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

Prepared for

Gulf of Mexico Alliance
Habitat Conservation and Restoration Priority Issue Team
Corpus Christi, TX 78411

August 10, 2011

warren pinnacle consulting, inc.
PO Box 315, Waitsfield VT, 05673
(802)-496-3476

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This model application was prepared for the Gulf of Mexico Alliance through a grant from the Gulf of Mexico Foundation to support the Habitat Conservation and Restoration Priority Issue Team, a part of the Governor's Gulf of Mexico Alliance.

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 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 Lower Suwannee 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 Lower Suwannee NWR as produced under this contract.

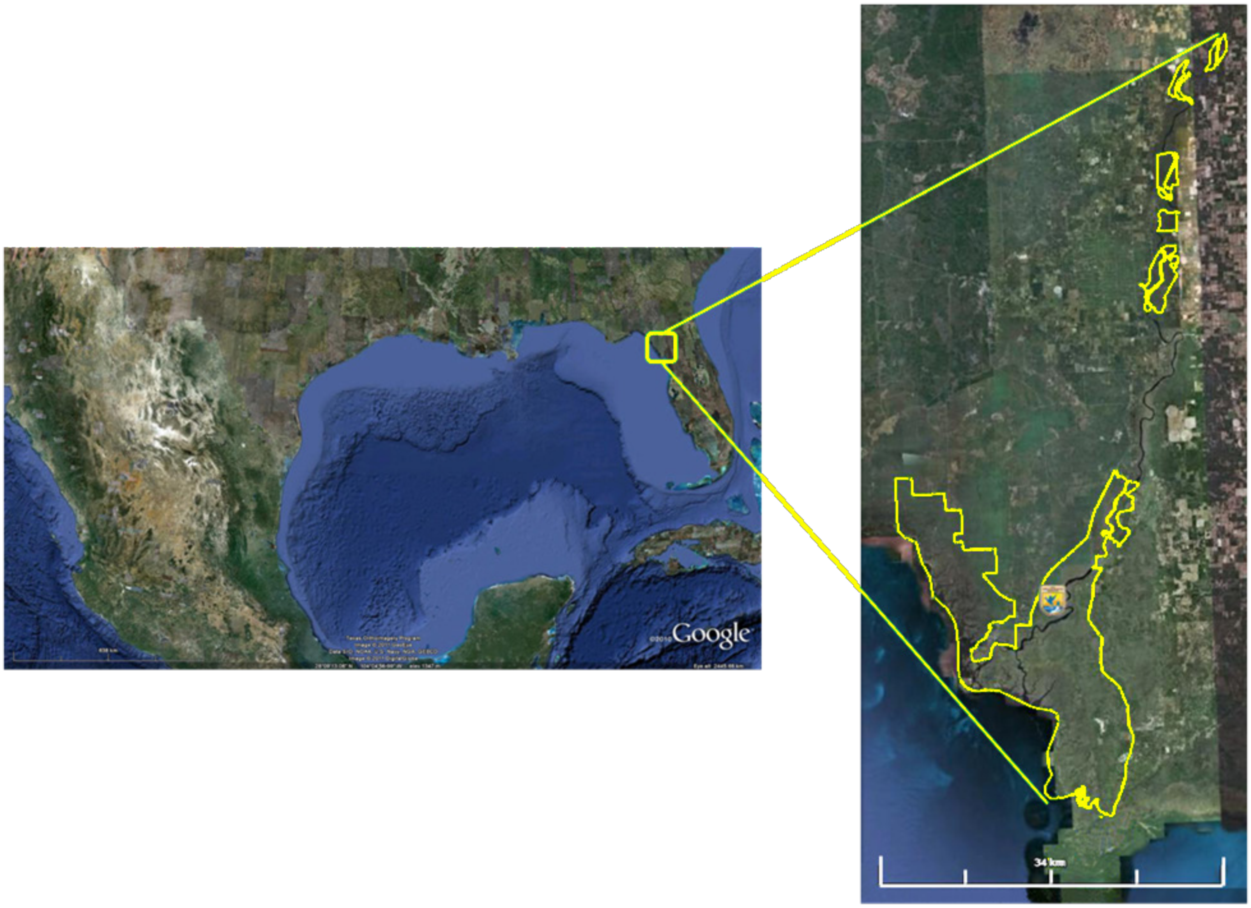

Figure 1. Location of study area within context of the Gulf of Mexico

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, 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 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 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 the simulations of Lower Suwannee NWR.

- 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 (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).

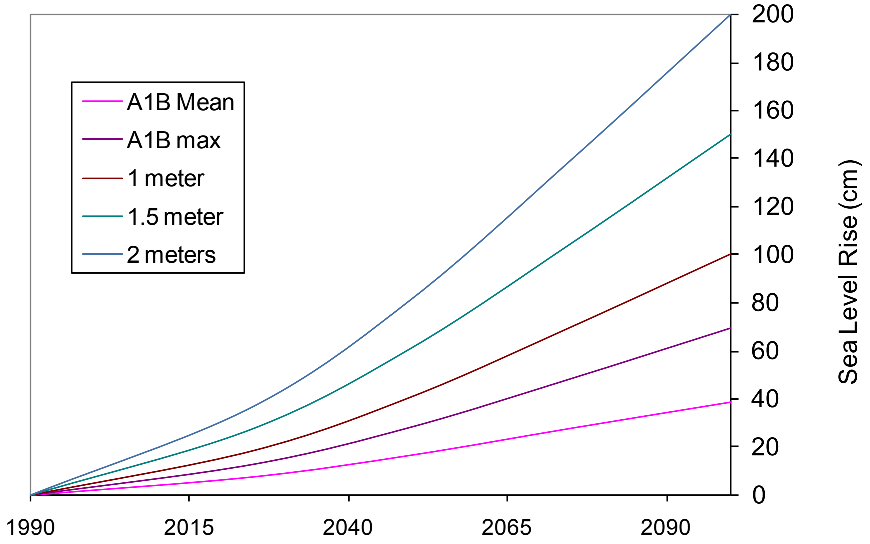

Figure 2. Summary of SLR scenarios utilized

When the model was run to estimate wetland changes in the past ("hindcasting"), the local rate of SLR from 1984 to 1990 was estimated to be 1.8 mm/year. This value is the observed average SLR trend observed between 1914 and 2006 at the gauge station of Cedar Key, FL (NOAA gauge # 8727520). The global rate of SLR from 1990 to the present was estimated to be 3 mm/year (Grinsted et al. 2009)[1].

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[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 wetland layer used as initial conditions for model predictions. This layer was obtained by combining recent National Wetlands Inventory (NWI) with photo dates of 2007-2010 for the majority of the refuge (Figure 4). Converting the NWI survey into 30 m cells indicated that the approximately 84,000 acre refuge (approved acquisition boundary including water) is composed of the following categories:

Land cover type		**Area (acres)**	**Percentage (%)**
🟩	Swamp	29,391	35
🟦	Regularly Flooded Marsh	18,788	22
🟥	Undeveloped Dry Land	12,493	15
🟦	Estuarine Open Water	10,795	13
🟩	Tidal Swamp	3,504	4
🟩	Inland Fresh Marsh	2,234	3
🟨	Estuarine Beach	1,954	2
🟦	Riverine Tidal	1,531	2
🟩	Cypress Swamp	1,007	1
🟪	Mangrove	946	1
🟩	Tidal Fresh Marsh	464	<1
🟧	Irregularly Flooded Marsh	395	<1
🟦	Inland Open Water	196	<1
🟦	Open Ocean	194	<1
🟫	Transitional Salt Marsh	136	<1
🟥	Developed Dry Land	28	<1
⬜	Tidal Flat	6	<1
🟫	Inland Shore	2	<1
	Total (incl. water)	**84,063**	**100**

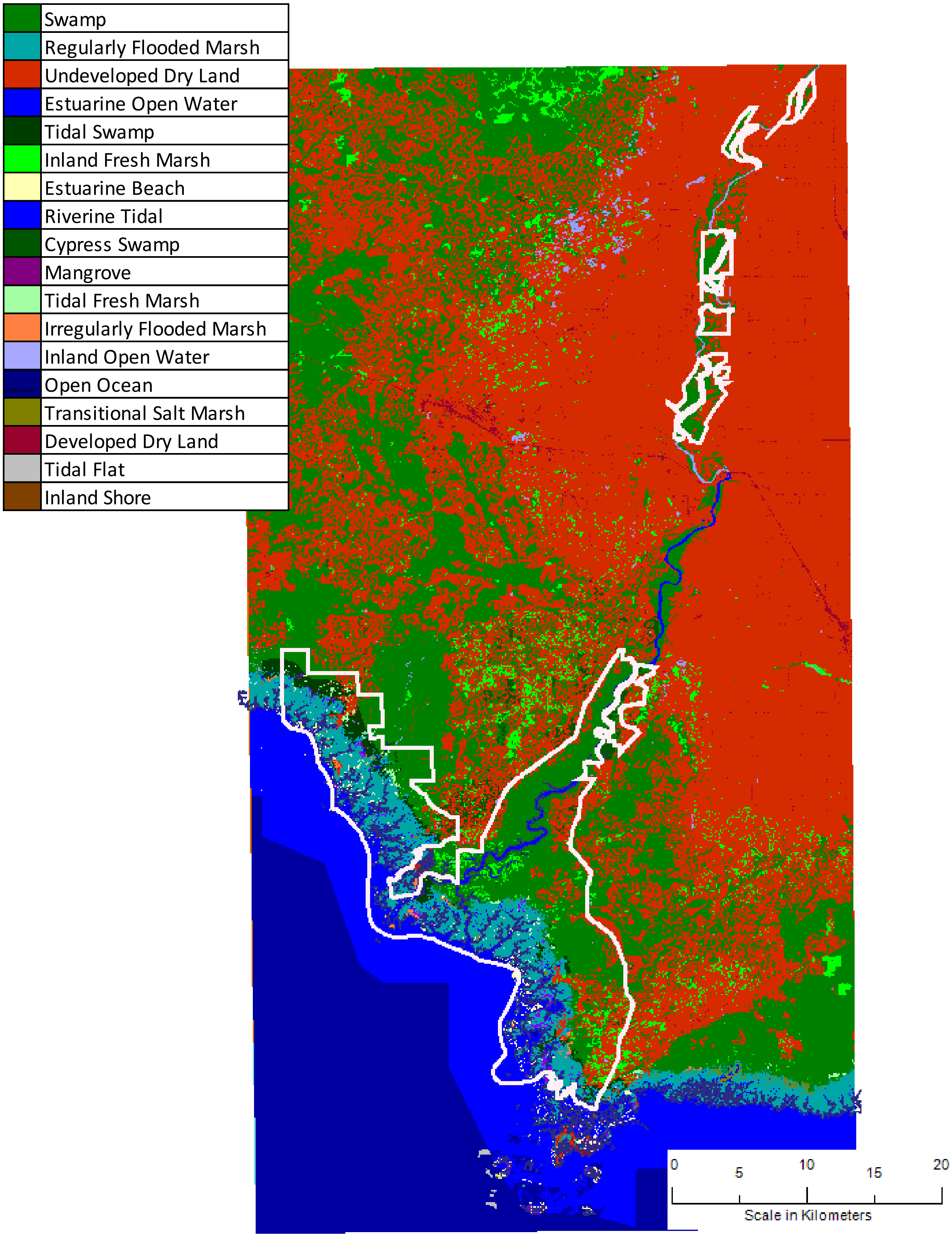


Figure 3. Recent wetland coverage of the study area. Refuge boundaries in white

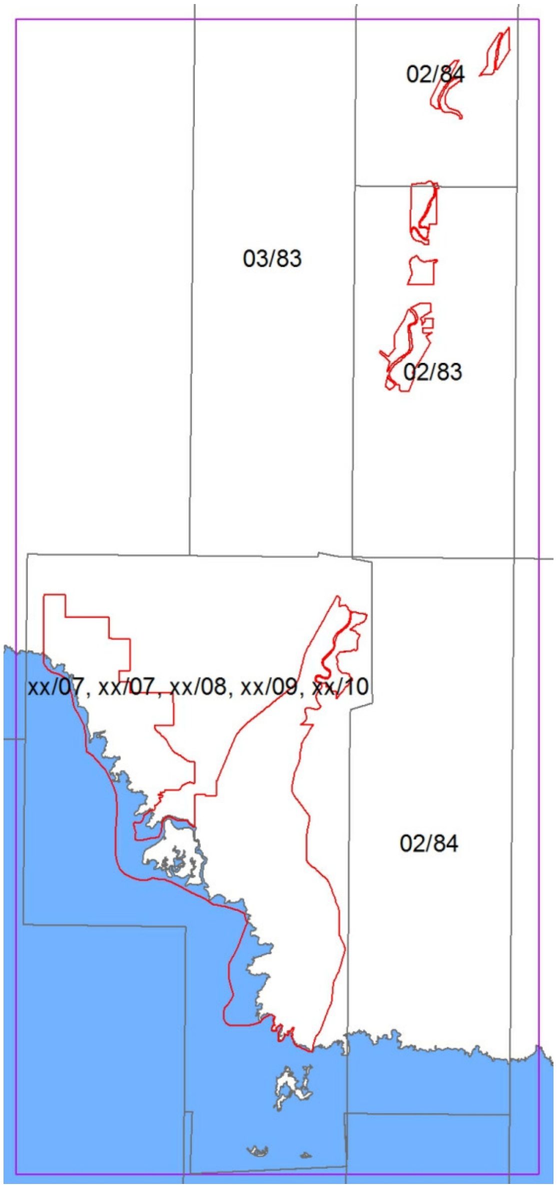


Figure 4. Recent NWI photo date

Elevation Data. The digital elevation map used in this simulation was derived from a combination of LiDAR data of the Florida Division of Emergency Management (FDEM) with a timestamp of 2007 and a small portion of 5-foot contour National Elevation Data (NED) with a timestamp of 1967 (Figure 5). While the vast majority of the NWR is covered by the LiDAR, a northern portion of the refuge, near the Hatchbend Conservation Area, lies within the NED data. Elevations of wetlands within this small NED-covered portion were estimated via the SLAMM preprocessor.

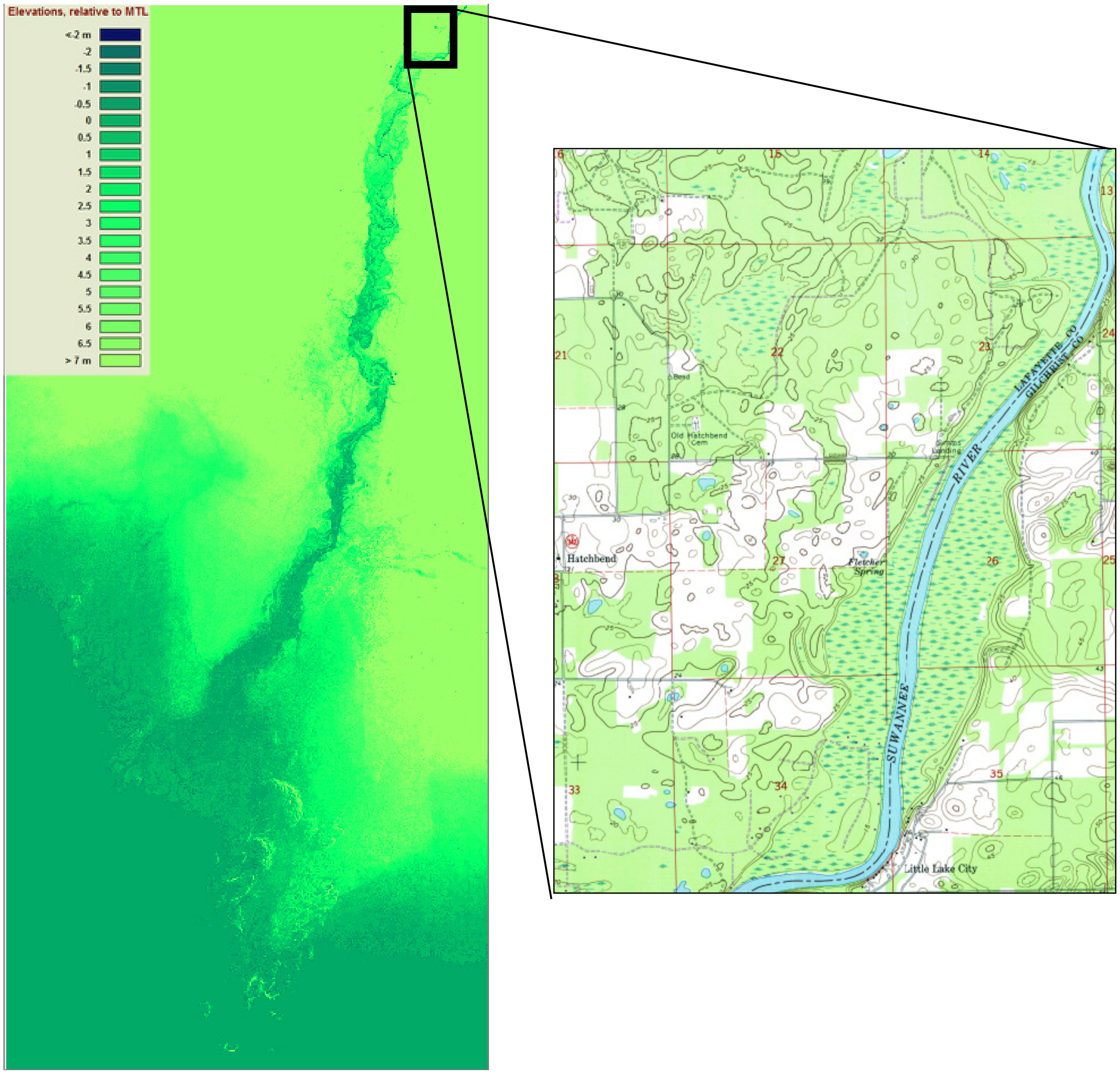


Figure 5. Shade-relief elevation map (left) of refuge. Inset area is covered with NED (right).

Historic wetland data. Figure 6 illustrates the older wetland coverage of the area, used for the hindcast. This layer is derived by combining NWI photos dated 1983 and 1984 (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 1983.

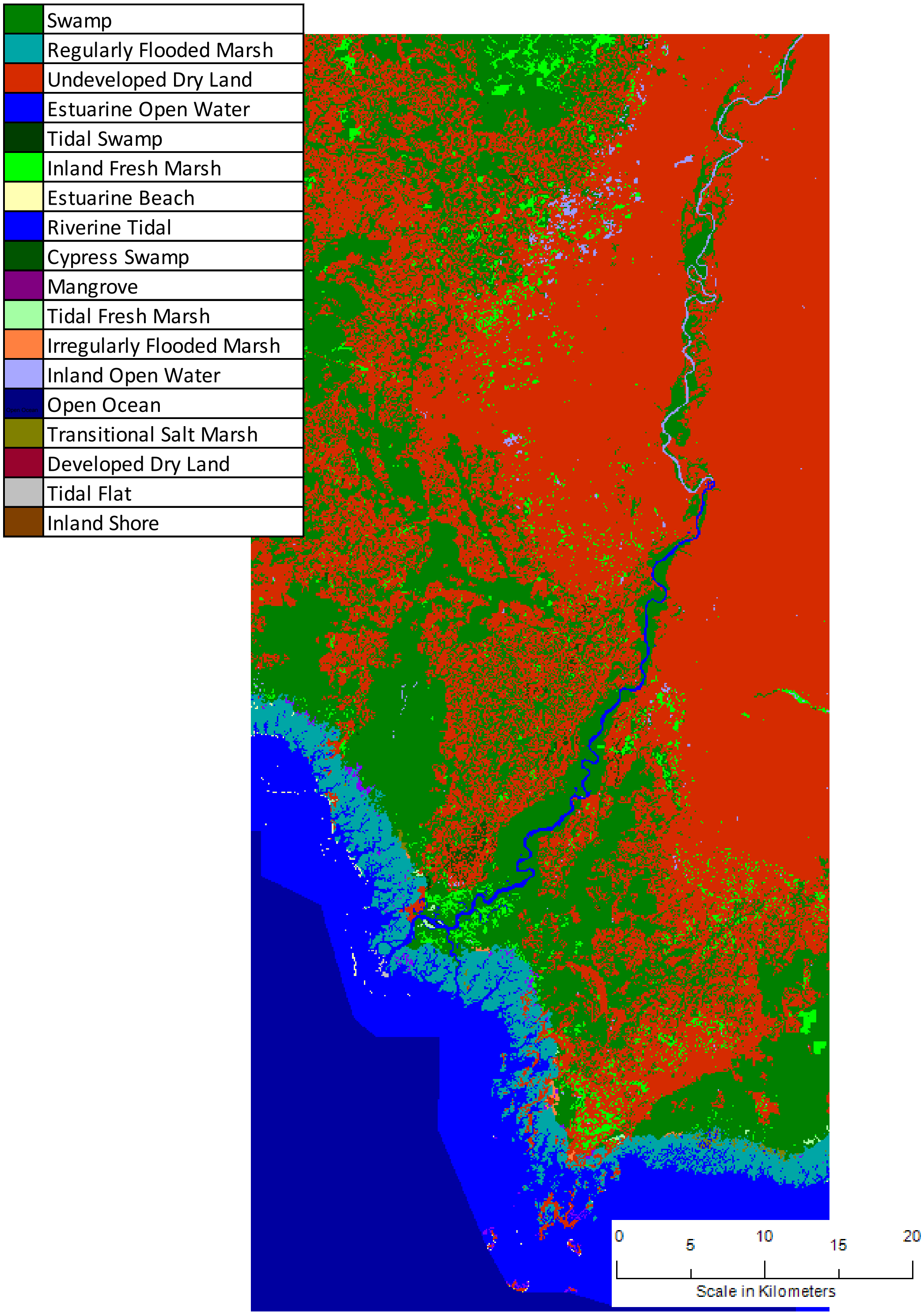


Figure 6. Historic wetland from 1983

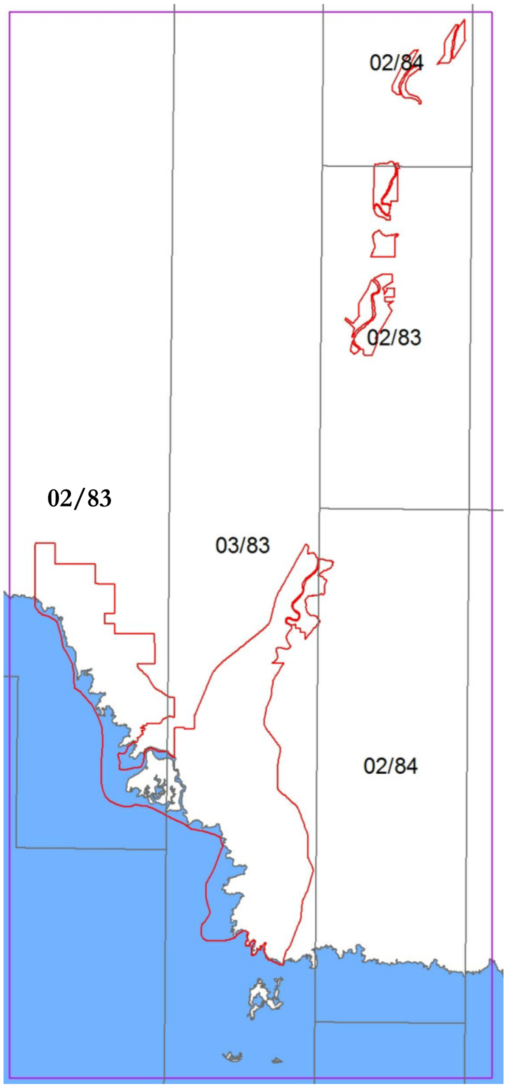


Figure 7. Historic NWI photo dates

Model Timesteps. Model outputs were produced in 5 year intervals for the hindcast starting from 1984 up to 2008, while forecasting outputs were chosen at years 2025, 2050, 2075 and 2100 with the most recent wetland data available as initial conditions (approximately 2008).

Dikes and Impoundments. According to the NWI, there are no impounded or diked areas within Lower Suwannee NWR. However, John Kasbohm, the refuge manager, indicated that several roads existing within the refuge – such as the Dixie Mainline Road shown in Figure 8 – may impact the hydrology of the refuge. In fact, these roads may act as functional levees; however they are not intended or designated as dikes. Any hydrological impact of these roads was modeled using the "connectivity" feature of the SLAMM model. This feature determines whether water can progress unimpeded by elevation features into a region to cause inundation effects. John Kasbohm also indicated that the tidal swamp west of Dixie Mainline Road was likely tidal in the 1980s and suggested that culverts along the road may allow tidal influence to extend into swamp east of the road.

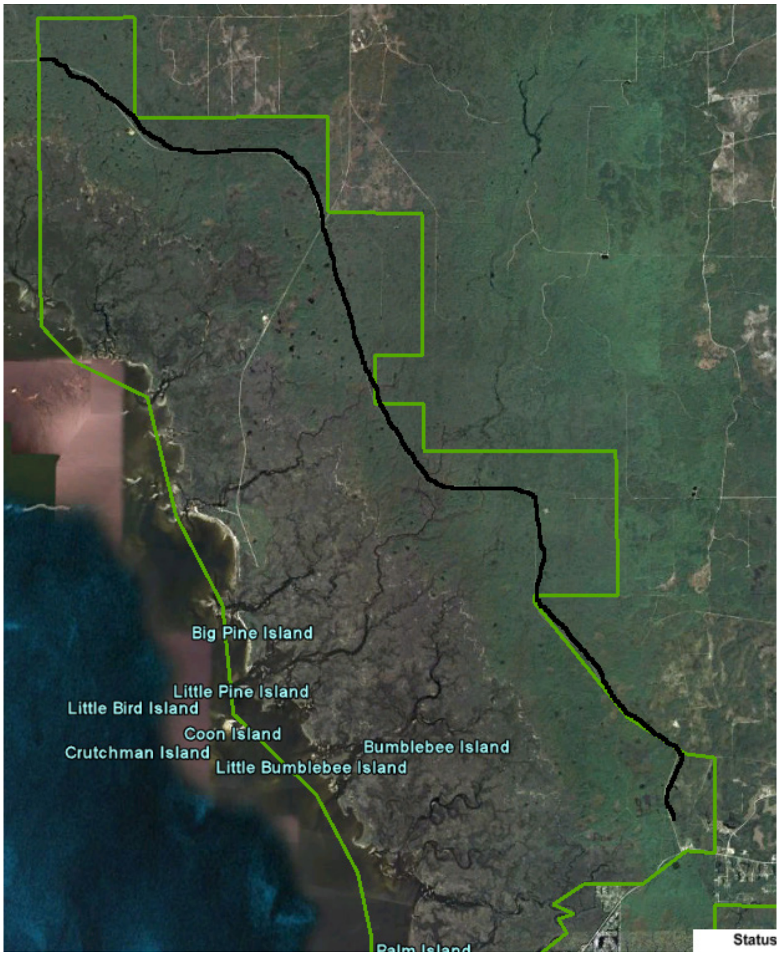


Figure 8. Dixie Mainline Road (black) within refuge boundary (green)

Historic sea level rise rates. The historic SLR rate was assigned to 1.8 mm/year based on the value recorded at the NOAA Tide Datum located at Cedar Key, FL (8727520). The rate of SLR for this refuge has been similar to the estimated global average for the last 100 years (approximately 1.7 mm/year, IPCC 2007).

Tide Ranges. Figure 9 shows the locations of the five tide gauge stations inside and close to the study area used to define the tide ranges for this site.

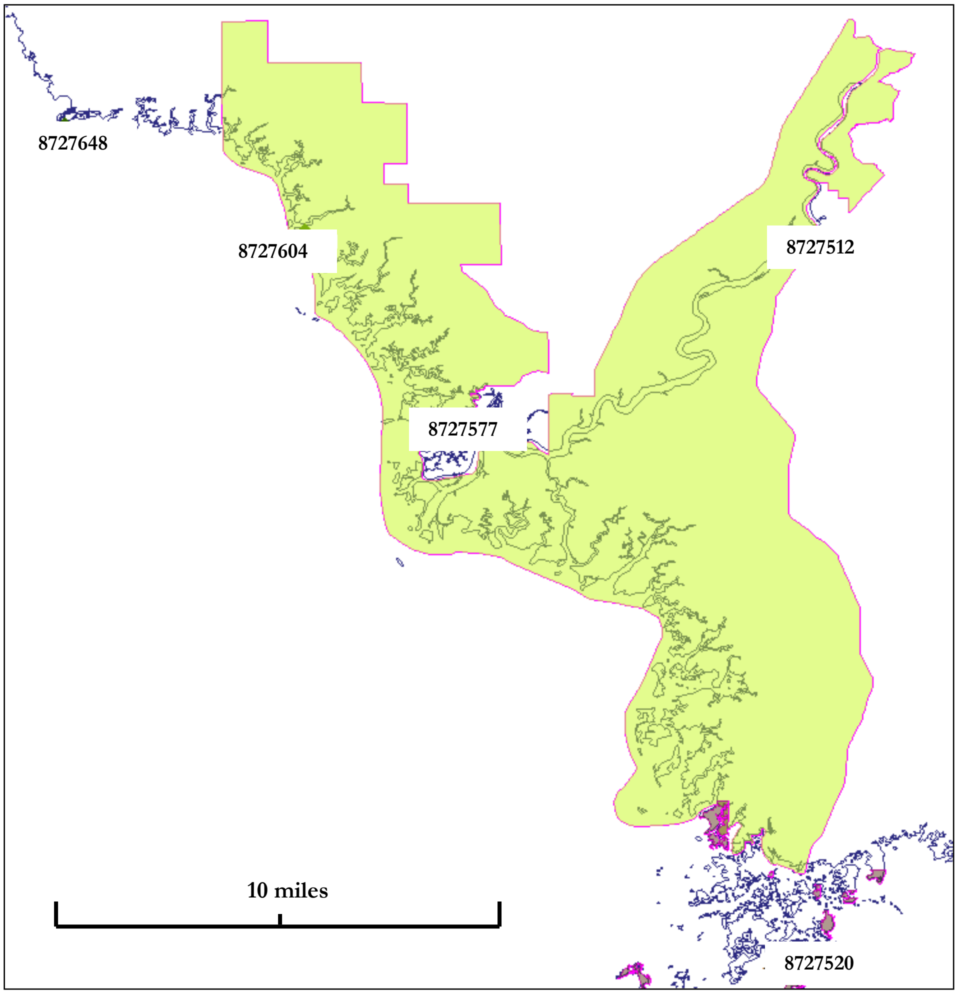


Figure 9. Locations of NOAA tide gauge stations used to define tide ranges for Lower Suwannee NWR

The great diurnal tide range, summarized in Table 1, varies from 0.66 m upstream the Suwannee River to 1.16 m on the open ocean. The observed gradient of decreasing tidal range from south to north was applied to this SLAMM simulation.

Table 1: NOAA tide gauge and values

Station ID	Site name	Relevant subsite	Tide range (m)	Salt elevation (m)
8727520	Cedar Key, FL	Cedar Key	1.16	0.94
8727577	Suwannee, FL	Global	1.05	0.86
8727512	Fowler Bluff, Suwannee River, FL	Fowler Bluff	0.66	0.53
8727604	Shired Island, FL	Global	1.06	0.86
8727648	Horseshoe Point, FL	Global	1.09	0.88

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 gauge data. For this application, the salt boundary was defined as the elevation above which inundation is predicted less than once per 30 days using data from the tide gauge station at Cedar Key, FL (8727520), which is roughly 12 miles south from the mouth of the Suwannee River. Based on the frequency of inundation analysis of the period 11/2006-11/2009, this salt elevation is estimated to be approximately 0.92 m above MTL, equivalent to an elevation of 1.7 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 0.53 m to 0.94 m above MTL as illustrated in Table 1.

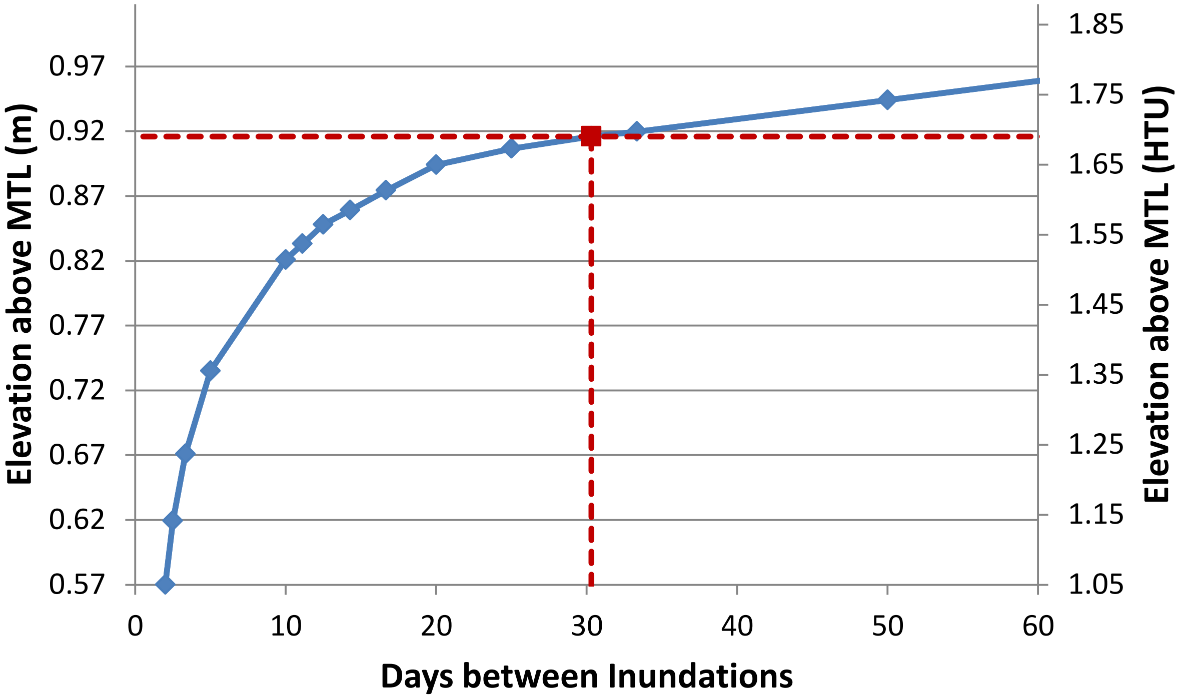


Figure 10. Frequency of inundation based on 3 years of data at Cedar Key, FL

Accretion Rates. Accretion rates in salt marshes were set to approximately 4 mm/year, based on several studies measuring marsh 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.

