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

U. S. Fish and Wildlife Service
National Wildlife Refuge System
Division of Natural Resources and Conservation Planning
Conservation Biology Program
4401 N. Fairfax Drive - MS 670
Arlington, VA 22203

February 15, 2012

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

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

Introduction 1

Model Summary 1

Sea-Level rise Scenarios 3

Data Sources and Methods 5

Results 14

Discussion 46

References 46

Appendix A: Contextual Results 49

Introduction

Tidal marshes are among the most susceptible ecosystems to climate change, especially accelerated sea-level rise (SLR). The Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) suggested that global sea level will increase by approximately 30 cm to 100 cm by 2100 (IPCC 2001). Rahmstorf (2007) suggests that this range may be too conservative and that the feasible range by 2100 is 50 to 140 cm. Rising sea levels may result in tidal marsh submergence (Moorhead and Brinson 1995) and habitat "migration" as salt marshes transgress landward and replace tidal freshwater and irregularly-flooded marsh (Park et al. 1991).

In an effort to plan for and potentially mitigate the effects of sea-level rise on the U.S. National Wildlife Refuge System (Refuge System), the U. S. Fish and Wildlife Service (FWS) uses a variety of analytical approaches, most notably the SLAMM model. FWS conducts some SLAMM analysis in-house and, more commonly, contracts the application of the SLAMM model. In most cases Refuge System SLAMM analyses are designed to assist in the development of comprehensive conservation plans (CCPs), land acquisition plans, habitat management plans, and other land and resource management plans.

Model Summary

Changes in tidal marsh area and habitat type in response to sea-level rise were modeled using the Sea Level Affecting Marshes Model (SLAMM 6) that accounts for the dominant processes involved in wetland conversion and shoreline modifications during long-term sea-level rise (Park et al. 1989; www.warrenpinnacle.com/prof/SLAMM).

Successive versions of the model have been used to estimate the impacts of sea-level rise on the coasts of the U.S. (Titus et al. 1991; Lee et al. 1992; Park et al. 1993; Galbraith et al. 2002; National Wildlife Federation & Florida Wildlife Federation 2006; Glick et al. 2007; Craft et al. 2009).

Within SLAMM, there are five primary processes that affect wetland fate under different scenarios of sea-level rise:

- **Inundation:** The rise of water levels and the salt boundary are tracked by reducing elevations of each cell as sea levels rise, thus keeping mean tide level (MTL) constant at zero. The effects on each cell are calculated based on the minimum elevation and slope of that cell.
- **Erosion:** Erosion is triggered based on a threshold of maximum fetch and the proximity of the marsh to estuarine water or open ocean. When these conditions are met, horizontal erosion occurs at a rate based on site- specific data.
- **Overwash:** Barrier islands of under 500 meters (m) width are assumed to undergo overwash during each specified interval for large storms. Beach migration and transport of sediments are calculated.
- **Saturation:** Coastal swamps and fresh marshes can migrate onto adjacent uplands as a response of the fresh water table to rising sea level close to the coast.

- **Accretion:** Sea-level rise is offset by sedimentation and vertical accretion using average or site-specific values for each wetland category. Accretion rates may be spatially variable within a given model domain and can be specified to respond to feedbacks such as frequency of flooding.

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

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

For a thorough accounting of SLAMM model processes and the underlying assumptions and equations, please see the SLAMM 6.0 *Technical Documentation* (Clough et al. 2010). This document is available at http://warrenpinnacle.com/prof/SLAMM

All model results are subject to uncertainty due to limitations in input data, incomplete knowledge about factors that control the behavior of the system being modeled, and simplifications of the system (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

Some SLAMM 6 predictions are obtained using SLR estimates from the Special Report on Emissions Scenarios (SRES) published by the Intergovernmental Panel on Climate Change (IPCC). All IPCC scenarios describe futures that are generally more affluent than today and span a wide range of future levels of economic activity, with gross world product rising to 10 times today's values by 2100 in the lowest, to 26-fold in the highest scenarios (IPCC 2007). Among the IPCC families of scenarios, two approaches were used, one that made harmonized assumptions about global population, economic growth, and final energy use, and those with an alternative approach to quantification. This is important to keep in mind as not all of the IPCC scenarios share common assumptions regarding the driving forces of climate change.

In this model application, the A1B scenario mean and maximum predictions are applied. Important assumptions were made in this scenario: reduction in the dispersion of income levels across economies (i.e. economic convergence), capacity building, increased cultural and social interactions among nations, and a substantial reduction in regional differences in per capita income, primarily from the economic growth of nations with increasing income (Nakicenovic et al. 2000). In addition, 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. Given today's global economic and political climate, as well as environmental and ecological constraints, these may not be feasible assumptions for the future.

In particular, the A1B scenario assumes that energy sources will be balanced across all sources, with an increase in use of renewable energy sources coupled with a reduced reliance on fossil fuels (Nakicenovic et al. 2000). Given this A1B scenario, the IPCC WGI Fourth Assessment Report (IPCC 2007) suggests a likely range of 0.21 m to 0.48 m of SLR by 2090-2099 "excluding future rapid dynamical changes in ice flow." The IPCC-produced 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. However, other scientists using the same set of economic growth scenarios have produced much higher estimates of SLR as discussed below.

Recent literature (Chen et al. 2006; Monaghan et al. 2006) indicates that eustatic sea-level rise is progressing more rapidly than was previously assumed. This underestimation may be due to the dynamic changes in ice flow omitted within the IPCC report's calculations, and a consequence of overestimating the possibilities for future reductions in greenhouse gas emissions while concurrently striving for economic growth.

A recent paper in the journal *Science* (Rahmstorf 2007) suggests that, taking into account possible model error, a feasible range of 50 to 140 cm by 2100. 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.

The variability of SLR predictions presented in the scientific literature illustrates the significant amount of uncertainty in estimating future SLR. Much of the uncertainty may be due to the unknown future of the drivers climate change, such as fossil fuel consumption and the scale of human enterprise. In order to account for these uncertainties, and to better reflect these uncertainties as well as recently published peer-reviewed measurements and projections of SLR as noted above, SLAMM was run not only assuming A1B-mean and A1B-maximum SLR scenarios, but also for 1 m, 1.5 m, and 2 m of eustatic SLR by the year 2100 as shown in Figure 1.

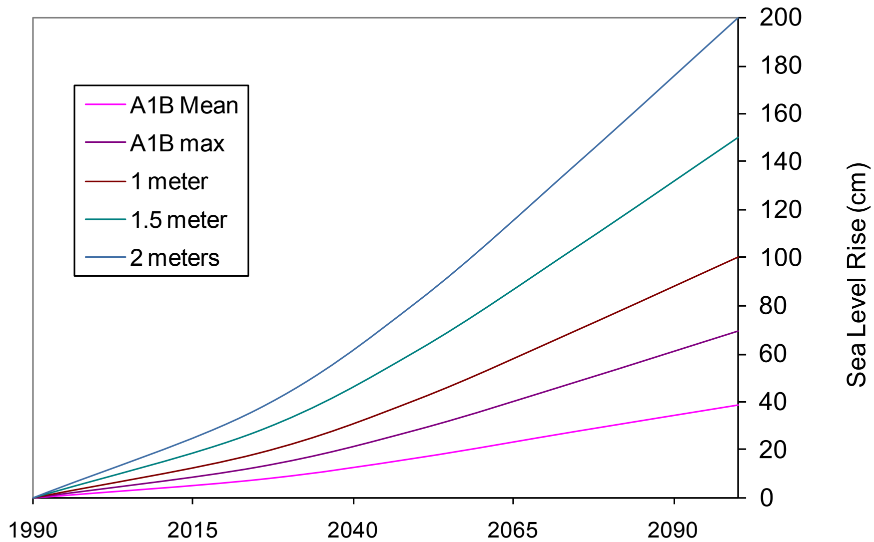


Figure 1. Summary of SLR scenarios utilized.

Data Sources and Methods

Wetland layer. Figure 2 shows the most recent available wetland layer obtained from a National Wetlands Inventory (NWI) photo dated 2006. Converting the NWI survey into 10 m x 10 m cells indicated that the approximately 46,500 acre Savannah NWR (approved acquisition boundary including water) is composed of the following categories:

Land cover type		Area (acres)	Percentage (%)
	Tidal Swamp	12586	27
	Swamp	11887	26
	Tidal Fresh Marsh	7577	16
	Undeveloped Dry Land	5754	12
	Inland Fresh Marsh	2418	5
	Irregularly-flooded Marsh	1826	4
	Riverine Tidal	1798	4
	Regularly-flooded Marsh	1693	4
	Inland Open Water	575	1
	Developed Dry Land	244	<1
	Estuarine Open Water	112	<1
	Transitional Salt Marsh	26	<1
	Inland Shore	23	<1
	Tidal Flat	5	<1
	Cypress Swamp	2	<1
	Total (incl. water)	**46526**	**100**

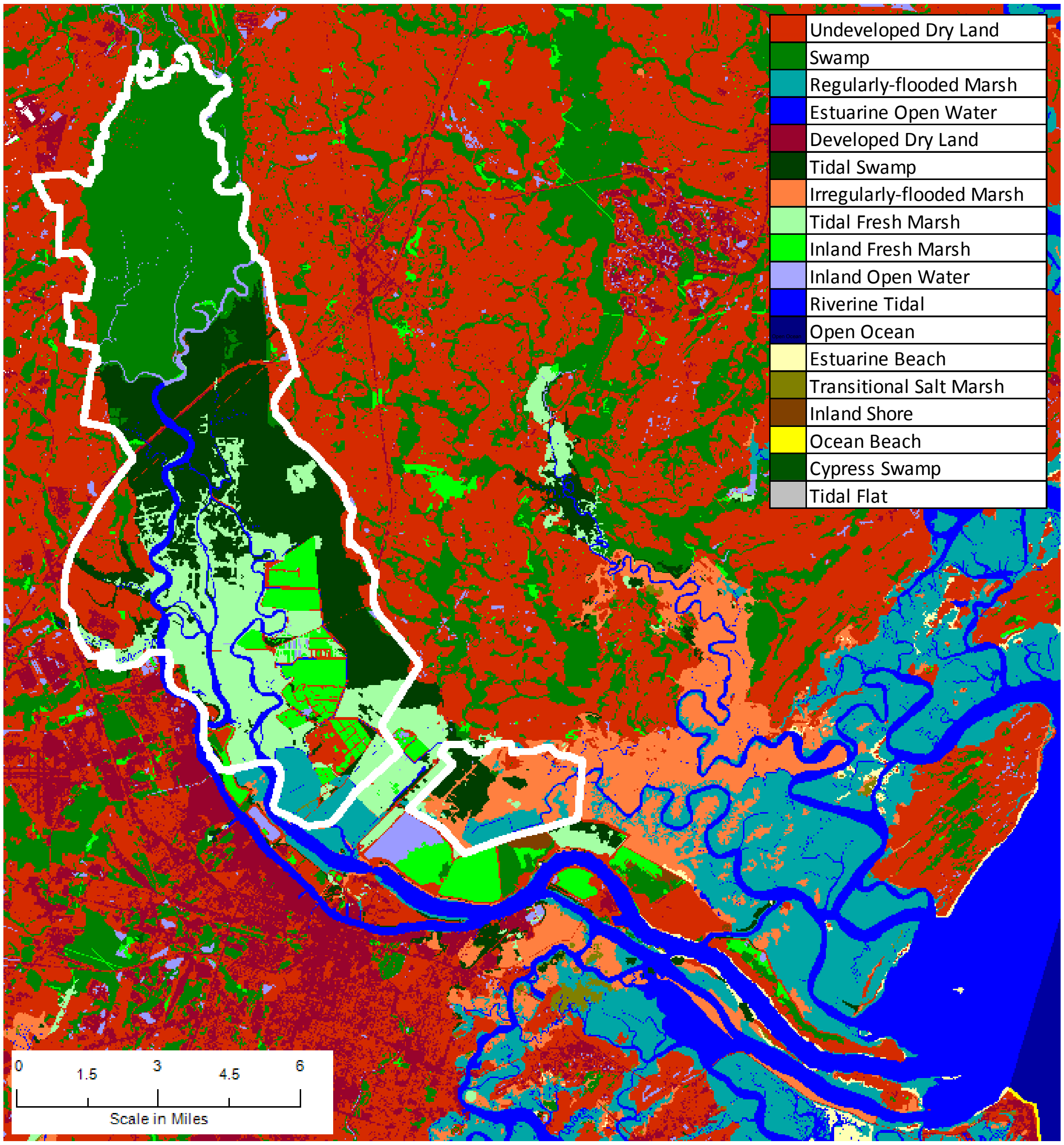


Figure 2. 2006 NWI coverage of the study area. Refuge boundaries are indicated in white.

Elevation Data. The refuge area elevations are from bare-earth LiDAR data of Jasper, Chatham and Effingham counties from 2007, 2009 and 2010 respectively.

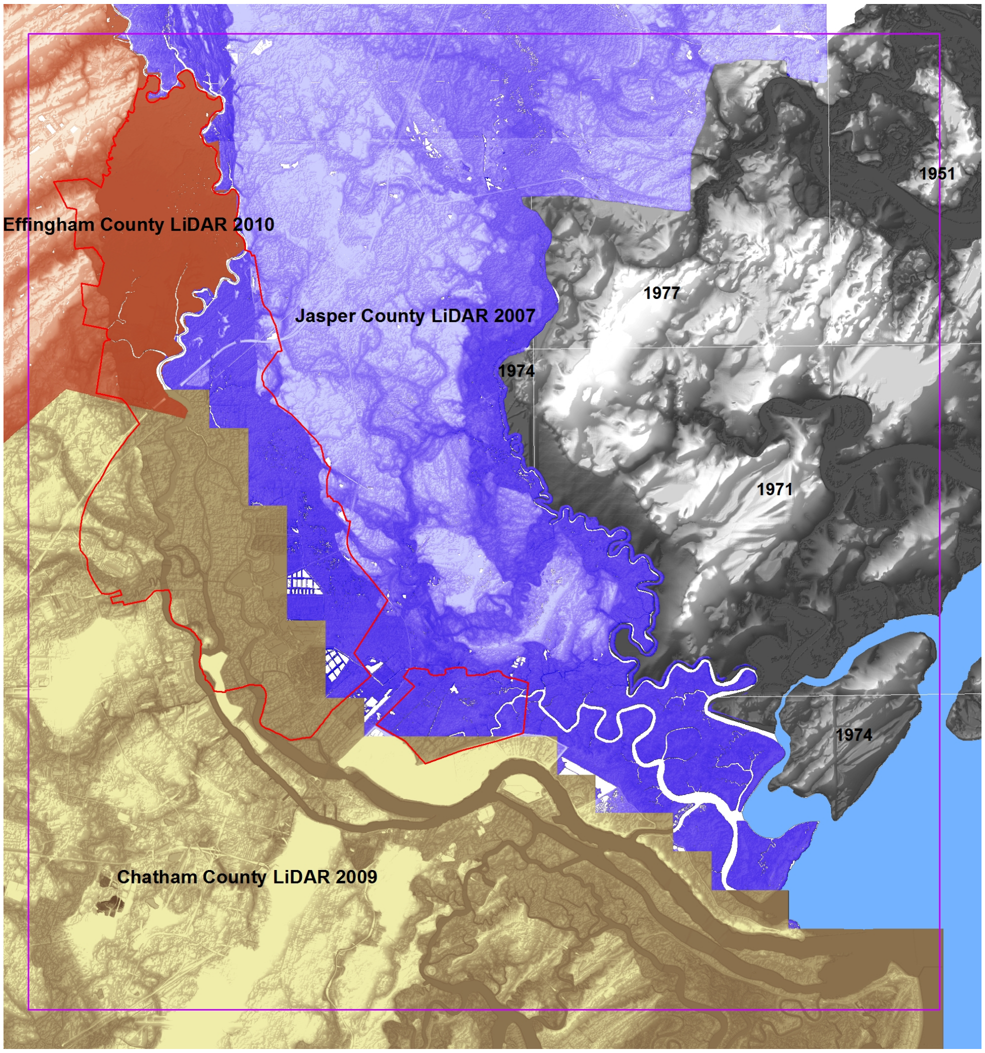


Figure 3. The coverage of the LiDAR data for the entire study area.
The red line shows the refuge boundaries.

The entire refuge is covered by LiDAR-based elevation data, however, elevations in the the north eastern part of the study area are based on NED contour maps of different years as shown in Figure 3. For this portion of the contextual area, the elevation pre-processor module of SLAMM was used to estimate elevations for wetlands as a function of the local tide range.

In addition, the LiDAR coverage of Jasper and Effingham counties contains several areas with no elevation due to data processing (for example, the cross-hatched white areas within the refuge boundaries in Figure 3 were probably fields filled with water at the time of data collecting and therefore no LiDAR data was taken). For these areas, elevations were derived from an older NED contour map.

Dikes and Impoundments. According to the National Wetland Inventory, there are several areas within the refuge that are protected by impoundments. These include freshwater pools that are drained in the spring/summer and flooded in late fall/winter by the refuge staff. However, some impoundments may have been classified as dry land or open water at the time the wetland picture was taken. As the NWI does not consider the status of open water or dry land these areas are not classified as protected. Communication with refuge staff confirmed that all the pools are managed. Therefore, some diked areas were manually added to the dike layer provided by NWI. All protected areas are shown in Figure 4.

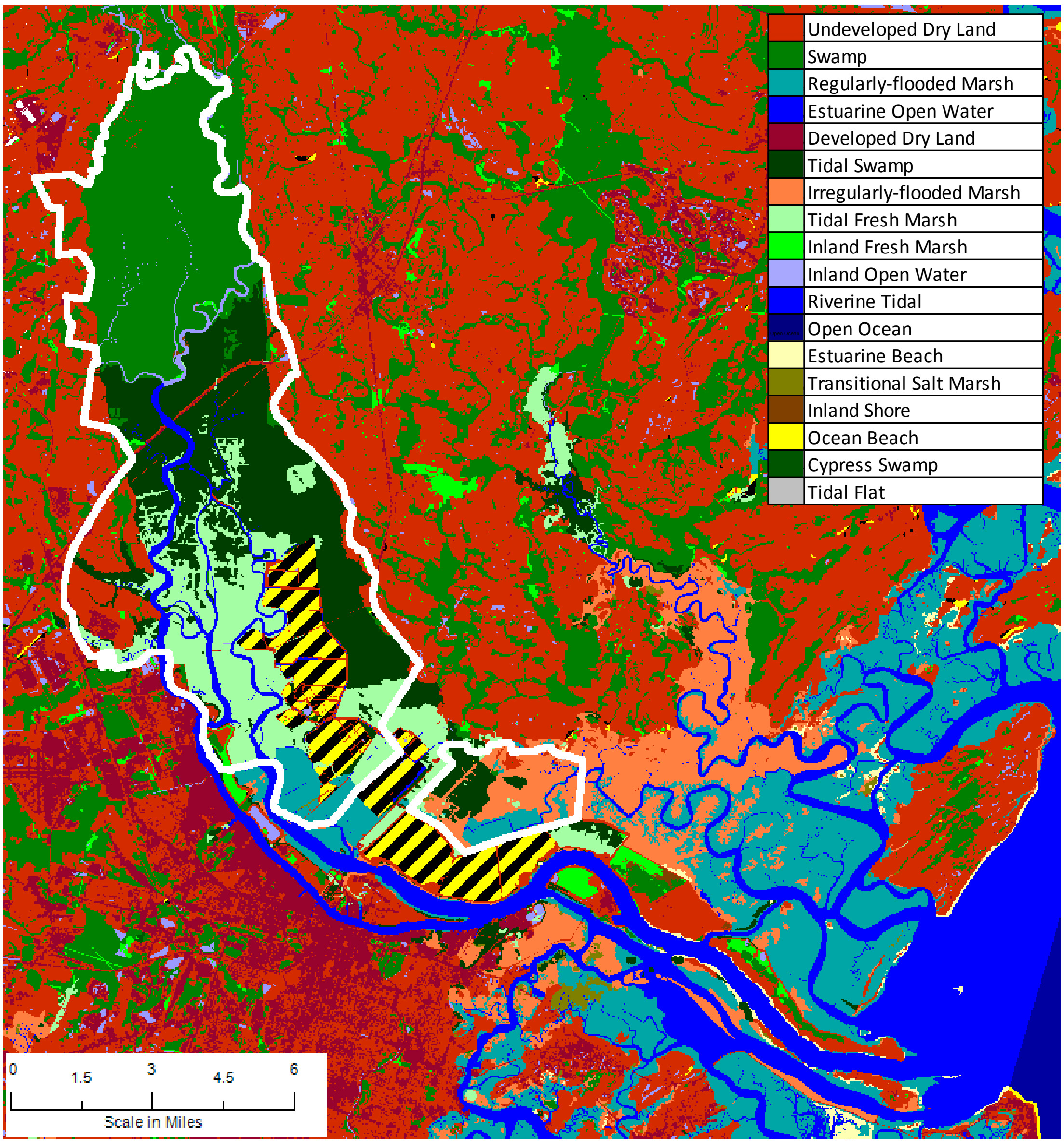


Figure 4. Dikes or impoundements indicated in black and yellow stripes. Refuge boundaries in white.

Model Timesteps. Model forecast data is output for years 2025, 2050, 2075 and 2100 with the initial condition date set to 2006, the most recent wetland data available.

Historic sea-level rise rates. The historic trend for relative sea-level rise rate was 2.98 mm/yr. This was recorded at the at the closest NOAA gauge to the refuge, Fort Pulaski, Georgia (#8670870). This rate is higher than the global (eustatic) SLR for the last 100 years (approximately 1.7 mm/yr), perhaps indicating some subsidence in this region.

Tide Ranges. The great diurnal range (GT) was estimated using the data from several NOAA gauge stations present in the area (shown in Figure 5). Different input subsites were defined reflecting these spatially variable tide ranges.

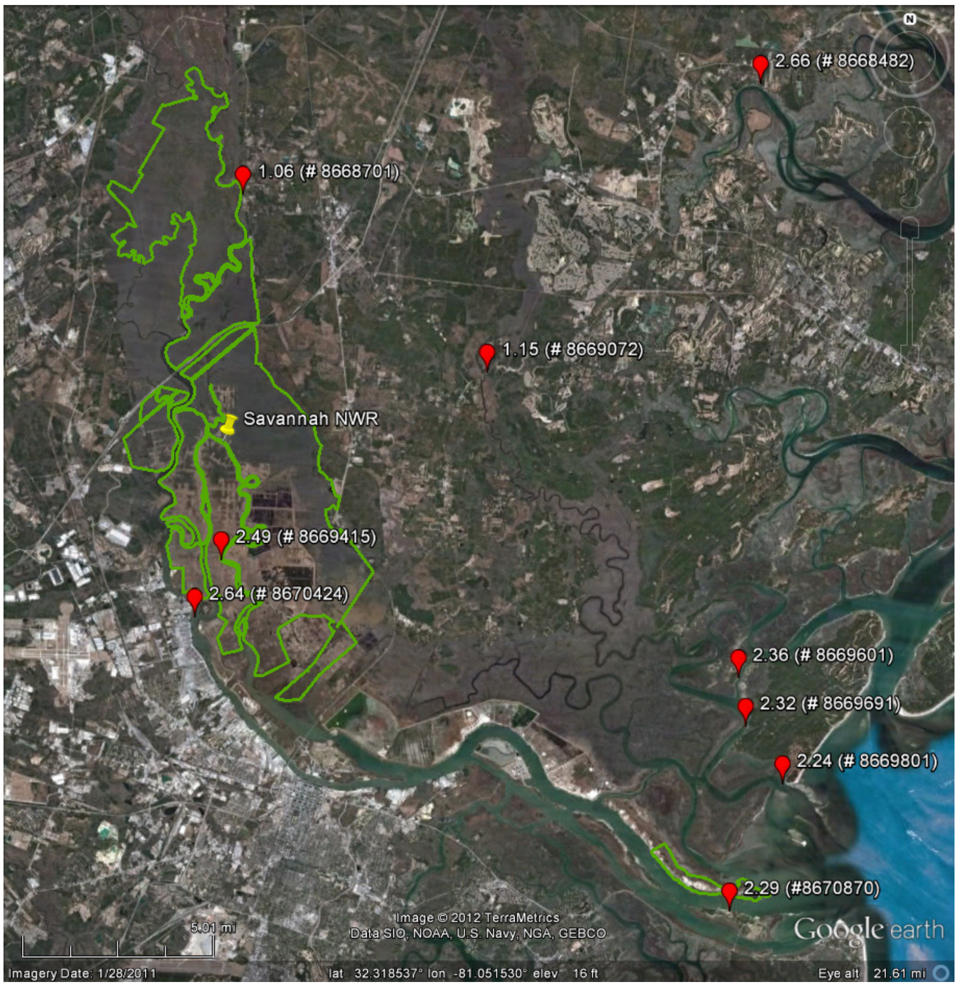


Figure 5. Spatial variability of the great diurnal range (GT) estimates in meters. NOAA station number shown in parentheses.

Salt elevation. This parameter within SLAMM designates the boundary between wet and dry lands or saline wetlands and fresh water wetlands. Based on regional data for this application, salt elevation was estimated at 1.2 Half Tide Units (HTU) for all input subsites by analyzing historical tidal data at NOAA gauge station #8670424.

Accretion rates. Accretion rates for regularly-flooded marshes were set to 1.9 mm/yr, irregularly-flooded marshes to 4.3 mm/yr and tidal fresh marshes to 4.8 mm/yr based on data from 36 cores gathered in the surrounding area (Craft, personal communication). Lacking site-specific information, accretion rates of other wetland types were set to the SLAMM default values.

Erosion rates. Erosion rates for marshes, swamps, and tidal flats were set to the SLAMM defaults of 2 m/yr, 1 m/yr and 0.2 mm/yr, respectively. Horizontal erosion of marshes and swamps occurs only at the wetland-to-open-water interface and only when adequate open water (fetch) exists for wave setup.

Elevation correction. MTL to NAVD88 corrections derived using data from NOAA gauges ranged from -0.116 to -1.006 m, moving away from the coast towards the interior, as shown in Figure 6. Modeled subsites reflect this spatial variability.

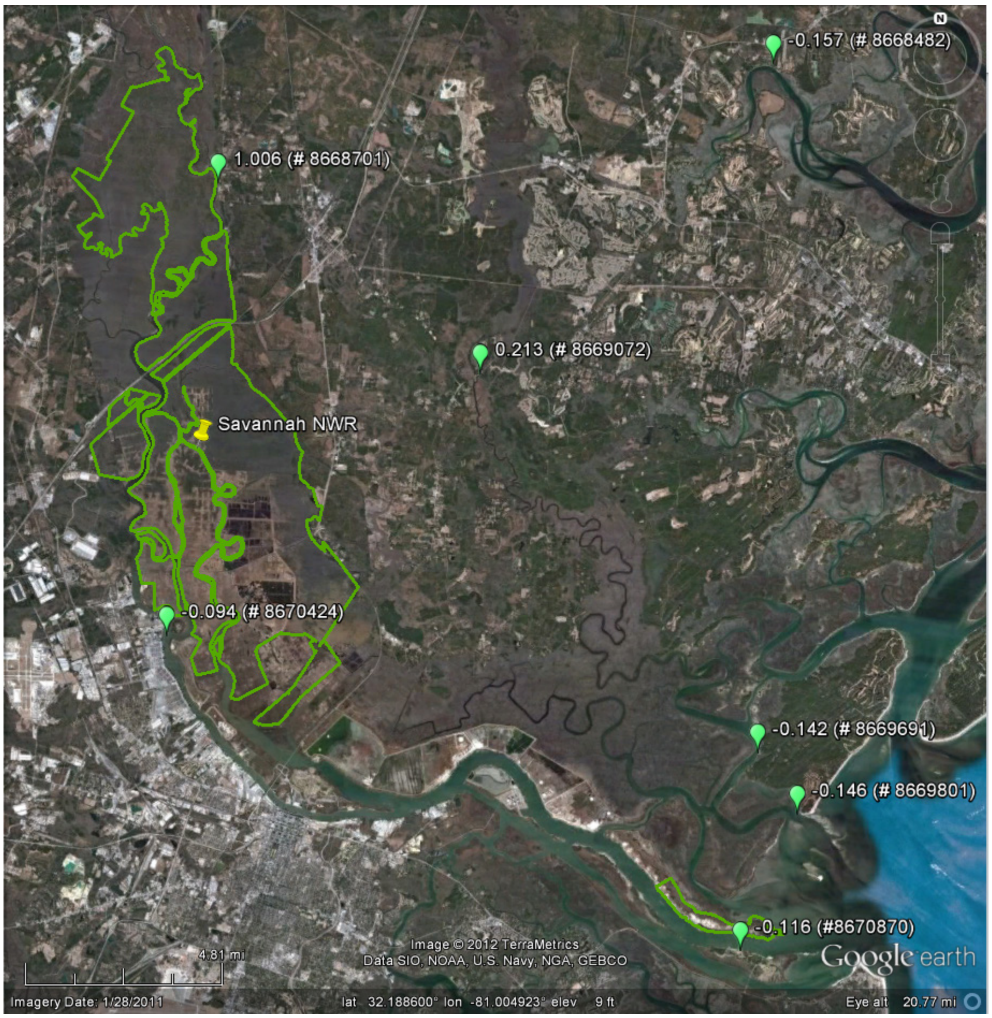


Figure 6. Spatial variability of MTL to NAVD88 correction estimates.

The MTL to NAVD88 correction of 1.006 m measured at NOAA gauge station #8668701 was an outlier (when compared to other local gauges) by nearly one meter. Using this correction resulted in swamp and tidal swamp elevations being lowered by nearly one meter and immediately converting to salt marsh and open water. While the gauge's measurement is likely accurate, it occurs far upstream in the fresh-water portion of the river and therefore does not reflect saline inundation of wetlands. (Swamp and tidal swamps are not sensitive to fresh-water inundation.) This outlier was therefore omitted and an MTL to NAVD88 correction of -0.09 m was used in this area of the refuge reflecting the next closest gauge downstream.

Effects of freshwater flow. Within SLAMM 6, when an area is defined as being influenced by freshwater flows, several changes are made to the SLAMM wetland flow chart. Previously, swamp and inland-fresh marsh always converted to transitional marsh upon inundation with salt water. Within SLAMM 6, when an area is defined as being influenced by fresh-water flows, swamp and inland fresh marsh are predicted to convert to tidal swamp and tidal-fresh marsh respectively, when they fall below their lower-elevation boundaries. The defined extent of freshwater flow for the Savannah NWR site is shown in Figure 7.

