Application of the Sea-Level Affecting Marshes Model (SLAMM 6) to Ten Thousand Islands 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 (R. A. 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 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 Ten Thousand Islands NWR (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 a final report (second draft) for Ten Thousand Islands as produced under this contract.

Figure 1. Ten thousand islands within context of the Gulf of Mexico

Model Summary

Changes in tidal marsh area and habitat type in response to SLR 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 SLR (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 -- the hindcast step; (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 SLR 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 SLR:

- **Inundation:** The rise of water levels and the salt boundary are tracked by reducing elevations of each cell as SLR, 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:** SLR 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 was not incorporated into the analysis of Ten Thousand Islands.
- 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 was not utilized in simulations reported herein.

- 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 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.
- 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 (J. L. 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 sea-level rise by the year 2100. The A1B- maximum scenario was scaled up to produce these bounding scenarios (Figure 2).

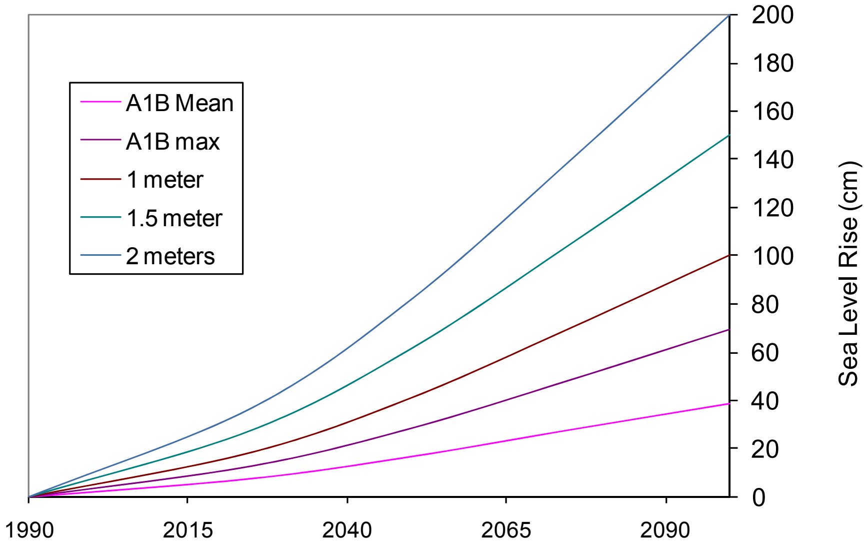


Figure 2. Summary of SLR scenarios utilized

When the model was run to estimate wetland changes in the past ("hindcasting"), the global rate of SLR from 1990 to the present was estimated to be 3 mm/year (Grinsted et al. 2009)[1]. Prior to 1990, the local measured historic trend of 2.02 mm/year was used at this site.

Data Sources and Methods

Historic Wetland Data. The wetland layer used as initial conditions for hindcasting was derived from 1940s aerial imagery developed by the Institute for Regional Conservation (Barry 2009, Figure 3). Michael Barry of IRC, who constructed the historic wetlands layer from photos, notes that there is considerable uncertainty since the photos were not georeferenced and the data can only be compared to modern ground truthing.

[1] Due to the predicted increase in the rate of SLR over the next 90 years, to get SLAMM to predict 3 mm/year of SLR from 1990 to 2025, one enters a "custom" eustatic SLR of 0.54 by 2100 within the SLAMM interface.

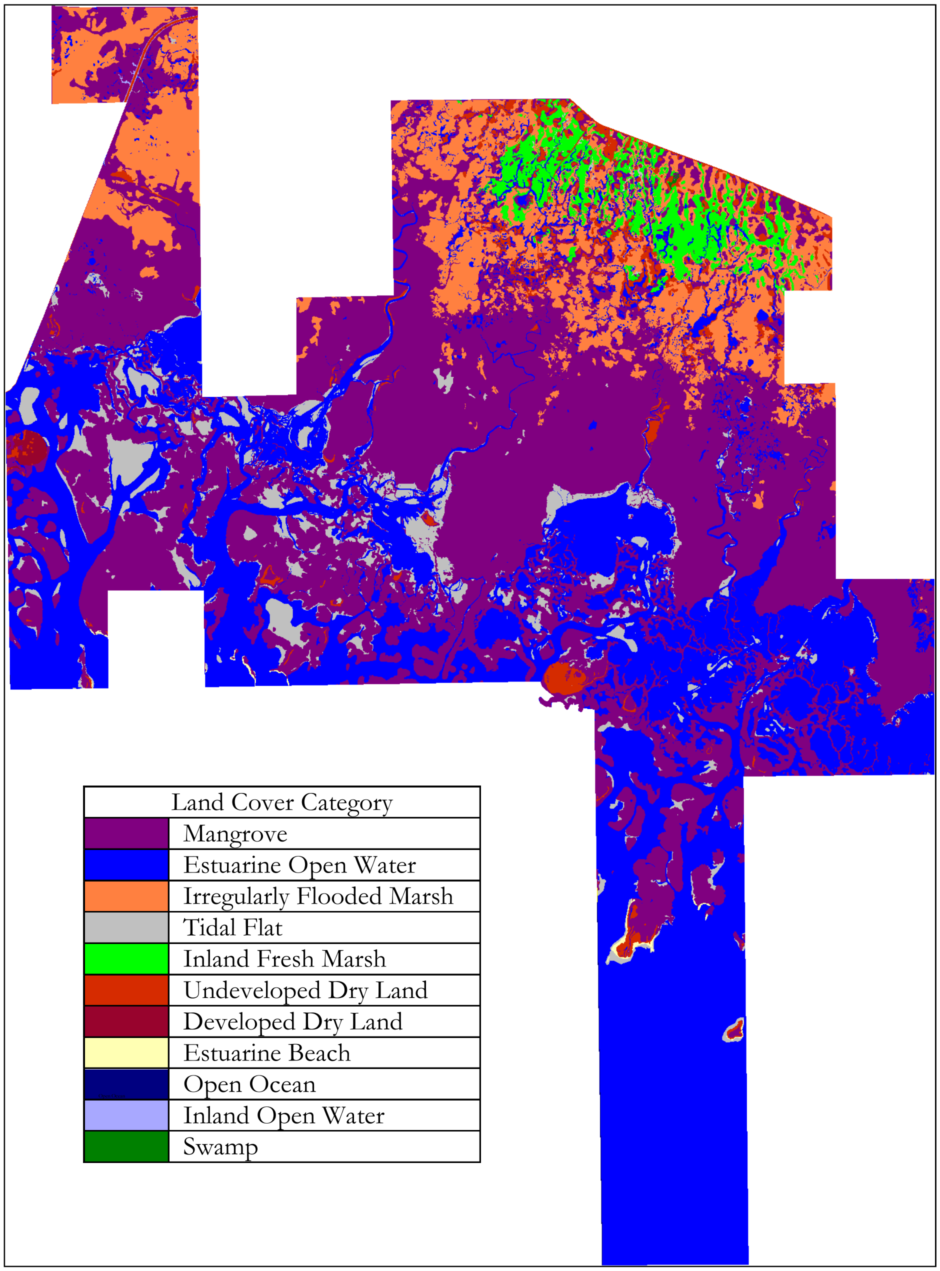


Figure 3. Historic wetland data from 1940

Most Recent Wetland Data. The Institute for Regional Conservation (IRC) report also includes land-cover data for 2007 which were used to calibrate the model in the hindcasting step and as the initial condition for model forecasts. This map was overlaid on the latest NWI data (2009) as shown in Figure 4. Converting the IRC survey into 10 meter cells indicated that the approximately 34,800 acres refuge (approved acquisition boundary including water) is composed of the following categories (excluding categories below 1%):

	Mangrove	53.02%
	Estuarine Open Water	34.54%
	Tidal Flat	4.56%
	Regularly Flooded Marsh	2.60%
	Undeveloped Dry Land	2.35%
	Inland Fresh Marsh	1.40%

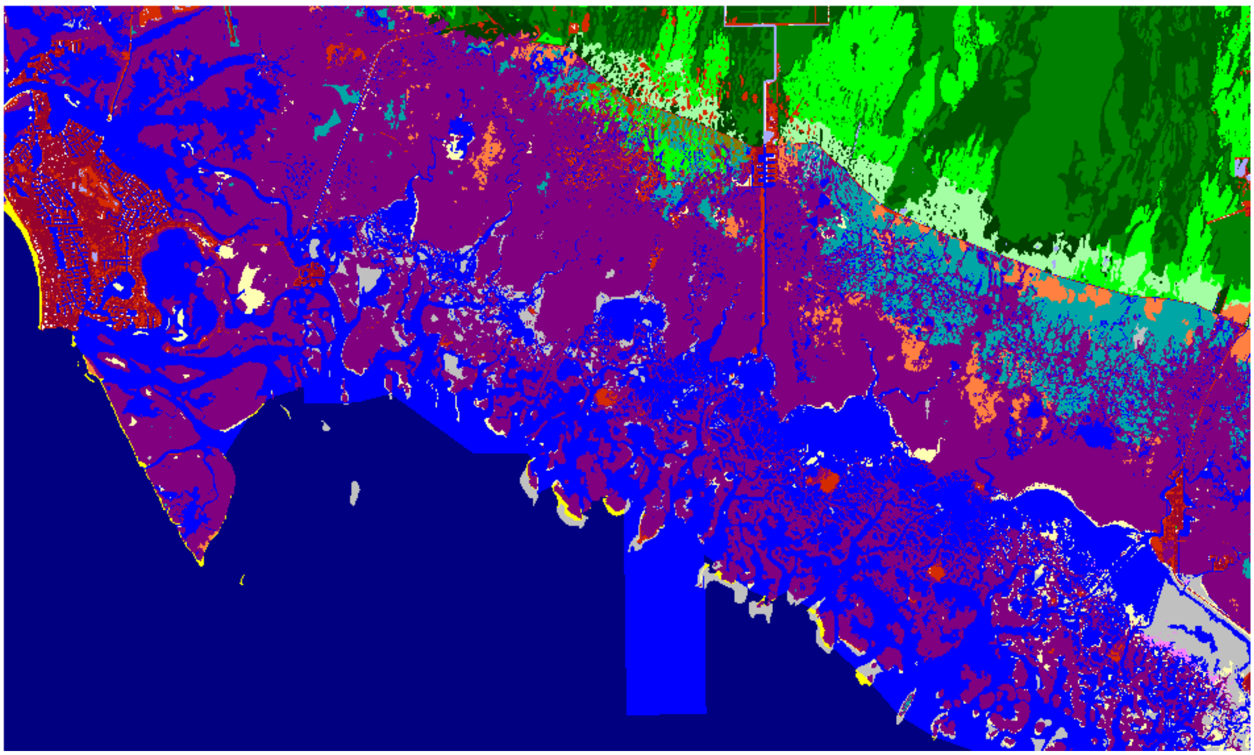


Figure 4. SLAMM wetland classes from latest land cover datasets (2007, 2009)

Model Timesteps. Model timesteps and output were produced in five-year intervals for the hindcast with the last timestep of 6 years in order to match the latest data used in the projection. Forecasting outputs were chosen at years 2025, 2050, 2075, and 2100.

Dikes and Impoundments. According to the latest National Wetlands Inventory coverage, there are no impounded or diked areas within Ten Thousand Islands NWR.

Elevation Estimates. The digital elevation map used in this simulation was derived from Florida Division of Emergency Management (FDEM) LiDAR data with a timestamp of 2006 (Figure 5).

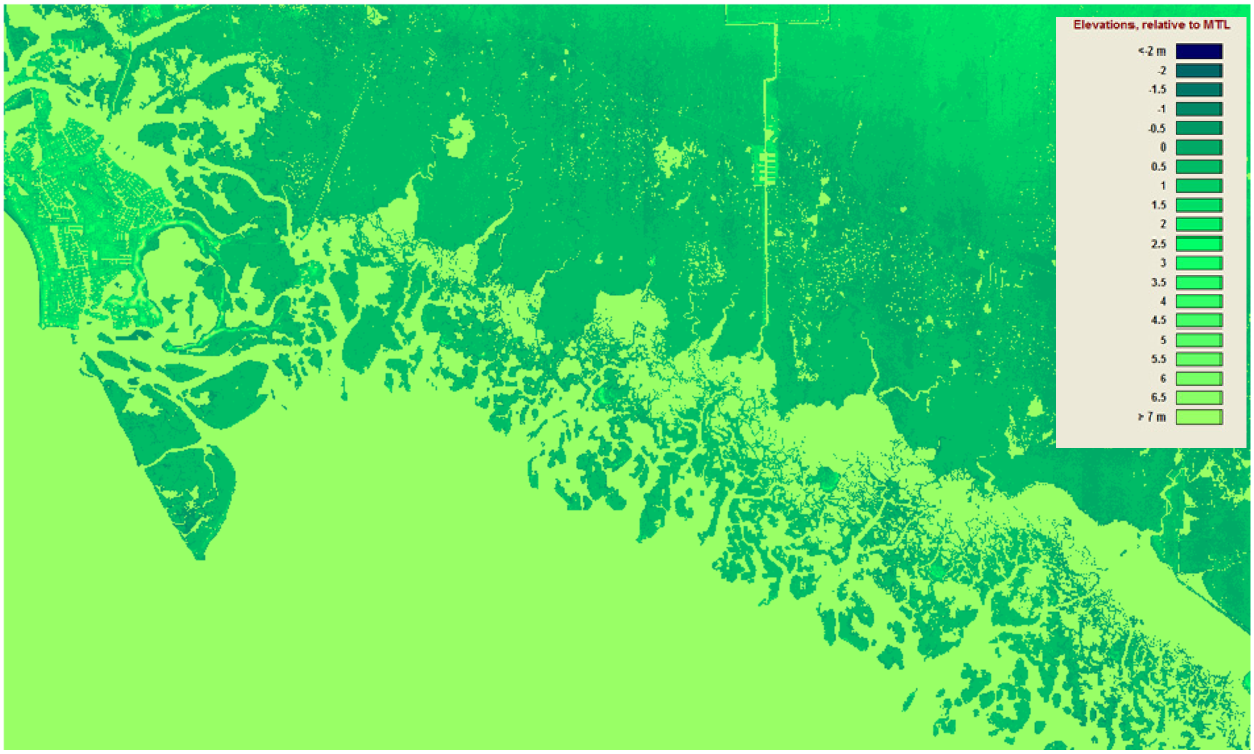


Figure 5. Shade-relief elevation map of refuge and surrounding area

In the digital elevation map used for projection, the majority of beach and tidal flat areas in the refuge lack elevation values. As a result, the SLAMM elevation preprocessor was used to estimate elevations for beach and tidal flat without elevation values, considerably increasing model uncertainty for these categories. In addition, an area of inland-fresh marsh in the northern portion of the study area lacked elevation data,

Historic Sea Level Rise Rates. The historic SLR trend at the NOAA Tide Datum located at Naples, FL (Station #8725110) of 2.02 mm/yr was applied throughout the model extent. This rate of SLR is similar to the global average for the last 100 years (approximately 1.7 mm/year, IPCC 2007a).

Tide Ranges. Several tide gauges were used to define the tide ranges for this site (Table 1 and Figure 6). The majority of the tide ranges are approximately 1 m. The observed gradient of decreasing tidal range from south to north was applied to this SLAMM simulation.

Table 1. NOAA tide gauges and values.

Station ID	Site Name	Tide Range (m)	Salt Elevation	Subsite
8724964	Coon Key Pass, Gullivan Bay, FL	1.155	0.768	Global
8724963	Dismal Key, Pumpkin Bay, FL	1.137	0.756	Global
8724951	Panther Key, FL	1.286	0.855	1
8724975	Blackwater River Entrance, FL	0.985	0.655	2
8724970	Faka Union Bay, FL	0.853	0.849	3

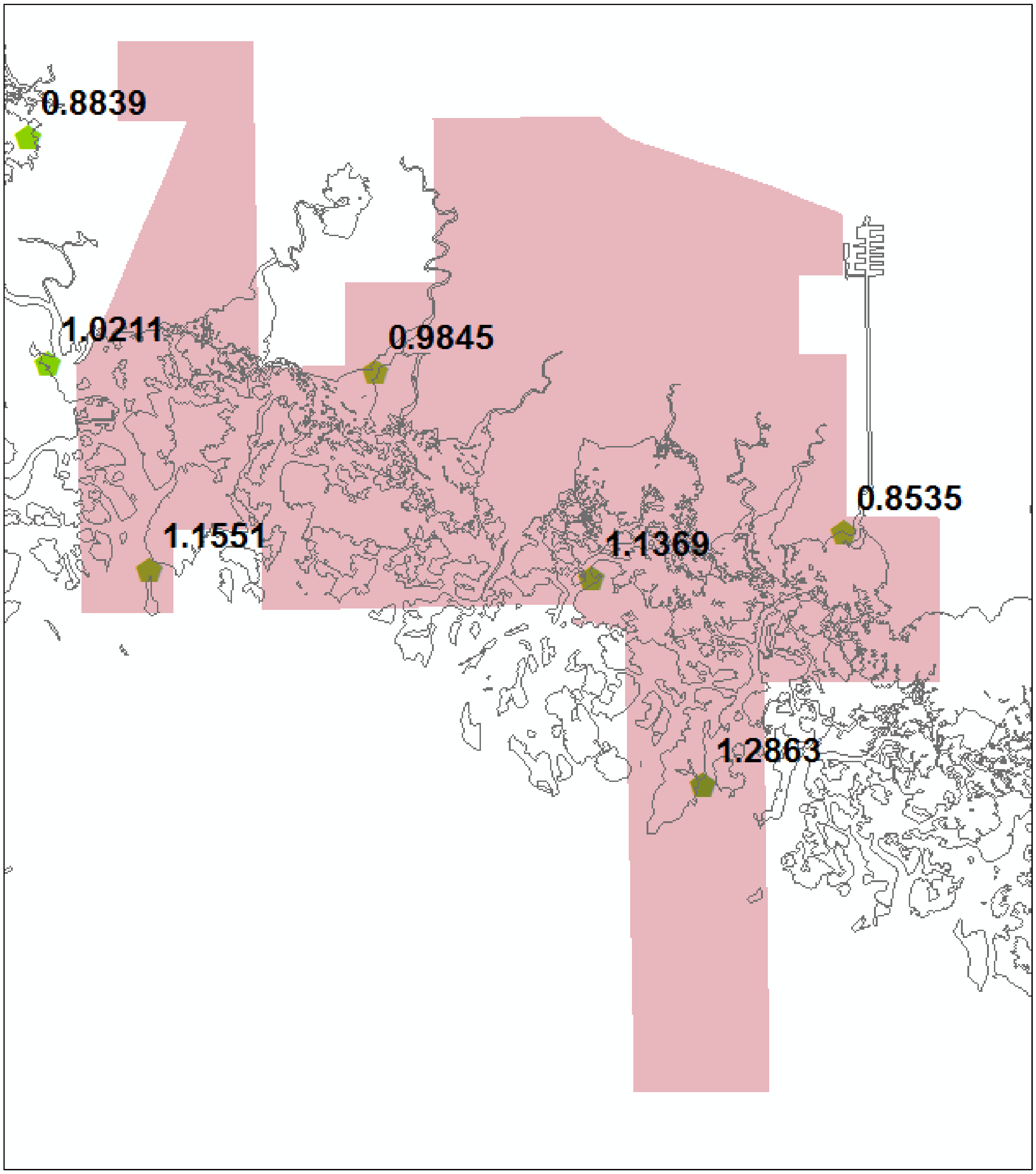


Figure 6. Location of NOAA tides gauges used for Ten Thousand Islands NWR. Approved acquisition boundary is represented in pink

The "Salt Elevation" 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 gauge 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 at Naples, FL (Station #8725110) as shown in Figure 7.

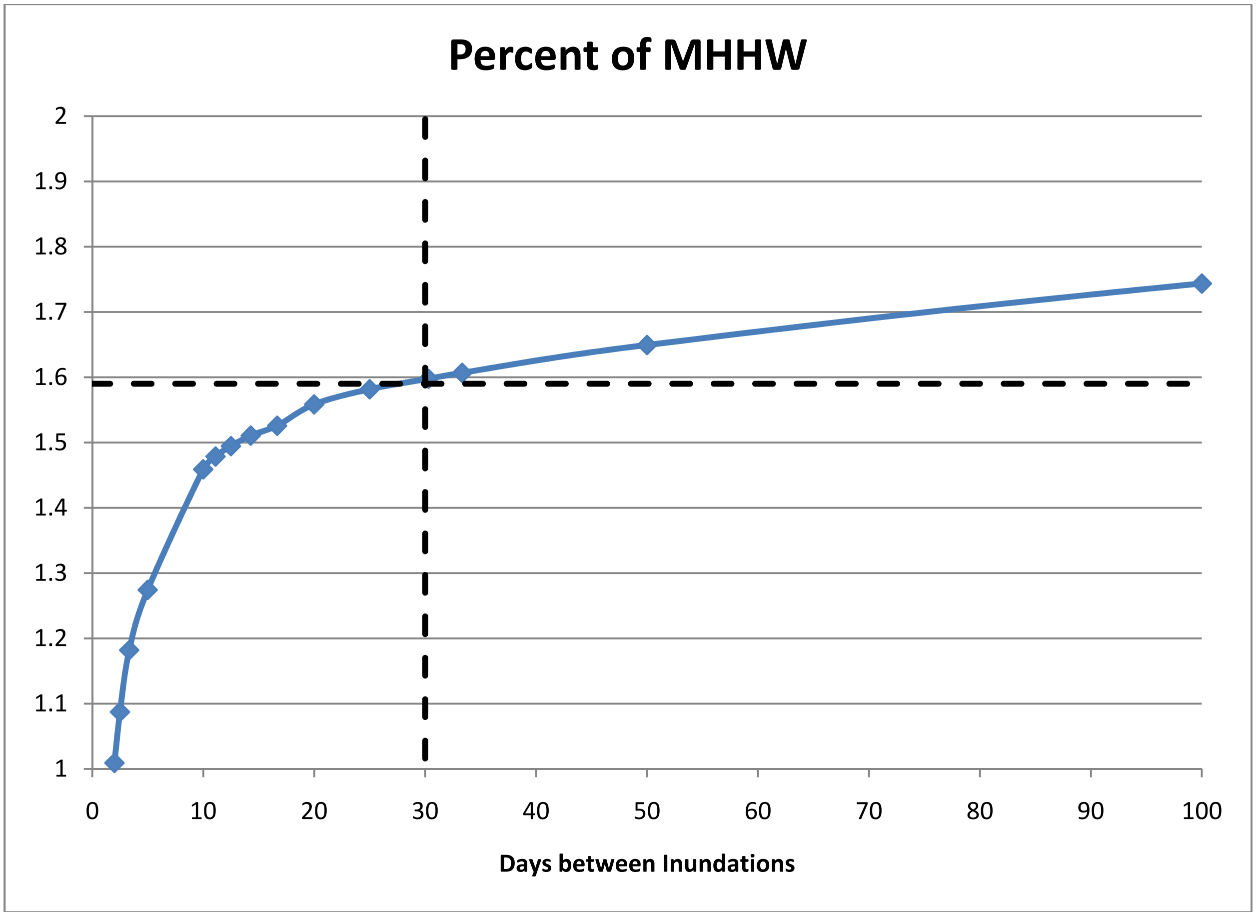


Figure 7. Frequency of inundation based upon 5 years of data.

Accretion Rates. Accretion rates in salt marshes were set to 4.0 mm/year, based on several studies measuring accretion rates on the Gulf Coast of Florida (St. Marks FL, 4.0 mm/year from Cahoon et al. 1995, and Hendrickson 1997; Ochlockonee River FL, 4.05 mm/year from Hendrickson 1997). There are no local accretion data for irregularly flooded or tidal fresh marsh, so model defaults were used based on a previous study in Chesapeake Bay.

Accretion rates for mangrove used the model default of 7.0 mm/yaear measured by Cahoon and Lynch (1997). Although this rate represents the model default, this accretion rate is also the best known site-specific data available for mangrove accretion in Ten Thousand Islands. Cahoon and Lynch measured mangrove accretion via SET tables placed in Rookery Bay National Estuarine Research Reserve (1997), which lies just northwest of the Ten Thousand Islands NWR as shown in Figure 8. Mangrove accretion rates were kept constant throughout the model simulation.

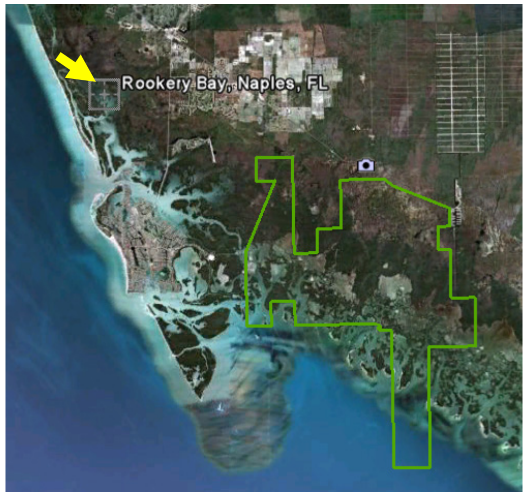


Figure 8. Location of Rookery Bay, FL in relationship to study area (outlined in green)

Elevation Correction. A raster of MTL to NAVD88 correction values was created for the study area using NOAA's VDATUM software and applied to this simulation (Figure 9).

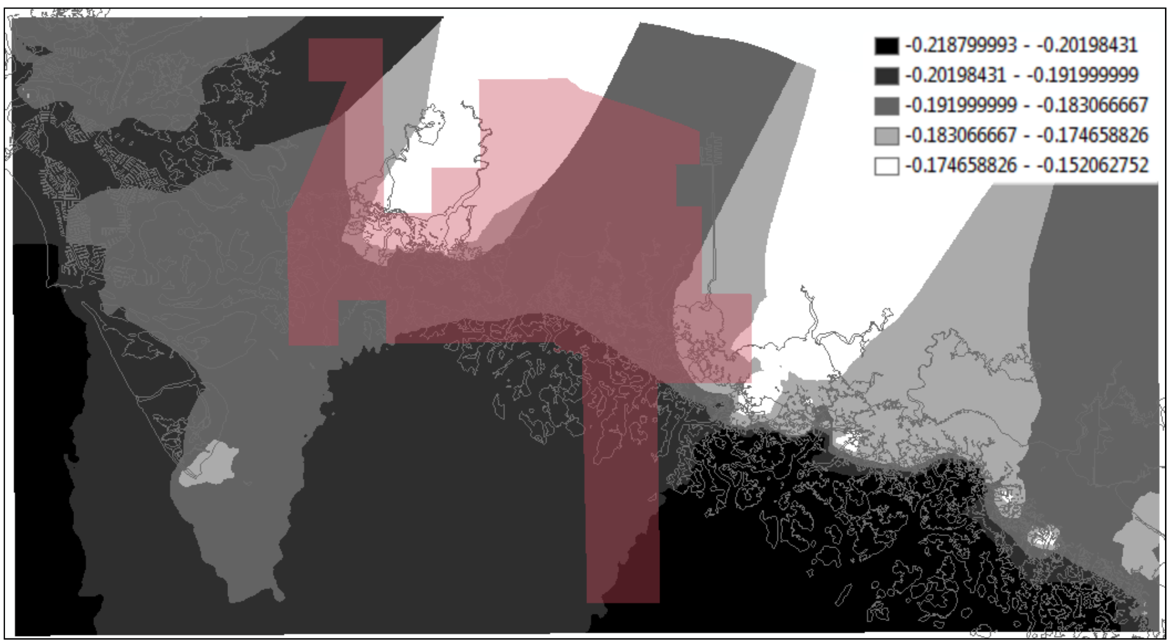


Figure 9: VDATUM correction raster over shoreline with Ten Thousand Islands NWR shown in red (m).

Simulation Boundaries. Modeled U.S. Fish and Wildlife Service refuge boundaries for Florida 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 meter by 10 meter cells.

Simulation Subsites. Based on the different observed tidal ranges (Table 1), four simulation subsites (Figure 10) with different SLAMM input parameters were selected for this refuge. Based on the frequency of inundation analysis (see Figure 7) SLAMM salt elevations were set, on a subsite basis, to between 0.65 m and 0.85 m above MTL, or 159% of the MHHW. Table 2 summarizes SLAMM input parameters for each subsite. The "Global" subsite is all the study area that is not within any other subsites boundaries.

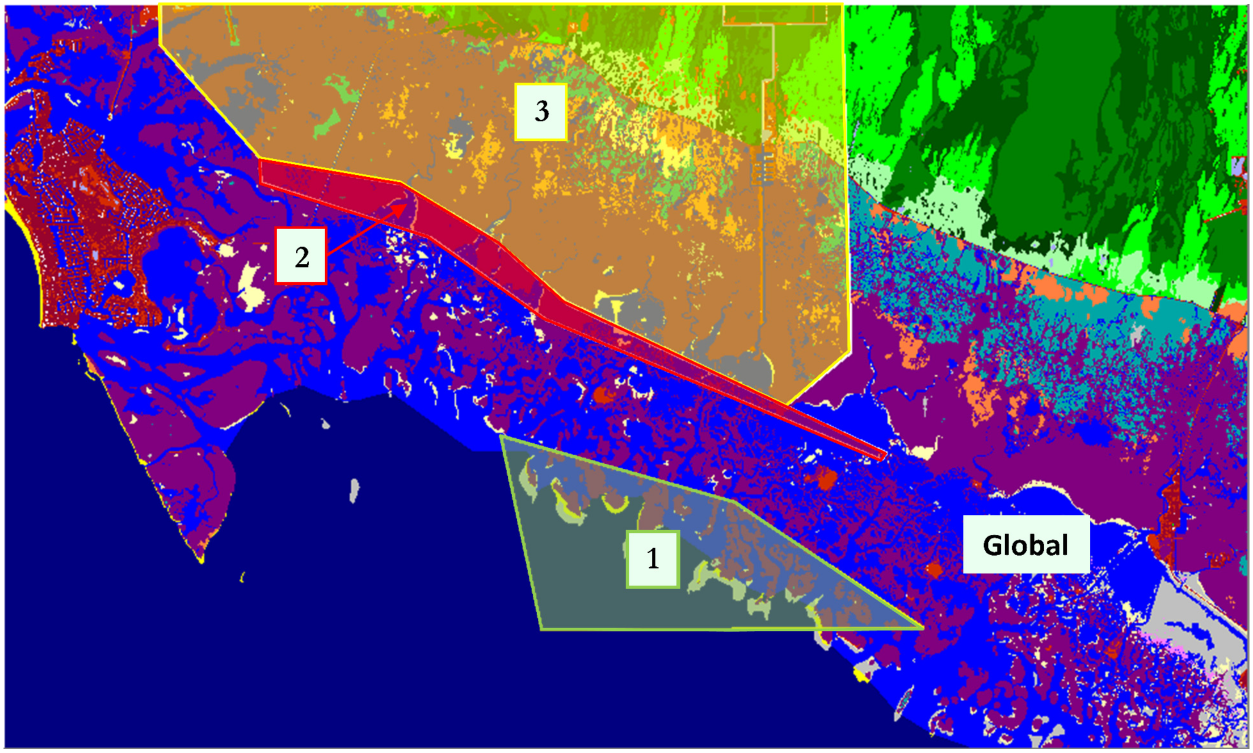


Figure 10: Input subsites for model application.

Table 2. Summary of SLAMM input parameters for Ten Thousand Islands NWR

Parameter	Global	Subsite 1	Subsite 2	Subsite 3
NWI Photo Date (YYYY)	2009	2009	2009	2009
DEM Date (YYYY)	2006	2006	2006	2006
Direction Offshore [n,s,e,w]	South	South	South	South
Historic Trend (mm/yr)	2.02	2.02	2.02	2.02
MTL-NAVD88 (m)	†	†	†	†
GT Great Diurnal Tide Range (m)	1.146	1.2863	0.9845	0.8535
Salt Elev. (m above MTL)	0.76209	0.85538	0.65469	0.84887
Marsh Erosion (horz. m /yr)	1.8	1.8	1.8	1.8
Swamp Erosion (horz. m /yr)	1	1	1	1
T.Flat Erosion (horz. m /yr)	0.5	0.5	0.5	0.5
Reg. Flood Marsh Accr (mm/yr)	4	4	4	4
Irreg. Flood Marsh Accr (mm/yr)	4.7	4.7	4.7	4.7
Tidal Fresh Marsh Accr (mm/yr)	5.9	5.9	5.9	5.9
Beach Sed. Rate (mm/yr)	0.5	0.5	0.5	0.5
Freq. Overwash (years)	50	50	50	50
Use Elev Pre-processor [True,False]	Hindcast Beaches/ Tidal Flats only	Hindcast Beaches/ Tidal Flats only	Hindcast Beaches/ Tidal Flats only	Hindcast Beaches/ Tidal Flats only

† Spatially variable raster map used in place of fixed values.