Elevation corrections. The MTL to NAVD88 correction was derived using NOAA's VDATUM software. A raster of MTL to NAVD88 correction values was created for the study area using VDATUM software (Figure 11). Data were extrapolated inland where VDATUM corrections are not available.

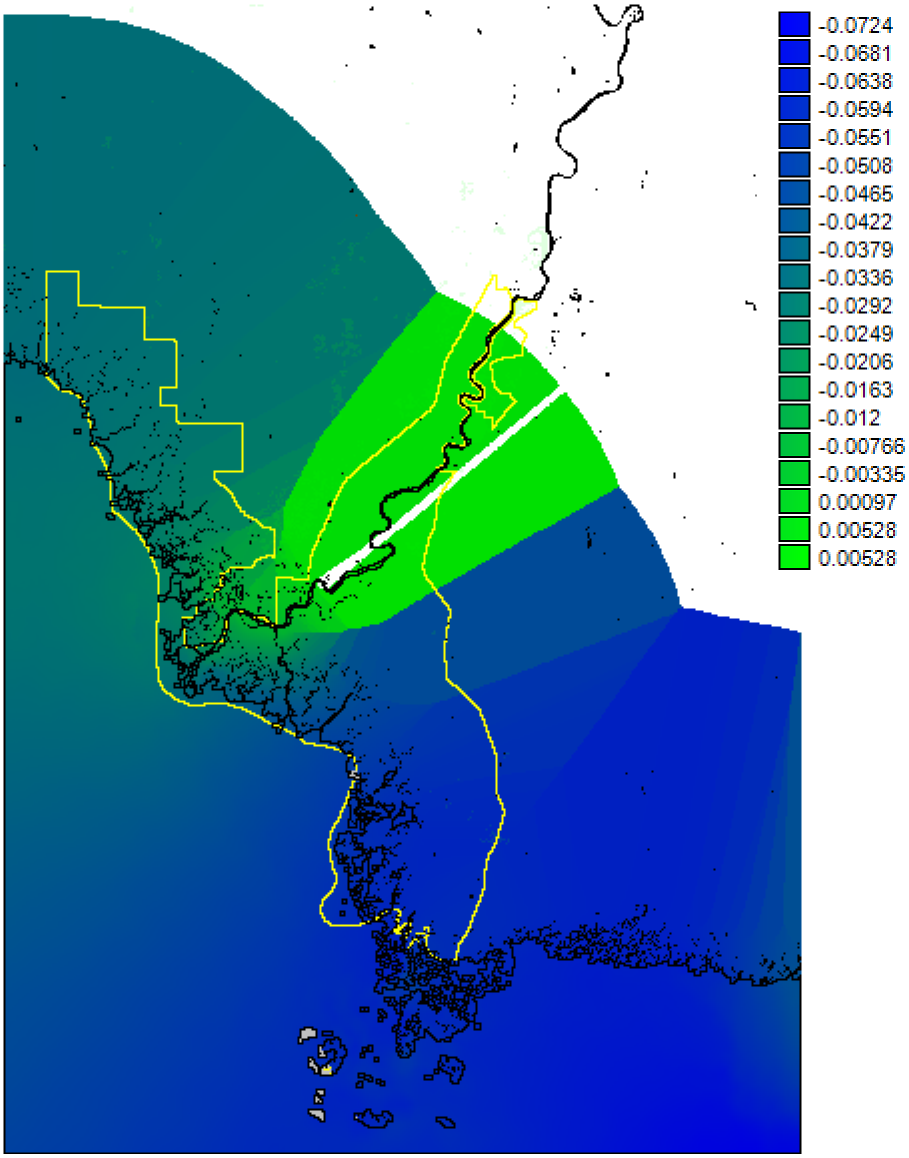


Figure 11. MTL-NAVD correction raster (m) over shoreline of the study area

Effects of freshwater flow. Based on the effects of freshwater flow, several changes were made to the SLAMM wetland flow chart. Previously, in non-salinity-model implementations of SLAMM, swamp and inland-fresh marsh converted to transitional marsh upon inundation. With a recent update to SLAMM, when an area is defined as being significantly "influenced by fresh-water," swamp and inland-fresh marsh will convert to tidal swamp and tidal marsh, respectively, when they fall below their lower-elevation boundaries. This procedure also helped to refine the hindcast calibration. The assumed extent of freshwater flow for the Lower Suwannee site is shown in Figure 12.

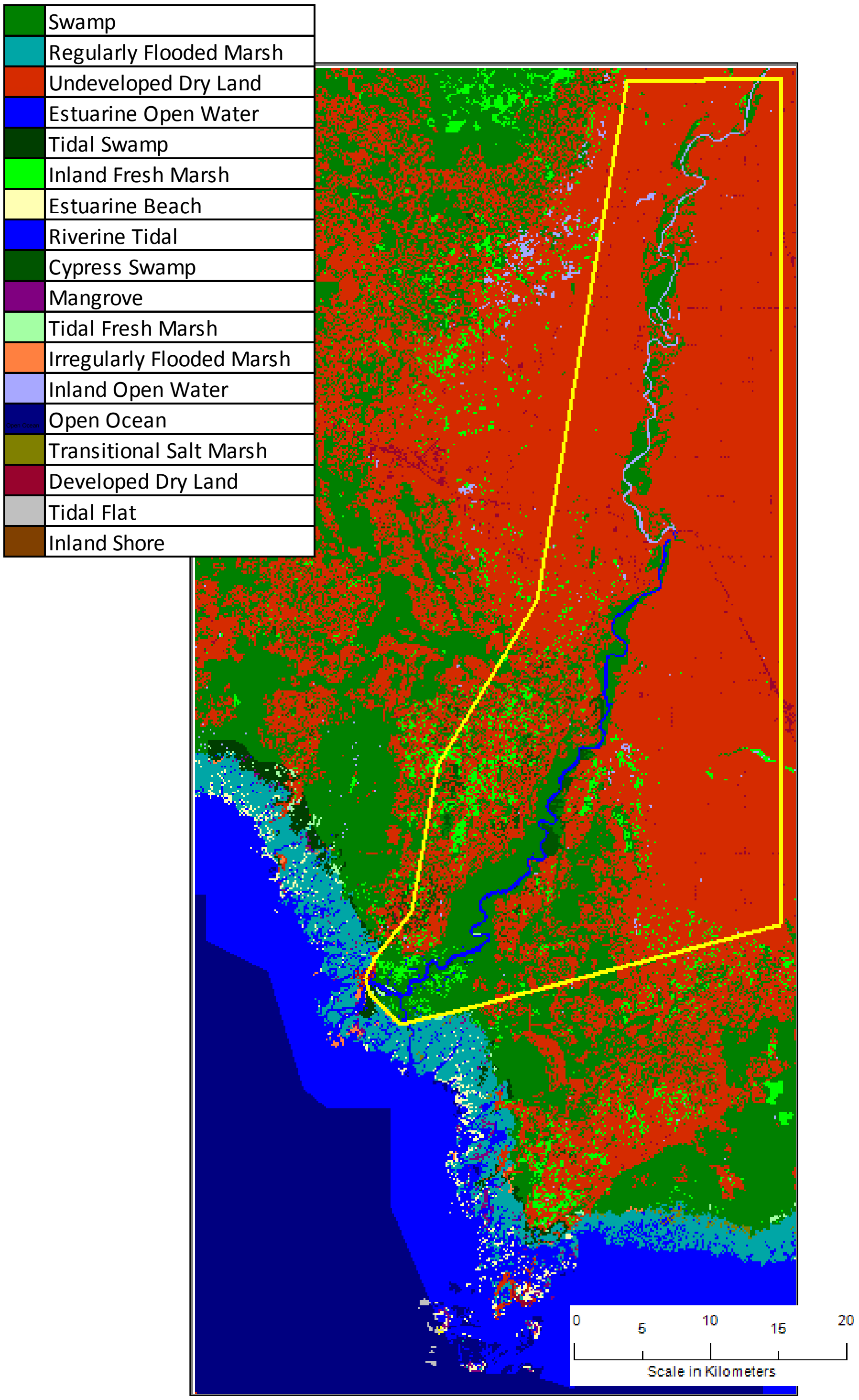


Figure 12. Fresh flow polygon drawn along the Lower Suwannee River

Refuge boundaries. Modeled USFWS 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 30 m by 30 m. Note that the SLAMM model will track also partial conversion of cells based on elevation and slope.

Input subsites and parameter summary. Based on spatial variability within various input parameters, NWI photo dates, and LiDAR flight dates, 5 different simulation subsites (Figure 13) were utilized.

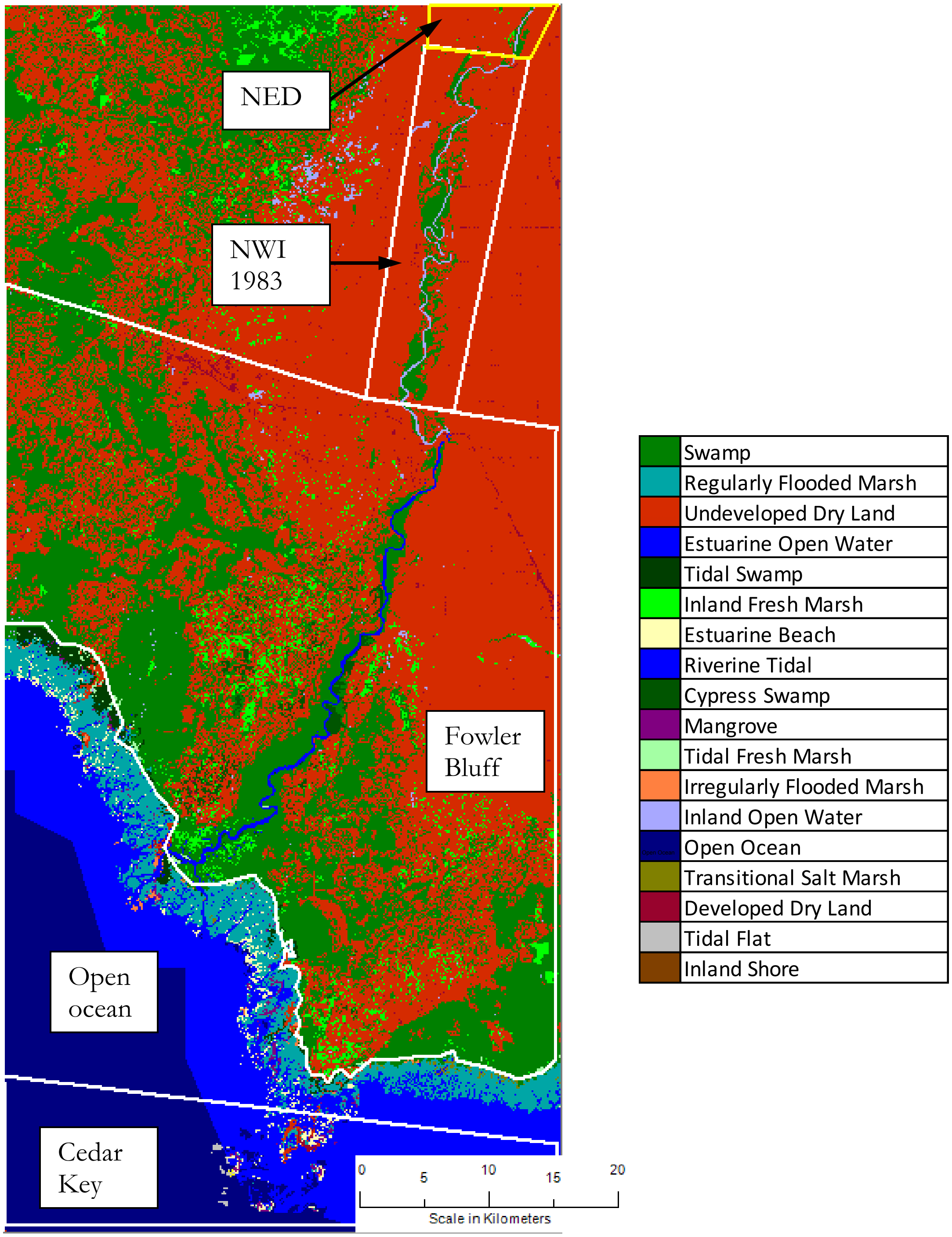


Figure 13. Input Subsites for model application

Table 2 summarizes SLAMM input parameters and description for each subsite of the study area. Values for parameters with no specific local information were kept at their default value.

Table 2. Summary of SLAMM input parameters for Lower Suwannee NWR

Description	Open Ocean	NED	NWI 1983	Cedar Key	Fowler Bluff
NWI Photo Date (YYYY)	1983	1984	1983	1983	1983
DEM Date (YYYY)	2007	1967	2007	2007	2007
Direction Offshore [n,s,e,w]	South	South	South	South	South
Historic Trend (mm/yr)	1.8	1.8	1.8	1.8	1.8
MTL-NAVD88 (m)	†	†	†	†	†
GT Great Diurnal Tide Range (m)	1.0576	0.6584	0.6584	1.1582	0.6584
Salt Elev. (m above MTL)	0.8577	0.5334	0.5334	0.9393	0.5334
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)	3.9	3.9	3.9	3.9	3.9
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)	6	7	6	7	6
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
Freq. Overwash (years)	100	100	100	100	100
Use Elev Pre-processor [True,False]	FALSE	TRUE	FALSE	FALSE	FALSE

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

When applying the SLAMM model, the available data suggested that elevations for freshwater swamps and inland fresh marshes are lower than the ones that are normally found for these wetland categories at other sites, i.e. below the derived salt elevation in many cases. For this reason, the minimum elevation for the swamp category was reduced to just above MHHW. In addition, after discussion with refuge staff and visual inspection of available satellite images, it is possible that the fresh marshes close to the river mouth are actually tidal marshes not well categorized by the NWI survey. Therefore, the minimum elevation for inland fresh marsh was set to 1.3 times the MHHW relative to MTL. These changes to the conceptual model prevented SLAMM from predicting immediate inundation of these areas. Boundaries for tidal swamp and tidal fresh marsh were also lowered based on site-specific data. Lower elevation boundaries for these categories are generally site-specific depending on the extent of fresh-water flows. These modifications are summarized in Table 3 with units given in half-tide units (HTU) relative to MTL (1.0 HTU is equivalent to MHHW and negative 1.0 HTU is equivalent to MLLW) as well as the 90% interval of observed elevations for each wetland category.

Table 3: Modifications to SLAMM Conceptual Model.

SLAMM Category	Min (HTU)	5th Pct.(HTU)	95th Pct.(HTU)
Swamp	1.1	1.4	57.0
Inland Fresh Marsh	1.3	1.3	50.0
Tidal Fresh Marsh	0.7	0.6	3.6
Tidal Swamp	0.7	0.7	3.0

Results and Discussion

The analysis of Lower Suwannee NWR included a hindcasting and a forecast 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 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.

As is usually the case, high vertical-resolution historical DEM data were not available. For this reason, the present-day, high-resolution DEM was used as the best-available dataset to reflect land elevations in 1983. This obviously ignores changes due to erosion, accretion, or sedimentation. Vertical land movement is attempted to be accounted for, but based on historical SLR trends, very little local uplift or subsidence is occurring at this site (see *Historic sea level rise rates* above).

From the historical-wetland coverage date, the hindcast predicts wetland coverage up to the present day as a function of changes in sea level. To determine if SLAMM can accurately predict growth or loss trends for major land-cover categories the there are several metrics that may be employed to judge the accuracy of the model. In this study, the primary metric used to evaluate SLAMM results is the fraction of the land cover lost during model simulations for the primary wetland/vegetation types. However due to the data uncertainty of the historical and recent datasets, this metric is of limited utility.

Hindcast Results

Based on historical records, during the period between 1983 and 2008, approximately 4.3 cm of local SLR occurred (see *Sea Level Rise Scenarios* section above). This value is one third of the RMSE of the elevation data (FDEM 2008) making a meaningful prediction based on this SLR unlikely.

Observed wetland coverage from 2008 and 1983 are compared in Figure 14.

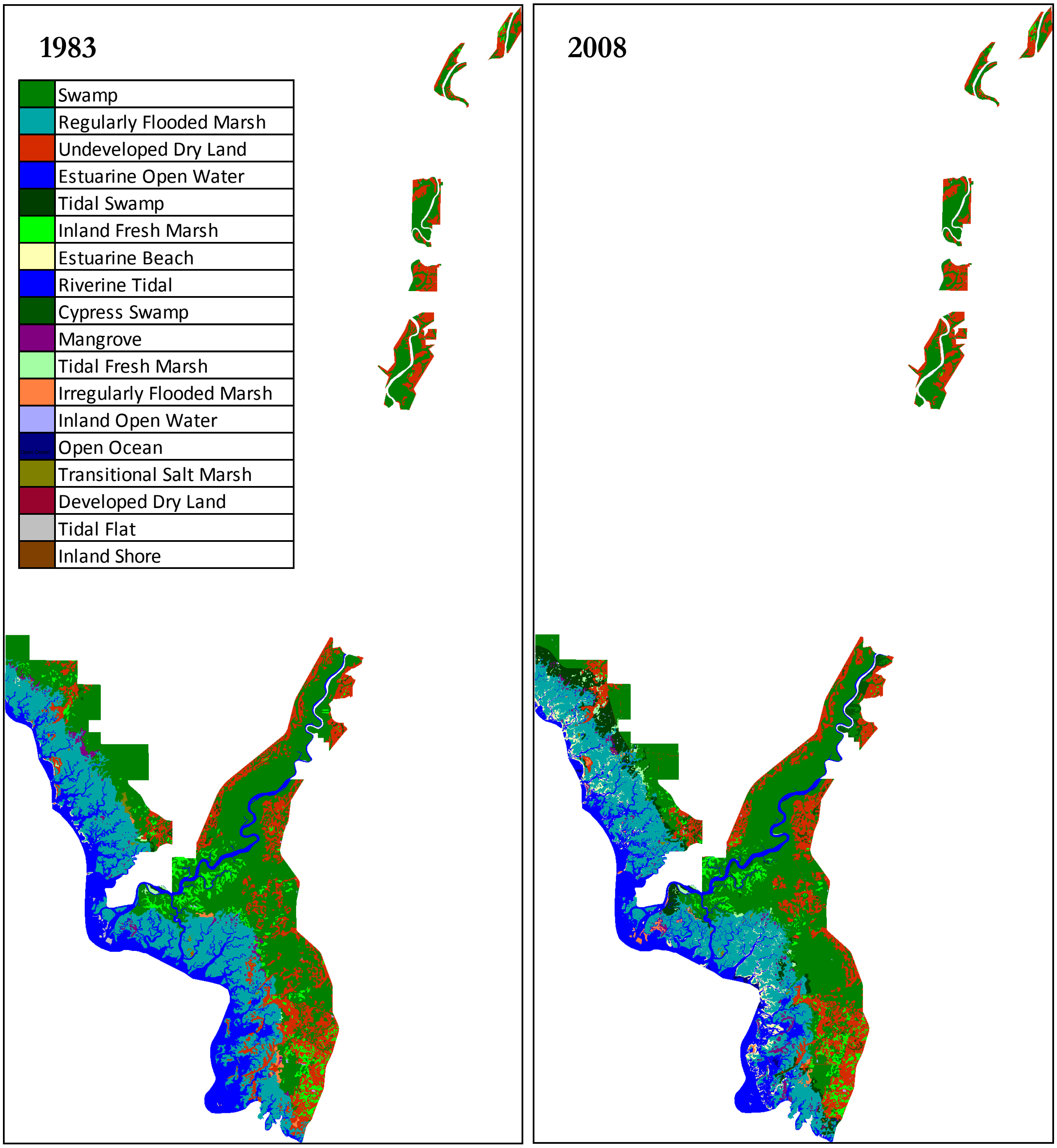


Figure 14. Observed wetland changes (NWI data)

A comparison of the observed wetland layers shows that, of the 86,000 acres of the refuge, swamps have reduced from 33,400 acres to 29,400 acres while tidal swamp, increased from 64 acres to approximately 5,500 acres mostly in the east section of the refuge. Regularly-flooded marshes have experienced minimal losses, from 19,100 acres to 18,800 acres while irregularly-flooded marshes are observed to have added around 120 acres. Inland fresh marsh coverage in 2008 is almost 25% less than what observed in 1983, 2,200 acres from an initial 2,900 acres. In part this land cover has been converted to tidal fresh marshes that have globally increased their coverage by 300 acres.

Overall, it is not clear if these changes are real or if they are due to a change in characterization of the land cover in one or both surveys.

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)
Swamp	33424	29391	26151	4032	12	7273	22
Regularly-Flooded Marsh	19107	18788	20354	318	2	-1247	-7
Undeveloped Dry Land	13333	12493	11188	840	6	2145	16
Estuarine Open Water	11817	10795	12883	1023	9	-1065	-9
Tidal Swamp	64	3504	3652	-3441	-5409	-3588	-5641
Inland-Fresh Marsh	2920	2234	2871	686	23	49	2

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

In Figure 15 the SLAMM model prediction for 2008 is compared to the observed wetland coverage. In general, SLAMM predicts minimal changes as a result of 4.5 cm of SLR. However, as discussed above there were changes in the observed layer that may be due to changes in NWI classification techniques. Overall, predicted and observed maps are very similar with only minimal changes occurring on the shoreline.

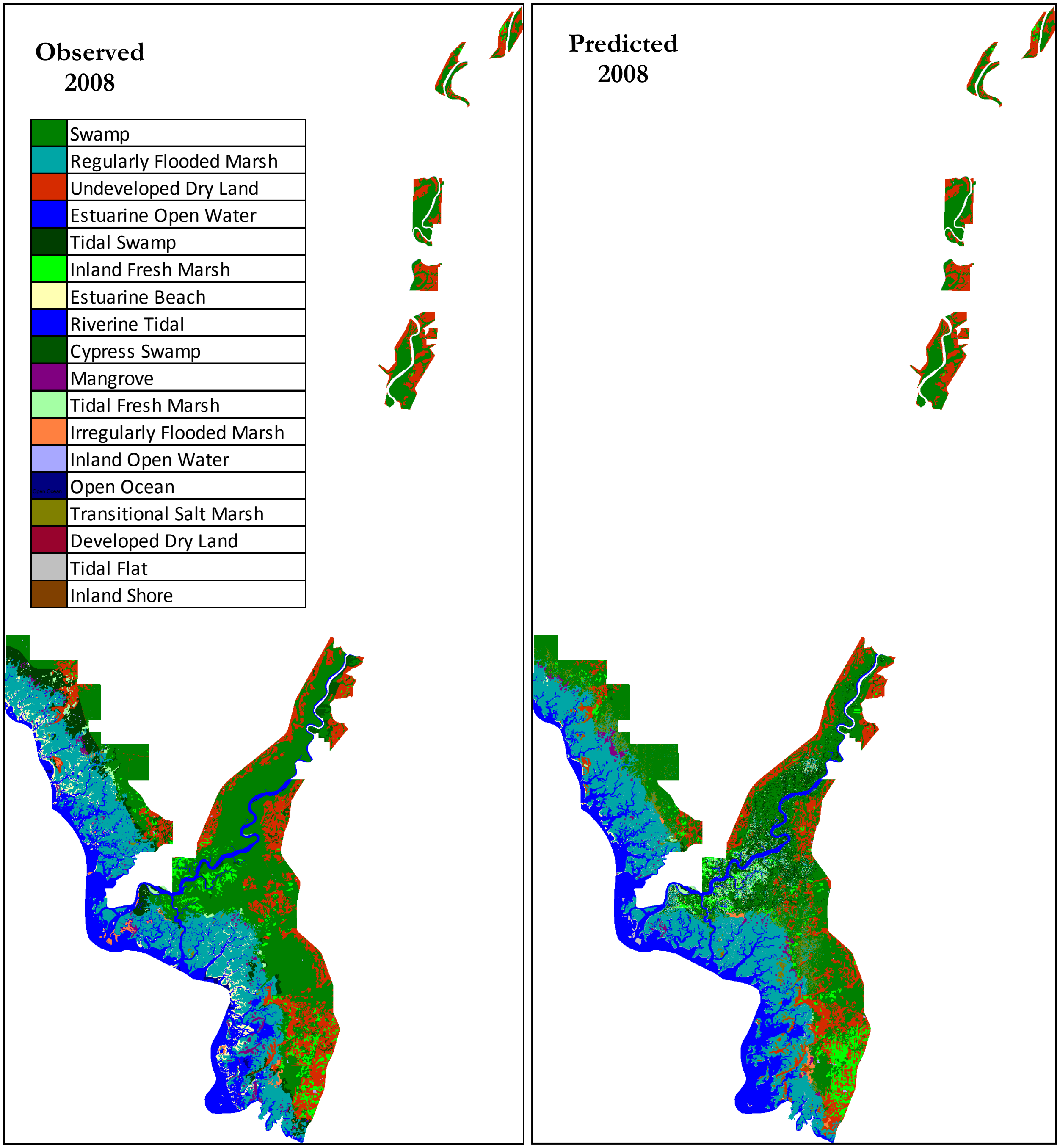


Figure 15. Observed and predicted wetland coverage, 2008

Spatially, the main differences between the two layers are observed around the river towards its mouth where several spots of tidal swamps and tidal fresh marshes are predicted instead of the observed swamps and *inland* (non-tidal) fresh marsh. We confirmed with refuge staff that these areas are covered with fresh-water marshes but are likely to be subject to tidal influence in this location. Furthermore, this area is a location where LiDAR data are particularly spatially variable with large fluctuations in elevation over a short distance. It is possible that the processing of LiDAR data into bare-earth coverage is particularly uncertain in this region due to dense marsh coverage or other data issues.

Based on the LiDAR data, a large section of elevations in this area are quite low, below high-tide level. The data in this region are also highly spatially variable, with areas well under MHHW and others above it as shown in Figure 16 where land covers are shown for water level at MTL and MHHW. This figure suggests that on the average day, tides are predicted to cover these fresh marsh locations but not uniformly.

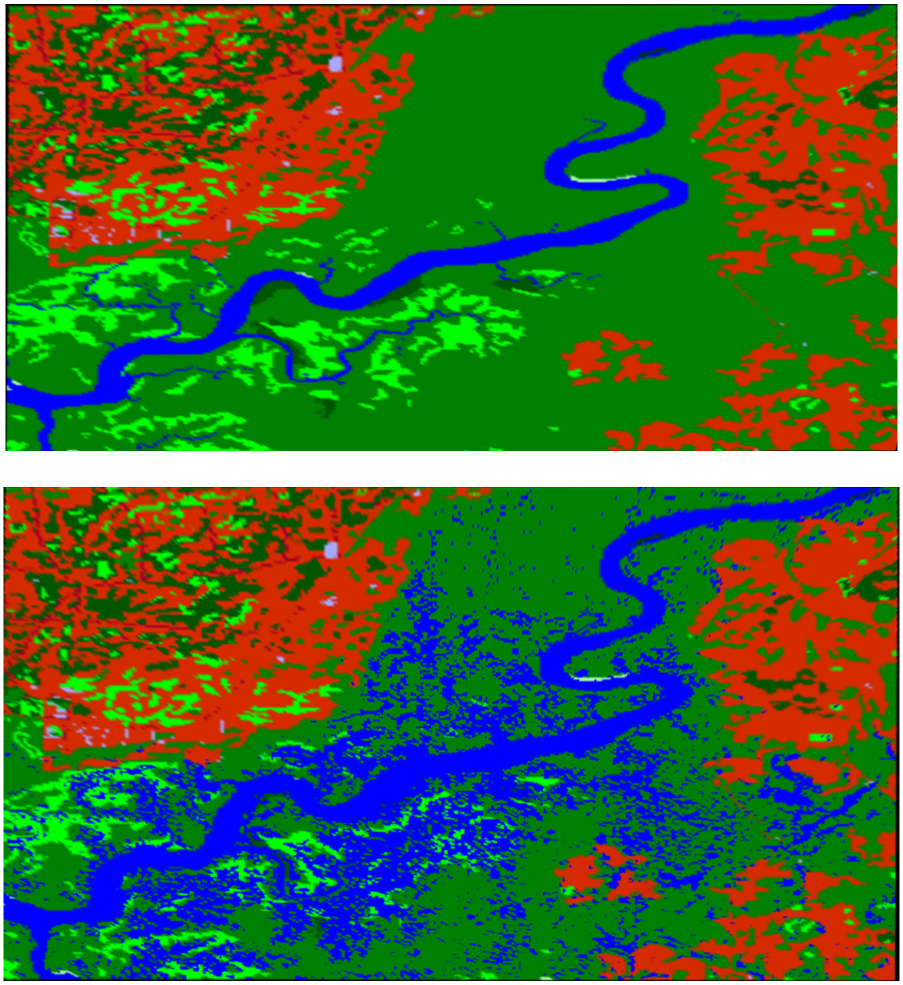


Figure 16. Mouth of the river with water level at MTL (above) and MHHW (below)

Other significant discrepancies between observed and predicted land-covers are as follows:

- In the southern part of the refuge elevations for dry land are low, and SLAMM therefore predicts a potential conversion to inland fresh marsh based on soil saturation.
- In the west section of the refuge, swamps have a higher elevation that does not suggest tidal influence and therefore a conversion to tidal swamp as observed in the most recent NWI layer.

Overall, the computed hindcast results should be interpreted with caution. The SLR signal over 24 years of the model hindcast is only 4.3 cm, a number much lower than the error (RMSE) of the LiDAR data (13.4 cm, FDEM 2008). Given that a meaningful hindcast should be performed over a longer period of time (long enough to see land-cover changes in response to SLR) and given the fact that elevation data and wetland characterization are uncertain, no additional effort was put into calibration of the SLAMM model for this site. However, future model hindcasting efforts at Lower Suwannee could benefit from older historical wetland datasets and more standardization in terms of wetland classifications.

Forecast

SLAMM predicts that Lower Suwannee NWR will be significantly affected by each of the five SLR scenarios examined. Table 4 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 Lower Suwannee 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
Swamp	29391	51%	66%	74%	81%	89%
Regularly Flooded Marsh	18788	-21%(1)	-38%	2%	61%	68%
Undeveloped Dry Land	12493	17%	25%	33%	46%	59%
Tidal Swamp	3504	-118%	32%	65%	76%	33%
Inland Fresh Marsh	2234	-4%	4%	16%	40%	74%
Estuarine Beach	1954	10%	47%	61%	91%	99%
Riverine Tidal	1531	66%	80%	87%	89%	89%
Cypress Swamp	1007	54%	72%	81%	91%	97%
Mangrove	946	1%	1%	4%	42%	73%
Tidal Fresh Marsh	464	-656%	-621%	-327%	-191%	-161%
Irregularly Flooded Marsh	395	-191%	-232%	-173%	24%	70%

(1)A negative value indicates a net gain

Simulation results predict that of the over 86,000 acres in this refuge from 14,000 to 62,000 will be covered by open water or tidal flat by 2100 depending on the SLR scenario (up from the 13,000 acres observed today).

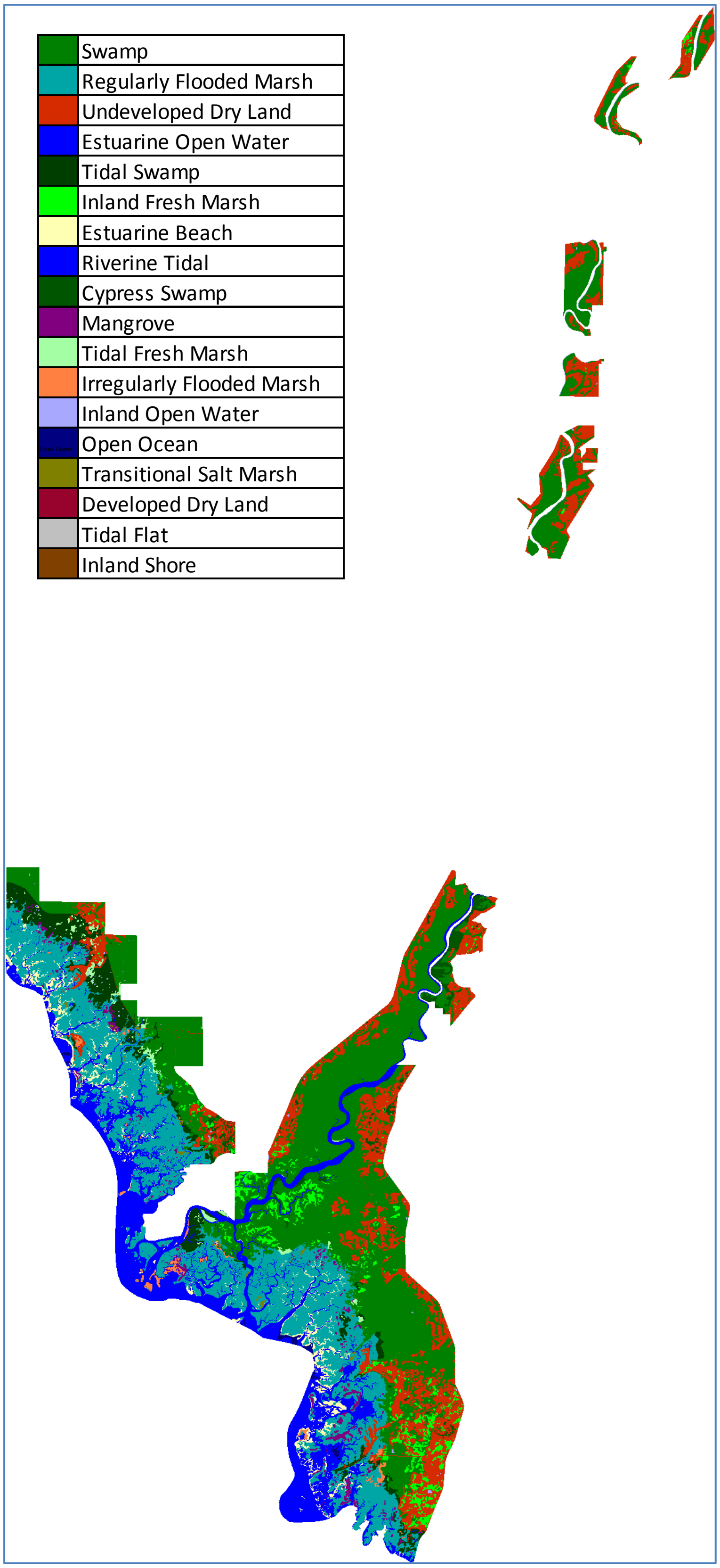
Between 50% and 90% of refuge swamp – which comprises approximately one third of the refuge today – is predicted to be lost by 2100 across all SLR scenarios. Tidal swamps are expected to initially gain coverage but as sea level continues to rise they are then predicted to experience significant losses within the refuge boundaries. Regularly flooded marshes are predicted to increase their acreages for SLR below 1 m as a result of inundation of swamps and dry lands. However, these marshes are then also predicted to be inundated given higher SLR scenario. Cypress swamp and Mangrove are also predicted to be lost under all SLR scenarios.