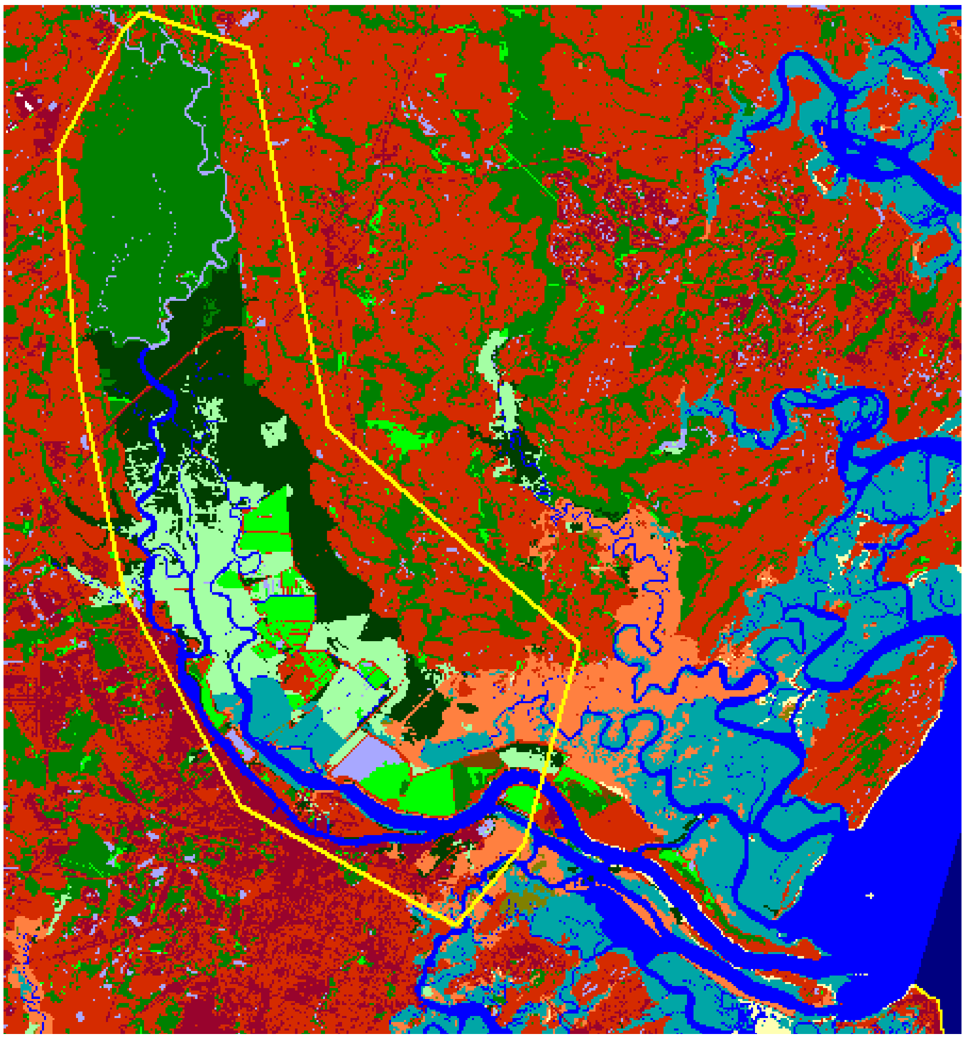


Figure 7. Fresh flow polygon drawn along the Savannah River basin

Refuge boundaries. Modeled USFWS refuge boundaries for Georgia are based on Approved Acquisition Boundaries as published on the USFWS National Wildlife Refuge Data and Metadata website. The cell-size used for this analysis was 10 m.

Input subsites and parameter summary. Based on spatial variability of the tide ranges and elevation corrections the study area was subdivided into the subsites illustrated in Figure 8.

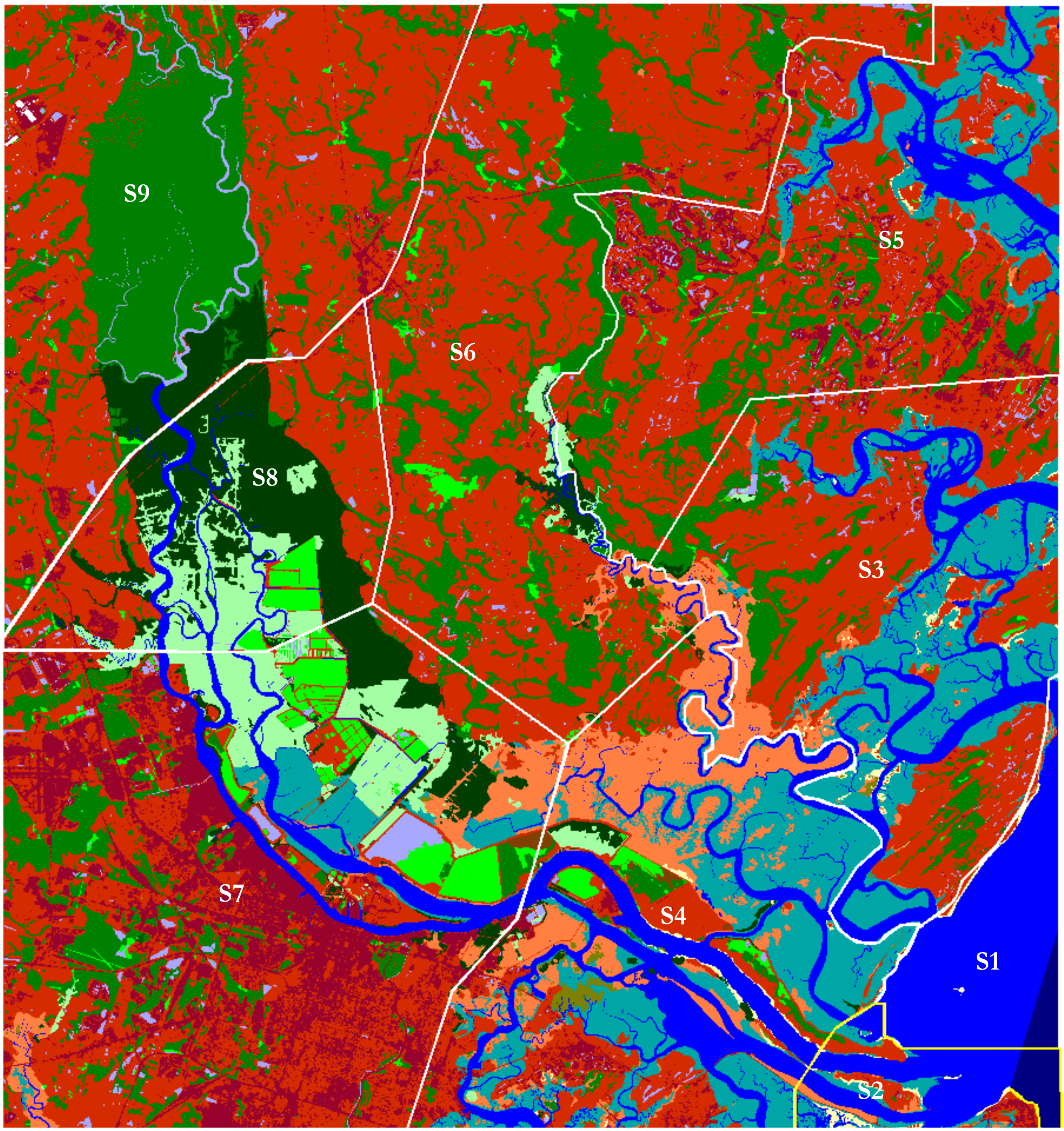


Figure 8. Input subsites for model application.

Table 1 summarizes all SLAMM input parameters for the input subsites. Values for parameters with no specific local information were kept at the model default value. The refuge extends across subsites S4,S7,S8, and S9, highlighted in the table below.

Table 1. Summary of SLAMM input parameters for Savannah NWR.

Parameter	S1	S2	S3	S4	S5	S6	S7	S8	S9
NWI Photo Date (YYYY)	2006	2006	2006	**2006**	2006	2006	**2006**	**2006**	**2006**
DEM Date (YYYY)	2009	2009	2009	**2009**	2009	2009	**2009**	**2009**	**2009**
Direction Offshore [n,s,e,w]	East	East	East	**East**	East	East	**East**	**East**	**East**
Historic Trend (mm/yr)	2.98	2.98	2.98	**2.98**	2.98	2.98	**2.98**	**2.98**	**2.98**
MTL-NAVD88 (m)	-0.15	-0.12	-0.14	**-0.11**	-0.16	0.21	**-0.09**	**-0.09**	**-0.09**
GT Great Diurnal Tide Range (m)	2.24	2.29	2.34	**2.4**	2.66	1.15	**2.57**	**1.84**	**1.01**
Salt Elev. (m above MTL)	1.44	1.37	1.4	**1.44**	1.6	0.69	**1.54**	**1.1**	**0.61**
Marsh Erosion (horz. m /yr)	2	2	2	**2**	2	2	**2**	**2**	**2**
Swamp Erosion (horz. m /yr)	1	1	1	**1**	1	1	**1**	**1**	**1**
T.Flat Erosion (horz. m /yr)	0.2	0.2	0.2	**0.2**	0.2	0.2	**0.2**	**0.2**	**0.2**
Reg.-Flood Marsh Accr (mm/yr)	1.9	1.9	1.9	**1.9**	1.9	1.9	**1.9**	**1.9**	**1.9**
Irreg.-Flood Marsh Accr (mm/yr)	4.3	4.3	4.3	**4.3**	4.3	4.3	**4.3**	**4.3**	**4.3**
Tidal-Fresh Marsh Accr (mm/yr)	4.8	4.8	4.8	**4.8**	4.8	4.8	**4.8**	**4.8**	**4.8**
Inland-Fresh Marsh Accr (mm/yr)	4	4	4	**4**	4	4	**4**	**4**	**4**
Mangrove Accr (mm/yr)	7	7	7	**7**	7	7	**7**	**7**	**7**
Tidal Swamp Accr (mm/yr)	1.1	1.1	1.1	**1.1**	1.1	1.1	**1.1**	**1.1**	**1.1**
Swamp Accretion (mm/yr)	0.3	0.3	0.3	**0.3**	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	0.5	**0.5**	**0.5**	**0.5**
Freq. Overwash (years)	25	25	25	**25**	25	25	**25**	**25**	**25**
Use Elev Pre-processor [True,False]	TRUE	FALSE	TRUE	**FALSE**	TRUE	FALSE	**FALSE**	**FALSE**	**FALSE**

Elevation Analysis: Based on site-specific data, for this refuge, the minimum elevations for tidal fresh marsh and tidal swamp were set to 0.3 HTU and 0.5 HTU respectively.

Results

The initial land coverage in acres, and predicted wetland losses by 2100 under different SLR scenarios are presented in Table 2. Land-cover losses are calculated in comparison to the initial 2006 NWI wetland coverage.

Table 2. Predicted loss rates of land categories by 2100 given simulated scenarios of eustatic SLR at Savannah 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
Tidal Swamp	12586	17%	31%	49%	73%	63%
Swamp	11887	2%	6%	24%	46%	73%
Tidal Fresh Marsh	7577	-23%([1])	-23%	-48%	-10%	32%
Undeveloped Dry Land	5754	14%	17%	21%	28%	37%
Inland Fresh Marsh	2418	2%	2%	2%	3%	18%
Irregularly-flooded Marsh	1826	9%	29%	60%	98%	99%
Regularly-flooded Marsh	1693	-32%	-173%	-243%	-270%	40%

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

Tidal swamp, the most prevalent wetland cover in the Savannah NWR, is predicted to experience losses across all SLR scenarios, from 17% loss under the most conservative SLR scenario to 73% under the 1.5 m SLR by 2100 scenario. At the highest SLR rate (2 m), losses are partially compensated for by non-tidal swamp areas become tidal. Non-tidal swamp is predicted to gradually lose coverage with major losses at scenarios higher than 1 m SLR by 2100.

Alternatively, tidal-fresh marsh is predicted to gain coverage given SLR scenarios below 1.5 m by 2100. Tidal-fresh marshes are predicted to appear when tidal swamps become too-frequently inundated by saline water and are predicted to convert. However, when sea levels exceed 1.5 meters by 2100, losses are observed for this tidal-fresh marshes as well.

Losses of inland -resh marsh are predicted to be limited even at high sea-level rise rates. However, this result is most likely due to the fact that the areas covered by this marsh type are managed and protected by dikes.

Irregularly-flooded marsh, that today covers around 4% of the refuge area, is predicted to gradually disappear as sea-level rise rates continue to increase, with an almost total loss of this marsh habitat under the 2 m SLR by 2100 scenario.

For SLR scenarios lower than 1.5 m by 2100, irregularly-flooded marsh areas are mostly converted to regularly-flooded marsh. However at higher rates regularly-flooded marshes are also predicted to sustain losses.

Major land cover gains are summarized in Table 3. Open water, which initially covers just more than 5% of the refuge, is predicted to increase coverage as sea level rises, more than doubling coverage under the 2 m SLR by 2100 scenario. In addition, tidal flat is predicted to gradually occupy areas that were previously covered by marshes, comprising 44% of the total refuge area in 2100 under the highest SLR scenario examined (2 m by 2100).

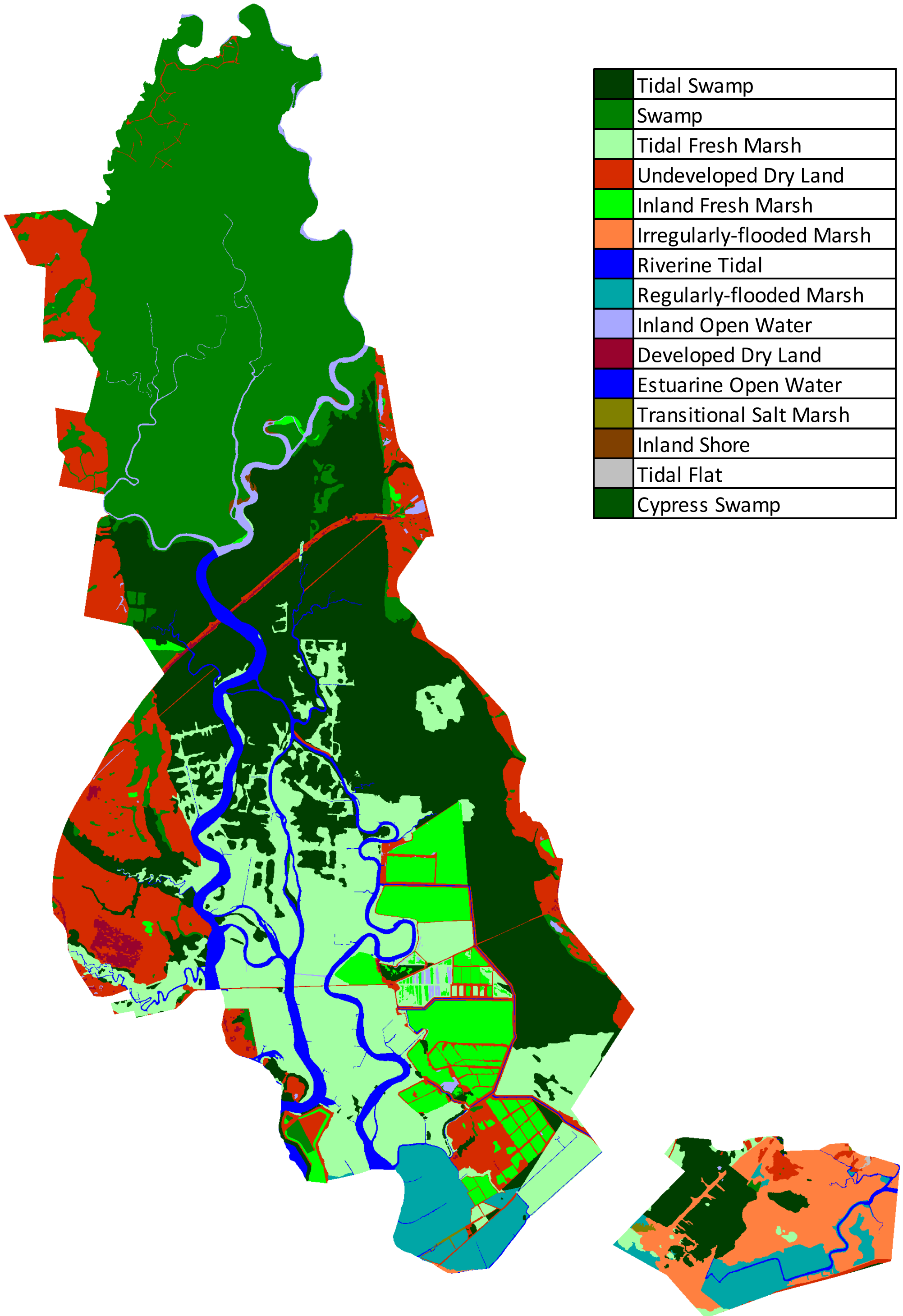
Table 3. Predicted land cover gains by 2100 given simulated scenarios of eustatic SLR at Savannah NWR.

Land cover category	Initial coverage (acres)	Land cover by 2100 for different SLR scenarios (acres)				
		0.39 m	0.69 m	1 m	1.5 m	2 m
Open water	2485	2572	2674	2826	3425	5511
Tidal Flat	5	697	1080	3089	11622	20658

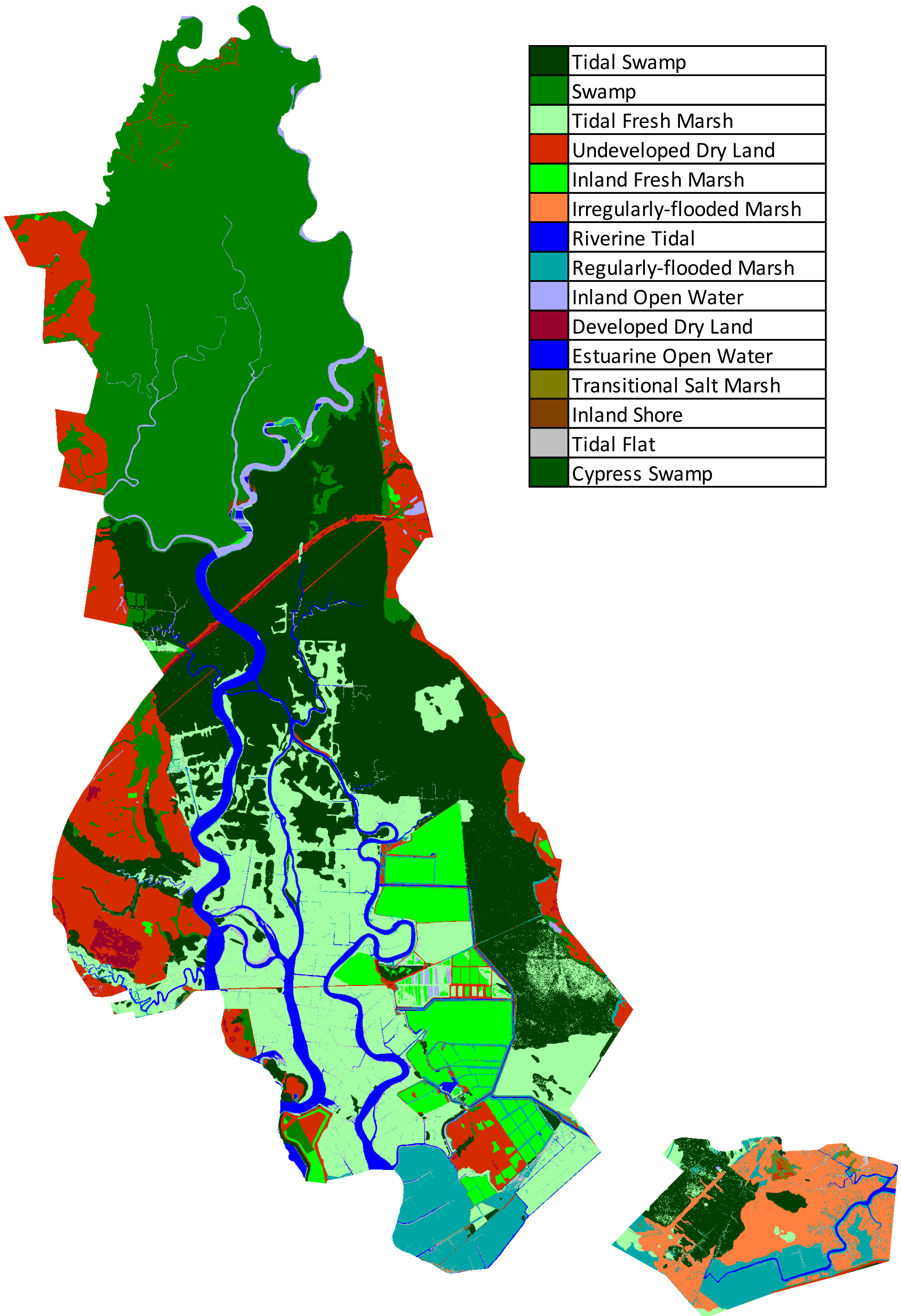
Savannah NWR
IPCC Scenario A1B-Mean, 0.39 m SLR eustatic by 2100

Results in Acres

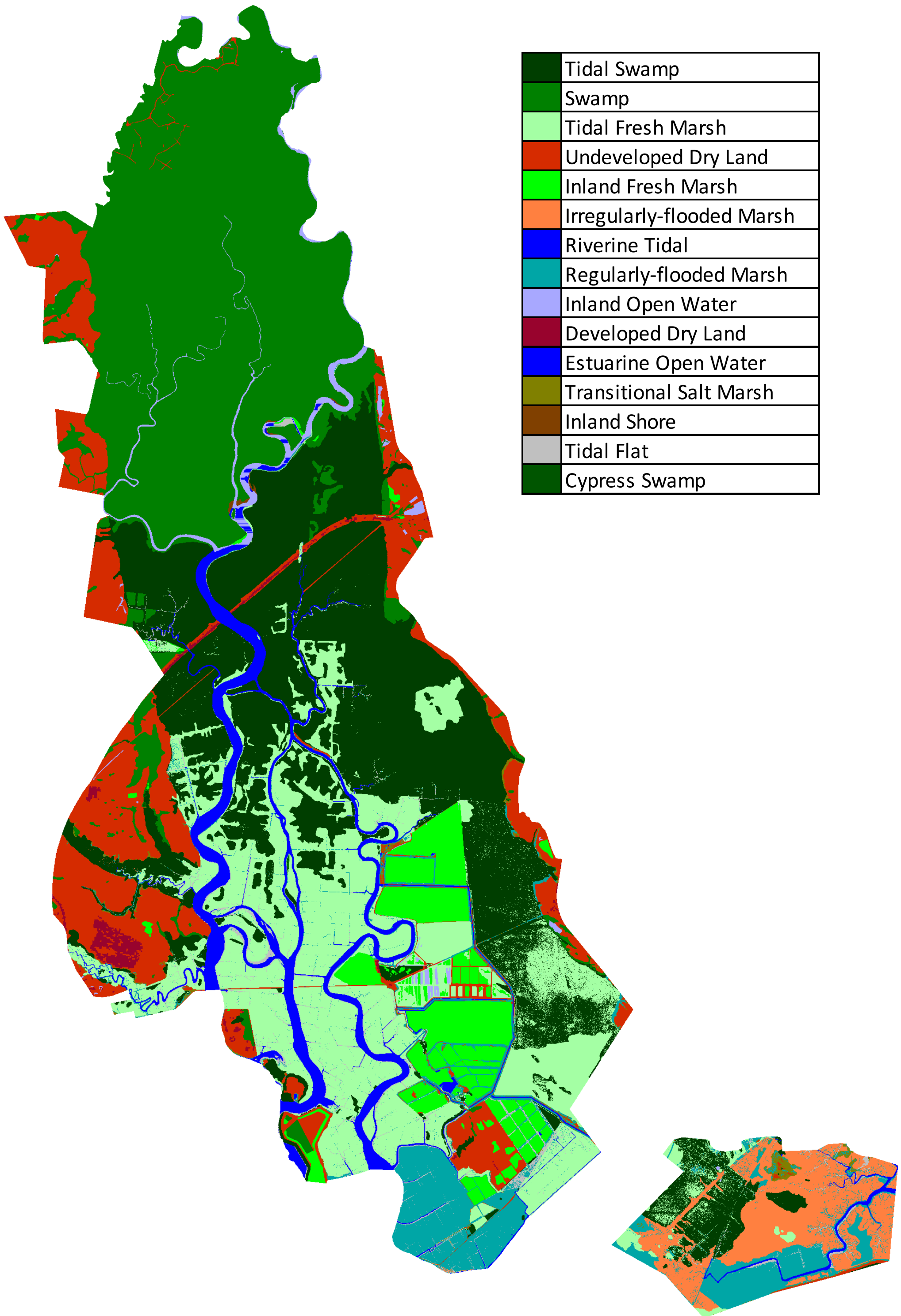
		Initial	2025	2050	2075	2100
	Tidal Swamp	12586	12090	11728	11163	10490
	Swamp	11887	11827	11816	11790	11671
	Tidal Fresh Marsh	7577	7654	8005	8576	9313
	Undeveloped Dry Land	5754	5166	5091	5011	4938
	Inland Fresh Marsh	2418	2381	2380	2379	2378
	Irregularly-flooded Marsh	1826	1667	1669	1656	1653
	Riverine Tidal	1798	559	352	340	327
	Regularly-flooded Marsh	1693	2455	2375	2310	2231
	Inland Open Water	575	528	489	451	445
	Developed Dry Land	244	242	242	241	240
	Estuarine Open Water	112	1414	1682	1753	1801
	Transitional Salt Marsh	26	155	222	276	323
	Inland Shore	23	18	18	18	18
	Tidal Flat	5	368	455	561	697
	Cypress Swamp	2	2	2	2	2
	Total (incl. water)	**46526**	**46526**	**46526**	**46526**	**46526**



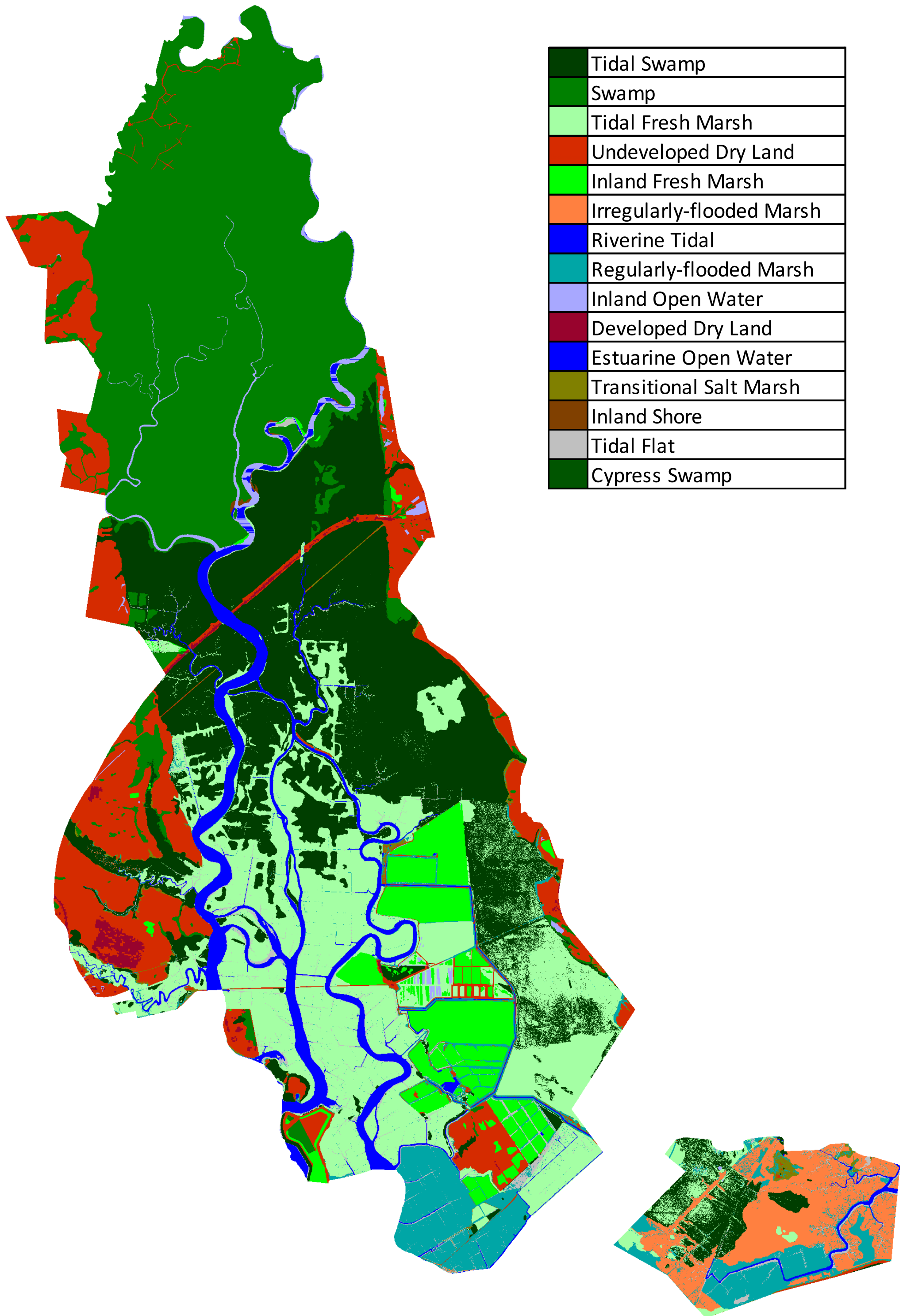
Savannah NWR, Initial Condition.



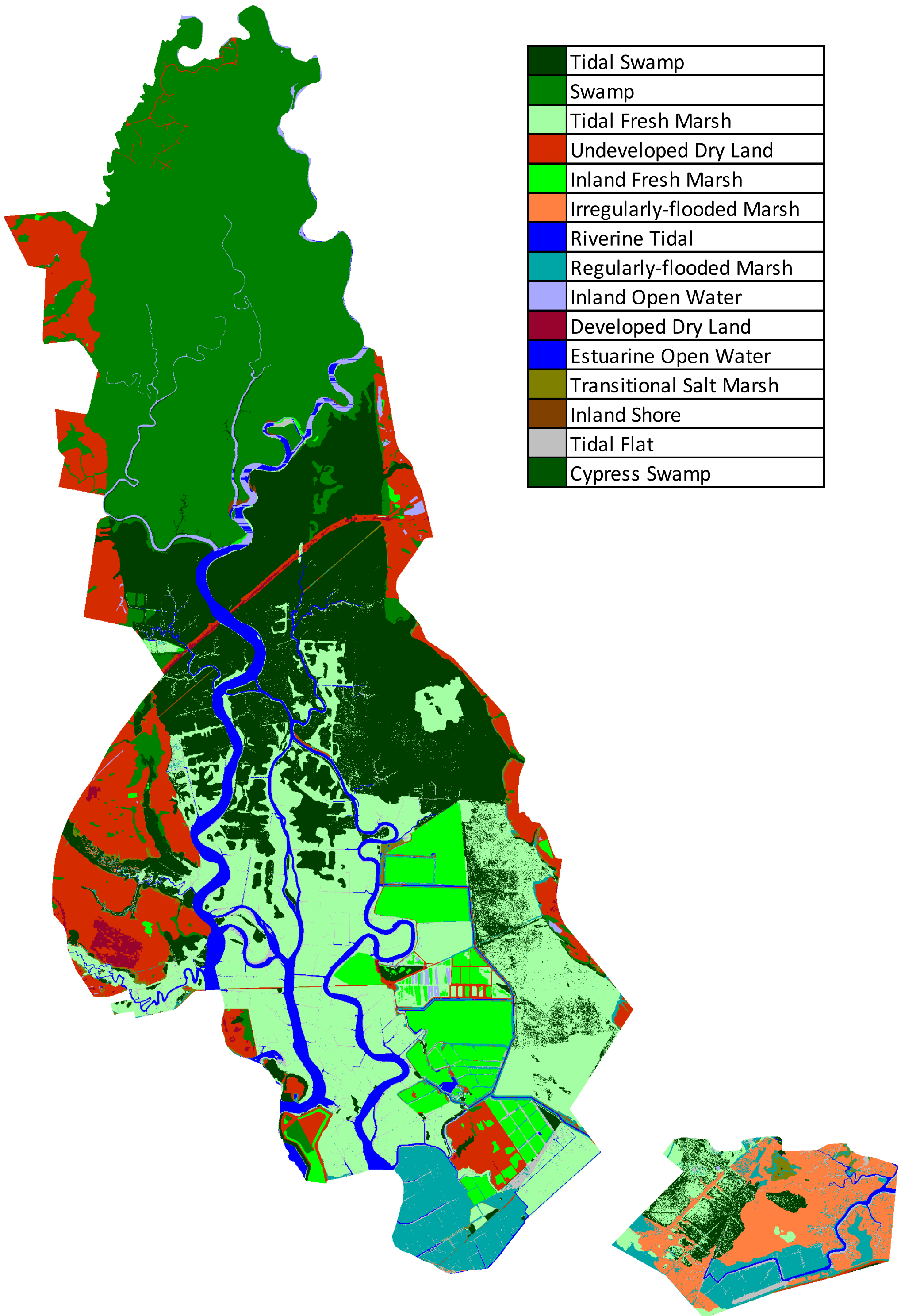
Savannah NWR, 2025, Scenario A1B Mean, 0.39 m SLR by 2100.