Results and Discussion

The current modeling study included a "hindcasting" analysis. 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 model output to present day observed land cover data. The primary goals of hindcasting are to assess the predictive capacity of a model and potentially to improve model predictions through calibration. In the case of SLAMM, hindcasting is used to determine whether or not the model is correctly predicting the effect of the observed sea level signal on the wetland types in a given study area.

As with all environmental models, uncertainty within input data and model processes limit model precision. Some error within hindcast results are likely caused by the relative simplicity of the SLAMM model. Inclusion of wetland data may introduce error due to lack of horizontal precision or misclassified land coverage, while the DEM may introduce error due to limitations in LiDAR accuracy. Additional error is encountered when the DEM data and wetland data were collected during different time-periods (not temporally synoptic). Lack of precise tidal data or other spatial coverages may further reduce model accuracy.

Although historical DEM data is usually not used (since older technology generally produced low-vertical-resolution data) SLAMM has two methods to compensate for a lack of historical DEM data. The first method is by implementing 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 and DEM dates. This process ignores changes due to erosion, accretion, or sedimentation, however. Because the historical data is relatively recent, the second approach was used in analysis of Ten Thousand Islands NWR.

There are two categories of error in these hindcasting analyses, the first being the minor differences predicted by SLAMM even without a SLR signal. A simulation with no SLR signal is referred to as a "time-zero" simulation in which SLAMM tries to predict the initial condition. Due to local factors, DEM and wetland uncertainty, and simplifications within the SLAMM conceptual model, some cells inevitably fall below their lowest allowable elevation category and are immediately converted. These cells represent outliers on the distribution of elevations for a given land-cover type. Generally, a threshold tolerance of up to 5% change is allowed for in major land cover categories in our analyses.

The second source of error would be errors in SLAMM predictions given a SLR signal. This source of error is generally more interesting and important. It is necessary to determine if SLAMM can accurately predict growth or loss trends for major land-cover categories. For this reason, SLAMM hindcast accuracy is assessed on results after the "time-zero" model adjustment has taken place.

There are several metrics that may be employed to judge the accuracy of the model based on the hindcast results. One possibility would be to see whether SLAMM can predict a given cell's wetland type correctly. Because of the high potential for local uncertainty the method used for evaluation focuses on assessing the capability of the model to predict overall trends in land-cover over time. Additionally, assessing model accuracy on a cell-by-cell basis is a metric that has been shown to be sensitive to the cell size utilized (Chen & Pontius 2010).

The primary metric used to evaluate SLAMM hindcast results in this study is the percent of the land cover lost during the model simulation for the primary wetland/vegetation types. The percentage loss predicted by the model is compared to the percentage of the actual land cover lost determined by comparing the historical and contemporary wetland datasets. In addition, if there are significant spatial trends visible when comparing historical data to present day data (e.g. the majority of marsh lost occurs in the upper-right quadrant) maps of hindcasting predictions are qualitatively assessed to ensure that these trends are also captured within the model results itself.

Hindcast Results

Based on historical records, during the period between 1940 and 2007, approximately 14.2 cm of eustatic SLR occurred (see *Sea Level Rise Scenarios* section above). The initial wetland land cover is shown in Figure 11, while predicted and observed wetland land cover changes are shown in Figure 12 and Figure 13 respectively. A quantitative comparison of the overall results with respect to the observed land cover losses is summarized in Table 3.

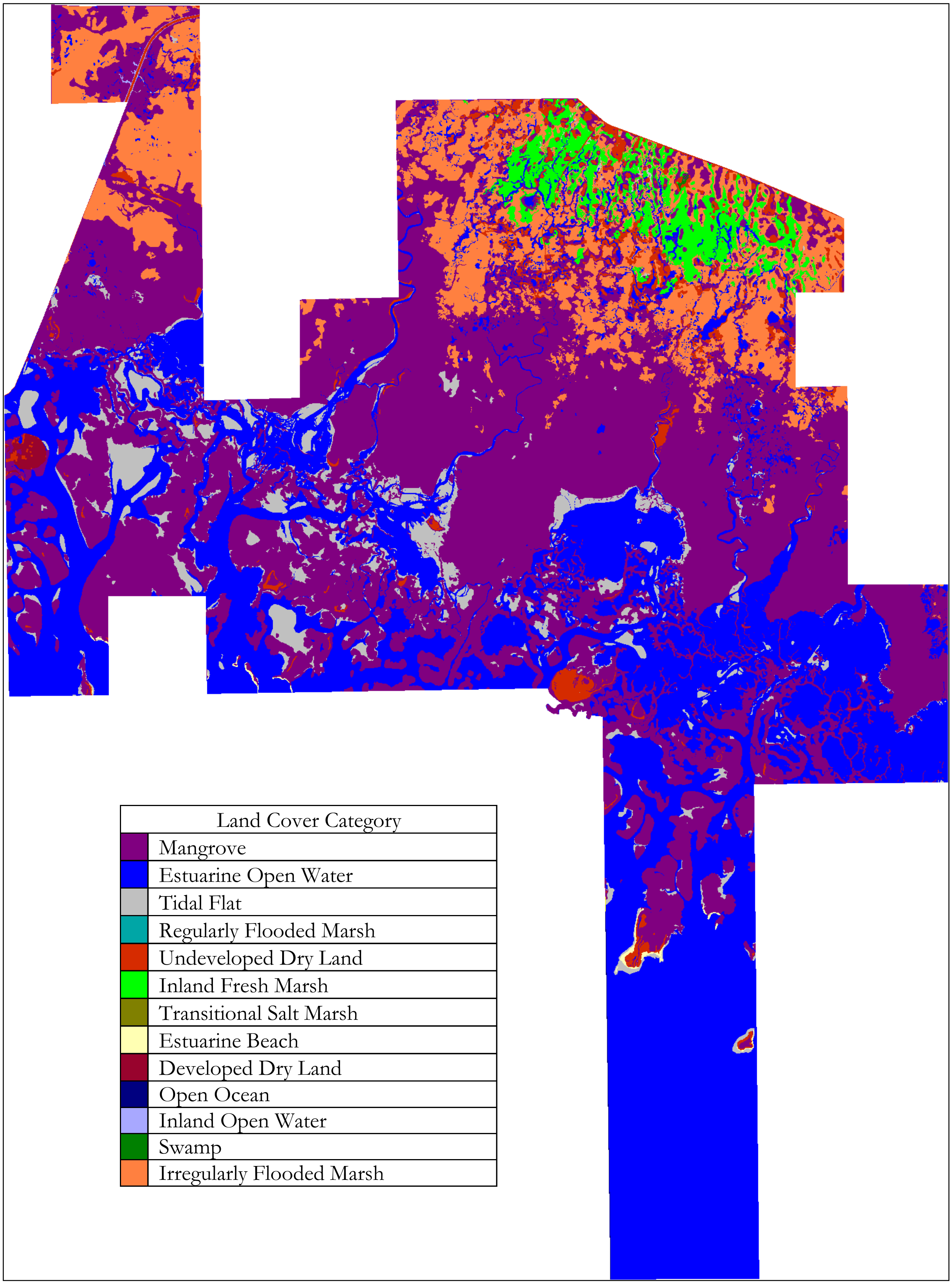


Figure 11. Ten Thousand Islands NWR, Hindcast Initial Condition (1940)

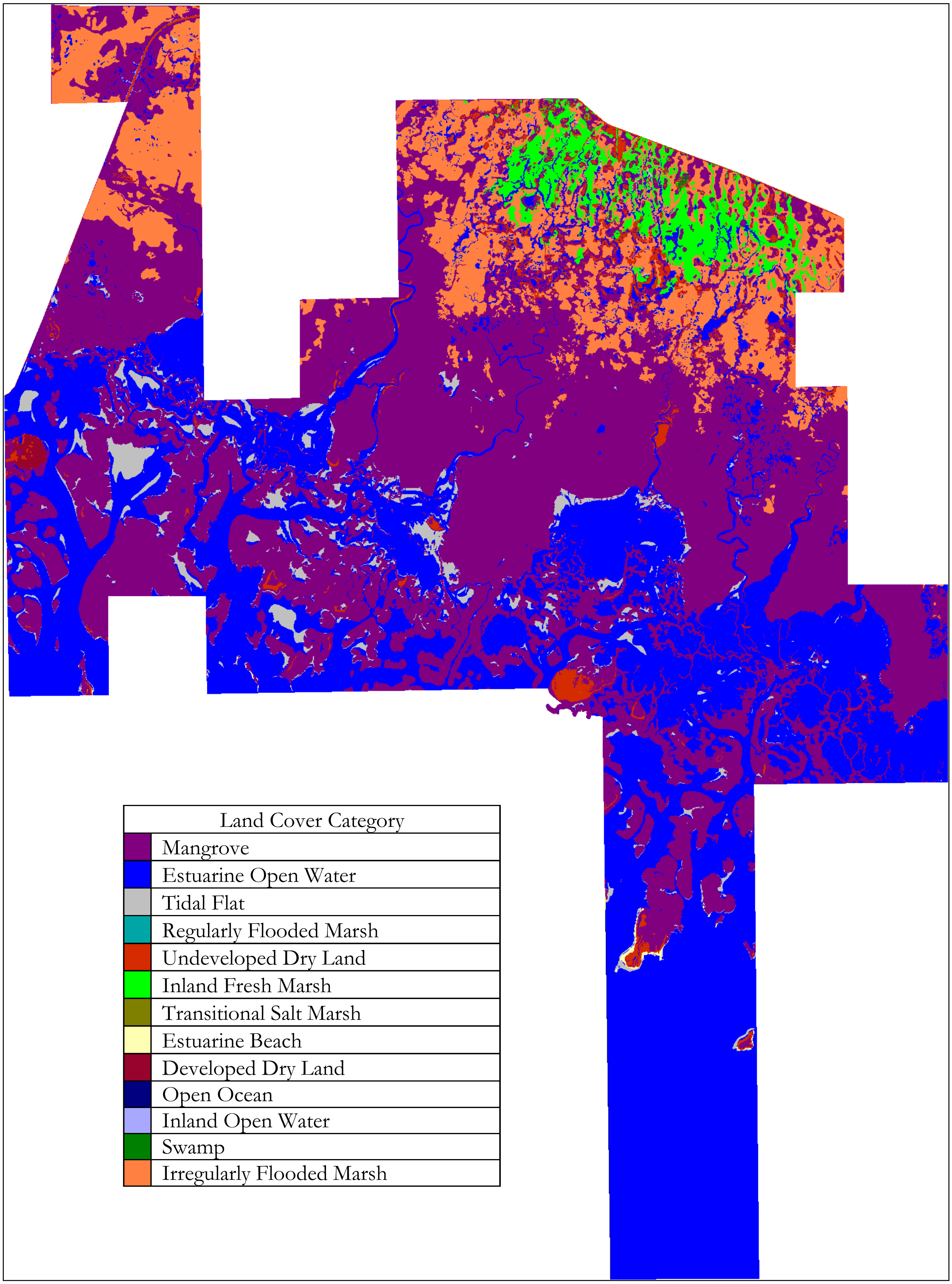


Figure 12. Ten Thousand Islands NWR, hindcast result (2007)

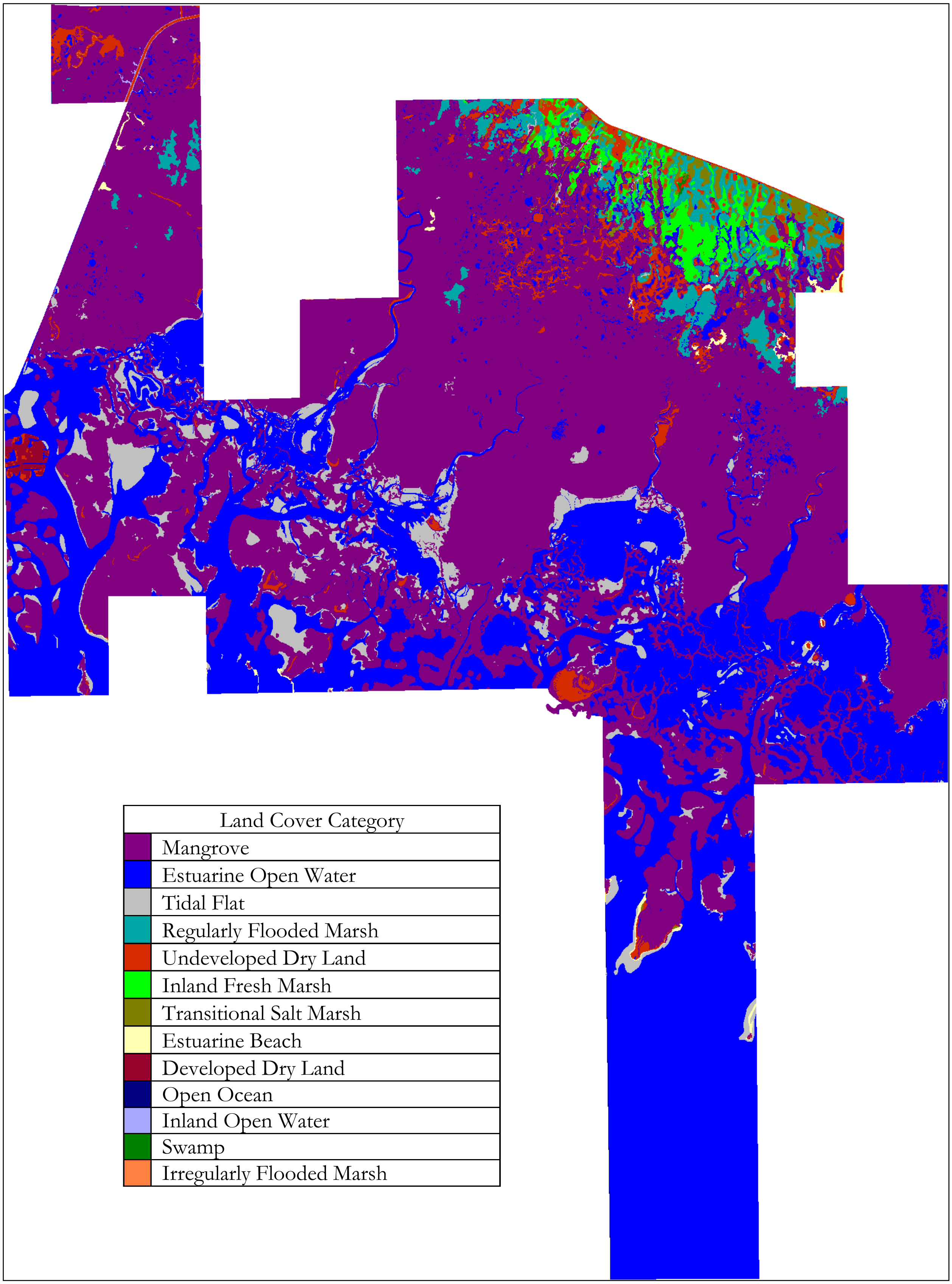


Figure 13. Ten Thousand Islands NWR, observed (2007)

Table 3: Land cover changes comparison between observed and hindcast simulations.

Land cover	Time-zero land cover in 1940 (acres)	Observed land cover in 2007 (acres)	Land cover predicted by hindcast (acres)	Observed loss 1940-2007 ([1])		Predicted loss 1940-2007 ([1])	
				(acres)	(%)([2])	(acres)	(%)([2])
Mangrove	15482	18455	15596	-2974	*-19*	-114	*-1*
Tidal Flat	1614	1588	883	26	*2*	731	*45*
Regularly Flooded Marsh	0	905	0	-905	*NA*	0	*0*
Undeveloped Dry Land	765	817	591	-51	*-7*	175	*23*
Inland Fresh Marsh	886	487	911	398	*45*	-25	*-3*
Transitional Salt Marsh	0	341	0	-341	*NA*	0	*0*
Estuarine Beach	32	85	21	-53	*-165*	11	*33*
Developed Dry Land	58	74	56	-16	*-27*	2	*3*
Swamp	4	5	4	-1	*-38*	0	*1*
Irregularly Flooded Marsh	3806	2	3806	3804	*100*	0	*0*

([1]) A negative sign indicates a land cover gain.
([2]) Percentage loss with respect of the initial area of the land cover category considered.

Based on the numbers in this table, one may conclude that the SLAMM hindcast did not work well for this refuge. However, by visual comparison of the maps above, one can verify that overall the predicted and observed land covers in 2007 do not greatly differ with the exclusion of the northern portion of the refuge where mangrove expansion could not be correctly predicted by the SLAMM model. In particular, Figure 14 shows that the entire distribution of irregularly flooded marsh and part of the inland fresh marsh present in 1940 converted to mangrove, regularly flooded marsh and transitional salt marsh by 2007.

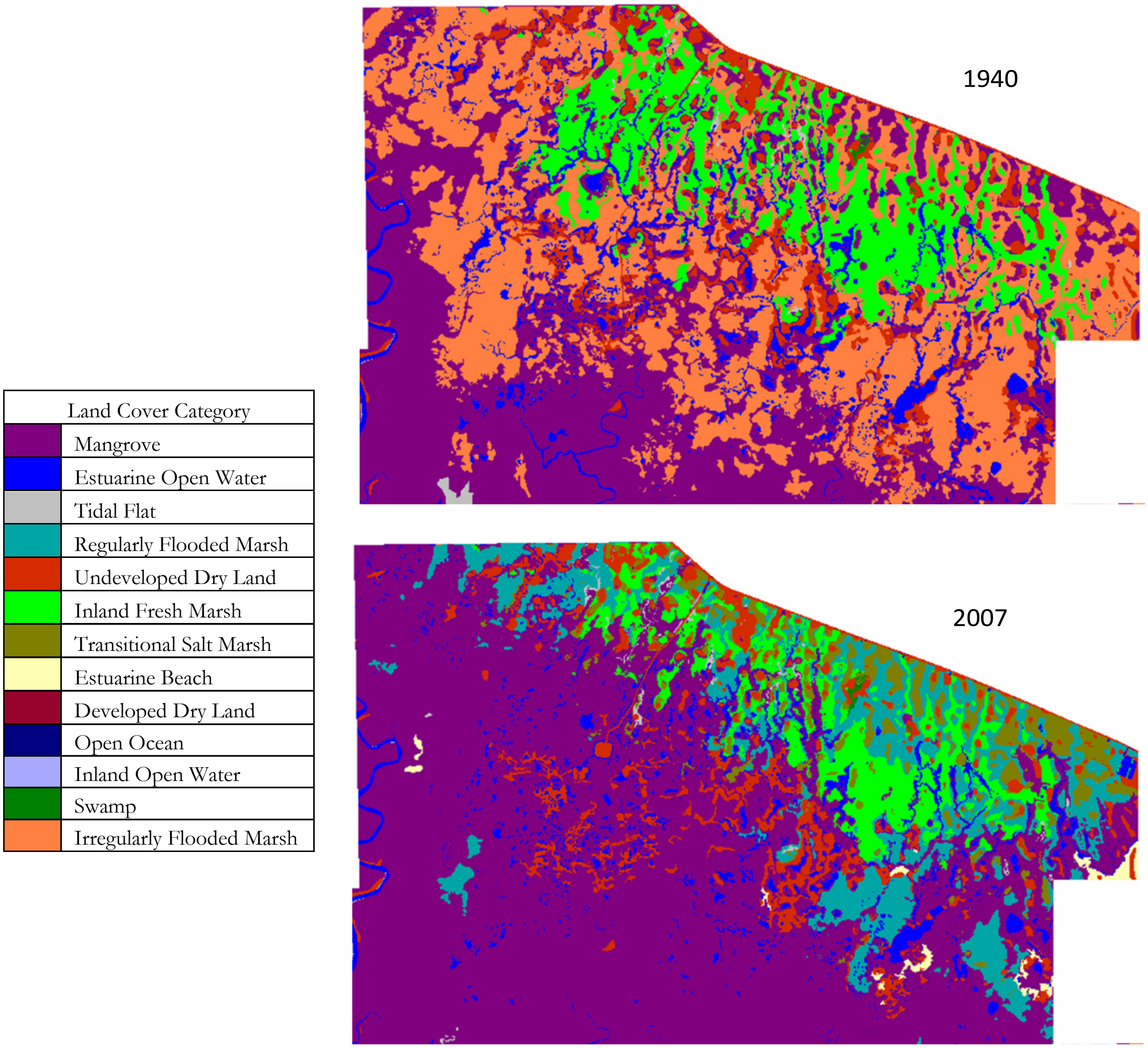


Figure 14. Observed northern portion of refuge in 1940 vs. 2007

The SLAMM hindcast does not predict this conversion. This is because the distribution of mangroves in the northern Gulf of Mexico is controlled primarily by freezing temperatures (Davis, 1940; Lugo and Patterson-Zucca, 1977; Kangas and Lugo 1990) while the SLAMM model predicts the distribution of mangroves as a function of SLR only (assuming that air temperature remains constant over time). Air-temperature and frequency of hard-freezes is not an input into the SLAMM model. Therefore, this type of mangrove expansion into regions previously occupied by marsh lands cannot be captured by SLAMM simulations. An additional change predicted mostly for this portion of the refuge is dry land loss of roughly one quarter of the initial cover while a net gain is actually observed. Again, this result may be related to the fact that in this part of the refuge SLR is not the only environmental (or anthropogenic) parameter affecting wetland dynamics. (SLAMM will never predict a net gain of dry land as a function of sea-level rise.)

Additional source of uncertainty of the results may be due to the lack of elevation data. In fact, for every land-cover cell lacking elevation data, elevation estimates were derived using a relationship between wetland categories and tidal ranges. As a result, the majority of beach, as well as tidal flat and a small amount of mangrove elevations were estimated. This however, introduces significant uncertainty into model results for these categories that, coupled with the small SLR rate during the simulated 69 years, makes very difficult to correctly predict a loss or gain for these land cover categories.

Finally, as often happens in these types of studies, other uncertainties may have been introduced by the differences in data designation procedures during different wetland coverage surveys.

However, given the similarity for most part of the predicted and the observed wetland coverage (excluded the northern portion of the refuge) we did not pursue calibrating the model further. On the other hand, forecast results for the northern portion of the refuge should be interpreted as predictions of wetland land cover in response to SLR only and not to other likely controlling parameters (i.e. air temperature changes).

Forecast

Table 4 presents the land coverage predicted by SLAMM modeling for the primary categories in the Ten Thousand Islands NWR for different SLR scenarios. The percentage loss with respect to the initial coverage is also reported for each SLR scenario.

Table 4. Predicted loss rates of land categories by 2100 given simulates scenarios of eustatic SLR

Land Cover Category	**2007 Coverage (acres)**	**SLR by 2100 (m)**									
		0.39		**0.69**		**1**		**1.5**		**2**	
Mangrove	18455	18986	*-3%([1])*	19275	*-4%*	19301	*-5%*	7396	*60%*	492	*97%*
Tidal Flat	1588	1167	*27%*	1125	*29%*	1436	*10%*	1177	*26%*	840	*47%*
Regularly Flooded Marsh	905	905	*0%*	900	*1%*	516	*43%*	15	*98%*	7	*99%*
Undeveloped Dry Land	817	144	*82%*	91	*89%*	67	*92%*	49	*94%*	40	*95%*
Inland Fresh Marsh	487	487	*0%*	461	*5%*	251	*49%*	154	*68%*	153	*69%*
Estuarine Beach	84.9	78.3	*8%*	77.7	*8%*	73.0	*14%*	18.4	*78%*	11.5	*87%*
Developed Dry Land	73.6	64.0	*13%*	41.8	*43%*	21.7	*70%*	9.6	*87%*	4.6	*94%*

([1])A negative percentage variation indicates a gain

The graph in Figure 15 illustrates the trends of land cover loss as a function of SLR scenarios. These curves suggest that there is a break-point for SLR above which effects become severe. Below 1 m SLR, the majority of the refuge remains resistant to inundation by 2100. On the contrary, at and above 1.5 m SLR losses become important with more than 50% of the land covers predicted to change into open water by 2100.

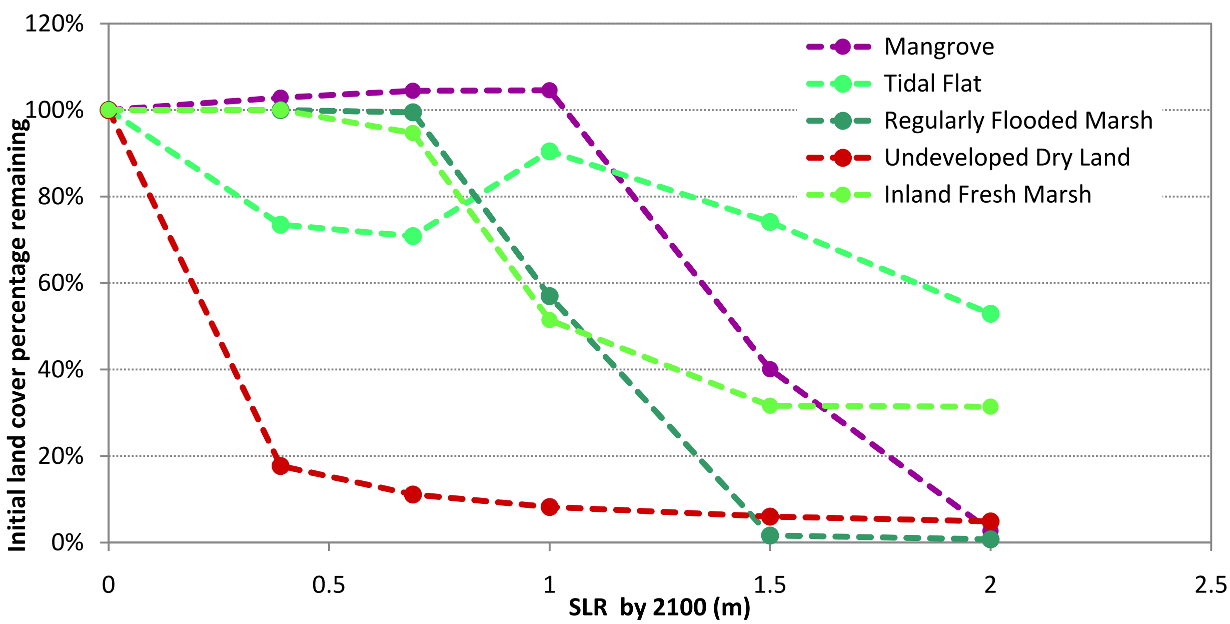


Figure 15. Refuge wetland change per scenario

Only islands with relatively high land elevations such as the dry land hammock at Dismal Key, shown in Figure 16, and a stretch of irregularly flooded marsh along the Pumpkin River are predicted to survive, given 2 m SLR by 2100. A lack of elevation for the area of inland fresh marsh in the north of the study area also leads to its persistence at SLR up to 2 m by 2100 even when surrounded by open water. It is highly unlikely that this inland fresh marsh will persist once the surrounding areas are inundated.

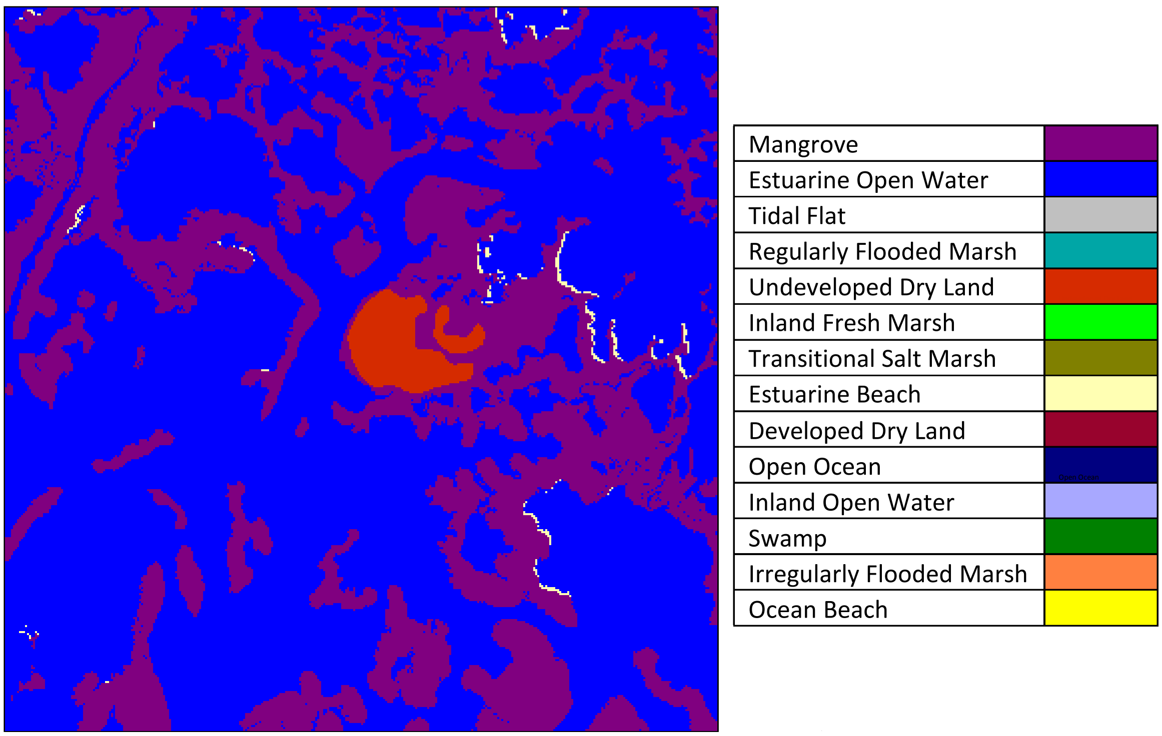


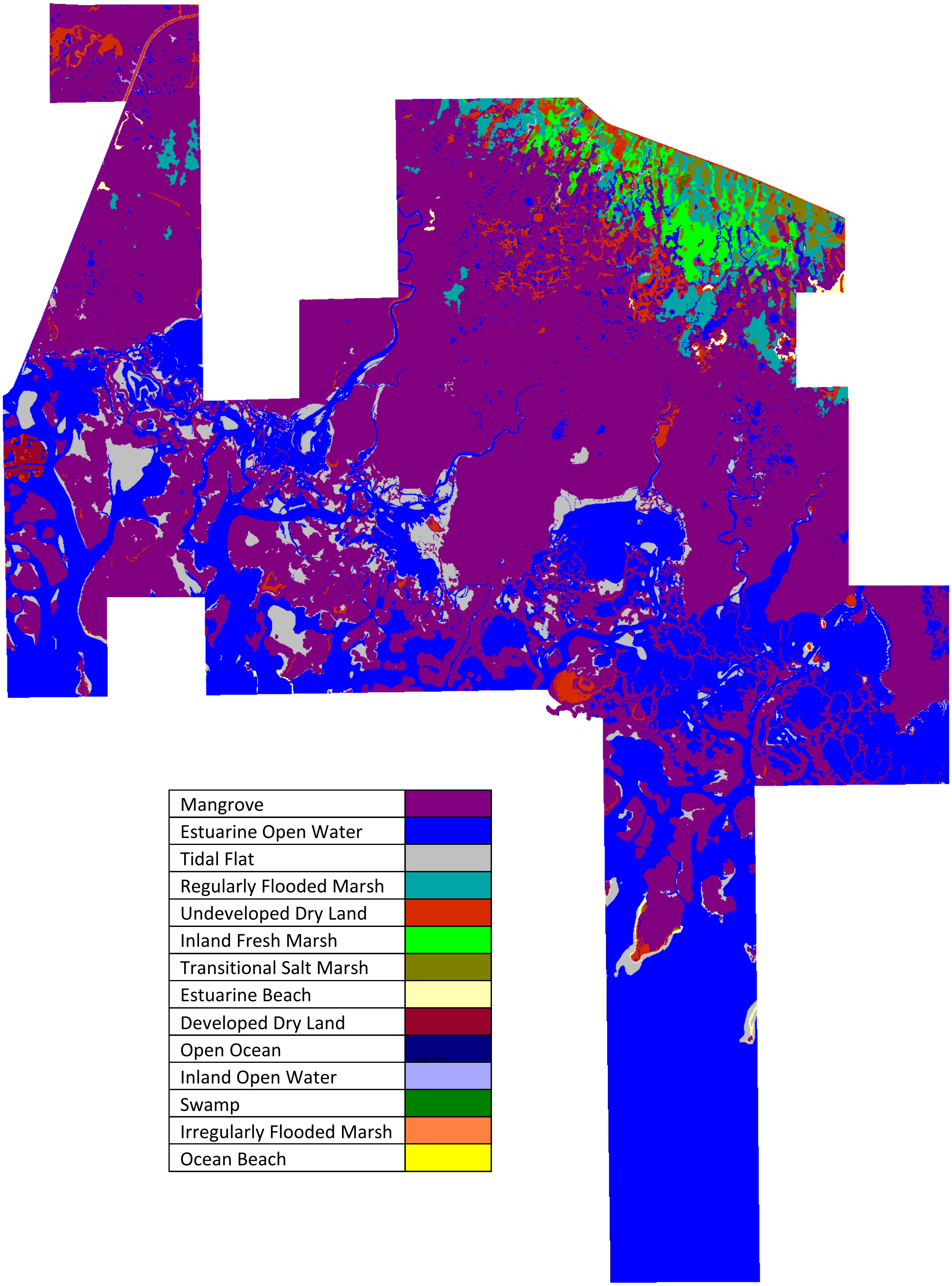
Figure 16. Hammock of dry land on Dismal Key by 2100

The detailed result predictions for the different SLR scenarios results along with the intermediate estimations at 2025, 2050, and 2075 are presented below.