Similar to hindcast results, early predictions of land-cover change at the river delta have to be taken with caution as this area is affected by high variability of the elevation data. Further up-river, the refuge is not predicted to be greatly influenced by SLR under most scenarios. However, for a 2 m SLR by 2100 this section of the refuge is also predicted to experience tidal influence.

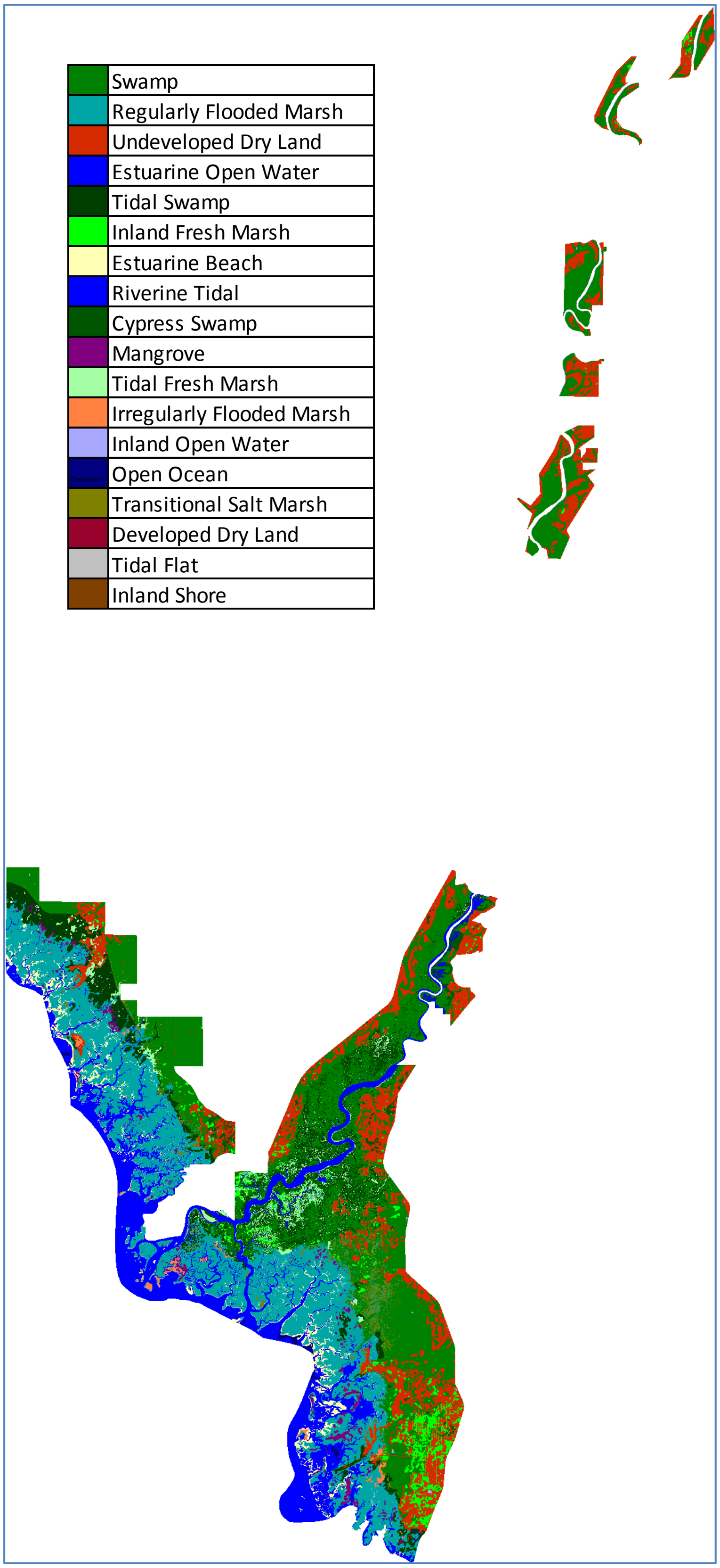
Lower Suwannee NWR
IPCC Scenario A1B-Mean, 0.39 m SLR eustatic by 2100

Results in Acres

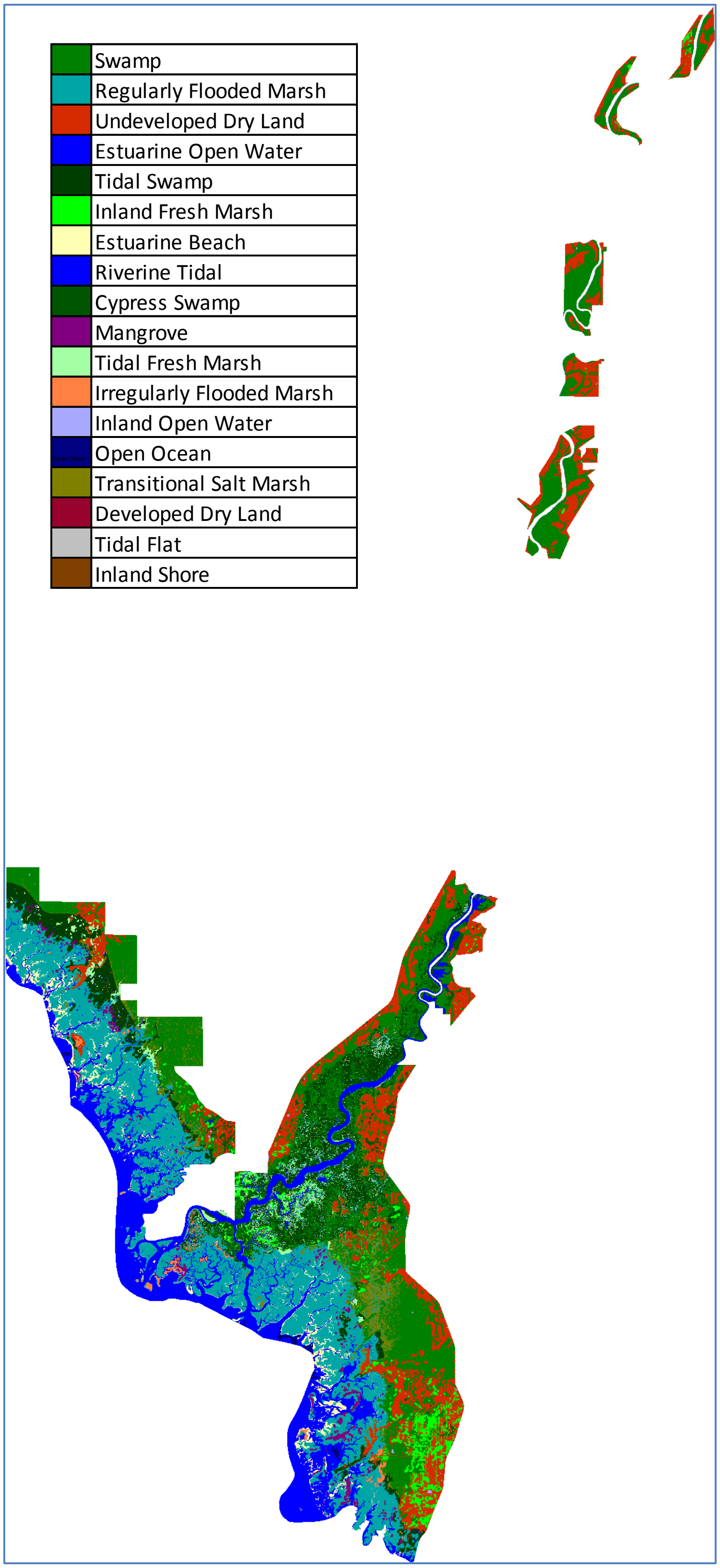
		Initial	**2025**	**2050**	**2075**	**2100**
🟩	Swamp	29391	24128	20925	17220	14474
🟦	Regularly Flooded Marsh	18788	18916	19415	20474	22661
🟥	Undeveloped Dry Land	12493	11482	11169	10762	10313
🟦	Estuarine Open Water	10795	11399	11691	12632	13013
🟩	Tidal Swamp	3504	7107	8783	9473	7651
🟩	Inland Fresh Marsh	2234	2118	2169	2250	2323
🟨	Estuarine Beach	1954	1914	1854	1800	1750
🟦	Riverine Tidal	1531	1325	1289	648	517
🟩	Cypress Swamp	1007	724	632	534	462
🟪	Mangrove	946	938	936	936	933
🟩	Tidal Fresh Marsh	464	1568	1394	2224	3505
🟧	Irregularly Flooded Marsh	395	382	588	770	1150
🟦	Inland Open Water	196	183	178	169	154
🟦	Open Ocean	194	194	194	194	194
🟩	Transitional Salt Marsh	136	1134	2175	3437	4428
🟥	Developed Dry Land	28	27	27	27	26
⬜	Tidal Flat	6	521	641	513	507
🟫	Inland Shore	2	2	2	2	2
	Total (incl. water)	**84063**	**84063**	**84063**	**84063**	**84063**



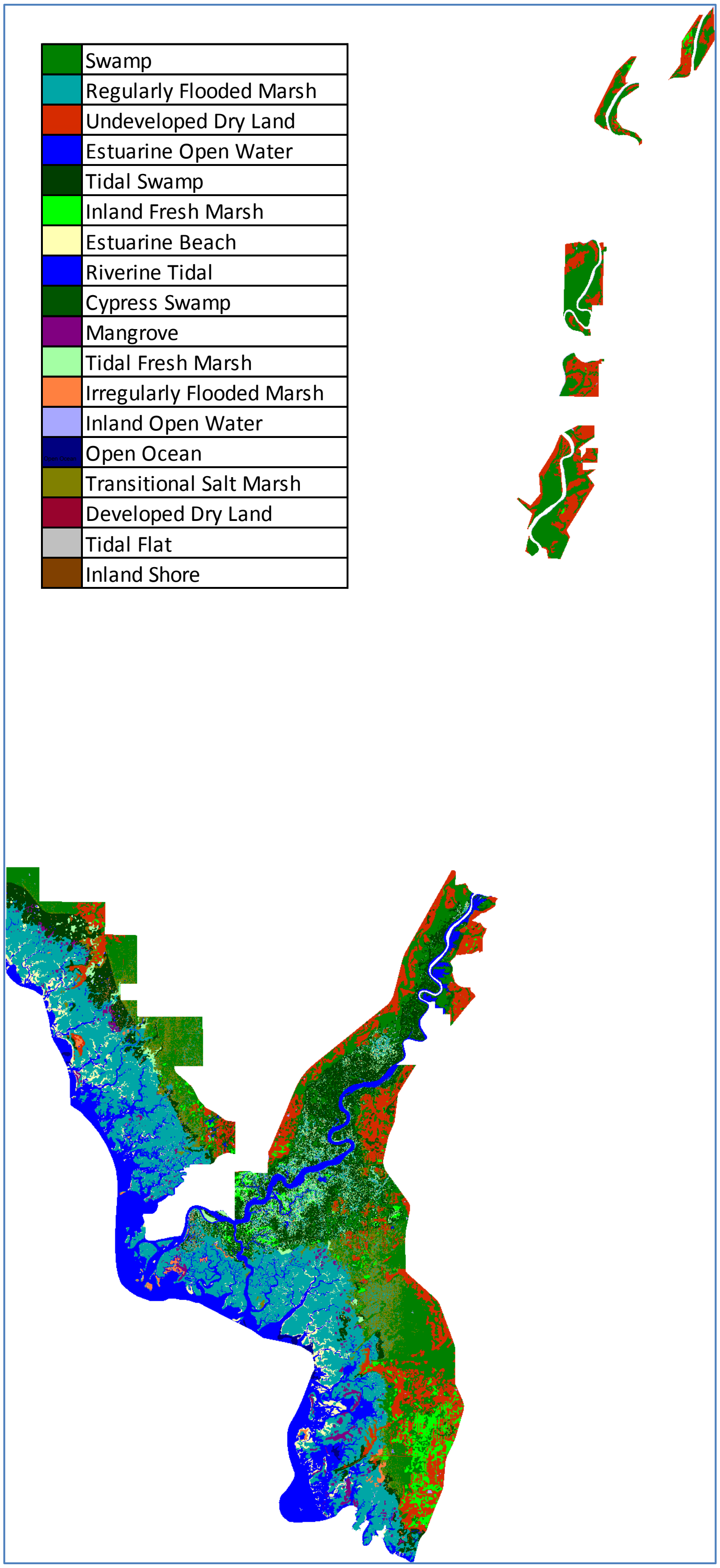
Lower Suwannee NWR, Initial Condition



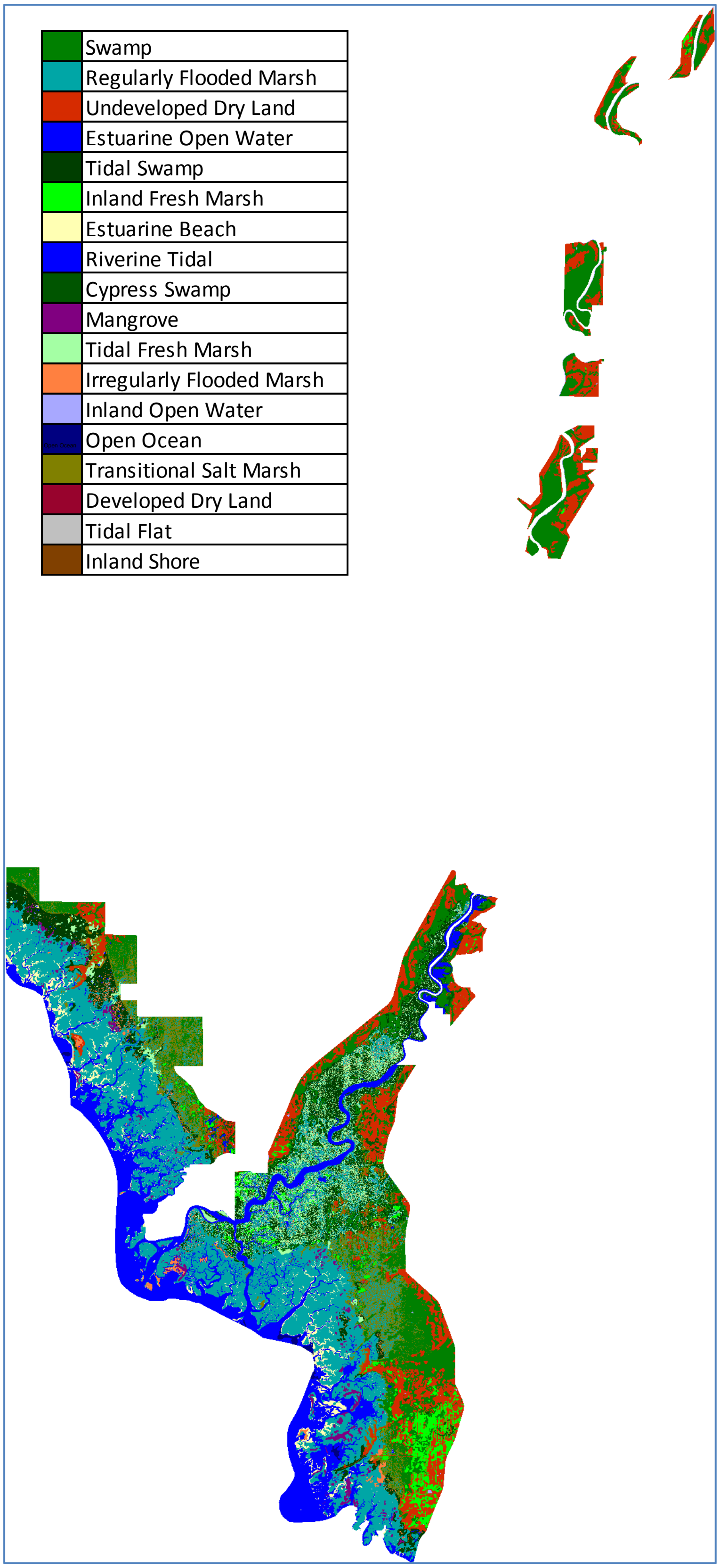
Lower Suwannee NWR, 2025, Scenario A1B Mean



Lower Suwannee NWR, 2050, Scenario A1B Mean, 0.39 m SLR



Lower Suwannee NWR, 2075, Scenario A1B Mean, 0.39 m SLR

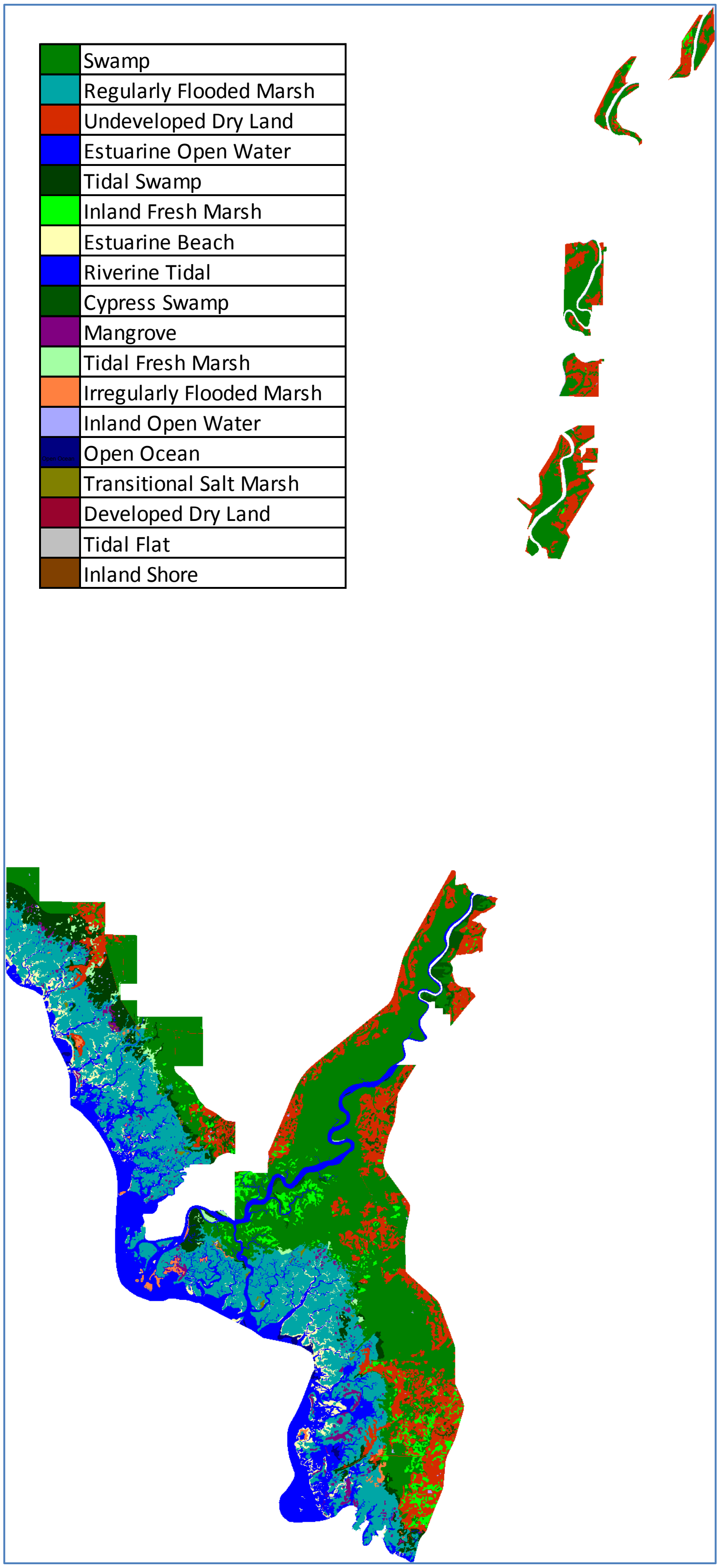


Lower Suwannee NWR, 2100, Scenario A1B Mean

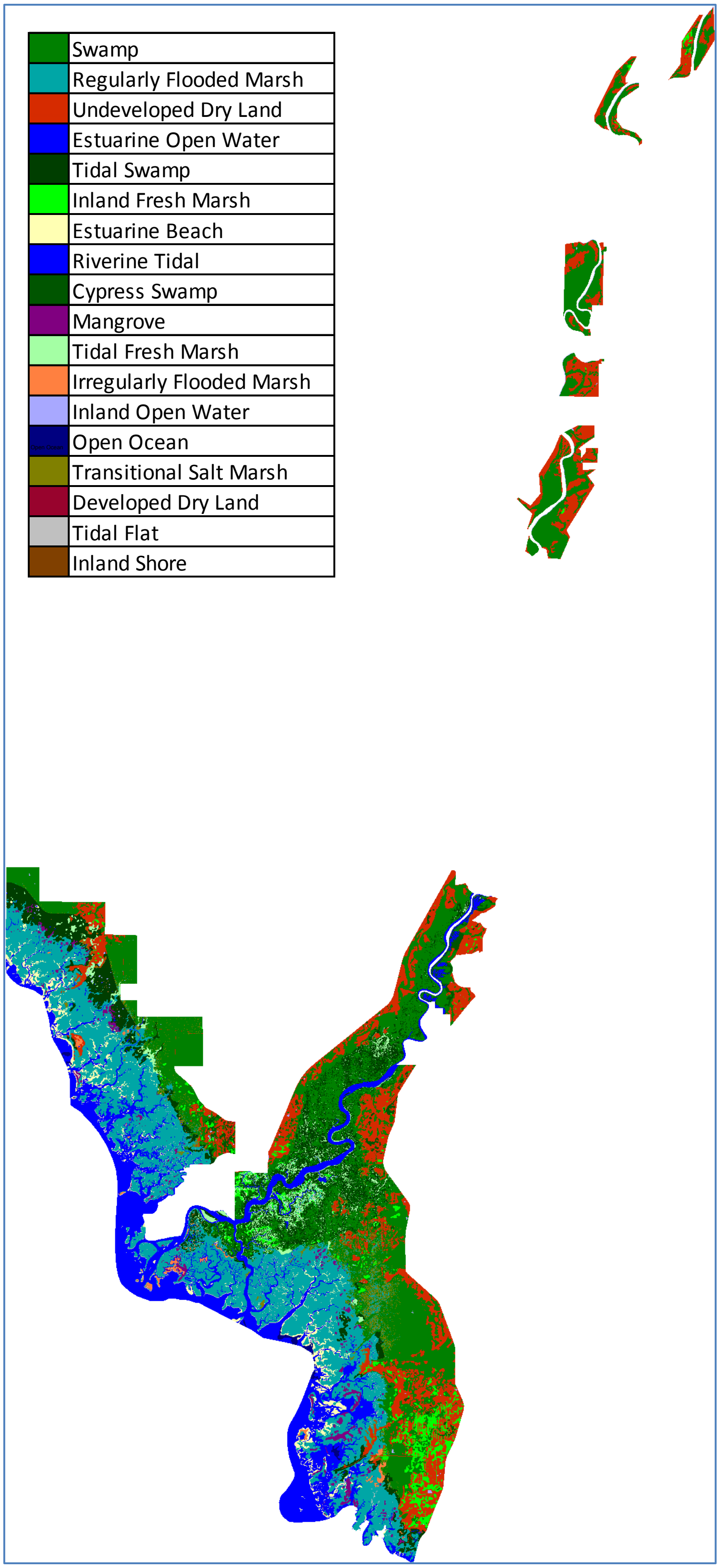
Lower Suwannee NWR
IPCC Scenario A1B-Max, 0.69 m SLR eustatic by 2100

Results in Acres

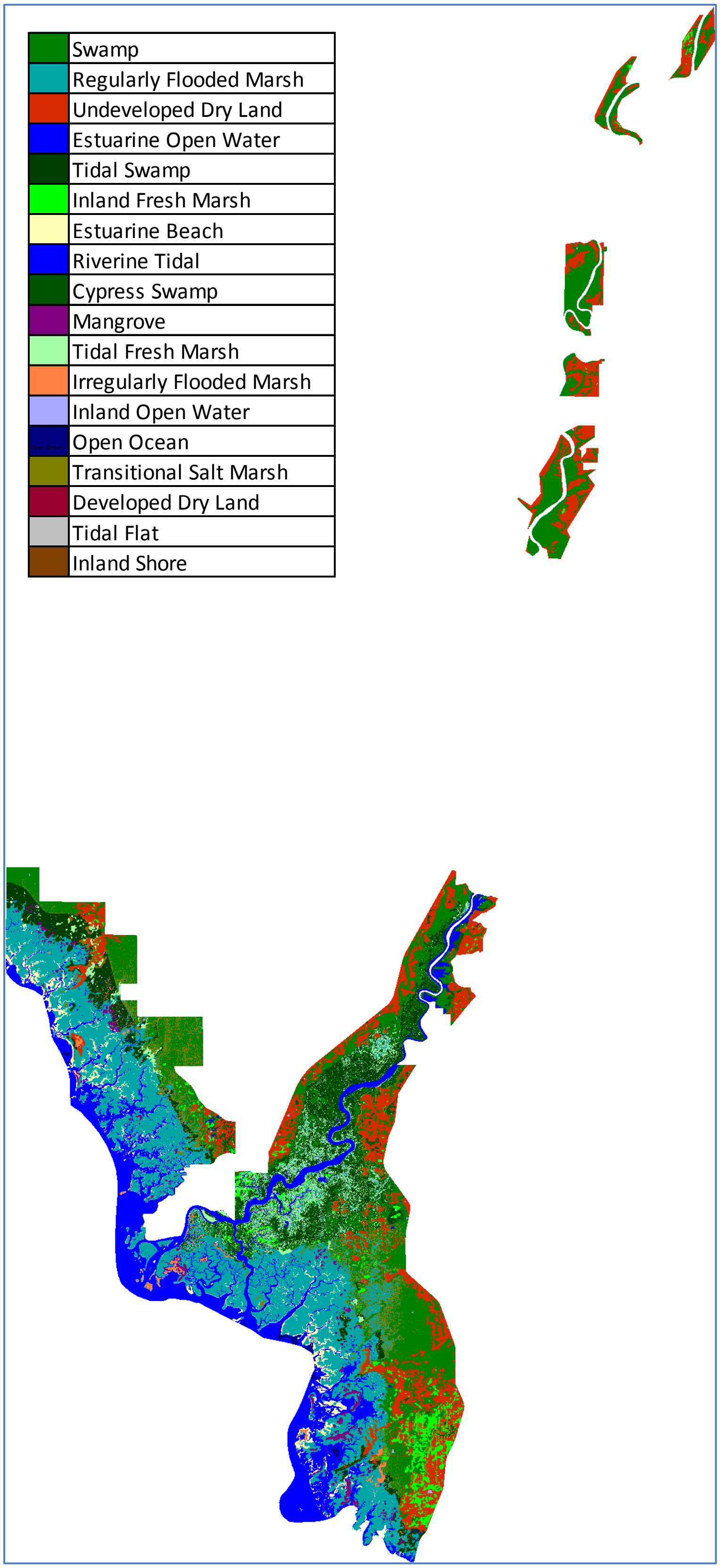
		Initial	**2025**	**2050**	**2075**	**2100**
🟩	Swamp	29391	23206	17648	12796	9932
🟦	Regularly Flooded Marsh	18788	19036	20100	22839	25907
🟥	Undeveloped Dry Land	12493	11440	10966	10184	9325
🟦	Estuarine Open Water	10795	11433	11884	13136	15139
🟩	Tidal Swamp	3504	7557	9138	5084	2375
🟩	Inland Fresh Marsh	2234	2117	2160	2185	2153
🟨	Estuarine Beach	1954	1914	1853	1785	1045
🟦	Riverine Tidal	1531	1323	1248	577	302
🟩	Cypress Swamp	1007	698	551	417	278
🟪	Mangrove	946	938	936	935	933
🟩	Tidal Fresh Marsh	464	1782	2724	6120	3343
🟧	Irregularly Flooded Marsh	395	385	516	1056	1312
🟦	Inland Open Water	196	182	175	154	139
🟦	Open Ocean	194	194	194	194	194
🟫	Transitional Salt Marsh	136	1310	2849	4143	3488
🟥	Developed Dry Land	28	27	27	26	23
⬜	Tidal Flat	6	520	1092	2429	8173
🟫	Inland Shore	2	2	2	2	2
	Total (incl. water)	**84063**	**84063**	**84063**	**84063**	**84063**



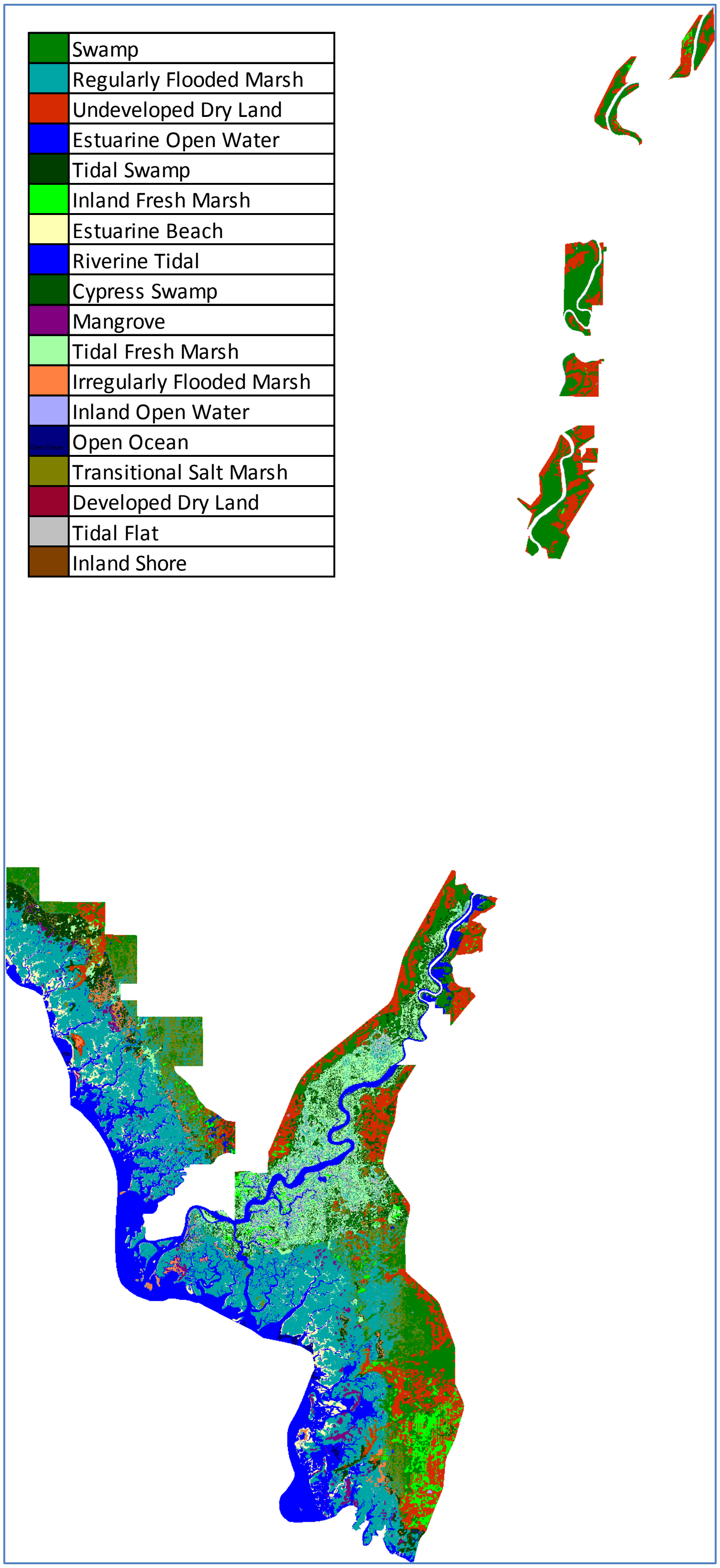
Lower Suwannee NWR, Initial Condition



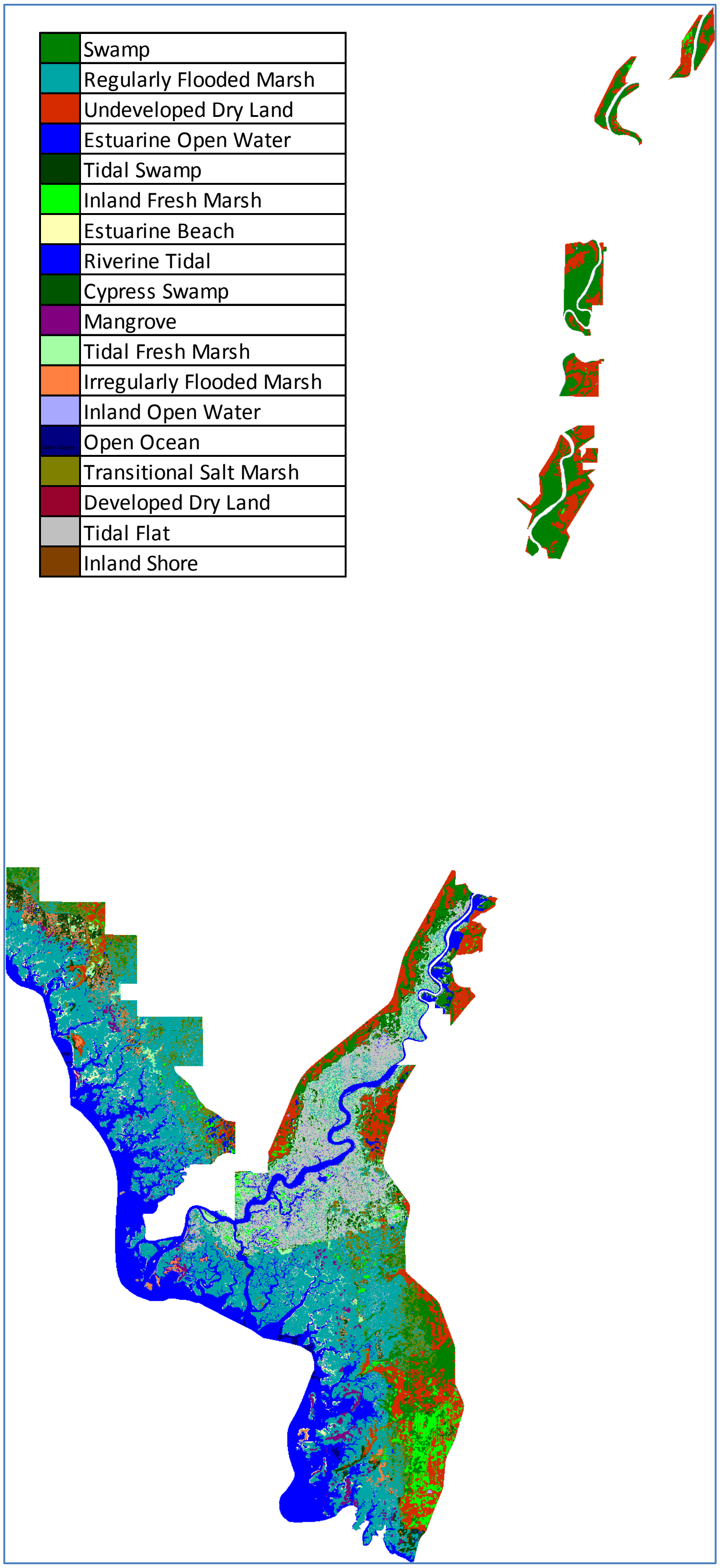
Lower Suwannee NWR, 2025, Scenario A1B Maximum



