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

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Introduction

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

In an effort to address the potential effects of sea level rise on United States national wildlife refuge system, the U. S. Fish and Wildlife Service contracted the application of the SLAMM model for many coastal refuges. This analysis is designed to assist in the production of comprehensive conservation plans (CCPs) for each refuge along with other long-term management plans.

This is the second application of SLAMM to Cape Romain NWR. The first application was carried out in 2008. Previous simulations did not include LiDAR-derived elevation data while the current application incorporates a bare-earth LiDAR elevation dataset for the coastal strip of the study area and an updated National Wetlands Inventory data layer. In addition, the scenario of 2 m of eustatic SLR by 2100, which was not considered in the 2008 model application, was modeled in the current study.

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.

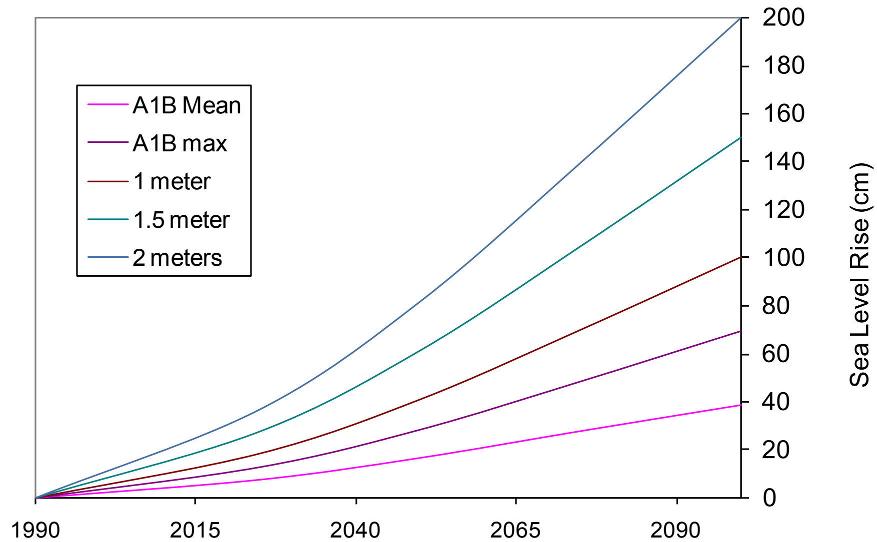


Figure 1. Summary of SLR scenarios utilized.

Data Sources and Methods

Wetland layer. Figure 2 shows the most recent available wetland layer obtained from a National Wetlands Inventory (NWI) photo dated 2009. Converting the NWI survey into 10 m x 10 m cells indicated that the approximately 63,000 acre Cape Romain NWR (approved acquisition boundary including water) is composed of the following categories:

Land cover type		Area (acres)	Percentage (%)
	Regularly-flooded Marsh	28013	44
	Estuarine Open Water	20116	32
	Open Ocean	5885	9
	Undeveloped Dry Land	2373	4
	Estuarine Beach	2000	3
	Irregularly-flooded Marsh	1598	3
	Swamp	775	1
	Tidal Swamp	515	1
	Transitional Salt Marsh	483	1
	Inland Open Water	471	1
	Ocean Beach	386	1
	Inland Fresh Marsh	260	< 1
	Tidal Flat	72	< 1
	Tidal Fresh Marsh	35	< 1
	Developed Dry Land	4	< 1
	Total (incl. water)	**62986**	**100**

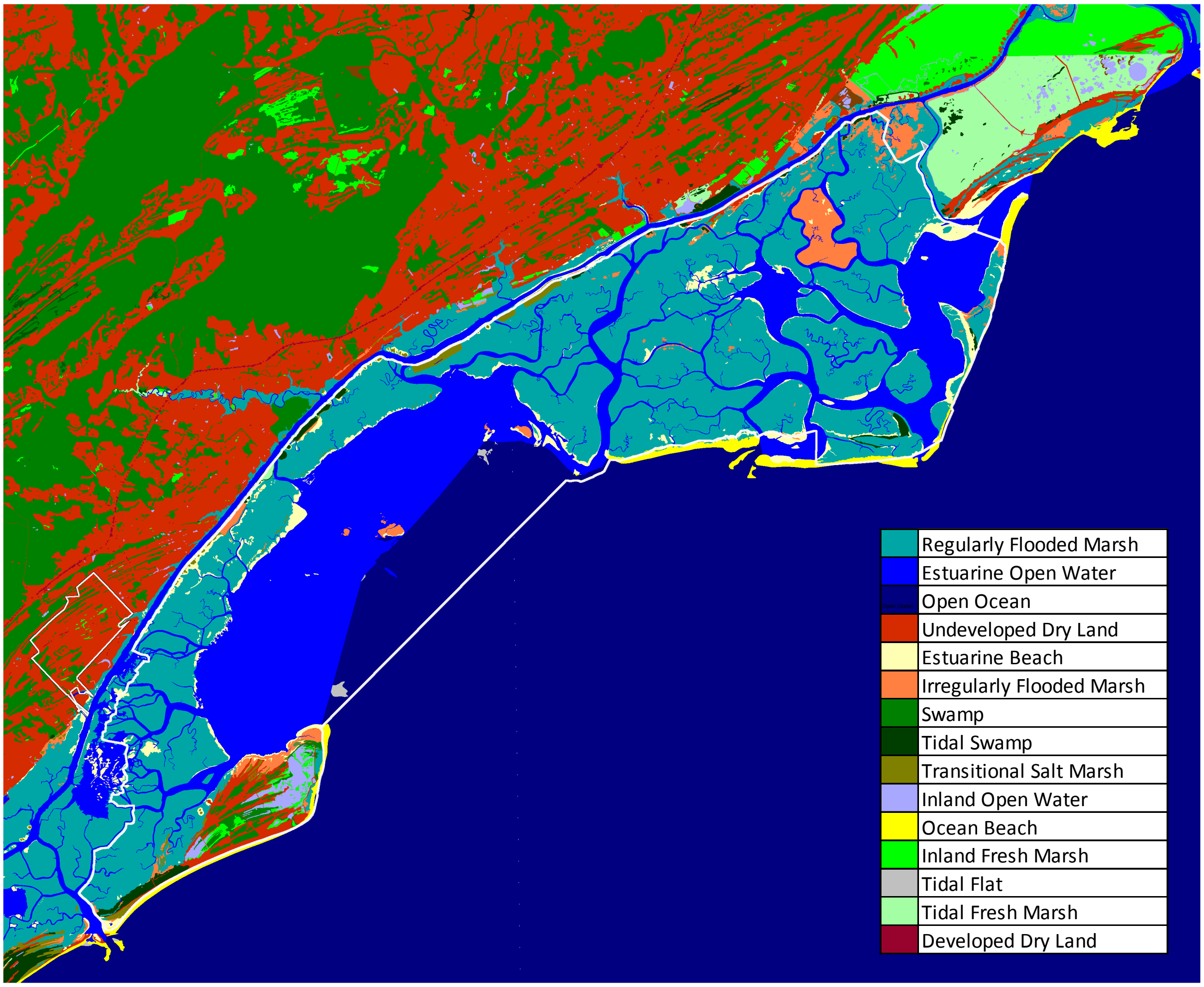


Figure 2. 2009 NWI coverage of the study area. Refuge boundaries are indicated in white.

Elevation Data. LiDAR elevation data were only available for portions of the refuge directly in contact with open ocean (the "coastal strip"). These data were collected in 2000 and 2006. The majority of the refuge was not covered by LiDAR-derived elevation data, but instead elevations were based on datasets released between 1942 and 1957. The contour intervals of these data were 5 to 20 m which resulted in poorly characterized wetland elevations. As a consequence of this lack of vertical accuracy, the SLAMM elevation pre-processor was used for the entire site. This module assigns elevations for wetlands as a function of the local tide range (Clough et al. 2010). This process causes additional uncertainty in model results as covered in the *Discussion* section below.

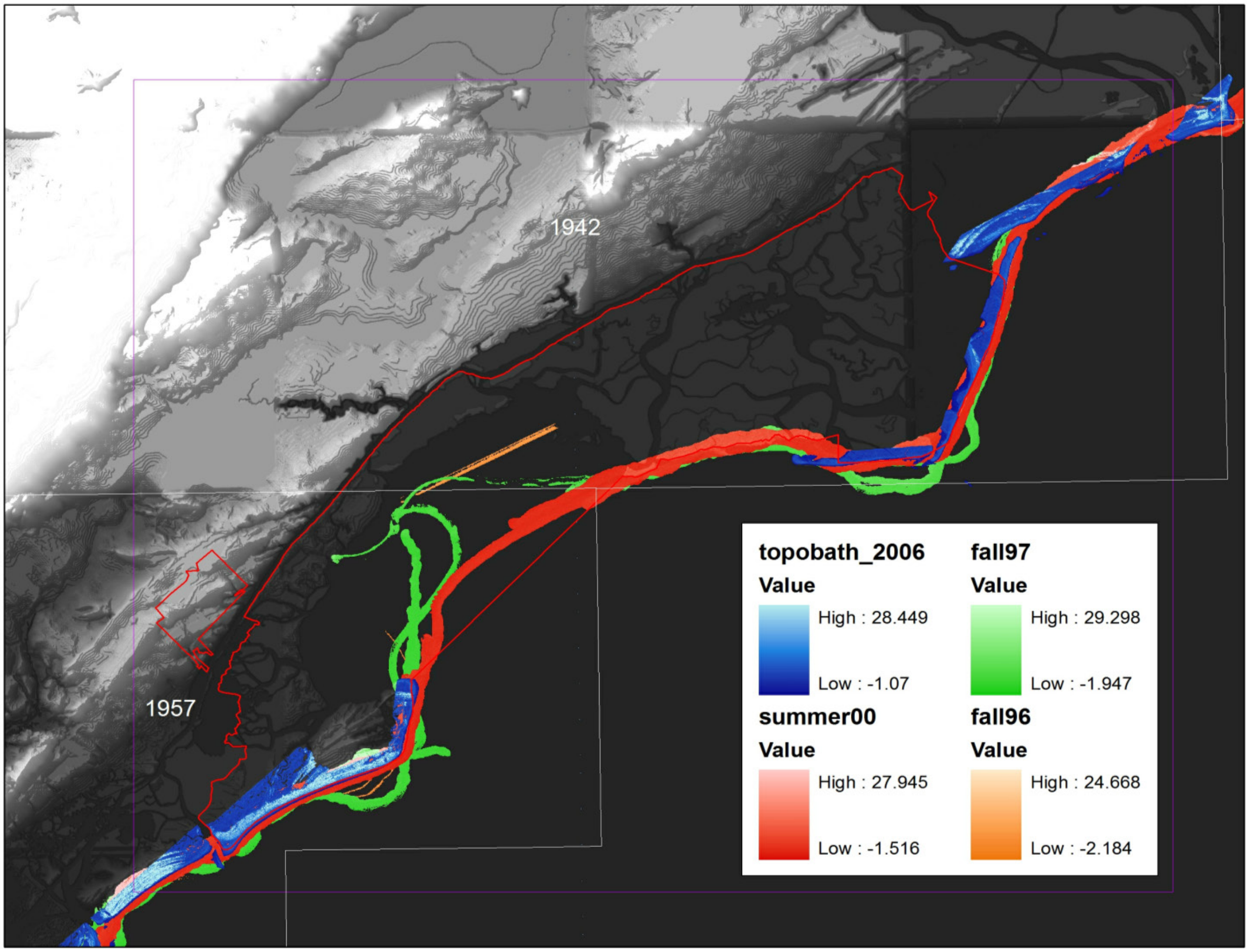


Figure 3. LiDAR coverage for the entire study area.
Refuge boundaries shown in thin red lines.

Dikes and Impoundments. According to the National Wetland Inventory, there are areas protected by dikes within the refuge. The majority of the diked areas are located in the southern portion of the refuge, as shown in Figure 4. These areas are assumed to remain protected from the effects of SLR until local SLR exceeds 2 meters.

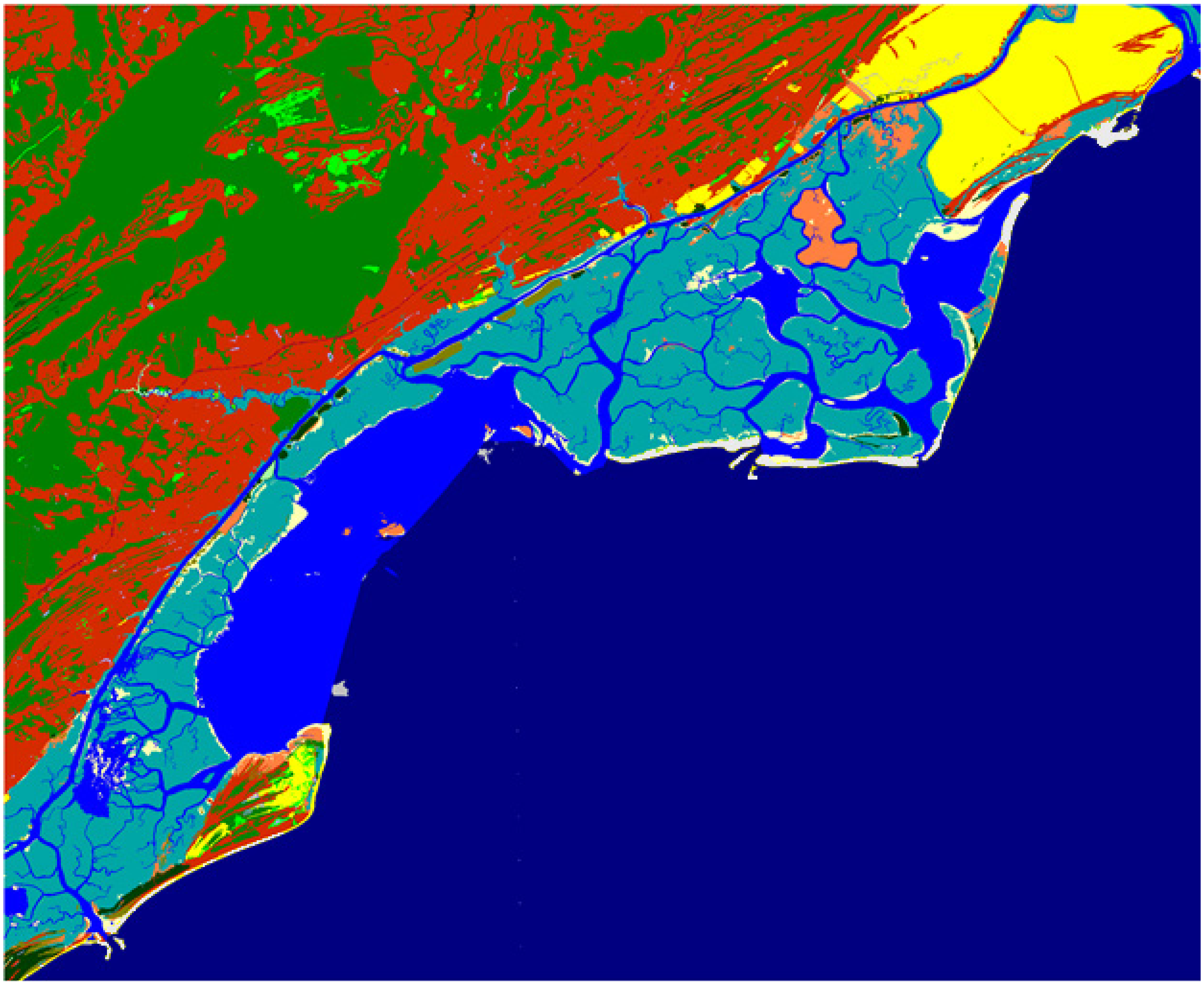


Figure 4. Diked areas in and around Cape Romain NWR
(diked areas are shown in yellow)

Model Timesteps. Model forecast data is output for years 2025, 2050, 2075 and 2100 with the initial condition date set to 2009, the most recent wetland data available.

Historic sea level rise rates. The Charleston, SC (#8670870) NOAA gauge is adjacent to Cape Romain Island NWR. The historic trend for relative sea level rise rates recorded at this station is 3.15 mm/yr., which was applied to the entire study area. 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 area.

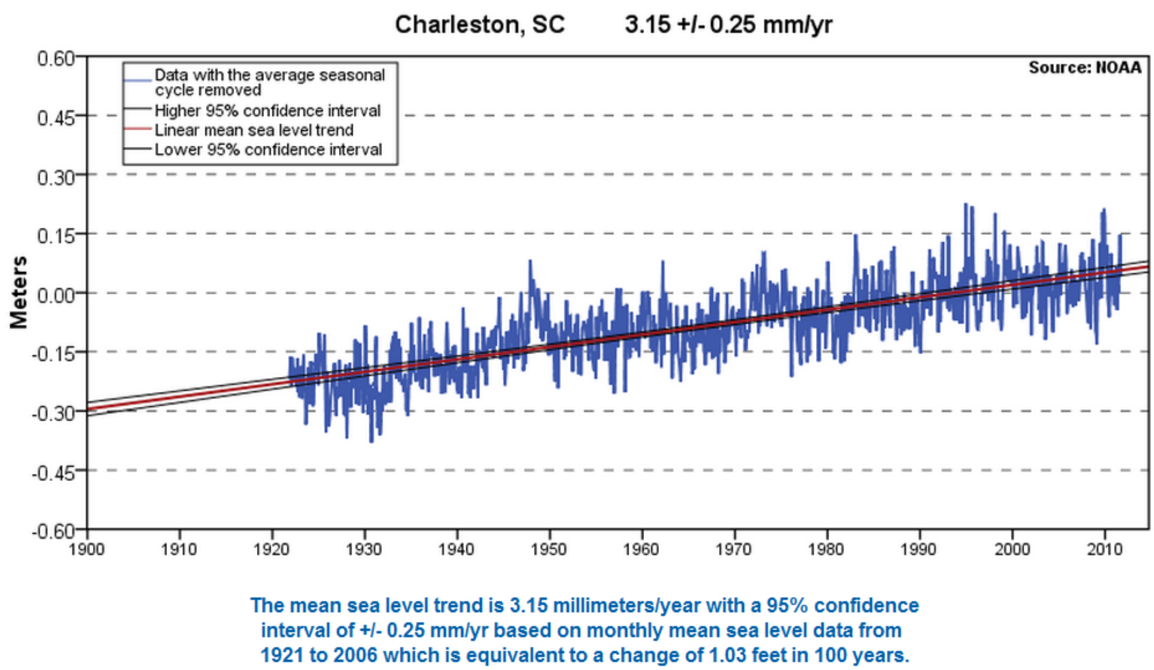


Figure 5. Historic Sea level trend at Charleston, SC.

Tide Ranges. The great diurnal range (GT) was applied using the average tide range observed at NOAA gauge stations in and around Cape Romain NWR. The data considered are shown in The average GT observed along the coast was 1.6 m, and this value was applied to the entire study area. NOAA tide table data for the study area supported this decision. A higher tide range was observed further inland (Big Paradise Island, Wando River) however, this tide station represented tidal ranges that were further inland than the refuge itself and was not included.

Table 1. NOAA Tide range data in and around Cape Romain NWR

Station Name	ID	GT (m)
South Dewees Island, Dewees Inlet, SC	8665111	1.7
North Dewees Island, SC	8664992	1.6
South Capers Island, SC	8664941	1.6
Big Paradise Island, Wando River, SC	8664611	2.1
Old Capers Landing, Capers Island, SC	8664878	1.7
Price Creek, North Capers Island, SC	8664801	1.6
McClellanville, Jeremy Creek, SC	8663618	1.7
Casino Creek, SC	8663461	1.5

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 1.5 Half Tide Units (HTU) for all input subsites, corresponding to 1. 2 m above MTL within the majority of the refuge area.

Accretion rates. Because of the availability of data and the prevalence of regularly-flooded marsh in the refuge, accretion feedbacks were applied for this habitat type. A linear relationship between accretion and marsh elevation with respect to MTL was applied. The minimum accretion applied was 1.9 mm/yr based on measured rates of accretion in Georgia Marshes (Craft, personal communication) while the maximum accretion applied was 5.1 mm/yr based on measurements by Morris and coworkers in the North Inlet Estuary, SC (2002), resulting in an average accretion value of 3.4 mm/yr.

Irregularly-flooded marsh was assigned a rate of 4.3 mm/yr and tidal fresh marsh was assigned an accretion rate of 4.8 mm/yr based on measured rates of accretion in Georgia marshes (Craft, personal communication). Tidal fresh and inland fresh marsh accretion rates were set to the SLAMM default value of 4 mm/yr.

Erosion rates. 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. Due to lack of site-specific values, erosion rates were set to the SLAMM defaults. Tidal flat erosion was set to 0.2 m/yr., marshes were set to 2 m/yr., and a rate of 1 m/yr. was applied to swamps.

Elevation correction. MTL to NAVD88 corrections determined using NOAA's VDATUM software varied from -0.048 m to -0.078 m (n = 10). Since this range was quite small, the average correction of -0.066 m was applied.

Refuge boundaries. Modeled USFWS refuge boundaries for South Carolina 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 is 10 m.

Input subsites and parameter summary. Based on spatial variability of the tide ranges and different elevation datasets, the study area was subdivided in the subsites illustrated in Figure 6.

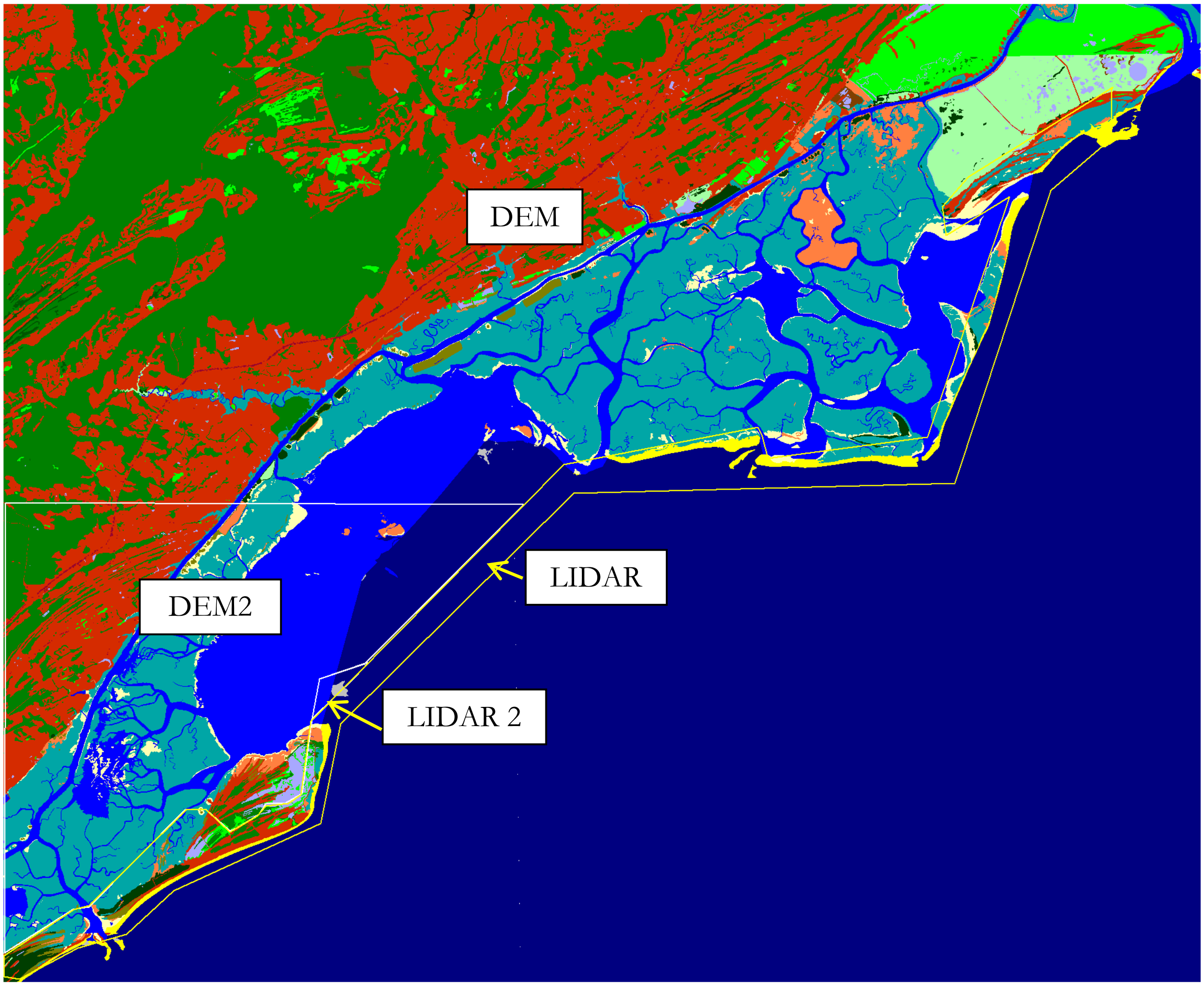


Figure 6. Input subsites for parameter application.

Table 2 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 majority of the refuge lies within subsite 2. The connectivity module of SLAMM was used in this model application in order to ensure dry land only converts to wetland if there is an unimpeded path from open water to the dry land in question.

Table 2. Summary of SLAMM input parameters for Cape Romain NWR.

Parameter	DEM1	DEM2	LiDAR and LiDAR2
NWI Photo Date (YYYY)	2009	2009	2009
DEM Date (YYYY)	1942	1957	2003
Direction Offshore [n,s,e,w]	East	East	East
Historic Trend (mm/yr)	3.15	3.15	3.15
MTL-NAVD88 (m)	-0.066	-0.066	-0.066
GT Great Diurnal Tide Range (m)	1.6	1.6	1.6
Salt Elev. (m above MTL)	1.2	1.2	1.2
Marsh Erosion (horz. m /yr)	2	2	2
Swamp Erosion (horz. m /yr)	1	1	1
T.Flat Erosion (horz. m /yr)	0.2	0.2	0.2
Irreg.-Flood Marsh Accr (mm/yr)	4.3	4.3	4.3
Tidal-Fresh Marsh Accr (mm/yr)	4.8	4.8	4.8
Inland-Fresh Marsh Accr (mm/yr)	4	4	4
Mangrove Accr (mm/yr)	7	7	7
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)	25	25	25
Use Elev Pre-processor [True,False]	TRUE	TRUE	FALSE
Reg Flood Use Model [True,False]	TRUE	TRUE	TRUE
Reg Flood Max. Accr. (mm/year)	5.1	5.1	5.1
Reg Flood Min. Accr. (mm/year)	1.9	1.9	1.9
Reg Flood Elev a coeff. (cubic)	0	0	0
Reg Flood Elev b coeff. (square)	0	0	0
Reg Flood Elev c coeff. (linear)	1	1	1

Results

Table 3 presents the predicted losses for each land-cover by 2100 within the approved acquisition boundary for each of the five SLR scenarios examined. Land-cover losses are calculated in comparison to the initial 2009 NWI wetland coverage and wetland categories are sorted by decreasing initial land cover excluding open water.

