Application of the Sea-Level Affecting Marshes Model (SLAMM 6) to San Bernard and Big Boggy NWR

Prepared for

Gulf of Mexico Alliance
Habitat Conservation and Restoration Priority Issue Team
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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 (Park et al. 1991).

In 2010, the Gulf of Mexico Alliance Habitat Conservation and Restoration Team (HCRT), in assistance to the U. S. Fish and Wildlife Service (USFWS) effort through a contract with the Gulf of Mexico Foundation, funded additional model application to six coastal refuges in the Gulf of Mexico, including the San Bernard and Big Boggy NWRs (Figure 1). This study is part of a larger effort that the HCRT is undertaking with the Florida and Texas chapters of TNC to understand the Gulf-wide vulnerability of coastal natural communities to SLR and thus to identify appropriate conservation and restoration strategies and actions. This contract includes funding for two draft reports, stakeholder outreach and feedback, and a calibration of the model to historical data. This is the final report for San Bernard and Big Boggy NWRs as produced under this contract.

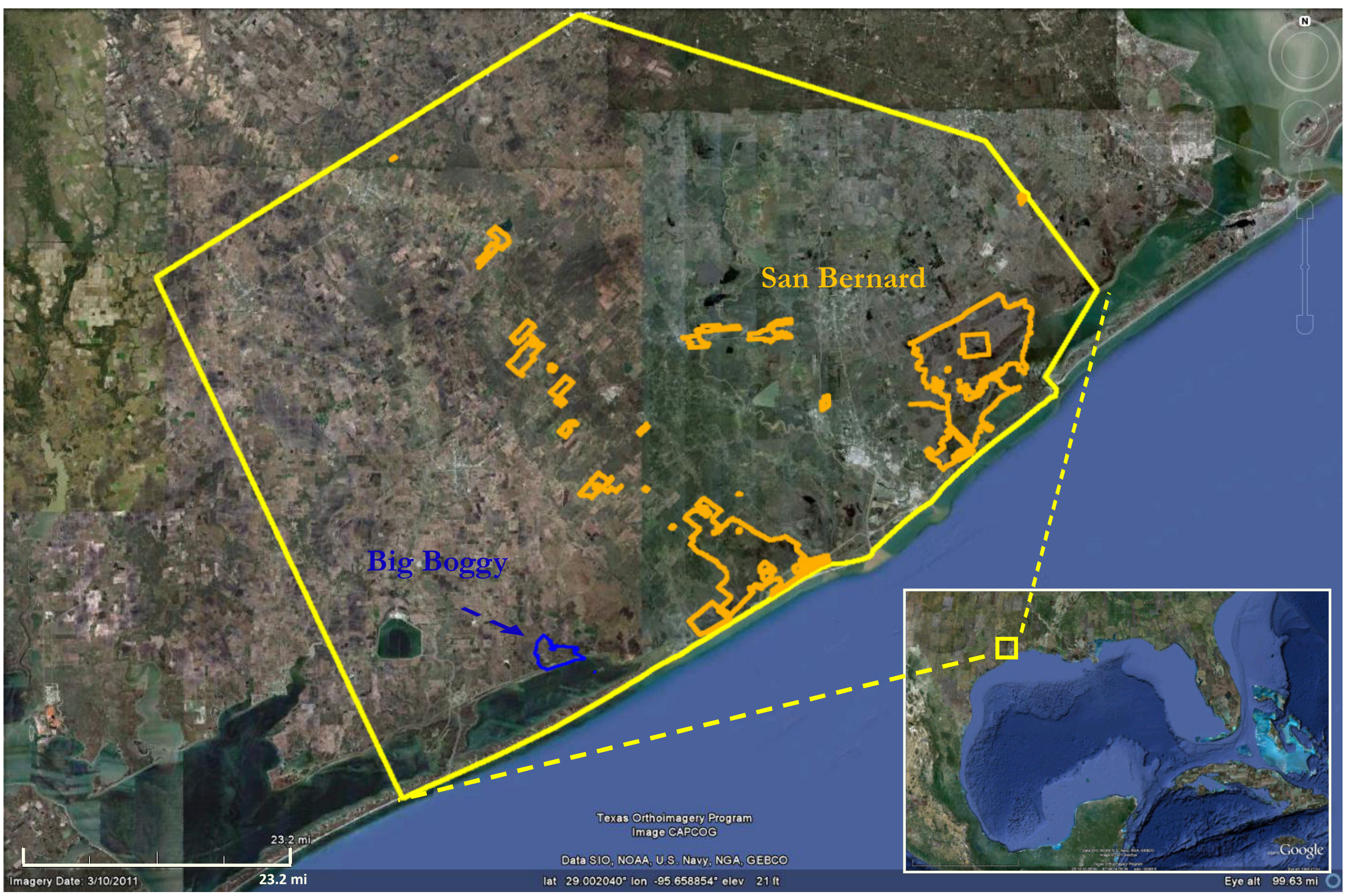


Figure 1. Refuges boundary. **Orange** – San Bernard NWR acquired boundary,
Blue – Big Boggy approved acquisition boundary, **Yellow** – San Bernard NWR approved acquisition boundary

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).

SLAMM predictions are generally obtained by two consecutive steps: (1) calibration of the model using available historical wetland and SLR data, referred to as the "hindcast;" (2) starting from the most recent available wetland and elevation data, the calibrated model is run to predict wetland changes in response to estimated future SLR.

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).

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 (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 and 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 will be used in these simulations, but only 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 simulations of San Bernard and Big Boggy.

- 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 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. 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 (Council for Regulatory Environmental Modeling 2008). Site-specific factors that increase or decrease model uncertainty may be covered in the *Discussion* section of this report.

Sea Level Rise Scenarios

SLAMM 6 was run using 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 SLR 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 SLR 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 SLRs 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, 1.5 m, and 2 m of eustatic SLR by the year 2100. The A1B- maximum scenario was scaled up to produce these bounding scenarios (Figure 2).

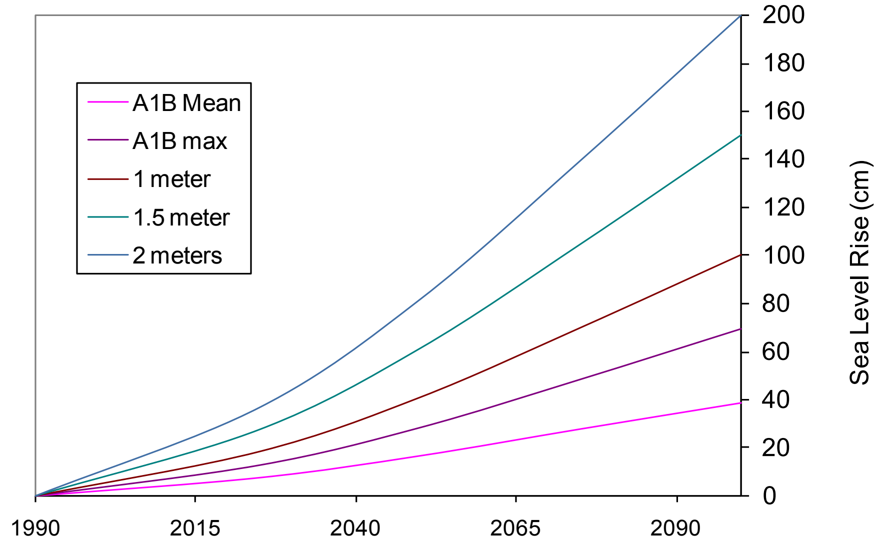


Figure 2. Summary of SLR scenarios utilized

When the model was run to estimate wetland changes in the past ("hindcasting"), the local rate of relative SLR from 1984 to 1990 was estimated to be 4.3 mm/year. This value is the observed average SLR trend observed between 1954 and 2006 at the nearby gauge station of Freeport, TX (NOAA gauge # 8772440). The global rate of (eustatic) SLR from 1990 to the 2006 was estimated to be 3 mm/year (Grinsted et al. 2009)[1].

[1] Due to the predicted increase of SLR over the next 90 years, this is achieved by entering a "custom" eustatic SLR of 0.57 by 2100 within the SLAMM interface.

Data Sources and Methods

Most recent wetland data. Figure 3 shows the most recent available wetlands layer obtained by combining recent National Wetlands Inventory (NWI) photos dated 1992, 2001 and 2006 (Figure 4) to obtain coverage for the entire study area. Converting the NWI survey into 30 m cells indicated that the approximately 5,000 acre Big Boggy NWR (approved acquisition boundary including water) is composed of the following categories:

Land cover type – Big Boggy NWR		Area (acres)	Percentage (%)
	Irregularly Flooded Marsh	2012	40
	Undeveloped Dry Land	824	17
	Regularly Flooded Marsh	748	15
	Estuarine Open Water	717	14
	Inland Fresh Marsh	357	7
	Inland Open Water	254	5
	Estuarine Beach	25	<1
	Swamp	17	<1
	Inland Shore	15	<1
	Developed Dry Land	4	<1
	Total (incl. water)	**4975**	**100**

While for the over 2 million acre San Bernard NWR (approved acquisition boundary including water) the land cover is composed as follows:

Land cover type		Area (acres)	Percentage (%)
	Undeveloped Dry Land	1580181	77
	Inland Fresh Marsh	100208	5
	Estuarine Open Water	99359	5
	Swamp	80502	4
	Irregularly Flooded Marsh	57071	3
	Developed Dry Land	44375	2
	Inland Open Water	44187	2
	Regularly Flooded Marsh	30871	2
	Estuarine Beach	6269	<1
	Inland Shore	3595	<1
	Tidal Fresh Marsh	3082	<1
	Riverine Tidal	2578	<1
	Open Ocean	2421	<1
	Ocean Beach	1200	<1
	Tidal Swamp	325	<1
	Mangrove	66	<1
	Rocky Intertidal	38	<1
	Cypress Swamp	4	<1
	Total (incl. water)	**2056332**	**100**

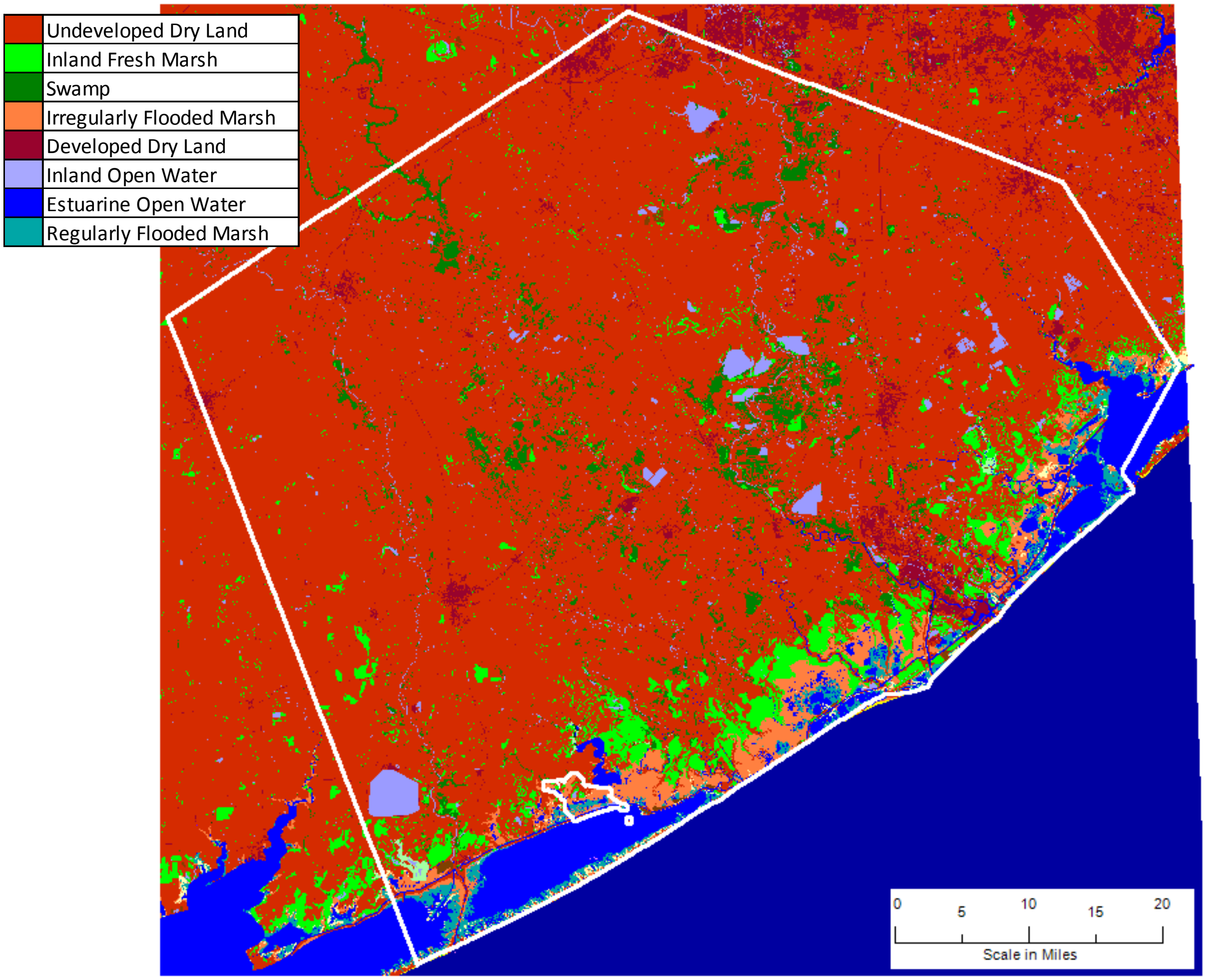


Figure 3. Wetland coverage of the study area. Modeling boundaries indicated in white

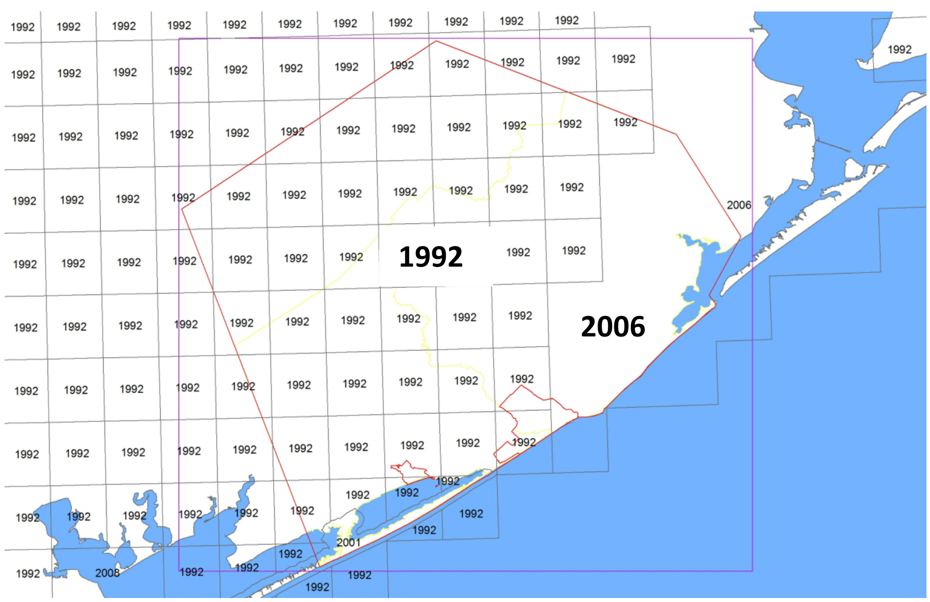


Figure 4. Most Current NWI photo dates

Elevation Data. The digital elevation map (DEM) used in this simulation is a bare-earth dataset that was derived from a Texas Water Board LiDAR via NOAA dated 2006 (Figure 5) for Matagorda and Brazoria counties. Available elevation data for inland regions of the study area were much older and not covered by LiDAR. However, these elevations are generally over 15 m above MTL and thus this region is not likely to be influenced by SLR.

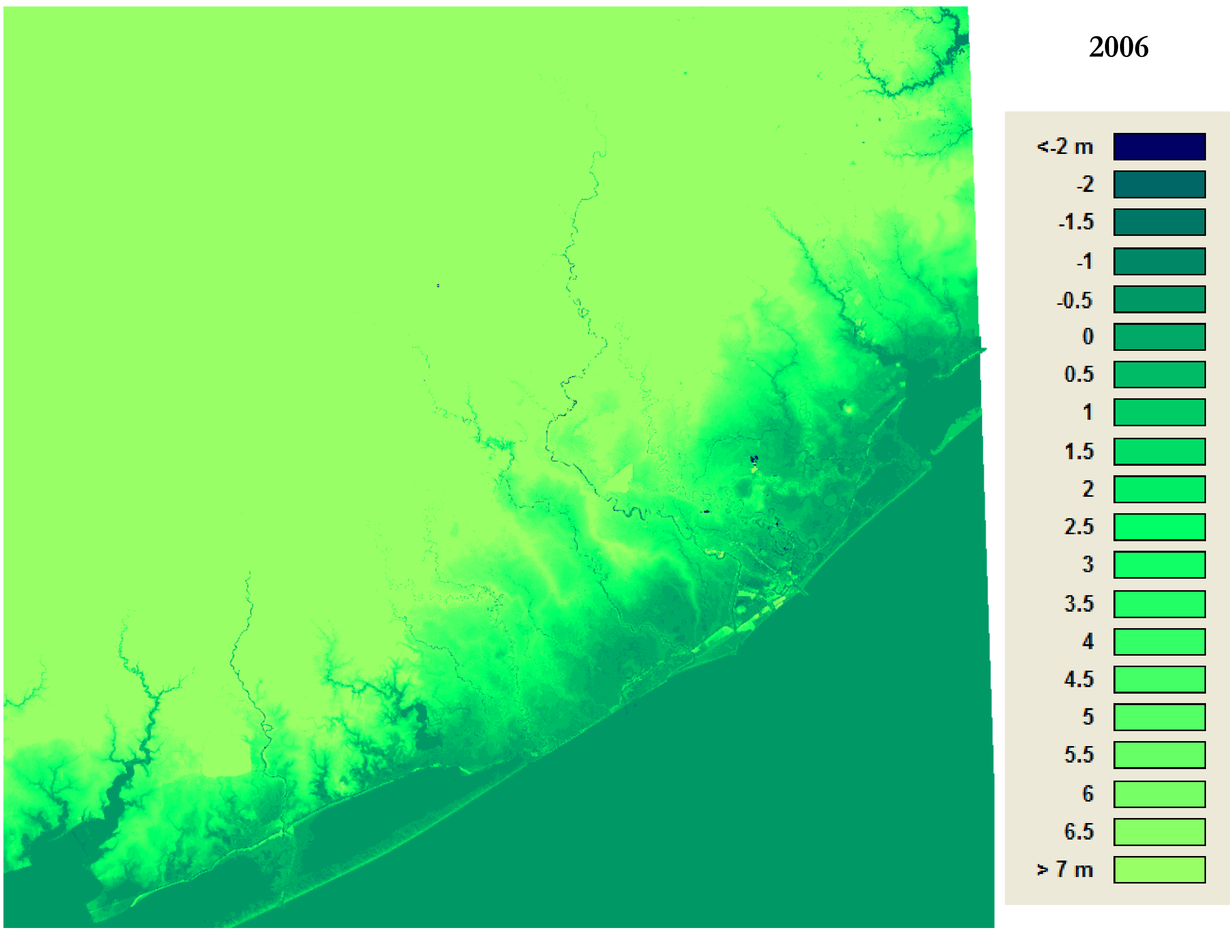


Figure 5. Shade-relief elevation map of the study area.

Historic wetland data. Figure 6 shows the layer describing the older wetland coverage of the area that is used for the hindcast. This layer is derived from NWI photos dated 1992 (Figure 7). Although it is preferable to have a longer period between historical and most recent layers for improving model calibration, we were unable to obtain detailed wetland land cover data older than 1992.

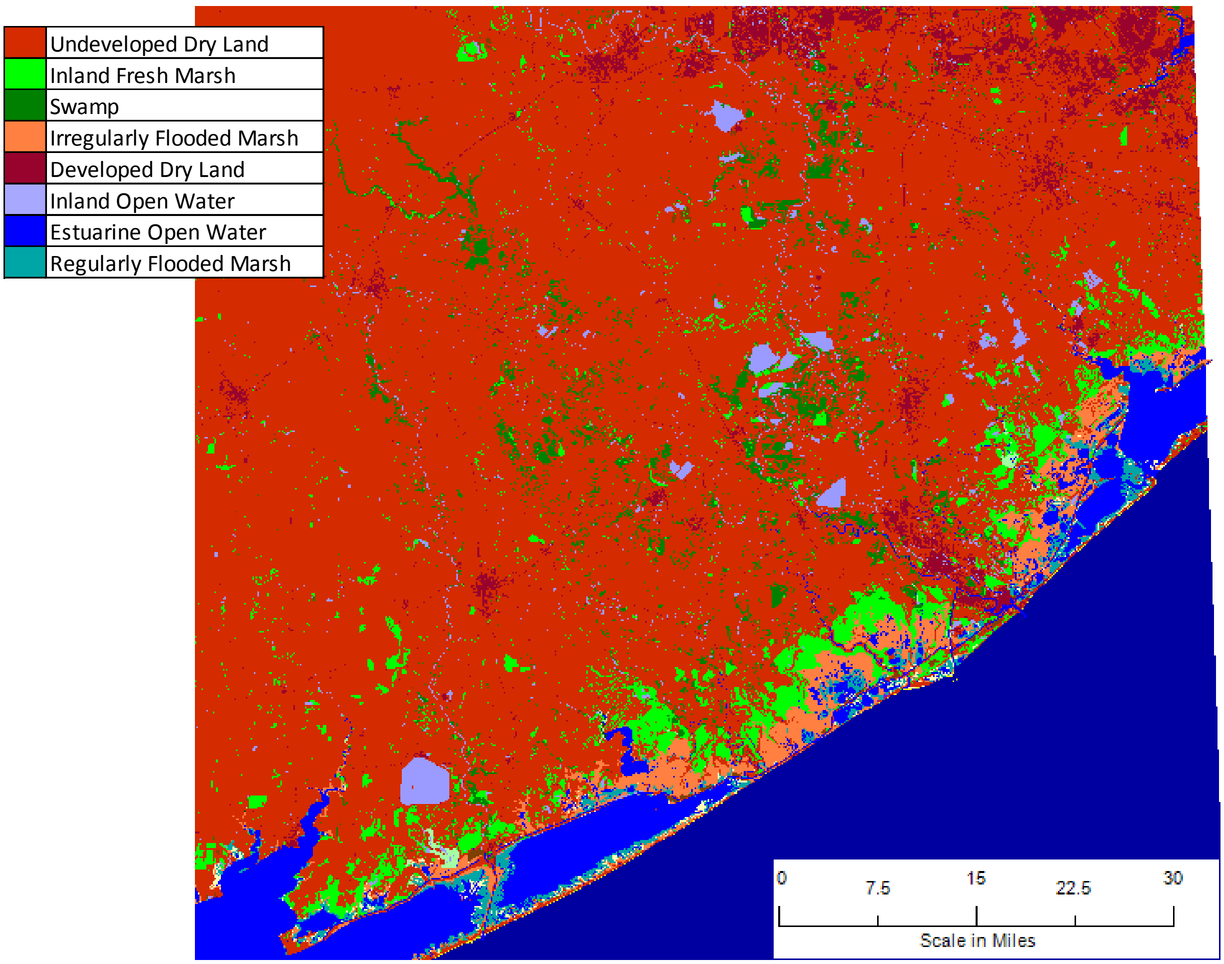


Figure 6. Historical wetland coverage (1992)

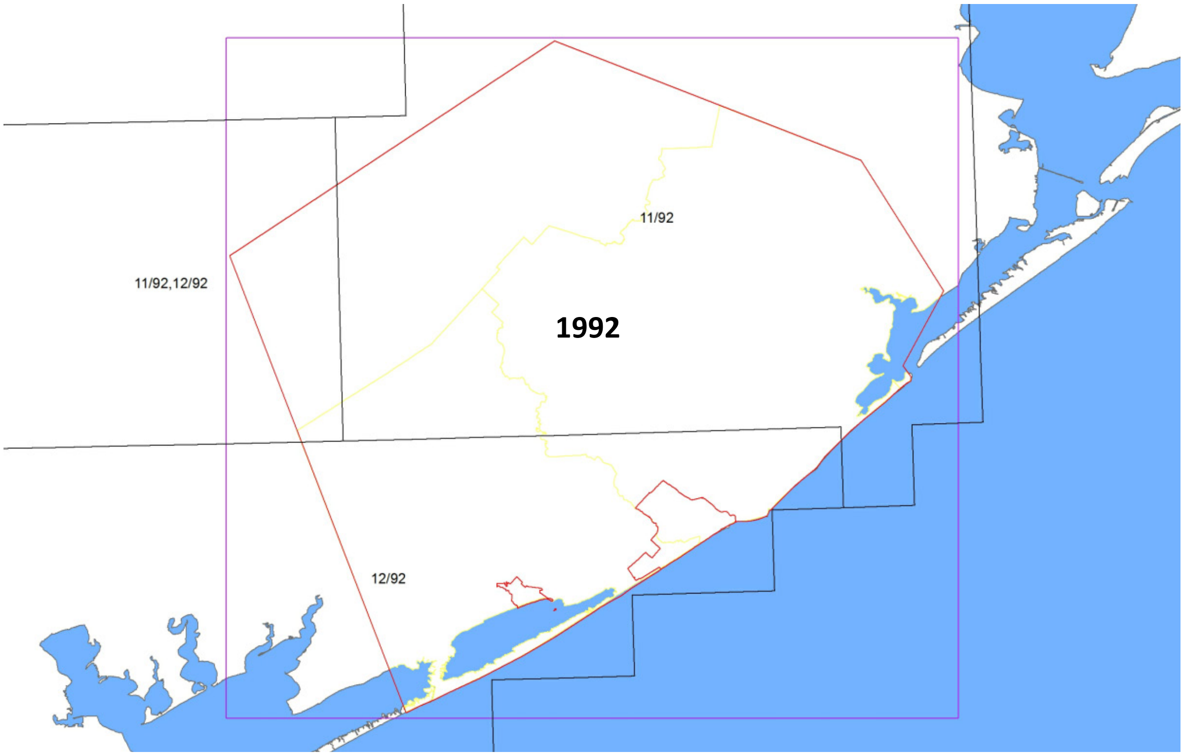


Figure 7. Historic NWI photo dates

Model Timesteps. Model output was produced in 3-year intervals for the hindcast from 1992 to 2006, while forecast outputs were chosen at years 2025, 2050, 2075 and 2100 with the initial condition date set to most recent wetland data available (approximately 2006).

Dikes and Impoundments. According to the National Wetland Inventory, there are some inland-fresh marsh and open water areas that are protected by dikes, as shown in Figure 8.

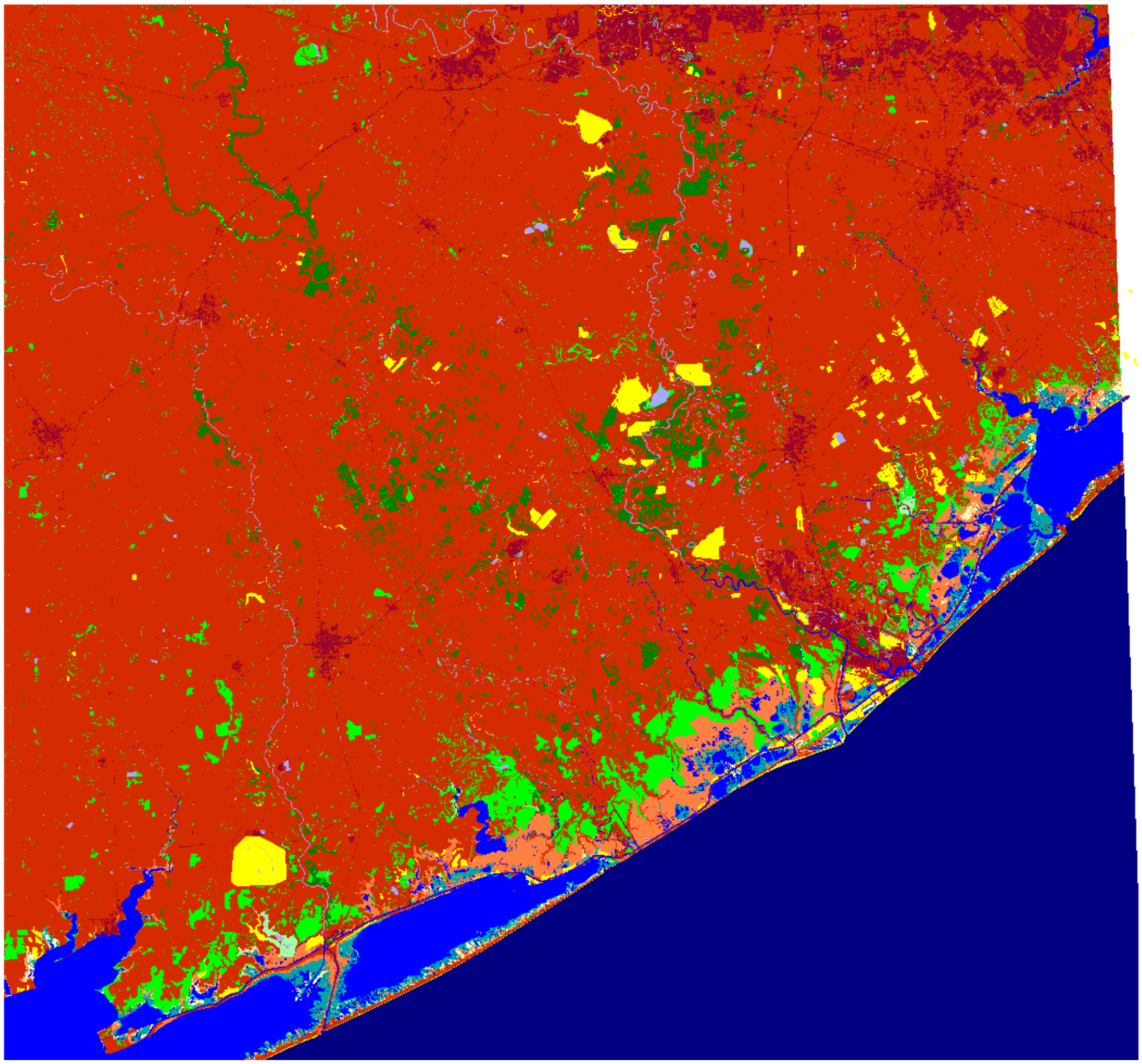


Figure 8. Dikes present in the study area (represented in yellow)

Historic sea level rise rates. The historic SLR trend of 4.35 mm/yr recorded at the NOAA Tide Datum located at Freeport, TX (ID 8772440) was applied throughout the model extent. This rate of SLR is higher than the global average for the last 100 years (approximately 1.7 mm/year, IPCC 2007a) potentially reflecting land subsidence at this site. This differential between local and global SLR rates was projected to remain constant through 2100.

Tide Ranges. Figure 9 shows the locations of the 4 tide gauge stations (red marks) closest to the study area used to define the tide ranges for this site.

Figure 9. Location of NOAA tides gages used for San Bernard/Big Boggy/Brazoria NWR

The great diurnal tide range, summarized in Table 1, varies from 0.13 m inside the barrier island to 0.55 m on the open ocean. The observed gradient of decreasing tidal range from south to north was applied to this SLAMM simulation. For East Galveston Bay a tide range of 0.3 m was obtained from NOAA tide tables.

Table 1. NOAA tide gauges and values.

Station ID	Site Name	Tide Range (m)	Salt Elevation (m)	Subsite
8773701	Port O'Connor, TX	0.12	0.28	1
8773963	North Matagorda, TX	0.13	0.15	1
8772132	Christmas Bay, TX	0.25	0.29	2, 3
8772447	Freeport, TX	0.55	0.64	5

Salt elevation. This parameter within SLAMM designates the boundary between wet lands and dry lands or saline wetlands and fresh water wetlands. As such, this value may be best derived by examining historical tide gage data. For this application, the salt boundary was defined as the elevation above which inundation is predicted less than once per thirty days using data from the gauge station at Freeport, TX (ID 8772440). Based on the frequency of inundation analysis of the period 03/2005-03/2008, salt elevation is estimated to be approximately 0.58 m above MTL, equivalent to an elevation of 2.34 Half Tide Units (HTU), as shown in Figure 10. Using this factor to estimate salt elevations results in the parameter being set, on a spatially variable basis, to elevations ranging from 0.15 m to 0.64 m above MTL as illustrated in Table 1.

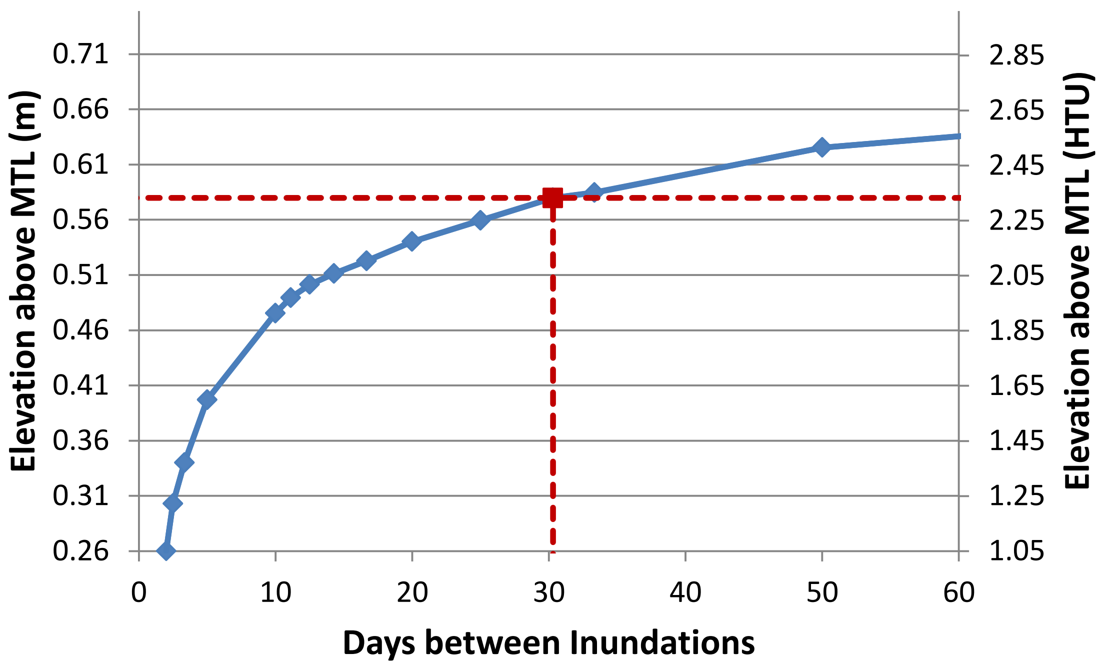


Figure 10. Frequency of inundation based upon 3 years of data

Accretion rates. Accretion rates for regularly and irregularly flooded marsh were set to 8.2 mm/year and 4.7 mm/year respectively based on a study by Callaway et al. (1997) on sediment accretion rates observed in the San Bernard NWR. There are no local accretion data for tidal-fresh marsh, so model defaults were used based on a previous study in Chesapeake Bay.

Elevation correction. Elevation data were provided with a vertical datum of NAVD88 which is not precisely the same thing as mean-tide level (MTL). To convert data to a mean-tide level basis, an MTL-to-NAVD88 correction was derived using NOAA's VDATUM software. A spatial (raster) map of MTL-to-NAVD88 corrections was created for the study area (Figure 11). Data were extrapolated inland where VDATUM corrections are not available.

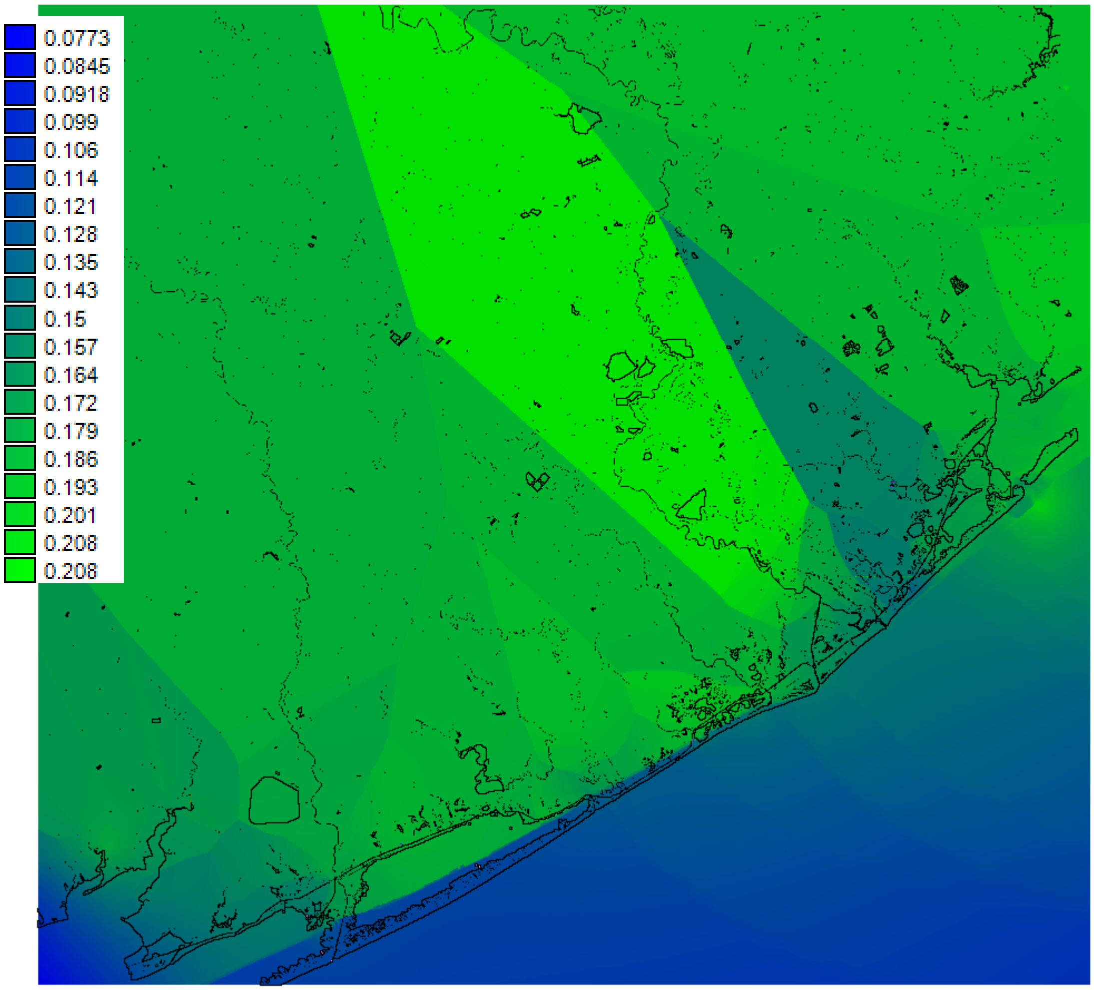


Figure 11. Difference between MTL and NAVD88 in meters over the shoreline of the study area

Refuge boundaries. Modeled USFWS 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 30 m by 30 m cells.

