Application of the Sea-Level Affecting Marshes Model (SLAMM 6) to MS Sandhill Crane NWR

Prepared for

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

August 31, 2011

warren pinnacle consulting, inc.

PO Box 315, Waitsfield VT, 05673
(802)-496-3476

Application of the Sea-Level Affecting Marshes Model (SLAMM 6) to MS Sandhill Crane NWR

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 (Park et al. 1991).

In 2010, the Gulf of Mexico Alliance Habitat Conservation and Restoration Team (HCRT), in assistance to the U. S. Fish and Wildlife Service effort through a contract with the Gulf of Mexico Foundation, funded additional model application to six coastal refuges in the Gulf of Mexico, including the Mississippi Sandhill Crane 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 the final report for MS Sandhill Crane NWR as produced under this contract.

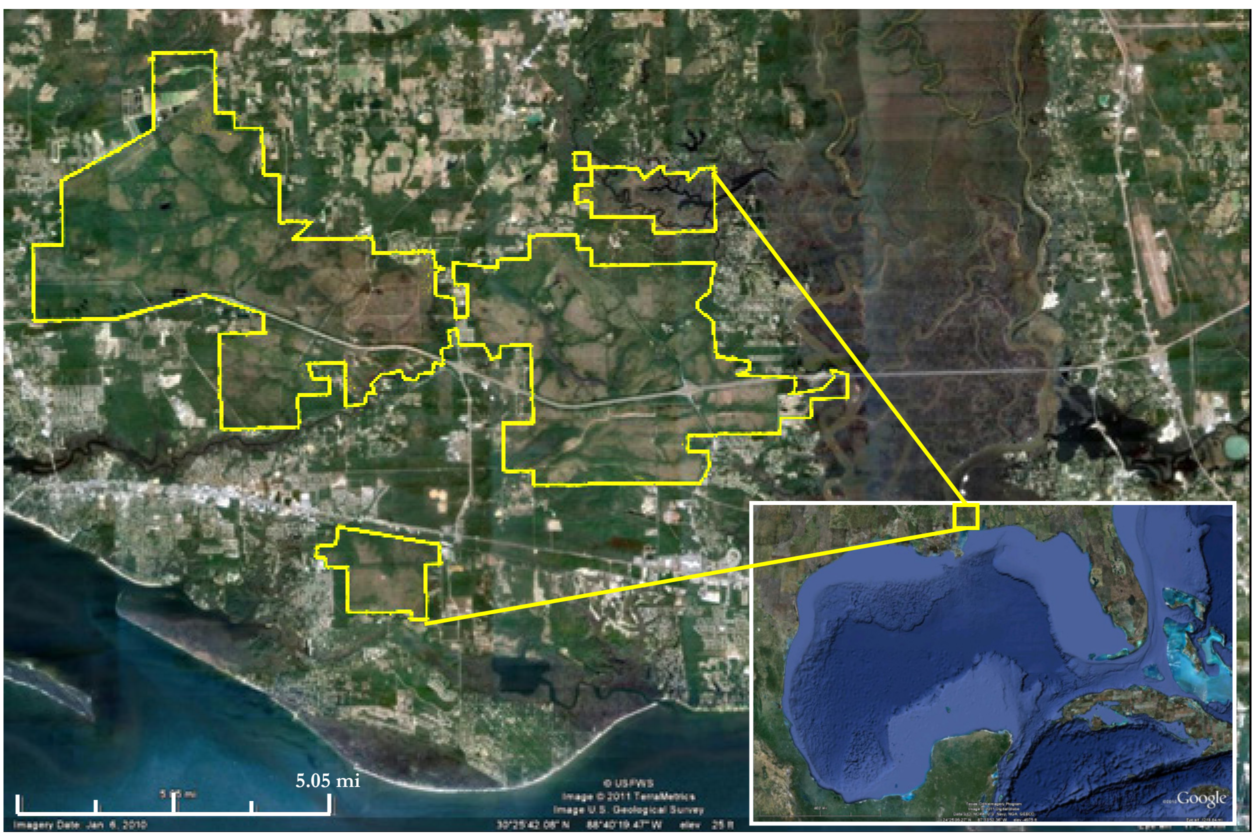


Figure 1. Mississippi Sandhill Crane NWR within context of Gulf of Mexico

Model Summary

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

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

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

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

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

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

- Accretion Feedback Component: Feedbacks based on wetland elevation, distance to channel, and salinity may be specified. This feedback is used where adequate data exist for parameterization.
- Salinity Model: Multiple time-variable freshwater flows may be specified. Salinity is estimated and mapped at MLLW, MHHW, and MTL. Habitat switching may be specified as a function of salinity. This optional sub-model is not utilized in simulations of MS Sandhill Crane 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. 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

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 SLRby 2090-2099 "excluding future rapid dynamical changes in ice flow." The A1B-mean scenario that was run as a part of this project falls near the middle of this estimated range, predicting 0.39 m of global SLR by 2100. A1B-maximum predicts 0.69 m of global SLR by 2100.

The latest literature (Chen et al. 2006; Monaghan et al. 2006) indicates that the eustatic rise in sea levels is progressing more rapidly than was previously assumed, perhaps due to the dynamic changes in ice flow omitted within the IPCC report's calculations. A recent paper in the journal *Science* (Rahmstorf 2007) suggests that, taking into account possible model error, a feasible range by 2100 of 50 to 140 cm. This work was recently updated and the ranges were increased to 75 to 190 cm (Vermeer and Rahmstorf 2009). Pfeffer et al. (2008) suggests that 2 m by 2100 is at the upper end of plausible scenarios due to physical limitations on glaciological conditions. A recent US intergovernmental report states "Although no ice-sheet model is currently capable of capturing the glacier speedups in Antarctica or Greenland that have been observed over the last decade, including these processes in models will very likely show that IPCC AR4 projected SLRs for the end of the 21st century are too low." (Clark 2009) A recent paper by Grinsted et al. (2009) states that "sea level 2090-2099 is projected to be 0.9 to 1.3 m for the A1B scenario…" Grinsted also states that there is a "low probability" that SLR will match the lower IPCC estimates.

To allow for flexibility when interpreting the results, SLAMM was also run assuming 1 m, 1.5 m, and 2 m of eustatic SLR by the year 2100. The A1B- maximum scenario was scaled up to produce these bounding scenarios (Figure 2).

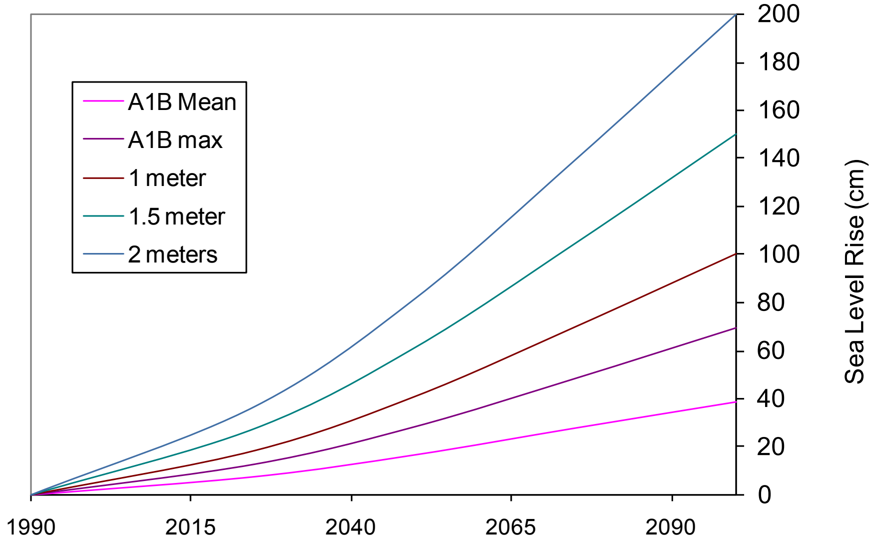


Figure 2. Summary of SLR scenarios utilized

When the model was run to estimate wetland changes in the past ("hindcasting"), the local rate of SLR from 1984 to 1990 was estimated to be 2.8 mm/year. This value is the observed average SLR trend observed between 1966 and 2006 at the nearby gauge station of Dauphin Island, AL (NOAA gauge # 8735180). The global rate of SLR from 1990 to the present was estimated to be 3 mm/year (Grinsted et al. 2009)[1].

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

Data Sources and Methods

Most recent wetland data: Figure 3 shows the most recent wetlands layer available for the study area. This layer was obtained by combining National Wetlands Inventory (NWI) photos dated 2005-2007 covering the entire study area except a small portion in the north-west section of the refuge where a NWI 1980 image was available instead (Figure 4). Converting the NWI survey into 30 m cells indicated that the approximately 23,500 acre refuge (approved acquisition boundary including water) is composed of the following categories:

Land cover type		Area (acres)	Percentage (%)
	Undeveloped Dry Land	16268	69
	Swamp	4321	18
	Inland Fresh Marsh	1067	5
	Irregularly Flooded Marsh	594	3
	Tidal Swamp	268	1
	Estuarine Open Water	252	1
	Tidal Fresh Marsh	217	<1
	Cypress Swamp	201	<1
	Developed Dry Land	193	<1
	Inland Open Water	112	<1
	Riverine Tidal	3	<1
	Total (incl. water)	**23496**	**100**

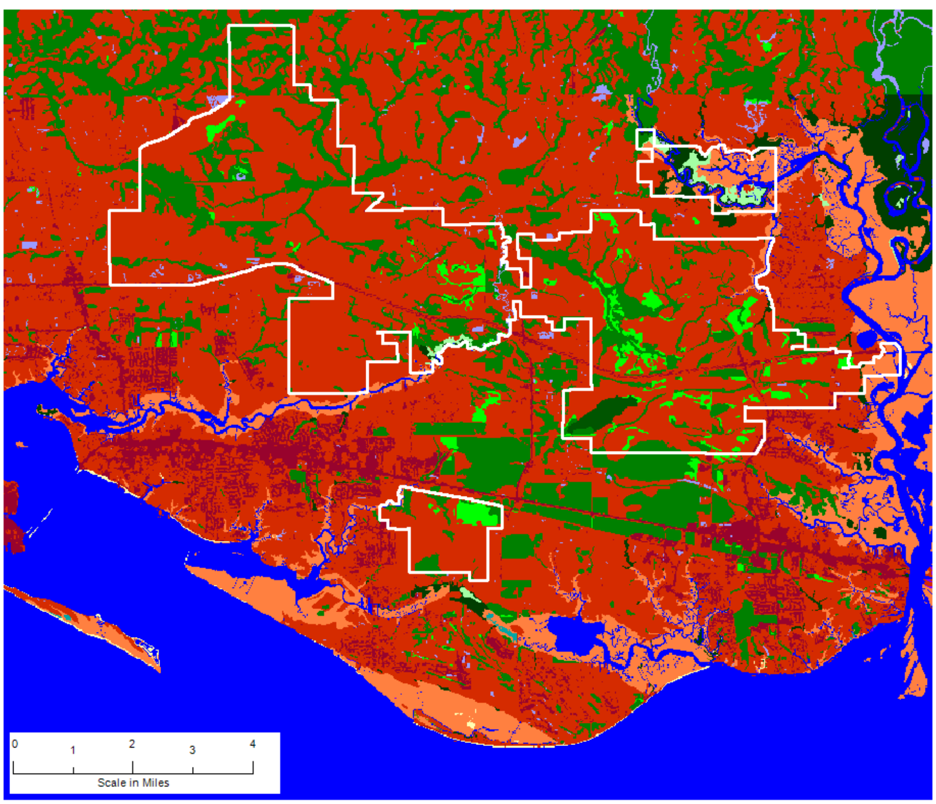


Figure 3. Recent wetland coverage of the study area. Refuge boundaries in white

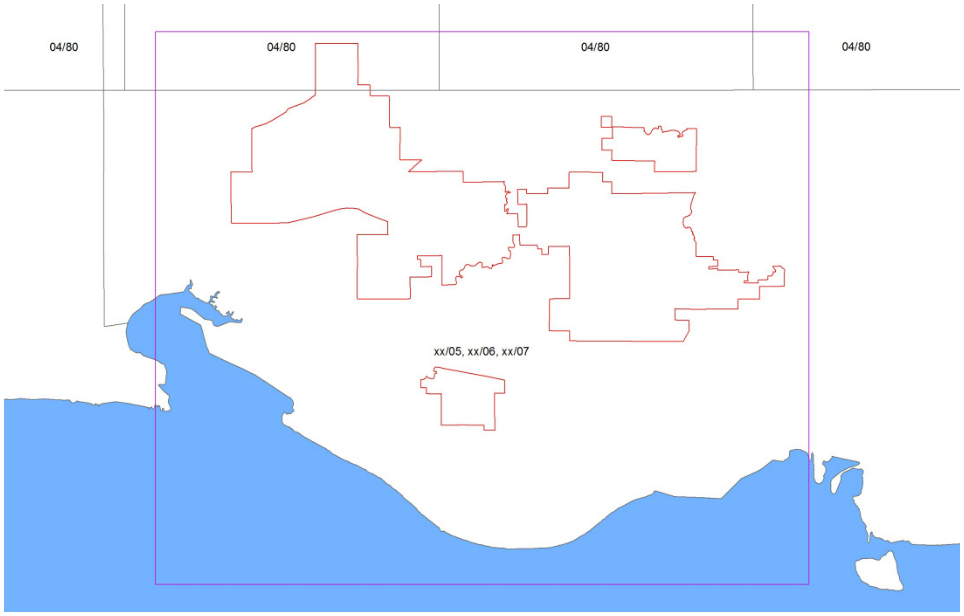


Figure 4. Recent NWI photo dates

Elevation Data. The digital elevation map used in this simulation was derived from a FEMA MS merged LiDAR produced for floodplain mapping. The two merged components include 2005 pre-Katrina and 2005 post-Katrina LiDAR, both bare earth datasets. The elevation data has a timestamp of 2005 (Figure 5).

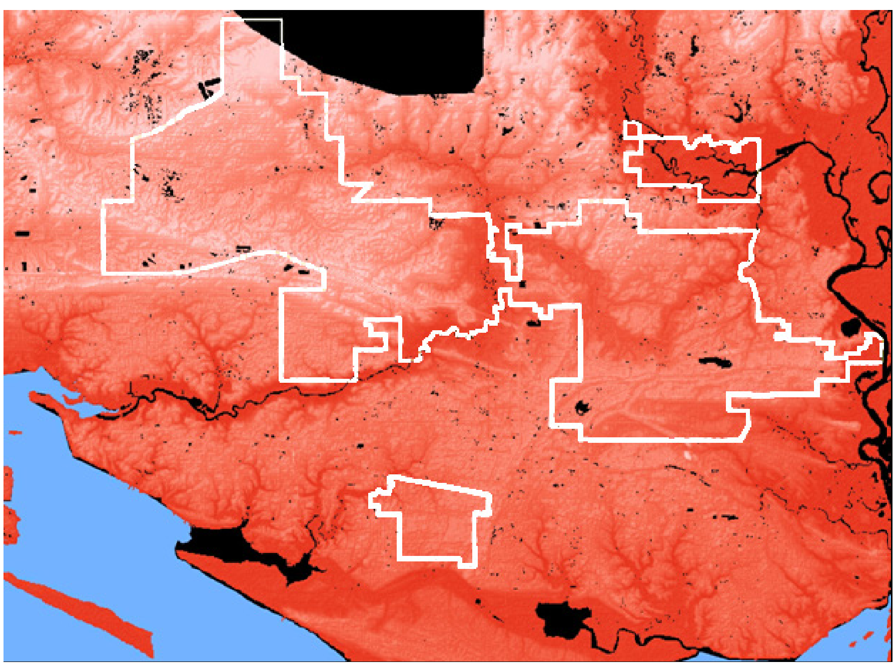


Figure 5. Shade-relief elevation map of refuge (white) and surrounding area.

Historic wetland data. Figure 6 illustrates the historical wetland coverage used for the hindcast. This layer is derived from NWI photos dated 1996 and 1980 (Figure 7). While it would be preferable to have a longer period between historical and current layers, older data were unavailable.

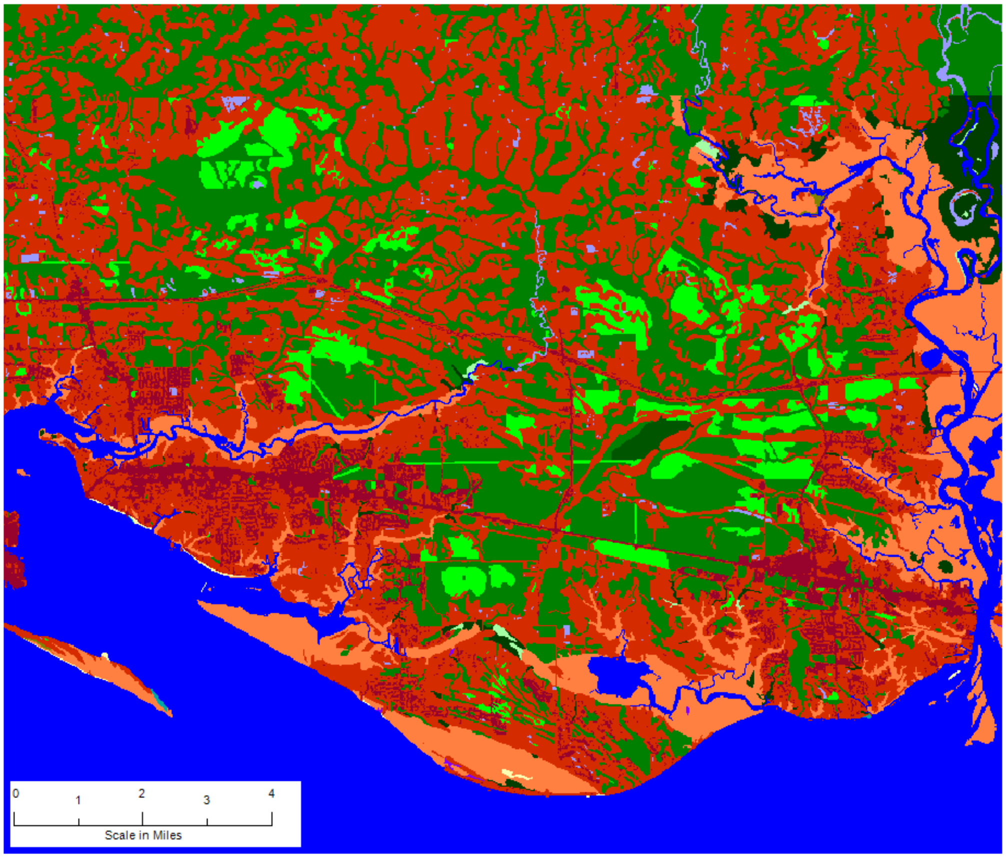


Figure 6. Historical wetland coverage (1996)

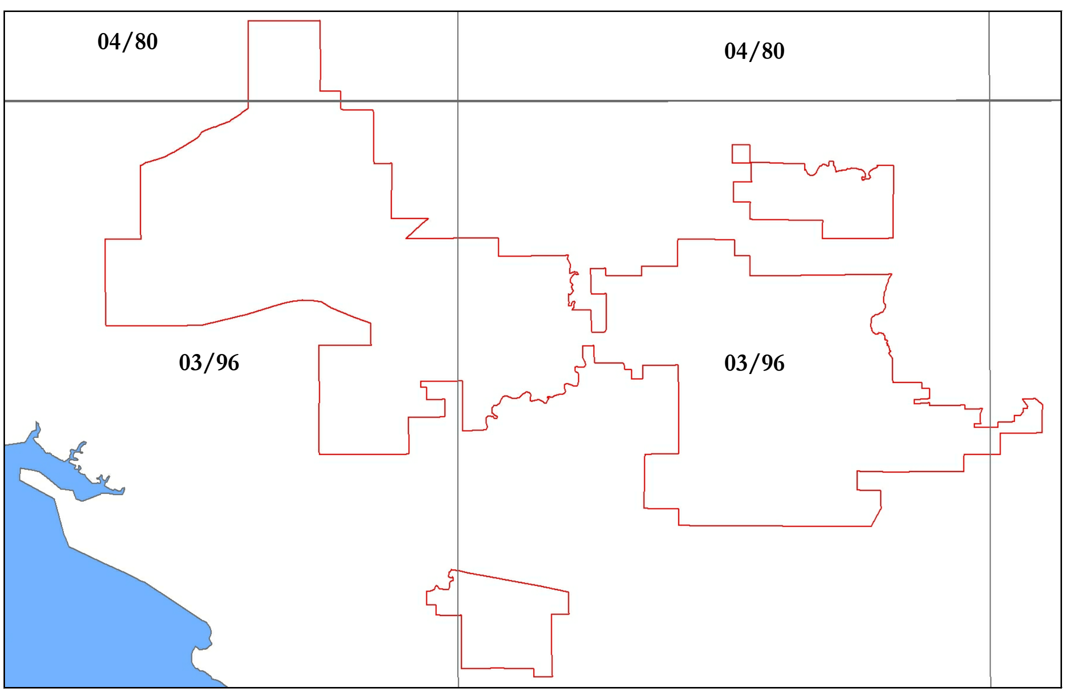


Figure 7. Historic NWI photo dates

Model Timesteps. Model timesteps and output were produced in 3-year intervals for the hindcast starting from 1996 up to 2006, while forecasting outputs were chosen at years 2025, 2050, 2075 and 2100 with the most recent wetland data available as initial conditions (2006).

Dikes and Impoundments. According to the National Wetland Inventory, there are essentially no impounded or diked areas within MS Sandhill Crane NWR except for a few acres of swamp and open water in the Ocean Springs Unit. These areas were designated as "diked" within the current SLAMM analysis.

Historic sea level rise rates. The historic SLR trend of 2.98 mm/yr recorded between 1966 and 2006 at the NOAA Tide Datum located at Dauphin Island, AL (8735180, approximately 40 miles south west of the refuge) was applied throughout the model extent. This rate of SLR is higher than the global average for the last 100 years (approximately 1.7 mm/year, IPCC 2007a) potentially reflecting minor land subsidence at this site (or other factors such as water volume effects causing local SLR to slightly outpace global SLR). This differential between local and global SLR was considered to remain constant through 2100.

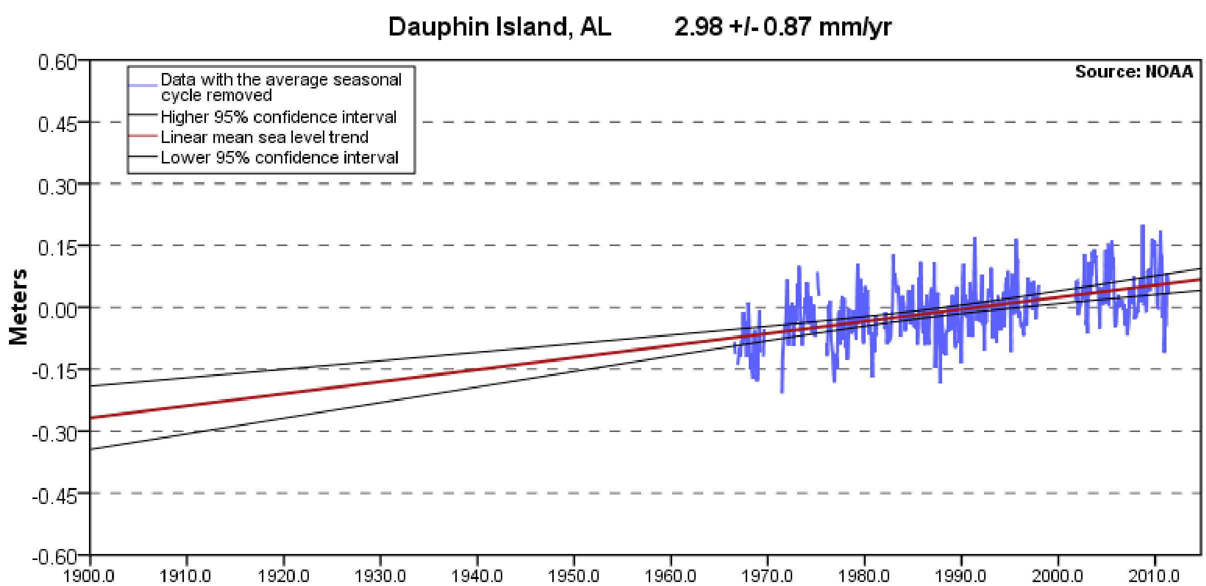


Figure 8. Historic sea level trend recorded at NOAA gauge station located in Dauphin Island based on monthly mean sea level data from 1966 to 2006

Tide Ranges. Figure 9 shows the locations of the five tide-gauge stations (red marks) closest to the study area used to define the tide ranges for this site. The great diurnal tide range, summarized in Table 1, varies from 0.47 m to 0.63 m. The observed gradient of decreasing tidal range from south to north was applied to this SLAMM simulation.

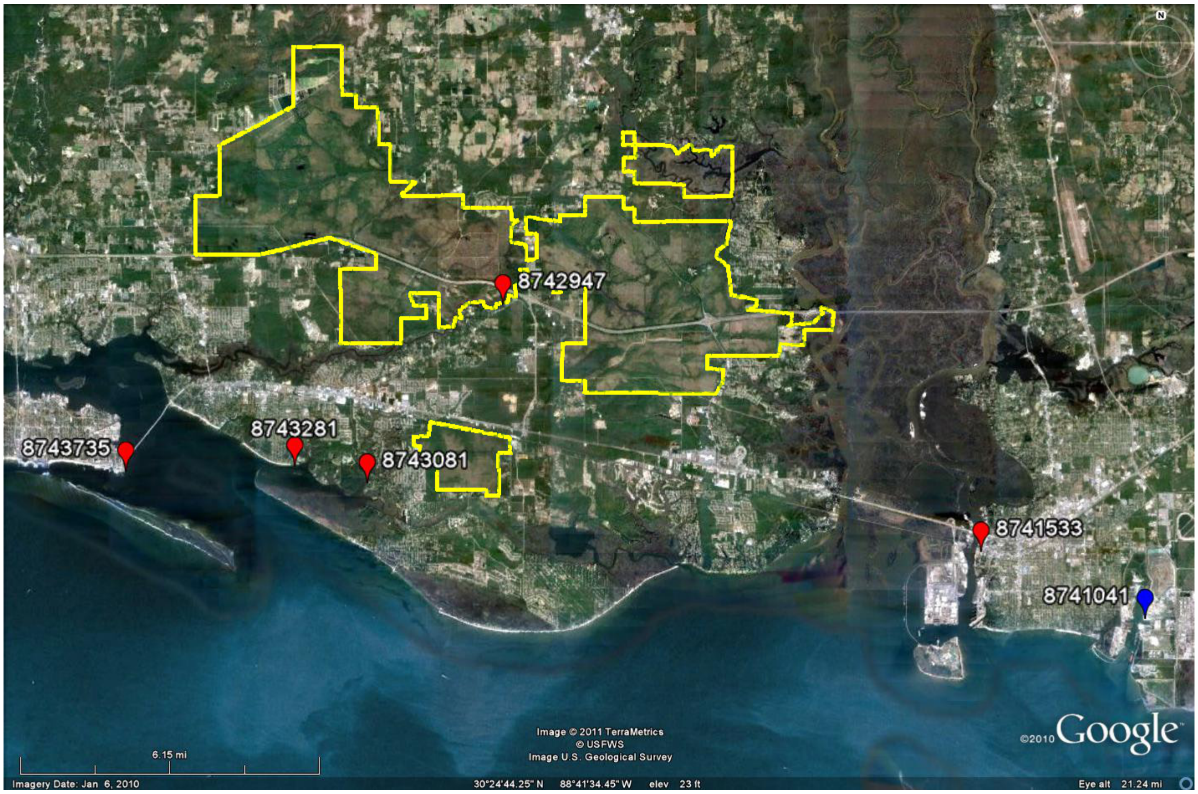


Figure 9. Location of NOAA tides gages used for MS Sandhill Crane NWR

Table 1. NOAA tide gauges and values.

Station ID	Site Name	Tide Range (m)	Salt Elevation	Subsite
8742947	EASTERN OLD FORT BAYOU, MS	0.63	0.71	Subsite 1
8743081	HOLLINGSWORTH POINT, DAVIS BAYOU, MS	0.55	0.62	Global
8743281	OCEAN SPRINGS, MS	0.53	0.59	Global
8741533	PASCAGOULA NOAA LAB, PASCAGOULA RIVER, MS	0.47	0.53	Subsite 2
8743735	BILOXI (CADET POINT), BILOXI BAY, MS	0.54	0.61	Global

Notably lacking from this spatial tide information are any data describing tide ranges in the northeast section of the study area, most notably the wetlands surrounding Paige Lake. Lacking these data, a tidal range from the nearest gauge in Pascagoula was utilized which potentially overestimates the tide range in this location.

Salt elevation. This parameter within SLAMM designates the boundary between wet and dry lands or saline wetlands and fresh water wetlands. As such, this value may be best derived by examining historical tide gage data. For this application, the salt boundary was defined as the elevation above which inundation is predicted less than once per thirty days using data from the gauge station at Dock E, Port of Pascagoula, MS (ID 8741041, blue mark in Figure 9). Based on the frequency of inundation analysis the salt elevation is estimated to be approximately 0.65 m above MTL, equivalent to an elevation of 2.21 Half Tide Units (HTU), as shown in Figure 10. This factor was used to estimate "salt elevations" at gauge stations where inundation data are not available. The resulting elevations range from 0.53 m to 0.71 m above MTL as illustrated in Table 1.

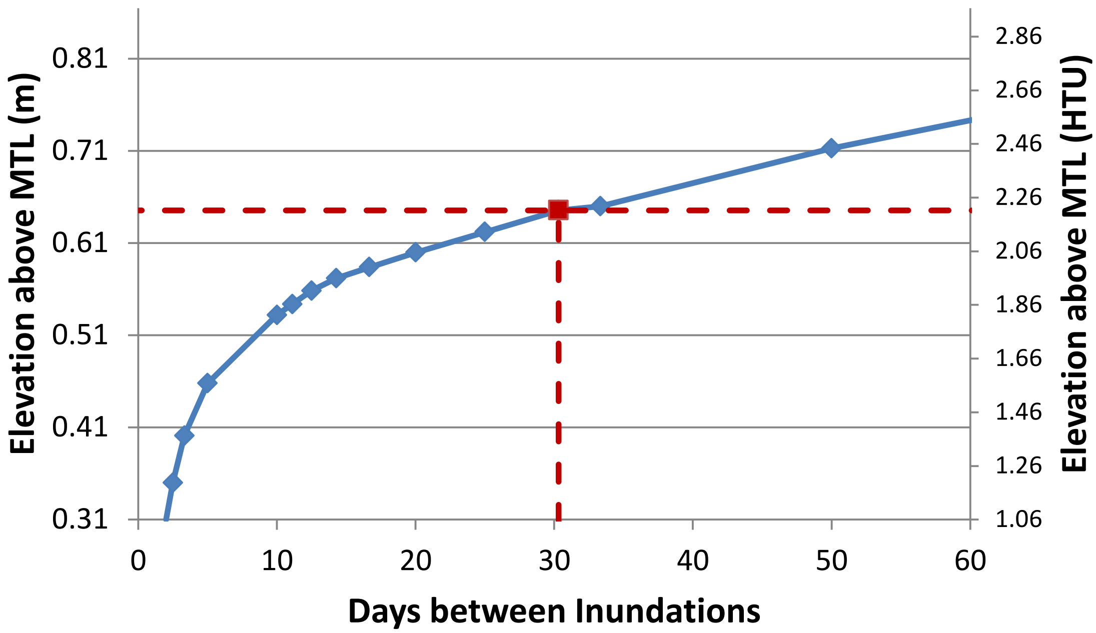


Figure 10. Frequency of inundation based upon 5 years of data.

Accretion rates. Accretion rates for regularly and irregularly flooded marsh were set to 6.7 mm/year and 4.7 mm/year respectively based on a study by Callaway et al. (1997) in nearby Biloxi Bay.

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

There is uncertainty within this correction between NAVD88 and MTL and this is addressed as part of in the *Elevation Uncertainty Analysis* on page 39 of this report.

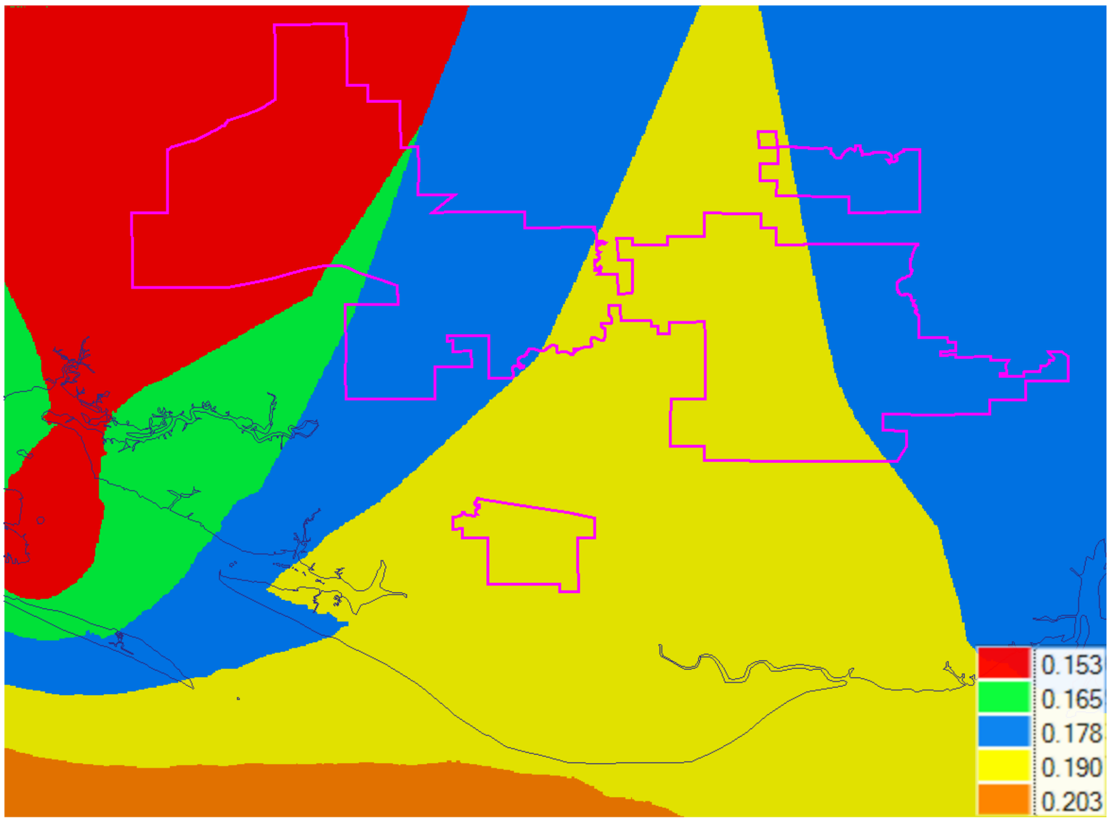


Figure 11. VDATUM correction raster over shoreline with MS Sandhill Crane NWR boundaries (m)

Refuge boundaries. Modeled USFWS refuge boundaries for Mississippi are based on Approved Acquisition Boundaries as published on the FWS National Wildlife Refuge Data and Metadata website. The cell-size used for this analysis was 30 m by 30 m cells.