Lower Suwannee NWR, 2050, Scenario A1B Maximum



Lower Suwannee NWR, 2075, Scenario A1B Maximum

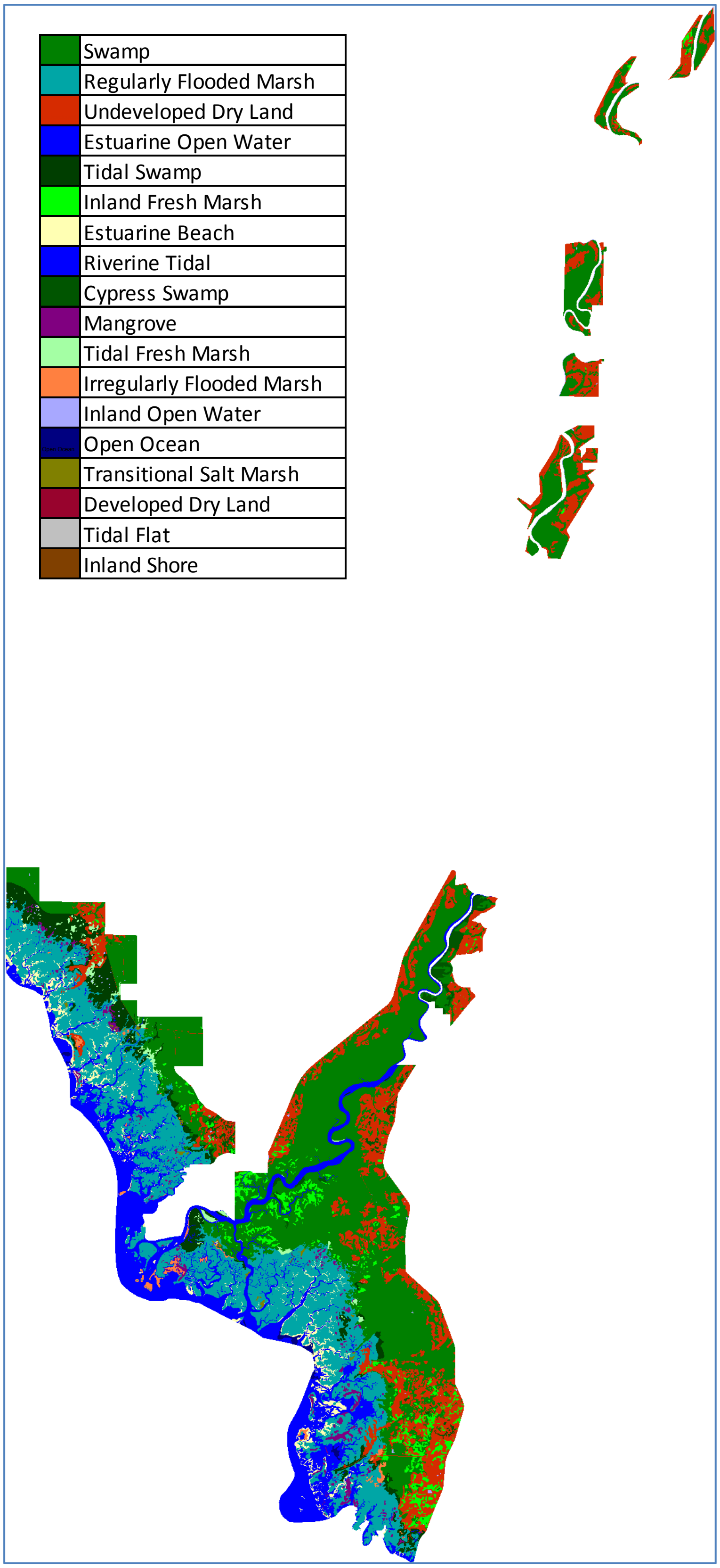


Lower Suwannee NWR, 2100, Scenario A1B Maximum

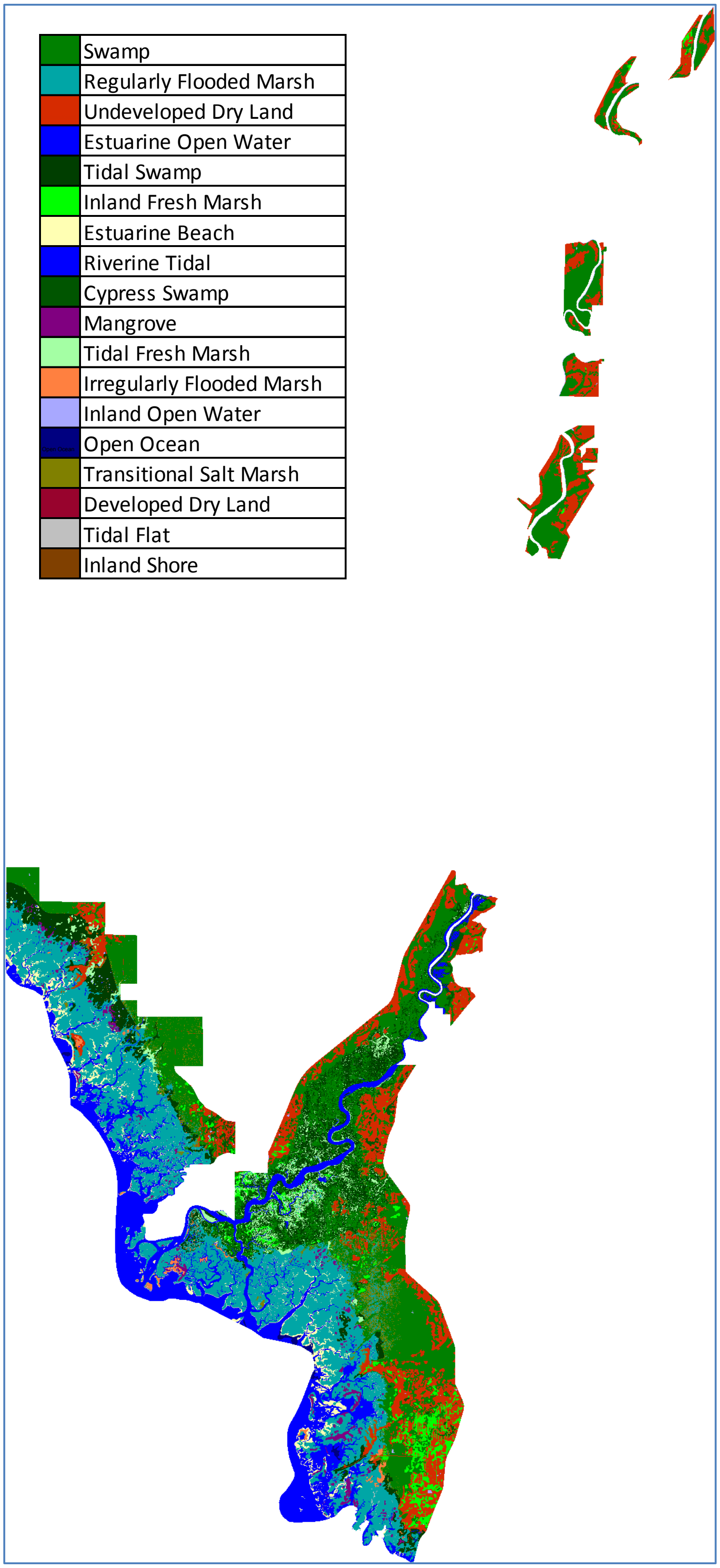
Lower Suwannee NWR
1 m eustatic SLR by 2100

Results in Acres

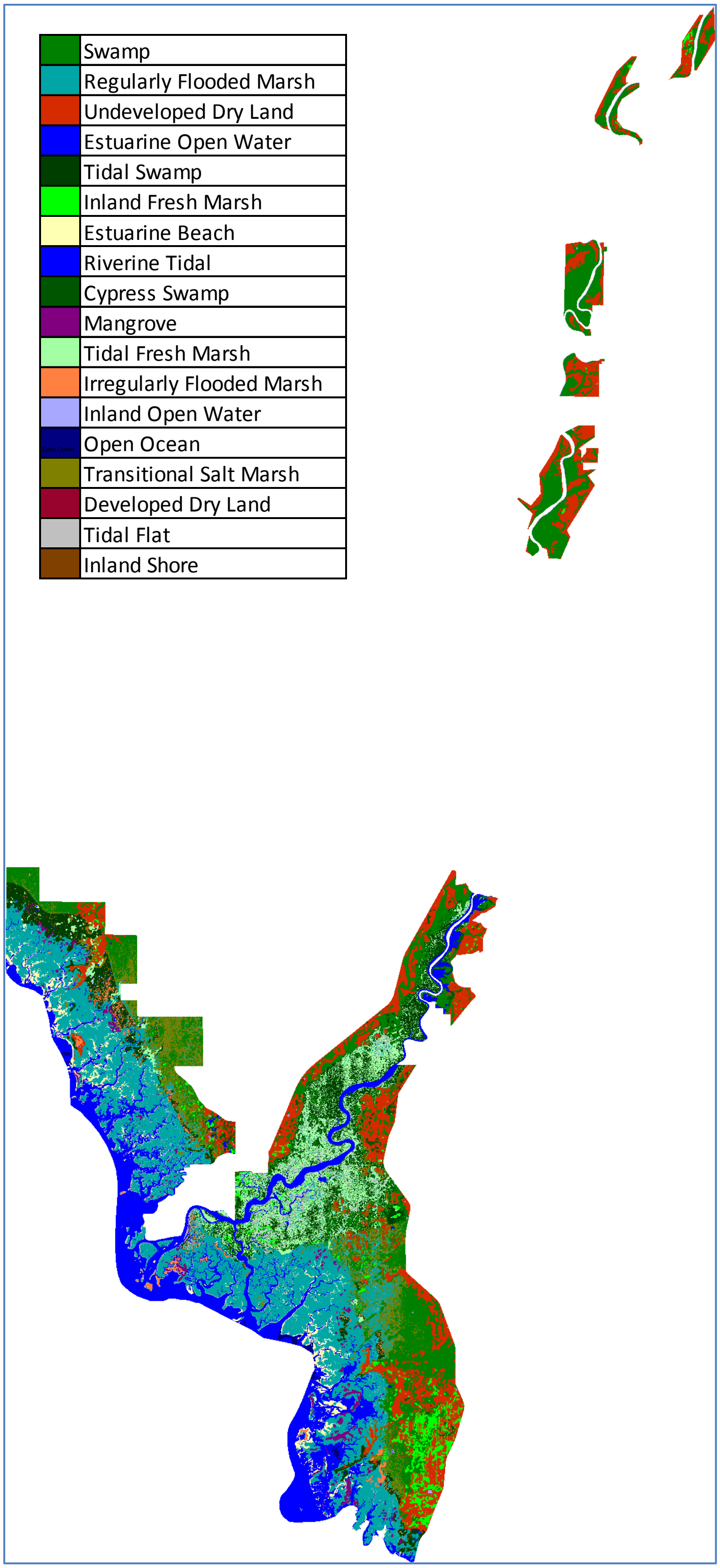
		Initial	2025	2050	2075	2100
🟩	Swamp	29391	22154	14864	10058	7576
🟦	Regularly Flooded Marsh	18788	19089	20032	22003	18437
🟥	Undeveloped Dry Land	12493	11389	10713	9544	8345
🟦	Estuarine Open Water	10795	11476	12059	14553	20717
🟩	Tidal Swamp	3504	7997	7310	2896	1239
🟩	Inland Fresh Marsh	2234	2114	2037	1913	1874
🟨	Estuarine Beach	1954	1913	1850	1372	763
🟦	Riverine Tidal	1531	1321	1239	509	195
🟩	Cypress Swamp	1007	670	480	285	192
🟪	Mangrove	946	938	934	922	909
🟩	Tidal Fresh Marsh	464	2067	5218	5247	1980
🟧	Irregularly Flooded Marsh	395	396	835	1664	1079
🟪	Inland Open Water	196	182	169	143	135
🟦	Open Ocean	194	194	194	194	194
🟫	Transitional Salt Marsh	136	1521	4038	4645	3019
🟥	Developed Dry Land	28	27	26	24	18
⬜	Tidal Flat	6	612	2063	8089	17389
🟫	Inland Shore	2	2	2	2	2
	Total (incl. water)	**84063**	**84063**	**84063**	**84063**	**84063**



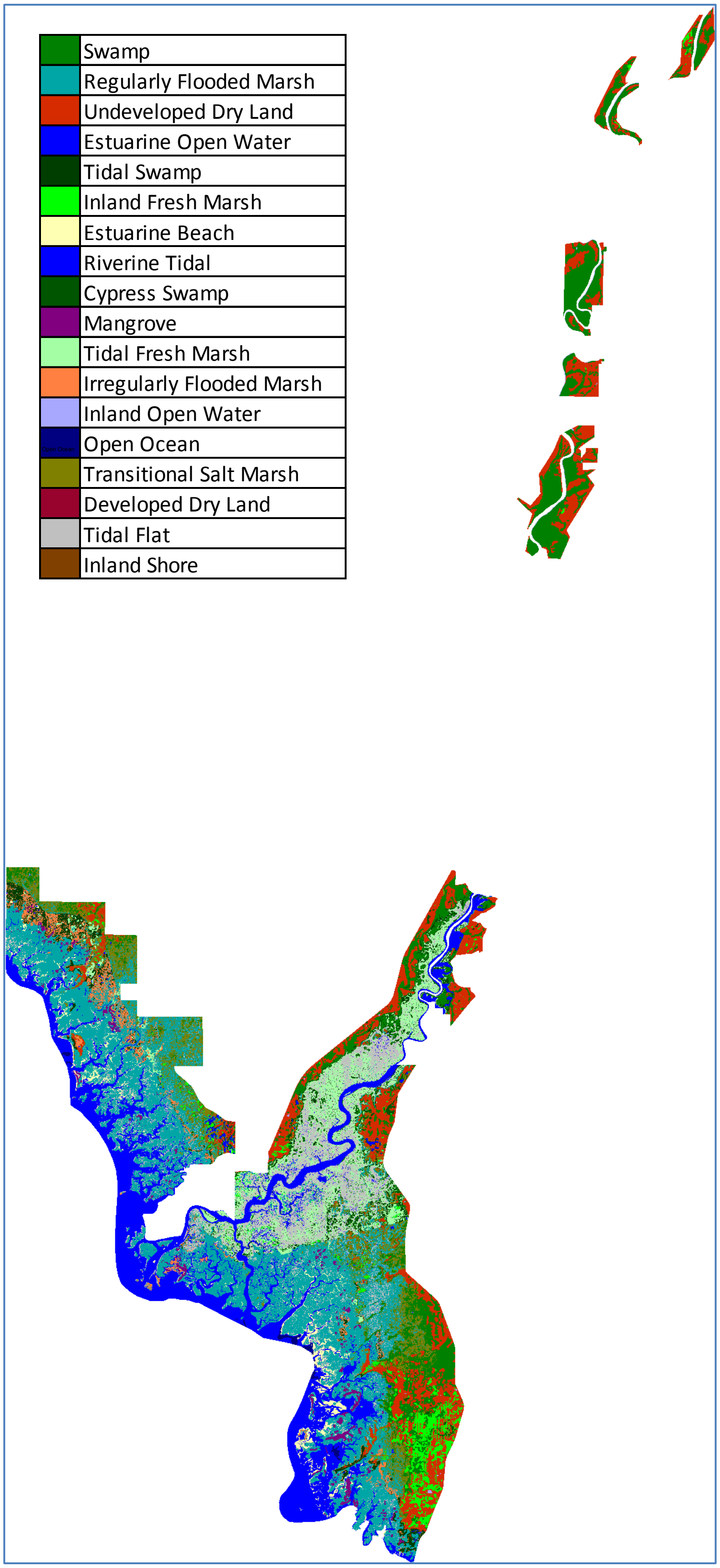
Lower Suwannee NWR, Initial Condition



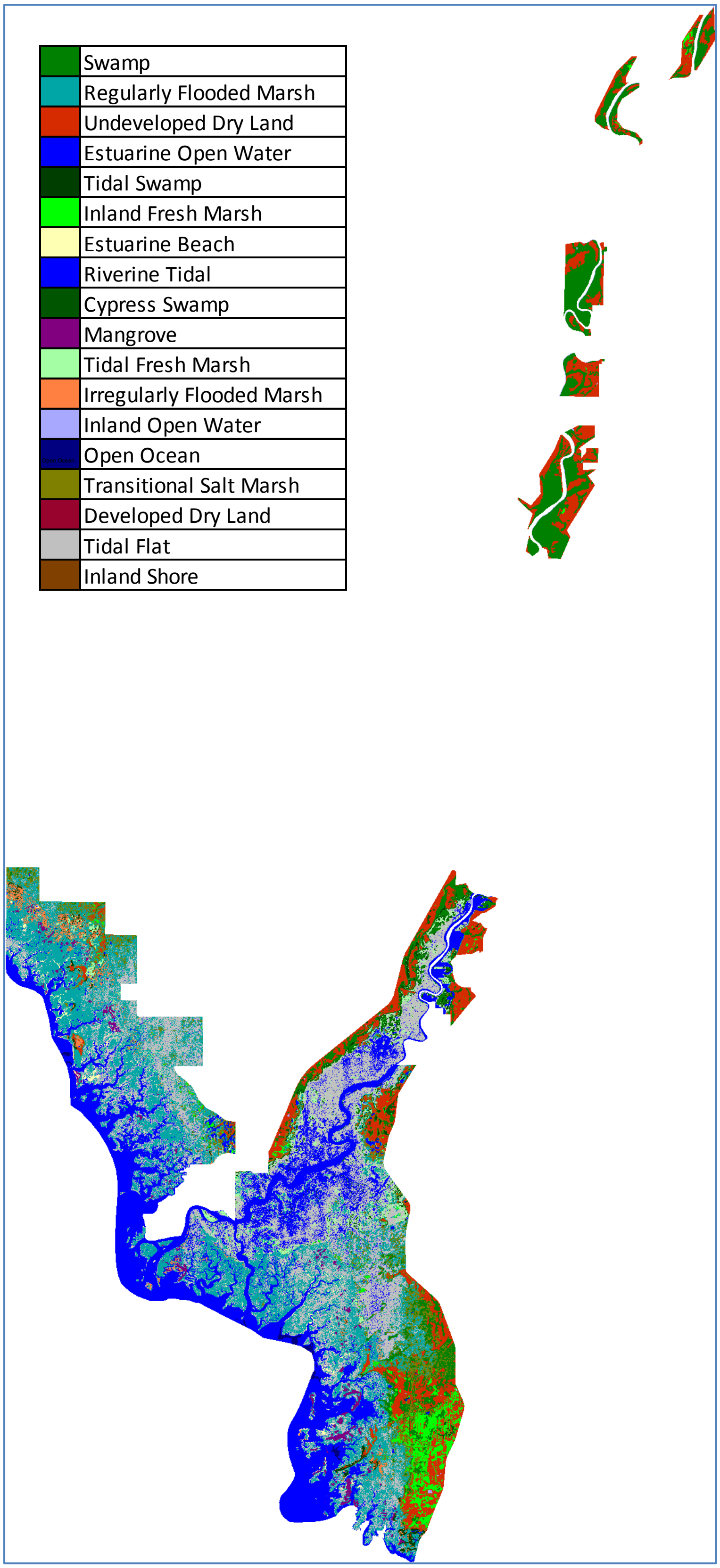
Lower Suwannee NWR, 2025, 1 Meter



Lower Suwannee NWR, 2050, 1 Meter



Lower Suwannee NWR, 2075, 1 m SLR

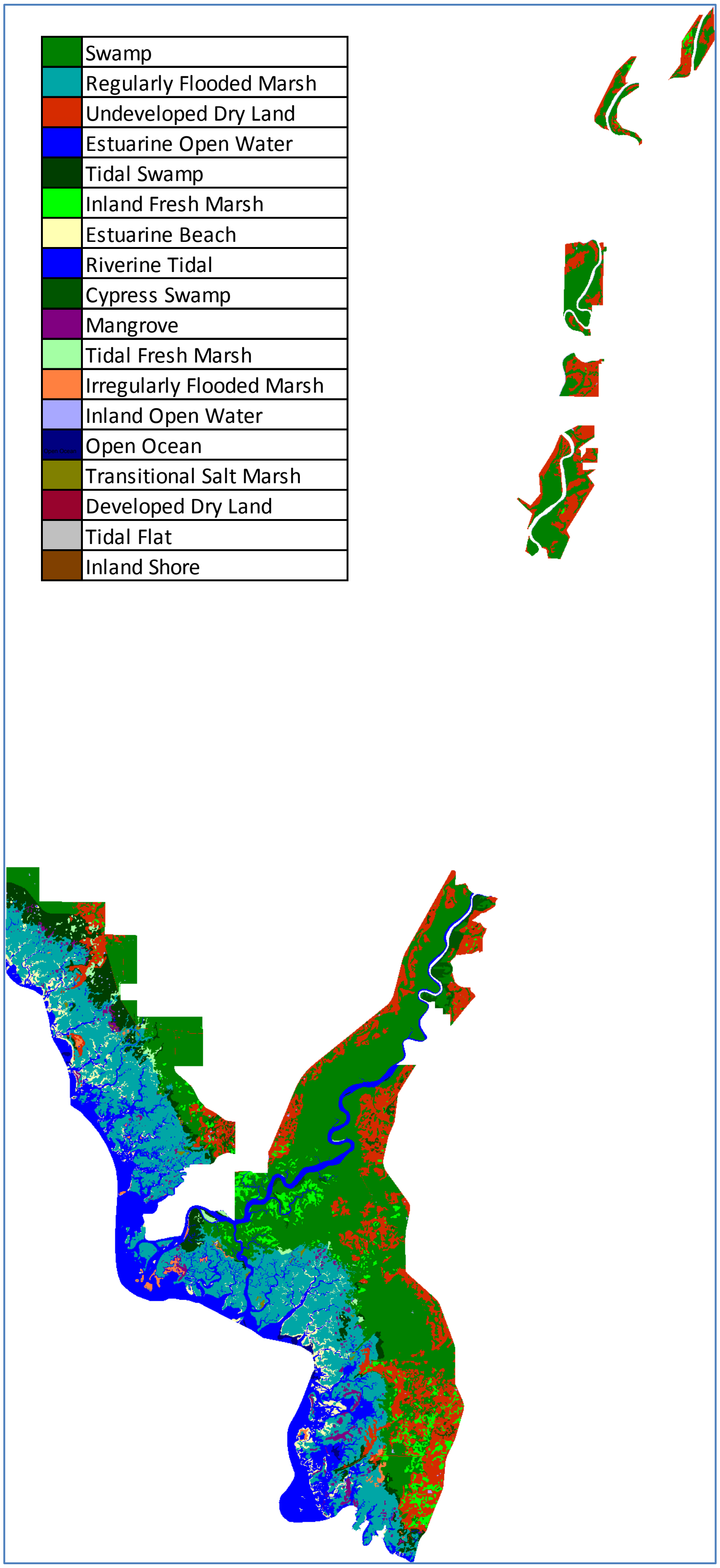


Lower Suwannee NWR, 2100, 1 Meter

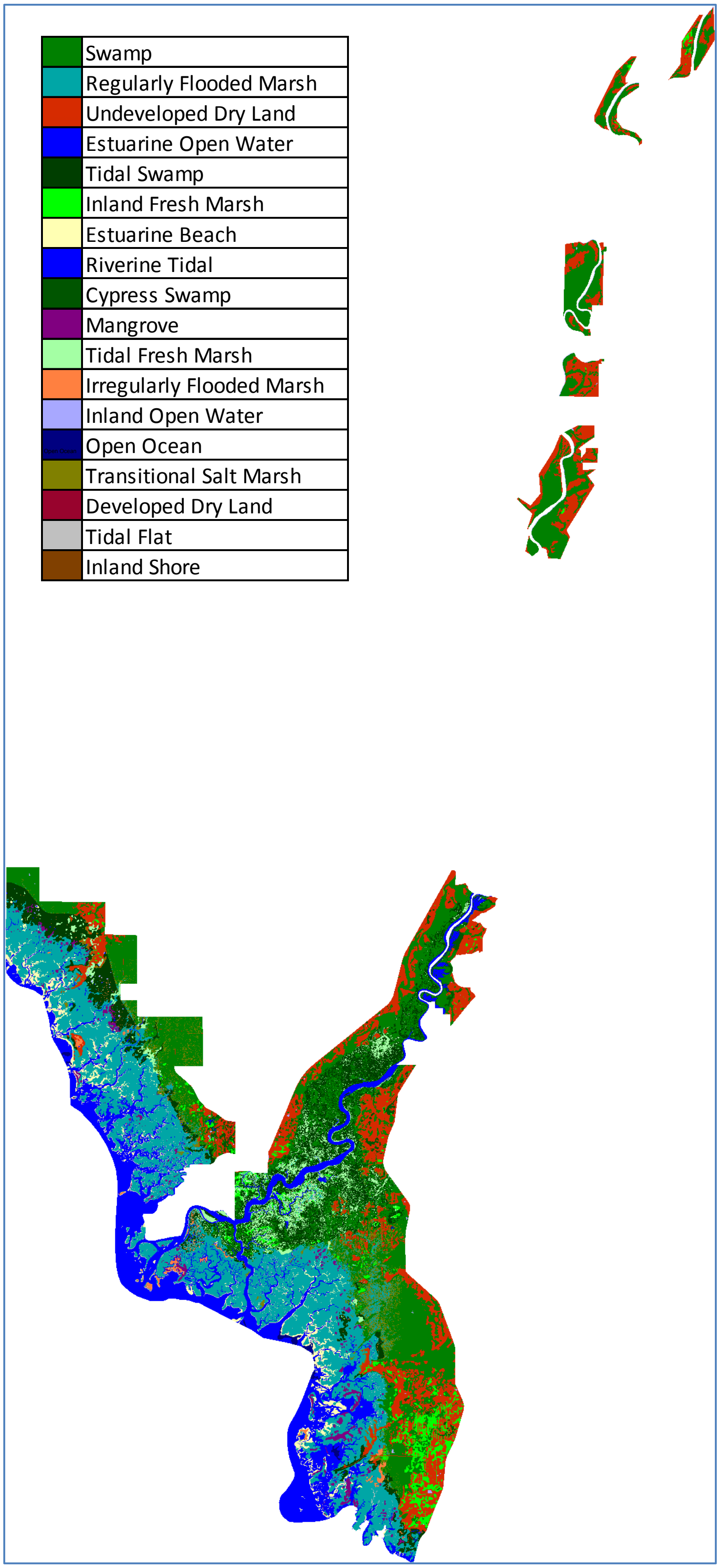
Lower Suwannee NWR
1.5 m eustatic SLR by 2100

Results in Acres

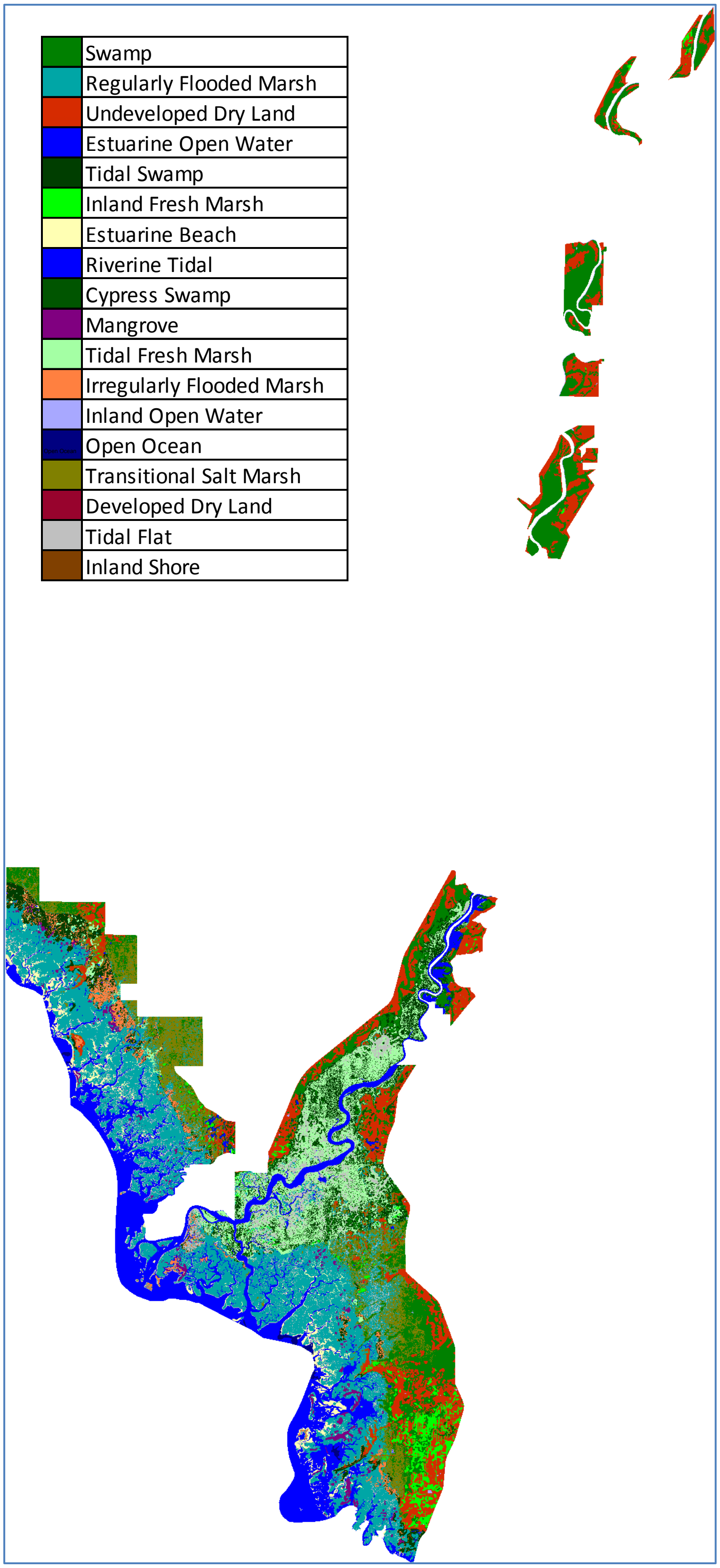
		Initial	**2025**	**2050**	**2075**	**2100**
🟩	Swamp	29391	20351	11671	7489	5577
🟦	Regularly Flooded Marsh	18788	19111	19398	15753	7416
🟥	Undeveloped Dry Land	12493	11303	10197	8456	6783
🟦	Estuarine Open Water	10795	11553	12469	18471	34549
🟩	Tidal Swamp	3504	8594	5999	1691	826
🟩	Inland Fresh Marsh	2234	2047	1816	1687	1339
🟨	Estuarine Beach	1954	1913	1820	762	184
🟦	Riverine Tidal	1531	1315	1206	406	175
🟩	Cypress Swamp	1007	620	360	191	92
🟪	Mangrove	946	937	919	851	549
🟩	Tidal Fresh Marsh	464	2702	6058	4309	1348
🟧	Irregularly Flooded Marsh	395	466	1526	1658	301
🟦	Inland Open Water	196	180	163	135	131
🟦	Open Ocean	194	194	194	194	194
🟩	Transitional Salt Marsh	136	1920	5879	4710	3237
🟥	Developed Dry Land	28	27	25	18	14
⬜	Tidal Flat	6	828	4358	17279	21347
🟫	Inland Shore	2	2	2	2	2
	Total (incl. water)	**84063**	**84063**	**84063**	**84063**	**84063**