Input subsites and parameter summary. Based on the spatial tidal differences (see Table 1), five different simulation input subsites were identified as illustrated in Figure 12. Table 2 summarizes all SLAMM input parameters for each subsite of the study area. Values for parameters with no specific local information were kept at their default value.

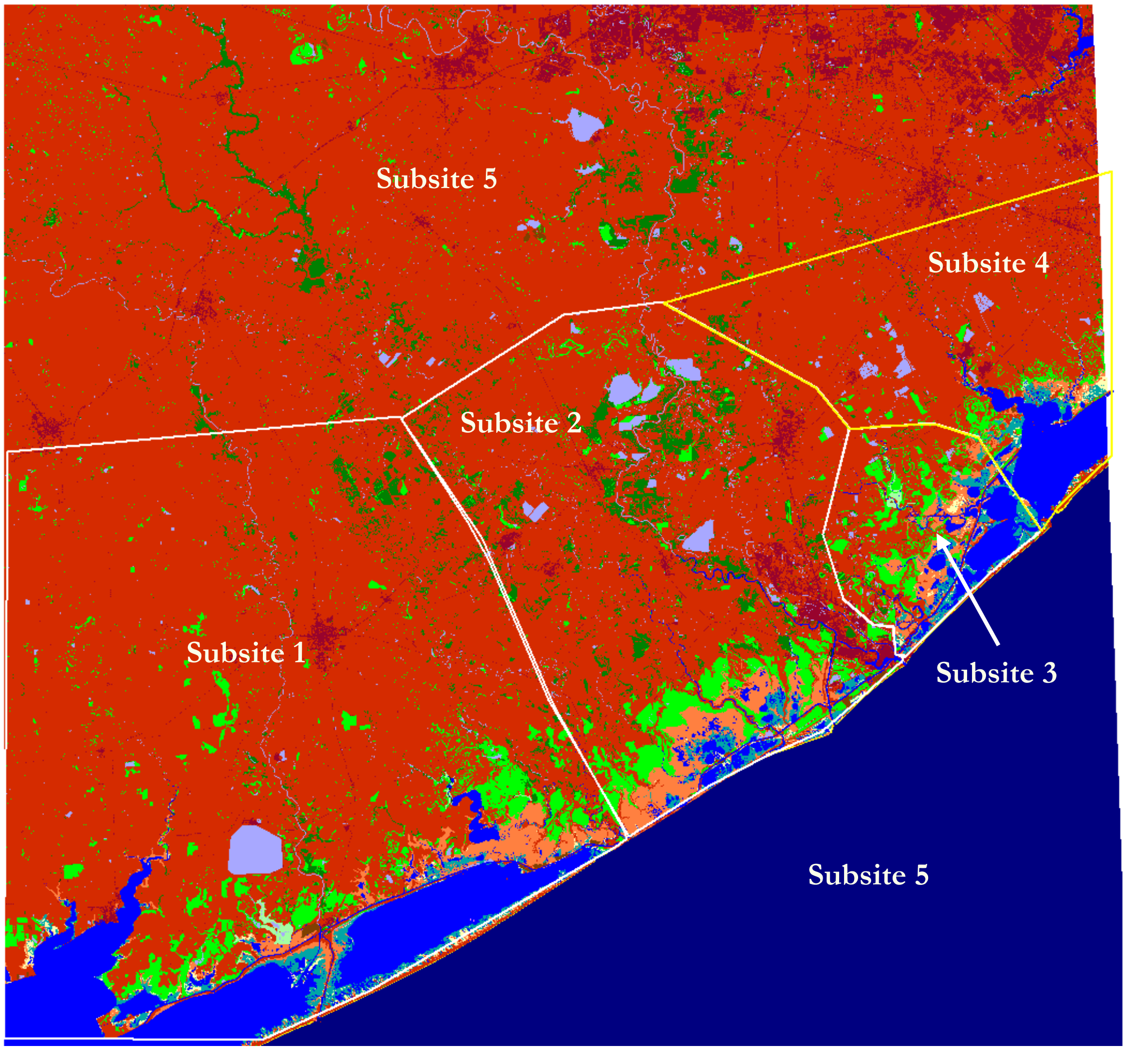


Figure 12. Input subsites for model application

Table 2. Summary of SLAMM input parameters for San Bernard and Big Boggy NWR

Parameter	SubSite 1	SubSite 2	SubSite 3	SubSite 4	SubSite 5
Description	West	East	Central	Galveston	Inland-Ocean
NWI Photo Date (YYYY)	1992	2006	1992	2006	1992
DEM Date (YYYY)	2006	2006	2006	2006	2006
Direction Offshore [n,s,e,w]	South	South	South	South	South
Historic Trend (mm/yr)	4.35	4.35	4.35	4.35	4.35
MTL-NAVD88 (m)	†	†	†	†	†
GT Great Diurnal Tide Range (m)	0.14	0.25	0.25	0.3	0.55
Salt Elev. (m above MTL)	0.16	0.29	0.29	0.35	0.64
Marsh Erosion (horz. m /yr)	1.8	1.8	1.8	1.8	1.8
Swamp Erosion (horz. m /yr)	1	1	1	1	1
T.Flat Erosion (horz. m /yr)	0.5	0.5	0.5	0.5	0.5
Reg.-Flood Marsh Accr (mm/yr)	8.2	8.2	8.2	8.2	8.2
Irreg.-Flood Marsh Accr (mm/yr)	4.7	4.7	4.7	4.7	4.7
Tidal-Fresh Marsh Accr (mm/yr)	5.9	5.9	5.9	5.9	5.9
Inland-Fresh Marsh Accr (mm/yr)	5.9	5.9	5.9	5.9	5.9
Mangrove Accr (mm/yr)	3.3	3.3	3.3	3.3	3.3
Tidal Swamp Accr (mm/yr)	1.1	1.1	1.1	1.1	1.1
Swamp Accretion (mm/yr)	0.3	0.3	0.3	0.3	0.3
Beach Sed. Rate (mm/yr)	0.5	0.5	0.5	0.5	0.5

† Spatially-variable raster used for MTL-NAVD88 corrections

Results

The analysis of San Bernard and Big Boggy NWR includes both hindcast and forecast analyses. Hindcasting is performed by starting a simulation at the photo date of the oldest available wetlands data, running it through the present day, and comparing the output to present-day wetland data. The primary goal of this step is to assess the predictive capacity of the model and, when needed, to calibrate model parameters in order to better reproduce the observed effect of the historical sea level signal on the wetland types in a given study area. Once this step is completed, the forecast is performed by running the SLAMM model from the present day into the future under different SLR scenarios.

As with all environmental models, uncertainty within input data and model processes limit model precision. Some uncertainty within results may be caused by the relative simplicity of the SLAMM model. Additionally, the wetland data may be inaccurate due to lack of horizontal precision or misclassified land coverage, while the DEM may have errors in the elevation measurements of the LiDAR data. Another source of uncertainty is encountered when the DEM data and wetland coverage data were collected during different time-periods (not temporally synoptic). Limited tidal information, both in time and space, may further reduce model accuracy.

In a recent communication with the head of the National Wetlands Inventory, a strong recommendation was made that if any future hindcasting be undertaken using the SLAMM model that this only be undertaken using "back dated" wetland layers. It is NWI policy to only make comparisons of historical to contemporary wetland layers after this process has been completed. The back dating process involves integrating contemporary wetland coding methods, current satellite imagery, and also the older wetland imagery to ensure that the historical and current data are comparable. Otherwise a wetland increase is nearly always predicted due to the change in imagery technology. Having NWI produce a back-dated historical image was out of the scope of this project and also impossible to complete within the period of performance.

Since historical DEM data is usually not used (older technology generally produced low-vertical-resolution data), SLAMM has two methods to compensate for the lack of historical elevations. The first method is by using the elevation pre-processor, which estimates elevation ranges as a function of tide ranges and estimated relationships between wetland types and tide ranges (Clough et al. 2010). As an alternative, the second method involves a modification of present-day, high-resolution DEM so that it reflects the historical land-cover date by reversing the estimated land uplift or subsidence which took place in the years between wetland survey and DEM dates. This process ignores changes due to erosion, accretion, or sedimentation, however. Because the historical wetland data is relatively recent, the second approach was used for this study.

Hindcast Results

For this study, the historic and recent wetland layers have the same time stamp of 1992 except in the east section (see Figure 13), around Christmas and Chocolate Bays where the most recent land cover data is dated 2006 (see Figure 4 and Figure 6). Therefore, the hindcast effort was focused only on this area.

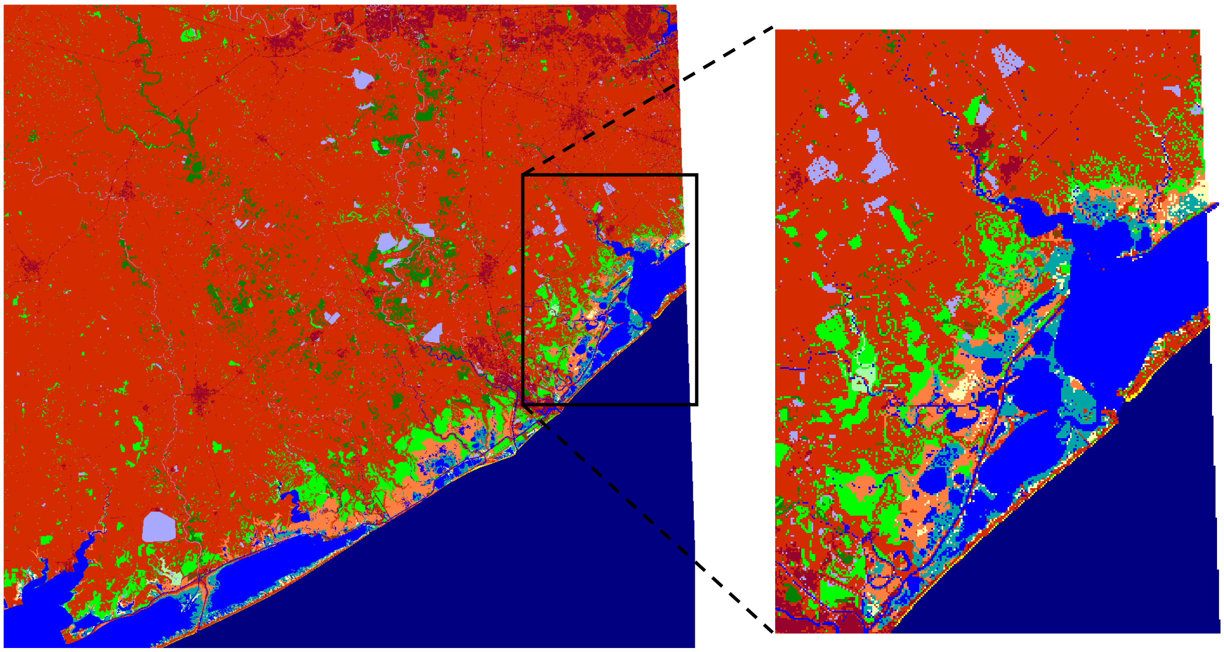


Figure 13. Area used for hindcast analysis

Based on historical records, during the period from 1992 to 2006, approximately 4 cm of local SLR occurred (see Sea Level Rise Scenarios section above). Observed wetland coverage from 2006 and 1992 are compared in Figure 14.

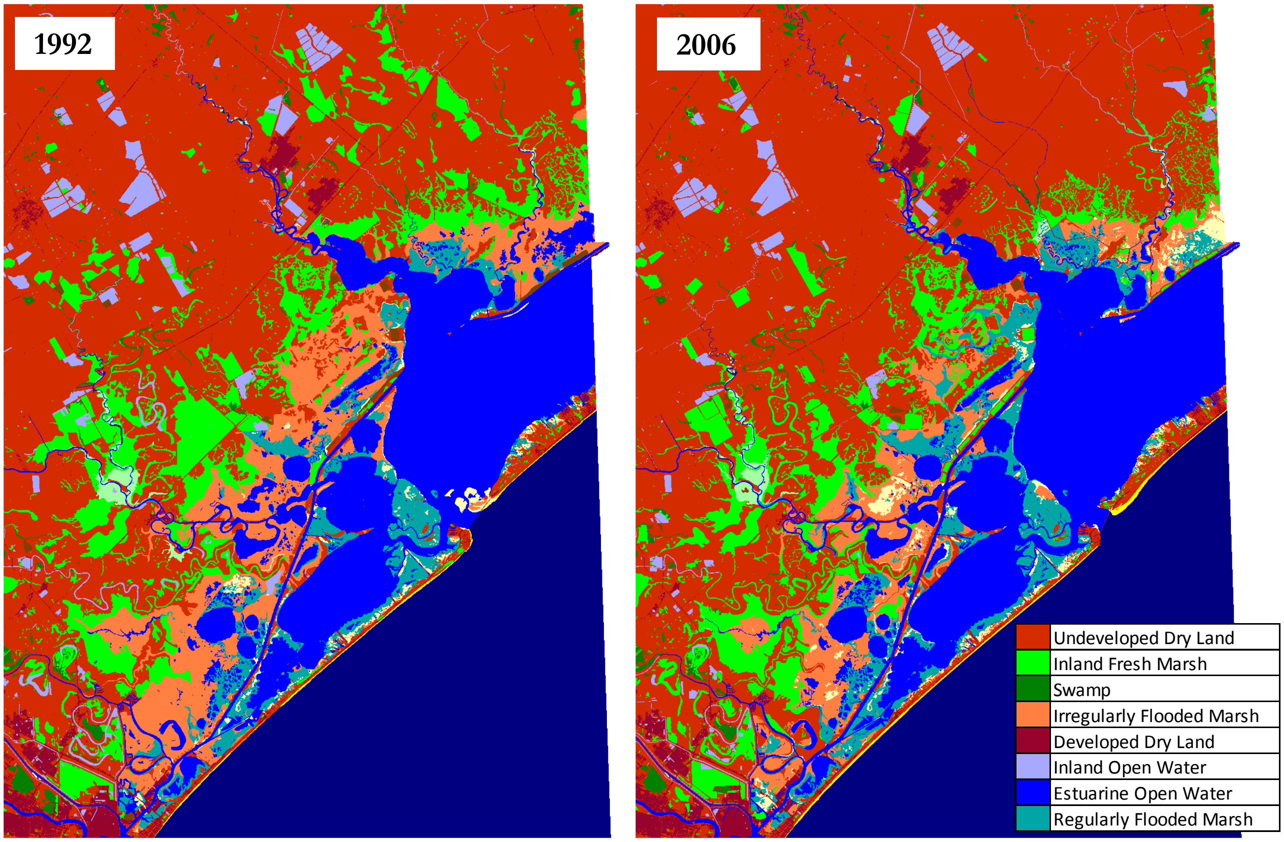


Figure 14. Observed wetland coverage in 1992 and 2006 (NWI surveys)

A comparison of the wetland layers shows that, of the 326,500 acre hindcast study area, around 10,000 acres are classified as dry land in 2006 but were designated inland fresh marsh or irregularly flooded marsh in 1992. It is not clear if these changes are real or if they are due to a mischaracterization of the land cover in one or both surveys (see the note about "back dating" above). However, the SLAMM model will not predict such cover changes as a result of the 4 cm of SLR that were applied over the period of the hindcast. Therefore, applying the SLAMM model from the available initial wetland layer leads to a prediction that does not closely fit the NWI 2006 layer, as illustrated by the differences in the observed and predicted images of the land cover in Figure 15.

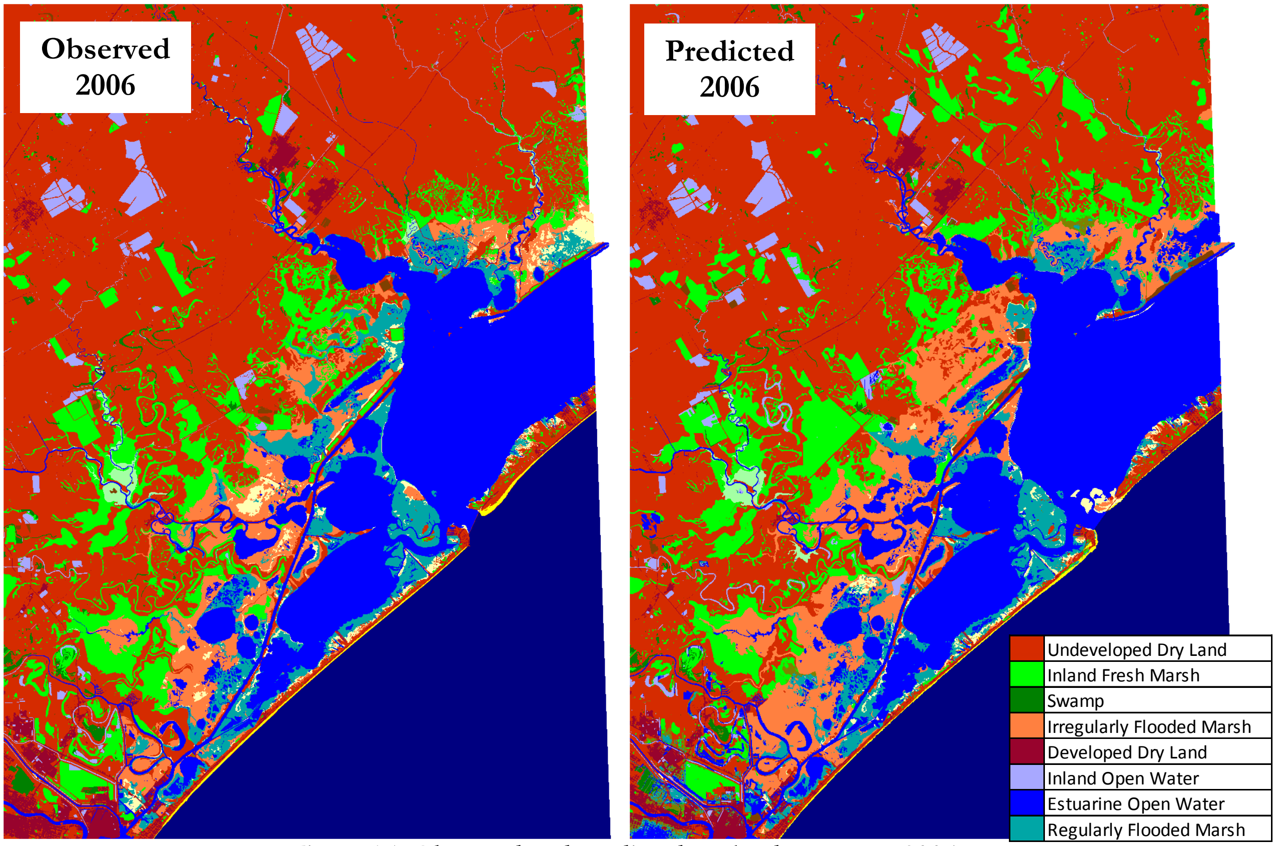


Figure 15. Observed and predicted wetland coverage, 2006

Despite non-SLR based changes in the wetland layers used, SLAMM is capable of predicting overall trends during the hindcast period. A quantitative comparison of the observed and predicted wetland changes is presented in Table 3.

Table 3. Wetland predicted results vs. observed wetland coverage changes from 1996 to 2006

Land cover	Observed land cover in 1996 (acres)	Observed land cover in 2007 (acres)	Land cover predicted by hindcast (acres)	Observed loss 1984-2008 (1)		Predicted loss 1984-2008 (1)	
				(acres)	(%)(2)	(acres)	(%)(2)
Undeveloped Dry Land	124816	134577	123077	-9761	-8	1739	1
Open Ocean	62226	62137	62254	89	0	-27	0
Estuarine Open Water	44533	44052	46812	481	1	-2279	-5
Inland-Fresh Marsh	27938	23786	26807	4152	15	1131	4
Irreg.-Flooded Marsh	21693	14017	20897	7676	35	796	4
Regularly-Flooded Marsh	9957	12193	10949	-2236	-22	-992	-10
Inland Open Water	6624	5617	6240	1007	15	383	6
Developed Dry Land	5468	5422	4691	46	1	776	14
Estuarine Beach	1716	3071	1641	-1355	-79	75	4

(1) A negative number indicates a net gain

(2) Fractional loss with respect to initial coverage

Inland fresh marsh coverage is predicted to be reduced (although not converted to dry land), while part of the irregularly-flooded marsh is converted to regularly-flooded marsh. For irregularly-flooded marsh SLAMM predicts a gain of 10% while a 22% gain is observed.

Most of the developed-dry land in this section of the study area is around Freeport, TX, located the lower west corner of the maps in Figure 15. SLAMM predicts a 15% loss of developed dry land during the simulated time period while only 1% is observed. There are indications that the industrial area around the Old Brazos river is protected by dikes (Tremblay and Calnan 2011). However, no detailed information was available on the dike system and therefore it was not included in the simulation. As a consequence, the model predicts the formation of transitional salt marsh in this developed area that it is not actually observed.

Based on the hindcast simulation, the minimum elevation of regularly-flooded marsh was lowered in from the default value to an elevation that reflects the local observed wetland coverage. In addition, the minimum elevation for tidal fresh and estuarine beach categories were reduced based on site-specific elevation data.

Provided that a meaningful hindcast should be done over a longer period of time (long enough to see natural land-cover changes in response to SLR) and given the fact that for most of the study area hindcast data were not available, no additional effort was put into calibration of the SLAMM model for this site.

Forecast – Big Boggy NWR

SLAMM predicts that Big Boggy NWR will be affected by each of the five SLR scenarios examined. Table 5 presents the predicted loss of the major wetland categories by 2100 under each SLR scenario.

Table 4. Predicted loss rates of land categories by 2100 given simulated scenarios of eustatic SLR at Big Boggy NWR

Land cover category	Initial coverage (acres)	Land cover loss by 2100 for different SLR scenarios				
		0.39 m	0.69 m	1 m	1.5 m	2 m
Irregularly Flooded Marsh	2012	12%	43%	69%	87%	93%
Undeveloped Dry Land	824	14%	27%	41%	61%	77%
Regularly Flooded Marsh	748	-7%([1])	-20%	8%	36%	50%
Inland Fresh Marsh	357	0%	0%	0%	0%	1%
Estuarine Beach	25	13%	33%	51%	73%	88%

([1]) A negative loss indicates a gain with respect to initial coverage

Today irregularly-flooded marshes cover approximately 40% of the refuge. By 2100 SLAMM predicts the amount of irregularly-flooded marsh will be significantly reduced, with a loss ranging from 12% to 93%. This wetland type is initially converted to regularly-flooded marsh, which is observed to have a net gain under lower SLR scenarios. However, for SLR scenarios greater than 0.69 m, regularly-flooded marsh will also be lost and converted to tidal flats or open water.

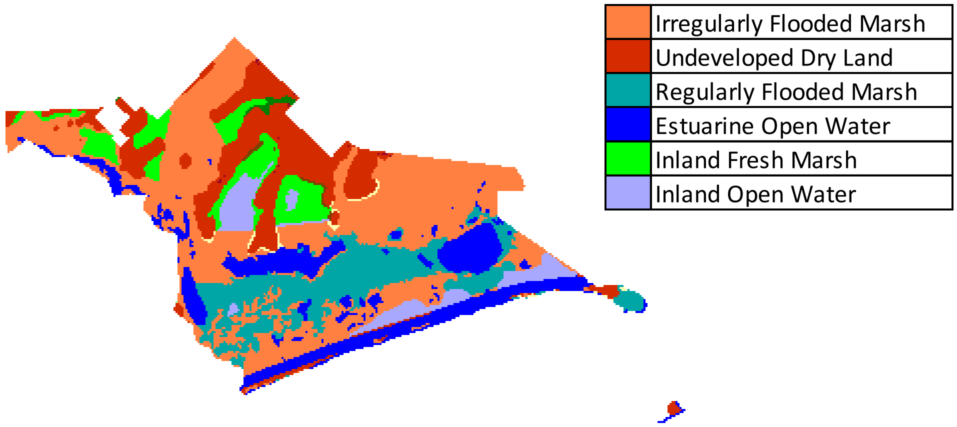
Undeveloped-dry land shows some of resilience to SLR in the lower scenarios. However, as sea levels continue to rise, losses of this of dry land become significant—up to 77% for 2 m SLR. Inland-fresh marsh areas, with a maximum predicted loss of 1%, are resilient to SLR because they are generally protected by dikes.

Aggregating all land-cover categories, simulation results predict that by 2100 approximately 25% (for 0.39 m SLR) to 75% (for 2 m SLR) of the overall refuge acreage will be covered by open water or tidal flat, as compared to 20% today. The south section of the refuge that faces East Matagorda Bay is predicted to be greatly affected under all SLR scenarios while the inland portions may be more resilient to SLR due to the higher elevations of this area.

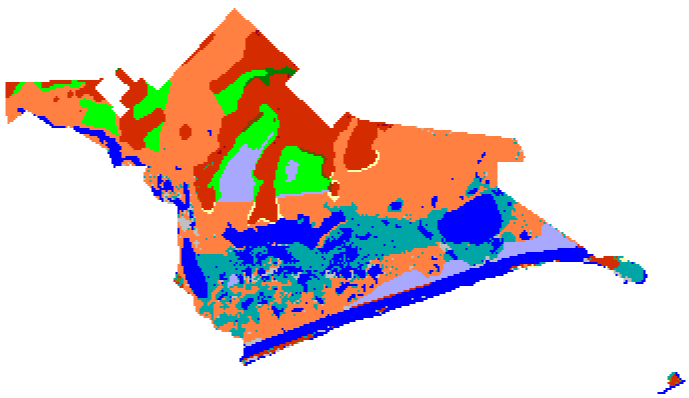
Big Boggy NWR
IPCC Scenario A1B-Mean, 0.39 m SLR eustatic by 2100

Results in Acres

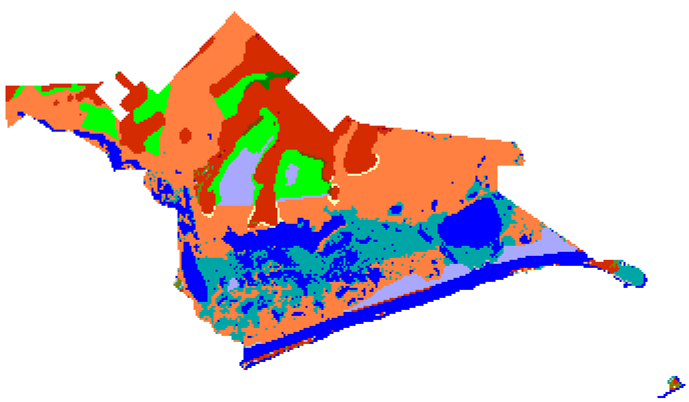
		Initial	2025	2050	2075	2100
	Irregularly Flooded Marsh	2012	1882	1862	1822	1762
	Undeveloped Dry Land	824	807	793	749	710
	Regularly Flooded Marsh	748	654	670	717	804
	Estuarine Open Water	717	885	945	956	964
	Inland Fresh Marsh	357	357	357	357	357
	Inland Open Water	254	254	254	254	254
	Estuarine Beach	25	25	24	23	22
	Swamp	17	17	17	17	17
	Inland Shore	15	15	15	15	15
	Developed Dry Land	4	4	4	4	3
	Transitional Salt Marsh	0	6	17	50	49
	Tidal Flat	0	68	15	12	17
	Total (incl. water)	**4975**	**4975**	**4975**	**4975**	**4975**



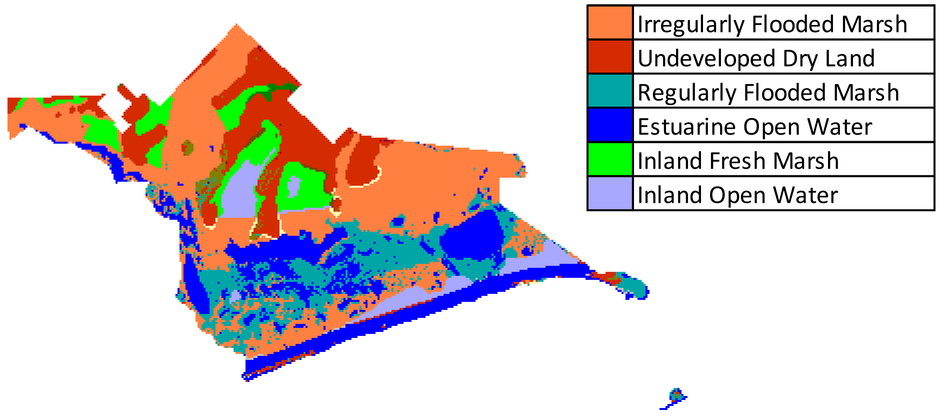
Big Boggy NWR, Initial Condition



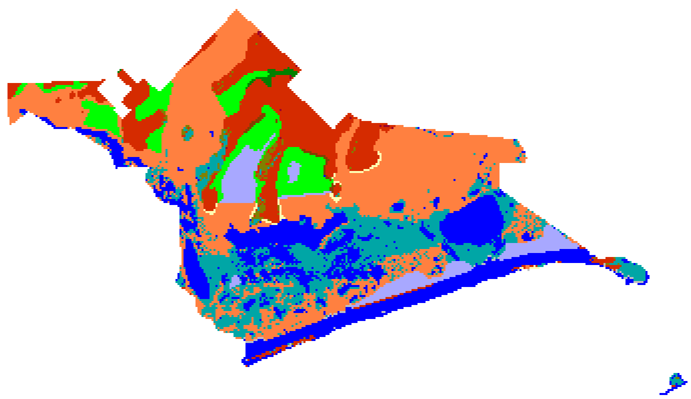
Big Boggy NWR, 2025, Scenario A1B Mean, 0.39 m SLR



Big Boggy NWR, 2050, Scenario A1B Mean, 0.39 m SLR



Big Boggy NWR, 2075, Scenario A1B Mean, 0.39 m SLR

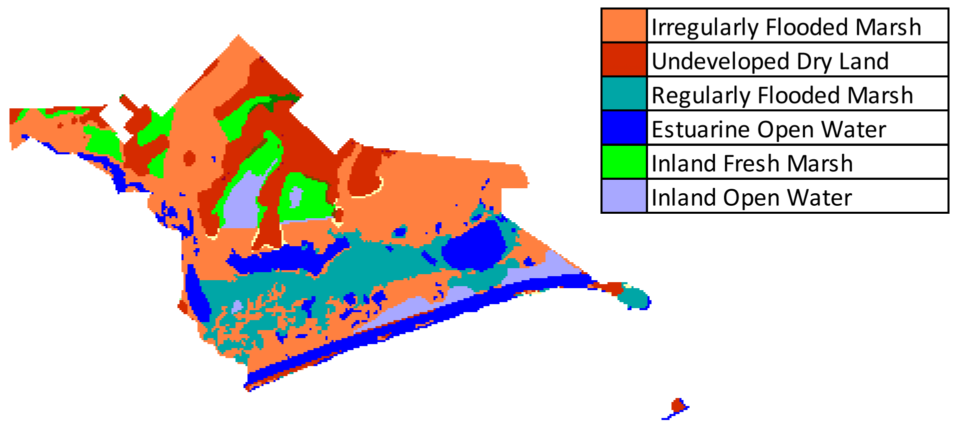


Big Boggy NWR, 2100, Scenario A1B Mean, 0.39 m SLR

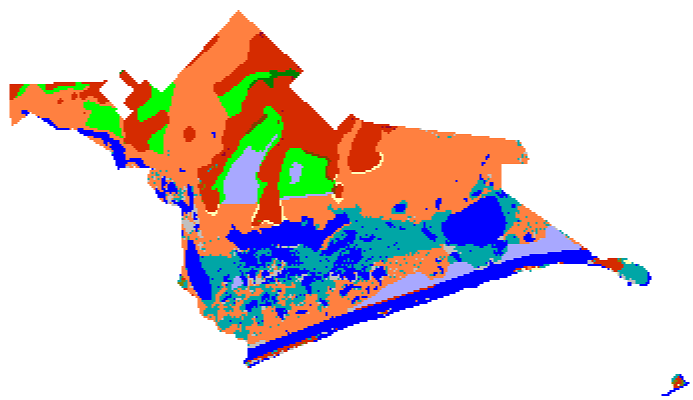
Big Boggy NWR
IPCC Scenario A1B-Max, 0.69 m SLR eustatic by 2100

Results in Acres

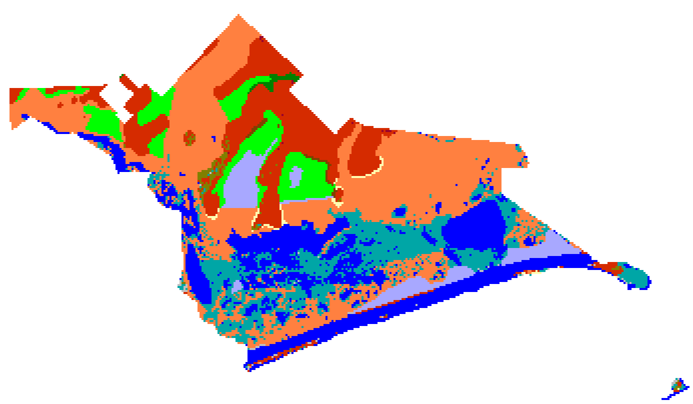
		Initial	2025	2050	2075	2100
	Irregularly Flooded Marsh	2012	1858	1775	1461	1146
	Undeveloped Dry Land	824	804	767	704	603
	Regularly Flooded Marsh	748	642	719	931	898
	Estuarine Open Water	717	906	985	1022	1178
	Inland Fresh Marsh	357	357	357	357	357
	Inland Open Water	254	254	254	254	254
	Estuarine Beach	25	25	24	22	17
	Swamp	17	17	17	17	17
	Inland Shore	15	15	15	15	14
	Developed Dry Land	4	4	4	3	3
	Transitional Salt Marsh	0	8	37	63	96
	Tidal Flat	0	84	21	127	391
	Total (incl. water)	**4975**	**4975**	**4975**	**4975**	**4975**



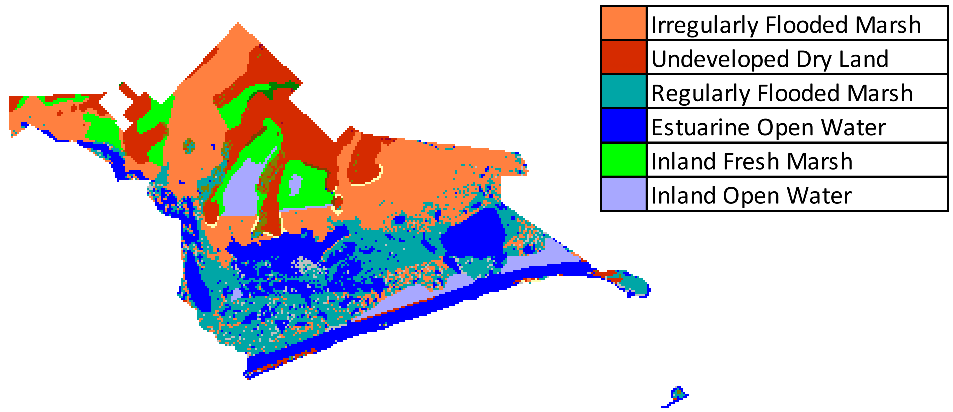
Big Boggy NWR, Initial Condition



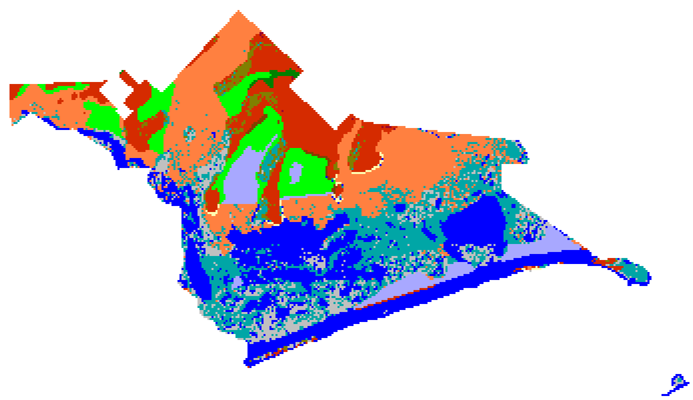
Big Boggy NWR, 2025, Scenario A1B Maximum, 0.69 m SLR



Big Boggy NWR, 2050, Scenario A1B Maximum, 0.69 m SLR



Big Boggy NWR, 2075, Scenario A1B Maximum, 0.69 m SLR

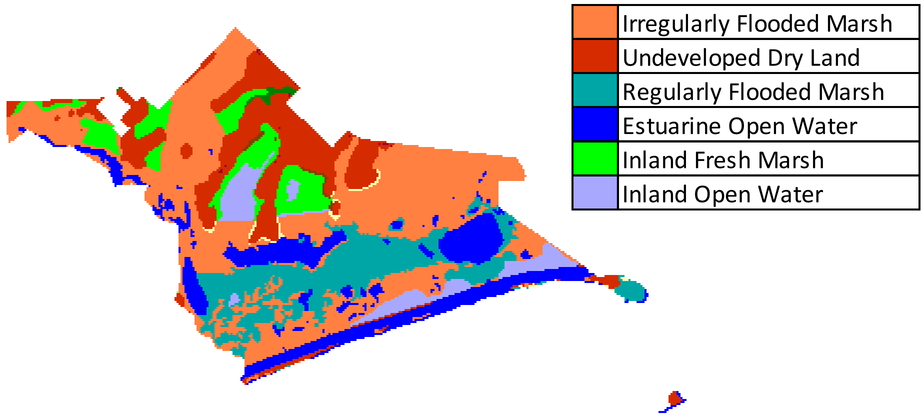


Big Boggy NWR, 2100, Scenario A1B Maximum, 0.69 m SLR

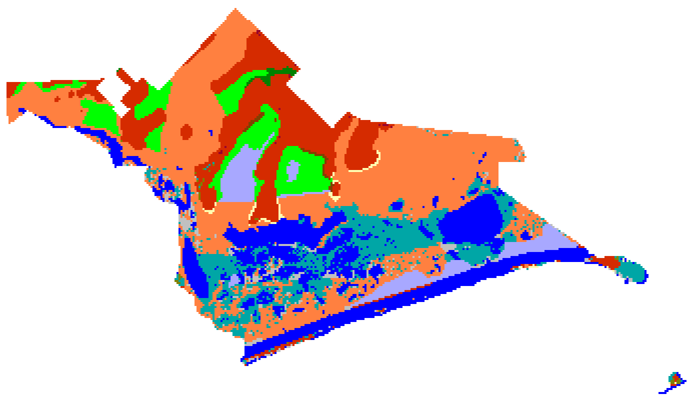
Big Boggy NWR
1 m eustatic SLR by 2100

Results in Acres

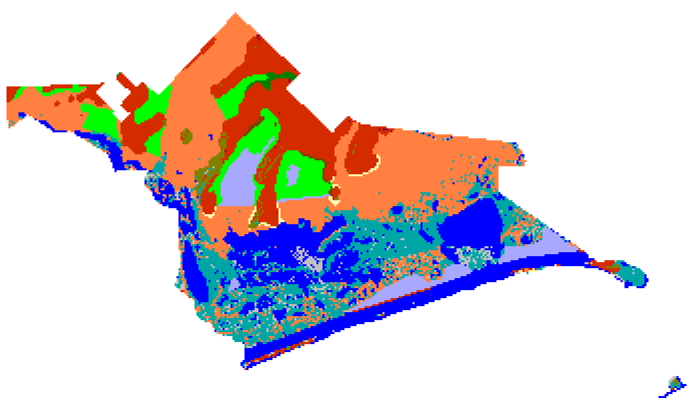
		Initial	2025	2050	2075	2100
	Irregularly Flooded Marsh	2012	1824	1532	1027	630
	Undeveloped Dry Land	824	799	735	631	485
	Regularly Flooded Marsh	748	633	790	924	685
	Estuarine Open Water	717	930	1045	1217	1675
	Inland Fresh Marsh	357	357	357	357	357
	Inland Open Water	254	254	254	254	254
	Estuarine Beach	25	25	23	19	12
	Swamp	17	17	17	17	17
	Inland Shore	15	15	15	14	13
	Developed Dry Land	4	4	4	3	3
	Transitional Salt Marsh	0	11	64	102	142
	Tidal Flat	0	105	139	409	701
	Total (incl. water)	**4975**	**4975**	**4975**	**4975**	**4975**