Refuge staff Scott Hereford notes that "Using the Acquisition Boundary is problematic" and he recommended using the current refuge boundary. He notes that approximately 950 acres of lands included in this study area are owned by the Jackson County Utility Authority and used for treatment of human wastewater and that USFWS will never own or manage those lands. In addition, he notes that USFWS is unlikely to own the 1800 acres in The Nature Conservancy's Old Fort Bayou Mitigation Bank. However, due to contractual requirements, this study area remains the approved acquisition boundary.

Input subsites and parameter summary. Based on the spatial tidal differences (see Table 1), three different simulation input subsites were identified as illustrated in Figure 12. The "Global" subsite is all the study area that is not within any other subsite boundary. Table 2 summarizes all SLAMM input parameters for each subsite of the study area.

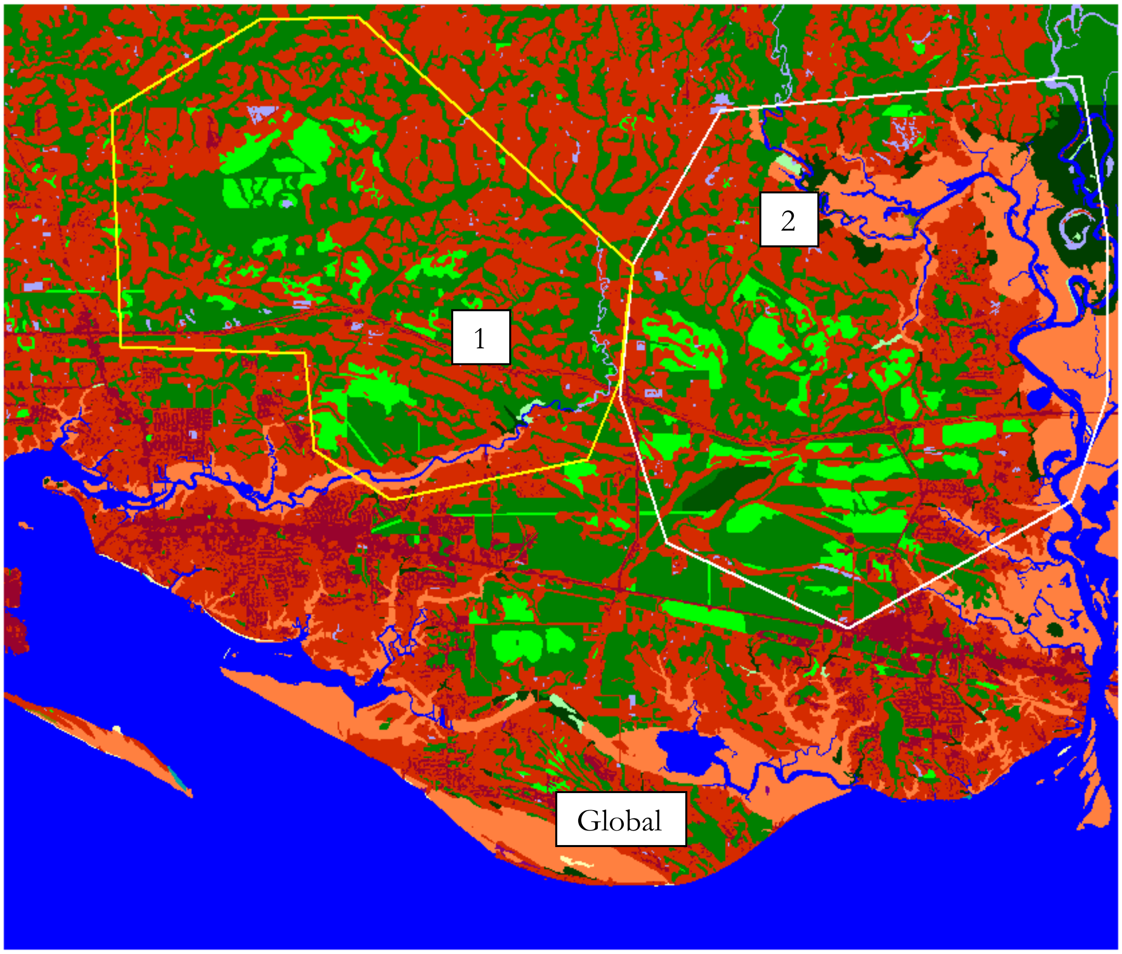


Figure 12. Input subsites for model application.

Table 2. Summary of SLAMM input parameters for MS Sandhill Crane NWR

Parameter	Global	SubSite 1	SubSite 2
NWI Photo Date (YYYY)	1996	1996	1996
DEM Date (YYYY)	2005	2005	2005
Direction Offshore [n,s,e,w]	South	South	East
Historic Trend (mm/yr)	2.98	2.98	2.98
MTL-NAVD88 (m)	†	†	†
GT Great Diurnal Tide Range (m)	0.54	0.63	0.53
Salt Elev. (m above MTL)	0.6	0.7	0.52
Marsh Erosion (horz. m /yr)	1.8	1.8	1.8
Swamp Erosion (horz. m /yr)	1	1	1
T.Flat Erosion (horz. m /yr)	0.5	0.5	0.5
Reg.-Flood Marsh Accr (mm/yr)	6.7	6.7	6.7
Irreg.-Flood Marsh Accr (mm/yr)	4.7	4.7	4.7
Tidal-Fresh Marsh Accr (mm/yr)	5.9	5.9	5.9
Inland-Fresh Marsh Accr (mm/yr)	5.9	5.9	5.9
Mangrove Accr (mm/yr)	3.3	3.3	3.3
Tidal Swamp Accr (mm/yr)	1.1	1.1	1.1
Swamp Accretion (mm/yr)	0.3	0.3	0.3
Beach Sed. Rate (mm/yr)	0.5	0.5	0.5
Freq. Overwash (years)	4	4	4
Use Elev Pre-processor [True,False]	FALSE	FALSE	FALSE

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

Results and Discussion

The analysis of MS Sandhill Crane NWR included "hindcast" and forecast simulations.

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. **However this step requires comparable wetland datasets not extensively affected by anthropogenic actions, a requirement that was apparently not met at this location.**

In a conversation with the head of the National Wetlands Inventory (Wilen 2011), he made a strong recommendation that any hindcasting using the SLAMM model only be undertaken using "back dated" wetland layers. It is NWI policy to only make comparisons of historical to contemporary wetland layers after this process has been completed. The "back dating" process involves integrating contemporary wetland coding methods, current satellite imagery, and also the older wetland imagery to ensure that the historical and current data are comparable. Otherwise a wetland increase is nearly always predicted due to the change in imagery technology. Having NWI produce a back-dated historical image was out of the scope of this project and also impossible to complete within the period of performance.

A communication with George Ramseur (MS Dept. of Marine Resources) also indicated that extensive anthropogenic activities have occurred in this location and that "trees and shrubs have been removed, either mechanically or by intense burning activity."

Since historical DEM data was not available, SLAMM modified the present-day, high-resolution DEM so that it reflects the historical land-cover date by reversing the estimated land uplift or subsidence which took place in the years between wetland survey and DEM dates. This process ignores changes due to erosion, accretion, or sedimentation, however.

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 dramatic differences in inland coverages between historical and contemporary datasets, this metric is of limited utility.

Hindcast Results

Based on historical records, during the period between 1996 and 2007, approximately 3 cm of eustatic SLR occurred (see Sea Level Rise Scenarios section above). Wetland coverage from 1996 and 2006 are compared in Figure 13 and Figure 14, while observed and predicted wetland land cover changes are shown in Figure 15 and Figure 16 respectively.

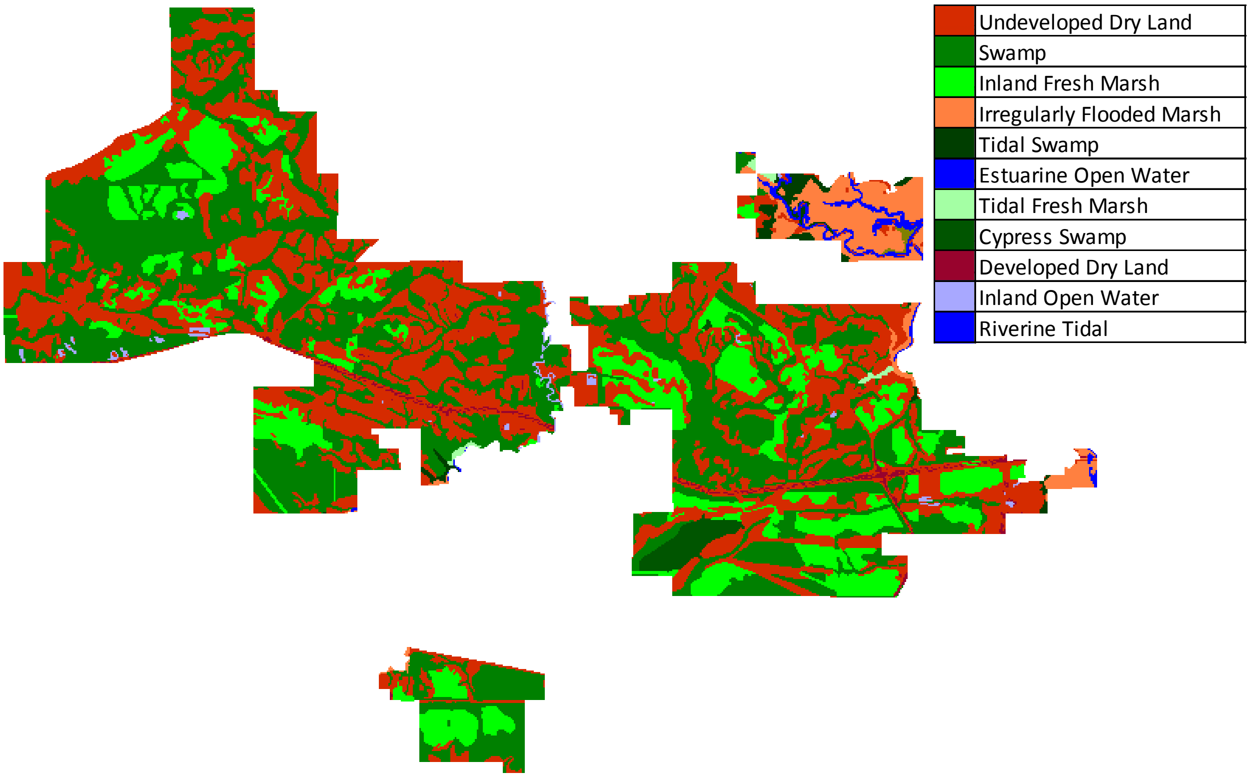


Figure 13. Observed MS Sandhill Crane NWR wetland coverage, 1996 (NWI Data)

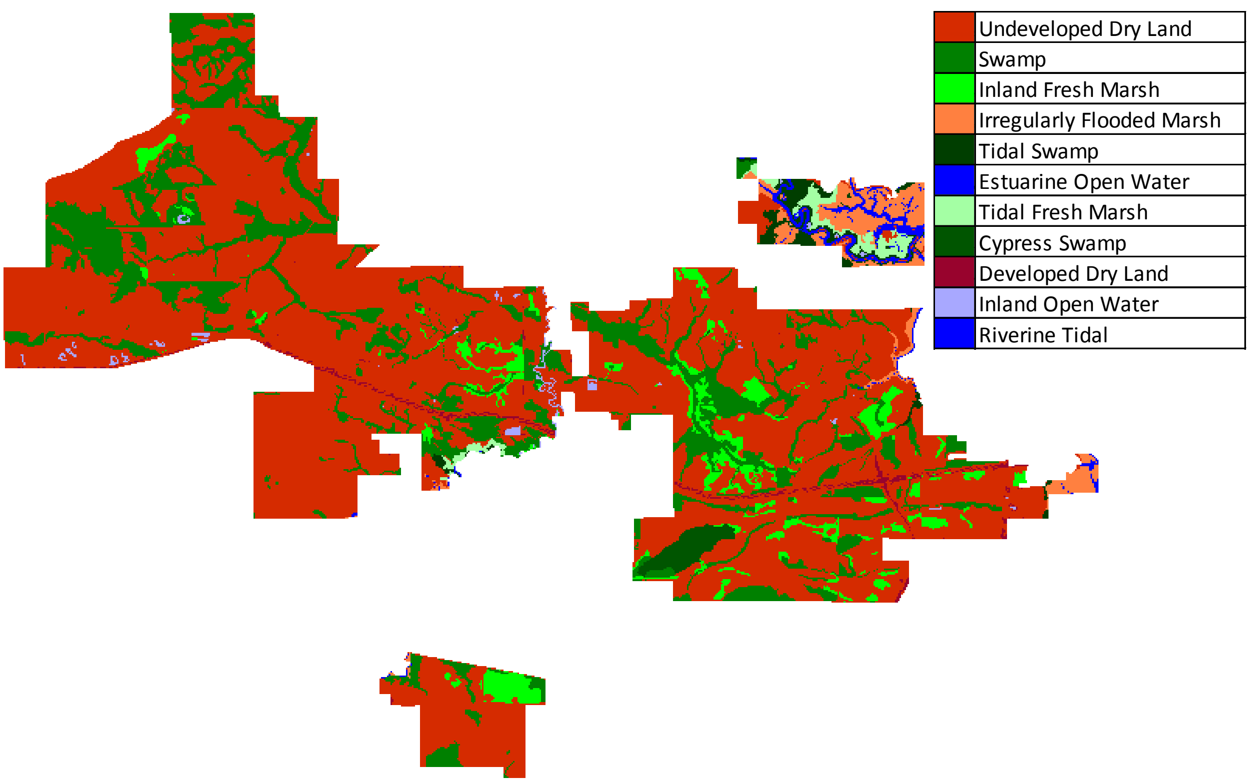


Figure 14. Observed MS Sandhill Crane wetland coverage, 2006 (NWI data)

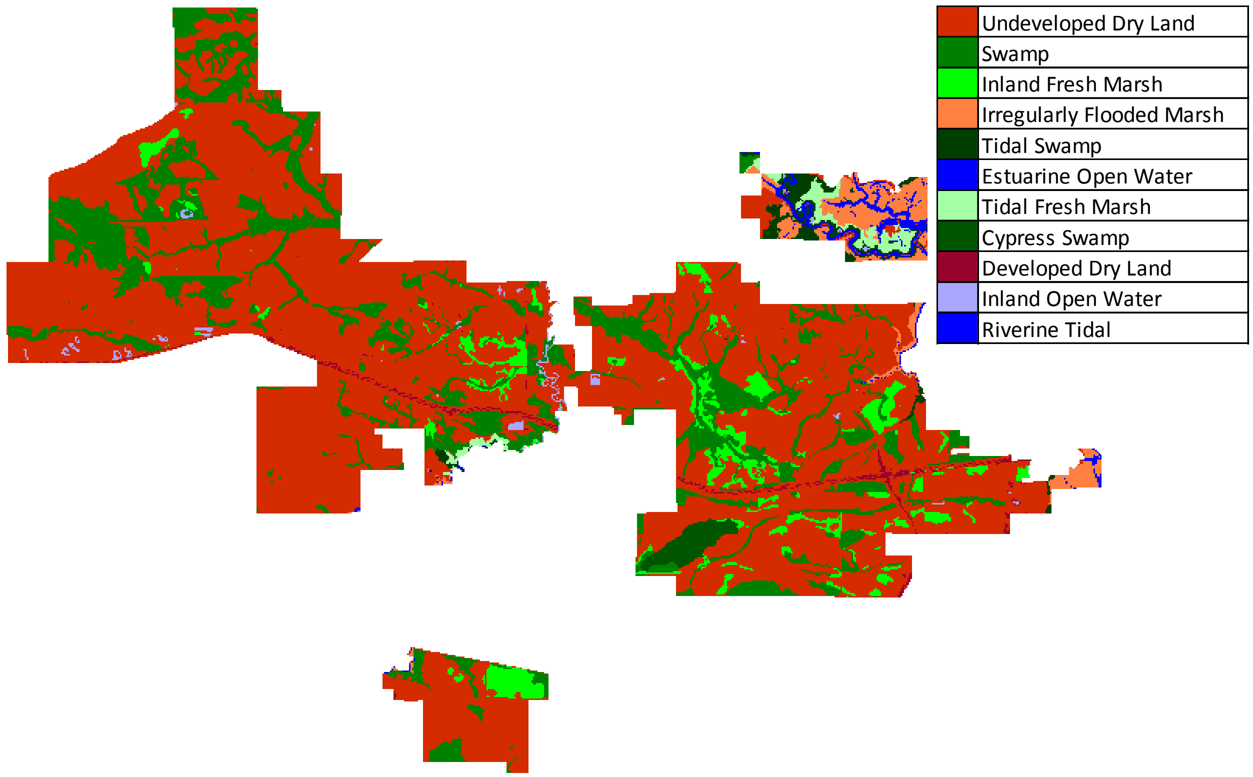


Figure 15. Observed MS Sandhill Crane wetland coverage, 2006 (NWI data)

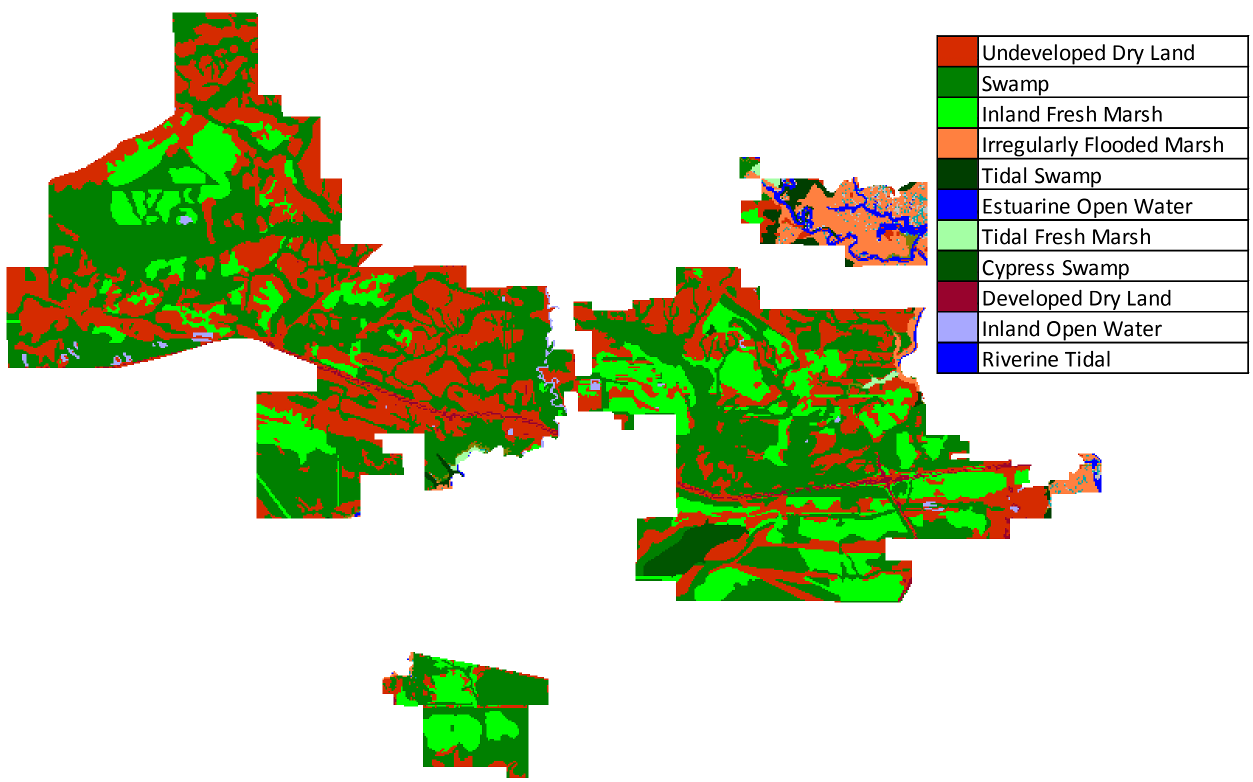


Figure 16. Predicted MS Sandhill Crane NWR wetland coverage, 2006 (Hincast result)

Although the historic wetland layer is not much older than the most recent layer (only 10 years separate them and a predicted 3cm of SLR) the differences between these two layers are striking. Much of the land classified as swamp or inland-fresh marsh in 1996 is represented as dry land in the 2006 survey. Conversations with the refuge staff and information gathered from the refuge website suggest that some land-cover types may be misclassified in one or both surveys (Hereford, 2011). Whatever the case, the SLAMM model will not predict such an extensive set of land-cover changes as a result of 3 cm of sea-level rise.

Therefore, applying the SLAMM model from the available initial wetland layer leads to an imperfect prediction of the coverage in 2006, as illustrated by the differences in the observed and predicted images of the land cover, Figure 15 and Figure 16 respectively.

Provided that a meaningful hindcast should be done over a longer period of time, long enough to see natural land-cover changes in response to SLR, and given the fact that the available historic wetland layer may not reflect the 1996 land cover, no additional effort was put into trying calibrate the SLAMM model using this analysis.

With regards to calculated metrics, it is our assertion that the observed and initial dataset are too dramatically different for metrics to have any relevance.

Land cover	Observed land cover in 1996 (acres)	Observed land cover in 2006 (acres)	Land cover predicted by hindcast (acres)	Observed loss 1996-2006 ([1])		Predicted loss 1996-2006 ([1])	
				(acres)	(%)([2])	(acres)	(%)([2])
Undeveloped Dry Land	8704	16268	7687	-7564	-87	1017	12
Swamp	9242	4321	9855	4921	53	-613	-7
Inland-Fresh Marsh	3676	1067	4021	2609	71	-345	-9
Irreg.-Flooded Marsh	860	594	749	266	31	111	13
Tidal Swamp	191	268	181	-77	-40	10	5
Estuarine Open Water	207	252	221	-46	-22	-14	-7
Tidal-Fresh Marsh	47	217	45	-170	-360	2	4
Developed Dry Land	182	193	181	-11	-6	1	0

While this hindcasting exercise provided little-or-no utility due to data limitations, the reliability of the SLAMM model applied in this area of the Gulf of Mexico has been shown in the applications to Grand Bay (WPC 2011) and southeast Louisiana (Glick et al. 2011). These two analyses bracket the MS Sandhill Crane NWR to the east and west, respectively.

Forecast Results

SLAMM predicts that MS Sandhill Crane NWR will be relatively resilient under all studied SLR scenarios for most of the wetland categories present in the refuge today. Table 3 presents the predicted loss of each wetland category by 2100 for each of the five SLR scenarios examined.

Table 3. Predicted loss rates of land categories by 2100 given simulates scenarios of eustatic SLR

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	9242	-7%([1])	-7%	-6%	-6%	-6%
Undeveloped Dry Land	8705	15%	16%	17%	18%	21%
Inland Fresh Marsh	3676	-14%	-14%	-14%	-14%	-14%
Irregularly Flooded Marsh	860	9%	37%	71%	95%	96%
Cypress Swamp	244	0%	0%	0%	0%	0%

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

Simulation results predict that a maximum of 6% (for 2 m SLR) of the overall refuge acreage will be converted to open water or tidal flat by 2100, mostly on the east boundary and the north-east detached section of the refuge.

By 2100 dry land experiences an overall loss ranging from 15% to 21%. The majority of this land is predicted to convert to swamp and inland-fresh marsh due to the soil-saturation algorithm within SLAMM. The SLAMM soil-saturation algorithm allows coastal swamps and fresh marshes to migrate onto adjacent uplands as a response of the fresh water table to rising sea level close to the coast. However, this estimate is subject to some uncertainty due to both the estimate of the fresh water-table height and the uncertain relationship between the fresh-water table and salt water elevations. Overall, swamp is predicted to gain 6%-7% with respect to initial conditions, while for inland fresh marsh is predicted a 14% gain across all the SLR scenarios.

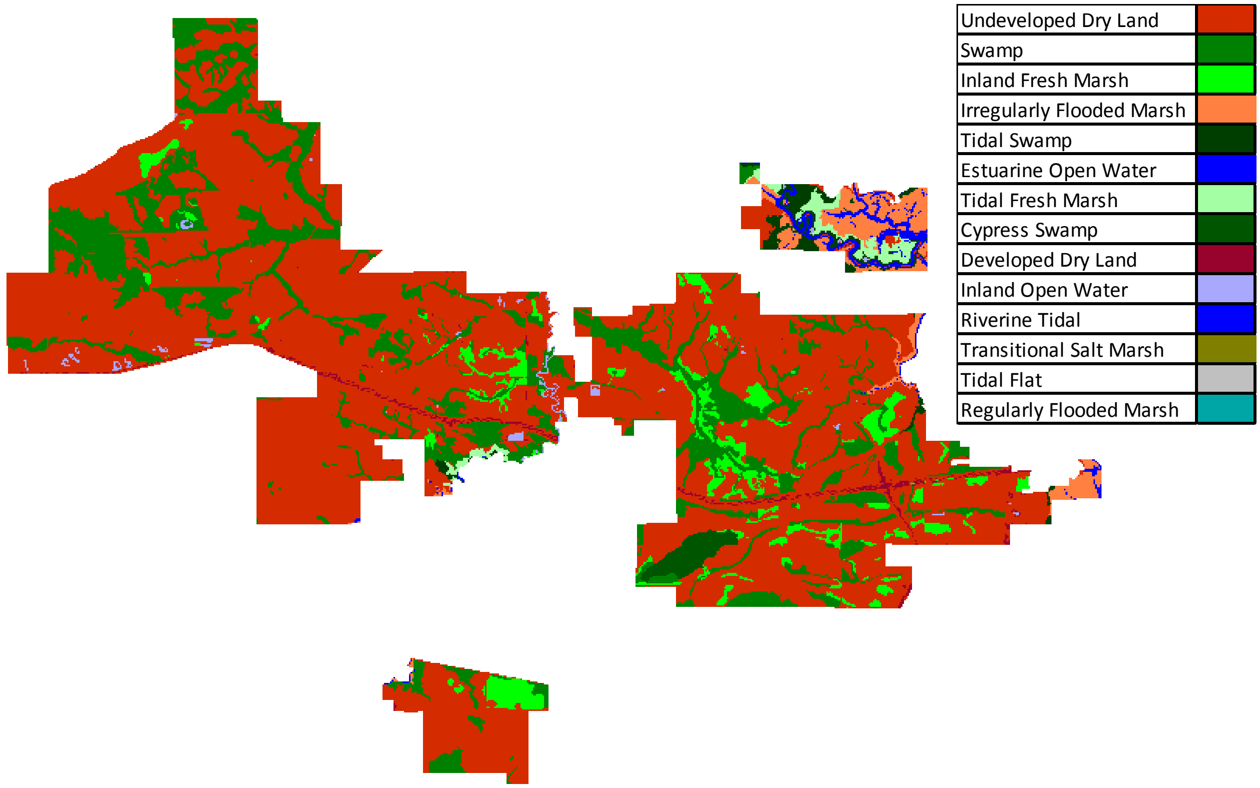
Irregularly-flooded marshes (high marshes) cover approximately 4% of the refuge. By 2100 SLAMM predicts they will be significantly reduced, with losses ranging from 9% to 96%. Irregularly-flooded marshes initially convert to regularly-flooded marsh (low marshes). Regularly-flooded marshes reach their maximum predicted acreage under 1 m SLR. However, if sea level continues to rise beyond that, regularly-flooded marsh also converts to tidal flats or open water.

Tidal-swamp is also significantly reduced for all SLR scenarios, although its total acreage today is relatively small (less than 1% of the refuge area).