Savannah NWR, 2050, Scenario A1B Mean, 0.39 m SLR by 2100.



Savannah NWR, 2075, Scenario A1B Mean, 0.39 m SLR by 2100.

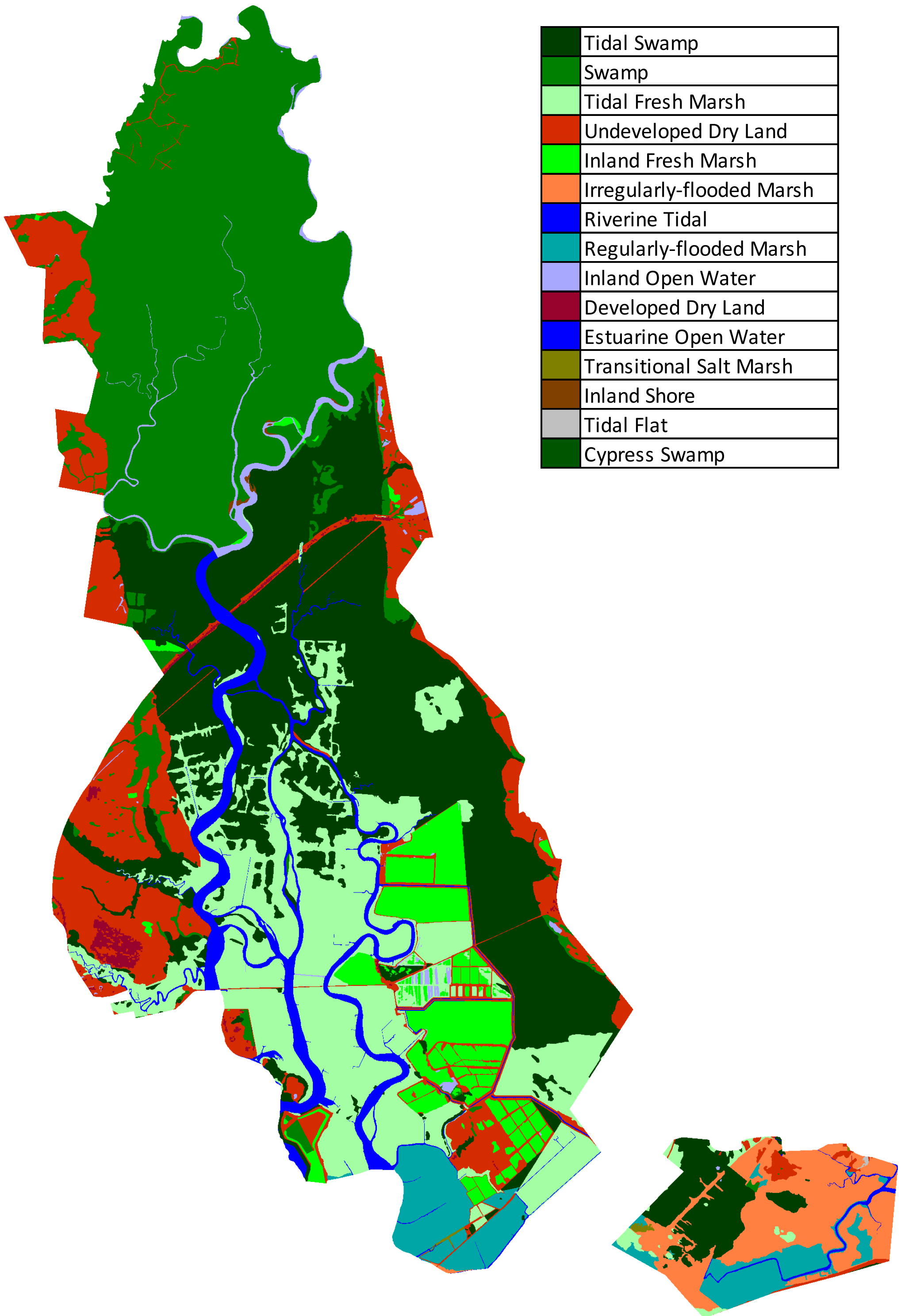


Savannah NWR, 2100, Scenario A1B Mean, 0.39 m SLR by 2100.

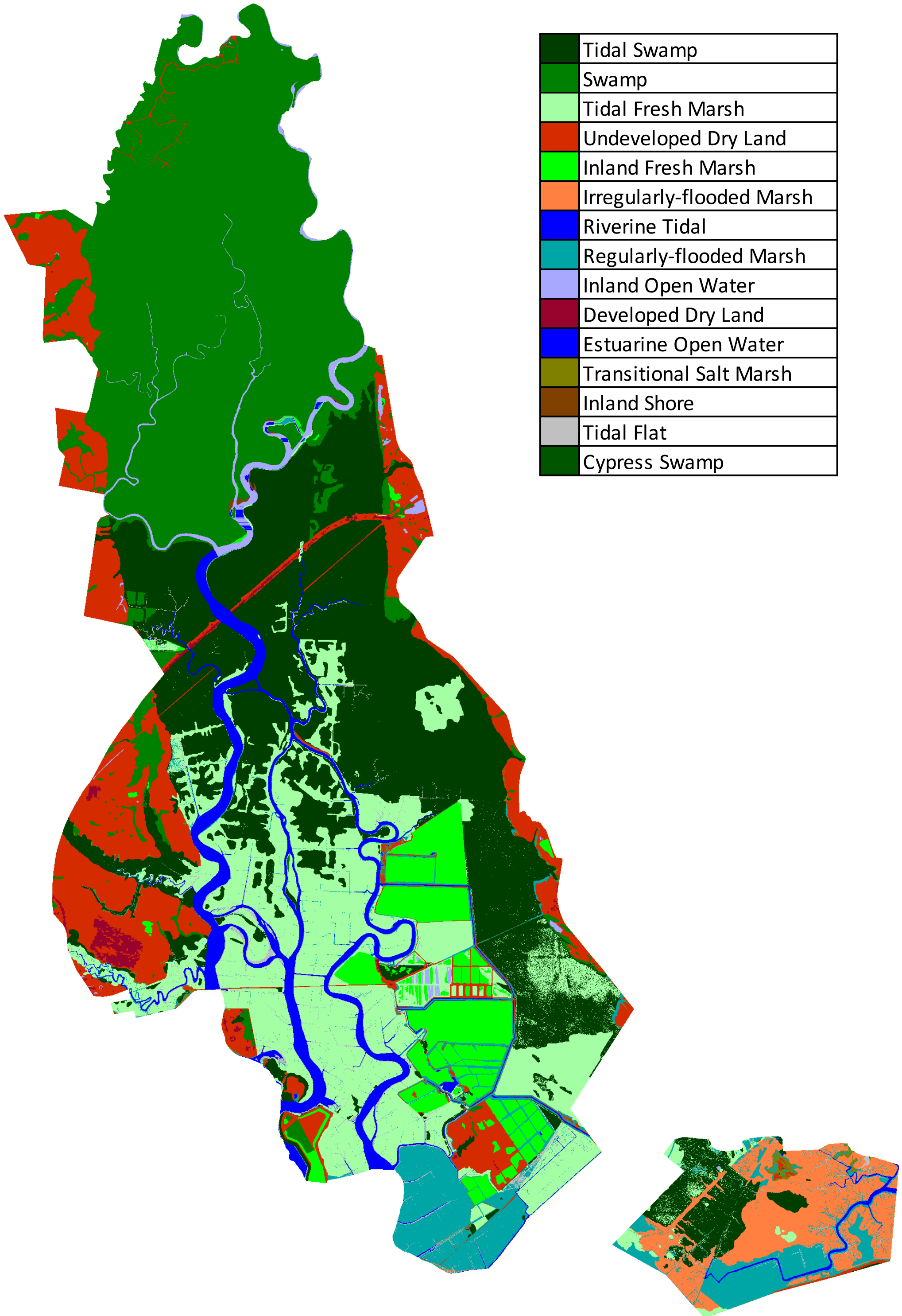
Savannah NWR
IPCC Scenario A1B-Max, 0.69 m SLR eustatic by 2100

Results in Acres

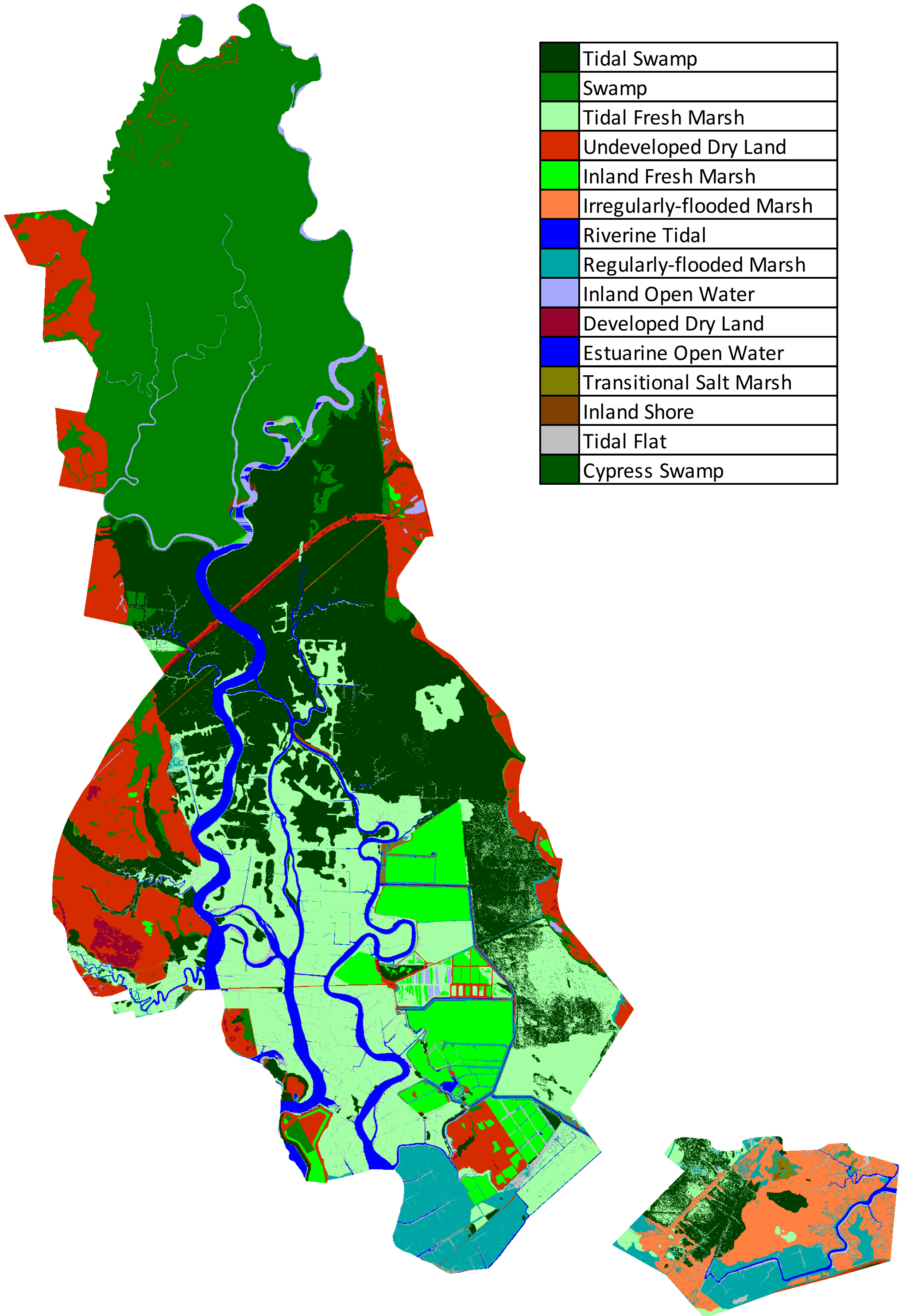
		Initial	2025	2050	2075	2100
	Tidal Swamp	12586	11995	11292	10057	8691
	Swamp	11887	11824	11798	11641	11208
	Tidal Fresh Marsh	7577	7737	8349	9363	9351
	Undeveloped Dry Land	5754	5147	5036	4915	4774
	Inland Fresh Marsh	2418	2380	2378	2375	2374
	Irregularly-flooded Marsh	1826	1661	1622	1523	1291
	Riverine Tidal	1798	558	337	290	189
	Regularly-flooded Marsh	1693	2473	2459	2739	4626
	Inland Open Water	575	528	489	439	415
	Developed Dry Land	244	242	241	240	237
	Estuarine Open Water	112	1417	1706	1855	2070
	Transitional Salt Marsh	26	160	224	210	204
	Inland Shore	23	18	18	18	15
	Tidal Flat	5	383	574	858	1080
	Cypress Swamp	2	2	2	2	2
	Total (incl. water)	**46526**	**46526**	**46526**	**46526**	**46526**



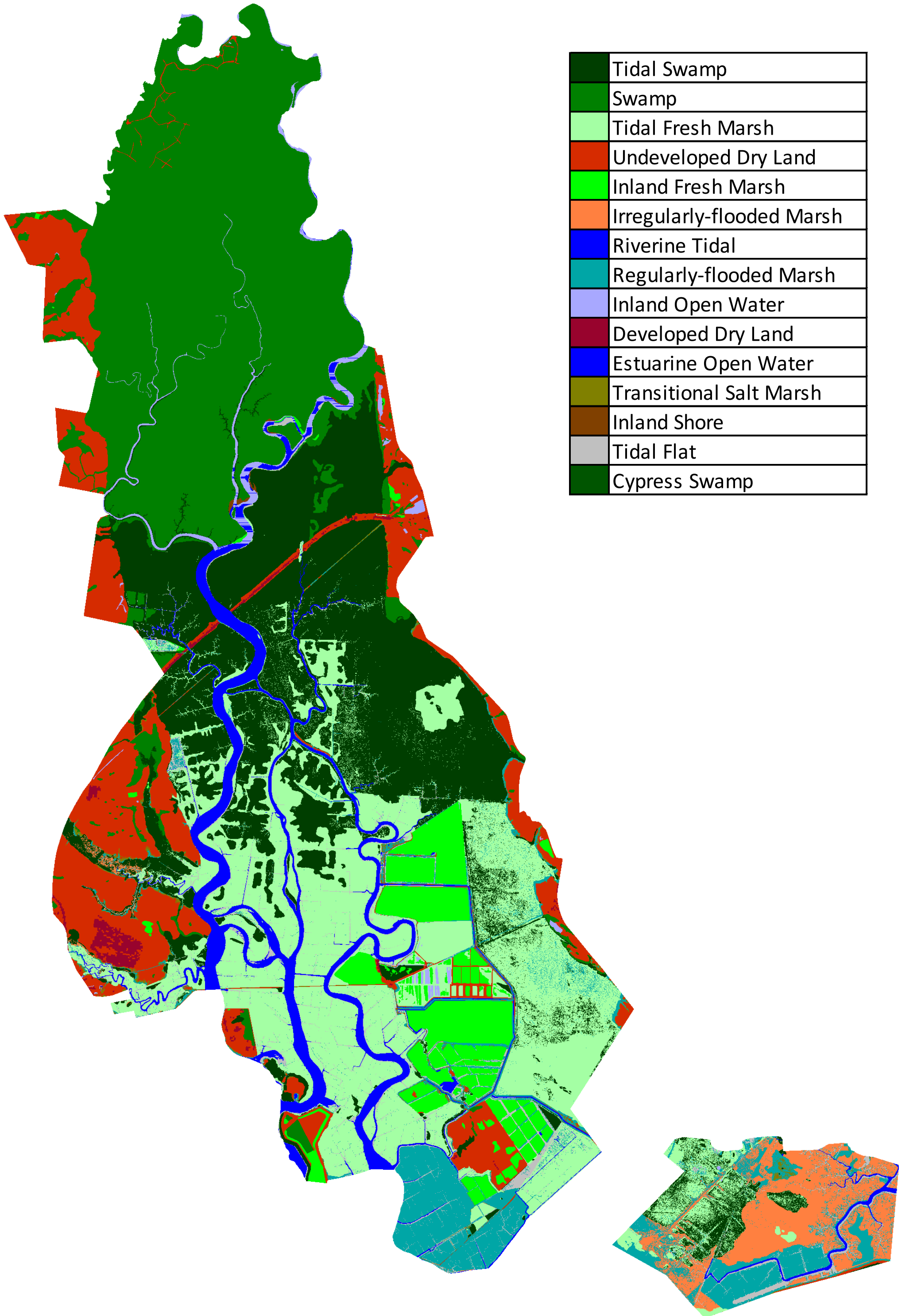
Savannah NWR, Initial Condition.



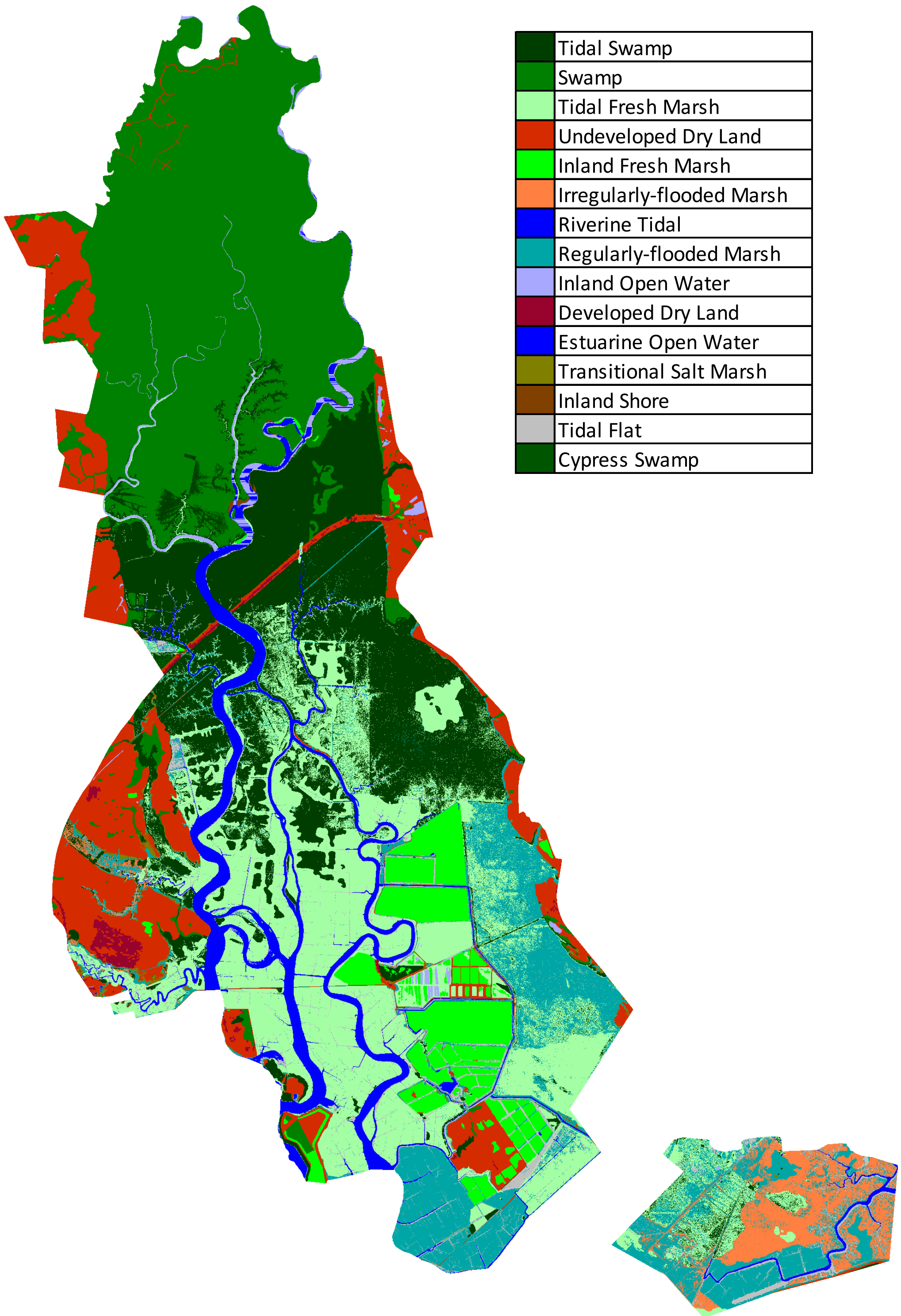
Savannah NWR, 2025, Scenario A1B Maximum, 0.69 m SLR by 2100.



Savannah NWR, 2050, Scenario A1B Maximum, 0.69 m SLR by 2100.



Savannah NWR, 2075, Scenario A1B Maximum, 0.69 m SLR by 2100.

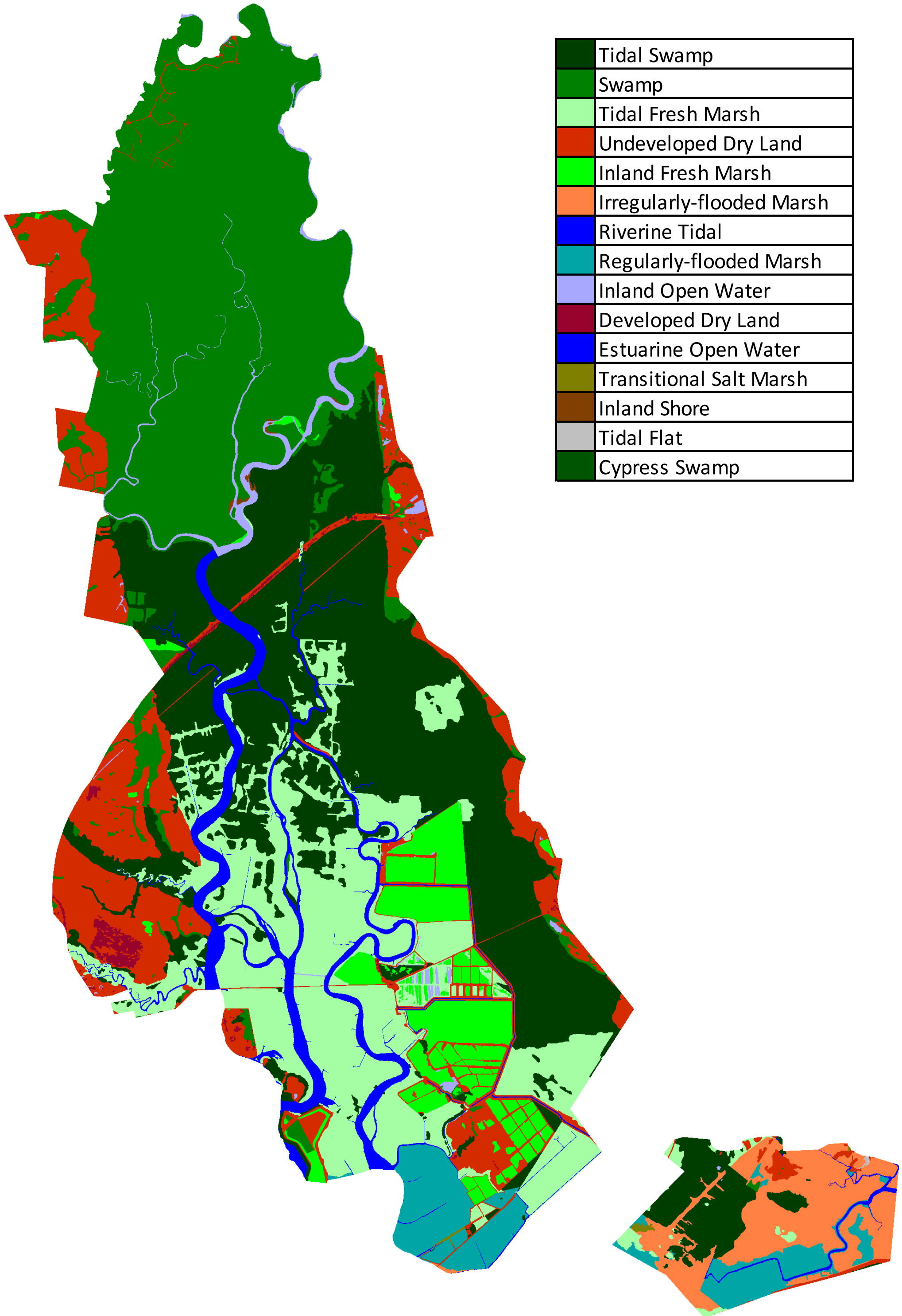


Savannah NWR, 2100, Scenario A1B Maximum, 0.69 m SLR by 2100.

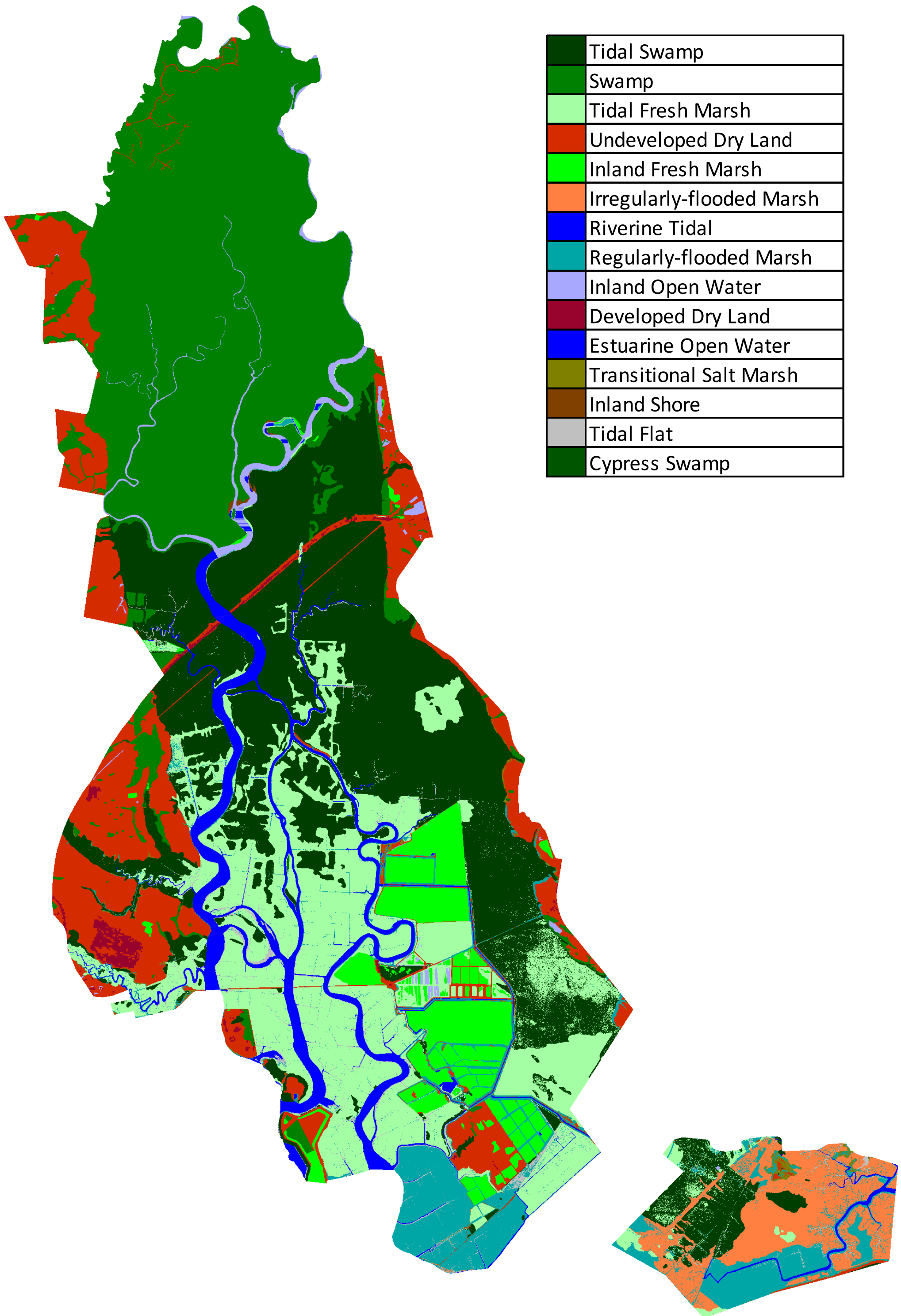
Savannah NWR
1 m eustatic SLR by 2100

Results in Acres

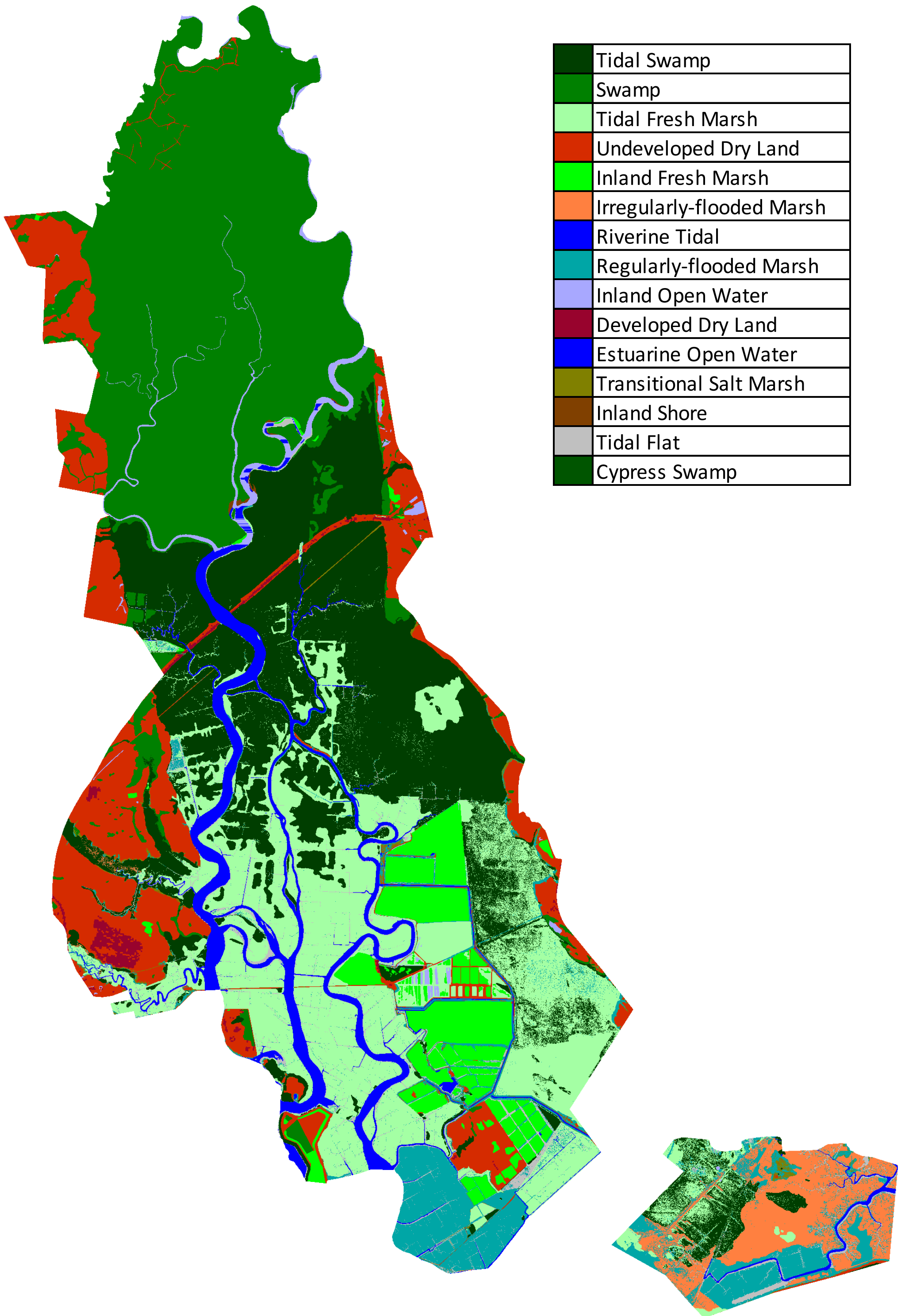
		Initial	2025	2050	2075	2100
	Tidal Swamp	12586	11880	10644	8814	6396
	Swamp	11887	11821	11779	11406	9020
	Tidal Fresh Marsh	7577	7816	8816	9124	11211
	Undeveloped Dry Land	5754	5126	4984	4807	4539
	Inland Fresh Marsh	2418	2380	2377	2373	2370
	Irregularly-flooded Marsh	1826	1645	1536	1211	735
	Riverine Tidal	1798	557	313	235	91
	Regularly-flooded Marsh	1693	2522	2635	4556	5806
	Inland Open Water	575	528	488	426	399
	Developed Dry Land	244	242	241	238	228
	Estuarine Open Water	112	1419	1744	1991	2336
	Transitional Salt Marsh	26	165	206	199	290
	Inland Shore	23	18	18	16	14
	Tidal Flat	5	404	745	1129	3089
	Cypress Swamp	2	2	2	2	2
	Total (incl. water)	**46526**	**46526**	**46526**	**46526**	**46526**



