimates. The A1 family of scenarios assumes that the future world includes 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 (IPCC 2007) suggests a likely range of 0.21 to 0.48 m 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 0.39 m of global sea level rise by 2100. A1B-maximum predicts 0.69 m of global SLR 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 of 50 to 140 cm. This work was recently updated and the ranges were increased to 75 to 190 cm (Vermeer and Rahmstorf 2009). Pfeffer et al. (2008) suggests that 2 m 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." (Clark 2009) 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…" Grinsted also states that there is a "low probability" that SLR will match the lower IPCC estimates.

To allow for flexibility when interpreting the results, SLAMM was also run assuming 1 m, 1½ m, and 2 m of eustatic sea-level rise by the year 2100. The A1B- maximum scenario was scaled up to produce these bounding scenarios (Figure 1).

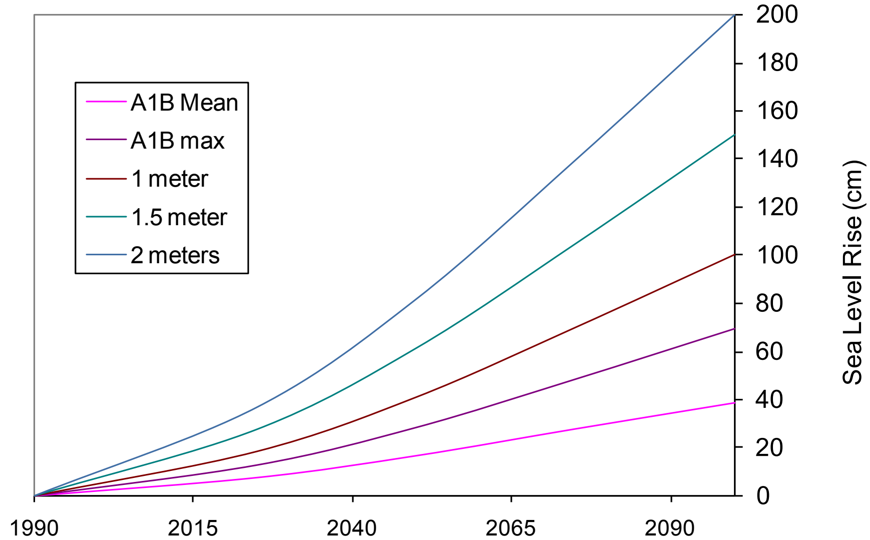


Figure 1: **Summary of SLR scenarios utilized**

Methods and Data Sources

The digital elevation map used in this simulation was derived from Sanborn 2007 and Tropical Storm Allison Recovery Project (TSARP) 2002 LiDAR (received from Harte Research Institute) and 2009 1/9 arc second NED (Figure 2) (Texas Water Development Board 2010).

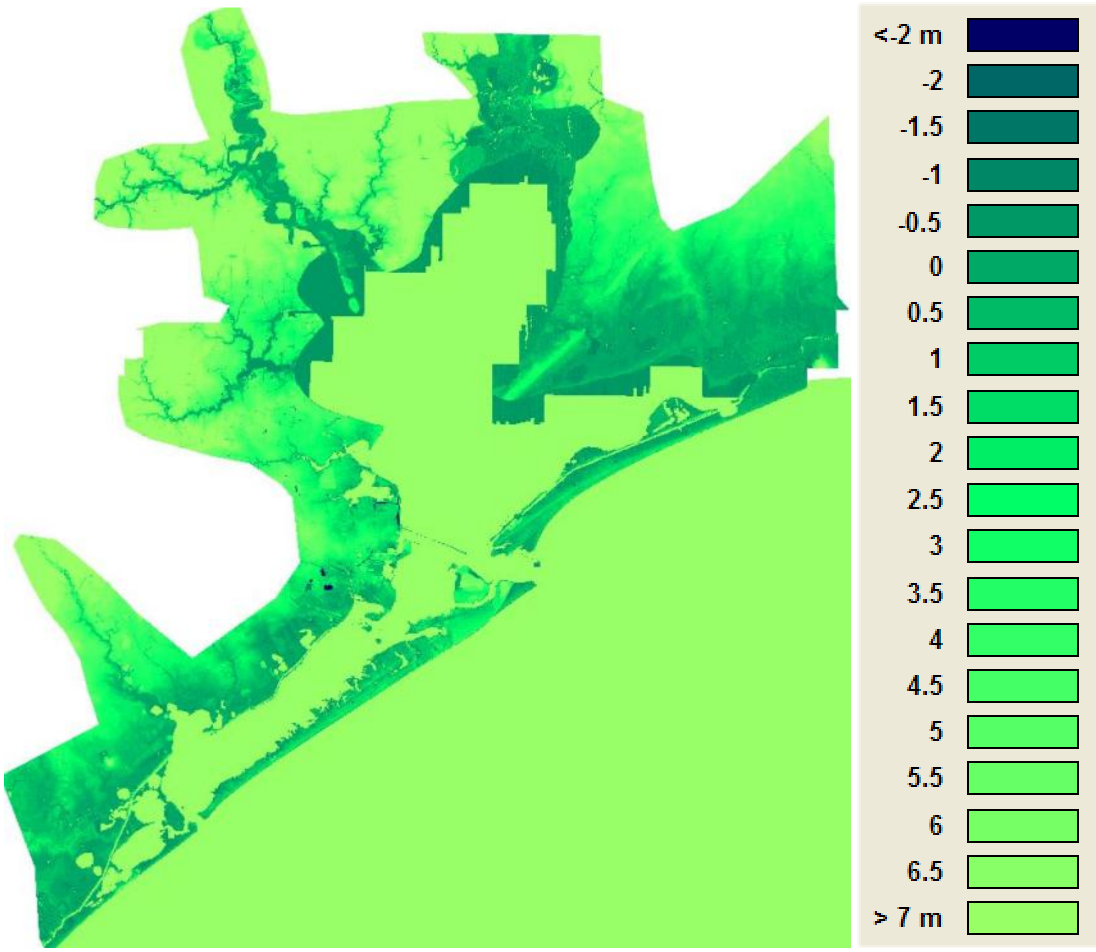


Figure 2. Shade-relief elevation map of Galveston study area

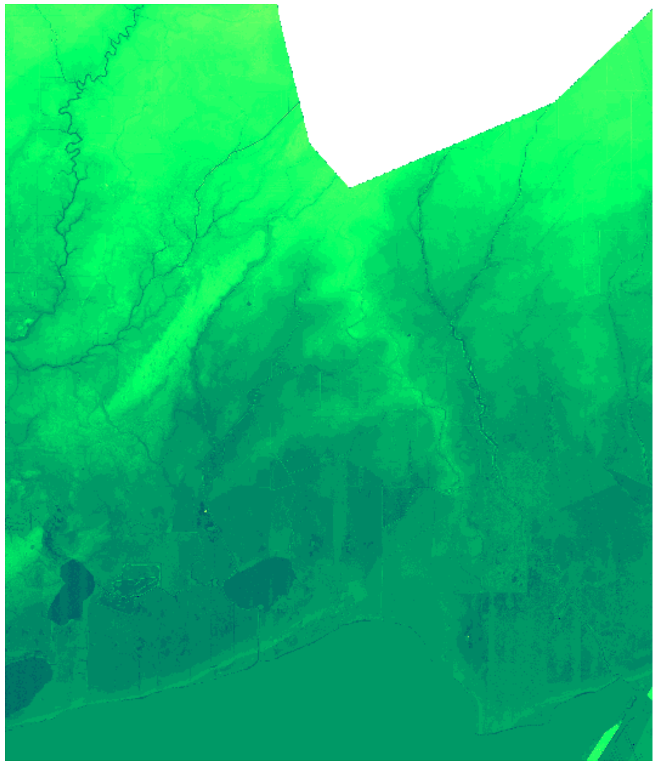


Figure 3. Detail elevation data in Anahuac NWR

The wetlands layer for the study area was produced in 2009 by the National Wetlands Inventory (Figure 4), but was based on aerial photos taken in August and October of 2004. Therefore, in this report the 2009 NWI layer will be referred to as the 2004 NWI layer. Figure 4 presents the 2004 wetlands data layer. It is important to note that the far northern tip of the refuge is not included in this analysis.

Converting the NWI survey into 10 m cells indicated that the approximately 73,361 acre refuge (approved acquisition boundary including water) is composed of the following categories:

Land cover type		Area (acres)	Percentage (%)
	Inland Fresh Marsh	32,815	45
	Irregularly Flooded Marsh	21,303	29
	Undeveloped Dry Land	13,378	18
	Estuarine Open Water	2,434	3
	Inland Open Water	2,289	3
	Developed Dry Land	480	1
	Swamp	268	< 1
	Open Ocean	82	< 1
	Ocean Beach	80	< 1
	Regularly Flooded Marsh	77	< 1
	Estuarine Beach	72	< 1
	Inland Shore	45	< 1
	Riverine Tidal	35	< 1
	Transitional Salt Marsh	3	< 1
	Total (incl. water)	**73,361**	**100**

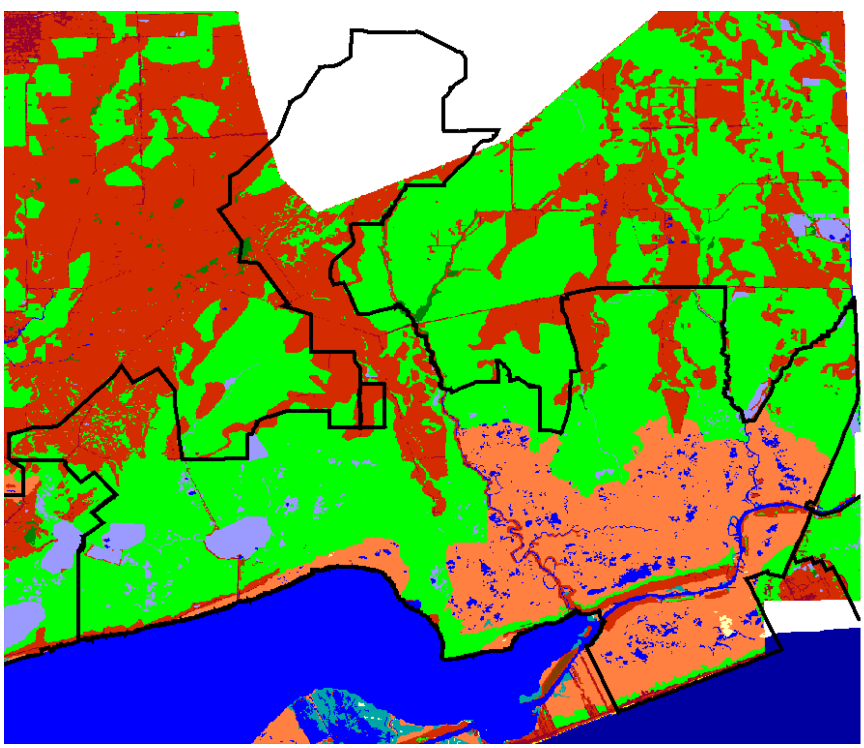


Figure 4. Study area for Anahuac NWR. Black line indicates refuge boundary. Note northern inland portion is missing from this analysis

According to the National Wetland Inventory, there are diked areas within Anahuac NWR. Dikes protecting the eastern portion of Anahuac NWR were added based on information from Patrick Walther who indicated this portion of the study area is diked and subject to considerable management (Walther 2011). In addition, the dike near High Island was added based on information obtained during a project applying SLAMM to Jefferson County, TX (Clough and Larson 2009). Figure 5 shows the diked areas.

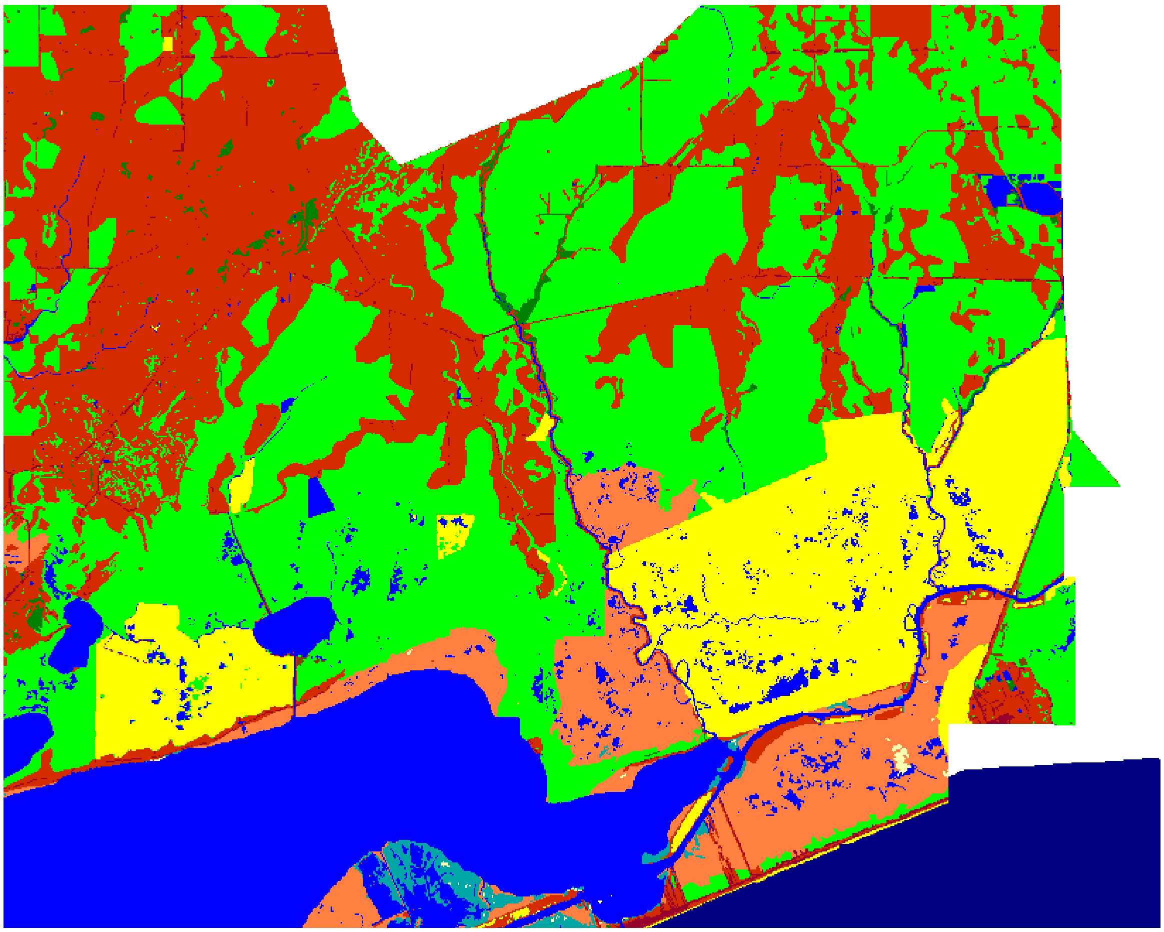


Figure 5. Location of diked areas (yellow) within Anahuac NWR

Historic SLR trends have been measured at two sites in the study area: Galveston Pier 21 (6.39 ± 0.28 mm/year) on the Bay side of Galveston Island and Galveston Pleasure Pier (6.84 ±0.81 mm/year) on the Ocean side of Galveston Island. The observed rate of SLR at these gauges has been significantly higher than the average for the last 100 years (approximately 1.7 mm/year, IPCC 2007).

The higher-than-average historic SLR observed in Galveston Bay can be attributed to land subsidence. However, because of decreased groundwater withdrawals, the pattern of subsidence in the Galveston area significantly changed after 1978 (Gabrysch and Coplin 1990). In addition, recent measurements in East Houston have shown that historic subsidence in this area has stopped completely (Buckley et al. 2003). Given that these simulations started well after 1978, a rate of 0.305 m/century (1 ft./century) was applied to both the hindcast and forecast modeling efforts. This parameter choice was based on information from the Harris-Galveston Subsidence District who advised that subsidence from anthropogenic sources is not anticipated in the future (Michel 2010).

This "natural subsidence rate" of 3.05 mm/yr. was applied within the model by modifying the "Historic Trend" parameter for model forecasts (Table 2)[1]. A rate of 3.05 mm/year is lower than subsidence that would be estimated using measured historic SLR trends from Galveston Island (5.1 mm/year at Galveston Pleasure pier and 4.7 mm/yr. at Pier 21)[2]. This discrepancy may be caused by the averaging period for these gauges as they include years prior to 1978, when subsidence in the Houston-Galveston area was more substantial (Buckley et al. 2003; Gabrysch and Coplin 1990; Michel 2010).

The portion of the study area that included Anahuac NWR included several input subsites. Figure 6 presents the three subsites in the Anahuac NWR area. Although depicted on the map, only a small amount of Anahuac NWR fell in the Northern Bay subsite.

The "salt elevation" parameter within SLAMM designates the boundary between coastal wetlands and dry lands or fresh water wetlands. An estimate of this elevation may be derived by examining historical tide gauge data to determine how frequently different elevations are flooded with ocean water. Within SLAMM modeling simulations this elevation is usually defined as the elevation over which flooding is predicted less than once in every 30 days. Dry lands and fresh-water wetlands are assumed to be located above the salt elevation. In this study, the value of the salt elevation depended on the subsite as shown in Table 1.

Table 1. Salt Elevations

Input Subsite	Salt Elev. (m above MTL)
Middle Bay	0.35
East Bay	0.35
Smith Point/Anahuac	0.30
Open Ocean	0.48

The Galveston study area was divided into high and low sediment areas. Anahuac NWR is located in both high (Middle Bay) and low sediment supply area (East Bay, Smith Point/Anahuac, Open Ocean) Accretion rates in salt marshes were subject to feedbacks based on elevation. For the Middle Bay subsite (high-sediment supply area) the maximum accretion rate applied was 10 mm/yr. and minimum was 3.8 mm/yr. resulting in an average rate of 7.7 mm/yr. For the East Bay Smith Point/Anahuac subsites (low sediment supply), the maximum accretion rate applied was 4 mm/yr. and minimum was 1.6 mm/yr., resulting in an average rate of 3.1 mm/yr. Feedbacks for the low sediment-supply areas were based on data reported by Ravens et al. 2009 and for high sediment-supply areas from data collected by Williams (2003).

[1] The "Historic Trend" parameter is used to input an estimate of historic local SLR. The difference between this historic local trend and the historic eustatic trend is then used to adjust global estimates of SLR utilized by SLAMM. In model forecasts the "Historic Trend" parameter was set to 4.75 mm/yr., which is equal to the 1.7 mm/year historic eustatic SLR trend plus the 3.05 mm/yr. local subsidence rate. The model then interprets this parameter by applying a subsidence rate of 3.05 mm/year throughout the study area.

[2] For example, at Galveston Pleasure Pier, 6.8 mm/year observed minus 1.7 mm/year of eustatic SLR observed would suggest a rate of 5.1 mm/year due to subsidence.

Erosion rates observed from 1931-2000 were applied to the SLAMM model based on data from the Texas Hazard Mitigation Package (Texas Geographic Society, http://www.thmp.info/data_layers/coastal-erosion.html). Rates were determined individually for each input subsite and applied equally to Marsh, Swamp, and Tidal Flat categories. For the Middle Bay subsite an erosion rate of 1 meter per year was applied while the Smith Point/Anahuac and East Bay subsites a rate of 0.77 m/yr. was used.

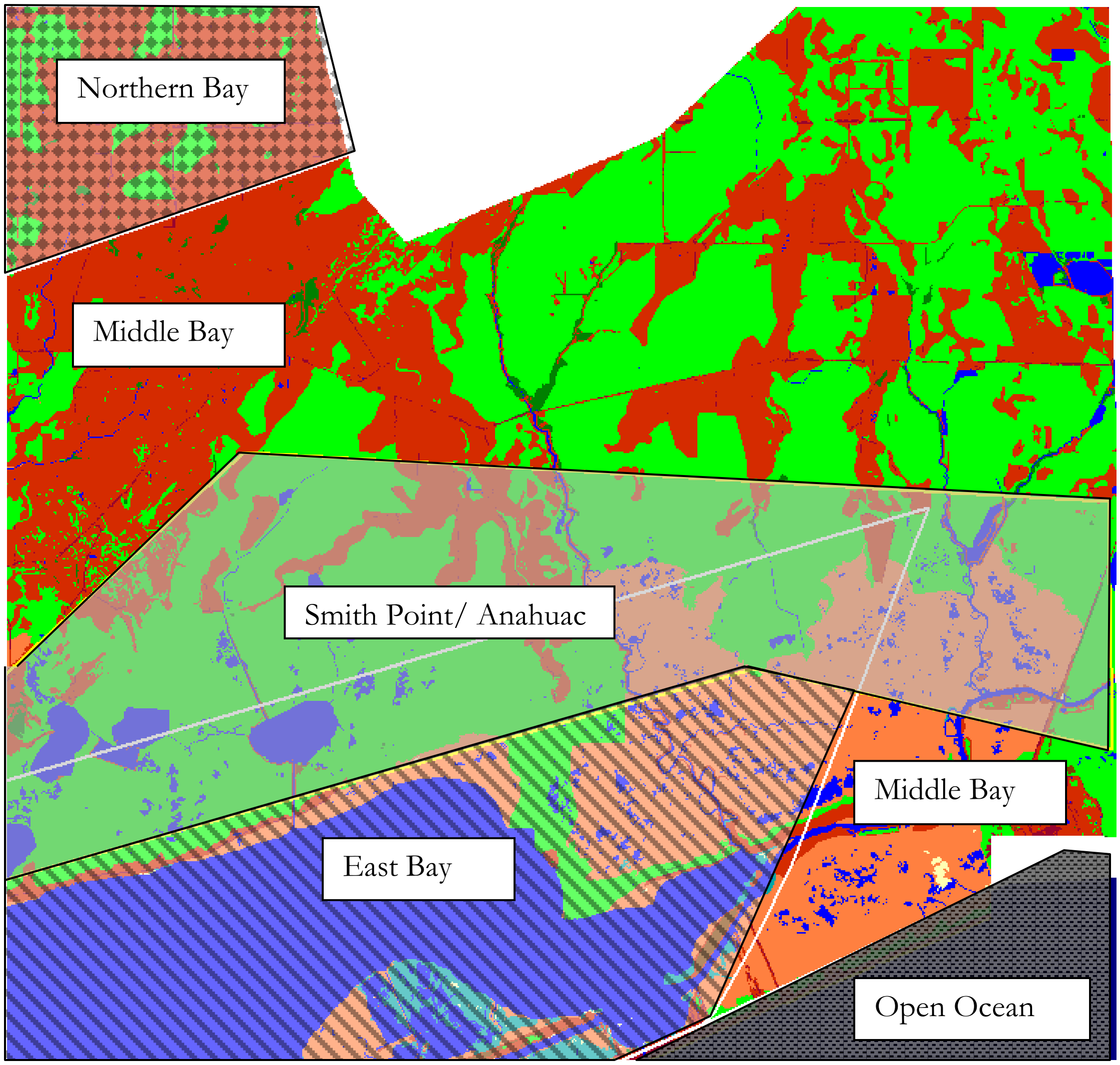


Figure 6. Input subsites

The MTL to NAVD88 correction was applied the Galveston study area via input raster. The correction value for the Anahuac NWR varied spatially within a range of 0.17 and 0.21 meters.

Modeled U.S. Fish and Wildlife Service refuge boundaries for Texas 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 10 m by 10 m cells. Note that the SLAMM model will track partial conversion of cells based on elevation and slope.

Table 2. Summary of SLAMM input parameters for Anahuac NWR

Subsite Description	Middle Bay	Smith Point/ Anahuac	East Bay	Open Ocean
NWI Photo Date (YYYY)	2004	2004	2004	2004
DEM Date (YYYY)	2007	2007	2007	2007
Direction Offshore [n,s,e,w]	East	East	West	East
Historic Trend (mm/yr.)	4.75	4.75	4.75	4.75
GT Great Diurnal Tide Range (m)	0.34	0.25	0.37	0.60
Salt Elev. (m above MTL)	0.35	0.30	0.35	0.48
Marsh Erosion (horz. m /yr)	1	0.77	0.77	1.68
Swamp Erosion (horz. m /yr.)	1	0.77	0.77	1.68
T.Flat Erosion (horz. m /yr)	1	0.77	0.77	1.68
Inland-Fresh Marsh Accr (mm/yr.)	2.9	2.9	2.9	2.9
Tidal Swamp Accr (mm/yr.)	1.1	1.1	1.1	1.1
Swamp Accretion (mm/yr.)	0.3	0.3	0.3	0.3
Beach Sed. Rate (mm/yr.)	1	1	1	1
Hindcast - Use Elev Pre-processor [True,False]	TRUE	TRUE	TRUE	TRUE
Forecast - Use Elev Pre-processor [True,False]	FALSE	FALSE	FALSE	FALSE
Reg Flood Max. Accr. (mm/year)	10	4	4	4
Reg Flood Min. Accr. (mm/year)	3.8	1.6	1.6	1.6
Reg Flood Elev a coeff. (cubic)	-1	-1	-1	-1
Reg Flood Elev b coeff. (square)	0.8	0.8	0.8	0.8
Reg Flood Elev c coeff. (linear)	1	1	1	1
Irreg Flood Max. Accr. (mm/year)	10	4	4	4
Irreg Flood Min. Accr. (mm/year)	3.8	1.6	1.6	1.6
Irreg Flood Elev a coeff. (cubic)	-1	-1	-1	-1
Irreg Flood Elev b coeff. (square)	0.8	0.8	0.8	0.8
Irreg Flood Elev c coeff. (linear)	1	1	1	1
Irreg Flood D.Effect Max (meters)	0	0	0	0
Irreg Flood D min. (unitless)	1	1	1	1
Tidal Fresh Max. Accr. (mm/year)	6.5	6.5	6.5	6.5
Tidal Fresh Min. Accr. (mm/year)	3.2	3.2	3.2	3.2
Tidal Fresh Elev a coeff. (cubic)	0	0	0	0
Tidal Fresh Elev b coeff. (square)	0	0	0	0
Tidal Fresh Elev c coeff. (linear)	1	1	1	1

Results

This simulation of the Anahuac NWR was completed using a SLAMM model that was calibrated to historical data for a previous project (Clough et al. 2011). This calibrated model predicts that Anahuac NWR will be severely impacted depending on the SLR scenario and wetland class. Table 3 presents the predicted loss of each wetland category by 2100 for each of the five SLR scenarios examined.

Inland fresh marsh comprises 45% of the land in the refuge and is predicted to sustain considerable losses under each SLR scenario examined, as shown in Table 3. This can be explained in part by the uncertainty in the NWI wetland layer used. SLAMM simulates a "time zero" step, in which model results for the NWI photo date are produced. As there is no sea level rise, accretion, or erosion imposed in this time step, conversions in land cover types at "time zero" are based solely on comparisons between land elevations and the SLAMM conceptual model. A large amount of conversion of tidal fresh marsh to transitional marsh was observed at time-zero in the Smith Point area. Discussions with area experts indicated the area around Smith Point is suspected to be under limited tidal influence (Dick 2010) and that the NWI maps of this area do not accurately describe the current salinity of the marshes in this area. In reality the salinity of these marshes is around 10 ppt, making these marshes more likely to be transitional salt marshes rather than inland fresh (Walther 2011).