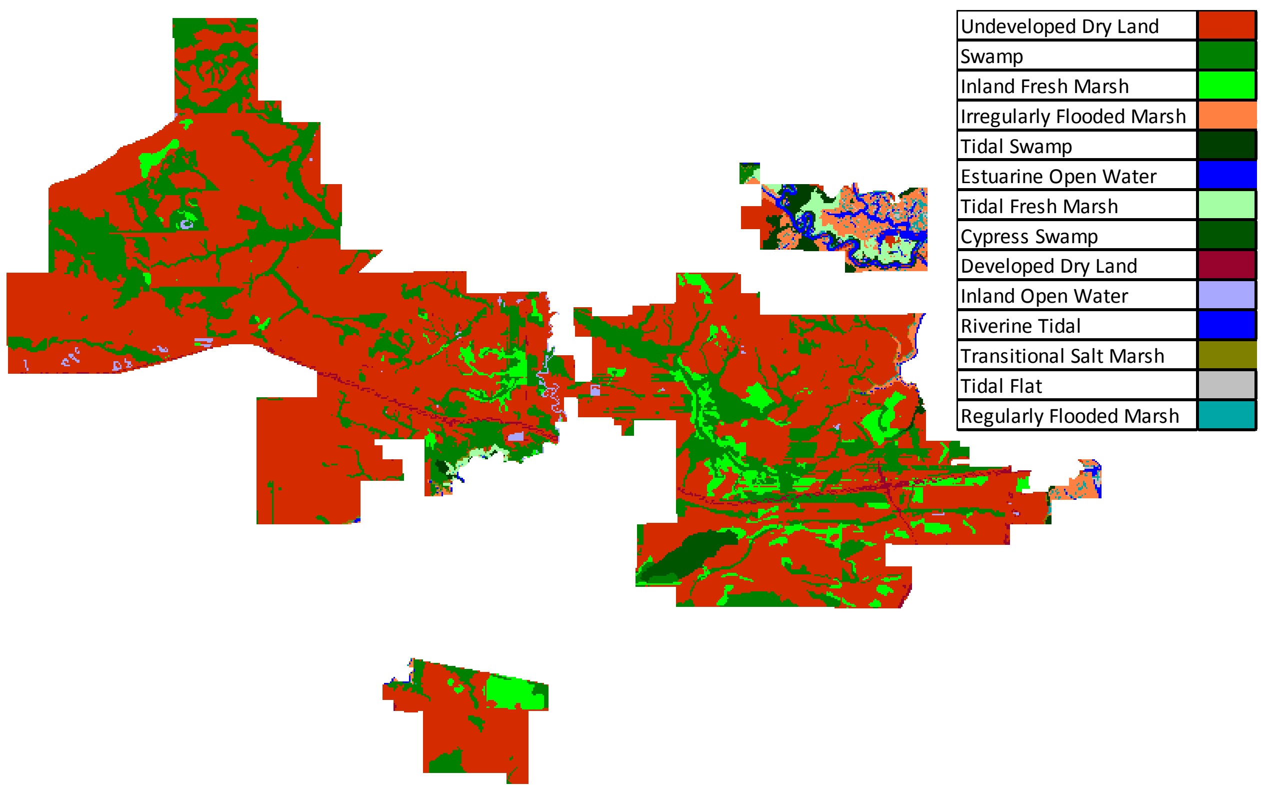
MS Sandhill Crane NWR
IPCC Scenario A1B-Mean, 0.39 m SLR eustatic by 2100

Results in Acres

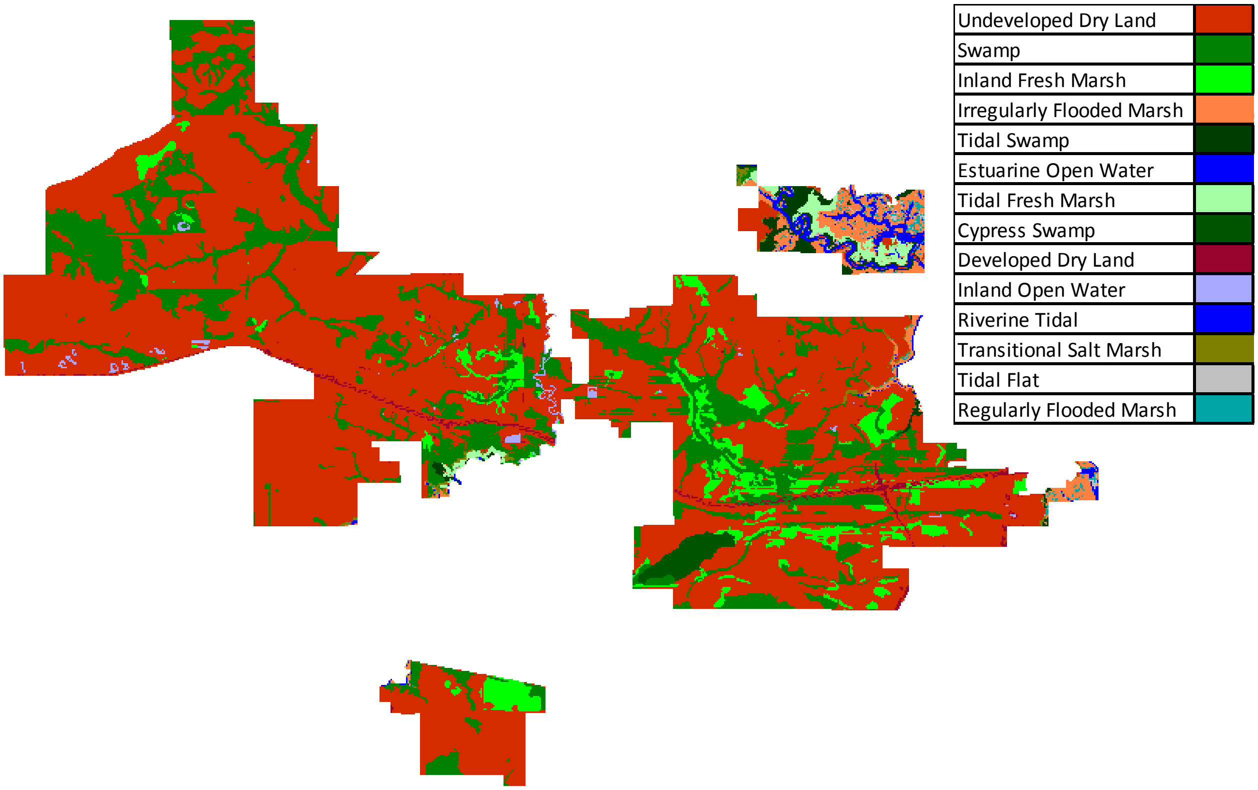
		Initial	2025	2050	2075	2100
	Undeveloped Dry Land	16268	15576	15506	15428	15234
	Swamp	4321	4848	4836	4819	4929
	Inland Fresh Marsh	1067	1166	1213	1259	1287
	Irregularly Flooded Marsh	594	502	509	518	533
	Tidal Swamp	268	250	243	227	194
	Estuarine Open Water	252	260	274	298	308
	Tidal Fresh Marsh	217	207	207	207	207
	Cypress Swamp	201	201	201	201	201
	Developed Dry Land	193	193	193	193	193
	Inland Open Water	112	109	108	107	105
	Riverine Tidal	3	2	2	2	2
	Transitional Salt Marsh	0	50	84	131	180
	Tidal Flat	0	34	32	9	1
	Regularly Flooded Marsh	0	98	88	97	123
	Total (incl. water)	**23496**	**23496**	**23496**	**23496**	**23496**



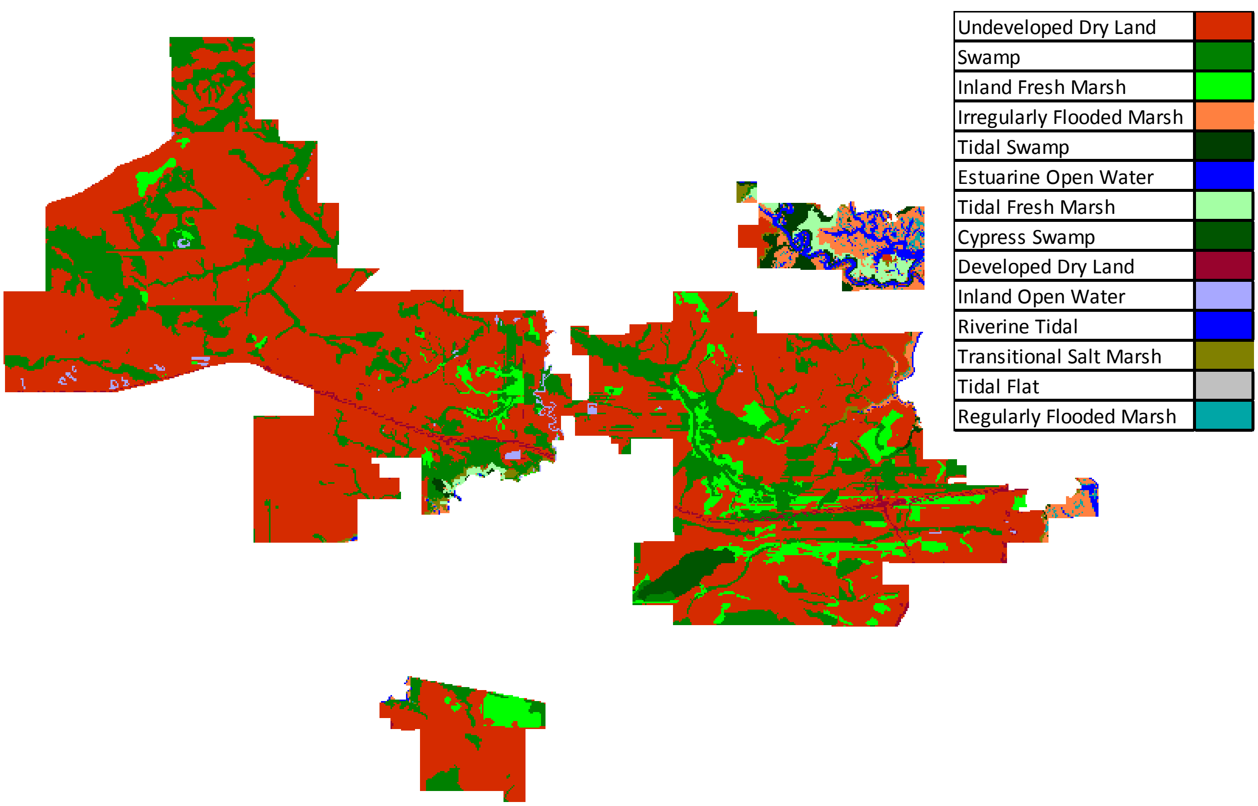
MS Sandhill Crane NWR, Initial Condition



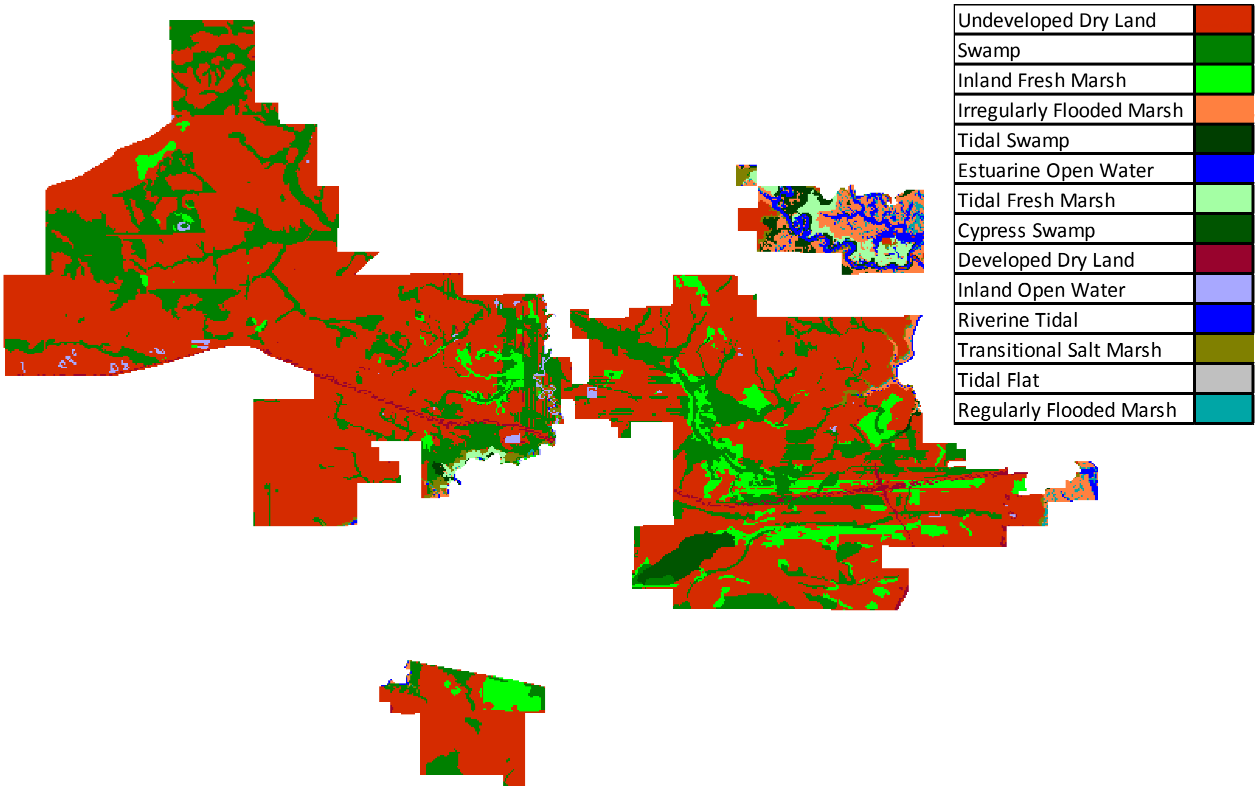
MS Sandhill Crane NWR, 2025, scenario A1B Mean (0.39 m SLR)



MS Sandhill Crane NWR, 2050, scenario A1B Mean (0.39 m SLR)



MS Sandhill Crane NWR, 2075, scenario A1B Mean (0.39 m SLR)

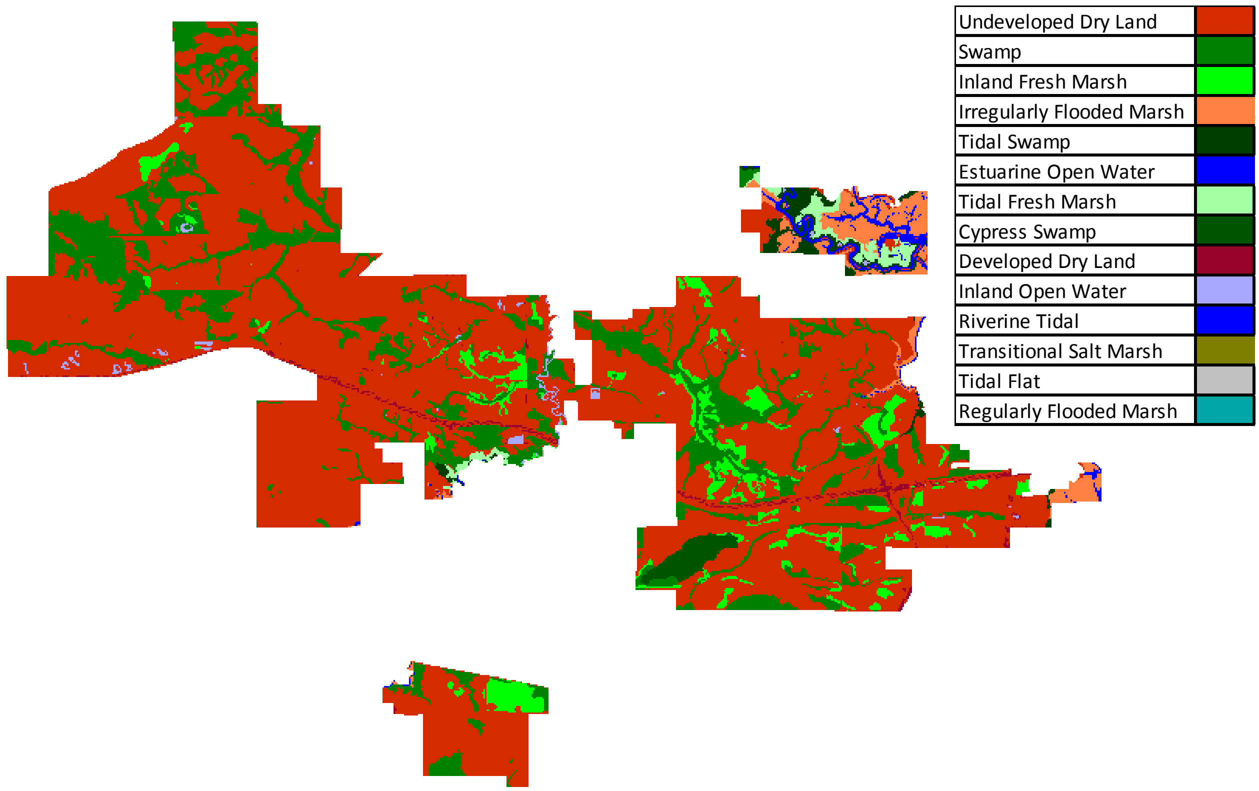


MS Sandhill Crane NWR, 2100, scenario A1B Mean (0.39 m SLR)

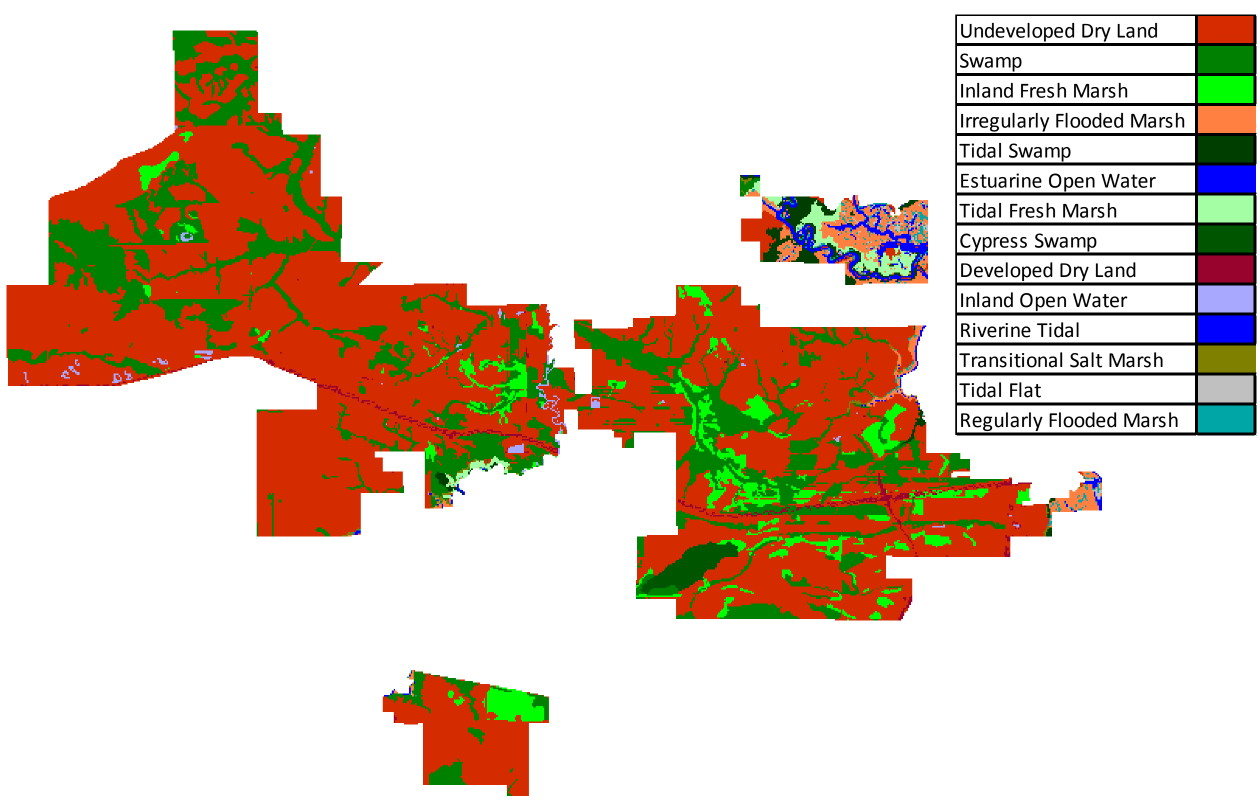
MS Sandhill Crane NWR
IPCC Scenario A1B-Max, 0.69 m SLR eustatic by 2100

Results in Acres

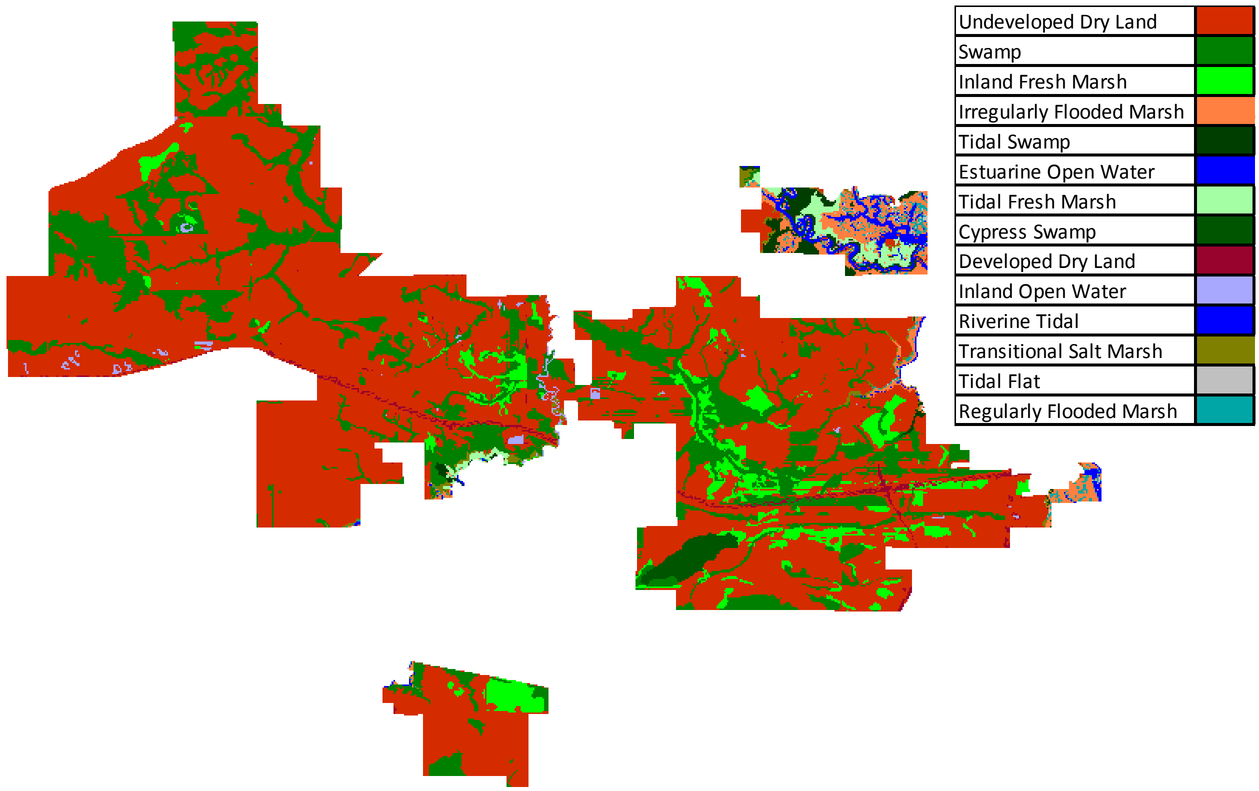
		Initial	2025	2050	2075	2100
	Undeveloped Dry Land	16268	15573	15479	15249	15168
	Swamp	4321	4844	4821	4931	4942
	Inland Fresh Marsh	1067	1166	1211	1259	1287
	Irregularly Flooded Marsh	594	500	478	445	359
	Tidal Swamp	268	248	230	159	90
	Estuarine Open Water	252	260	289	329	361
	Tidal Fresh Marsh	217	207	205	196	180
	Cypress Swamp	201	201	201	201	201
	Developed Dry Land	193	193	193	193	192
	Inland Open Water	112	108	107	103	97
	Riverine Tidal	3	2	2	2	1
	Transitional Salt Marsh	0	55	122	159	139
	Tidal Flat	0	41	35	24	109
	Regularly Flooded Marsh	0	97	124	245	369
	Total (incl. water)	**23496**	**23496**	**23496**	**23496**	**23496**



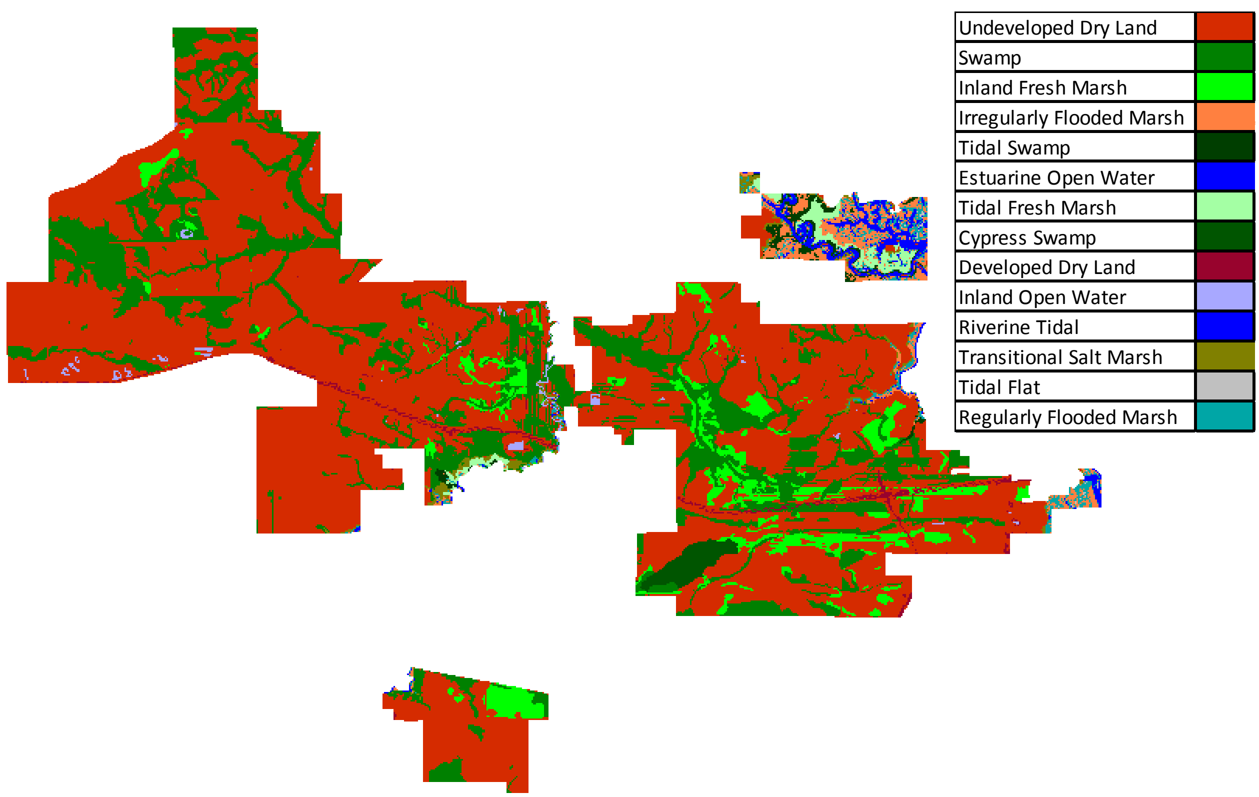
MS Sandhill Crane NWR, Initial Condition (0.69 m SLR)



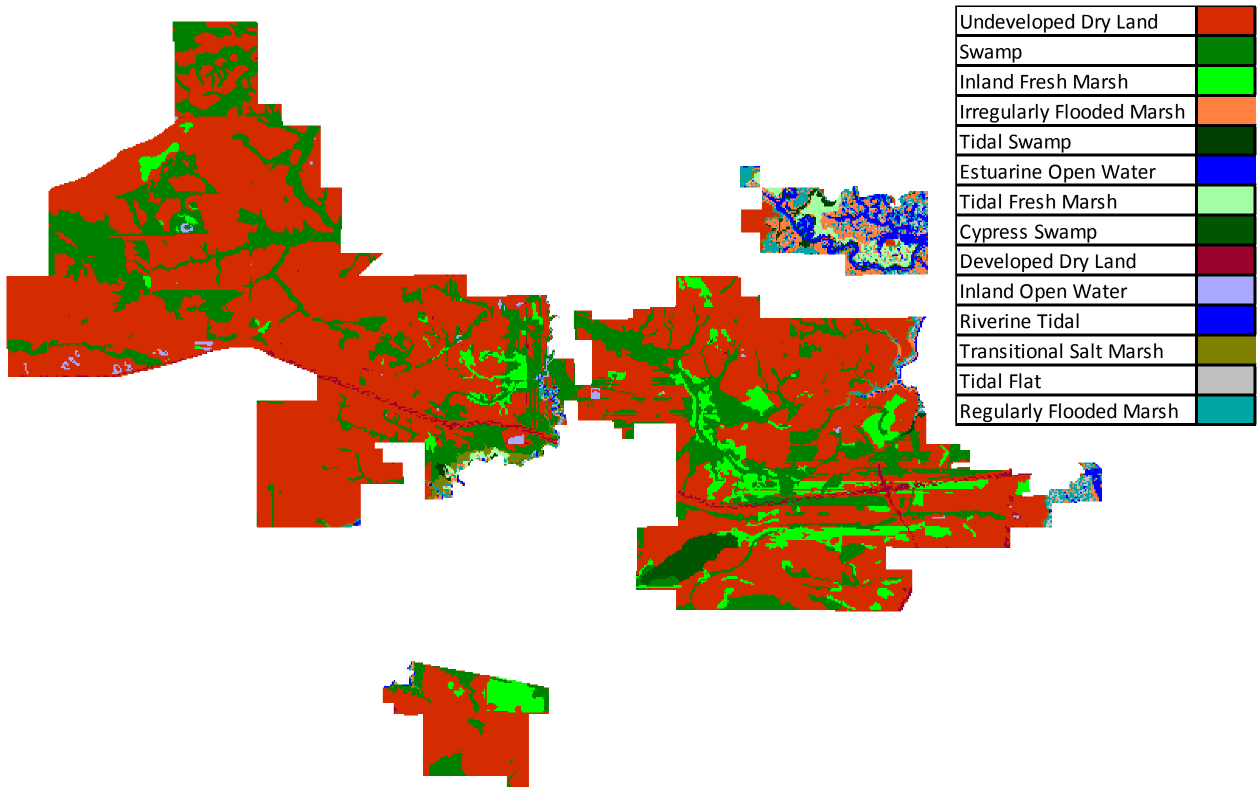
MS Sandhill Crane NWR, 2025, Scenario A1B Maximum (0.69 m SLR)



MS Sandhill Crane NWR, 2050, Scenario A1B Maximum (0.69 m SLR)



MS Sandhill Crane NWR, 2075, Scenario A1B Maximum (0.69 m SLR)

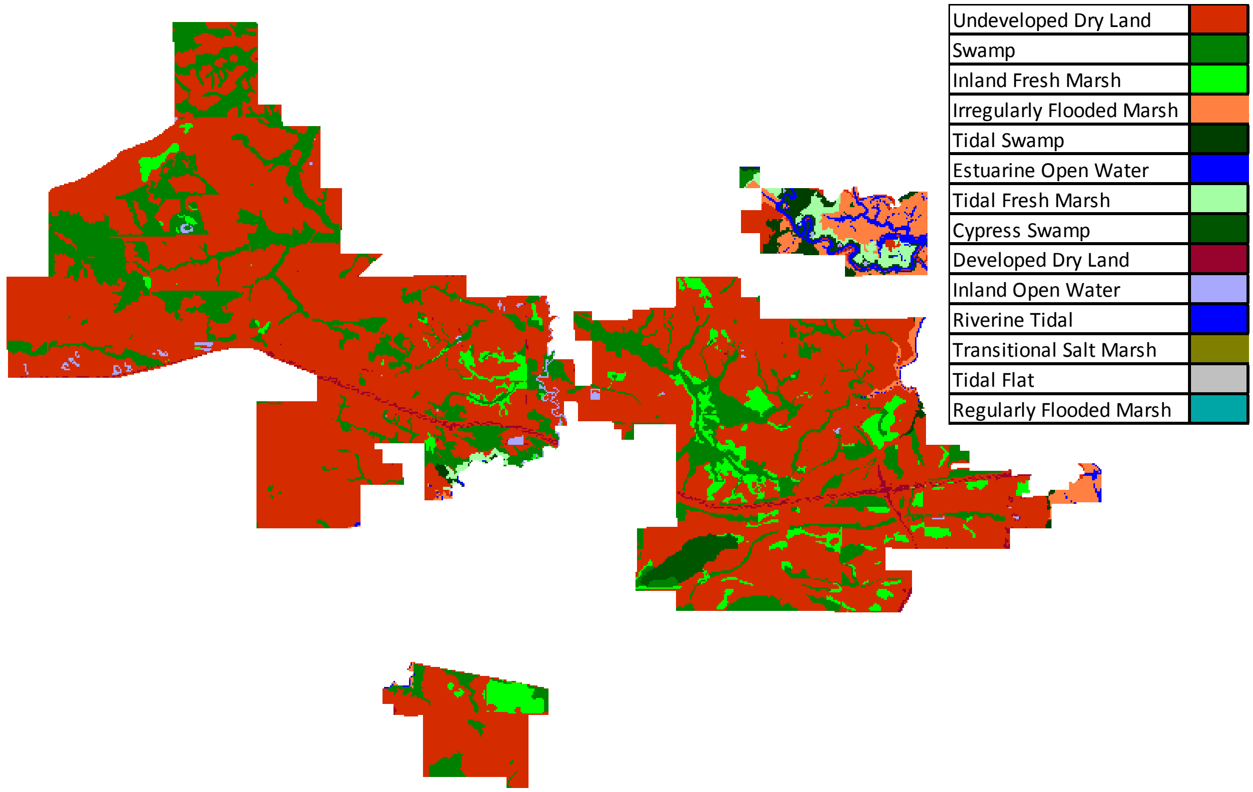


MS Sandhill Crane NWR, 2100, Scenario A1B Maximum (0.69 m SLR)

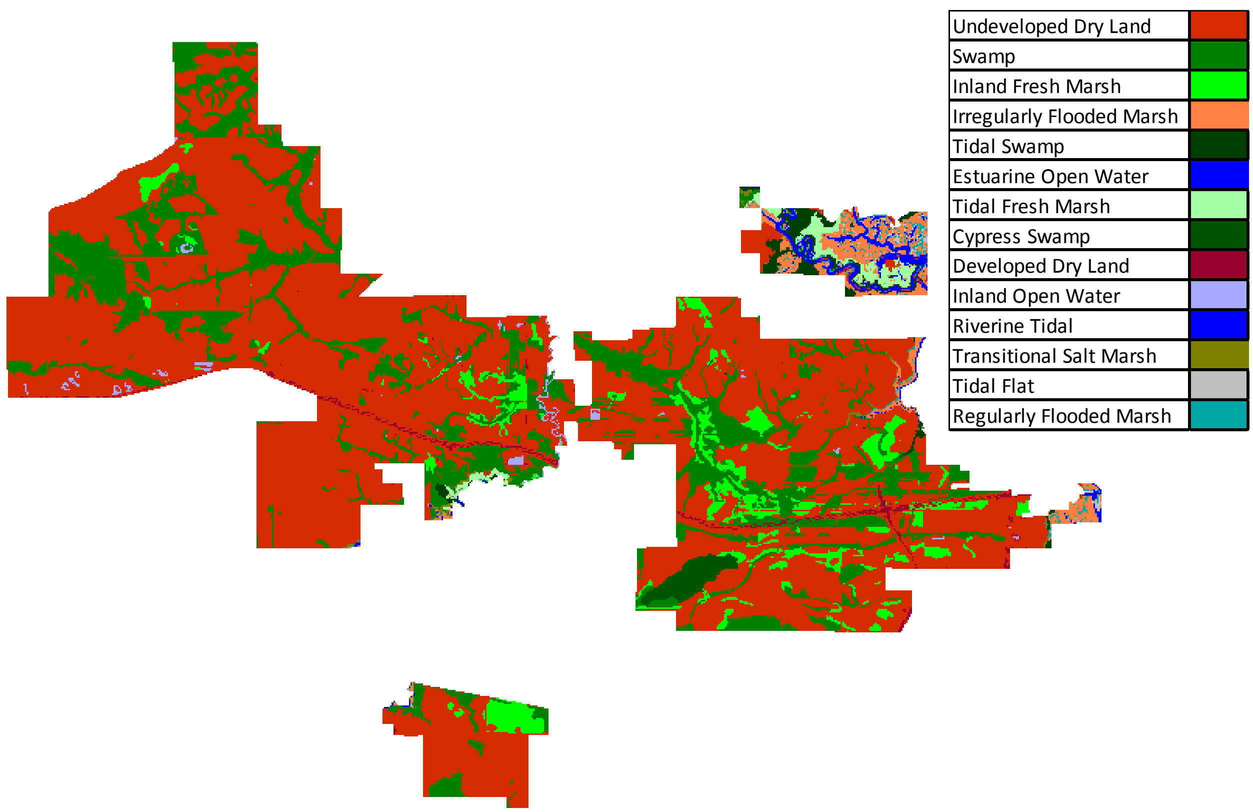
MS Sandhill Crane NWR
1 m eustatic SLR by 2100