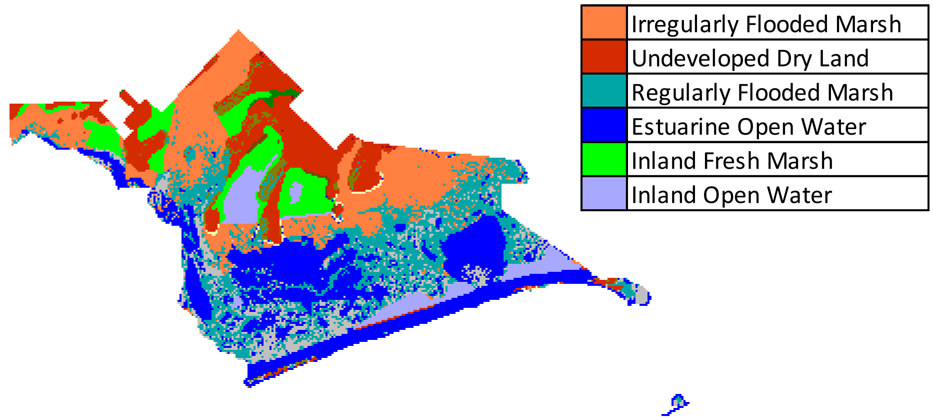
Big Boggy NWR, Initial Condition



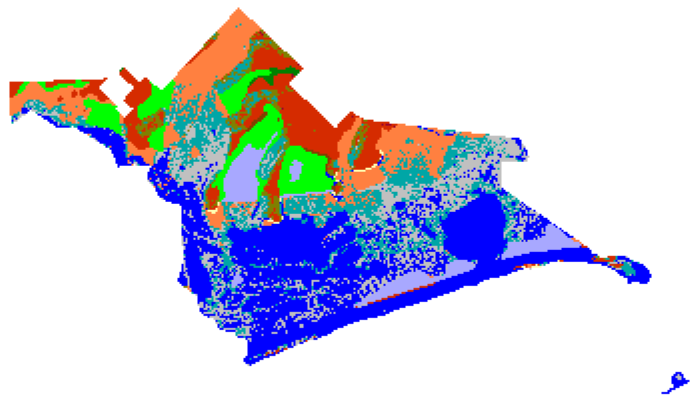
Big Boggy NWR, 2025, 1 m SLR



Big Boggy NWR, 2050, 1 m SLR



Big Boggy NWR, 2075, 1 m SLR

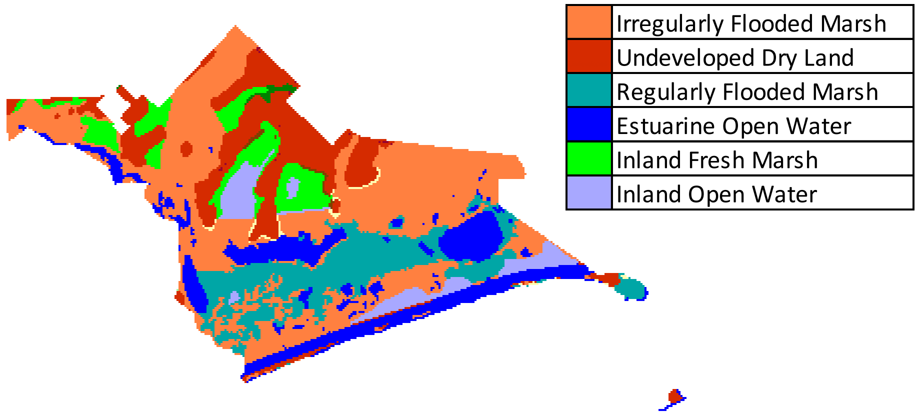


Big Boggy NWR, 2100, 1 m SLR

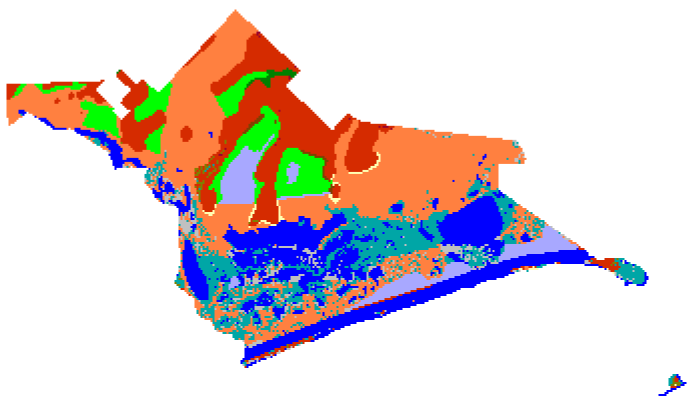
Big Boggy NWR
1.5 m eustatic SLR by
2100

Results in Acres

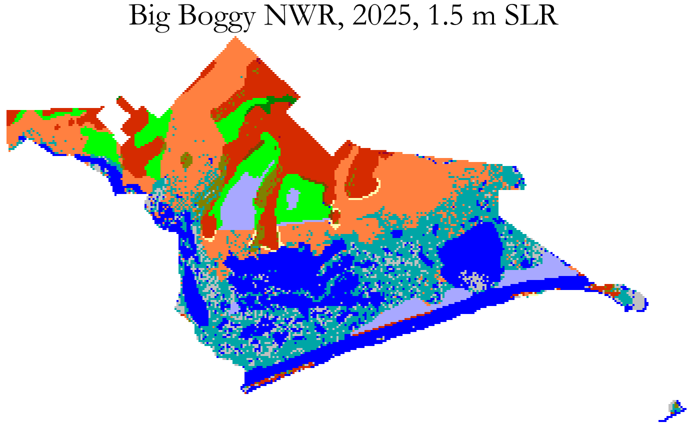
		Initial	2025	2050	2075	2100
	Irregularly Flooded Marsh	2012	1725	1115	539	253
	Undeveloped Dry Land	824	787	689	494	323
	Regularly Flooded Marsh	748	622	951	716	481
	Estuarine Open Water	717	972	1169	1513	2407
	Inland Fresh Marsh	357	357	357	357	357
	Inland Open Water	254	254	254	254	254
	Estuarine Beach	25	24	22	13	7
	Swamp	17	17	17	17	17
	Inland Shore	15	15	14	13	9
	Developed Dry Land	4	4	3	3	1
	Transitional Salt Marsh	0	20	98	191	167
	Tidal Flat	0	177	286	865	699
	Total (incl. water)	**4975**	**4975**	**4975**	**4975**	**4975**



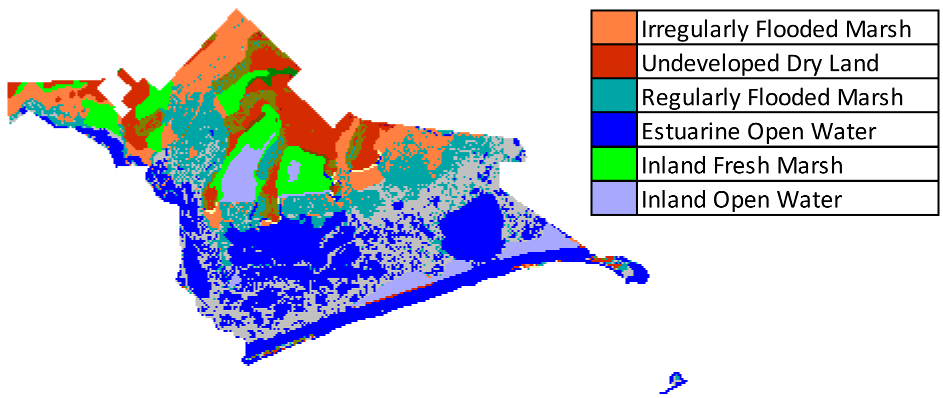
Big Boggy NWR, Initial Condition



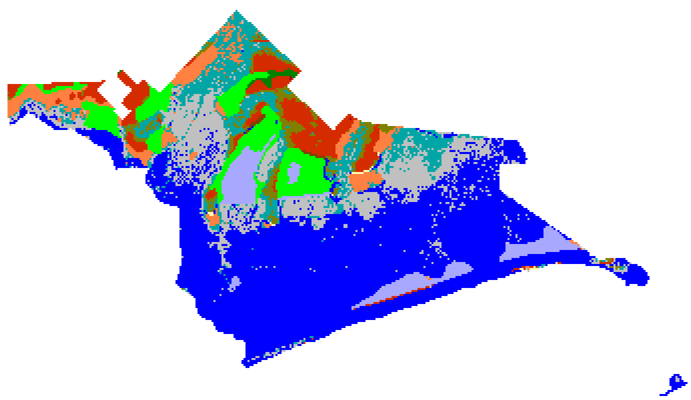
Big Boggy NWR, 2025, 1.5 m SLR



Big Boggy NWR, 2050, 1.5 m SLR



Big Boggy NWR, 2075, 1.5 m SLR

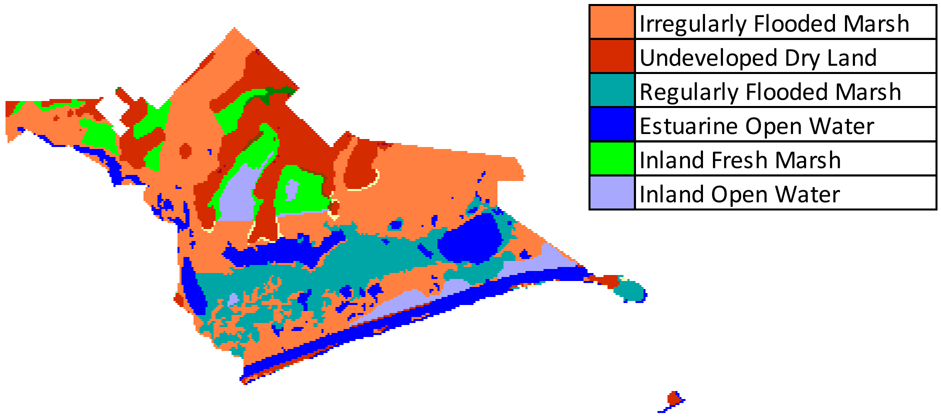


Big Boggy NWR, 2100, 1.5 m SLR

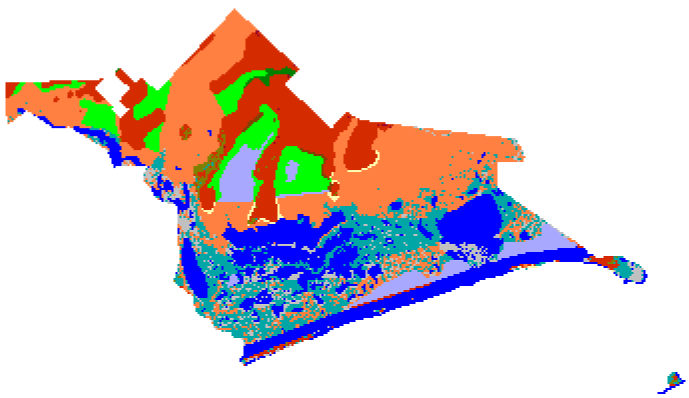
Big Boggy NWR
2 m eustatic SLR by 2100

Results in Acres

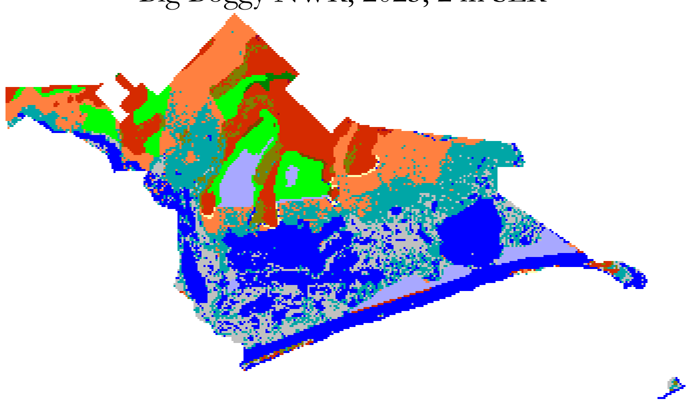
		Initial	2025	2050	2075	2100
	Irregularly Flooded Marsh	2012	1532	742	277	138
	Undeveloped Dry Land	824	766	612	372	186
	Regularly Flooded Marsh	748	702	928	622	374
	Estuarine Open Water	717	1006	1304	1928	2846
	Inland Fresh Marsh	357	357	357	357	352
	Inland Open Water	254	254	254	254	254
	Estuarine Beach	25	24	17	9	3
	Swamp	17	17	17	17	17
	Inland Shore	15	15	14	11	5
	Developed Dry Land	4	4	3	1	1
	Transitional Salt Marsh	0	40	152	236	183
	Tidal Flat	0	259	574	890	617
	Total (incl. water)	**4975**	**4975**	**4975**	**4975**	**4975**



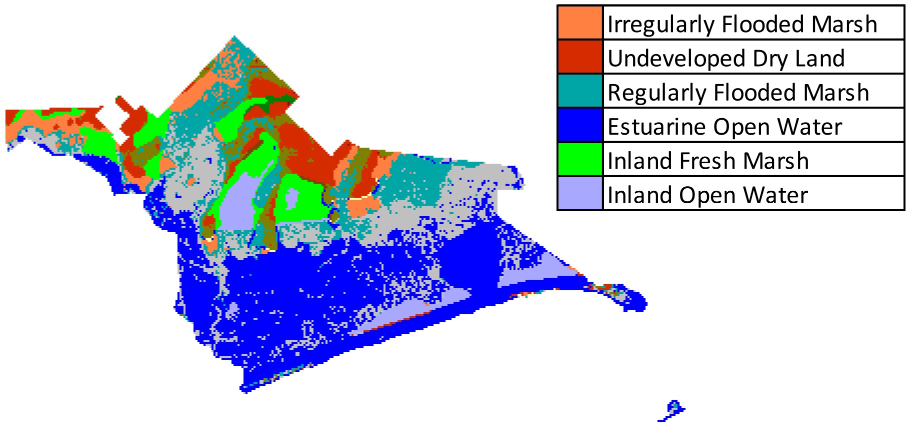
Big Boggy NWR, Initial Condition



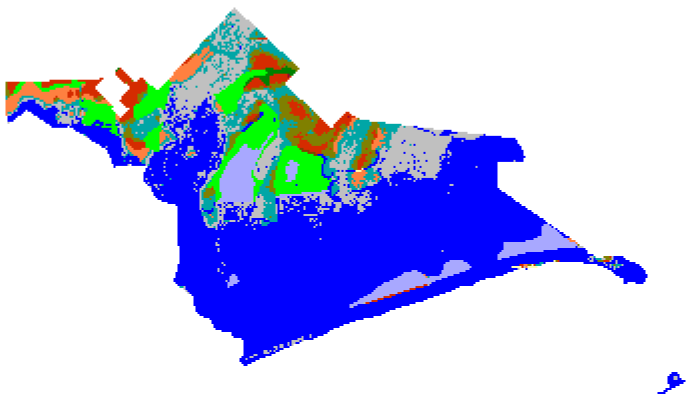
Big Boggy NWR, 2025, 2 m SLR



Big Boggy NWR, 2050, 2 m SLR



Big Boggy NWR, 2075, 2 m SLR



Big Boggy NWR, 2100, 2 m SLR

Forecast – San Bernard NWR

SLAMM predicts that San Bernard NWR will be significantly affected by all studied SLR scenarios. Table 5 presents the predicted loss of the major wetland categories by 2100 under each of the five SLR scenarios examined.

Table 5. Predicted loss rates of land categories by 2100 given simulated scenarios of eustatic SLR at San Bernard NWR

Land cover category	Initial coverage (acres)	Land cover loss by 2100 for different SLR scenarios				
		0.39 m	0.69 m	1 m	1.5 m	2 m
Undeveloped Dry Land	1580181	1%	2%	3%	5%	7%
Inland Fresh Marsh	100208	3%	10%	21%	34%	44%
Swamp	80502	1%	2%	3%	5%	7%
Irregularly Flooded Marsh	57071	14%	60%	84%	96%	99%
Developed Dry Land	44375	6%	8%	10%	15%	19%
Regularly Flooded Marsh	30871	-46%([1])	-111%	-53%	-47%	-73%
Estuarine Beach	6269	67%	79%	81%	87%	93%
Inland Shore	3595	15%	19%	23%	31%	35%
Tidal Fresh Marsh	3082	2%	16%	51%	87%	97%
Riverine Tidal	2578	25%	33%	41%	51%	61%
Open Ocean	2421	-16%	-29%	-53%	-100%	-142%
Ocean Beach	1200	-44%	-72%	-76%	-16%	62%

([1]) A negative loss indicates a gain with respect to initial coverage

Aggregating all land-cover categories, simulation results predict that of the over 2 million-acre refuge 8% to 15% will be covered by open water or tidal flat by 2100, up from the current 7% coverage. By 2100, dry land and swamp (which constitute 77% and 4% of the refuge area in 2006, respectively), experience an overall loss ranging from 1% to 7%. The relative resilience of these categories to SLR is likely due to their high elevations and distance from open water.

Irregularly-flooded marshes cover approximately 3% of the refuge in 2006 (57,000 acres). By 2100 SLAMM predicts this wetland habitat will be significantly reduced, with a loss ranging from 14% to 99%. This wetland type is initially converted to regularly-flooded marsh, which is observed to have a net gain for all SLR scenarios.

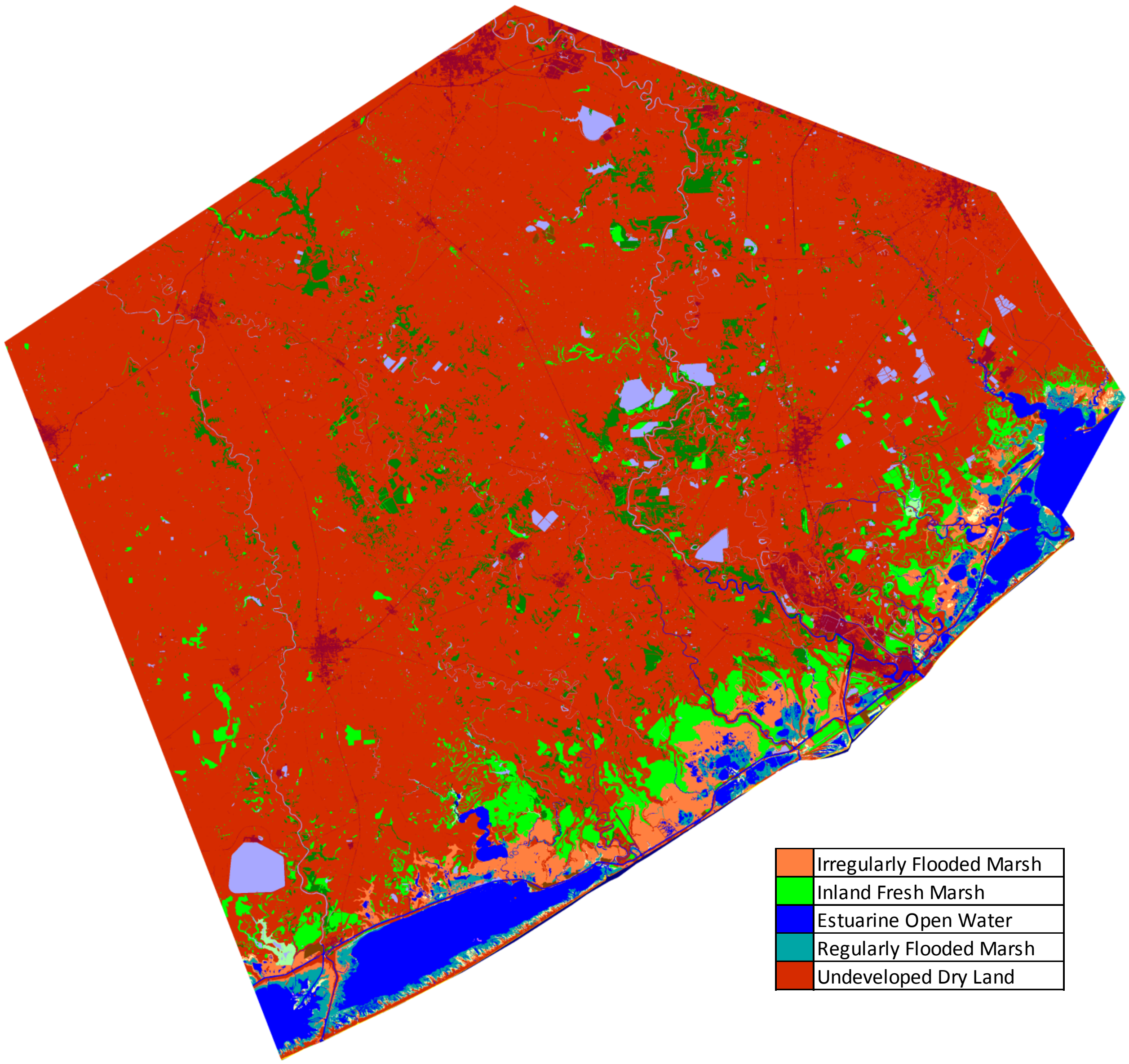
Tidal-fresh marshes are also predicted to be significantly reduced under all SLR scenarios, although their total acreage today is relatively small (3000 acres or less than 1% of the refuge). On the other hand, inland-fresh marsh areas, with a maximum predicted loss of 44%, seem more resilient to SLR.

Simulations also predict the formation of transitional marshes that are not currently present in the refuge. These categories are predicted to occur when dry lands or swamp lands become periodically flooded with salt water. By 2100 transitional marshes are forecast to cover 14,000 to 57,000 acres of the refuge depending on the SLR scenario.

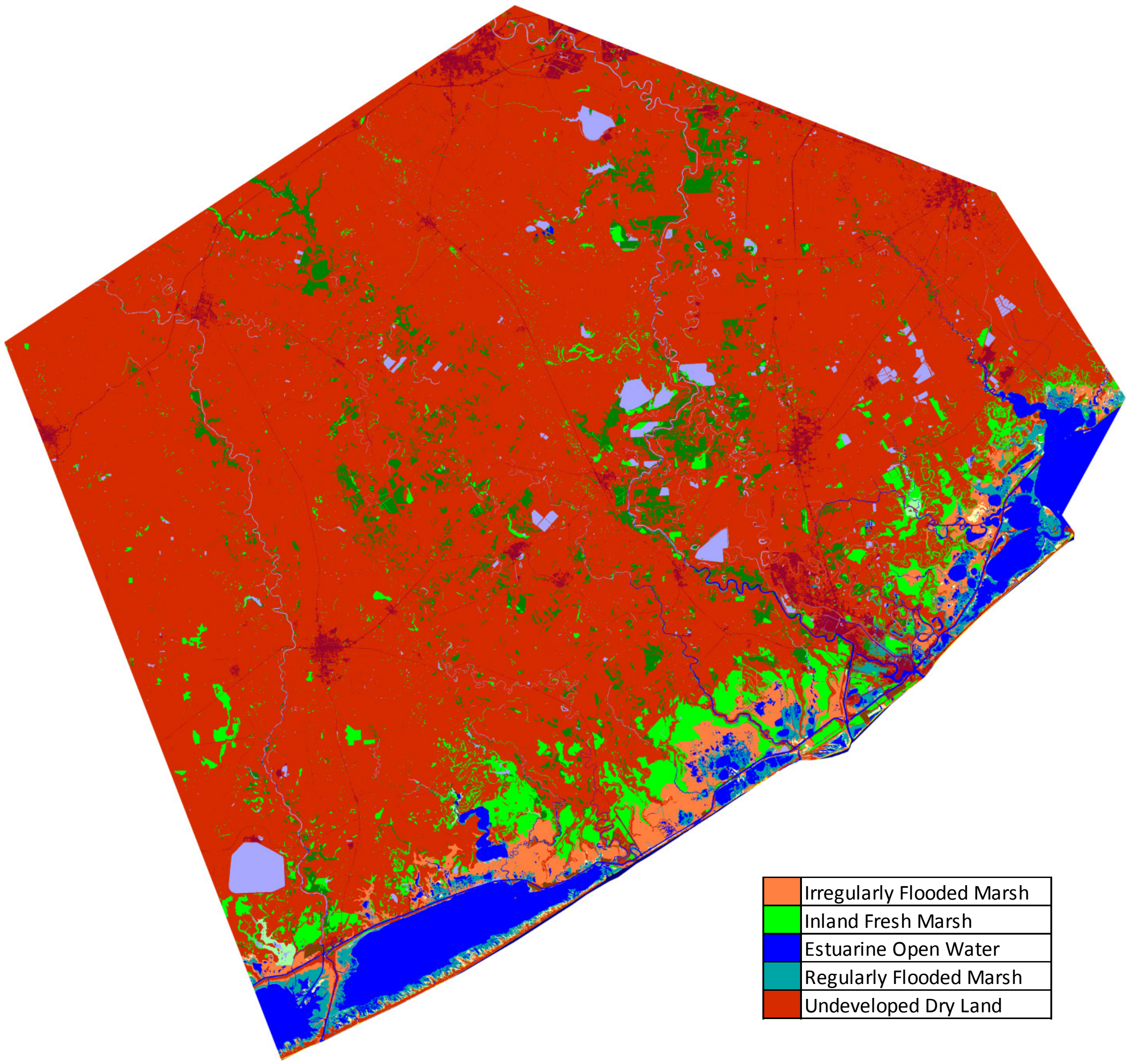
San Bernard NWR
IPCC Scenario A1B-Mean, 0.39 m SLR eustatic by 2100

Results in Acres

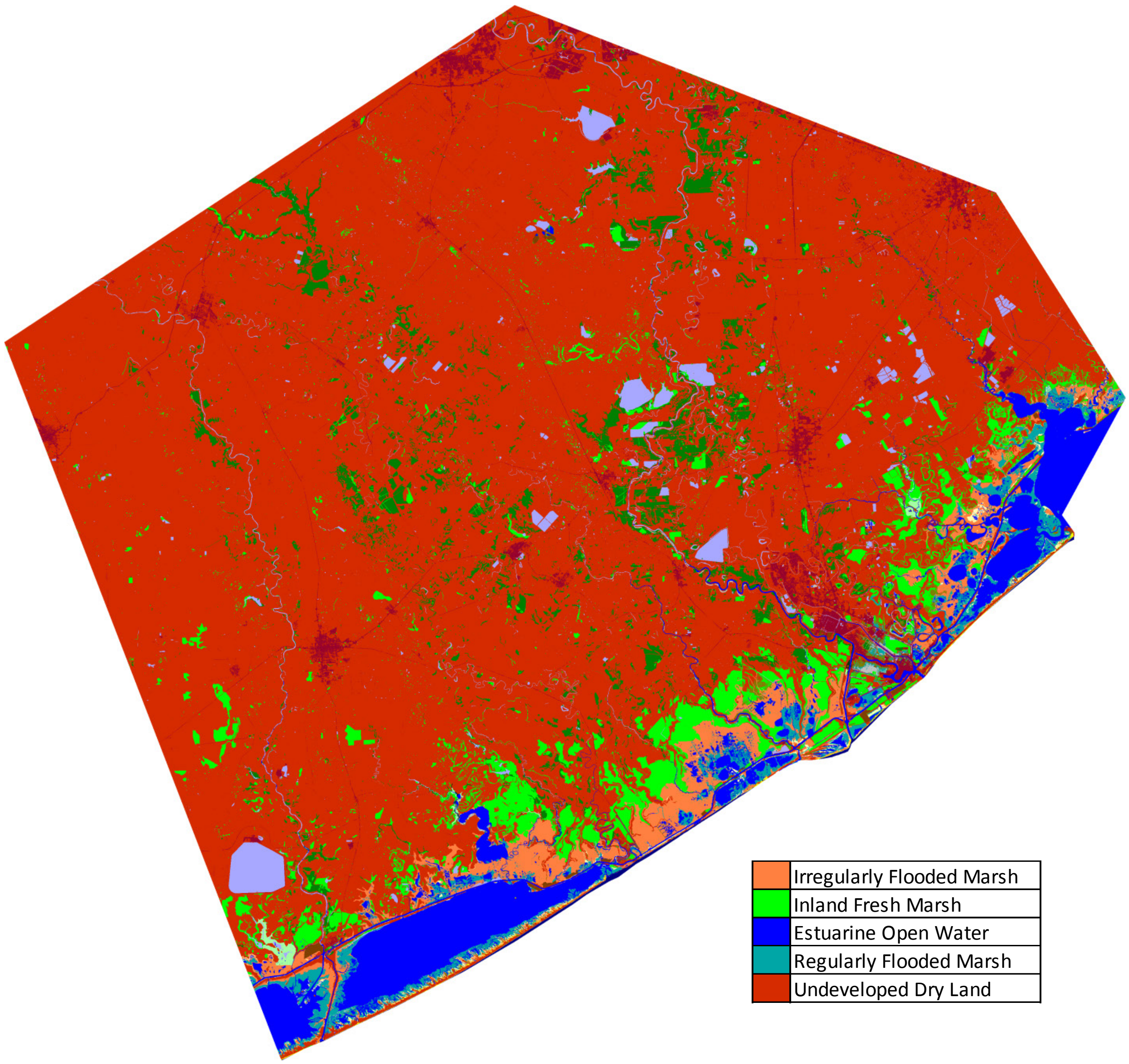
		Initial	2025	2050	2075	2100
	Undeveloped Dry Land	1580181	1575007	1571761	1566039	1558429
	Inland Fresh Marsh	100208	98330	98250	98029	97688
	Estuarine Open Water	99359	103138	105388	109904	112256
	Swamp	80502	80193	80070	79873	79669
	Irregularly Flooded Marsh	57071	54919	54257	52354	48838
	Developed Dry Land	44375	43290	42926	42447	41892
	Inland Open Water	44187	43163	43047	42869	42656
	Regularly Flooded Marsh	30871	34544	33480	37305	45150
	Estuarine Beach	6269	5919	5017	3491	2085
	Inland Shore	3595	3346	3301	3178	3070
	Tidal Fresh Marsh	3082	3023	3023	3017	3006
	Riverine Tidal	2578	2263	2190	2081	1940
	Open Ocean	2421	2497	2593	2686	2813
	Ocean Beach	1200	1451	1450	1560	1723
	Transitional Salt Marsh	0	3831	6792	10900	14442
	Tidal Flat	0	1052	2435	262	356
	Total (incl. water)	**2056332**	**2056332**	**2056332**	**2056332**	**2056332**



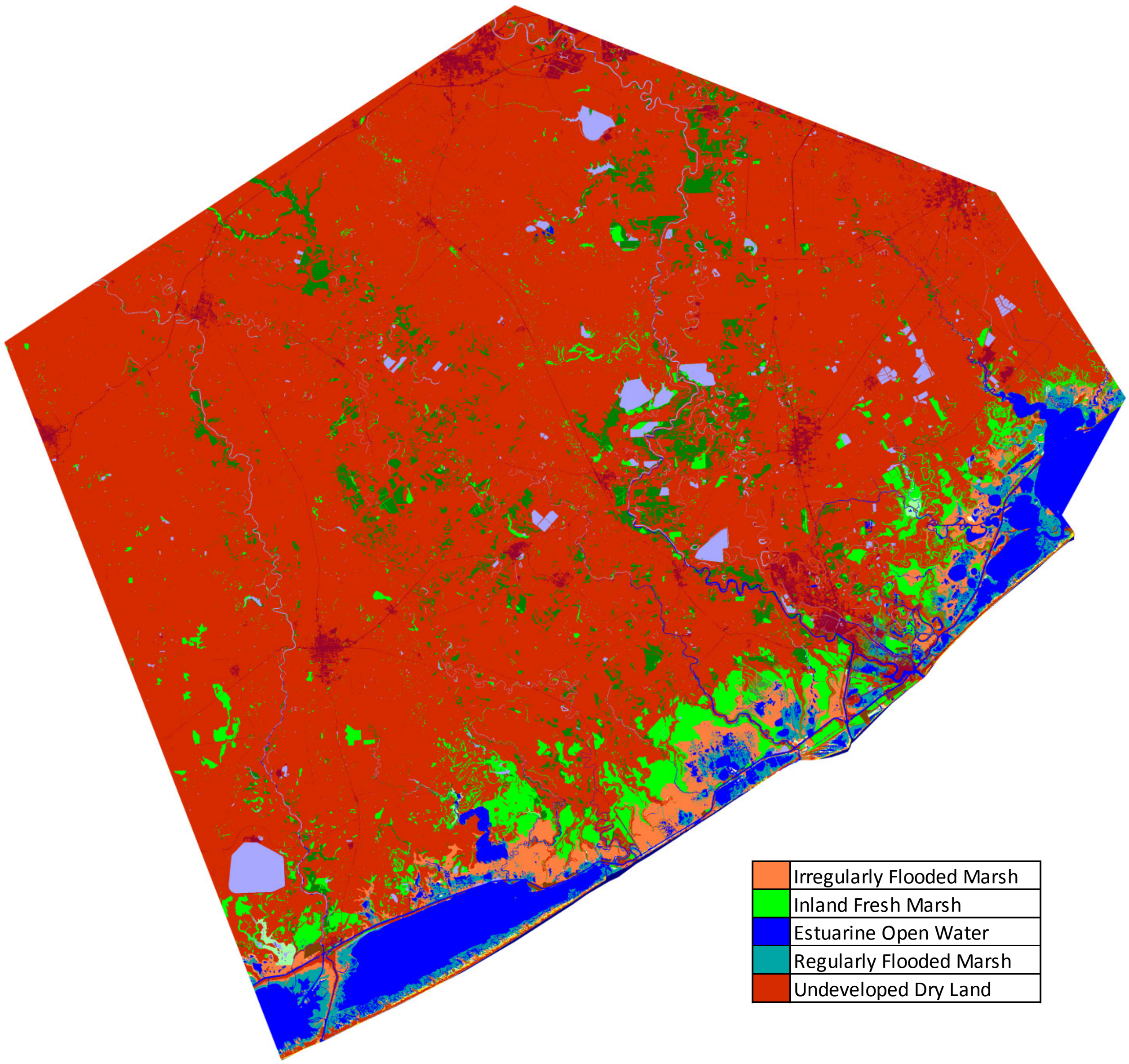
San Bernard NWR, Initial Condition



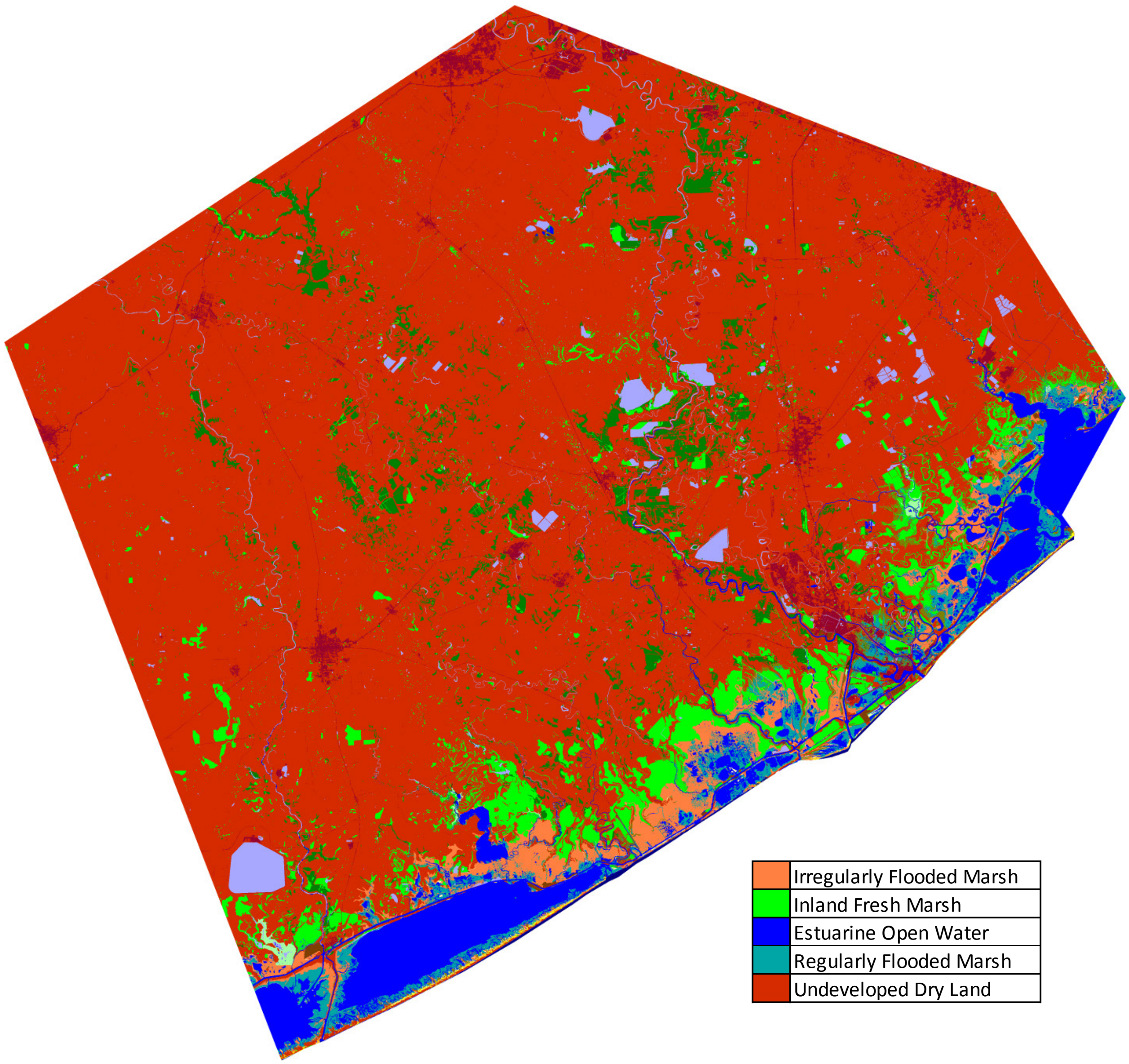
San Bernard NWR, 2025, Scenario A1B Mean, 0.39 m SLR