Table 3. Predicted Loss Rates of Land Categories by 2100 Given Simulated Scenarios of Eustatic Sea Level Rise. *Negative values indicate losses and positive indicate gains*

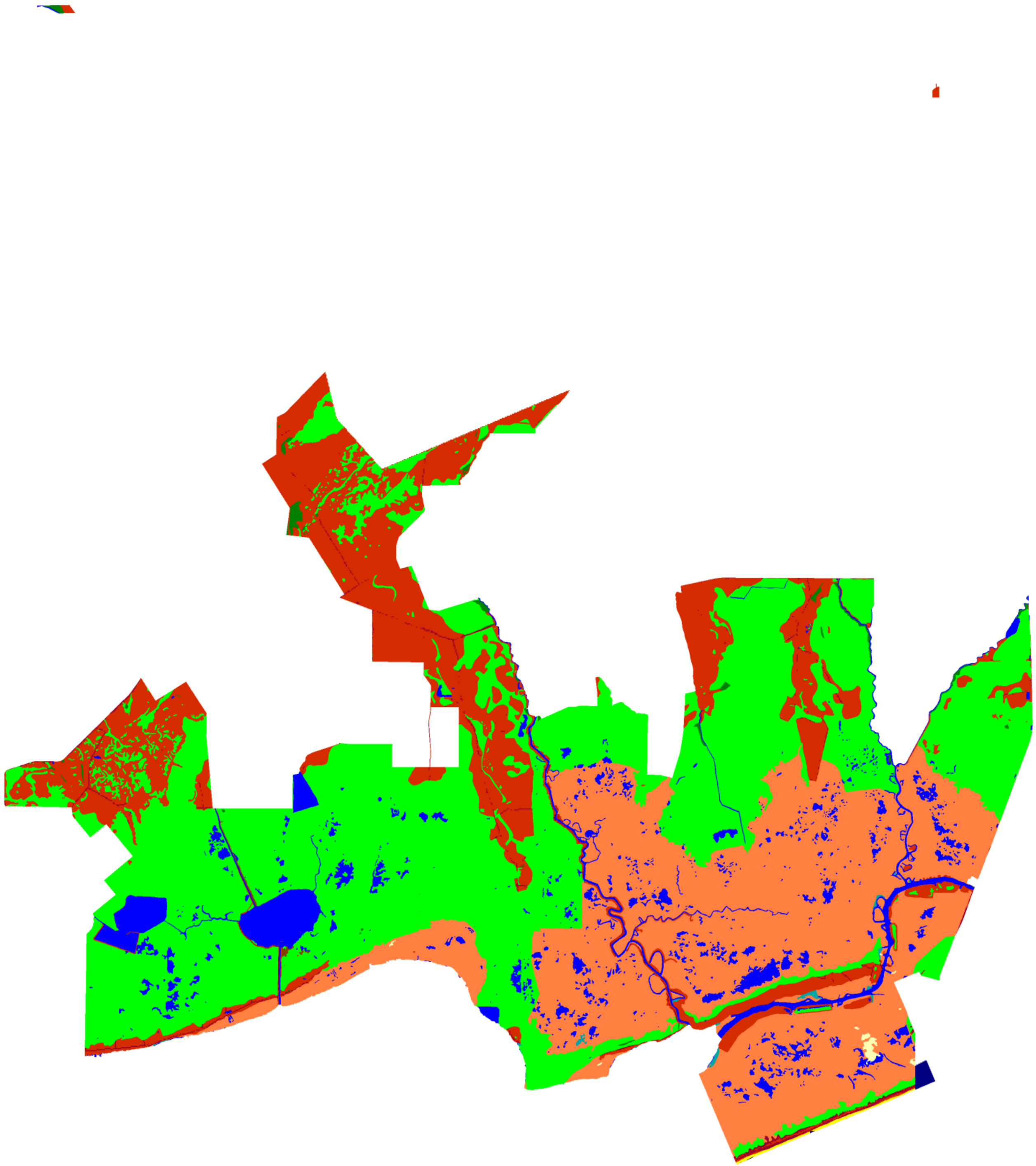
Land cover category	Land cover change by 2100 for different SLR scenarios (%)				
	0.39 m	0.69 m	1 m	1.5 m	2 m
Inland Fresh Marsh	-39	-51	-57	-63	-72
Irregularly Flooded Marsh	-19	-28	-48	-50	-61
Undeveloped Dry Land	-38	-44	-50	-60	-68
Developed Dry Land	-39	-56	-64	-74	-81
Swamp	-29	-41	-47	-53	-58
Ocean Beach	32	88	97	-1	-55
Regularly Flooded Marsh	8281	9028	10293	6387	6765
Estuarine Beach	-87	-97	-96	-99	-100

Despite the uncertainty associated with the wetland coverage maps, SLAMM analysis indicates that Anahuac NWR will be significantly impacted by SLR. At a sea level rise rate of 1 m by 2100, which is considered the "most likely" by climate scientists, nearly half of the irregularly flooded marsh, undeveloped dry land, and swamp are predicted to be lost. Moreover, as shown in the maps below, under all the SLR scenarios examined un-diked, low-lying areas are predicted to convert to open water and tidal flat.

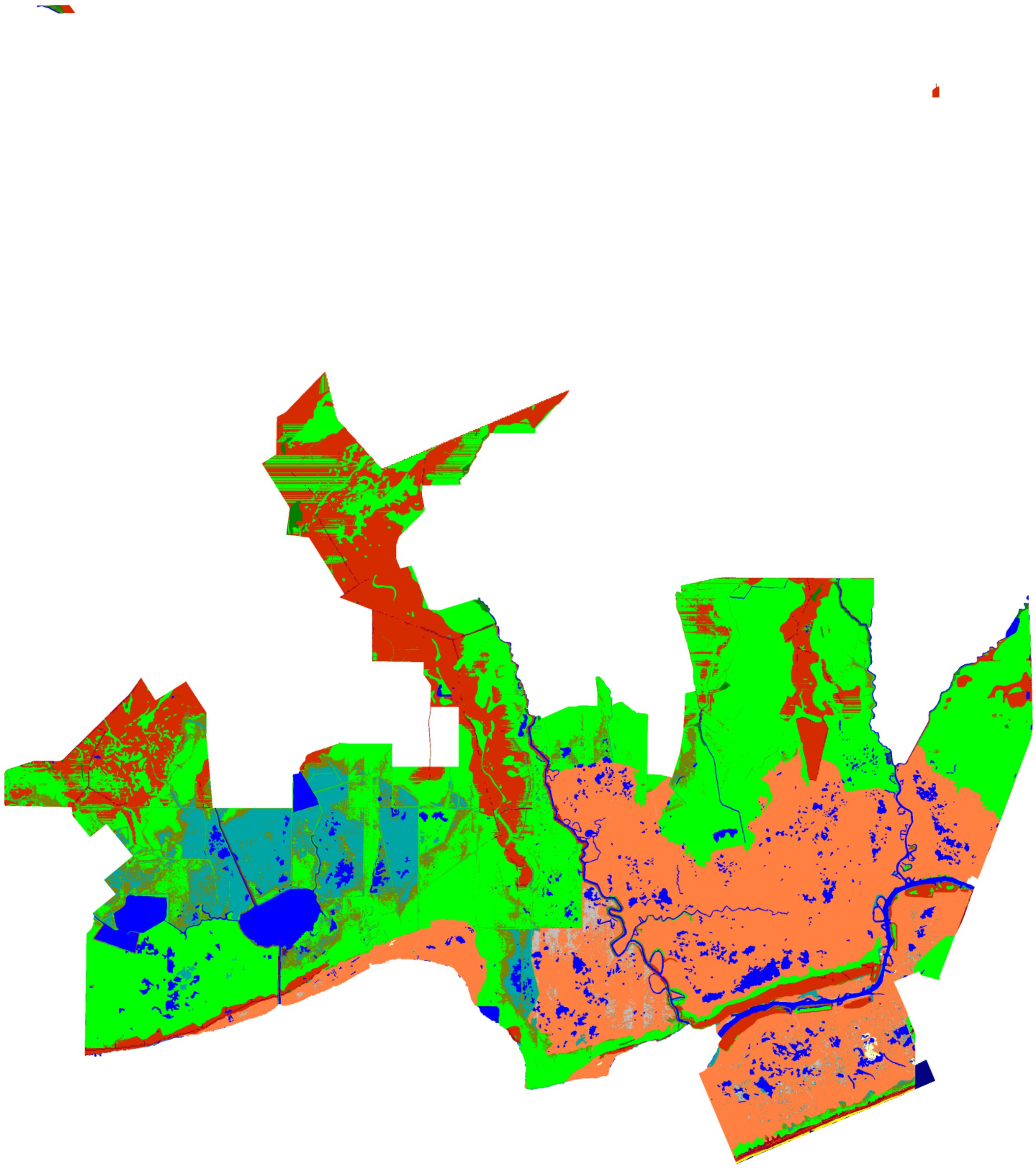
IPCC Scenario A1B-Mean, 0.39 m SLR eustatic by 2100

Results in Acres

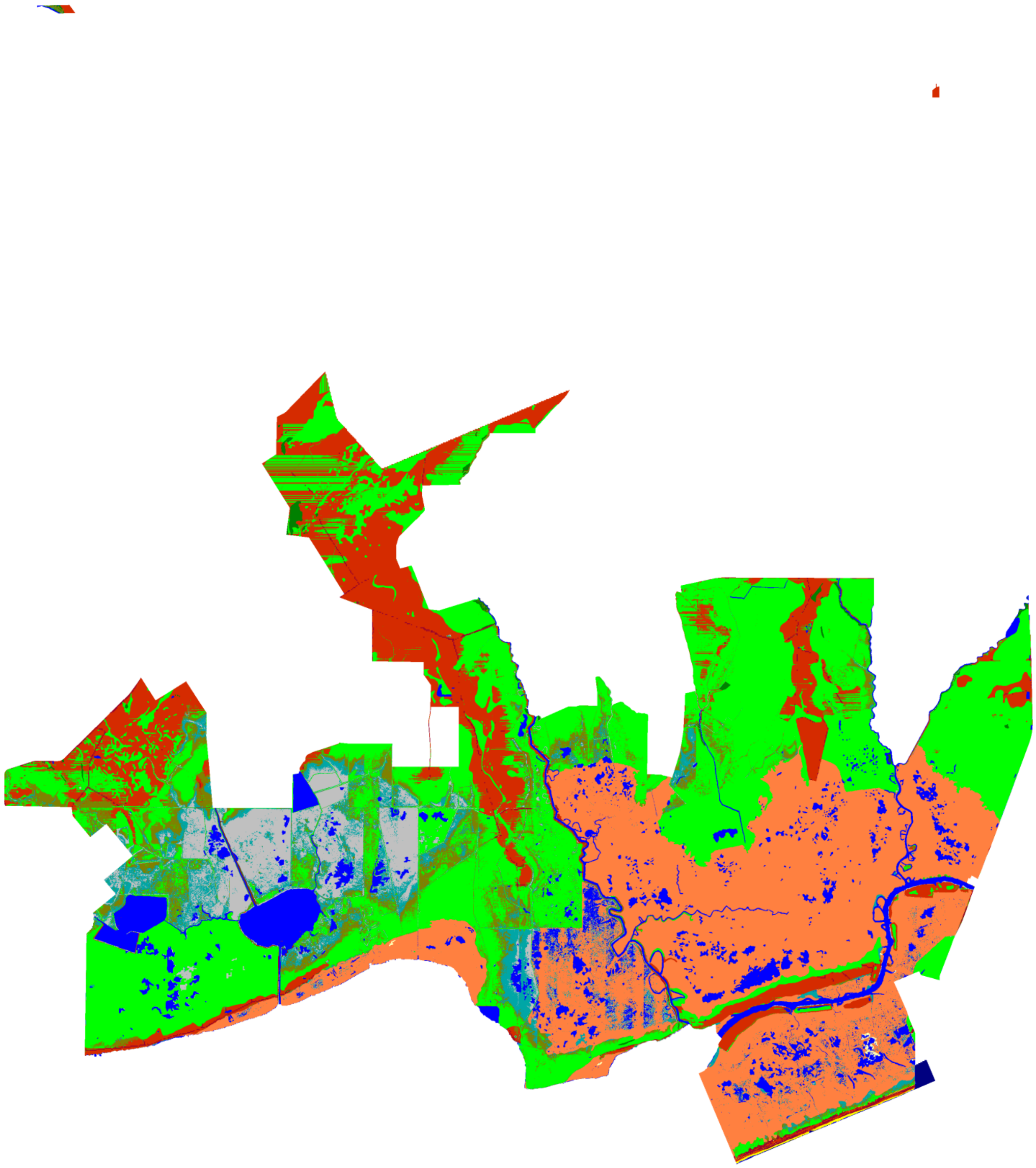
		Initial	2025	2050	2075	2100
	Inland Fresh Marsh	32815	27872	25888	22715	20143
	Irregularly Flooded Marsh	21303	20456	20166	19065	17259
	Undeveloped Dry Land	13378	10721	9874	9121	8335
	Estuarine Open Water	2434	3435	4111	7932	10906
	Inland Open Water	2289	1376	1321	1284	1259
	Developed Dry Land	480	451	421	361	291
	Swamp	268	244	229	209	189
	Open Ocean	82	87	93	97	99
	Ocean Beach	80	75	70	83	106
	Regularly Flooded Marsh	77	4765	3562	4569	6470
	Estuarine Beach	72	56	36	24	9
	Inland Shore	45	37	29	20	12
	Riverine Tidal	35	14	9	4	2
	Transitional Salt Marsh	3	3177	3841	4957	4545
	Tidal Flat	0	596	3712	2920	3737
	Total (incl. water)	**73361**	**73361**	**73361**	**73361**	**73361**



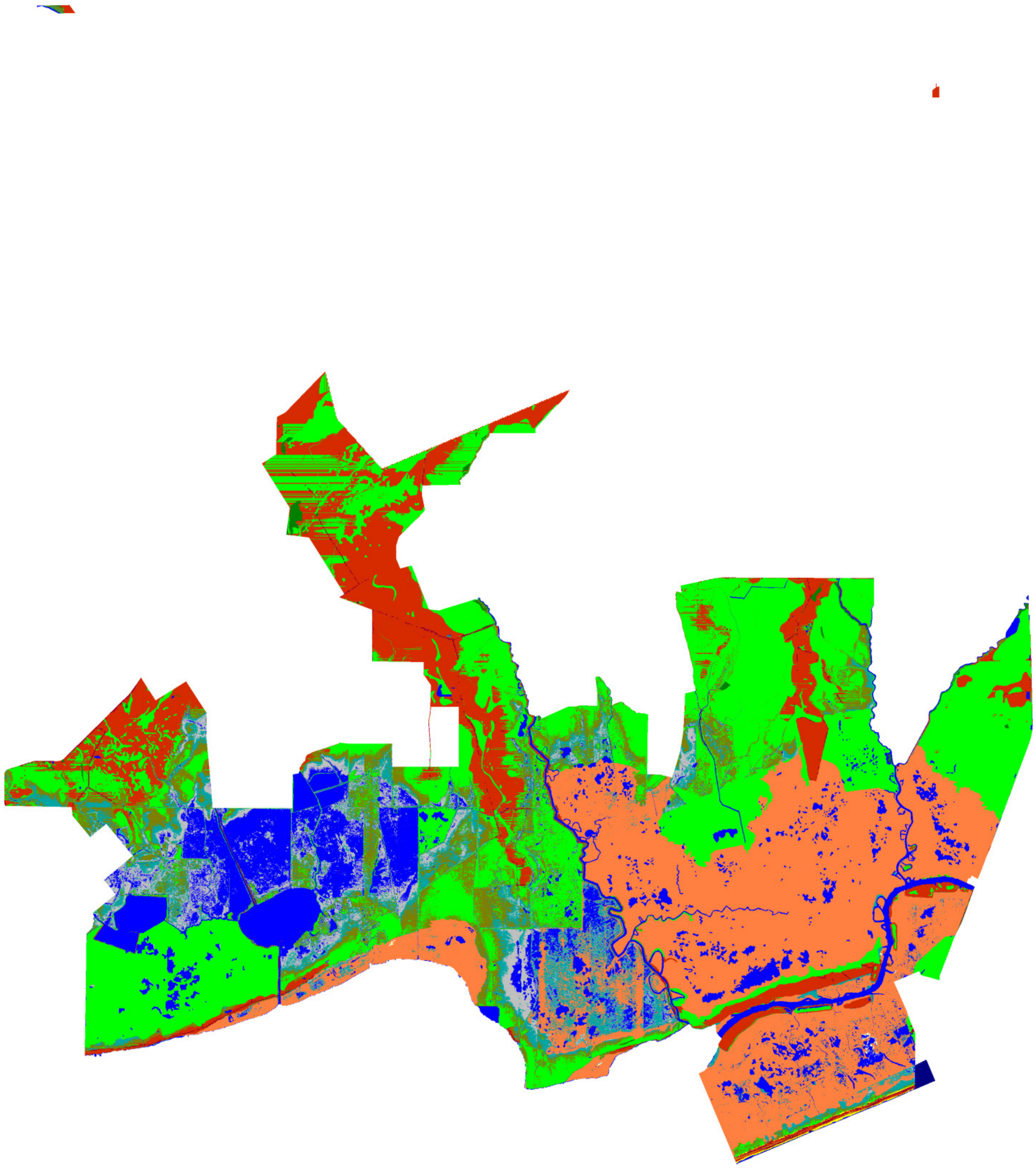
Anahuac NWR, Initial Condition



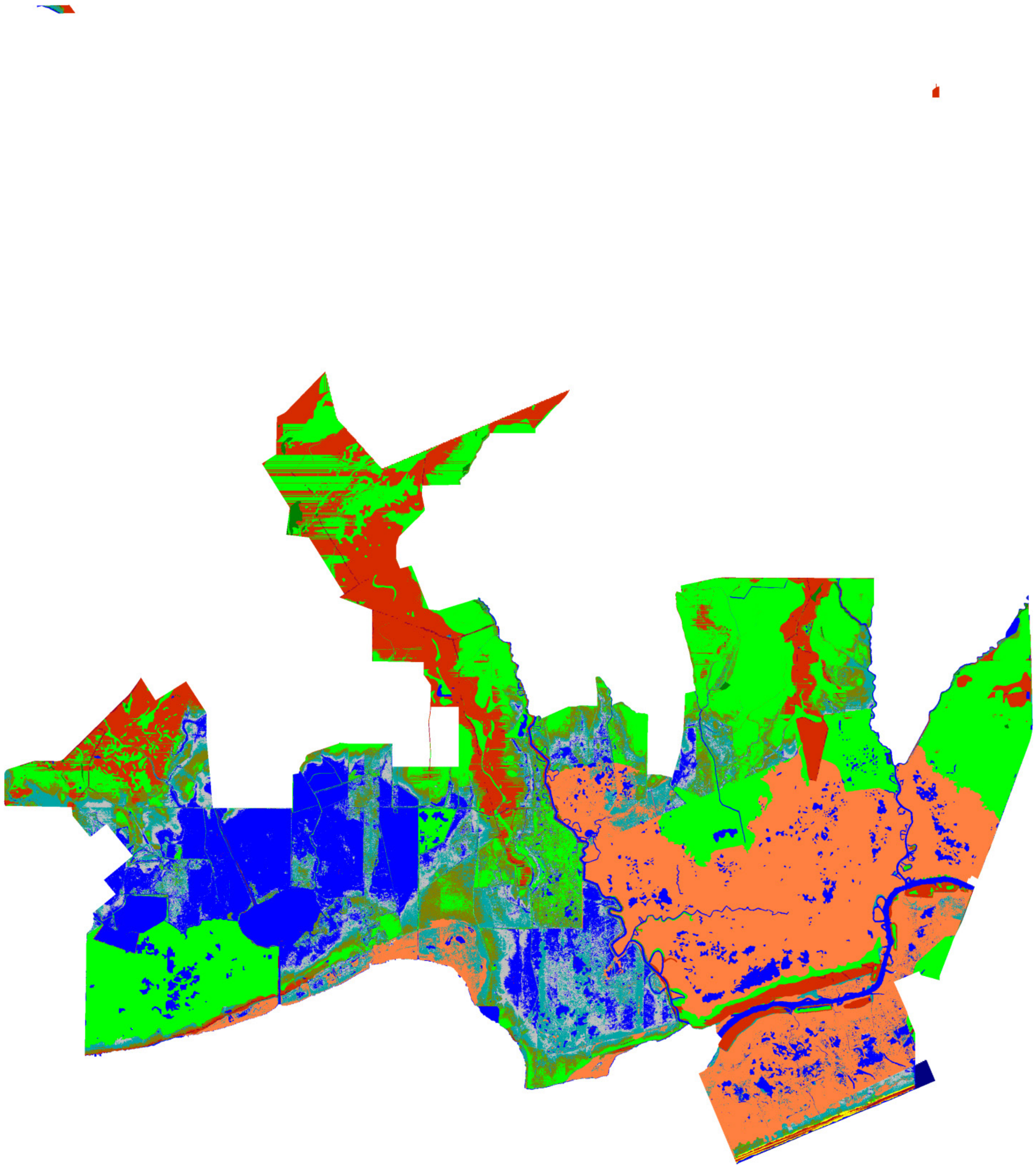
Anahuac NWR, 2025, Scenario A1B Mean



Anahuac NWR, 2050, Scenario A1B Mean



Anahuac NWR, 2075, Scenario A1B Mean

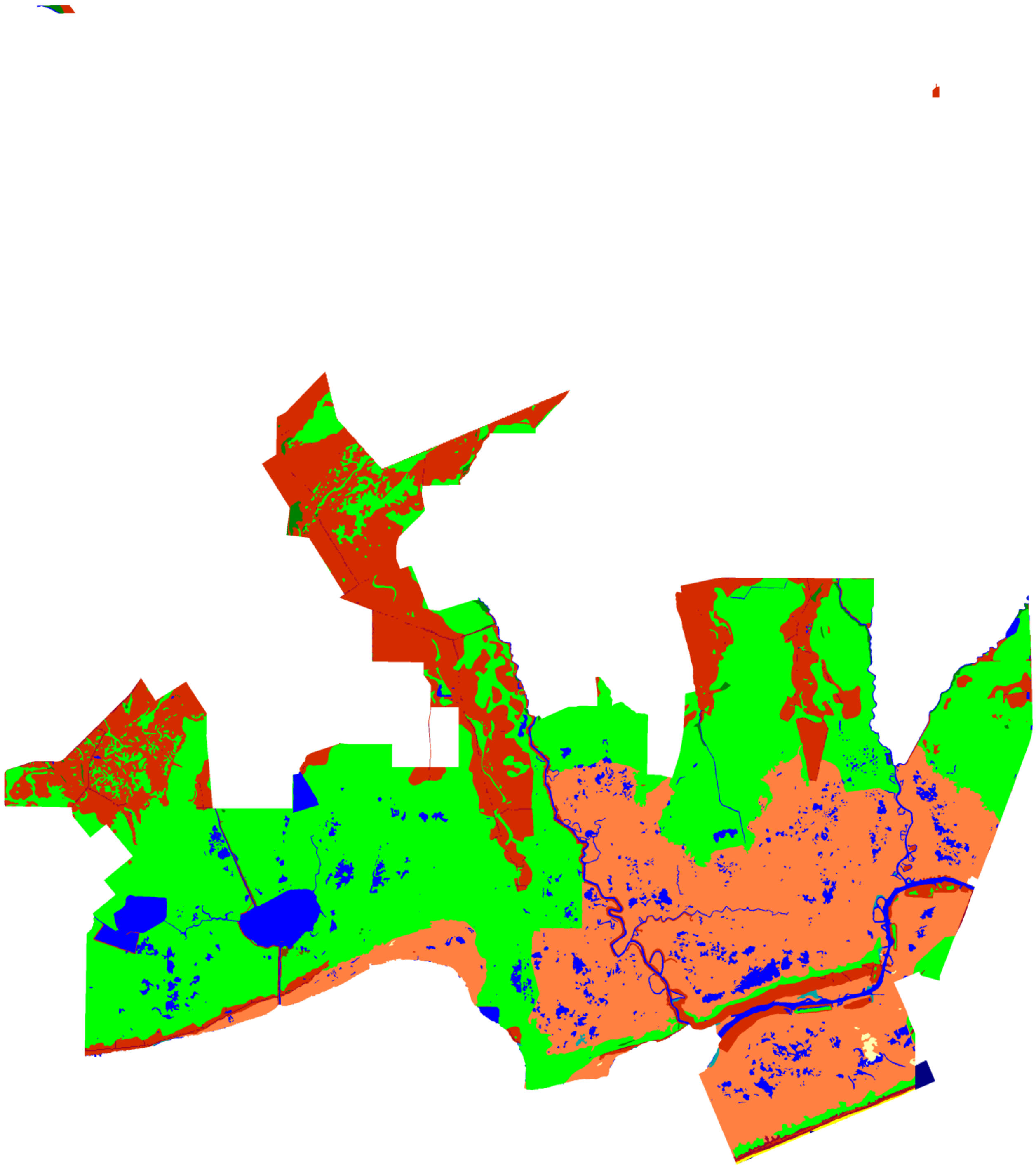


Anahuac NWR, 2100, Scenario A1B Mean

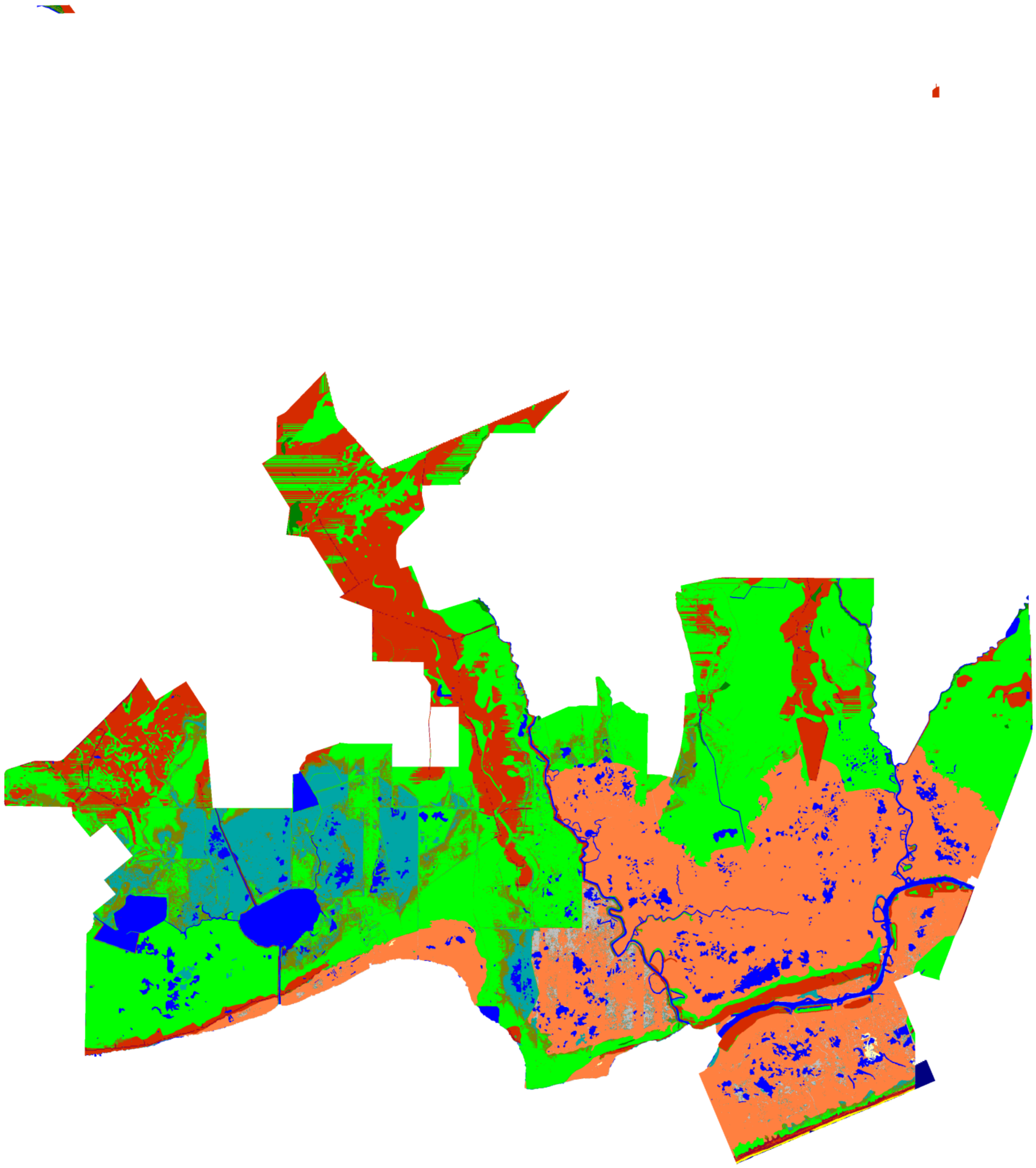
IPCC Scenario A1B-Max, 0.69 m SLR eustatic by 2100