Table 3. Predicted loss rates of land categories by 2100 given simulated scenarios of eustatic SLR at Cape Romain NWR. *Negative values indicate gains.*

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
Regularly-flooded Marsh	28013	4%	60%	86%	98%	98%
Undeveloped Dry Land	2373	3%	7%	13%	21%	30%
Estuarine Beach	2000	11%	28%	45%	64%	91%
Irregularly-flooded Marsh	1598	12%	58%	78%	87%	88%
Swamp	775	1%	6%	14%	39%	46%
Tidal Swamp	515	19%	30%	41%	57%	72%
Ocean Beach	386	7%	9%	11%	22%	43%
Inland Fresh Marsh	260	4%	13%	16%	31%	44%

Simulation results suggest Cape Romain NWR is fairly resilient to the effects of SLR under the lowest SLR scenario examined (0.39 m by 2100). However, at higher rates of accelerated SLR the refuge is predicted to undergo serious losses in habitat for the majority of habitat types. Simulations predict significant losses of regularly-and irregularly-flooded marsh, estuarine beach and tidal swamp, particularly at higher rates of SLR. Up to 30% of undeveloped dry land is also predicted to be lost.

Regularly-flooded marsh is currently the dominant wetland type in the refuge. SLAMM projections suggest the majority of this habitat type will be lost under accelerated SLR scenarios of 0.69 m by 2100 and greater. Under scenarios above 1 m of SLR by 2100 nearly all of the regularly-flooded marsh of the refuge is predicted to be lost. Maps on the following pages illustrate how regularly-flooded marsh converts to tidal flat and ultimately result in open water for scenarios of 0.69 m of eustatic SLR by 2100 and greater. Table 3 presents any increases in acreage of the habitat types that are predicted to increase as a result of losses of other habitat types.

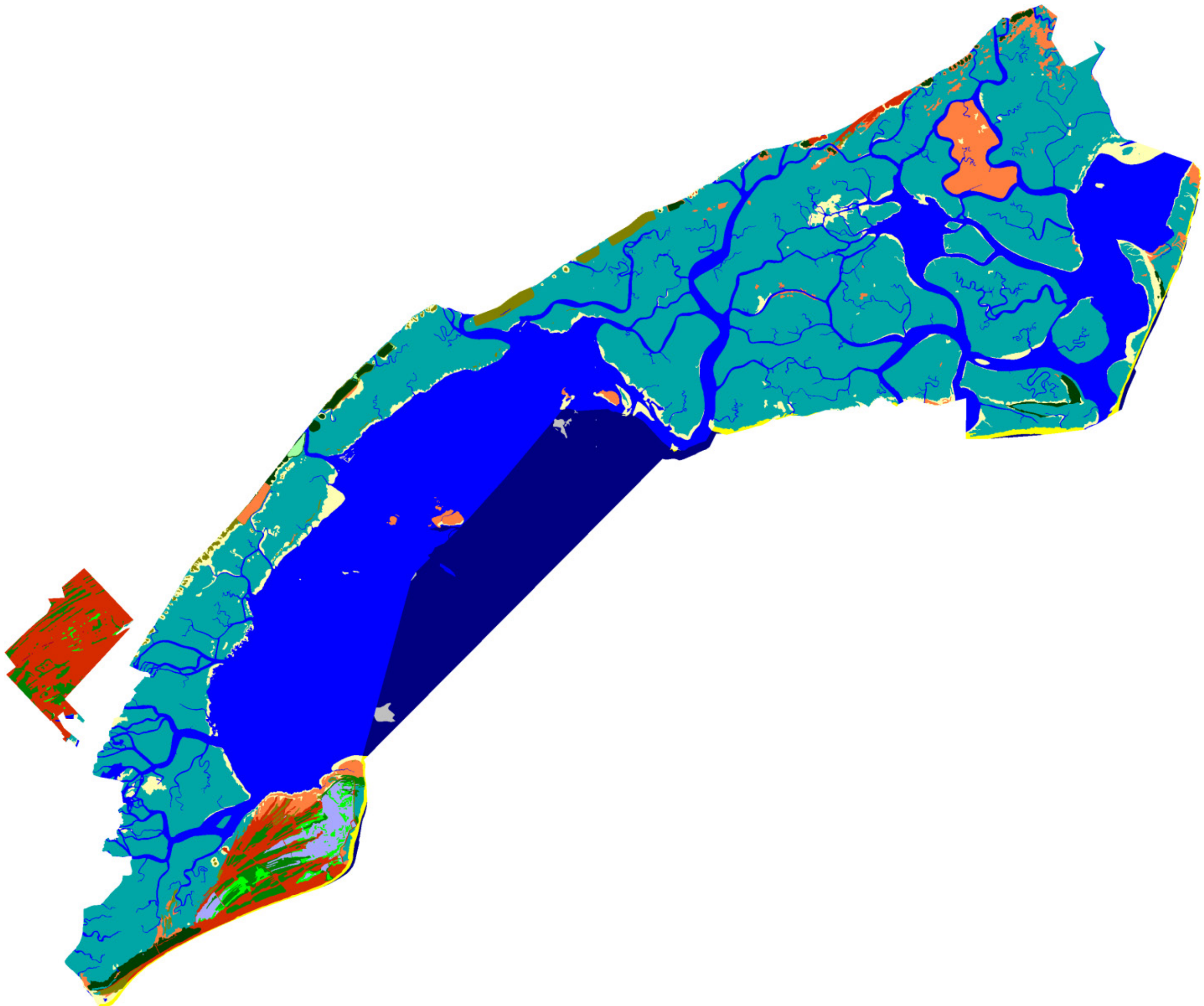
Table 4. Predicted increase in selected land categories by 2100 given simulated scenarios of eustatic SLR at Cape Romain NWR.

Land cover category	Initial coverage (acres)	Land cover change by 2100 for different SLR scenarios				
		0.39 m	0.69 m	1 m	1.5 m	2 m
Estuarine Open Water	20116	742	1502	2876	19842	30580
Open Ocean	5885	128	138	147	186	274
Tidal Flat	72	796	17270	24184	11266	1500

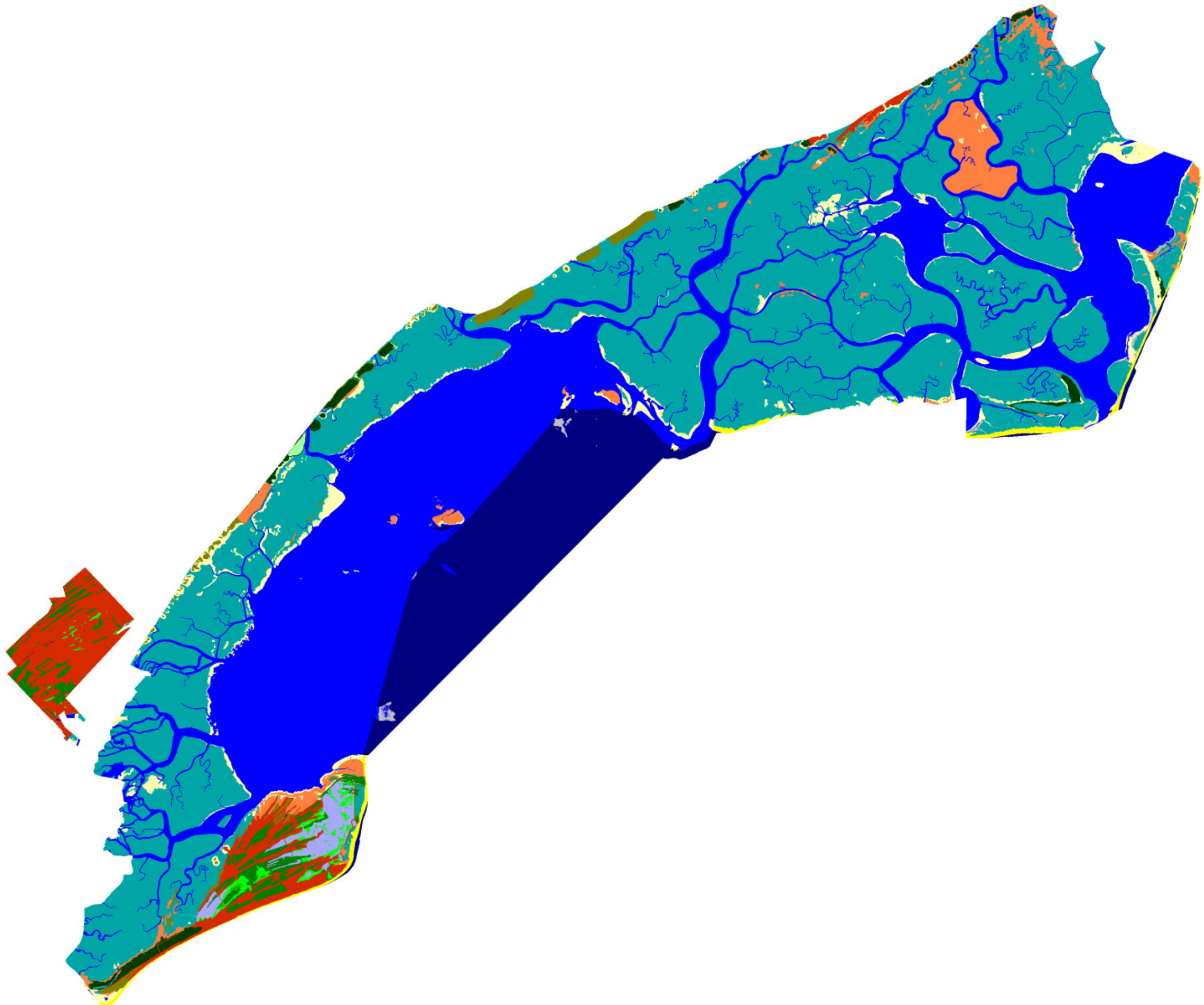
Cape Romain NWR
IPCC Scenario A1B-Mean, 0.39 m SLR eustatic by 2100

Results in Acres

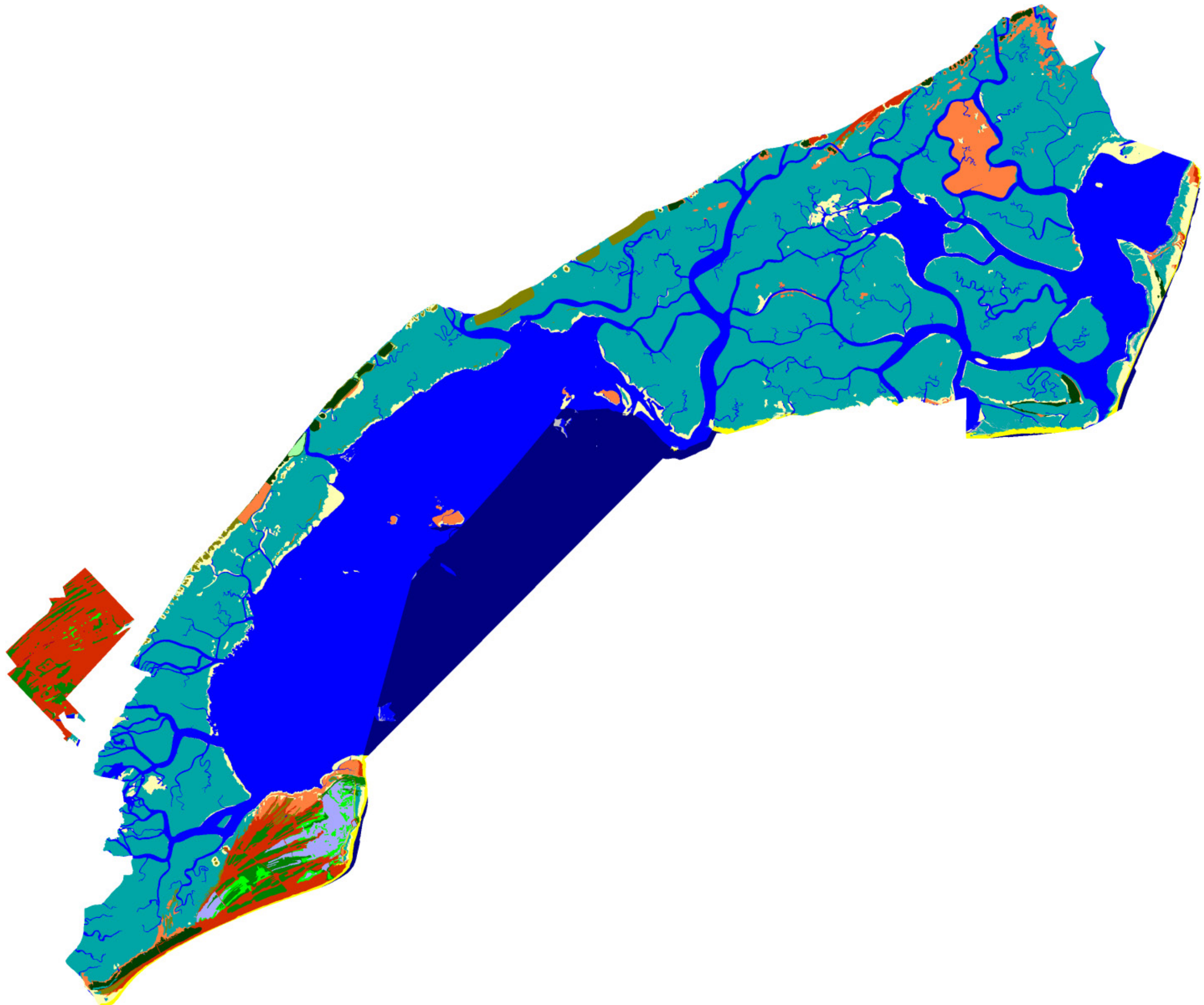
		Initial	2025	2050	2075	2100
	Regularly-flooded Marsh	28013	27944	27963	27864	27008
	Estuarine Open Water	20116	20206	20397	20550	20858
	Open Ocean	5885	5892	5903	5961	6013
	Undeveloped Dry Land	2373	2355	2336	2317	2294
	Estuarine Beach	2000	1935	1787	1837	1780
	Irregularly-flooded Marsh	1598	1617	1619	1506	1412
	Swamp	775	772	772	770	768
	Tidal Swamp	515	483	466	442	418
	Transitional Salt Marsh	483	491	507	486	454
	Inland Open Water	471	471	471	467	467
	Ocean Beach	386	380	370	370	359
	Inland Fresh Marsh	260	259	259	251	250
	Tidal Flat	72	140	97	126	867
	Tidal Fresh Marsh	35	35	35	35	35
	Developed Dry Land	4	4	4	4	4
	Total (incl. water)	**62986**	**62986**	**62986**	**62986**	**62986**



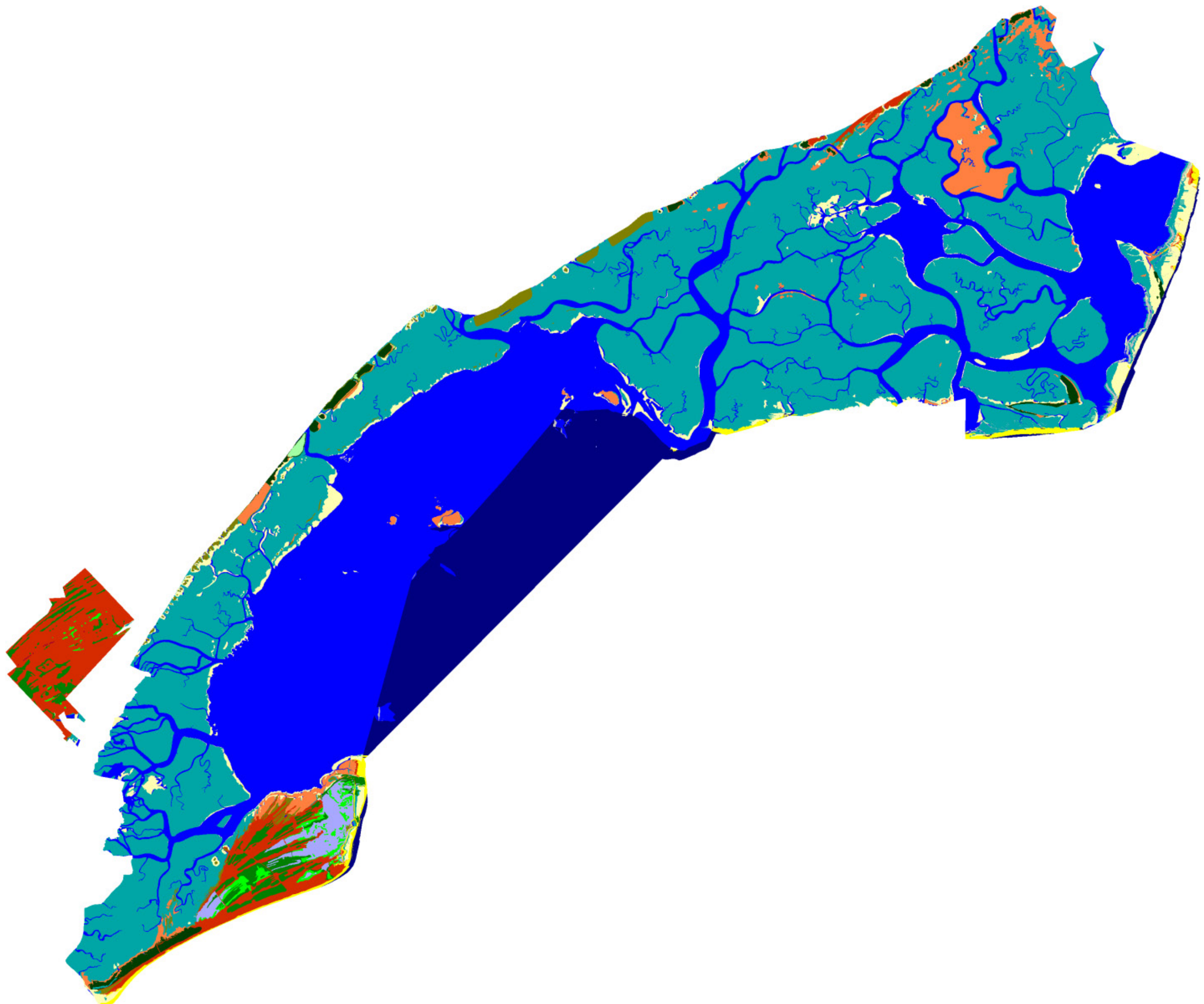
Cape Romain NWR, Initial Condition.



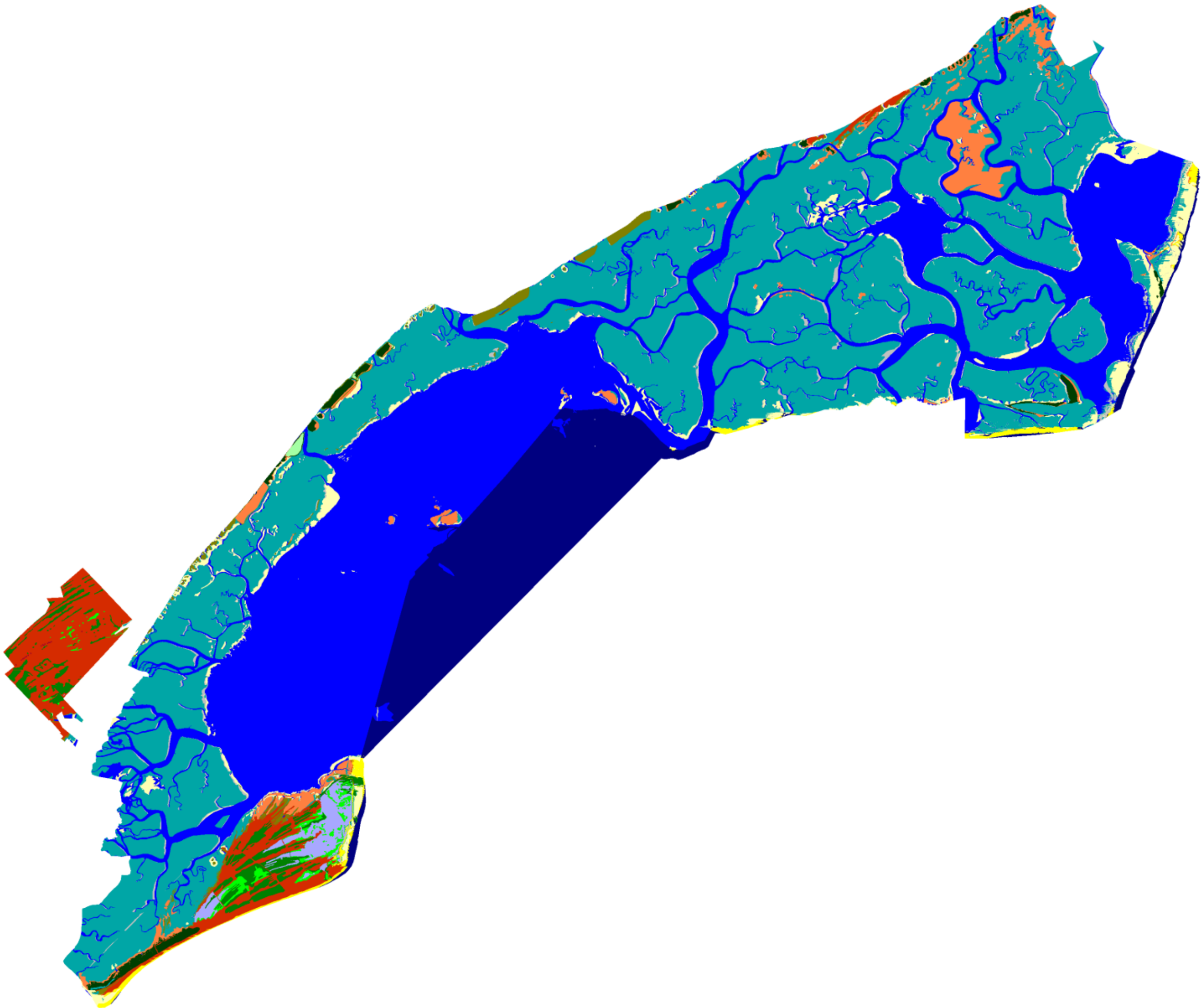
Cape Romain NWR, 2025, Scenario A1B Mean, 0.39 m SLR by 2100.



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



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

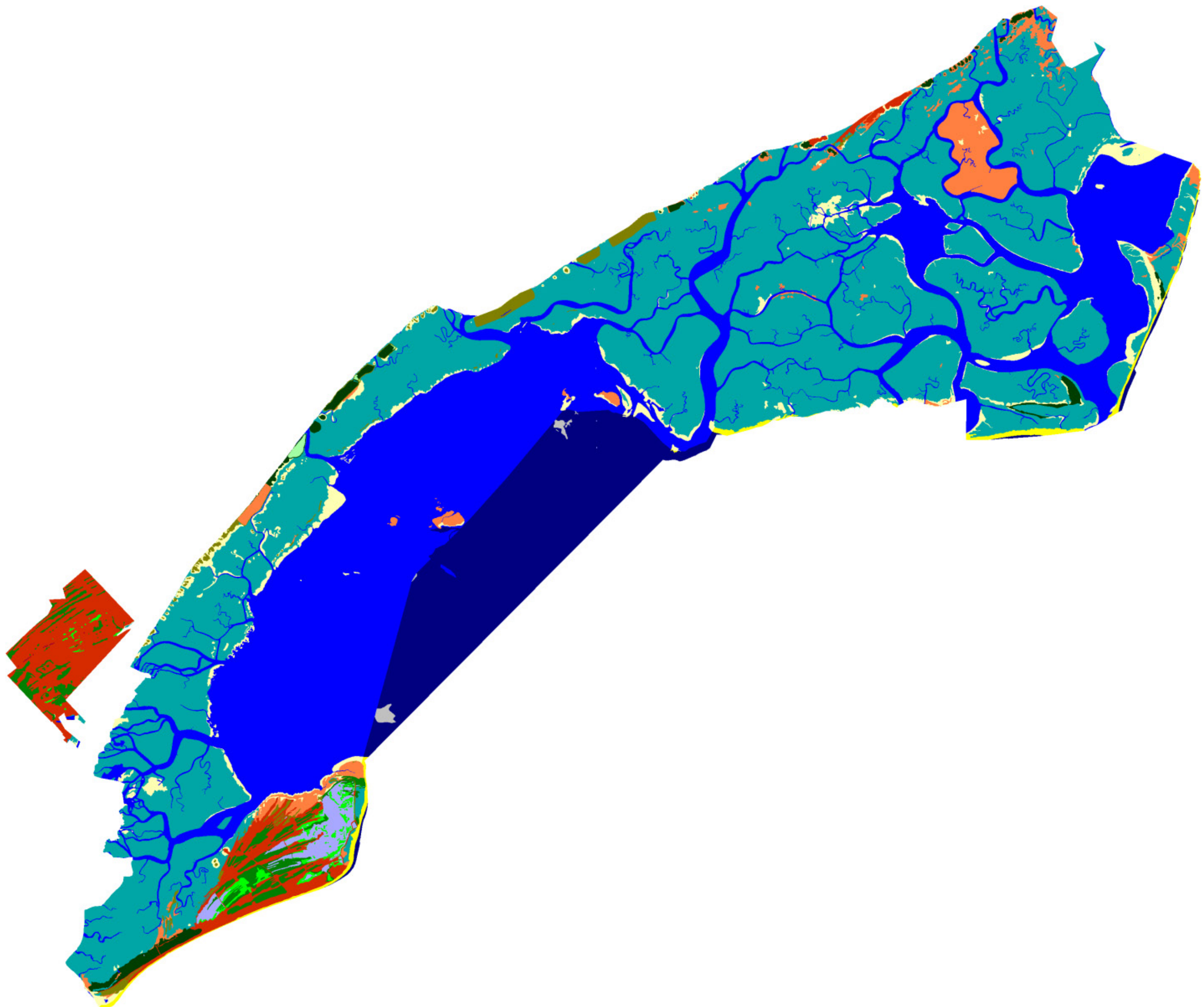


Cape Romain NWR, 2100, Scenario A1B Mean, 0.39 m SLR by 2100.