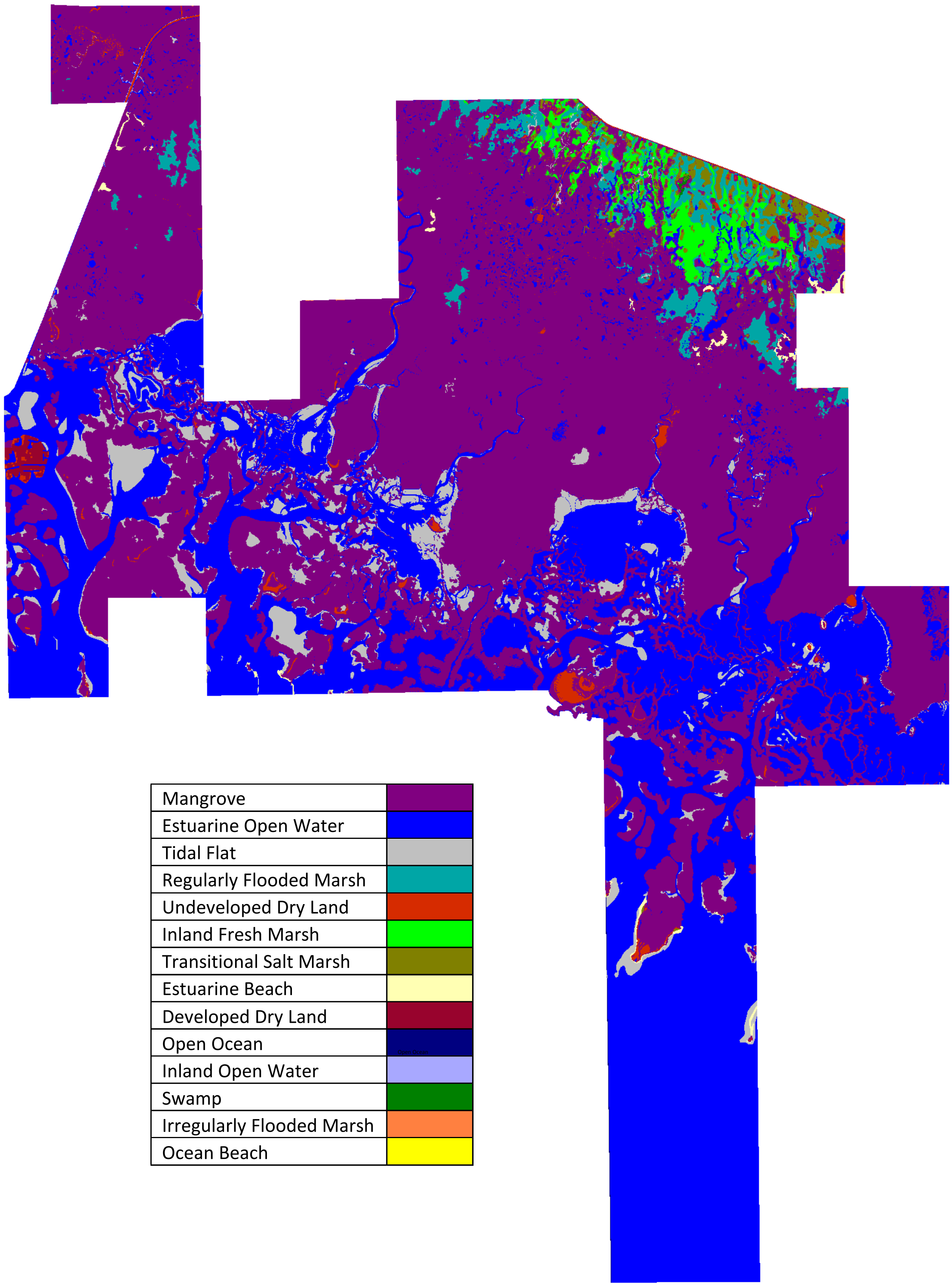
10K Forecast NWR Raster
IPCC Scenario A1B-Mean, 0.39 M SLR Eustatic by 2100

Results in Acres

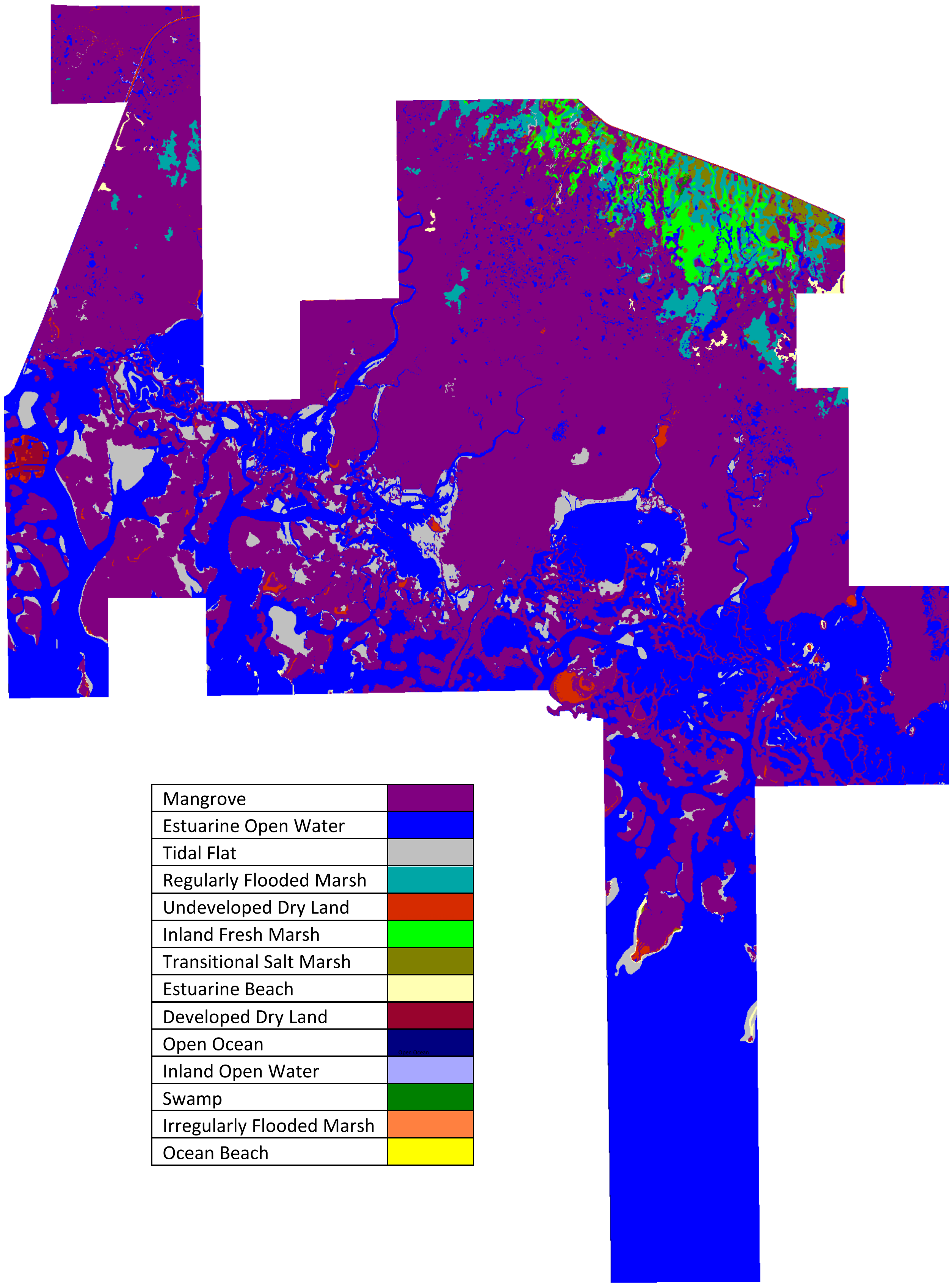
		Initial	2025	2050	2075	2100
	Mangrove	18455.3	18922.9	18961.7	18967.8	18986.1
	Estuarine Open Water	12022.3	12285.5	12435.8	12541.2	12642.8
	Tidal Flat	1587.9	1489.0	1340.8	1263.5	1167.1
	Regularly Flooded Marsh	905.3	905.3	905.3	905.3	905.3
	Undeveloped Dry Land	816.6	227.5	189.6	161.2	144.4
	Inland Fresh Marsh	487.5	487.3	487.4	487.5	487.5
	Transitional Salt Marsh	341.0	309.2	309.2	309.2	309.2
	Estuarine Beach	84.9	83.6	81.8	80.0	78.3
	Developed Dry Land	73.6	72.1	71.1	67.9	64.0
	Open Ocean	15.8	16.1	16.1	16.1	16.1
	Inland Open Water	12.2	3.9	3.7	3.4	3.3
	Swamp	5.2	5.2	5.2	4.7	3.5
	Irregularly Flooded Marsh	1.8	1.8	1.8	1.8	1.8
	Ocean Beach	0.4	0.3	0.3	0.3	0.5
	Total (incl. water)	**34809.8**	**34809.8**	**34809.8**	**34809.8**	**34809.8**



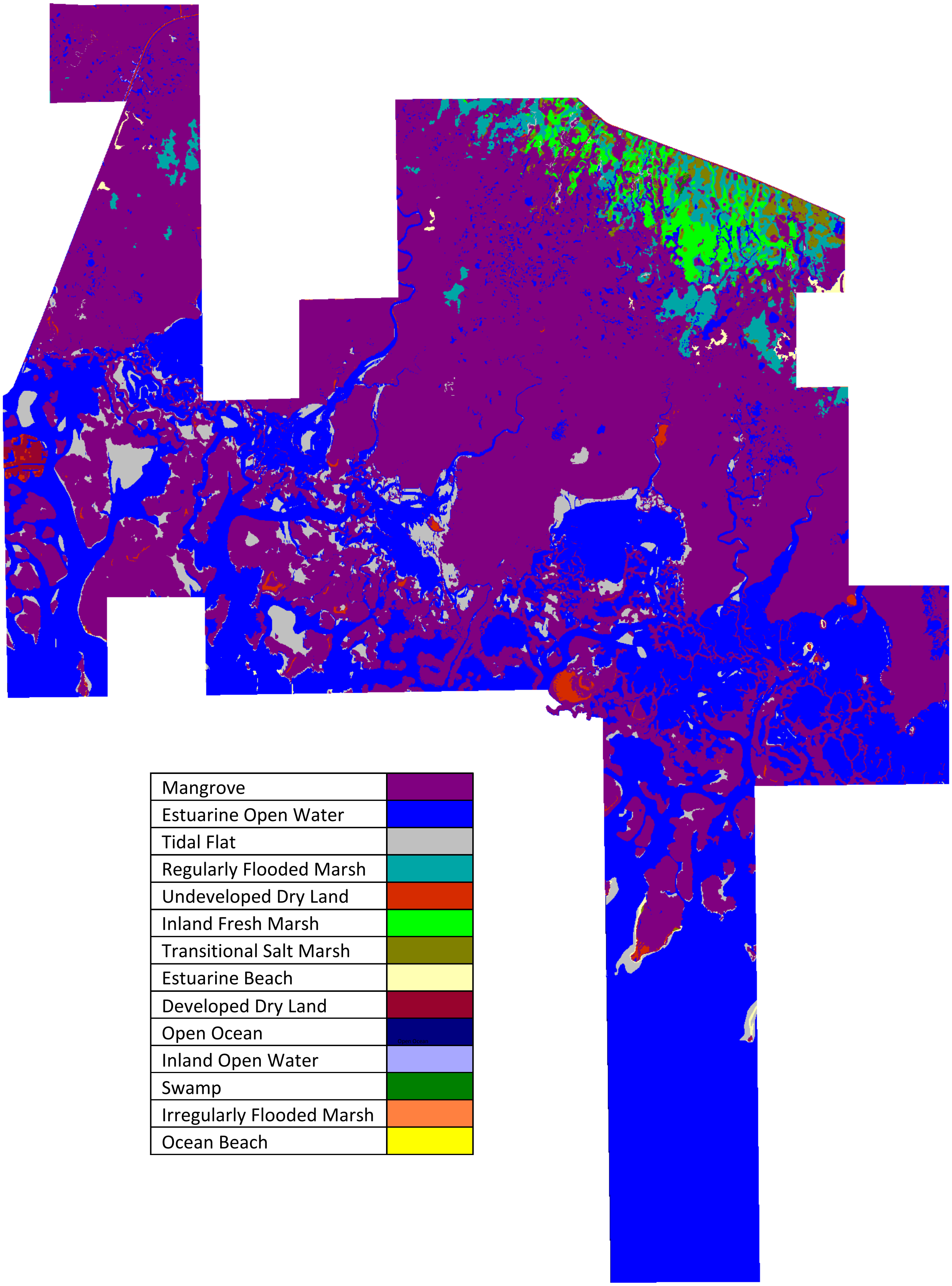
Ten Thousand Islands NWR, Initial Condition



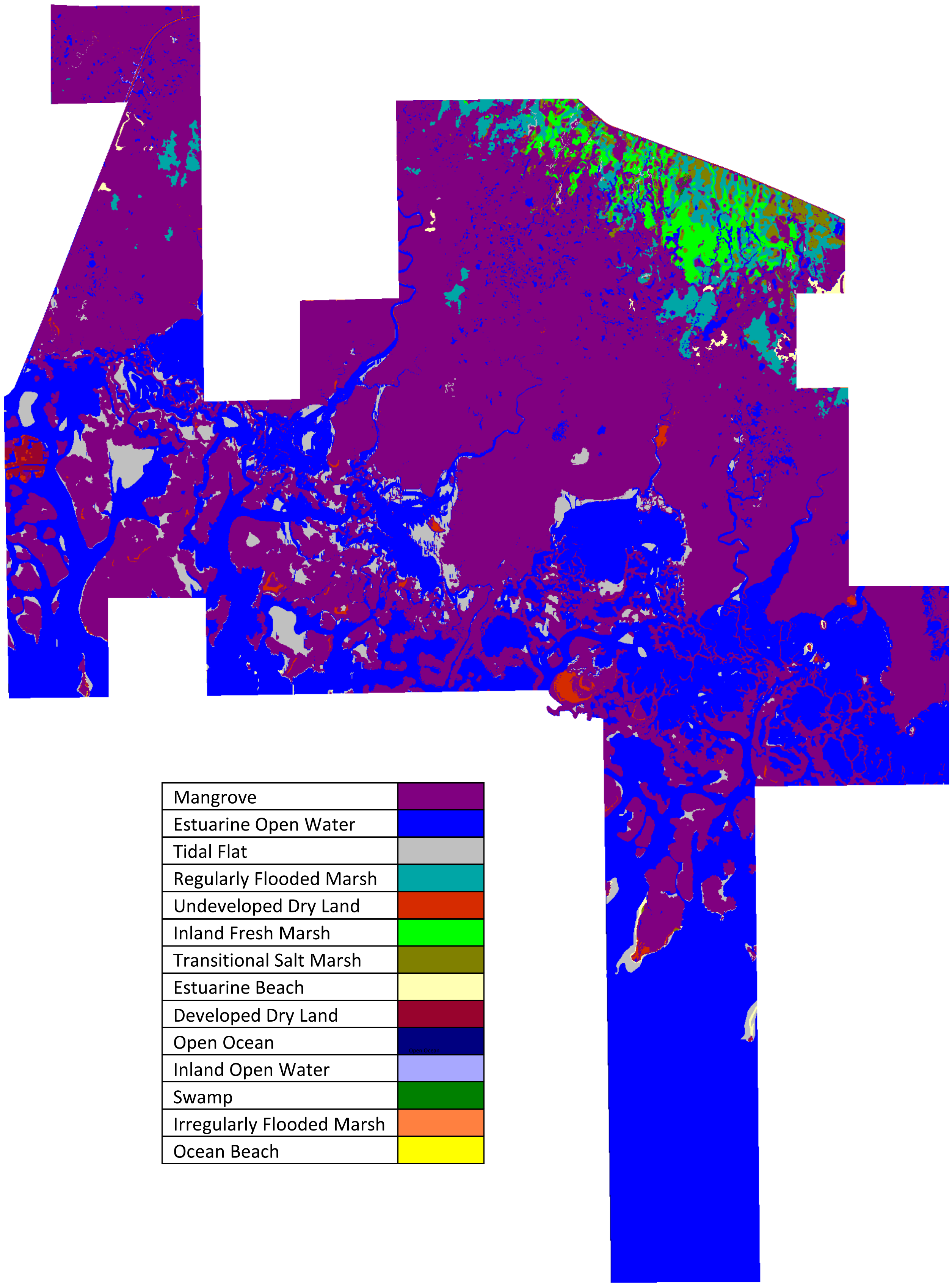
Ten Thousand Islands NWR, 2025, Scenario A1B Mean



Ten Thousand Islands NWR, 2050, Scenario A1B Mean



Ten Thousand Islands NWR, 2075, Scenario A1B Mean

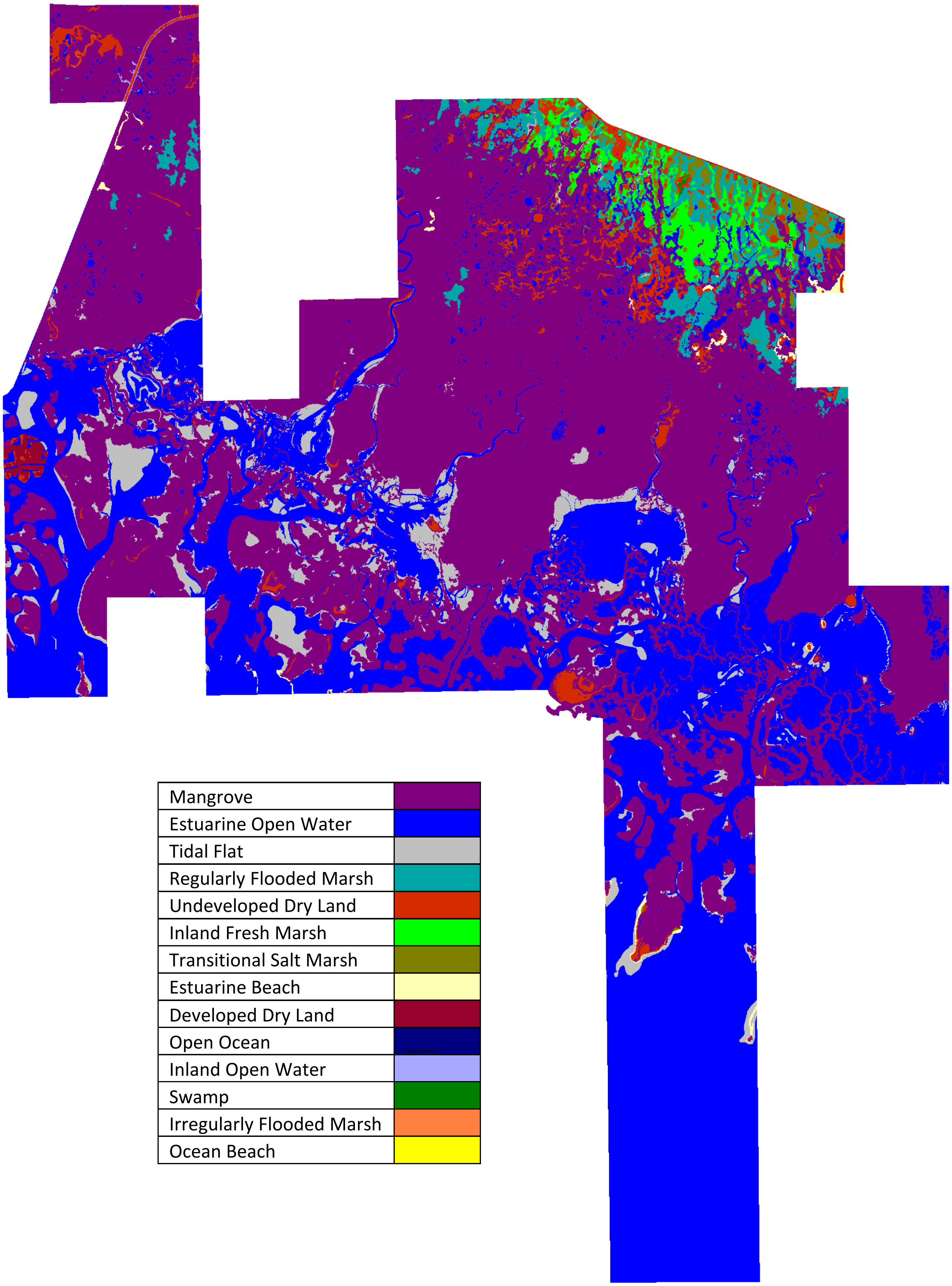


Ten Thousand Islands NWR, 2100, Scenario A1B Mean

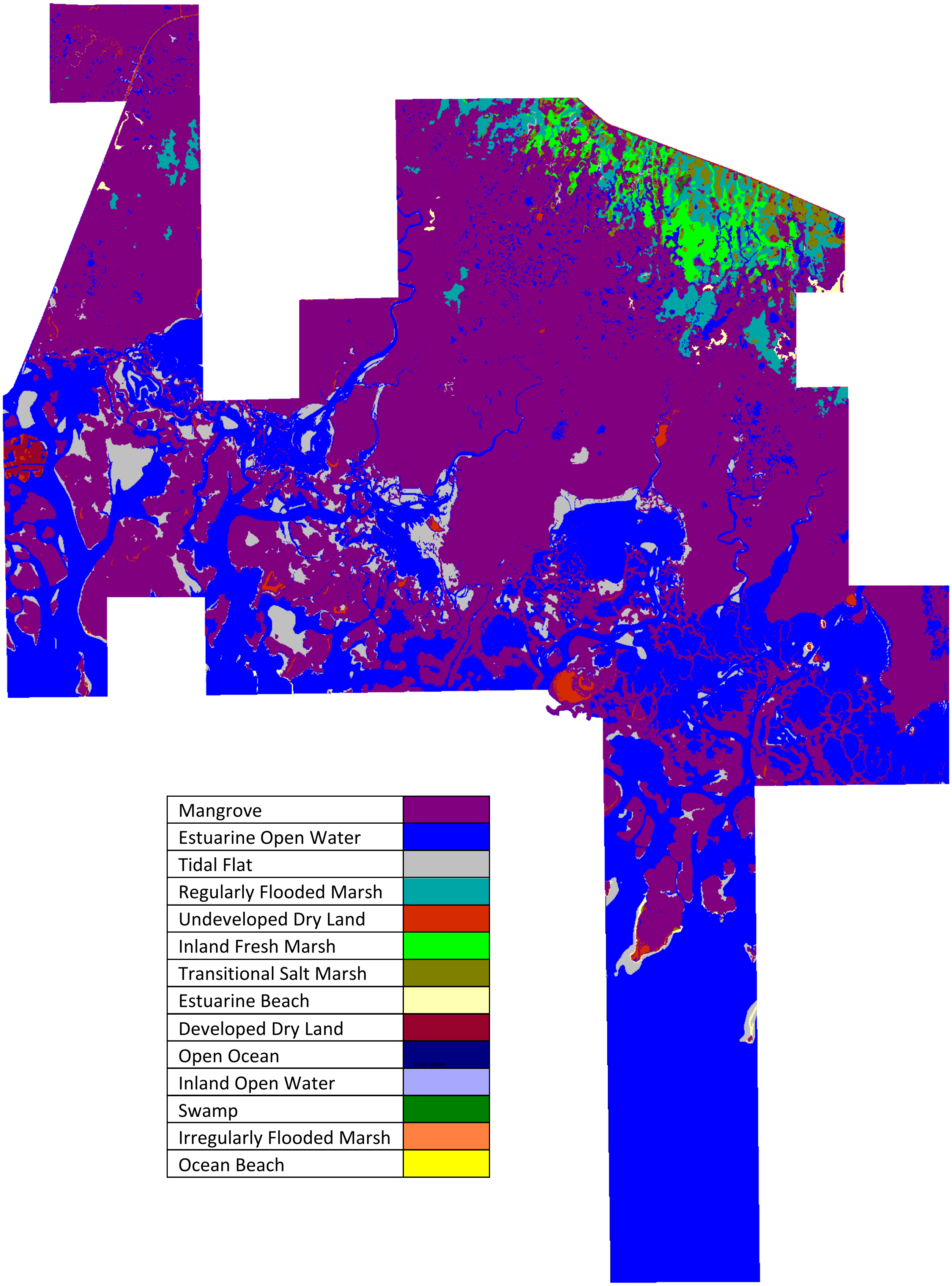
10K Forecast NWR Raster
IPCC Scenario A1B-Max, 0.69 M SLR Eustatic by 2100

Results in Acres

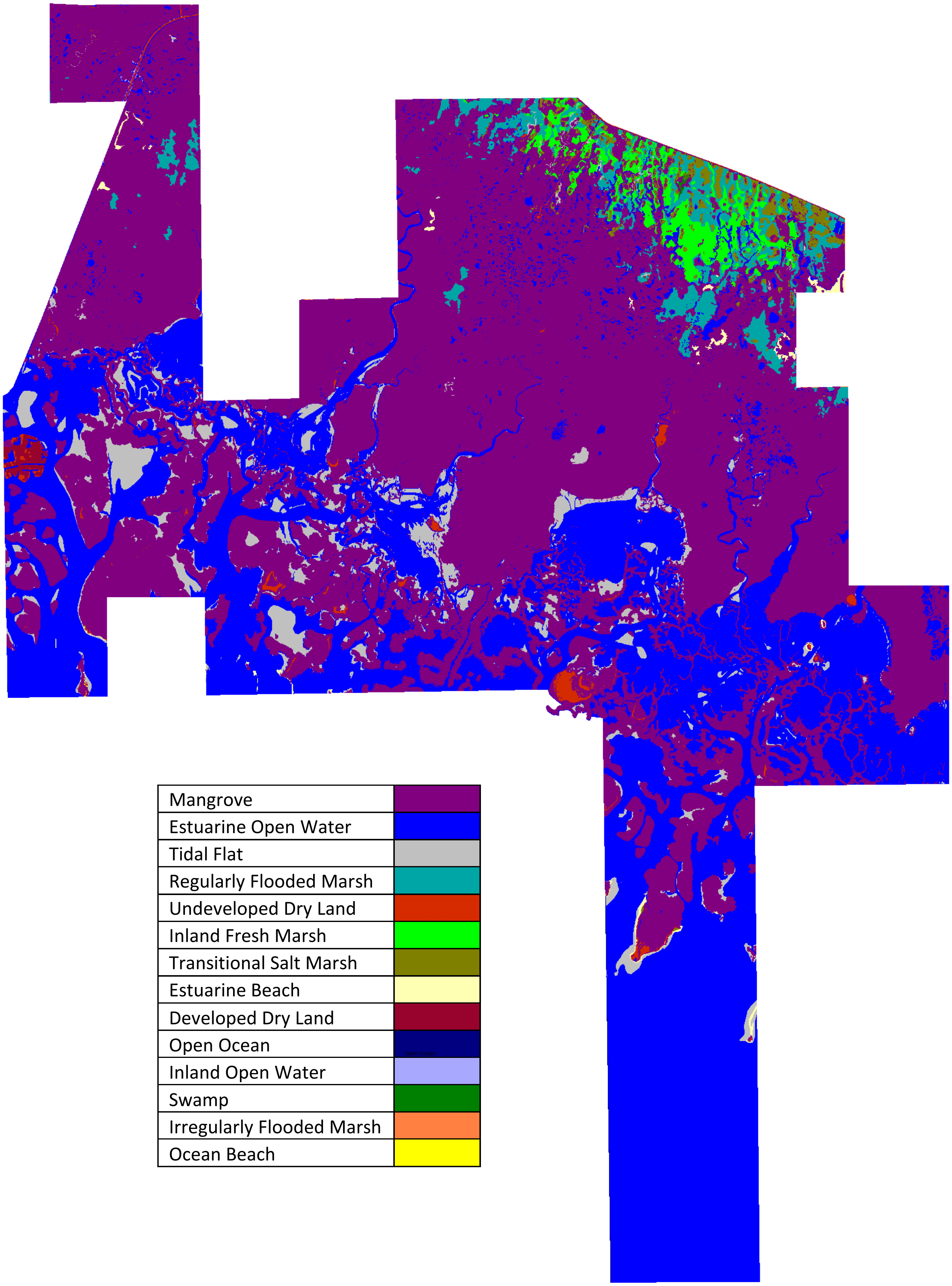
		Initial	2025	2050	2075	2100
	Mangrove	18455.3	18935.3	19012.0	19116.3	19275.2
	Estuarine Open Water	12022.3	12285.8	12438.5	12562.2	12699.2
	Tidal Flat	1587.9	1488.8	1338.3	1242.7	1125.0
	Regularly Flooded Marsh	905.3	905.3	905.3	905.3	900.5
	Undeveloped Dry Land	816.6	215.3	161.5	122.5	90.6
	Inland Fresh Marsh	487.5	487.4	487.4	483.5	461.5
	Transitional Salt Marsh	341.0	309.2	289.1	212.2	116.1
	Estuarine Beach	84.9	83.6	81.8	80.0	77.7
	Developed Dry Land	73.6	71.9	68.9	60.4	41.8
	Open Ocean	15.8	16.1	16.1	16.1	16.1
	Inland Open Water	12.2	3.8	3.5	3.3	3.2
	Swamp	5.2	5.2	4.9	2.4	0.4
	Irregularly Flooded Marsh	1.8	1.8	1.8	1.8	1.5
	Ocean Beach	0.4	0.3	0.6	0.9	1.1
	Total (incl. water)	**34809.8**	**34809.8**	**34809.8**	**34809.8**	**34809.8**



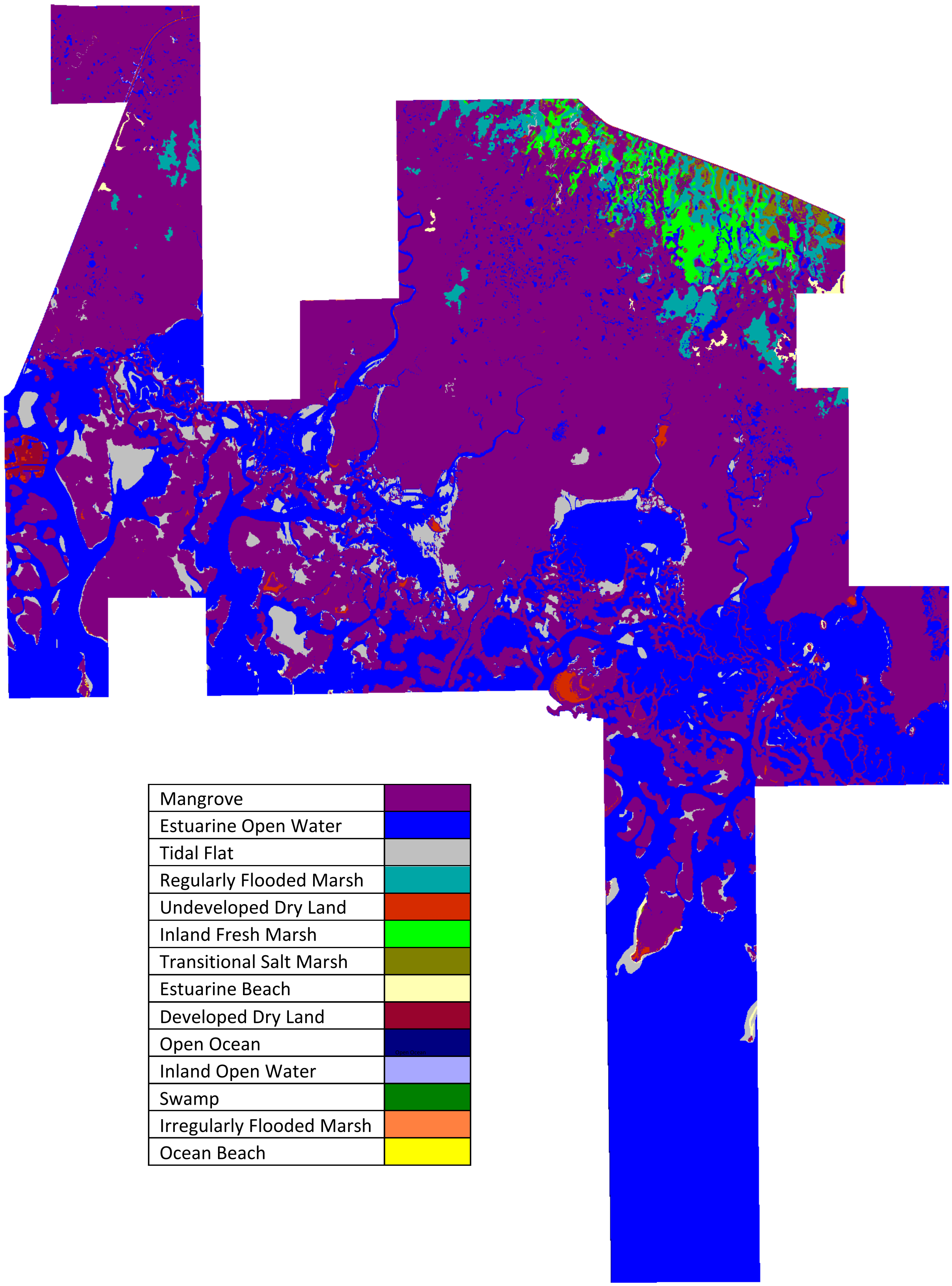
Ten Thousand Islands NWR, Initial Condition