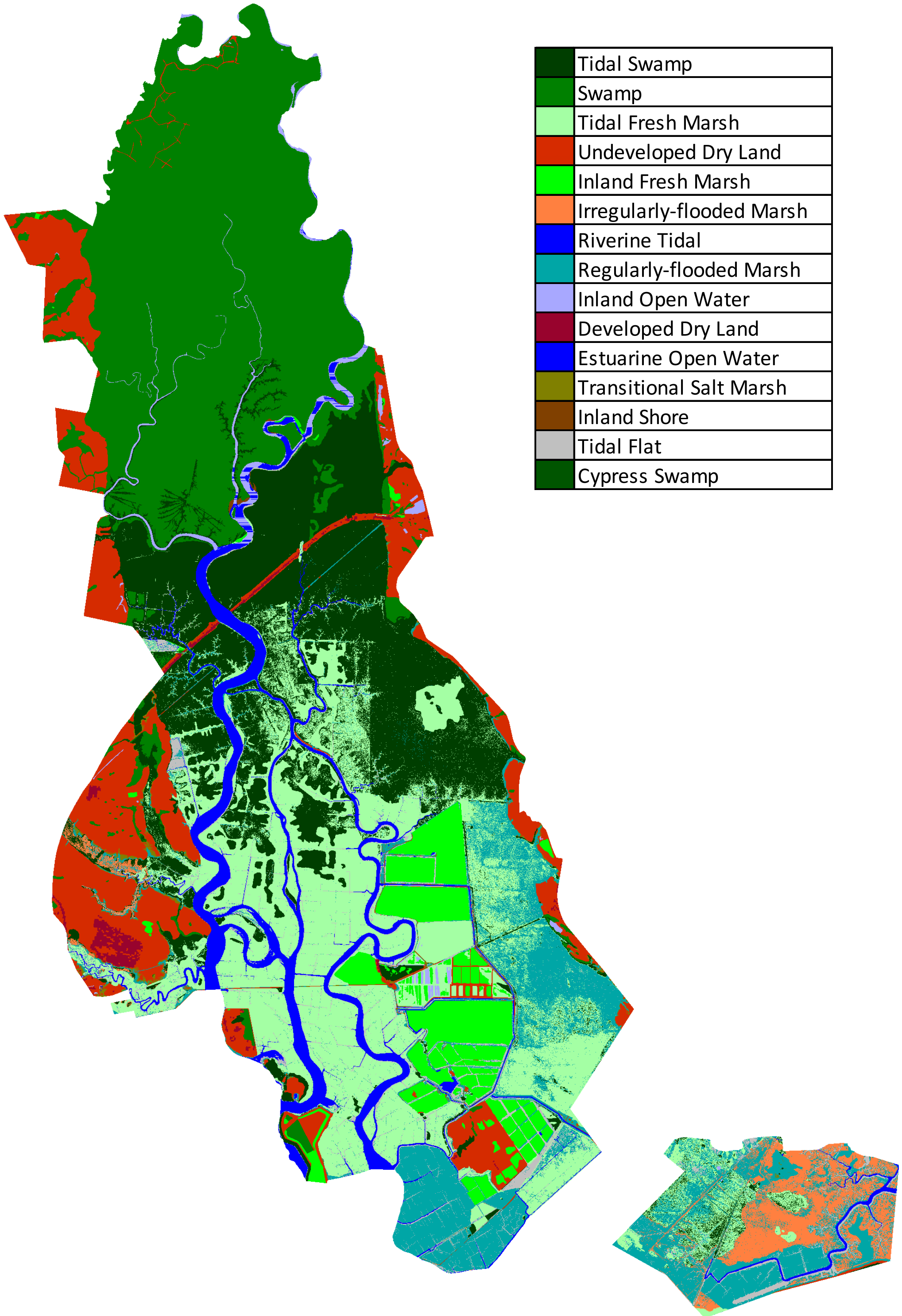
Savannah NWR, Initial Condition.



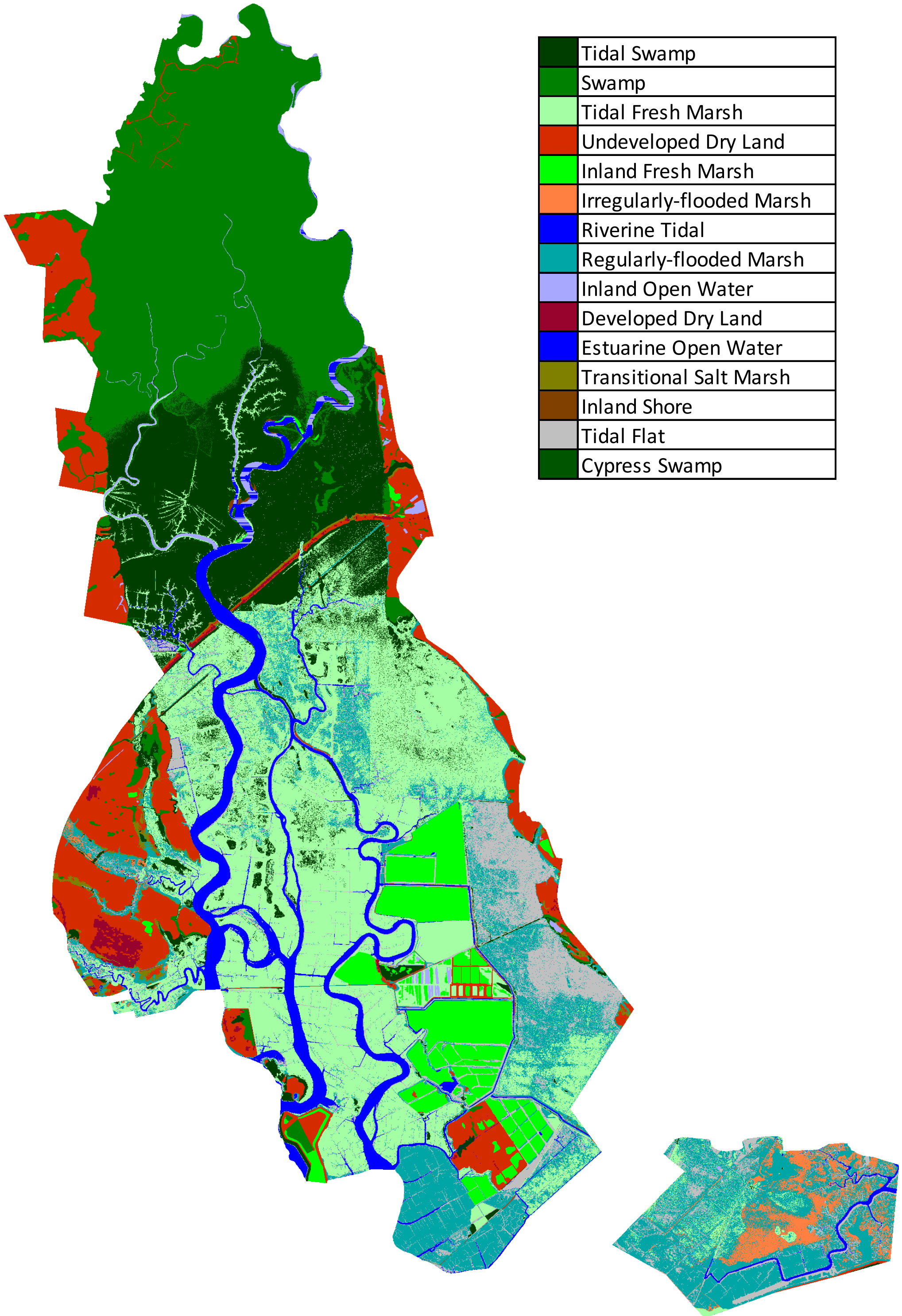
Savannah NWR, 2025, 1 m SLR by 2100.



Savannah NWR, 2050, 1 m SLR by 2100.



Savannah NWR, 2075, 1 m SLR by 2100.

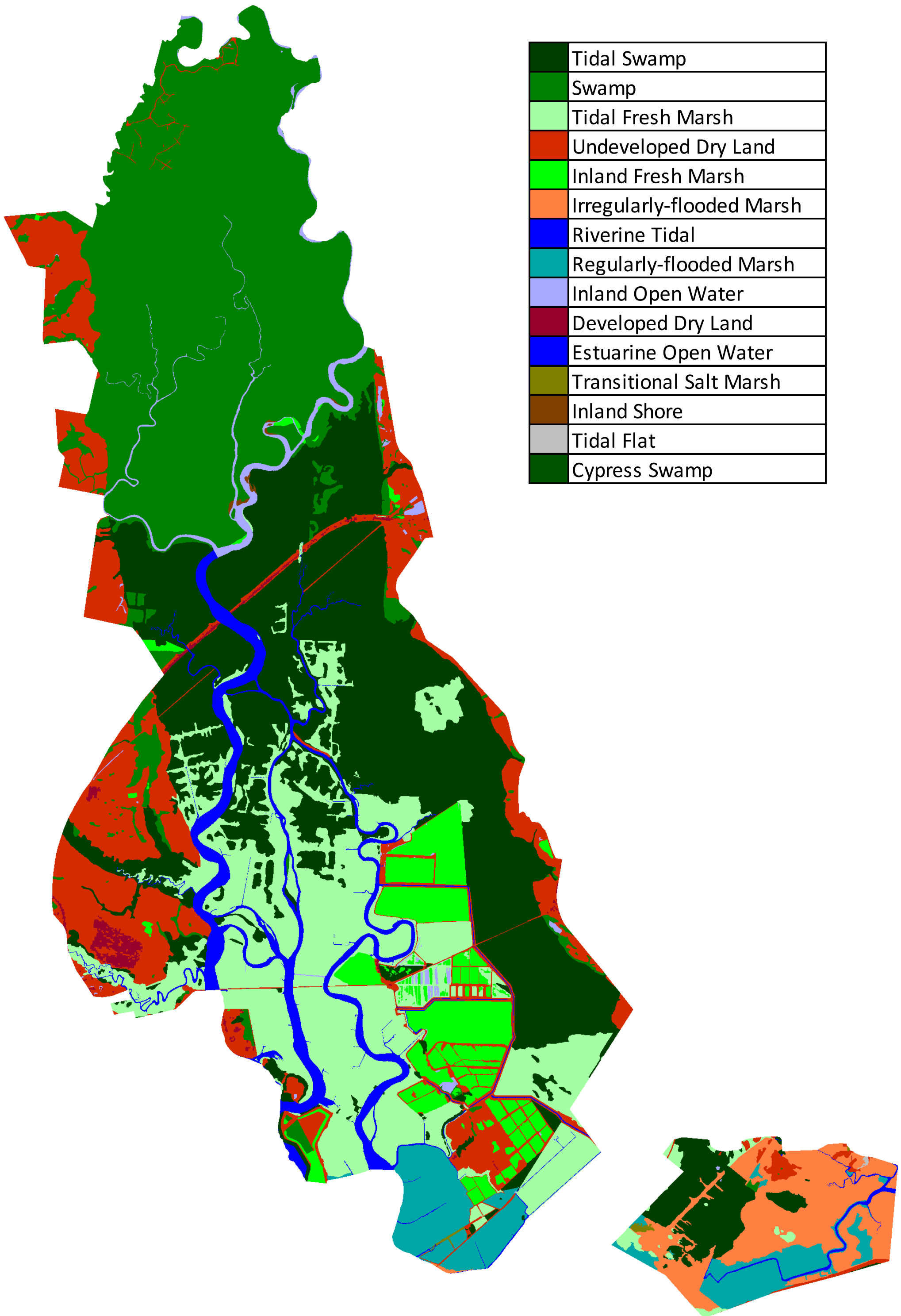


Savannah NWR, 2100, 1 m SLR by 2100.

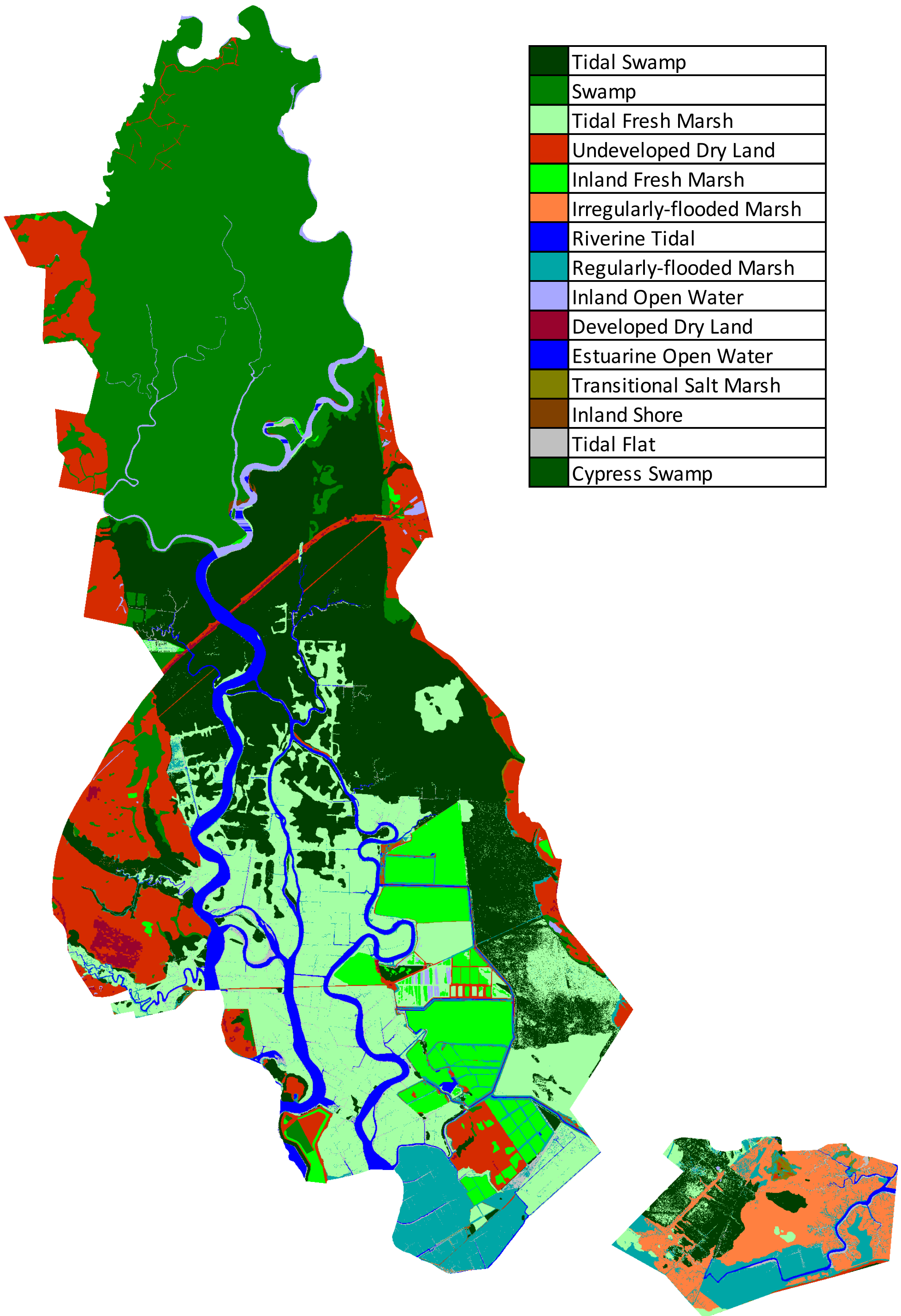
Savannah NWR
1.5 m eustatic SLR by 2100

Results in Acres

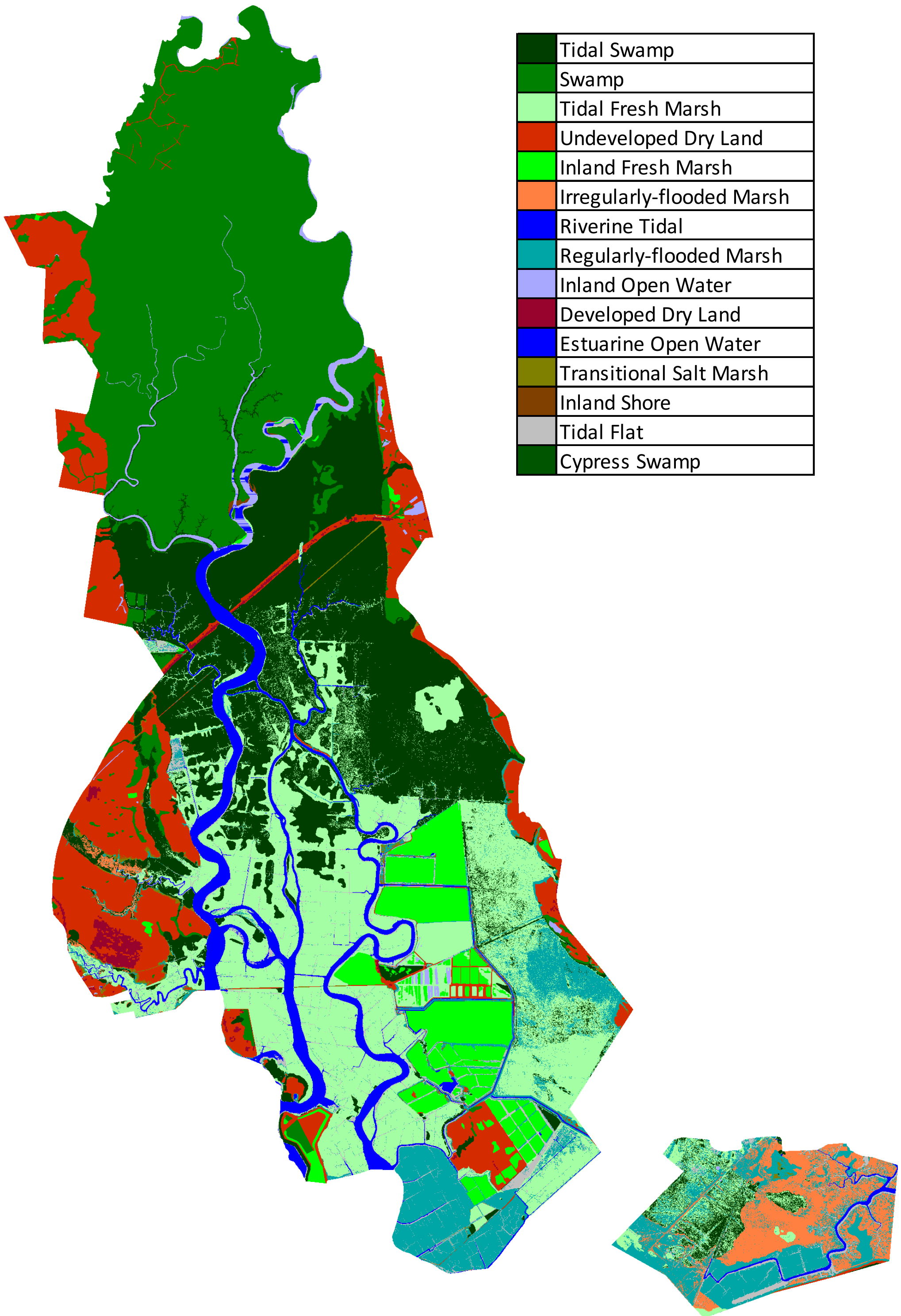
		Initial	2025	2050	2075	2100
	Tidal Swamp	12586	11669	9694	6381	3369
	Swamp	11887	11816	11603	9127	6364
	Tidal Fresh Marsh	7577	7964	9055	11776	8311
	Undeveloped Dry Land	5754	5098	4900	4558	4165
	Inland Fresh Marsh	2418	2378	2374	2368	2342
	Irregularly-flooded Marsh	1826	1617	1283	612	31
	Riverine Tidal	1798	556	287	184	50
	Regularly-flooded Marsh	1693	2575	3587	4821	6255
	Inland Open Water	575	528	481	408	387
	Developed Dry Land	244	242	239	229	219
	Estuarine Open Water	112	1423	1817	2219	2989
	Transitional Salt Marsh	26	168	209	360	407
	Inland Shore	23	18	18	14	14
	Tidal Flat	5	472	976	3468	11622
	Cypress Swamp	2	2	2	2	2
	Total (incl. water)	**46526**	**46526**	**46526**	**46526**	**46526**



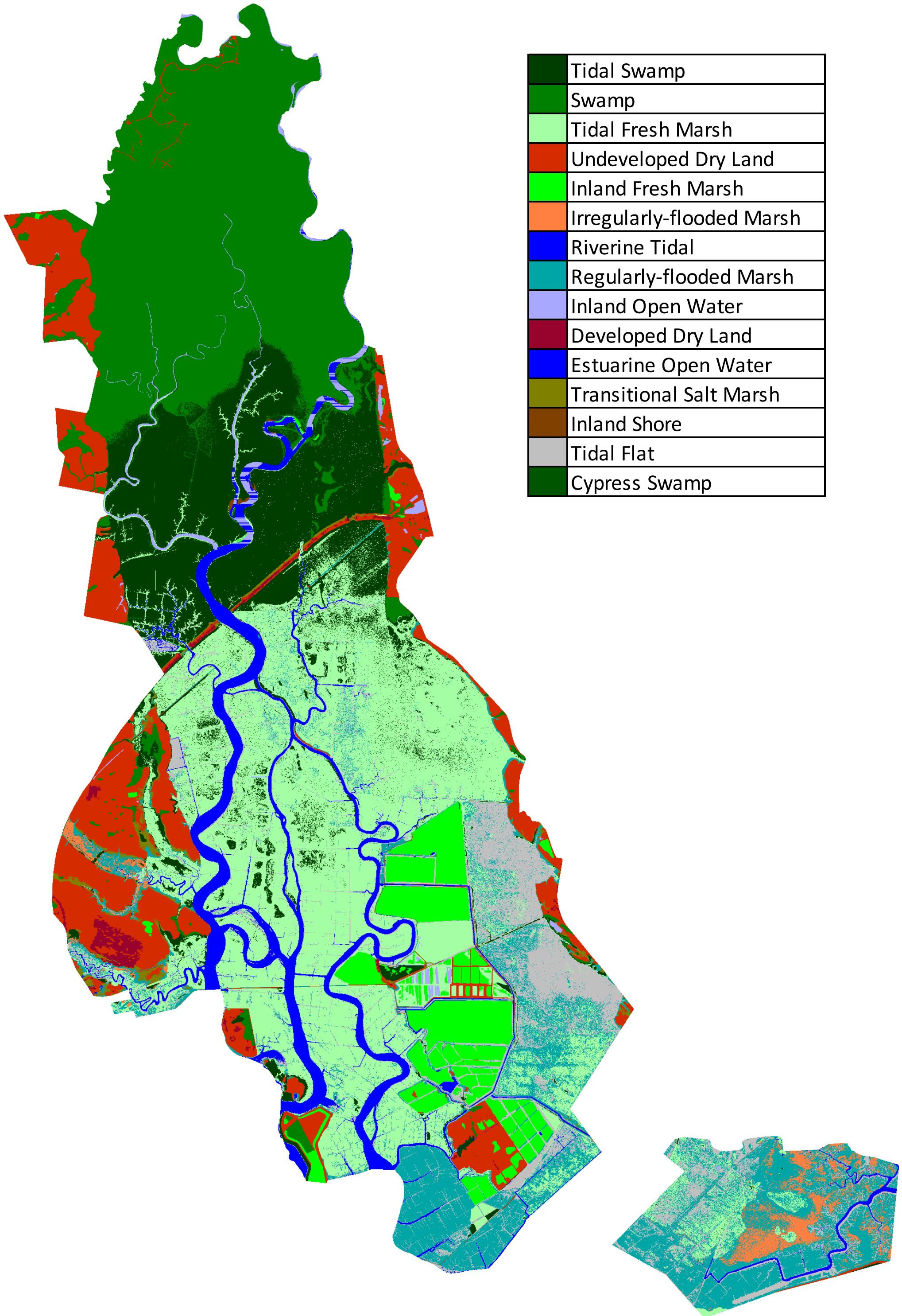
Savannah NWR, Initial Condition.



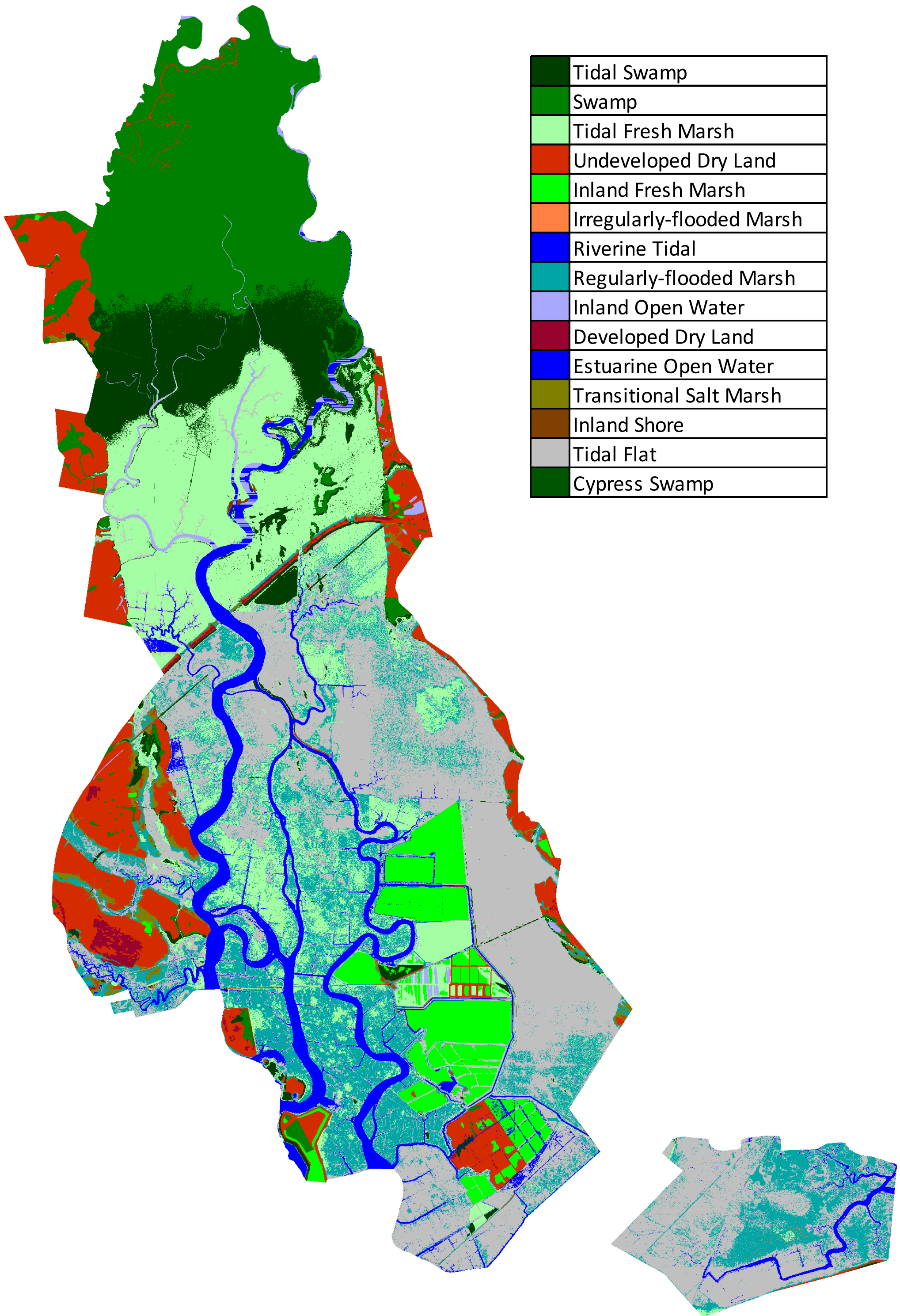
Savannah NWR, 2025, 1.5 m SLR by 2100.



Savannah NWR, 2050, 1.5 m SLR by 2100.



Savannah NWR, 2075, 1.5 m SLR by 2100.