San Bernard NWR, 2050, Scenario A1B Mean, 0.39 m SLR



San Bernard NWR, 2075, Scenario A1B Mean, 0.39 m SLR

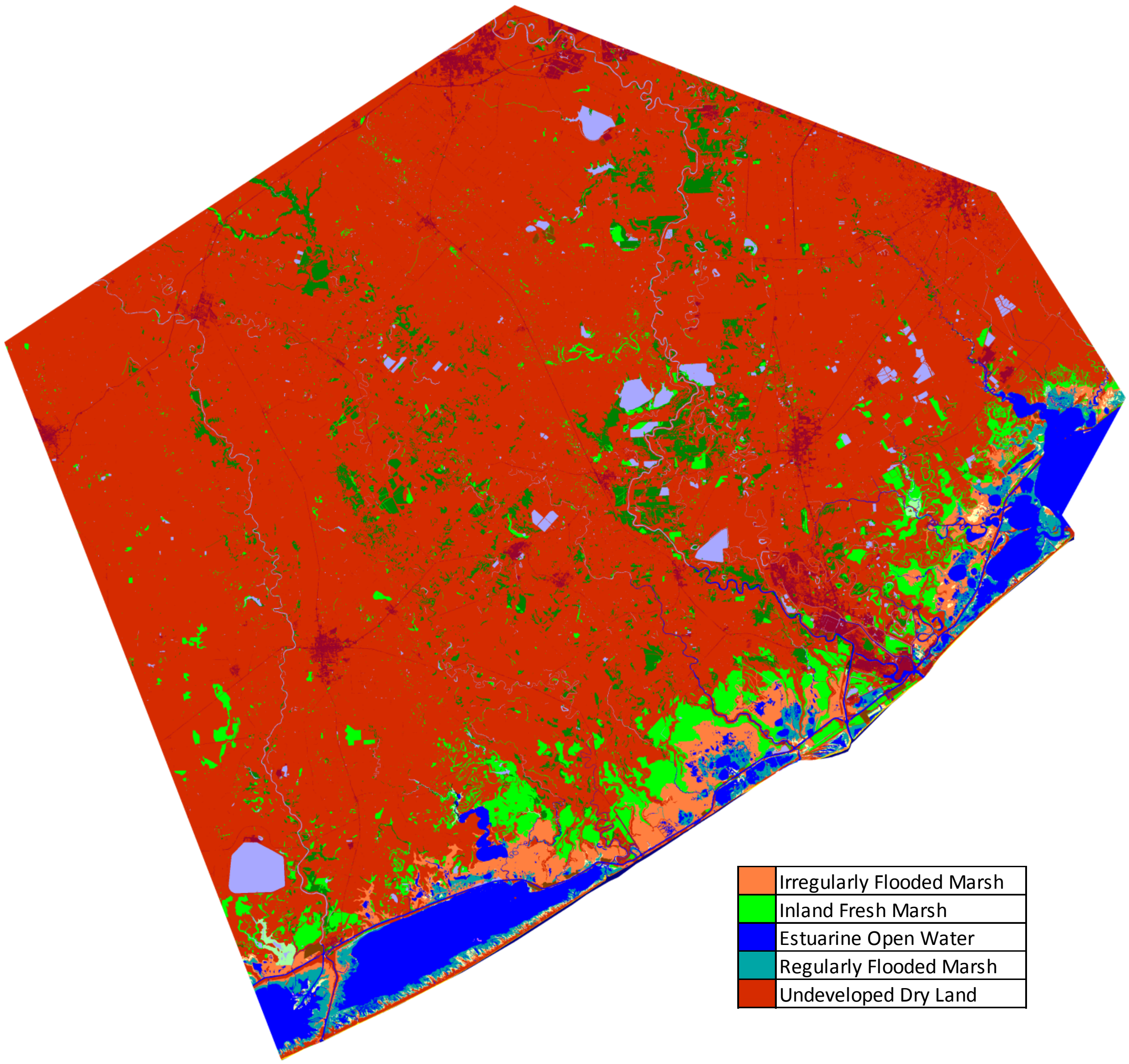


San Bernard NWR, 2100, Scenario A1B Mean, 0.39 m SLR

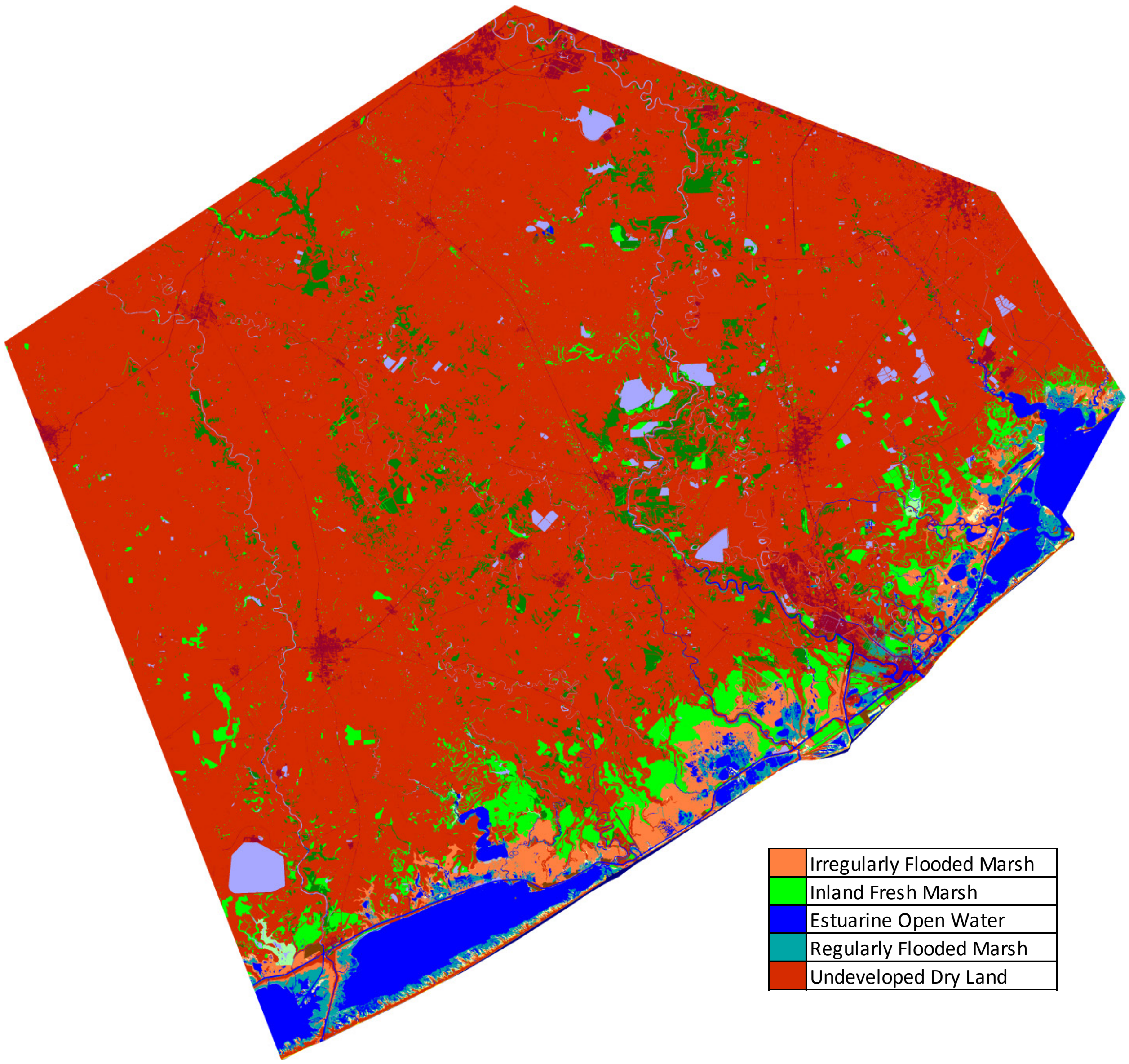
San Bernard NWR
IPCC Scenario A1B-Max, 0.69 m SLR eustatic by 2100

Results in Acres

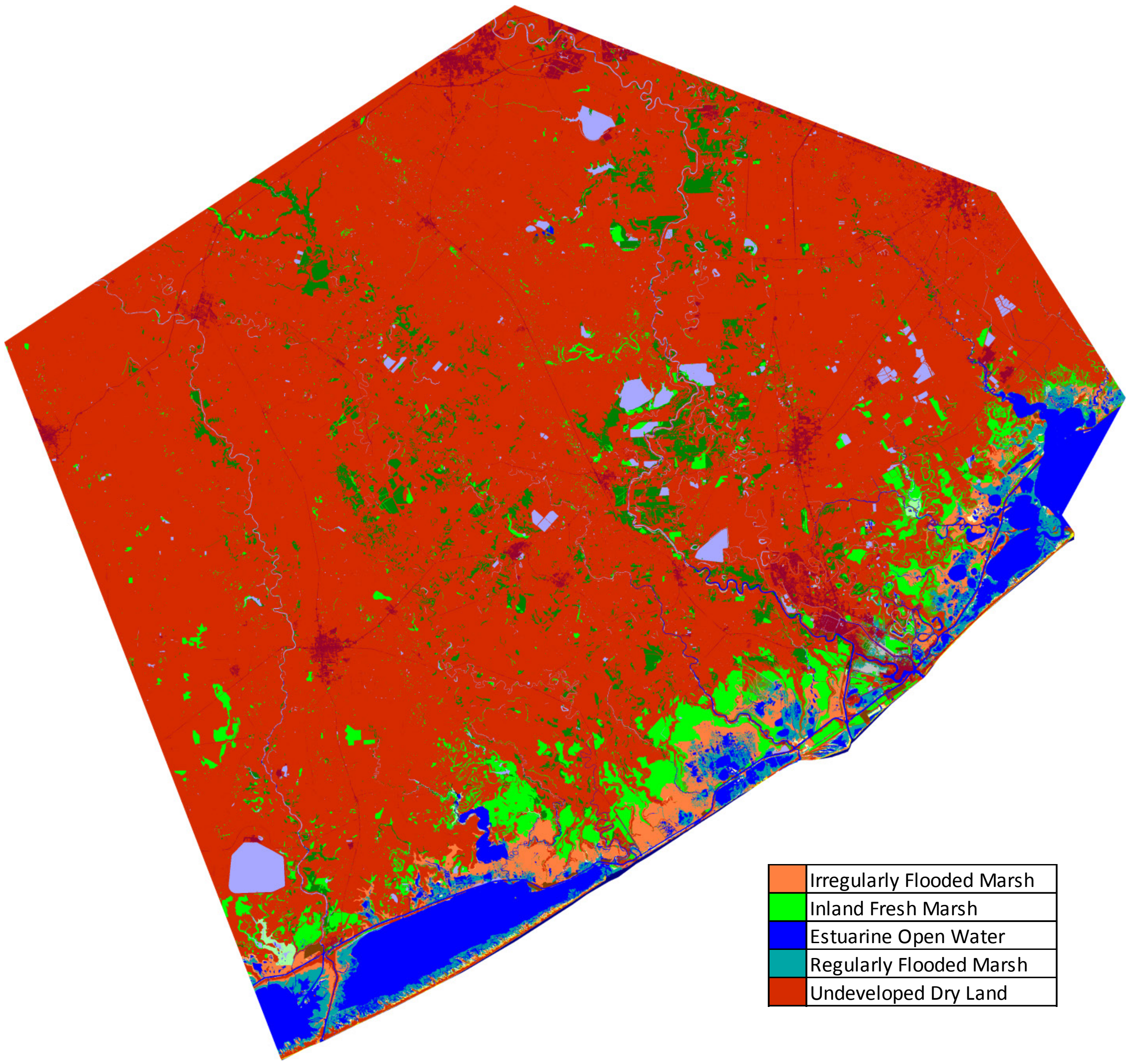
		Initial	2025	2050	2075	2100
	Undeveloped Dry Land	1580181	1574301	1568716	1557639	1543467
	Inland Fresh Marsh	100208	98100	97095	94436	90427
	Estuarine Open Water	99359	103504	106997	113711	119818
	Swamp	80502	80162	79956	79634	79184
	Irregularly Flooded Marsh	57071	54180	49689	35803	22969
	Developed Dry Land	44375	43186	42633	41814	40867
	Inland Open Water	44187	43138	42964	42693	42342
	Regularly Flooded Marsh	30871	35364	39027	56974	65205
	Estuarine Beach	6269	5775	4131	2014	1296
	Inland Shore	3595	3338	3230	3057	2895
	Tidal Fresh Marsh	3082	3018	2985	2860	2577
	Riverine Tidal	2578	2244	2136	1956	1717
	Open Ocean	2421	2531	2676	2876	3135
	Ocean Beach	1200	1487	1561	1780	2070
	Transitional Salt Marsh	0	4366	8935	15463	19714
	Tidal Flat	0	1277	3262	3311	18386
	Total (incl. water)	**2056332**	**2056332**	**2056332**	**2056332**	**2056332**



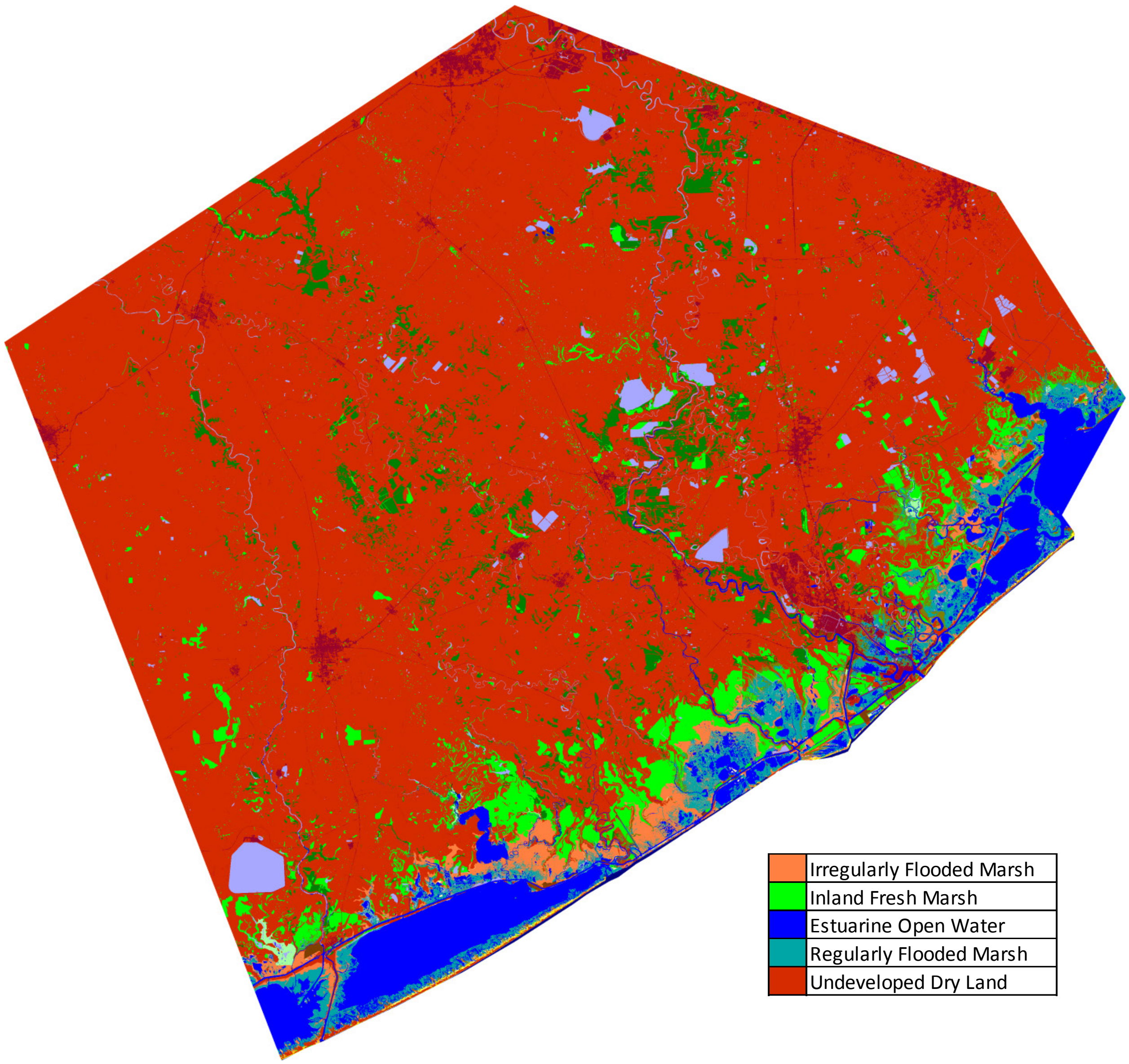
San Bernard NWR, Initial Condition



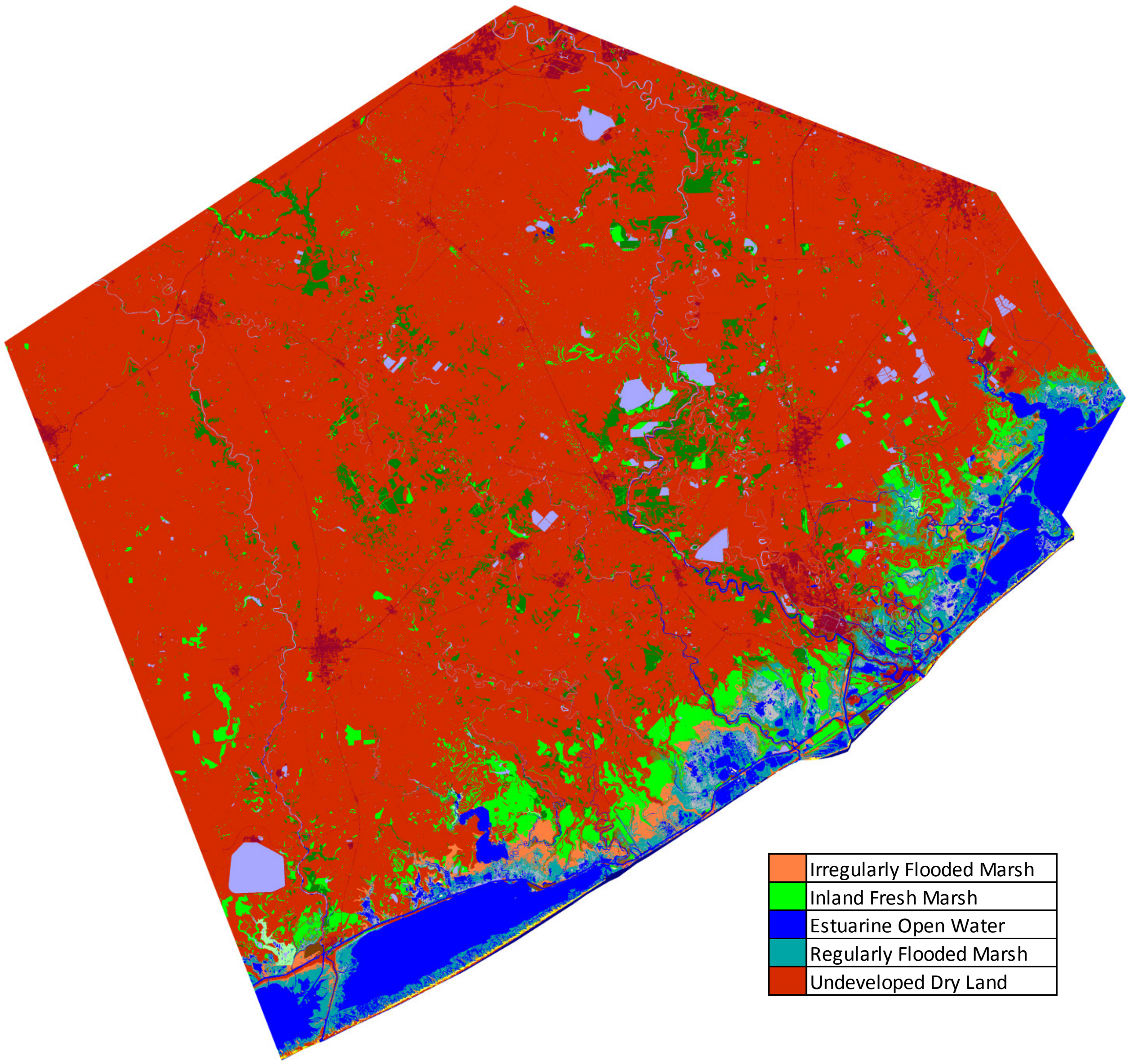
San Bernard NWR, 2025, Scenario A1B Maximum, 0.69 m SLR



San Bernard NWR, 2050, Scenario A1B Maximum, 0.69 m SLR



San Bernard NWR, 2075, Scenario A1B Maximum, 0.69 m SLR

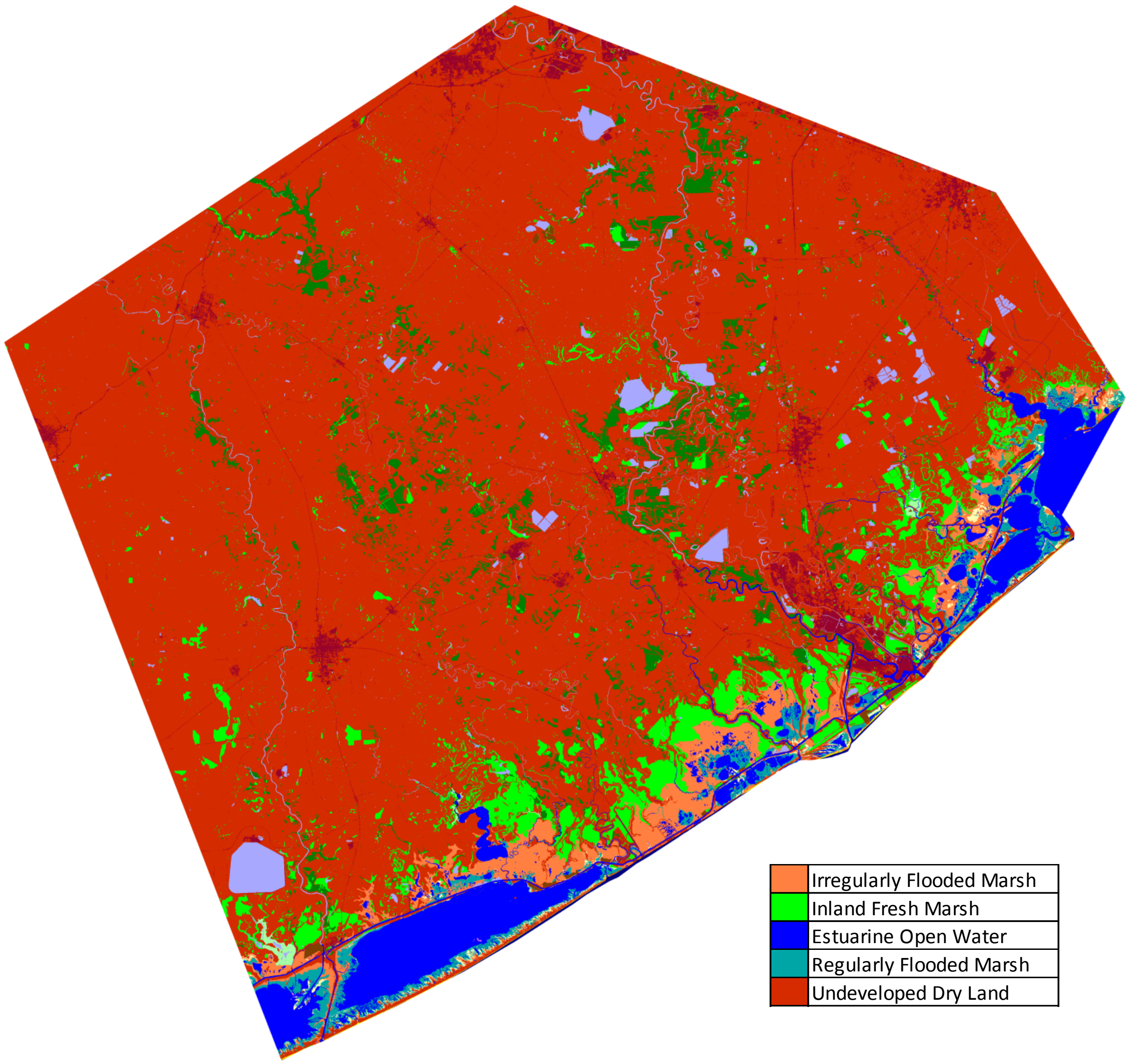


San Bernard NWR, 2100, Scenario A1B Maximum, 0.69 m SLR

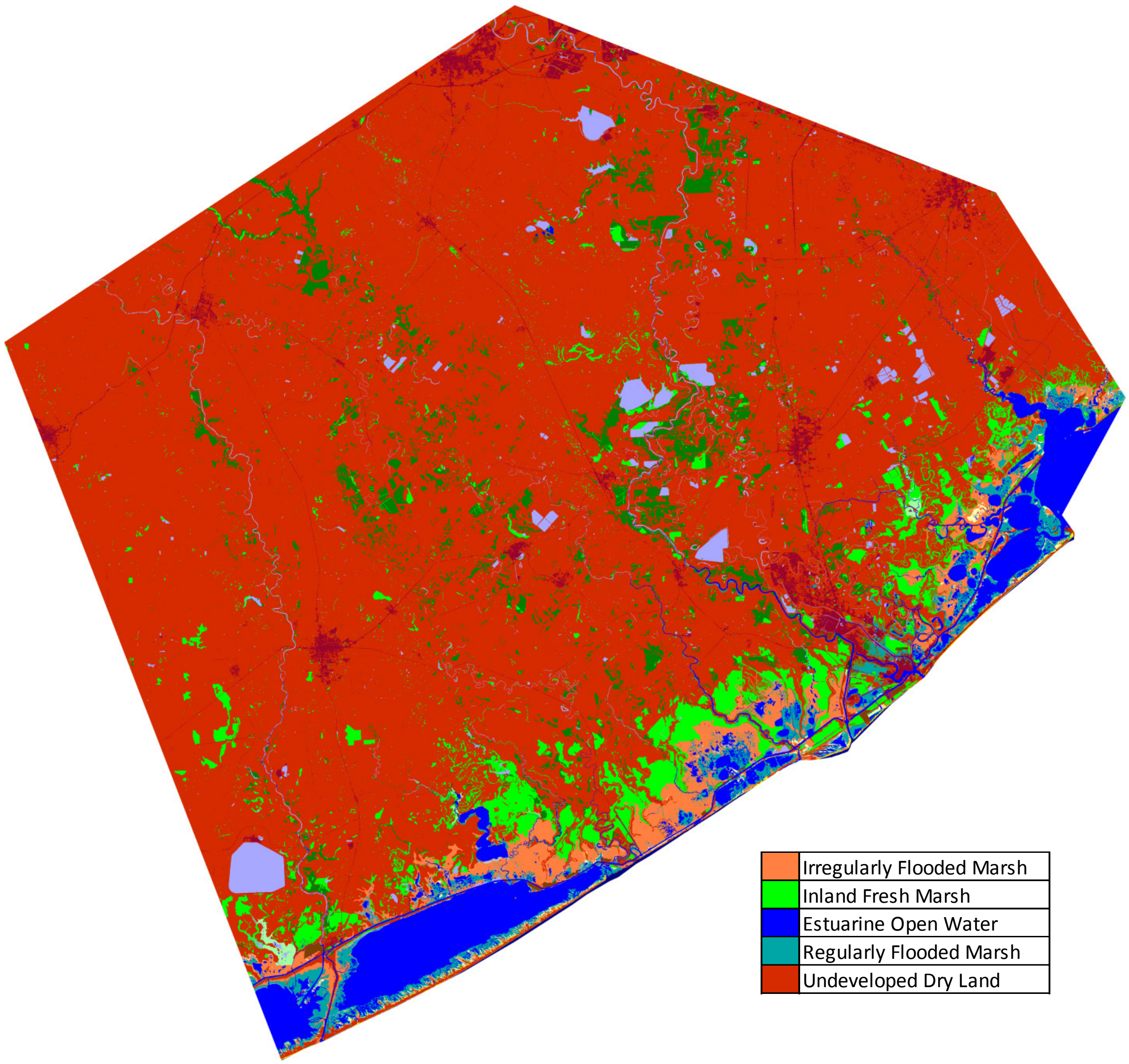
San Bernard NWR
1 m eustatic SLR by 2100

Results in Acres

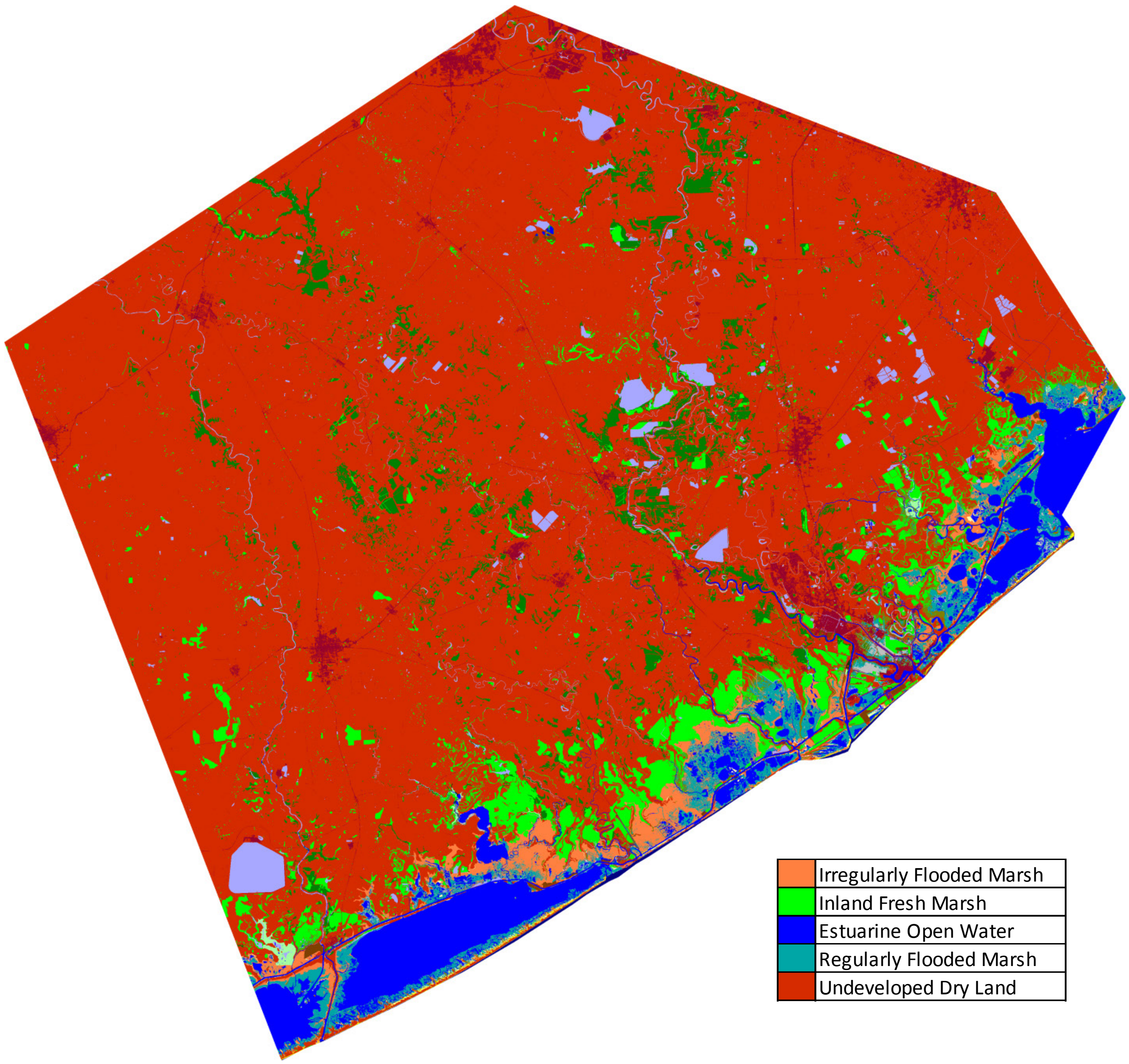
		Initial	2025	2050	2075	2100
	Undeveloped Dry Land	1580181	1573440	1564641	1547666	1528348
	Inland Fresh Marsh	100208	97640	94712	87907	79595
	Estuarine Open Water	99359	104020	109187	120109	148330
	Swamp	80502	80127	79814	79304	78443
	Irregularly Flooded Marsh	57071	52833	39227	19853	9259
	Developed Dry Land	44375	43071	42289	41123	39790
	Inland Open Water	44187	43108	42881	42483	41953
	Regularly Flooded Marsh	30871	36852	48332	55048	47131
	Estuarine Beach	6269	5510	3088	1448	1197
	Inland Shore	3595	3325	3142	2931	2785
	Tidal Fresh Marsh	3082	3004	2884	2339	1524
	Riverine Tidal	2578	2228	2076	1804	1526
	Open Ocean	2421	2573	2784	3087	3708
	Ocean Beach	1200	1526	1686	2049	2111
	Transitional Salt Marsh	0	5141	12523	24224	28592
	Tidal Flat	0	1576	6737	24688	41845
	Total (incl. water)	**2056332**	**2056332**	**2056332**	**2056332**	**2056332**