Results in Acres

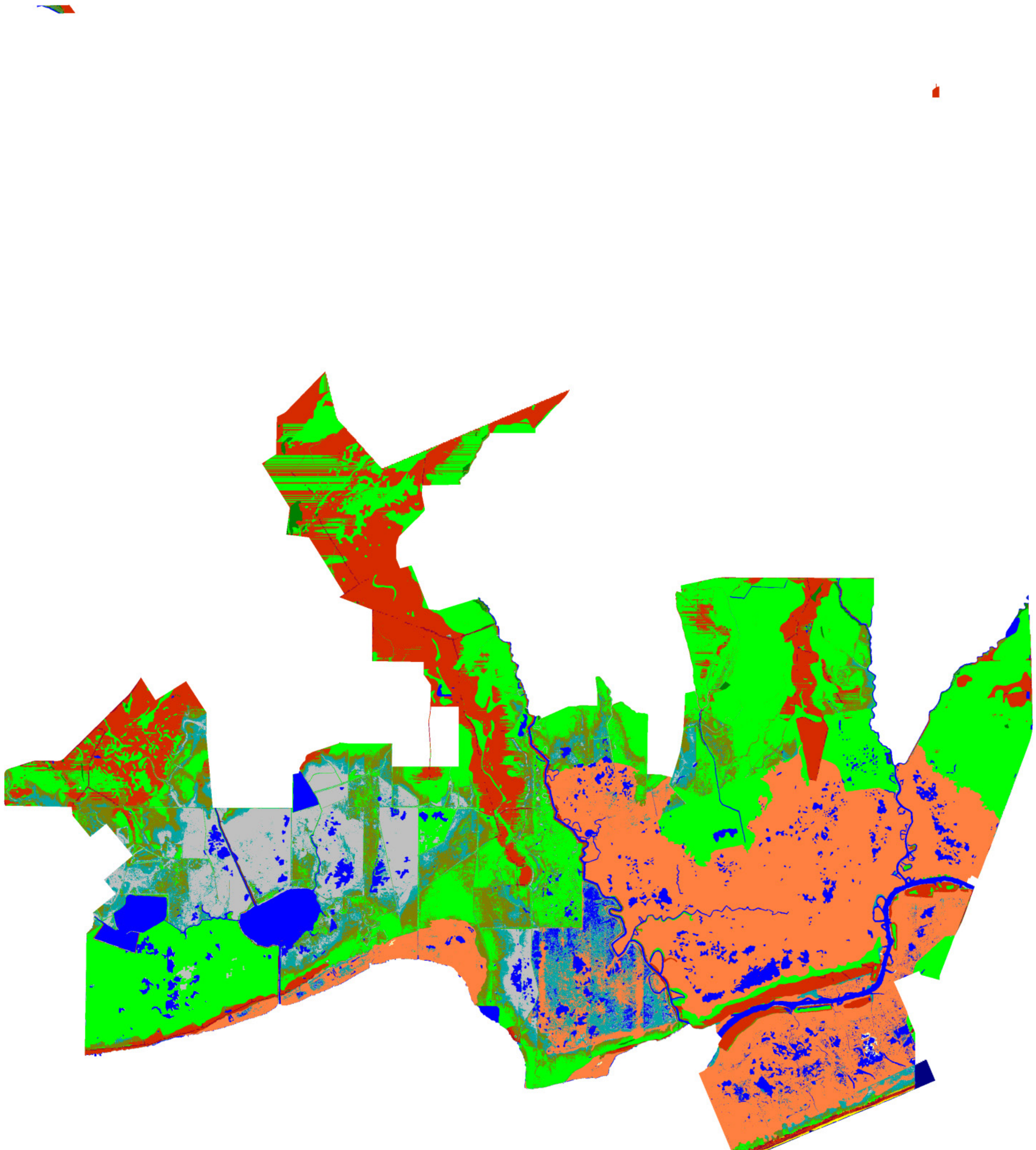
		Initial	2025	2050	2075	2100
	Inland Fresh Marsh	32815	27133	22948	18434	16120
	Irregularly Flooded Marsh	21303	20347	19056	16366	15388
	Undeveloped Dry Land	13378	10671	9661	8565	7524
	Estuarine Open Water	2434	3456	4284	9561	14203
	Inland Open Water	2289	1366	1302	1262	1241
	Developed Dry Land	480	447	392	291	213
	Swamp	268	241	219	188	158
	Open Ocean	82	88	97	102	108
	Ocean Beach	80	75	77	117	151
	Regularly Flooded Marsh	77	5420	4856	8338	7047
	Estuarine Beach	72	51	29	8	2
	Inland Shore	45	35	24	12	5
	Riverine Tidal	35	13	7	2	1
	Transitional Salt Marsh	3	3387	5326	5697	3418
	Tidal Flat	0	631	5083	4419	7782
	Total (incl. water)	**73361**	**73361**	**73361**	**73361**	**73361**



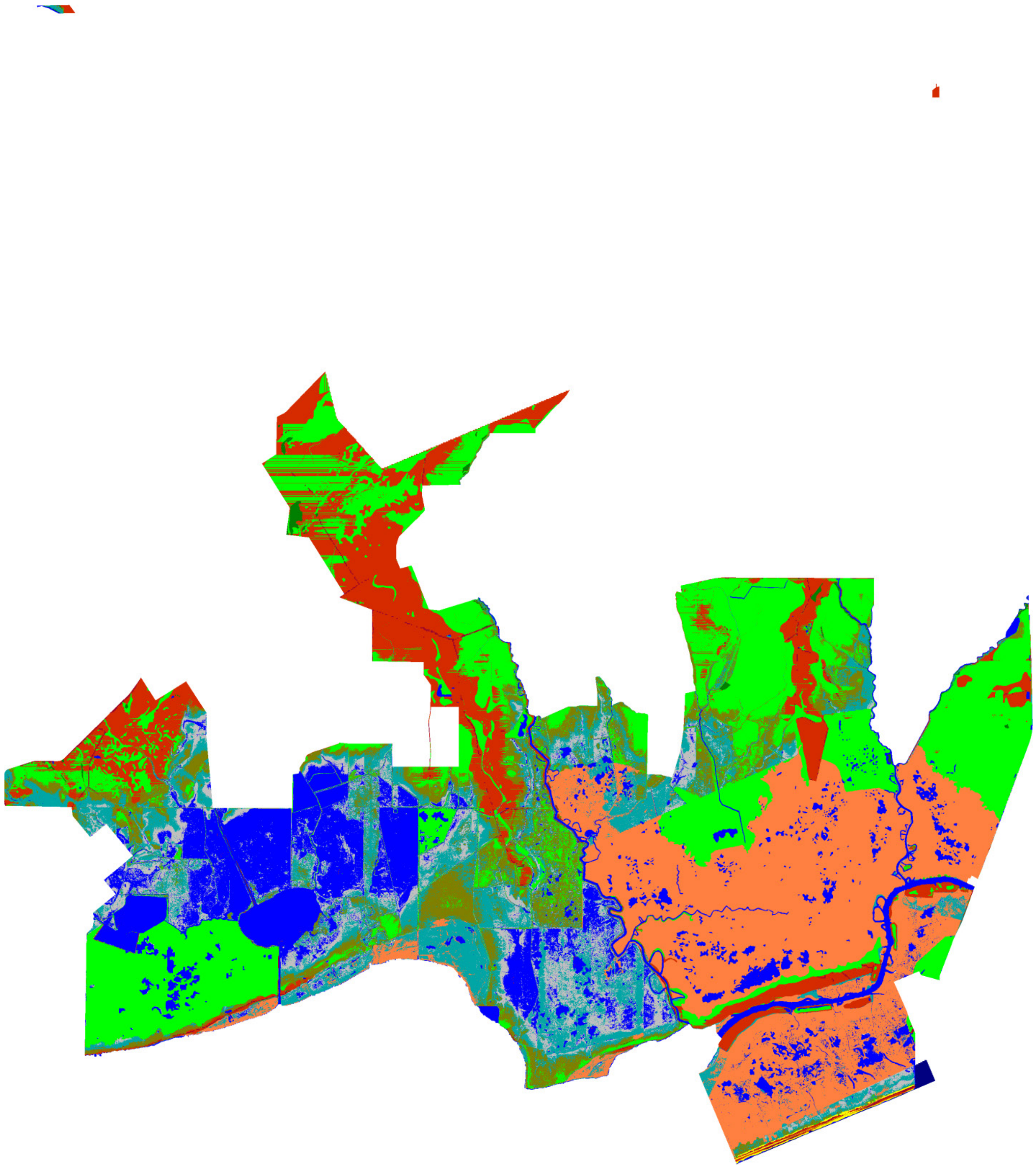
Anahuac NWR, Initial Condition



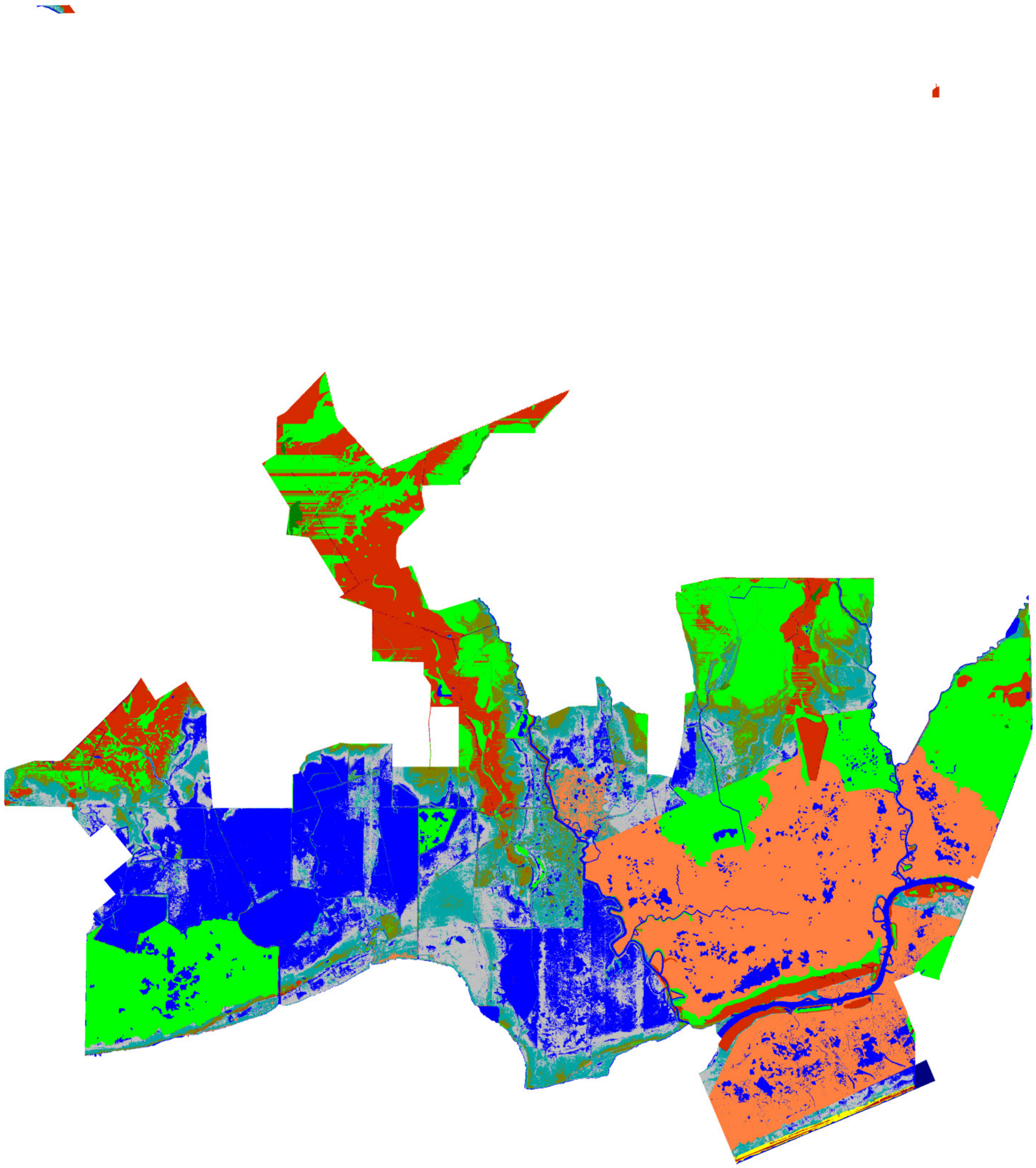
Anahuac NWR, 2025, Scenario A1B Maximum



Anahuac NWR, 2050, Scenario A1B Maximum



Anahuac NWR, 2075, Scenario A1B Maximum

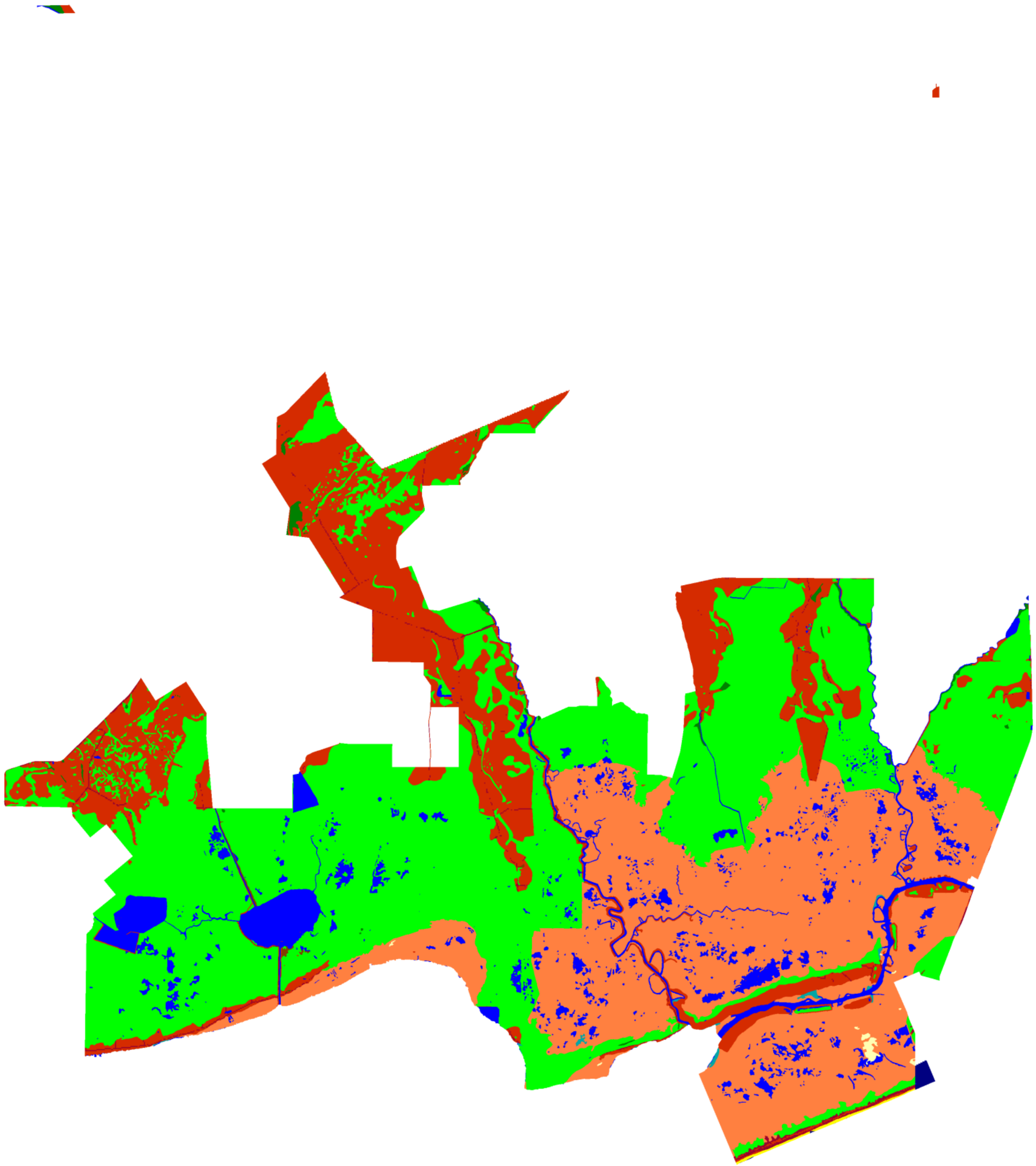


Anahuac NWR, 2100, Scenario A1B Maximum

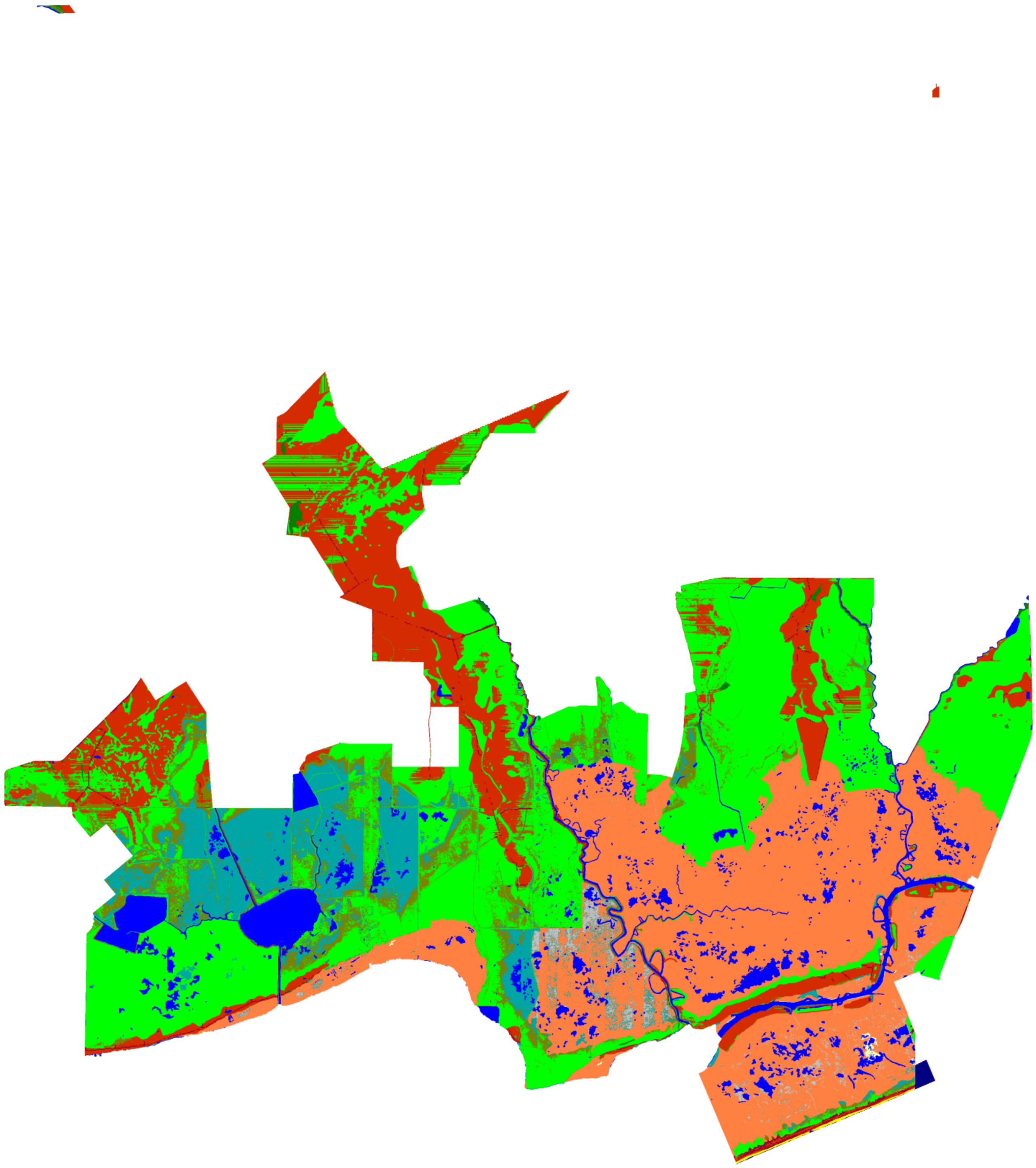
1 m eustatic SLR by 2100

Results in Acres

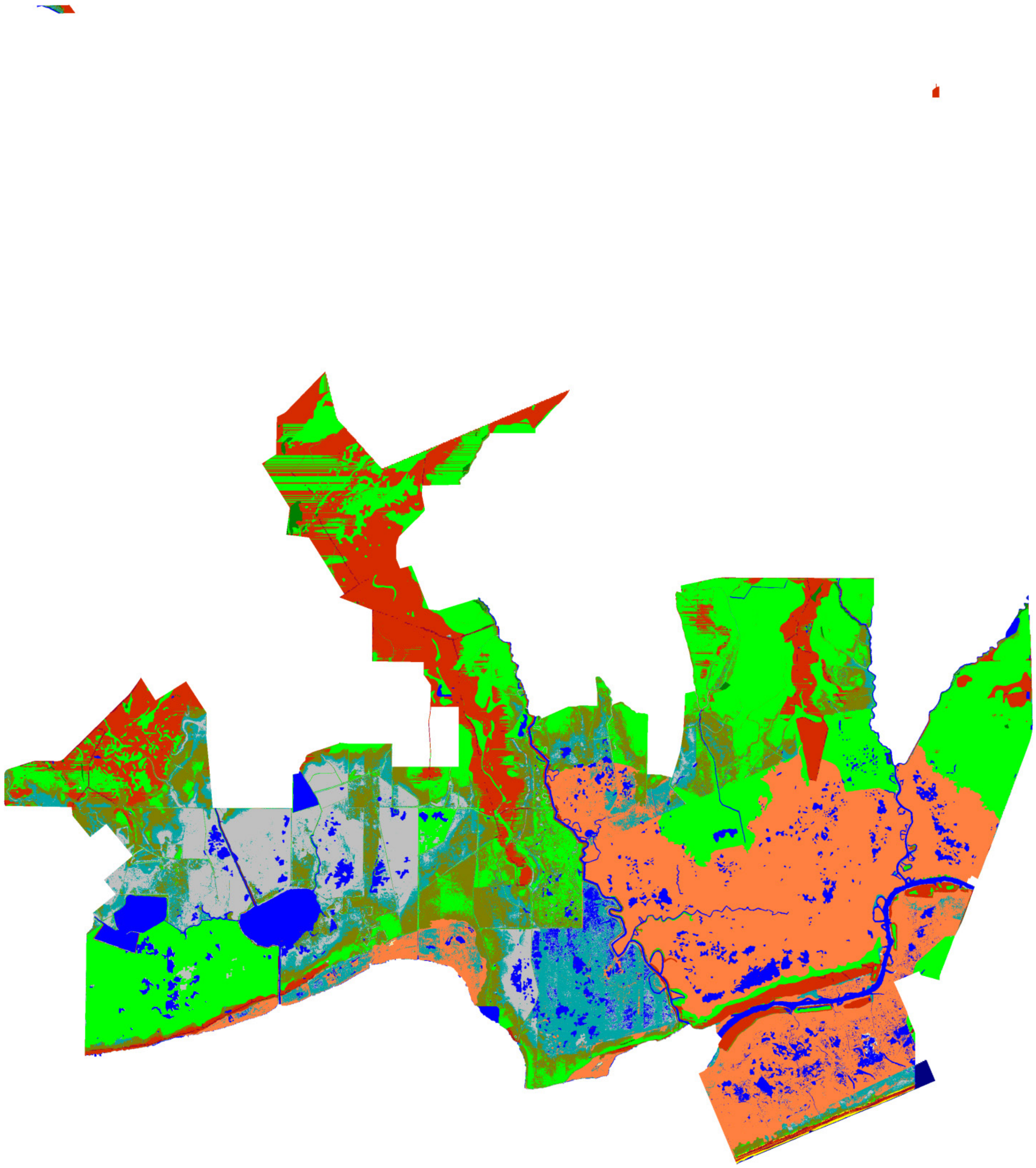
		Initial	2025	2050	2075	2100
	Inland Fresh Marsh	32815	26237	20231	16052	14226
	Irregularly Flooded Marsh	21303	20184	17374	13334	10988
	Undeveloped Dry Land	13378	10610	9387	8004	6735
	Estuarine Open Water	2434	3476	4374	10525	17535
	Inland Open Water	2289	1357	1289	1248	1232
	Developed Dry Land	480	441	357	232	172
	Swamp	268	238	207	168	142
	Open Ocean	82	90	101	108	135
	Ocean Beach	80	74	91	147	158
	Regularly Flooded Marsh	77	6146	6644	11394	8023
	Estuarine Beach	72	45	21	2	3
	Inland Shore	45	33	20	6	1
	Riverine Tidal	35	13	5	1	0
	Transitional Salt Marsh	3	3739	7321	5658	3139
	Tidal Flat	0	677	5941	6481	10872
	Total (incl. water)	**73361**	**73361**	**73361**	**73361**	**73361**