Results in Acres

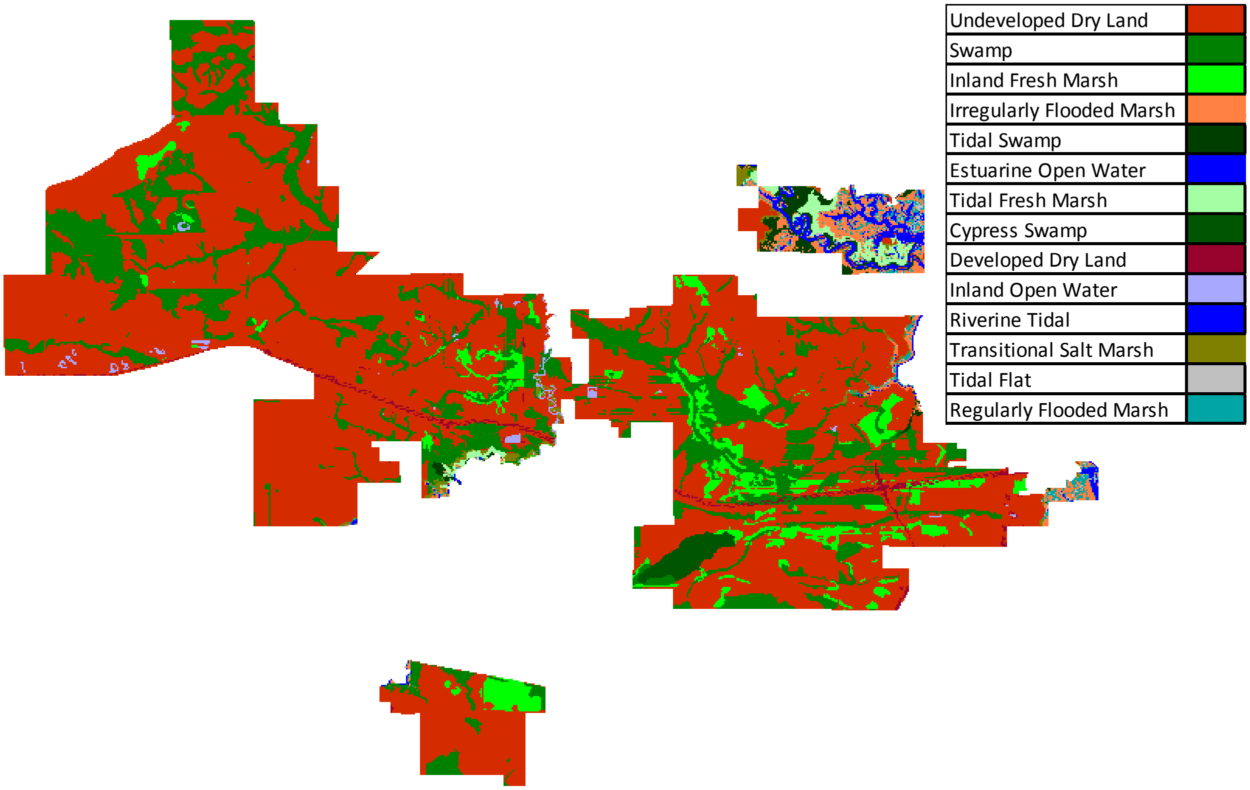
		Initial	2025	2050	2075	2100
	Undeveloped Dry Land	16268	15569	15456	15236	15140
	Swamp	4321	4840	4806	4912	4889
	Inland Fresh Marsh	1067	1166	1210	1259	1286
	Irregularly Flooded Marsh	594	487	427	374	191
	Tidal Swamp	268	246	209	98	42
	Estuarine Open Water	252	261	311	388	559
	Tidal Fresh Marsh	217	206	194	149	81
	Cypress Swamp	201	201	201	201	201
	Developed Dry Land	193	193	193	192	192
	Inland Open Water	112	108	107	98	92
	Riverine Tidal	3	2	2	2	1
	Transitional Salt Marsh	0	61	150	117	126
	Tidal Flat	0	49	56	140	254
	Regularly Flooded Marsh	0	107	174	332	442
	Total (incl. water)	**23496**	**23496**	**23496**	**23496**	**23496**



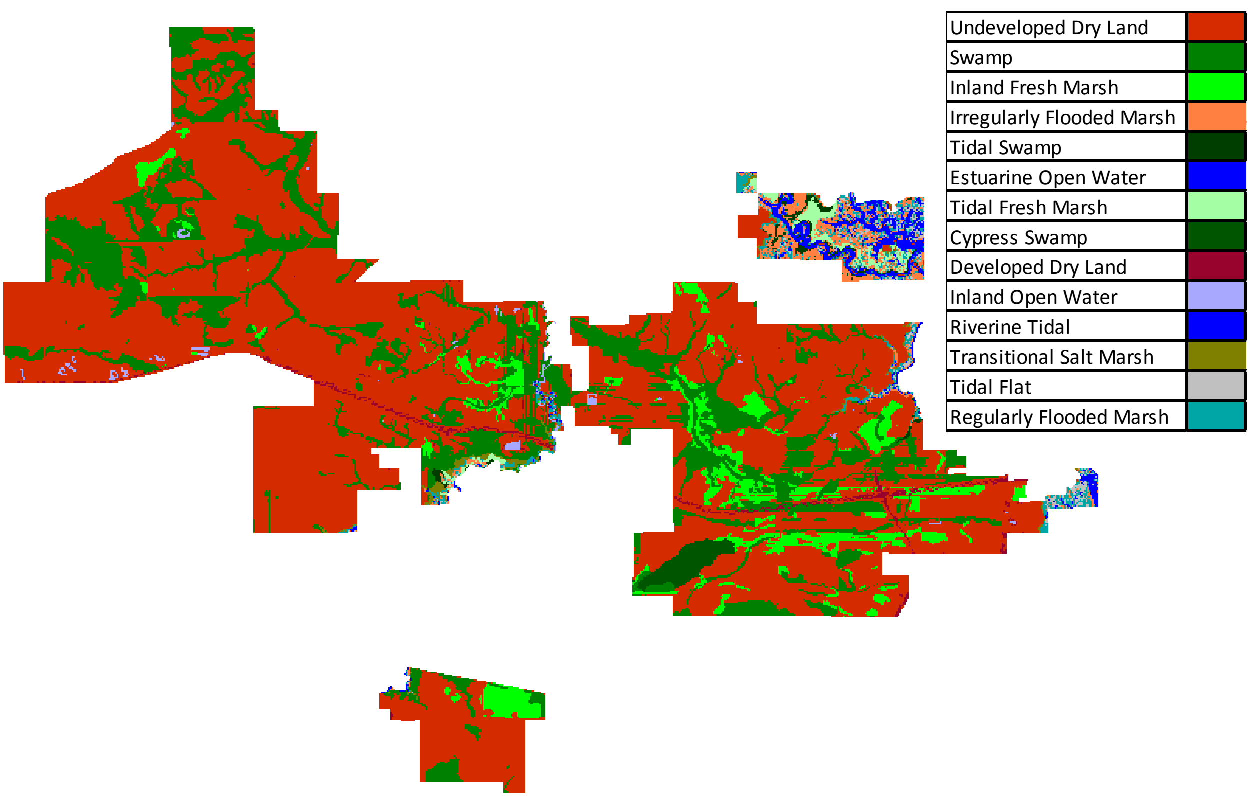
MS Sandhill Crane NWR, Initial Condition



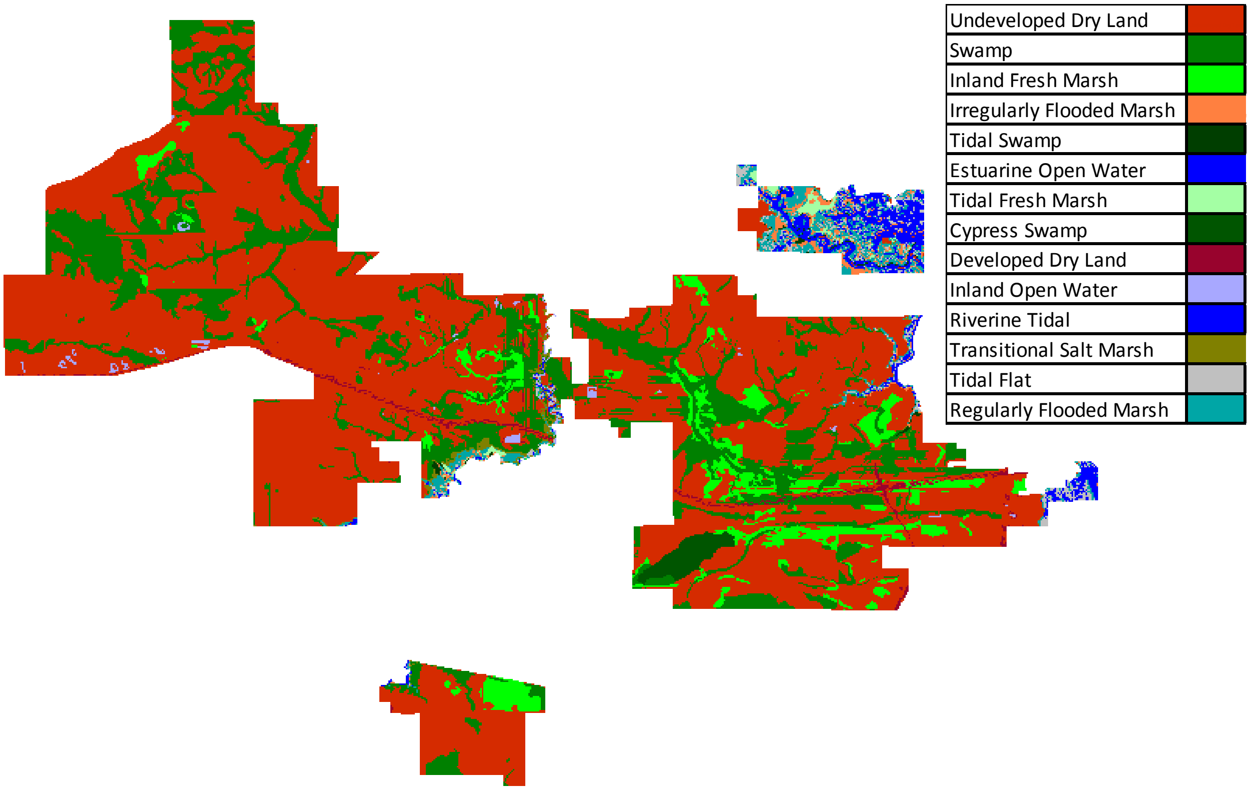
MS Sandhill Crane NWR, 2025, 1 m SLR



MS Sandhill Crane NWR, 2050, 1 m SLR



MS Sandhill Crane NWR, 2075, 1 m SLR

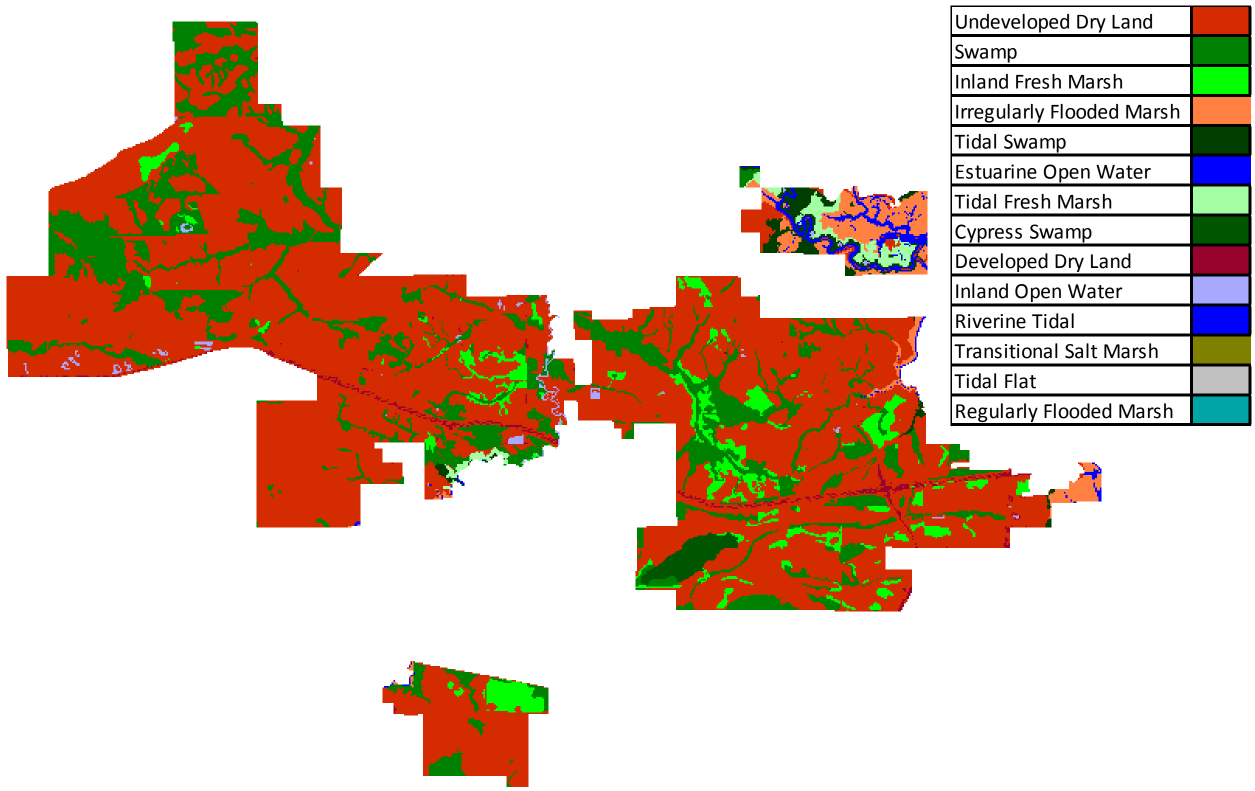


MS Sandhill Crane NWR, 2100, 1 m SLR

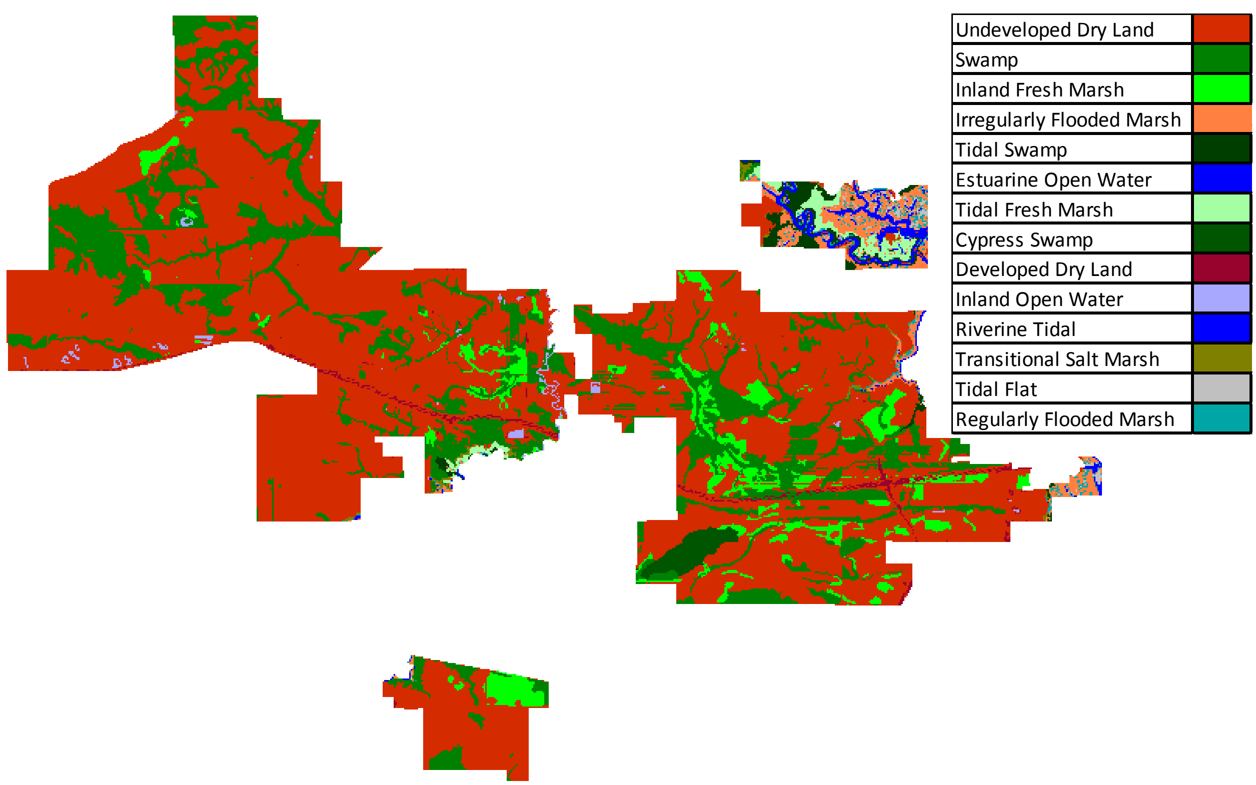
MS Sandhill Crane NWR
1.5 m eustatic SLR by
2100

Results in Acres

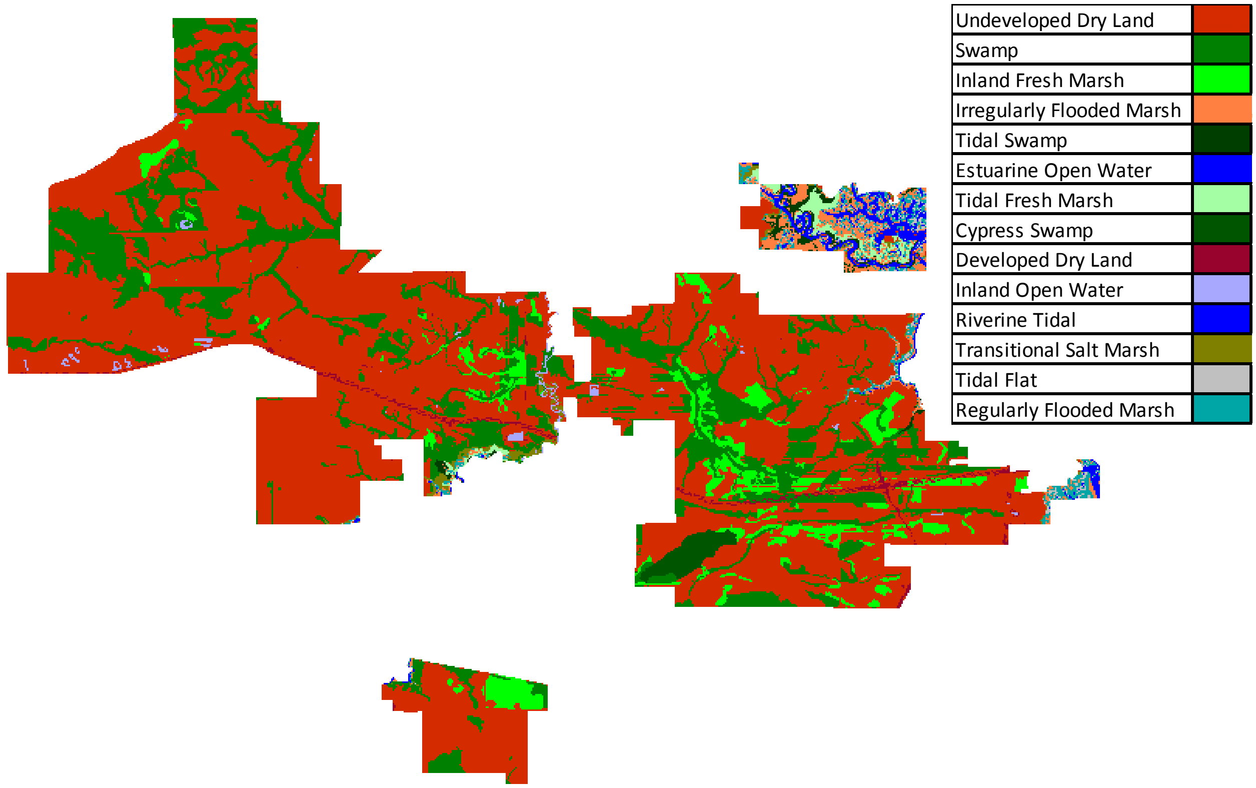
		Initial	2025	2050	2075	2100
	Undeveloped Dry Land	16268	15561	15434	15193	15026
	Swamp	4321	4831	4787	4867	4849
	Inland Fresh Marsh	1067	1166	1210	1260	1288
	Irregularly Flooded Marsh	594	465	389	188	37
	Tidal Swamp	268	241	138	42	30
	Estuarine Open Water	252	262	336	484	814
	Tidal Fresh Marsh	217	202	153	44	5
	Cypress Swamp	201	201	201	201	201
	Developed Dry Land	193	193	193	192	192
	Inland Open Water	112	108	107	94	84
	Riverine Tidal	3	2	2	1	1
	Transitional Salt Marsh	0	73	147	117	163
	Tidal Flat	0	65	111	289	506
	Regularly Flooded Marsh	0	126	288	523	300
	Total (incl. water)	**23496**	**23496**	**23496**	**23496**	**23496**



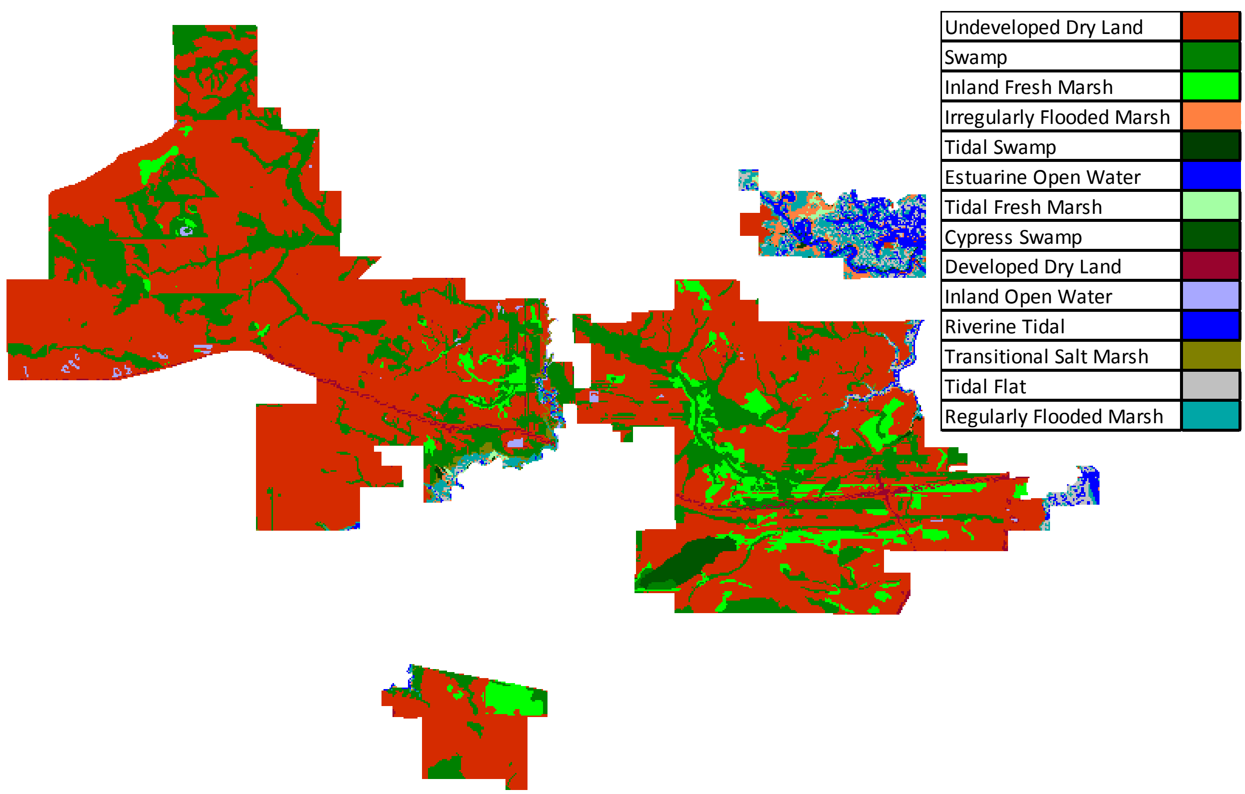
MS Sandhill Crane NWR, Initial Condition



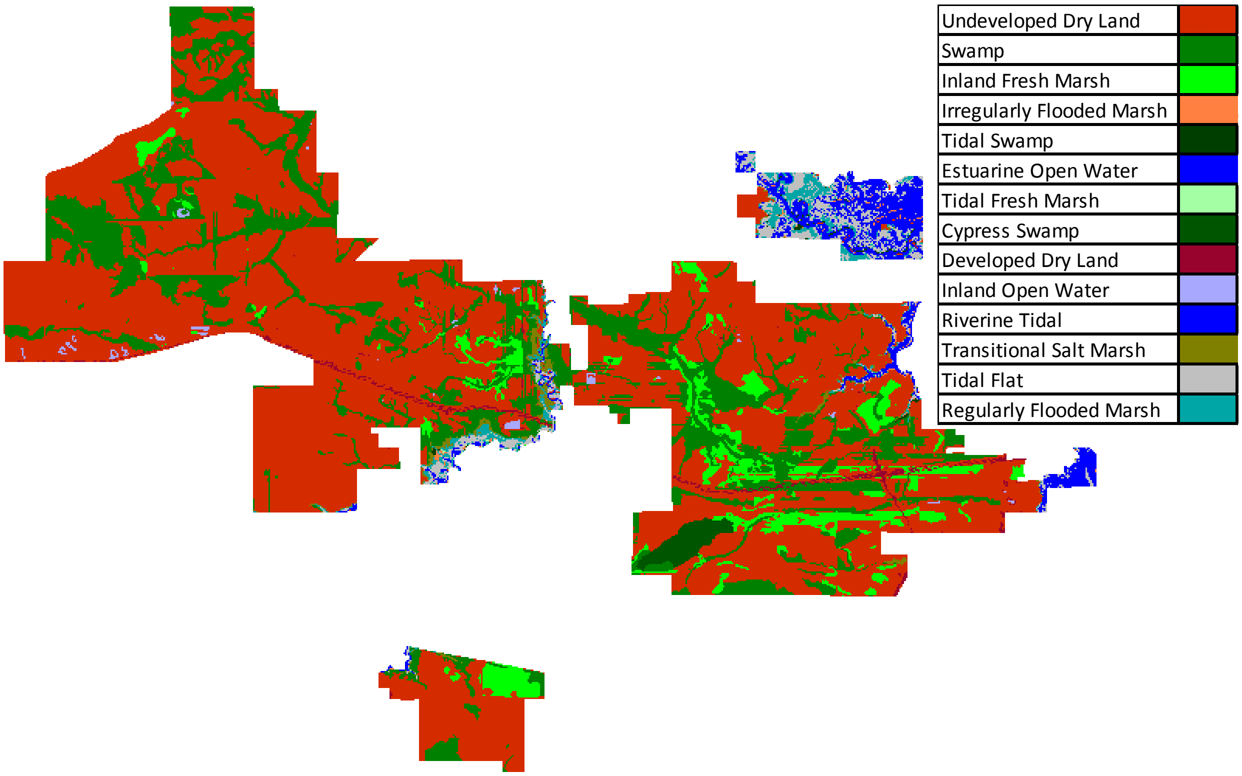
MS Sandhill Crane NWR, 2025, 1.5 m SLR



MS Sandhill Crane NWR, 2050, 1.5 m SLR



MS Sandhill Crane NWR, 2075, 1.5 m SLR

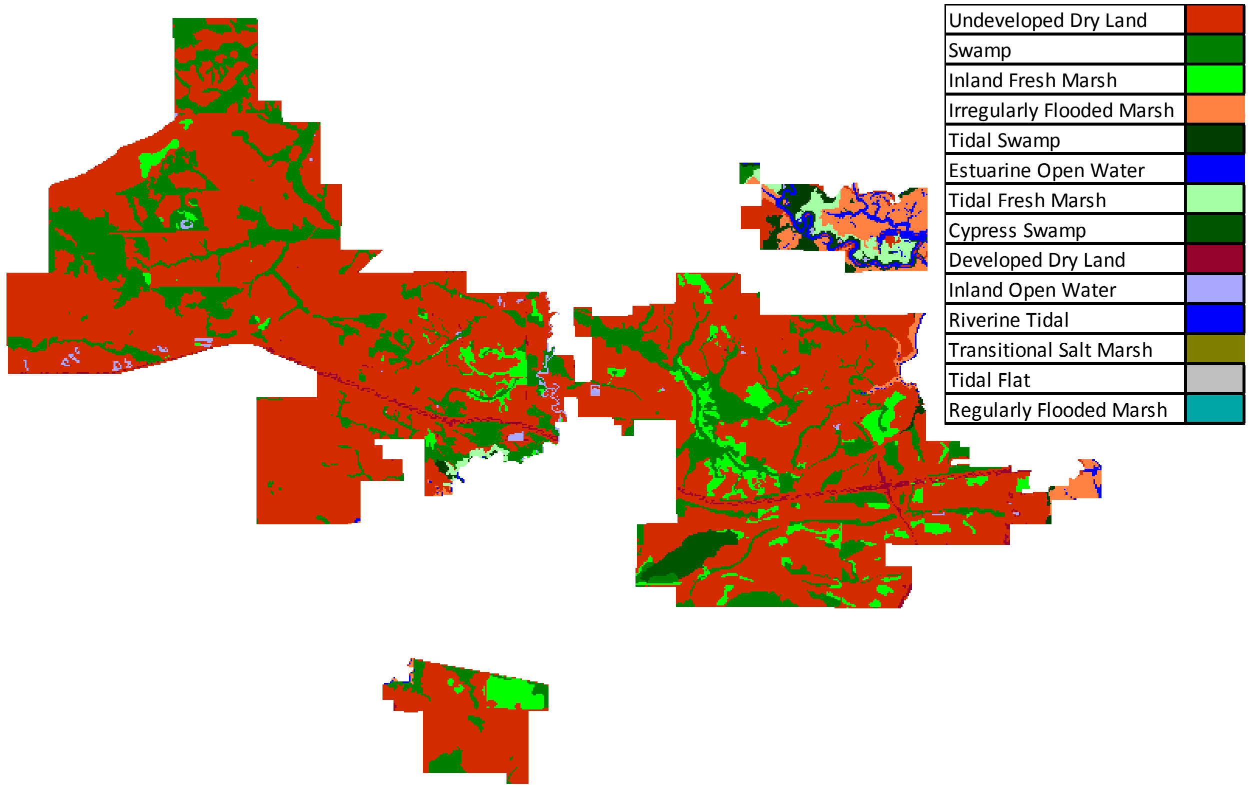


MS Sandhill Crane NWR, 2100, 1.5 m SLR

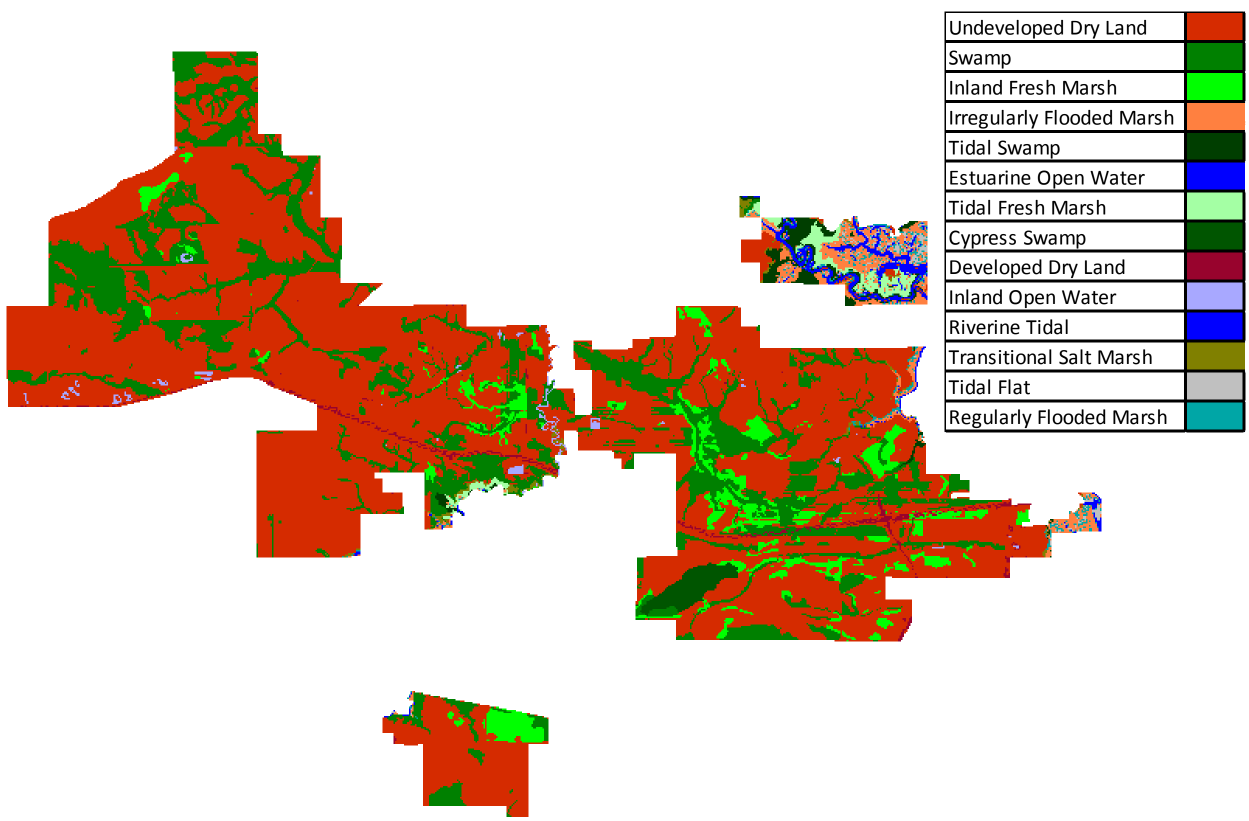
MS Sandhill Crane NWR
2 m eustatic SLR by 2100