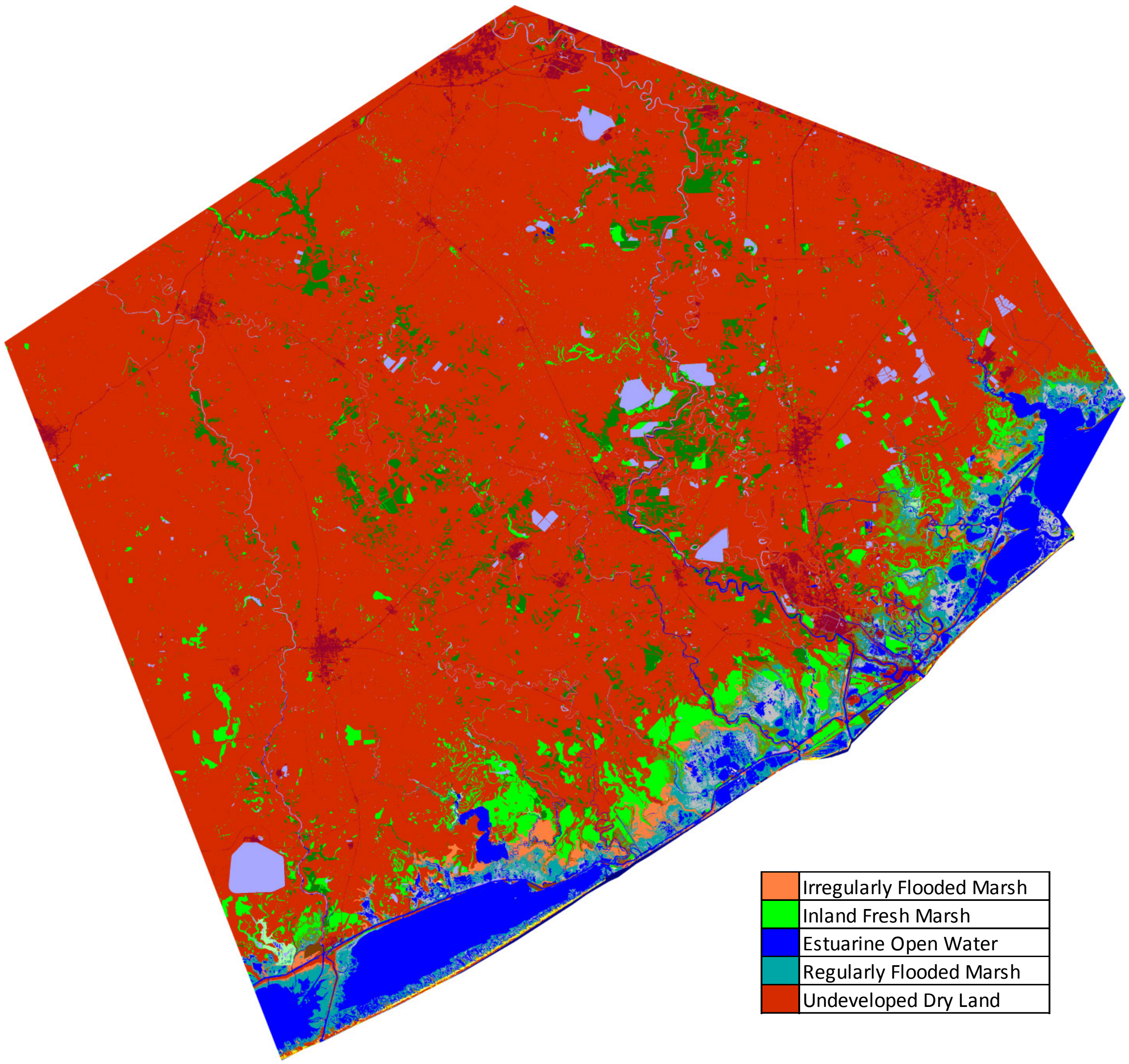
San Bernard NWR, Initial Condition



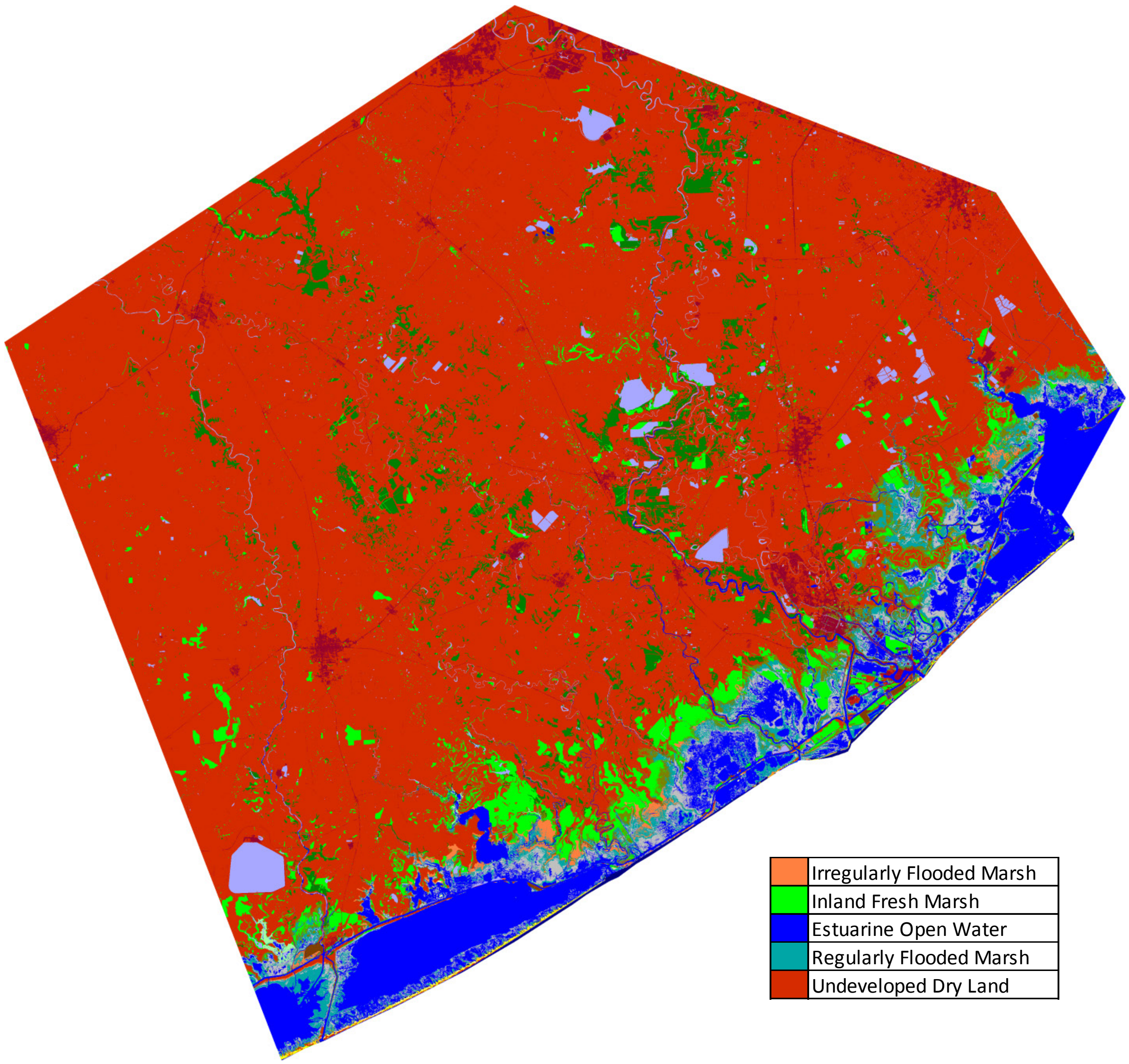
San Bernard NWR, 2025, 1 m SLR



San Bernard NWR, 2050, 1 m SLR



San Bernard NWR, 2075, 1 m SLR

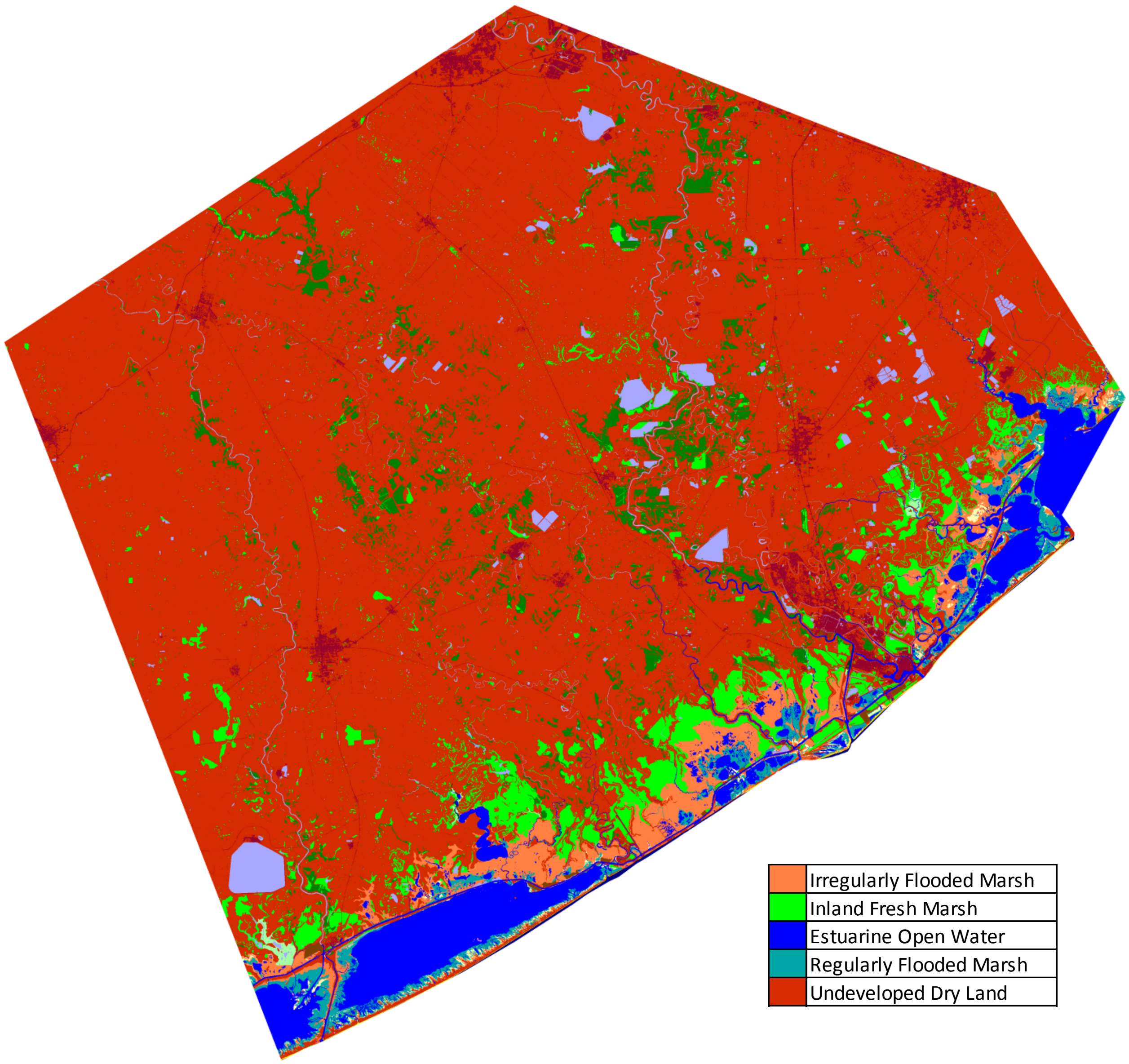


San Bernard NWR, 2100, 1 m SLR

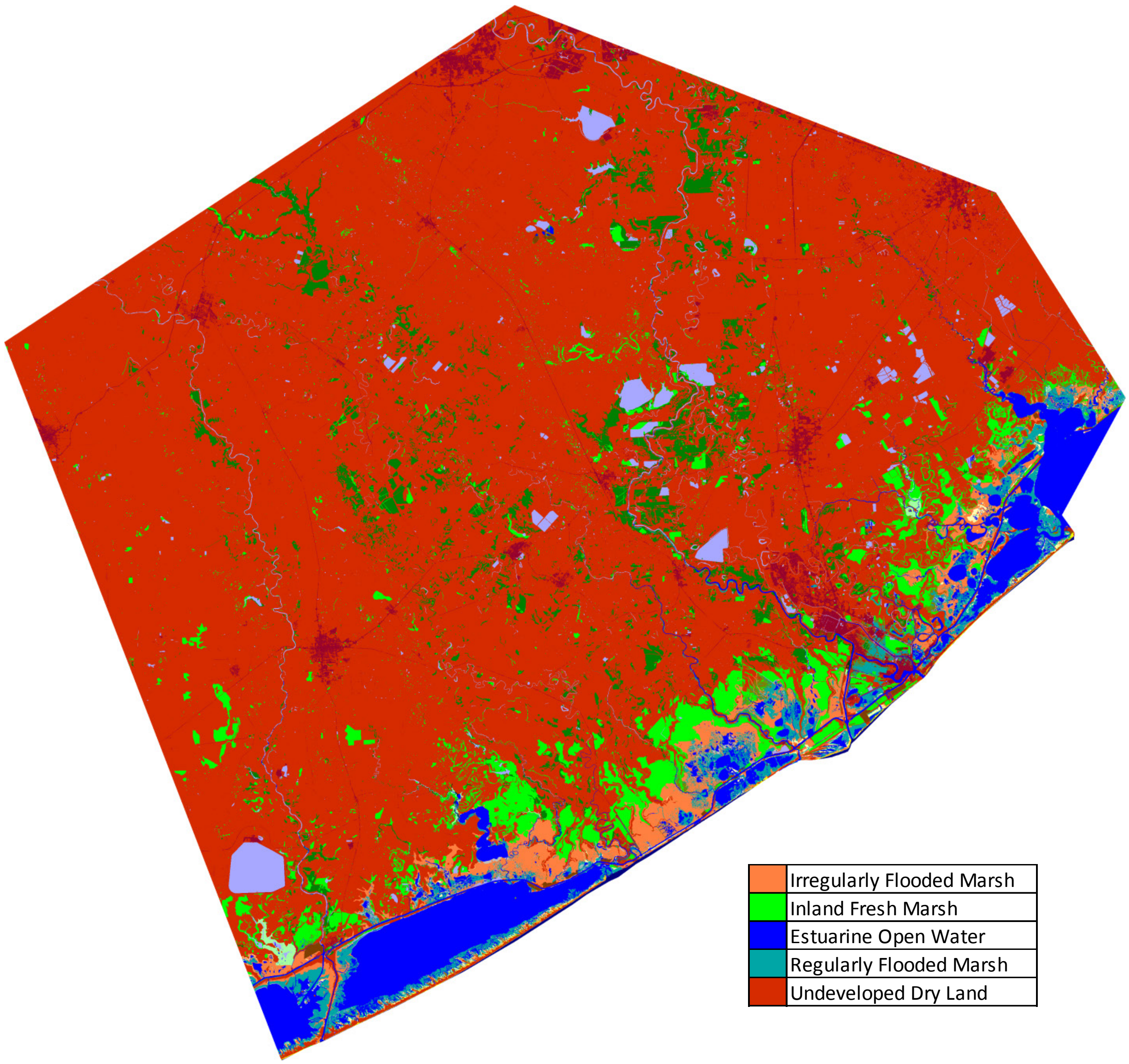
San Bernard NWR
1.5 m eustatic SLR by 2100

Results in Acres

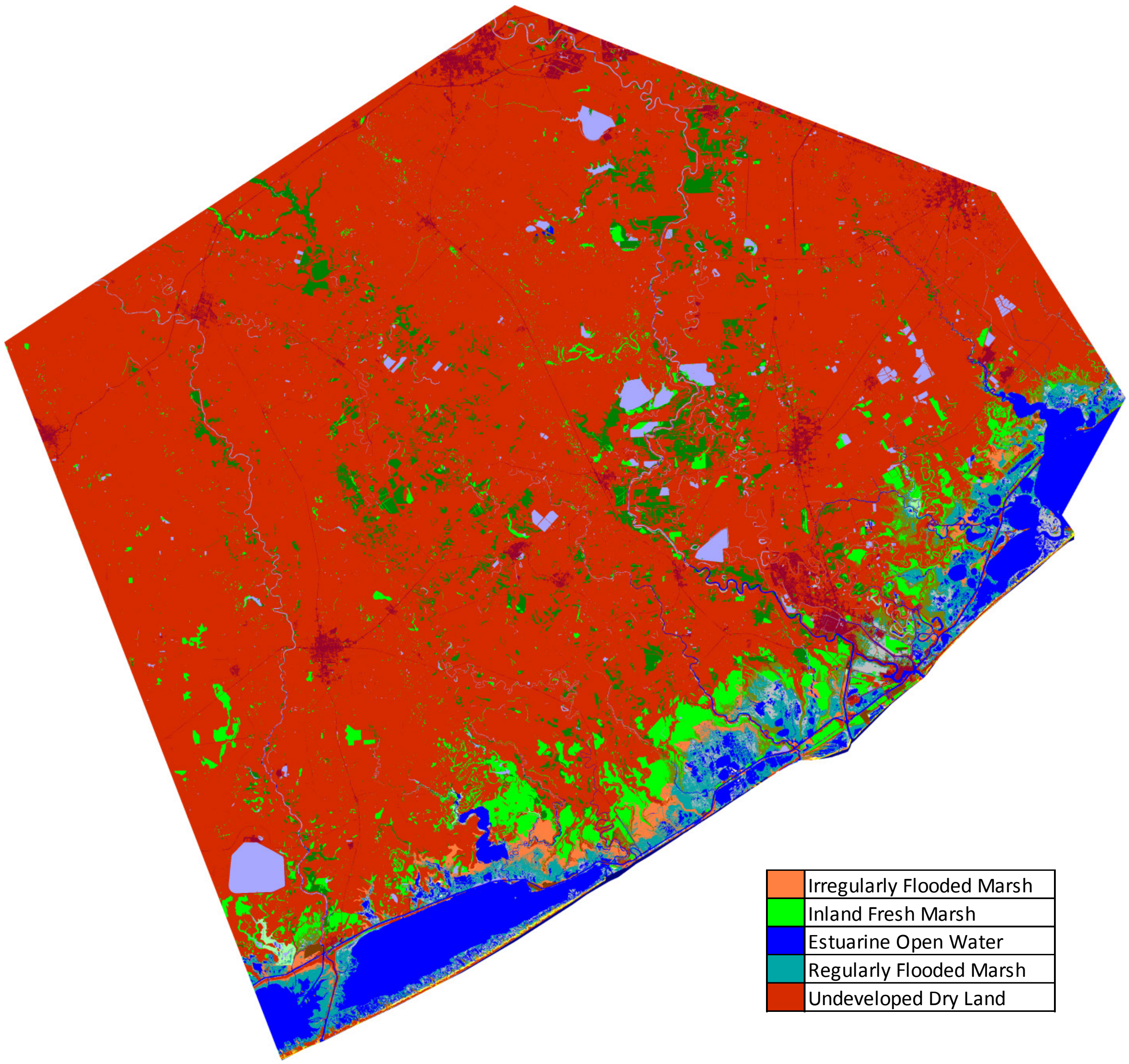
		Initial	2025	2050	2075	2100
	Undeveloped Dry Land	1580181	1571796	1556638	1530526	1501402
	Inland Fresh Marsh	100208	96525	88848	76151	66490
	Estuarine Open Water	99359	105099	113381	138134	188711
	Swamp	80502	80061	79575	78511	76810
	Irregularly Flooded Marsh	57071	48312	22936	6839	2035
	Developed Dry Land	44375	42869	41677	39895	37718
	Inland Open Water	44187	43060	42728	42124	41441
	Regularly Flooded Marsh	30871	40951	52305	44354	45504
	Estuarine Beach	6269	4961	1964	1371	844
	Inland Shore	3595	3286	3029	2796	2486
	Tidal Fresh Marsh	3082	2971	2436	1191	388
	Riverine Tidal	2578	2193	1982	1608	1255
	Open Ocean	2421	2642	2974	3636	4847
	Ocean Beach	1200	1593	1856	2149	1392
	Transitional Salt Marsh	0	6692	23318	39859	41623
	Tidal Flat	0	2976	20391	46994	43264
	Total (incl. water)	**2056332**	**2056332**	**2056332**	**2056332**	**2056332**



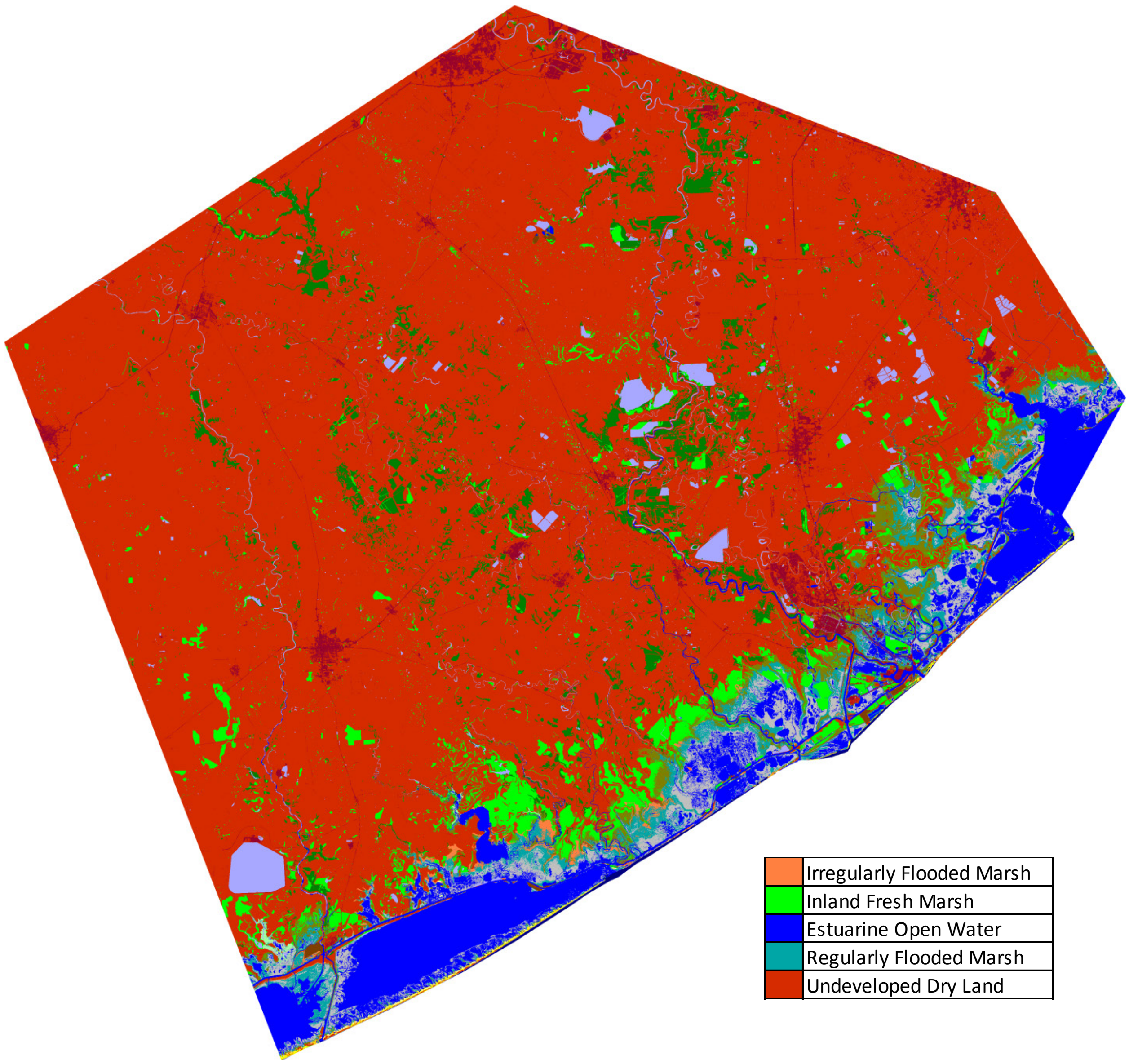
San Bernard NWR, Initial Condition



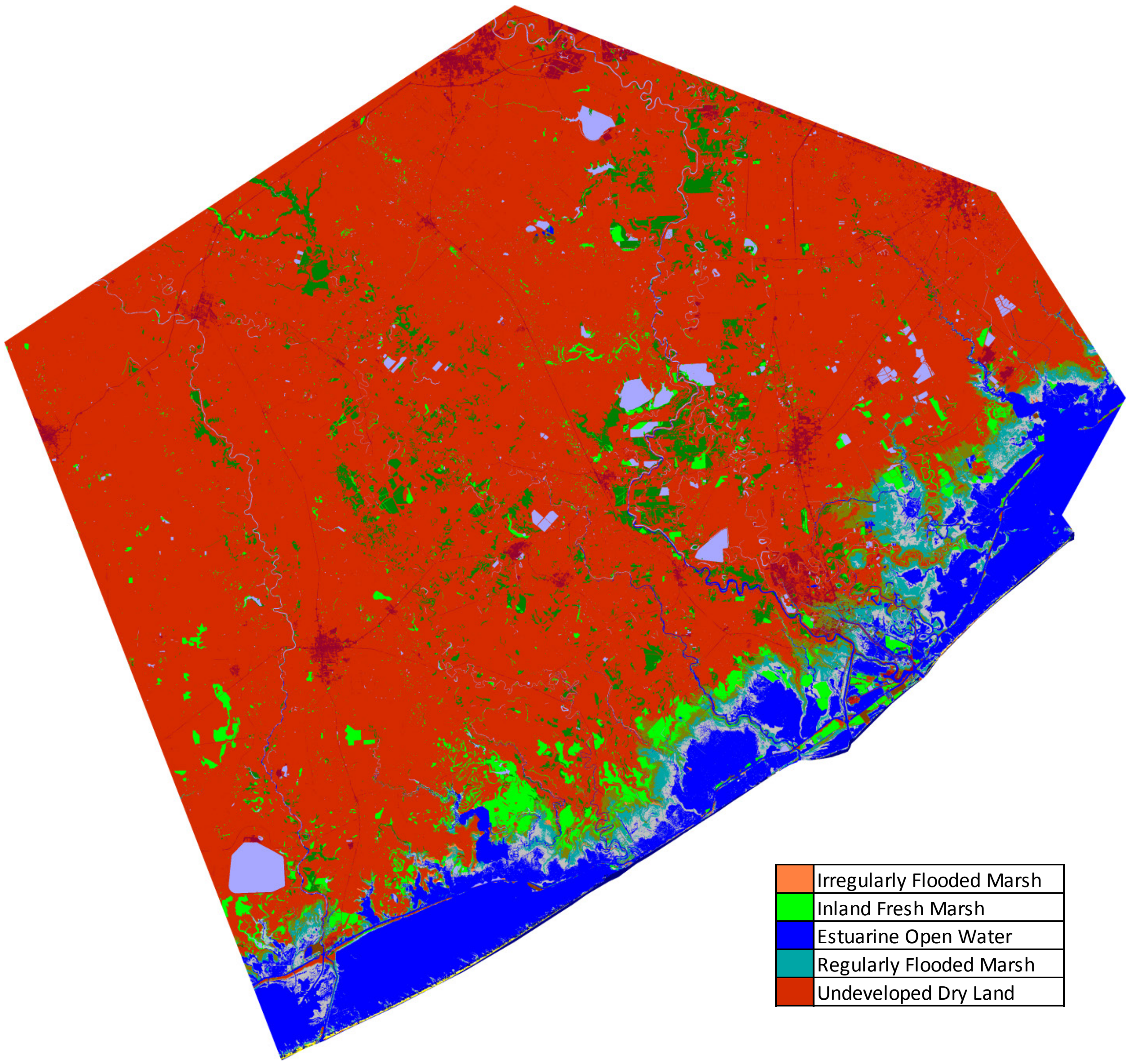
San Bernard NWR, 2025, 1.5 m SLR



San Bernard NWR, 2050, 1.5 m SLR



San Bernard NWR, 2075, 1.5 m SLR

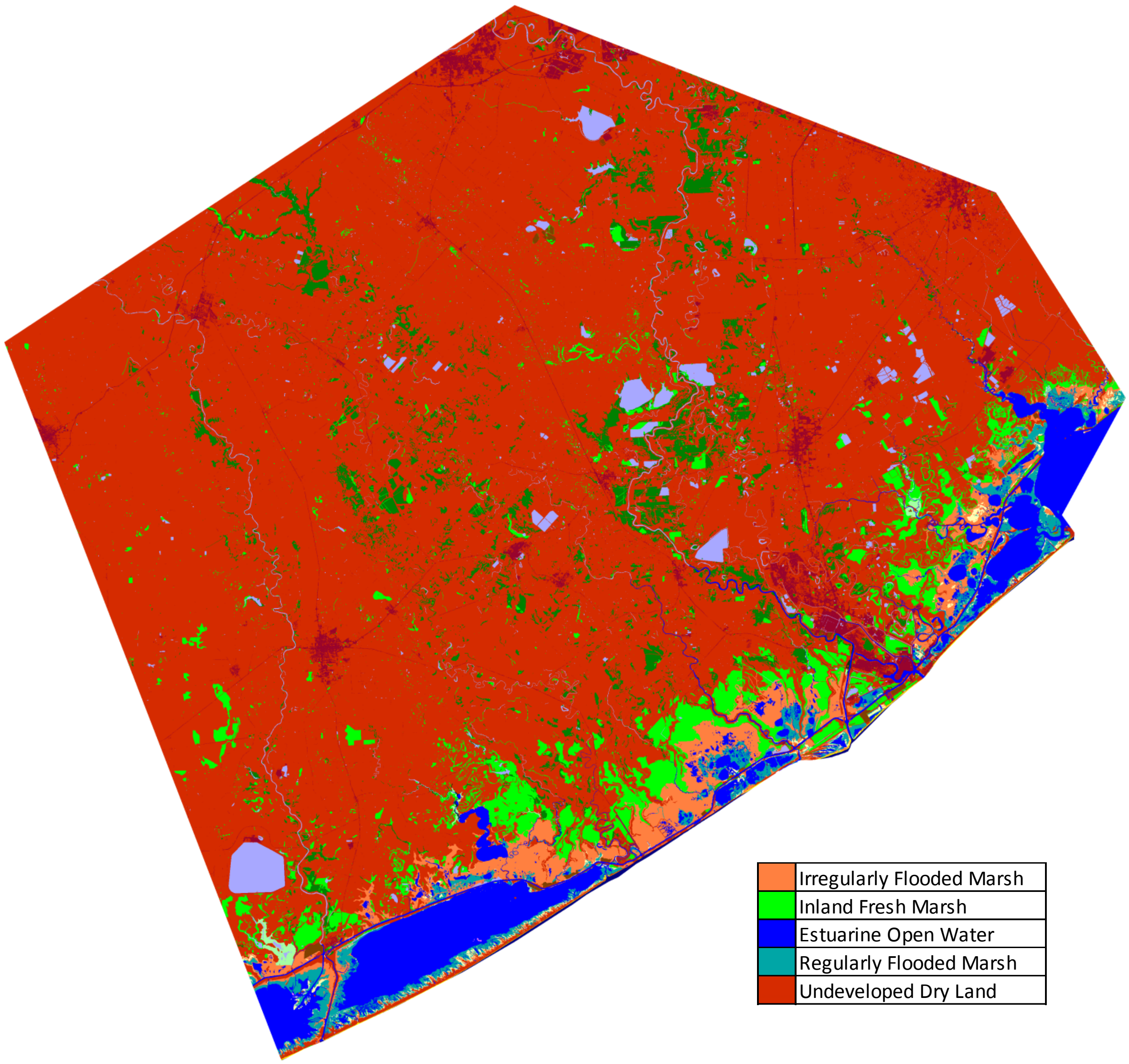


San Bernard NWR, 2100, 1.5 m SLR

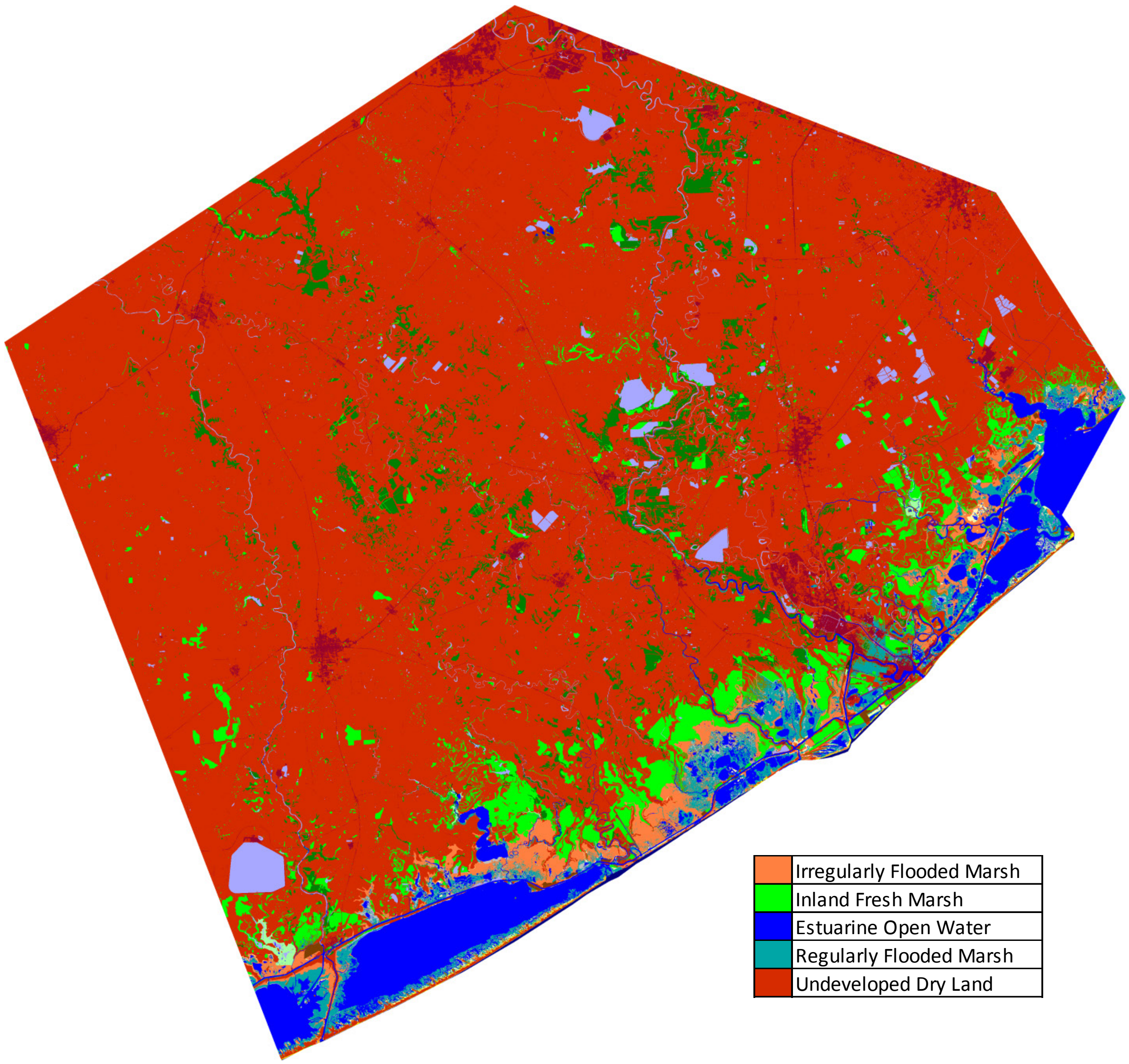
San Bernard NWR
2 m eustatic SLR by 2100

Results in Acres

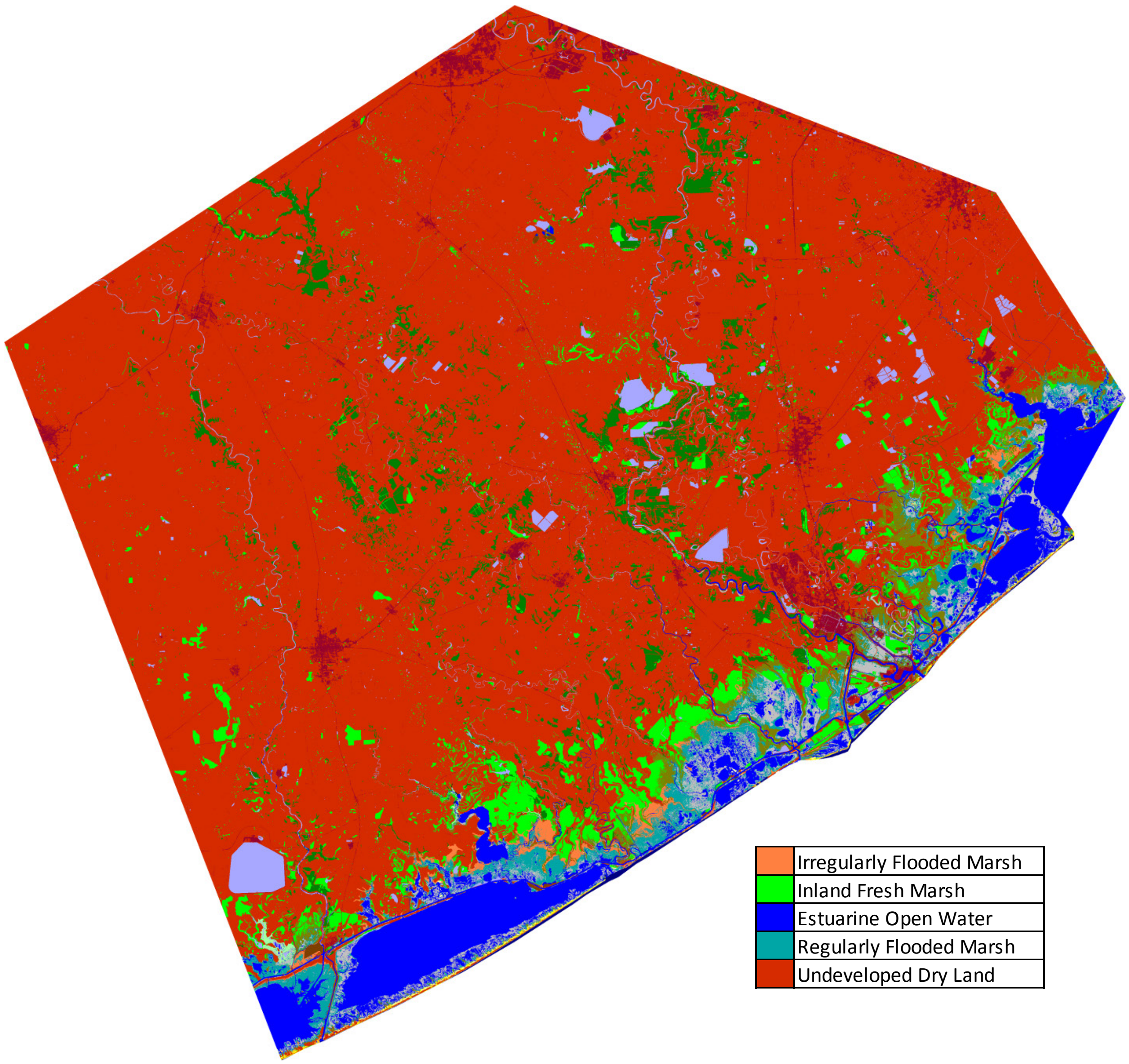
		Initial	2025	2050	2075	2100
	Undeveloped Dry Land	1580181	1569849	1547539	1512895	1470466
	Inland Fresh Marsh	100208	94914	81992	67388	56550
	Estuarine Open Water	99359	106317	118368	159273	209611
	Swamp	80502	79979	79252	77464	74815
	Irregularly Flooded Marsh	57071	41821	12707	2398	781
	Developed Dry Land	44375	42656	41012	38554	36113
	Inland Open Water	44187	43009	42563	41772	40949
	Regularly Flooded Marsh	30871	45758	46639	47044	53390
	Estuarine Beach	6269	4372	1601	1317	410
	Inland Shore	3595	3233	2910	2608	2320
	Tidal Fresh Marsh	3082	2914	1721	430	104
	Riverine Tidal	2578	2157	1882	1437	994
	Open Ocean	2421	2708	3175	4406	5859
	Ocean Beach	1200	1659	2080	1784	451
	Transitional Salt Marsh	0	8667	35824	51634	57134
	Tidal Flat	0	5980	36812	45792	46293
	Total (incl. water)	**2056332**	**2056332**	**2056332**	**2056332**	**2056332**



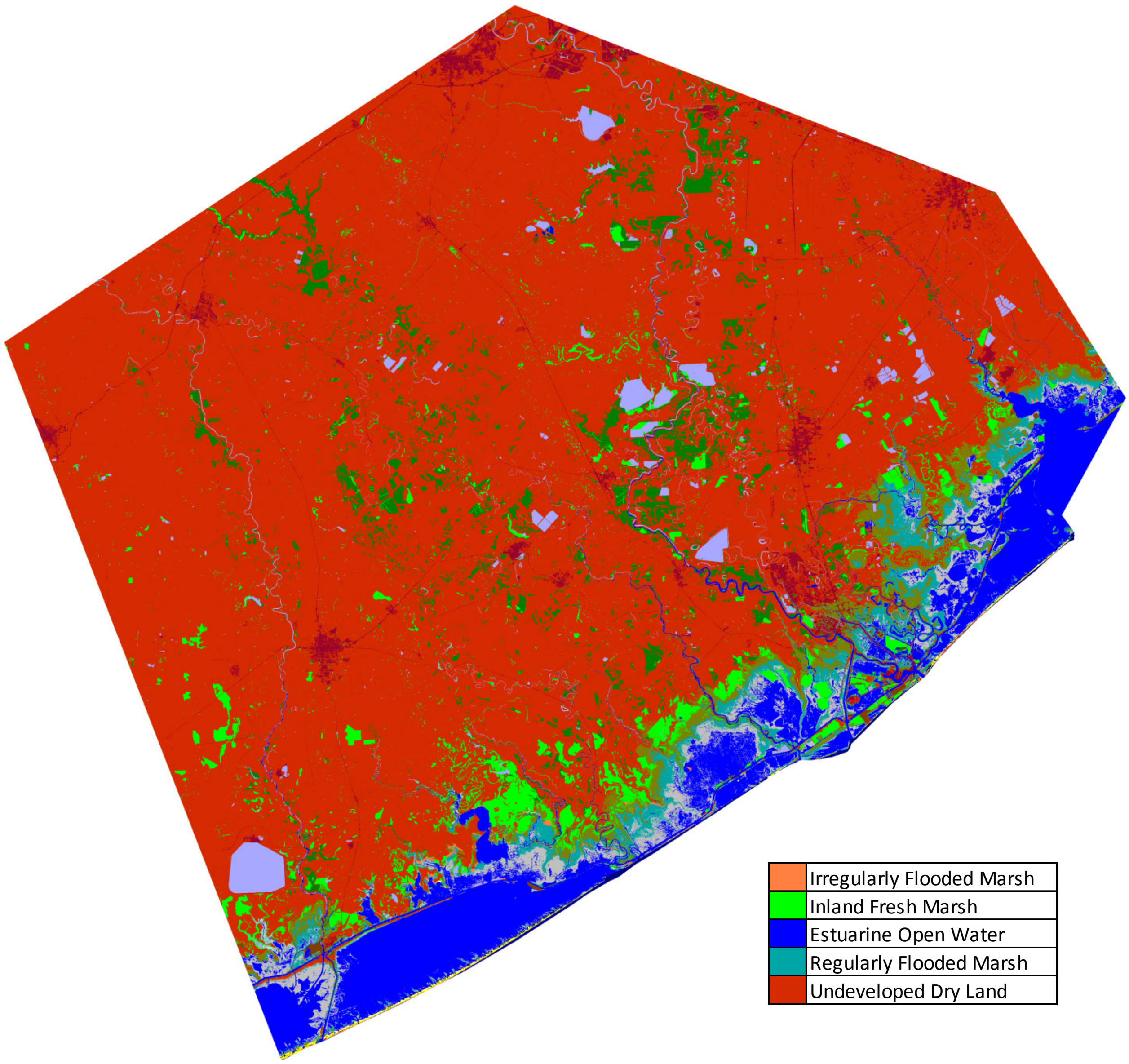
San Bernard NWR, Initial Condition



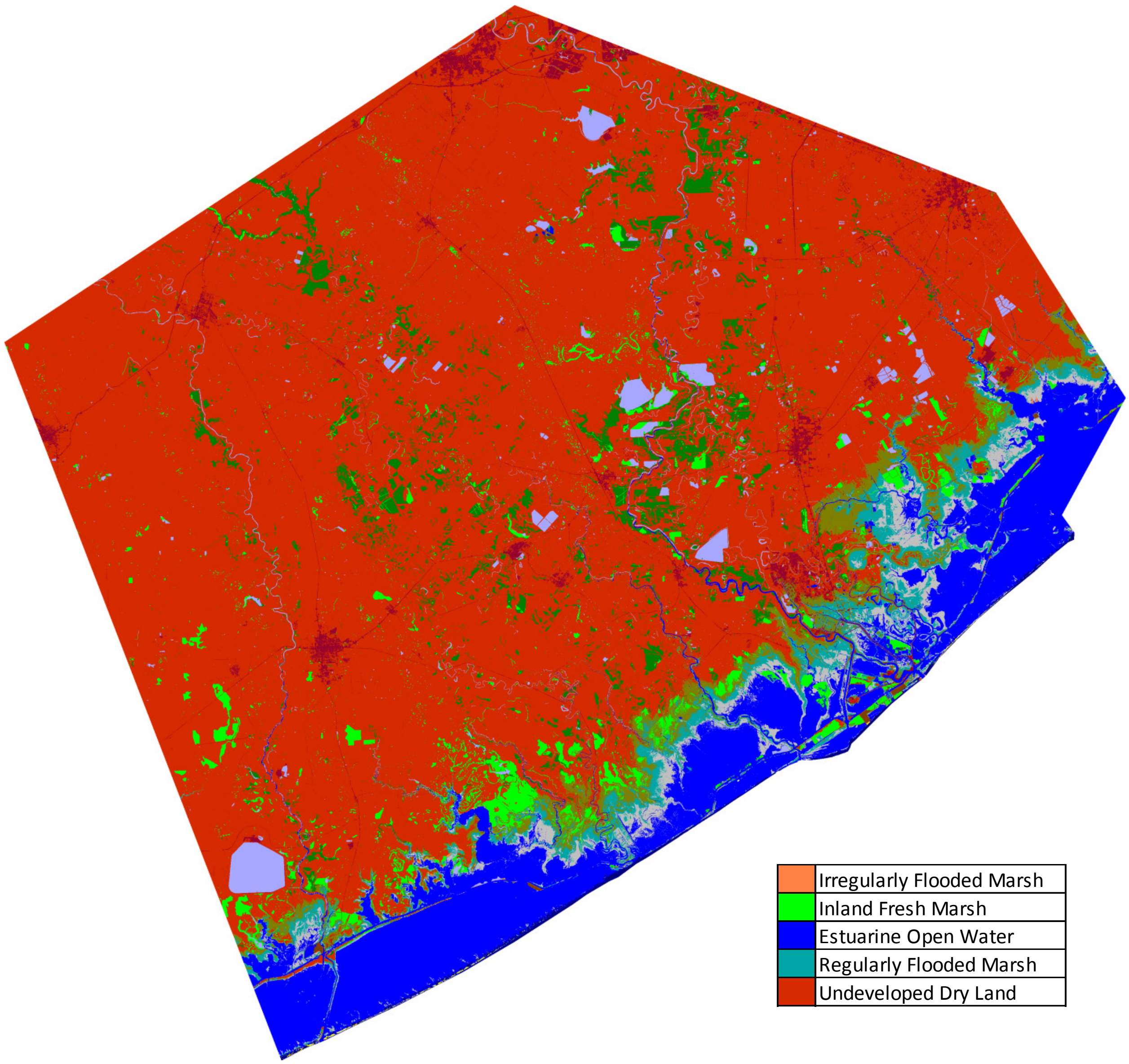
San Bernard NWR, 2025, 2 m SLR



San Bernard NWR, 2050, 2 m SLR



San Bernard NWR, 2075, 2 m SLR



San Bernard NWR, 2100, 2 m SLR

Accretion Sensitivity Analysis

Site-specific accretion rates are rarely available. In general accretion rates are obtained from the little available literature published on short to medium-term studies. Moreover, in this area of the Gulf of Mexico local rates of accretion are highly variable. To study the potential impact of having different accretion rates, an additional set of simulations was completed with an accretion rate of 4.4 mm/yr for both irregularly and regularly flooded marsh, the rate found in the Aransas NWR (Callaway et al. 1997). The simulation was run for the 1 m SLR by 2100 scenario. Comparison results for San Bernard NWR (approved acquisition boundary) are summarized in Table 6.