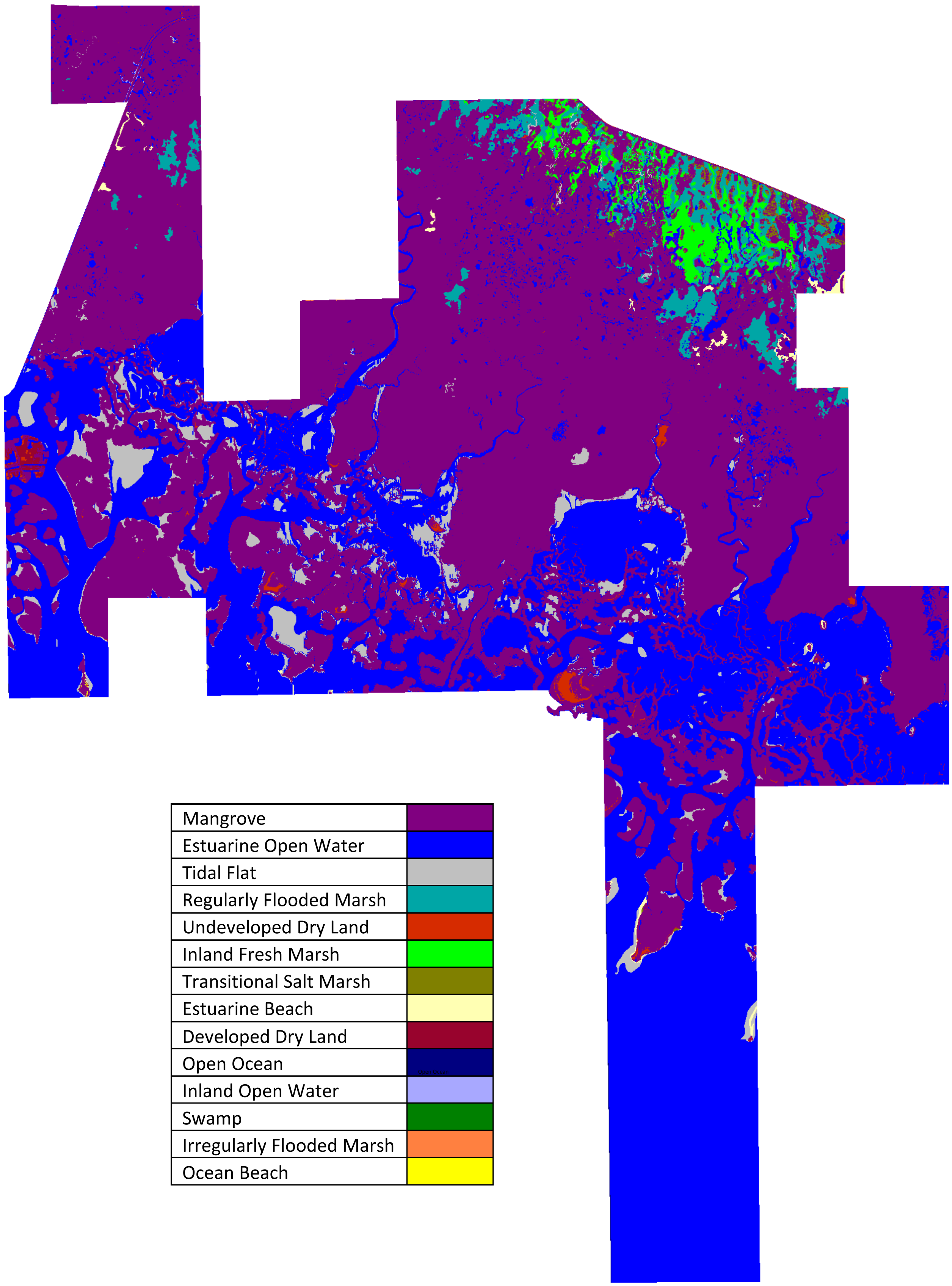
Ten Thousand Islands NWR, 2025, Scenario A1B Maximum



Ten Thousand Islands NWR, 2050, Scenario A1B Maximum



Ten Thousand Islands NWR, 2075, Scenario A1B Maximum

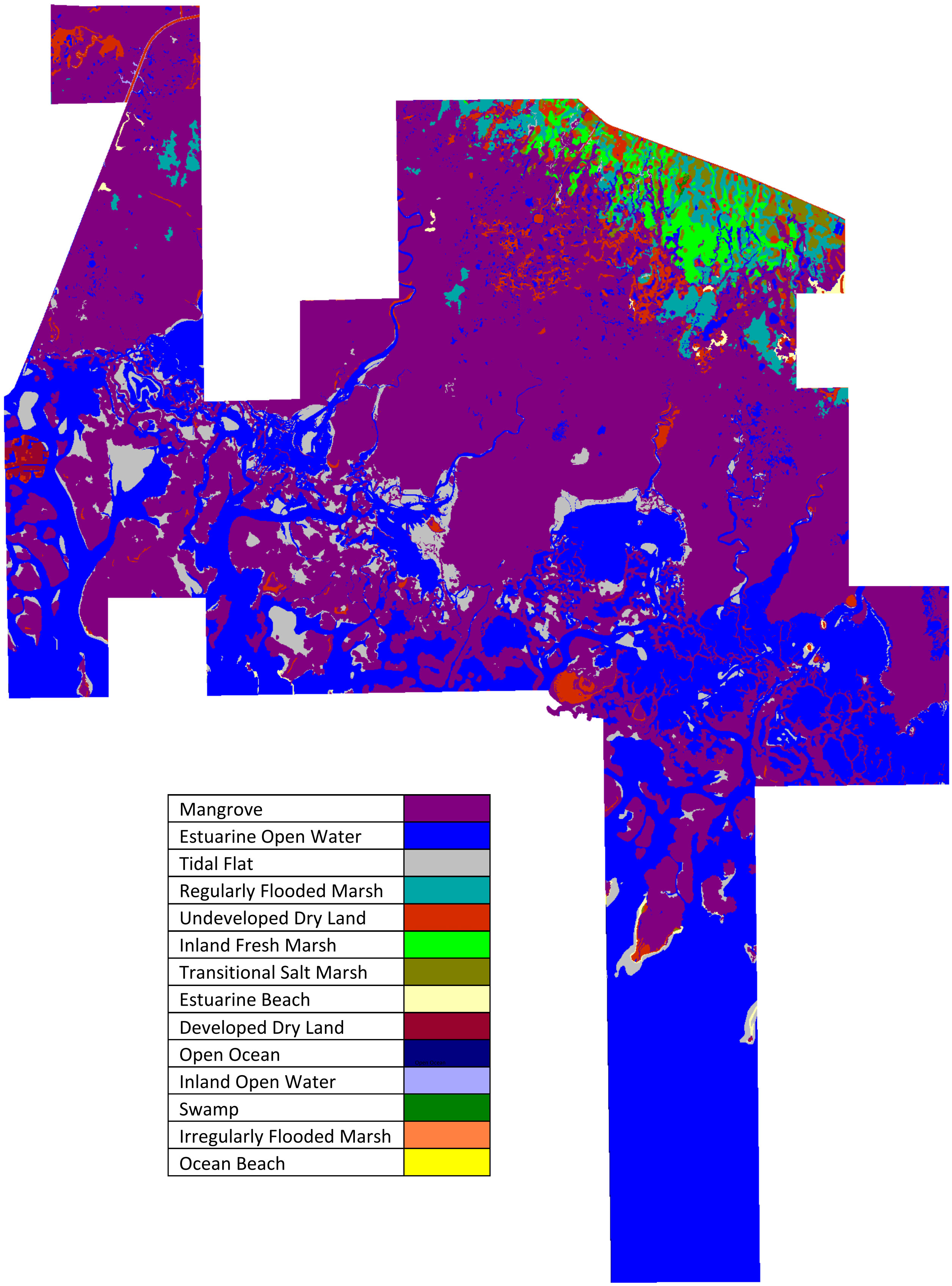


Ten Thousand Islands NWR, 2100, Scenario A1B Maximum

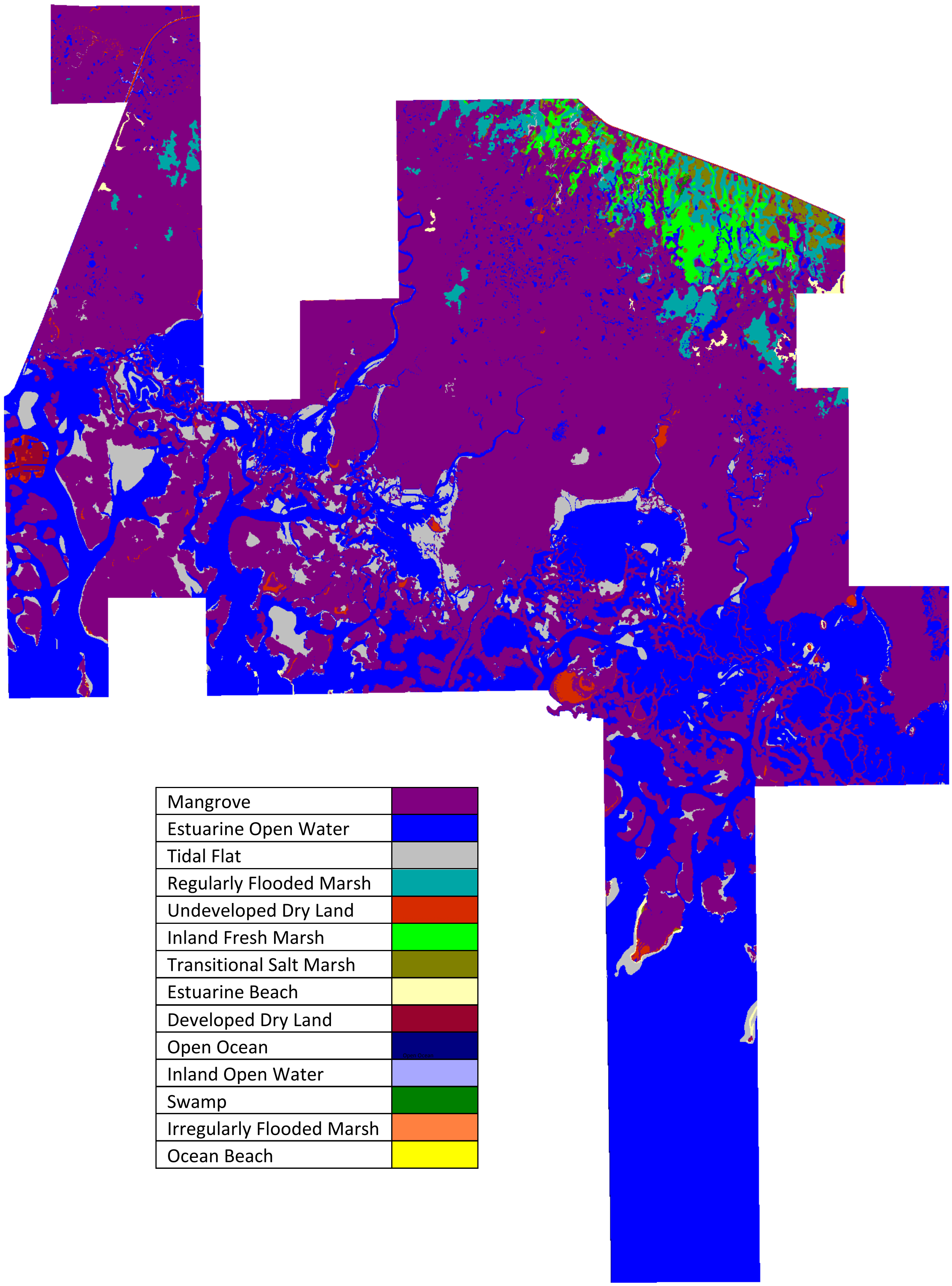
10K Forecast NWR Raster
1 Meter Eustatic SLR by 2100

Results in Acres

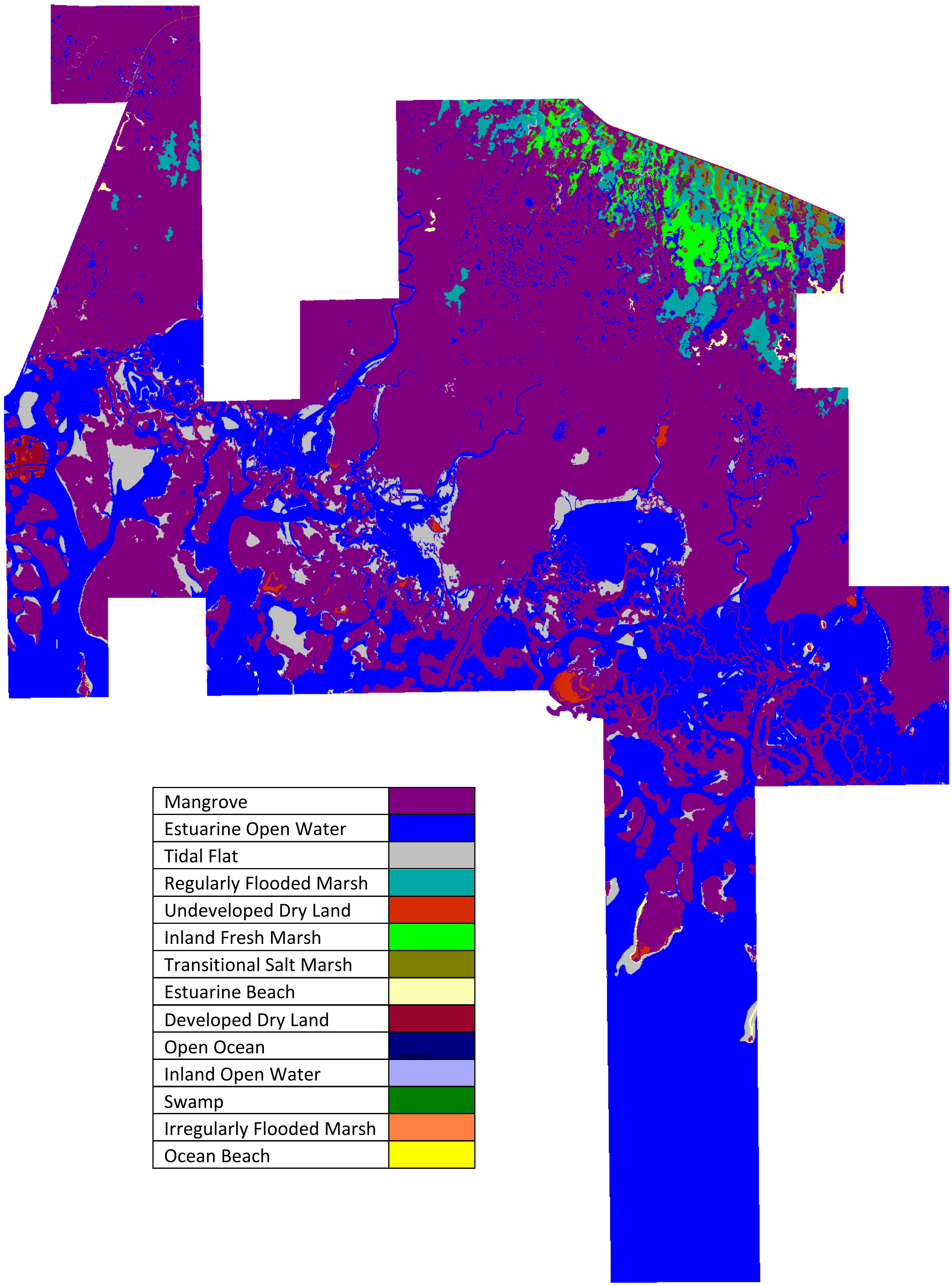
		Initial	2025	2050	2075	2100
	Mangrove	18455.3	18954.4	19114.6	19311.7	19300.5
	Estuarine Open Water	12022.3	12286.2	12463.8	12689.9	13114.3
	Tidal Flat	1587.9	1488.5	1331.7	1231.0	1436.1
	Regularly Flooded Marsh	905.3	905.3	905.3	884.1	515.8
	Undeveloped Dry Land	816.6	203.4	138.4	92.9	67.1
	Inland Fresh Marsh	487.5	487.4	473.6	397.0	250.7
	Transitional Salt Marsh	341.0	302.1	208.8	56.6	9.3
	Estuarine Beach	84.9	83.6	81.8	79.5	73.0
	Developed Dry Land	73.6	71.7	65.6	45.2	21.7
	Open Ocean	15.8	16.1	16.1	16.1	16.1
	Inland Open Water	12.2	3.7	3.4	3.2	3.2
	Swamp	5.2	5.2	3.9	0.5	0.0
	Irregularly Flooded Marsh	1.8	1.8	1.8	1.0	0.6
	Ocean Beach	0.4	0.4	0.8	1.1	1.2
	Total (incl. water)	**34809.8**	**34809.8**	**34809.8**	**34809.8**	**34809.8**



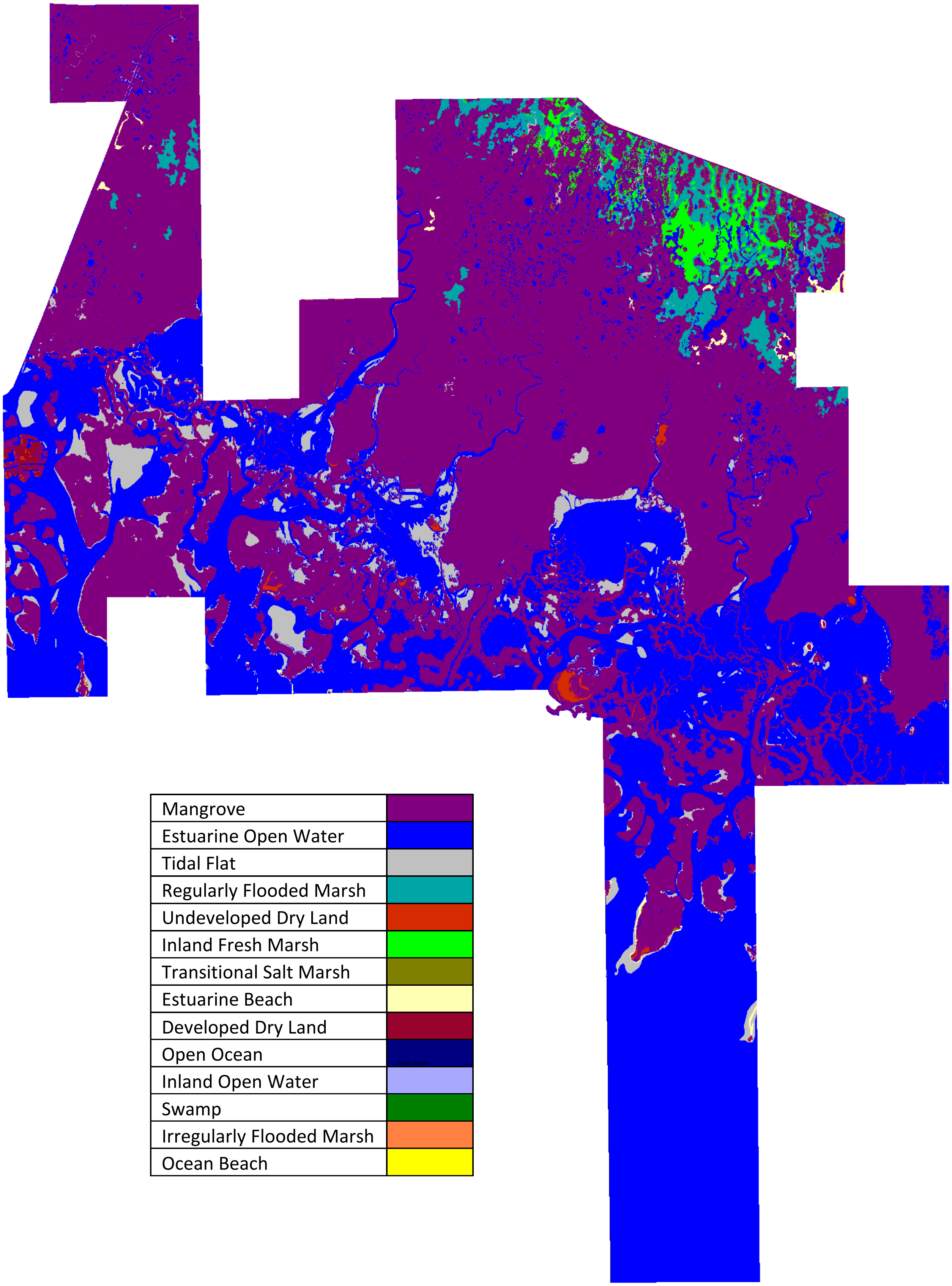
Ten Thousand Islands NWR, Initial Condition



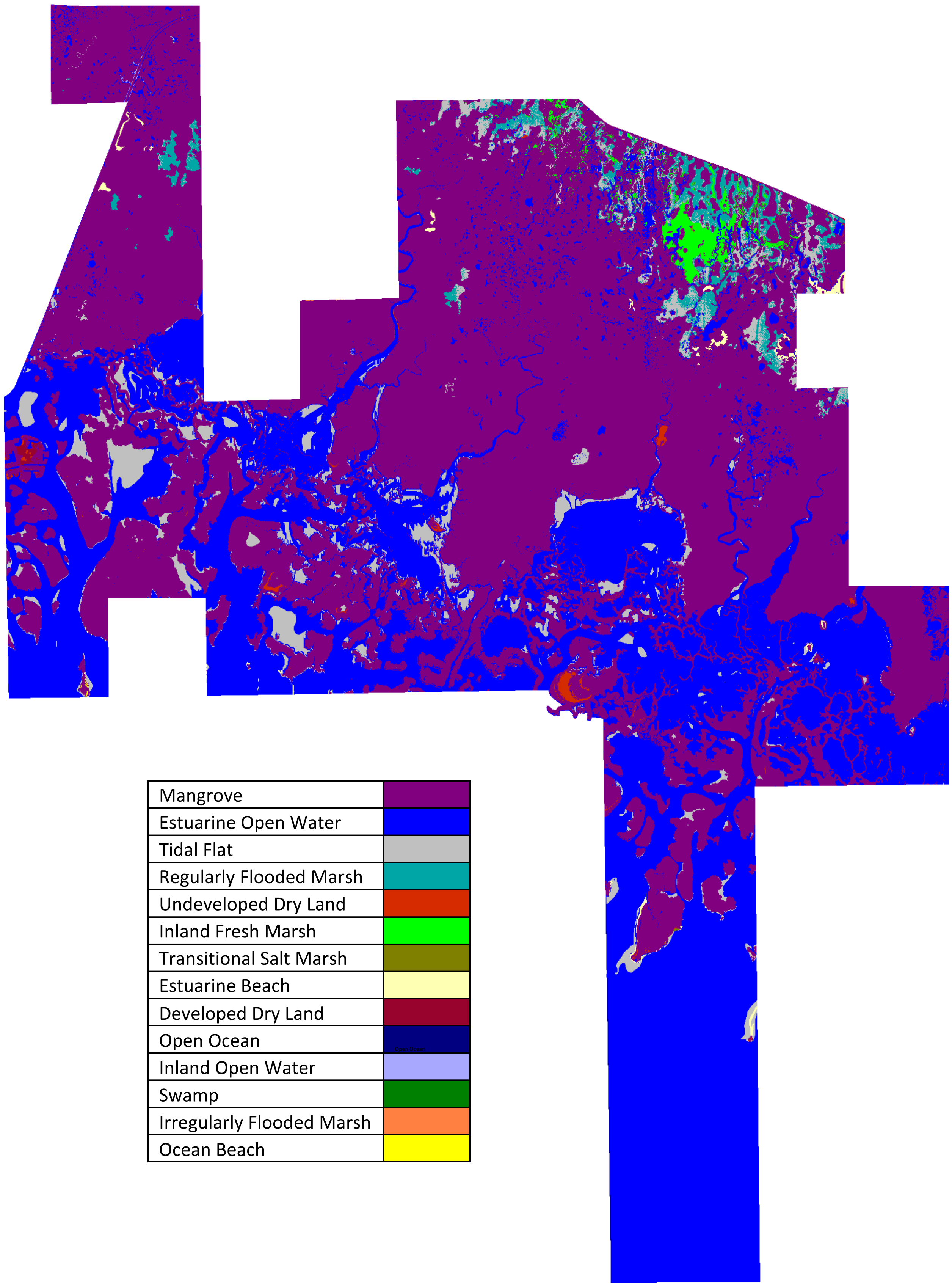
Ten Thousand Islands NWR, 2025, 1 Meter



Ten Thousand Islands NWR, 2050, 1 Meter



Ten Thousand Islands NWR, 2075, 1 Meter

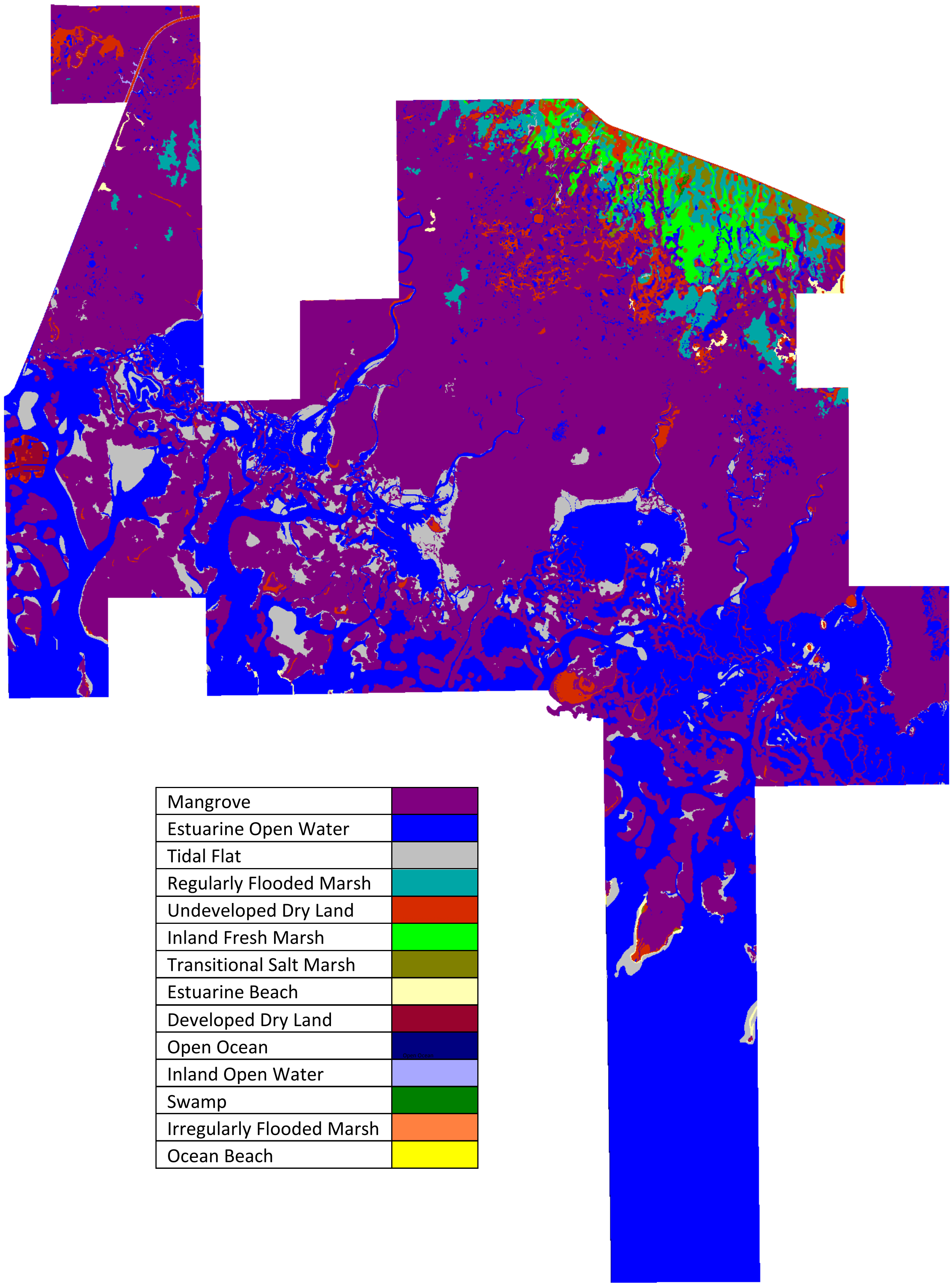


Ten Thousand Islands NWR, 2100, 1 Meter

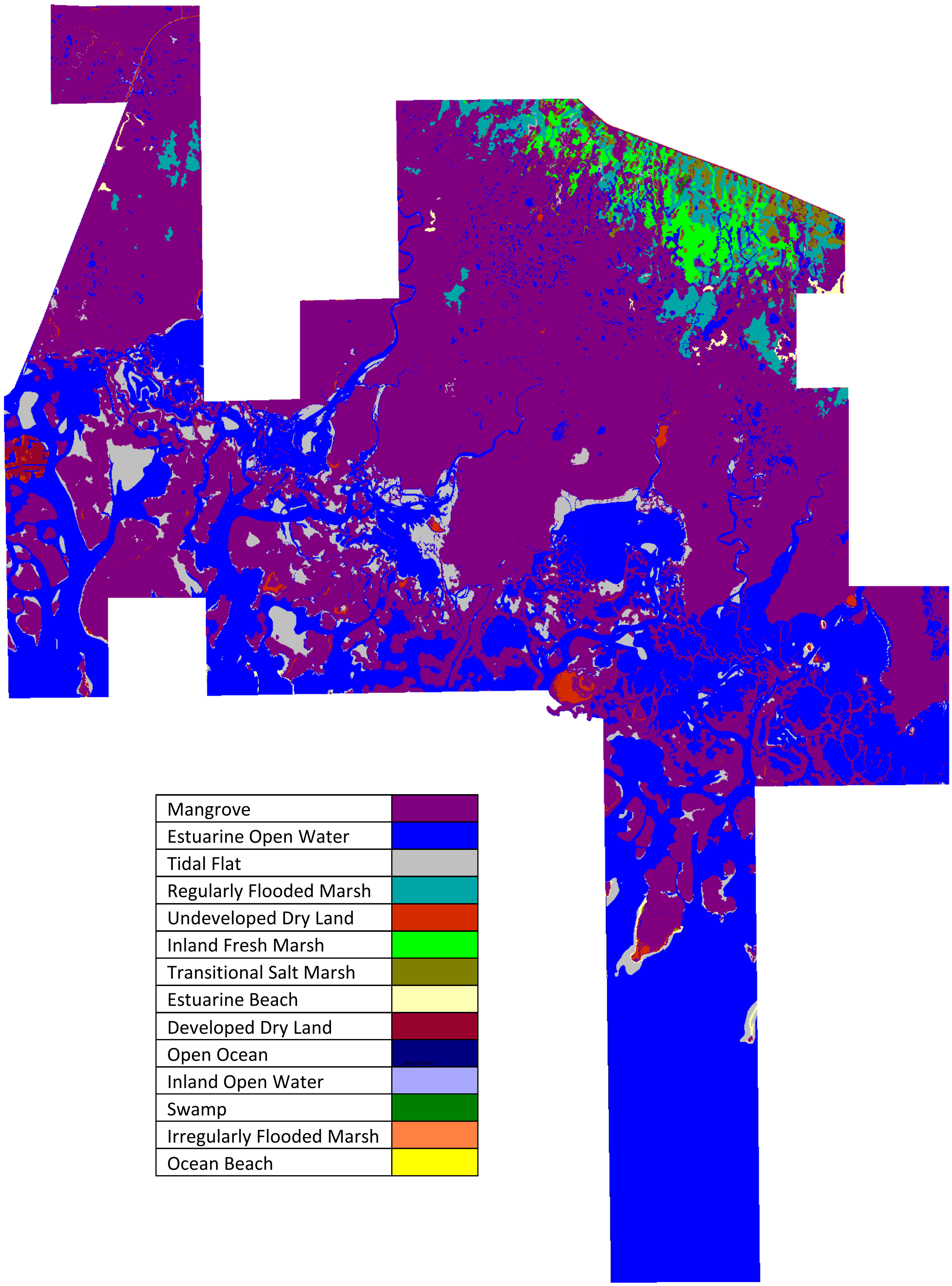
10K Forecast NWR Raster
1.5 Meters Eustatic SLR by 2100