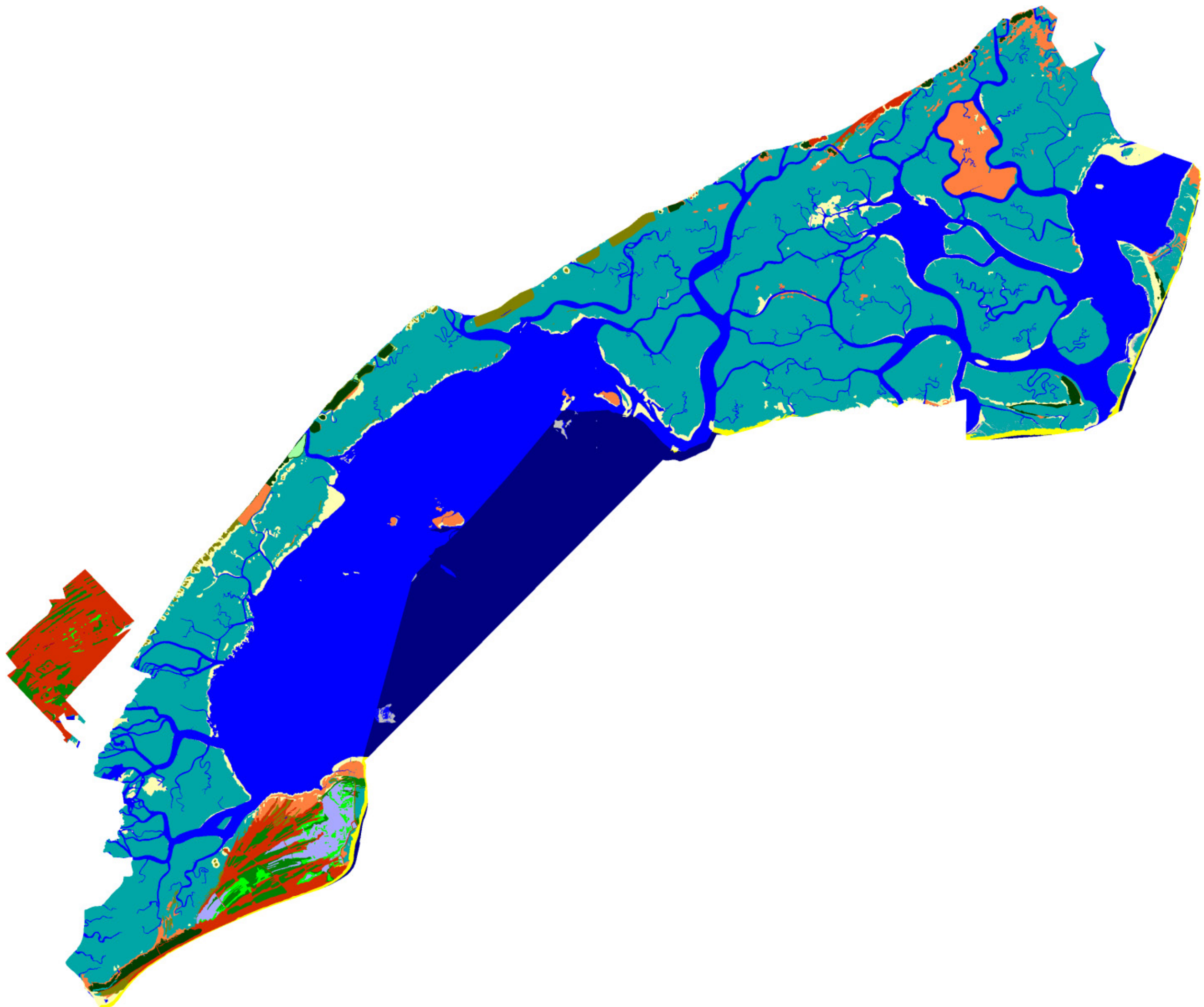
Cape Romain NWR
IPCC Scenario A1B-Max, 0.69 m SLR eustatic by 2100

Results in Acres

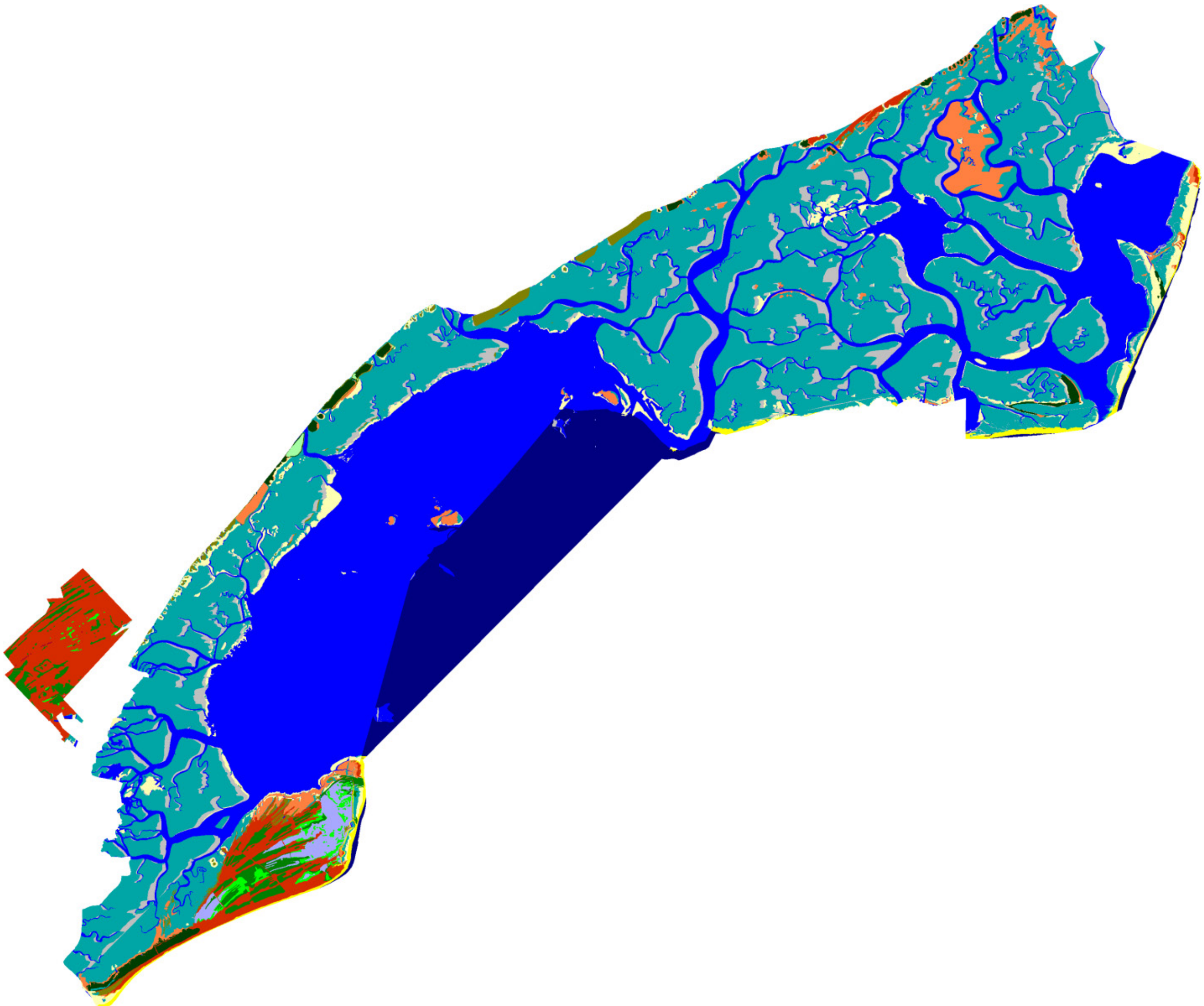
		Initial	2025	2050	2075	2100
	Regularly-flooded Marsh	28013	27971	25004	18711	11256
	Estuarine Open Water	20116	20243	20688	21127	21618
	Open Ocean	5885	5893	5904	5970	6023
	Undeveloped Dry Land	2373	2351	2316	2287	2203
	Estuarine Beach	2000	1909	1682	1622	1441
	Irregularly-flooded Marsh	1598	1598	1423	1054	664
	Swamp	775	772	771	767	726
	Tidal Swamp	515	479	449	406	362
	Transitional Salt Marsh	483	488	441	314	274
	Inland Open Water	471	471	467	467	466
	Ocean Beach	386	380	375	369	352
	Inland Fresh Marsh	260	259	251	248	225
	Tidal Flat	72	132	3177	9608	17342
	Tidal Fresh Marsh	35	35	34	32	30
	Developed Dry Land	4	4	4	4	4
	Total (incl. water)	**62986**	**62986**	**62986**	**62986**	**62986**



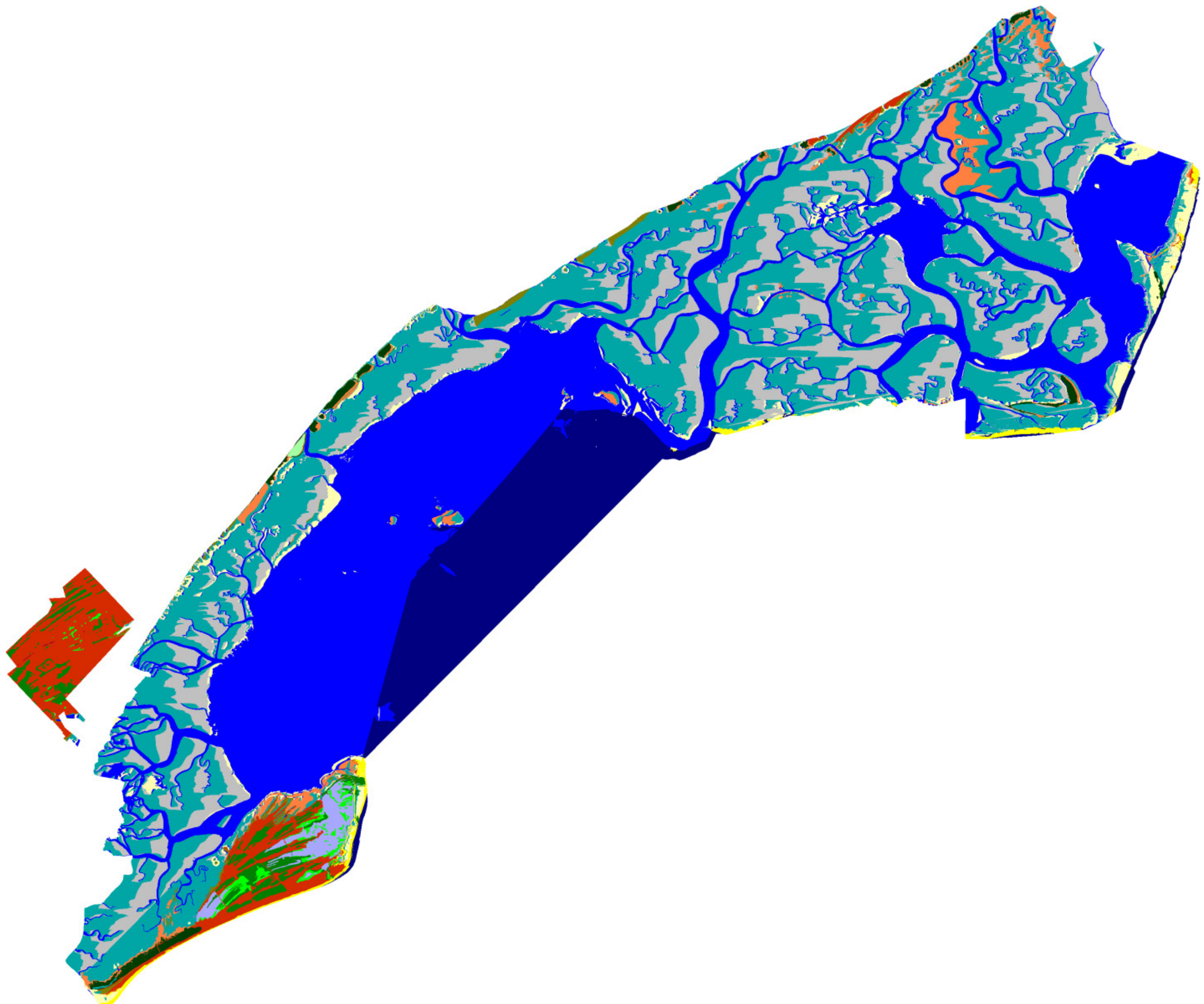
Cape Romain NWR, Initial Condition.



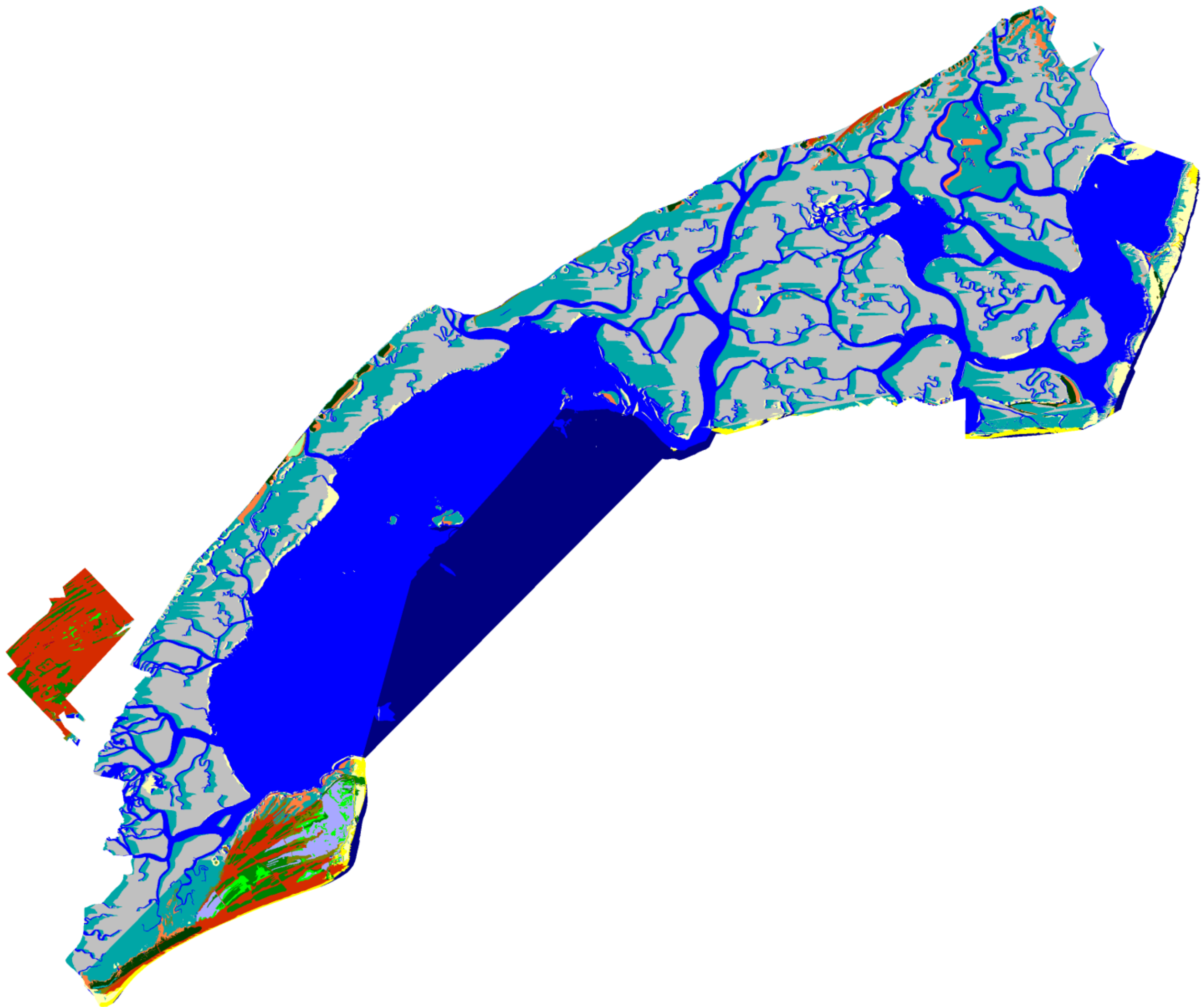
Cape Romain NWR, 2025, Scenario A1B Maximum, 0.69 m SLR by 2100.



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



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

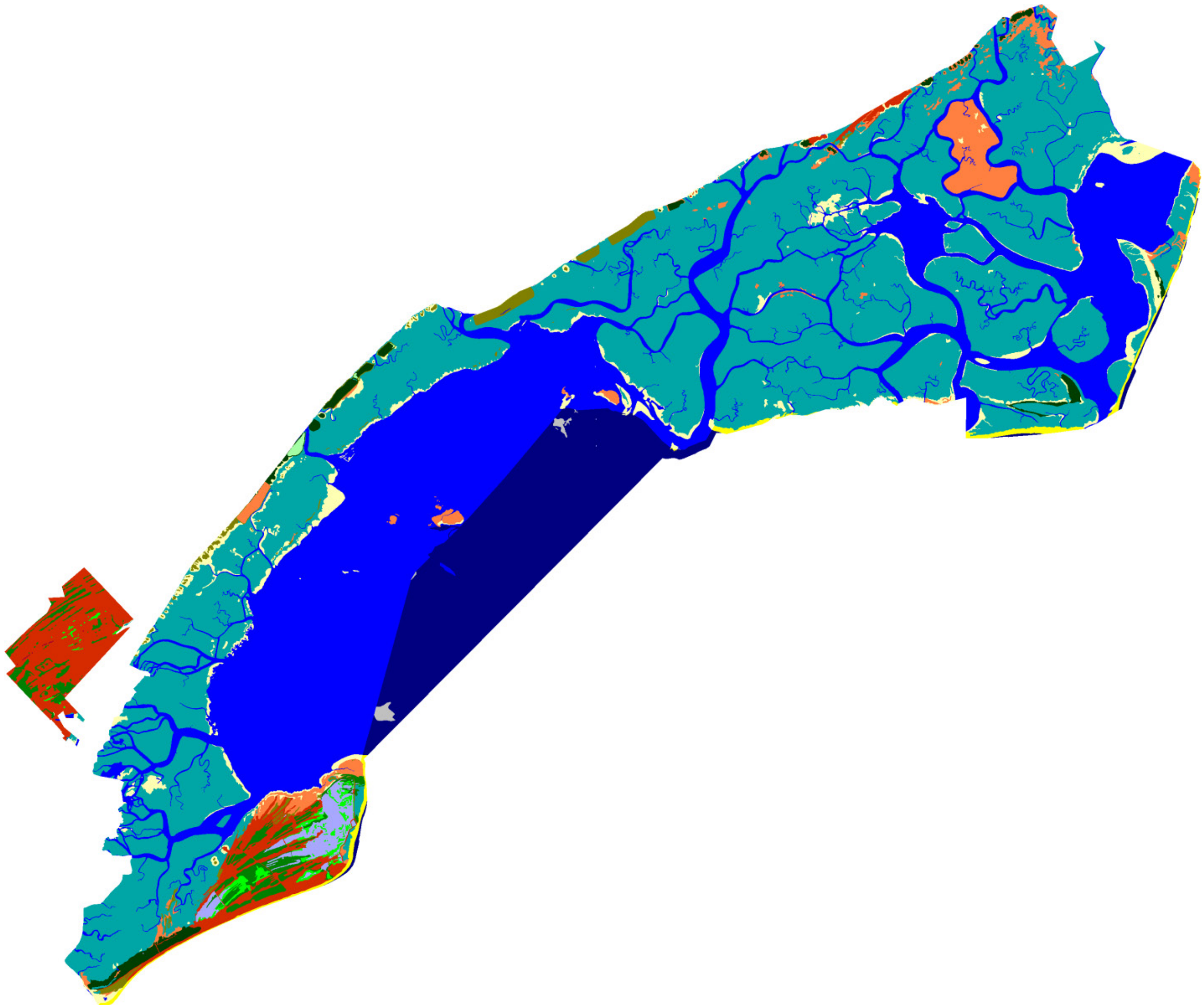


Cape Romain NWR, 2100, Scenario A1B Maximum, 0.69 m SLR by 2100.

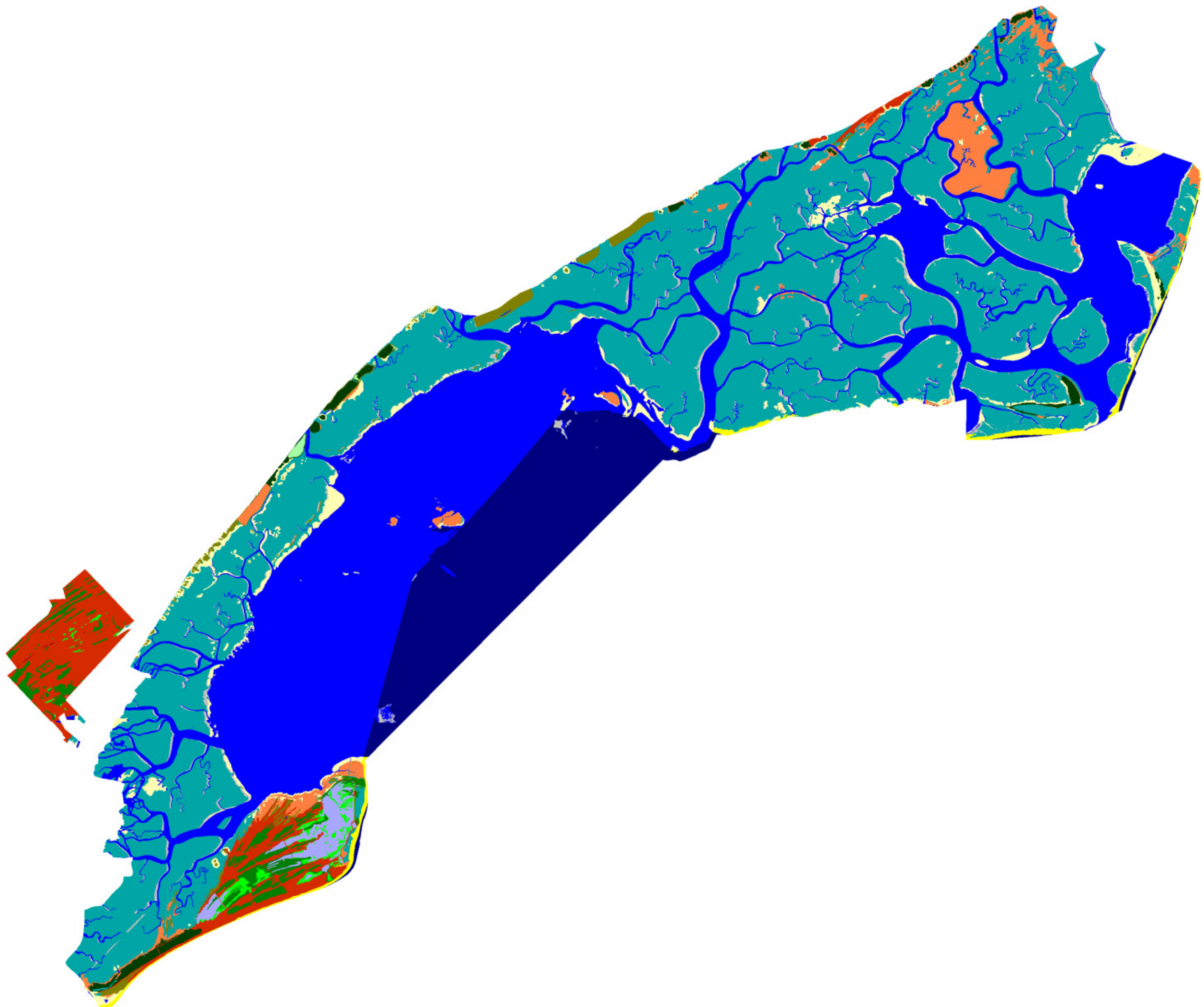
Cape Romain NWR
1 m eustatic SLR by 2100

Results in Acres

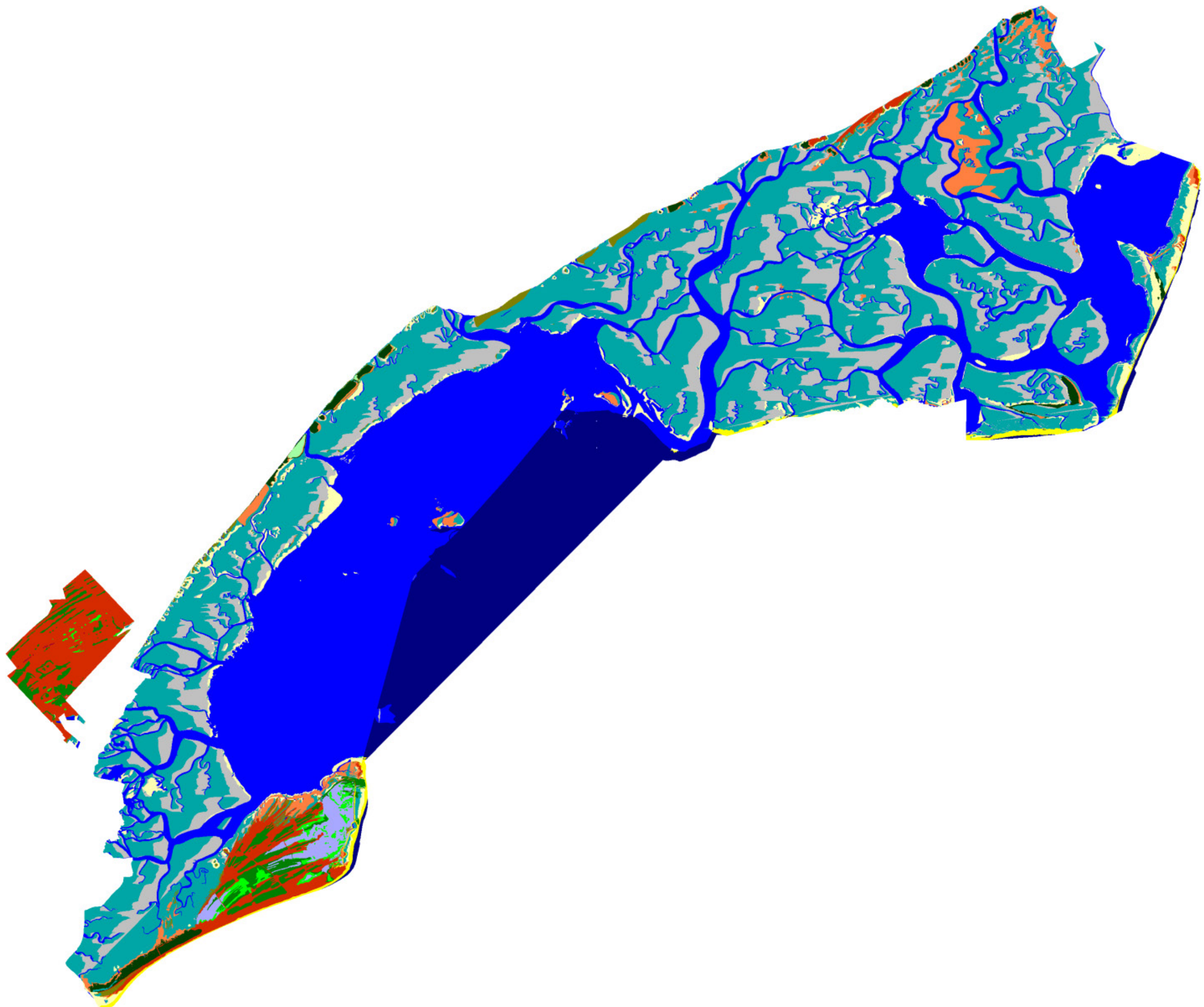
		Initial	2025	2050	2075	2100
	Regularly-flooded Marsh	28013	26962	20260	8757	3872
	Estuarine Open Water	20116	20372	20929	21476	22992
	Open Ocean	5885	5893	5906	5976	6032
	Undeveloped Dry Land	2373	2346	2299	2216	2076
	Estuarine Beach	2000	1880	1565	1400	1100
	Irregularly-flooded Marsh	1598	1546	1176	560	358
	Swamp	775	772	769	731	663
	Tidal Swamp	515	475	430	369	306
	Transitional Salt Marsh	483	470	353	226	281
	Inland Open Water	471	471	467	466	459
	Ocean Beach	386	380	374	365	343
	Inland Fresh Marsh	260	259	249	225	218
	Tidal Flat	72	1122	8171	20187	24256
	Tidal Fresh Marsh	35	35	33	29	25
	Developed Dry Land	4	4	4	4	4
	Total (incl. water)	**62986**	**62986**	**62986**	**62986**	**62986**