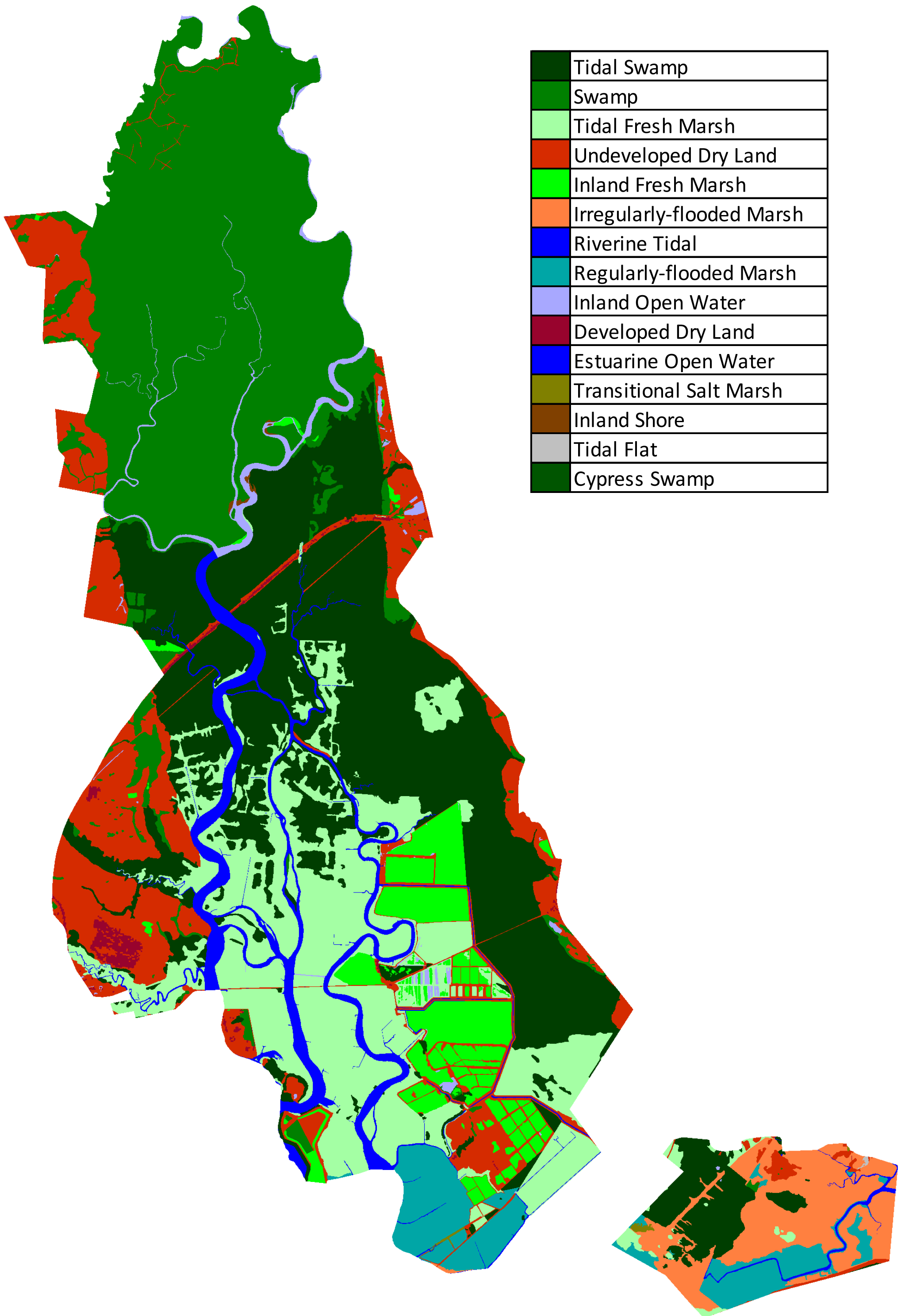


Savannah NWR, 2100, 1.5 m SLR by 2100.

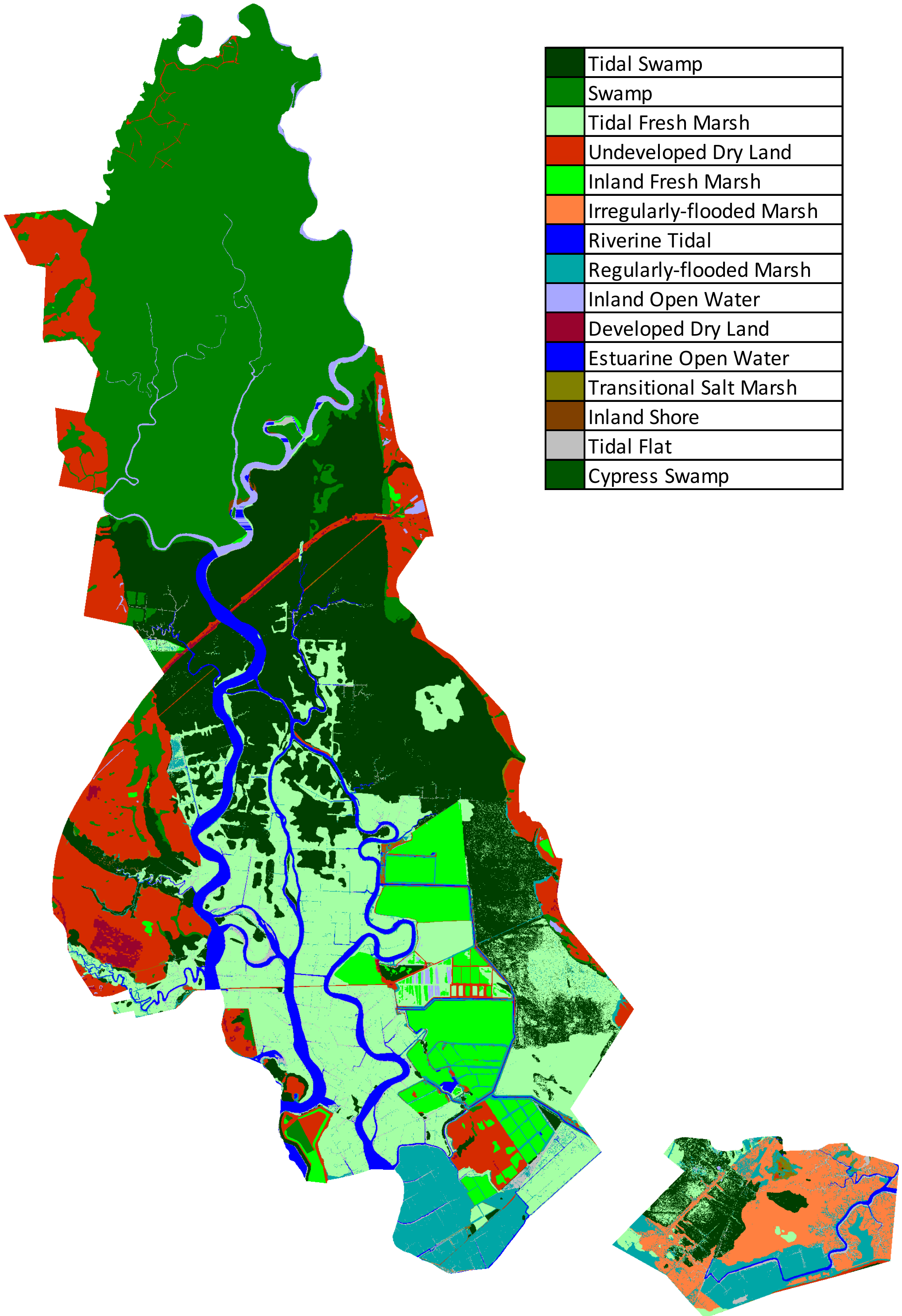
Savannah NWR
2 m eustatic SLR by 2100

Results in Acres

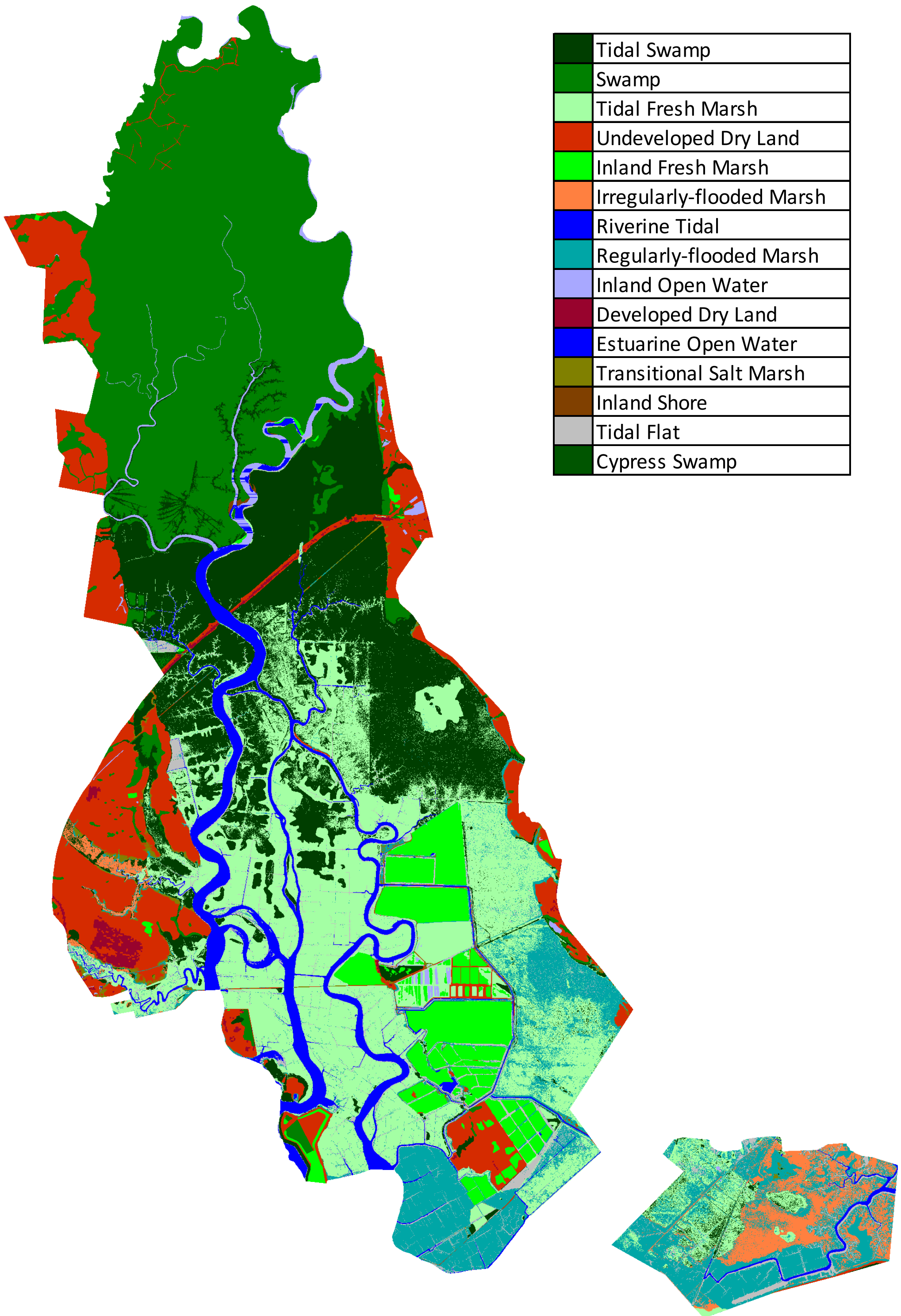
		Initial	2025	2050	2075	2100
	Tidal Swamp	12586	11446	8536	5067	4648
	Swamp	11887	11806	11366	7405	3176
	Tidal Fresh Marsh	7577	8116	9833	10740	5147
	Undeveloped Dry Land	5754	5067	4804	4321	3634
	Inland Fresh Marsh	2418	2378	2373	2357	1980
	Irregularly-flooded Marsh	1826	1579	1040	105	11
	Riverine Tidal	1798	554	263	163	43
	Regularly-flooded Marsh	1693	2663	4085	4960	1011
	Inland Open Water	575	528	475	399	370
	Developed Dry Land	244	242	238	222	214
	Estuarine Open Water	112	1428	1909	2559	5097
	Transitional Salt Marsh	26	174	271	510	530
	Inland Shore	23	18	16	14	5
	Tidal Flat	5	527	1317	7702	20658
	Cypress Swamp	2	2	2	2	2
	Total (incl. water)	**46526**	**46526**	**46526**	**46526**	**46526**



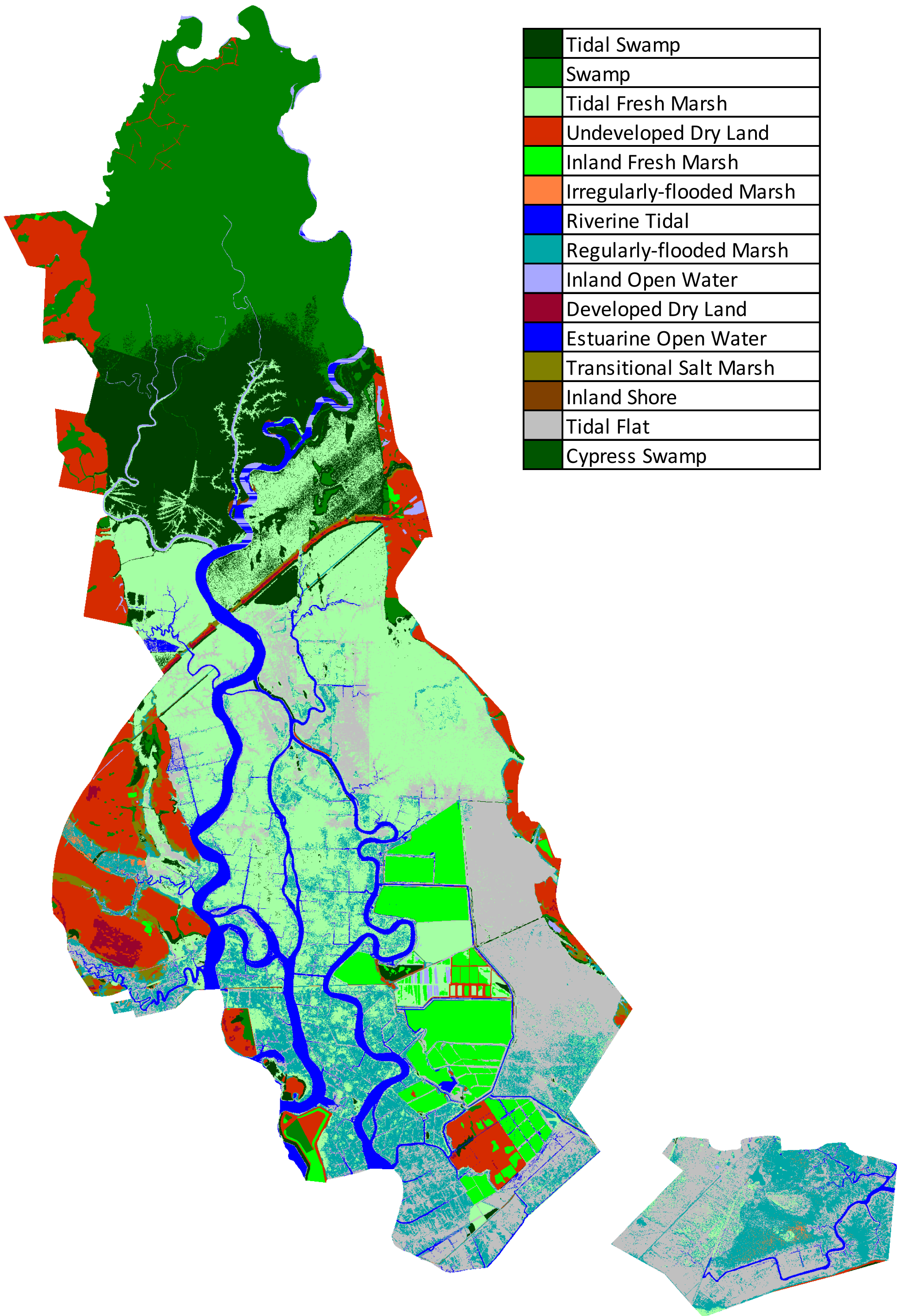
Savannah NWR, Initial Condition.



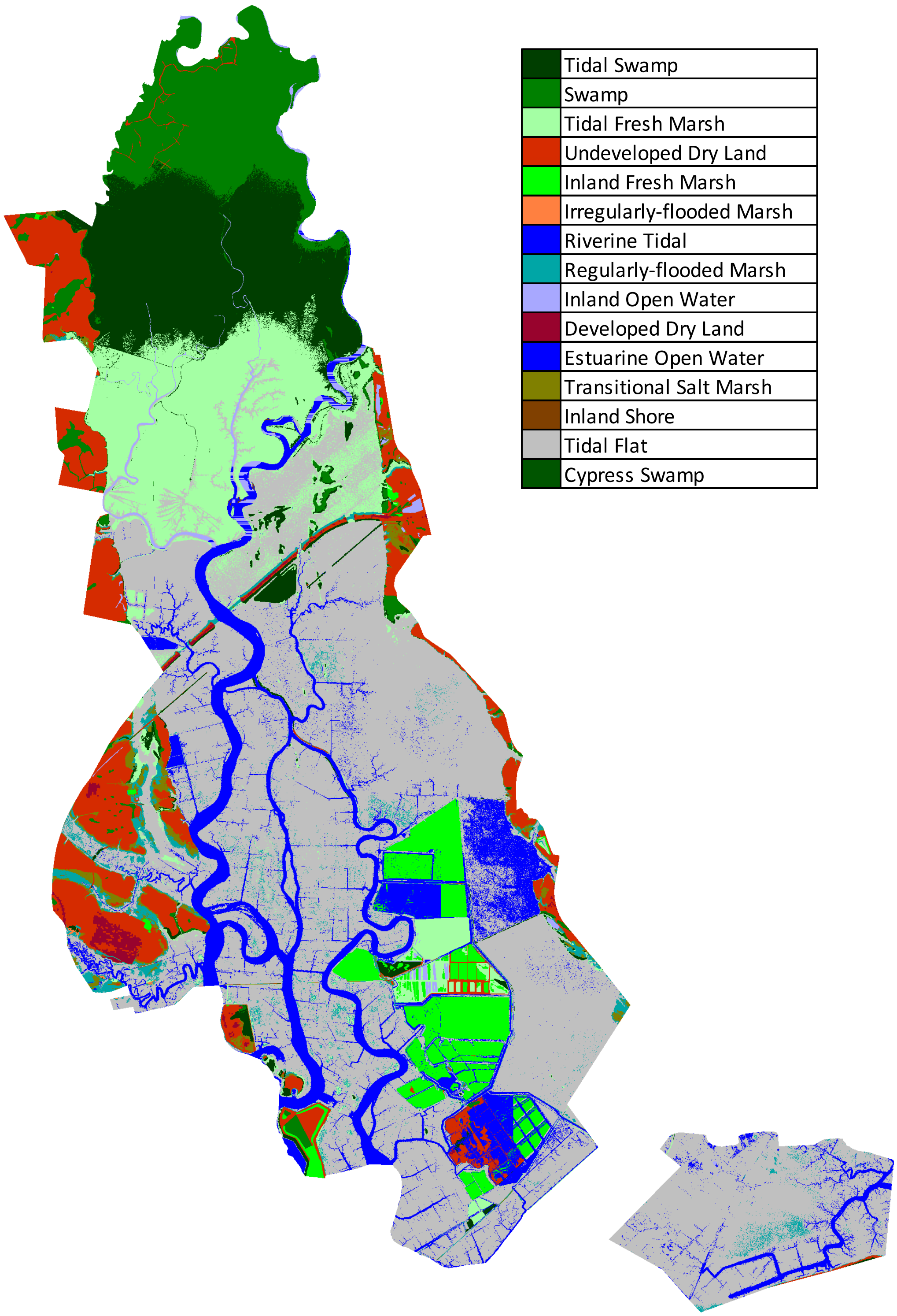
Savannah NWR, 2025, 2 m SLR by 2100.



Savannah NWR, 2050, 2 m SLR by 2100.



Savannah NWR, 2075, 2 m SLR by 2100.



Savannah NWR, 2100, 2 m SLR by 2100.

Discussion

SLAMM predictions for Savannah NWR suggest the refuge's wetland coverage will be substantially altered as a result of sea-level rise. Swamp and tidal swamp, which currently cover approximately 53% of the refuge, are predicted to convert to tidal fresh marsh and tidal flats as sea levels continue to rise. 70% of swamps in the refuge are predicted to be lost given 2 m of eustatic SLR by 2100. As expected, inland fresh marsh is not predicted to have great losses because of the actively managed levee system that protects them.

Comparison of these results to the 2008 SLAMM analysis of the refuge is not straightforward because NWI maps have been updated since the earlier analysis and several areas have different land-cover identification. In addition, a new version of the SLAMM model is being used. In terms of fractional losses, swamp and tidal swamp appear to be more resilient than the previous analysis indicated. This is likely because more accurate LiDAR elevation data suggest that these wetlands are located at a higher elevation than previously assumed. These land covers do remain somewhat susceptible to SLR in the current SLAMM analysis, however.

While data-layer updates have considerably improved the SLAMM projections reported here, input layers, parameter inputs, and the conceptual model continue to have uncertainties that should be kept in mind when interpreting these results. Perhaps most importantly, the extent of future sea-level rise is unknown, as are the drivers of climate change used by scientists when projecting SLR rates. Future levels of economic activity, fuel type (e.g., fossil or renewable, etc.), fuel consumption, and greenhouse gas emissions are unknown and estimates of these driving variables are speculative. To account for these uncertainties, results presented here investigated effects for a wide range of possible sea-level rise scenarios, from a more conservative rise (0.39 m by 2100) to a more accelerated process (2 m by 2100). To better support managers and decision-makers, the results presented here could be studied as a function of input-data uncertainty to provide a range of possible outcomes and their likelihood.

References

Cahoon, D. R., Reed, D. J., Day, J. W., and others. (1995). "Estimating shallow subsidence in microtidal salt marshes of the southeastern United States: Kaye and Barghoorn revisited." *Marine Geology*, 128(1-2), 1–9.

Chen, J. L., Wilson, C. R., and Tapley, B. D. (2006). "Satellite Gravity Measurements Confirm Accelerated Melting of Greenland Ice Sheet." *Science*, 313, 1958-1960.

Clark, P. U. (2009). *Abrupt Climate Change: Final Report, Synthesis and Assessment Product 3. 4*. DIANE Publishing.

Clough, J. S., Park, R. A., and Fuller, R. (2010). "SLAMM 6 beta Technical Documentation."

Council for Regulatory Environmental Modeling. (2008). *Draft guidance on the development, evaluation, and application of regulatory environmental models*. Draft, Washington, DC.

Craft, C., Clough, J. S., Ehman, J., Joye, S., Park, R. A., Pennings, S., Guo, H., and Machmuller, M. (2009). "Forecasting the effects of accelerated sea-level rise on tidal marsh ecosystem services." *Frontiers in Ecology and the Environment*, 7(2), 73-78.

Galbraith, H., Jones, R., Park, R., Clough, J., Herrod-Julius, S., Harrington, B., and Page, G. (2002). "Global Climate Change and Sea-level rise: Potential Losses of Intertidal Habitat for Shorebirds." *Waterbirds*, 25(2), 173.

Glick, P., Clough, J., and Nunley, B. (2007). *Sea-level Rise and Coastal Habitats in the Pacific Northwest: An Analysis for Puget Sound, Southwestern Washington, and Northwestern Oregon*. National Wildlife Federation.

Grinsted, A., Moore, J. C., and Jevrejeva, S. (2009). "Reconstructing sea level from paleo and projected temperatures 200 to 2100 AD." *Climate Dynamics*, 34(4), 461-472.

Hendrickson, J. C. (1997). "Coastal wetland response to rising sea-level: quantification of short-and long-term accretion and subsidence, northeastern Gulf of Mexico." Florida State University, Tallahassee, FL.

IPCC. (2001). *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom, 881.

IPCC. (2007). *Climate Change 2007: The Physical Science Basis*. Cambridge University Press, Cambridge, United Kingdom.

Lee, J. K., Park, R. A., and Mausel, P. W. (1992). "Application of geoprocessing and simulation modeling to estimate impacts of sea-level rise on the northeast coast of Florida." *Photogrammetric Engineering and Remote Sensing*, 58(11), 1579-1586.

Monaghan, A. J., Bromwich, D. H., Fogt, R. L., Wang, S.-H., Mayewski, P. A., Dixon, D. A., Ekaykin, A., Frezzotti, M., Goodwin, I., Isaksson, E., Kaspari, S. D., Morgan, V. I., Oerter, H., Van Ommen, T. D., Van der Veen, C. J., and Wen, J. (2006). "Insignificant Change in Antarctic Snowfall Since the International Geophysical Year." *Science*, 313(5788), 827-831.

Moorhead, K. K., and Brinson, M. M. (1995). "Response of Wetlands to Rising Sea Level in the Lower Coastal Plain of North Carolina." *Ecological Applications*, 5(1), 261-271.

Nakicenovic, N., Alcamo, J., Davis, G., de Vries, B., Fenhann, J., Gaffin, S., Gregory, K., Grubler, A., Jung, T. Y., Kram, T., La Rovere, E. L., Michaelis, L., Mori, S., Morita, T., Pepper, W., Pitcher, H. M., Price, L., Riahi, K., Roehrl, A., Rogner, H.-H., Sankovski, A., Schlesinger, M., Shukla, P., Smith, S. J., Swart, R., van Rooijen, S., Victor, N., and Dadi, Z. (2000). *Special Report on Emissions Scenarios : a special report of Working Group III of the Intergovernmental Panel on Climate Change*.

National Wildlife Federation, and Florida Wildlife Federation. (2006). *An Unfavorable Tide: Global Warming, Coastal Habitats and Sportfishing in Florida*.

Park, R. A., Lee, J. K., and Canning, D. J. (1993). "Potential Effects of Sea-Level Rise on Puget Sound Wetlands." *Geocarto International*, 8(4), 99.

Park, R. A., Lee, J. K., Mausel, P. W., and Howe, R. C. (1991). "Using remote sensing for modeling the impacts of sea-level rise." *World Resources Review*, 3, 184-220.

Park, R. A., Trehan, M. S., Mausel, P. W., and Howe, R. C. (1989). "The Effects of Sea-Level rise on U.S. Coastal Wetlands." *The Potential Effects of Global Climate Change on the United States: Appendix B - Sea-Level Rise*, U.S. Environmental Protection Agency, Washington, DC, 1-1 to 1-55.

Pfeffer, W. T., Harper, J. T., and O'Neel, S. (2008). "Kinematic Constraints on Glacier Contributions to 21st-Century Sea-Level Rise." *Science*, 321(5894), 1340-1343.

Rahmstorf, S. (2007). "A Semi-Empirical Approach to Projecting Future Sea-Level Rise." *Science*, 315(5810), 368-370.

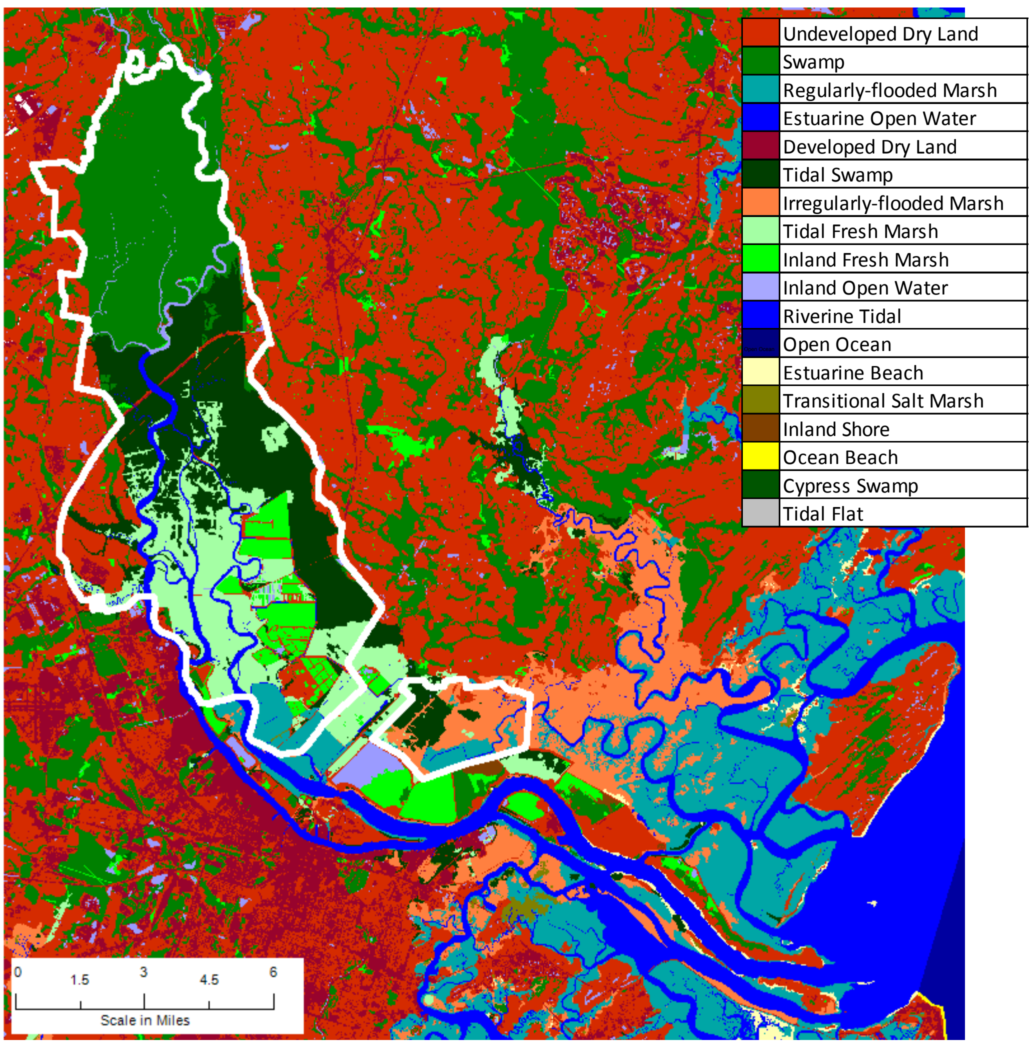
Titus, J. G., Park, R. A., Leatherman, S. P., Weggel, J. R., Greene, M. S., Mausel, P. W., Brown, S., Gaunt, C., Trehan, M., and Yohe, G. (1991). "Greenhouse effect and sea-level rise: the cost of holding back the sea." *Coastal Management*, 19(2), 171–204.

Vermeer, M., and Rahmstorf, S. (2009). "Global sea level linked to global temperature." *Proceedings of the National Academy of Sciences*, 106(51), 21527.