Table 6. Wetland coverage for 1 m SLR by 2100 scenario and different accretion rates (acres)

Land cover category		Initial	8.2 mm/yr, reg. 4.7 mm/yr, irreg.	4.4 mm/yr 4.4 mm/yr	Difference
	Estuarine Open Water	99,359	148,330	161,927	+13,597
	Irregularly Flooded Marsh	57,071	9,259	8,272	-987
	Regularly Flooded Marsh	30,871	47,131	35,081	-12,050

As expected, lowering accretion rates and increasing SLR have similar effects on marsh habitat. As a result of an accretion rate that is approximately half of previous simulations, regularly-flooded marshes are reduced by 25%. Irregularly-flooded marshes are reduced by 11%, though the accretion rate for this category is not very different in the two simulations. These lost wetland areas are practically all converted to open water.

Elevation Uncertainty Analysis

An elevation uncertainty analysis was performed for this model application in order to estimate the impact of terrain uncertainty on SLAMM outputs. This analysis took into account both the uncertainty related to the elevation data as well as uncertainty in the VDATUM correction values.

Elevation data uncertainty was evaluated using the application of a spatially autocorrelated error field to the existing digital elevation map in the manner of (Heuvelink 1998). In this application, an error field for both the DEM uncertainty and the VDATUM correction uncertainty were applied to the existing DEM. This approach uses the normal distribution as specified by the Root Mean Squared Error for the dataset and applies it randomly over the entire study area, but with spatial autocorrelation included (Figure 16). Since elevation error is generally spatially autocorrelated (Hunter and Goodchild 1997), this method provides a means to calculate a number of equally-likely elevation maps given error statistics about the data set. A stochastic analysis may then be run (running the model with each of these elevation maps) to assess the overall effects of elevation uncertainty. Heuvelink's method has been widely recommended as an approach for assessing the effects of elevation data uncertainty (Darnell et al. 2008; Hunter and Goodchild 1997). In this analysis, it was assumed that elevation errors were strongly spatially autocorrelated, using a "p-value" of 0.249 [2].

The declared vertical accuracy for the 2006 Texas Water Board LiDAR is 18 cm. This value was reflected in the RMSE parameters for this uncertainty analysis (Figure 16).

According the VDATUM website the RMSE for converting NAVD88 to MTL within the study region is a relatively large at 10.1 cm (NOAA 2010). This value was determined by combining the uncertainty associated with the NAVD 88 to MSL transformation (8.7 cm) and MSL to MTL transformation (1.4 cm) for the relevant region (Texas – Lagoons, Galveston Bay to south end of Matagorda Island).

[2] A p-value of zero is no spatial autocorrelation and 0.25 is perfect correlation (i.e. not possible). P-values must be less than 0.25.

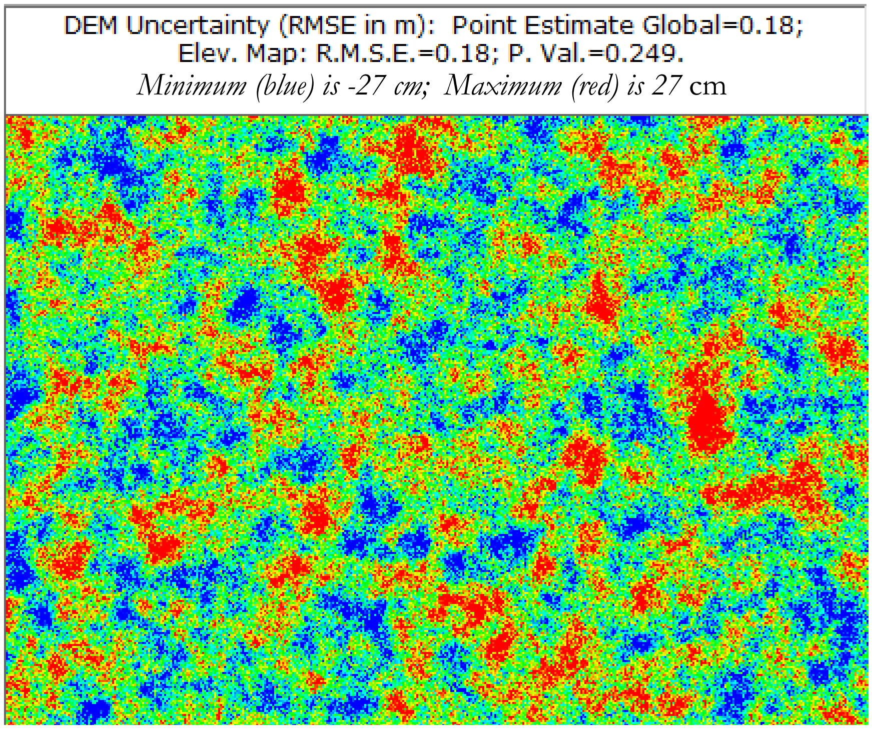


Figure 16. A sample of a spatially autocorrelated error field using LiDAR error parameters from this model application

In this model elevation uncertainty analysis, 65 iterations were run for the study area representing approximately 150 hours of CPU time. The model was run with 1 m of eustatic SLR by 2100 for each iteration.

In terms of overall acreage change, the effects of elevation uncertainty within this modeling analysis were fairly limited, with the coefficient of variance (CV) remaining below 1% for the four most prevalent land cover categories, as shown in Table 7. These results reveal that the most widespread land covers do not substantially change given uncertainty in elevation values (Figure 17 and Figure 18).

Table 7. Summary statistical results for elevation uncertainty analysis

Variable Name	Min	Mean	Max	Std. Dev.	Deterministic	CV
Undeveloped Dry Land	1,531,958	1,532,666	1,533,356	355	1,528,348	0.02%
Estuarine Open Water	147,136	149,745	151,903	1,098	148,330	0.73%
Inland-Fresh Marsh	80,220	80,935	81,575	279	79,595	0.35%
Swamp	78,693	78,814	78,960	60	78,443	0.08%
Regularly-Flooded Marsh	45,411	47,097	48,309	602	47,131	1.28%
Inland Open Water	42,776	42,852	42,936	39	41,953	0.09%
Developed Dry Land	39,804	39,991	40,207	102	39,790	0.25%
Tidal Flat	31,392	32,985	34,630	788	41,845	2.39%
Trans. Salt Marsh	25,788	27,200	28,603	605	28,592	2.22%
Irreg.-Flooded Marsh	10,449	11,005	11,821	306	9,259	2.78%
Open Ocean	3,621	3,688	3,762	30	3,708	0.81%
Inland Shore	2,714	2,766	2,823	22	2,785	0.81%
Ocean Beach	1,878	1,961	2,072	34	2,111	1.75%
Riverine Tidal	1,556	1,592	1,628	15	1,526	0.94%
Tidal-Fresh Marsh	1,435	1,583	1,753	73	1,524	4.63%
Estuarine Beach	1,192	1,260	1,327	25	1,197	1.97%

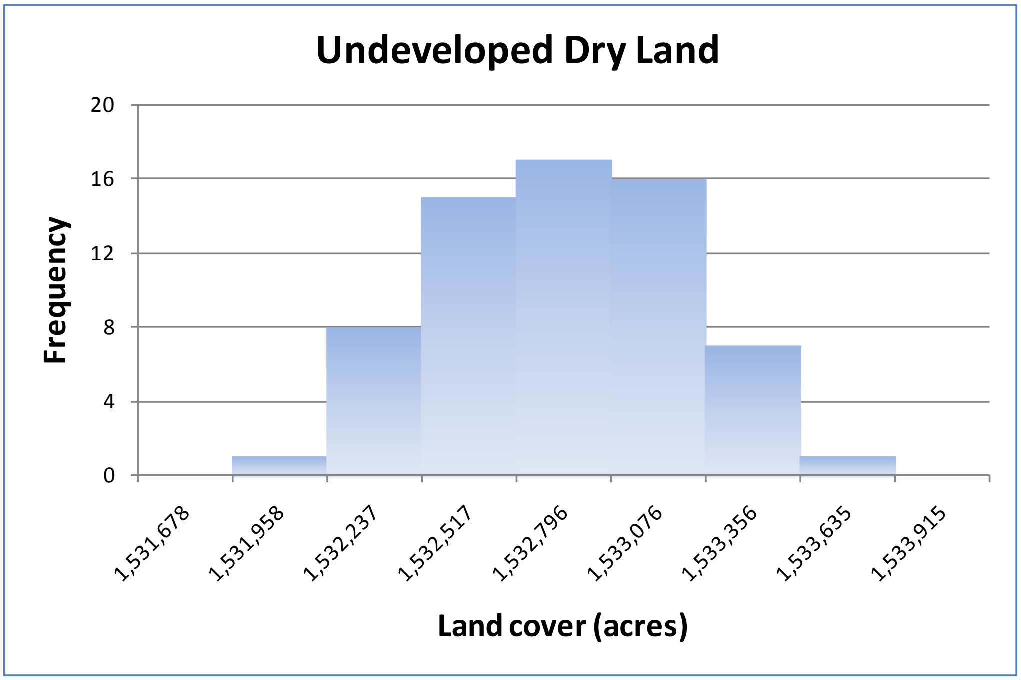


Figure 17. Elevation uncertainty result distribution for undeveloped dry land within the study area

Note, this shows predicted results in 2100 under 1 m of eustatic SLR. The initial condition for undeveloped-dry land was 1,580,181 acres.

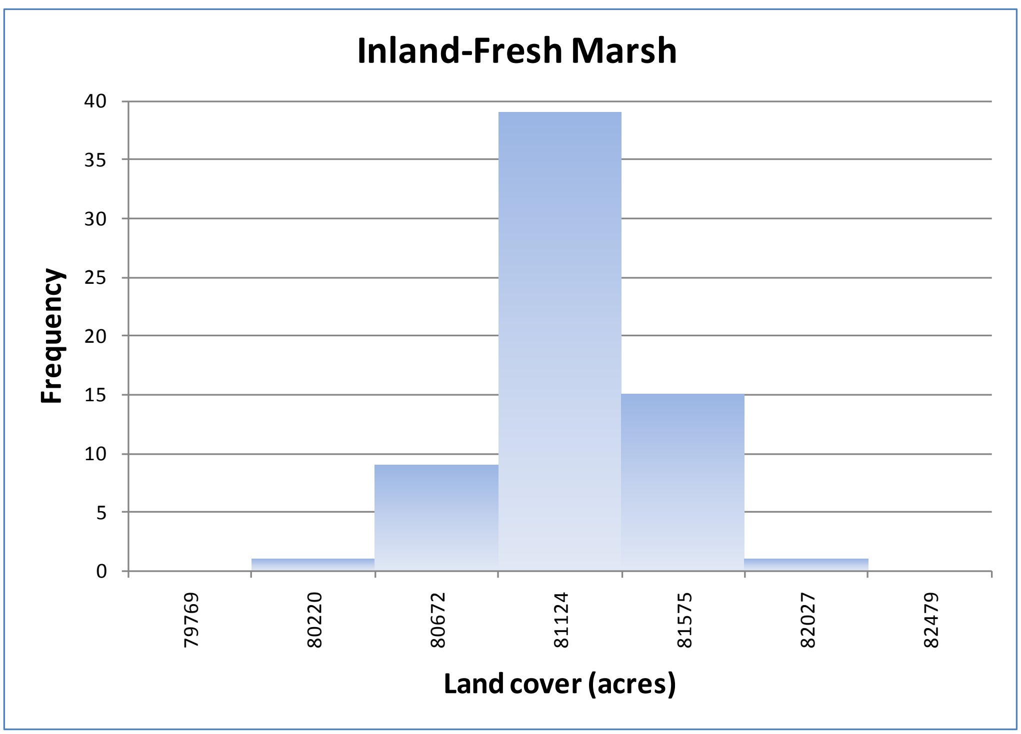


Figure 18. Elevation uncertainty result distribution for inland-fresh marsh within the study area

Note, this shows predicted results in 2100 under 1 m of eustatic SLR. The initial condition for inland-fresh marsh was 100,208 acres.

Discussion

Model results for San Bernard NWR indicate that lands within the refuge approved acquisition boundary are fairly resilient to the SLR scenarios examined. The majority of the refuge is located at elevations that preclude effects from SLR by 2100 (e.g., more than 75% of the study area is dry land, much of that located inland).

The most heavily affected areas are the coastal boundary. By 2100, most of these areas may be inundated given SLR scenarios of 1 m by 2100 and above. This model result is uncertain, especially in the Freeport area, given the lack of information on the presence of dikes to protect the developed dry land. In addition, local tide ranges in East Matagorda Bay are uncertain.

When rates of sea-level rise exceed predicted accretion rates (SLR>0.69 m by 2100), irregularly-flooded marsh are predicted to sustain considerable losses, over 60% in all scenarios examined. Irregularly-flooded marshes are converted to regularly-flooded marshes that are resilient to SLR as their accretion rate for this type of wetland category is estimated to be relatively high based on local data (Callaway et al., 1997).

Swamps are predicted to be resilient to all SLR scenarios because they are generally located far inland while all other wetland categories are vulnerable with high predicted losses.

Predictions for the Big Boggy NWR area show that this refuge is much more vulnerable to SLR, presumably due to its location relative to East Matagorda Bay. Land cover converted to open water or tidal flat is predicted to be 5% to 55% of the total refuge area depending on the SLR scenario considered. All major wetland categories are predicted to experience substantial losses except for inland-fresh marsh as it is generally protected by dikes. Regularly-flooded marshes are predicted to increase in the lower SLR scenarios simulated. However, as SLR rate exceeds marsh accretion rate (SLR> 0.82 m), this category is also predicted to be severely affected.

Local accretion data were taken from available literature and applied on the entire study area. An uncertainty analysis on the accretion rates applied shows that marsh prediction results are quite sensitive to the accretion rates applied. More specific measurements of accretion rates within the refuge could provide better predictions of marsh losses in the future.

A useful hindcast of the SLAMM model was only possible for a small section of the eastern portion of the study area where historic and recent wetlands were different. Therefore calibration results are limited. One of the limitations is the short period of time between the historic and current wetland layers (only 14 years), meaning the hindcast model only reflects 4 cm of global SLR. The second and more important limitation is that NWI maps were not "back dated" by NWI and are therefore perhaps inappropriate to compare.

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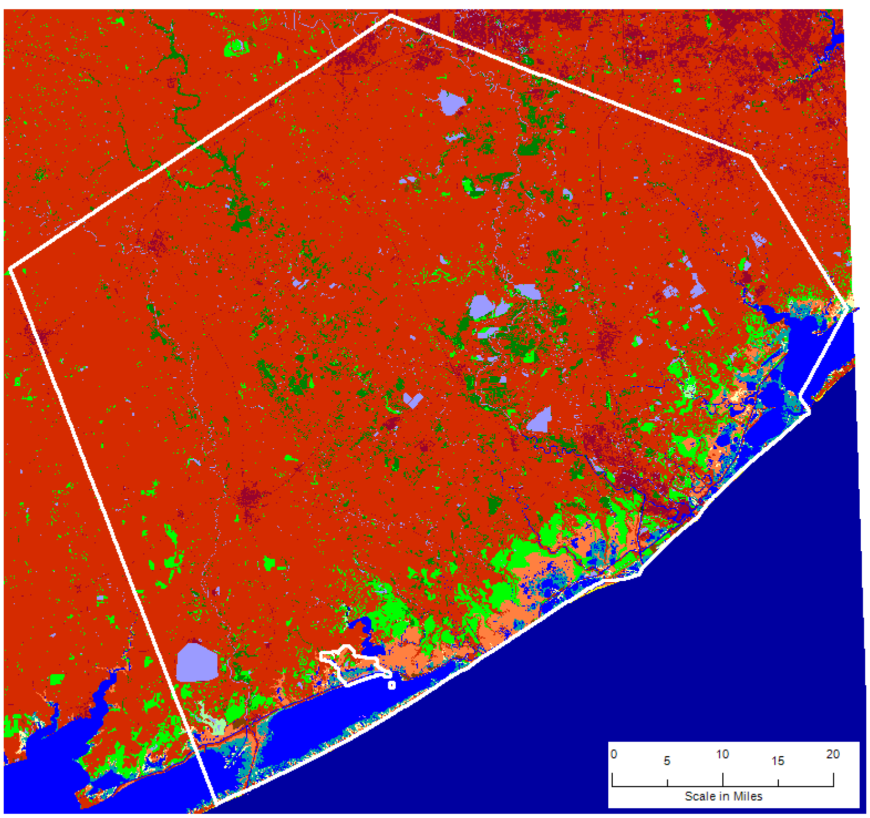
Appendix A: Contextual Results

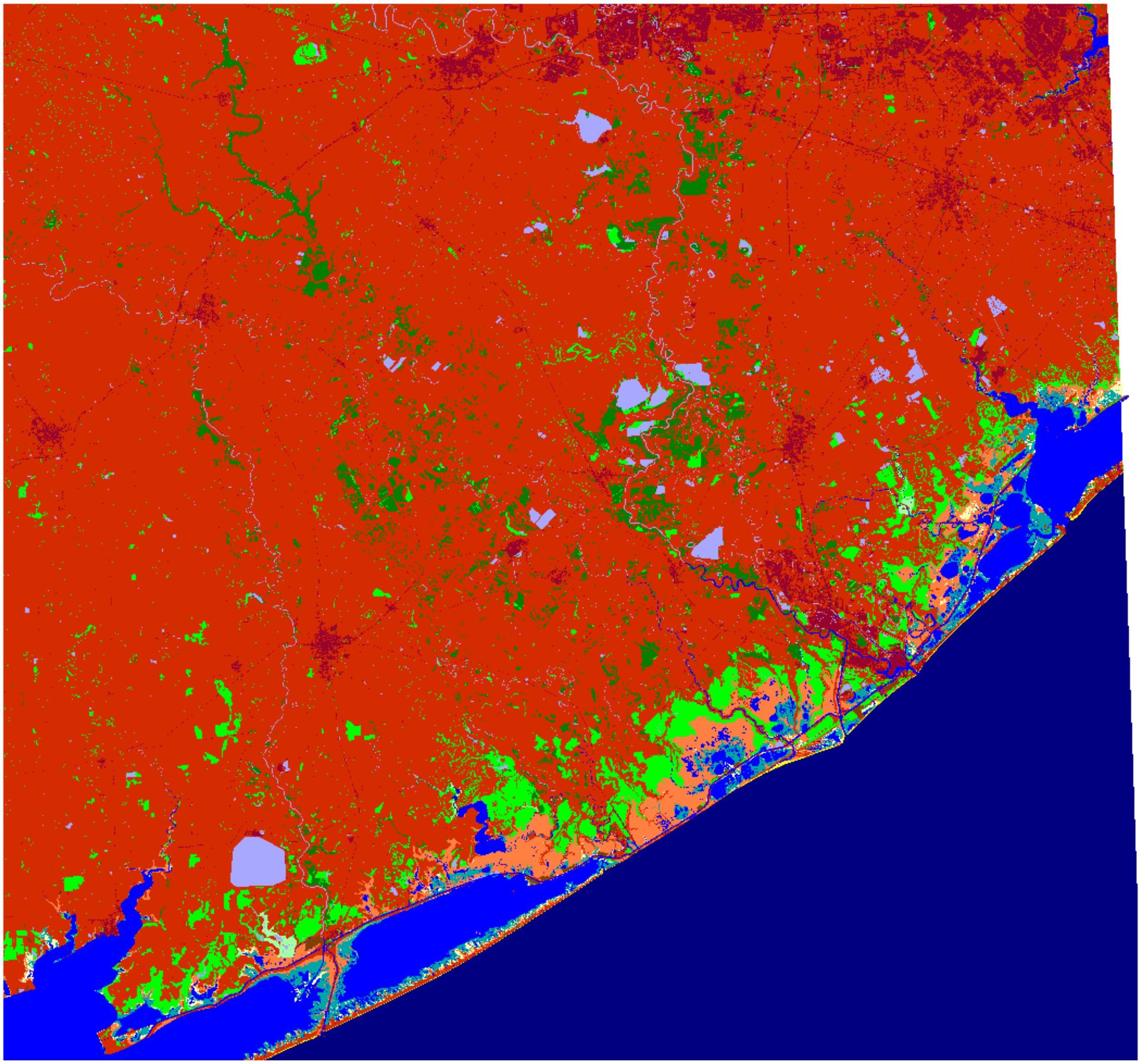
The SLAMM model does take into account the context of the surrounding lands or open water when calculating effects. For example, erosion rates are calculated based on the maximum fetch (wave action) which is estimated by assessing contiguous open water to a given marsh cell. Another example is that inundated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

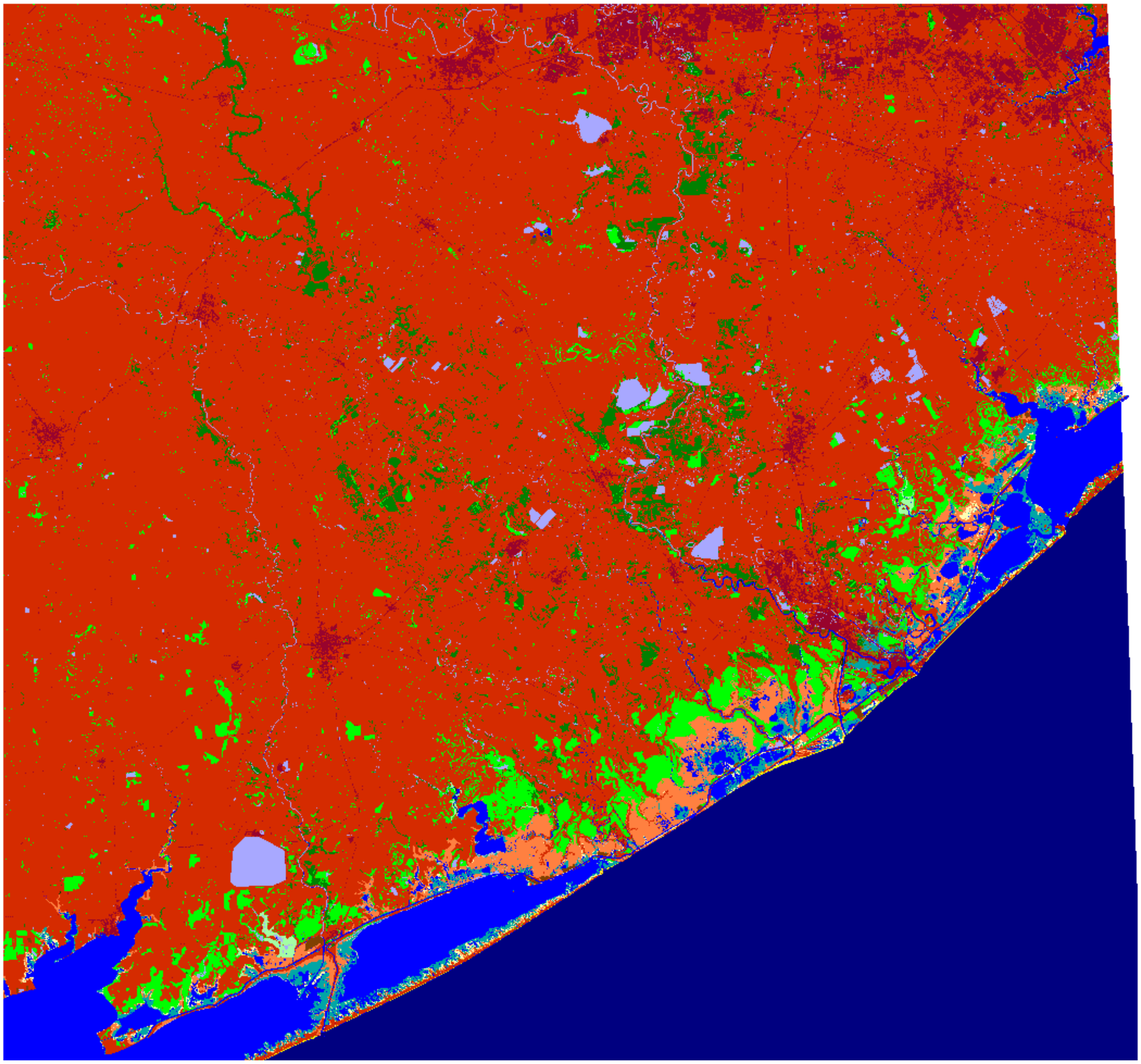
- Results were closely examined (quality assurance) within USFWS refuges but not closely examined for the larger region.
- Site-specific parameters for the model were derived for USFWS refuges whenever possible and may not be regionally applicable.
- Especially in areas where dikes are present, an effort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



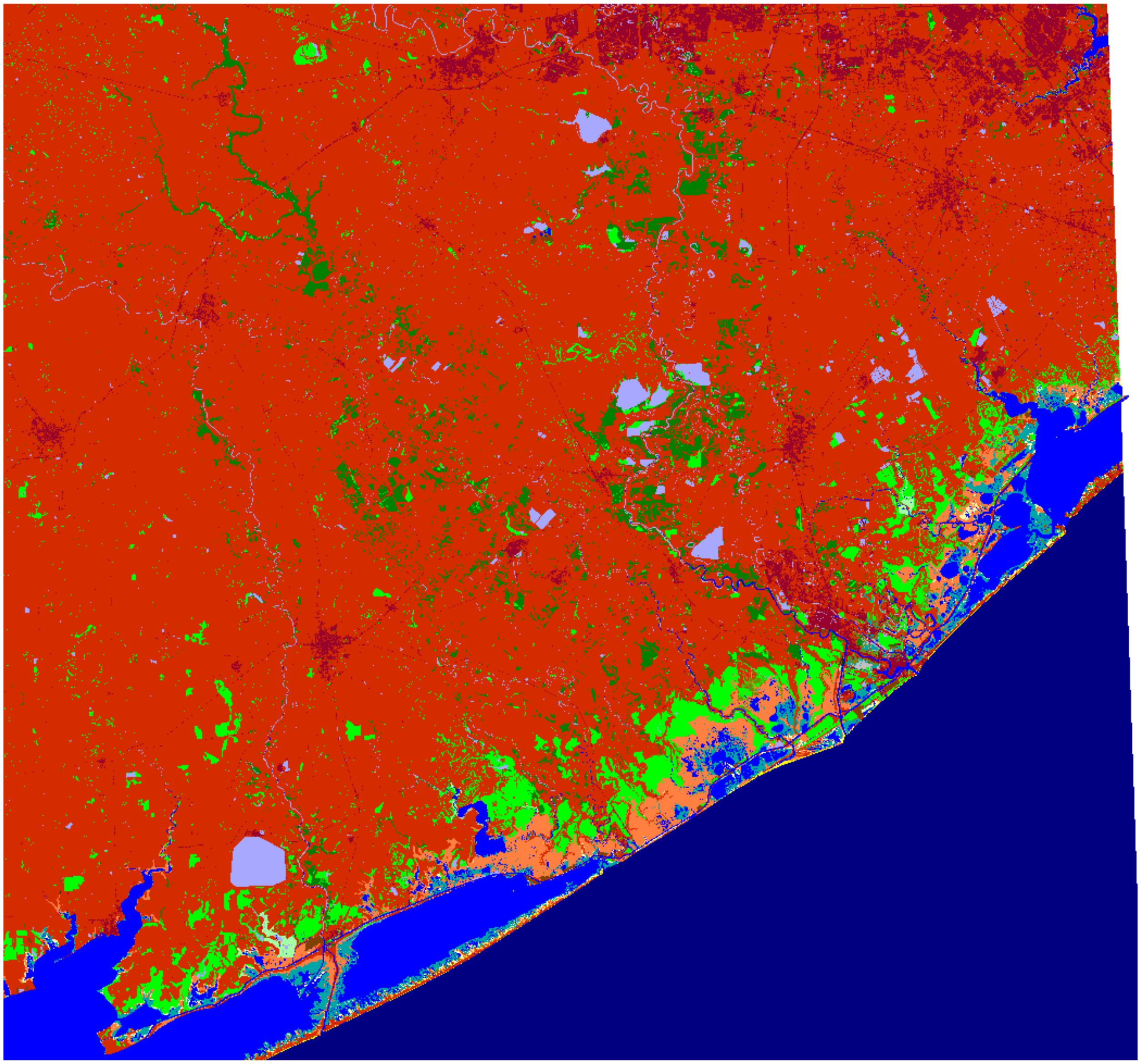
San Bernard and Big Boggy National Wildlife Refuges within simulation context (white).



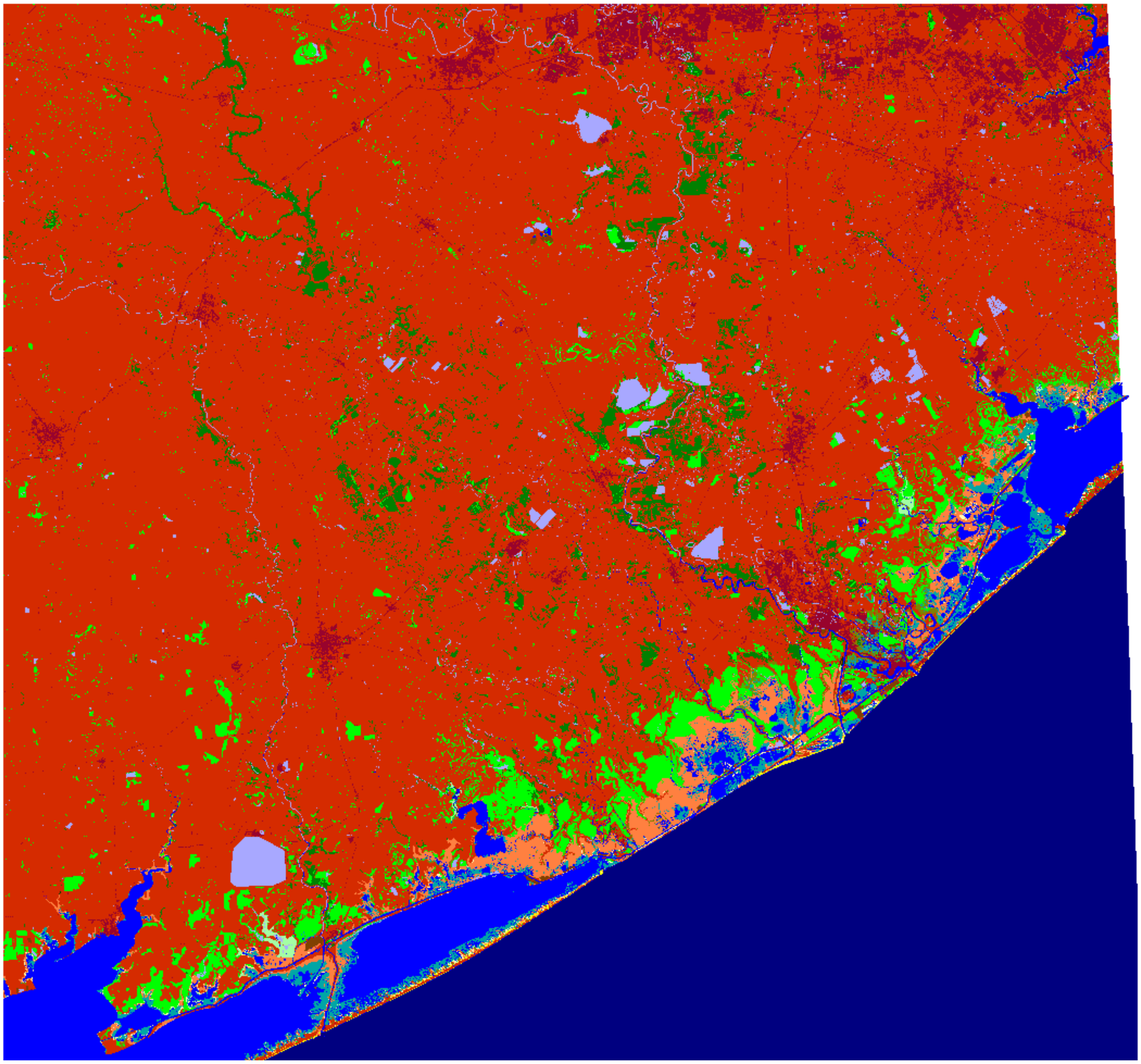
San Bernard and Big Boggy NWR, Initial Condition



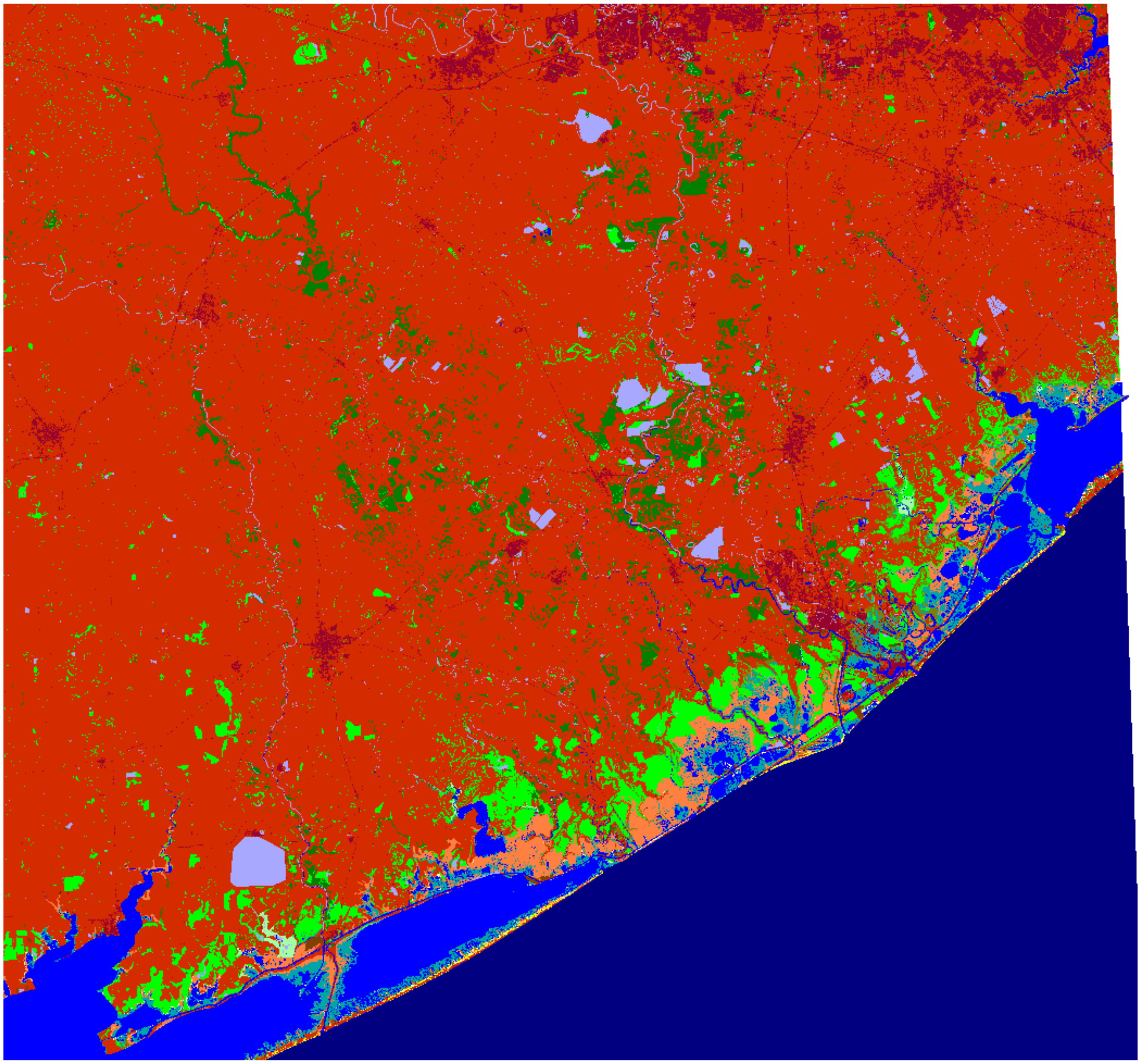
San Bernard and Big Boggy NWR, 2025, Scenario A1B Mean, 0.39 m SLR