Results in Acres

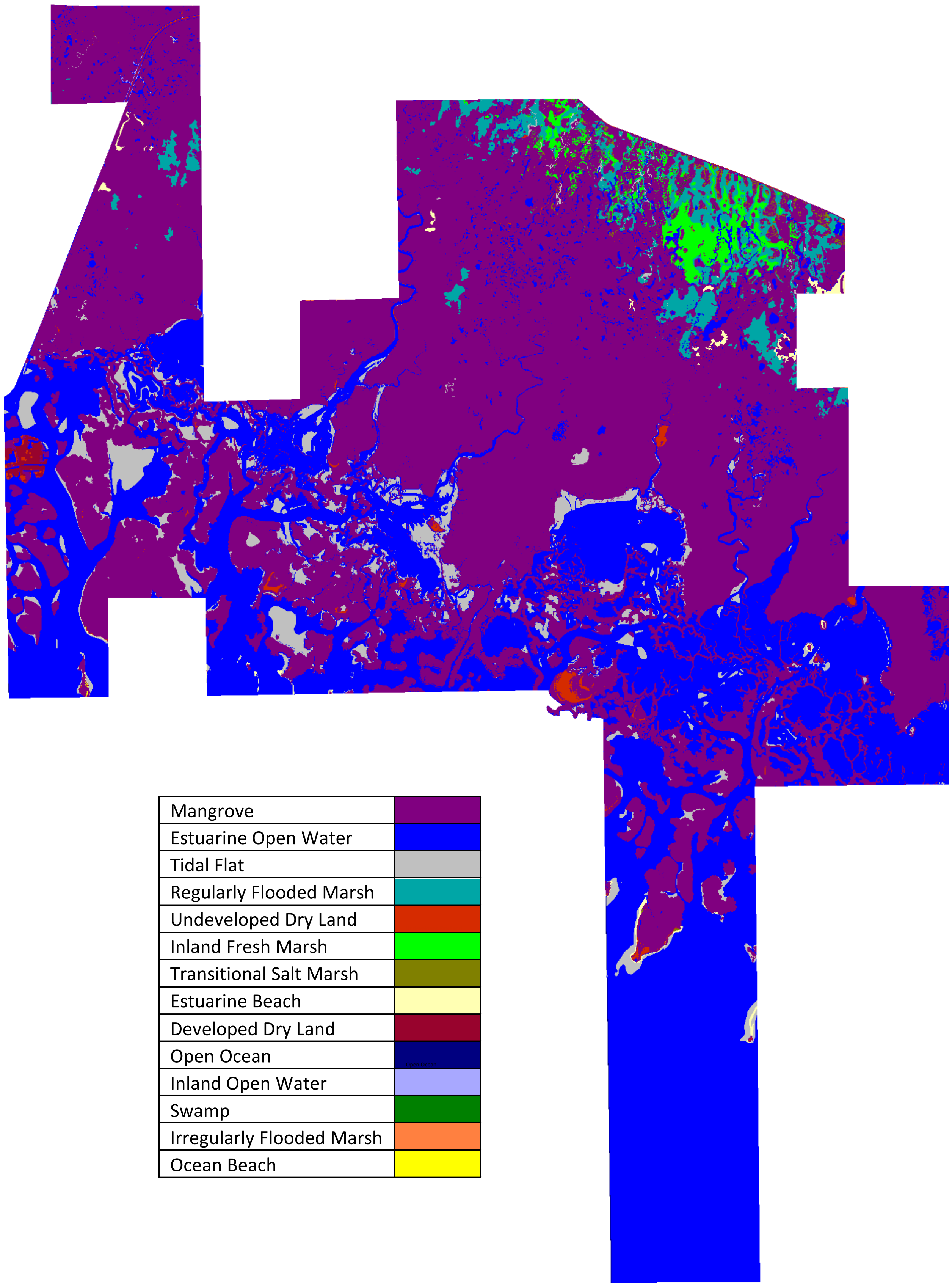
		Initial	2025	2050	2075	2100
	Mangrove	18455.3	18992.6	19263.3	17991.1	7396.1
	Estuarine Open Water	12022.3	12297.3	12594.5	14414.6	25968.2
	Tidal Flat	1587.9	1487.9	1315.4	1714.5	1176.7
	Regularly Flooded Marsh	905.3	905.3	897.0	312.1	14.6
	Undeveloped Dry Land	816.6	186.7	111.9	67.7	48.9
	Inland Fresh Marsh	487.5	485.1	392.7	187.3	154.1
	Transitional Salt Marsh	341.0	273.1	71.3	4.9	2.6
	Estuarine Beach	84.9	83.6	81.7	74.4	18.4
	Developed Dry Land	73.6	71.1	58.4	22.4	9.6
	Open Ocean	15.8	16.1	16.1	16.1	16.3
	Inland Open Water	12.2	3.7	3.3	3.2	3.2
	Swamp	5.2	5.2	1.9	0.0	0.0
	Irregularly Flooded Marsh	1.8	1.8	1.2	0.3	0.0
	Ocean Beach	0.4	0.5	1.0	1.2	1.1
	Total (incl. water)	**34809.8**	**34809.8**	**34809.8**	**34809.8**	**34809.8**



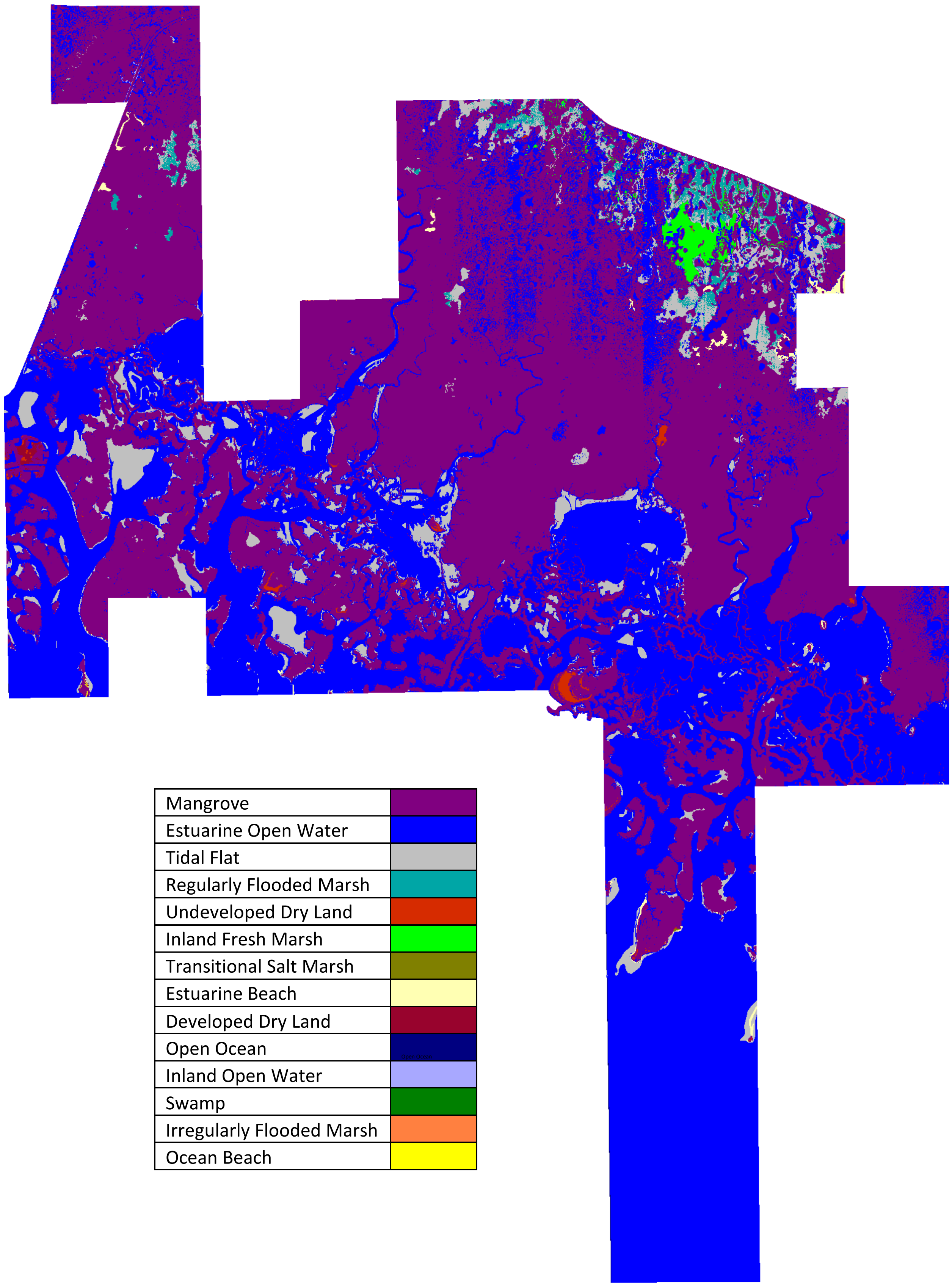
Ten Thousand Islands NWR, Initial Condition



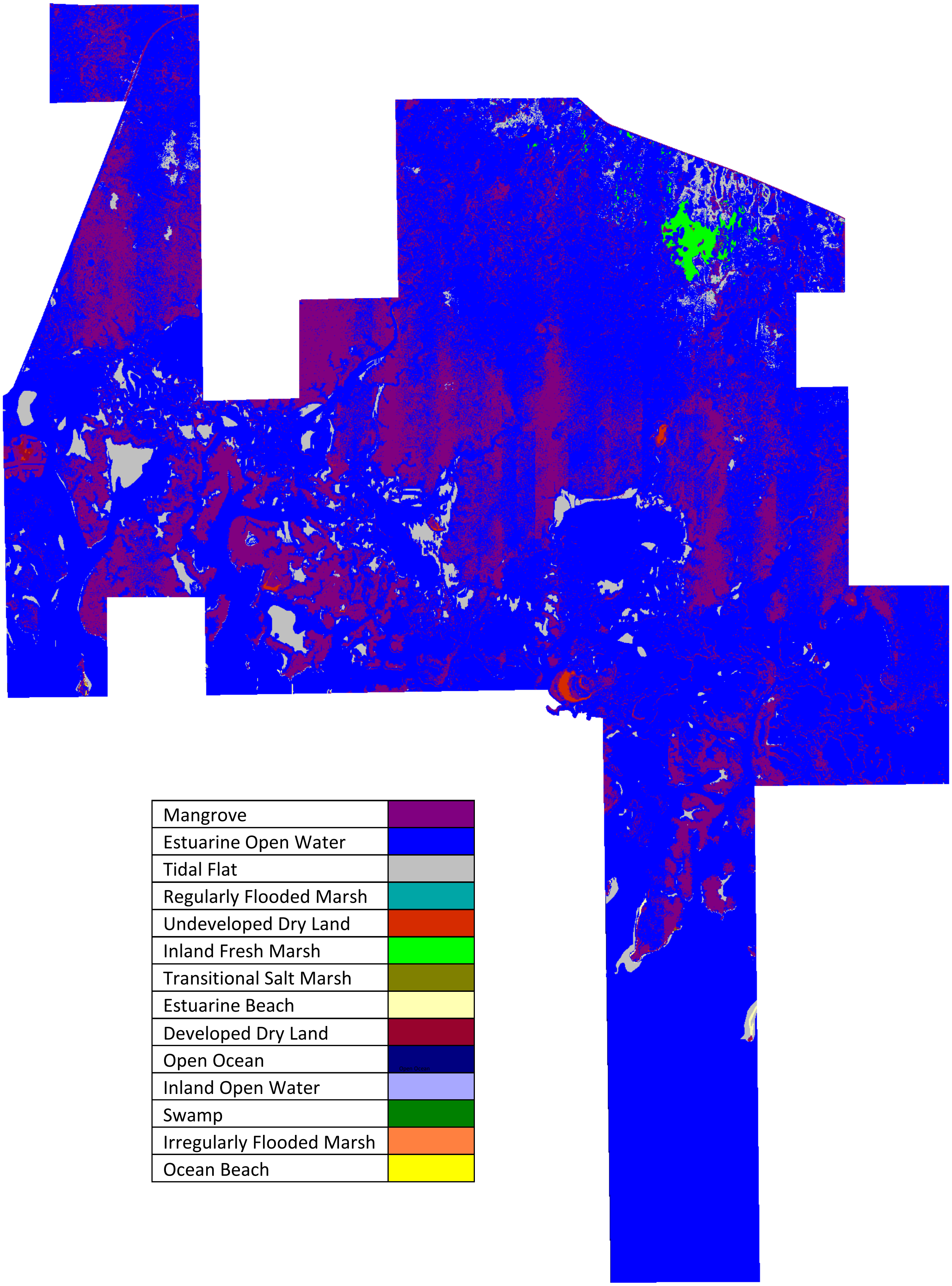
Ten Thousand Islands NWR, 2025, 1.5 M



Ten Thousand Islands NWR, 2050, 1.5 M



Ten Thousand Islands NWR, 2075, 1.5 M

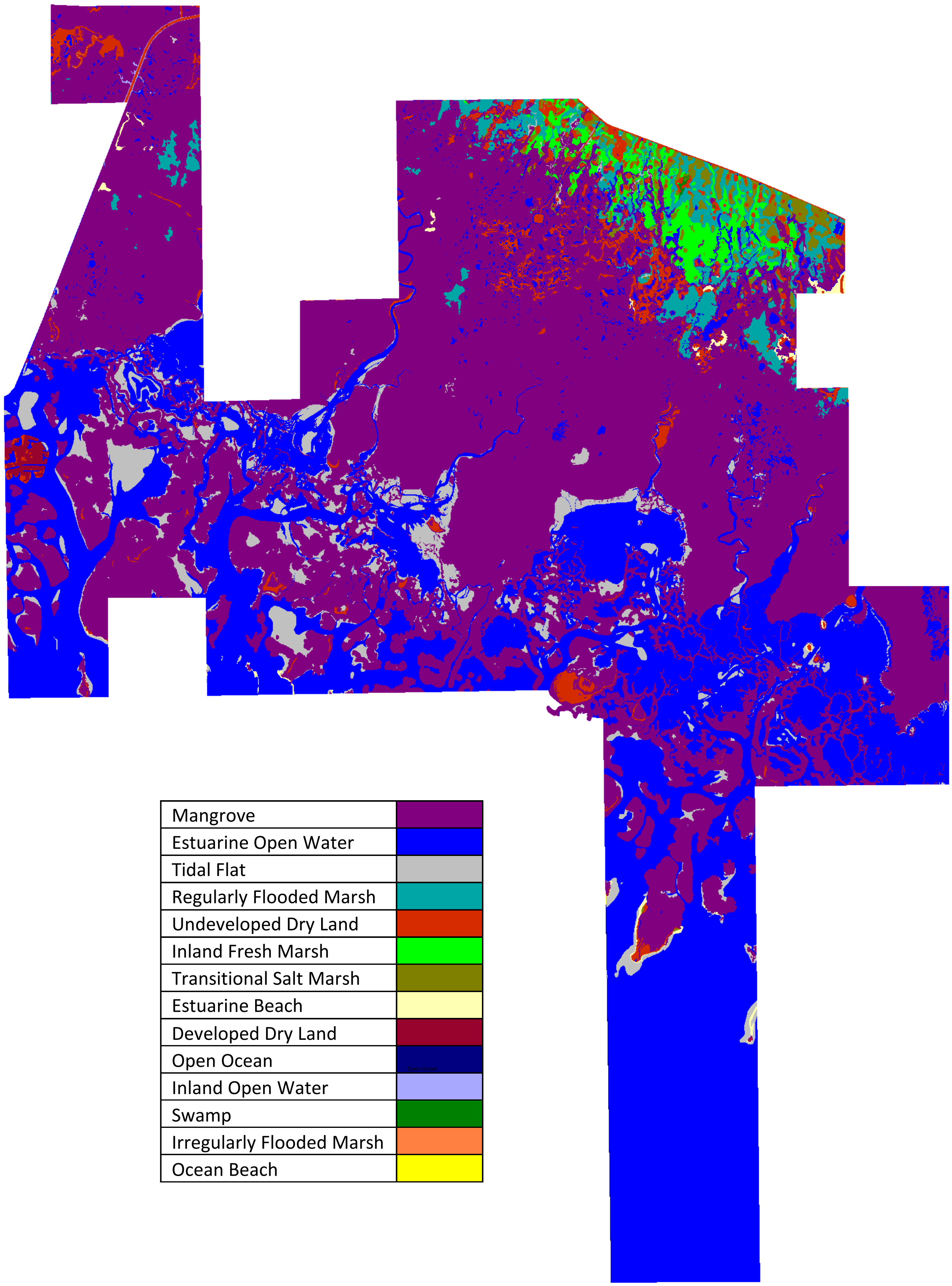


Ten Thousand Islands NWR, 2100, 1.5 M

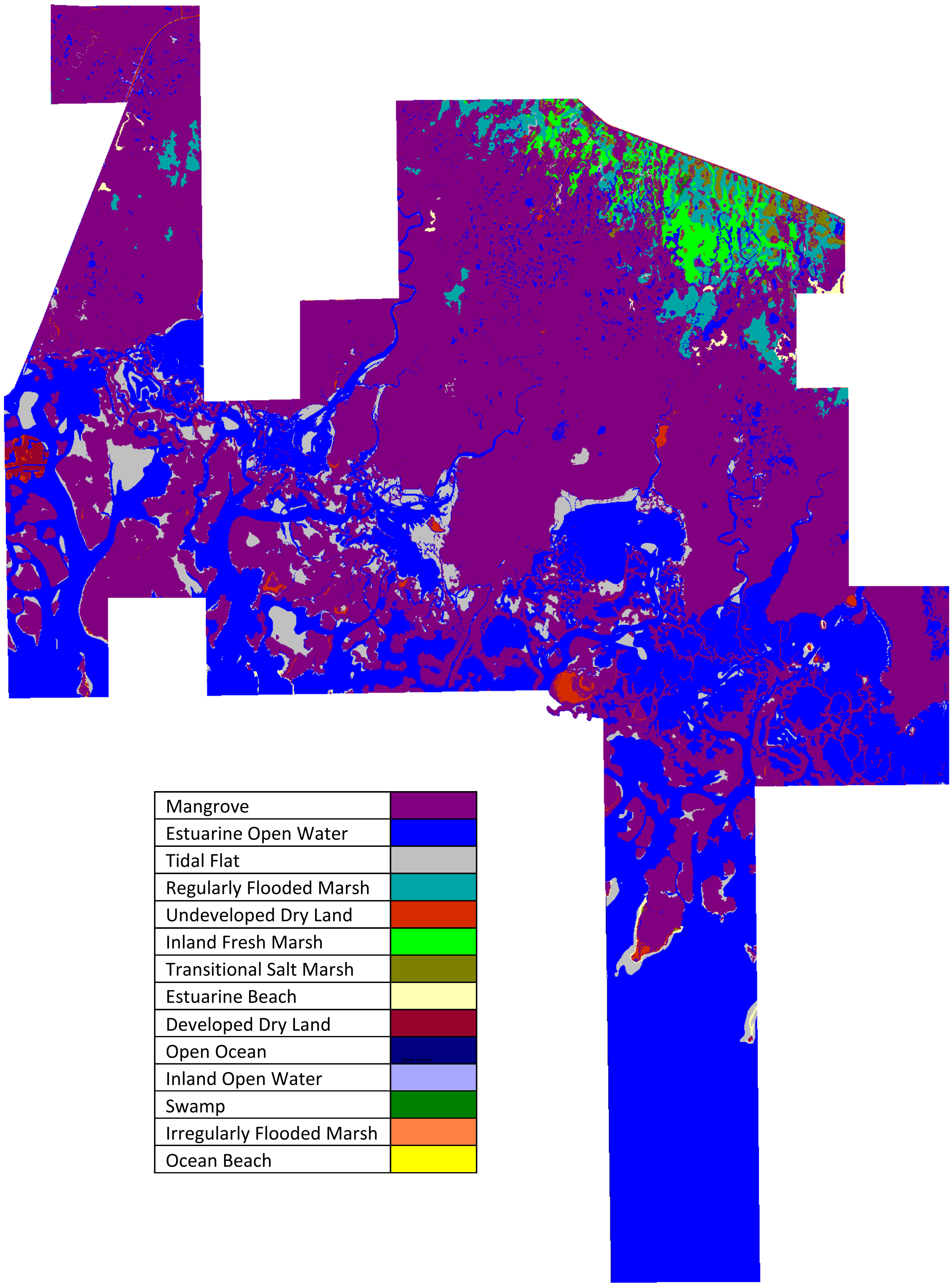
10K Forecast NWR Raster
2 Meters Eustatic SLR by 2100

Results in Acres

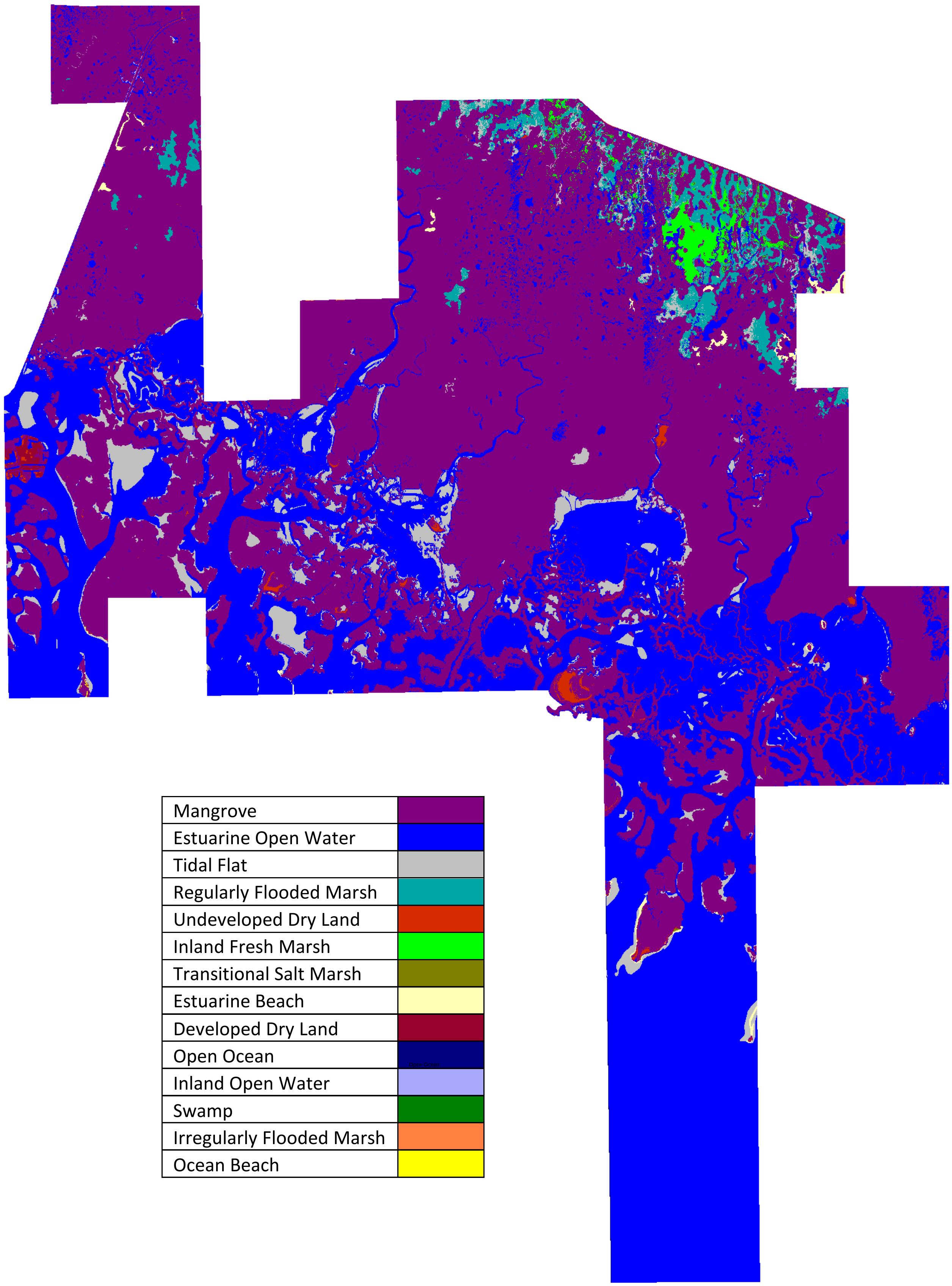
		Initial	2025	2050	2075	2100
	Mangrove	18455.3	19031.6	19130.0	6812.0	491.5
	Estuarine Open Water	12022.3	12321.6	12988.2	25970.3	33240.0
	Tidal Flat	1587.9	1486.2	1439.3	1727.7	839.8
	Regularly Flooded Marsh	905.3	905.3	745.9	24.3	6.6
	Undeveloped Dry Land	816.6	172.5	91.5	53.9	39.9
	Inland Fresh Marsh	487.5	473.8	252.6	155.0	153.1
	Transitional Salt Marsh	341.0	237.5	15.8	2.7	2.1
	Estuarine Beach	84.9	83.6	81.0	31.5	11.5
	Developed Dry Land	73.6	70.5	43.9	11.9	4.6
	Open Ocean	15.8	16.1	16.1	16.2	17.0
	Inland Open Water	12.2	3.6	3.2	3.2	3.2
	Swamp	5.2	5.1	0.4	0.0	0.0
	Irregularly Flooded Marsh	1.8	1.8	0.8	0.0	0.0
	Ocean Beach	0.4	0.5	1.1	1.1	0.3
	Total (incl. water)	**34809.8**	**34809.8**	**34809.8**	**34809.8**	**34809.8**



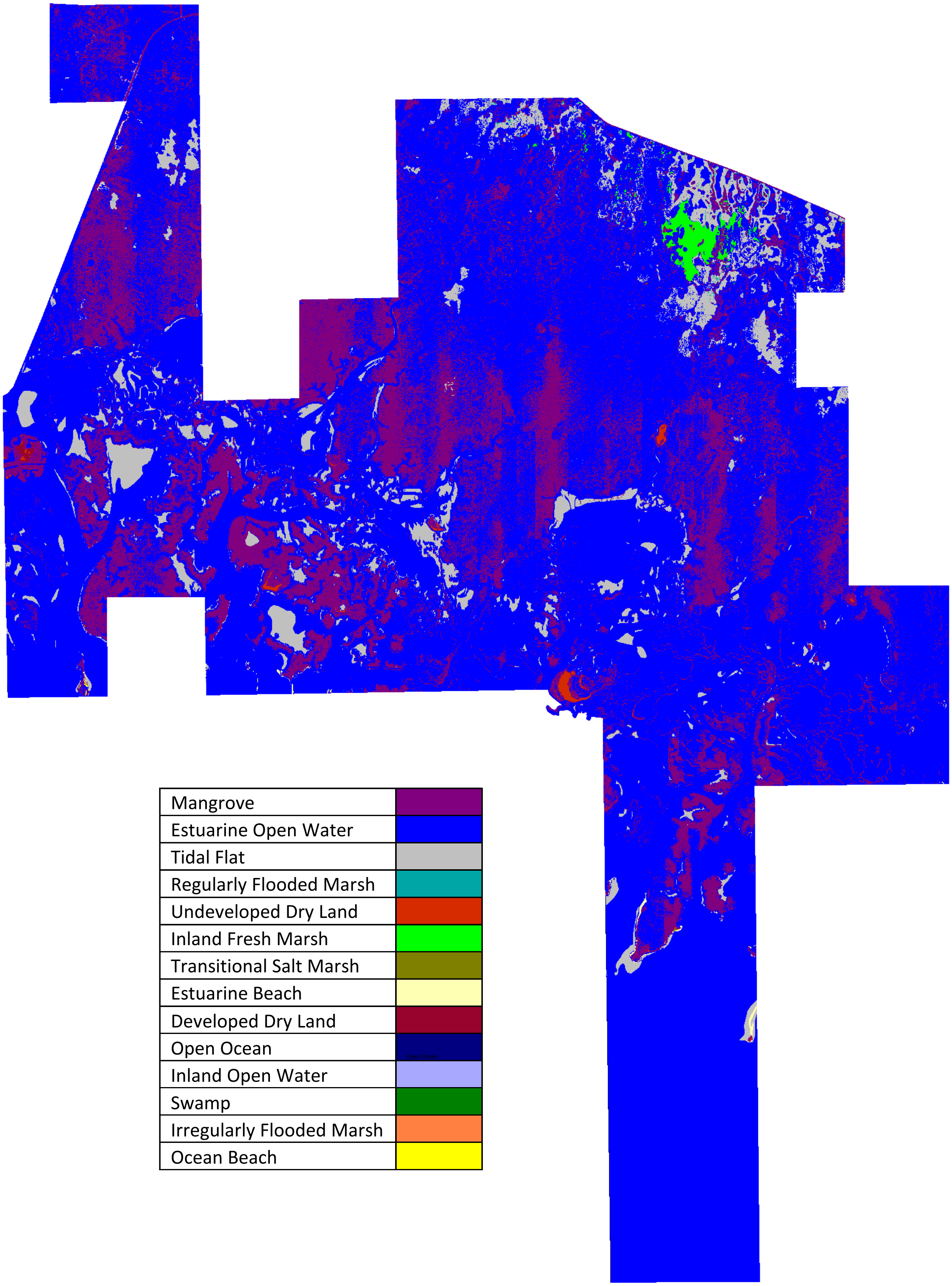
Ten Thousand Islands NWR, Initial Condition



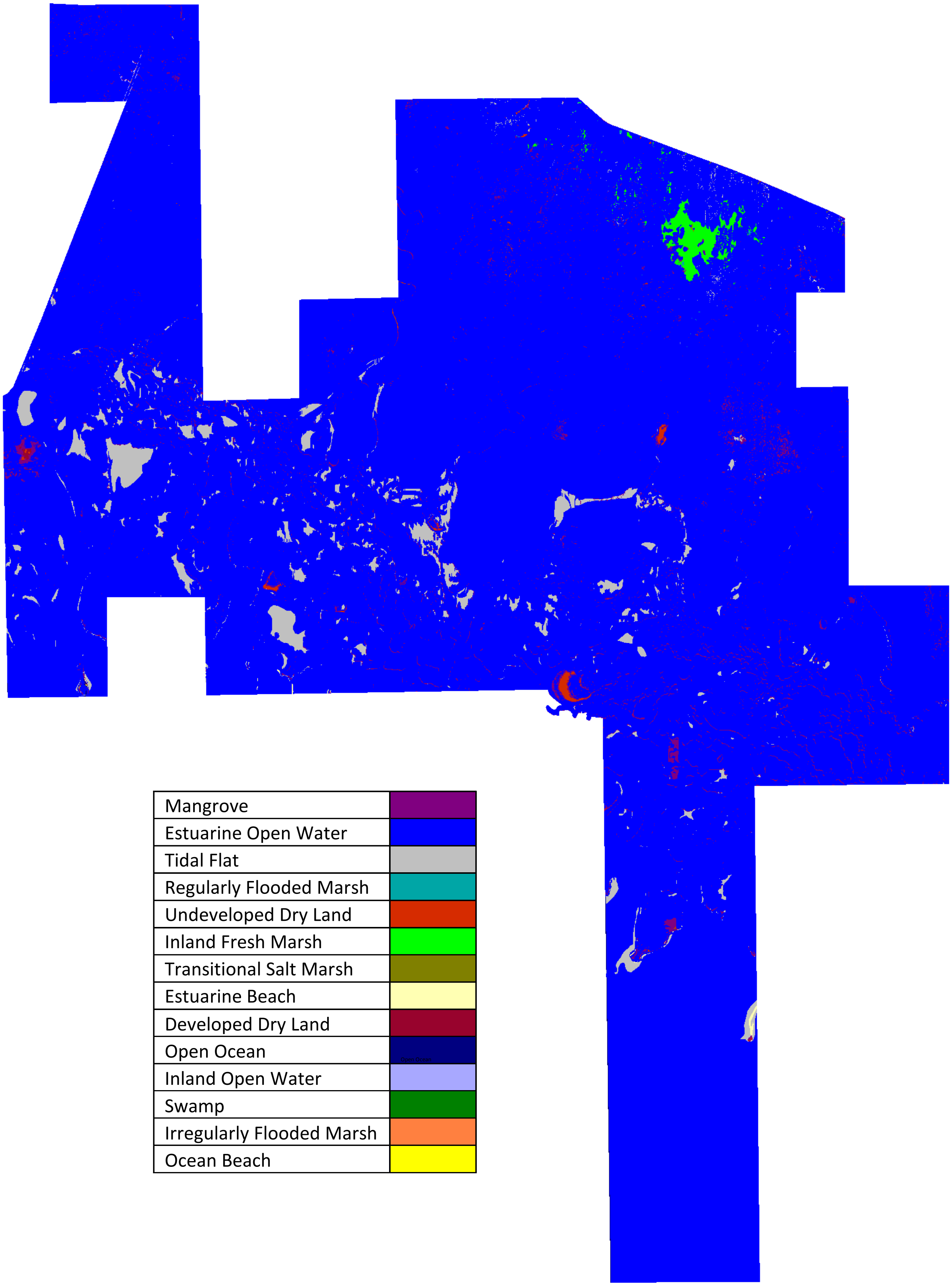
Ten Thousand Islands NWR, 2025, 2 M



Ten Thousand Islands NWR, 2050, 2 M



Ten Thousand Islands NWR, 2075, 2 M



Ten Thousand Islands NWR, 2100, 2 M

Erosion Map

Erosion is predicted to be particularly strong along the shorelines of regularly flooded marsh as illustrated in Figure 17. Not surprisingly, erosion is most extreme along low-lying coastal regions (>30 m).