Results in Acres

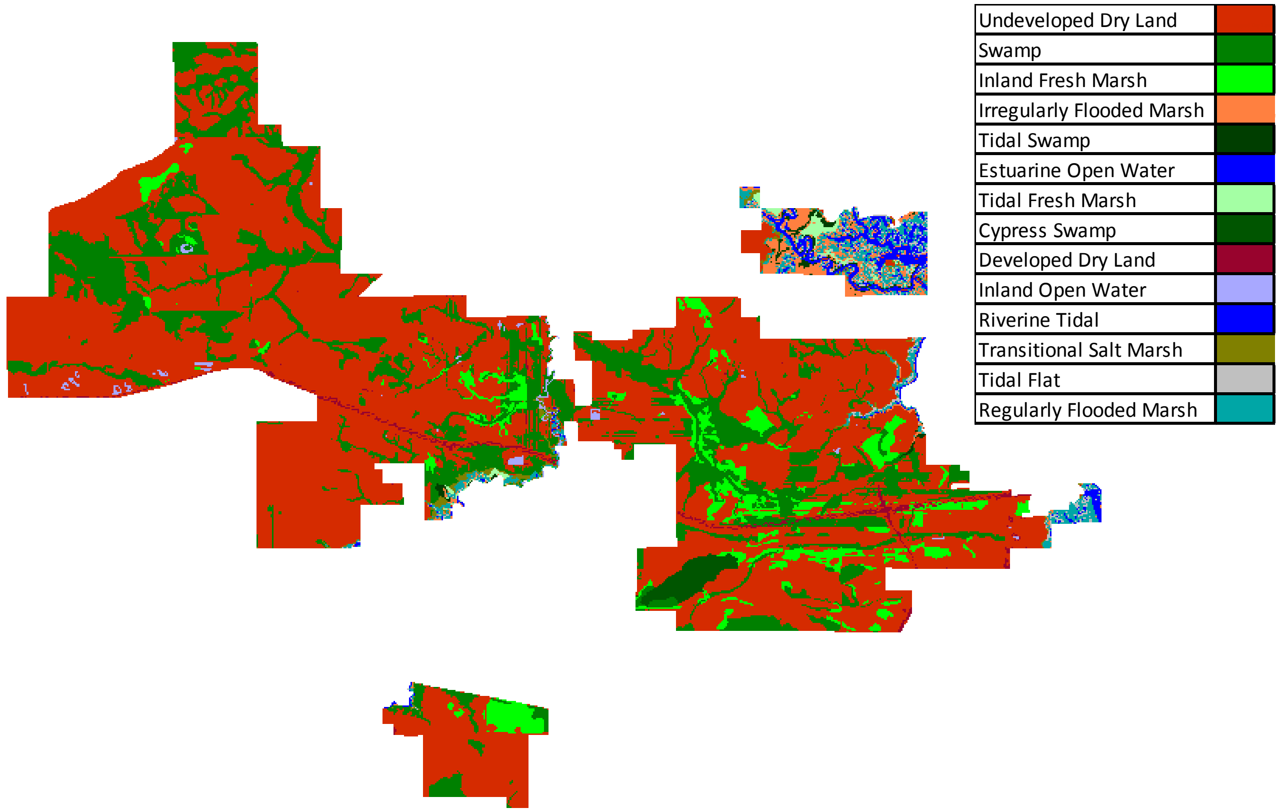
		Initial	2025	2050	2075	2100
	Undeveloped Dry Land	16268	15541	15294	15121	14824
	Swamp	4321	4821	4900	4854	4869
	Inland Fresh Marsh	1067	1163	1210	1258	1284
	Irregularly Flooded Marsh	594	439	331	83	28
	Tidal Swamp	268	234	89	33	26
	Estuarine Open Water	252	264	365	555	1063
	Tidal Fresh Marsh	217	196	93	5	2
	Cypress Swamp	201	201	201	201	201
	Developed Dry Land	193	193	192	192	191
	Inland Open Water	112	107	101	91	82
	Riverine Tidal	3	2	2	1	1
	Transitional Salt Marsh	0	102	126	171	257
	Tidal Flat	0	84	151	475	432
	Regularly Flooded Marsh	0	149	443	454	235
	Total (incl. water)	**23496**	**23496**	**23496**	**23496**	**23496**



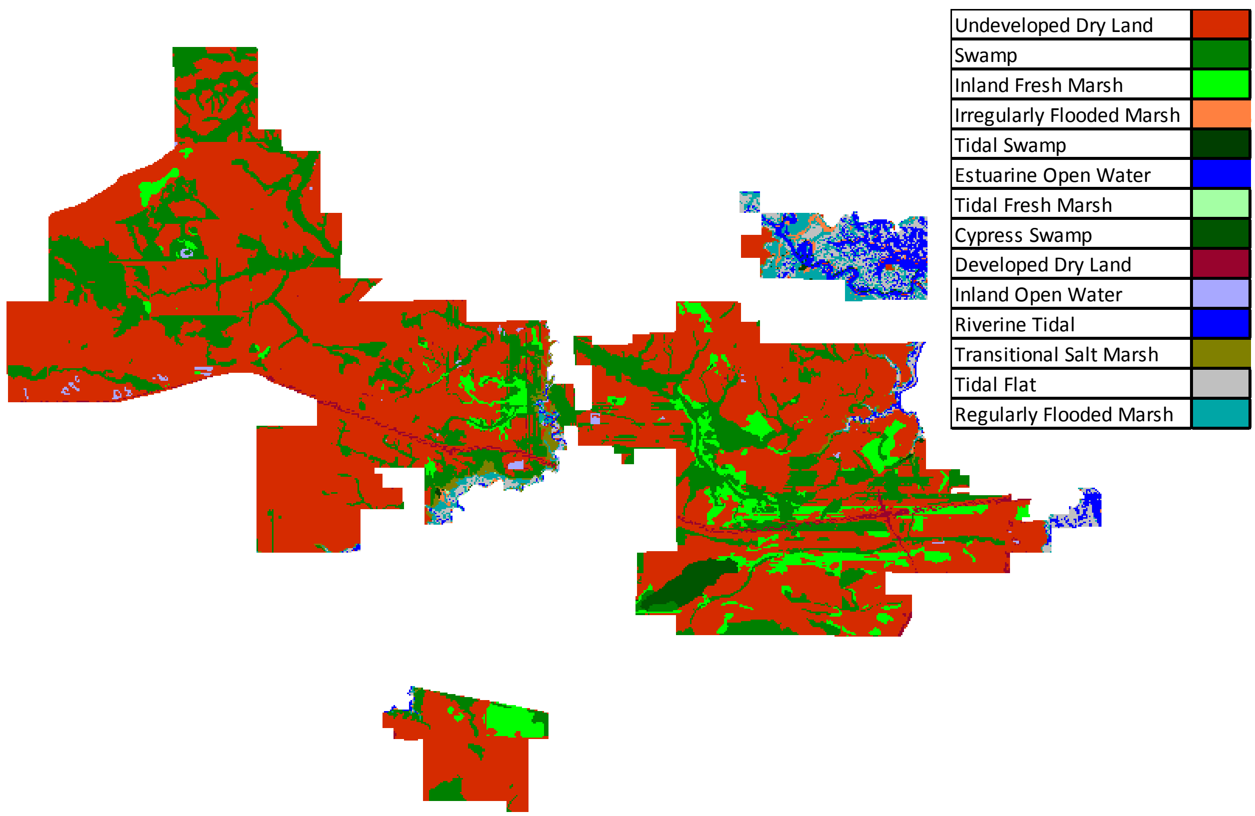
MS Sandhill Crane NWR, Initial Condition



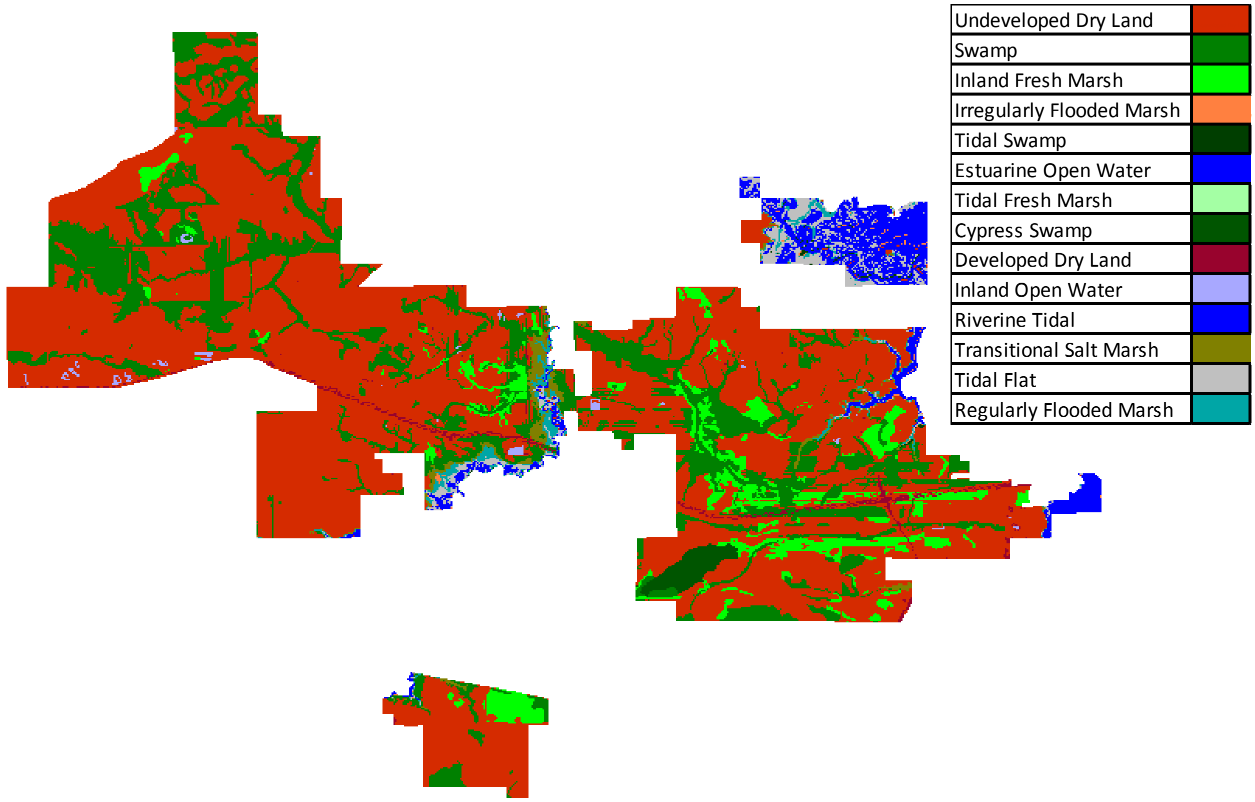
MS Sandhill Crane NWR, 2025, 2 m SLR



MS Sandhill Crane NWR, 2050, 2 m SLR



MS Sandhill Crane NWR, 2075, 2 m SLR



MS Sandhill Crane NWR, 2100, 2 m SLR

Elevation Uncertainty Analysis

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

Vertical accuracy was not specified in the metadata for the 2005 Mississippi Merged LiDAR Data. However, according to the LIDAR Topographic Data Compilation Report (FEMA, 2006 [2]) the vertical accuracy for Jackson County had a root mean square error (RMSE) of 7.5 cm with a maximum error of 11 cm. This value was reflected in the RMSE parameters for this uncertainty analysis (Figure 17).

According the VDatum website the RMSE for converting NAVD88 to MTL within the study region is a relatively large 15.6 cm (National Oceanic and Atmospheric Association 2010). This value was determined by combining the uncertainty associated with the NAVD to MSL transformation (14.8 cm) and MSL to MTL transformation (0.8 cm) for the relevant region (Louisiana/Mississippi - Eastern Louisiana to Mississippi Sound).

Elevation data uncertainty was evaluated using the application of a spatially autocorrelated error field to the existing digital elevation map in the manner of Heuvelink (1998). In this application, an error field for both the DEM uncertainty and the VDatum correction uncertainty were applied to the existing DEM. This approach uses the normal distribution as specified by the Root Mean Squared Error for the dataset and applies it randomly over the entire study area, but with spatial autocorrelation included (Figure 17). Since elevation error is generally spatially autocorrelated (Hunter and Goodchild 1997), this method provides a means to calculate a number of equally-likely elevation maps given error statistics about the data set. A stochastic analysis may then be run (running the model with each of these elevation maps) to assess the overall effects of elevation uncertainty. Heuvelink's method has been widely recommended as an approach for assessing the effects of elevation data uncertainty (Darnell et al. 2008; Hunter and Goodchild 1997). In this analysis, it was assumed that elevation errors were strongly spatially autocorrelated, using a "p-value" of 0.2495 [3].

---

[2] FEMA, 2006, Mississippi Coastal Analysis Project LIDAR Topographic Data Compilation Report July 10, 2006.

[3] 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.

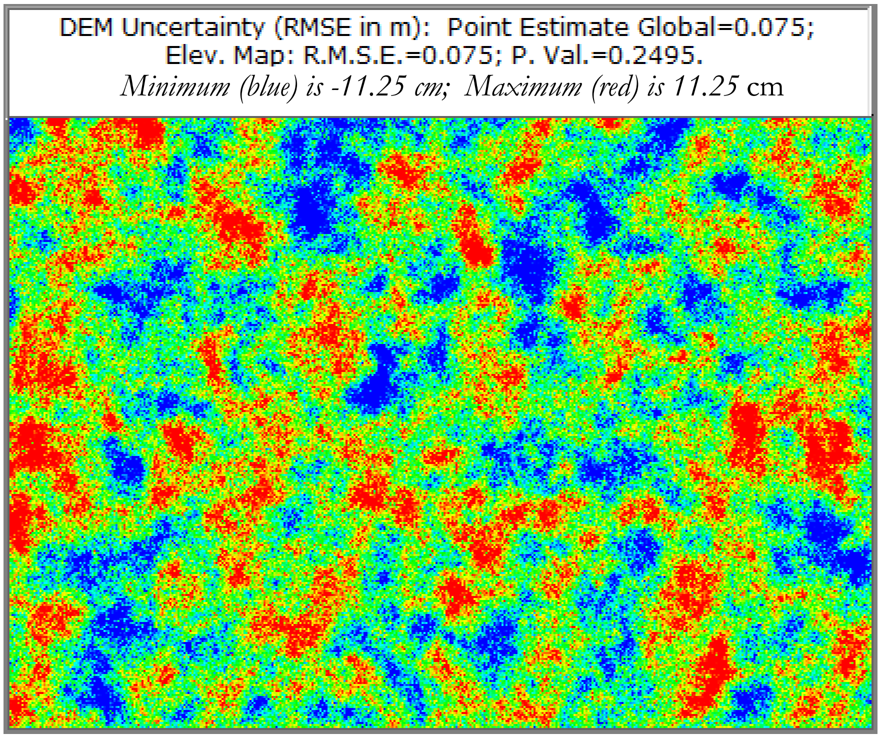


Figure 17. A sample of a spatially autocorrelated error field using LiDAR error parameters from this model application

In this model elevation uncertainty analysis, 200 iterations were run for the study area representing approximately 24 hours of CPU time. The model was run with 0.69 m of eustatic SLR by 2100 for each iteration.

In terms of overall acreage change, the effects of elevation uncertainty within this modeling analysis were fairly limited, with the coefficient of variance (CV) remaining below 1% for the three most prevalent land cover categories. These results reveal that the most widespread land covers do not substantially change given uncertainty in elevation values (Figure 18 and Figure 19). Irregularly-flooded marsh showed more variation as a function of elevation data ranging from 282 to 433 predicted acres (Figure 20). Depending on its initial condition elevation within the tidal frame, irregularly-flooded marsh is either more resilient or more subject to flooding.

Variable Name	Min	Mean	Max	Std. Dev.	Deterministic	CV
Undeveloped Dry Land	15,075.1	15,185.1	15,345.5	41.0	15,168.9	0.3%
Swamp	4,760.1	4,930.9	5,031.6	36.8	4,941.8	0.7%
Inland-Fresh Marsh	1,239.2	1,274.8	1,304.4	12.8	1,286.5	1.0%
Estuarine Open Water	337.0	387.8	460.2	23.5	359.7	6.1%
Irreg.-Flooded Marsh	282.8	362.5	433.4	30.9	361.4	8.5%
Regularly-Flooded Marsh	272.7	334.7	403.2	22.9	368.4	6.8%
Cypress Swamp	200.6	201.0	201.6	0.2	201.0	0.1%
Developed Dry Land	192.1	192.4	192.7	0.1	192.4	0.1%

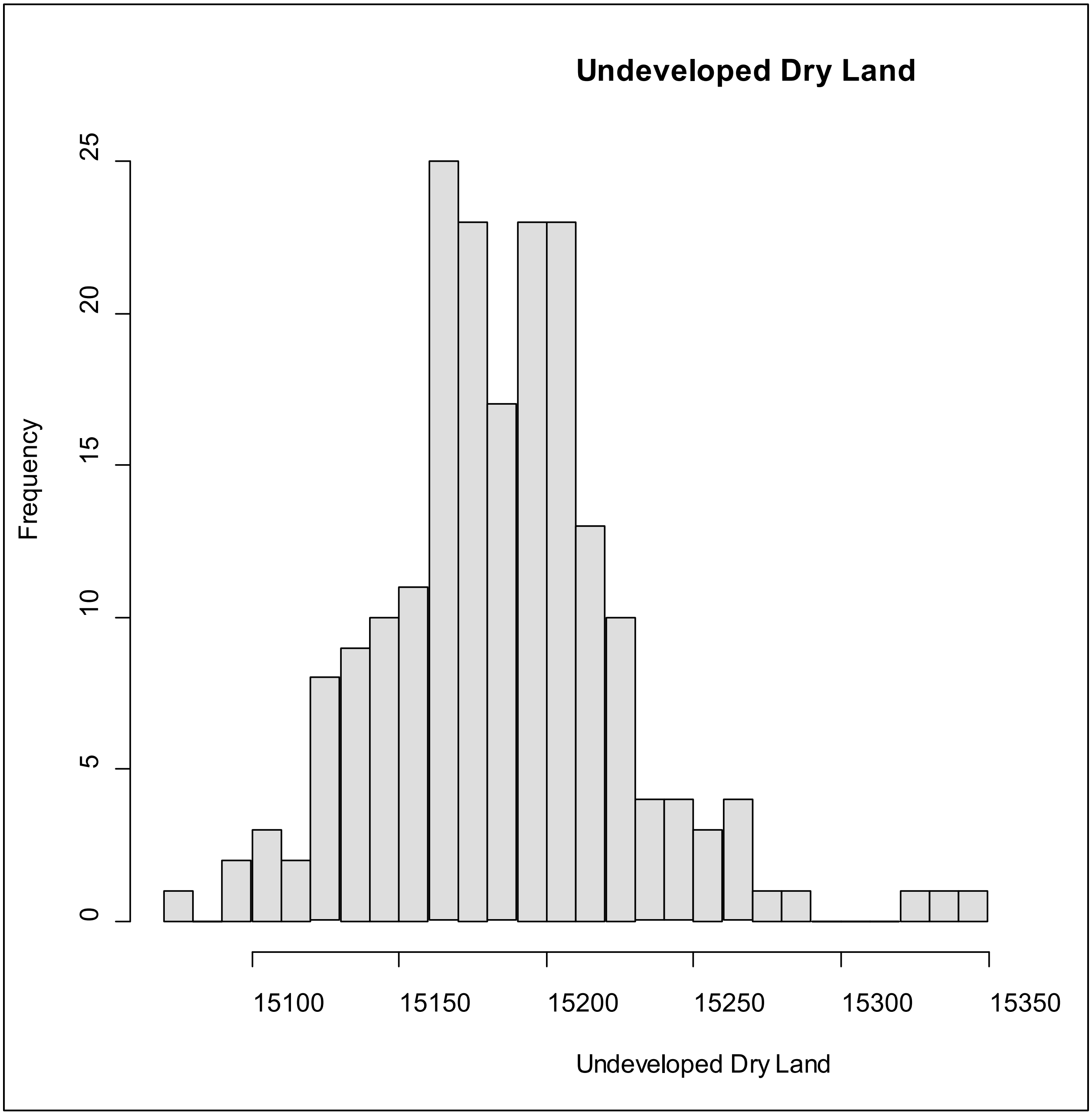


Figure 18. Elevation uncertainty result distribution for undeveloped dry land within the refuge

Note, this shows predicted results in 2100 under 0.69 meters of eustatic SLR. The initial condition for undeveloped-dry land was 16,268 acres.

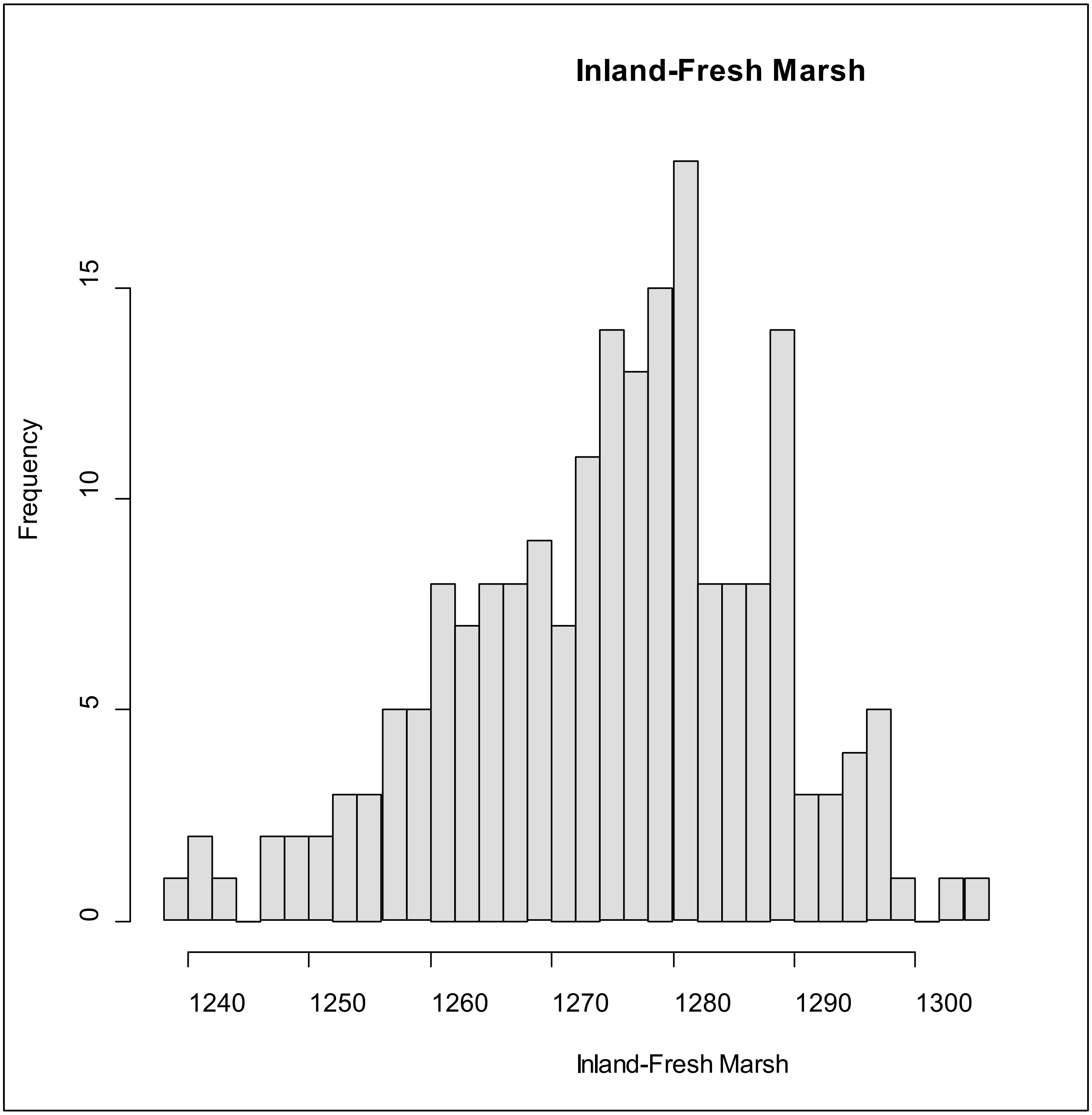


Figure 19. Elevation uncertainty result distribution for inland-fresh marsh within the refuge

Note, this shows predicted results in 2100 under 0.69 meters of eustatic SLR. The initial condition for inland-fresh marsh was 1,067 acres.

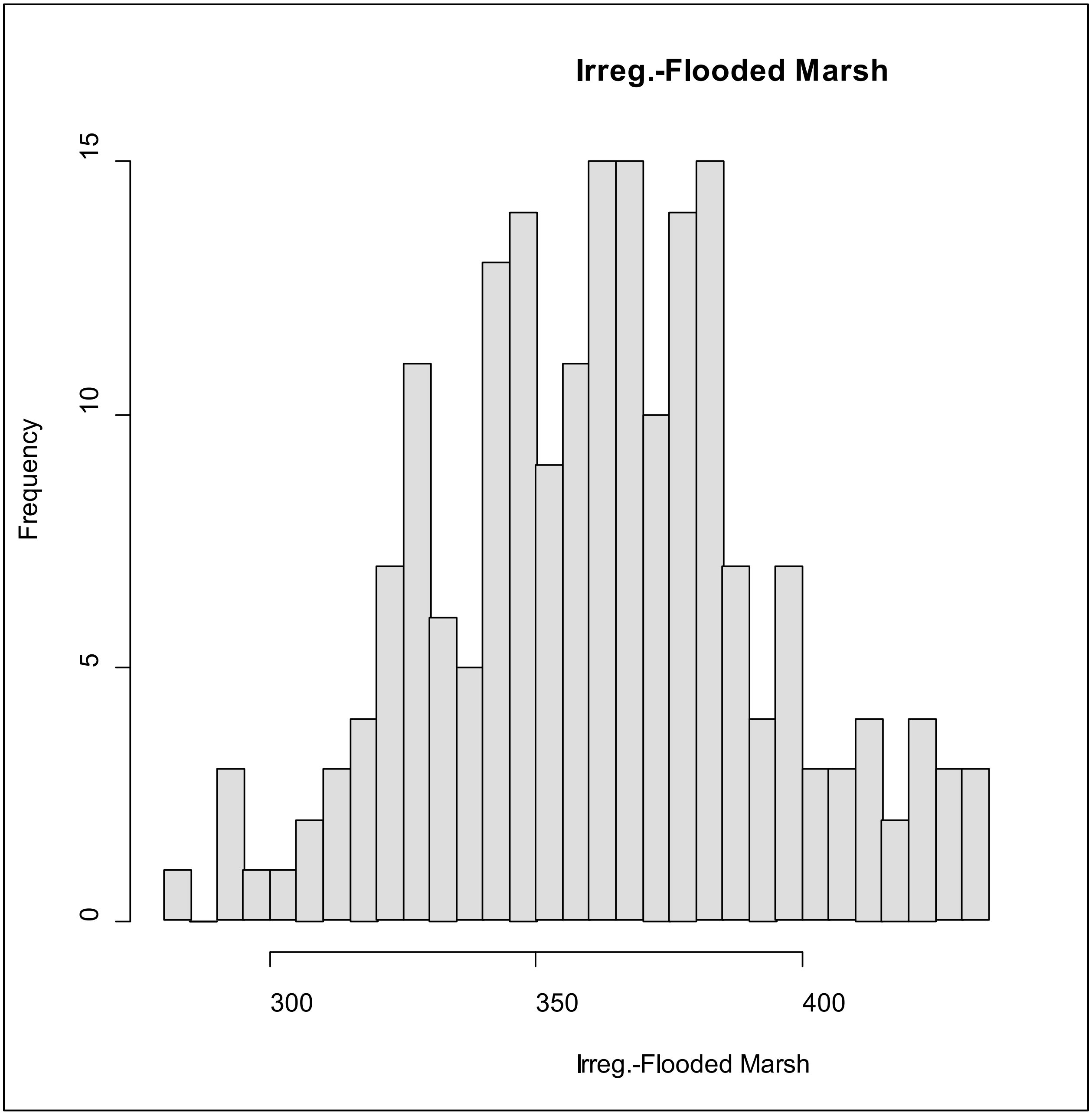


Figure 20. Elevation uncertainty result distribution for irregularly-flooded marsh within the refuge

Note, this shows predicted results in 2100 under 0.69 meters of eustatic SLR. The initial condition for irregularly-flooded marsh was 594 acres.

Discussion

Model results for MS Sandhill Crane NWR indicate that the refuge is fairly resilient to the SLR scenarios examined. The majority of the refuge is located at elevations that preclude effects from SLR by 2100.

The most heavily affected areas are the eastern boundary and the north-east detached section of the refuge. By 2100 these areas may be inundated given SLR scenarios of 1 m by 2100 and above. However, this model result may be affected by the lack of information on local tide ranges in the Paige Lake region and at other locations up the Pascagoula River.

When rates of sea-level rise exceed predicted accretion rates in this region (SLR>0.69 m by 2100), irregularly-flooded marsh are predicted to sustain considerable losses, over 40% in all scenarios run. Initially, irregularly-flooded marshes are converted to regularly-flooded marshes but for higher SLR scenarios regularly-flooded marshes start to be lost as well.

Tidal swamps are also predicted to be vulnerable with predicted losses of at least 28%. On the contrary, swamp and inland fresh marsh are predicted to have a net gain, approximately 13% and 20% respectively for all SLR scenarios due to predictions of soil saturation.

Local accretion data were not available for this site, and accretion values were estimated using data from Biloxi Bay. Measurements of accretion rates within the refuge itself could provide better predictions of marsh losses in the future.

Due to wetland data-layer limitations, a useful hindcast of the SLAMM model was not possible. The historic wetland layer available is only ten years older than the current wetland layer, meaning the hindcast model only reflects 3 cm of global SLR (a quantity well under the error in the elevation data set). Second and more importantly, the two NWI surveys do not appear to be comparable due to differences in imagery quality and interpretation.

References

Barry, M. Data Summary of Working Vegetation Maps of the MS Sandhill Crane National Wildlife Refuge. Institution for Regional Conservation, 2009.

Cahoon, D.R., J. W. Day, Jr., and D. J. Reed, 1999. "The influence of surface and shallow subsurface soil processes on wetland elevation: A synthesis." *Current Topics in Wetland Biogeochemistry*, 3, 72-88.

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

Chen, J. L., Wilson, C. R., Tapley, B. D., 2006 "Satellite Gravity Measurements Confirm Accelerated Melting of Greenland Ice Sheet" *Science* 2006 0: 1129007

Clark, J. S. and W. A. Patterson III. 1984. Pollen, Pb-210 and sedimentation in the intertidal environment. Journal of Sedimentary Petrology 54(4):1249-1263.

Clough, J.S. Park, R.A. and R. Fuller, 2010, *SLAMM Technical Documentation, Release 6.0 beta, Draft,* January 2010, http://warrenpinnacle.com/prof/SLAMM

Craft C, Clough J, Ehman J, Guo H, Joye S, Machmuller M, Park R, and Pennings S. Effects of Accelerated Sea Level Rise on Delivery of Ecosystem Services Provided by Tidal Marshes: A Simulation of the Georgia (USA) Coast. *Frontiers in Ecology and the Environment.* 2009; 7, doi:10.1890/070219

Council for Regulatory Environmental Modeling, (CREM) 2008. *Draft guidance on the development, evaluation, and application of regulatory environmental* models P Pascual, N Stiber, E Sunderland - Washington DC: Draft, August 2008

Darnell, A., Tate, N., and Brunsdon, C. (2008). "Improving user assessment of error implications in digital elevation models." *Computers, Environment and Urban Systems*, 32(4), 268-277.

Erwin, RM, GM Sanders, DJ Prosser, and DR Cahoon. 2006. High tides and rising seas: potential effects on estuarine waterbirds. Pages 214-228 in: Terrestrial Vertebrates of Tidal Marshes: Evolution, Ecology, and Conservation (R. Greenberg, J. Maldonado, S. Droege, and M.V. McDonald, eds.). Studies in Avian Biology No. 32, Cooper Ornithological Society.

Glick, Clough, et al. *Sea-level Rise and Coastal Habitats in the Pacific Northwest An Analysis for Puget Sound, Southwestern Washington, and Northwestern Oregon* July 2007 http://www.nwf.org/sealevelrise/pdfs/PacificNWSeaLevelRise.pdf

Glick, P., Clough, J., Polaczyk, A., and Nunley, B. (2011). *Sea-Level Rise and Coastal Habitats in Southeastern Louisiana: An Application of the Sea Level Affecting Marshes (SLAMM) Model. Draft Technical Report.* National Wildlife Federation.

Hawaii Office of State Planning, Coastal Zone Management Program, 1992, Aerial Photography Analysis of Coastal Erosion on the Islands of Kauai, Molokai, Lanai, Maui, and Hawaii, June 1991, Prepared by Makai Ocean Engineering, Inc and Sea Engineering, Inc.

Hereford, Scott (2011). Personal communication.

Heuvelink, G. B. M. (1998). *Error propagation in environmental modelling with GIS*. CRC Press.

Hunter, G. J., and Goodchild, M. F. (1997). "Modeling the uncertainty of slope and aspect estimates derived from spatial databases." *Geographical Analysis*, 29(1), 35–49.

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* [Houghton, J.T.,Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K.Maskell, and C.A. Johnson (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 881pp.

IPCC, 2007. *Climate Change 2007 - The Physical Science Basis: Contribution of Working Group I to the Fourth Assessment Report of the IPCC. Cambridge: Cambridge University Press.* ISBN 978 0521 88009-1.

Lee, J.K., R.A. Park, and P.W. Mausel. 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. *et al,* 2006 "Insignificant Change in Antarctic Snowfall Since the International Geophysical Year" *Science* 2006 313: 827-831.

National Wildlife Fed 'n et al., *An Unfavorable Tide: Global Warming, Coastal Habitats and Sportfishing in Florida* 4, 6 (2006). http://www.targetglobalwarming.org/files/AnUnfavorableTideReport.pdf

Park, R.A., J.K. Lee, and D. Canning. 1993. Potential Effects of Sea Level Rise on Puget Sound Wetlands. *Geocarto International* 8(4):99-110.