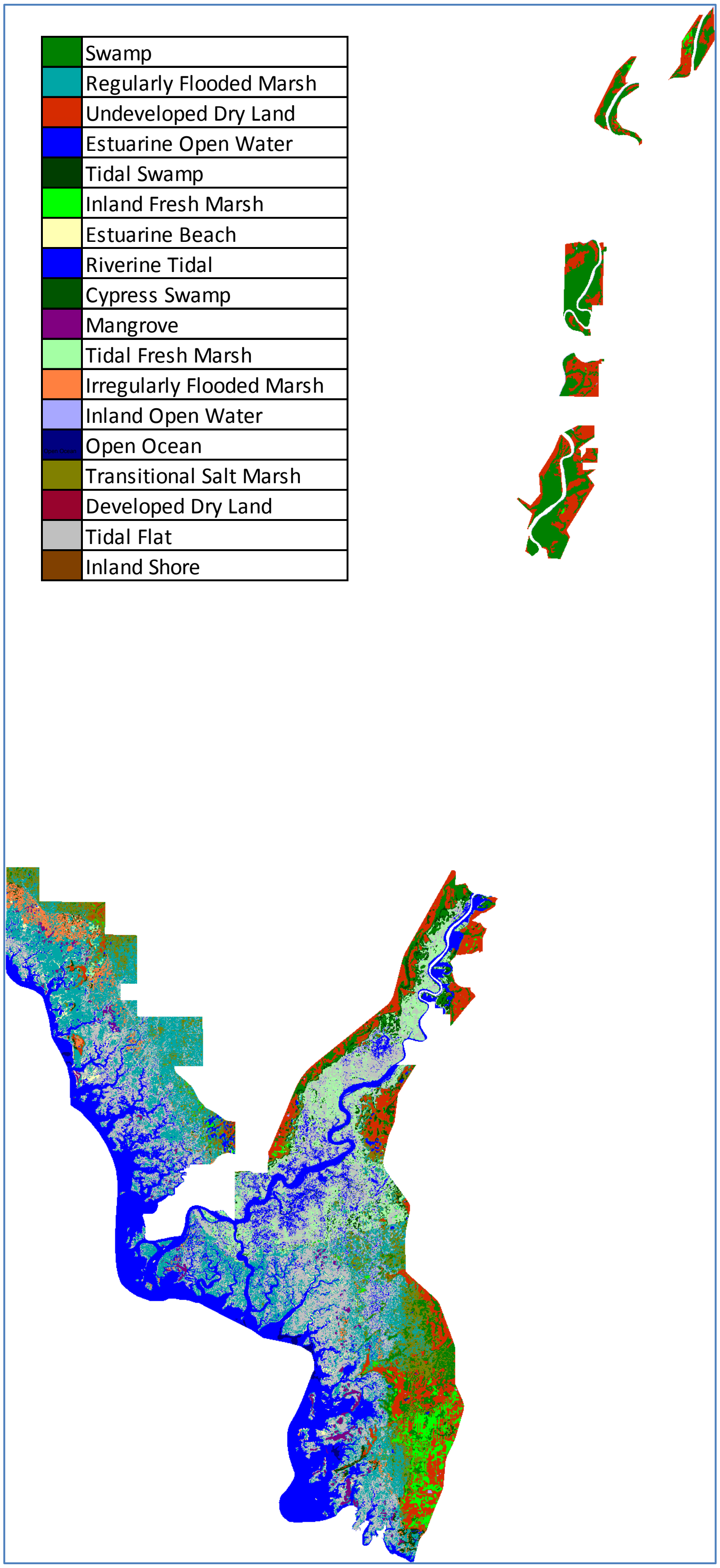
Lower Suwannee NWR, Initial Condition



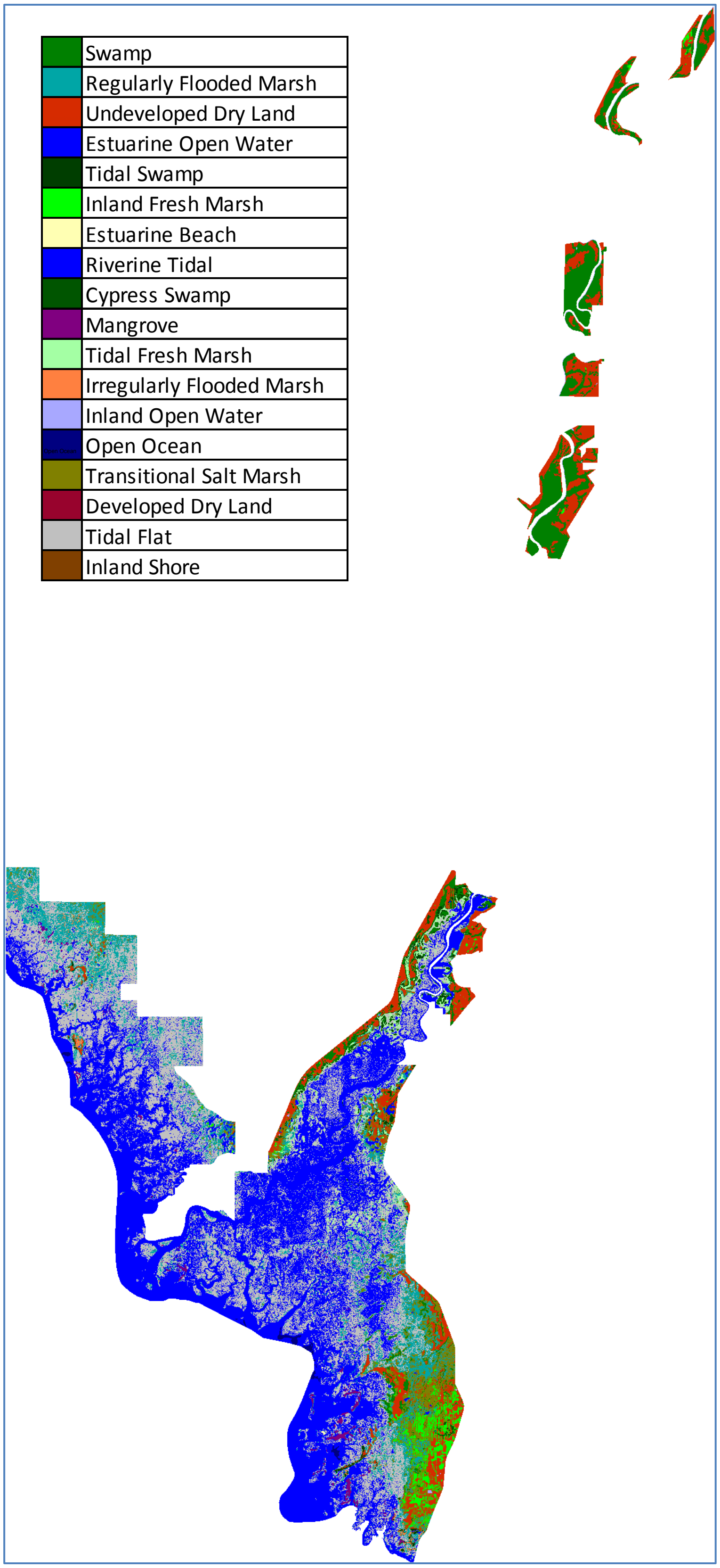
Lower Suwannee NWR, 2025, 1.5 Meters



Lower Suwannee NWR, 2050, 1.5 Meters



Lower Suwannee NWR, 2075, 1.5 Meters

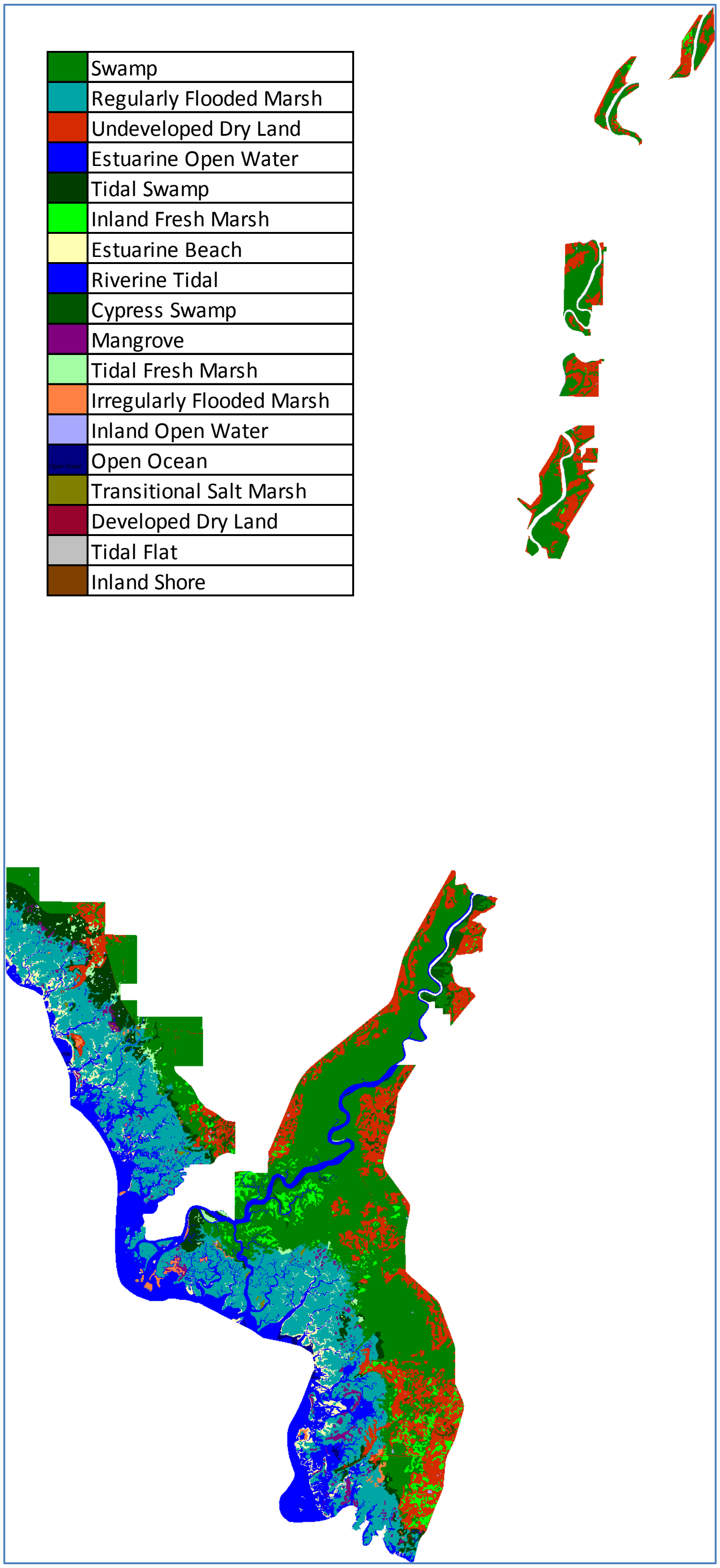


Lower Suwannee NWR, 2100, 1.5 Meters

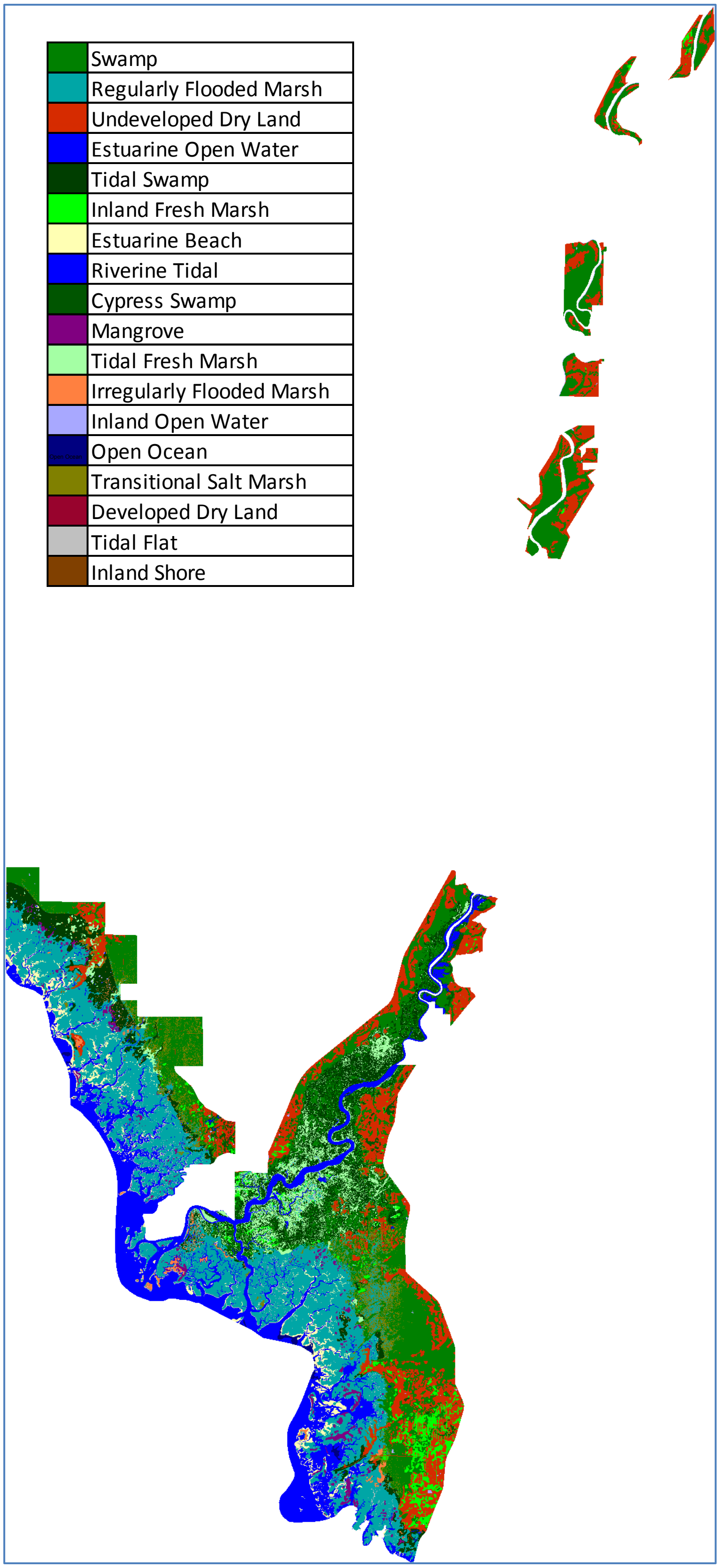
Lower Suwannee NWR
2 m eustatic SLR by 2100

Results in Acres

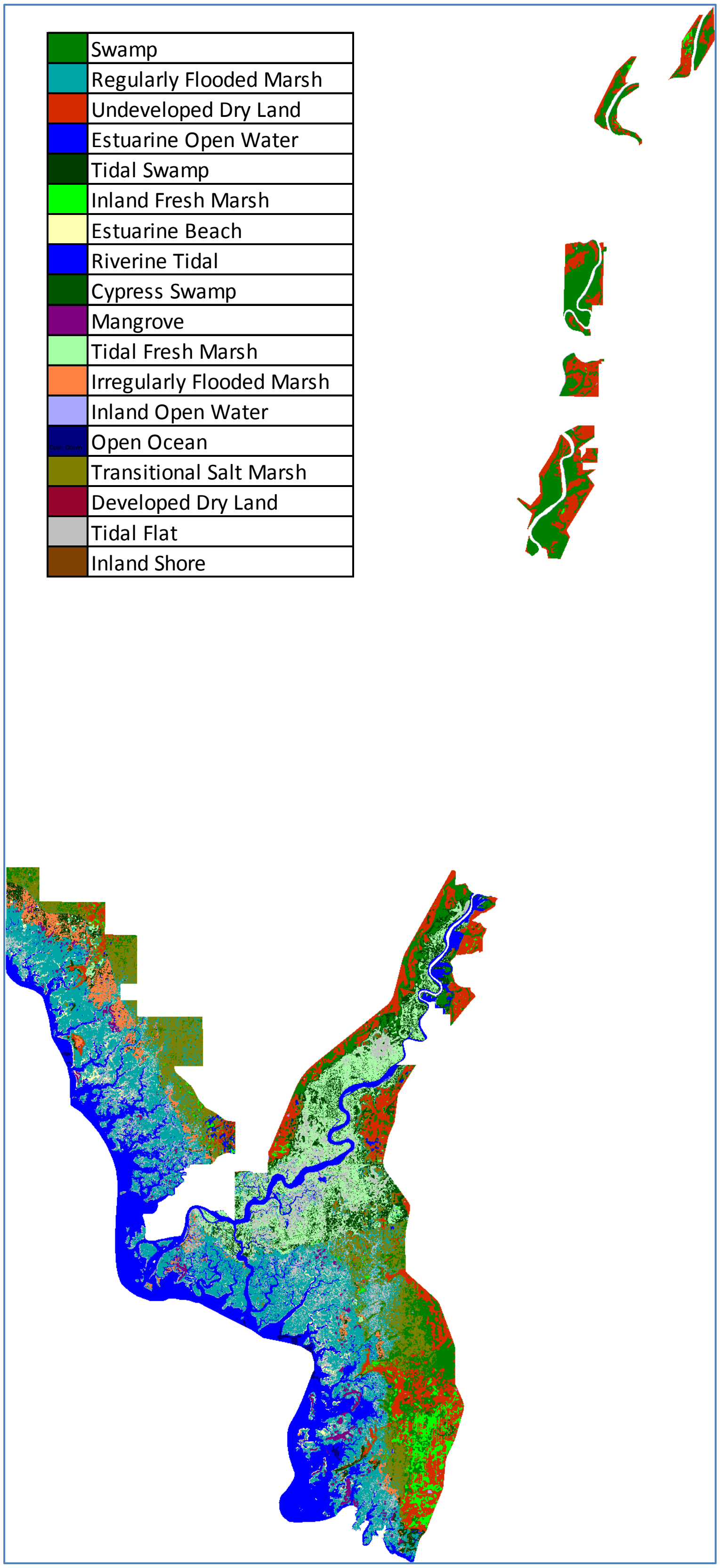
		Initial	2025	2050	2075	2100
🟩	Swamp	29391	18694	9638	5911	3130
🟦	Regularly Flooded Marsh	18788	19026	17235	10760	6103
🟥	Undeveloped Dry Land	12493	11201	9614	7410	5097
🟦	Estuarine Open Water	10795	11634	13935	24507	47127
🟩	Tidal Swamp	3504	8792	4669	1382	2353
🟩	Inland Fresh Marsh	2234	1973	1677	1309	578
🟨	Estuarine Beach	1954	1913	1007	363	22
🟦	Riverine Tidal	1531	1299	1183	320	163
🟩	Cypress Swamp	1007	581	274	107	32
🟪	Mangrove	946	930	899	524	258
🟩	Tidal Fresh Marsh	464	3495	6100	3645	1211
🟧	Irregularly Flooded Marsh	395	530	2204	950	120
🟪	Inland Open Water	196	179	157	131	125
🟦	Open Ocean	194	194	194	194	194
🟫	Transitional Salt Marsh	136	2564	7170	5069	3530
🟥	Developed Dry Land	28	27	24	15	10
⬜	Tidal Flat	6	1031	8081	21463	14006
🟫	Inland Shore	2	2	2	2	2
	Total (incl. water)	**84063**	**84063**	**84063**	**84063**	**84063**



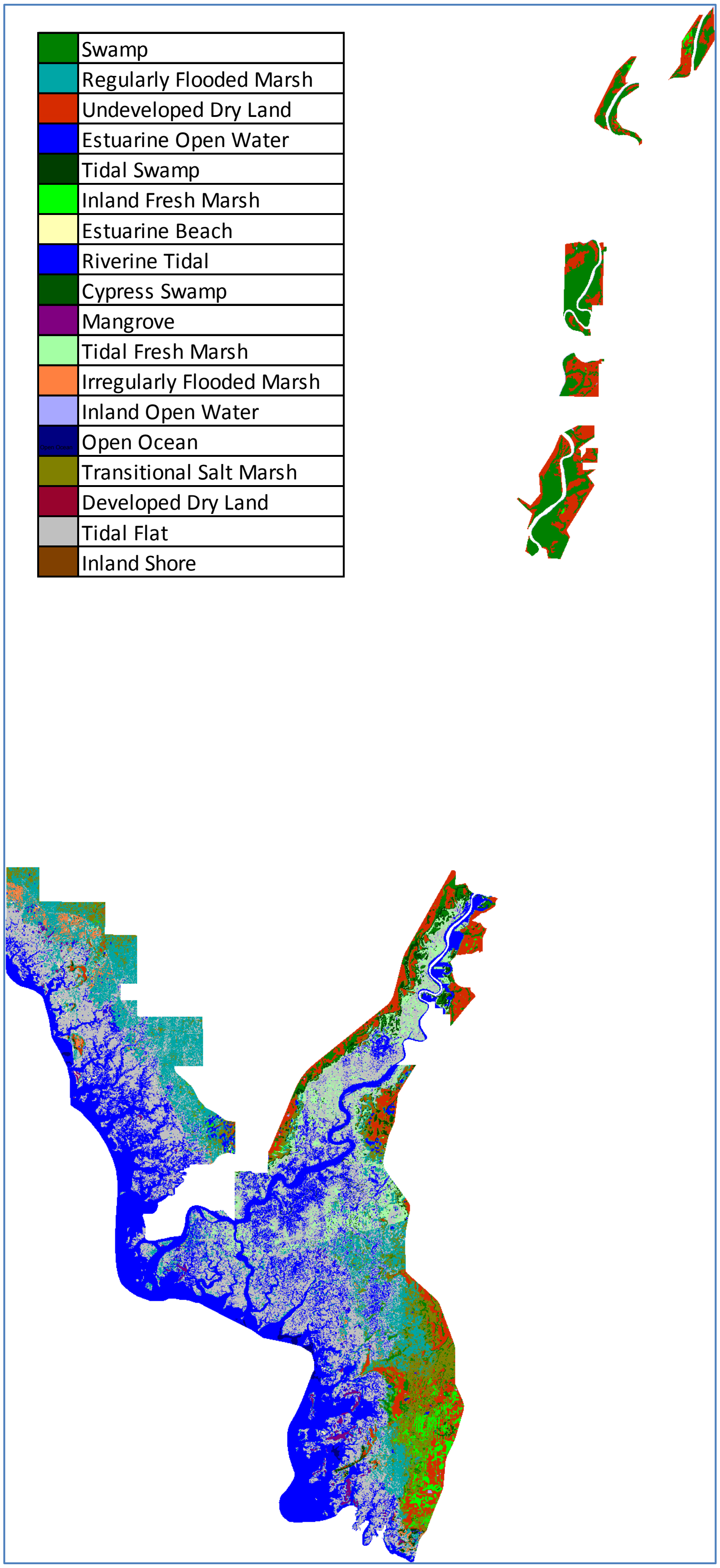
Lower Suwannee NWR, Initial Condition



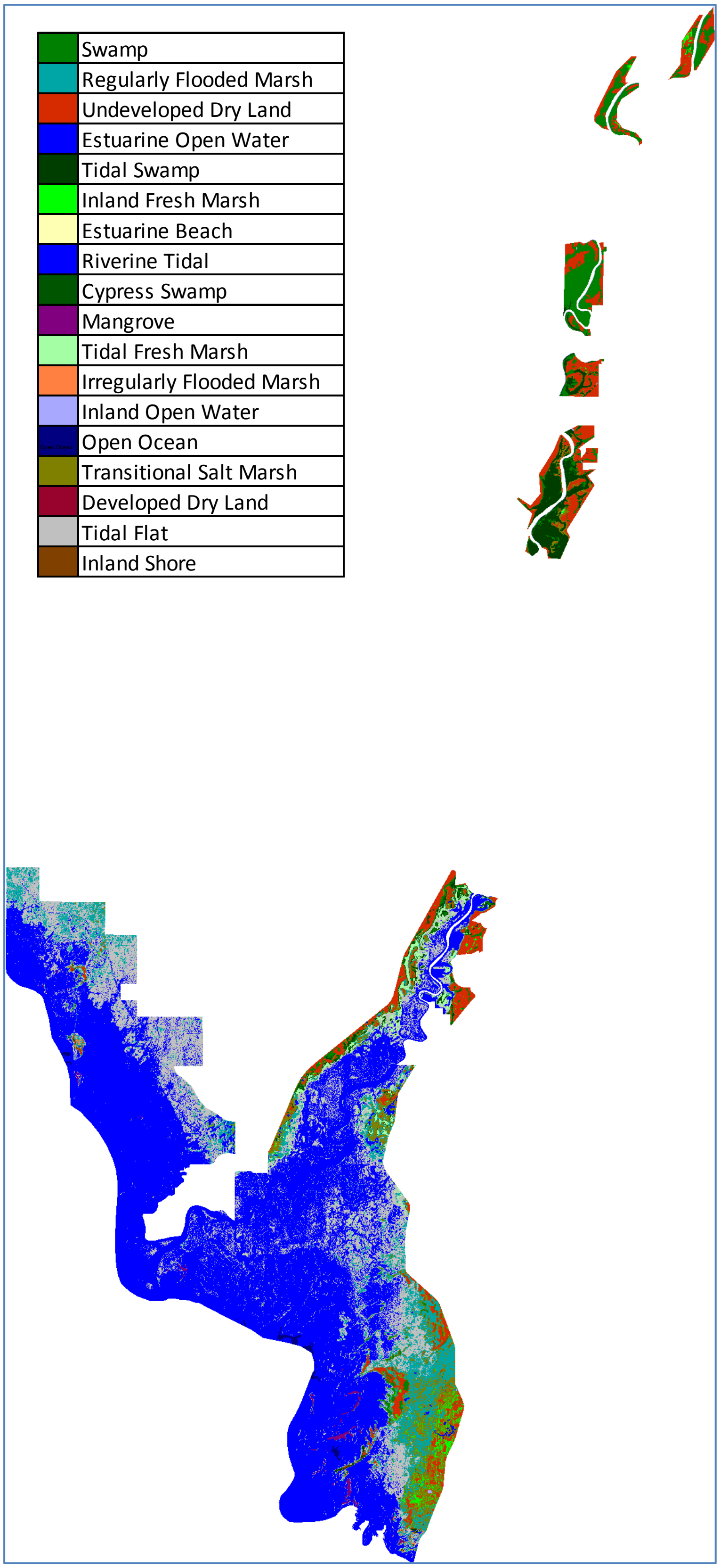
Lower Suwannee NWR, 2025, 2 Meters



Lower Suwannee NWR, 2050, 2 Meters



Lower Suwannee NWR, 2075, 2 Meters



Lower Suwannee NWR, 2100, 2 Meters

Erosion Map

Figure 17 shows a map of predicted erosion rates in marshes and swamps (given the one meter of SLR by 2100 scenario). Over 100 years, marsh erosion is predicted to be particularly strong along the boundaries of regularly flooded marsh and open water, especially near the Suwannee River delta.

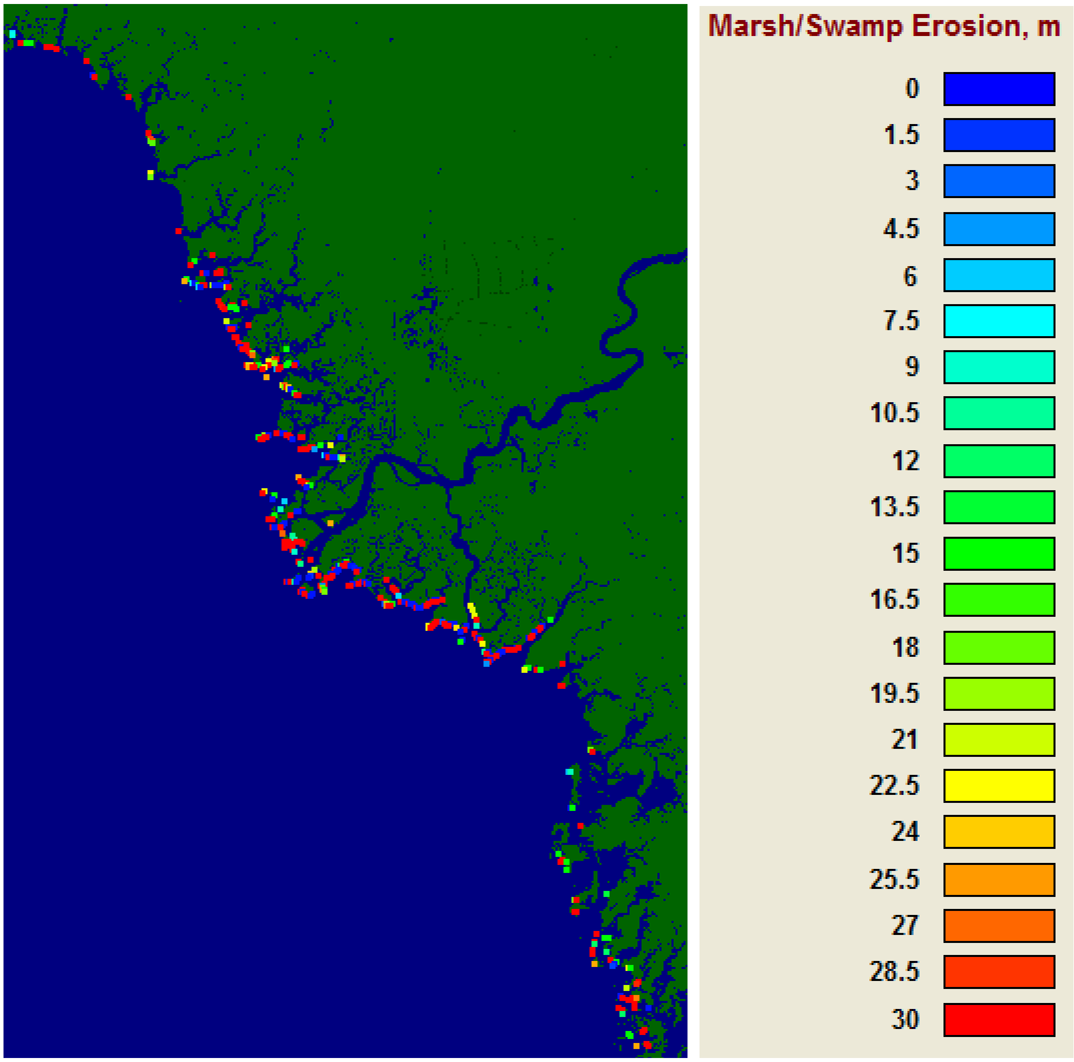


Figure 17. Horizontal marsh erosion (m)

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 0.134 m.

According the VDatum website the RMSE for the correction between MTL and NAVD88 in this study region is 0.05 meters (National Oceanic and Atmospheric Association 2010). This value was determined by combining the uncertainty associated with the NAVD to MSL transformation (0.034 meters) and MSL to MTL transformation (0.016 meters).

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 . 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 0.2499[2].

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 meters of eustatic SLR by 2100 for each iteration.

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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.

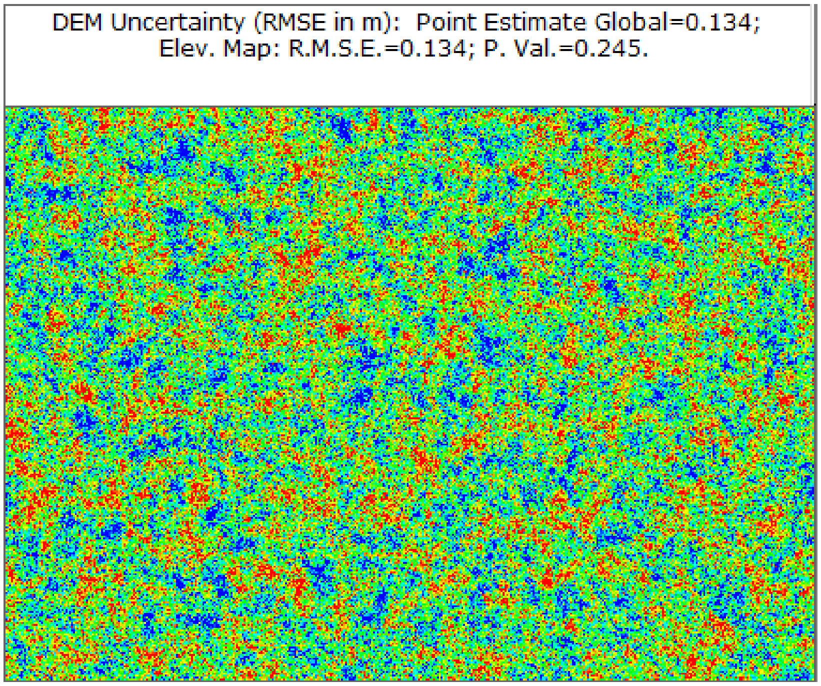

Figure 18: A spatially autocorrelated error field using parameters from this model application, units in meters.

The impacts of applying an elevation-uncertainty analysis to the study area were extremely limited, with the coefficient of variance lying below 2% for the majority of wetland categories. For regularly flooded marsh – which comprises roughly a quarter of the refuge – the resulting acreages vary by only 250 acres across all iterations.