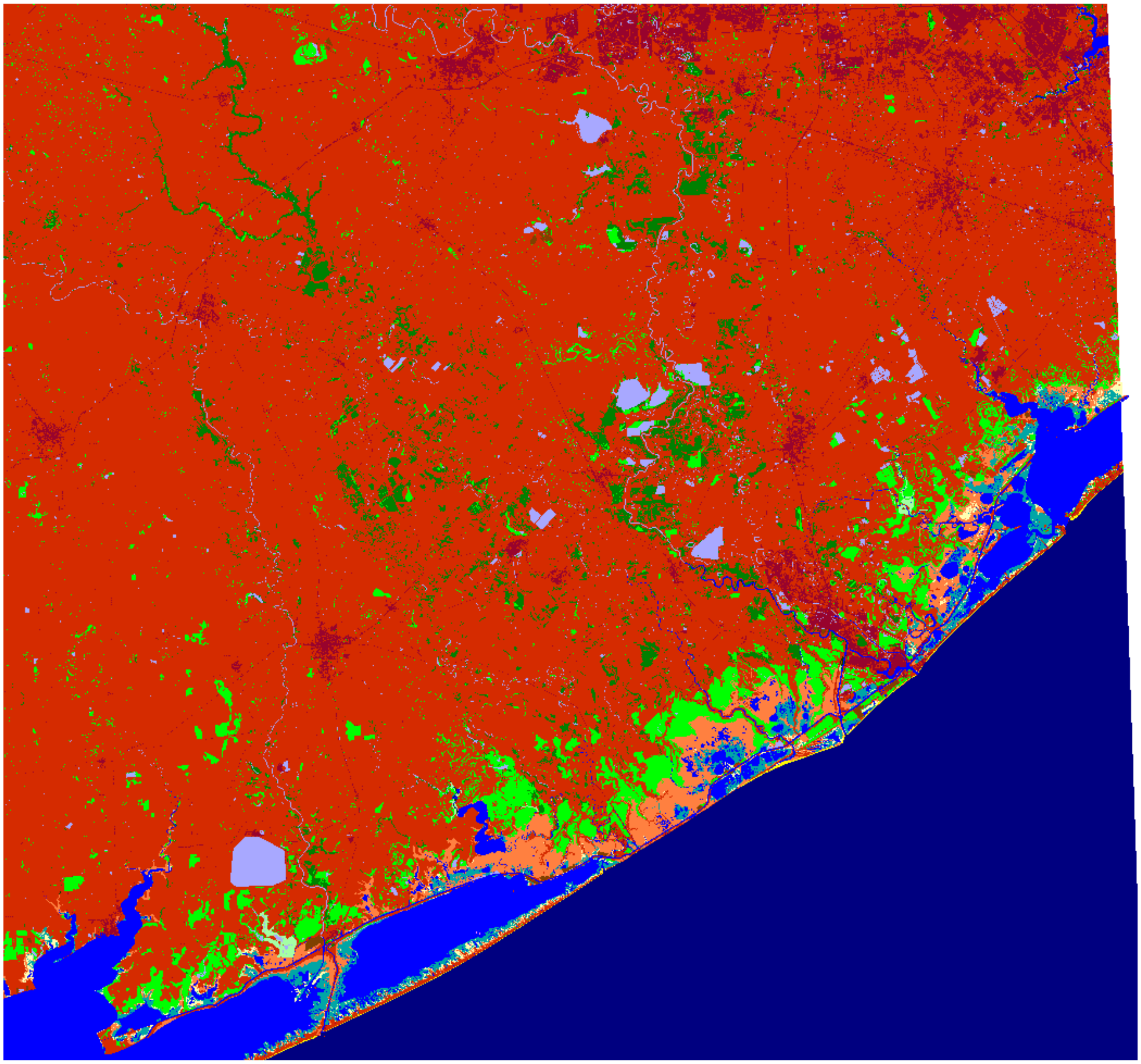
San Bernard and Big Boggy NWR, 2050, Scenario A1B Mean, 0.39 m SLR



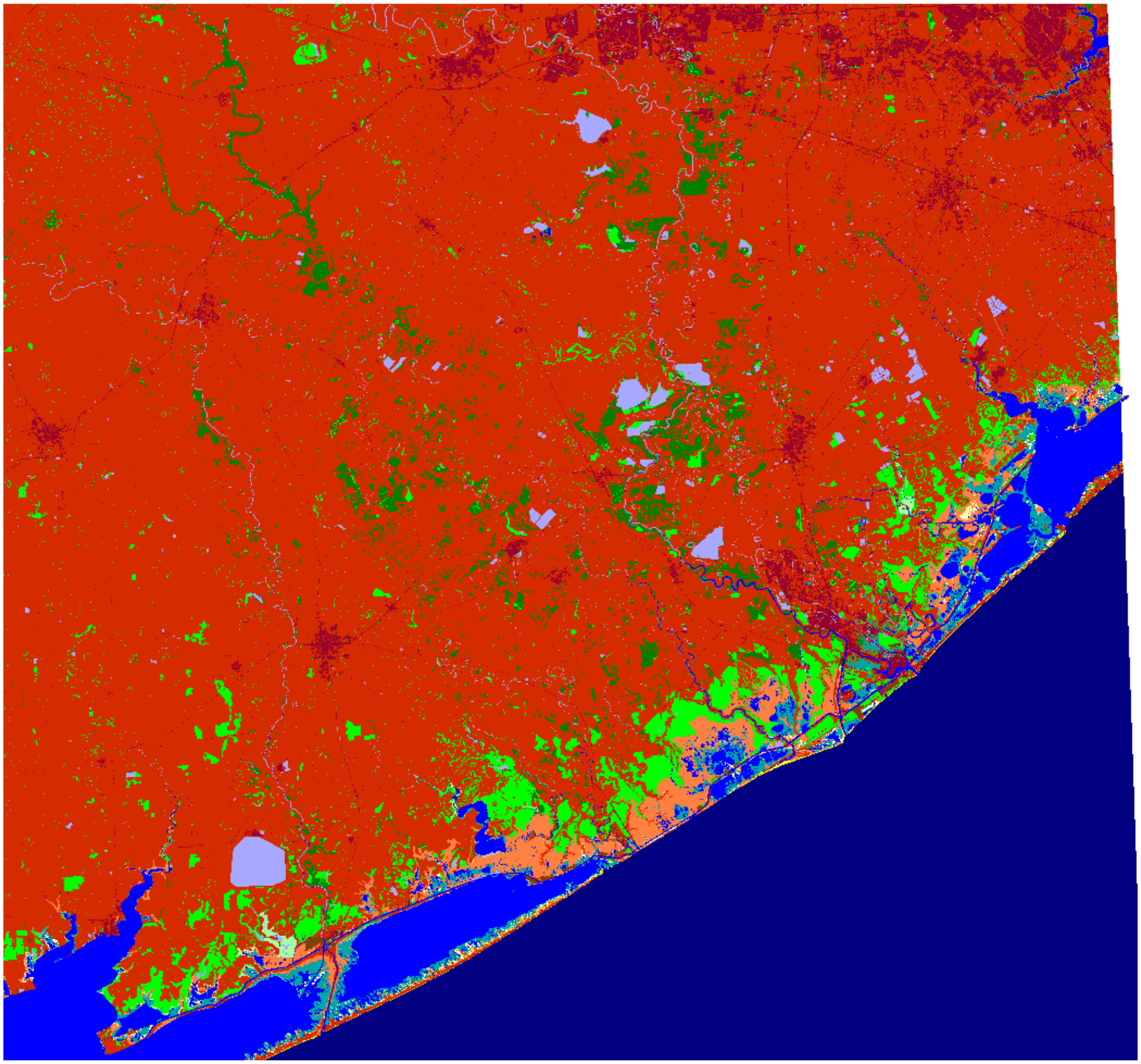
San Bernard and Big Boggy NWR, 2075, Scenario A1B Mean, 0.39 m SLR



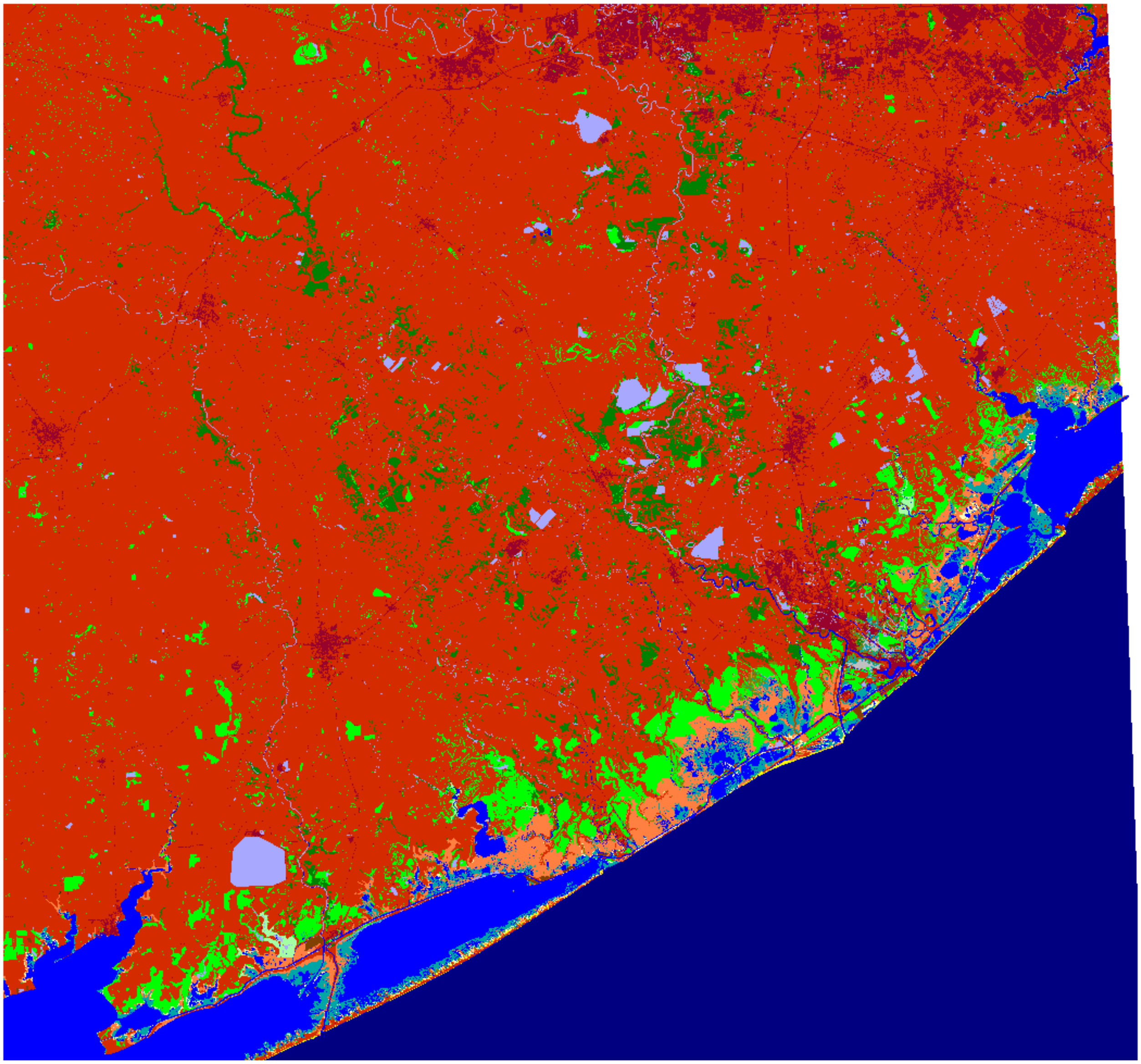
San Bernard and Big Boggy NWR, 2100, Scenario A1B Mean, 0.39 m SLR



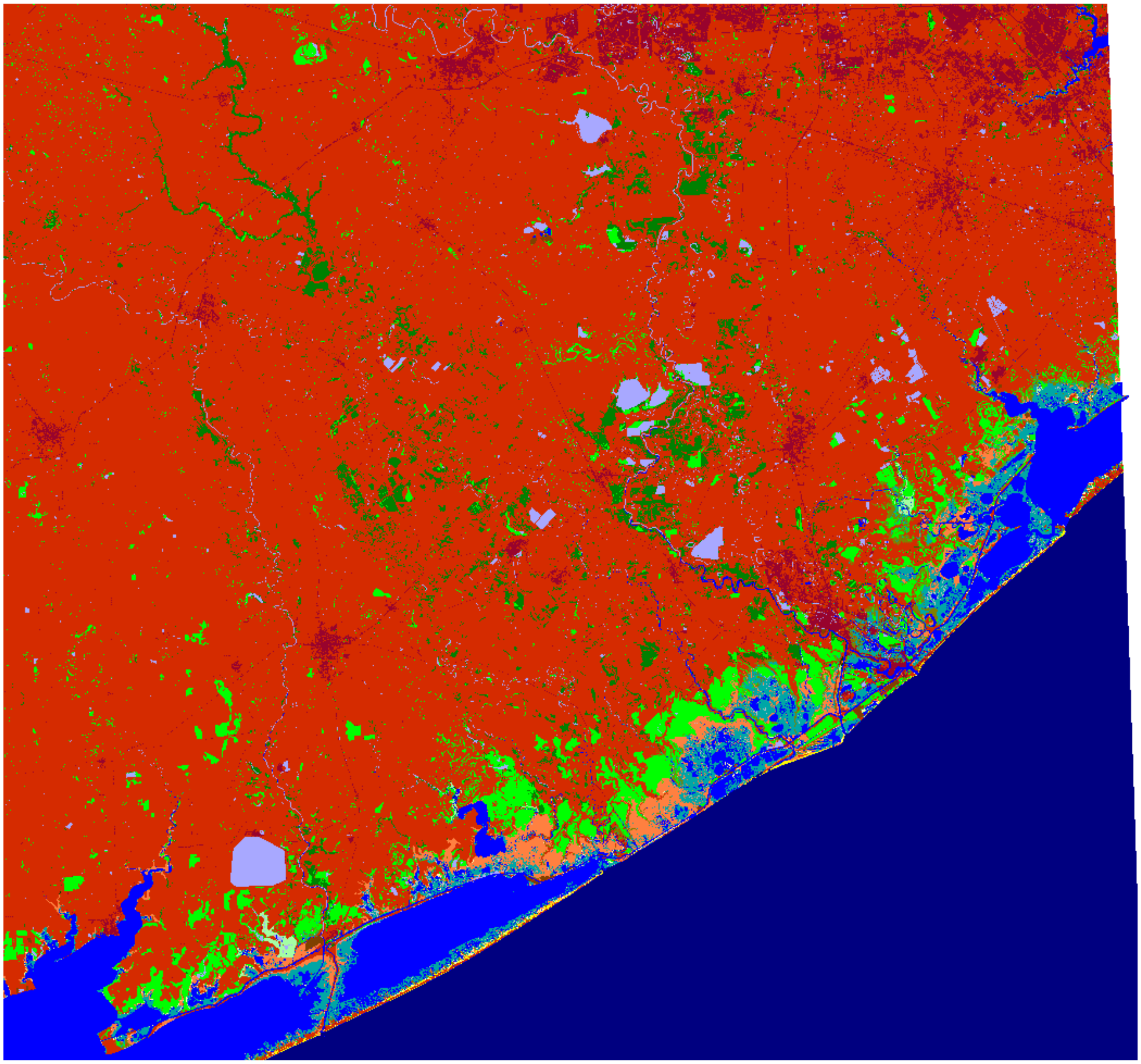
San Bernard and Big Boggy NWR, Initial Condition



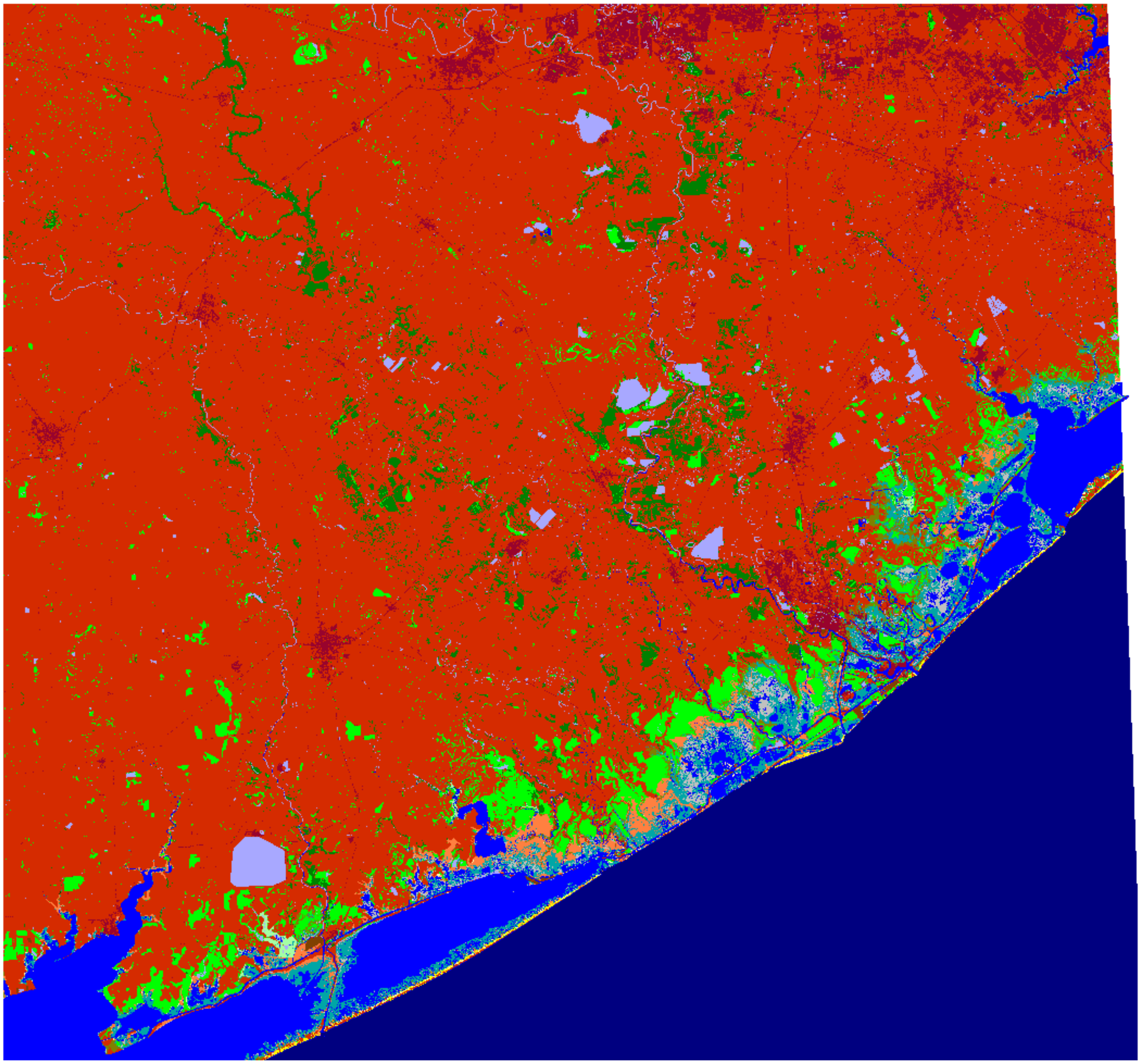
San Bernard and Big Boggy NWR, 2025, Scenario A1B Maximum, 0.69 m SLR



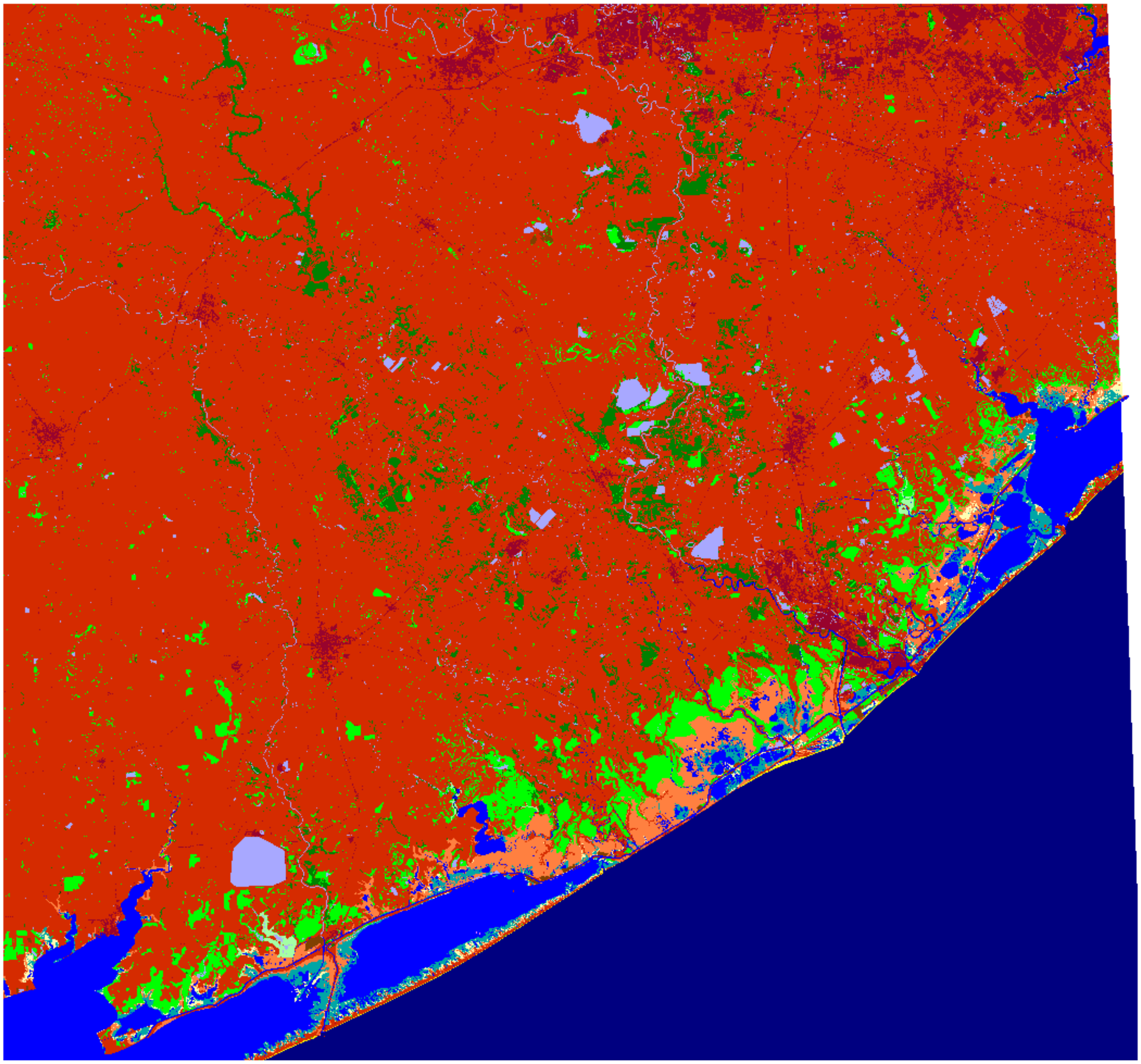
San Bernard and Big Boggy NWR, 2050, Scenario A1B Maximum, 0.69 m SLR



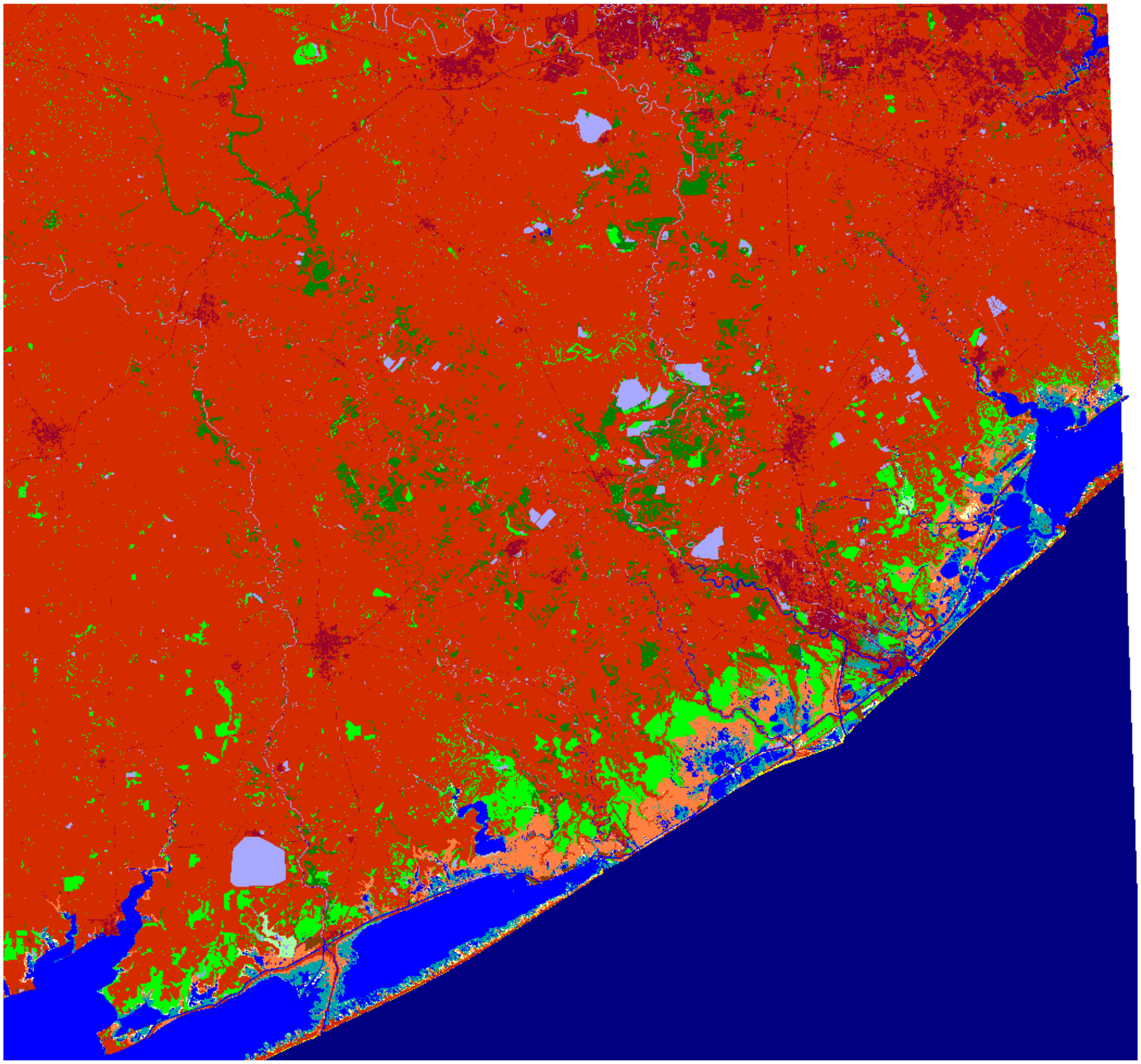
San Bernard and Big Boggy NWR, 2075, Scenario A1B Maximum, 0.69 m SLR



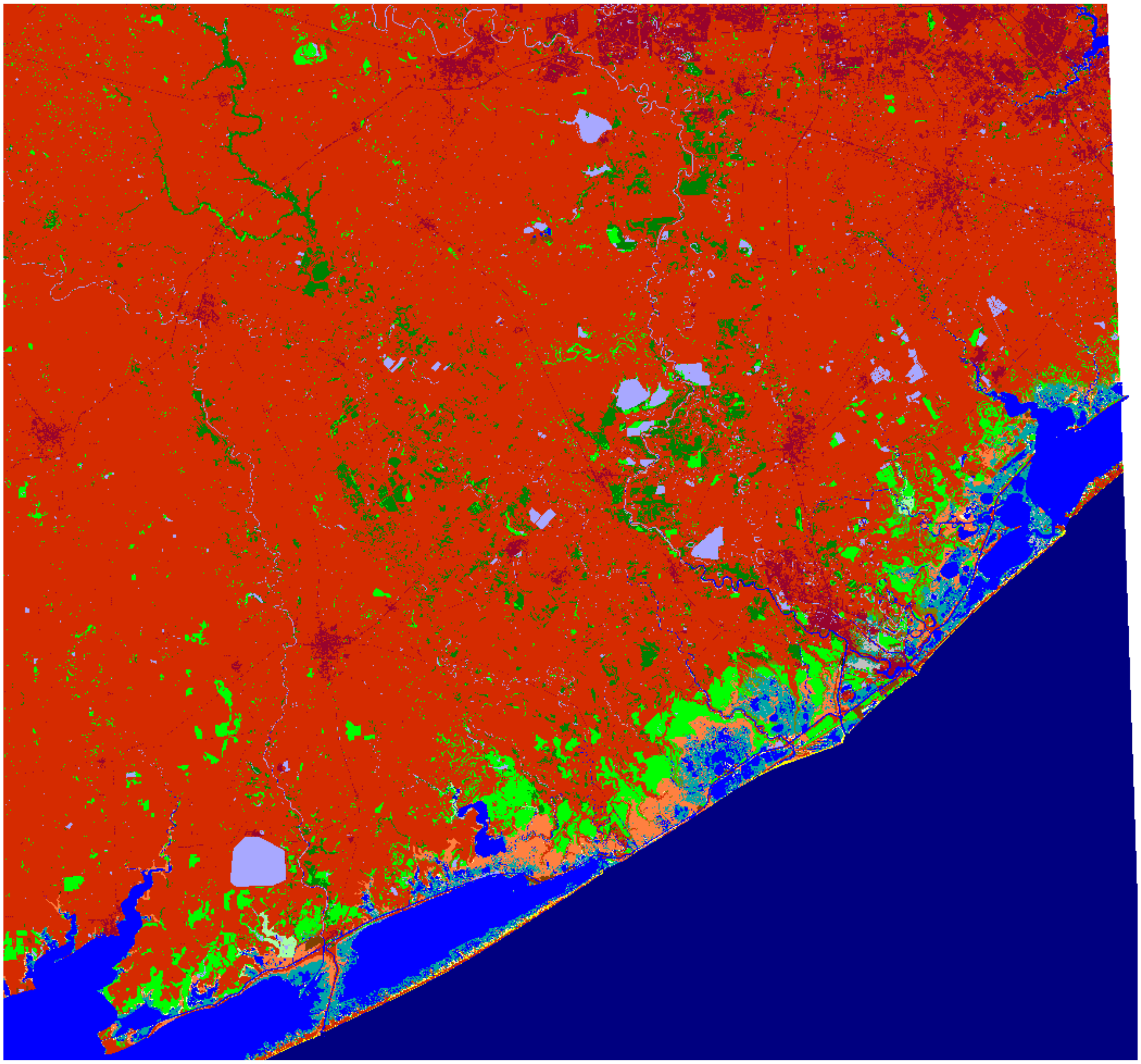
San Bernard and Big Boggy NWR, 2100, Scenario A1B Maximum, 0.69 m SLR



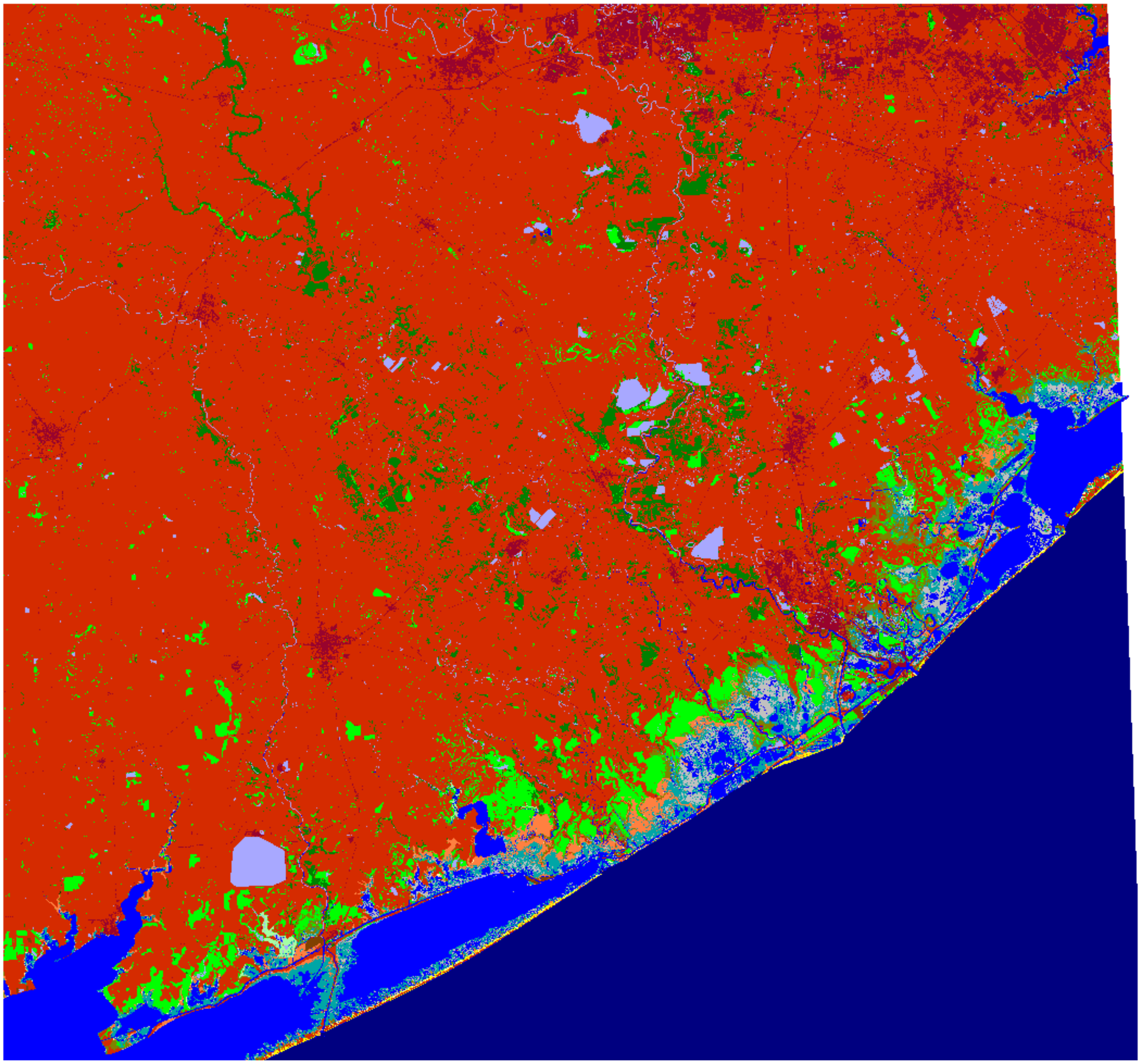
San Bernard and Big Boggy NWR, Initial Condition



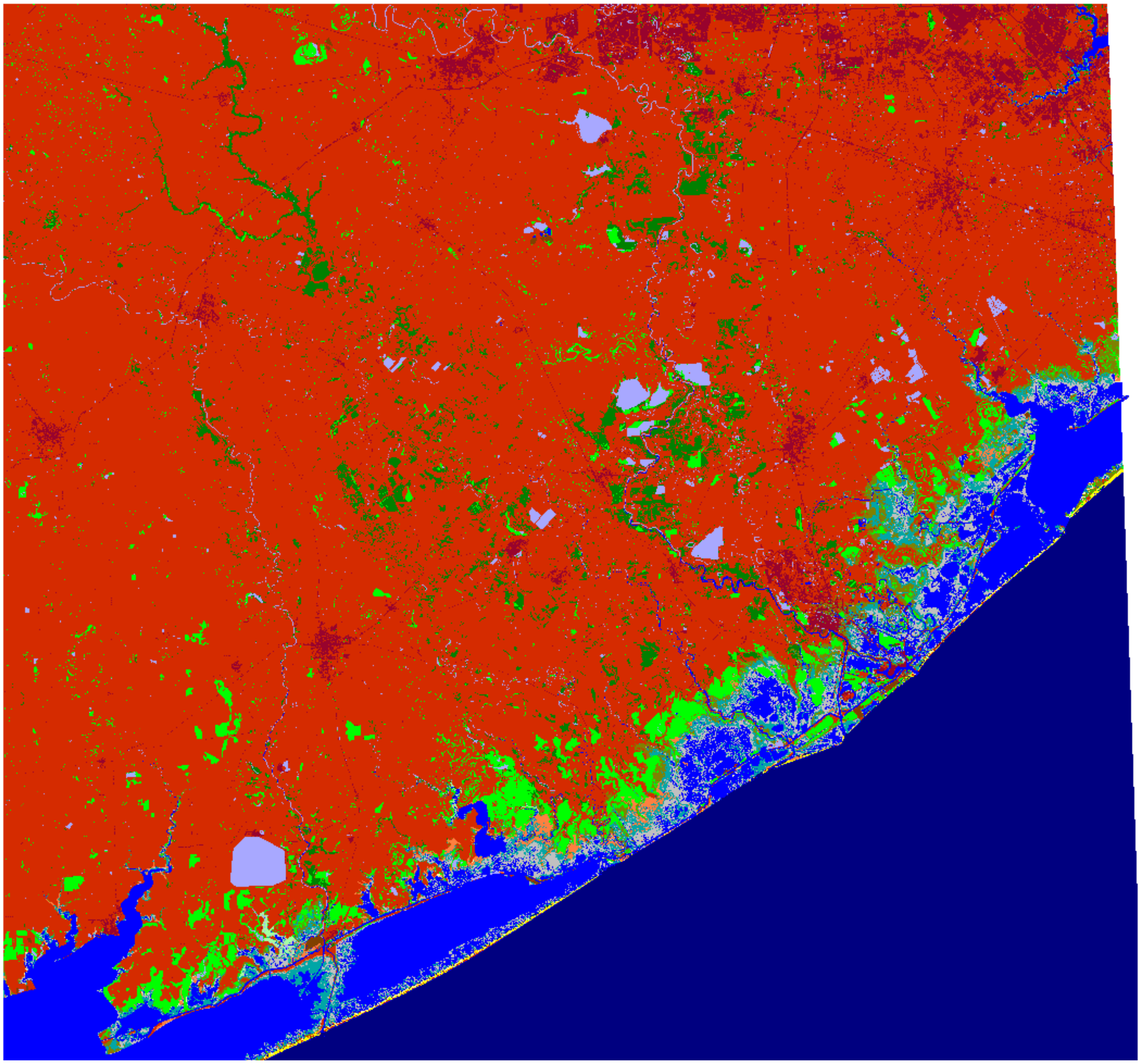
San Bernard and Big Boggy NWR, 2025, 1 m SLR