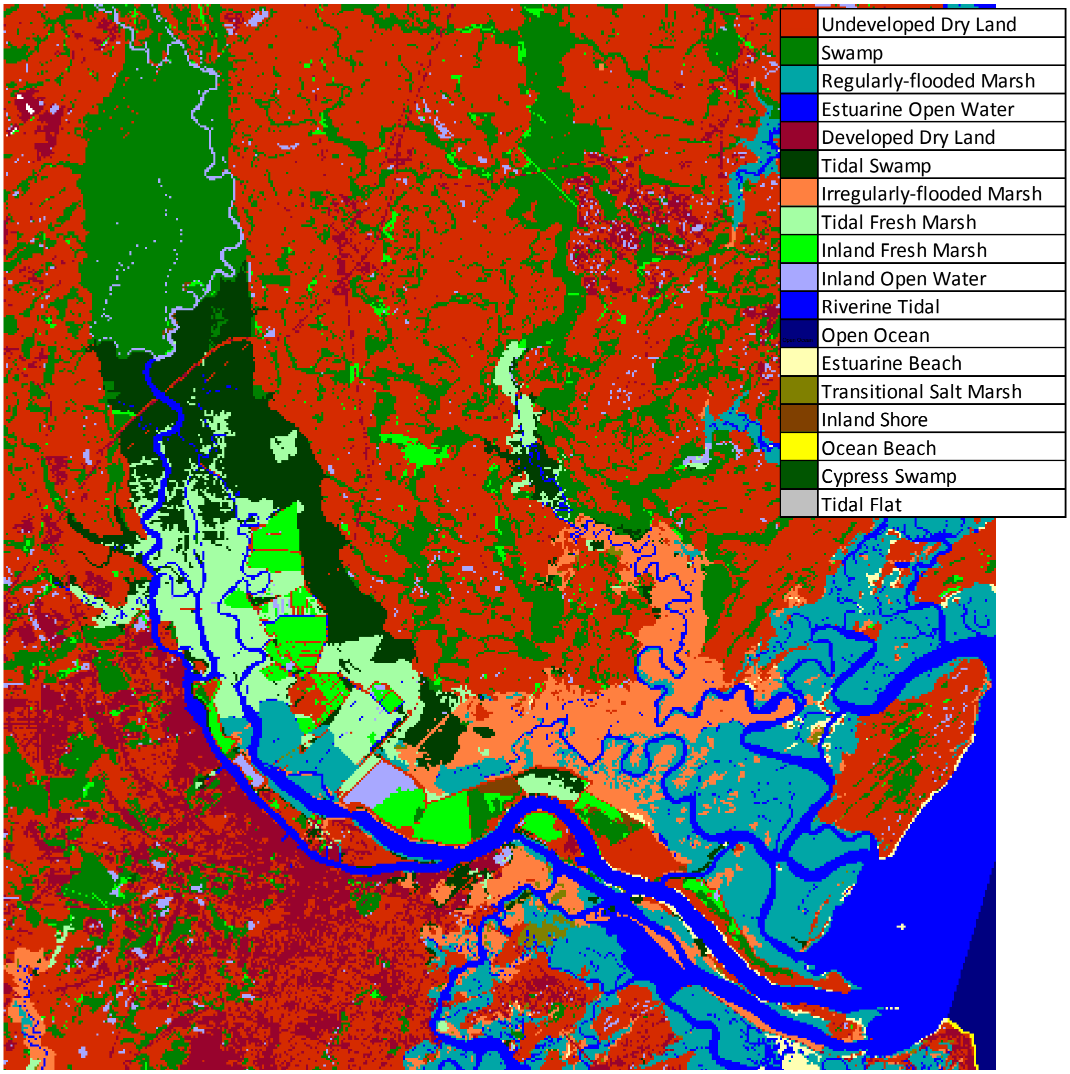
Appendix A: Contextual Results

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. Therefore, an area larger than the boundaries of the USFWS refuge was modeled. Maps of these results are presented here with the following caveats:

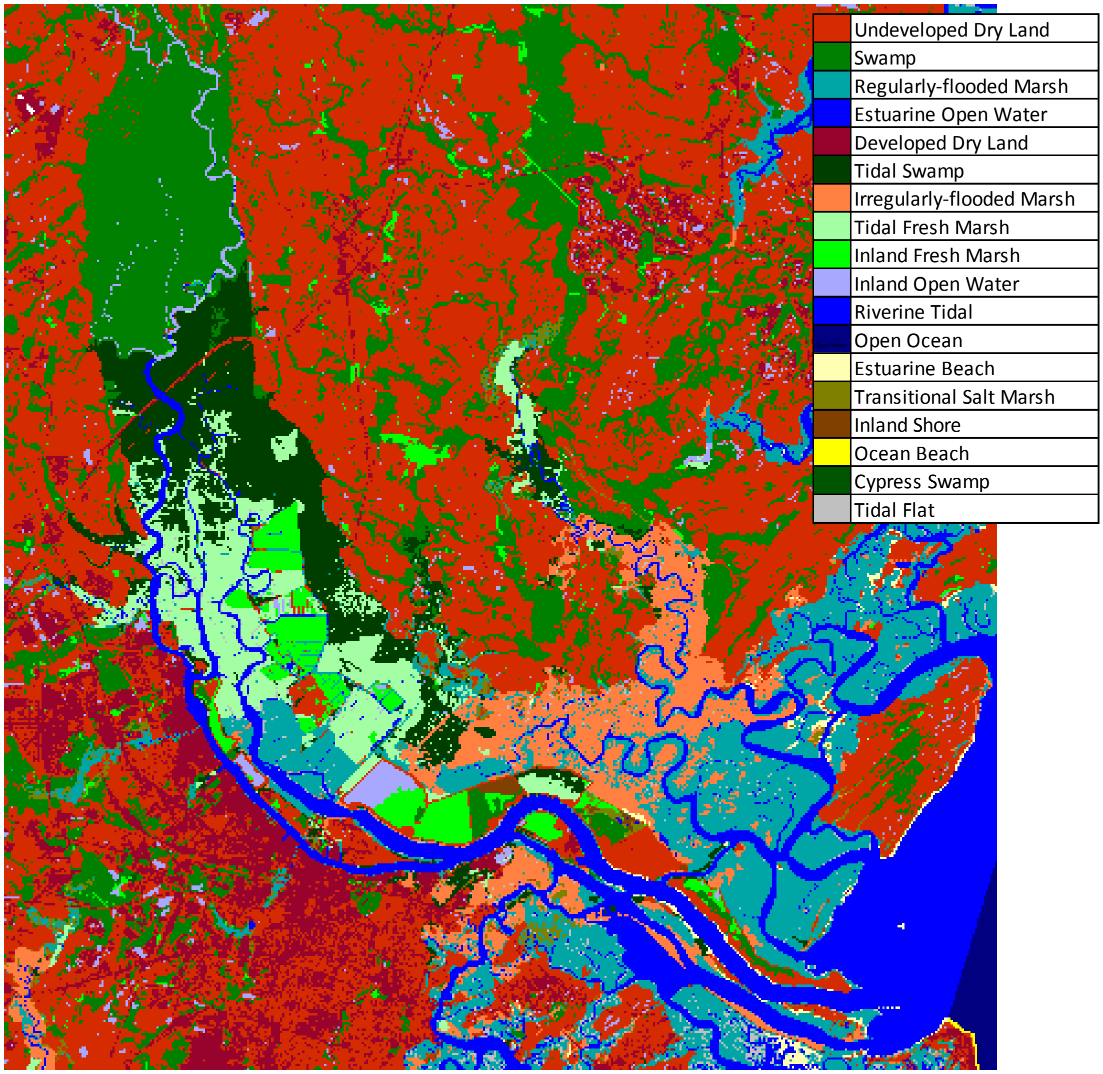
- Results were critically examined within USFWS refuges but not closely examined for the larger region.
- Site-specific parameters for the model were derived for USFWS refuges whenever possible and may not be regionally applicable.
- Especially in areas where dikes are present, an effort was made to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



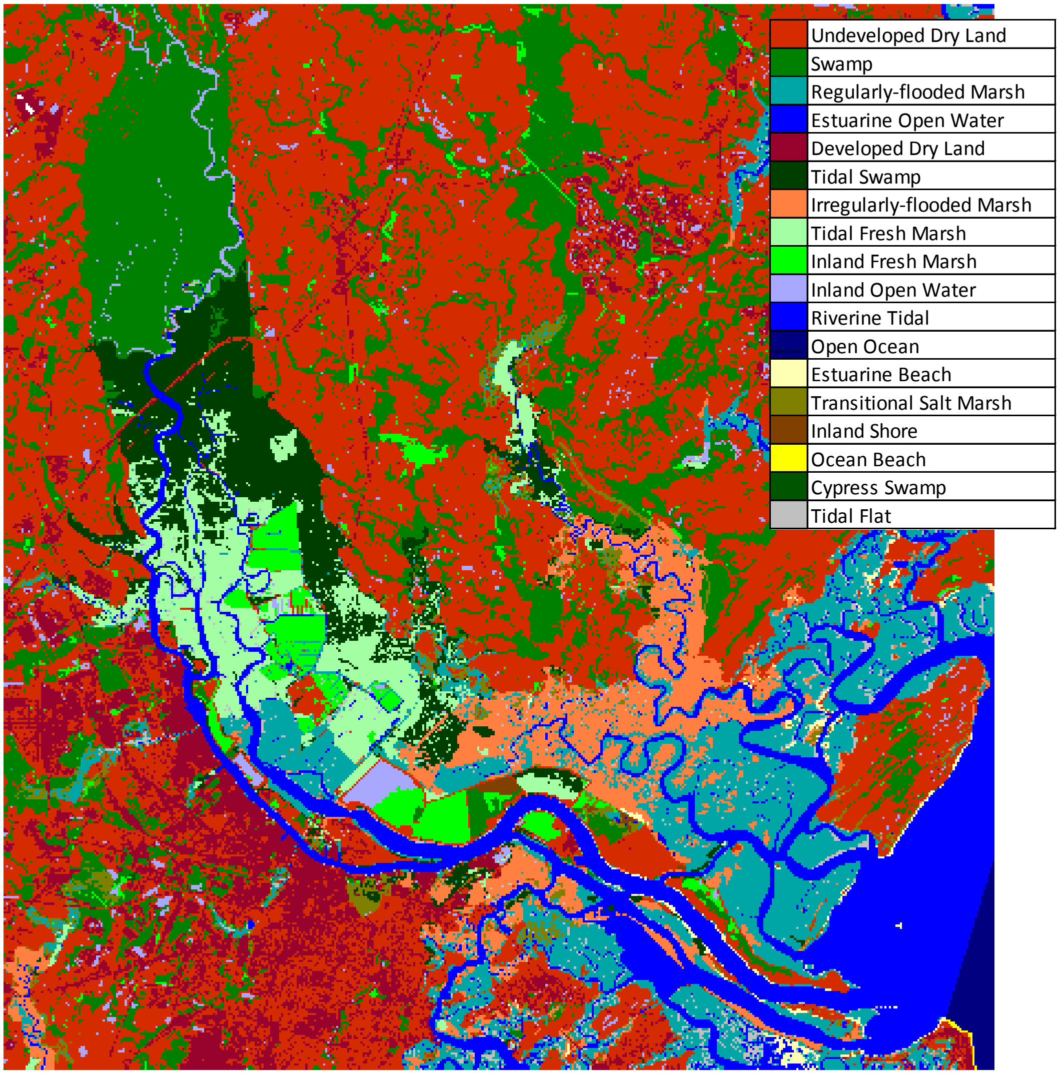
Savannah National Wildlife Refuge within simulation context (white).



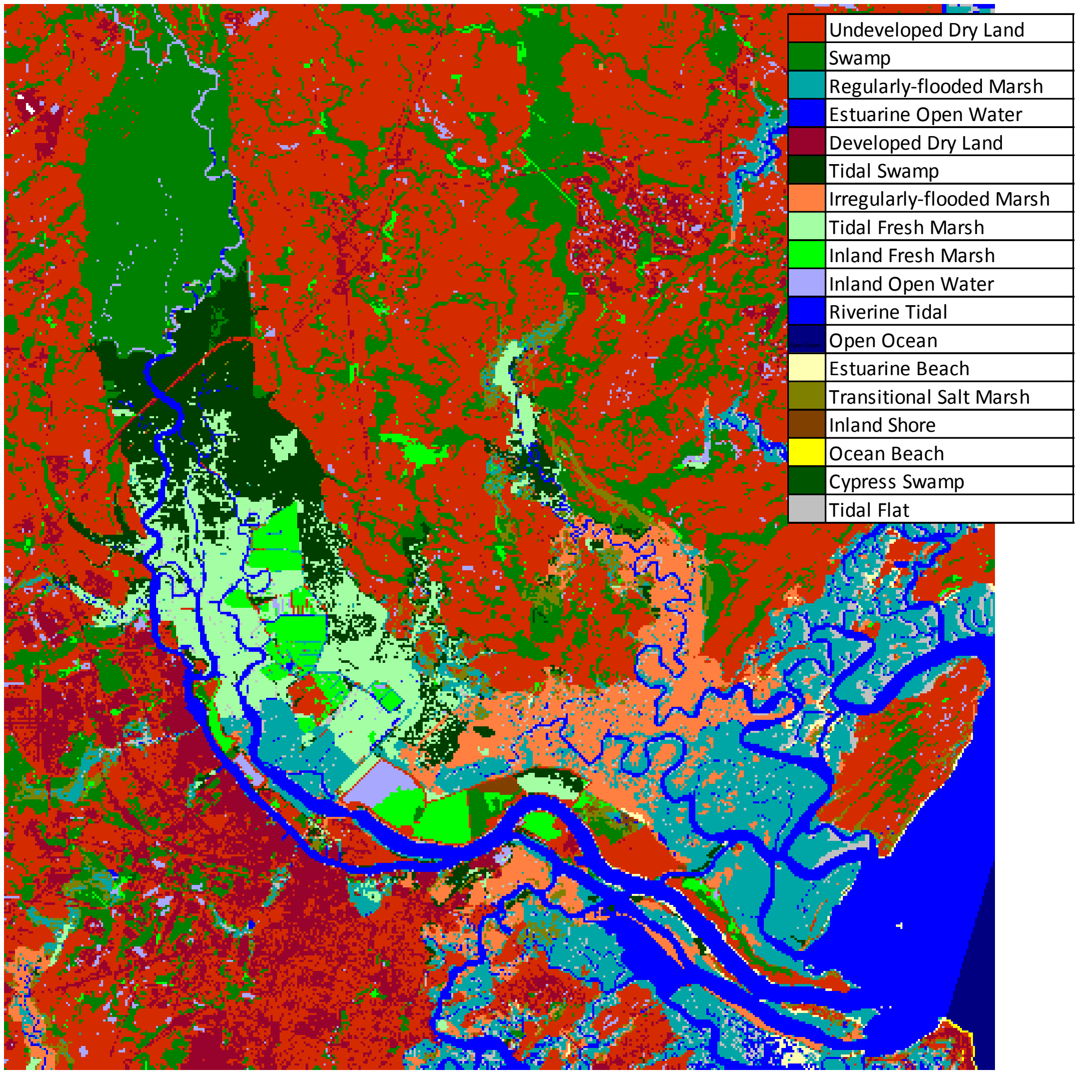
Savannah NWR, Initial Condition.



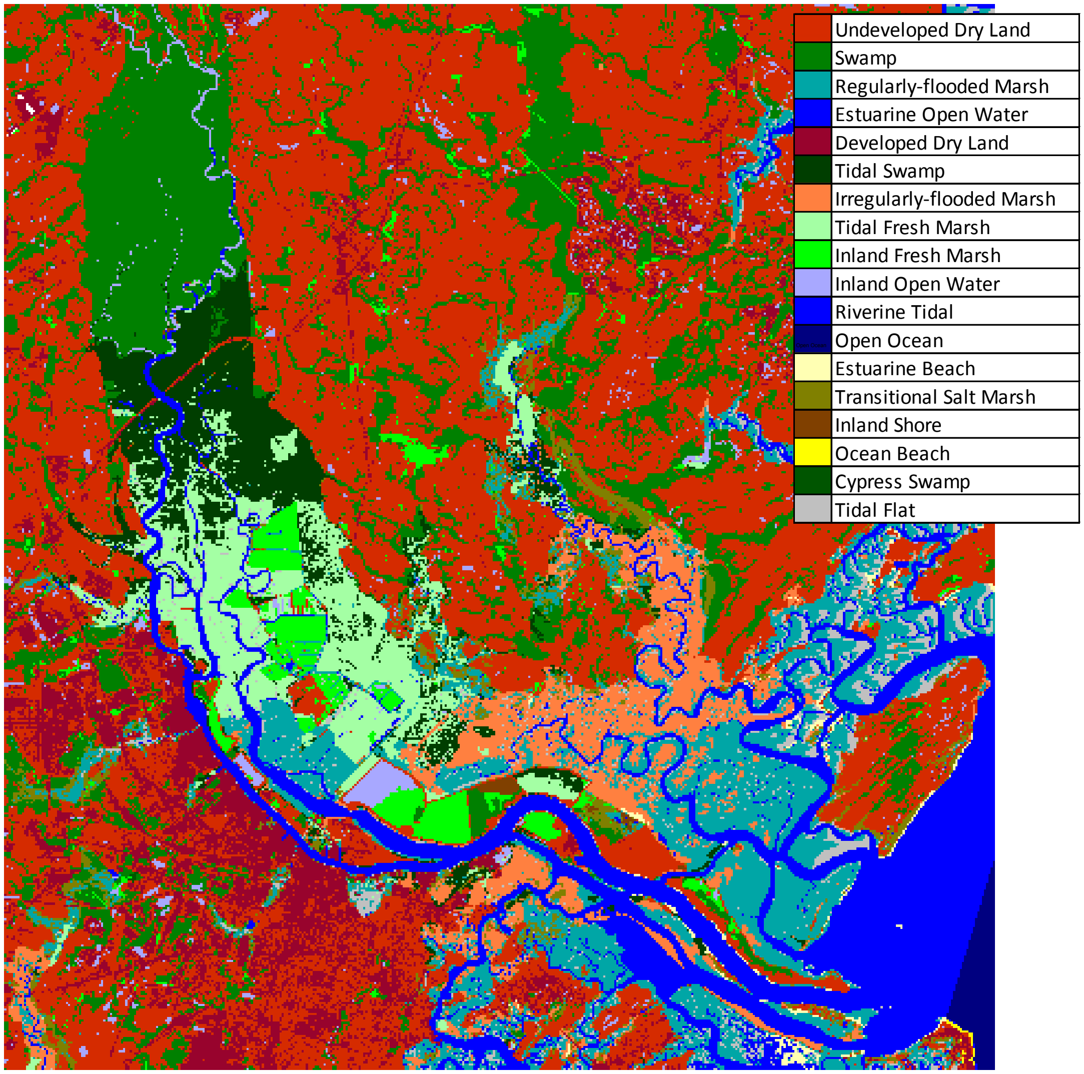
Savannah NWR, 2025, Scenario A1B Mean, 0.39 m SLR by 2100.



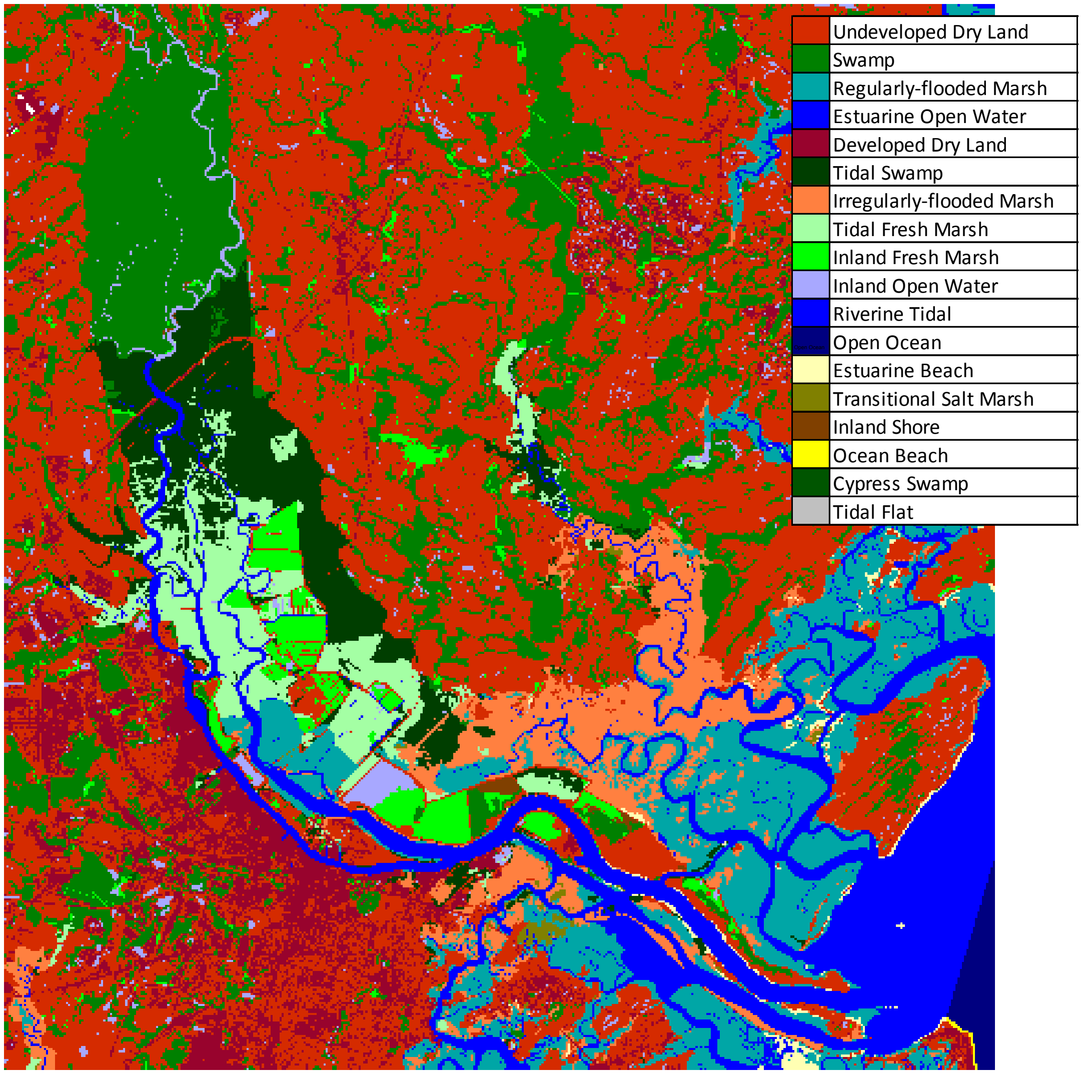
Savannah NWR, 2050, Scenario A1B Mean, 0.39 m SLR by 2100.



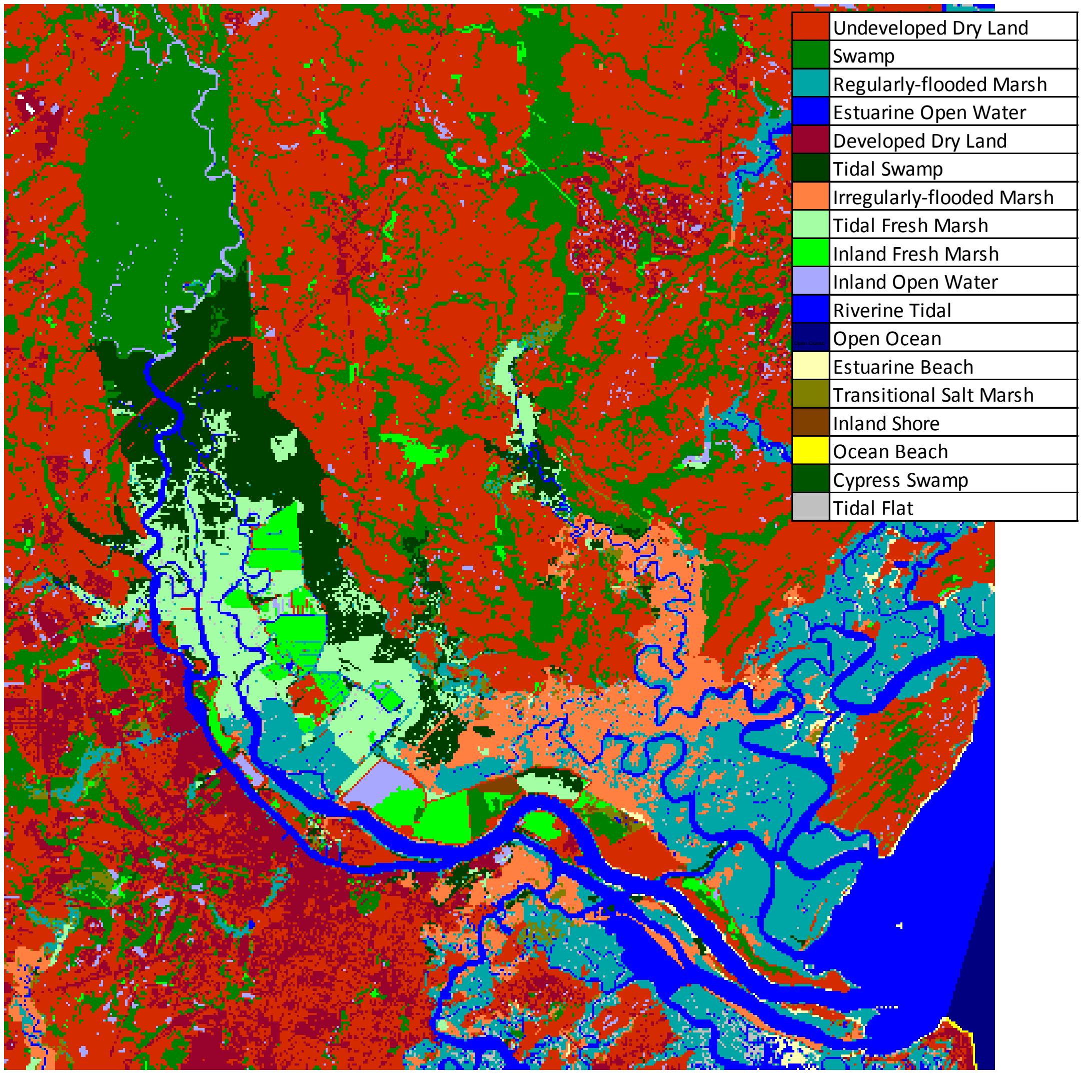
Savannah NWR, 2075, Scenario A1B Mean, 0.39 m SLR by 2100.



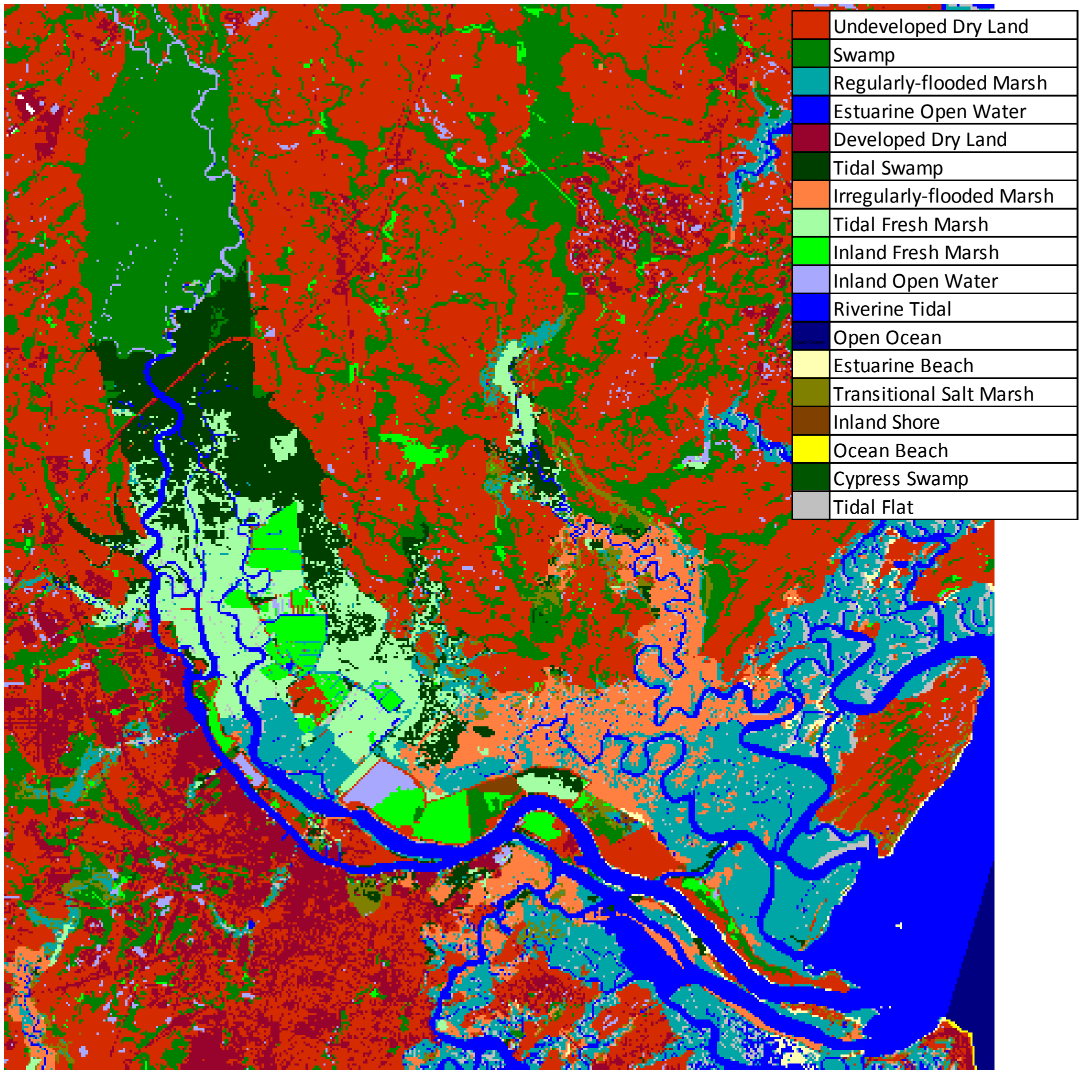
Savannah NWR, 2100, Scenario A1B Mean, 0.39 m SLR by 2100.