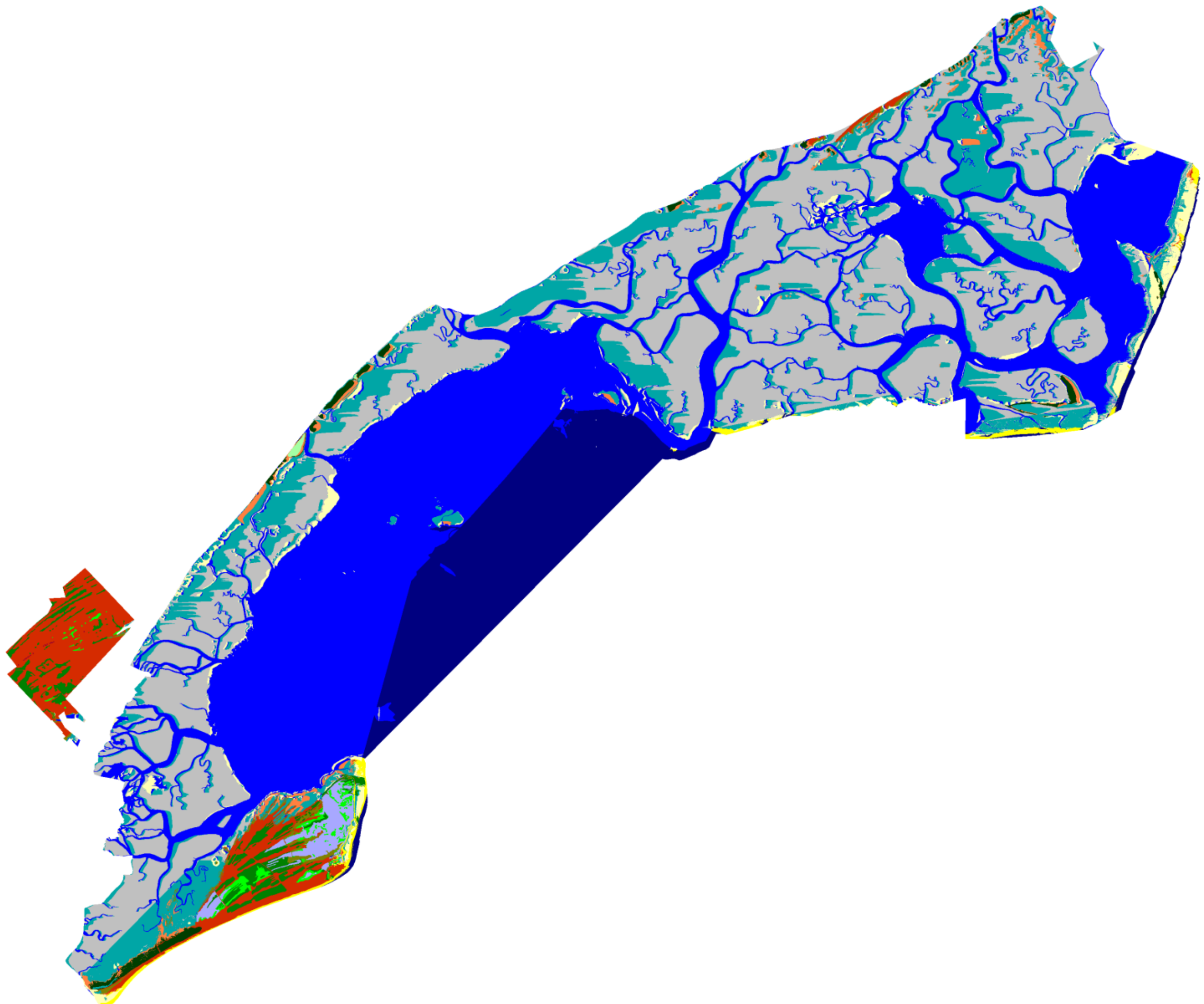
Cape Romain NWR, Initial Condition.



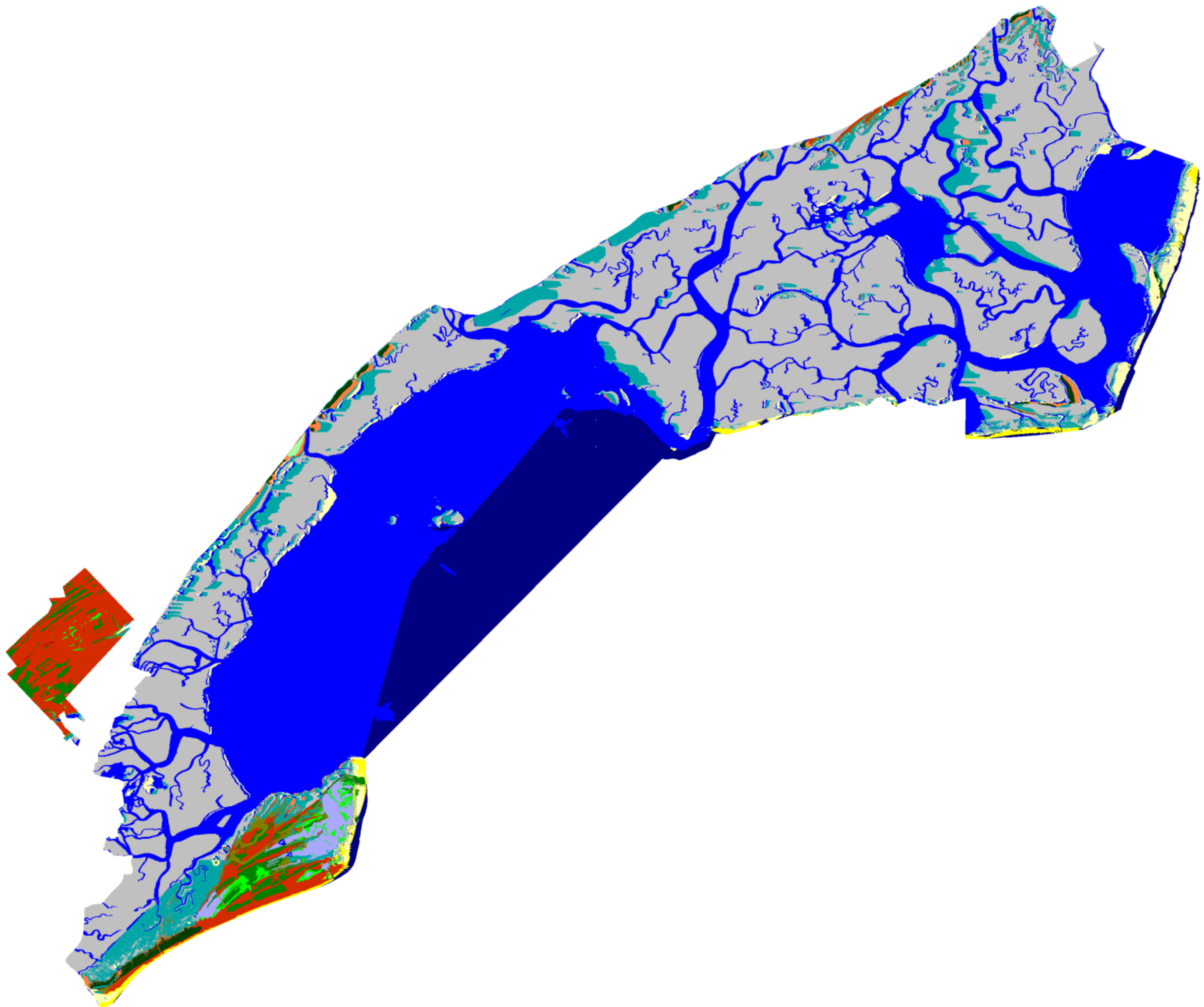
Cape Romain NWR, 2025, 1 m SLR by 2100.



Cape Romain NWR, 2050, 1 m SLR by 2100.



Cape Romain NWR, 2075, 1 m SLR by 2100.

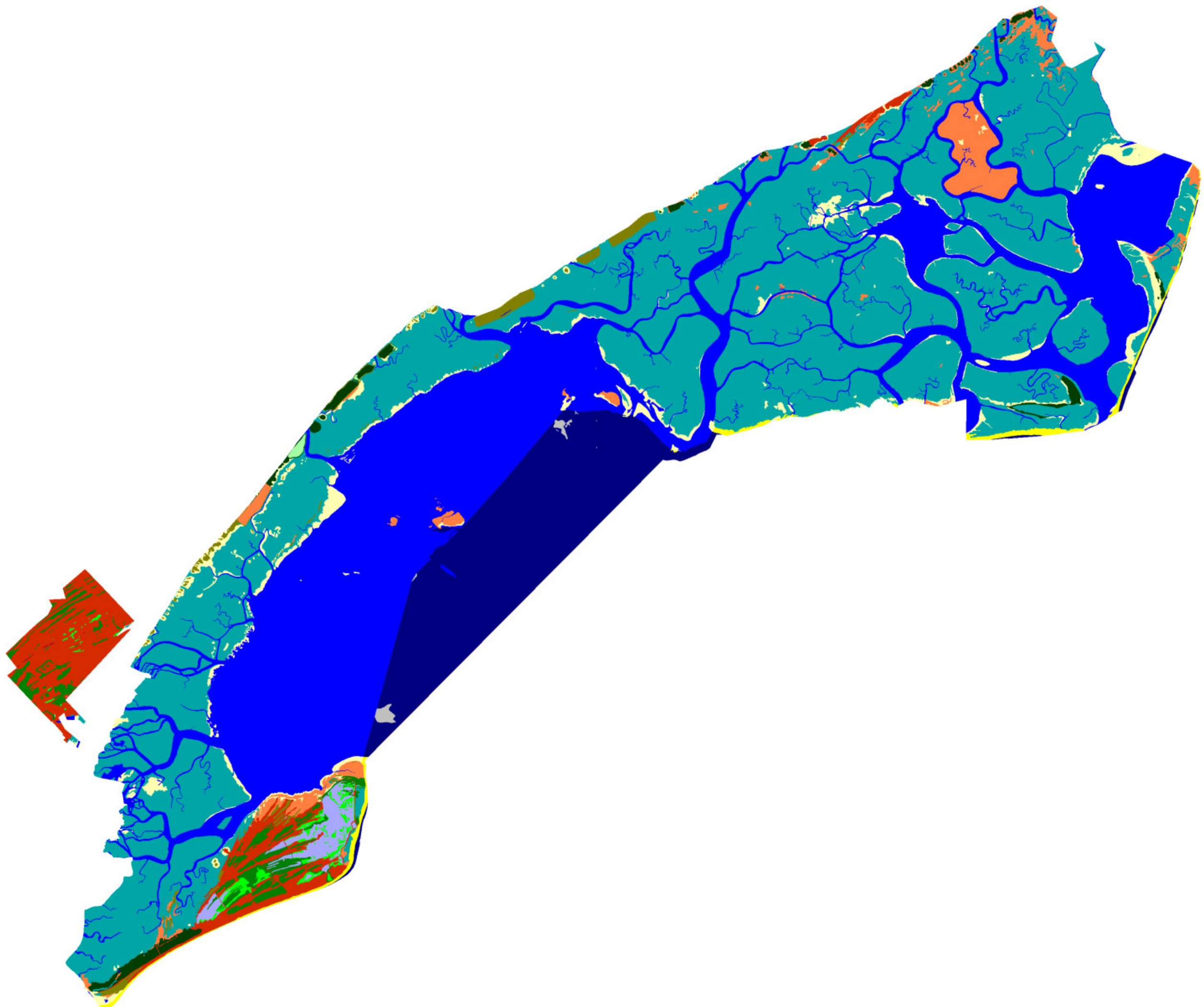


Cape Romain NWR, 2100, 1 m SLR by 2100.

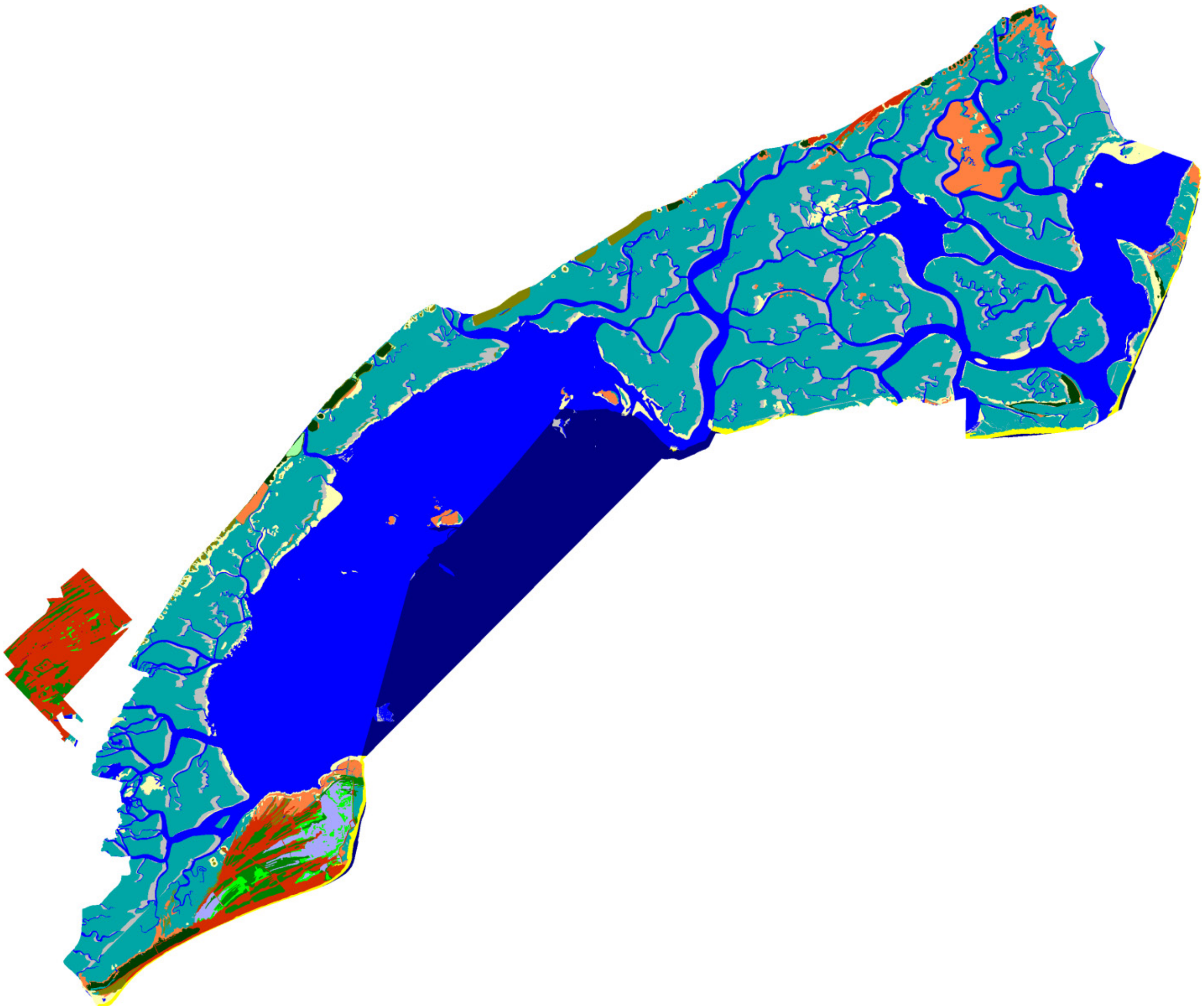
Cape Romain NWR
1.5 m eustatic SLR by 2100

Results in Acres

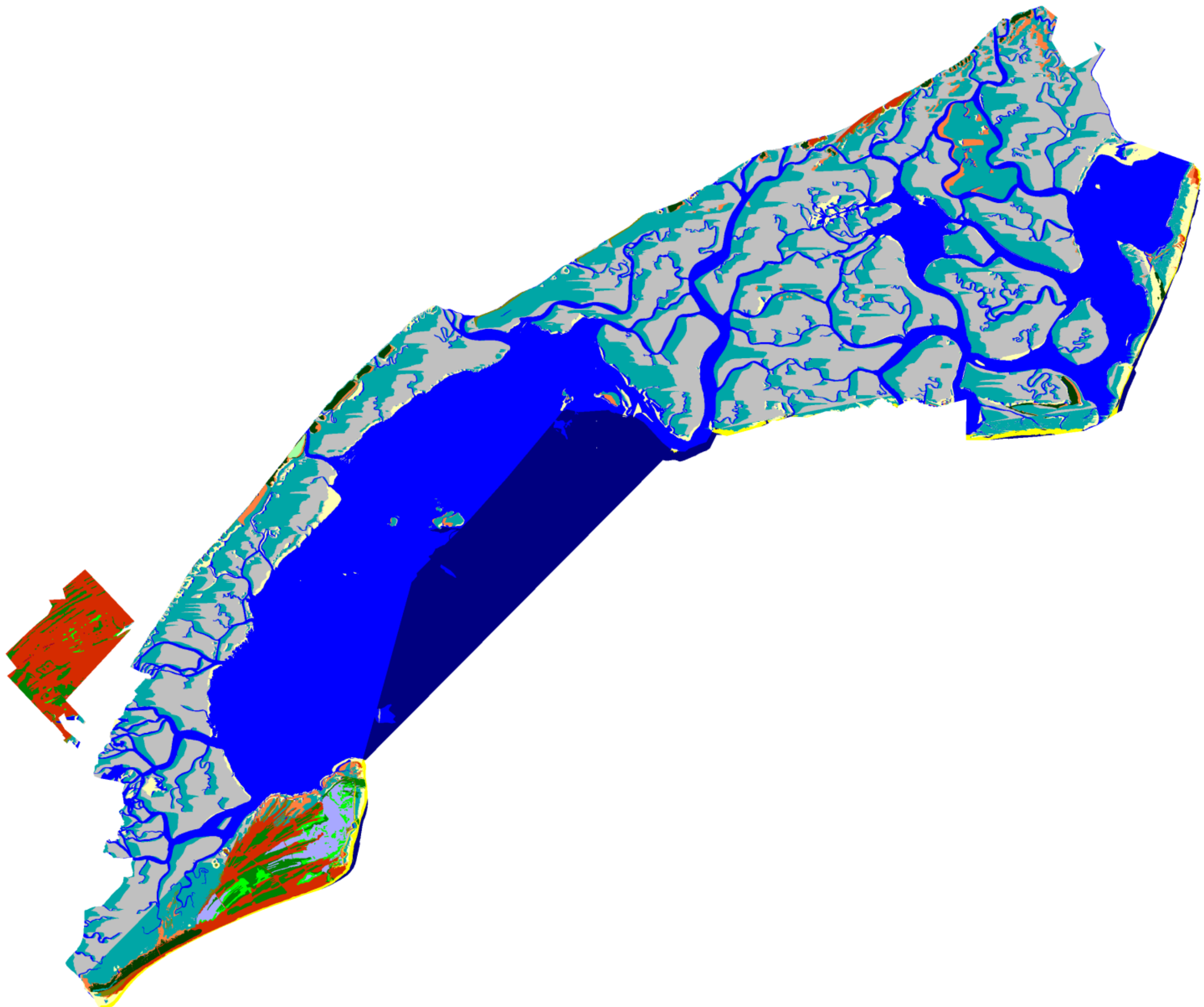
		Initial	2025	2050	2075	2100
	Regularly-flooded Marsh	28013	25050	12367	3012	638
	Estuarine Open Water	20116	20452	21160	24854	39958
	Open Ocean	5885	5893	5914	5986	6071
	Undeveloped Dry Land	2373	2341	2276	2099	1866
	Estuarine Beach	2000	1828	1372	1023	726
	Irregularly-flooded Marsh	1598	1449	739	299	213
	Swamp	775	772	767	694	471
	Tidal Swamp	515	467	399	309	223
	Transitional Salt Marsh	483	432	205	323	532
	Inland Open Water	471	471	467	466	450
	Ocean Beach	386	380	368	353	302
	Inland Fresh Marsh	260	259	247	217	179
	Tidal Flat	72	3155	16672	23325	11337
	Tidal Fresh Marsh	35	34	30	23	16
	Developed Dry Land	4	4	4	4	4
	Total (incl. water)	**62986**	**62986**	**62986**	**62986**	**62986**



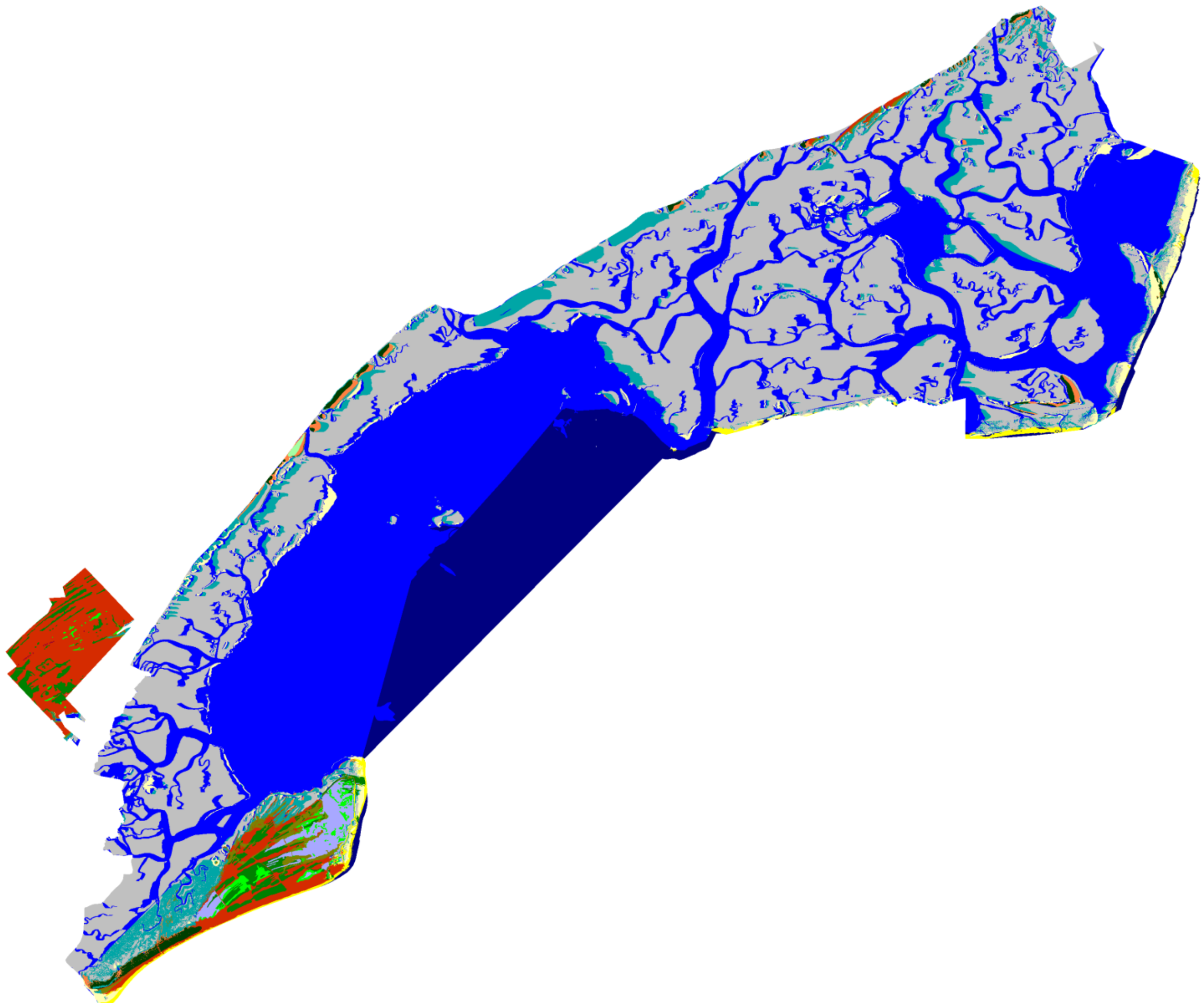
Cape Romain NWR, Initial Condition.



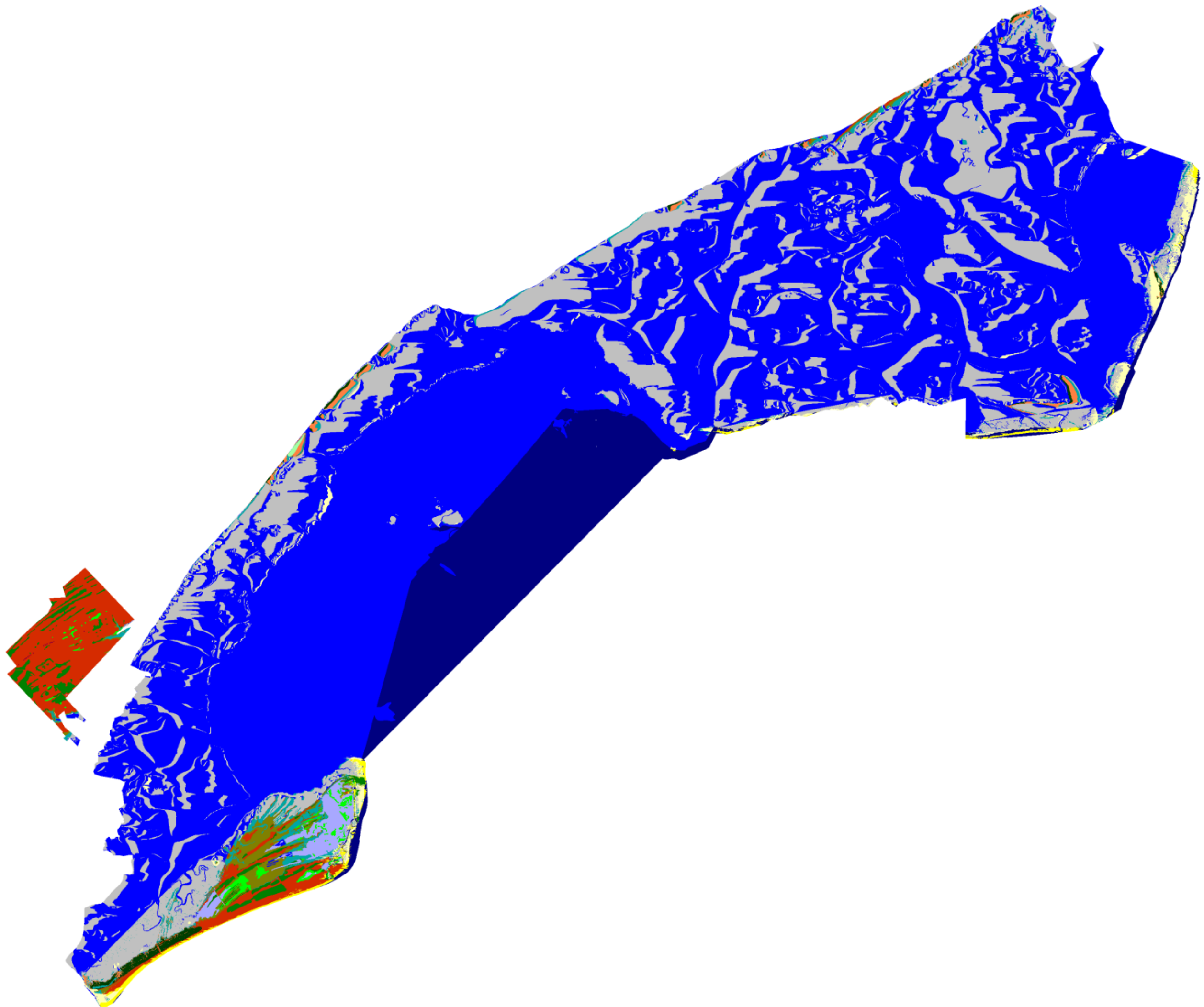
Cape Romain NWR, 2025, 1.5 m SLR by 2100.