Variable Name	Min	Mean	Max	Std. Dev.	Deterministic	CV
Regularly Flooded Marsh	27652	27851	28036	89	29144	0.3%
Estuarine Open Water	16326	16411	16493	33	16304	0.2%
Swamp	11277	11386	11517	52	10999	0.5%
Undeveloped Dry Land	10291	10371	10432	33	10400	0.3%
Irreg. Flooded Marsh	5755	5865	5990	52	7480	0.9%
Tidal Flat	4552	4710	485	73	3105	1.5%
Tidal Fresh Marsh	3830	3969	4075	48	3747	1.2%
Trans. Salt Marsh	3662	3779	3872	42	3847	1.1%
Tidal Swamp	2975	3079	3150	38	2634	1.2%
Inland Fresh Marsh	2311	2364	2439	26	2319	1.1%
Estuarine Beach	1345	1392	1436	18	1158	1.3%
Mangrove	1026	1029	1032	1	1034	0.1%
Cypress Swamp	302	319	340	7	309	2.3%
Riverine Tidal	264	290	321	12	335	4.2%
Open Ocean	215	215	215	0	215	0.0%
Inland Open Water	153	155	158	1	154	0.7%
Developed Dry Land	24	26	27	1	26	2.9%
Inland Shore	2	2	2	0.0	2	0.0%

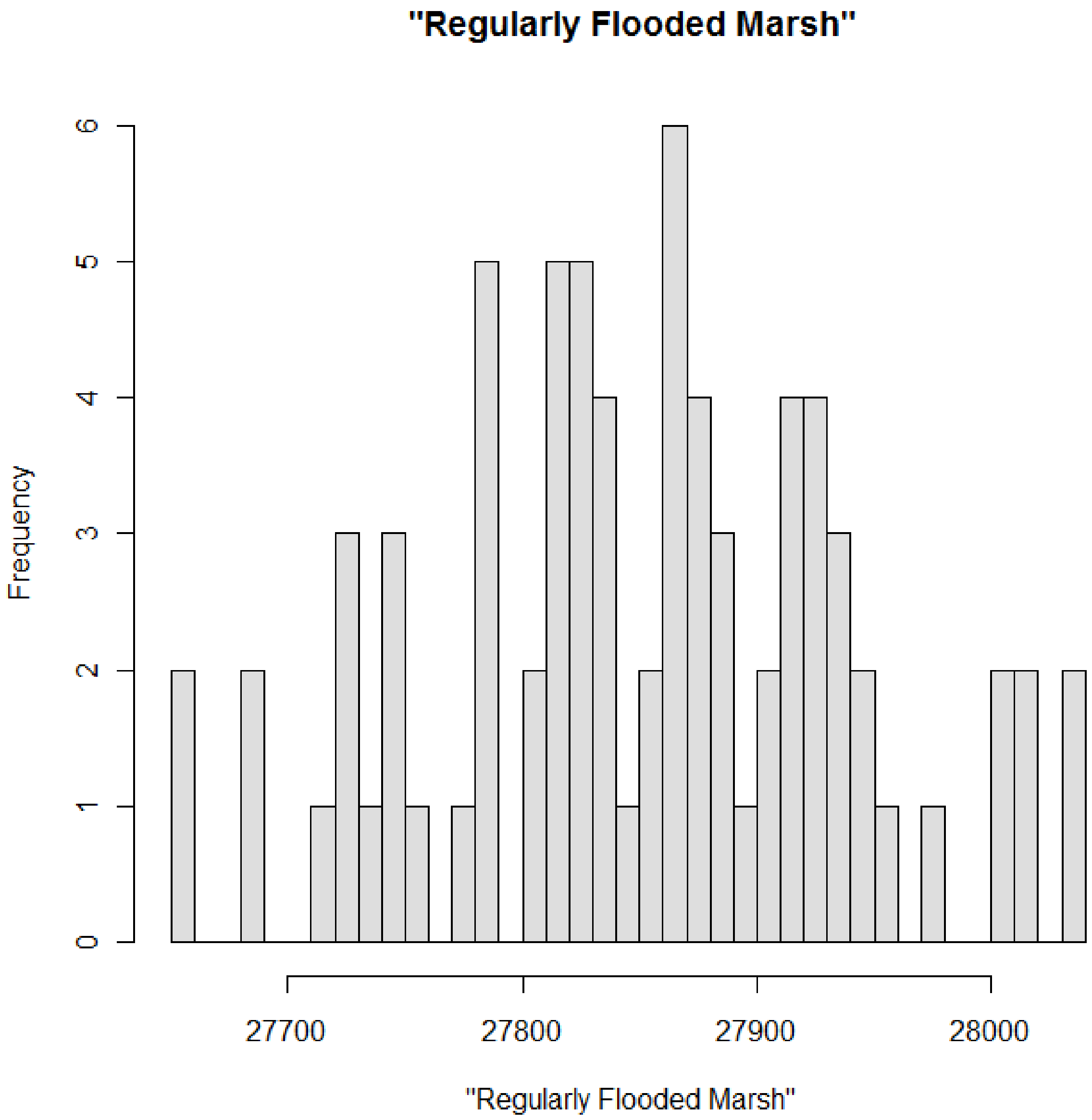

Figure 19: Elevation uncertainty result distribution for refuge regularly flooded marsh.

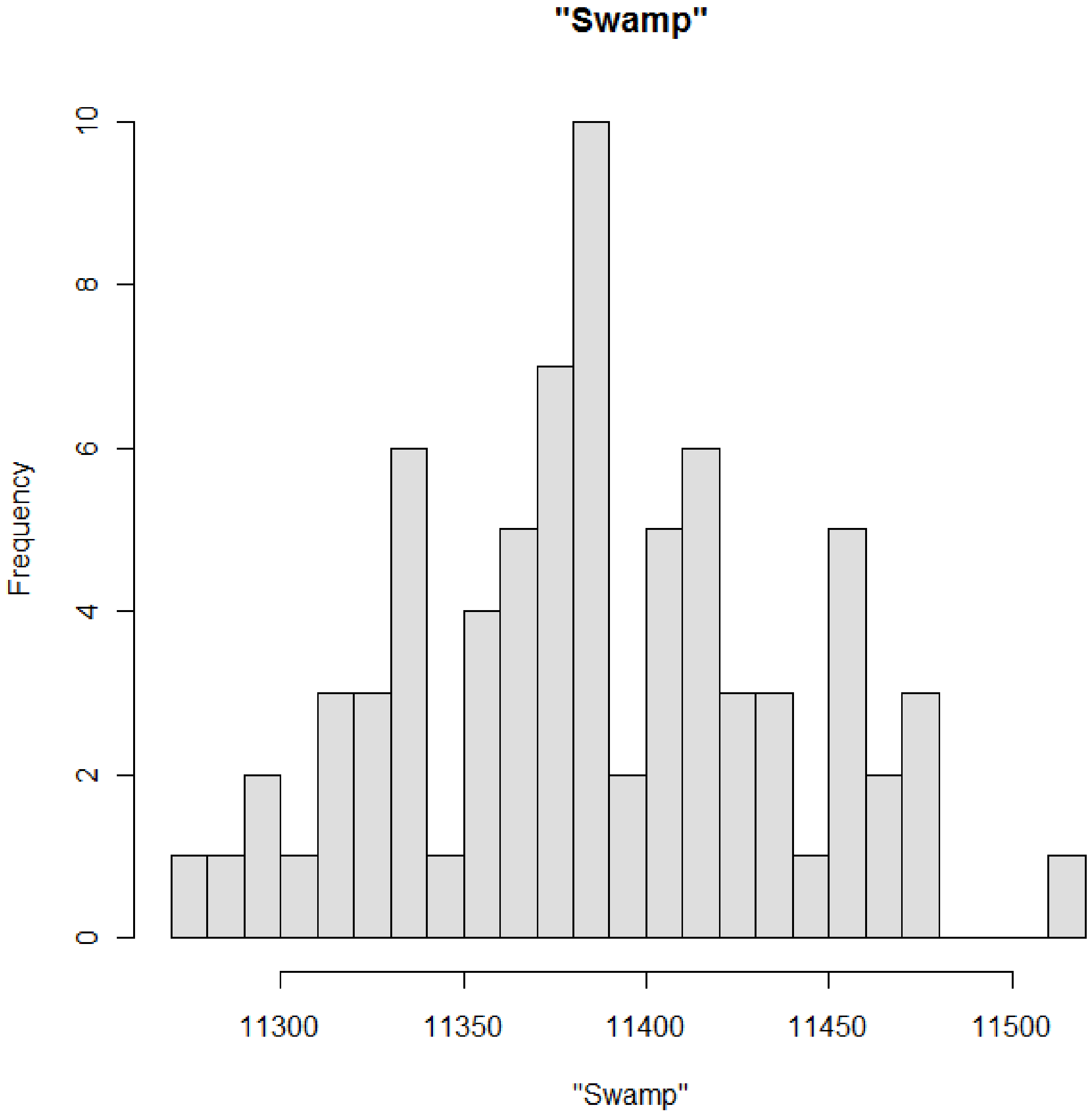

Figure 20: Elevation uncertainty result distribution for refuge swamp.

Discussion

Results for the SLAMM model forecast provide interesting insight into the potential transformation of this refuge under a variety of SLR scenarios over the next 100 years. Forecast results reveal a refuge greatly susceptible to inundation from SLR by 2100, as all wetland classes are predicted to undergo significant changes in response to SLR. A significant amount of land is predicted to be converted to open water or tidal flat by 2100, with overall combined wetland losses ranging between 2% and 50% of the current observed land cover in the refuge. Due to the low elevations in the region, even the northern portions of the refuge in Gilchrist County experience some inundation effects by 2100 at 2 meters SLR. Swamp, which covers approximately 30% of the refuge, is predicted to be the most affected wetland with losses between 50% and 90%. However, for SLR above 1 m almost all wetlands experience significant losses.

The nearly-immediate prediction of swamp and inland-fresh marsh loss near the mouth of the river in both the hindcast and forecast indicates that this is an area worth continued investigation. It is possible that these locations were mis-categorized by NWI and deserve further ground-truthing to determine their appropriate characterization. Also the highly variable elevations in this area deserve further investigation.

The addition of a freshwater-flow signal to the model to a large portion of the river basin decreased the predicted severity of marsh loss within this region. Without the fresh water assumptions the swamp and inland-fresh marsh within this low-lying river basin would have ultimately converted to tidal flat and open water. The strength and extent of the fresh water influence is uncertain, however, and future modeling efforts would benefit from more precise accounting of the freshwater influence within the refuge.

Upriver from Fowler Bluff (NOAA gauge 8727512 located approximately 15 miles upriver from the river mouth at Alligator Pass) tidal influence is uncertain because site-specific tidal data were not available at that location.

The sensitivity analysis with respect to elevations shows that the uncertainty of the LiDAR data does not greatly affect the results. However, as already noted, it is possible that some elevations in the river delta are subject to a higher uncertainty that should be further investigated.

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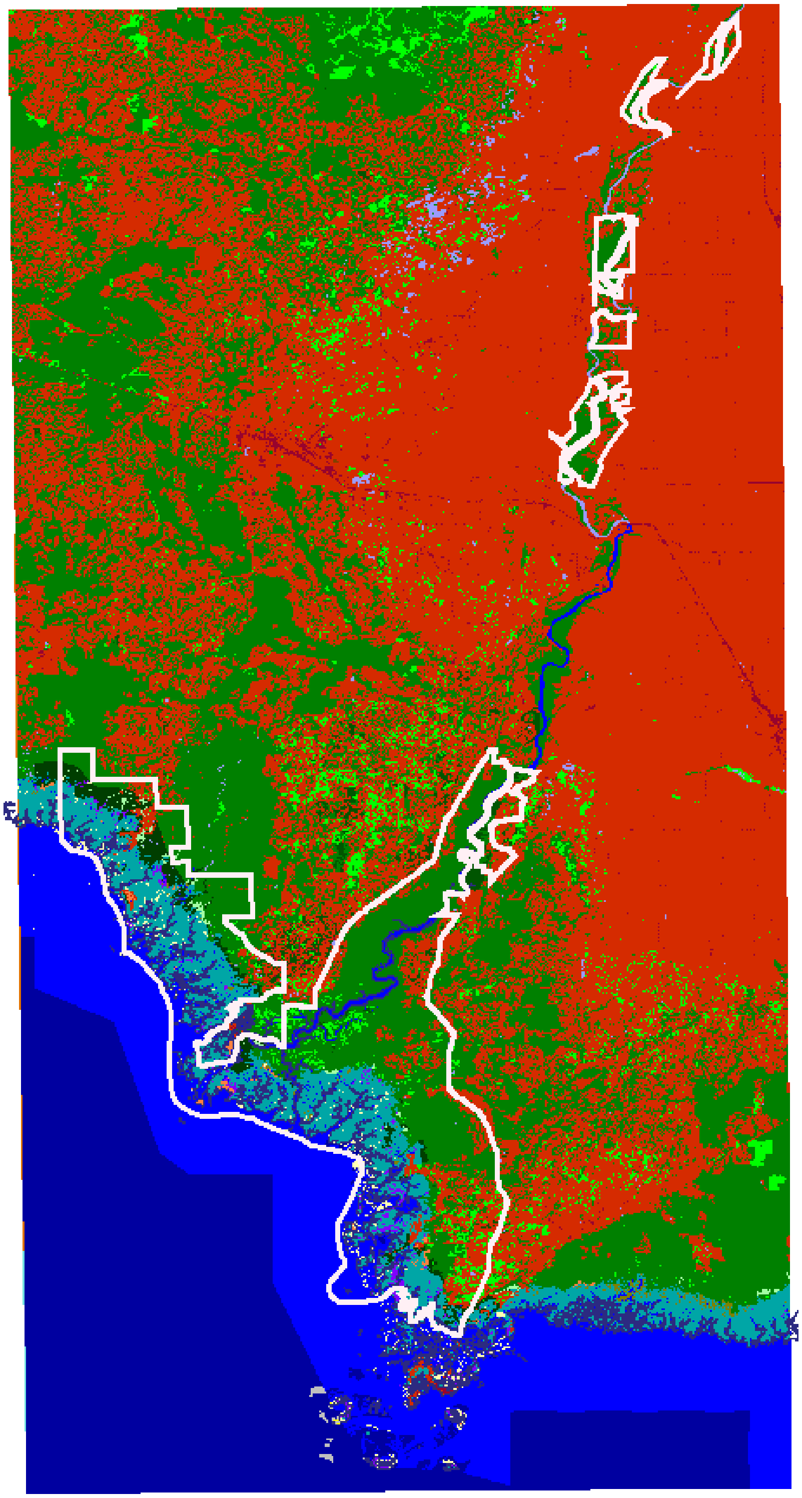
Appendix A: Contextual Results

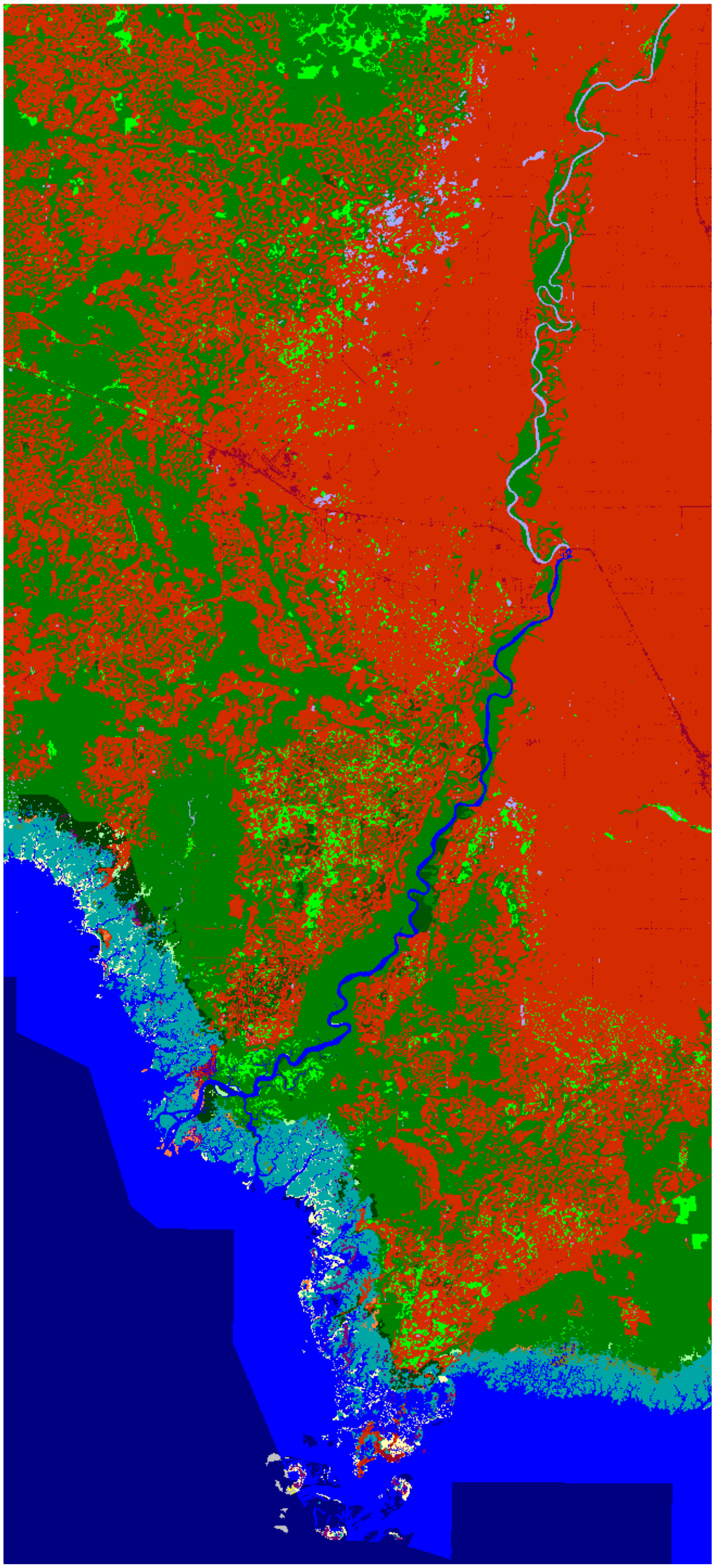
The SLAMM model does take into account the context of the surrounding lands or open water when calculating effects. For example, erosion rates are calculated based on the maximum fetch (wave action) which is estimated by assessing contiguous open water to a given marsh cell. Another example is that inundated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

For this reason, an area larger than the boundaries of the USFWS refuge was modeled. These results maps are presented here with the following caveats:

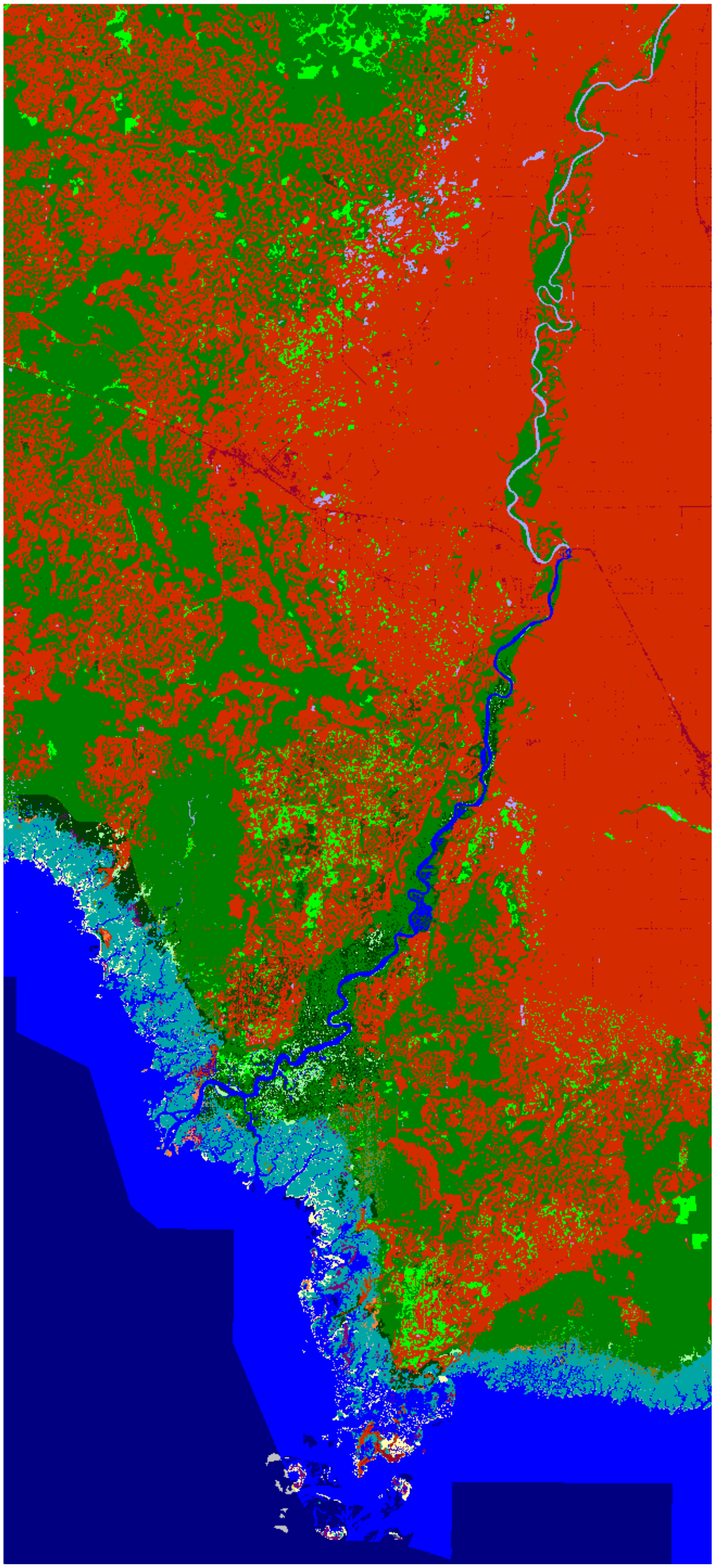
- Results were closely examined (quality assurance) within USFWS refuges but not closely examined for the larger region.
- Site-specific parameters for the model were derived for USFWS refuges whenever possible and may not be regionally applicable.
- Especially in areas where dikes are present, an effort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



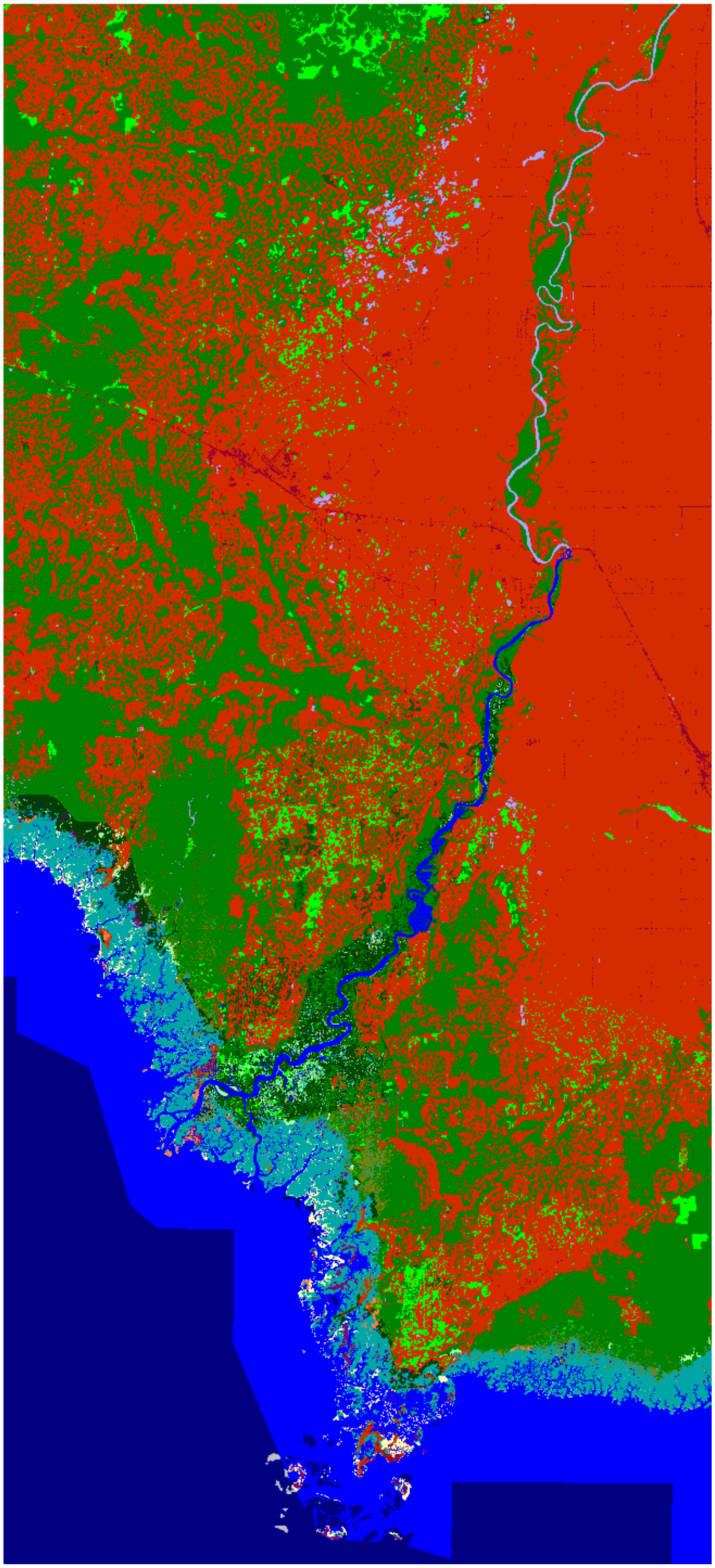
Lower Suwannee National Wildlife Refuge (white) within simulation context.



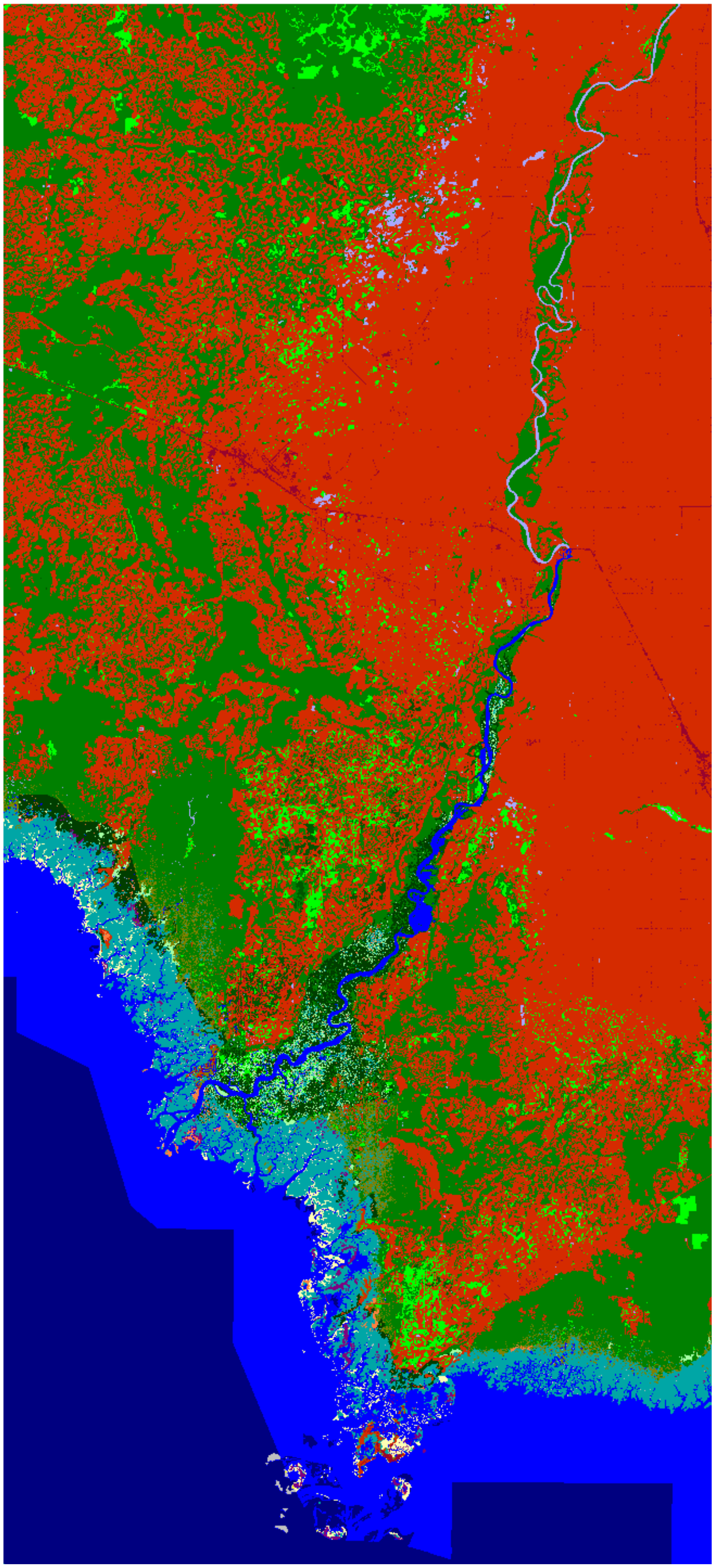
Lower Suwannee NWR, Initial Condition



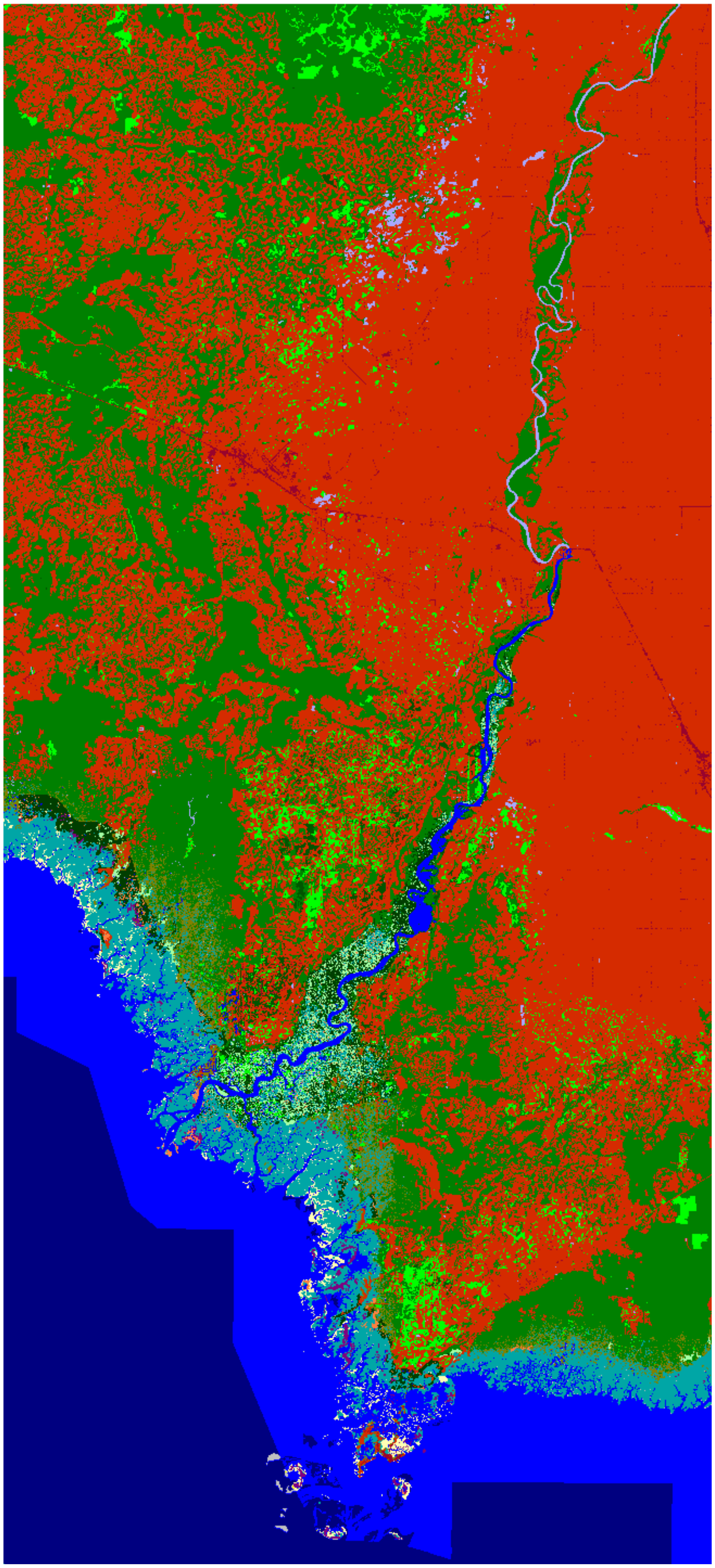
Lower Suwannee NWR, 2025, Scenario A1B Mean, 0.39 m SLR



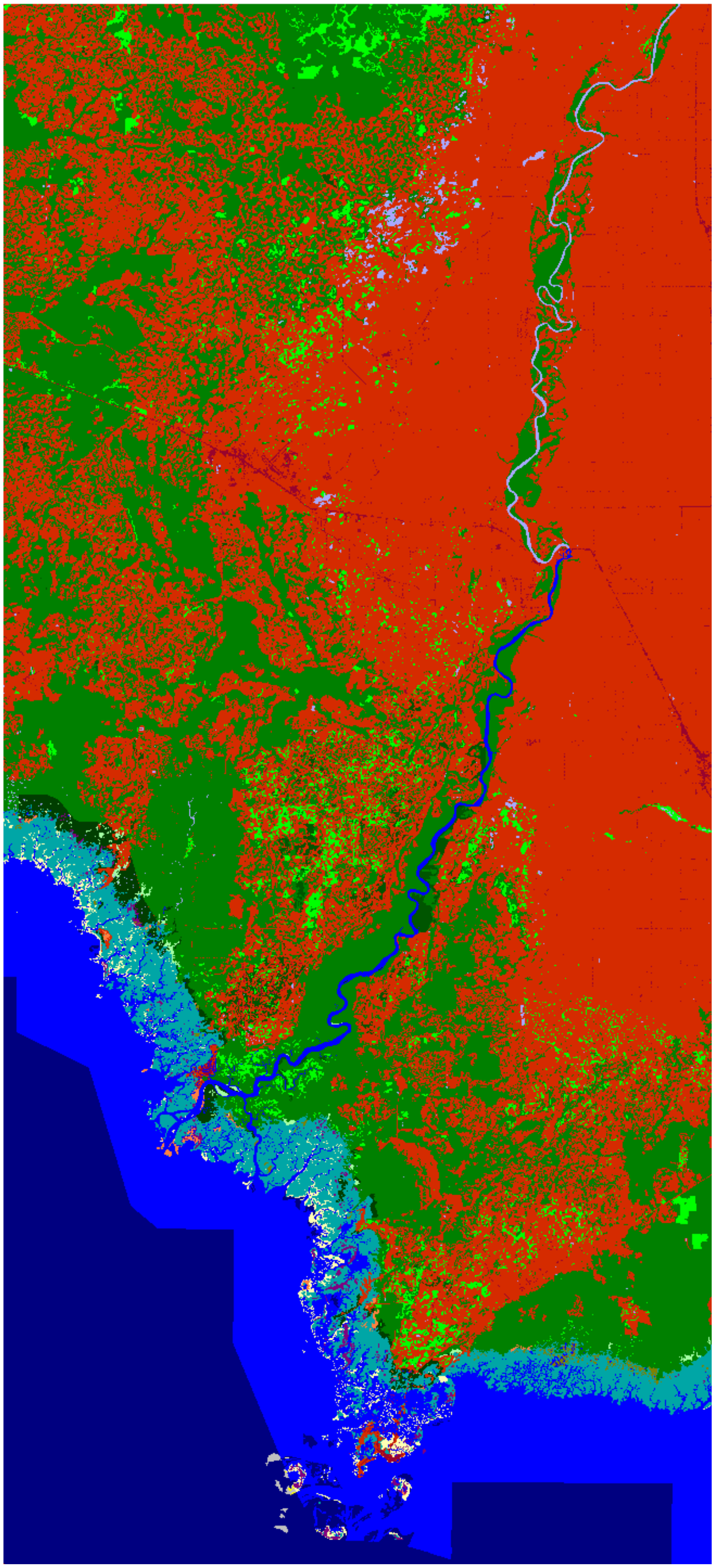
Lower Suwannee NWR, 2050, Scenario A1B Mean, 0.39 m SLR