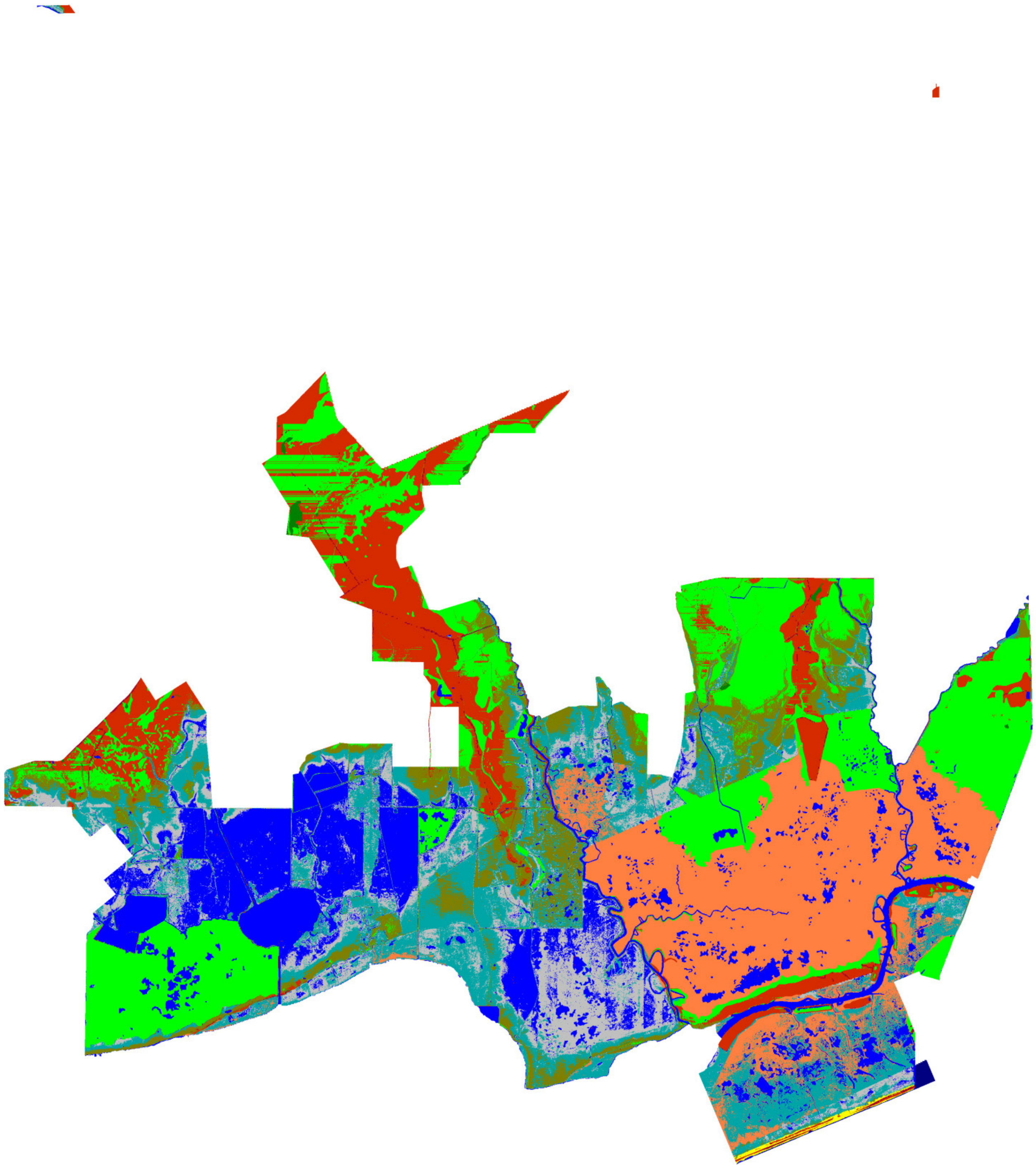
Anahuac NWR, Initial Condition



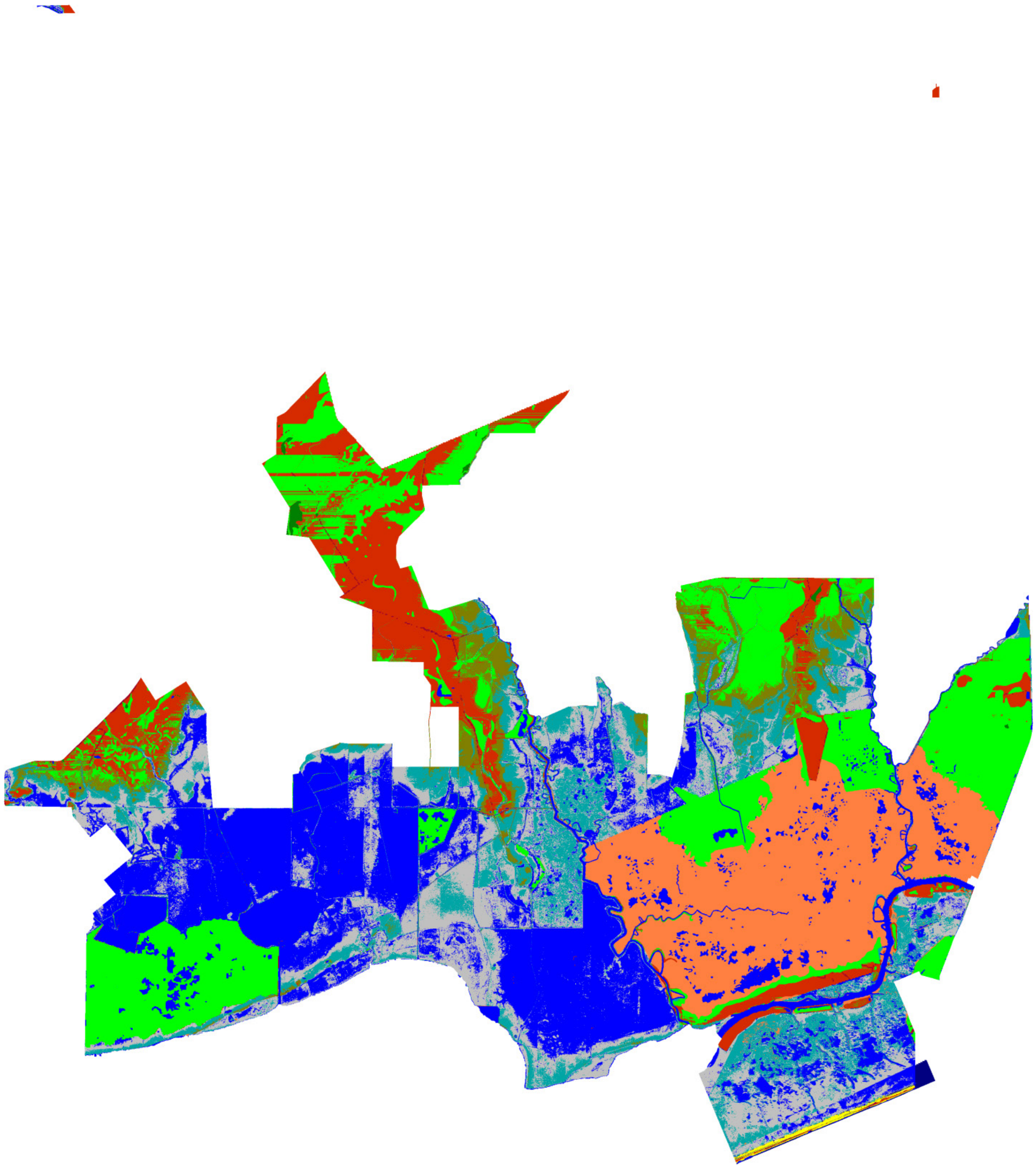
Anahuac NWR, 2025, 1 Meter



Anahuac NWR, 2050, 1 Meter



Anahuac NWR, 2075, 1 Meter

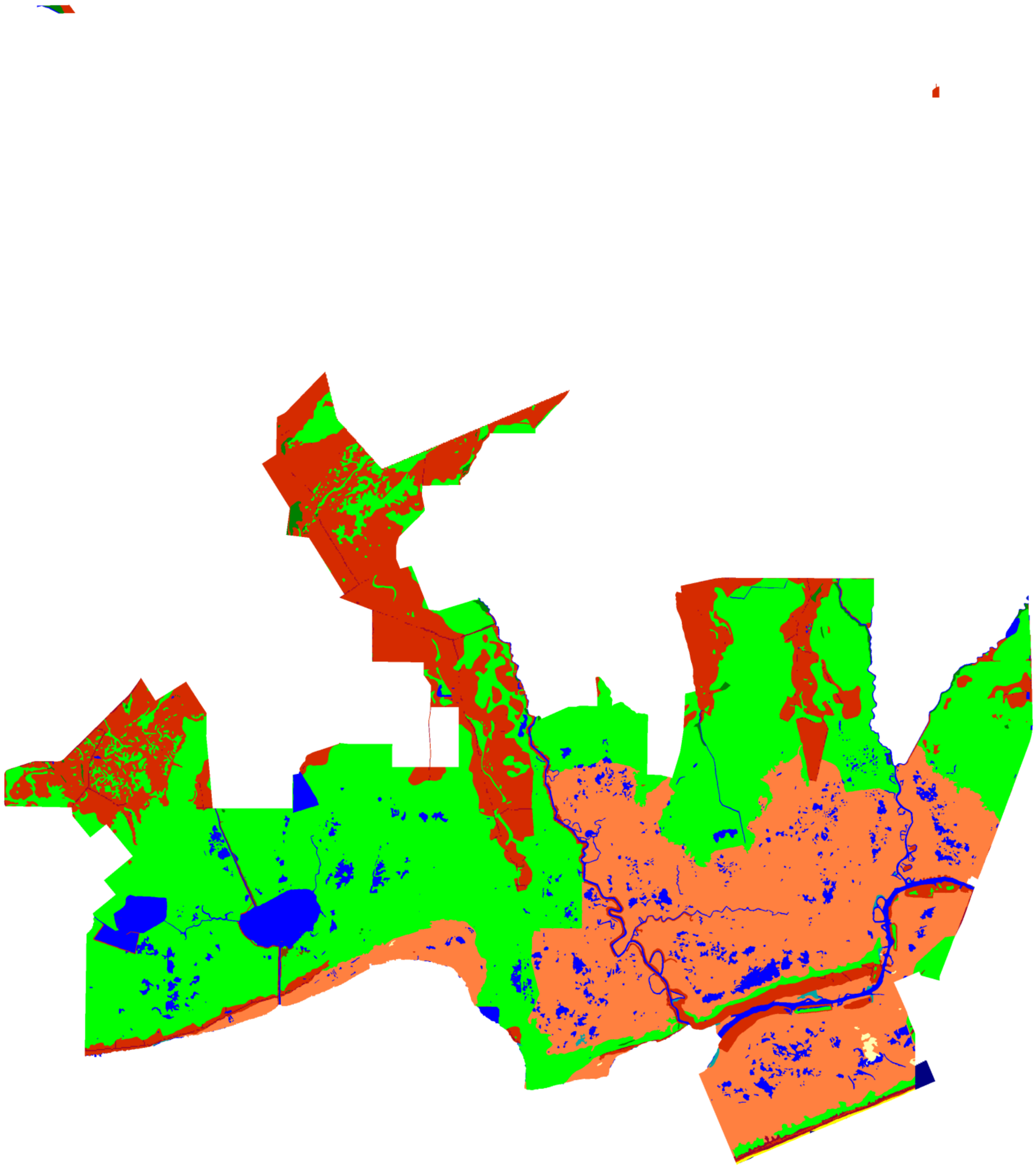


Anahuac NWR, 2100, 1 Meter

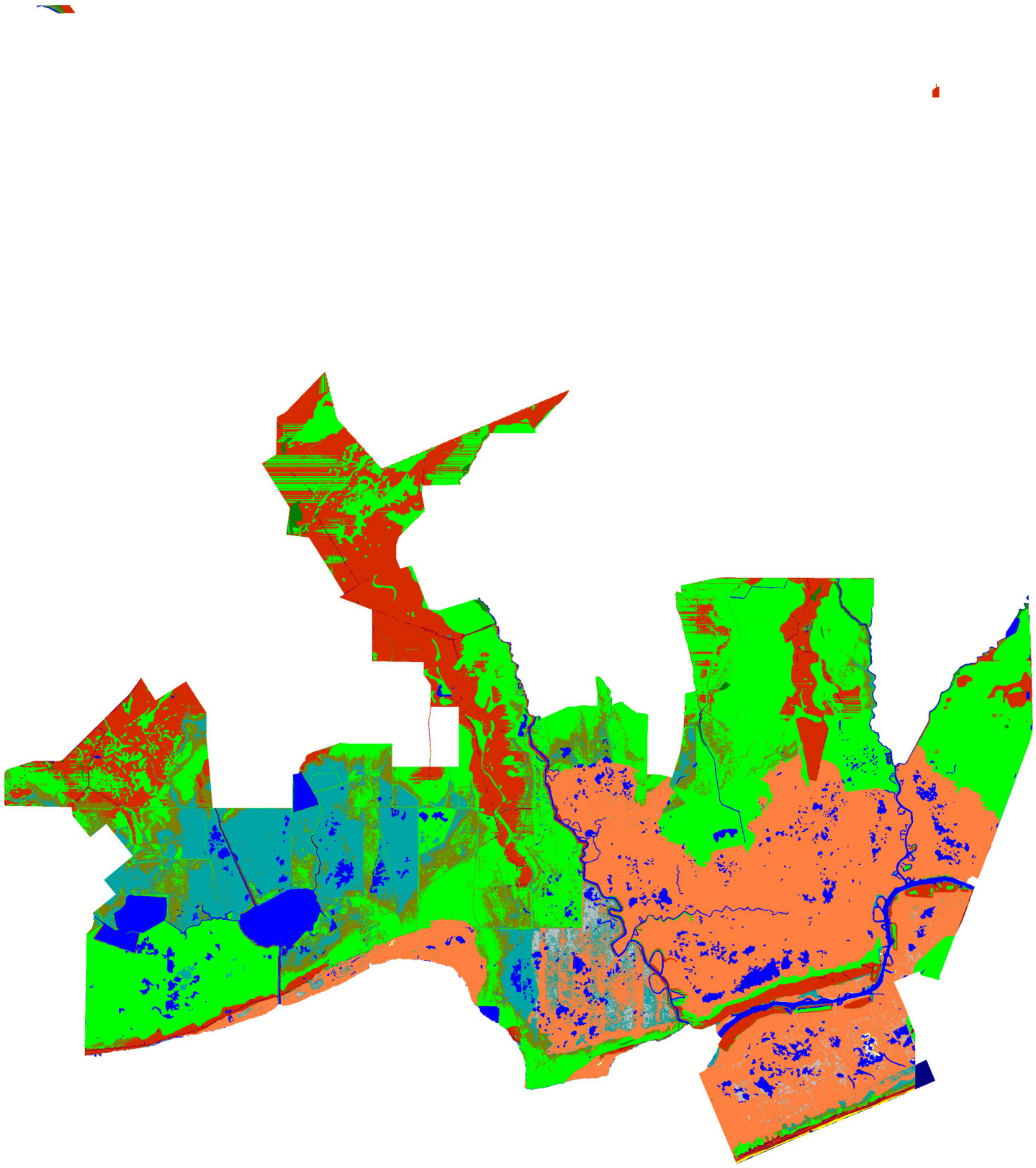
1.5 m eustatic SLR by 2100

Results in Acres

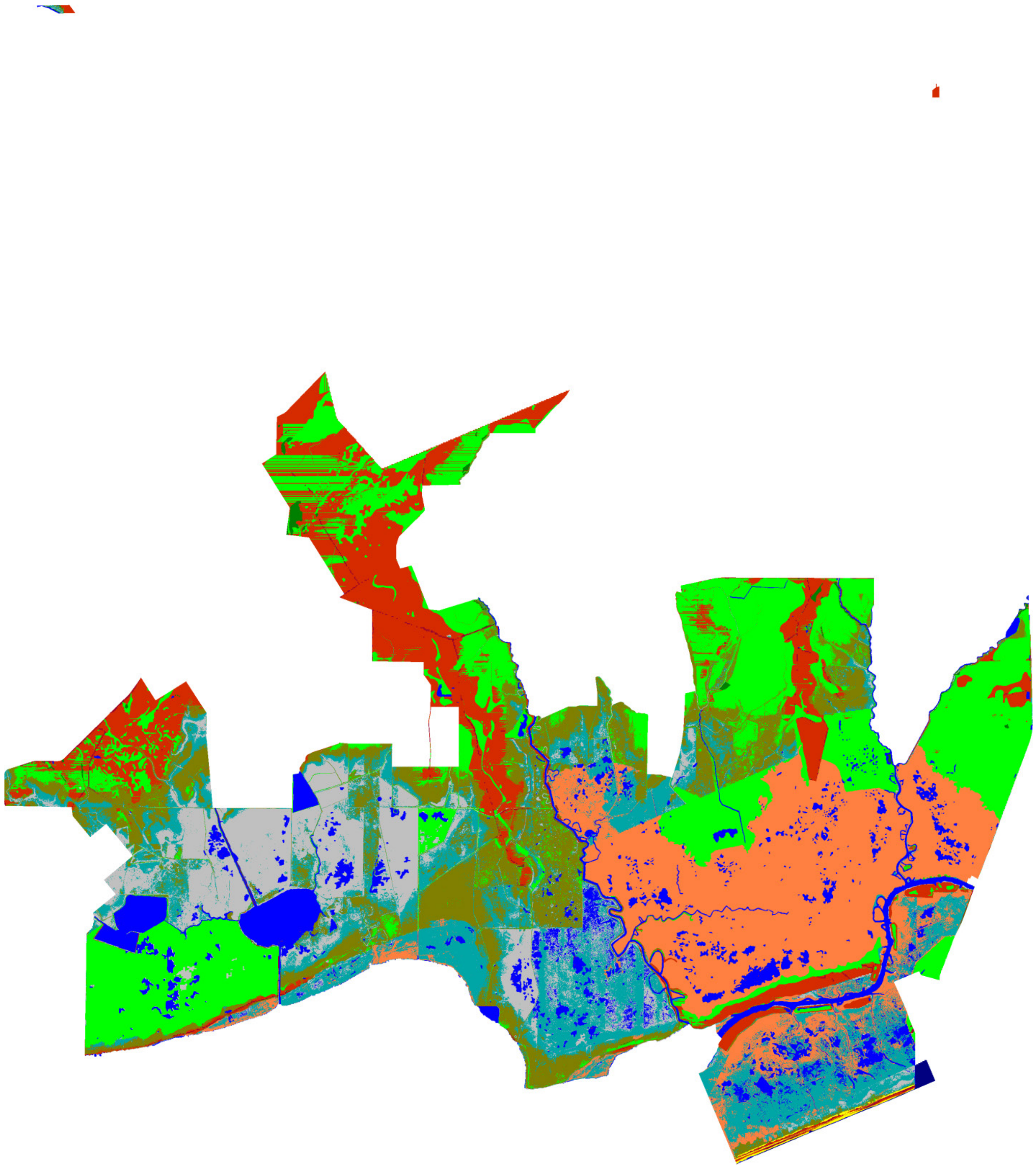
		Initial	2025	2050	2075	2100
	Inland Fresh Marsh	32815	24607	17116	14013	12155
	Irregularly Flooded Marsh	21303	19688	13738	10870	10641
	Undeveloped Dry Land	13378	10487	8862	7127	5326
	Estuarine Open Water	2434	3498	4481	12068	23150
	Inland Open Water	2289	1349	1272	1235	1224
	Developed Dry Land	480	431	293	180	124
	Swamp	268	233	188	145	127
	Open Ocean	82	93	105	132	241
	Ocean Beach	80	74	122	165	79
	Regularly Flooded Marsh	77	7276	10803	12122	5007
	Estuarine Beach	72	37	6	2	1
	Inland Shore	45	31	12	1	0
	Riverine Tidal	35	12	3	1	0
	Transitional Salt Marsh	3	4817	9239	4922	3647
	Tidal Flat	0	730	7123	10379	11637
	Total (incl. water)	**73361**	**73361**	**73361**	**73361**	**73361**