Cape Romain NWR, 2050, 1.5 m SLR by 2100.



Cape Romain NWR, 2075, 1.5 m SLR by 2100.

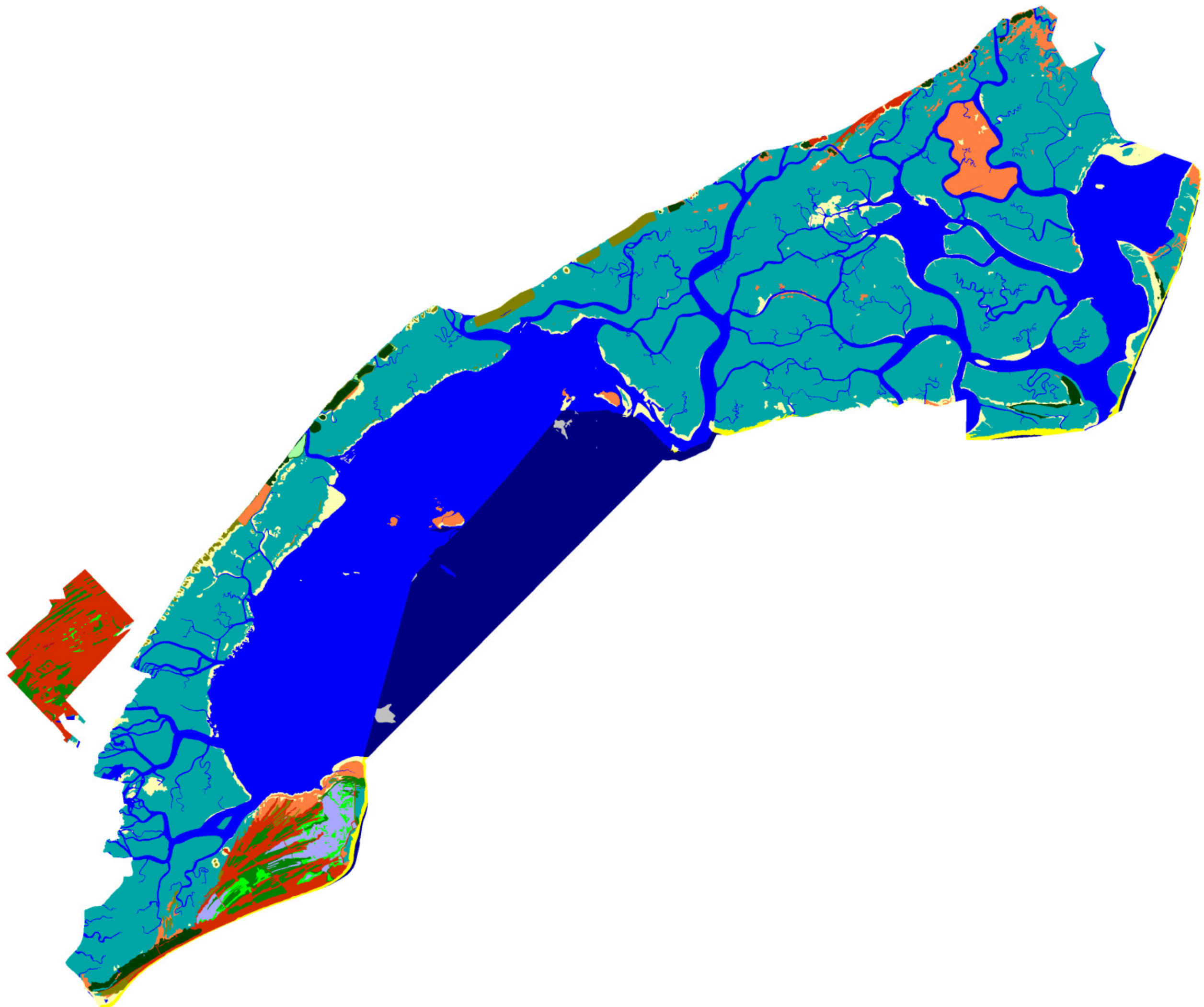


Cape Romain NWR, 2100, 1.5 m SLR by 2100.

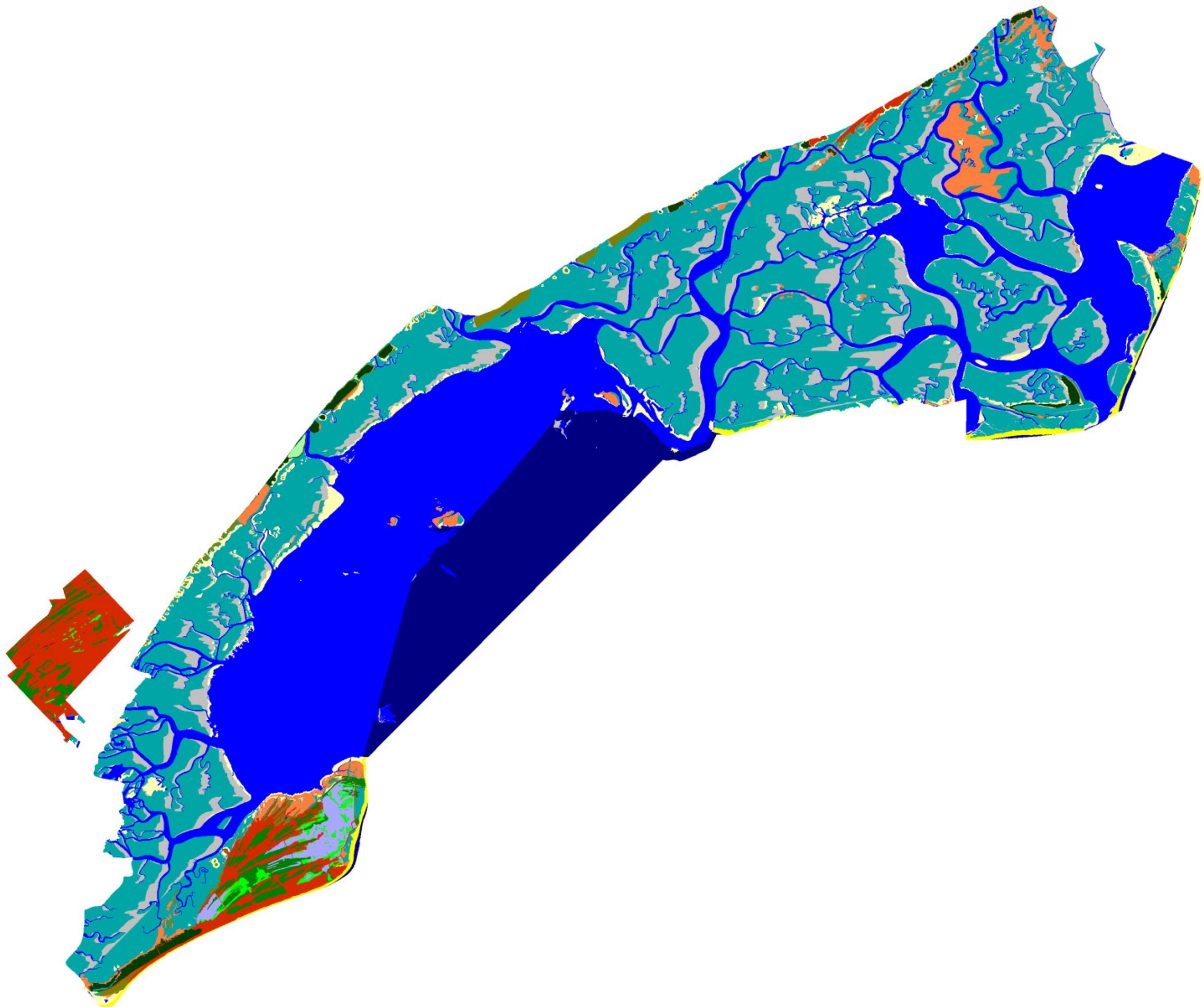
Cape Romain NWR
2 m eustatic SLR by 2100

Results in Acres

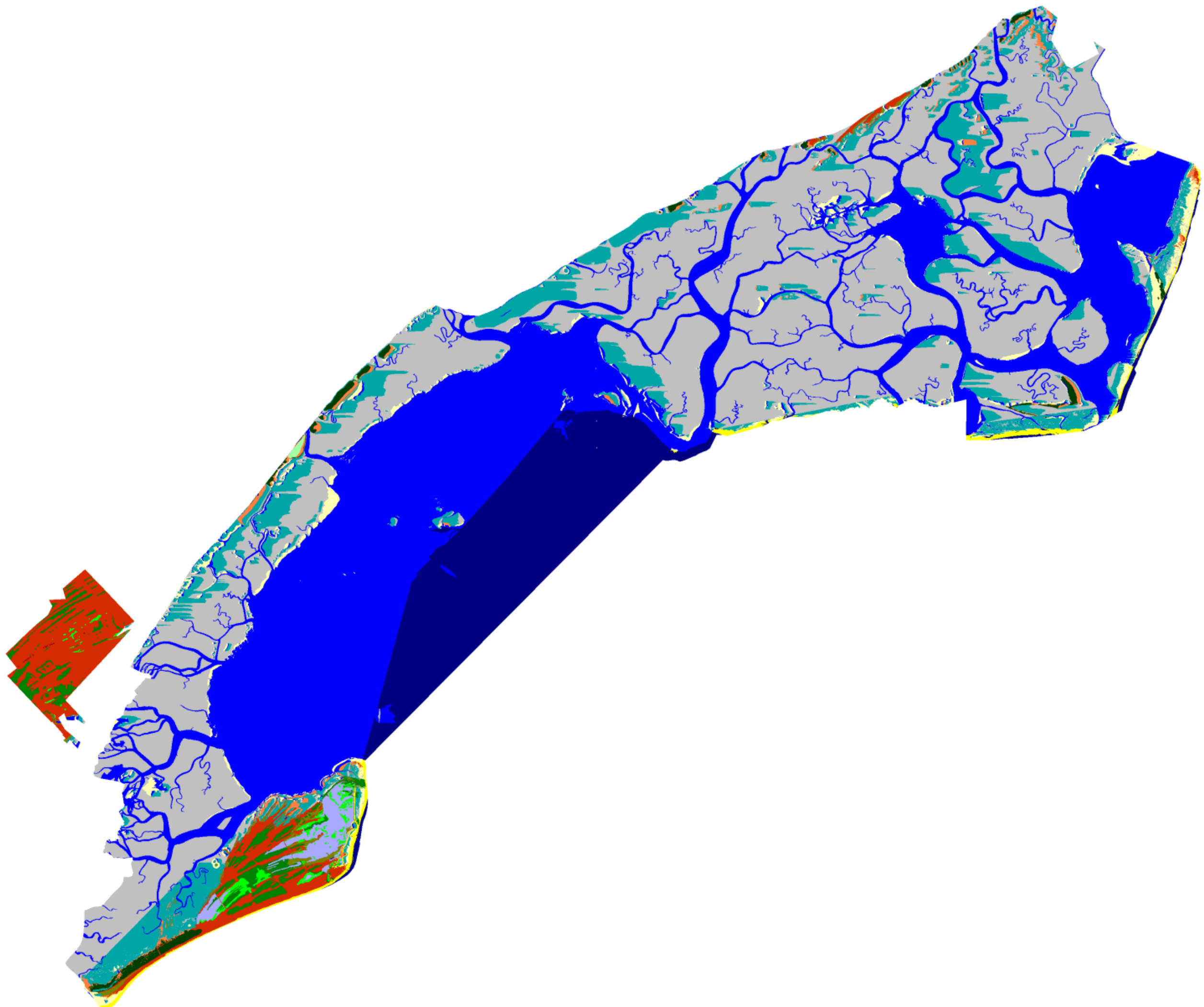
		Initial	2025	2050	2075	2100
	Regularly-flooded Marsh	28013	23095	6011	886	656
	Estuarine Open Water	20116	20519	21378	35931	50696
	Open Ocean	5885	5893	5917	6000	6159
	Undeveloped Dry Land	2373	2335	2210	1954	1665
	Estuarine Beach	2000	1777	1179	796	188
	Irregularly-flooded Marsh	1598	1344	484	211	185
	Swamp	775	772	731	557	422
	Tidal Swamp	515	459	367	253	143
	Transitional Salt Marsh	483	392	247	481	477
	Inland Open Water	471	471	466	453	447
	Ocean Beach	386	380	366	340	219
	Inland Fresh Marsh	260	259	224	201	145
	Tidal Flat	72	5256	23375	14903	1572
	Tidal Fresh Marsh	35	34	27	17	7
	Developed Dry Land	4	4	4	4	4
	Total (incl. water)	**62986**	**62986**	**62986**	**62986**	**62986**



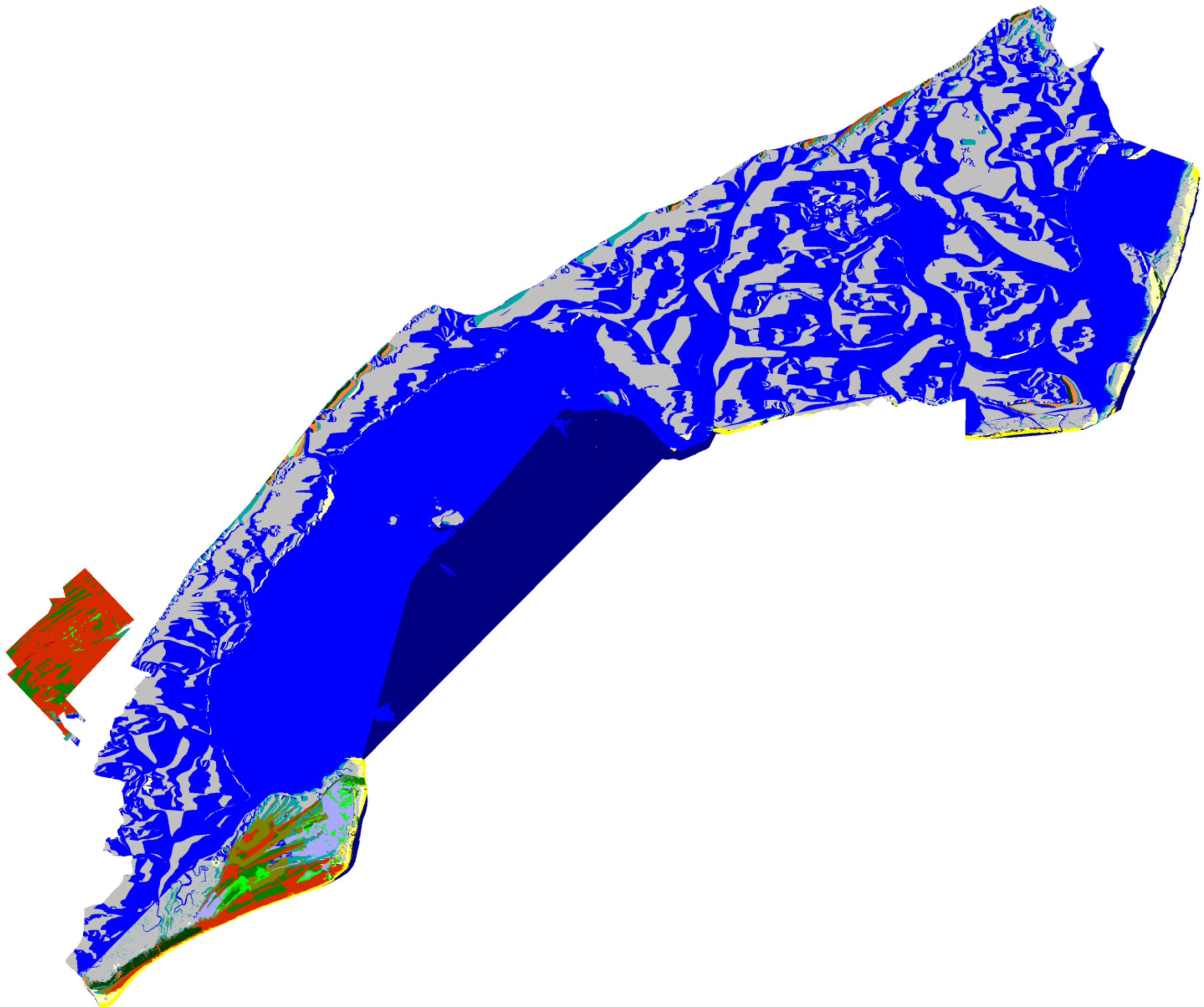
Cape Romain NWR, Initial Condition.



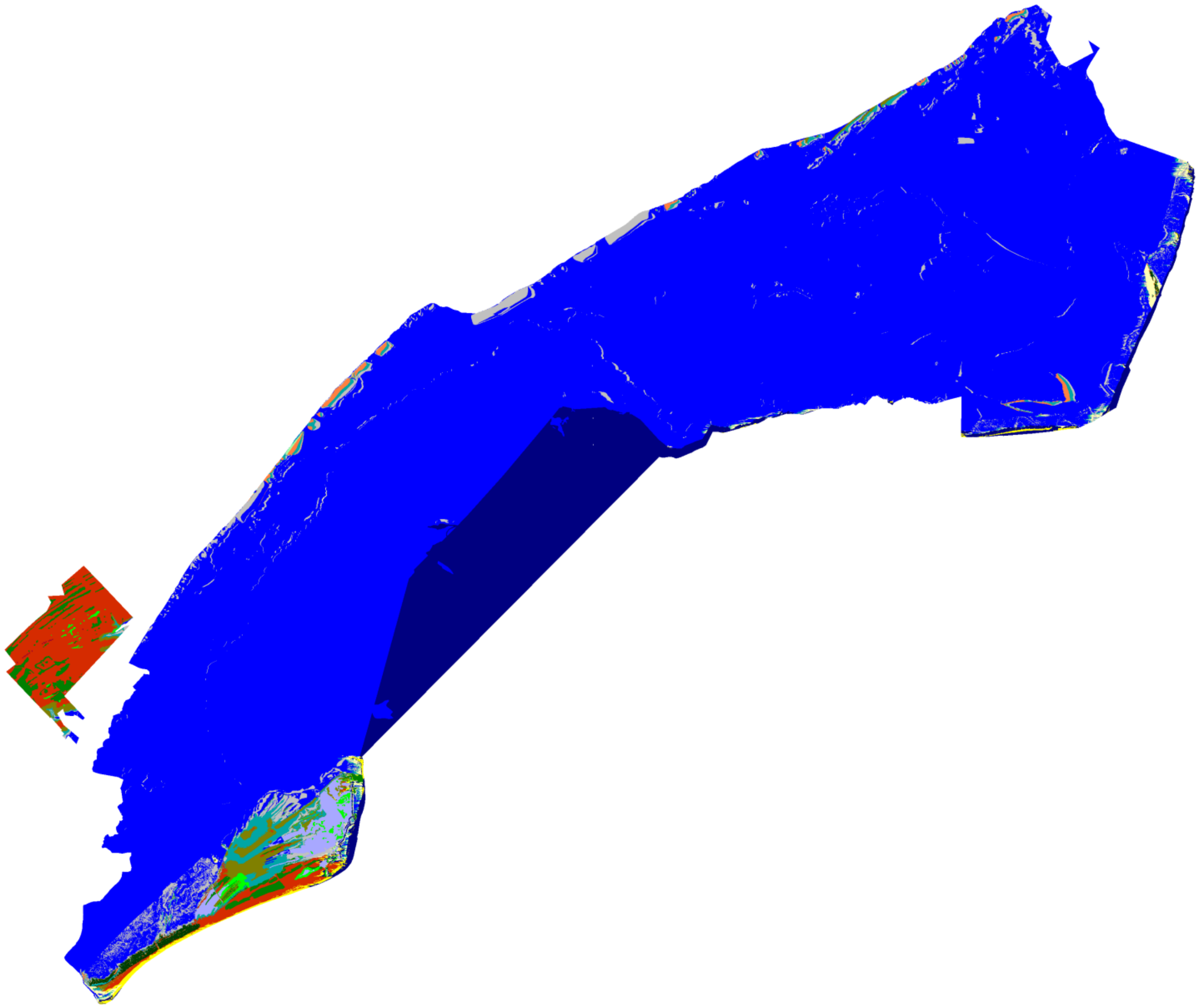
Cape Romain NWR, 2025, 2 m SLR by 2100.



Cape Romain NWR, 2050, 2 m SLR by 2100.



Cape Romain NWR, 2075, 2 m SLR by 2100.



Cape Romain NWR, 2100, 2 m SLR by 2100.

Discussion

SLAMM simulations project Cape Romain NWR to be widely affected by accelerated SLR under scenarios of 0.69 m of SLR by 2100 and above. However, an important caveat to this model application is the lack of LiDAR-derived elevation data for the majority of the refuge.

Because contour-derived elevation data were used for the majority of the refuge, the SLAMM pre-processor was utilized to estimate elevation ranges for all of the non-diked wetlands as a function of tide range and known relationships between wetland types and tide ranges. The pre-processor assumes wetland elevations to be uniformly distributed over their feasible vertical elevation ranges or "tidal frames"—an assumption that may not reflect reality. If wetlands elevations are actually clustered high in the tidal frame they would be less vulnerable to SLR. On the contrary, if in reality wetlands are towards the bottom, they are more vulnerable than what is predicted by the simulation results. It is notable that the wetlands that did have LiDAR elevation data appeared to be more resilient than those that were subjected to the elevation pre-processor. One strip of regularly-flooded marsh in the southeast of the study area persists in simulations up to 1 m of SLR by 2100.

An additional cause of uncertainty within these predictions is the model's estimation of marsh accretion rates. Vertical marsh accretion rates may react to an increase in sea level rise due to more frequent inundation and higher sediment trapping within marshes. For this study area, data were available to apply such a feedback to the regularly-flooded marsh wetland category. This led to some additional marsh resilience, particularly under the 0.39 m by 2100 eustatic SLR scenario. Future model runs for this site could potentially evaluate the extent of this feedback using additional data, or as part of a model sensitivity or uncertainty analysis.

While data-layer updates have 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). More in general, to better support managers and decision-makers, the range of possible outcomes and their likelihood could and should be studied as a function of all input-data uncertainties.

References

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.

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.

Morris, J. T., Sundareshwar, P. V., Nietch, C. T., Kjerfve, B., and Cahoon, D. R. (2002). "Responses of coastal wetlands to rising sea level." *Ecology*, 83(10), 2869–2877.

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.

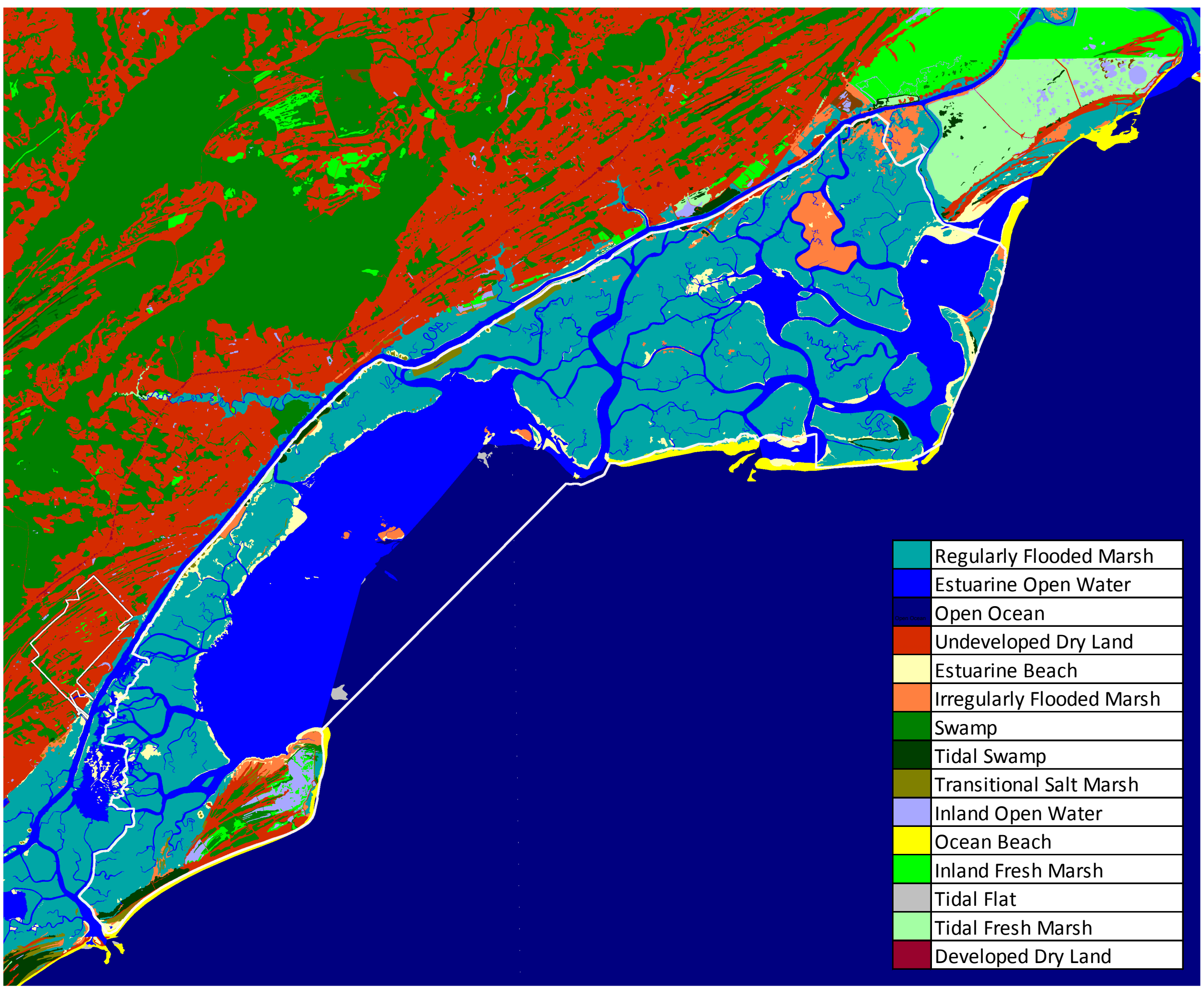
Titus, J. G., Park, R. A., Leatherman, S. P., Weggel, J. R., Greene, M. S., Mausel, P. W., Brown, S., Gaunt, C., Trehan, M., and Yohe, G. (1991). "Greenhouse effect and sea level rise: the cost of holding back the sea." *Coastal Management*, 19(2), 171–204.