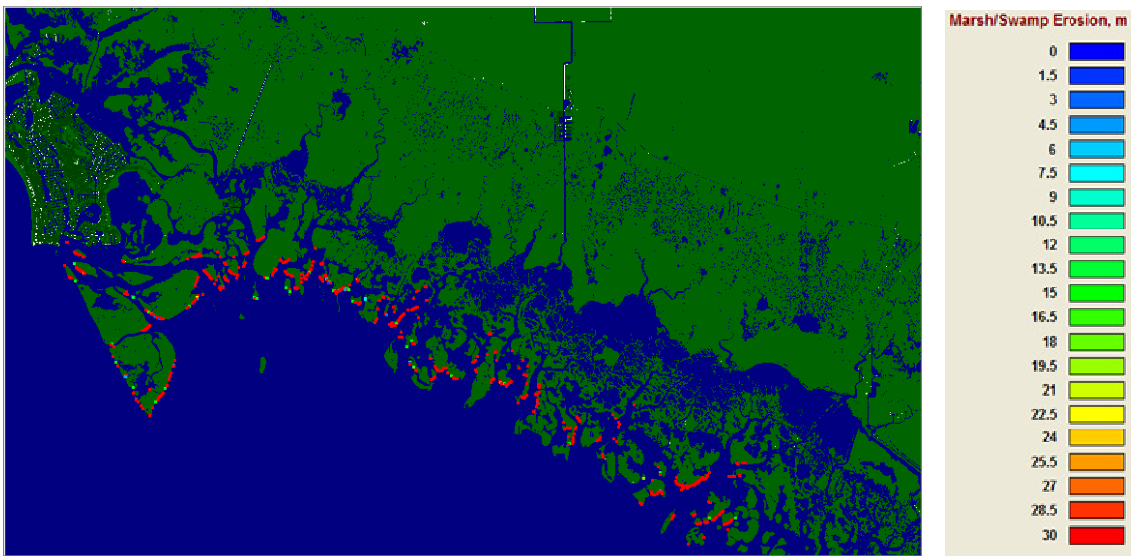


Figure 17. Horizontal marsh erosion (m)

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 the VDatum correction values.

According to the vertical accuracy report associated with these data (Florida Division of Emergency Management (FDEM) 2008), the root mean squared error (RMSE) for these LiDAR data is 0.091 m.

According the VDatum website the RMSE for the study region is 0.041 m (National Oceanic and Atmospheric Association 2010). This value was determined by combining the uncertainty associated with the NAVD to MSL transformation (0.03 m) and MSL to MTL transformation (0.011 m).

The means of evaluating elevation data uncertainty was 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 18). 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 (Hunter and Goodchild 1997) (Darnell et al. 2008). In this analysis, it was assumed that elevation errors were strongly spatially autocorrelated, using a "p-value" of 0.245[2].

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[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.

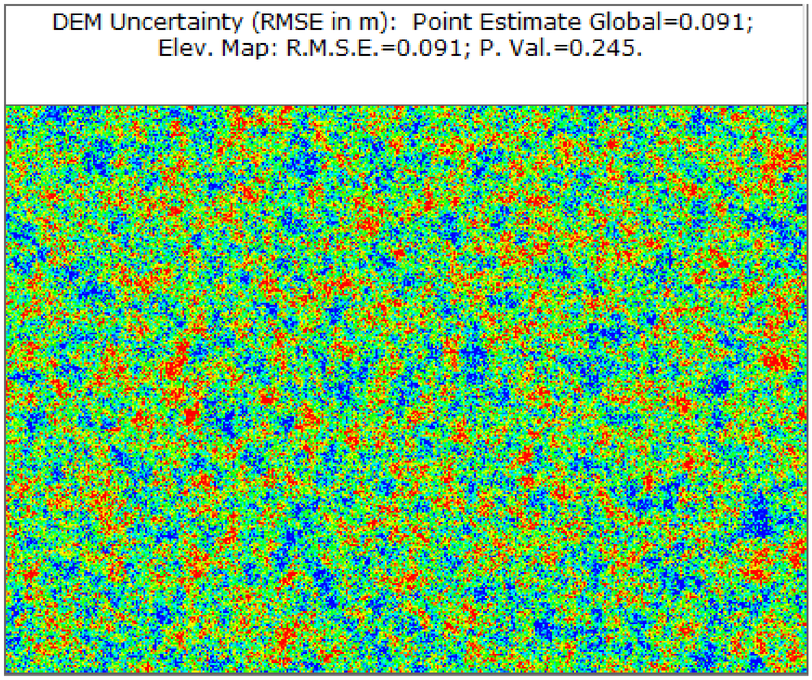

Figure 18. A spatially autocorrelated error field using parameters from this model application (m)

In this model elevation uncertainty analysis, 25 iterations were run for the study area representing approximately 50 hours of CPU time. The model was run with 0.69 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 quite limited, with the coefficient of variance (CV) remaining below 1% for the most prevalent land cover categories. These results reveal that the most widespread land covers do not substantially change given uncertainty in elevation values (Figure 19 and Figure 20). More generally, the results suggest that the model is not sensitive to errors on the scale of those measured for LiDAR data at this site, with standard deviations of the order of one to four acres. These model results suggest that methods that uniformly apply the 95th percentile uncertainty associated with the LiDAR data across an entire surface may be overly conservative (Gesch 2009).

Variable Name	Min	Mean	Max	Std. Dev.	Deterministic	CV
Mangrove	19,256.4	19,270.4	19,277.7	4.4	19,275.2	0.02%
Tidal Flat	1,142.1	1,144.5	1,147.1	1.4	1,125.0	0.12%
Regularly-Flooded Marsh	875.7	878.9	881.4	1.6	900.5	0.18%
Inland-Fresh Marsh	443.1	447.5	451.3	2.2	461.5	0.48%
Trans. Salt Marsh	117.8	127.2	136.8	3.4	116.1	2.93%
Undeveloped Dry Land	90.0	91.5	94.1	1.0	90.6	1.10%
Estuarine Beach	77.2	77.5	77.8	0.2	77.7	0.26%
Developed Dry Land	39.6	42.1	43.5	1.1	41.8	2.63%
Irreg.-Flooded Marsh	1.3	1.4	1.6	0.1	1.5	6.67%
Ocean Beach	1.0	1.1	1.1	0.0	1.1	0.00%

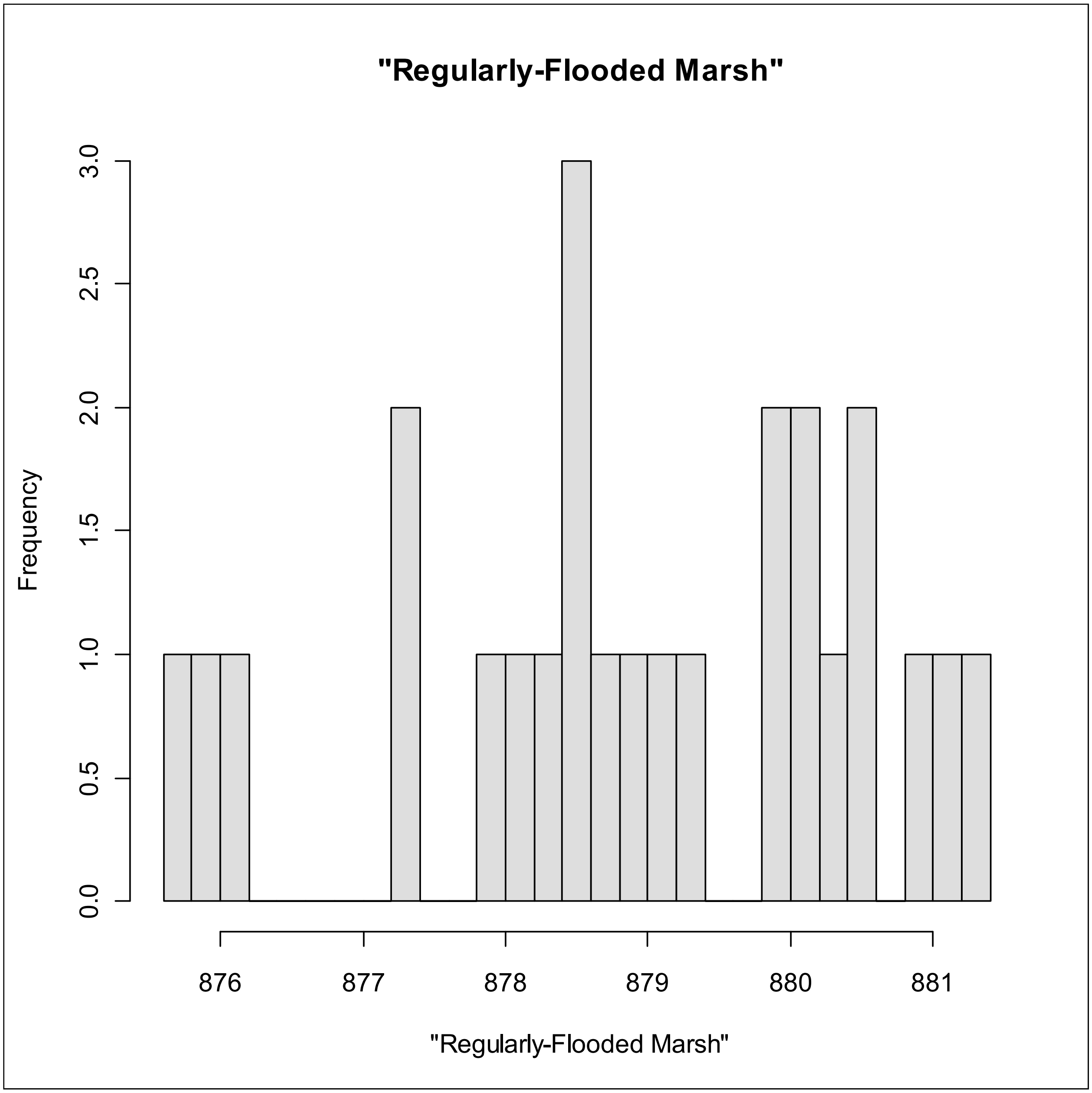

Figure 19. Elevation uncertainty result distribution for refuge regularly flooded marsh

Note, this shows predicted results in 2100 under 0.69 meters of eustatic SLR. The initial condition for regularly-flooded marsh was 905 acres.

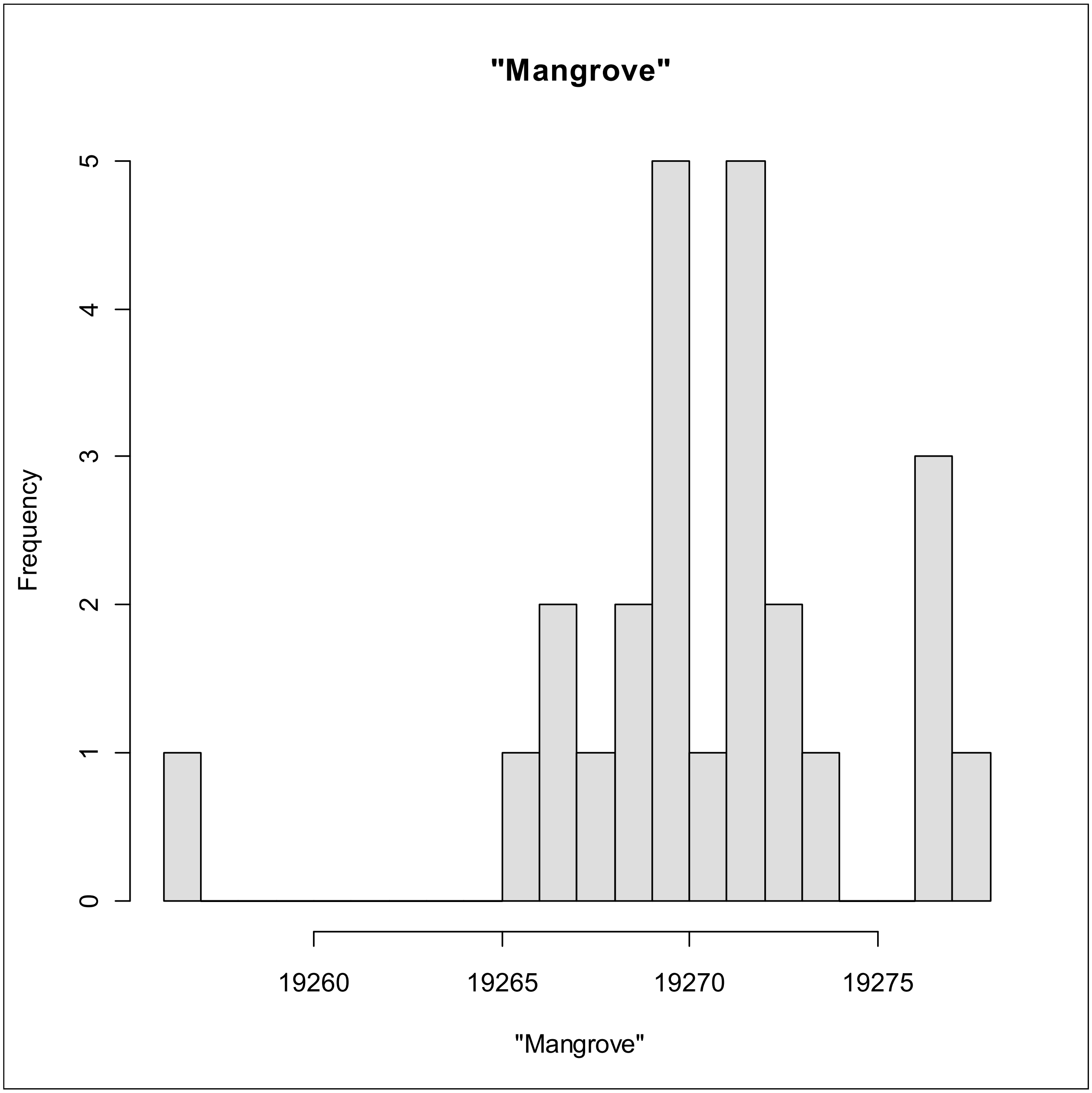

Figure 20. Elevation uncertainty result distribution for refuge mangrove

Note, this shows predicted results in 2100 under 0.69 meters of eustatic SLR. The initial condition for mangrove was 18455 acres.

Conclusions

Results for the SLAMM forecast for Ten Thousand Islands National Wildlife Refuge suggest that there is a break-point for SLR, between 1and 1.5 m, above which inundation effects become severe. Only islands with relatively high land elevations such as the dry land hammock at Dismal Key and a stretch of irregularly flooded marsh along the Pumpkin River are predicted to persist given a eustatic SLR of 2 m. Conversely, below a SLR rate of 1 m by 2100 most of the land appears to be relatively resistant to inundation.

Mangrove loss is minimal in the lowest SLR scenarios and actually a gain is observed due to mangrove accretion and expansion onto previously dry lands. At higher SLR scenarios however, mangrove accretion fails to keep up with SLR and the predicted mangrove acreage declines dramatically. Mangroves appear resilient to SLR in this study in part due to the accretion rate of 7 mm/yr. applied. This rate represents site-specific data measured in Rookery Bay, FL, which is less than 20 miles from the furthest point in the Ten Thousand Islands study area (Cahoon and Lynch 1997).

It is important to note that, for the northern portion of the refuge, mangrove expansion is influenced not only by SLR but also freezing temperatures. SLAMM does not incorporate changes in air temperatures within its prediction of mangrove habitat, which may introduce some uncertainty regarding the expansion and loss of mangroves to this analysis.

As the overwhelming majority of tidal flat and beach lacked elevation data, the elevations of these types of land cover were estimated as a function of the local tide range. This introduces important uncertainty into model results for these categories as model elevation assumptions may not reflect actual elevations for these land types.

An analysis of elevation uncertainty was conducted as part of this SLAMM application. Results suggested the most widespread land covers (i.e., mangrove, tidal flat, regularly-flooded and inland fresh marsh) do not change substantially given uncertainty in elevation values and that the model is not sensitive to errors on the scale of those measured for LiDAR data at this site.

References

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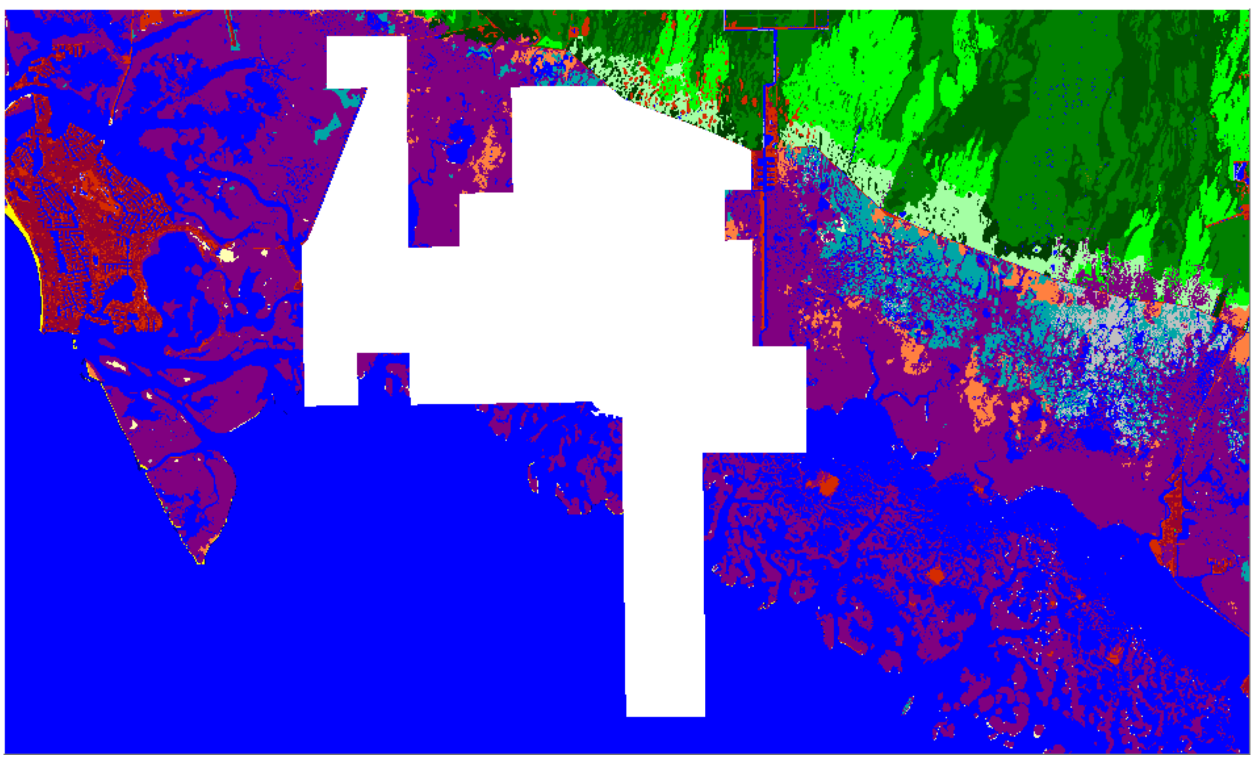
Appendix A: Contextual Results

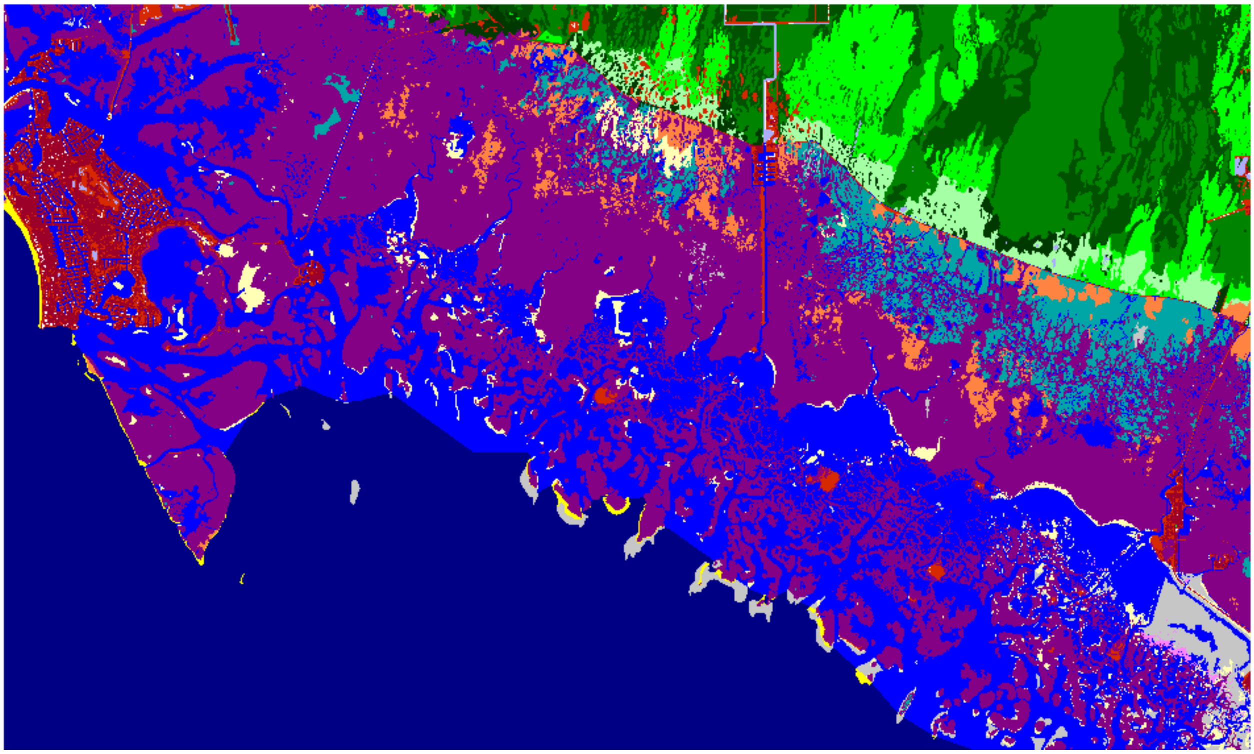
The SLAMM model does take into account the context of the surrounding lands or open water when calculating effects. For example, erosion rates are calculated based on the maximum fetch (wave action) which is estimated by assessing contiguous open water to a given marsh cell. Another example is that inundated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

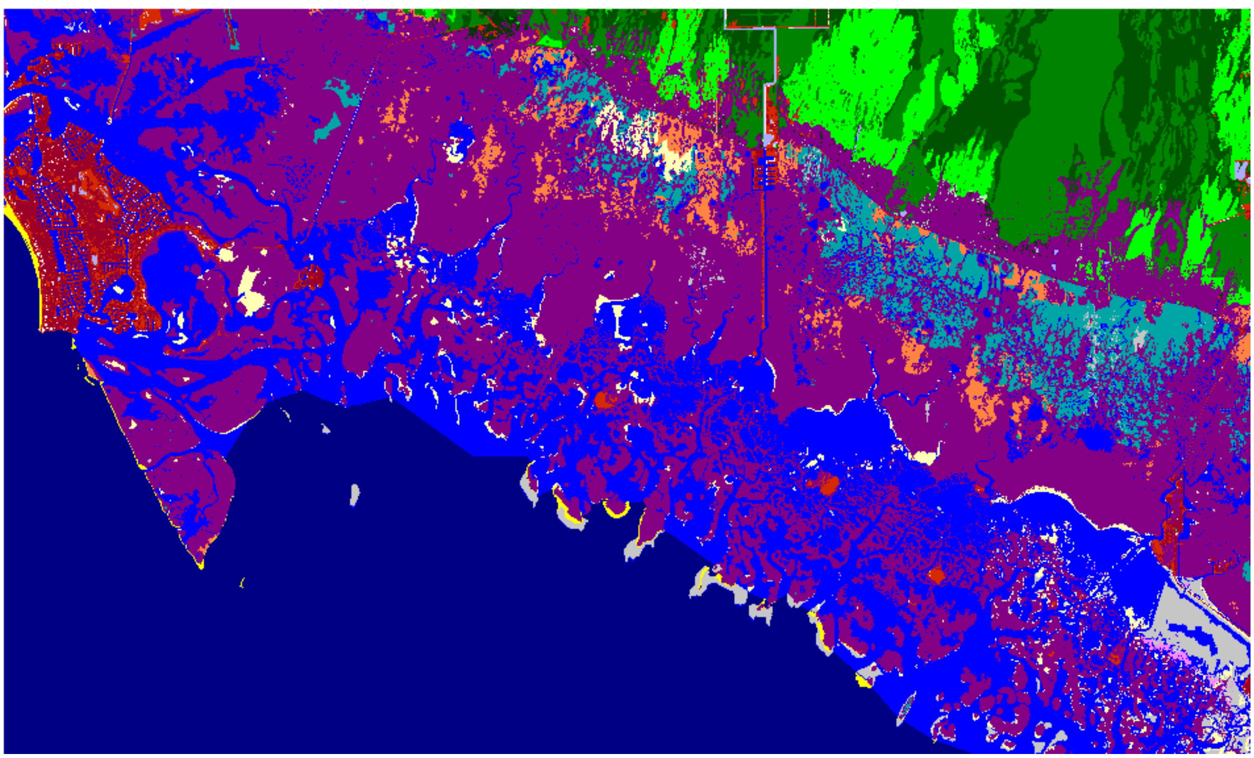
- Results were closely examined (quality assurance) within USFWS refuges but not closely examined for the larger region.
- Site-specific parameters for the model were derived for USFWS refuges whenever possible and may not be regionally applicable.
- Especially in areas where dikes are present, an effort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



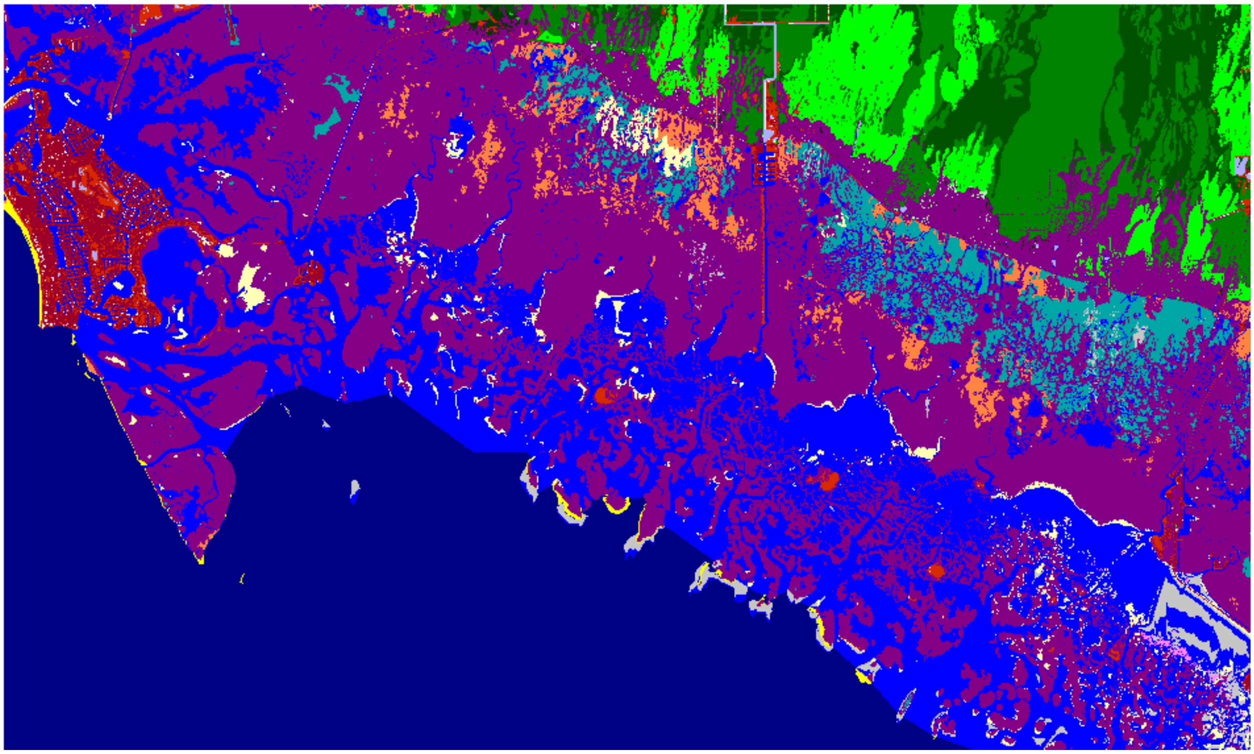
Ten Thousand Islands National Wildlife Refuge within simulation context (white).