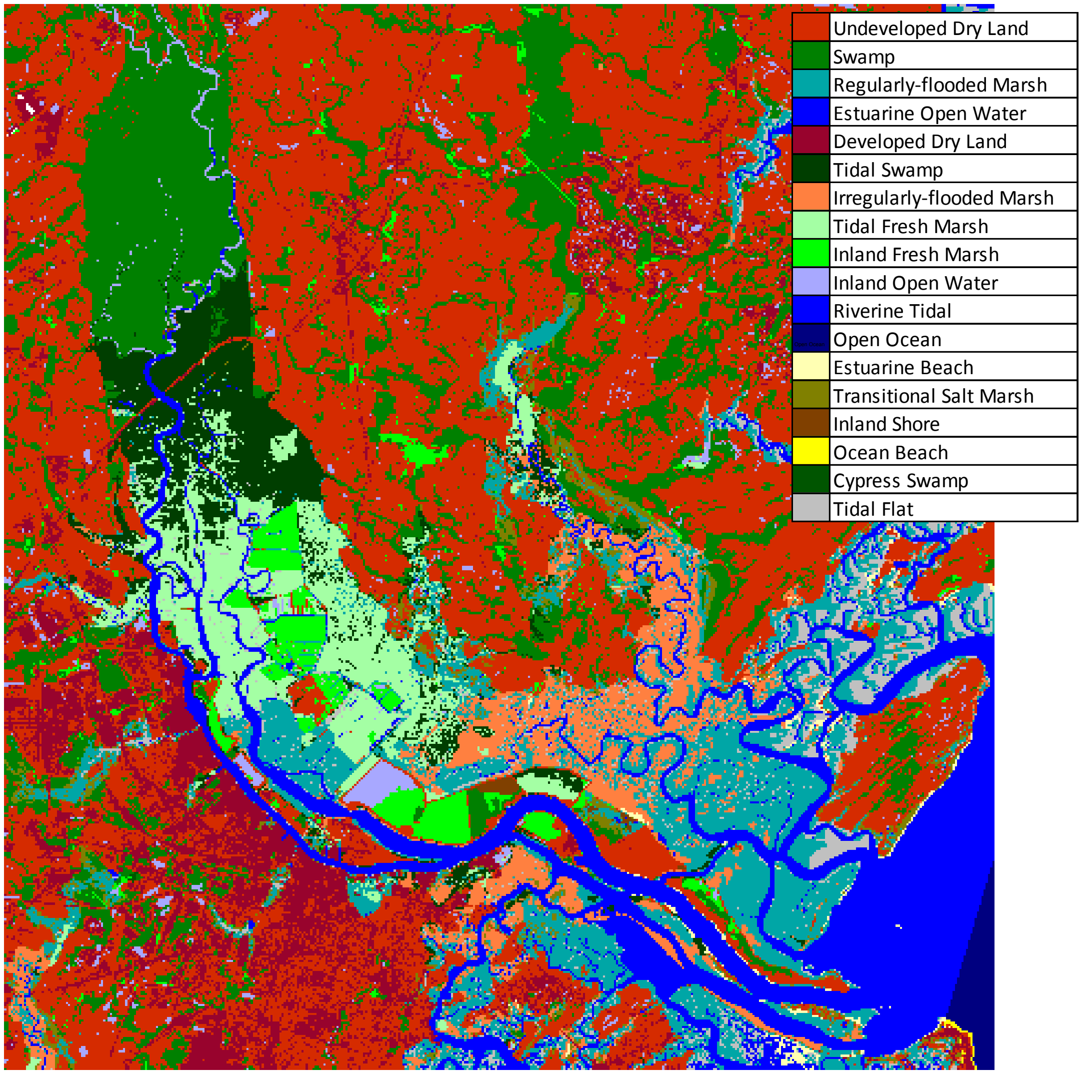
Savannah NWR, Initial Condition.



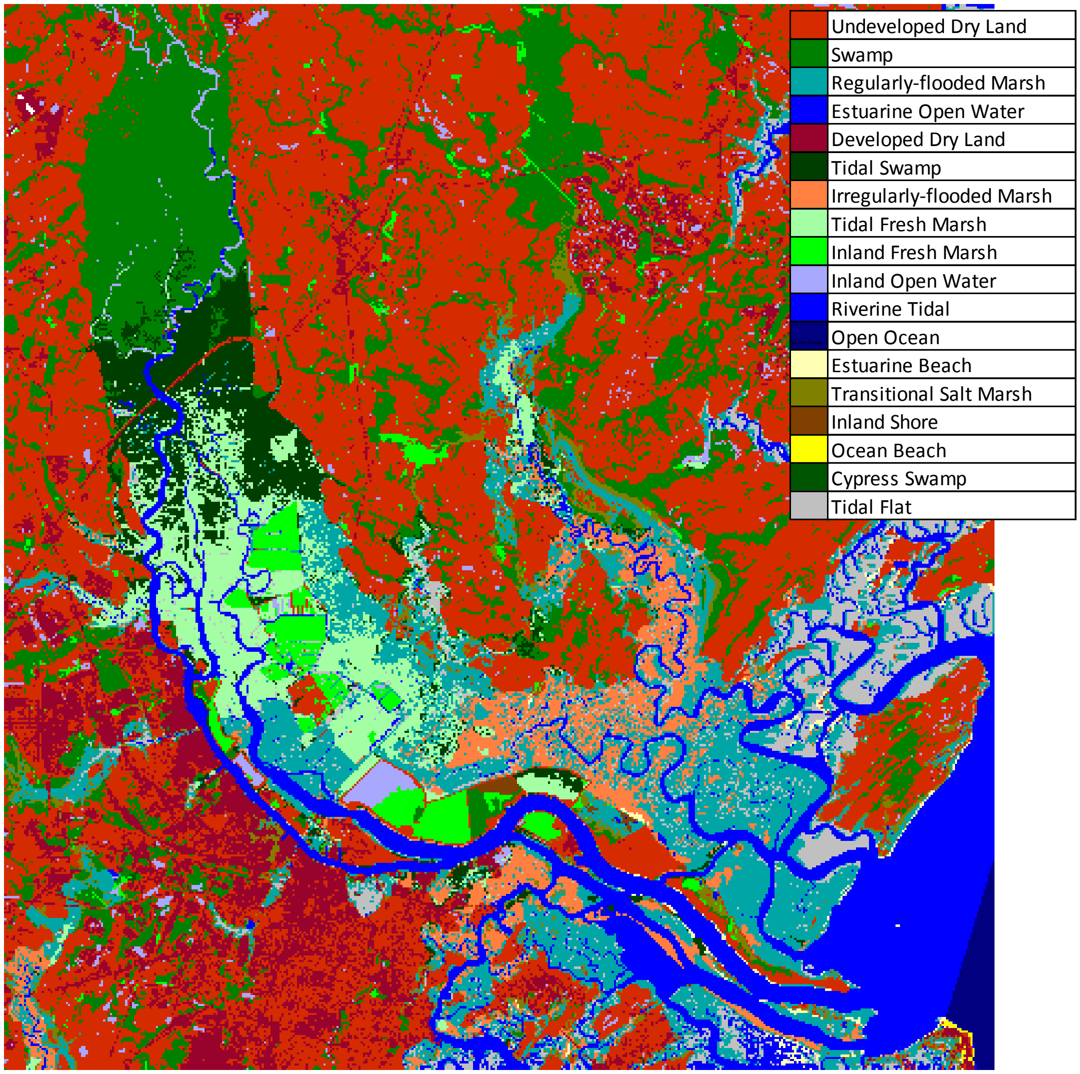
Savannah NWR, 2025, Scenario A1B Maximum, 0.69 m SLR by 2100.



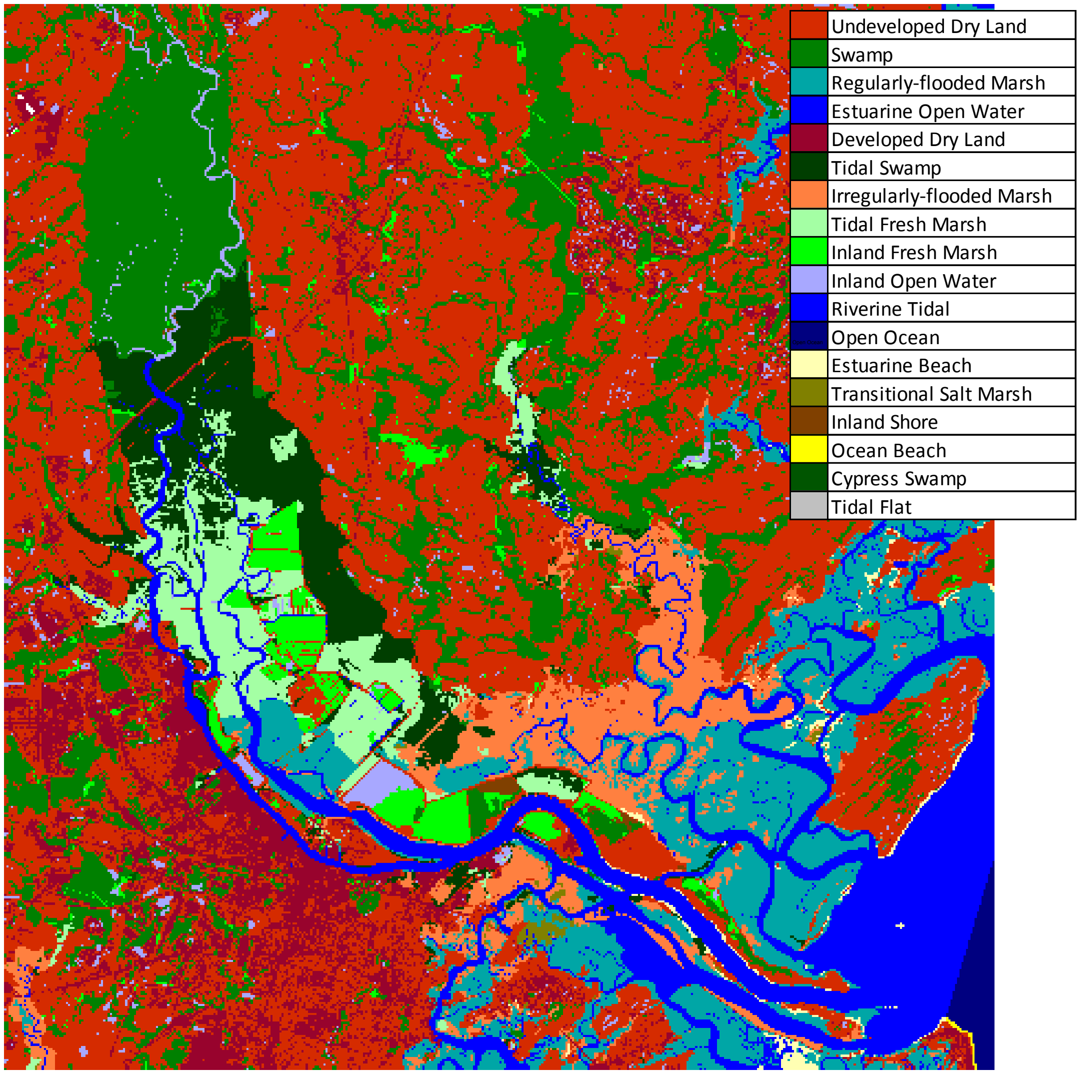
Savannah NWR, 2050, Scenario A1B Maximum, 0.69 m SLR by 2100.



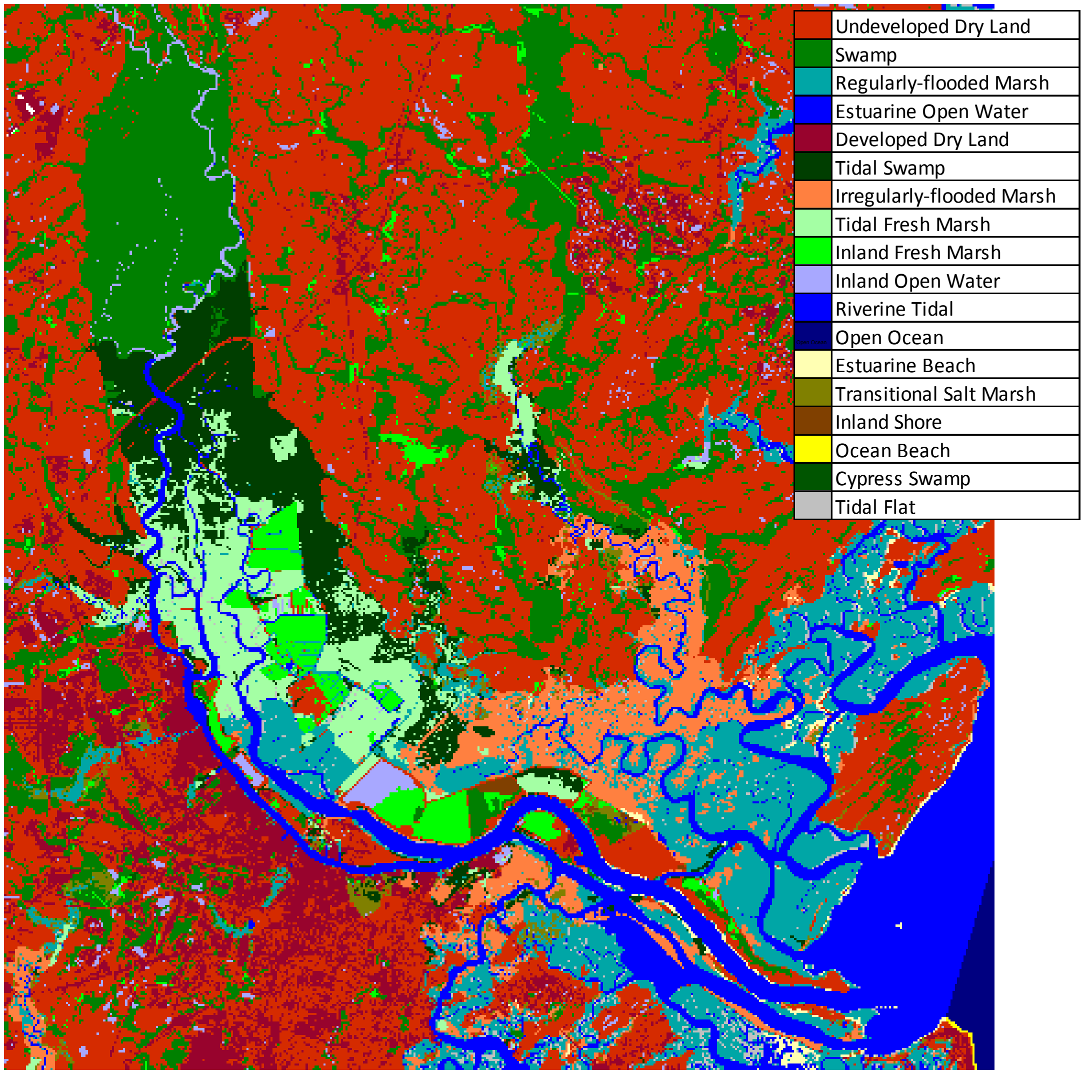
Savannah NWR, 2075, Scenario A1B Maximum, 0.69 m SLR by 2100.



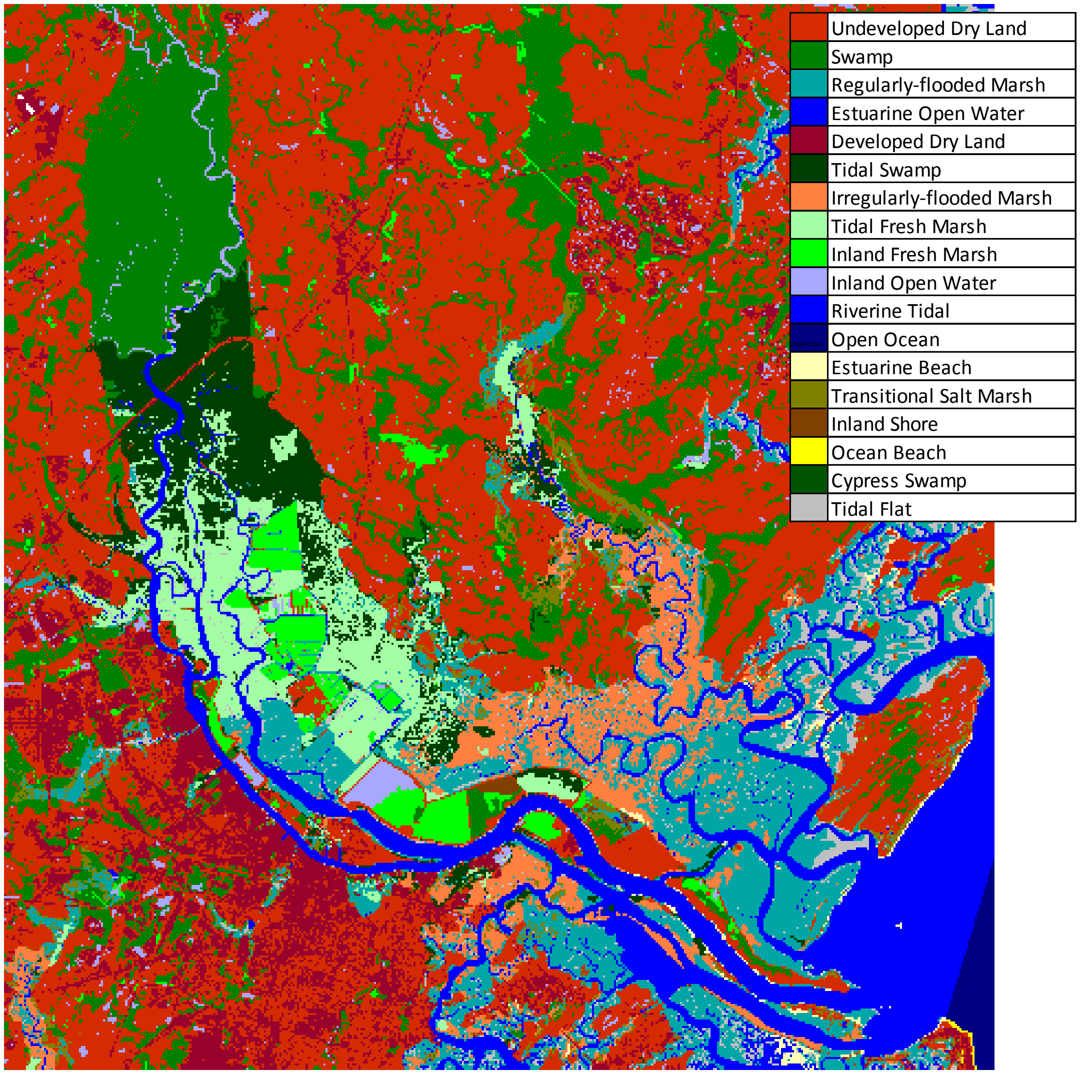
Savannah NWR, 2100, Scenario A1B Maximum, 0.69 m SLR by 2100.



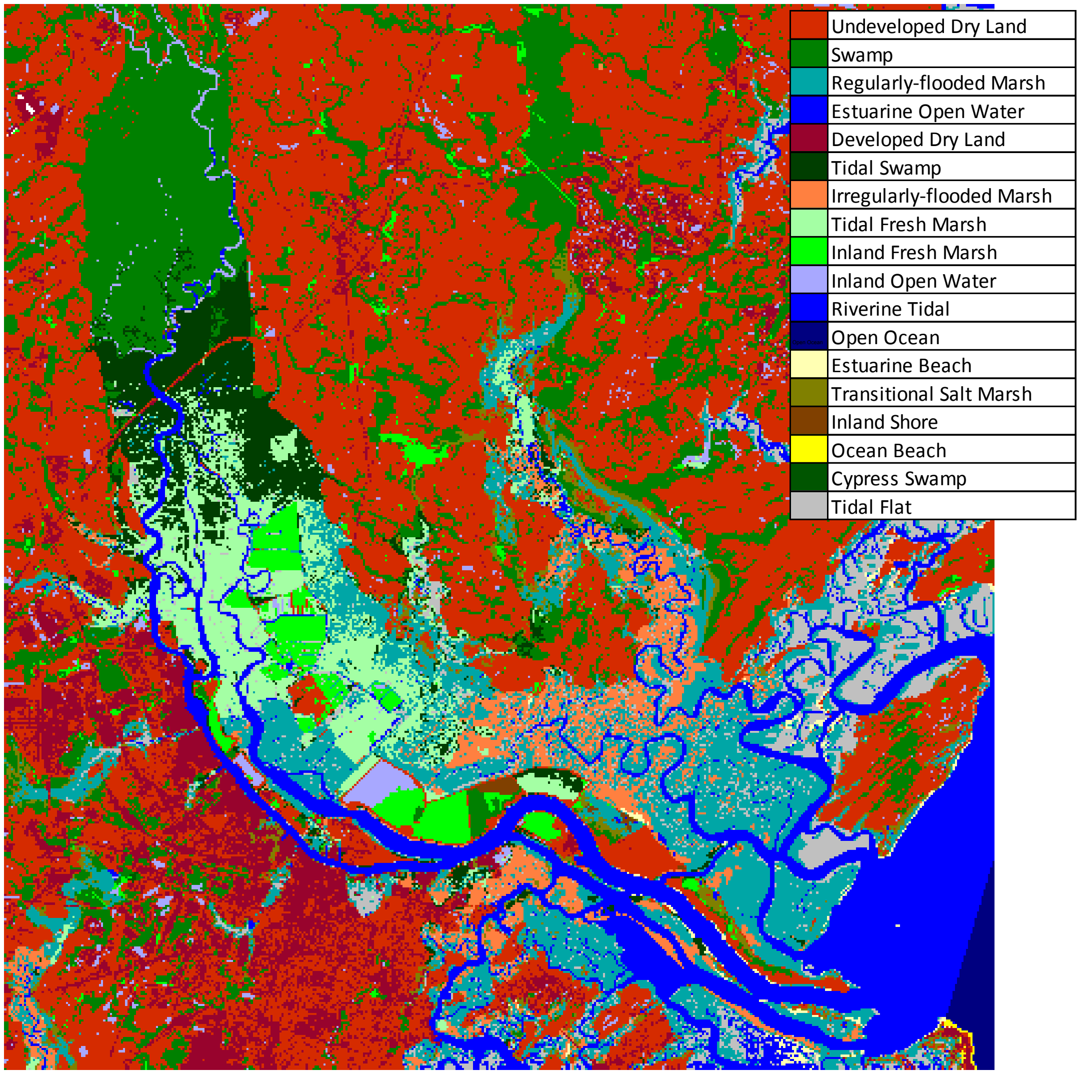
Savannah NWR, Initial Condition.



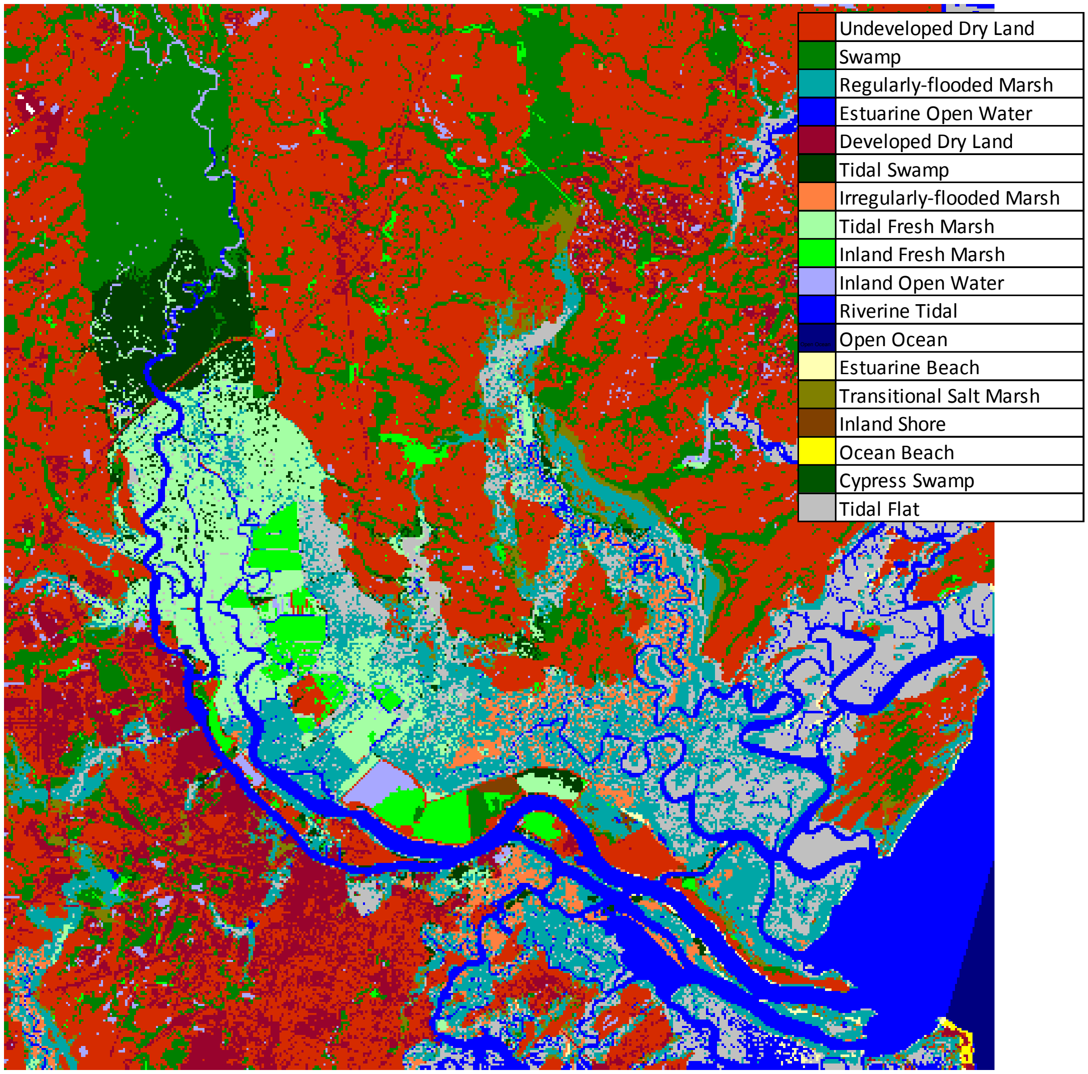
Savannah NWR, 2025, 1 m SLR by 2100.



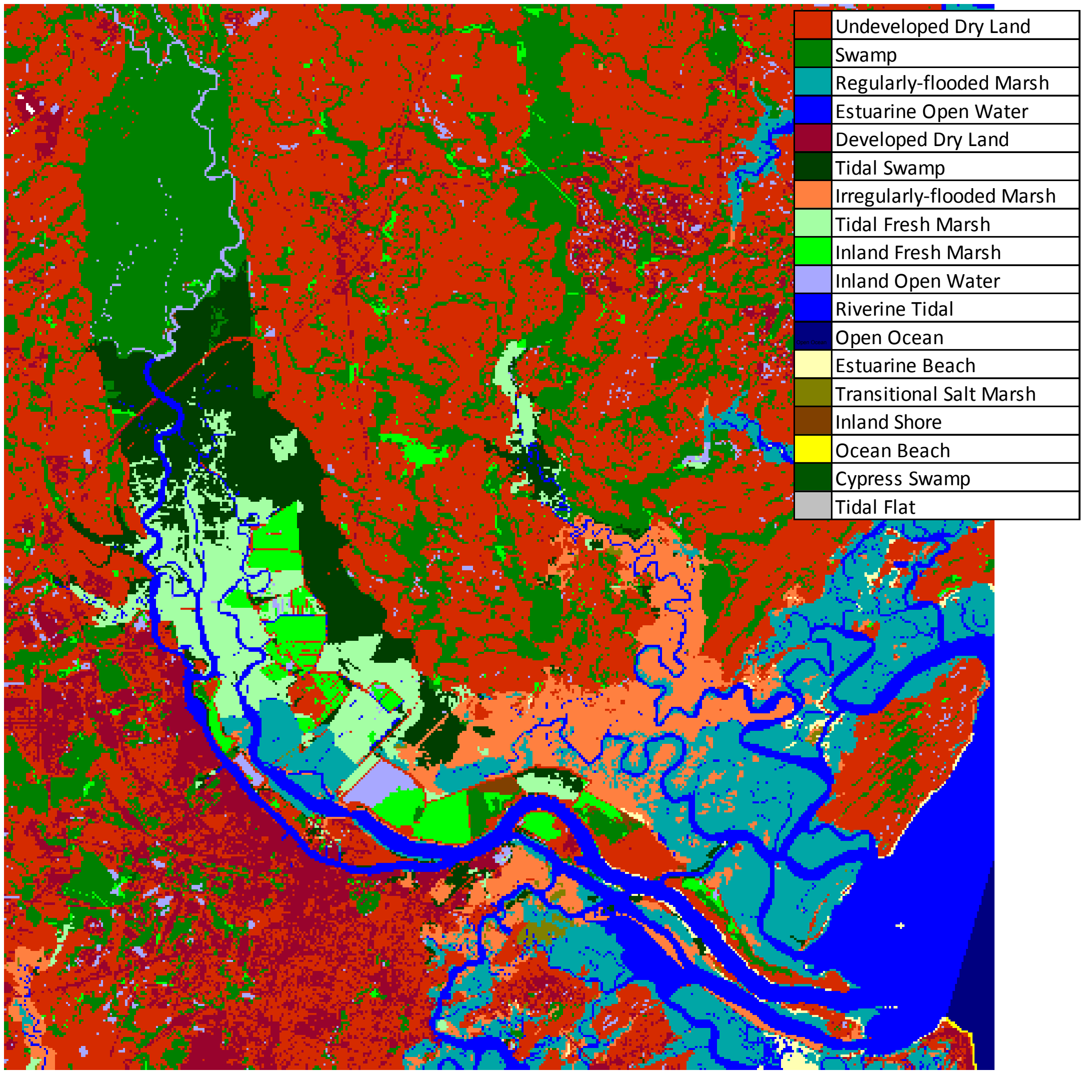
Savannah NWR, 2050, 1 m SLR by 2100.



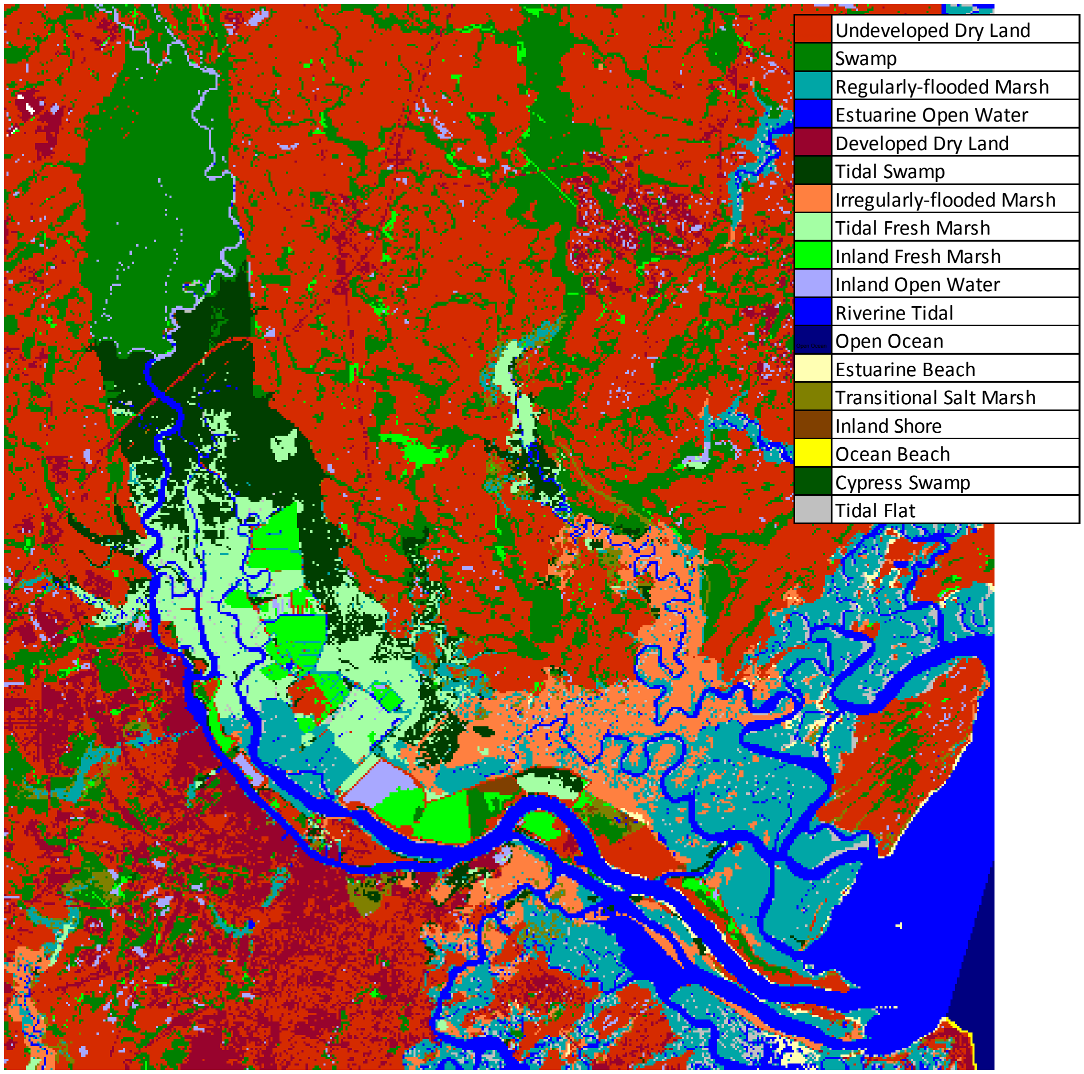
Savannah NWR, 2075, 1 m SLR by 2100.