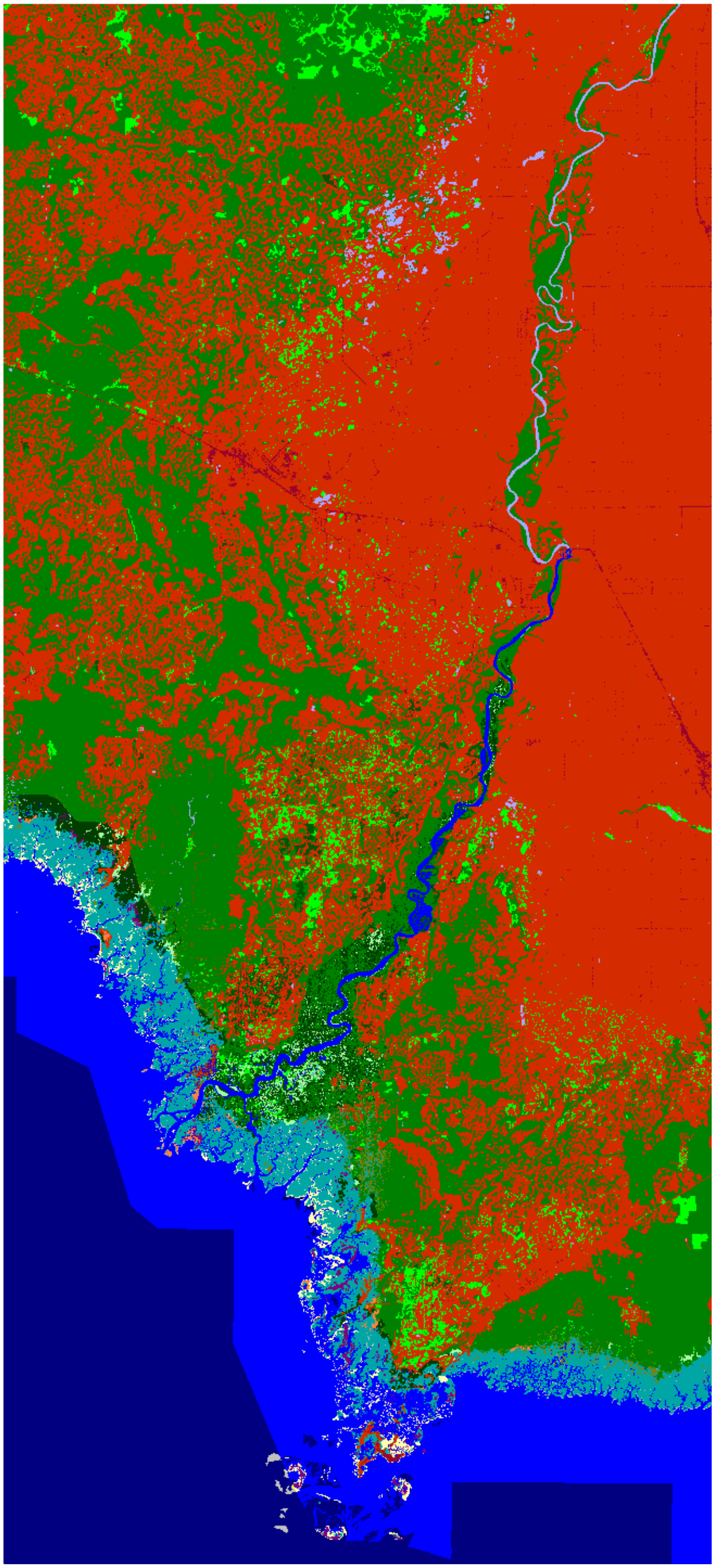
Lower Suwannee NWR, 2075, Scenario A1B Mean, 0.39 m SLR



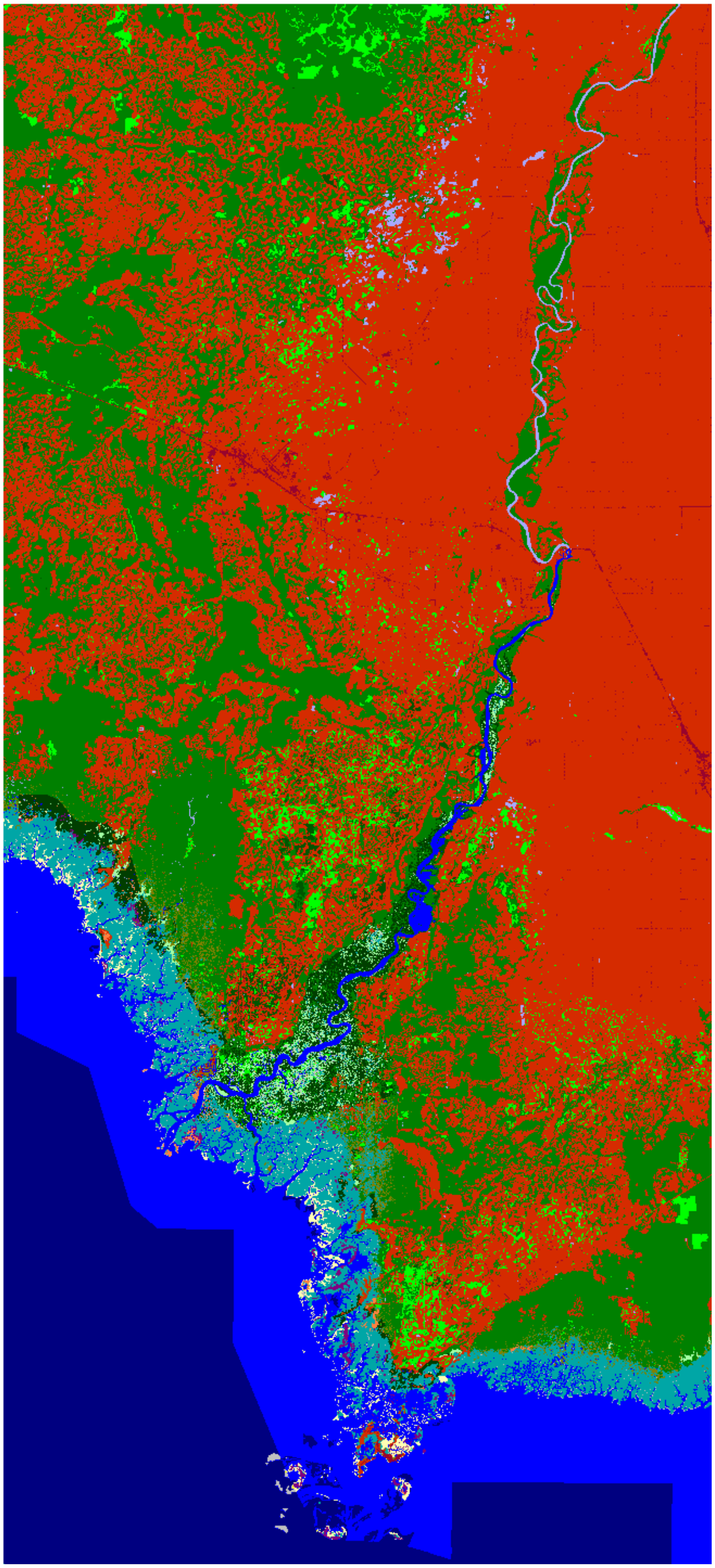
Lower Suwannee NWR, 2100, Scenario A1B Mean, 0.39 m SLR



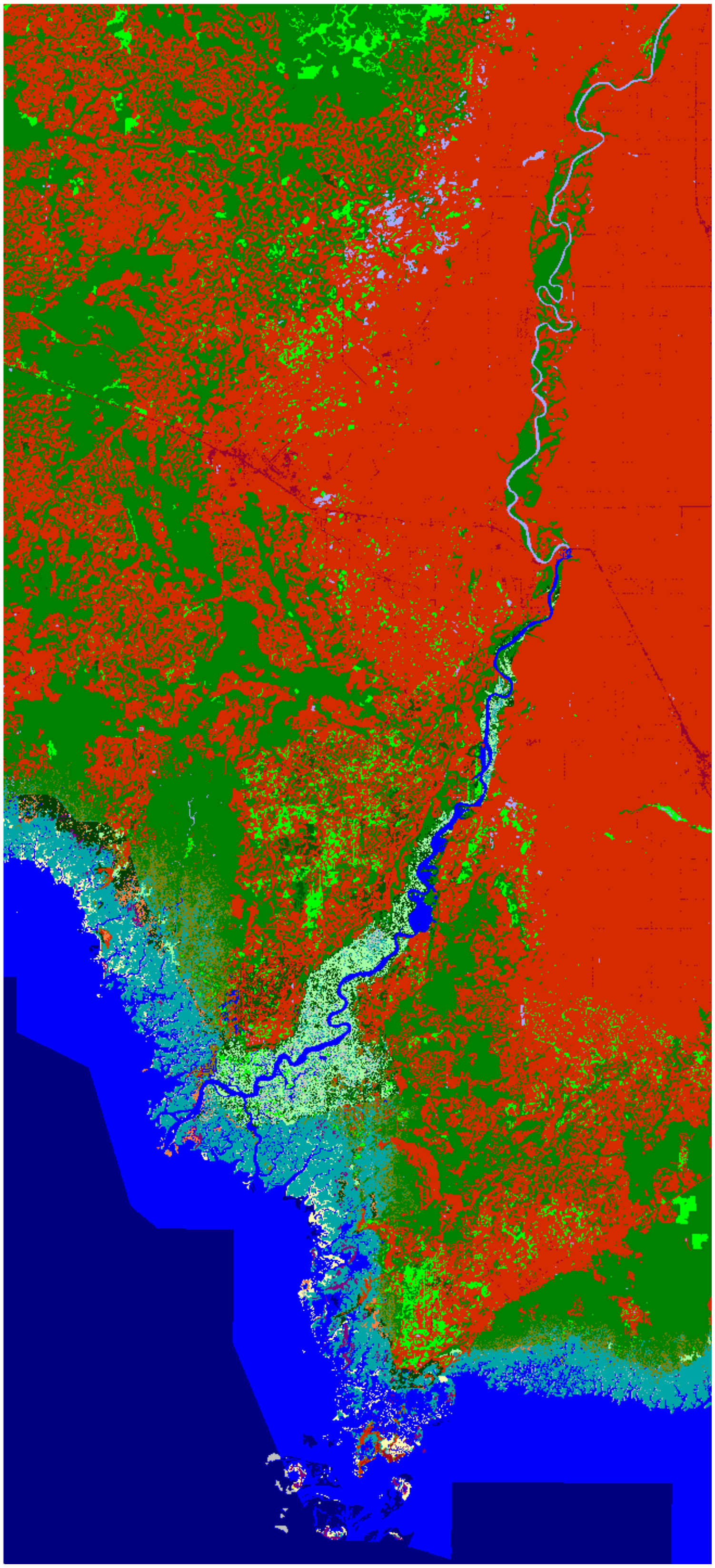
Lower Suwannee NWR, Initial Condition



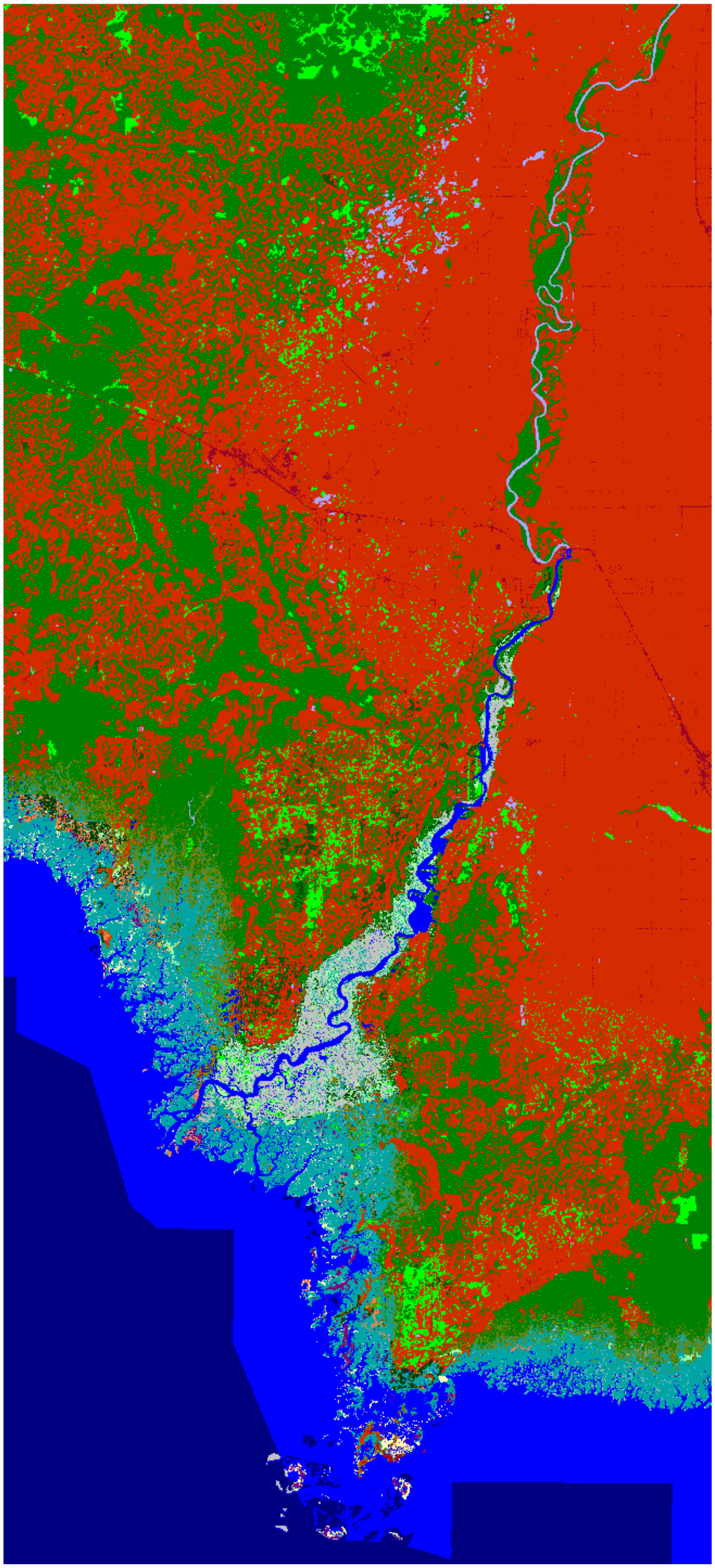
Lower Suwannee NWR, 2025, Scenario A1B Maximum, 0.69 m SLR



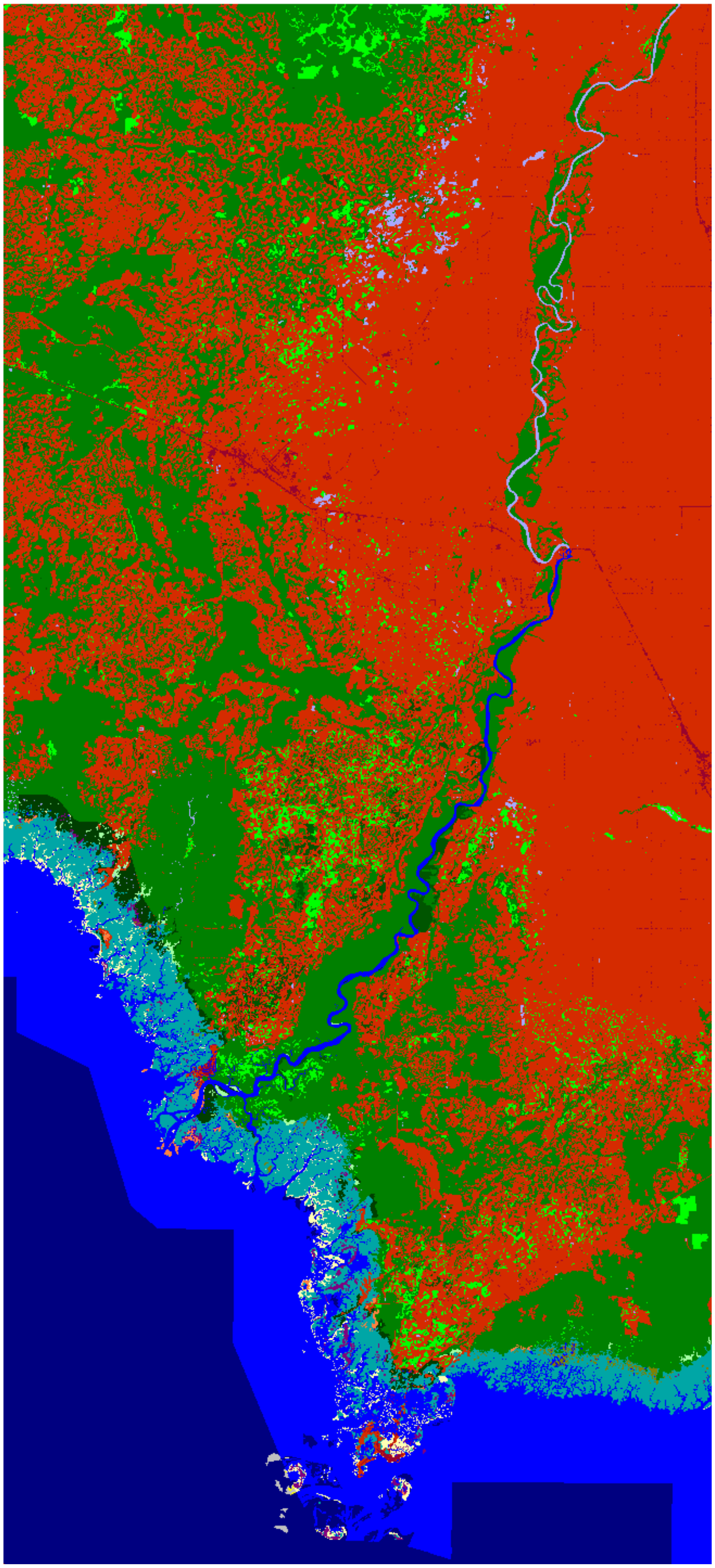
Lower Suwannee NWR, 2050, Scenario A1B Maximum, 0.69 m SLR



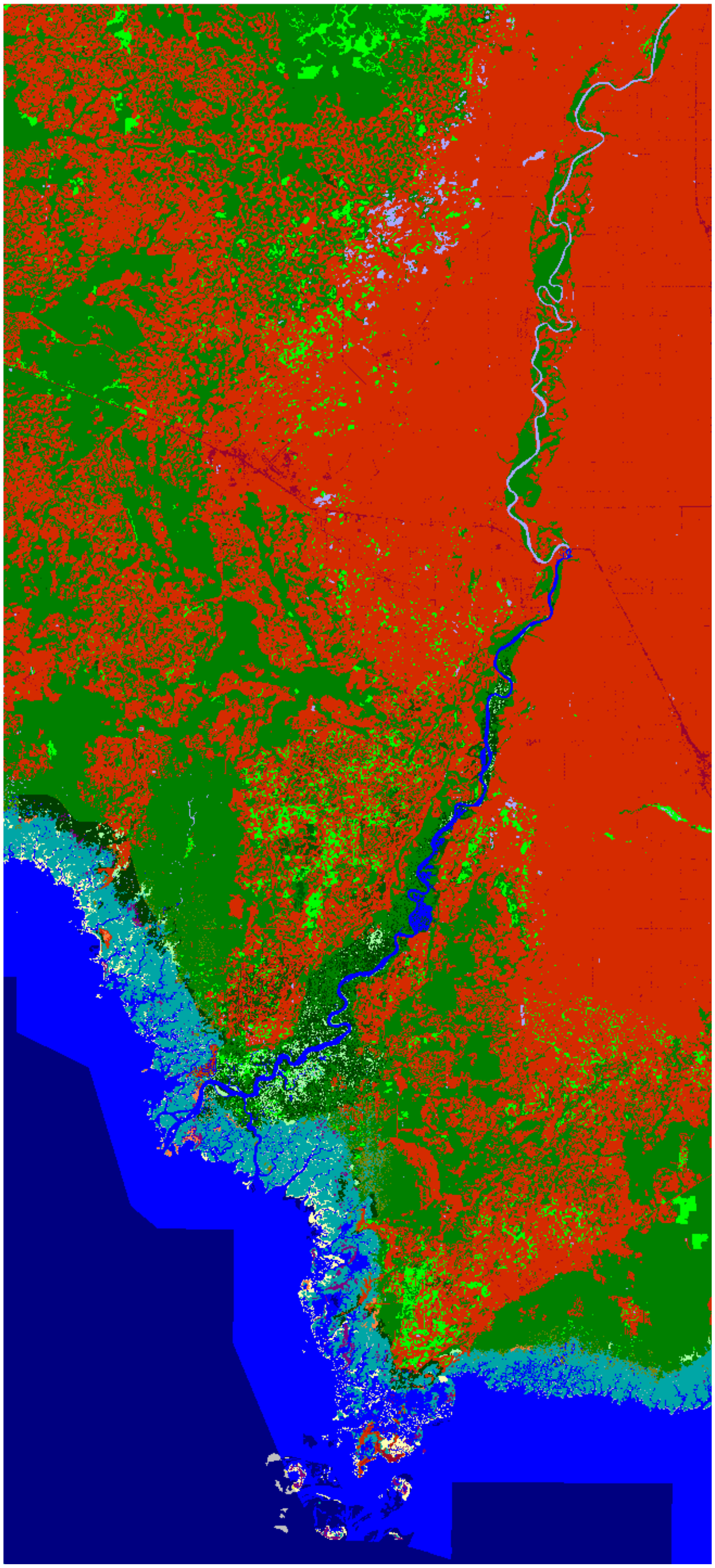
Lower Suwannee NWR, 2075, Scenario A1B Maximum, 0.69 m SLR



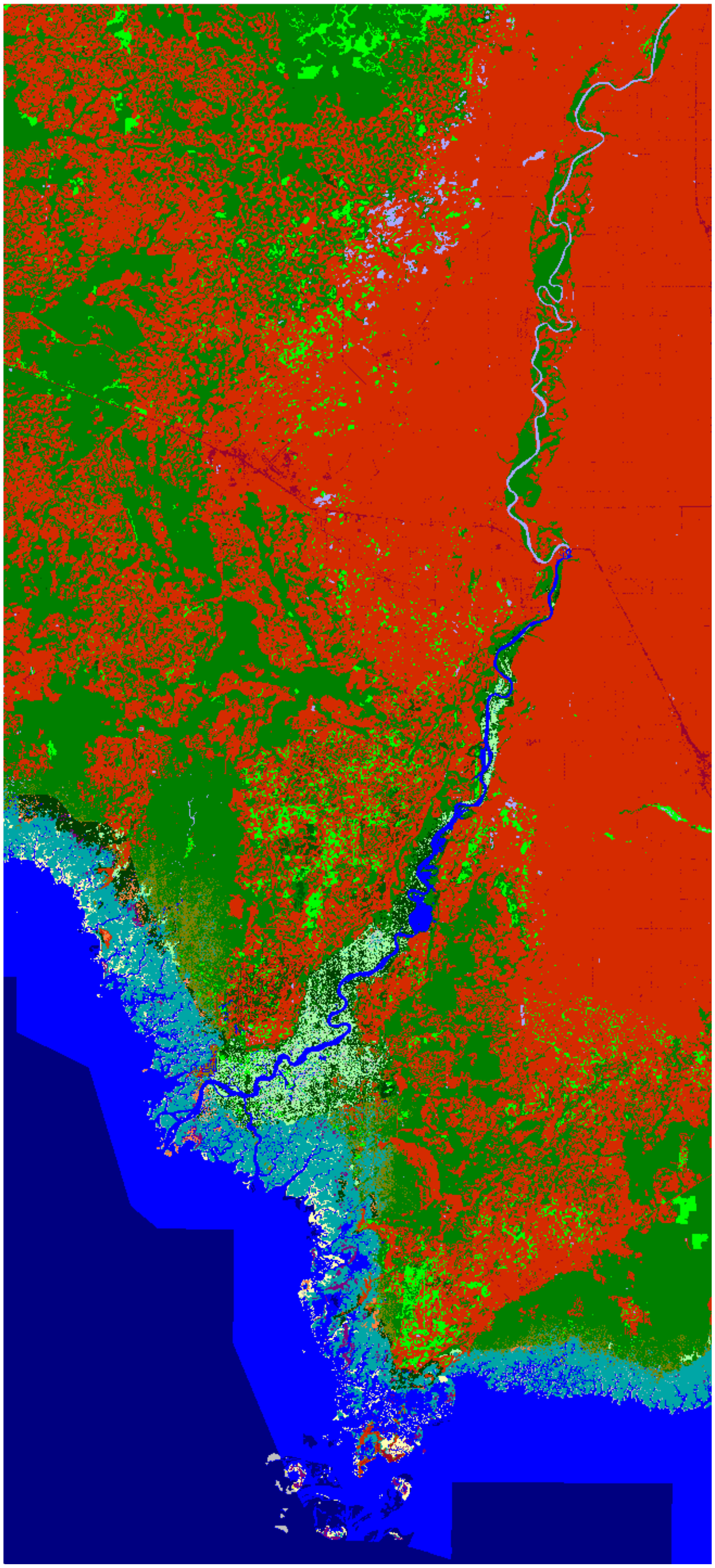
Lower Suwannee NWR, 2100, Scenario A1B Maximum, 0.69 m SLR



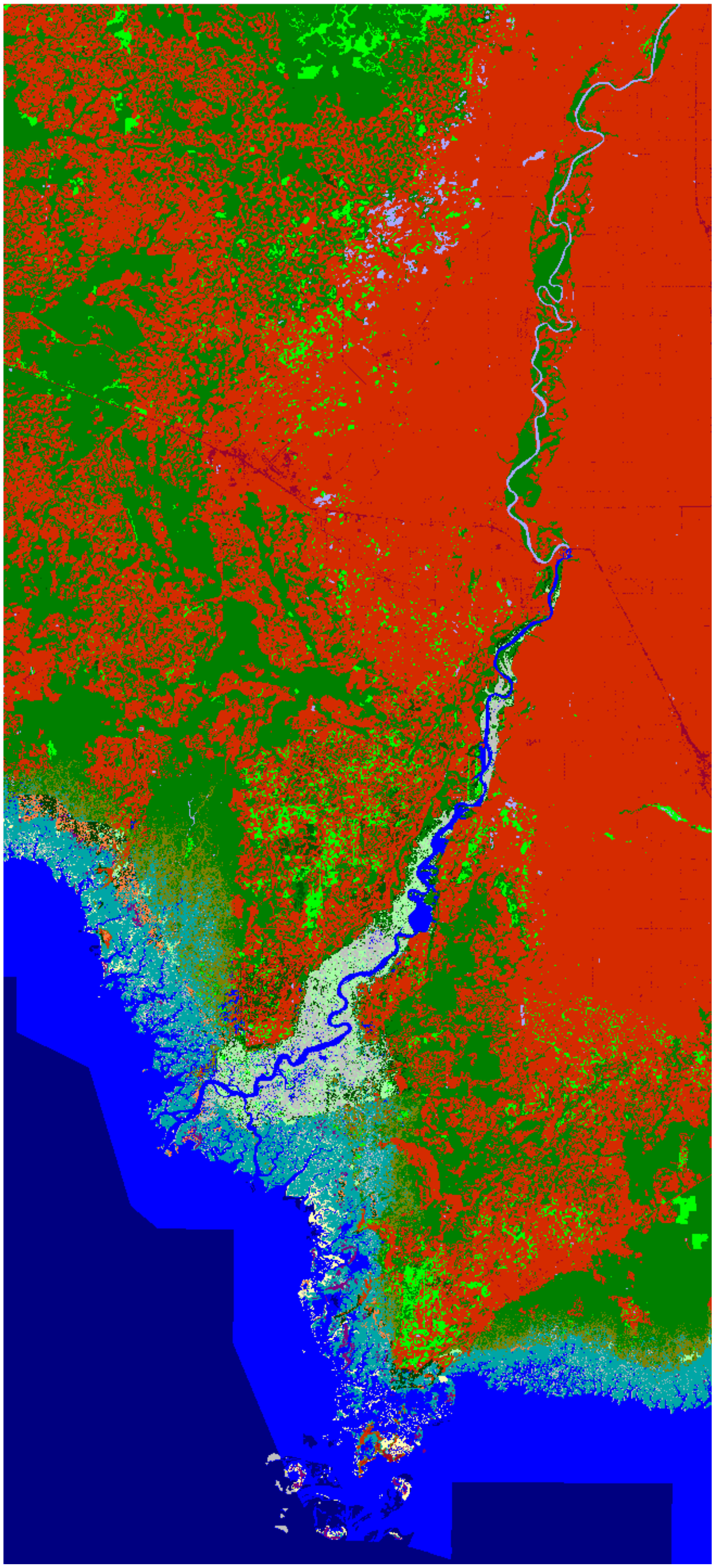
Lower Suwannee NWR, Initial Condition



Lower Suwannee NWR, 2025, 1 m SLR



Lower Suwannee NWR, 2050, 1 m SLR



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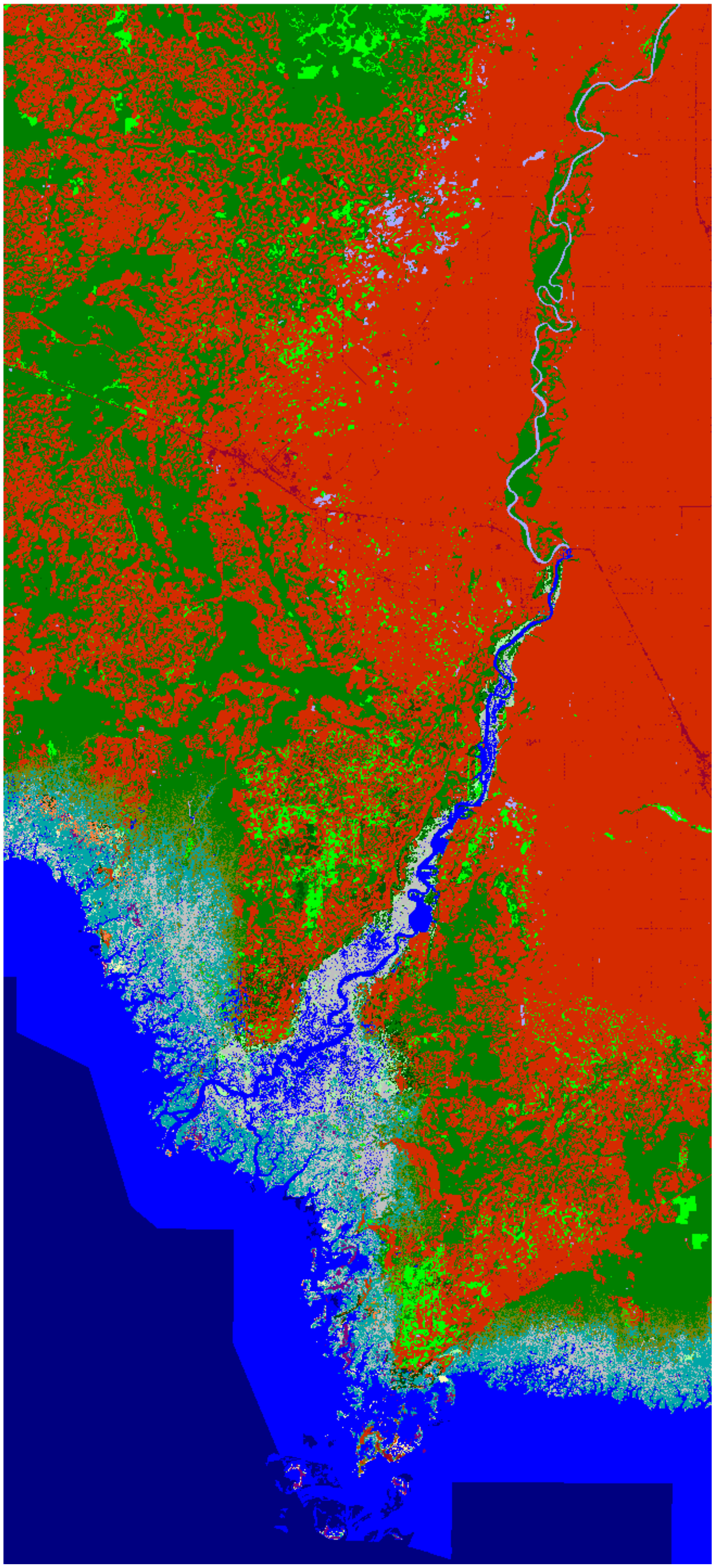