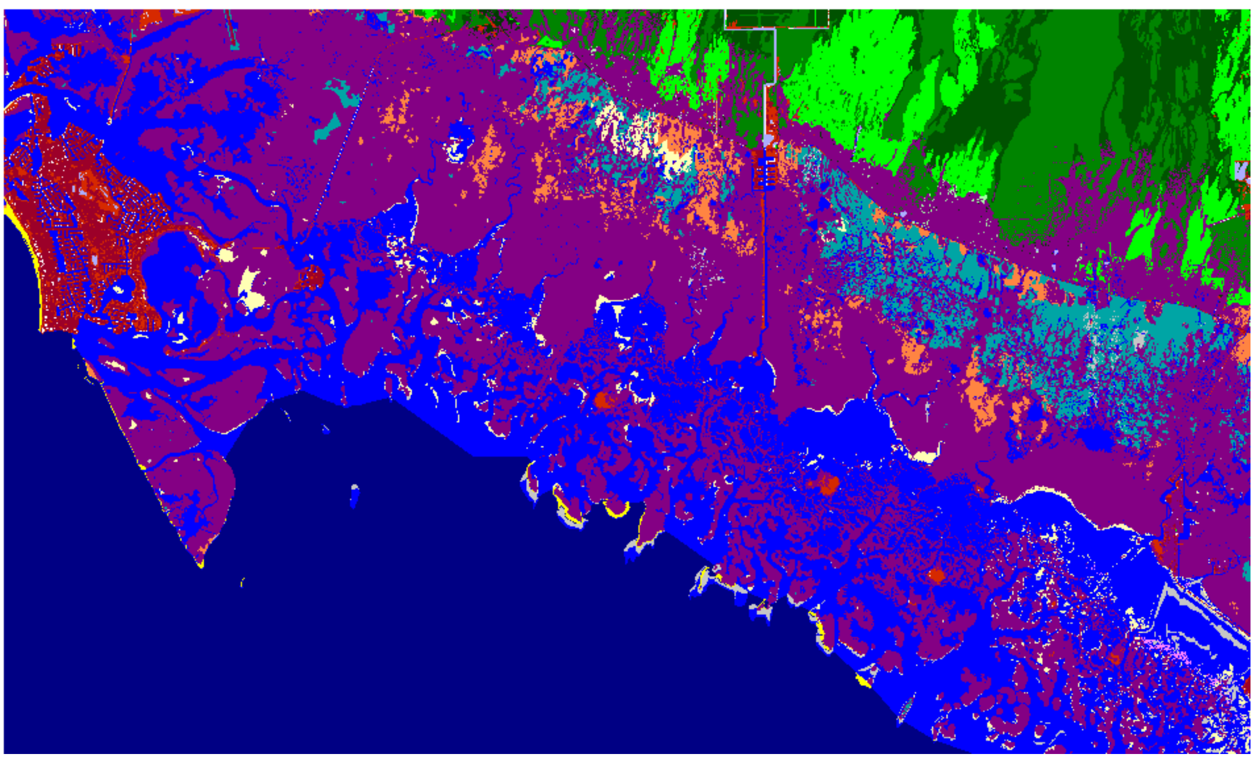
Ten Thousand Islands Context, Initial Condition



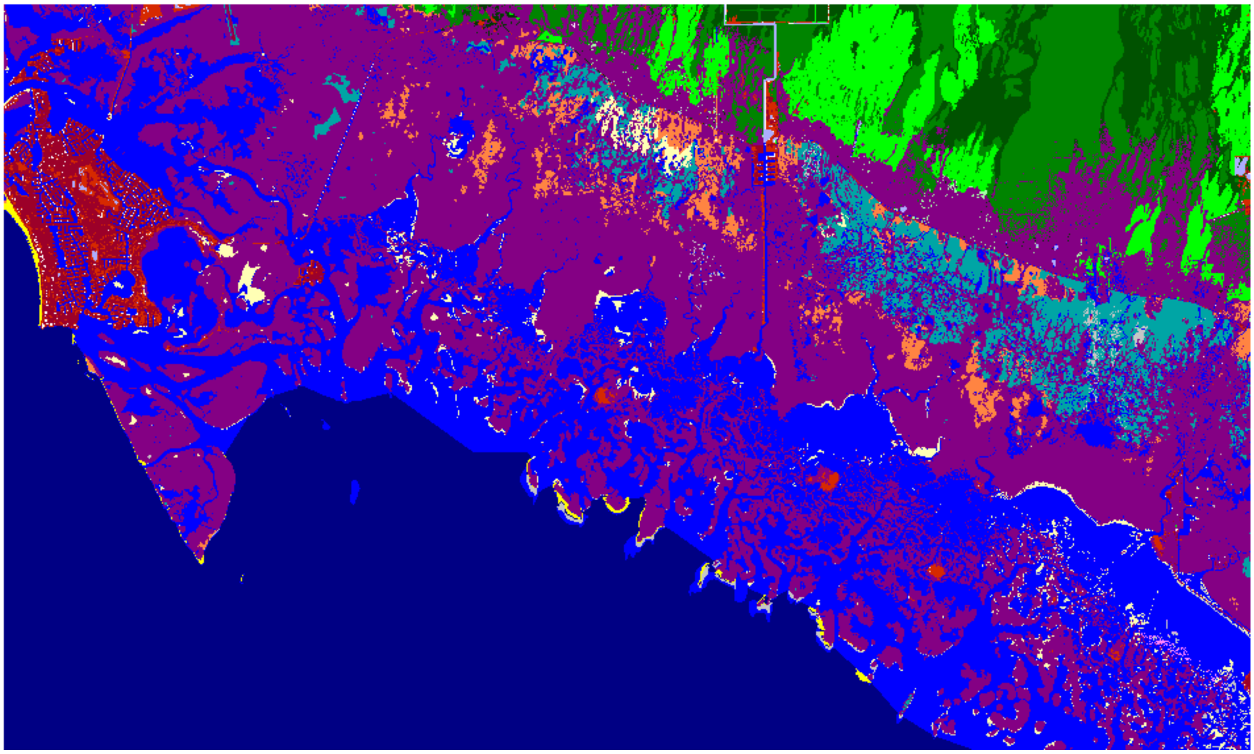
Ten Thousand Islands Context, 2025, Scenario A1B Mean



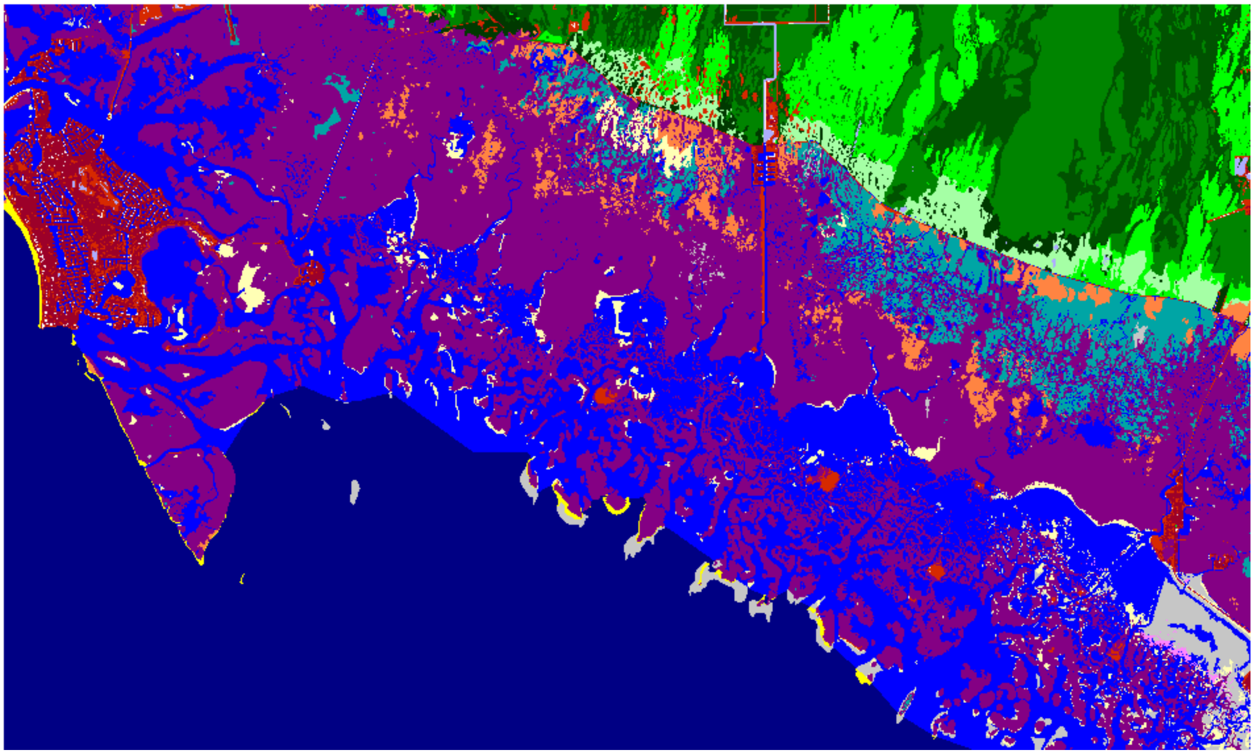
Ten Thousand Islands Context, 2050, Scenario A1B Mean

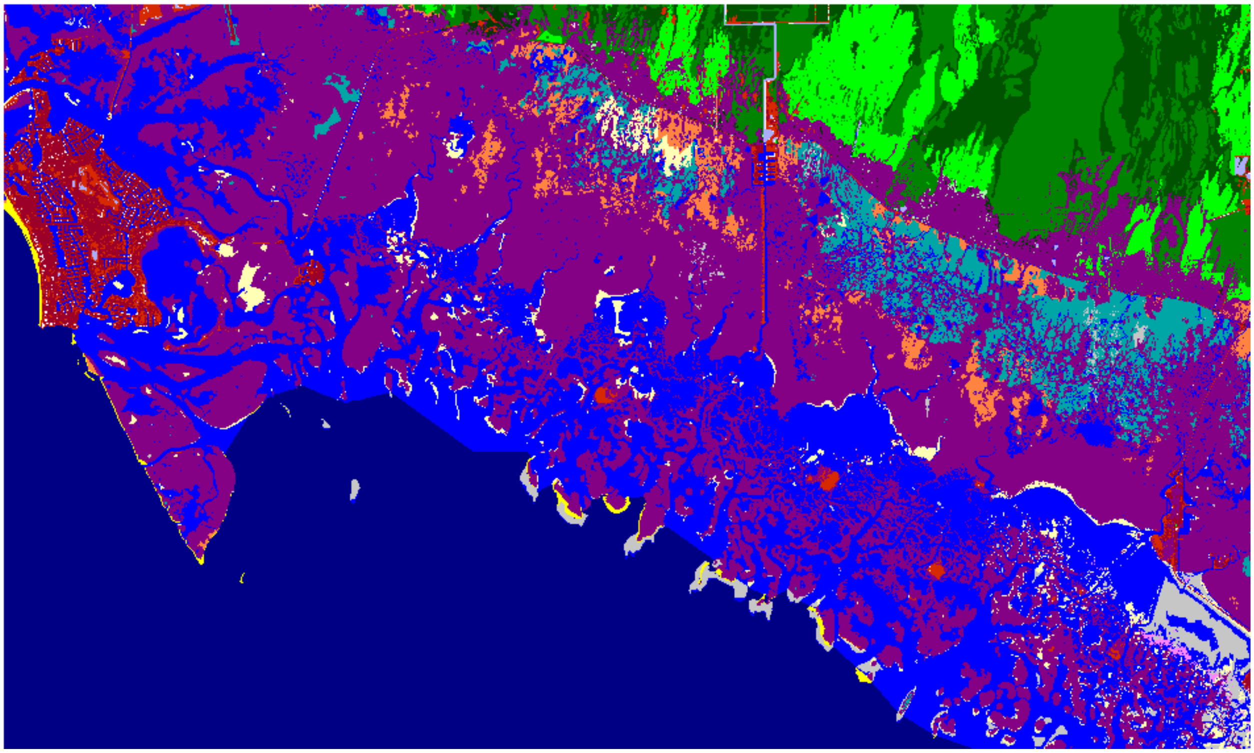


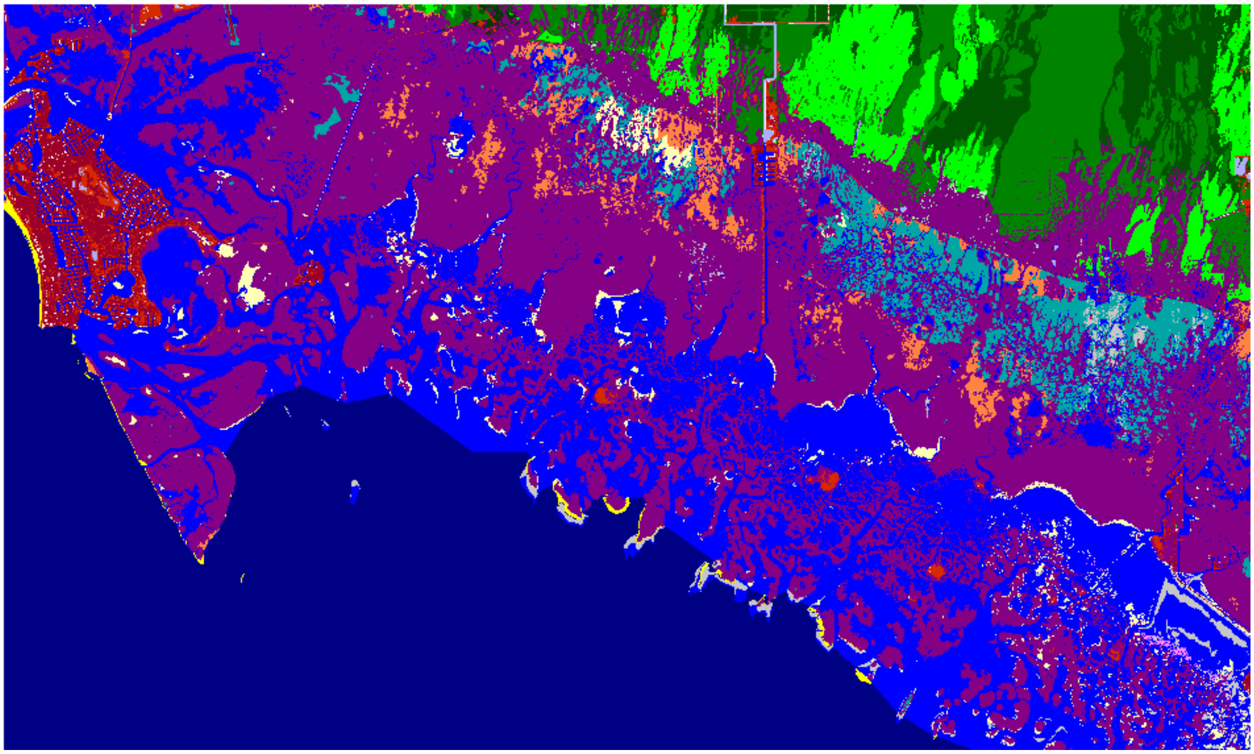
Ten Thousand Islands Context, 2075, Scenario A1B Mean

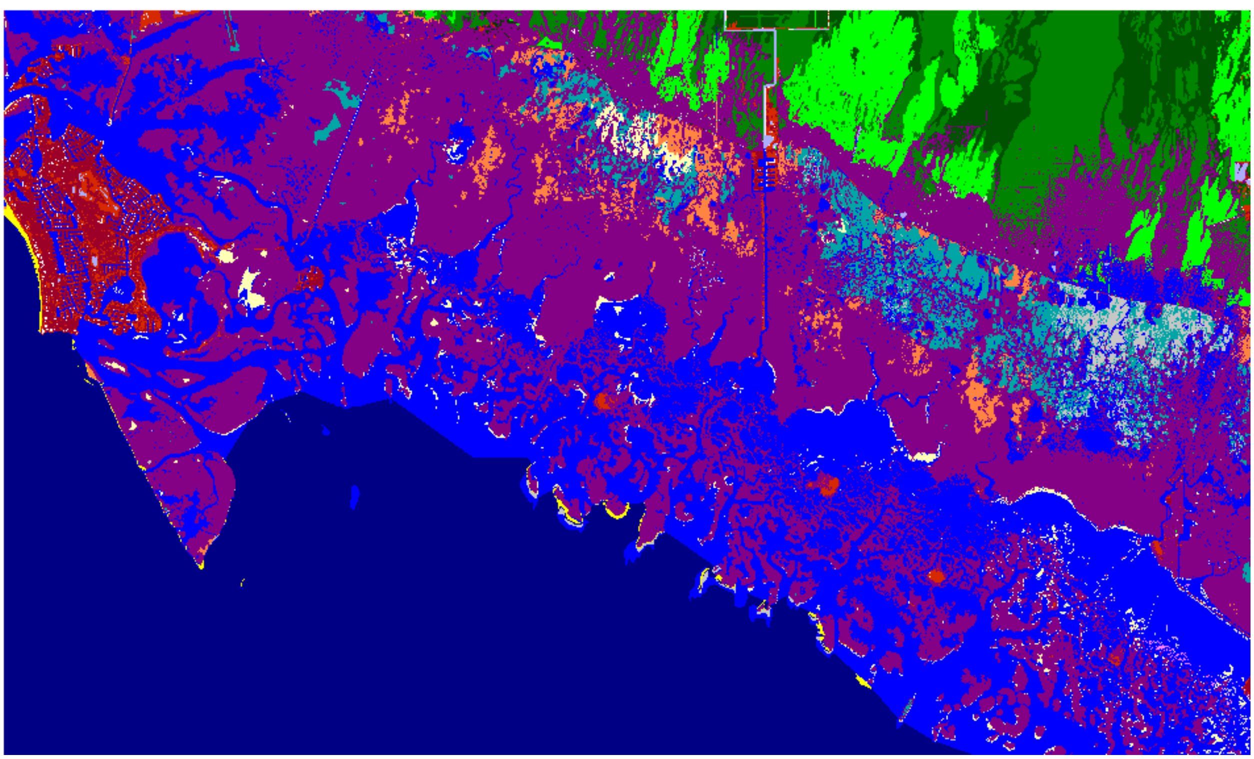


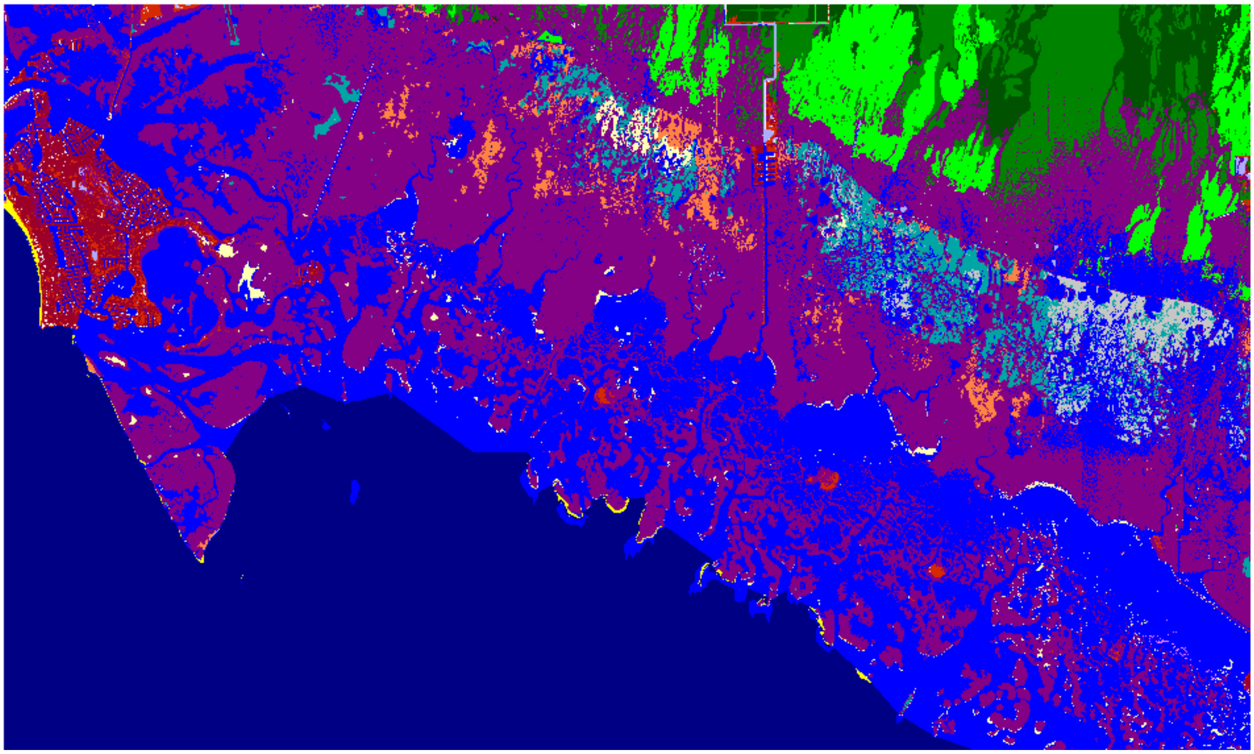
Ten Thousand Islands Context, 2100, Scenario A1B Mean


Ten Thousand Islands Context, Initial Condition

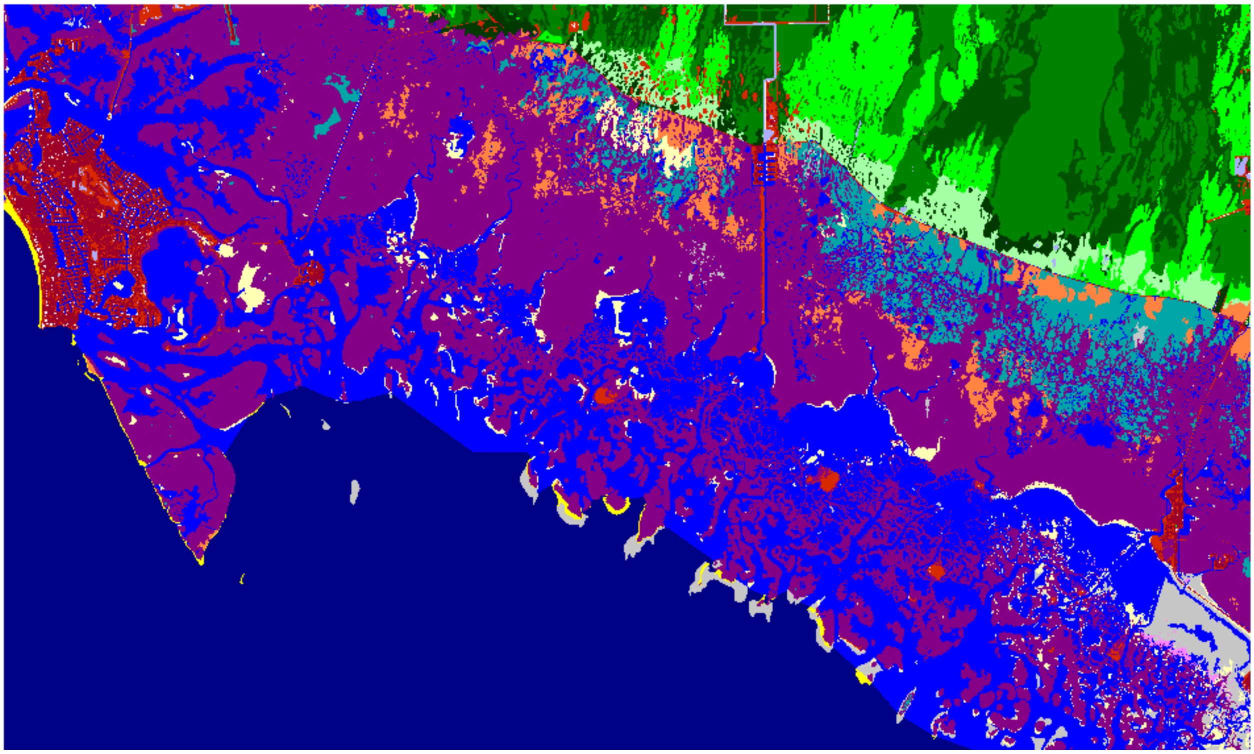

Ten Thousand Islands Context, 2025, Scenario A1B Maximum


Ten Thousand Islands Context, 2050, Scenario A1B Maximum

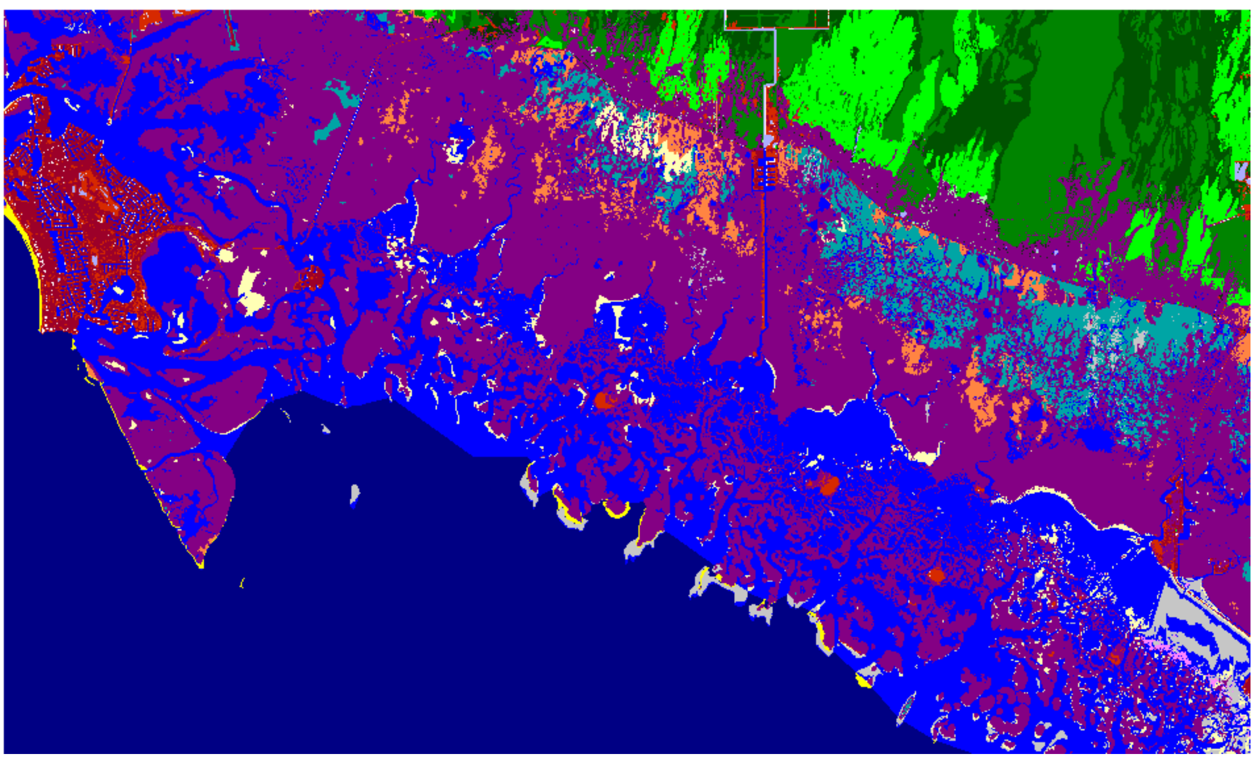

Ten Thousand Islands Context, 2075, Scenario A1B Maximum



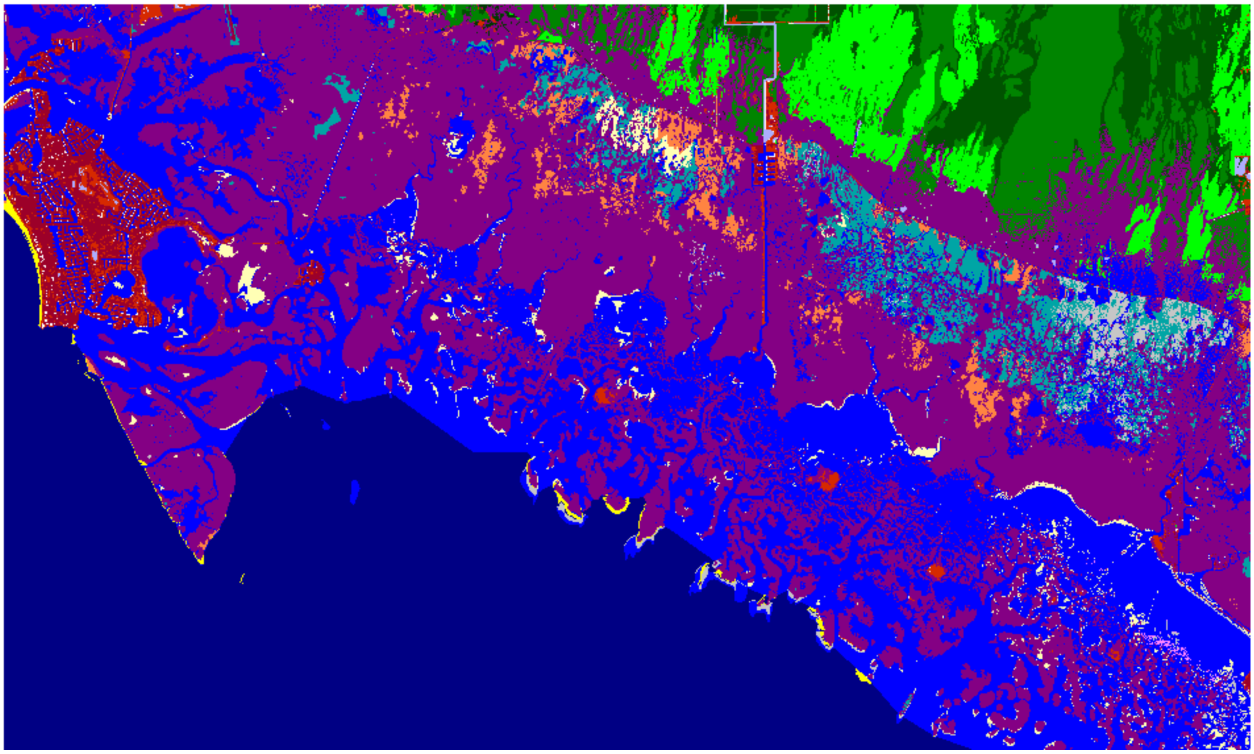
Ten Thousand Islands Context, 2100, Scenario A1B Maximum



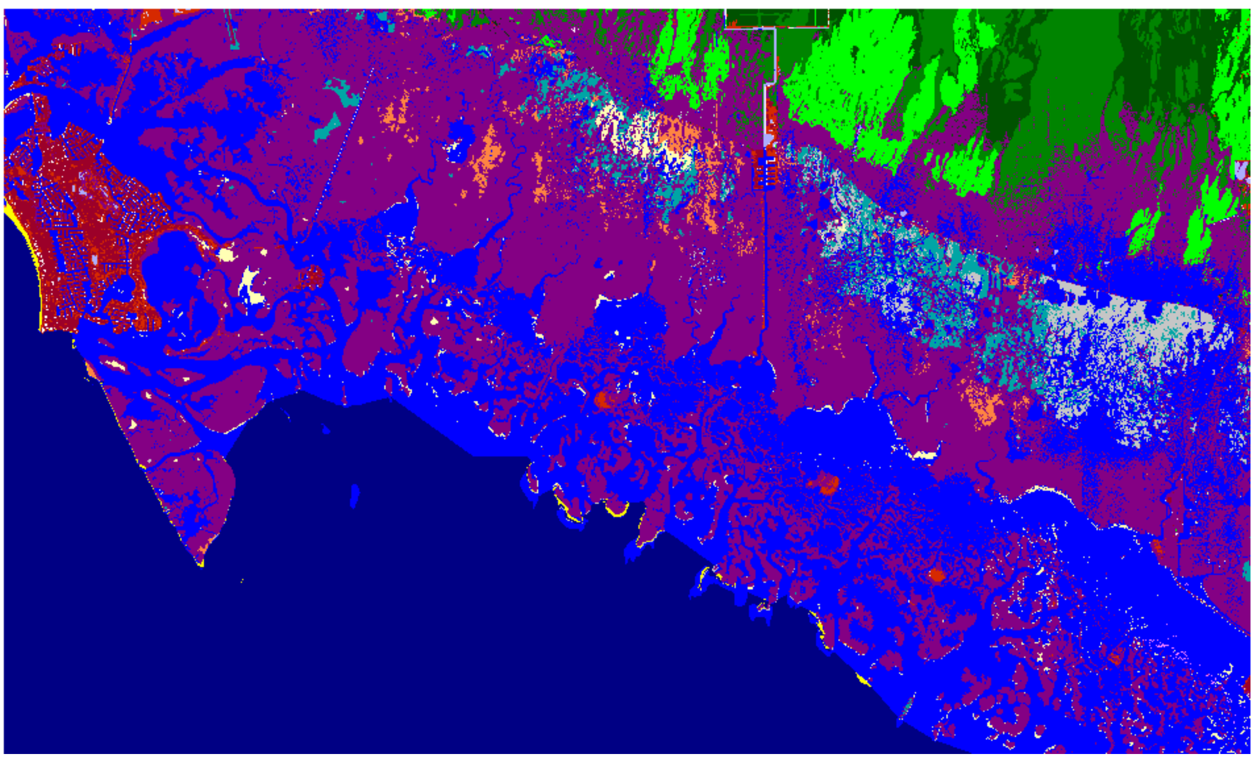
Ten Thousand Islands Context, Initial Condition