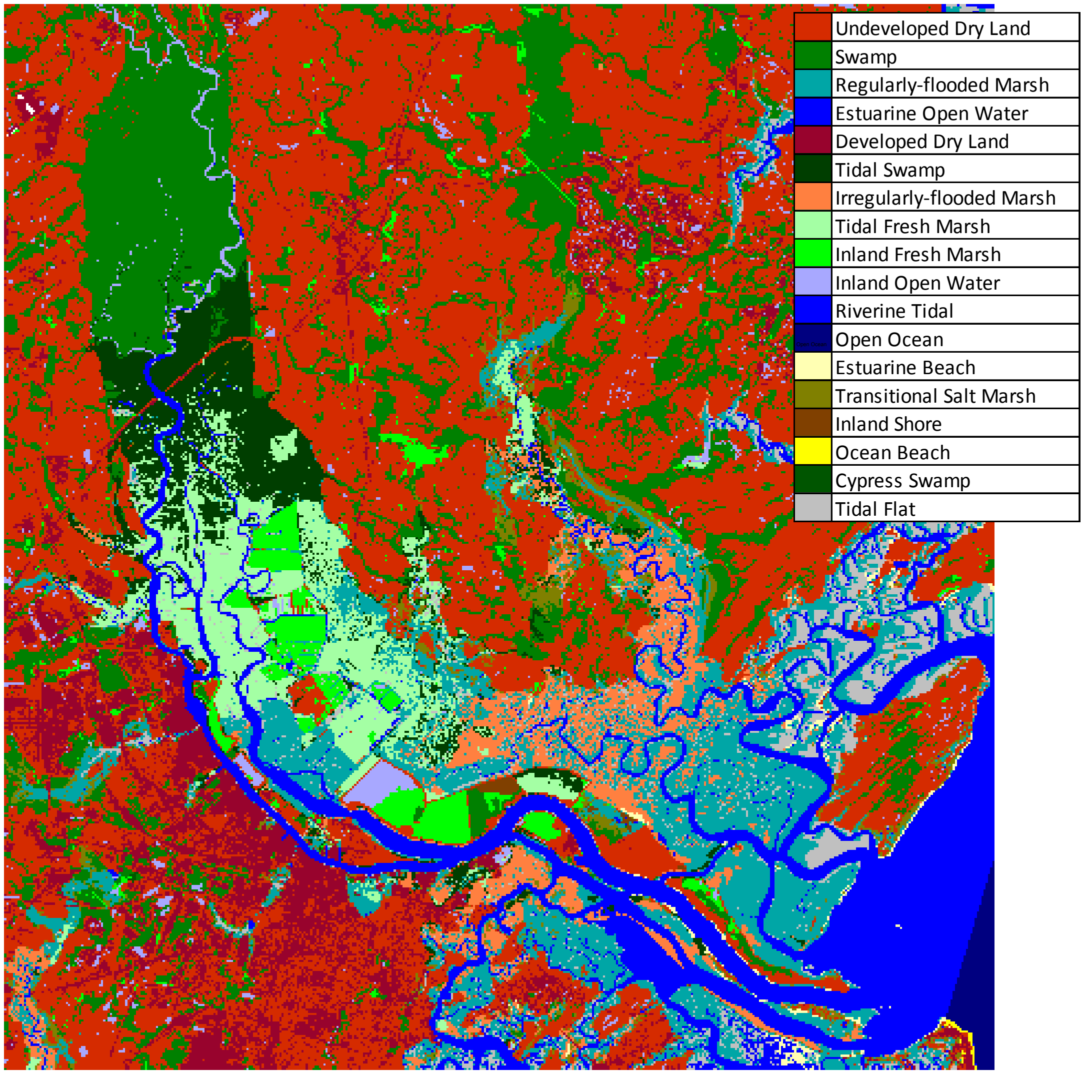
Savannah NWR, 2100, 1 m SLR by 2100.



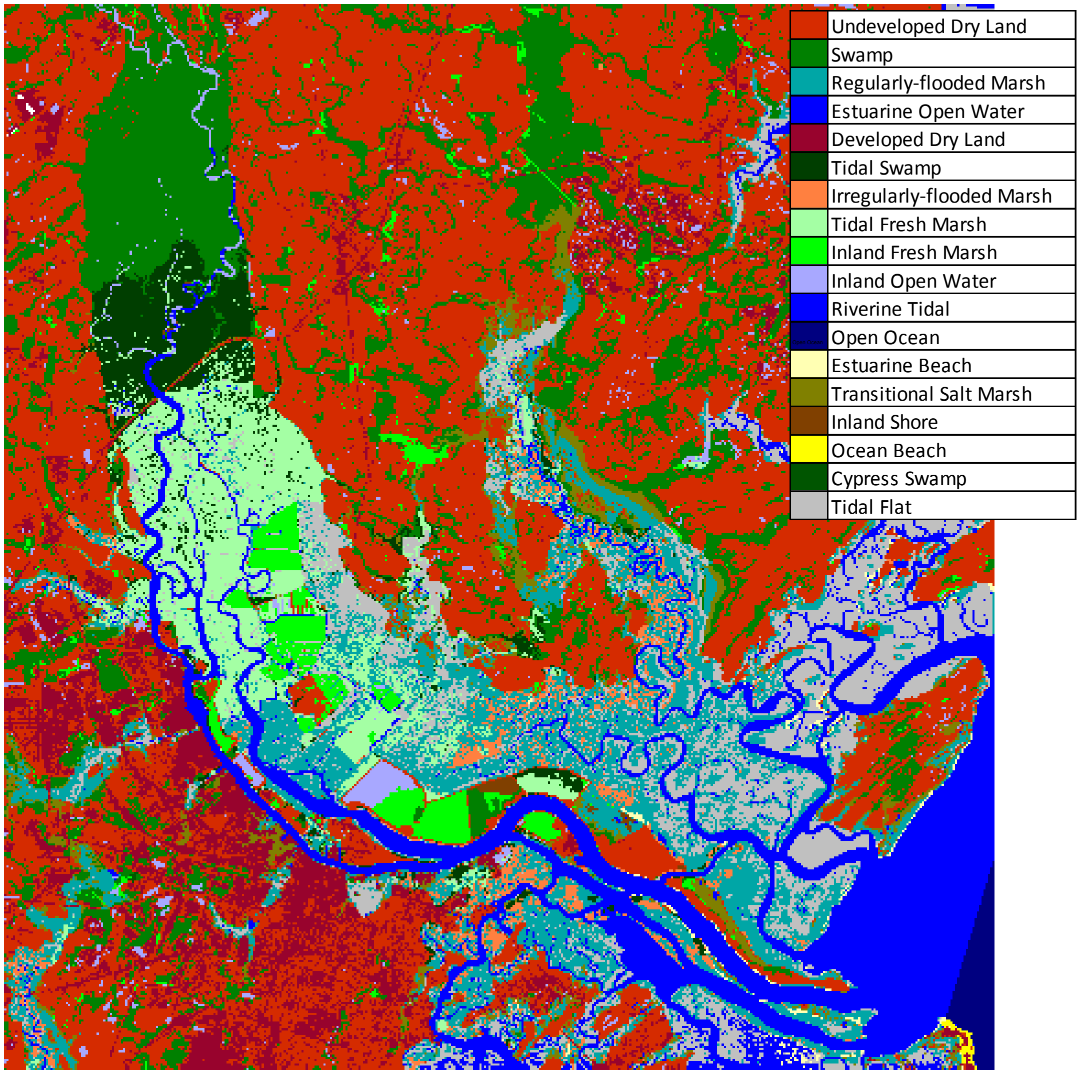
Savannah NWR, Initial Condition.



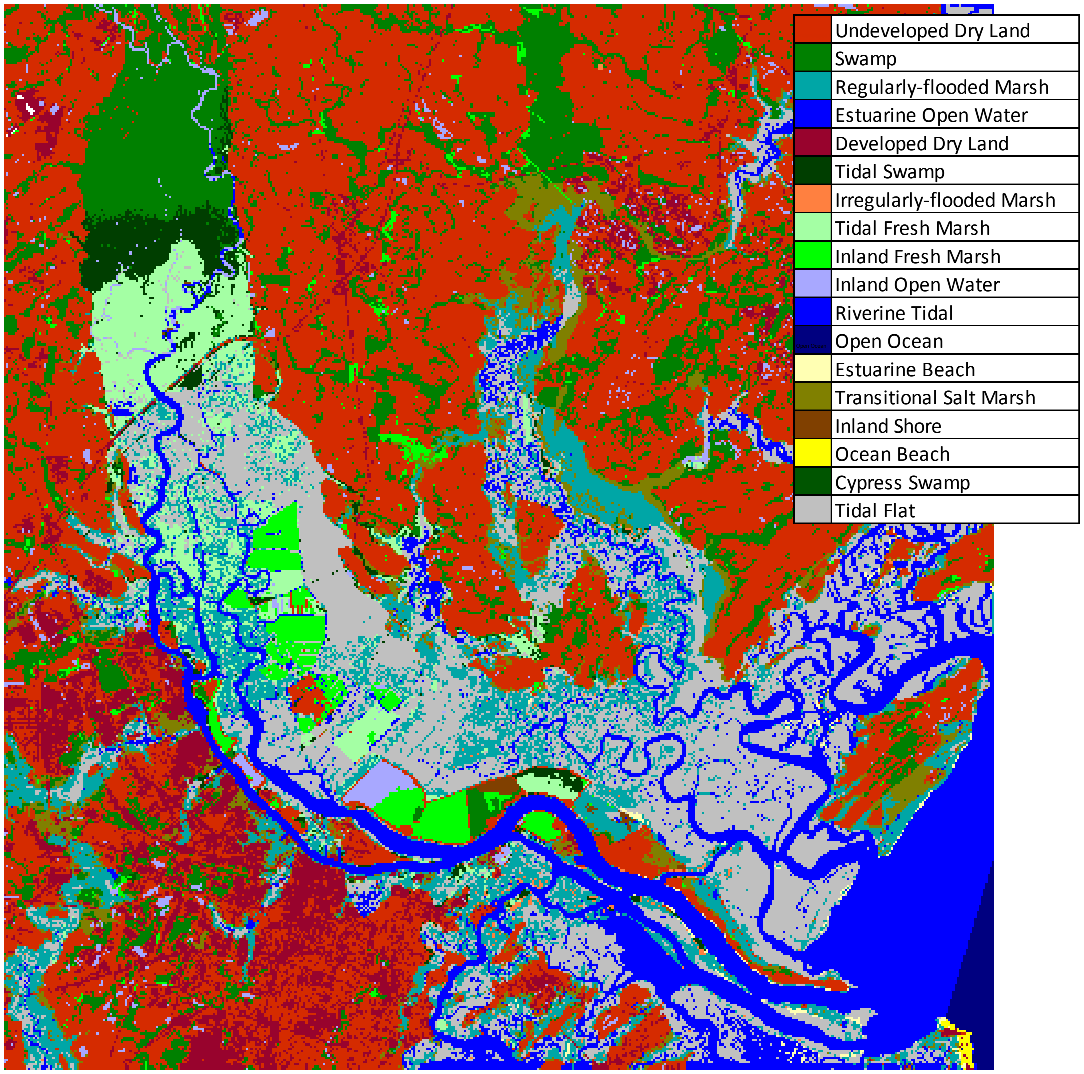
Savannah NWR, 2025, 1.5 m SLR by 2100.



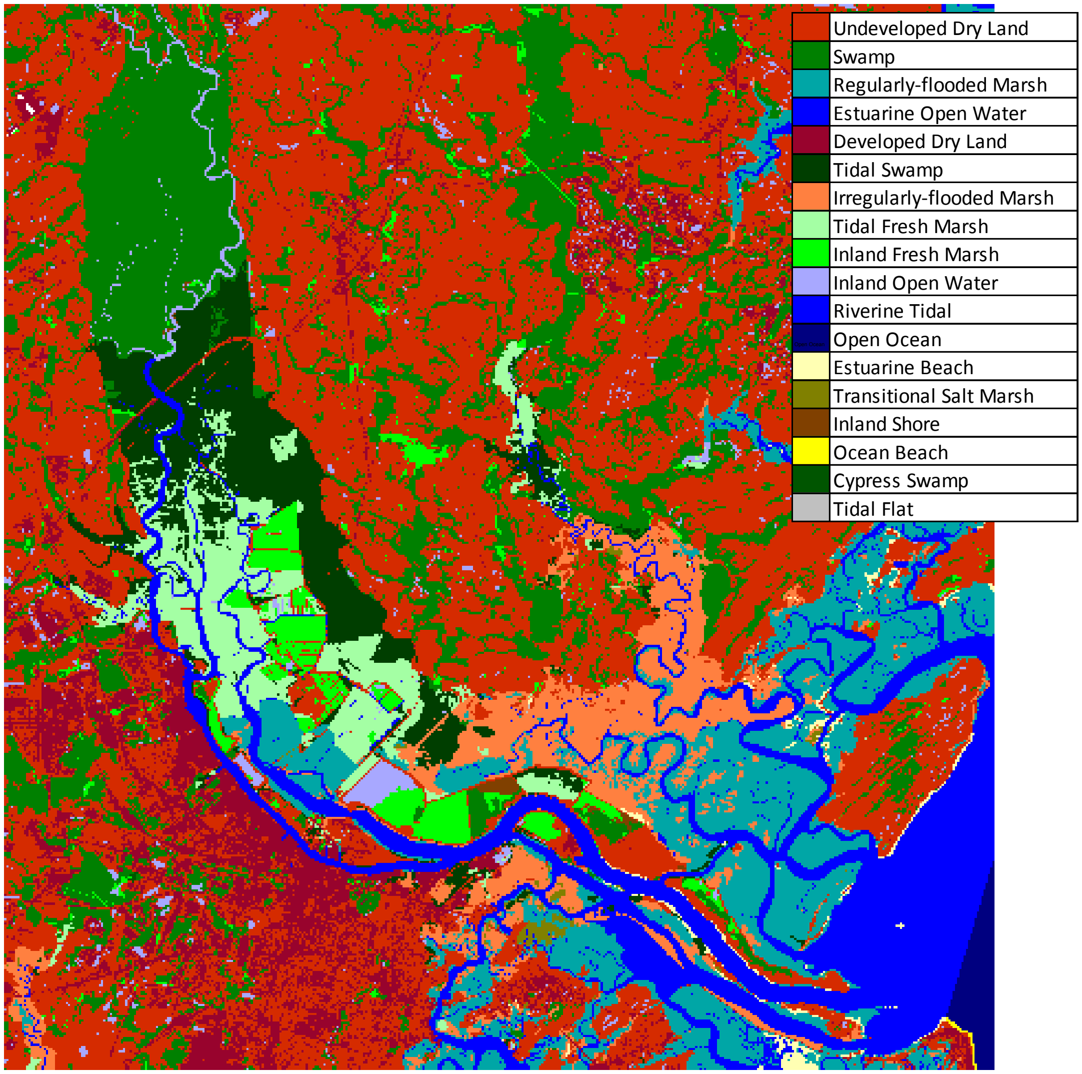
Savannah NWR, 2050, 1.5 m SLR by 2100.



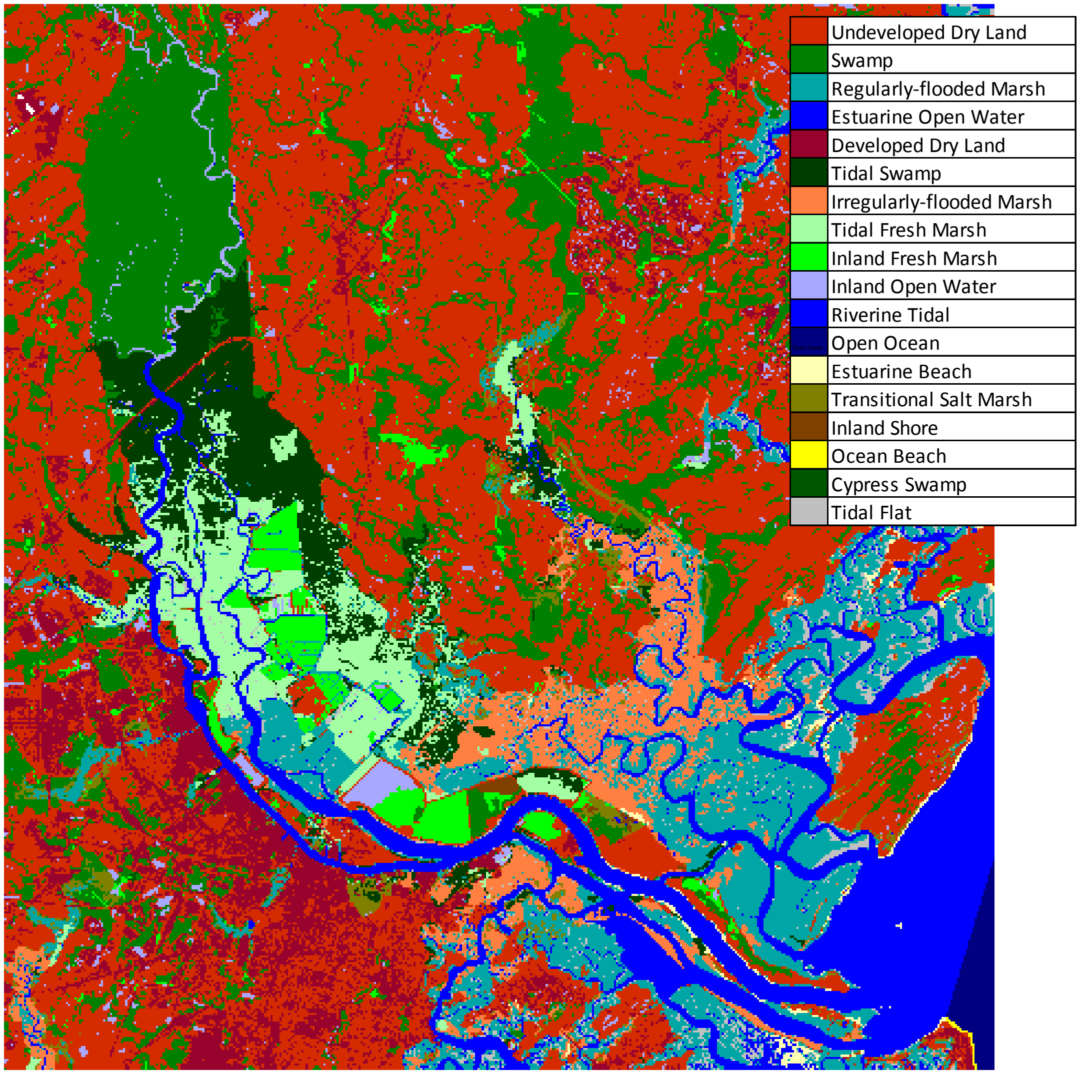
Savannah NWR, 2075, 1.5 m SLR by 2100.



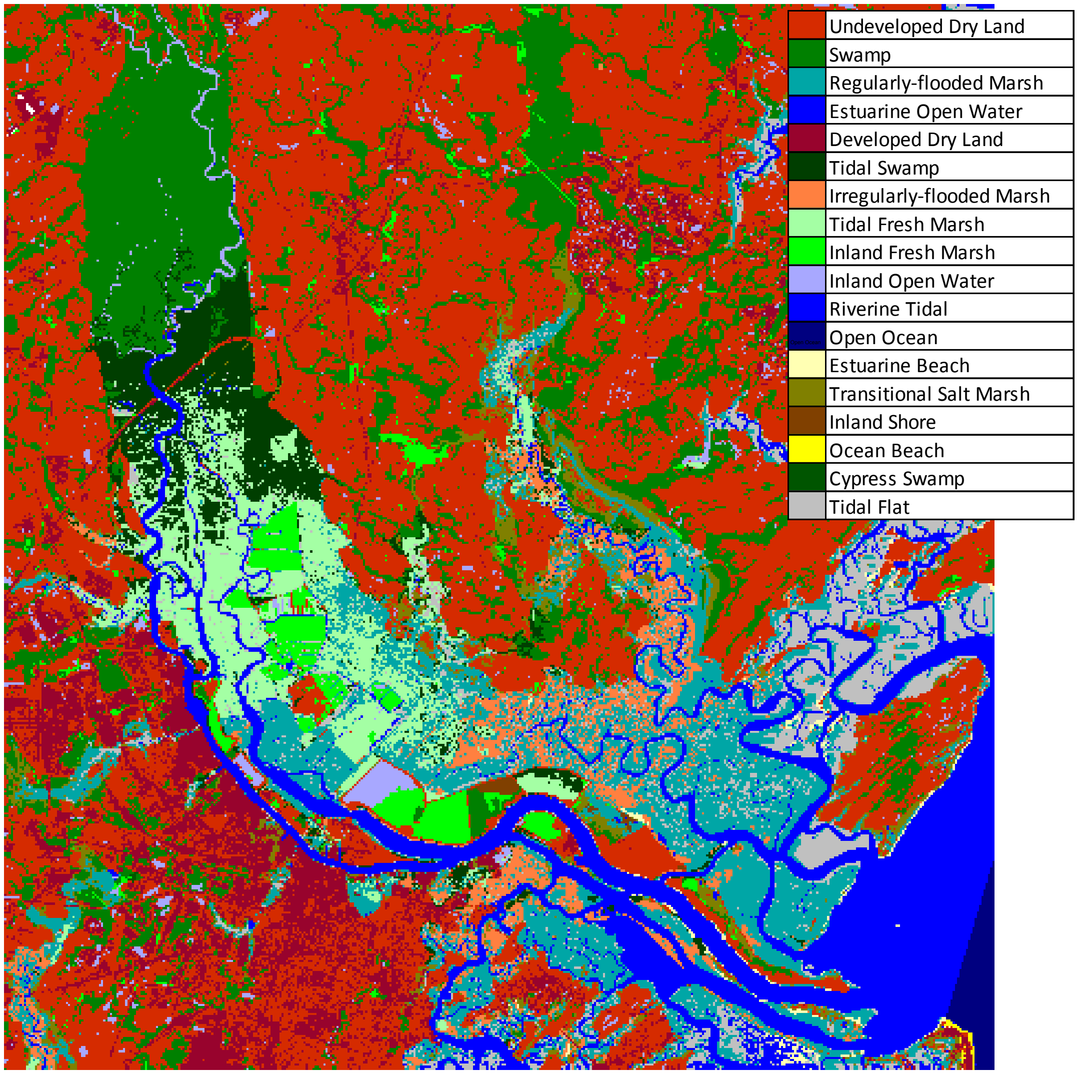
Savannah NWR, 2100, 1.5 m SLR by 2100.



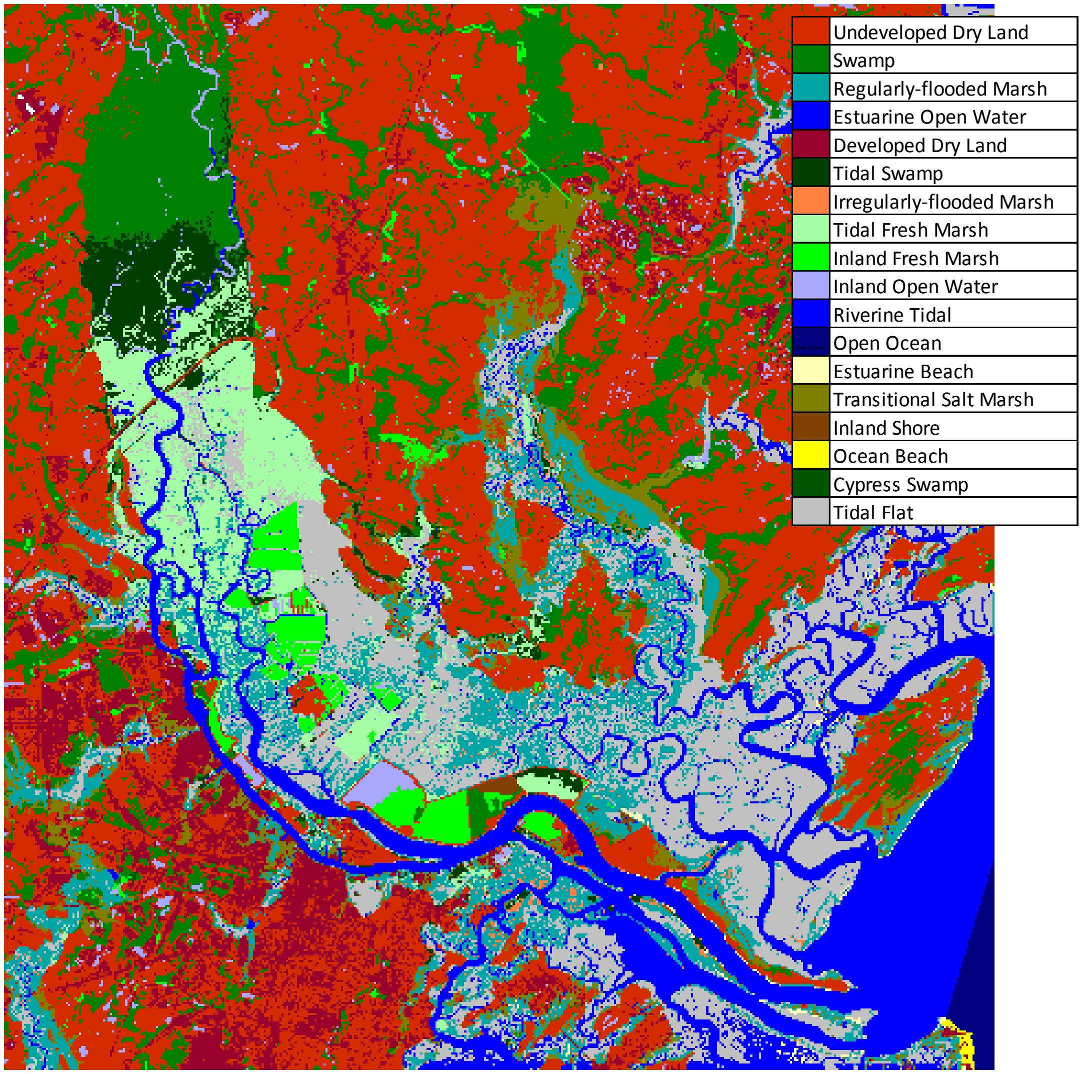
Savannah NWR, Initial Condition.



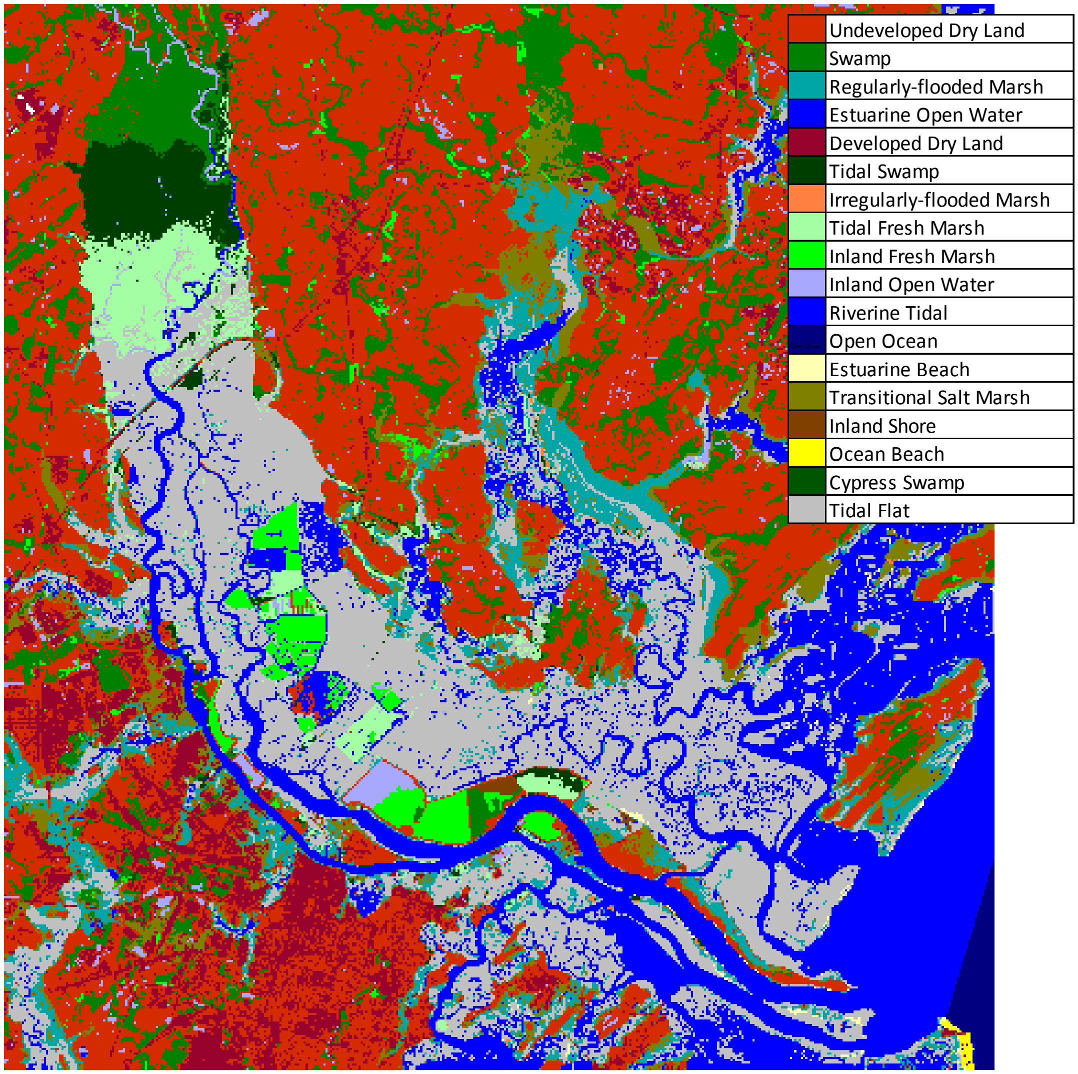
Savannah NWR, 2025, 2 m SLR by 2100.



Savannah NWR, 2050, 2 m SLR by 2100.



Savannah NWR, 2075, 2 m SLR by 2100.



Savannah NWR, 2100, 2 m SLR by 2100.