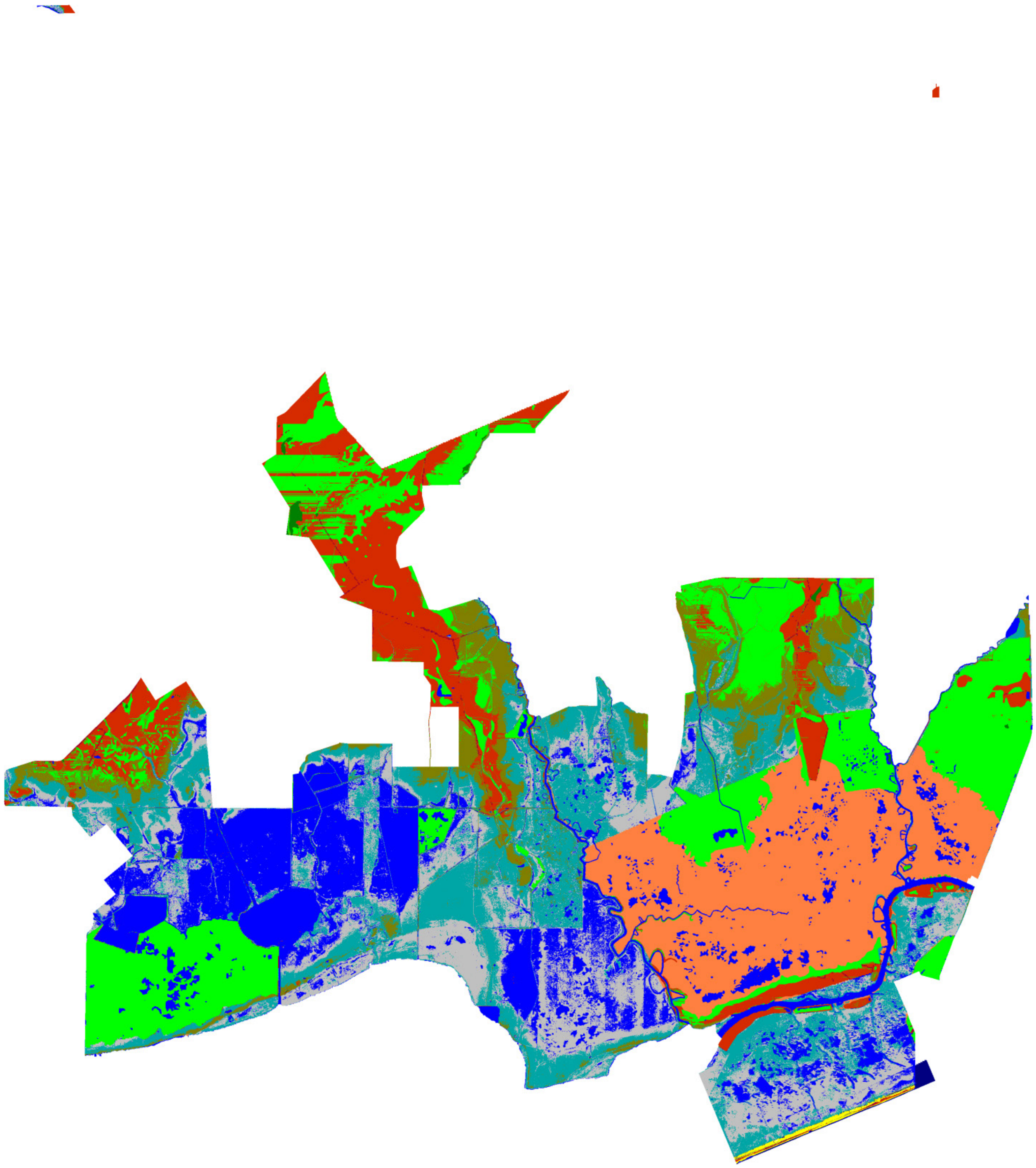
Anahuac NWR, Initial Condition



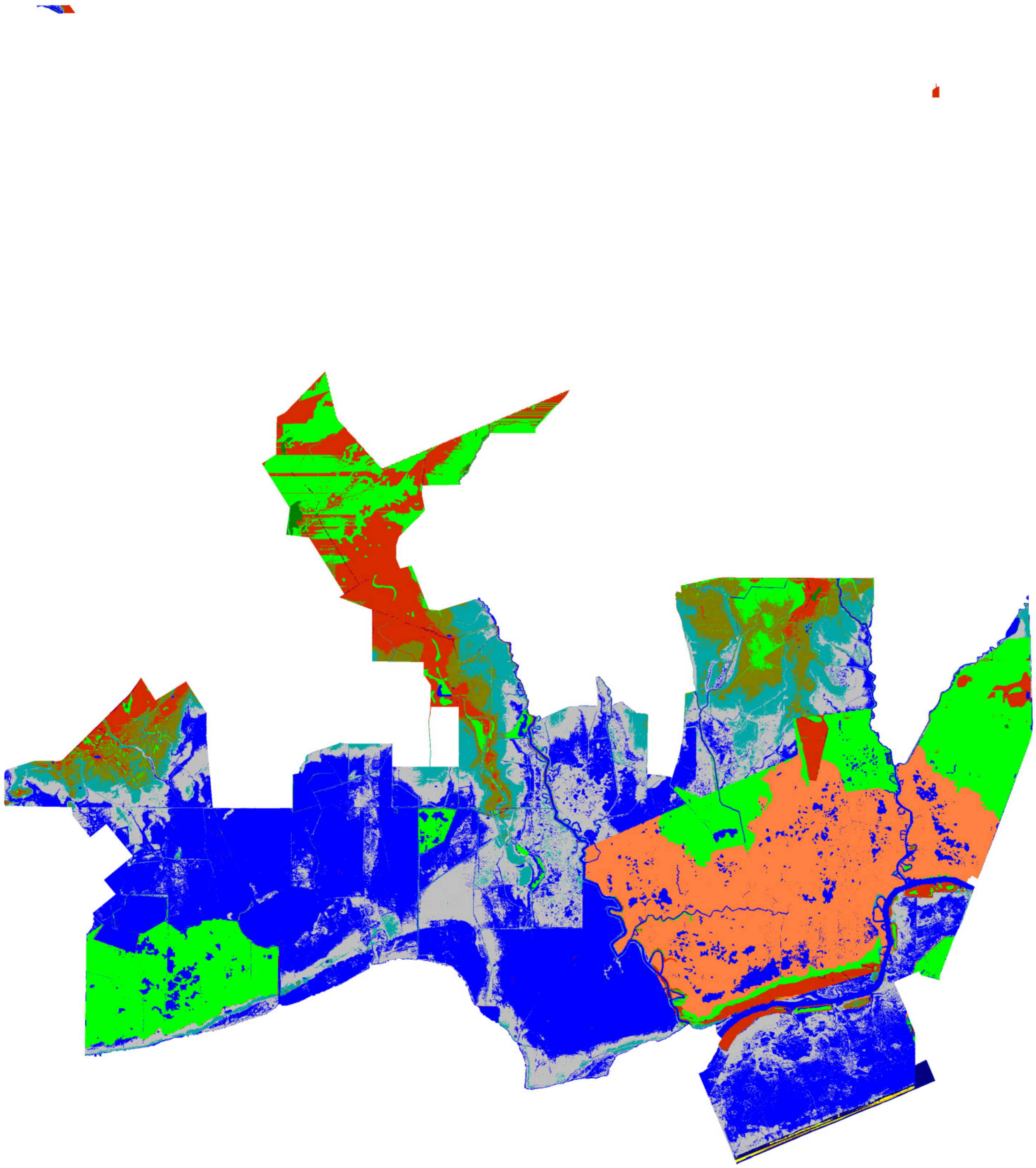
Anahuac NWR, 2025, 1.5 Meters



Anahuac NWR, 2050, 1.5 Meters



Anahuac NWR, 2075, 1.5 Meters

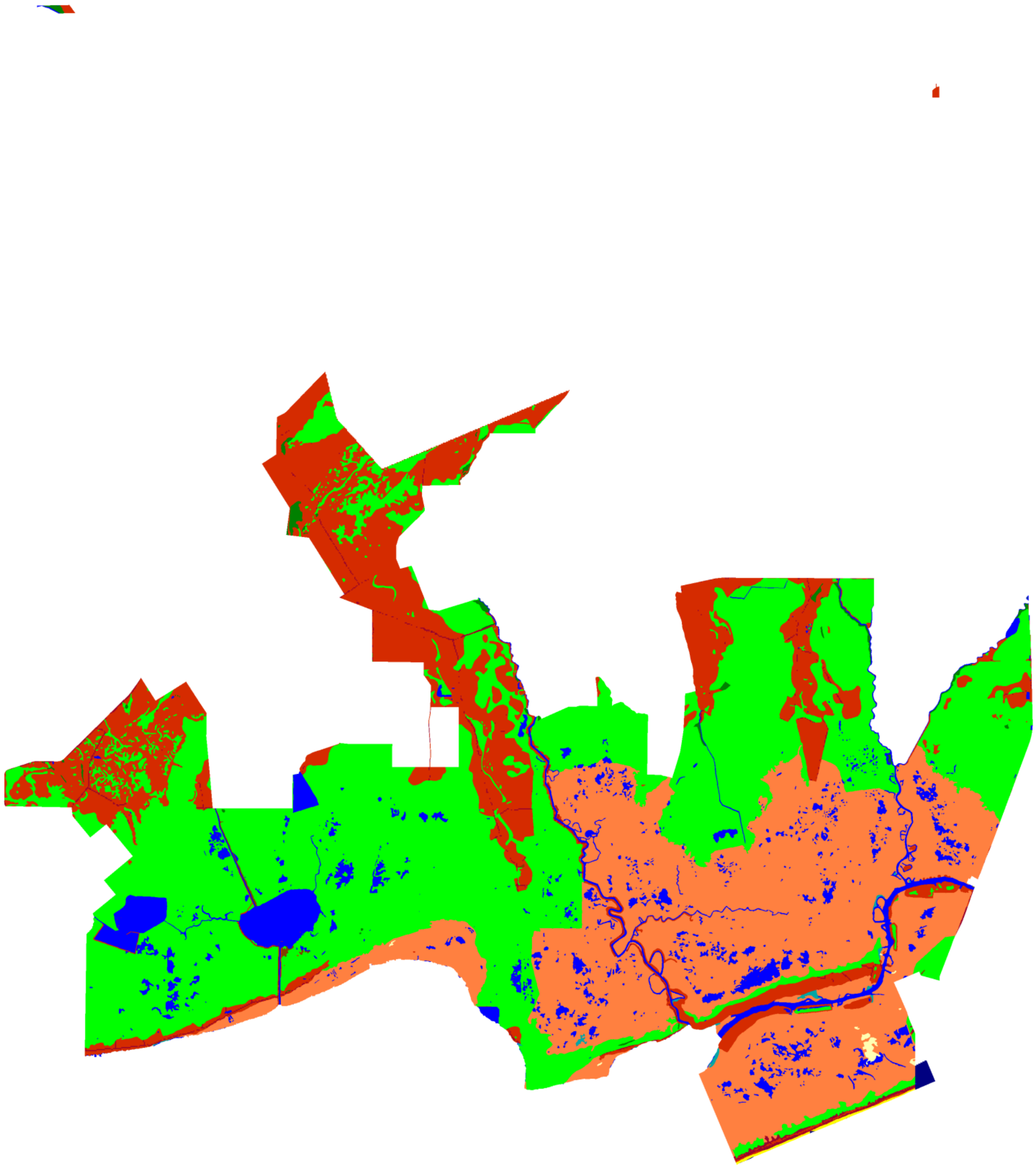


Anahuac NWR, 2100, 1.5 Meters

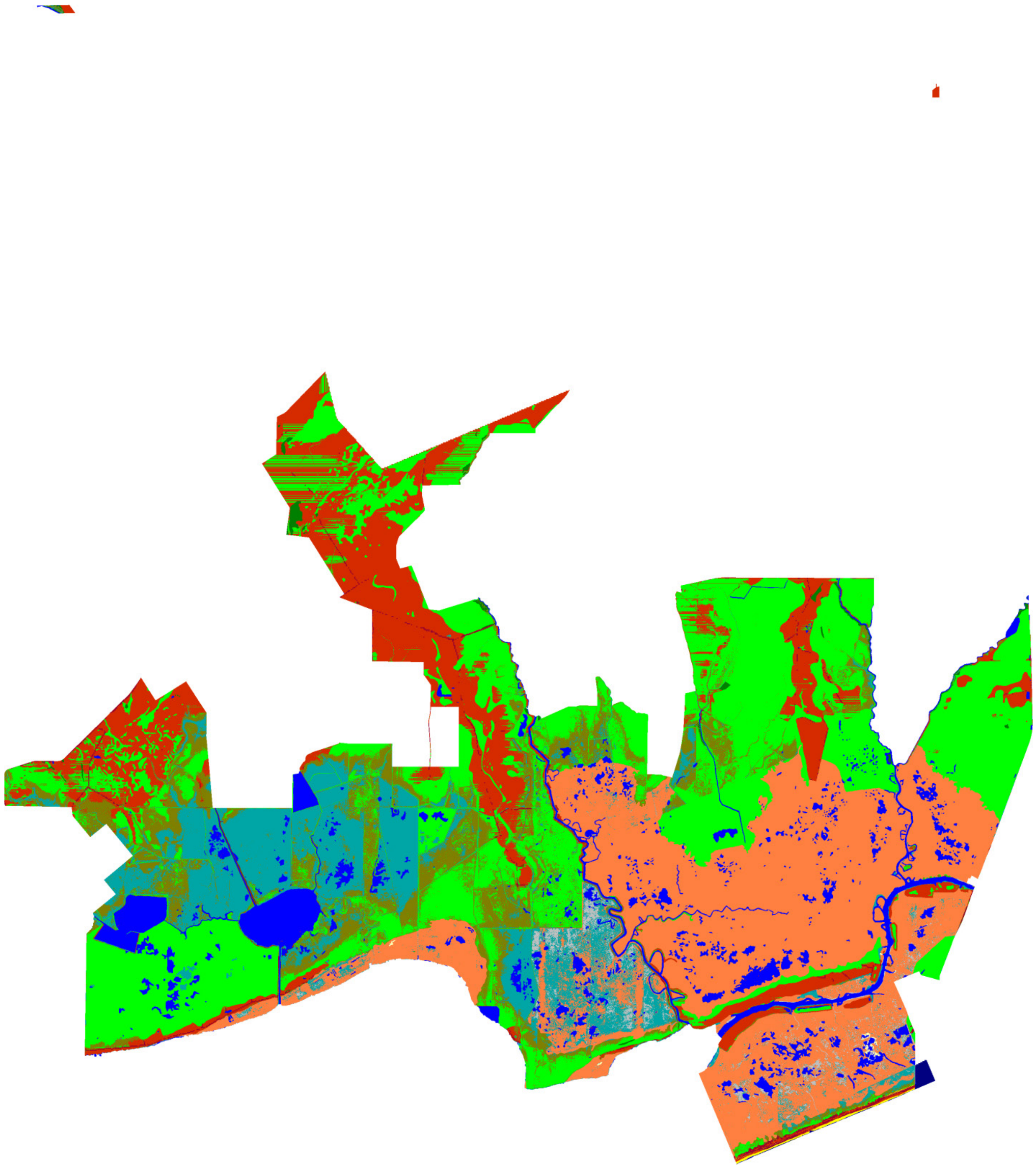
2 m eustatic SLR by 2100

Results in Acres

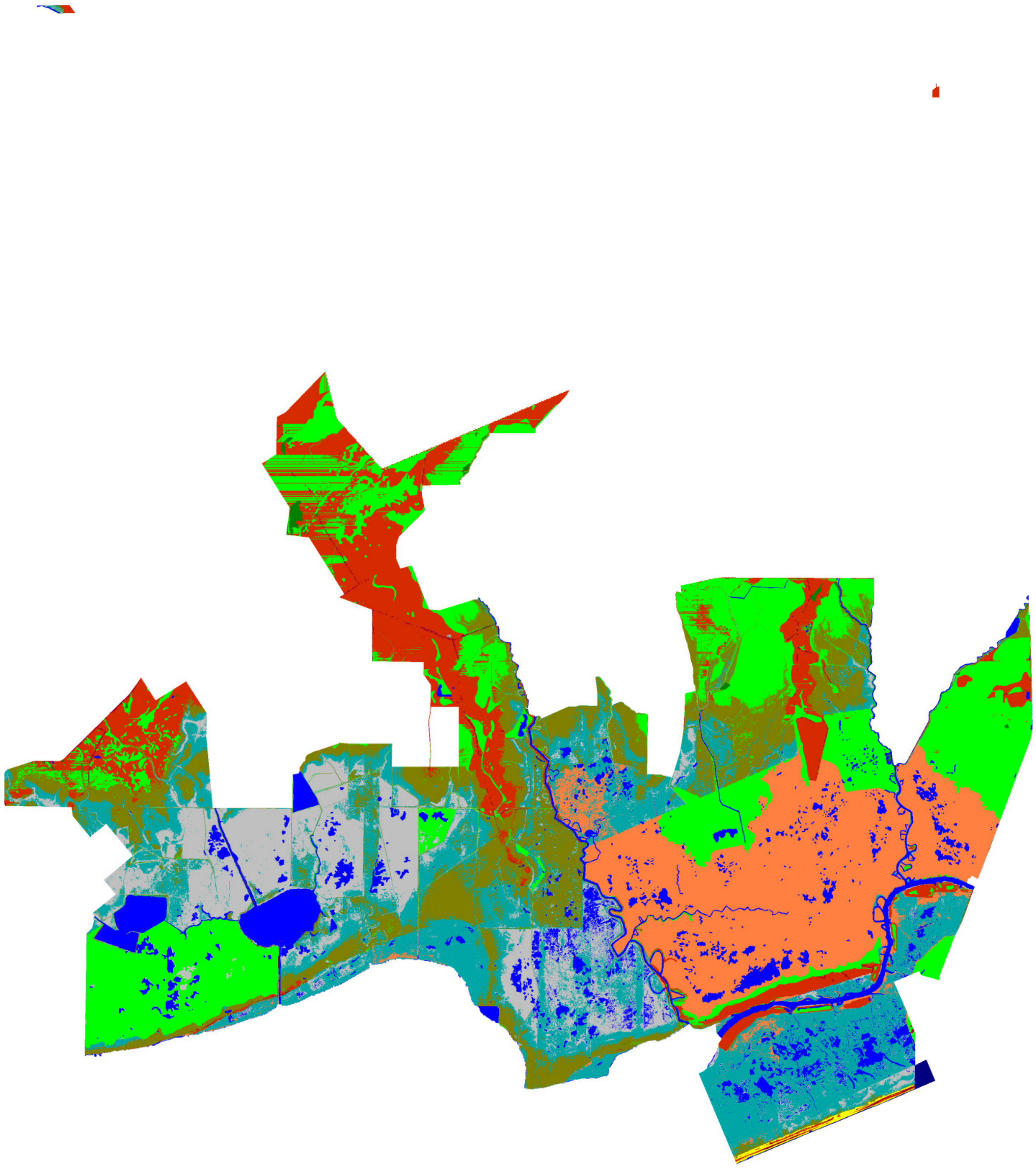
		Initial	2025	2050	2075	2100
	Inland Fresh Marsh	32815	22922	15443	12520	9129
	Irregularly Flooded Marsh	21303	18783	11671	10770	8272
	Undeveloped Dry Land	13378	10360	8343	6060	4300
	Estuarine Open Water	2434	3510	4521	13099	31517
	Inland Open Water	2289	1343	1261	1228	1215
	Developed Dry Land	480	419	240	144	91
	Swamp	268	227	171	133	113
	Open Ocean	82	96	110	199	297
	Ocean Beach	80	74	148	118	36
	Regularly Flooded Marsh	77	8203	13751	10521	5300
	Estuarine Beach	72	34	1	1	0
	Inland Shore	45	28	7	0	0
	Riverine Tidal	35	11	1	0	0
	Transitional Salt Marsh	3	6618	9642	5264	2852
	Tidal Flat	0	732	8050	13304	10240
	Total (incl. water)	**73361**	**73361**	**73361**	**73361**	**73361**



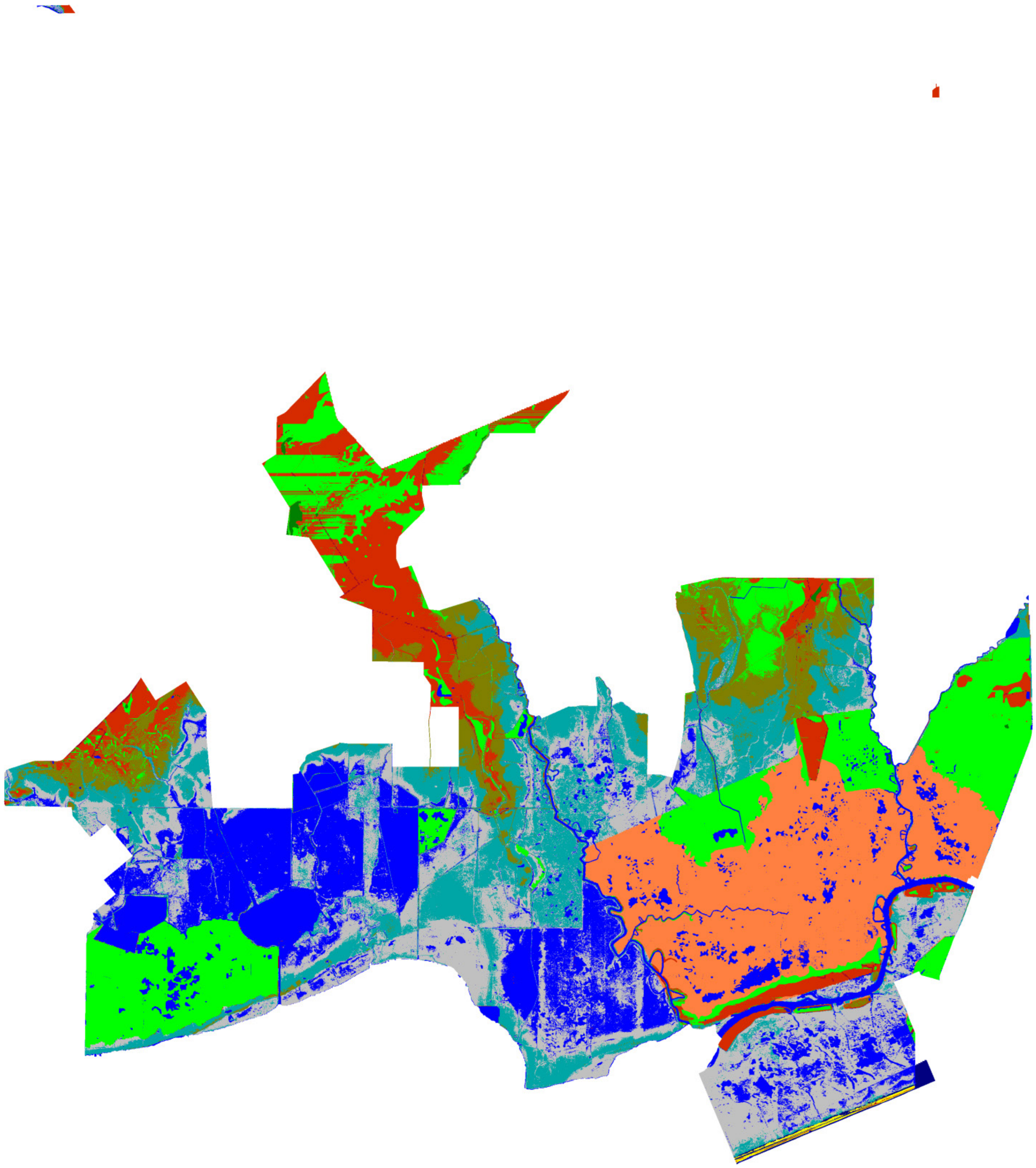
Anahuac NWR, Initial Condition



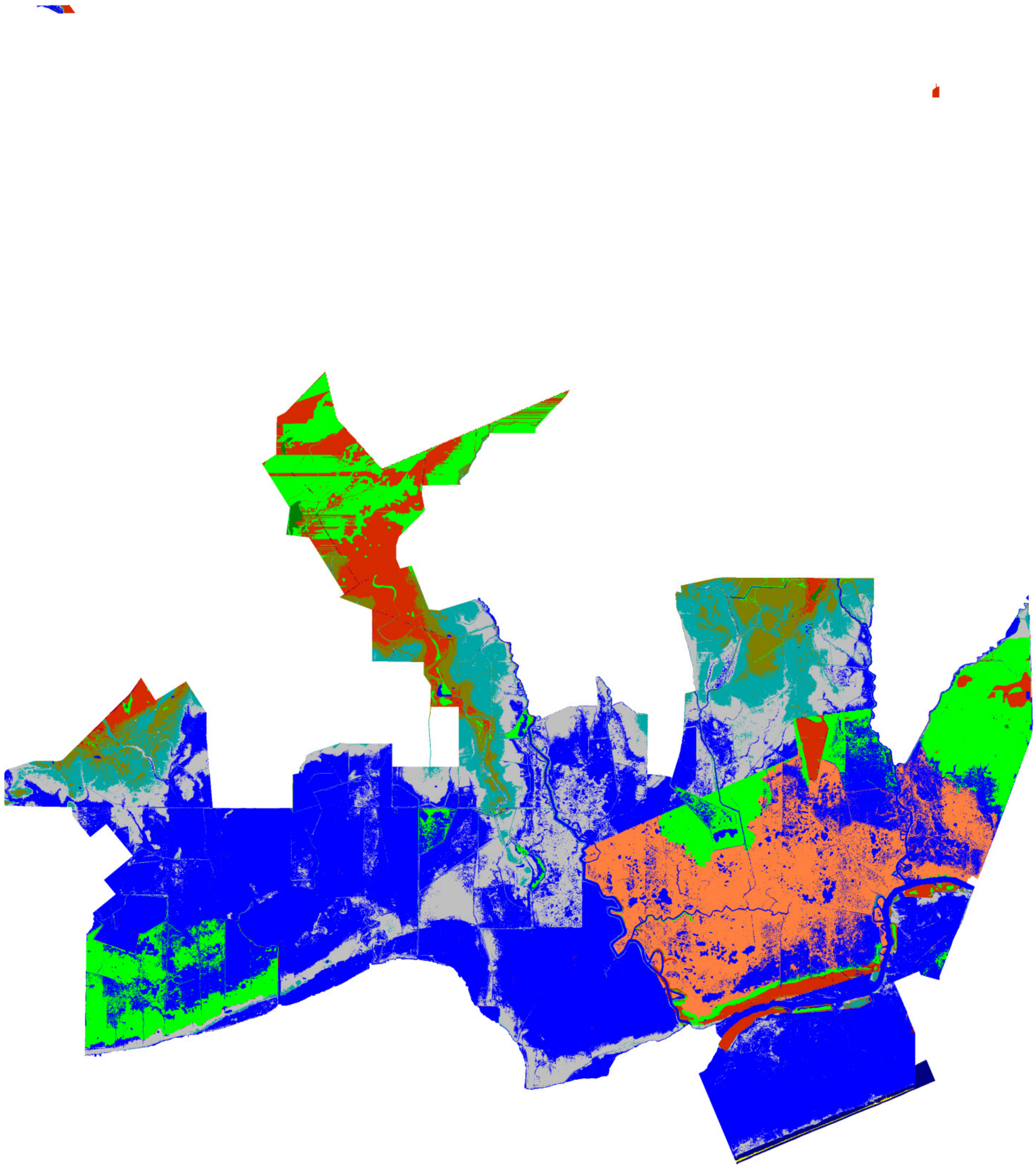
Anahuac NWR, 2025, 2 Meters



Anahuac NWR, 2050, 2 Meters



Anahuac NWR, 2075, 2 Meters



Anahuac NWR, 2100, 2 Meters

Discussion

Model results for Anahuac NWR indicate that it is vulnerable to sea level rise under each of the SLR scenarios examined. The inland fresh marsh category is predicted by SLAMM to sustain considerable losses under all the SLR scenarios simulated. This may be due to the improper classification of these land covers as inland fresh marsh rather than a more appropriate designation as transitional marsh in the initial wetlands data layer. Regardless of classification, non-diked, low-lying areas of the refuge are predicted to convert to tidal flat/open water in each of the SLR scenarios examined.

Model sensitivity analysis was also conducted as part of the previous study of Galveston Bay (Warren Pinnacle Consulting, Inc. 2011). These results suggests model predictions are quite sensitive to model inputs of accretion rates in the refuge. Local accretion data were not available for this subsite, and accretion values were estimated using data collected in the West Galveston Bay (Ravens et al. 2009). Local accretion data were taken from a study conducted nearby (East Bay Galveston; Ravens et al 2009). Despite being collected nearby, accretion data vary widely and may not be completely representative of the accretion rates in Anahuac NWR. Local data regarding accretion rates within the refuge itself could provide better predictions of marsh losses in the future.

Conversely, elevation data were based on high-vertical-resolution LiDAR data for the entire refuge, considerably reducing model uncertainty. An elevation uncertainty analysis found minimal variations in model predictions on the basis of elevation-data uncertainty (Clough et al. 2011).

The area surrounding Anahuac was studied in a previous SLAMM analysis funded by The Nature Conservancy (Warren Pinnacle Consulting, Inc. 2011). Maps of results for the larger study area are presented in the “contextual maps” below.

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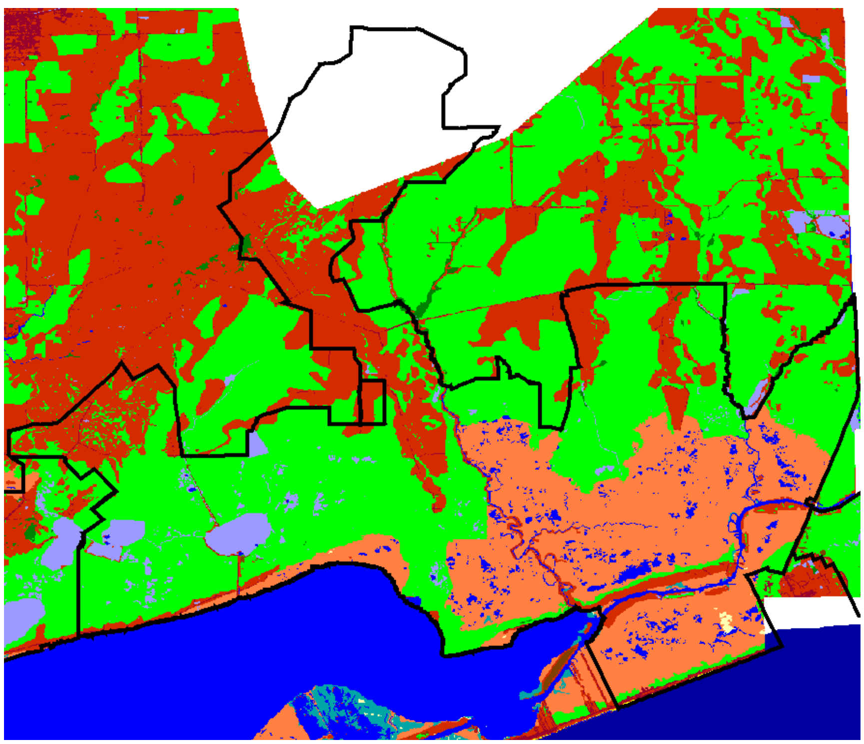
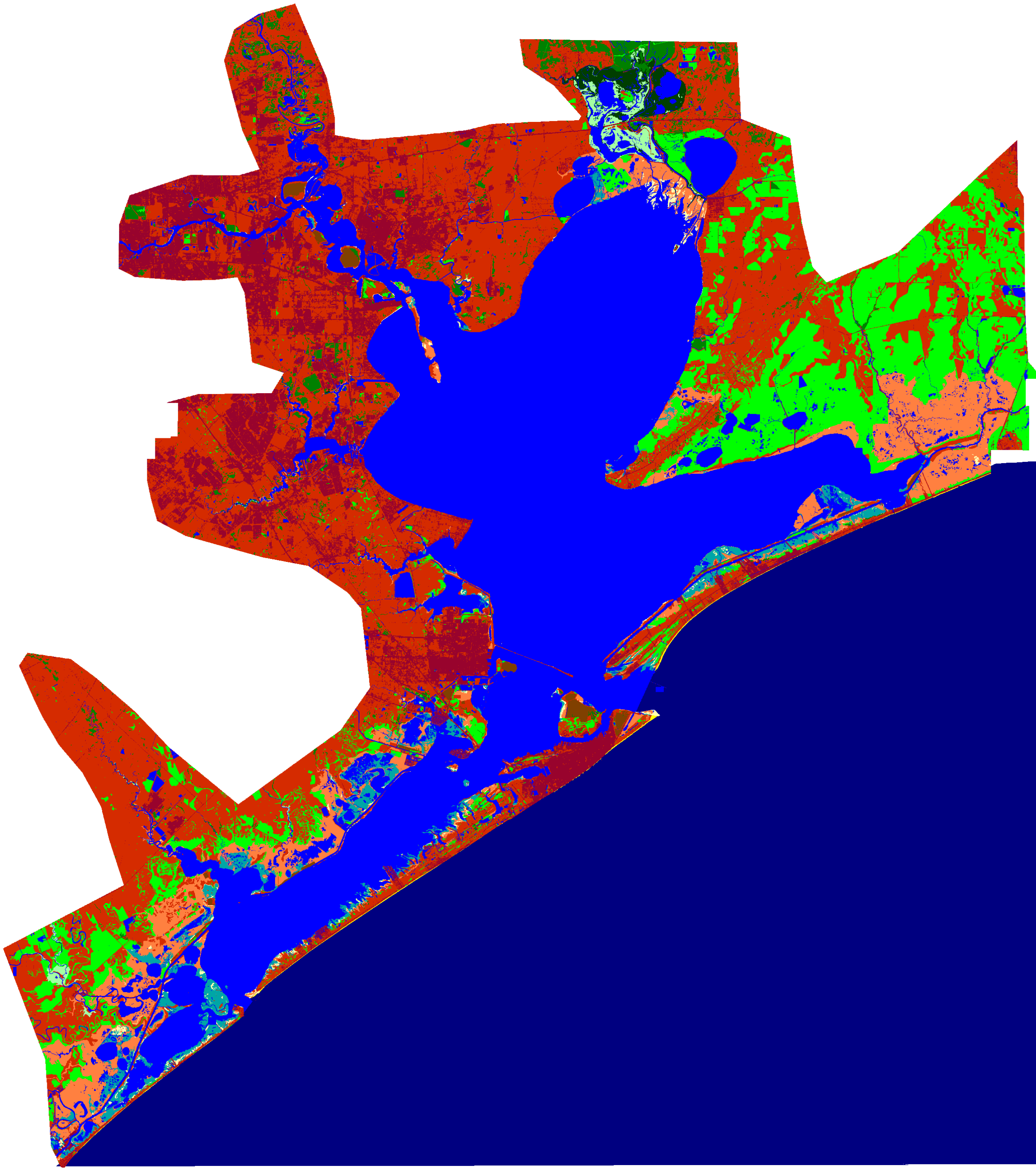
Appendix A: Contextual Results

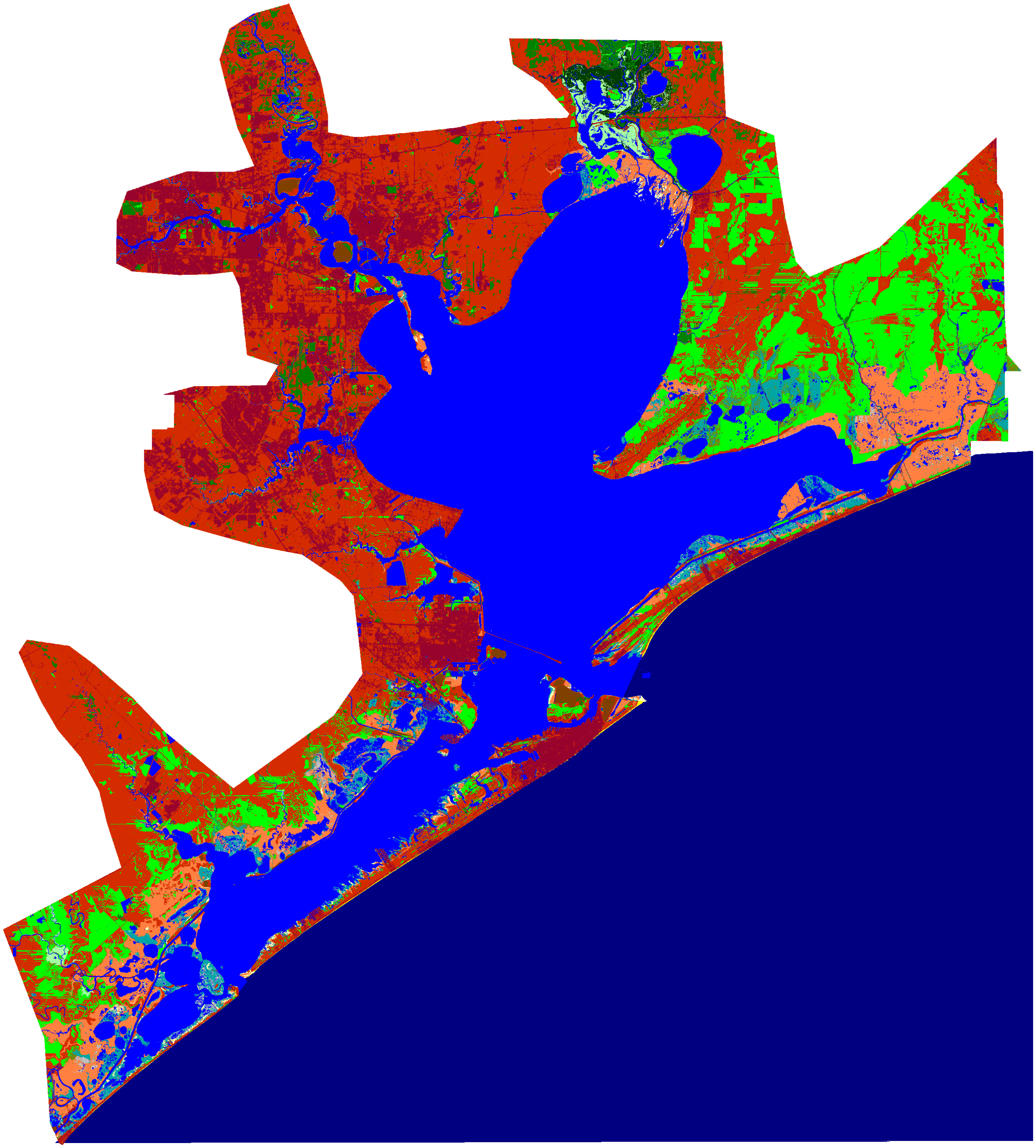
The SLAMM model does take into account the context of the surrounding lands or open water when calculating effects. For example, erosion rates are calculated based on the maximum fetch (wave action) which is estimated by assessing contiguous open water to a given marsh cell. Another example is that inundated 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. A full analysis of this study are was funded by the Sea-Level Rise and Conservation Project of The Nature Conservancy who also provided GIS processing in support of these analyses. Funding for this project of The Nature Conservancy was provided through a grant from the Gulf of Mexico Foundation, Inc., to support the Gulf of Mexico Alliance.