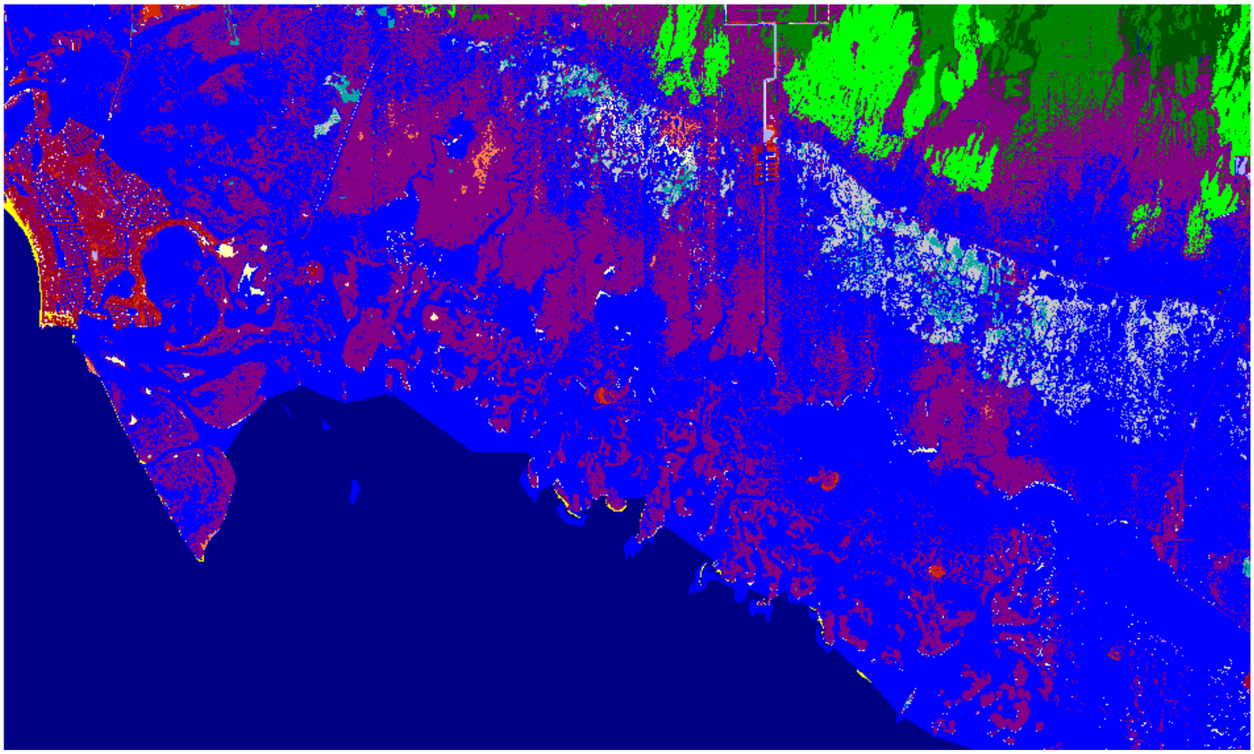
Ten Thousand Islands Context, 2025, 1 meter



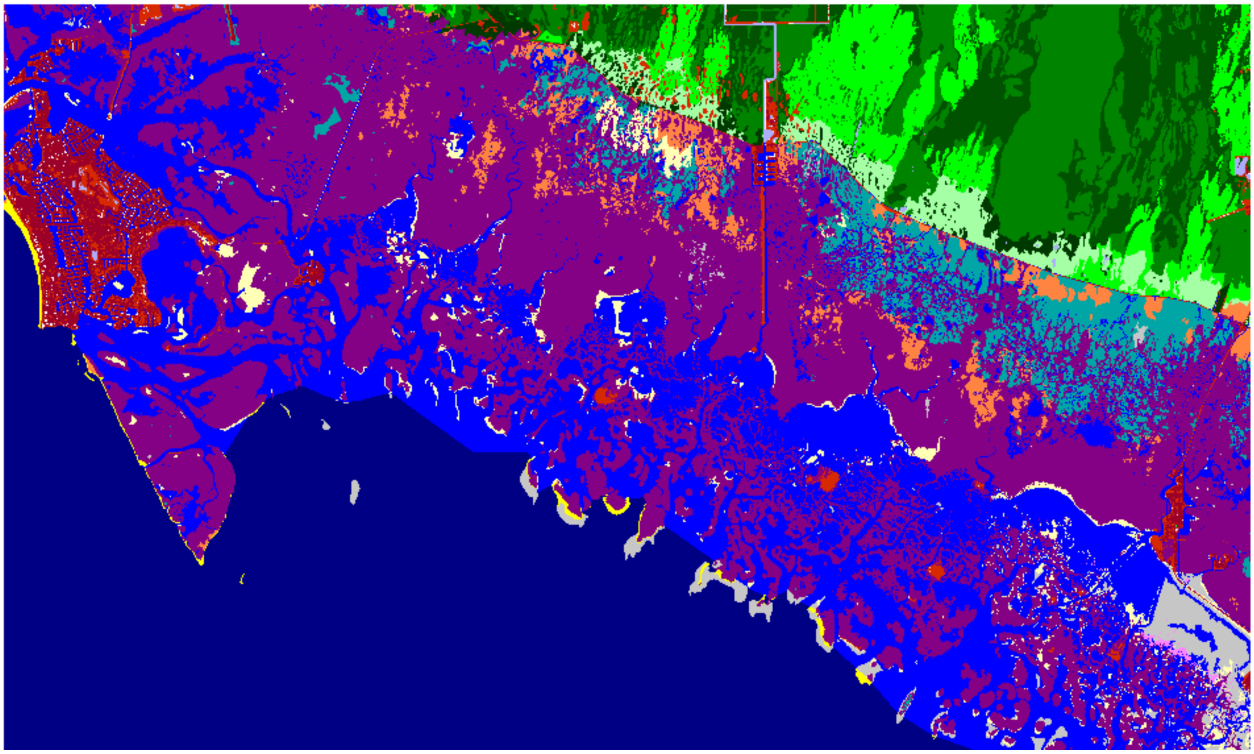
Ten Thousand Islands Context, 2050, 1 meter



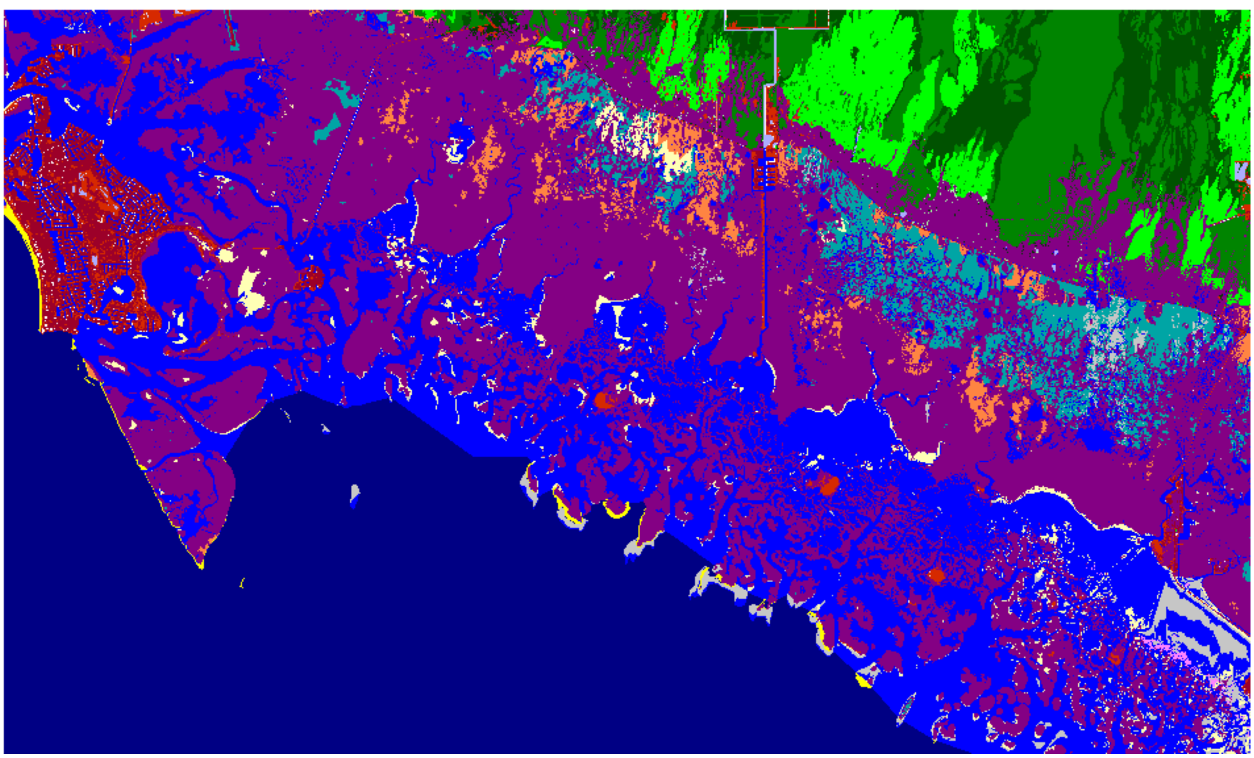
Ten Thousand Islands Context, 2075, 1 meter



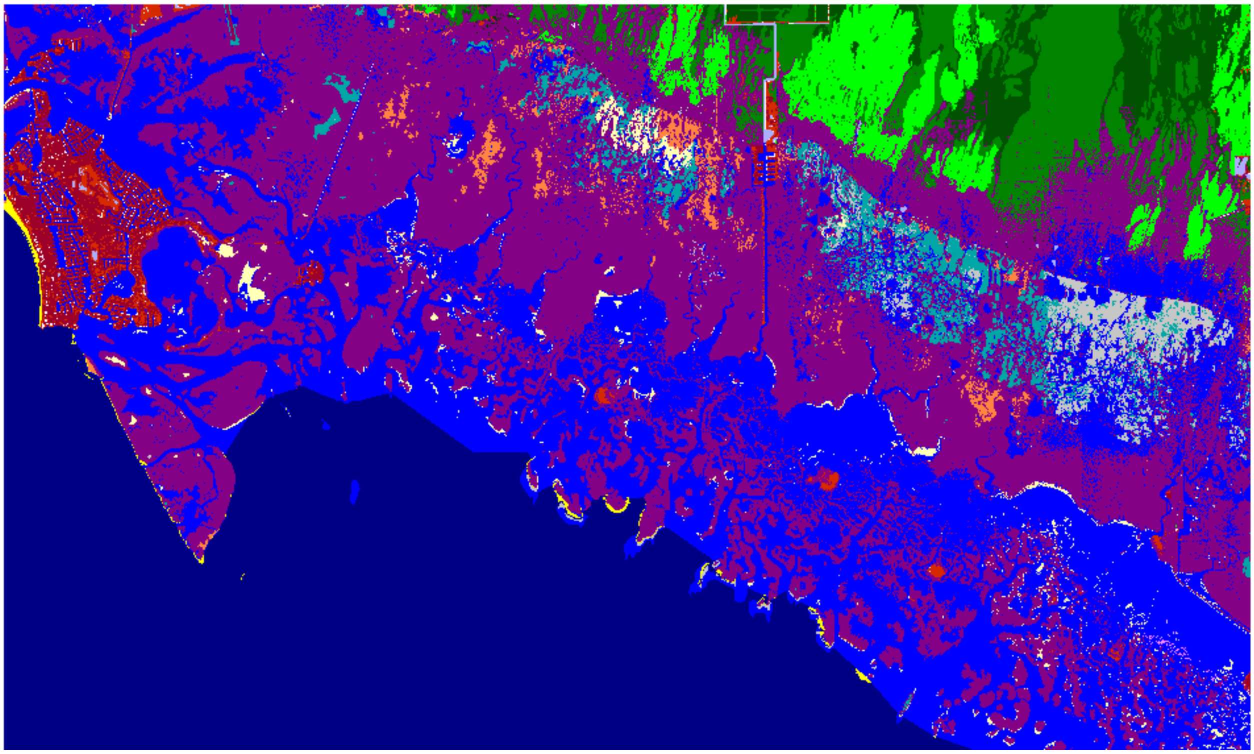
Ten Thousand Islands Context, 2100, 1 meter



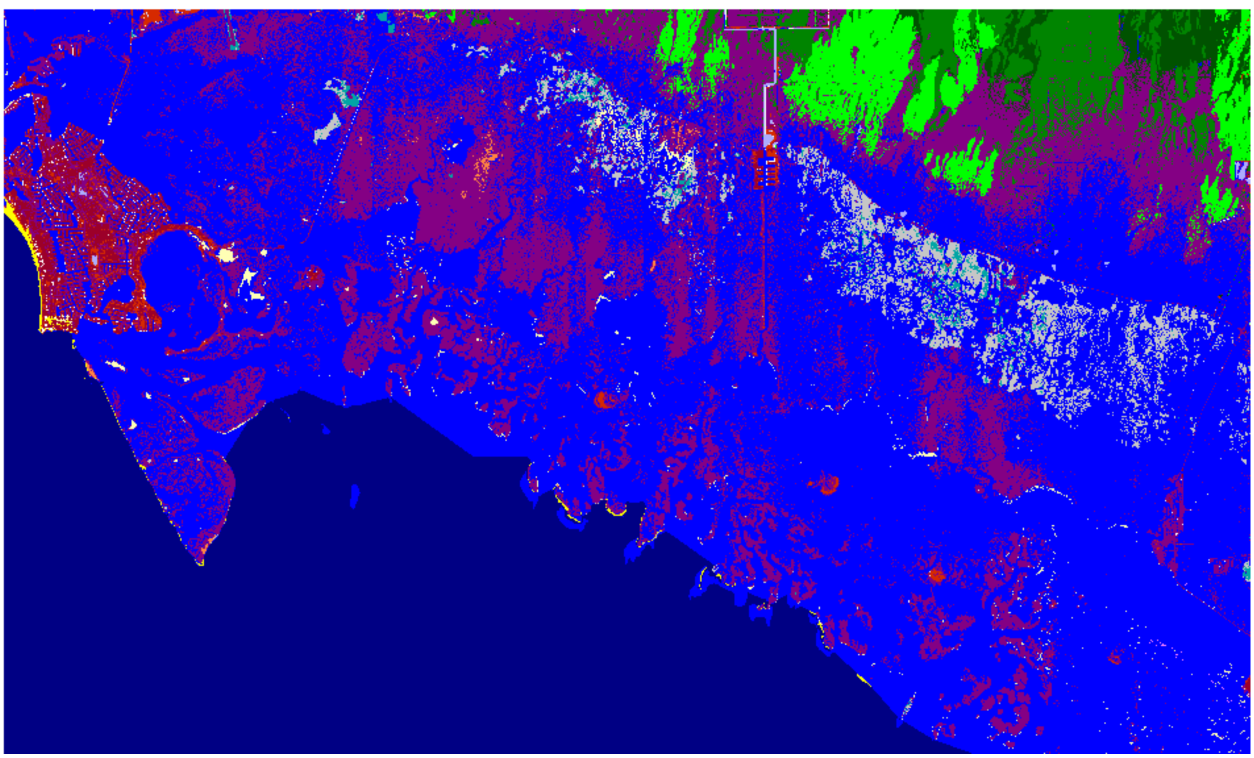
Ten Thousand Islands Context, Initial Condition



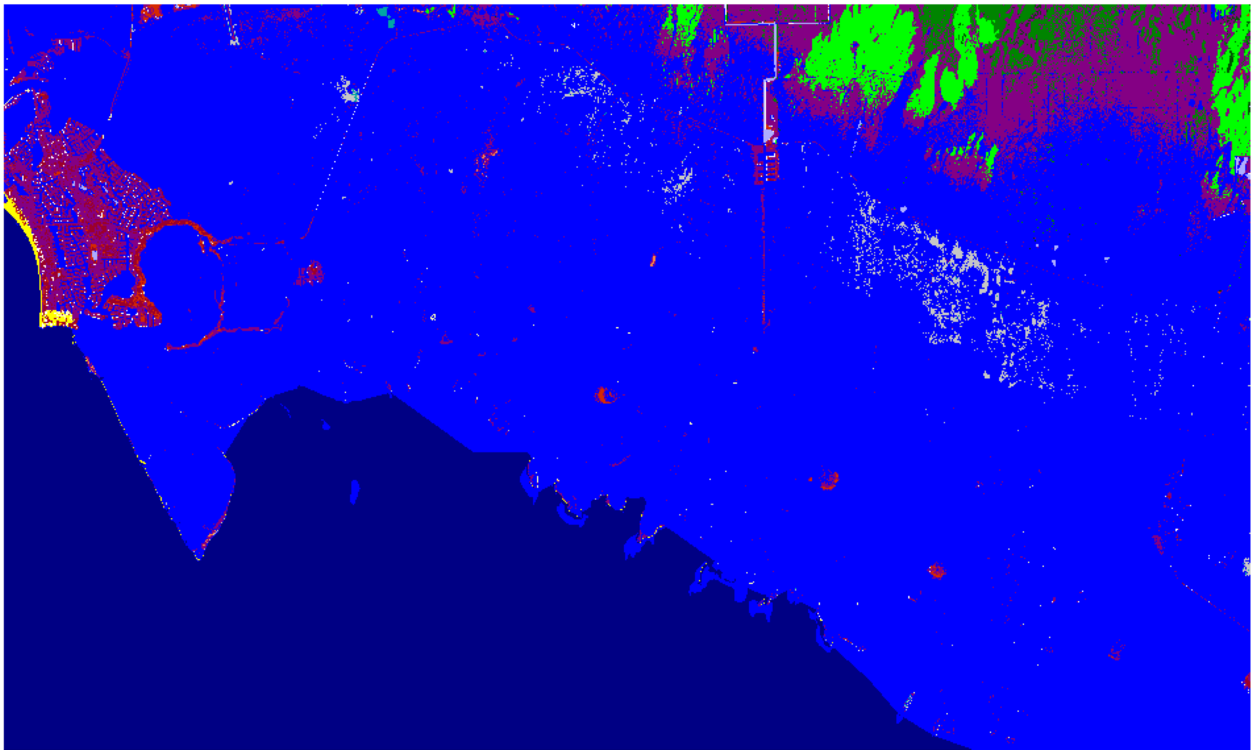
Ten Thousand Islands Context, 2025, 1.5 meter



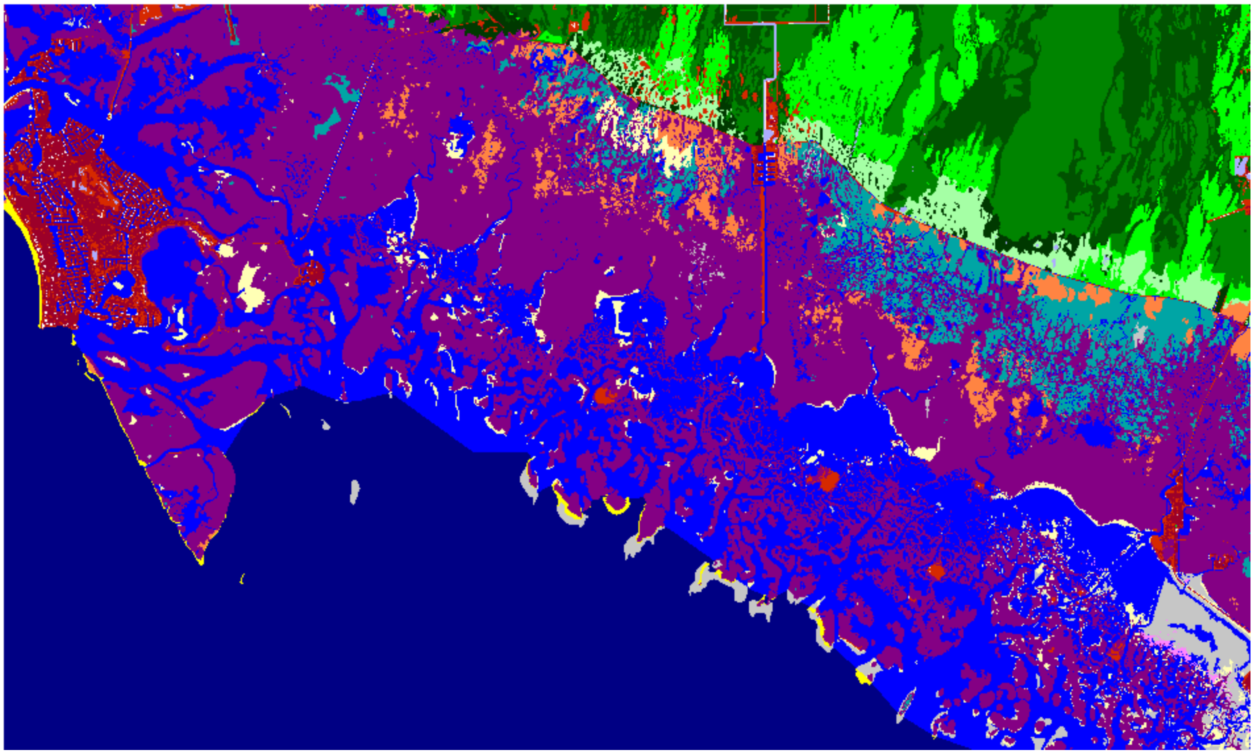
Ten Thousand Islands Context, 2050, 1.5 meter



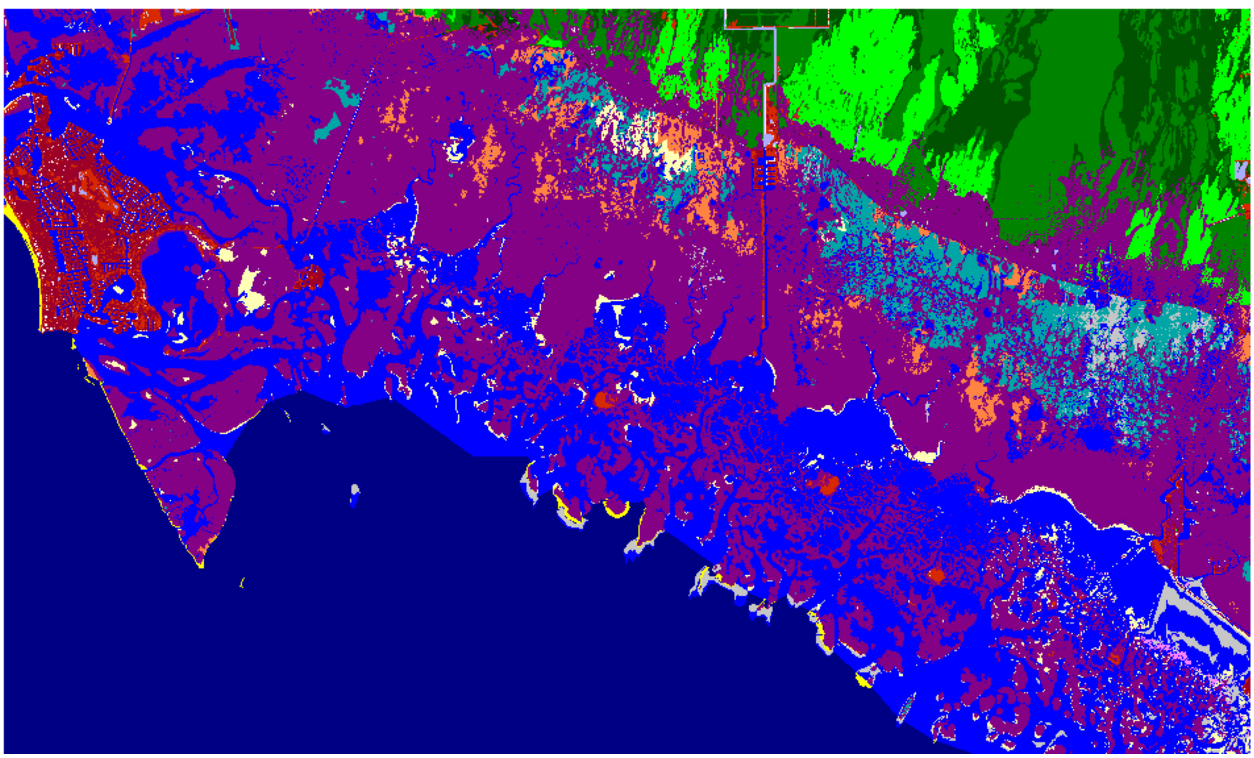
Ten Thousand Islands Context, 2075, 1.5 meter



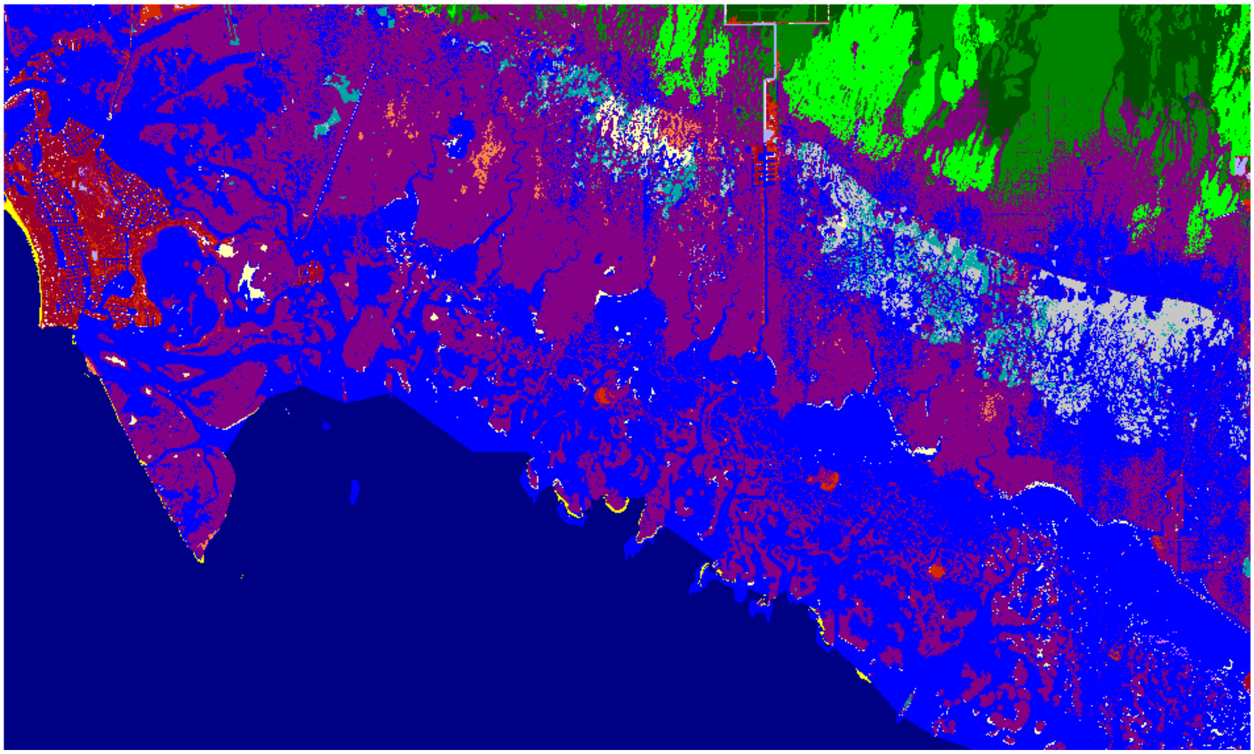
Ten Thousand Islands Context, 2100, 1.5 meter



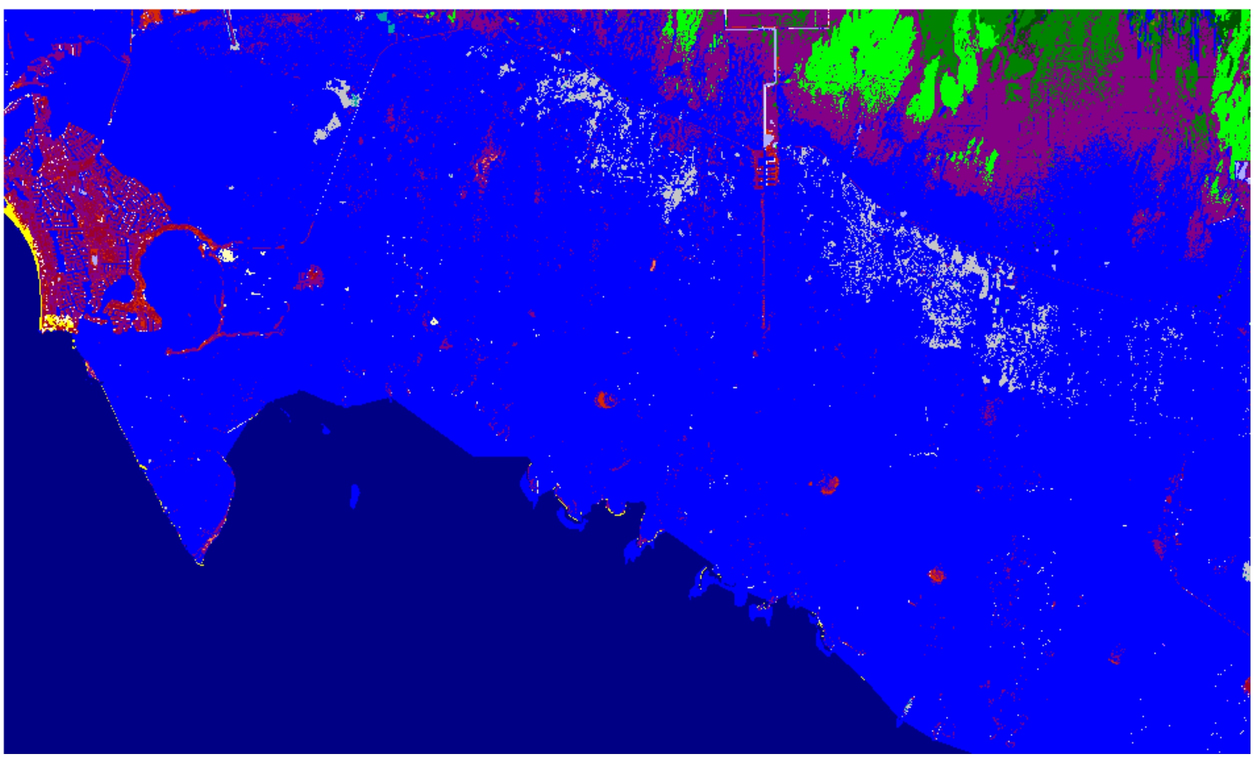
Ten Thousand Islands Context, Initial Condition



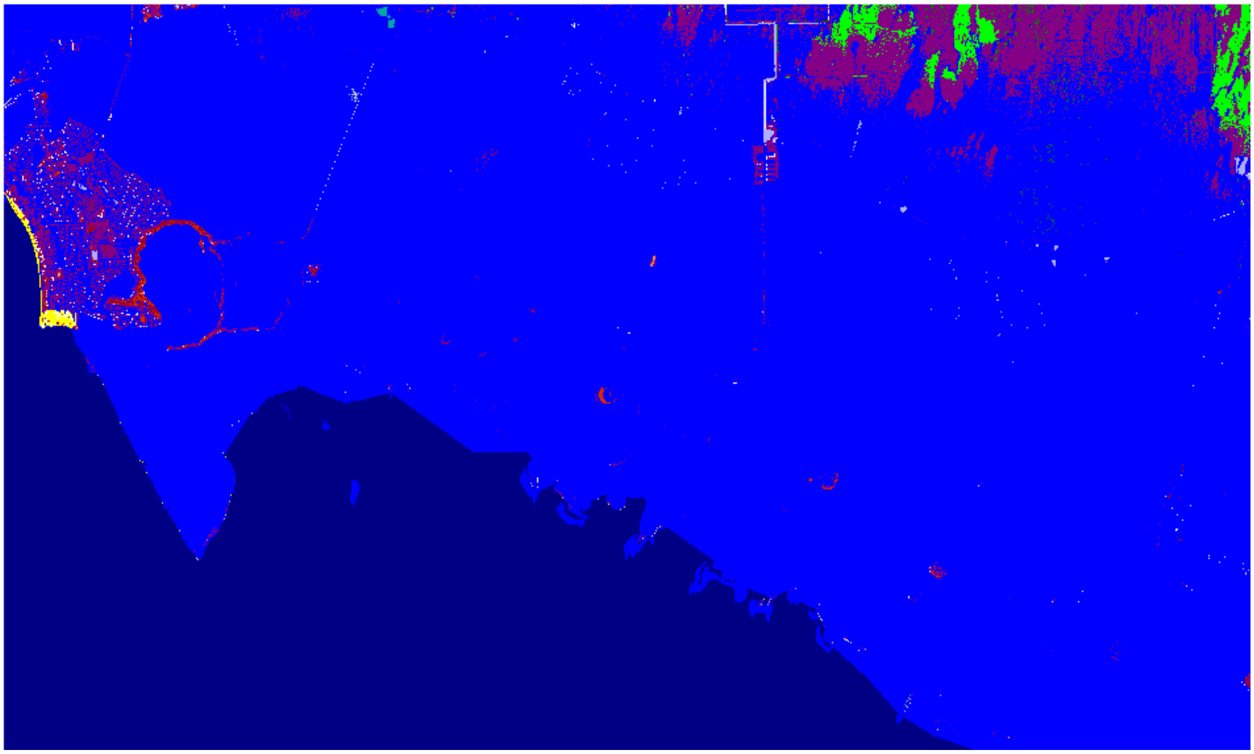
Ten Thousand Islands Context, 2025, 2 meter



Ten Thousand Islands Context, 2050, 2 meter



Ten Thousand Islands Context, 2075, 2 meter



Ten Thousand Islands Context, 2100, 2 meter