Park, R.A., M.S. Trehan, P.W. Mausel, and R.C. Howe. 1989a. The Effects of Sea Level Rise on U.S. Coastal Wetlands. In *The Potential Effects of Global Climate Change on the United States: Appendix B - Sea Level Rise,* edited by J.B. Smith and D.A. Tirpak, 1-1 to 1-55. EPA-230-05-89-052. Washington, D.C.: U.S. Environmental Protection Agency.

Park, RA, JK Lee, PW Mausel and RC Howe. 1991. Using remote sensing for modeling the impacts of sea level rise. *World Resources Review* 3:184-220.

Pfeffer, Harper, O'Neel, 2008. Kinematic Constraints on Glacier Contributions to 21st-Century Sea-Level Rise. *Science*, Vol. 321, No. 5894. (5 September 2008), pp. 1340-134

Rahmstorf, Stefan 2007, "A Semi-Empirical Approach to Projecting Future Sea-Level Rise," *Science* 2007 315: 368-370.

Stevenson and Kearney, 2008, "Impacts of Global Climate Change and Sea-Level Rise on Tidal Wetlands" Pending chapter of manuscript by University of California Press.

Titus, J.G., R.A. Park, S.P. Leatherman, J.R. Weggel, M.S. Greene, P.W. Mausel, M.S. Trehan, S. Brown, C. Grant, and G.W. Yohe. 1991. Greenhouse Effect and Sea Level Rise: Loss of Land and the Cost of Holding Back the Sea. *Coastal Management* 19:2:171-204.

United States Fish and Wildlife Service, Federal Highway Administration Western Federal Lands Highway Division. 2009. Environmental Assessment for the Ni-les'tun Unit of the MS Sandhill Crane National Wildlife Refuge Restoration and North Bank Land Improvement Project

Warren Pinnacle Consulting, Inc. (2011). *SLAMM Analysis of Grand Bay NERR and Environs.*

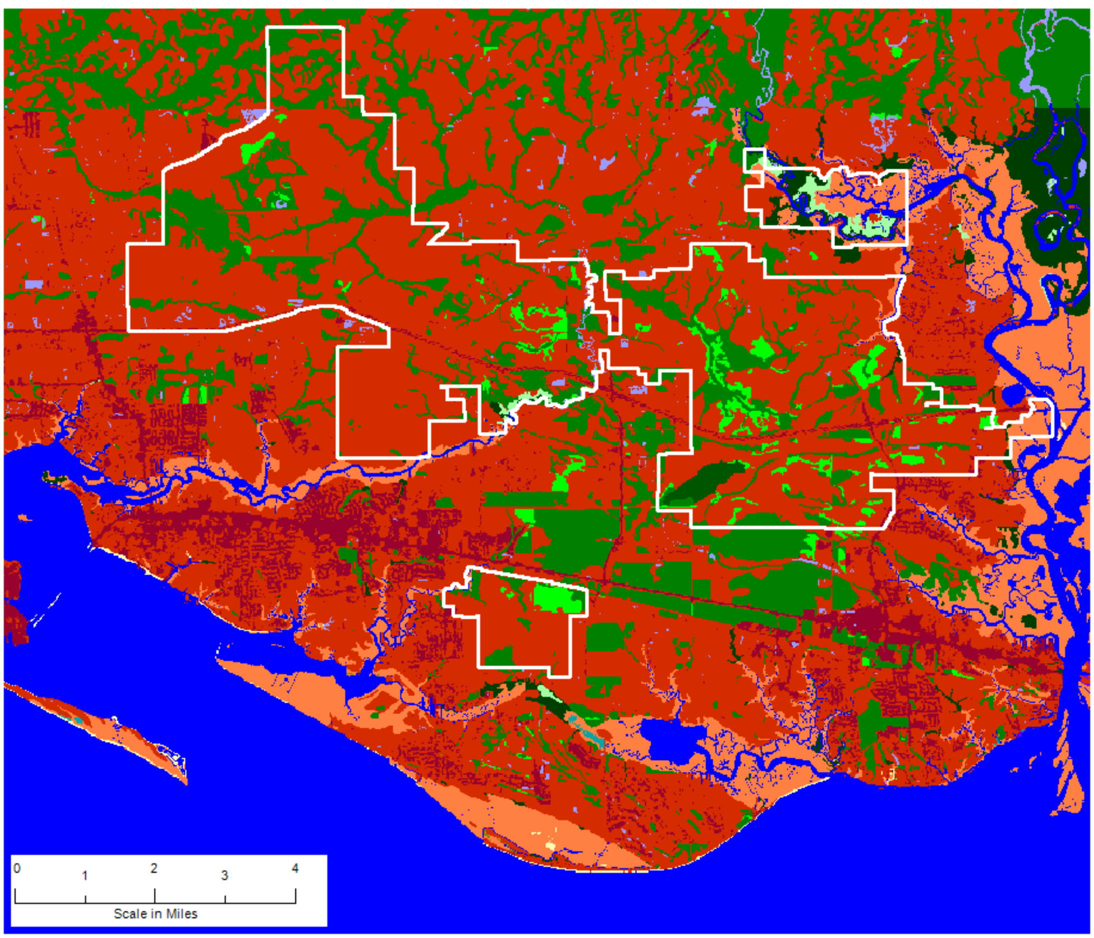
Wilen 2011, Personal Communication, Phone Conversation.

Appendix A: Contextual Results

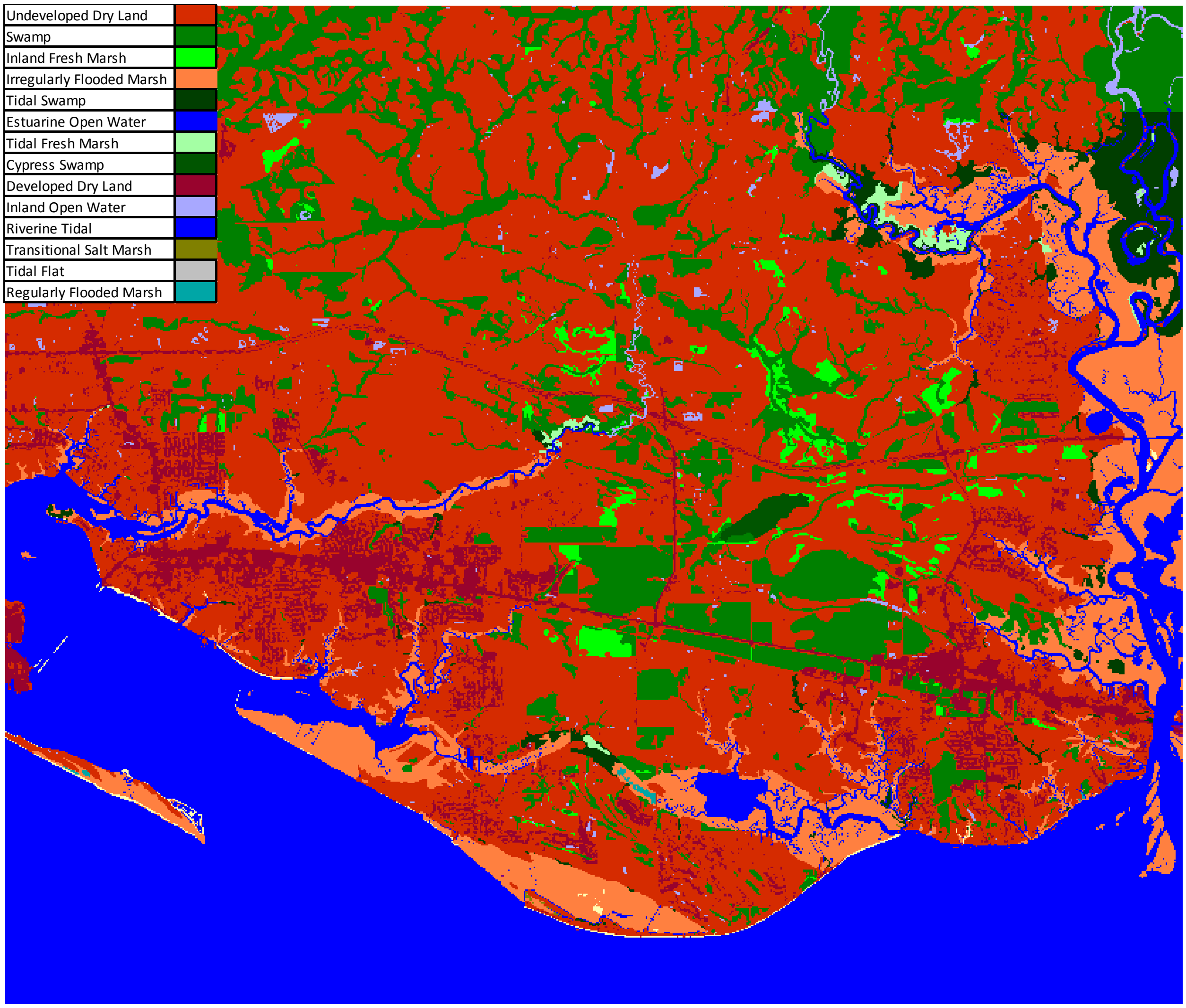
The SLAMM model does take into account the context of the surrounding lands or open water when calculating effects. For example, erosion rates are calculated based on the maximum fetch (wave action) which is estimated by assessing contiguous open water to a given marsh cell. Another example is that inundated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

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

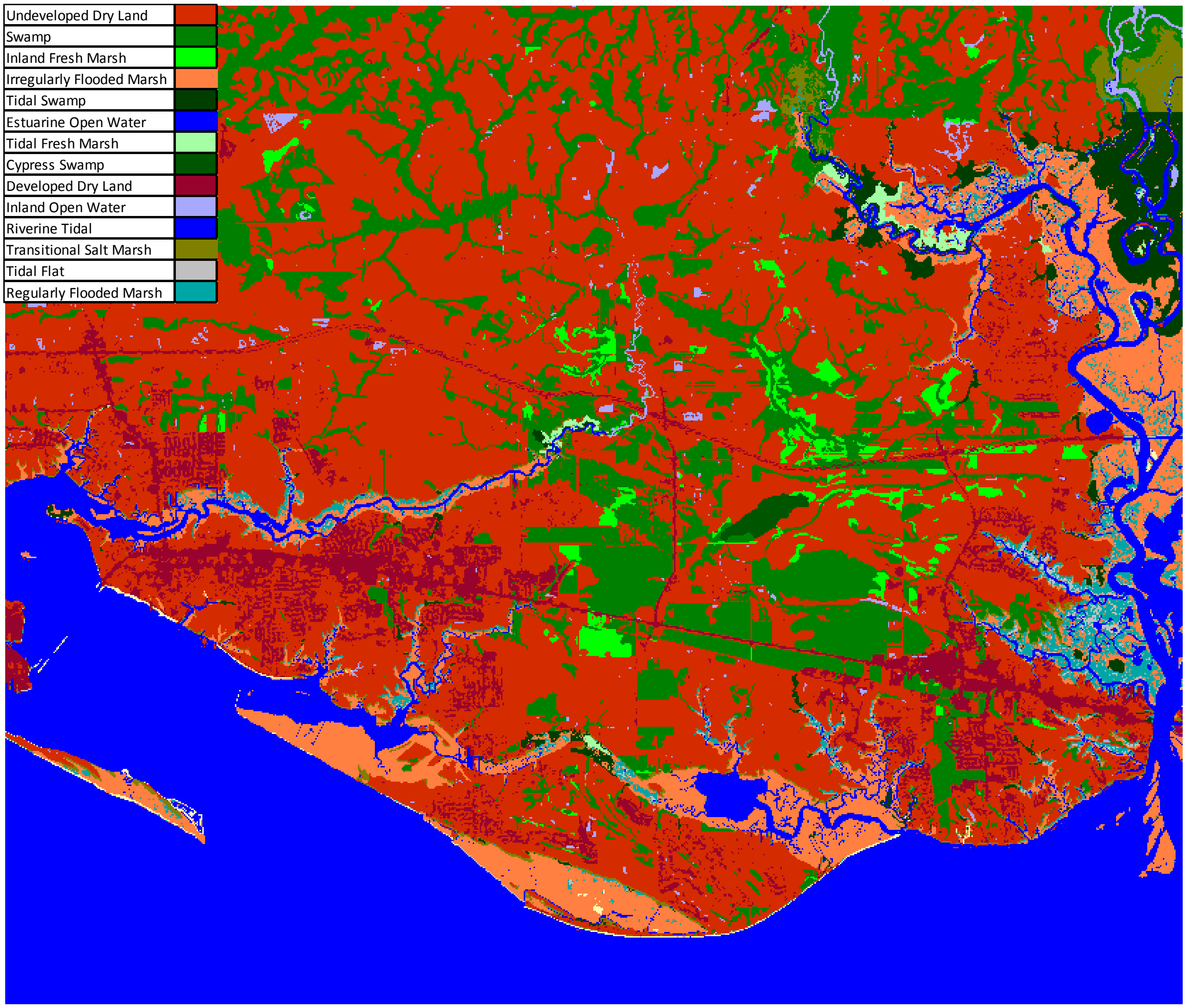
- Results were closely examined (quality assurance) within USFWS refuges but not closely examined for the larger region.
- Site-specific parameters for the model were derived for USFWS refuges whenever possible and may not be regionally applicable.
- Especially in areas where dikes are present, an effort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



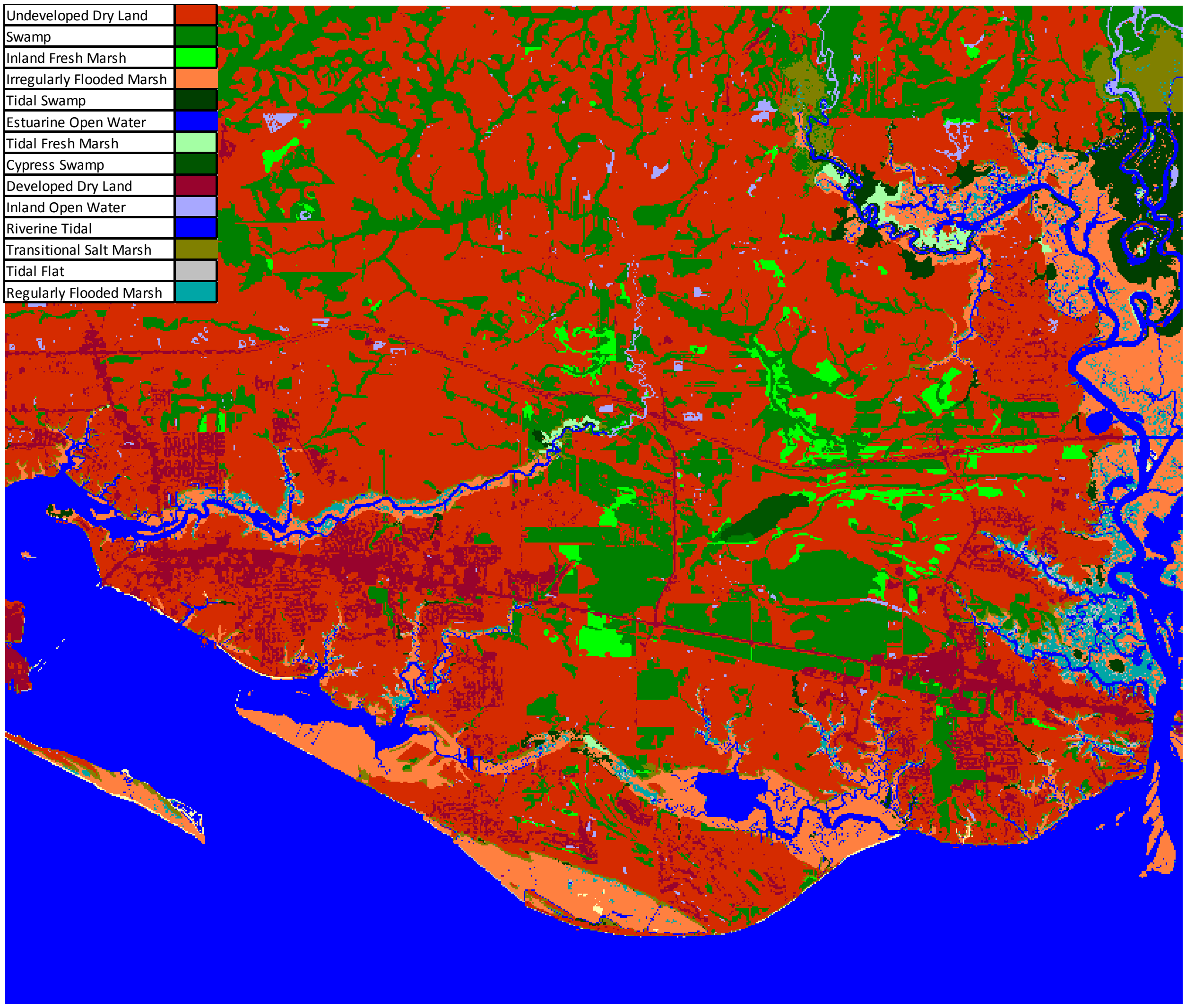
MS Sandhill Crane National Wildlife Refuge within simulation context (white).



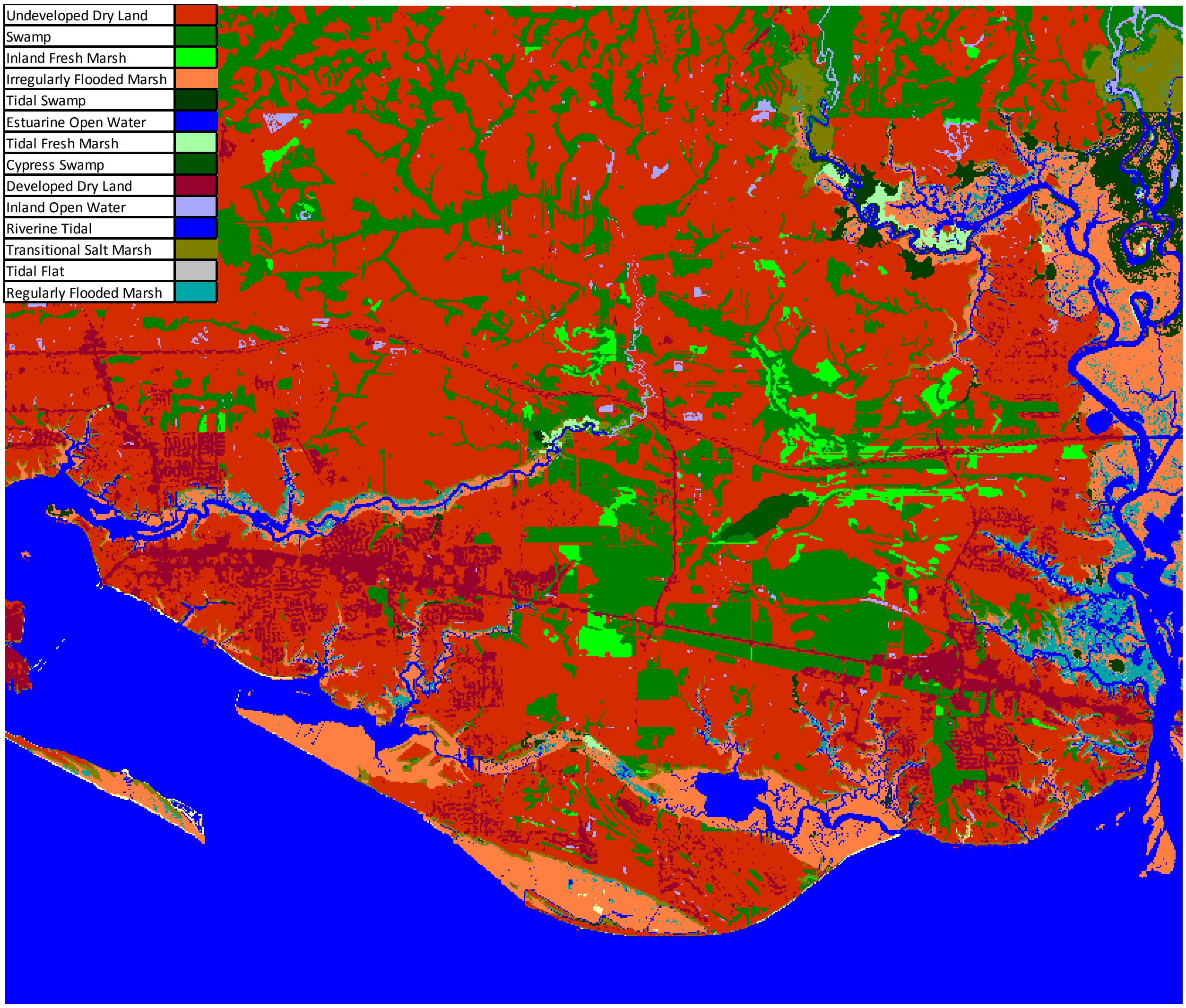
MS Sandhill Crane NWR, Initial Condition



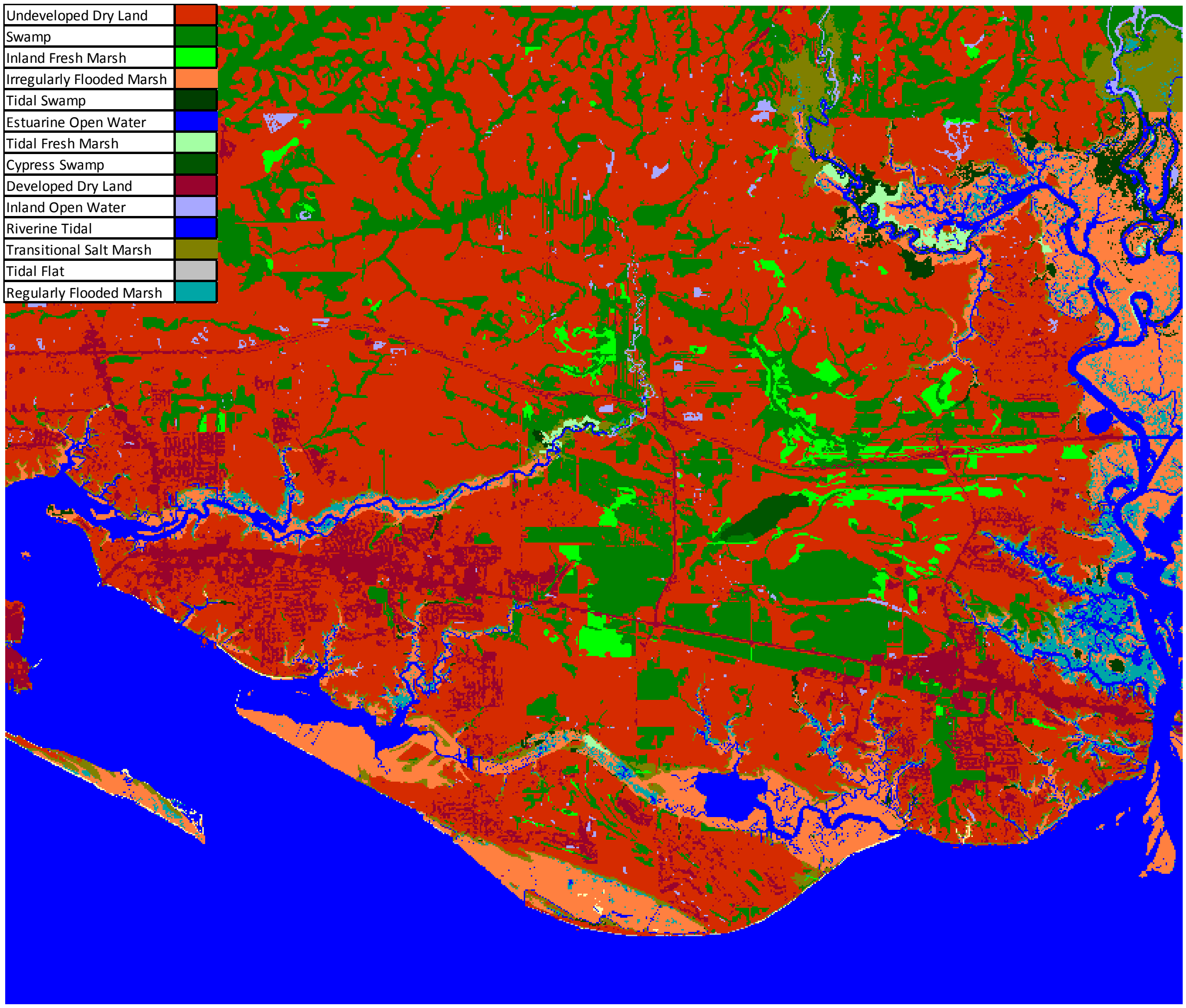
MS Sandhill Crane NWR, 2025, Scenario A1B Mean, 0.39 m SLR



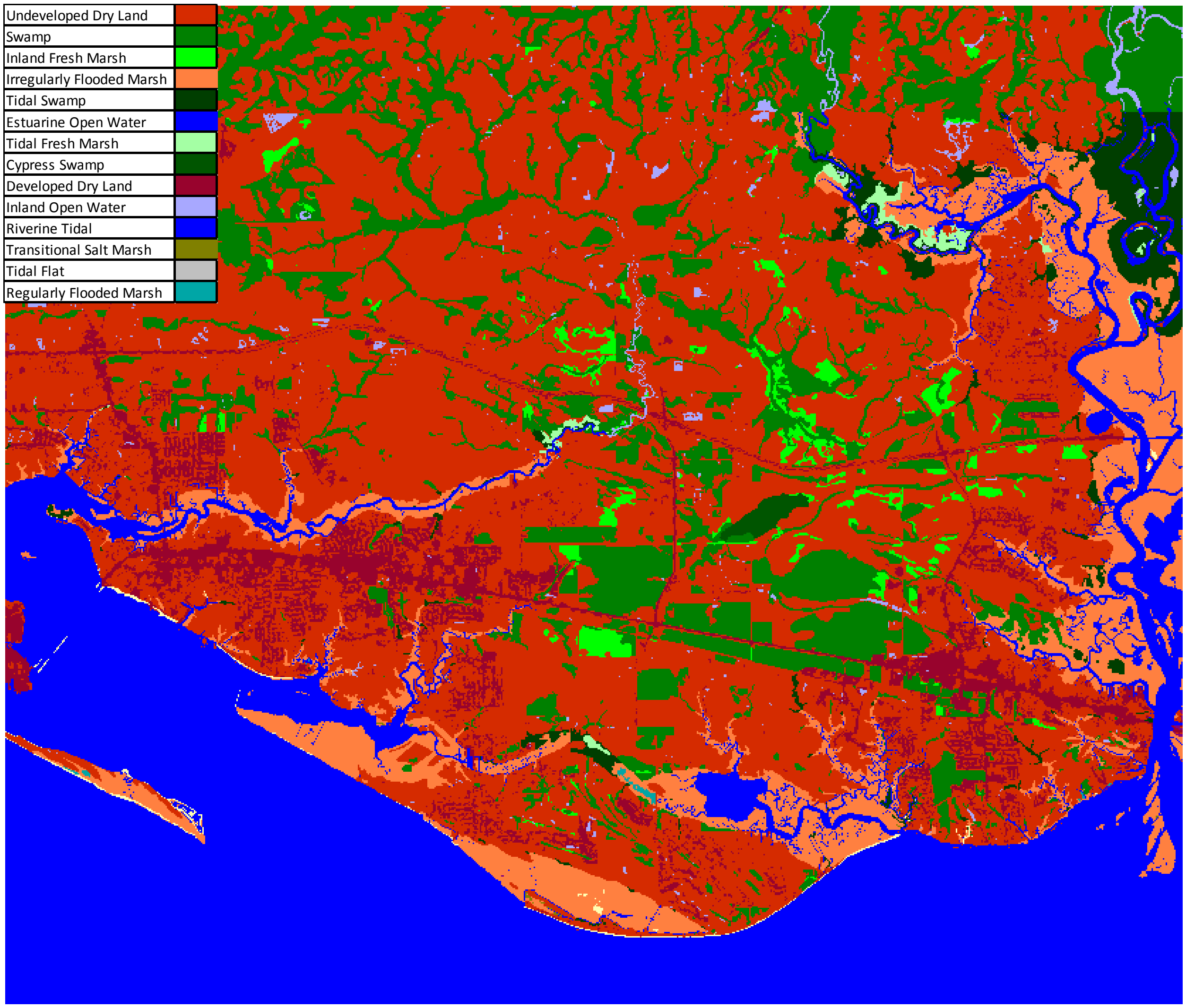
MS Sandhill Crane NWR, 2050, Scenario A1B Mean, 0.39 m SLR



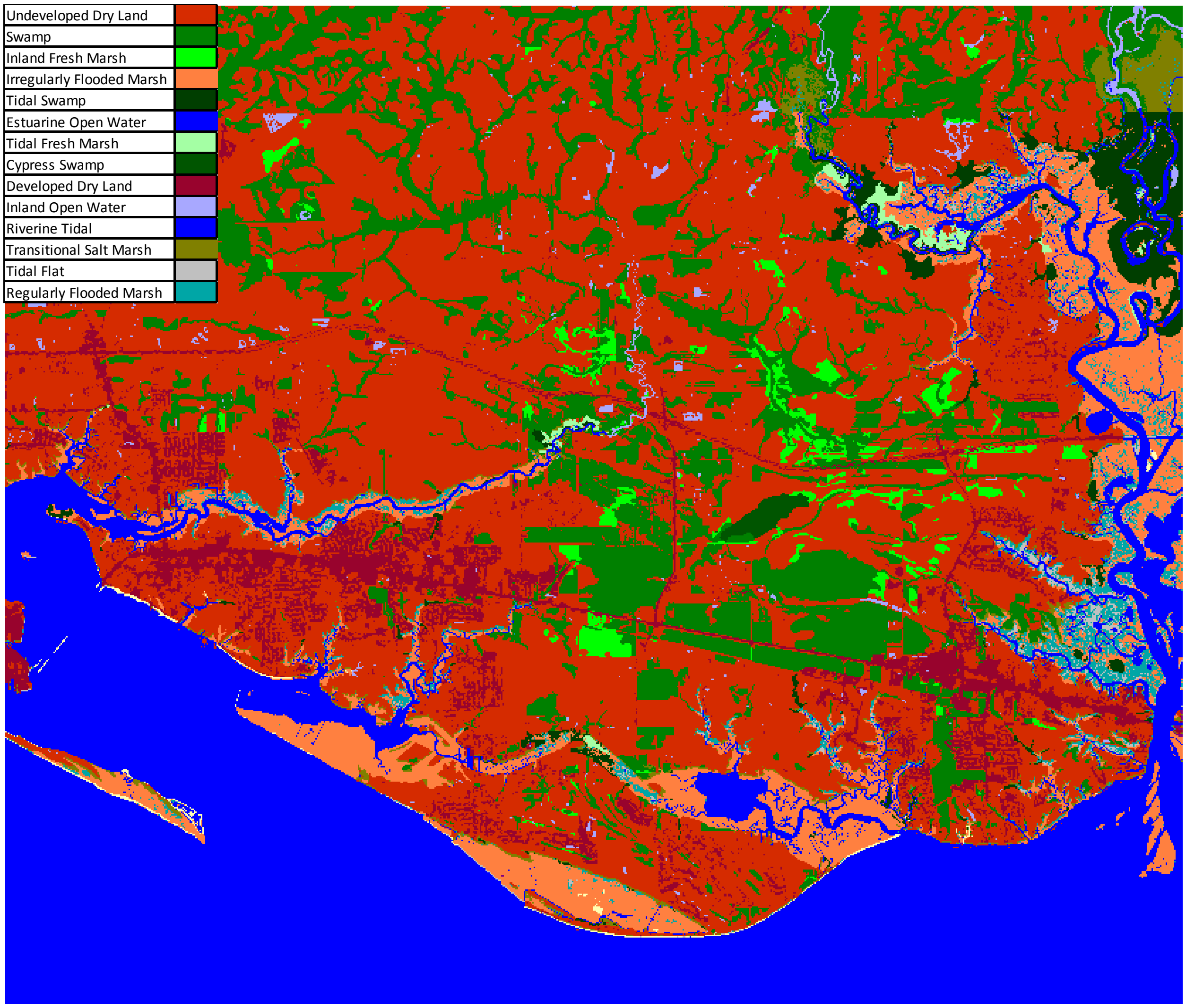
MS Sandhill Crane NWR, 2075, Scenario A1B Mean, 0.39 m SLR