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

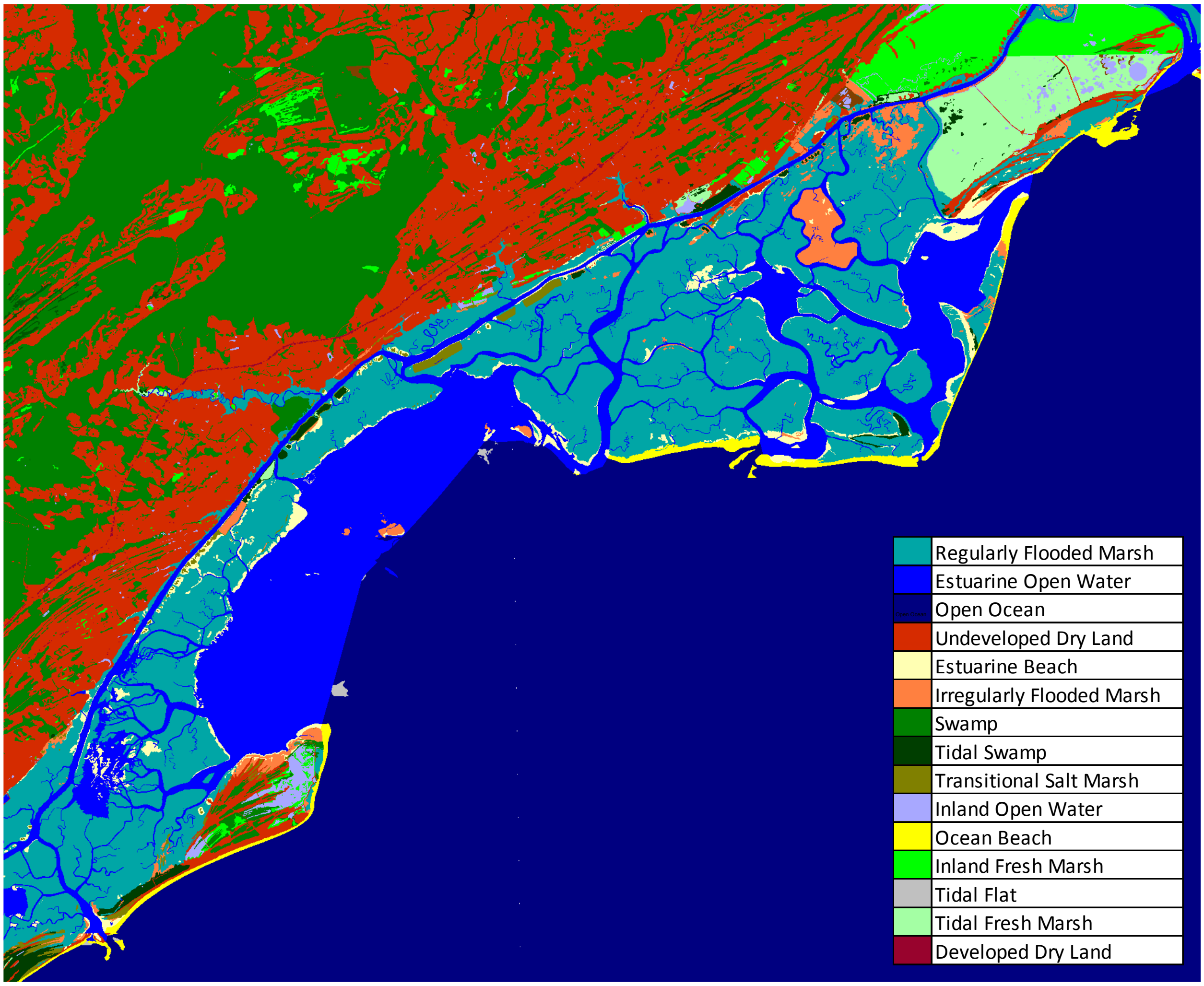
Appendix A: Contextual Results

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:

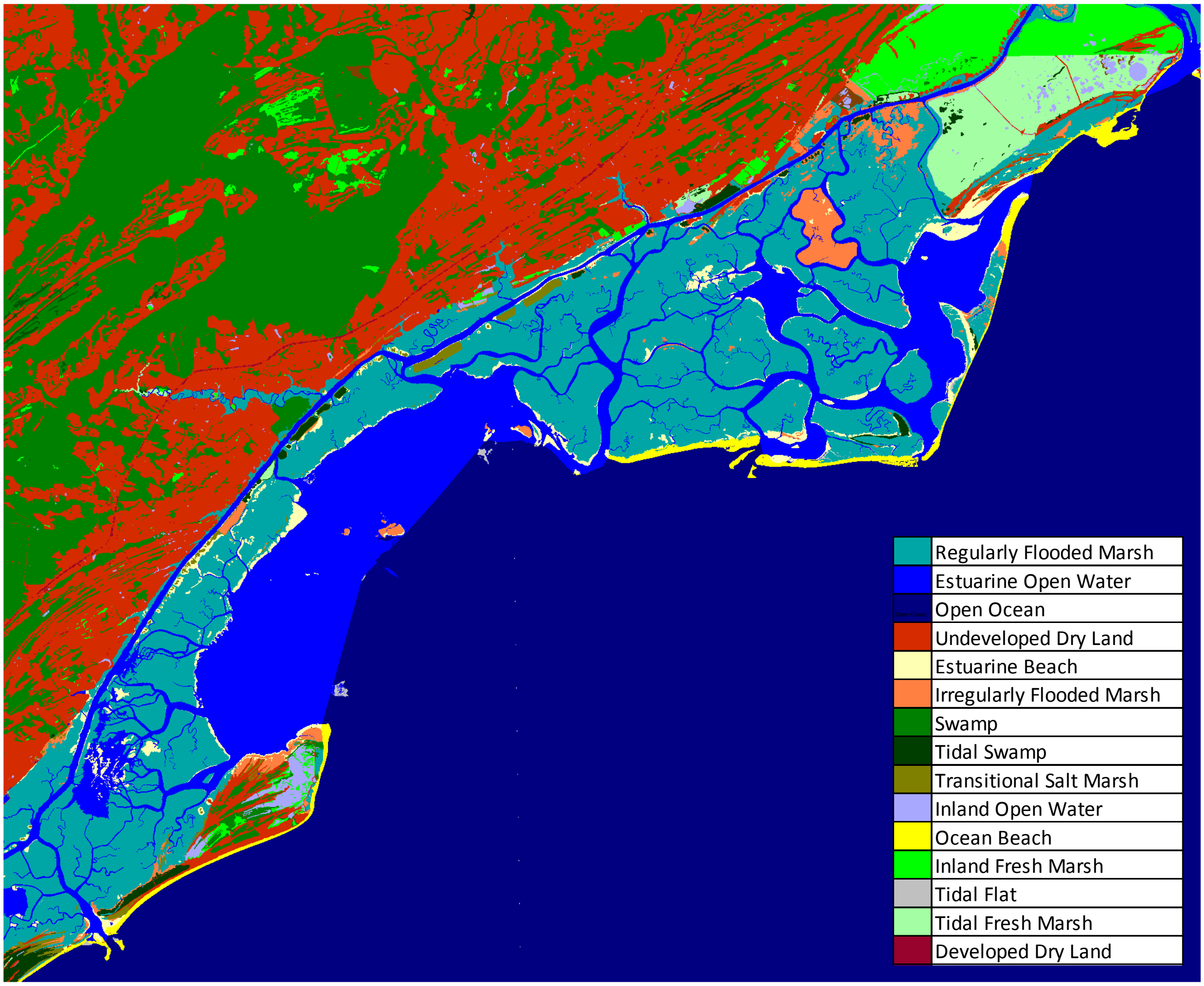
- Results were critically examined within USFWS refuges but not closely examined for the larger region.
- Site-specific parameters for the model were derived for USFWS refuges whenever possible and may not be regionally applicable.
- Especially in areas where dikes are present, an effort was made to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



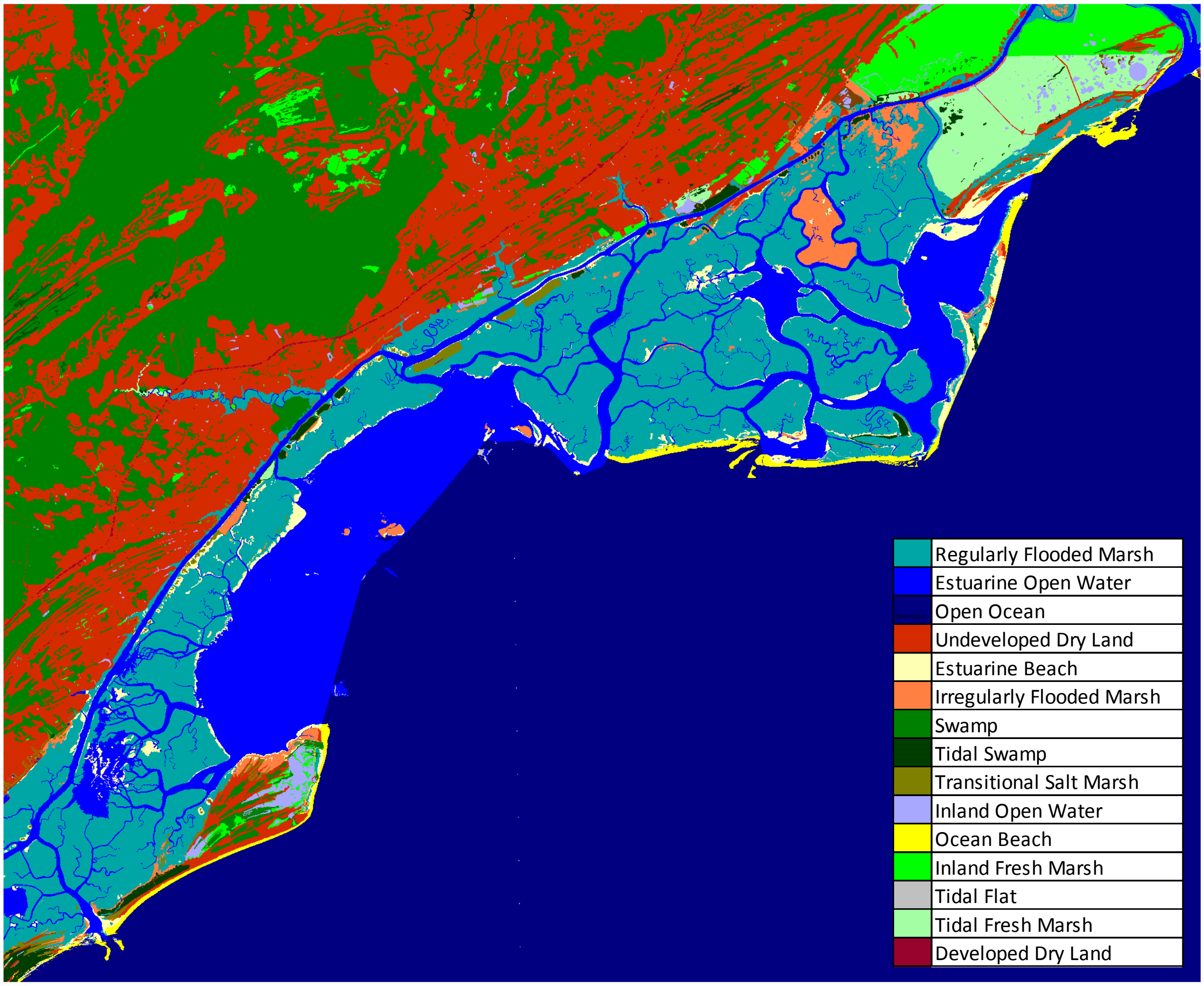
Cape Romain National Wildlife Refuge within simulation context (white).



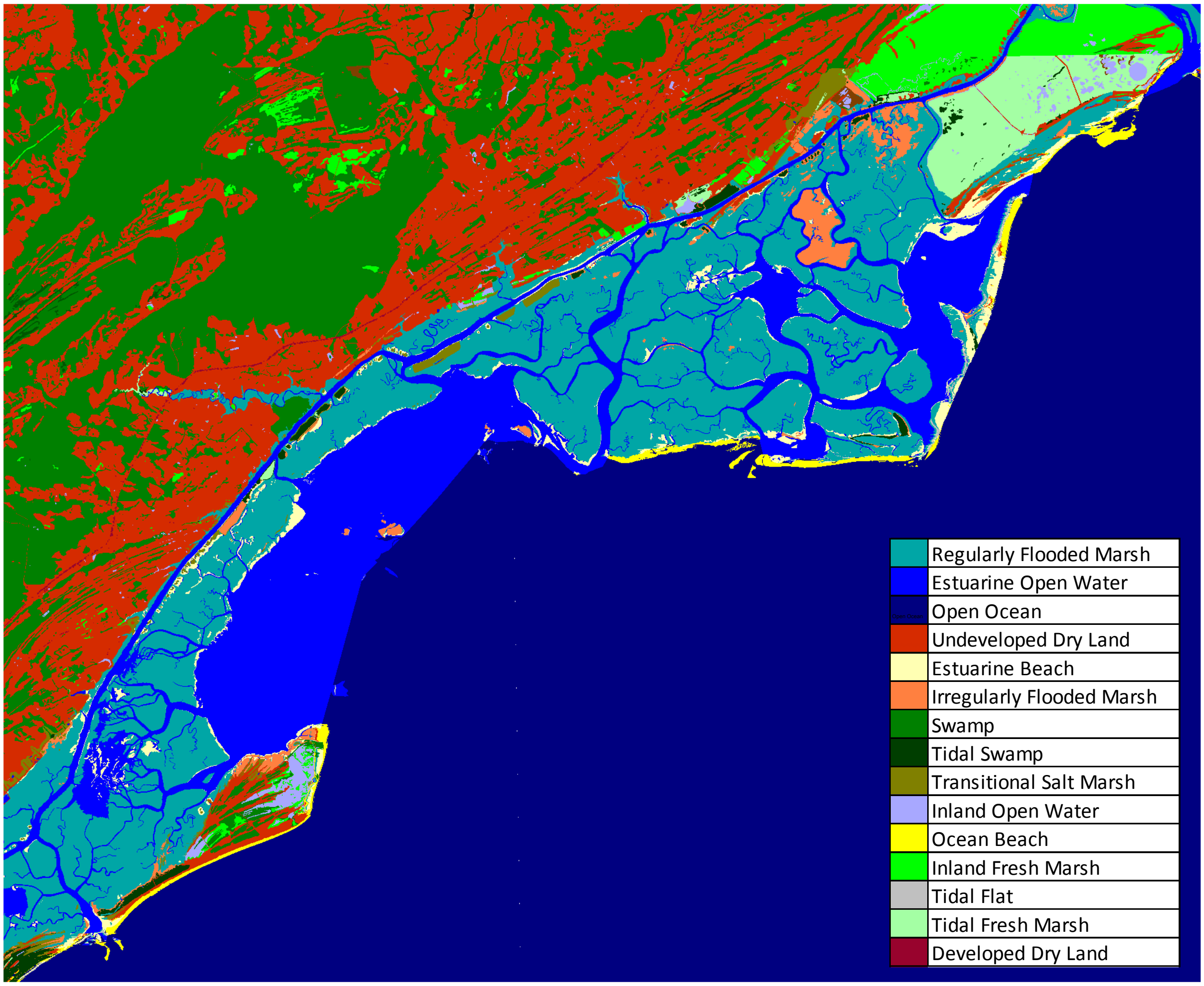
Cape Romain NWR, Initial Condition.



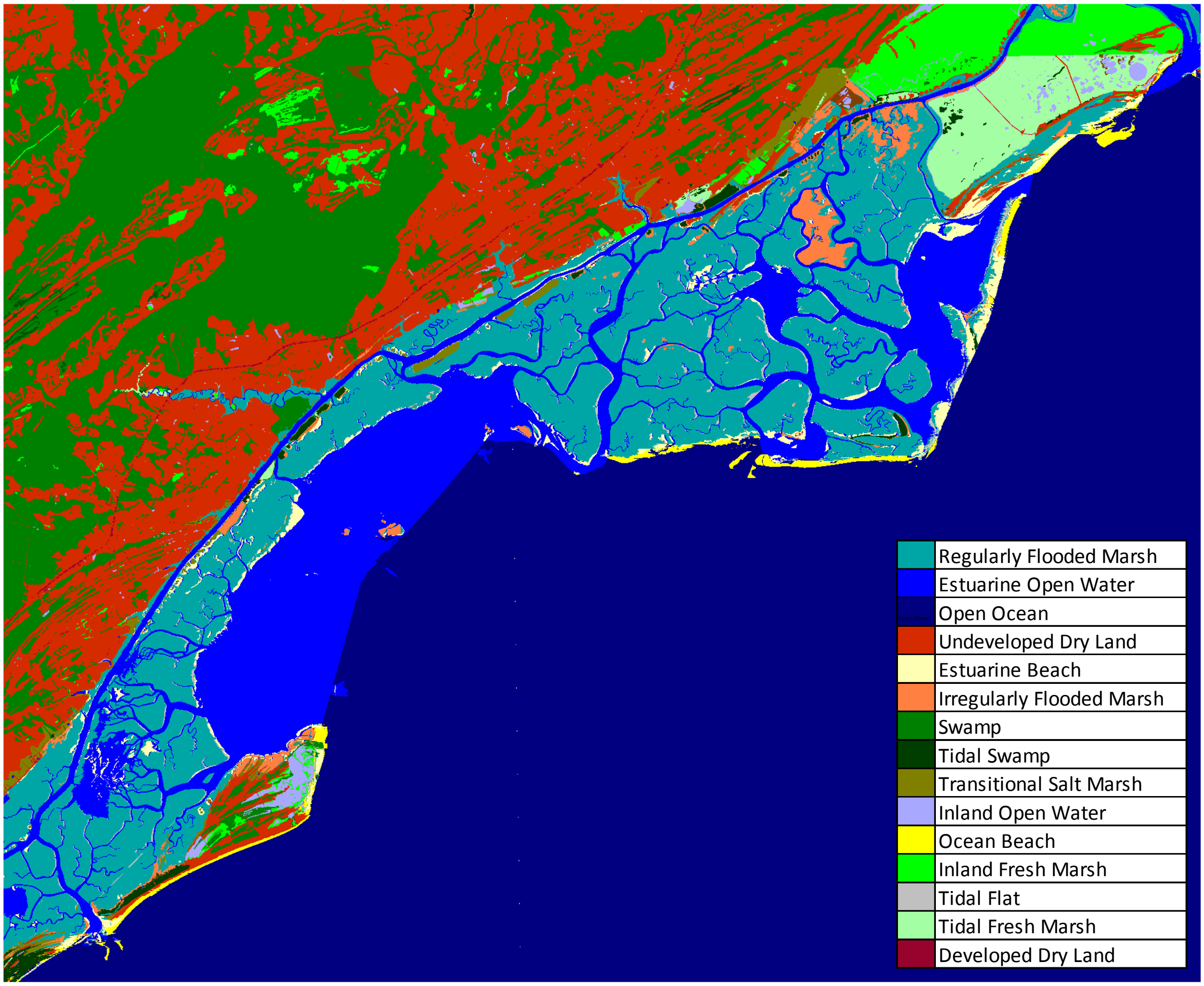
Cape Romain NWR, 2025, Scenario A1B Mean, 0.39 m SLR by 2100.



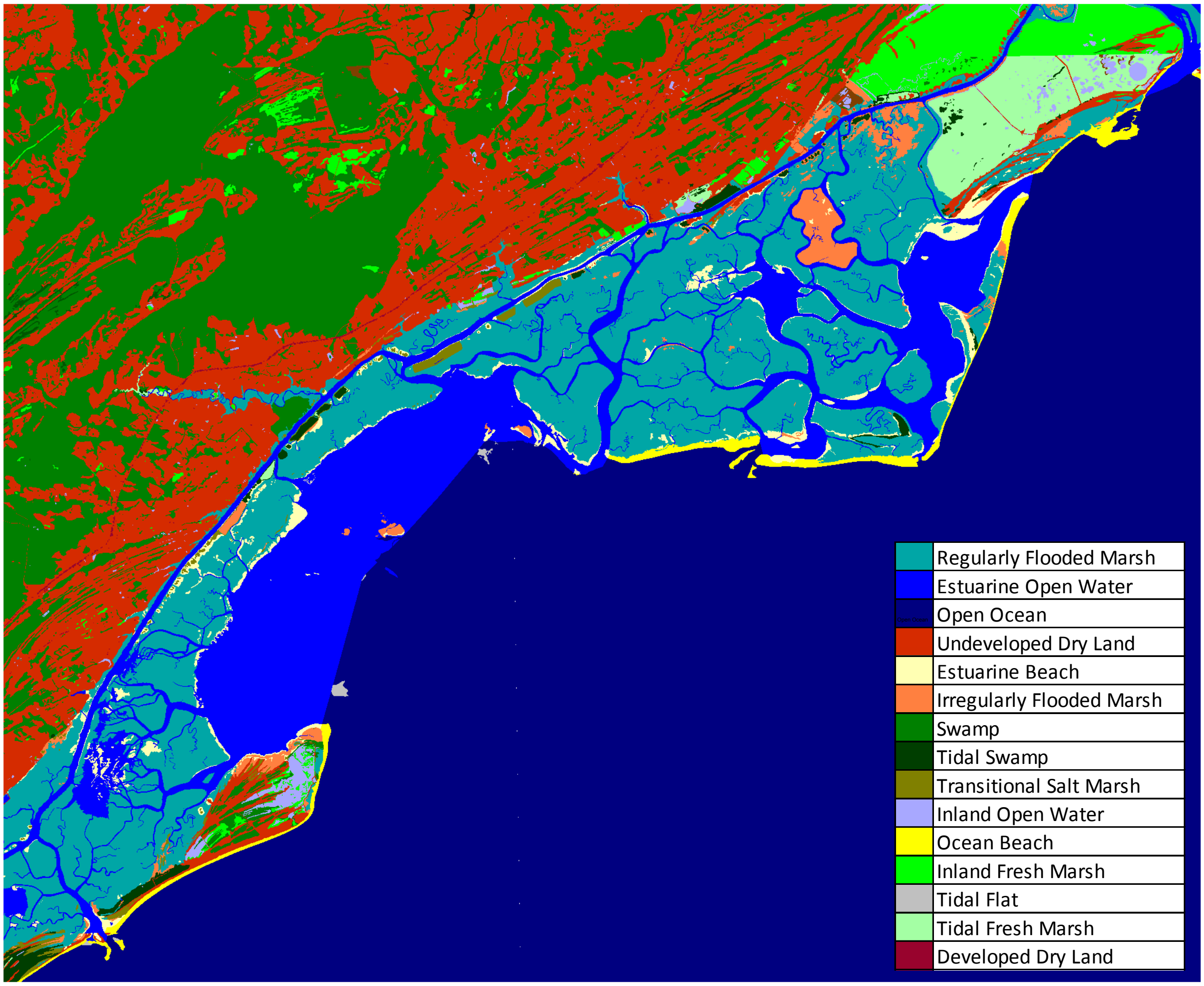
Cape Romain NWR, 2050, Scenario A1B Mean, 0.39 m SLR by 2100.



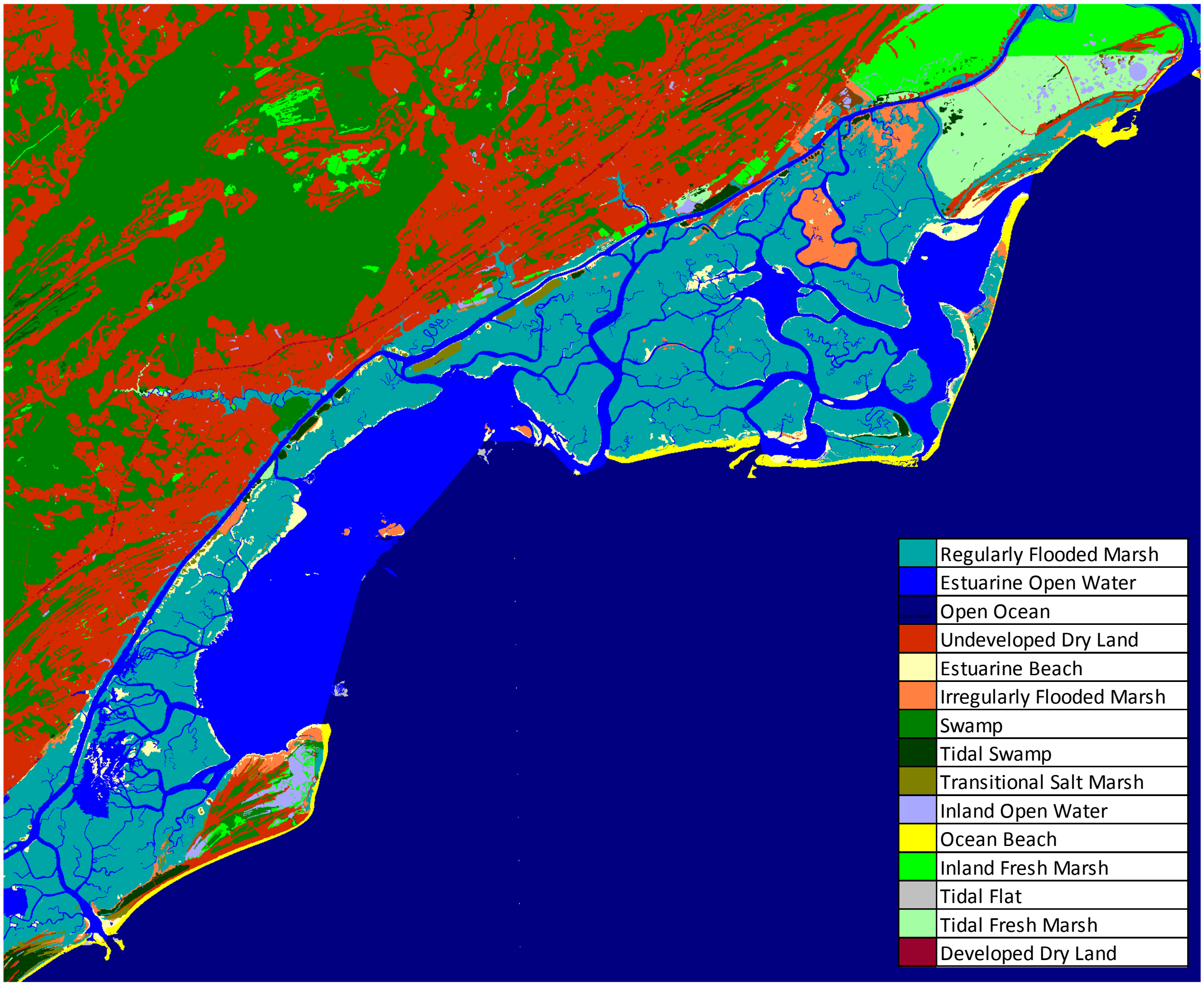
Cape Romain NWR, 2075, Scenario A1B Mean, 0.39 m SLR by 2100.