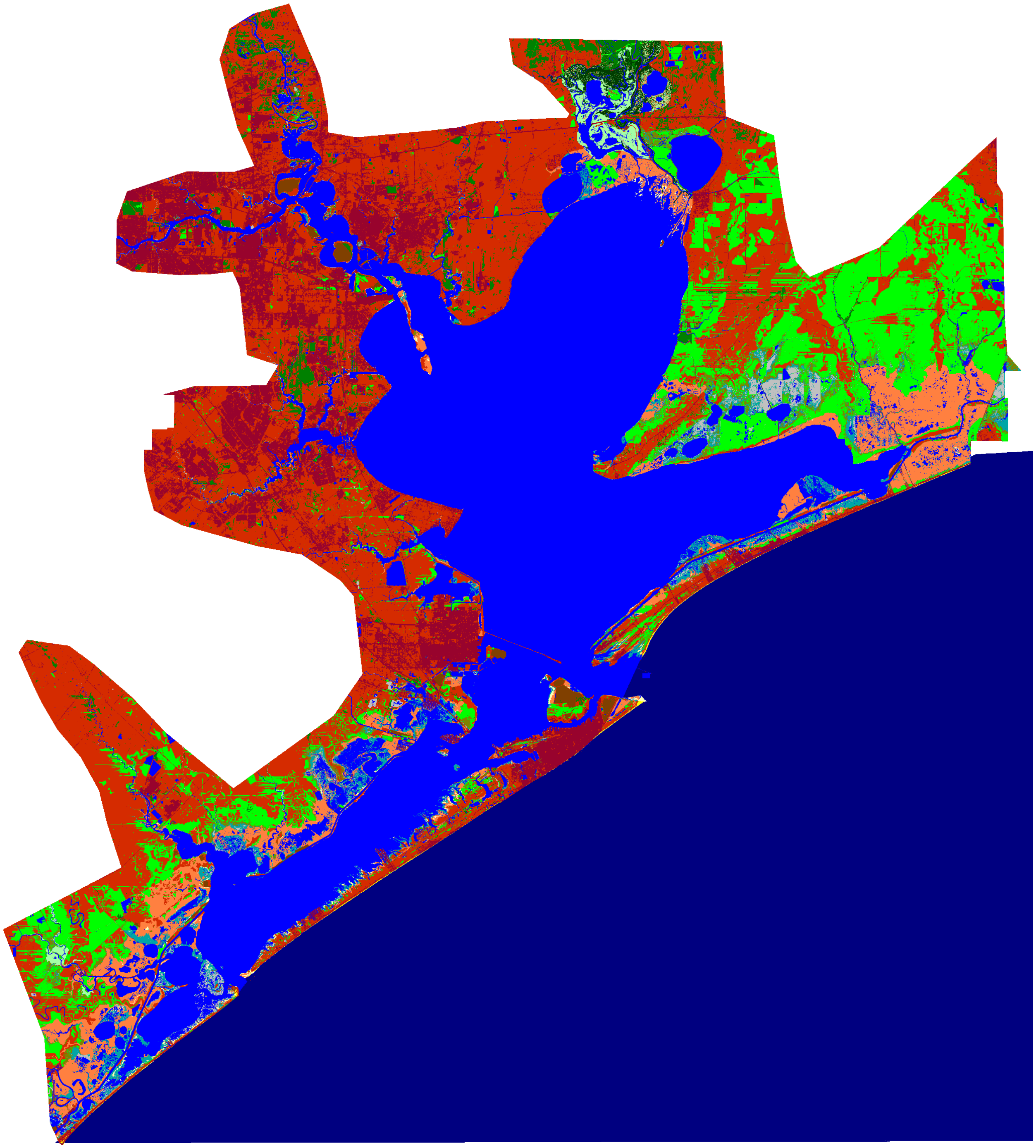
Anahuac National Wildlife Refuge within simulation context (outlined in black)



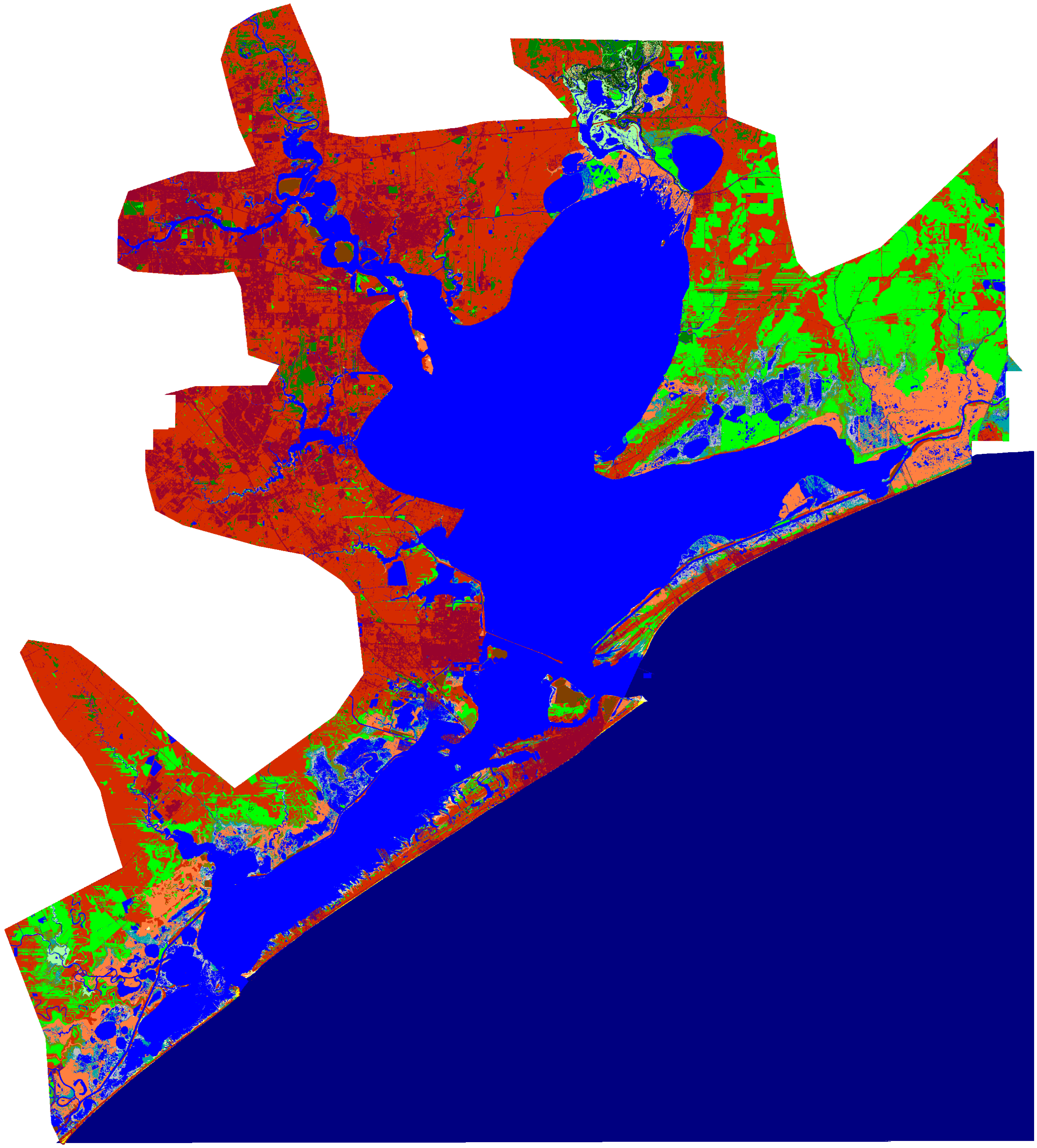
Anahuac Context, Initial Condition



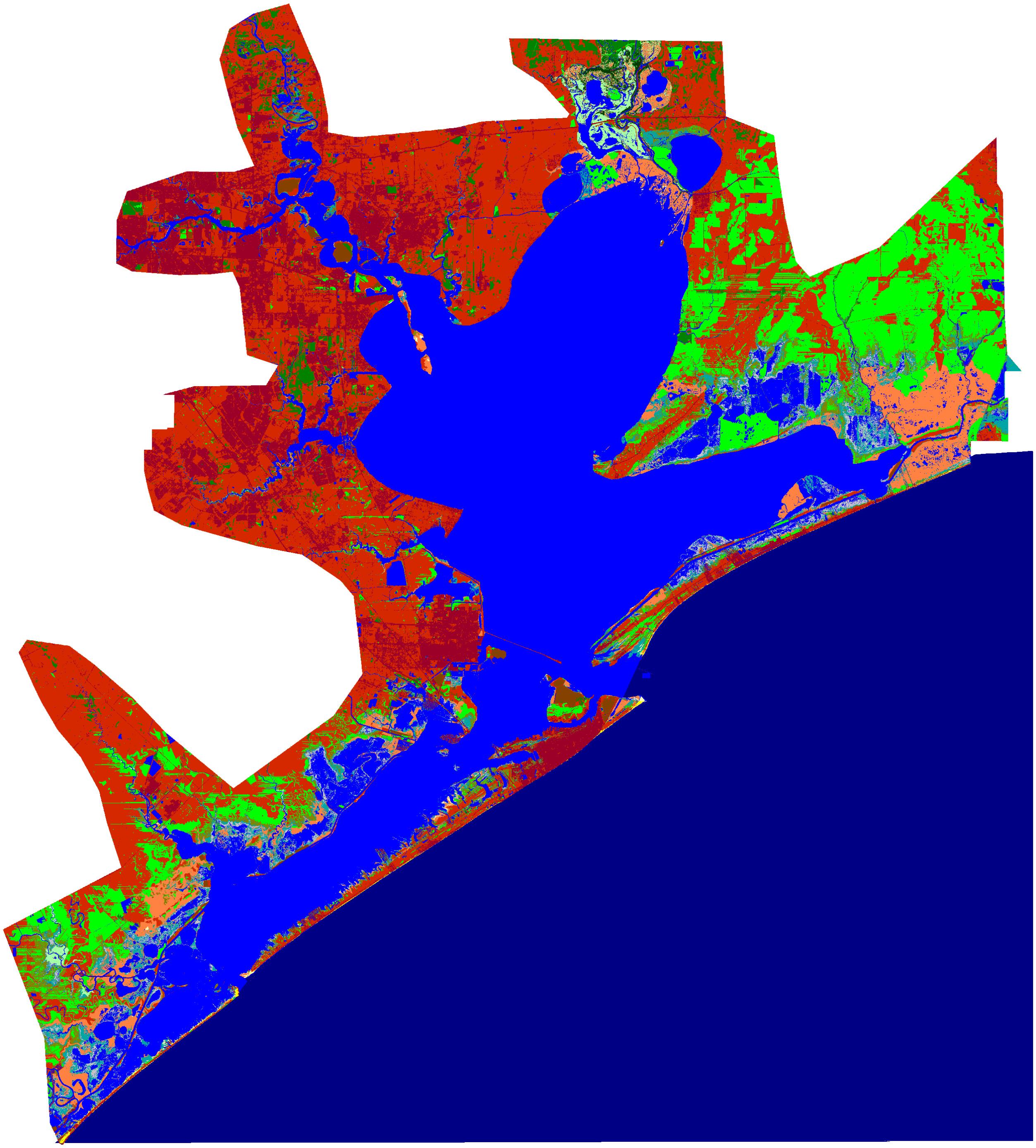
Anahuac Context, 2025, Scenario A1B Mean



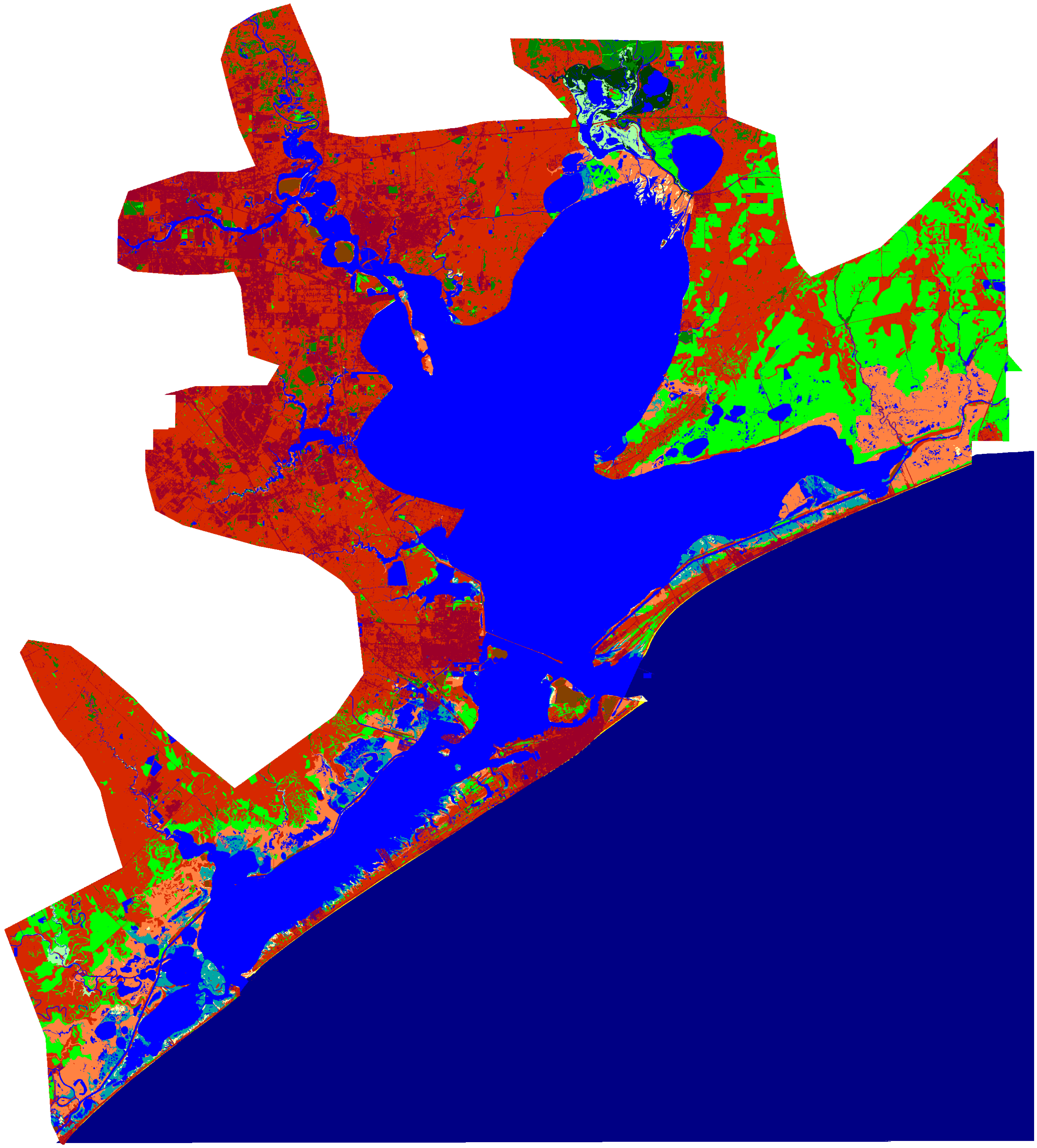
Anahuac Context, 2050, Scenario A1B Mean



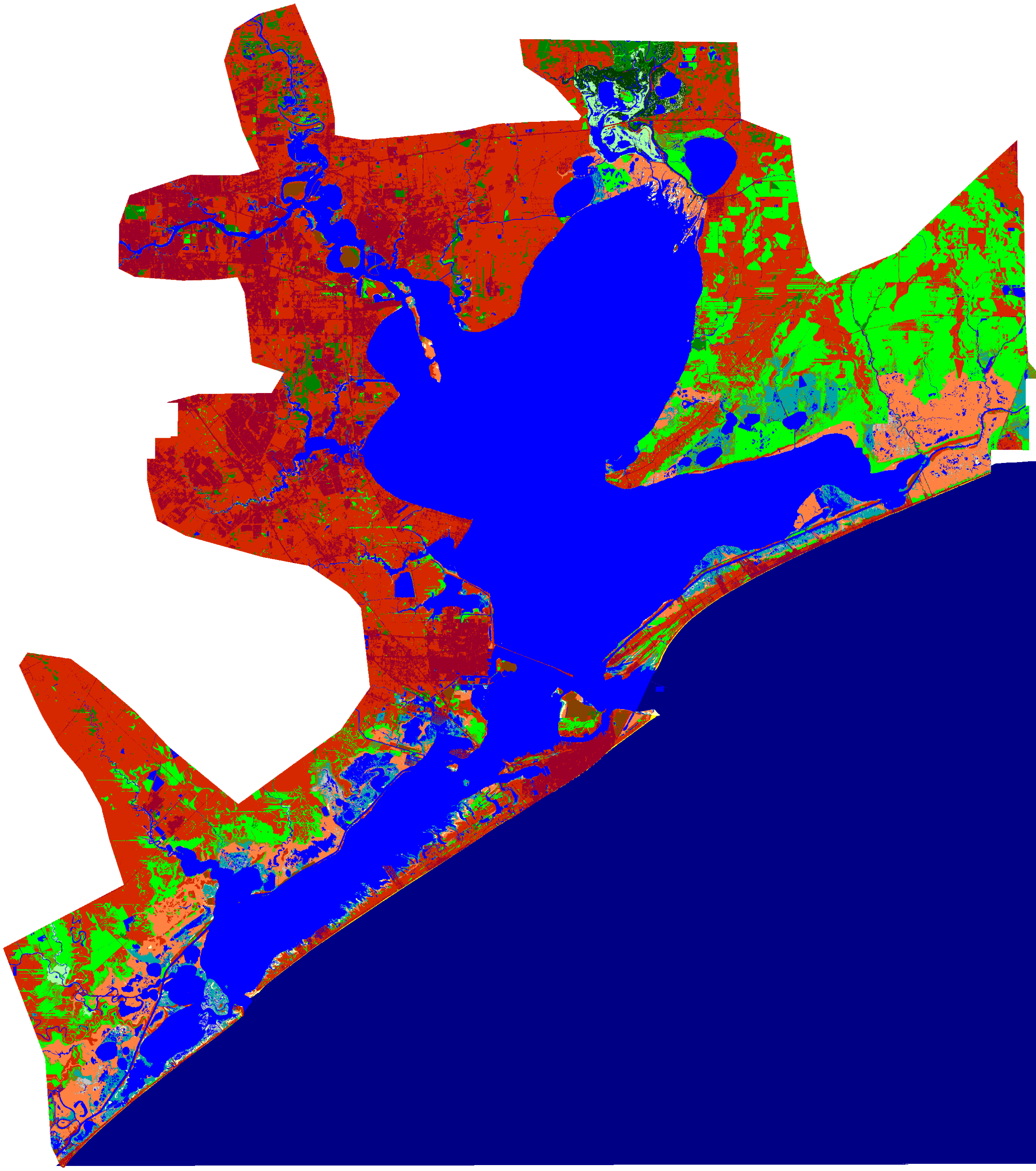
Anahuac Context, 2075, Scenario A1B Mean



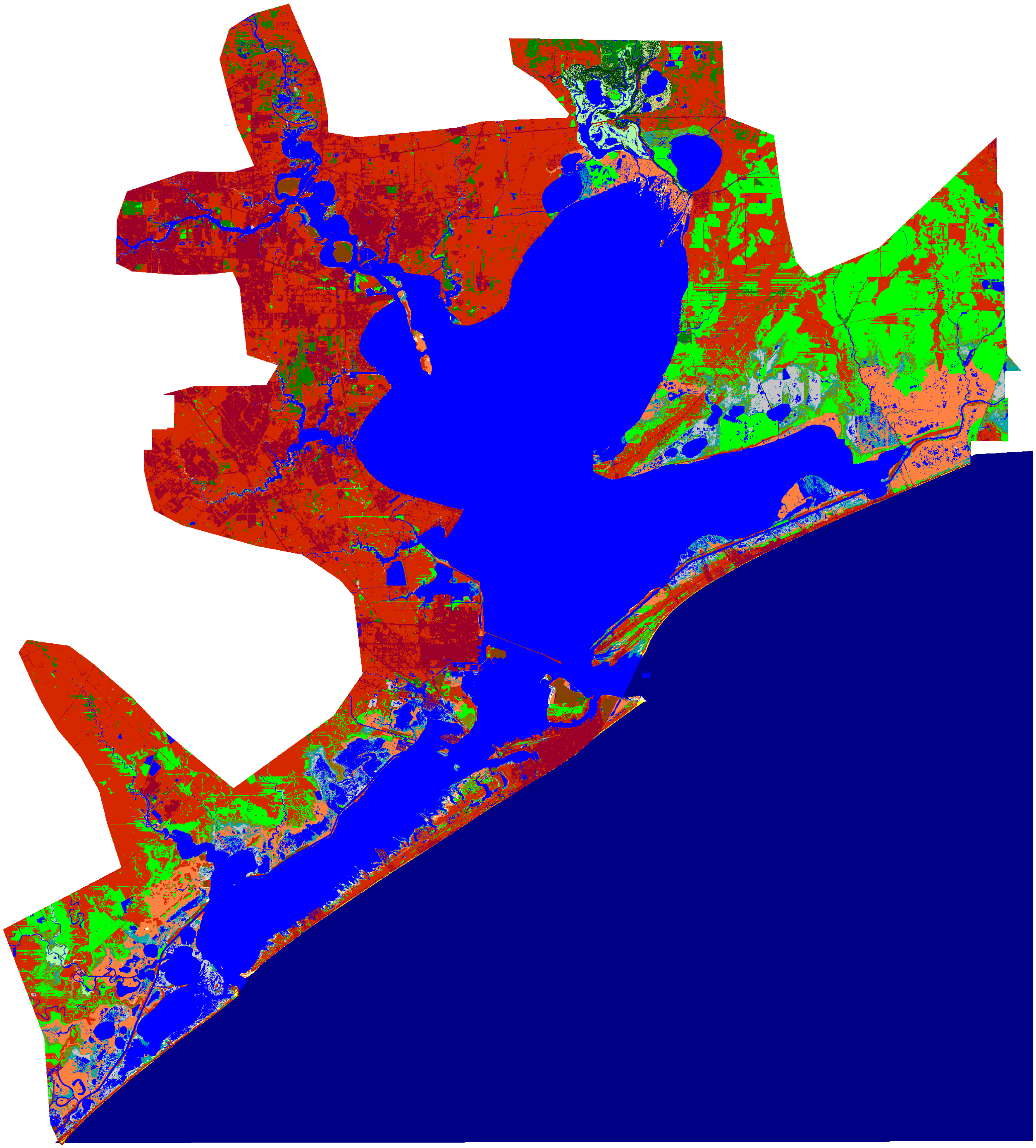
Anahuac Context, 2100, Scenario A1B Mean



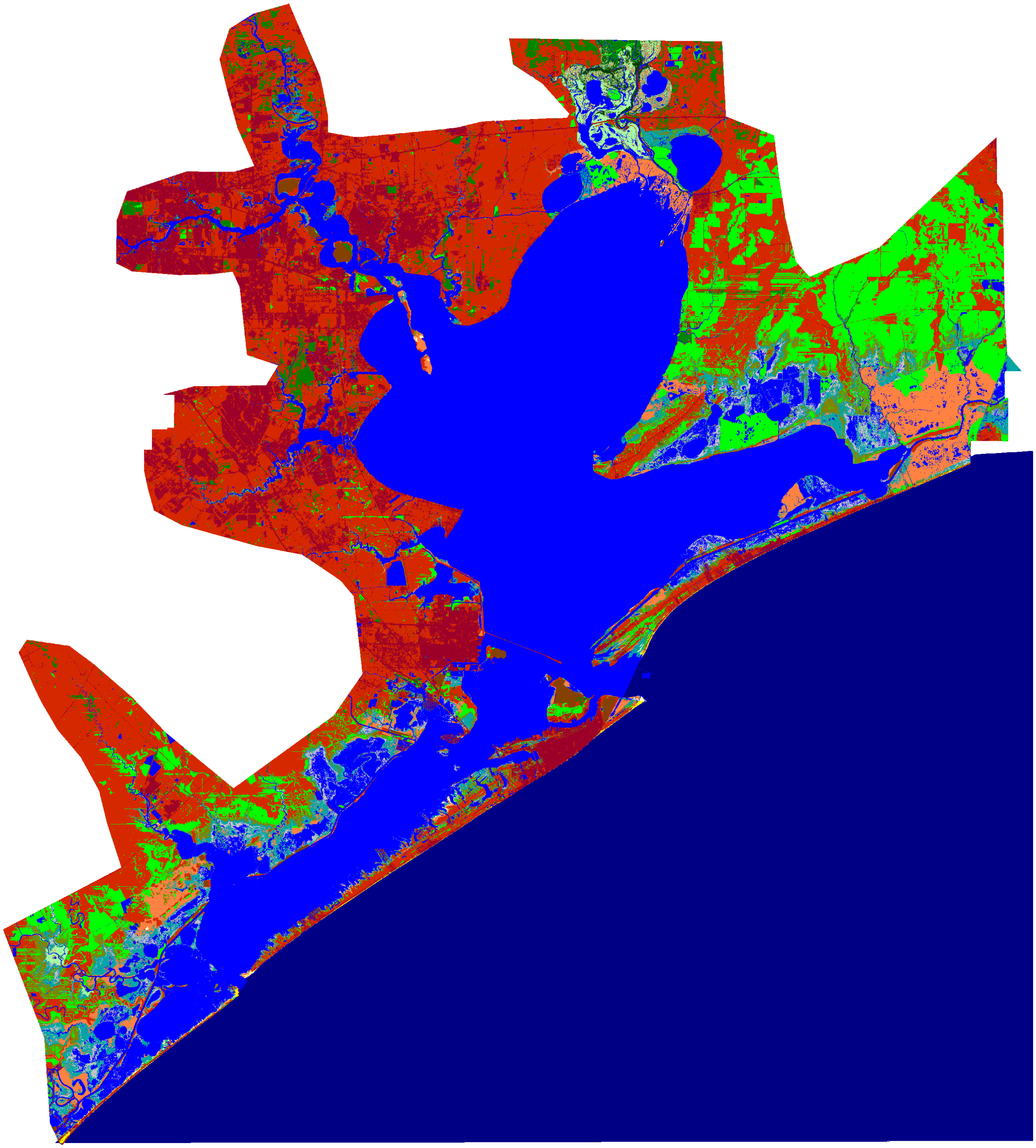
Anahuac Context, Initial Condition



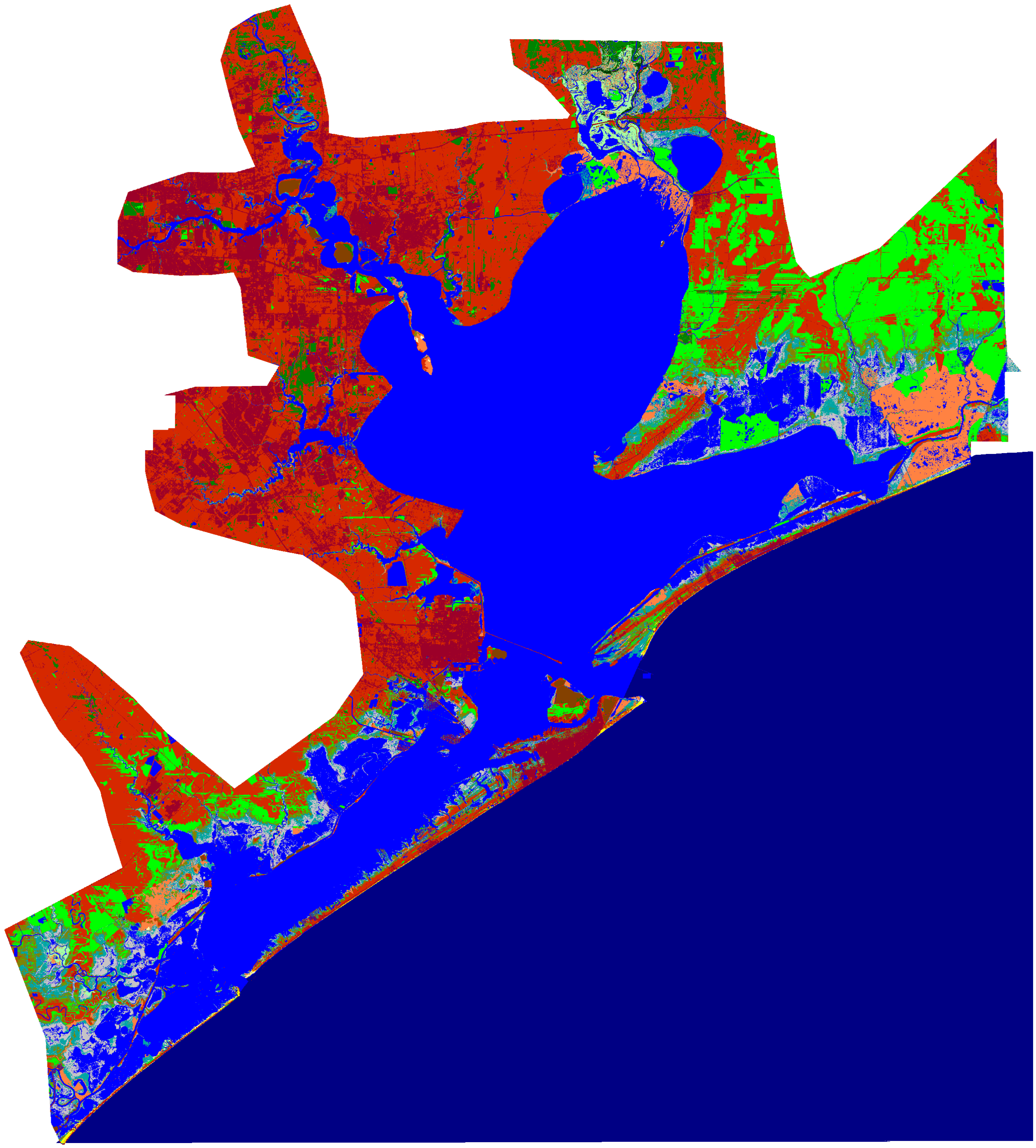
Anahuac Context, 2025, Scenario A1B Maximum