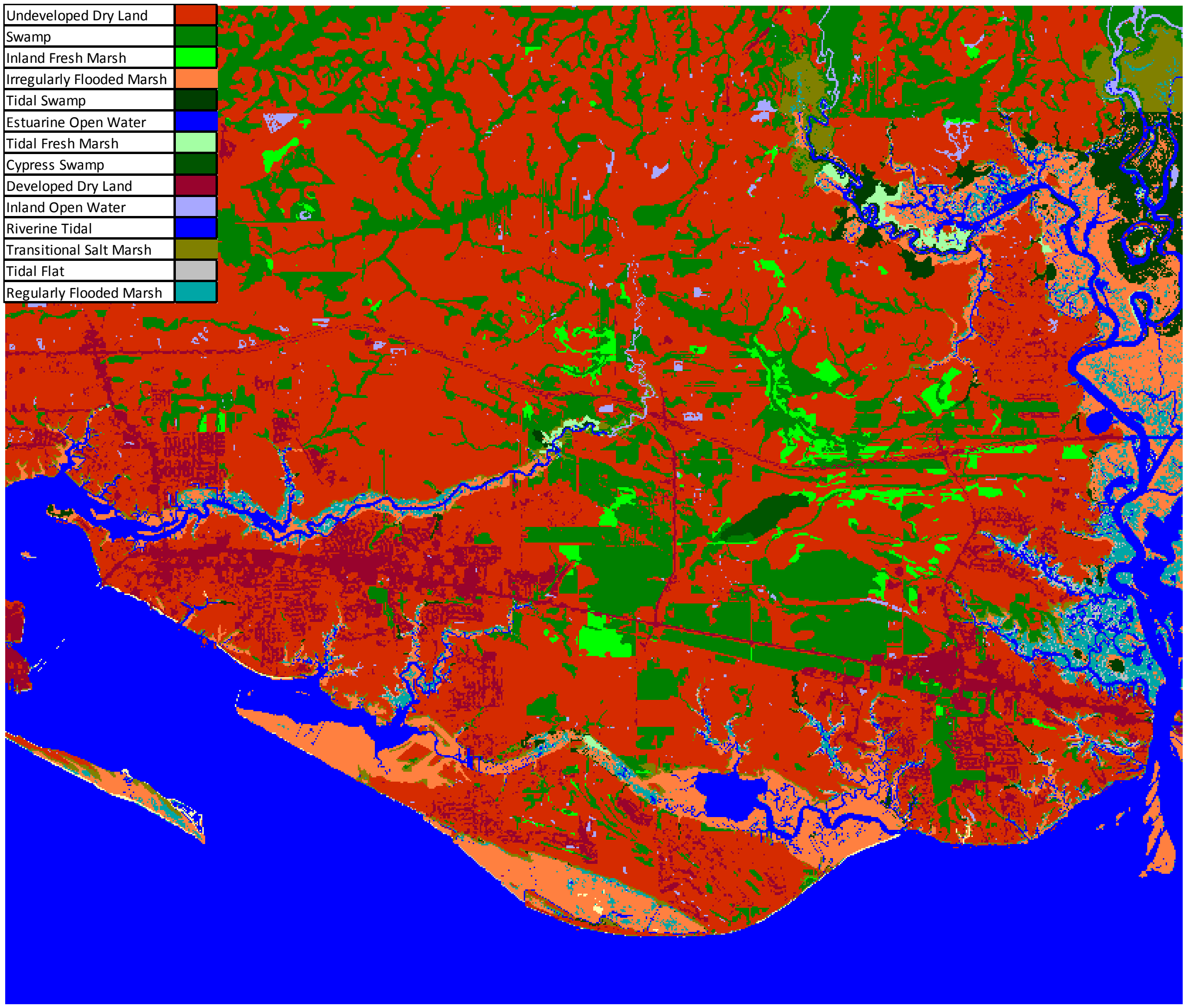
MS Sandhill Crane NWR, 2100, Scenario A1B Mean, 0.39 m SLR



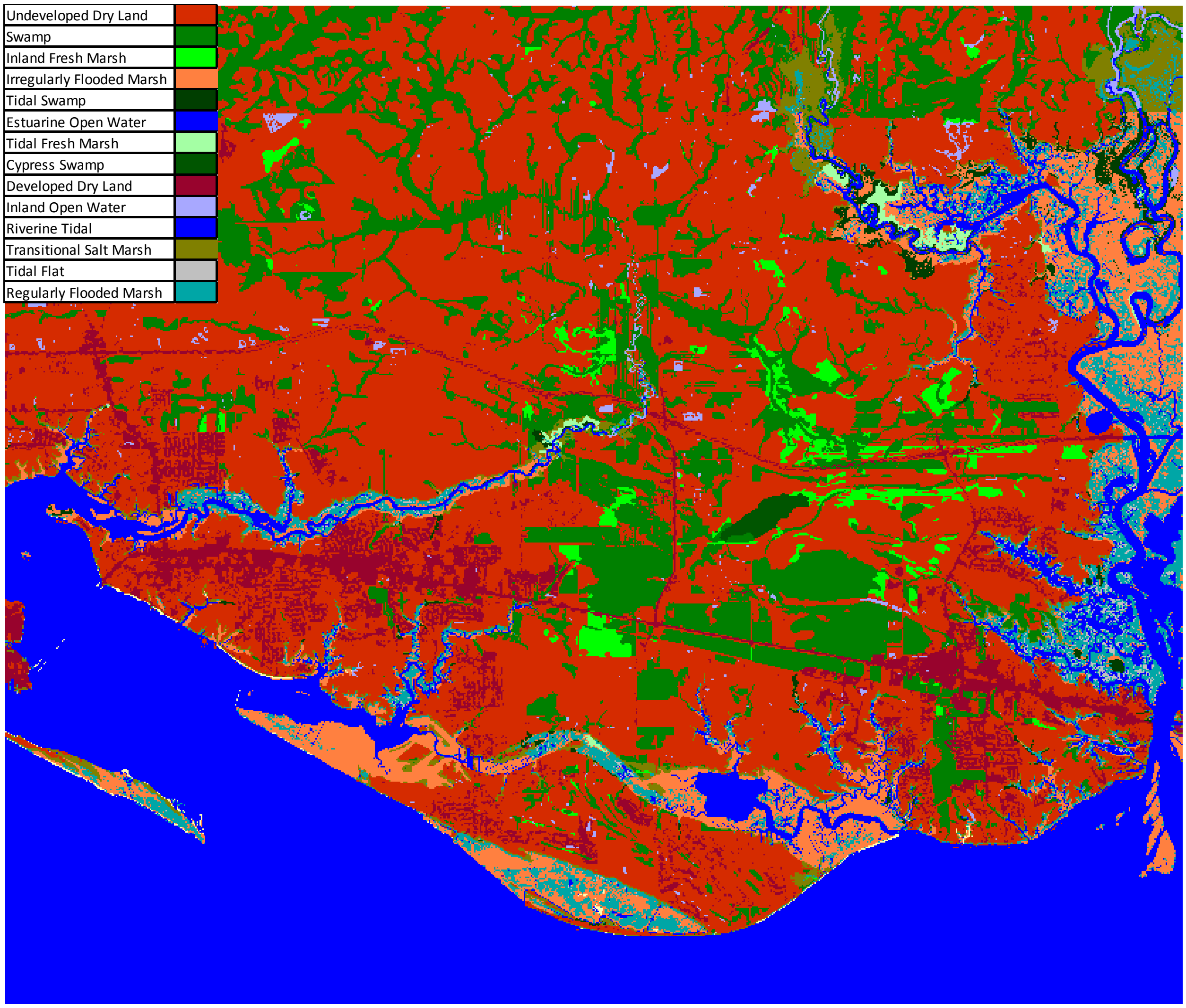
MS Sandhill Crane NWR, Initial Condition



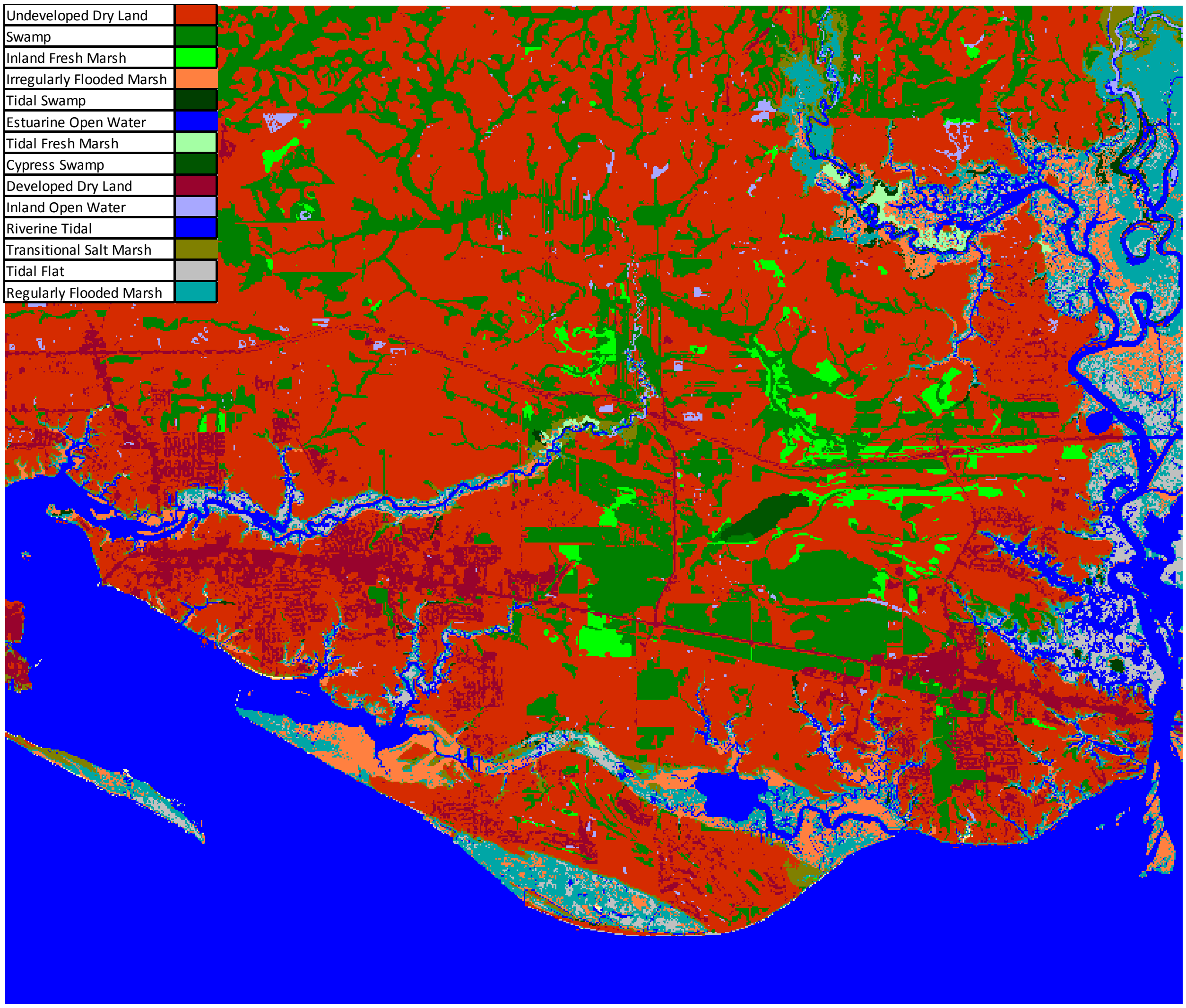
MS Sandhill Crane NWR, 2025, Scenario A1B Maximum, 0.69 m SLR



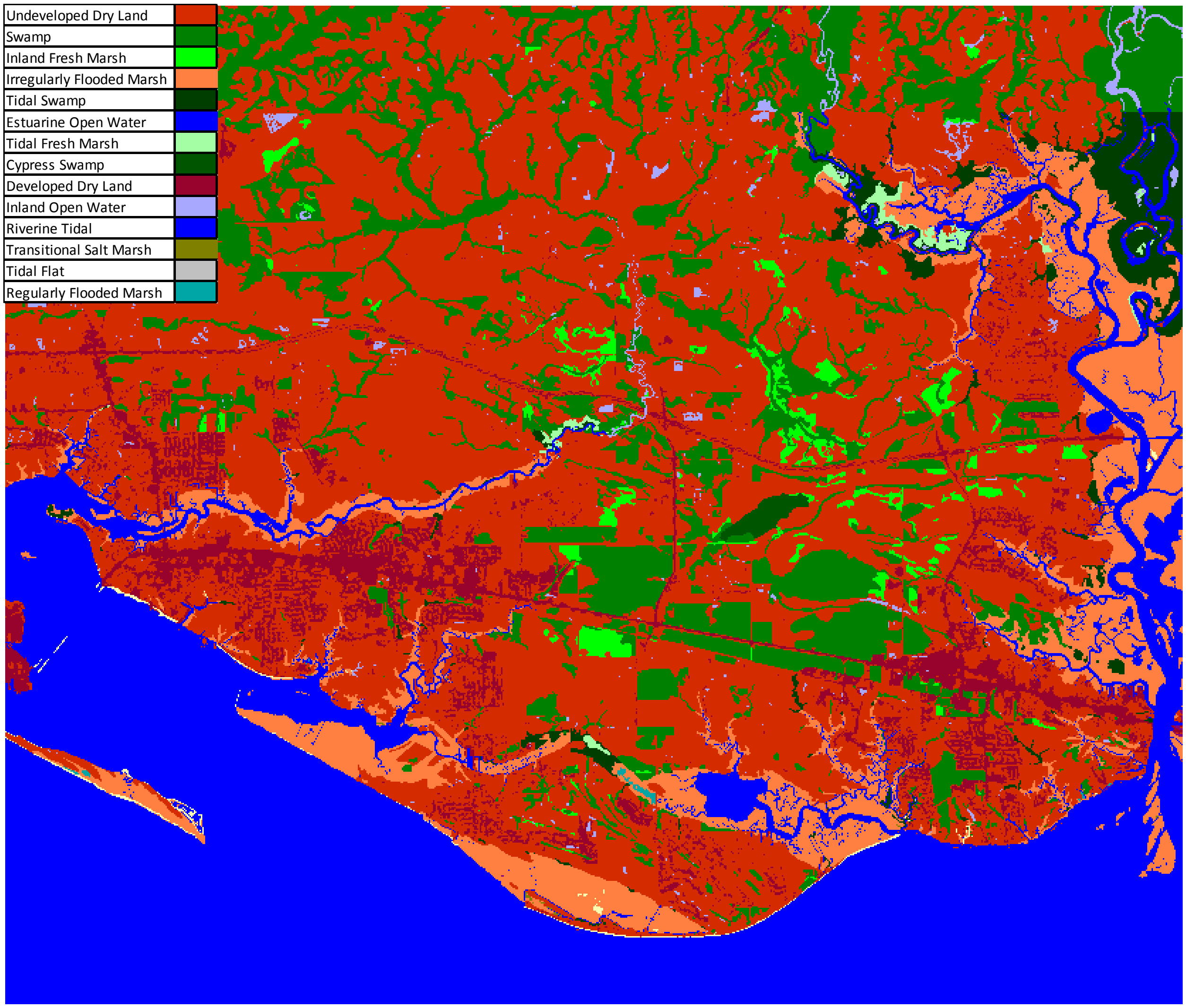
MS Sandhill Crane NWR, 2050, Scenario A1B Maximum, 0.69 m SLR



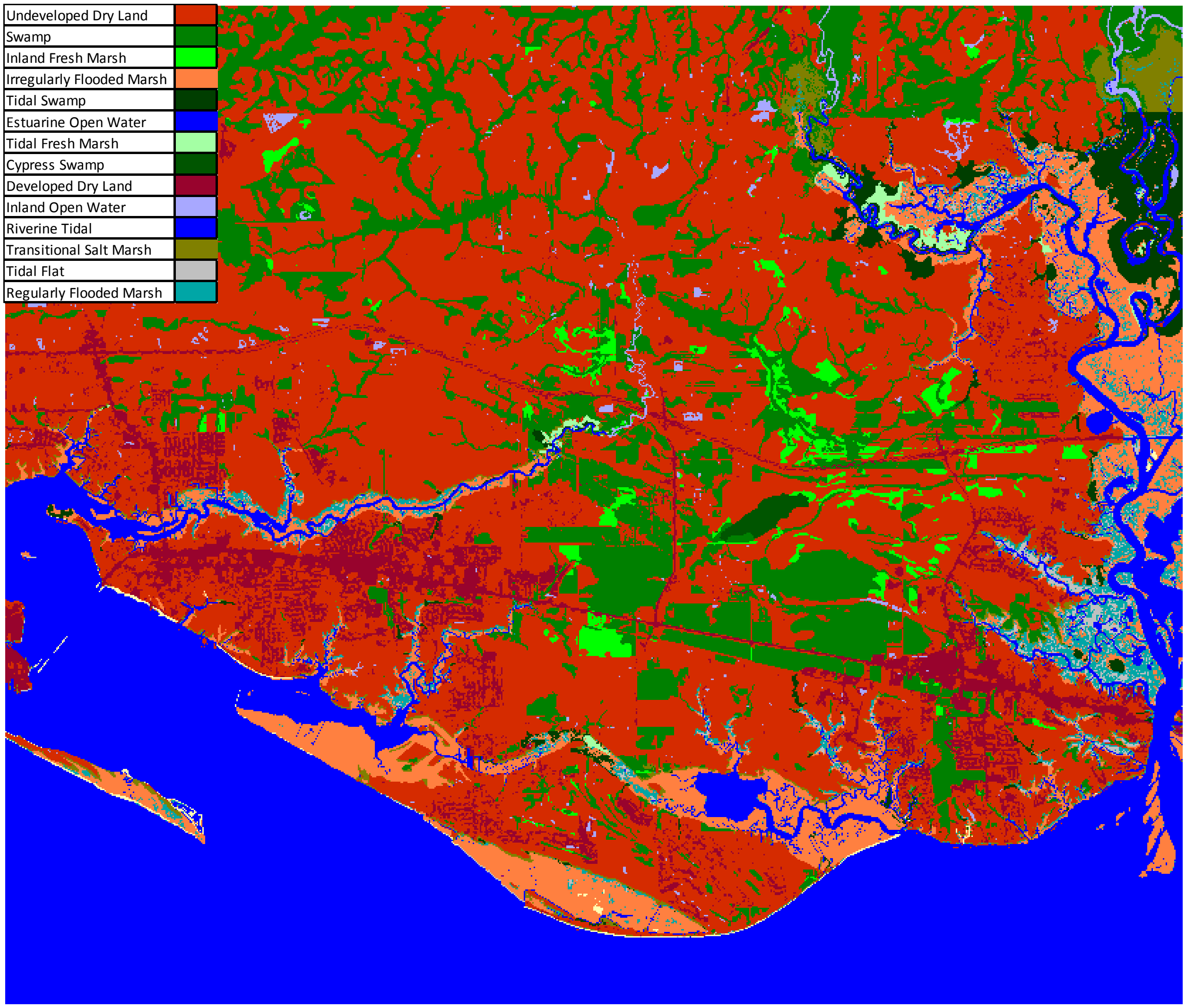
MS Sandhill Crane NWR, 2075, Scenario A1B Maximum, 0.69 m SLR



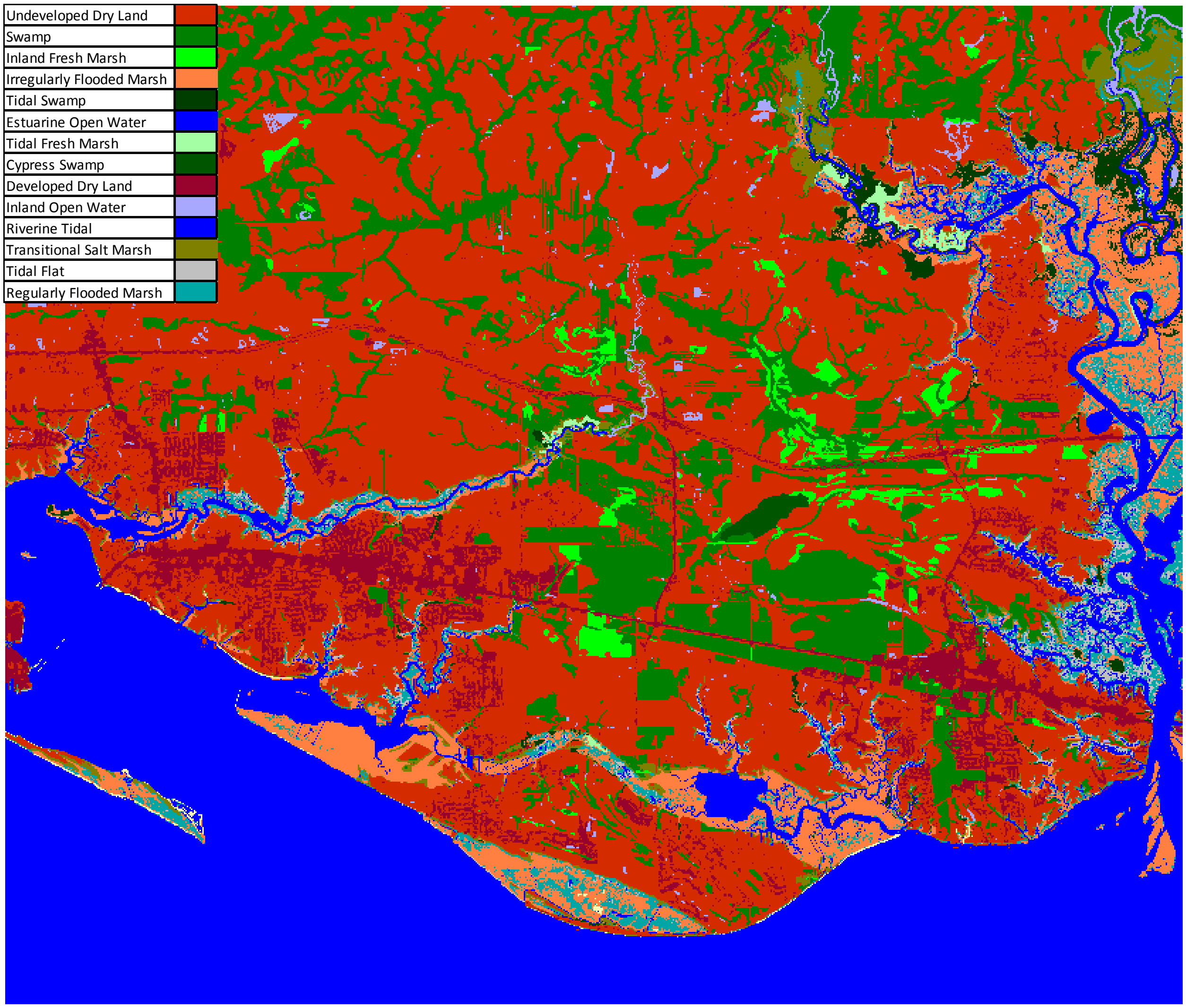
MS Sandhill Crane NWR, 2100, Scenario A1B Maximum, 0.69 m SLR



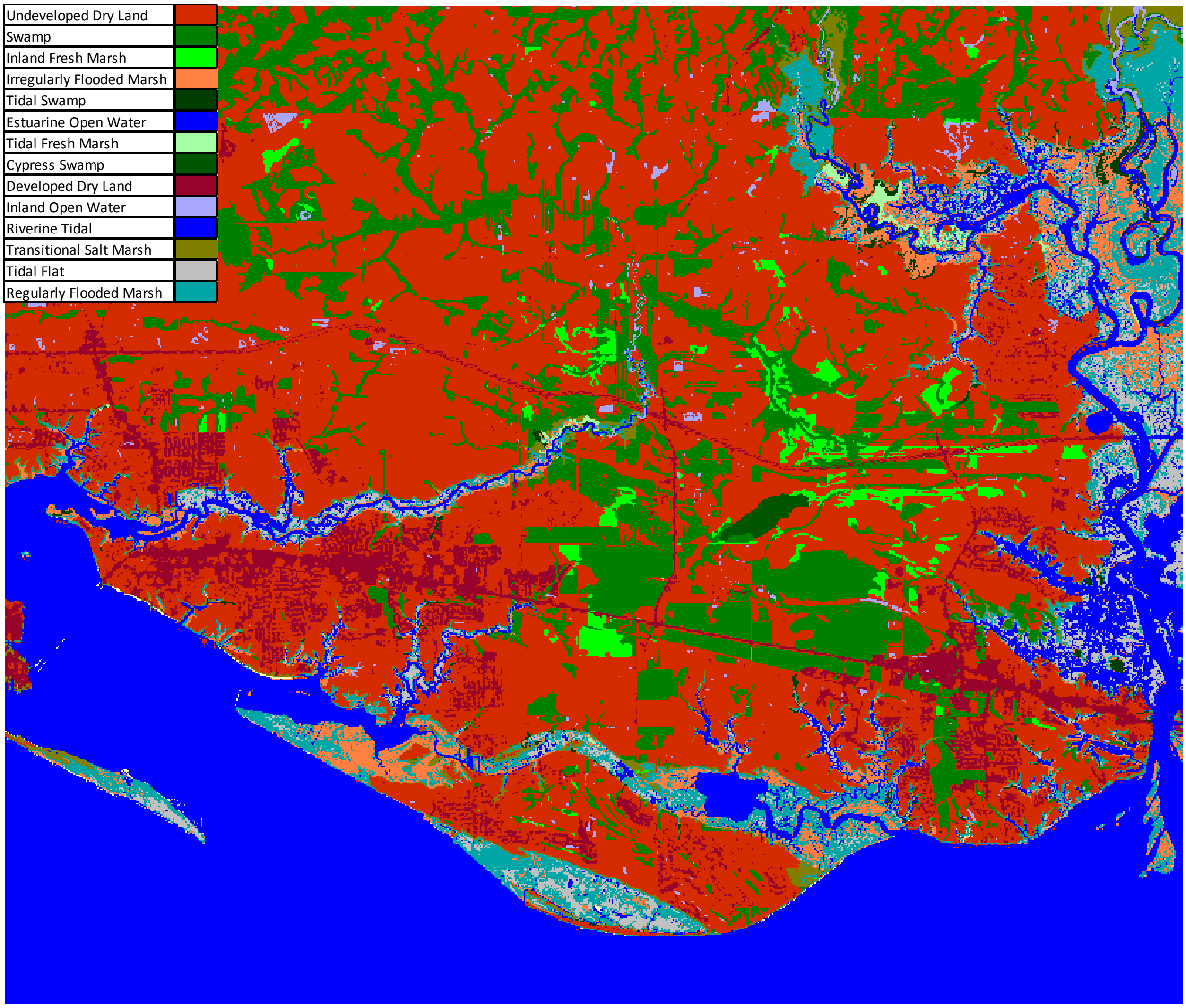
MS Sandhill Crane NWR, Initial Condition