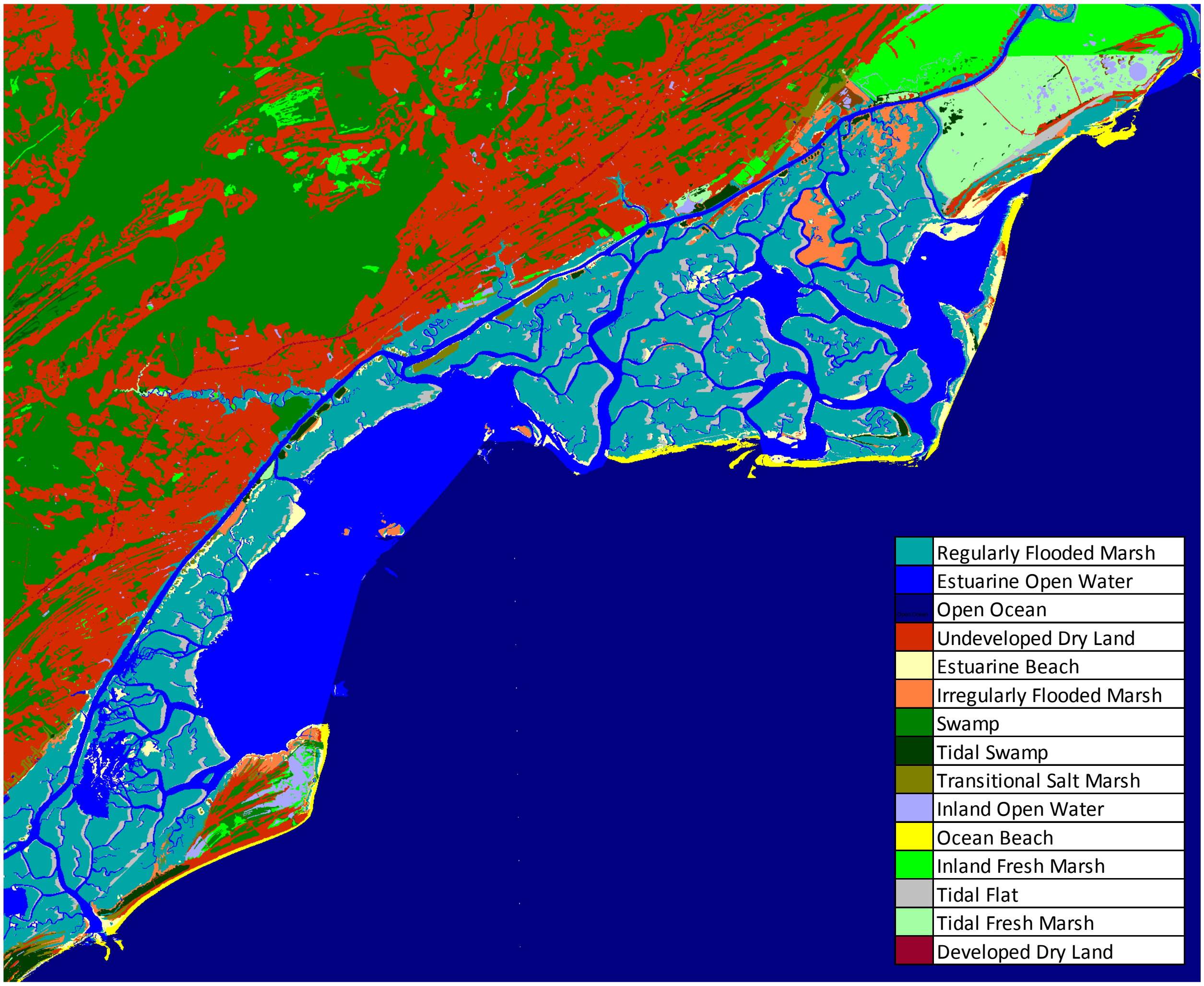
Cape Romain NWR, 2100, Scenario A1B Mean, 0.39 m SLR by 2100.



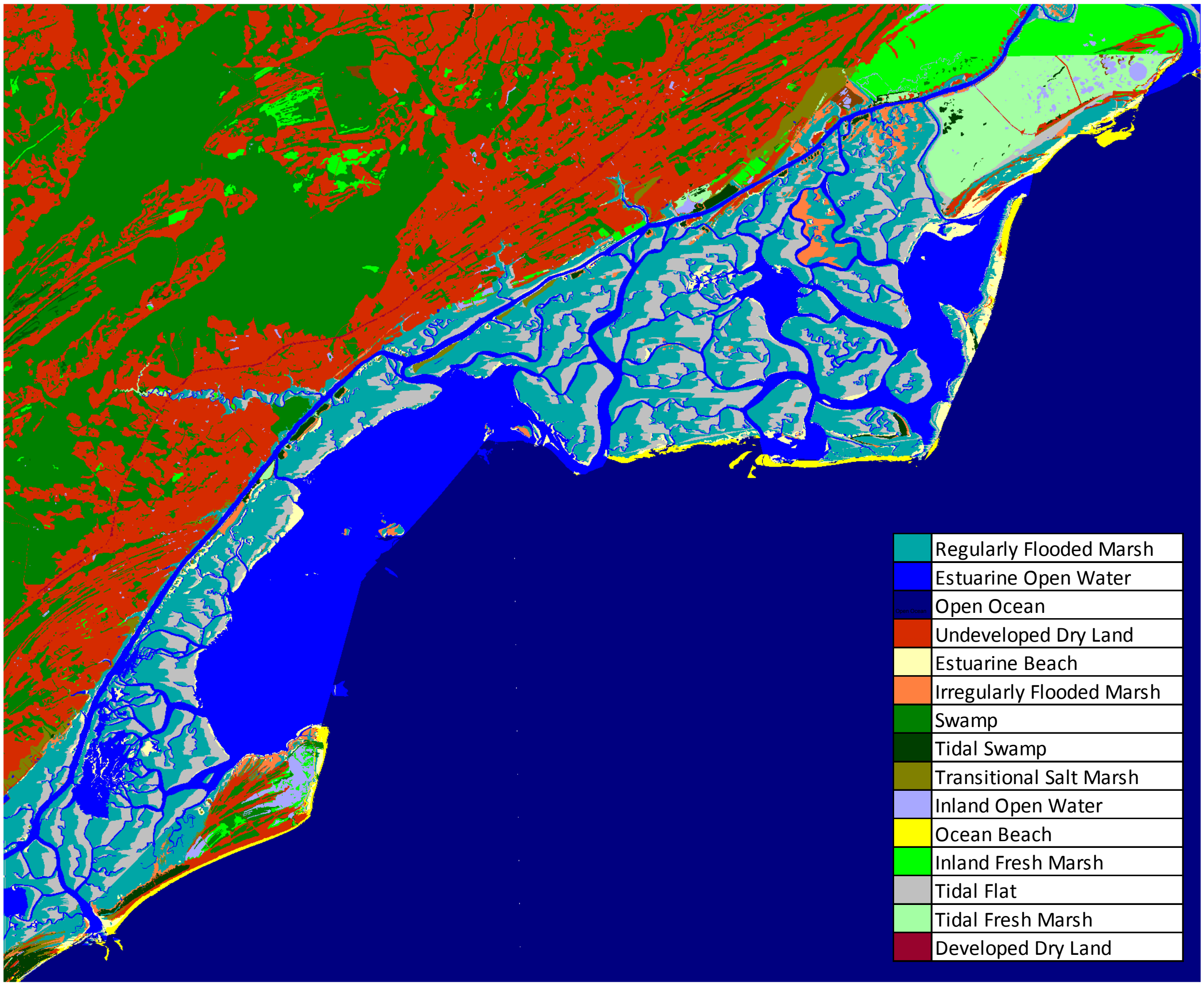
Cape Romain NWR, Initial Condition.



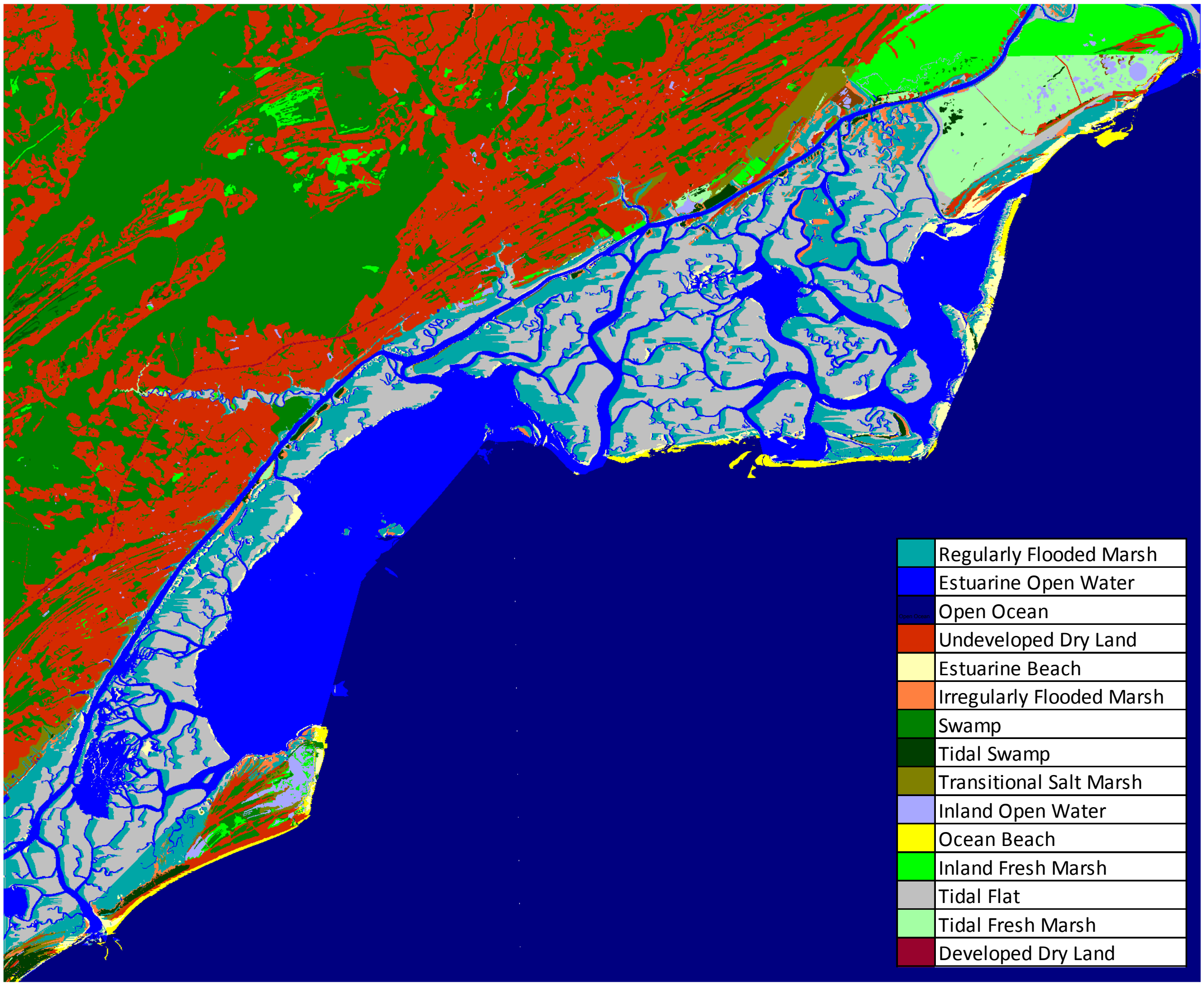
Cape Romain NWR, 2025, Scenario A1B Maximum, 0.69 m SLR by 2100.



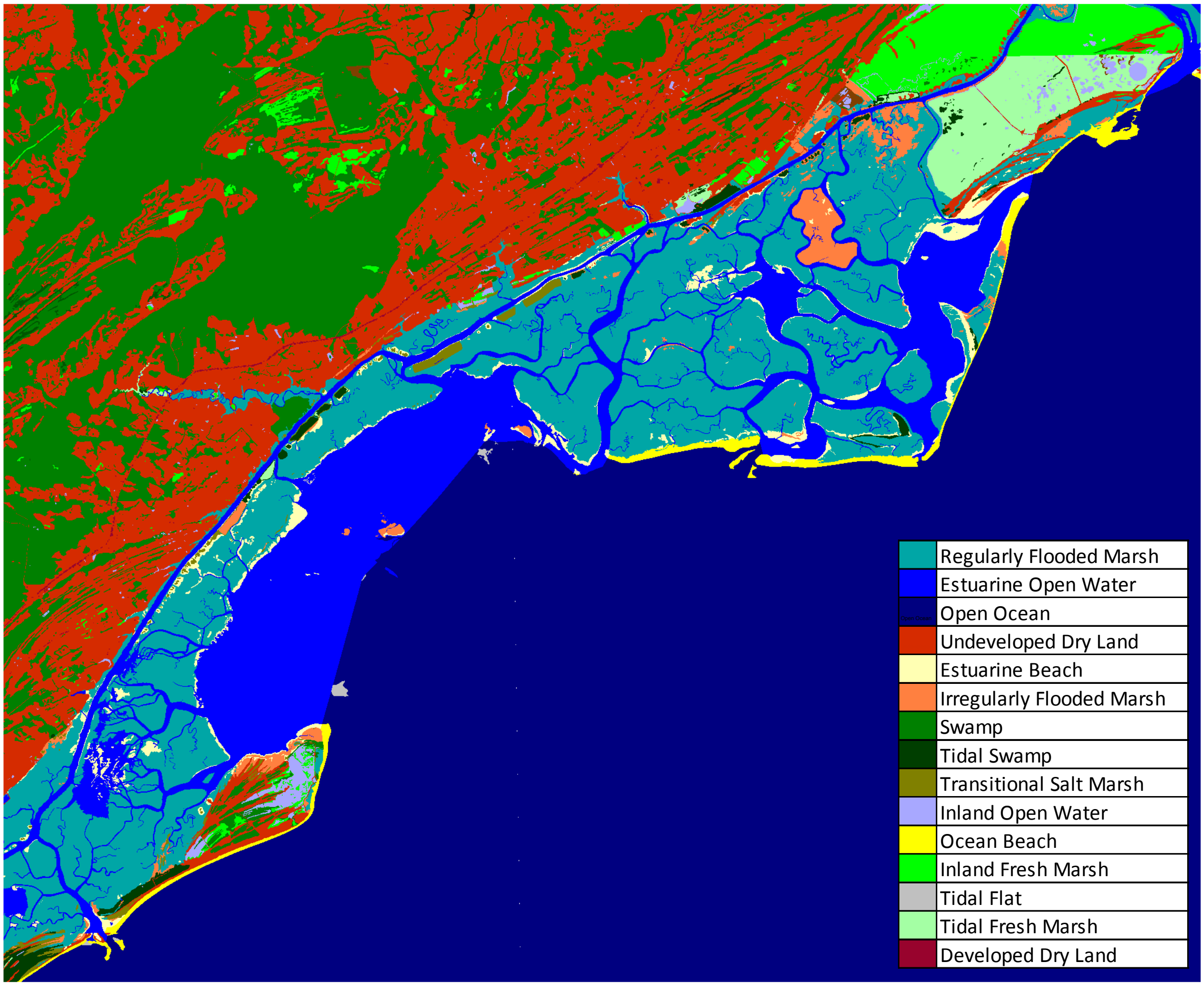
Cape Romain NWR, 2050, Scenario A1B Maximum, 0.69 m SLR by 2100.



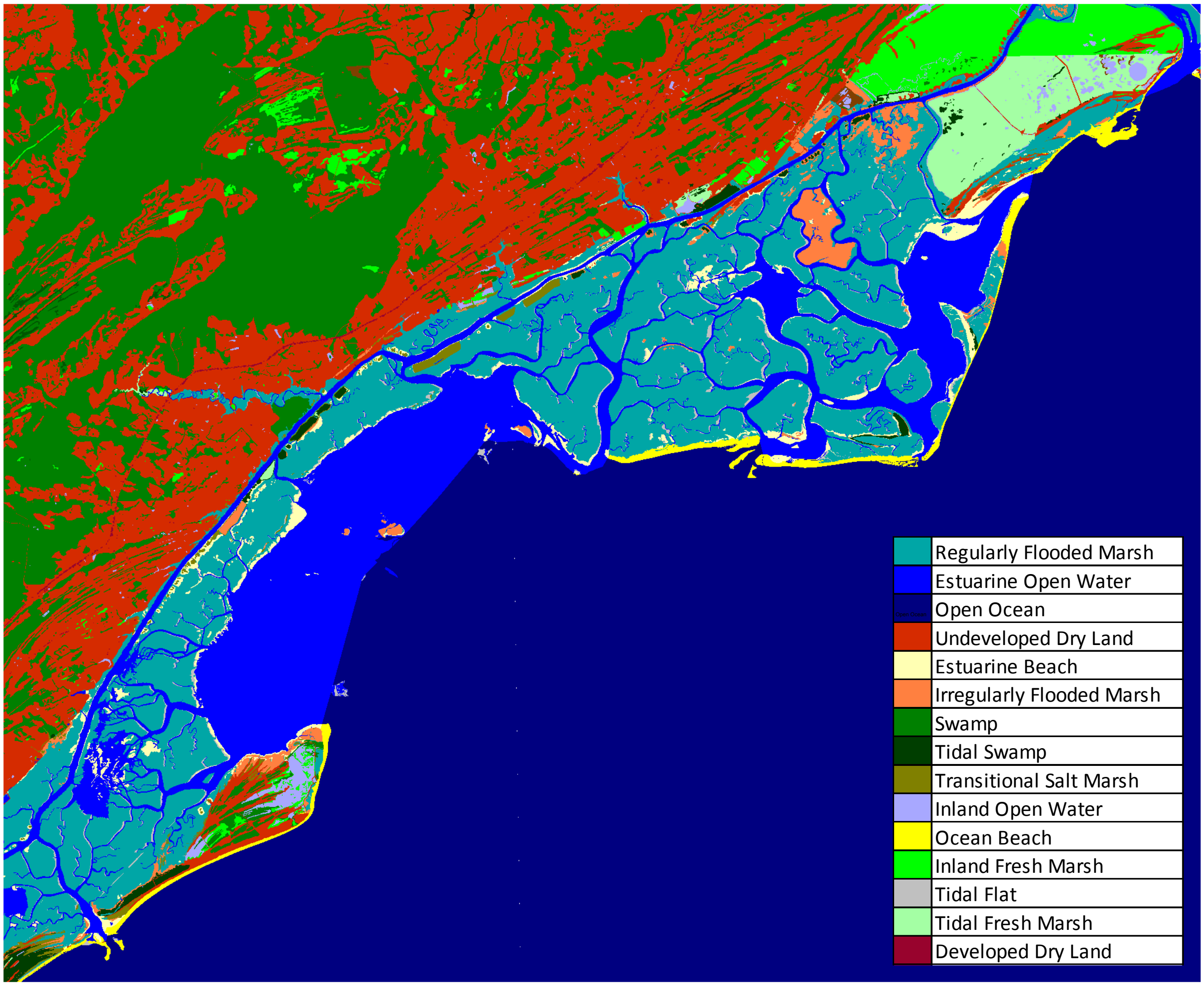
Cape Romain NWR, 2075, Scenario A1B Maximum, 0.69 m SLR by 2100.



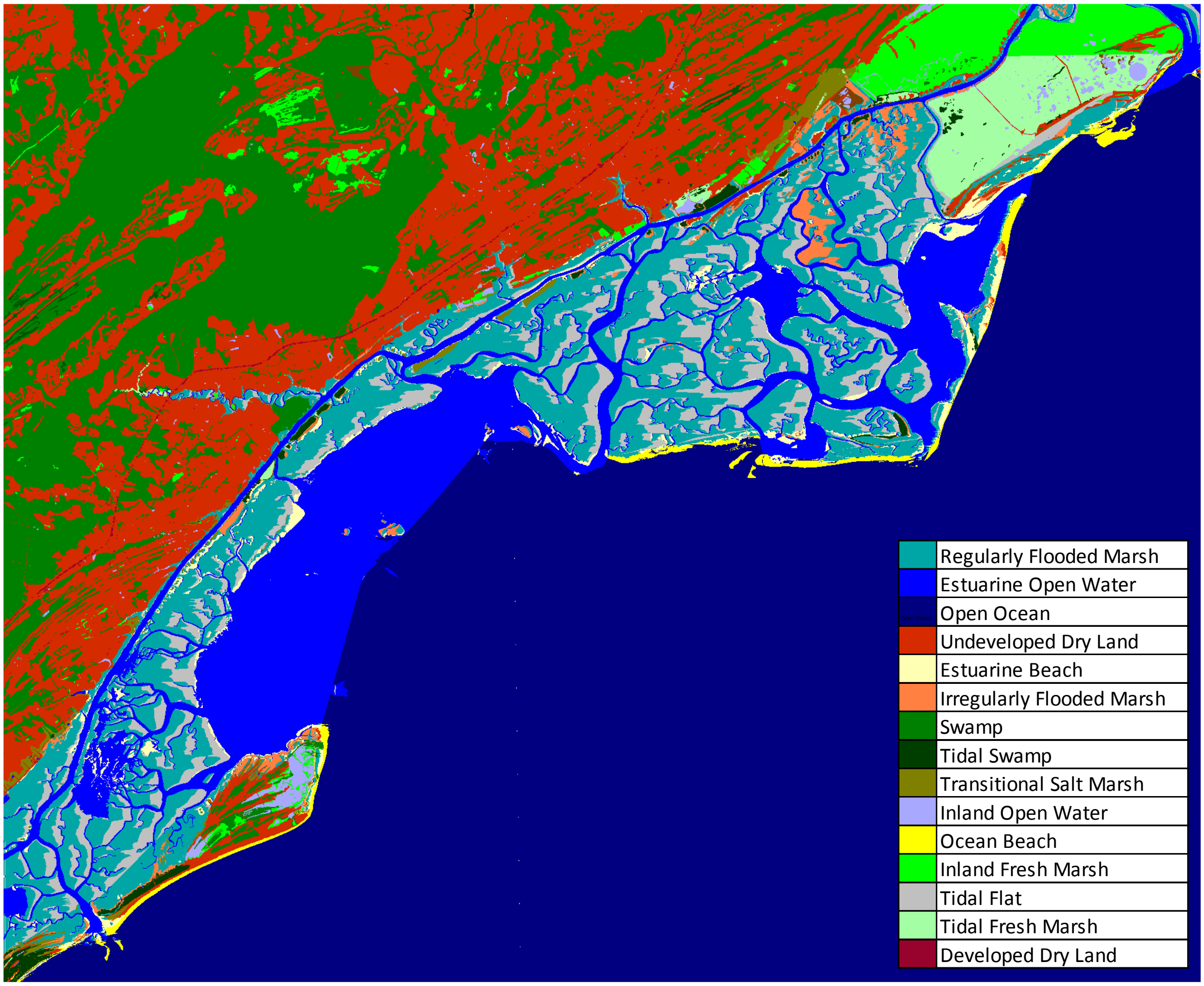
Cape Romain NWR, 2100, Scenario A1B Maximum, 0.69 m SLR by 2100.



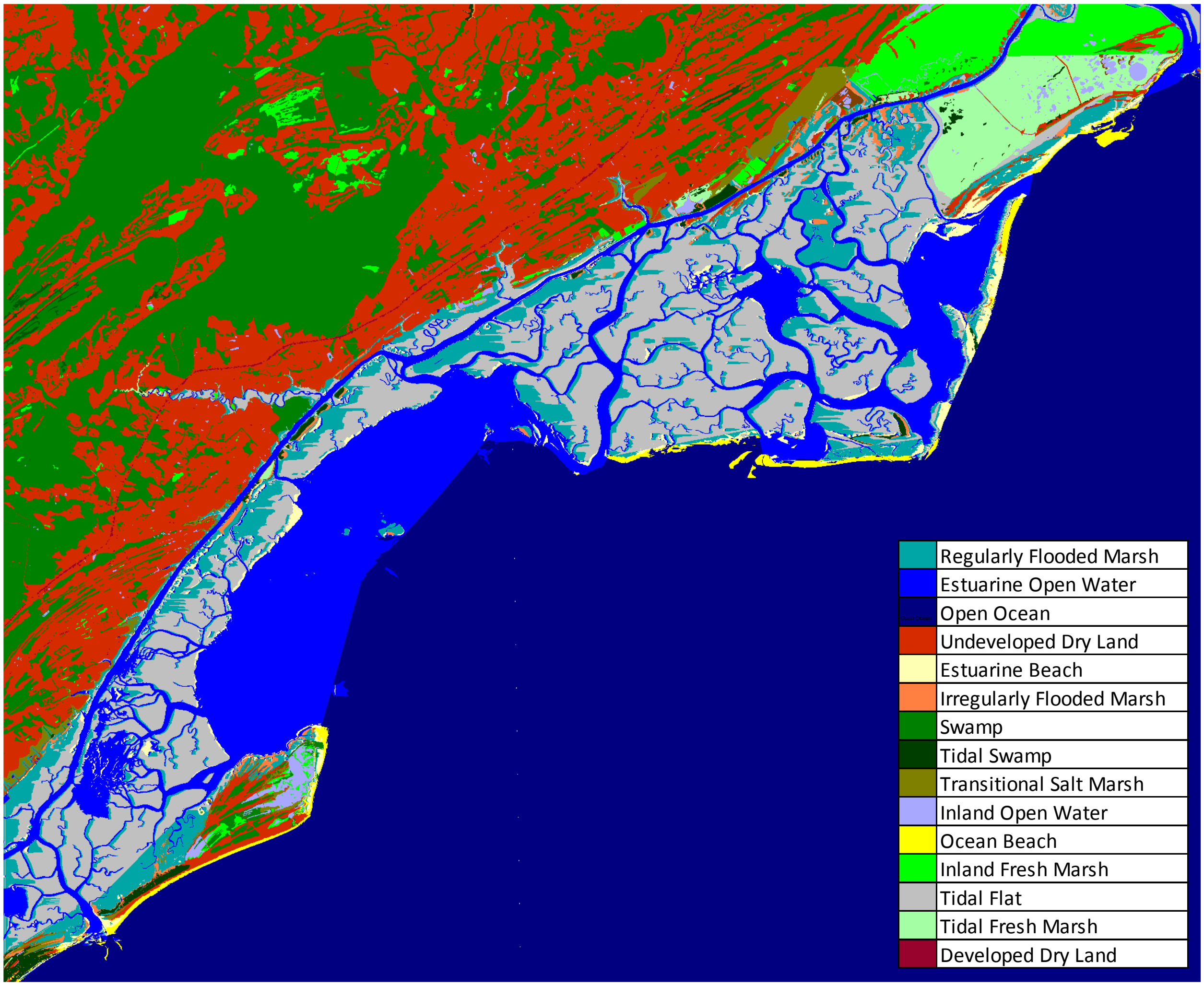
Cape Romain NWR, Initial Condition.