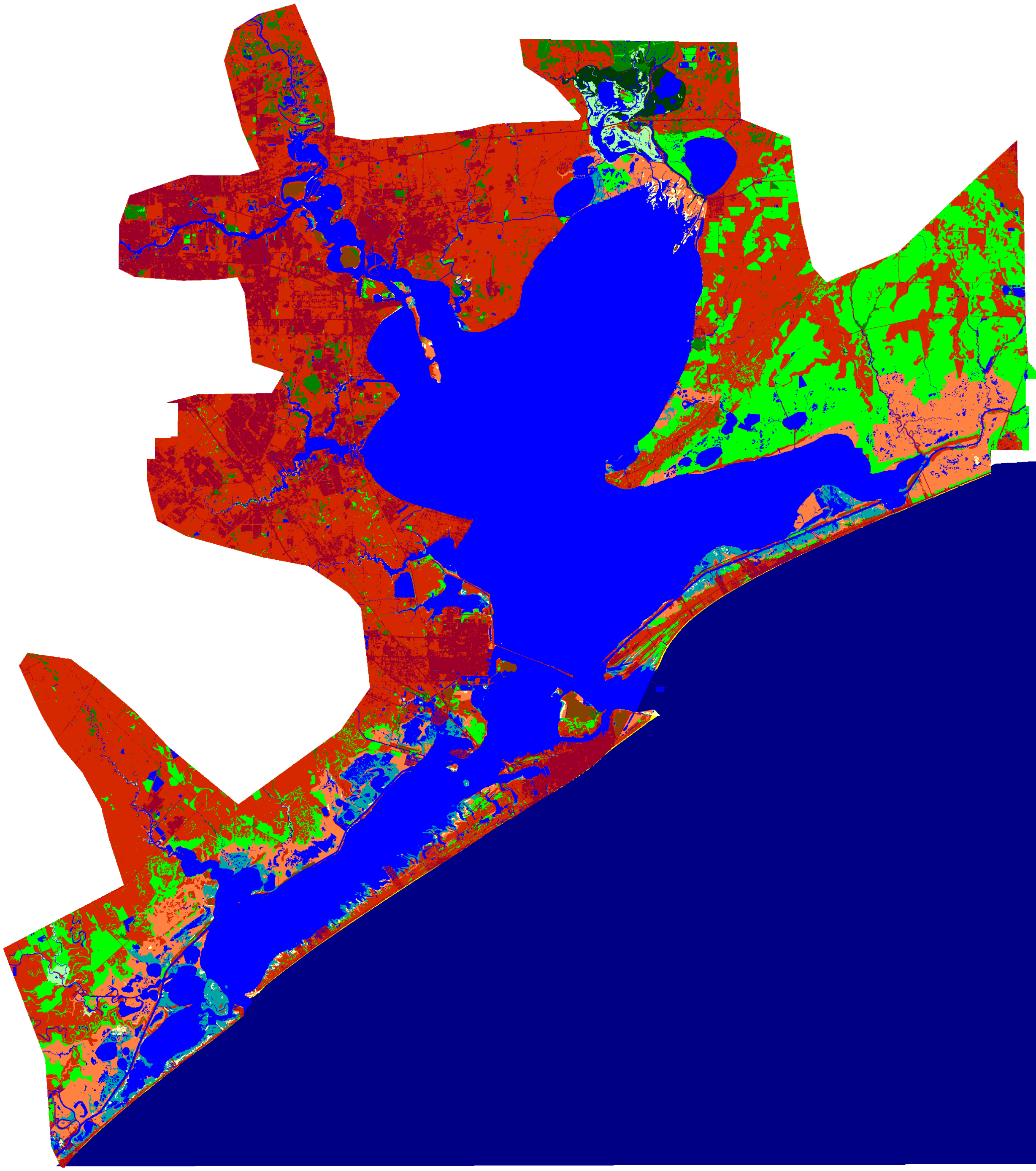
Anahuac Context, 2050, Scenario A1B Maximum



Anahuac Context, 2075, Scenario A1B Maximum



Anahuac Context, 2100, Scenario A1B Maximum



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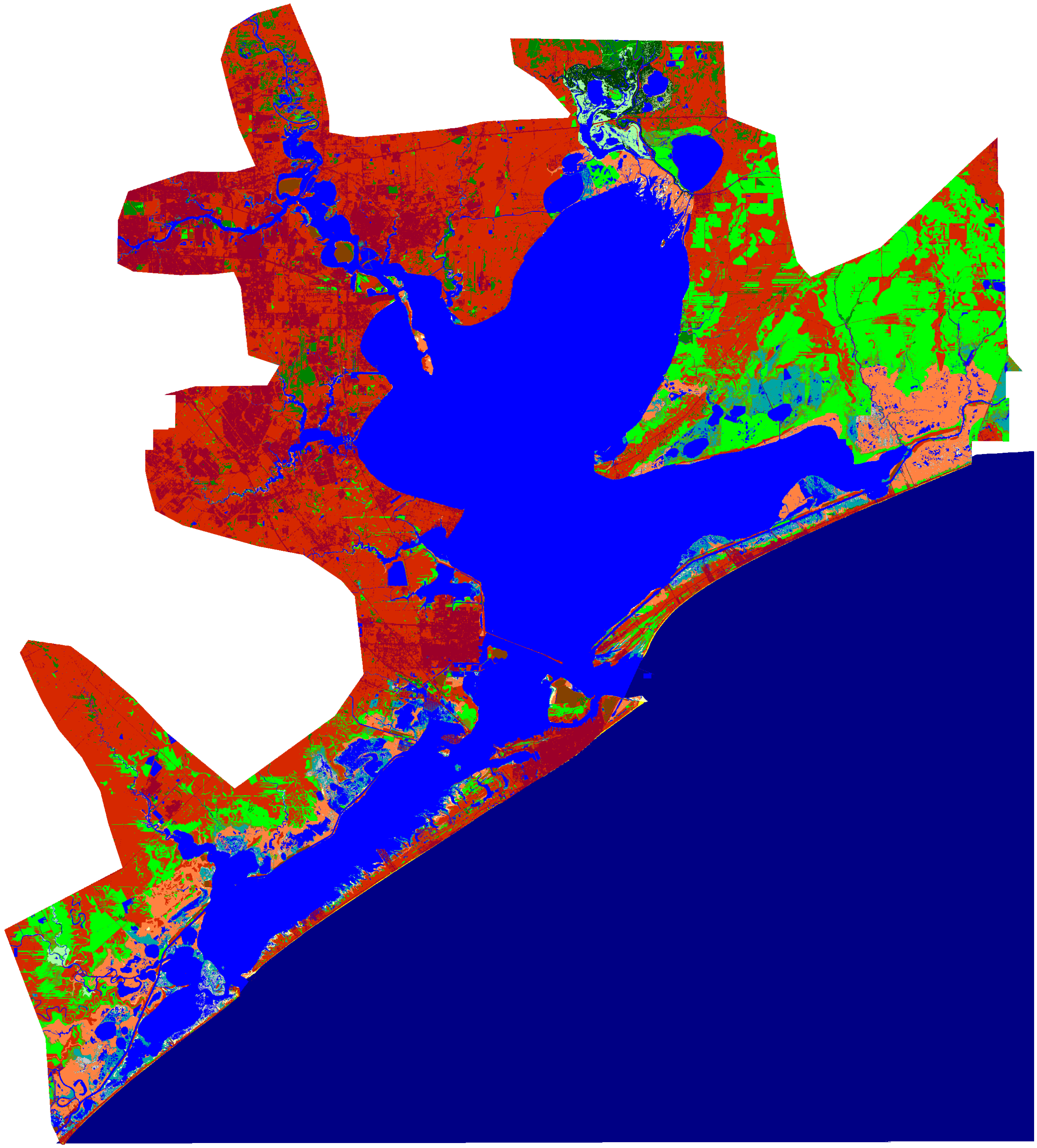
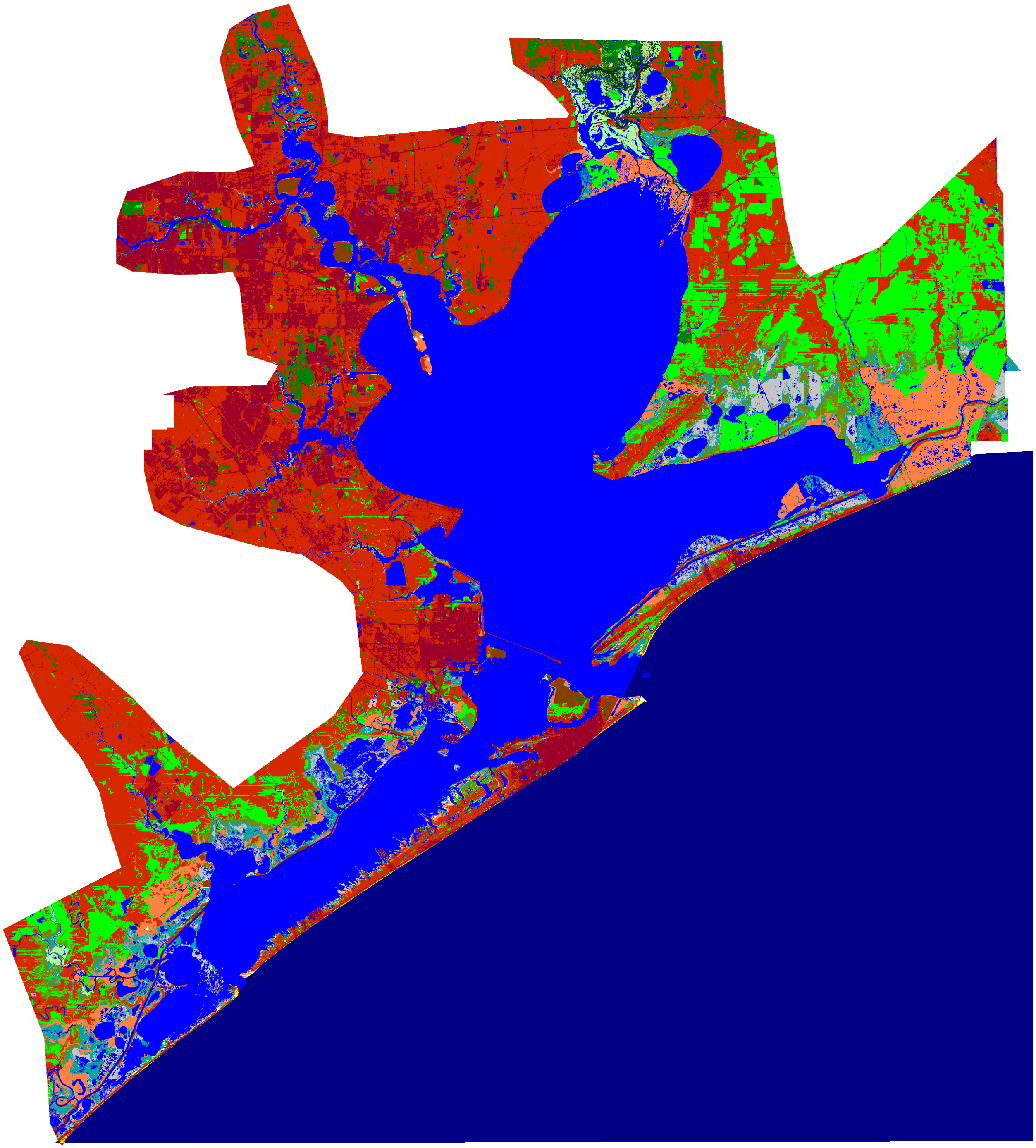
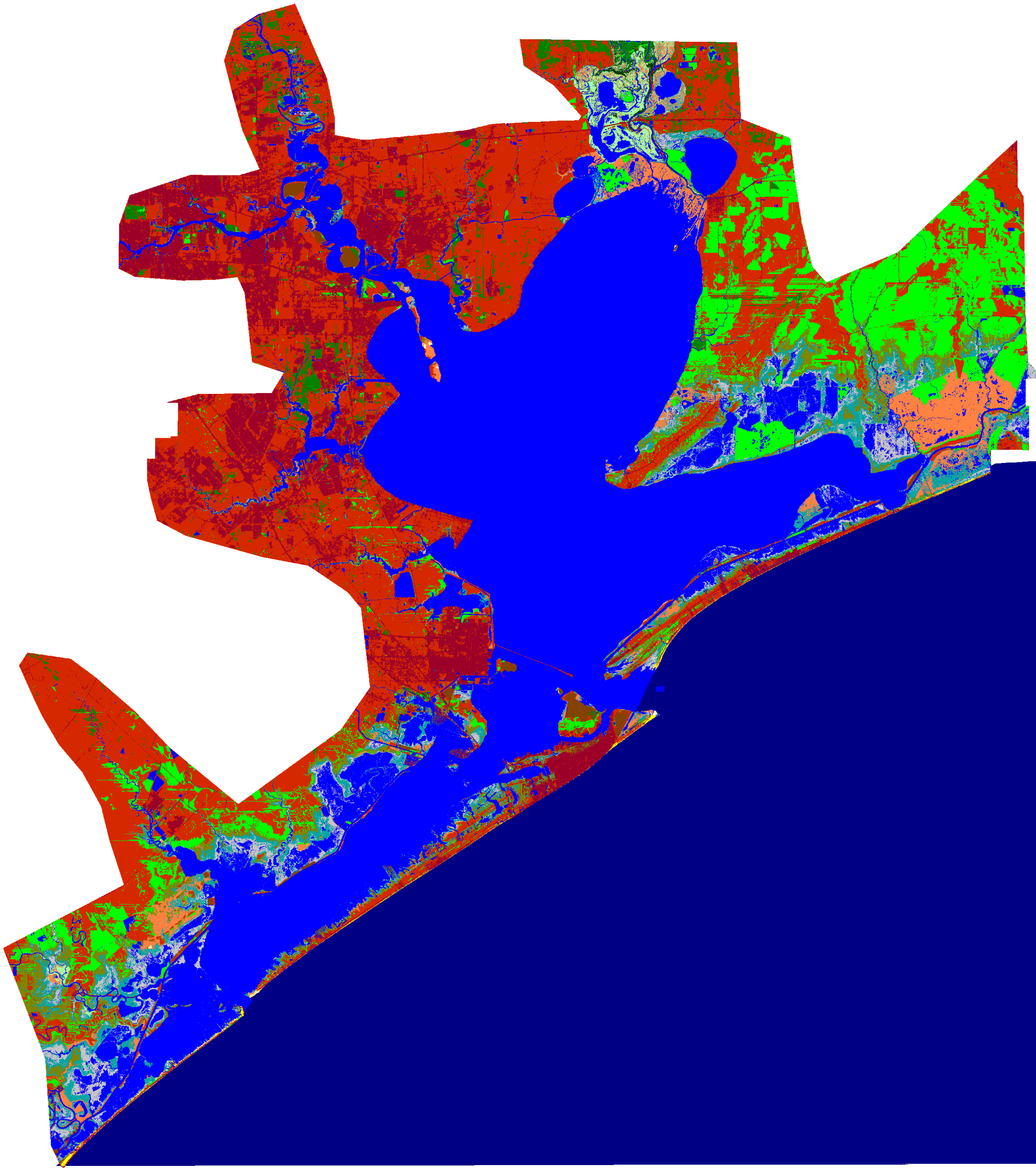