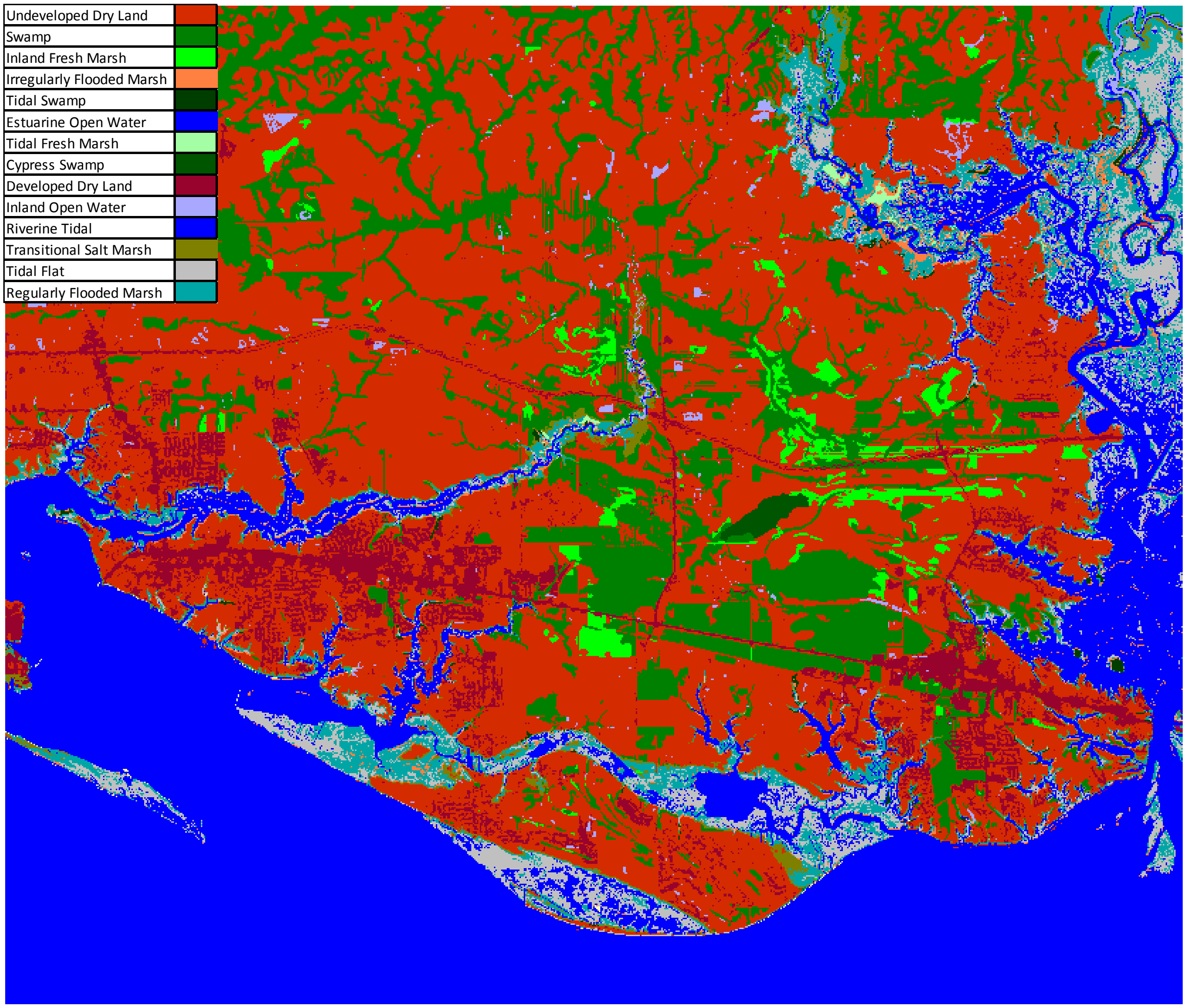
MS Sandhill Crane NWR, 2025, 1 m SLR



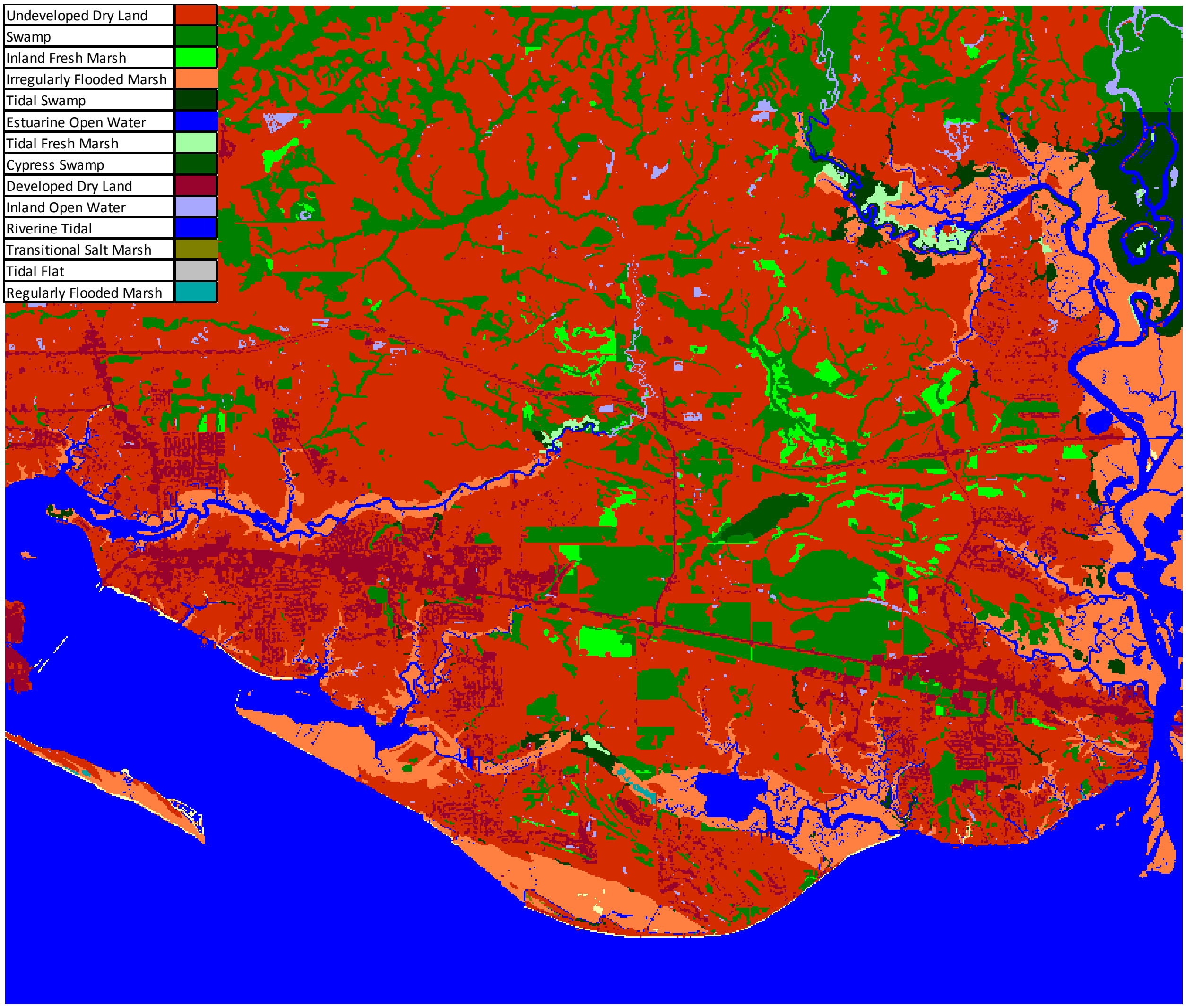
MS Sandhill Crane NWR, 2050, 1 m SLR



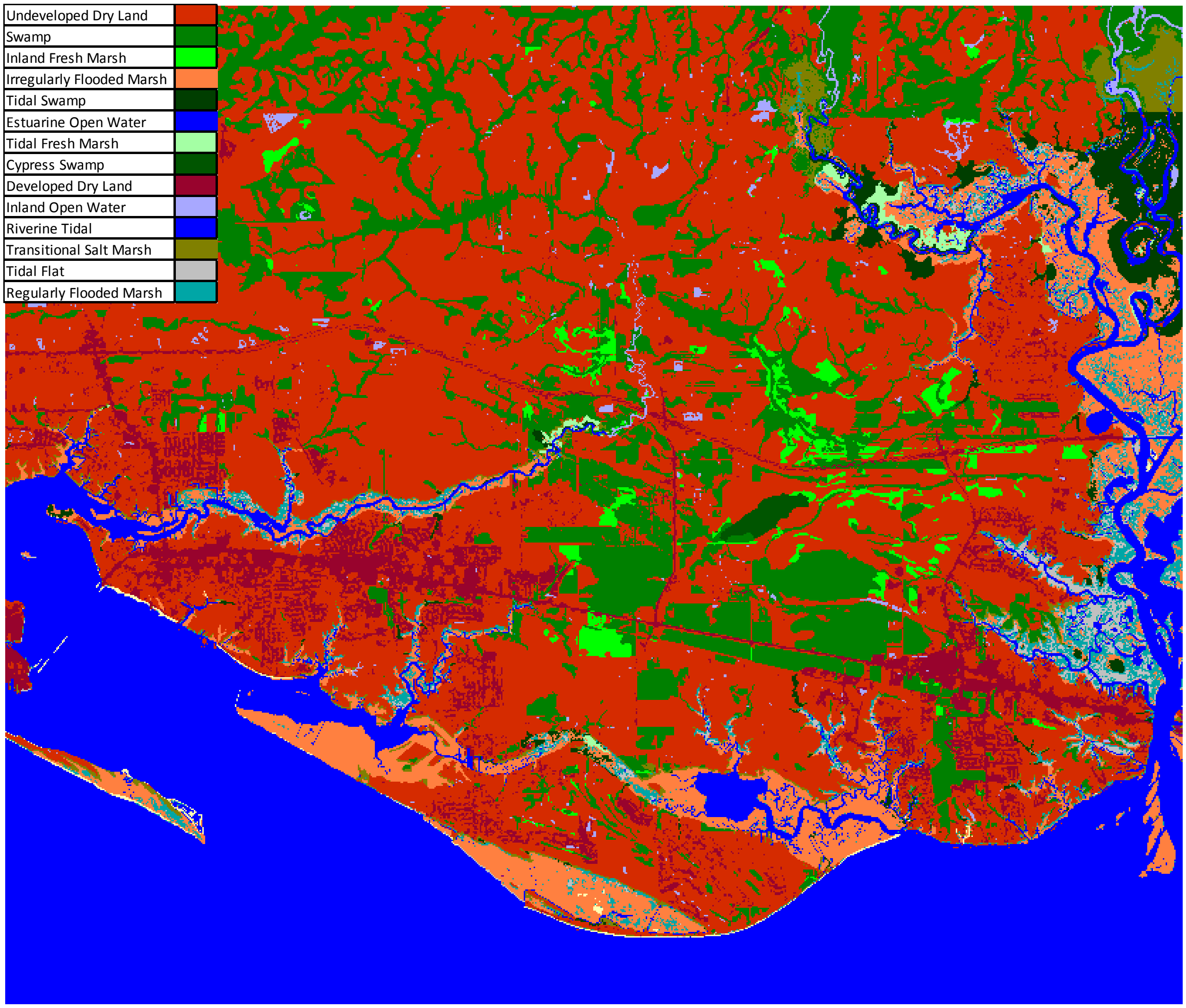
MS Sandhill Crane NWR, 2075, 1 m SLR



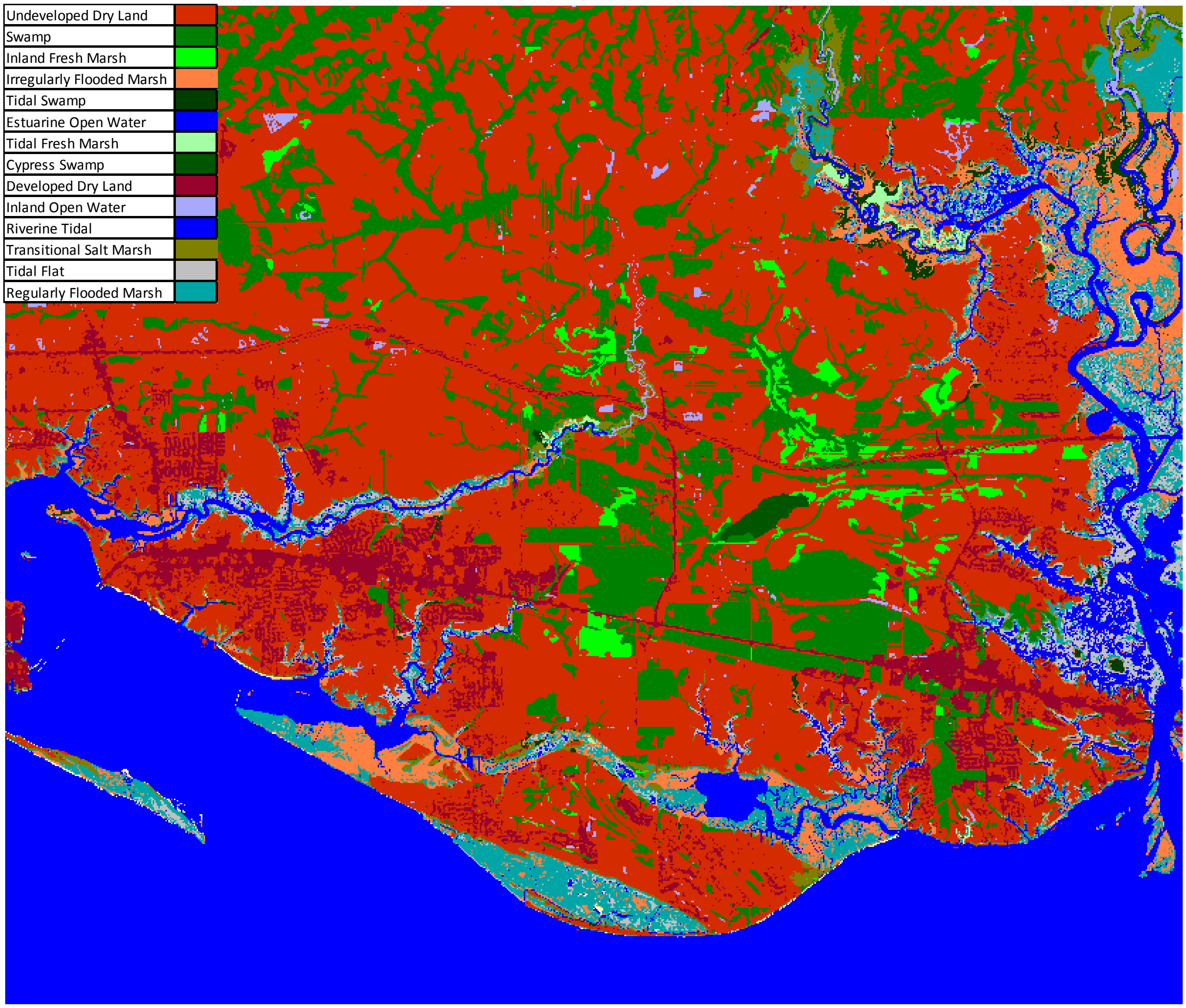
MS Sandhill Crane NWR, 2100, 1 m SLR



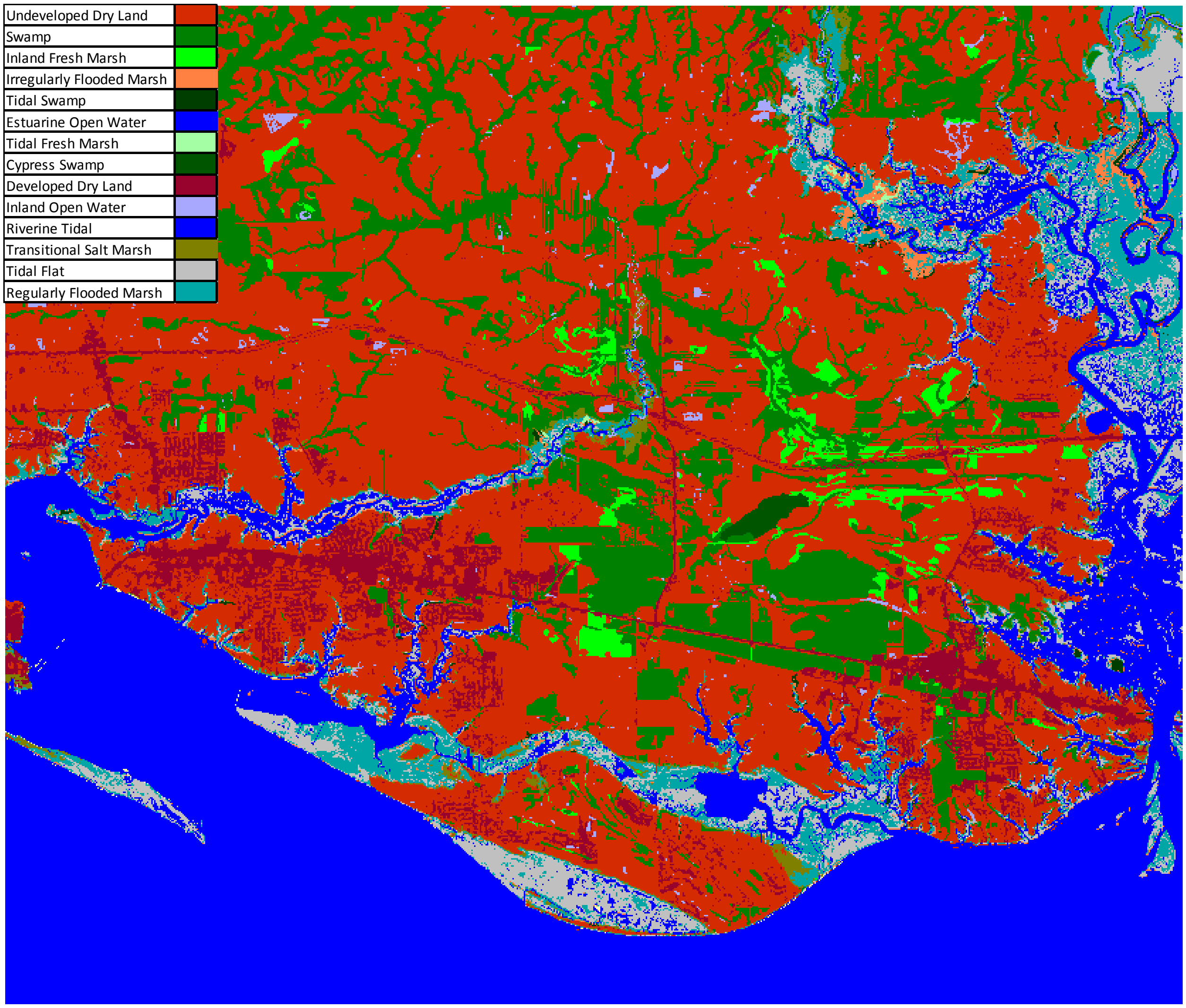
MS Sandhill Crane NWR, Initial Condition



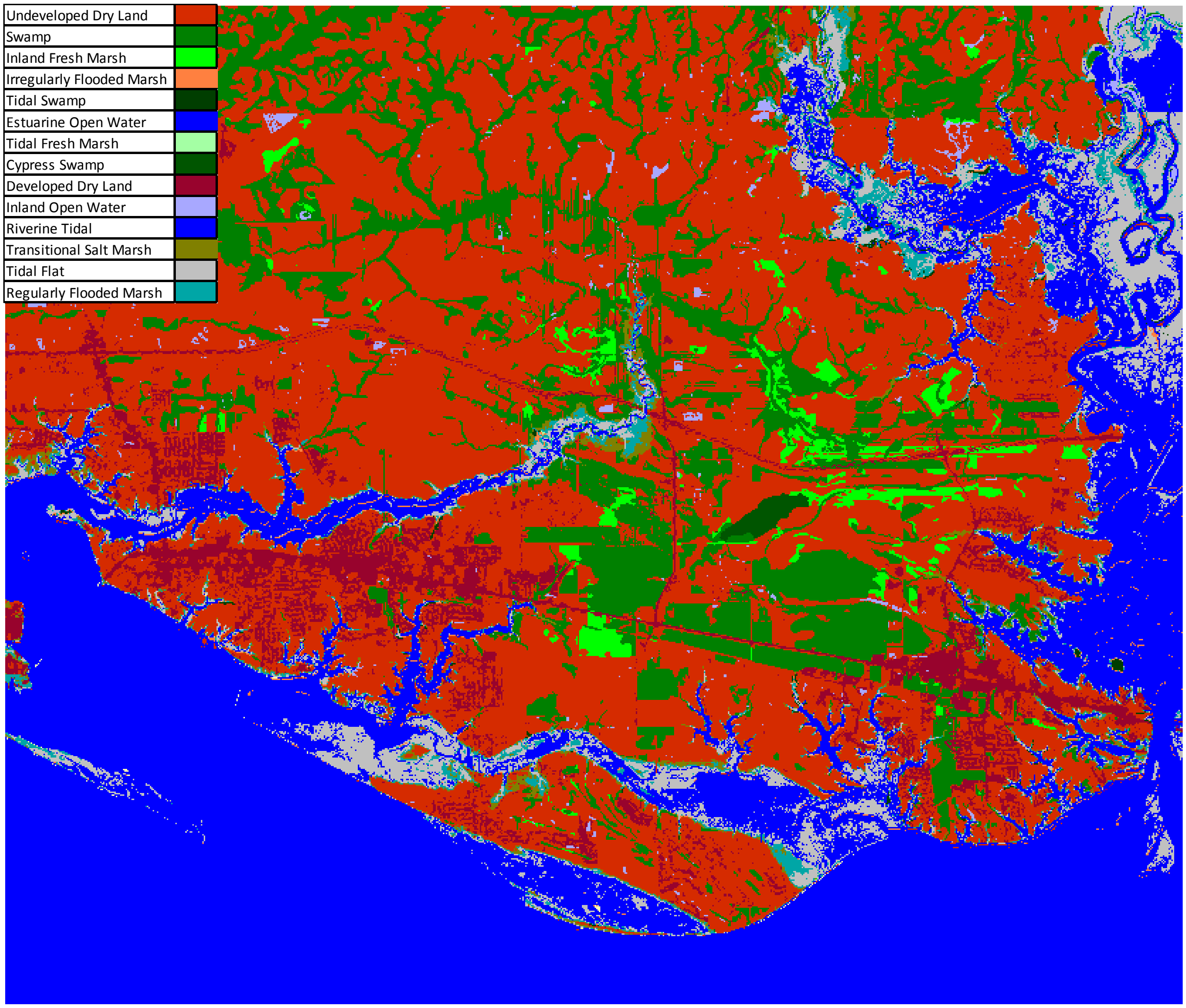
MS Sandhill Crane NWR, 2025, 1.5 m SLR



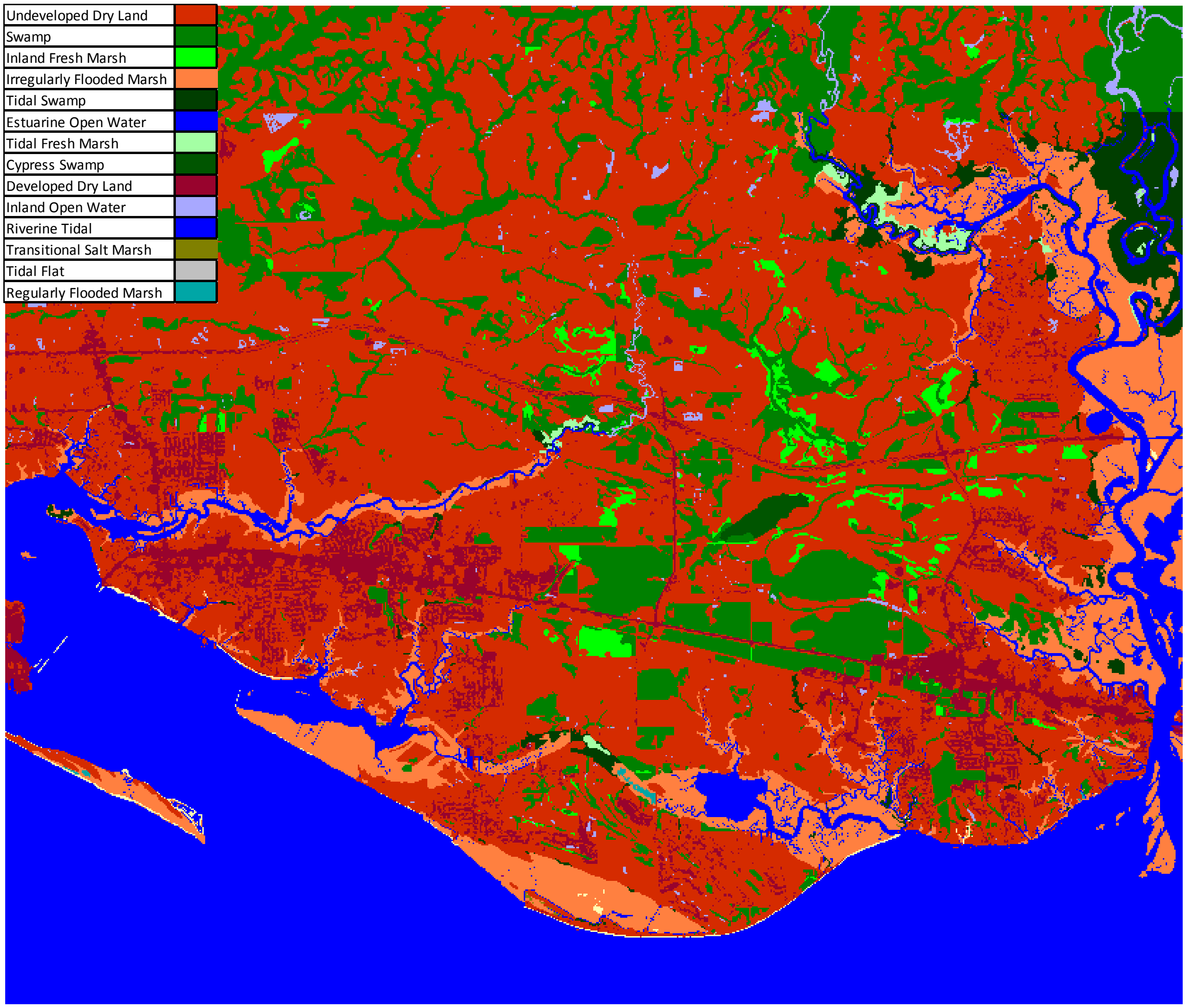
MS Sandhill Crane NWR, 2050, 1.5 m SLR



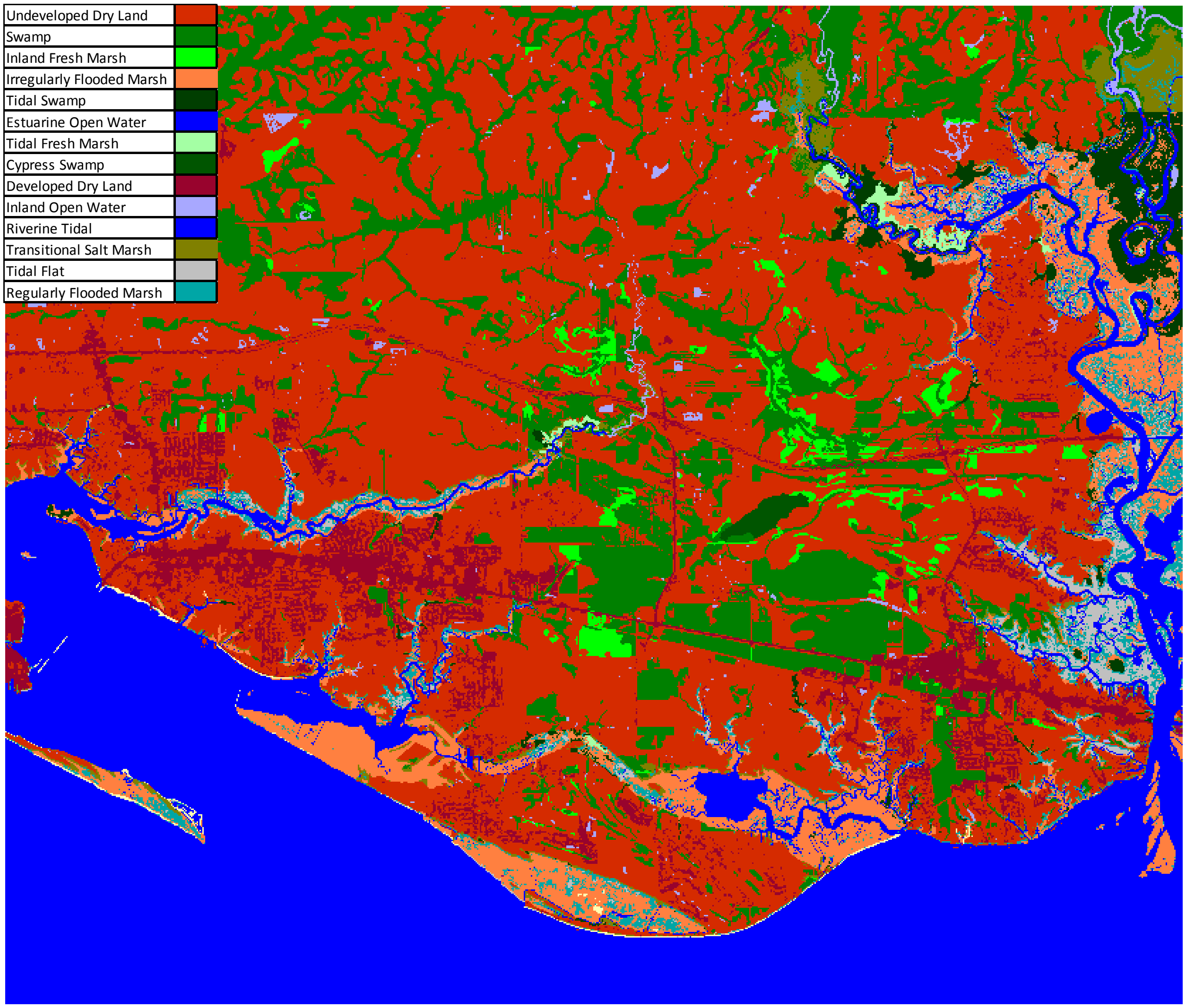
MS Sandhill Crane NWR, 2075, 1.5 m SLR



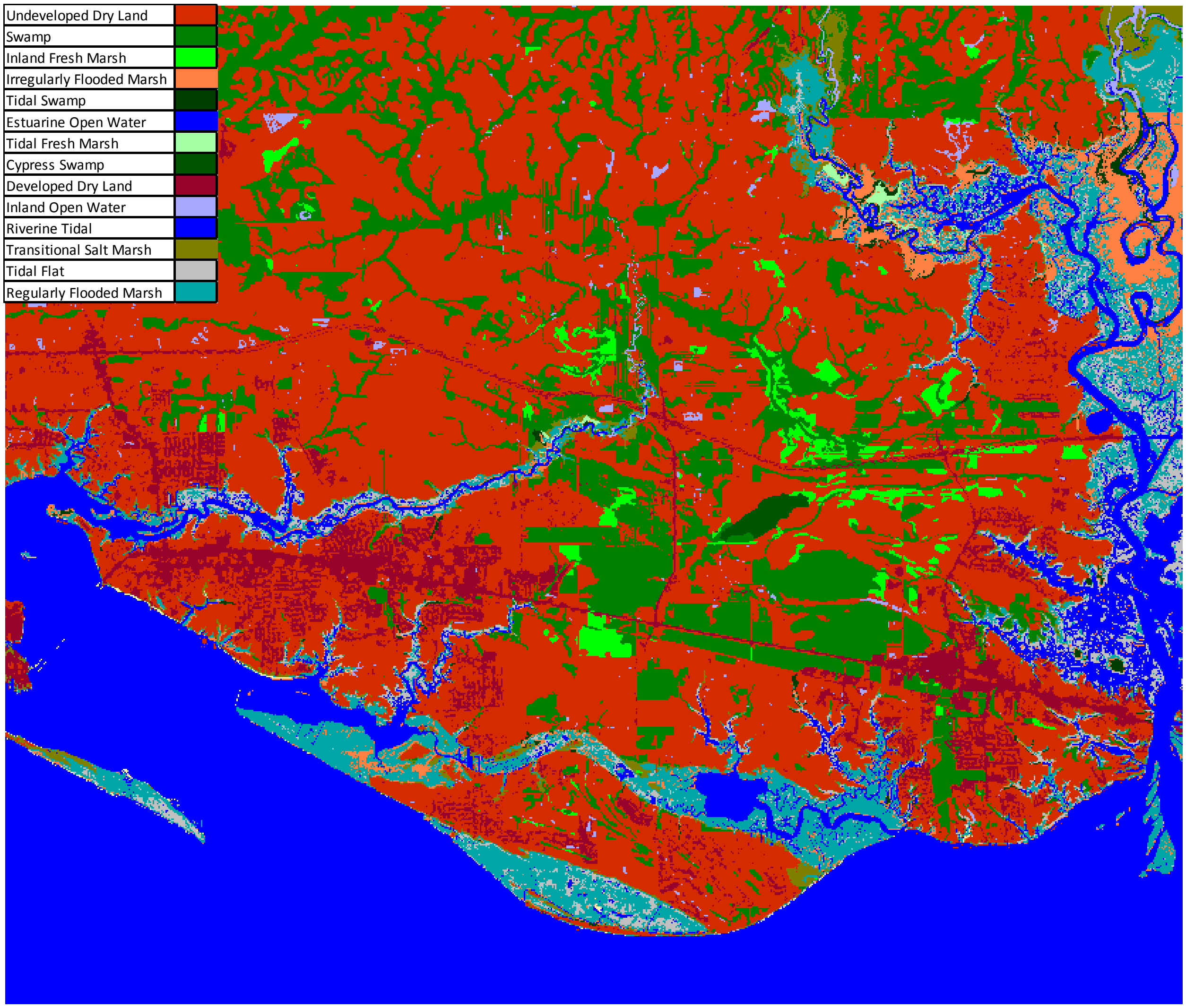
MS Sandhill Crane NWR, 2100, 1.5 m SLR



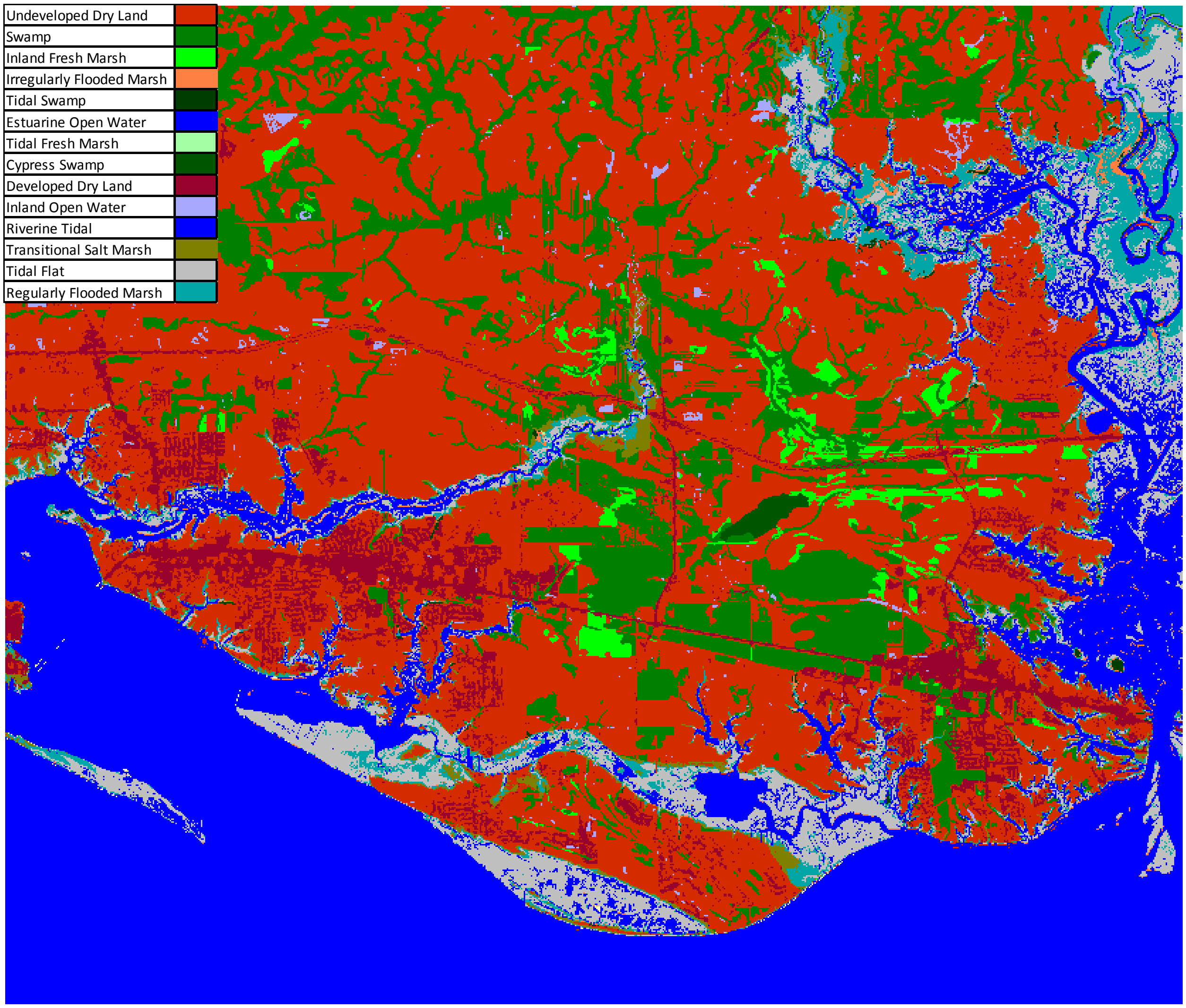
MS Sandhill Crane NWR, Initial Condition



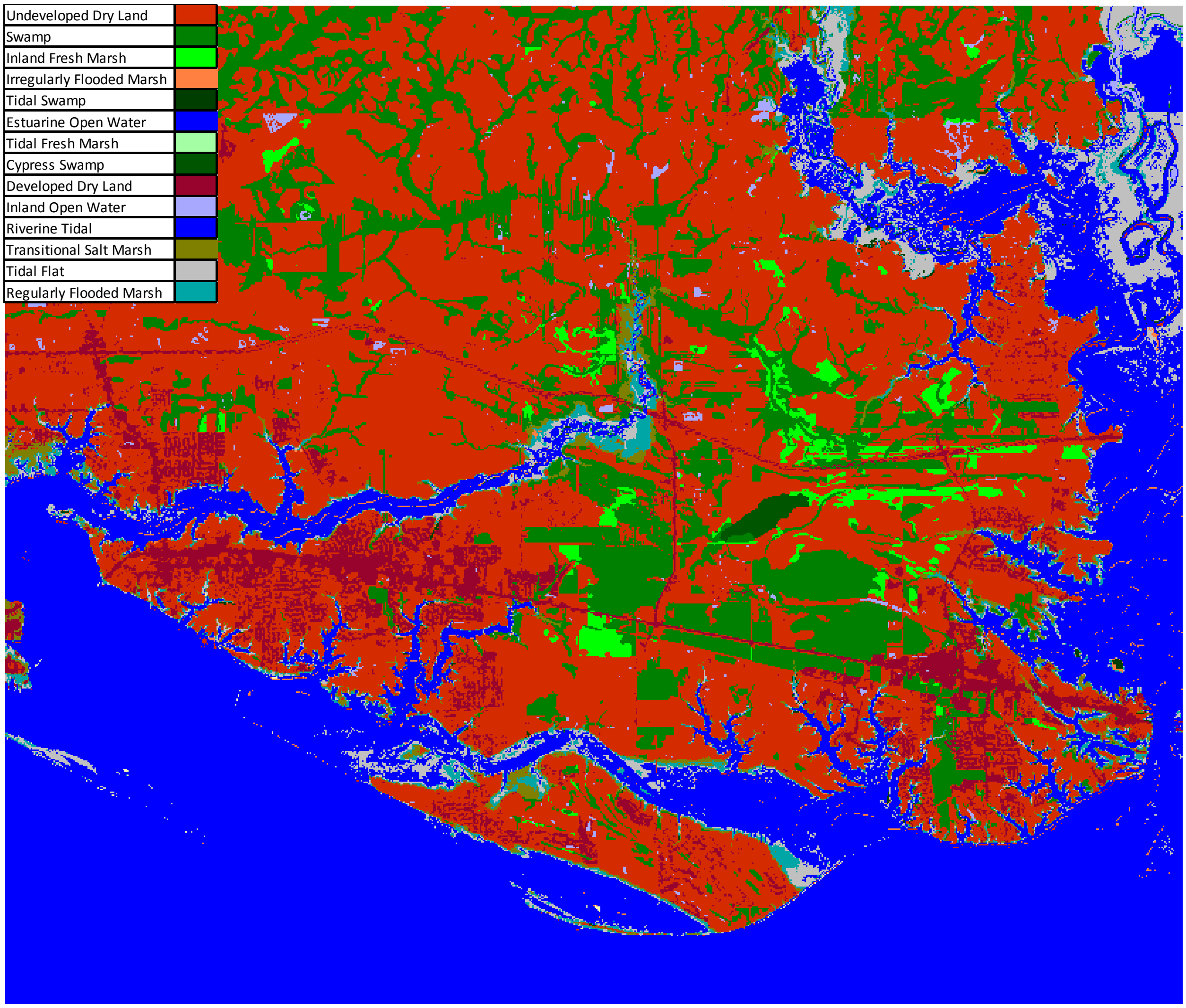
MS Sandhill Crane NWR, 2025, 2 m SLR



MS Sandhill Crane NWR, 2050, 2 m SLR



MS Sandhill Crane NWR, 2075, 2 m SLR



MS Sandhill Crane NWR, 2100, 2 m SLR