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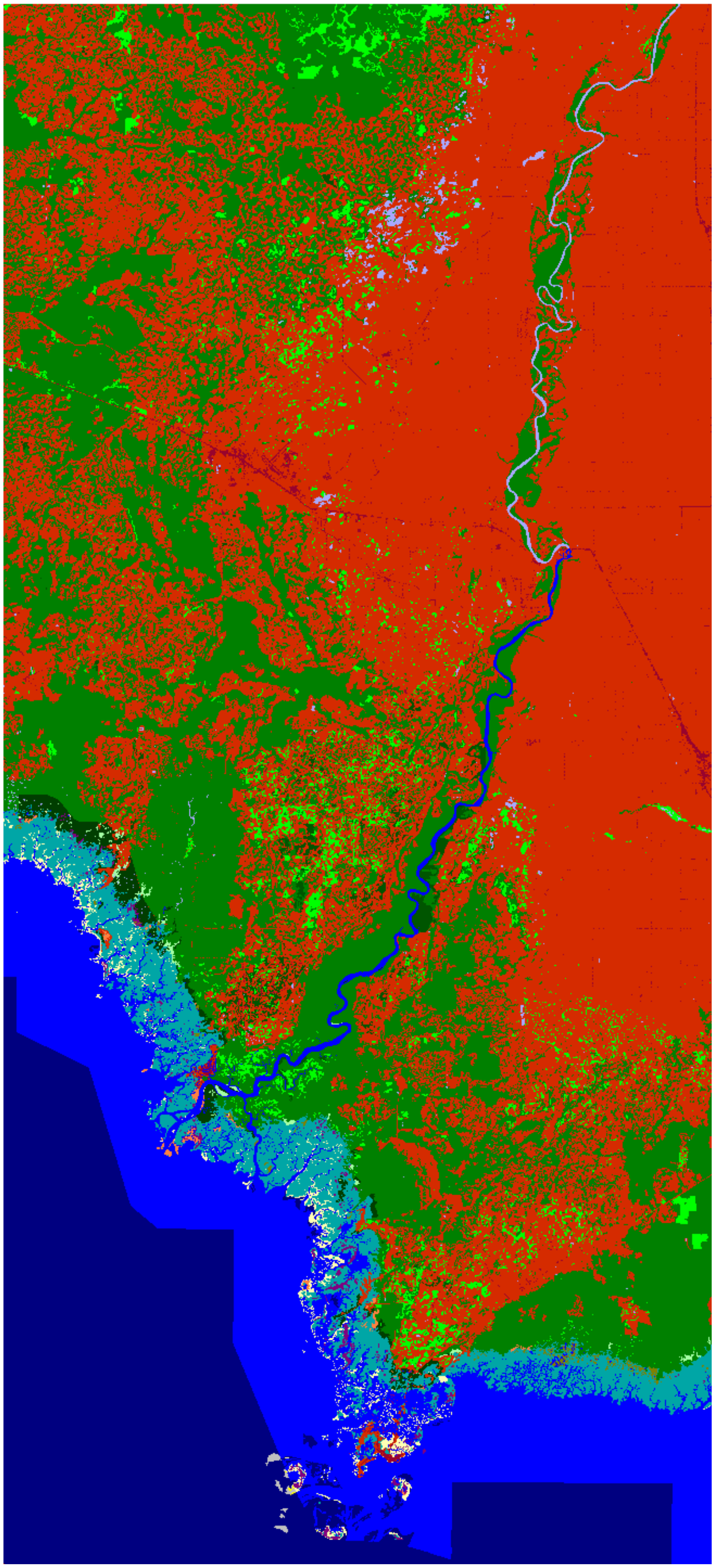
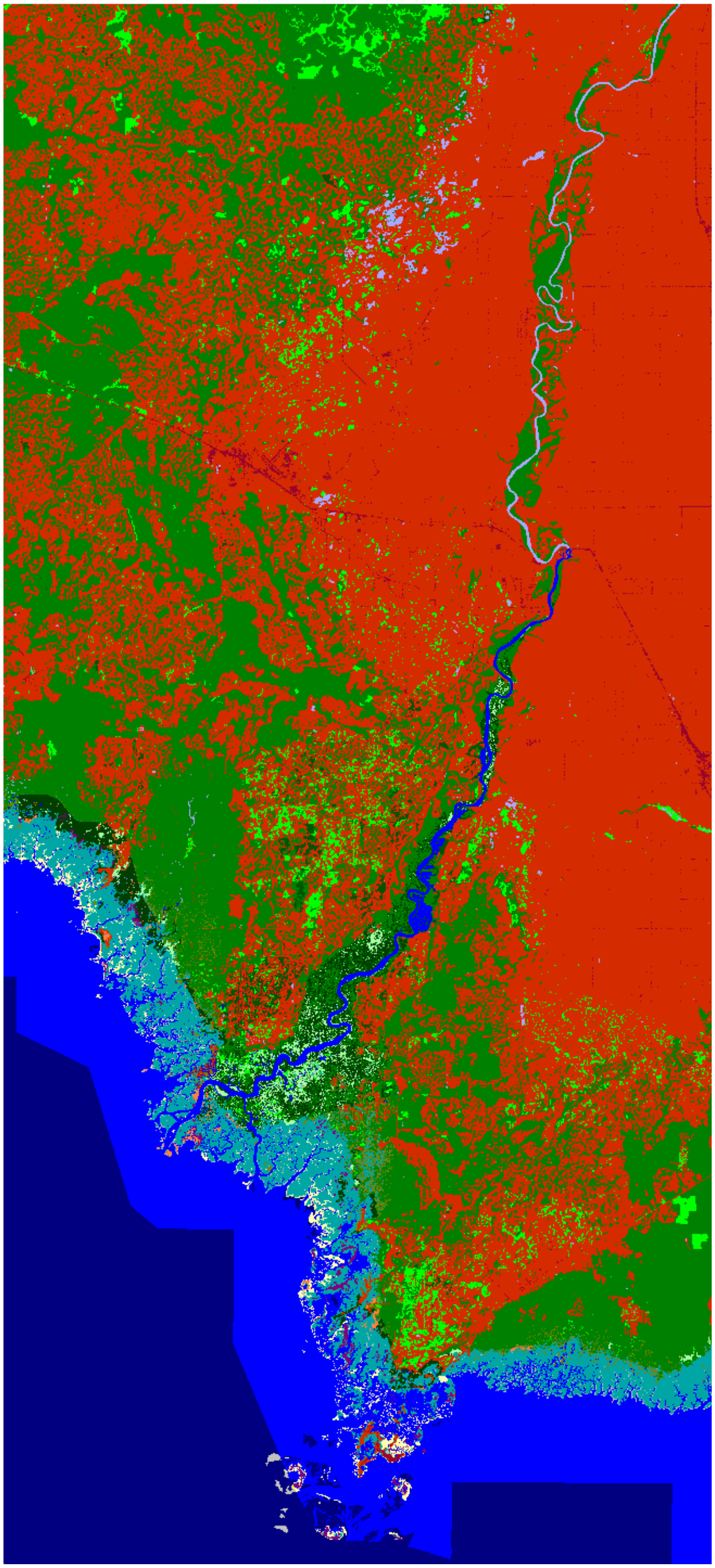


Lower Suwannee NWR, Initial Condition



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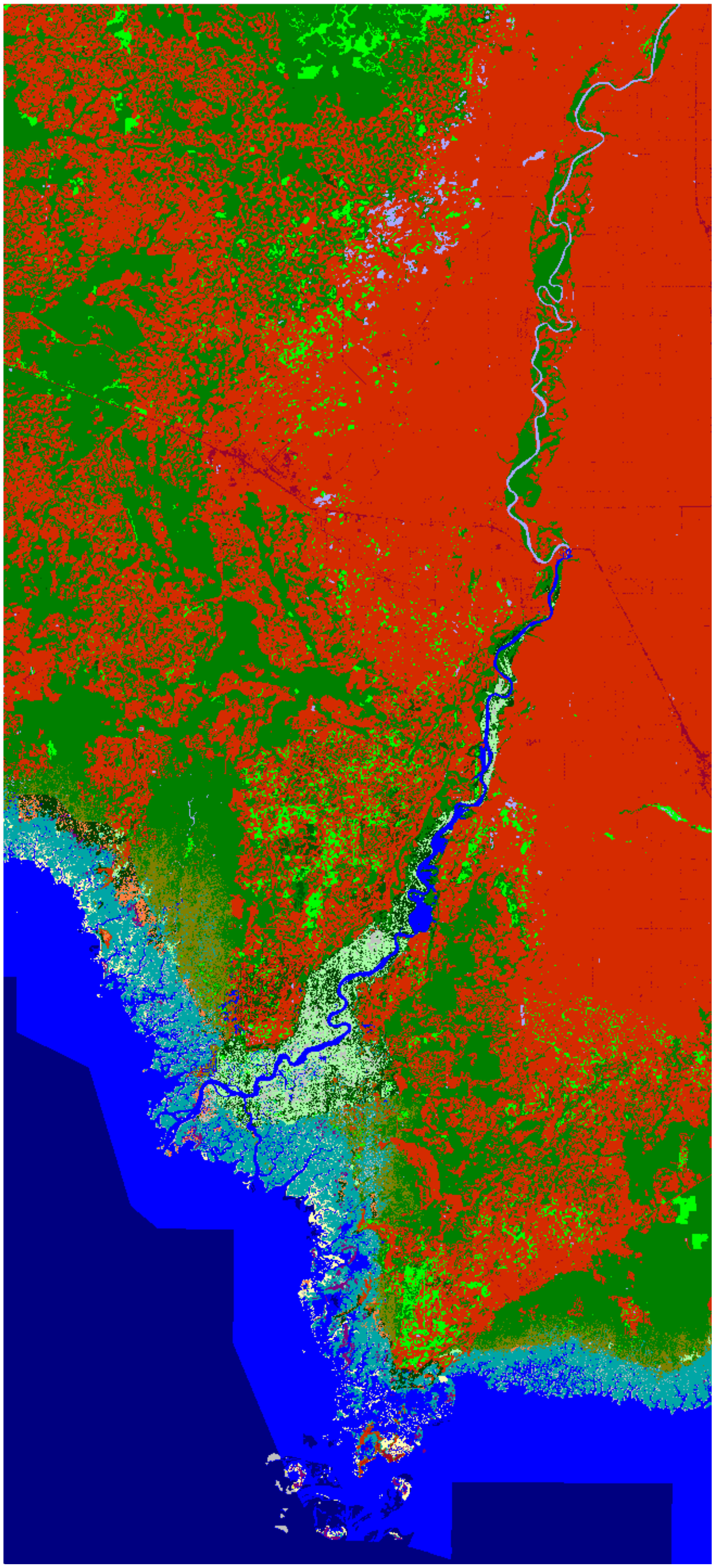
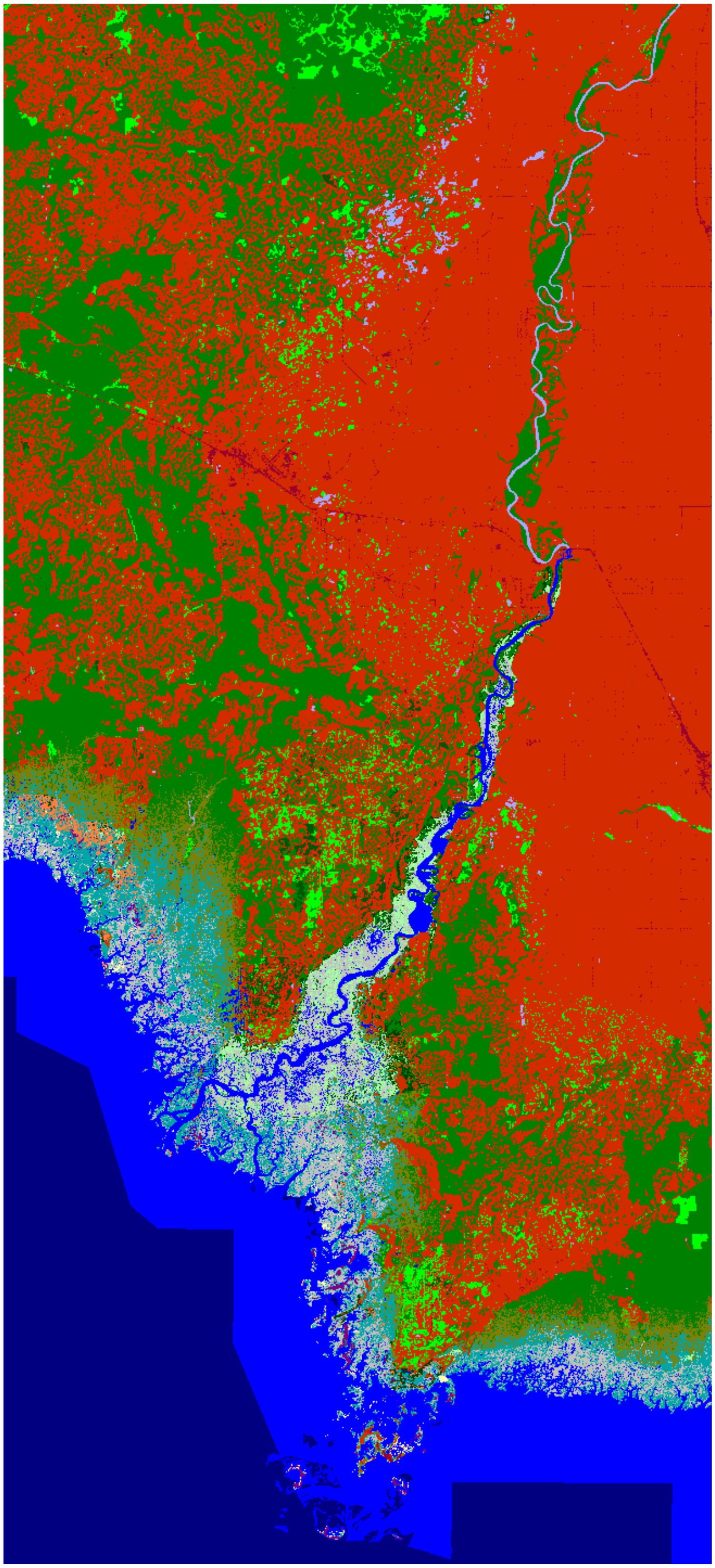
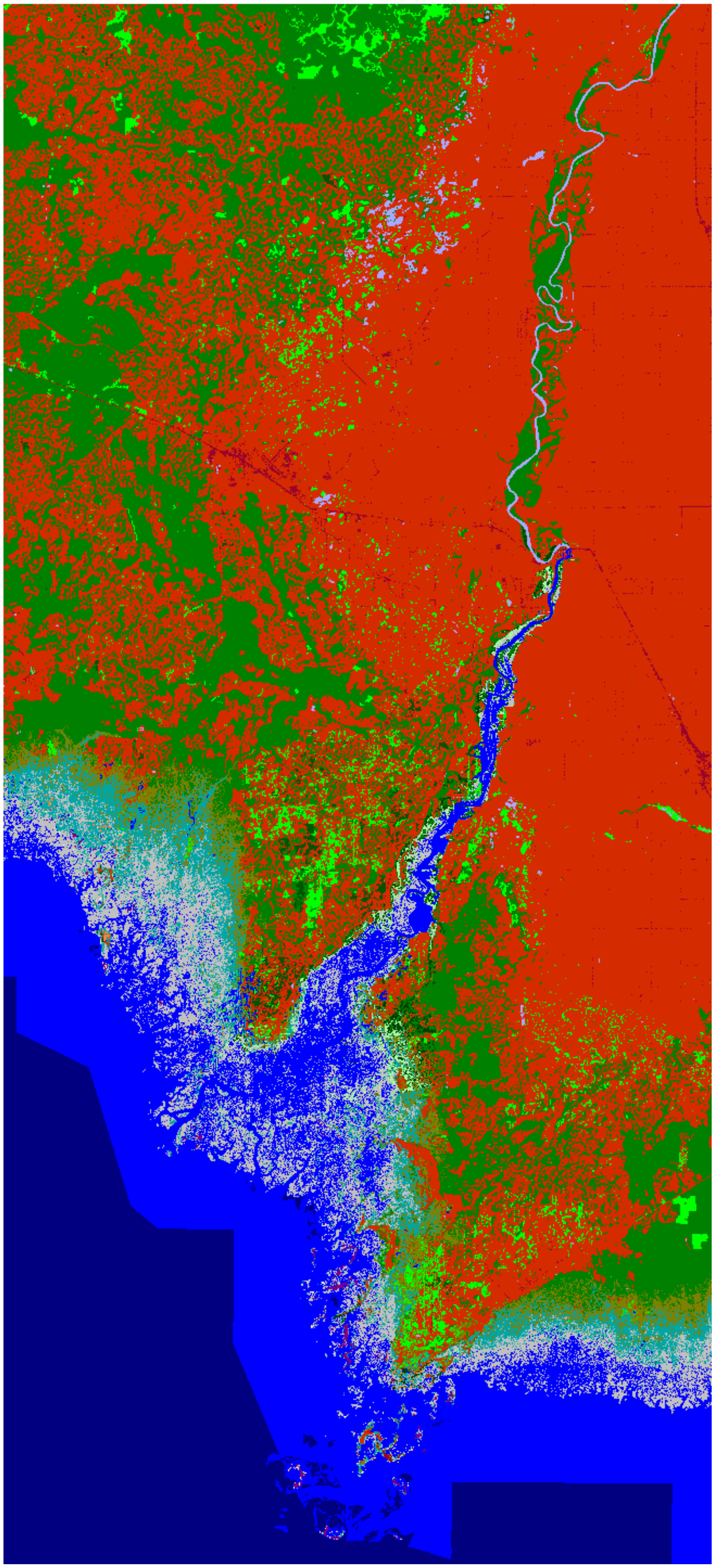


Lower Suwannee NWR, 2050, 1.5 m SLR



Lower Suwannee NWR, 2075, 1.5 m SLR



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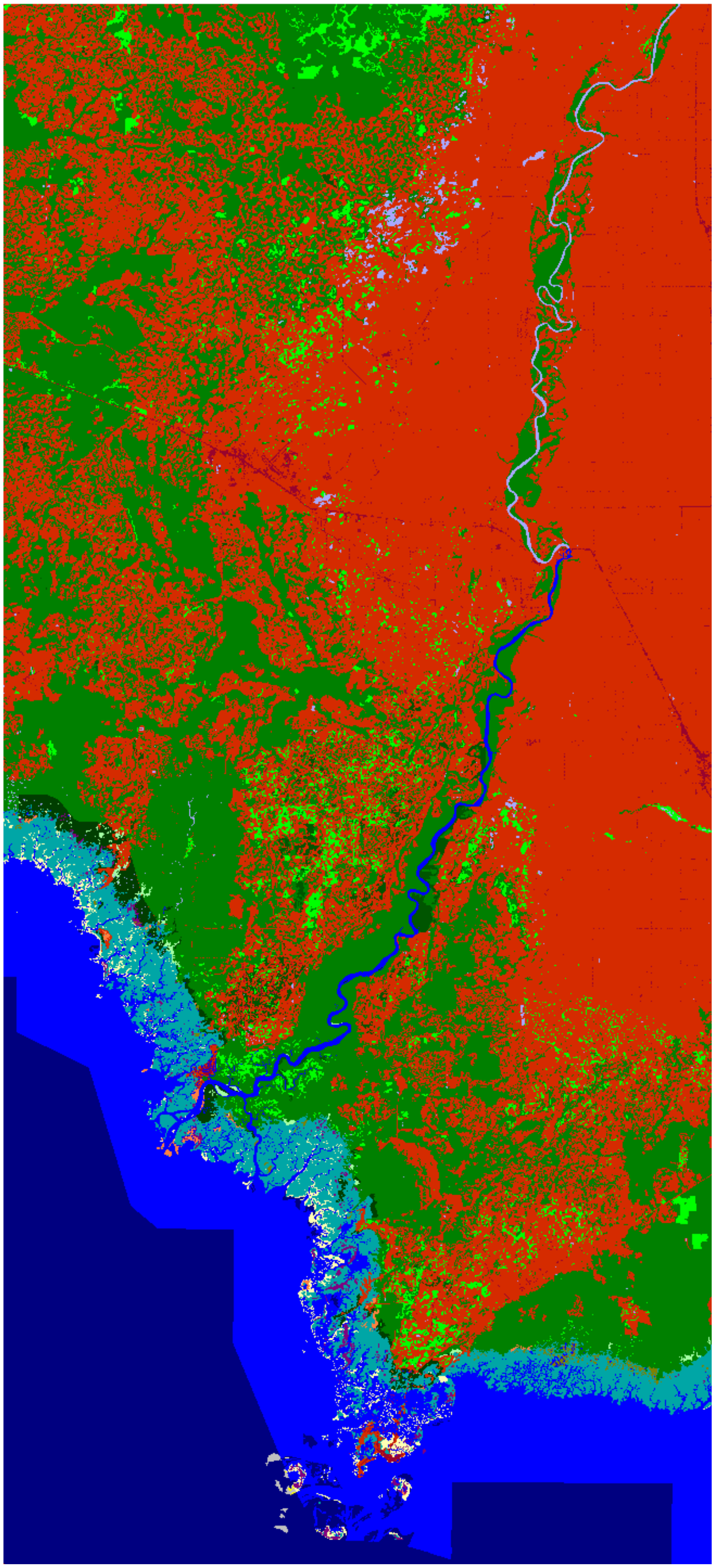
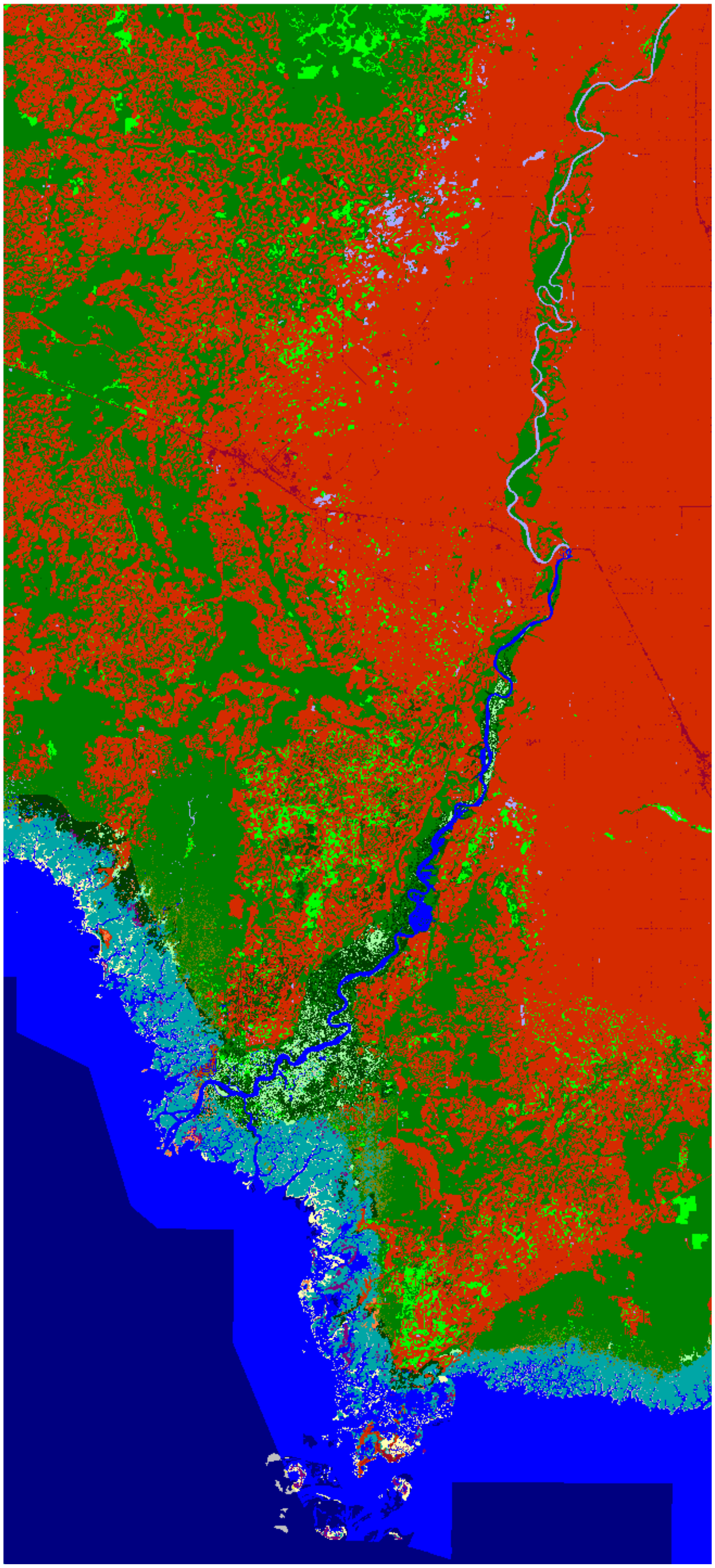
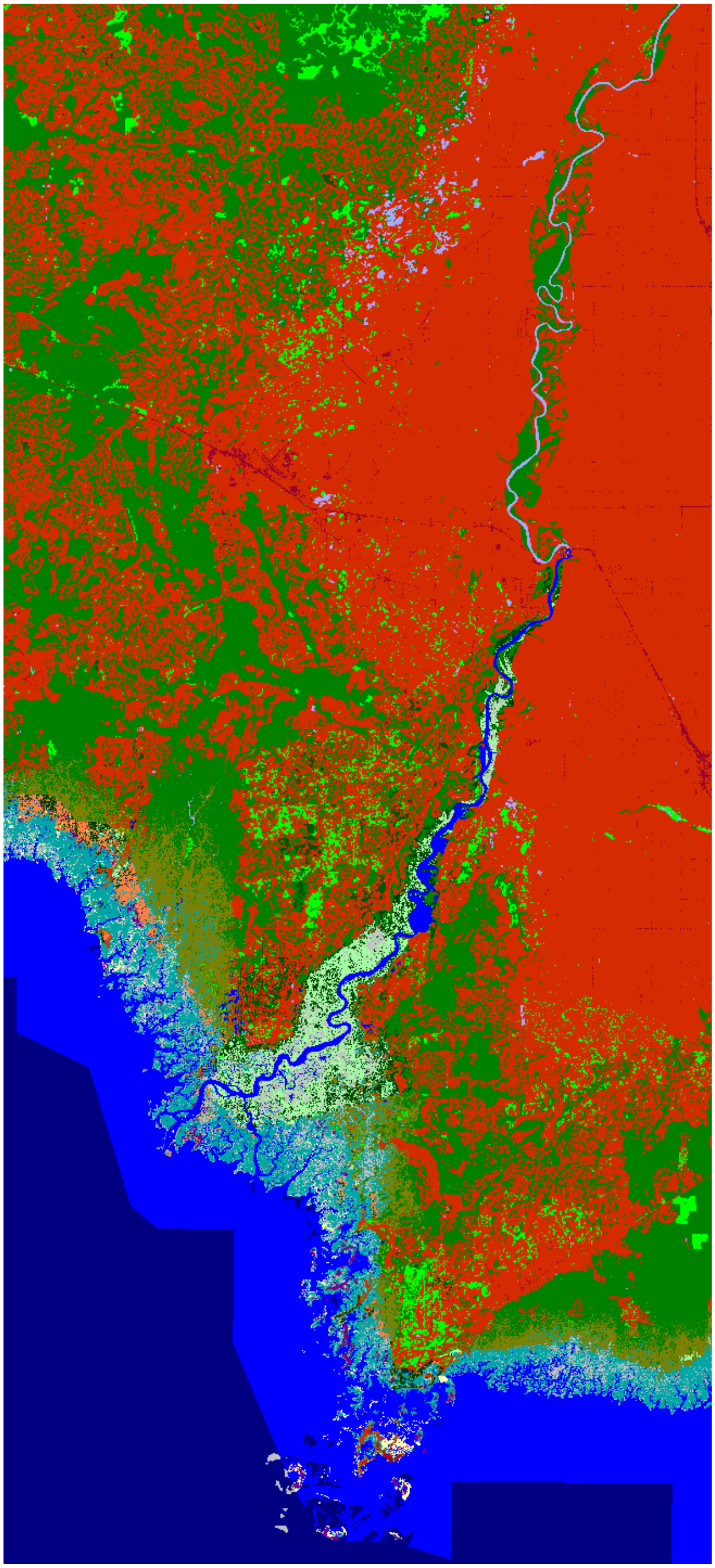


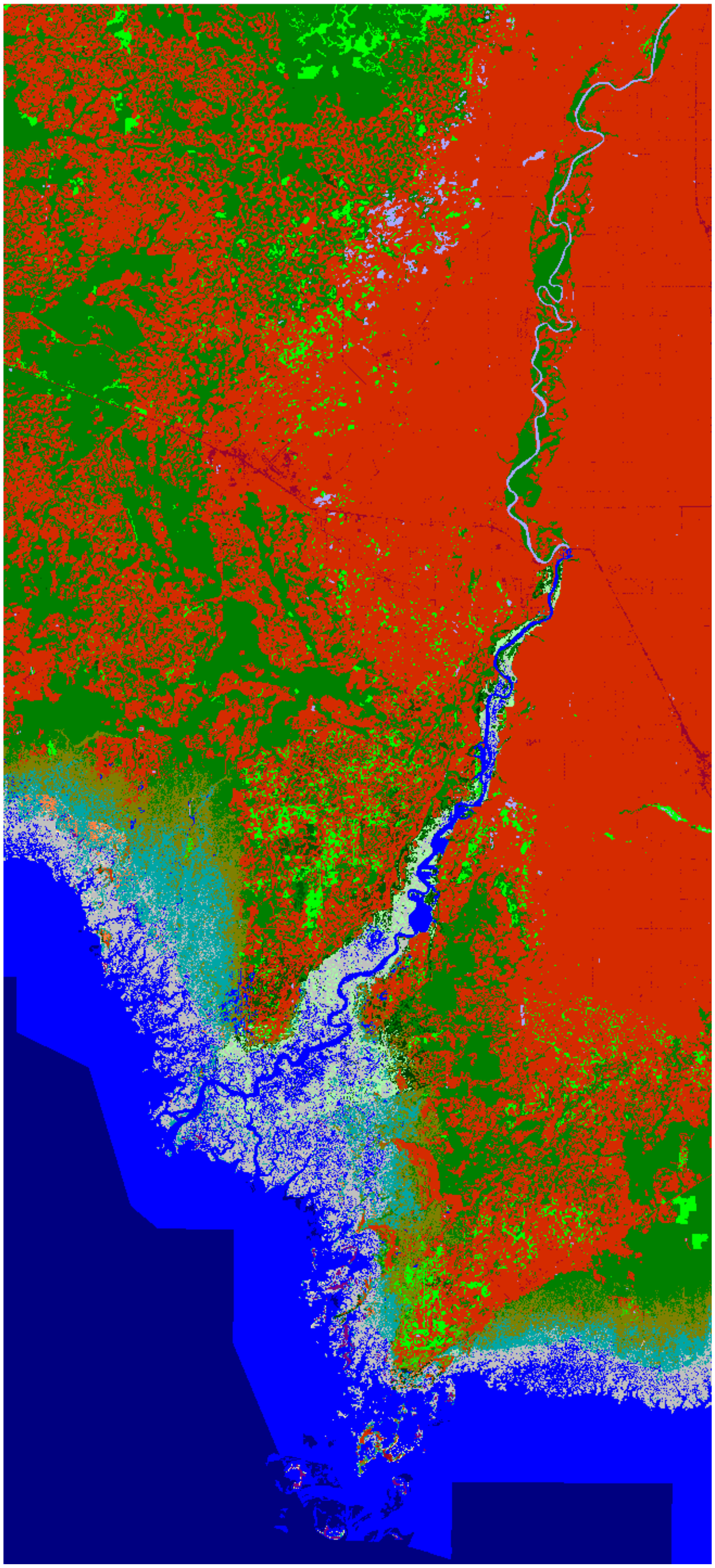
Lower Suwannee NWR, Initial Condition



Lower Suwannee NWR, 2025, 2 m SLR



Lower Suwannee NWR, 2050, 2 m SLR



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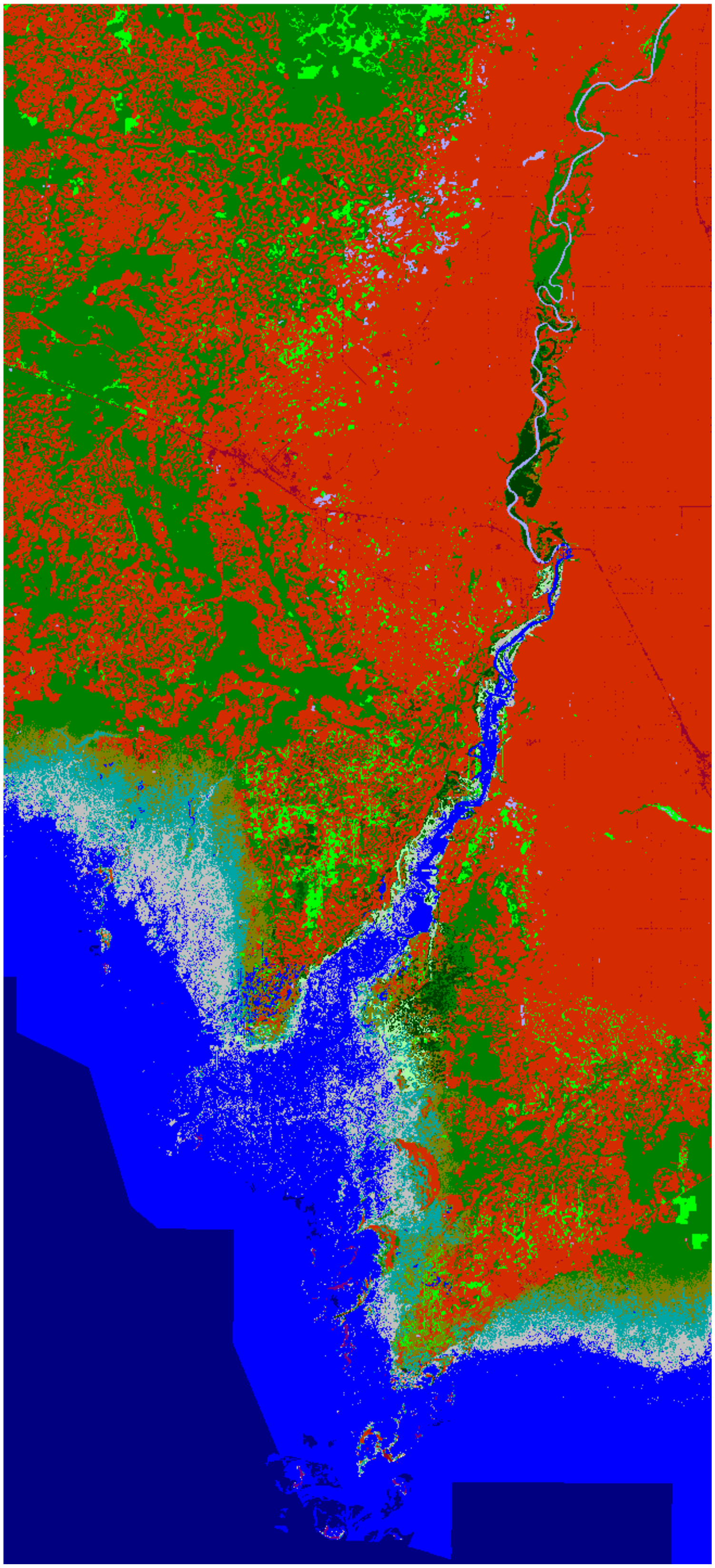

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