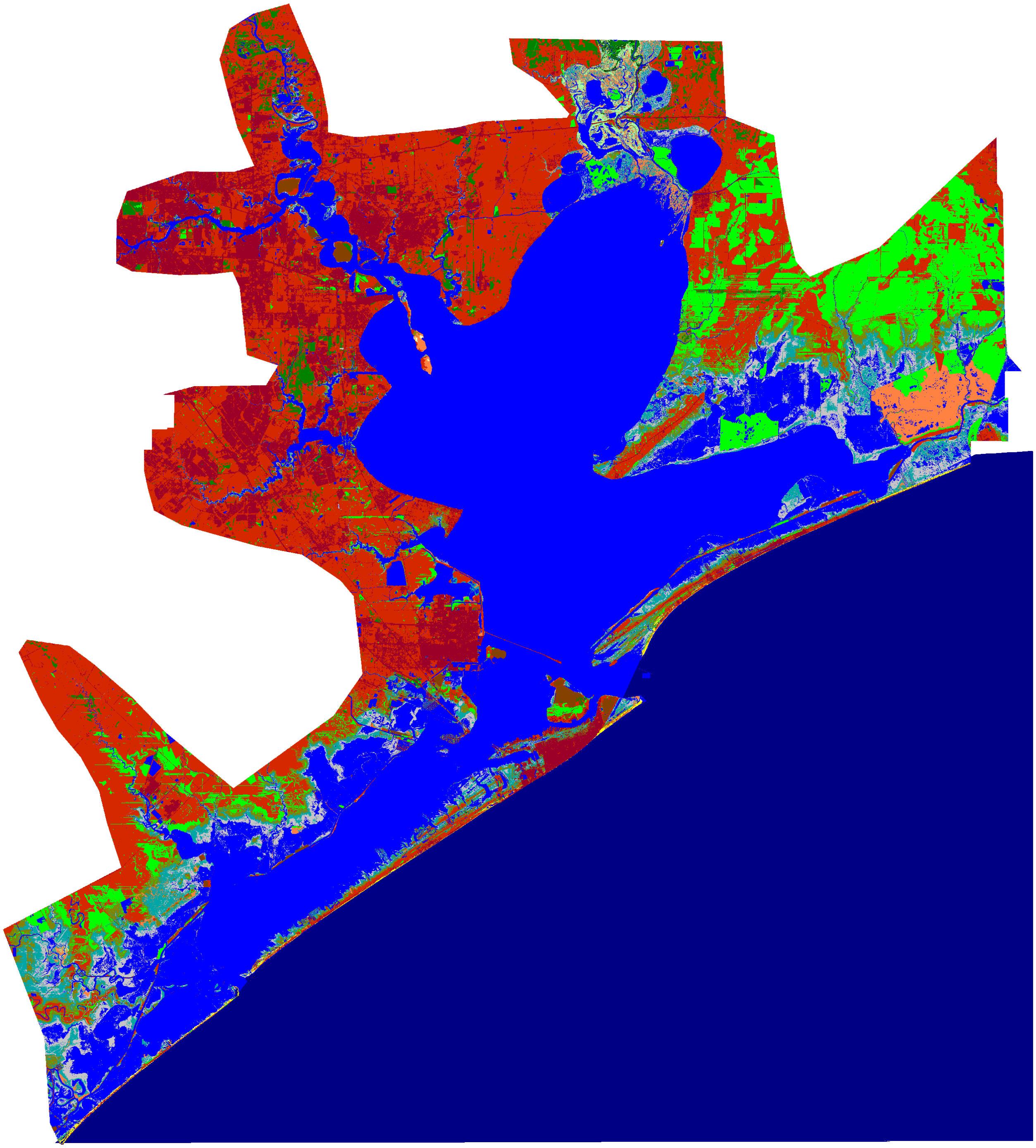
Anahuac Context, 2025, 1 m



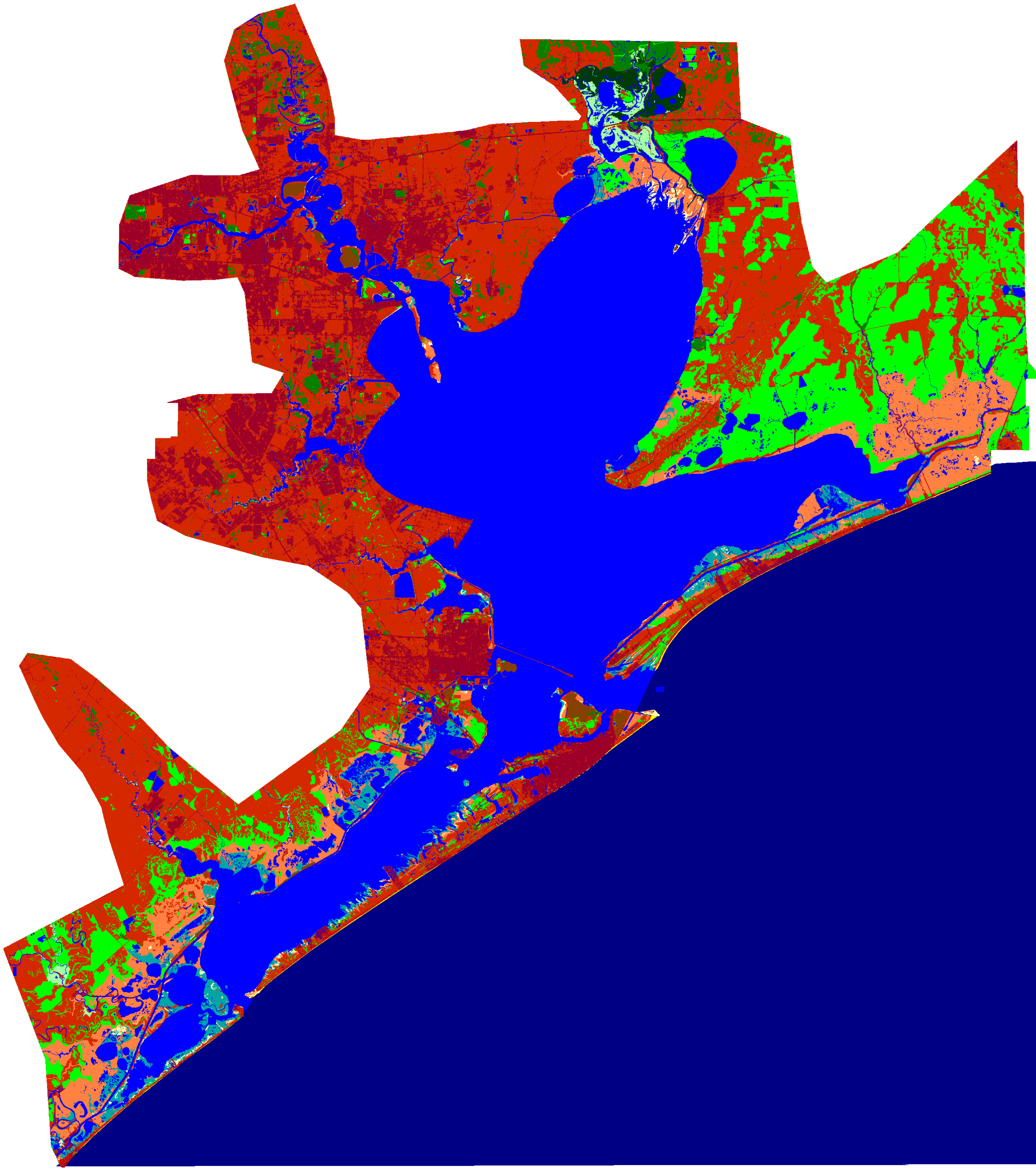
Anahuac Context, 2050, 1 m



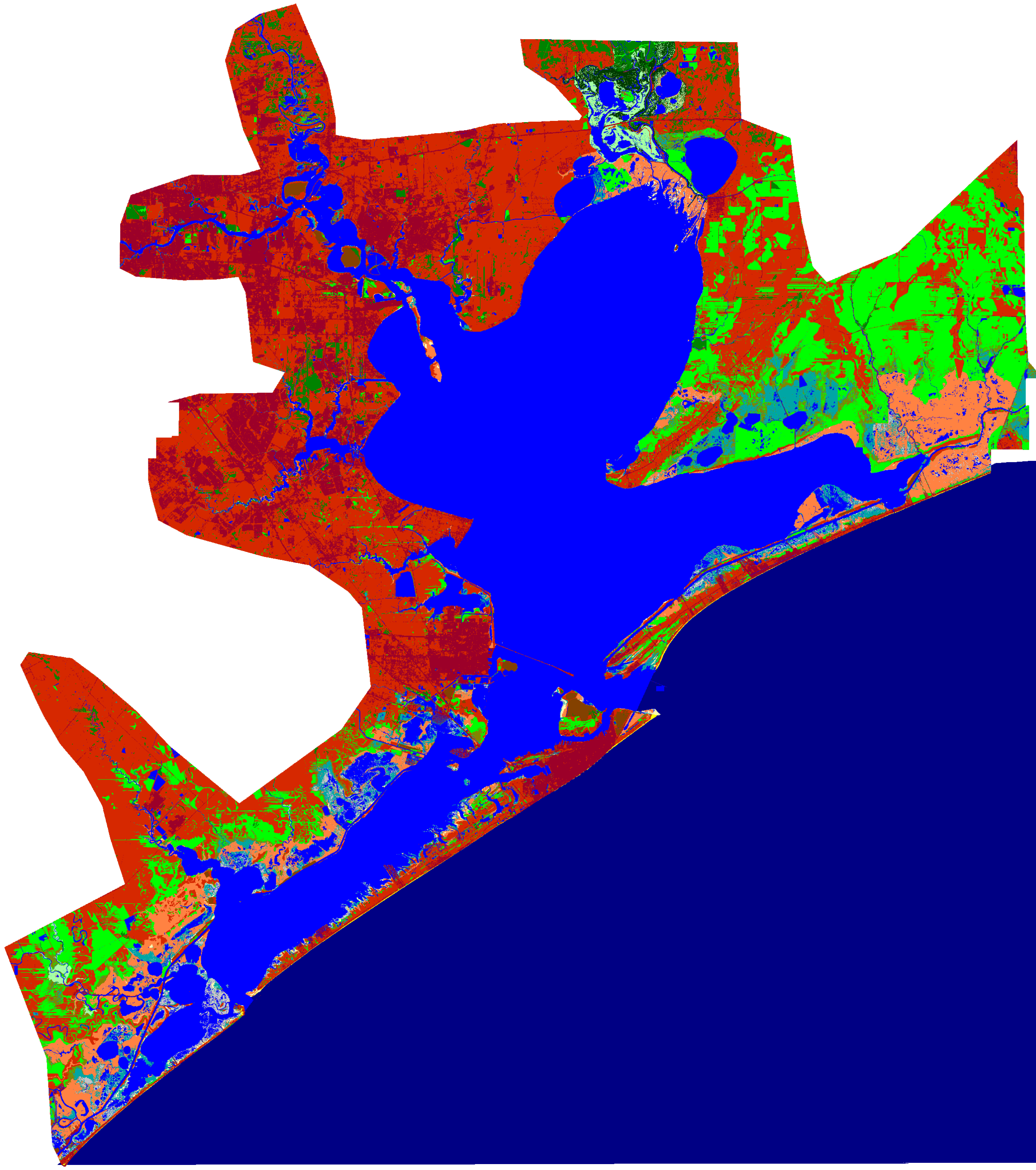
Anahuac Context, 2075, 1 m



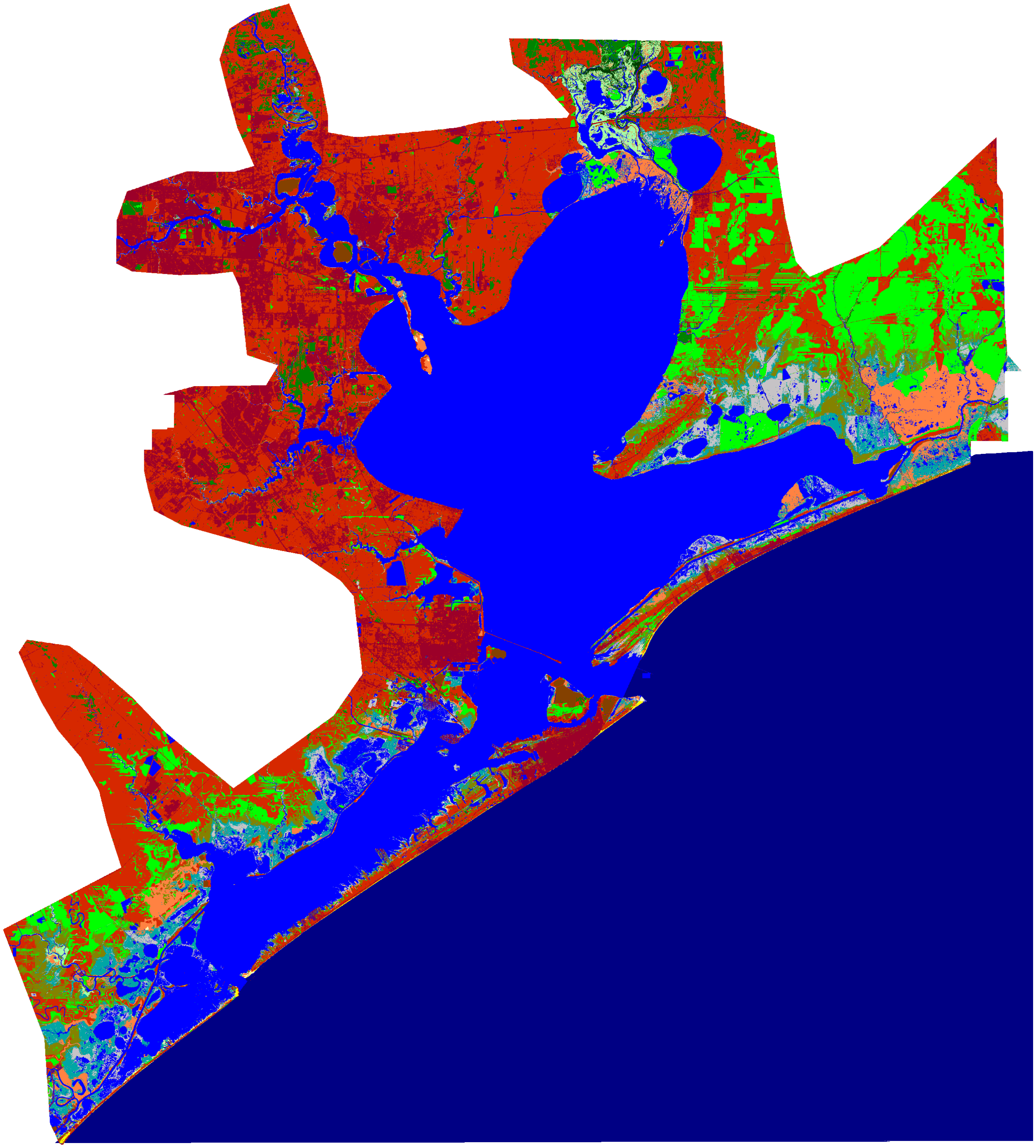
Anahuac Context, 2100, 1 m



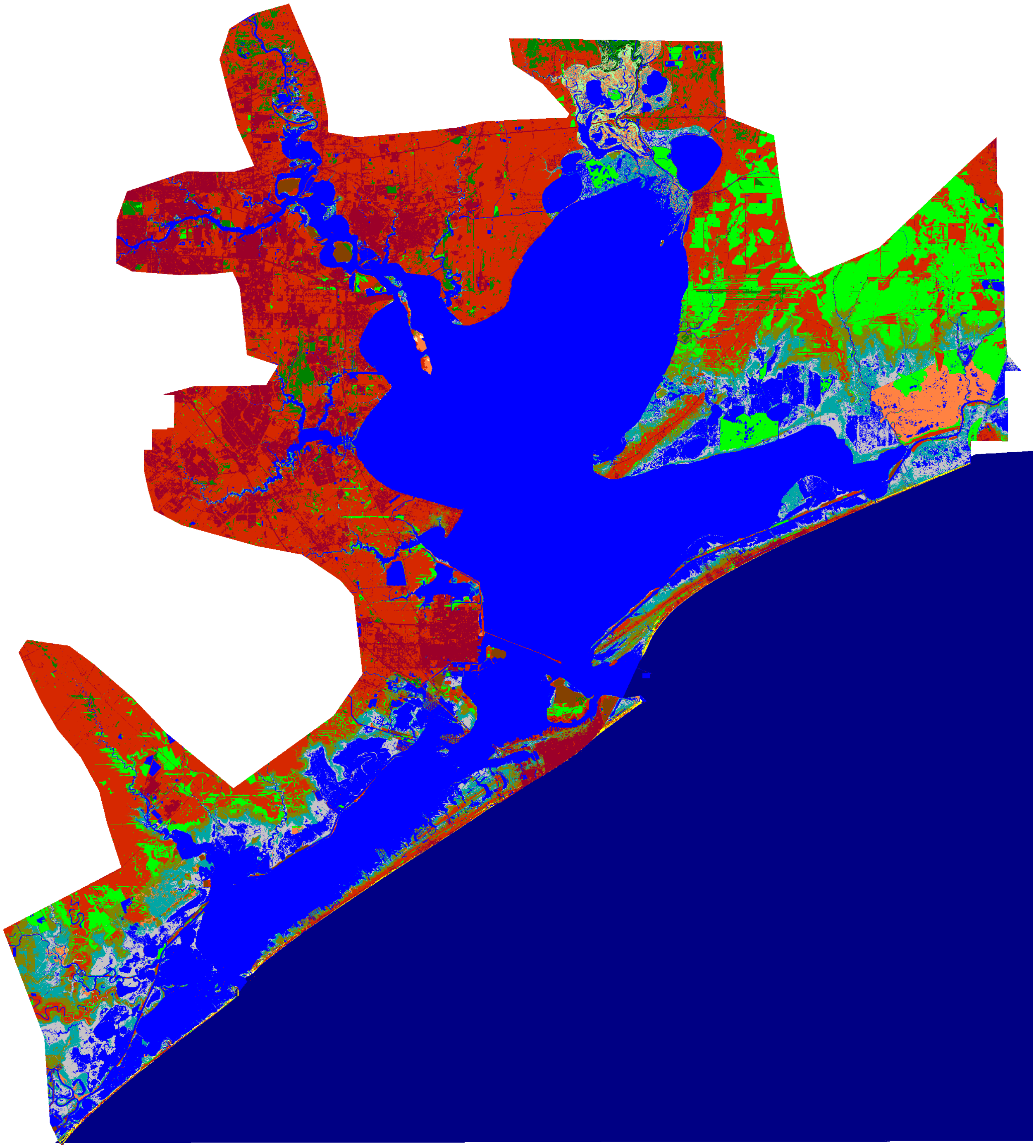
Anahuac Context, Initial Condition



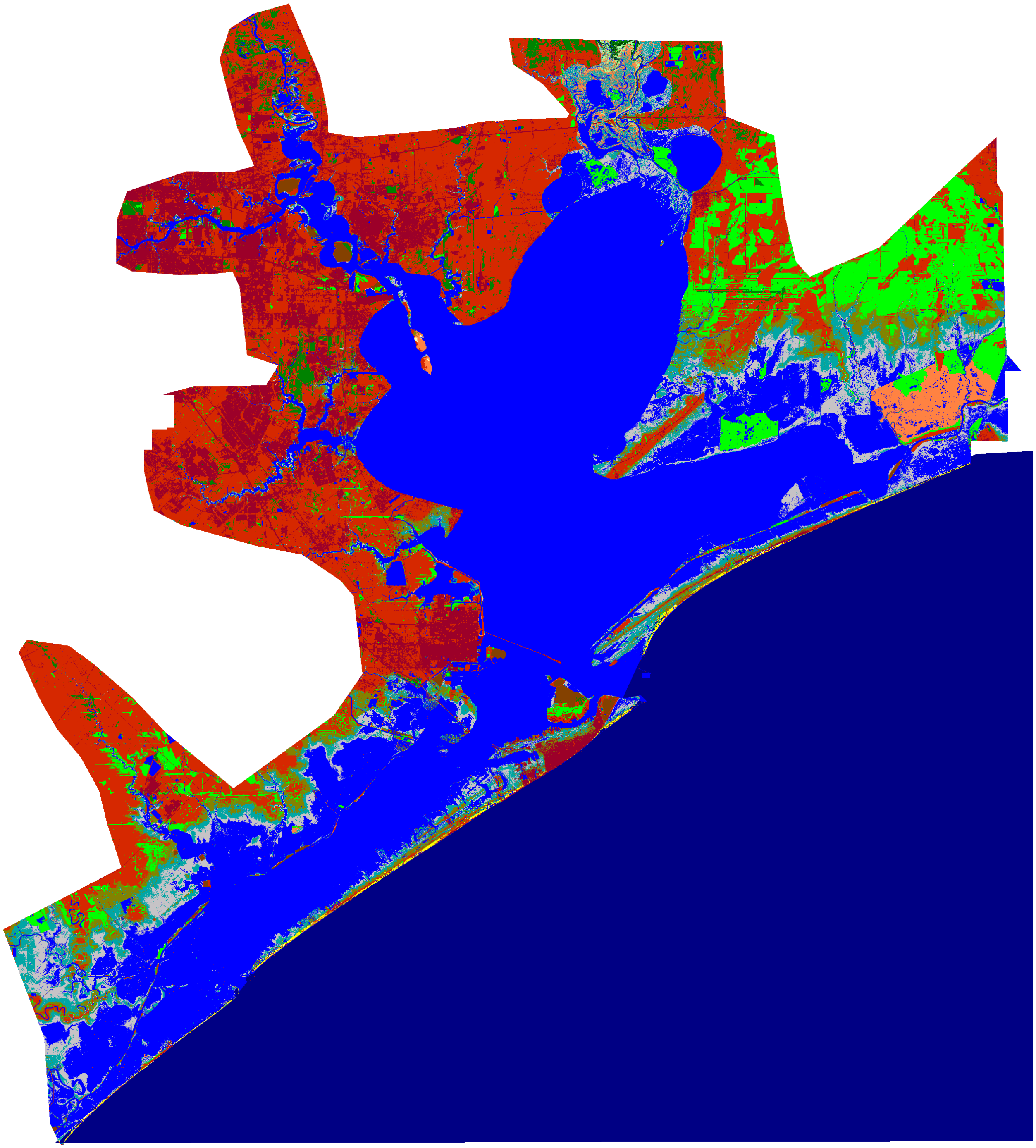
Anahuac Context, 2025, 1.5 m



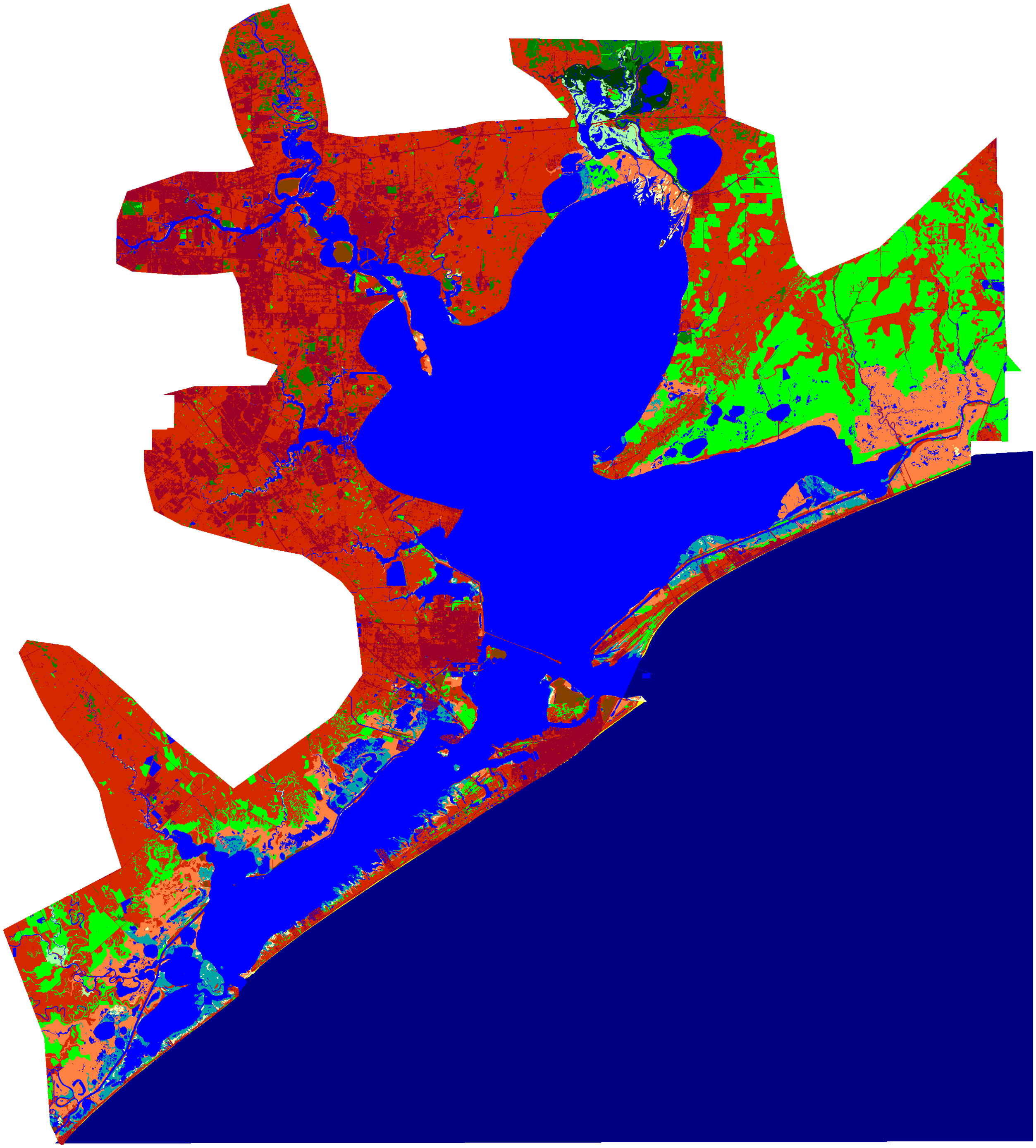
Anahuac Context, 2050, 1.5 m



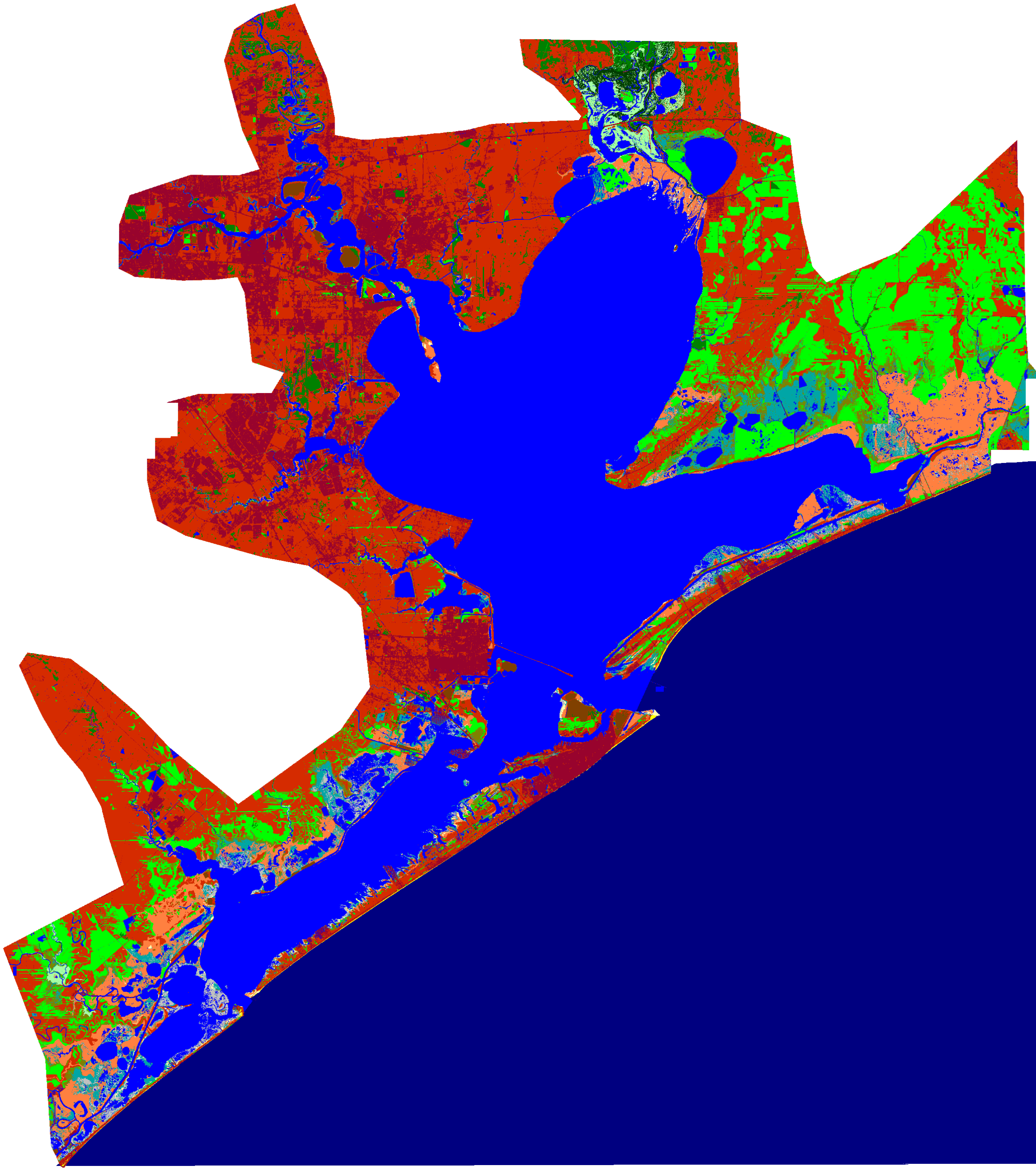
Anahuac Context, 2075, 1.5 m



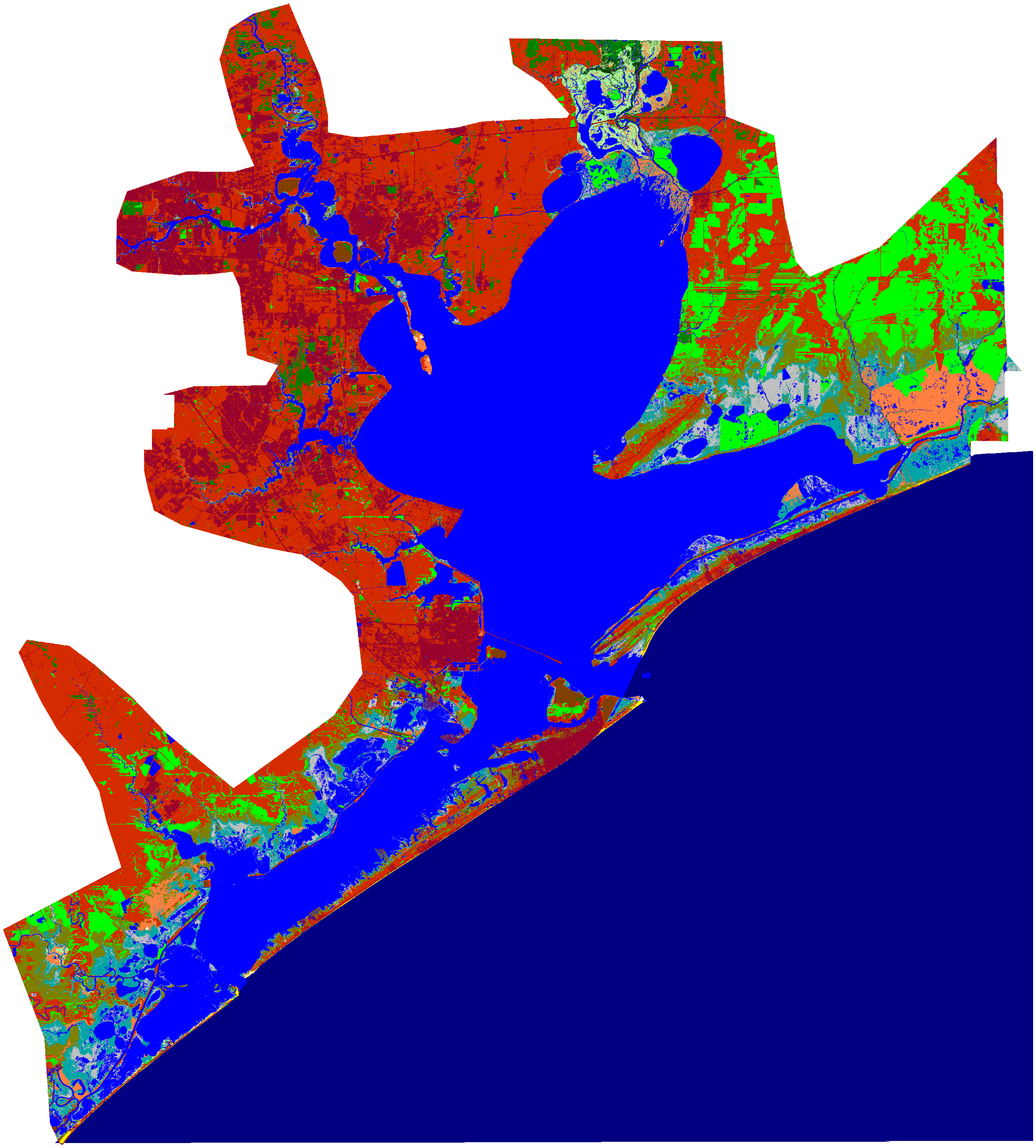
Anahuac Context, 2100, 1.5 m



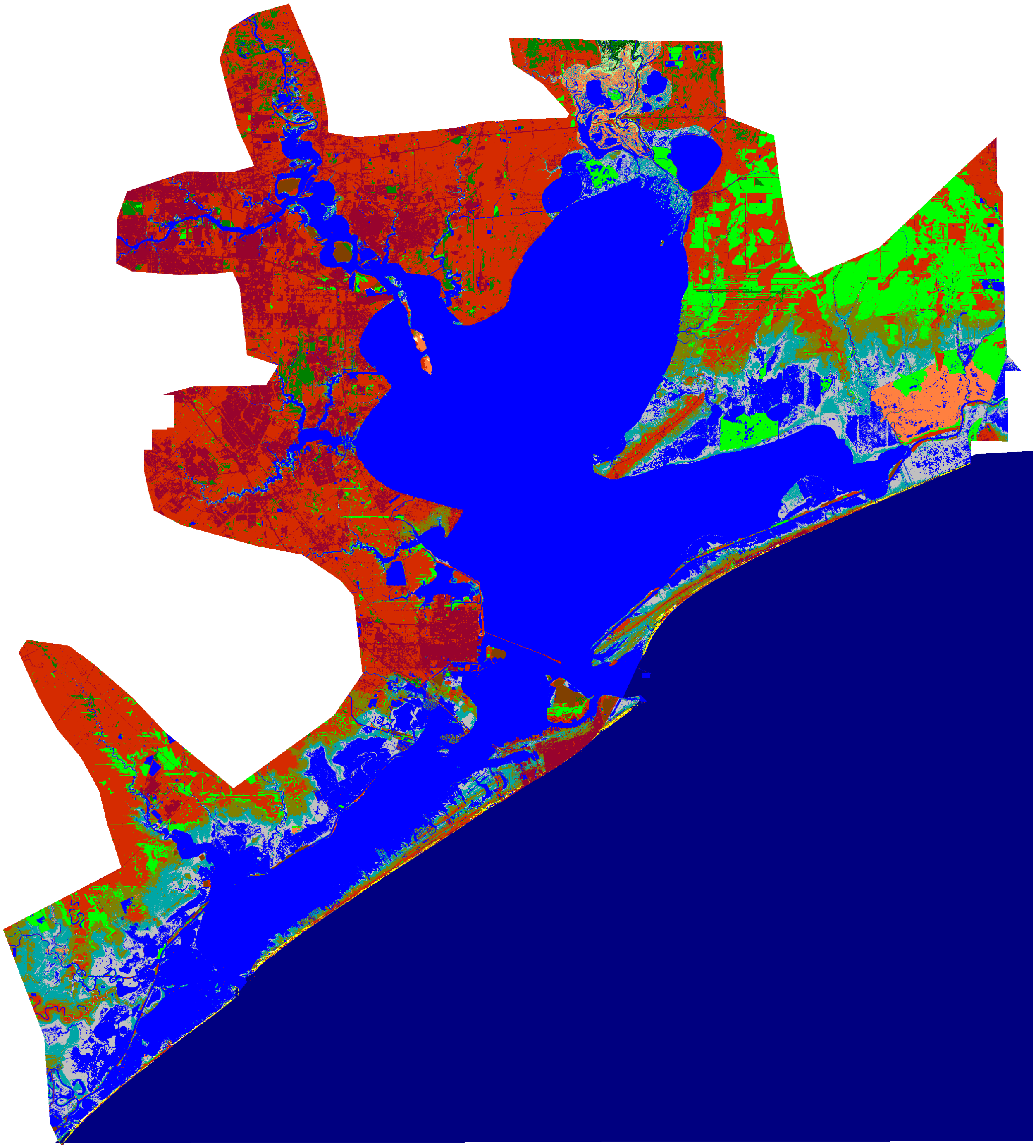
Anahuac Context, Initial Condition



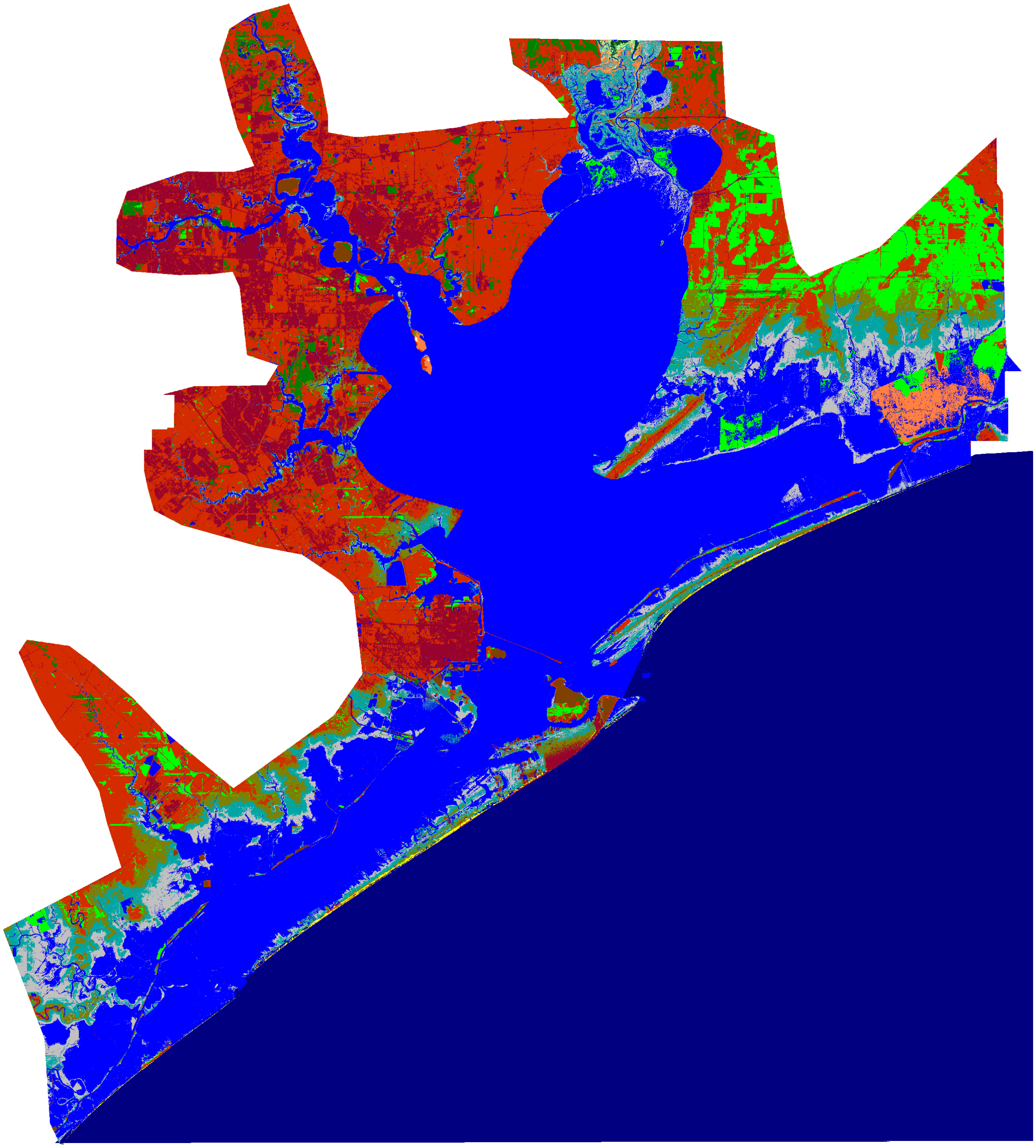
Anahuac Context, 2025, 2 m



Anahuac Context, 2050, 2 m



Anahuac Context, 2075, 2 m



Anahuac Context, 2100, 2 m