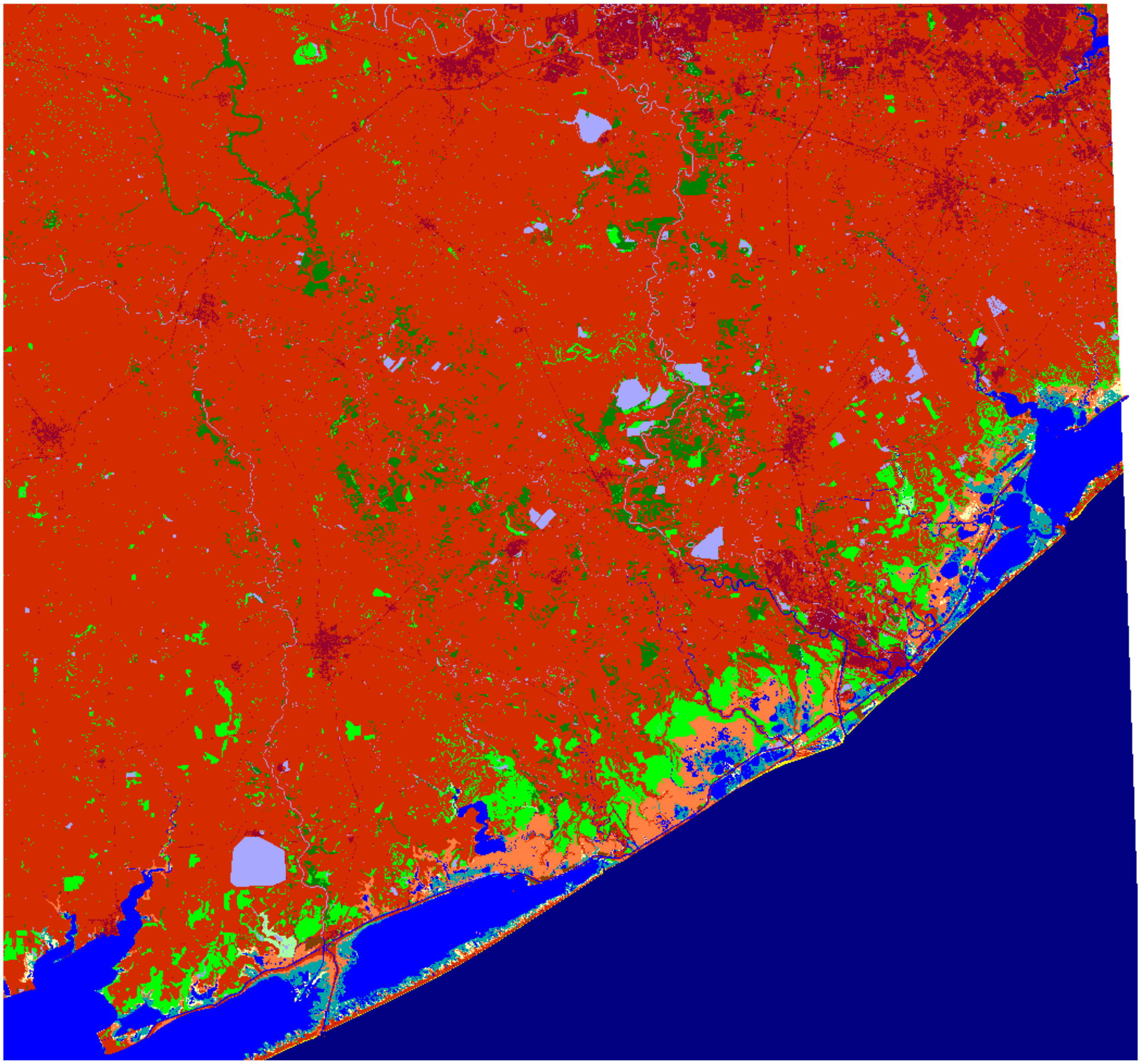
San Bernard and Big Boggy NWR, 2050, 1 m SLR



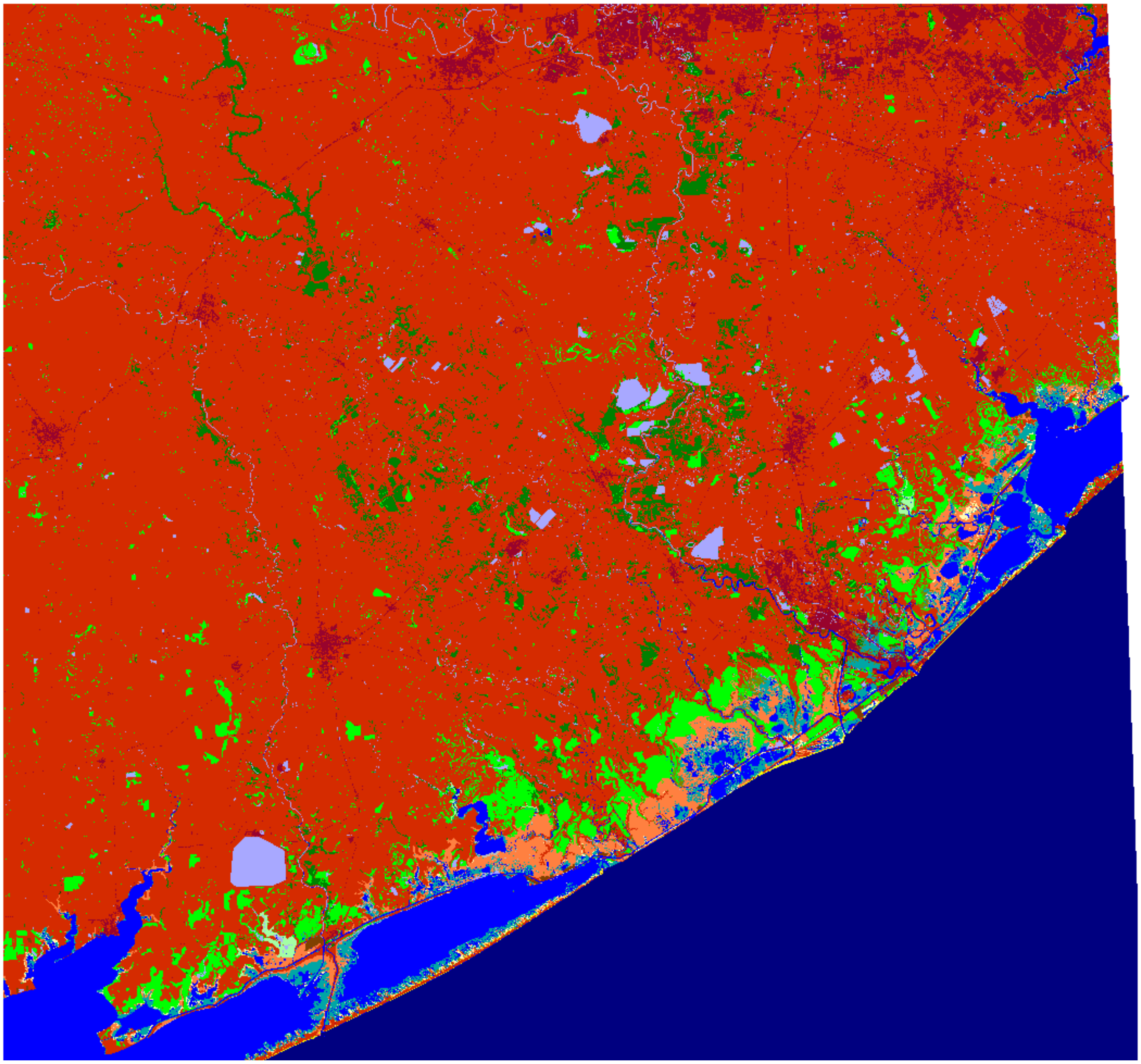
San Bernard and Big Boggy NWR, 2075, 1 meter



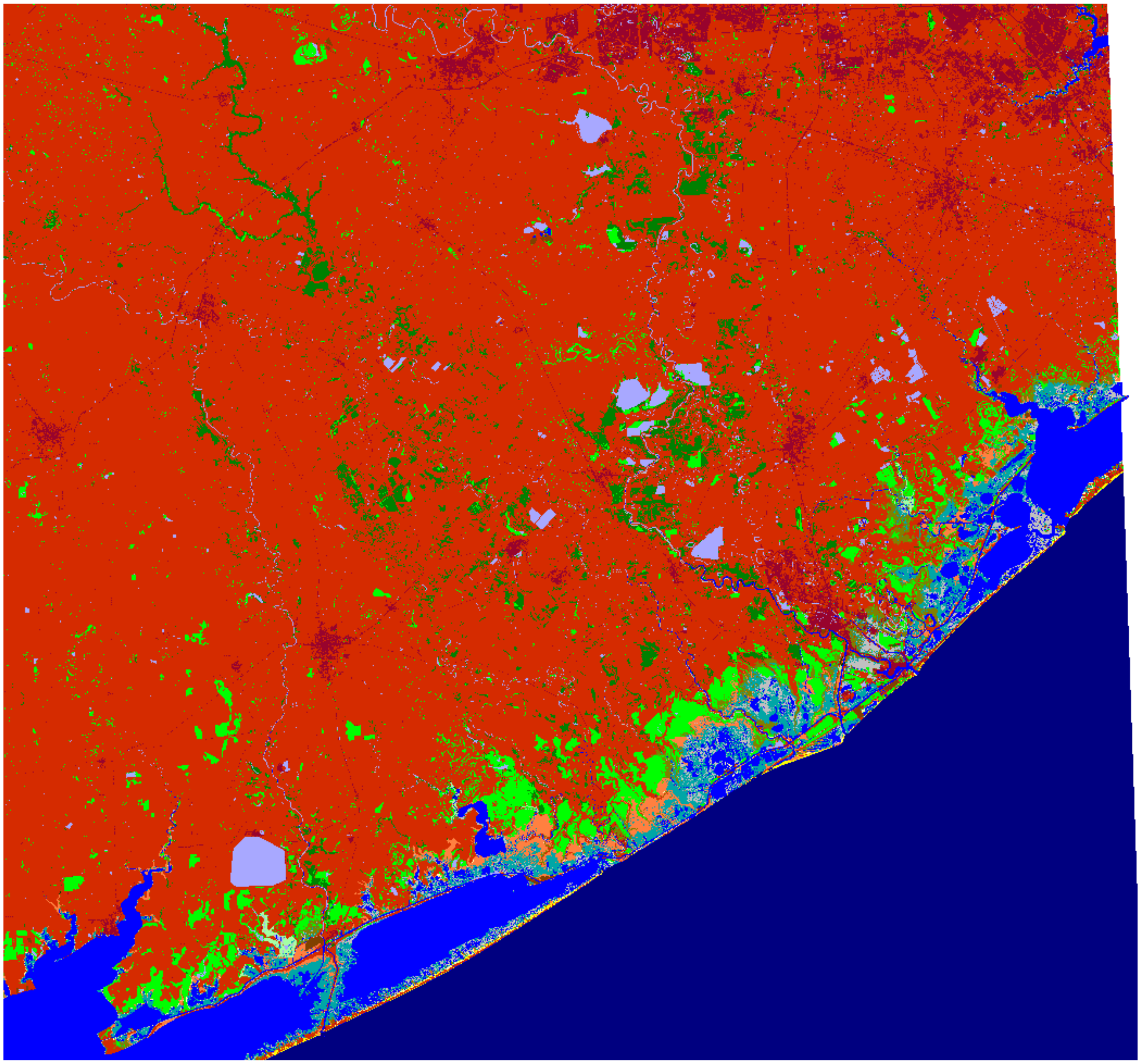
San Bernard and Big Boggy NWR, 2100, 1 m SLR



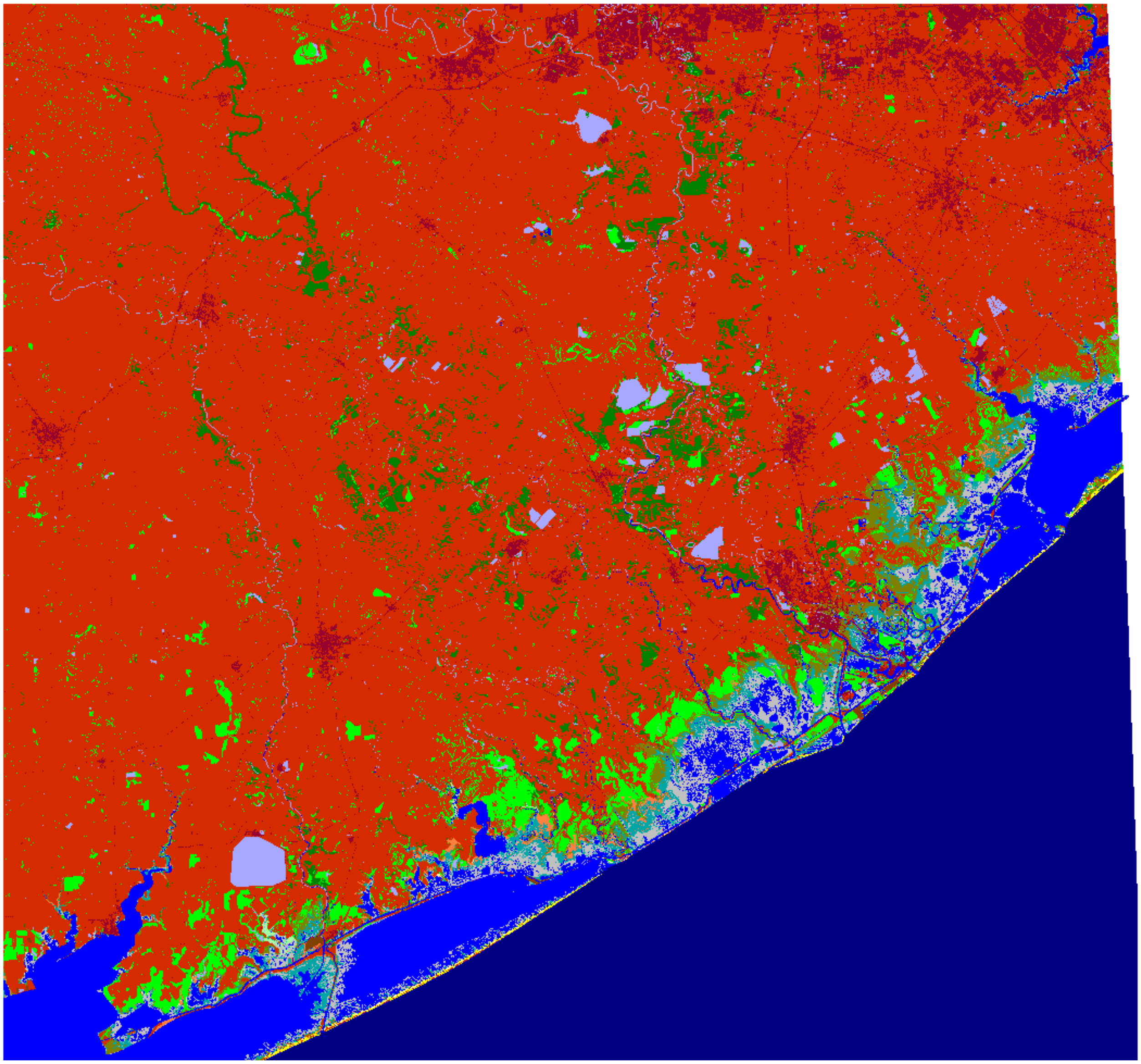
San Bernard and Big Boggy NWR, Initial Condition



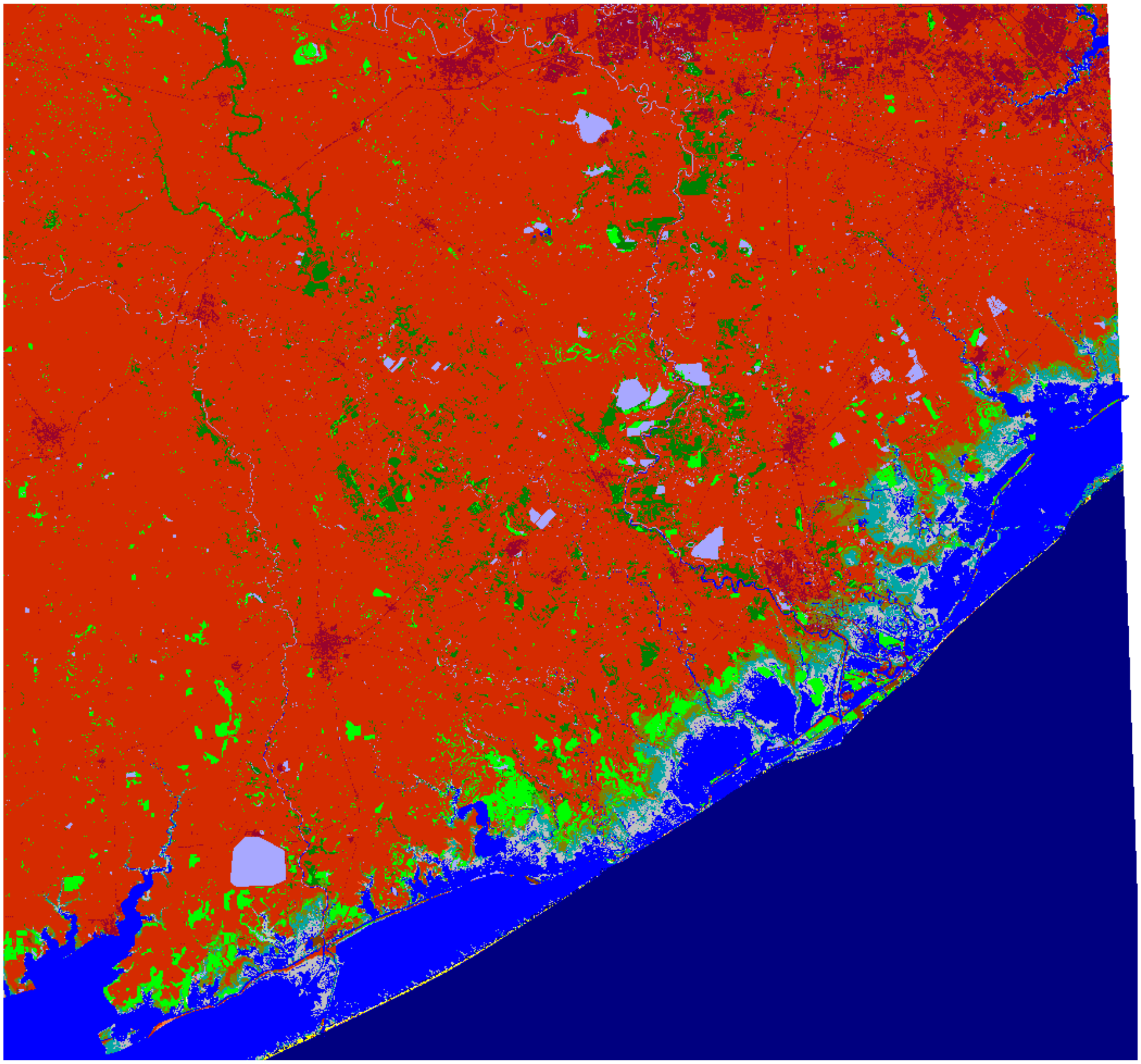
San Bernard and Big Boggy NWR, 2025, 1.5 m SLR



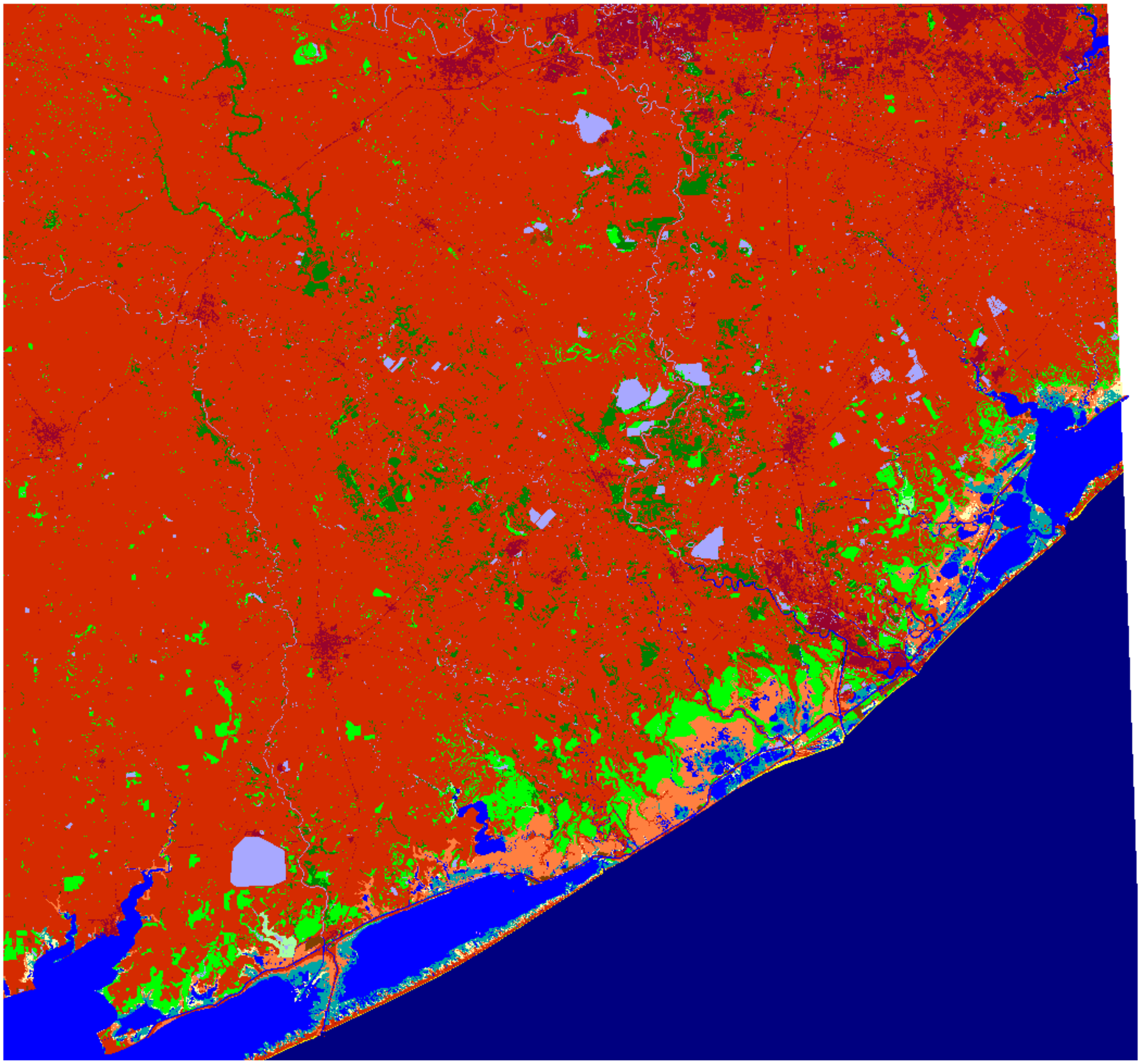
San Bernard and Big Boggy NWR, 2050, 1.5 m SLR



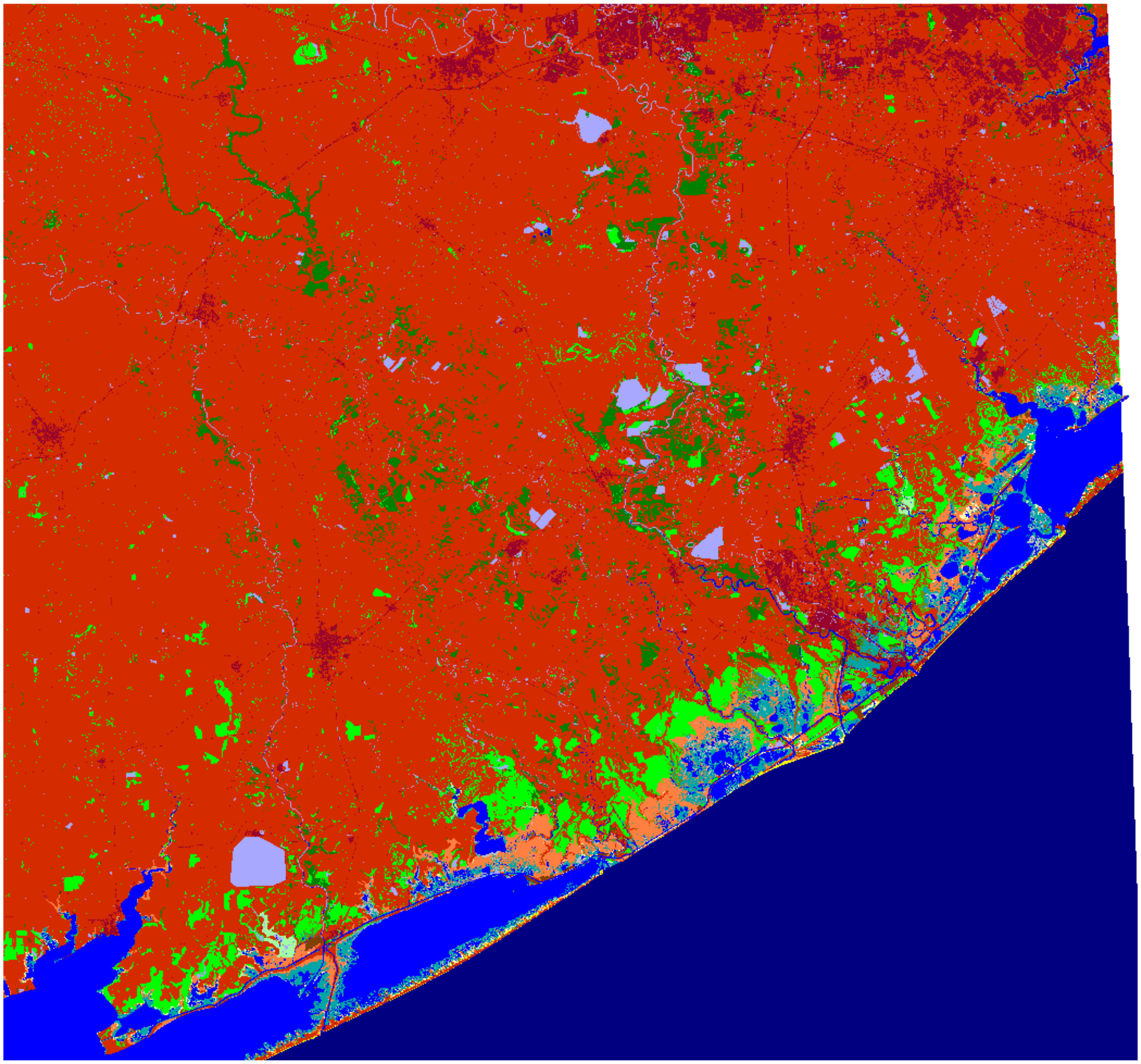
San Bernard and Big Boggy NWR, 2075, 1.5 m SLR



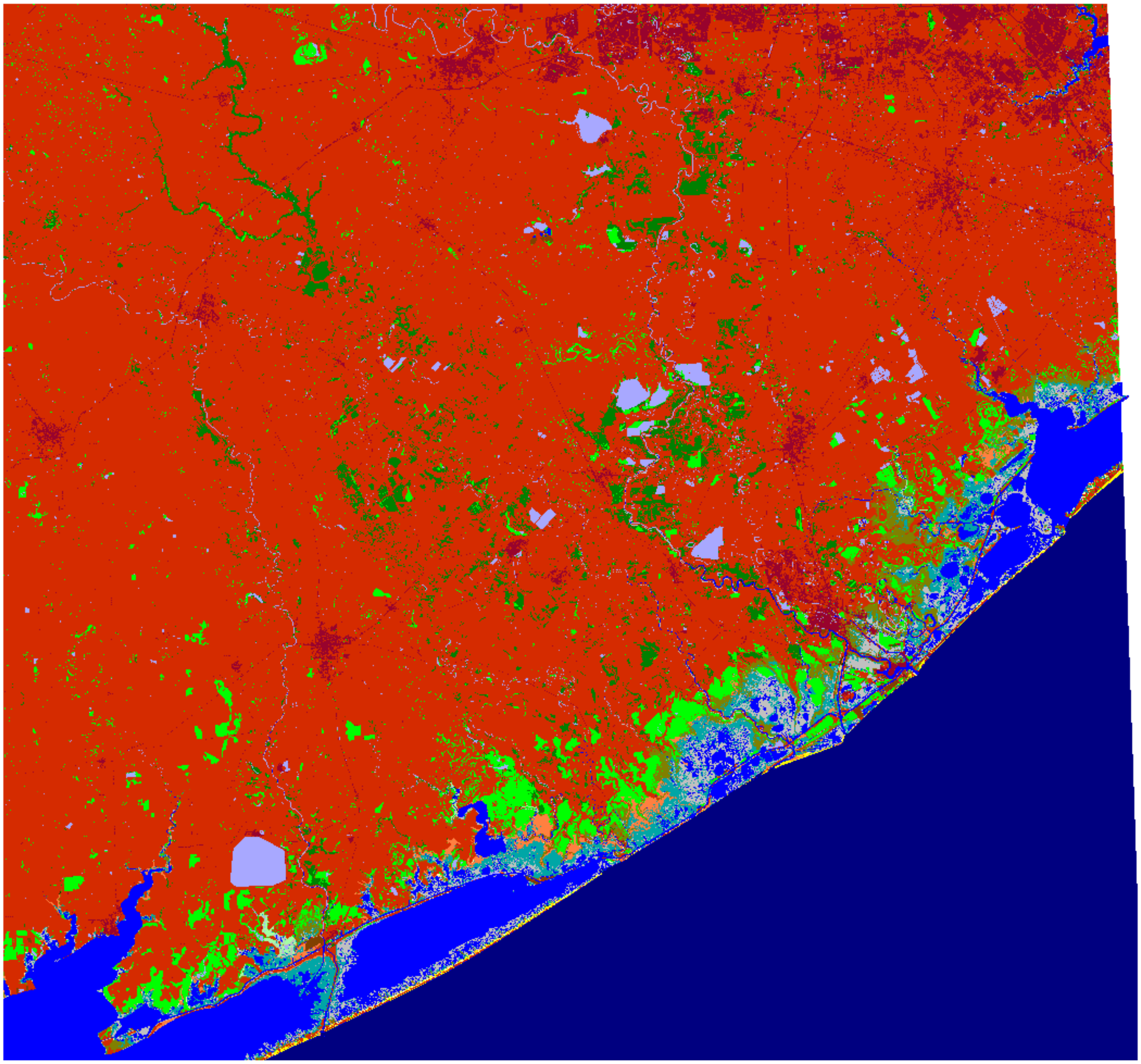
San Bernard and Big Boggy NWR, 2100, 1.5 m SLR



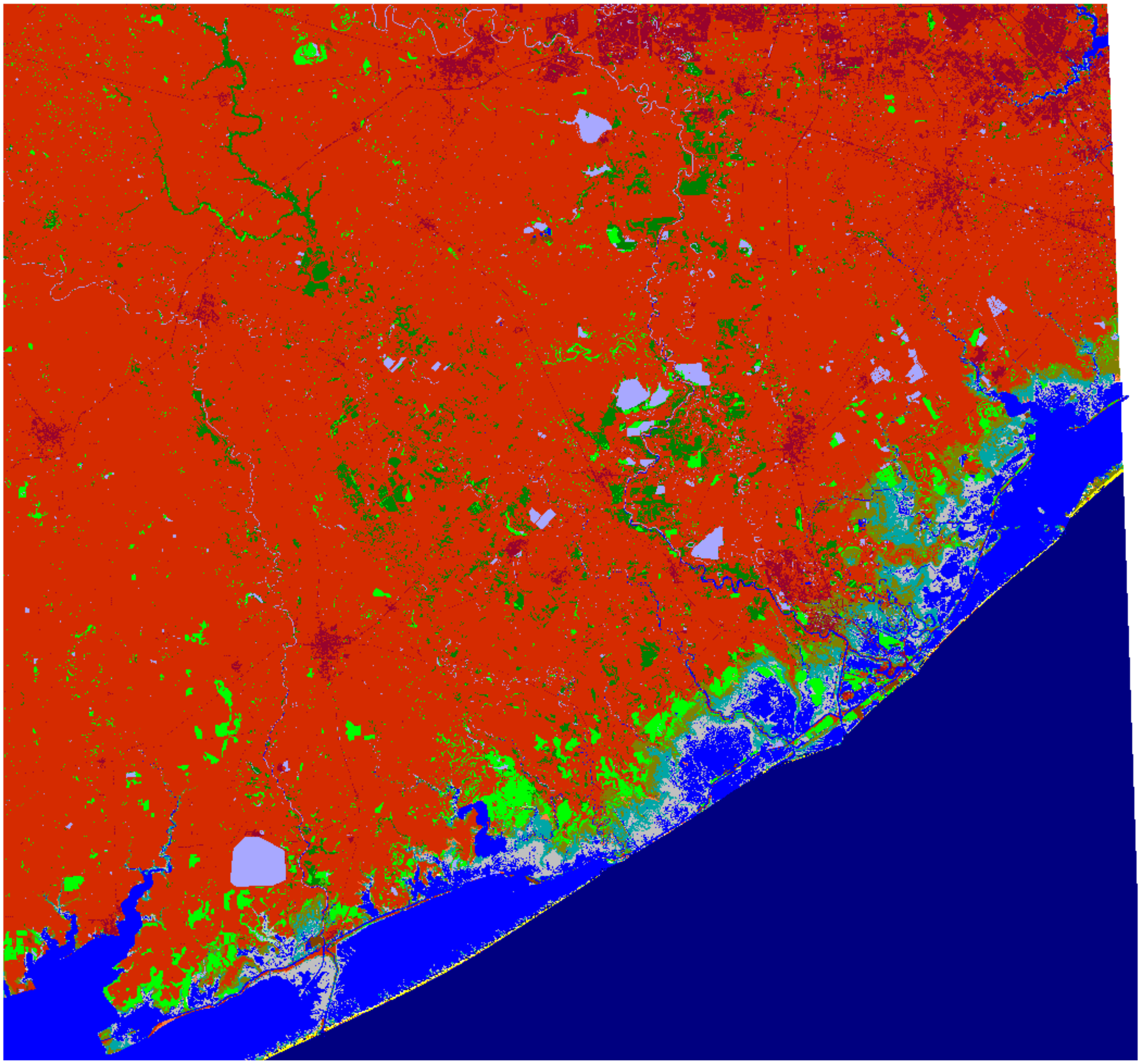
San Bernard and Big Boggy NWR, Initial Condition



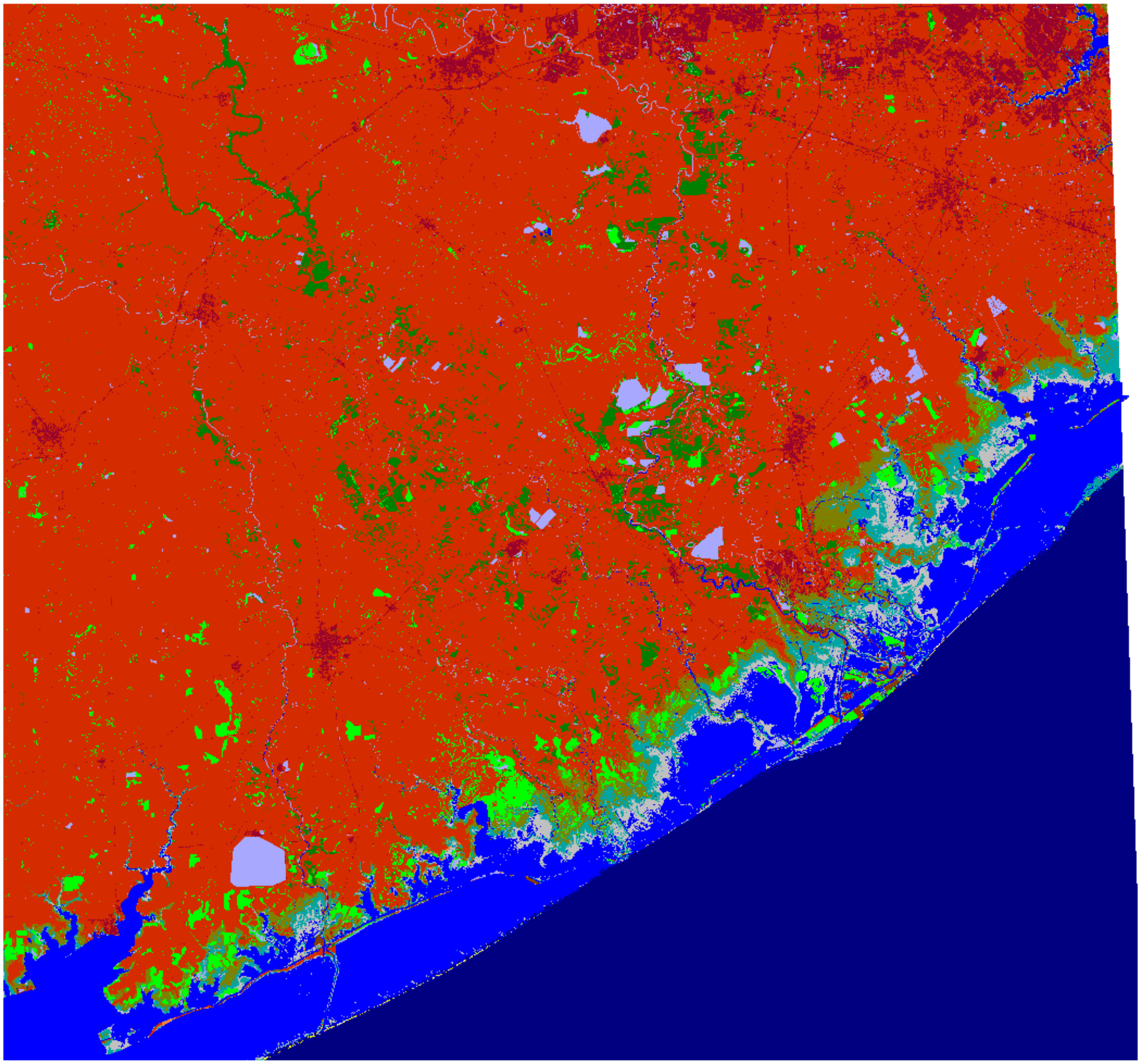
San Bernard and Big Boggy NWR, 2025, 2 m SLR



San Bernard and Big Boggy NWR, 2050, 2 m SLR



San Bernard and Big Boggy NWR, 2075, 2 m SLR



San Bernard and Big Boggy NWR, 2100, 2 m SLR