Cape Romain NWR, 2025, 1 m SLR by 2100.



Cape Romain NWR, 2050, 1 m SLR by 2100.



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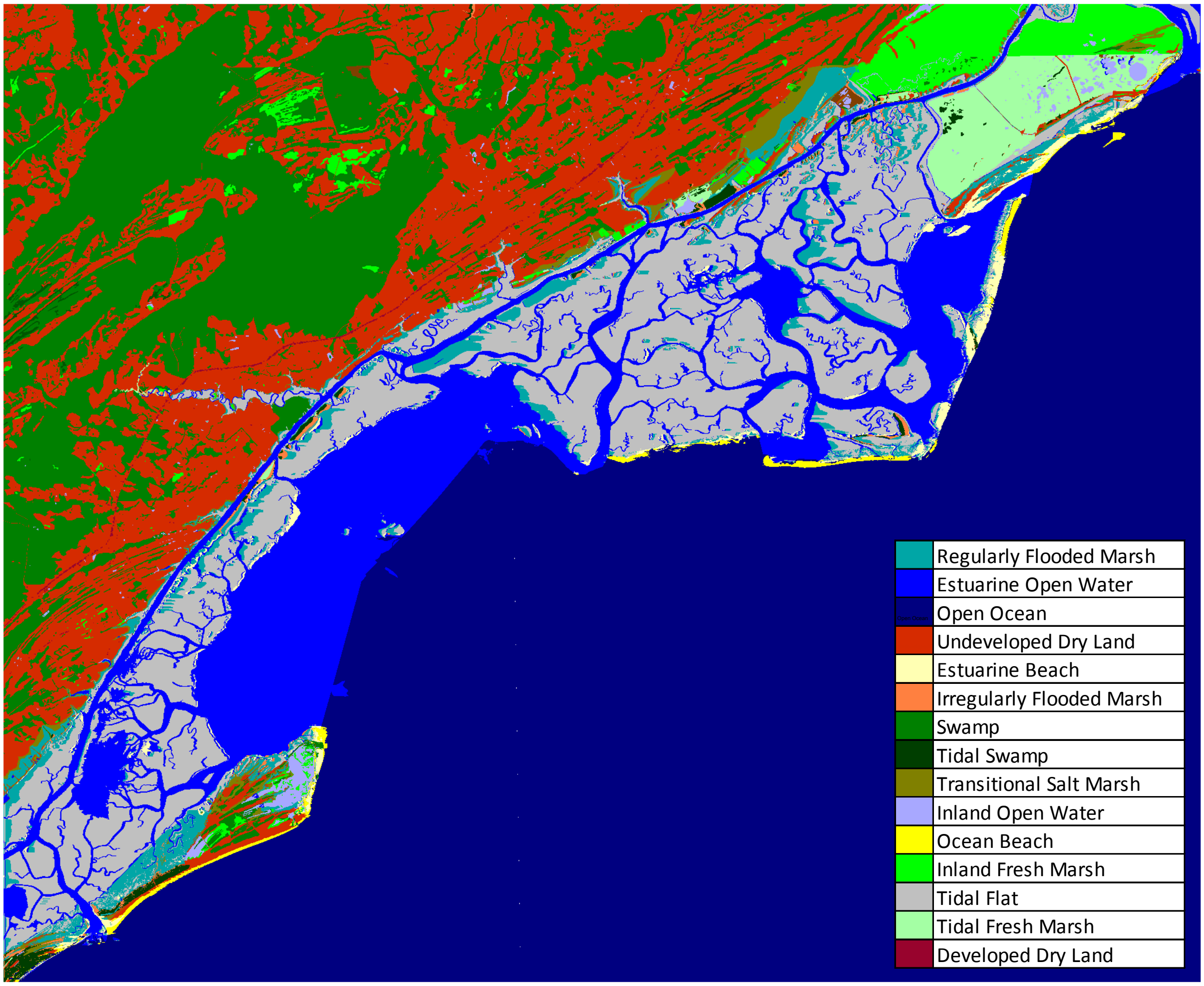

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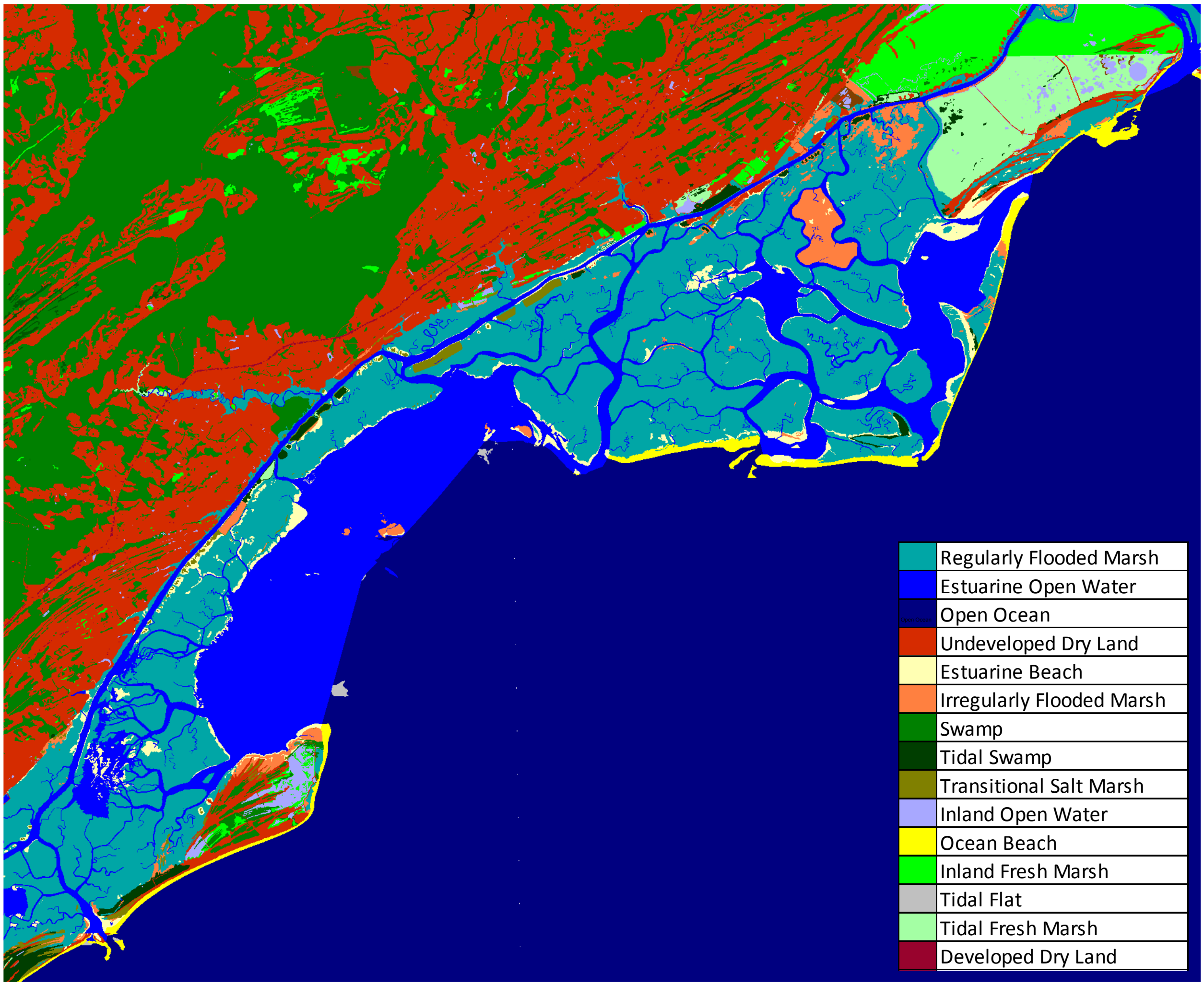
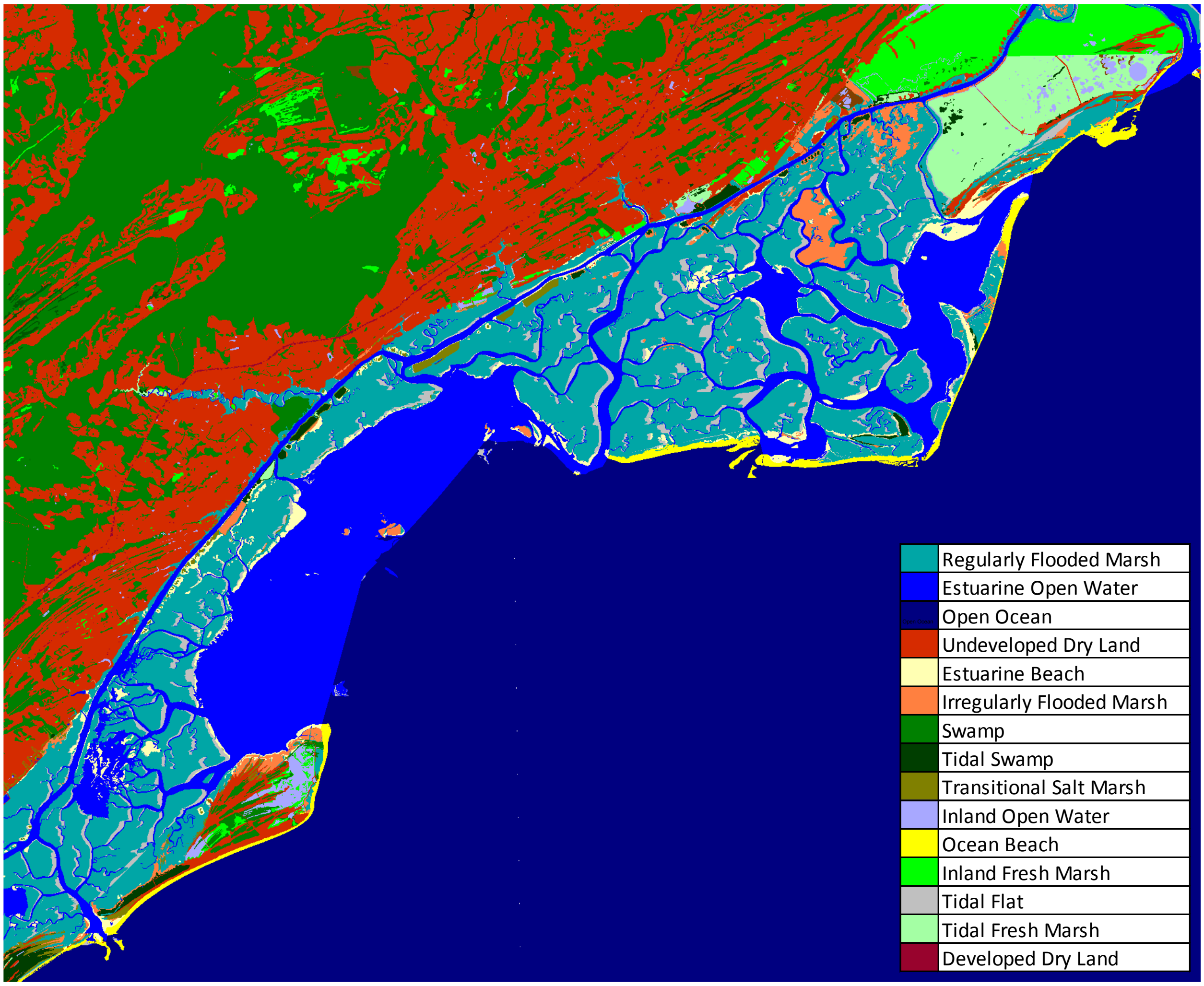
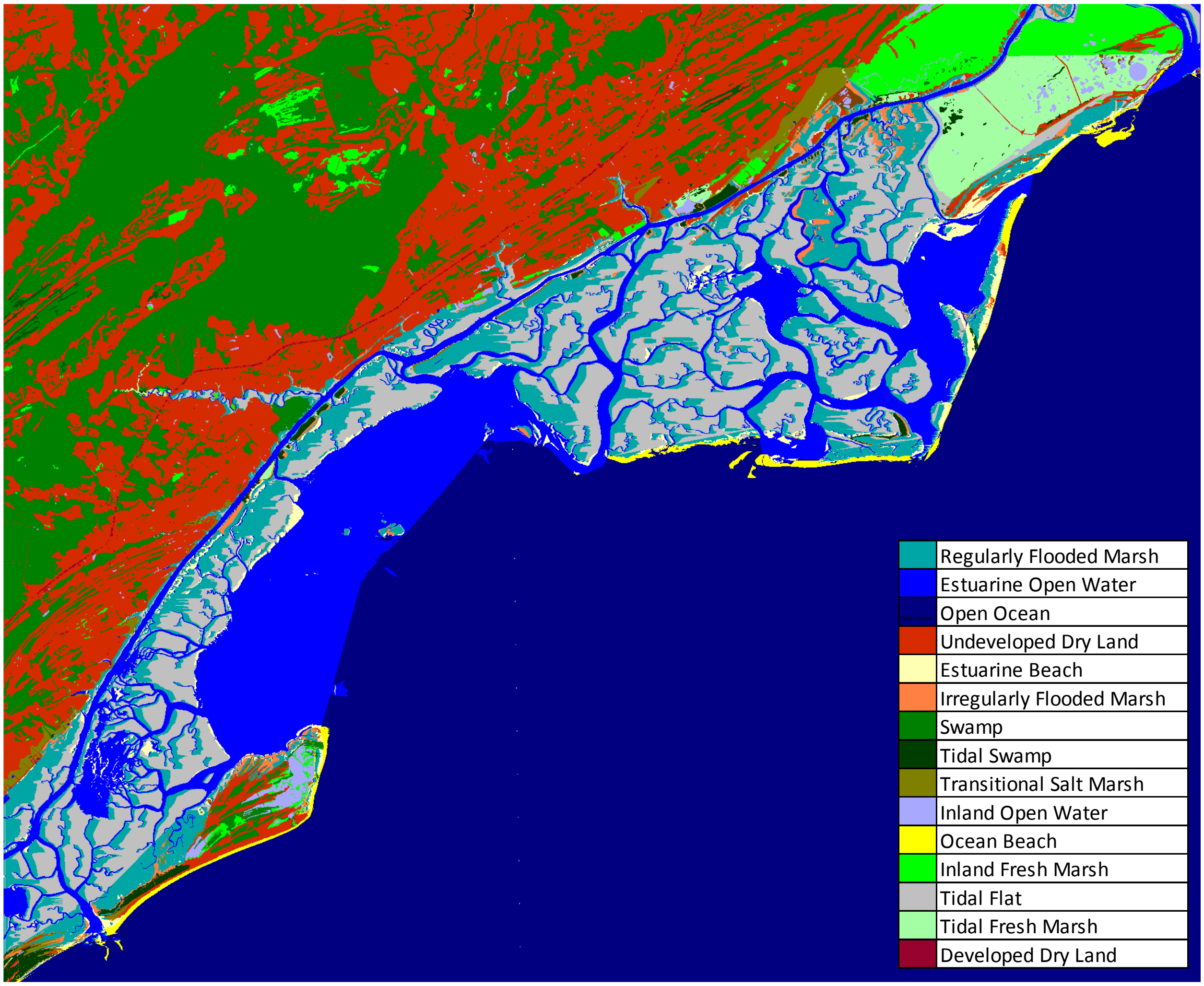


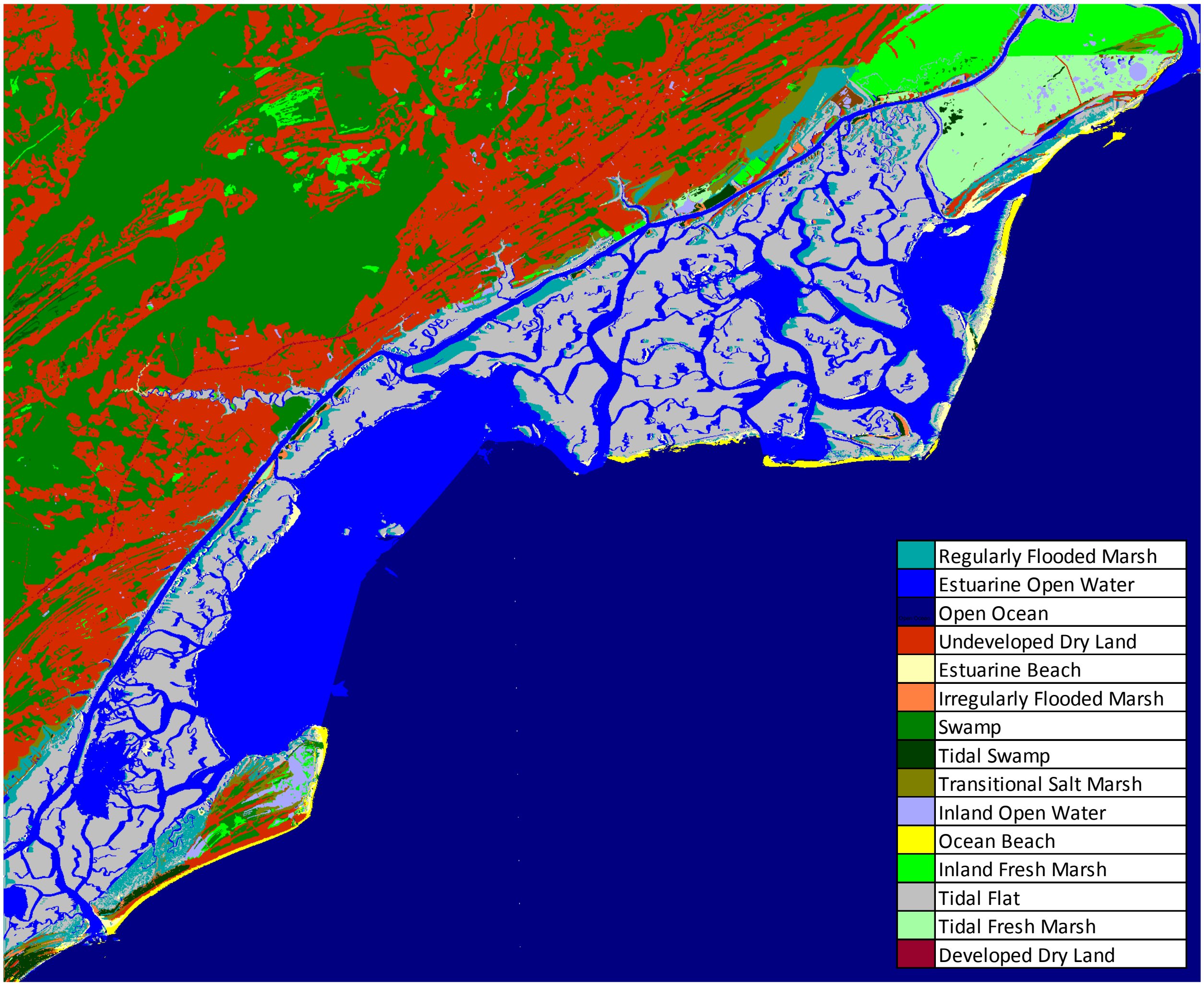
Cape Romain NWR, Initial Condition.



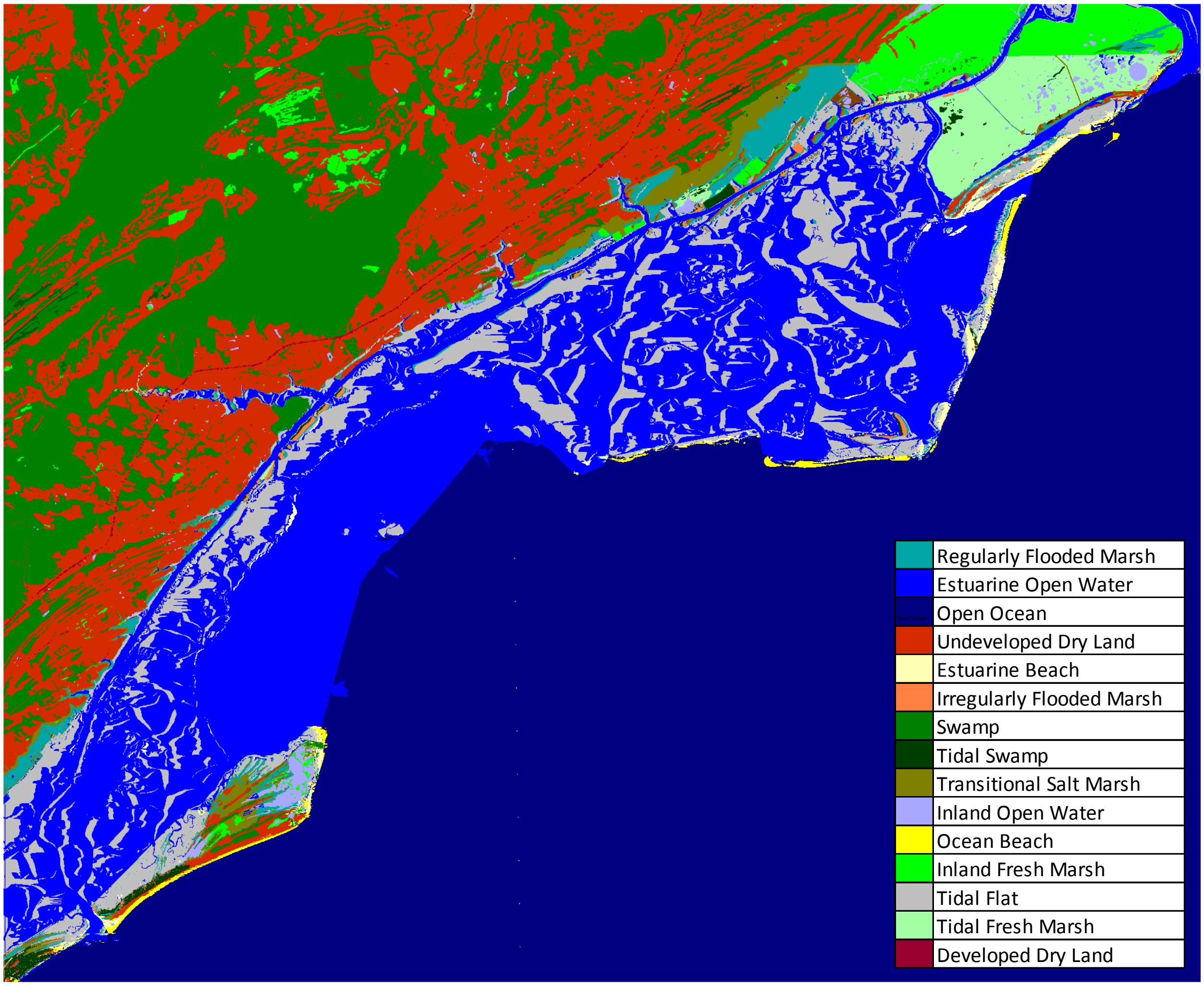
Cape Romain NWR, 2025, 1.5 m SLR by 2100.



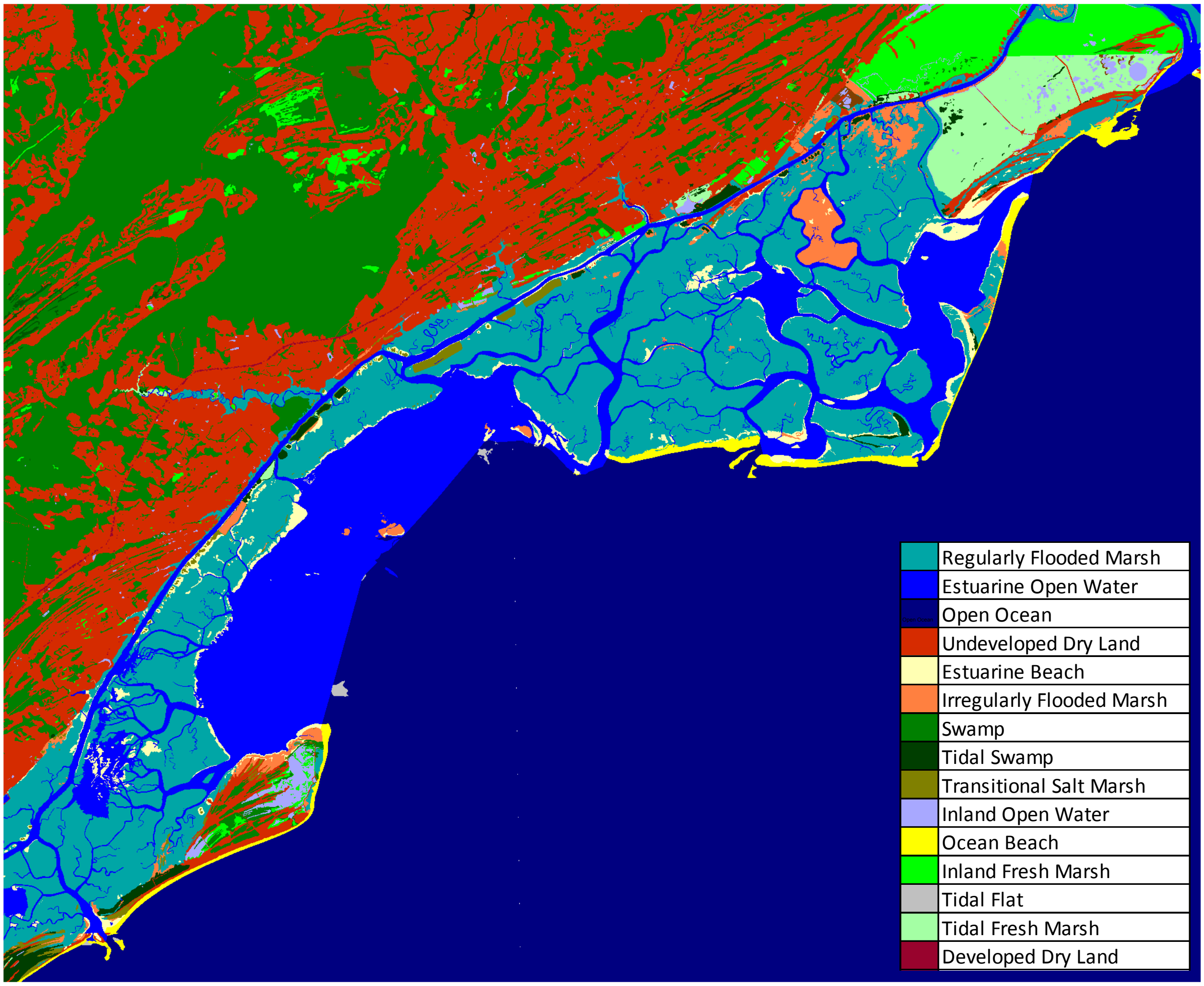
Cape Romain NWR, 2050, 1.5 m SLR by 2100.



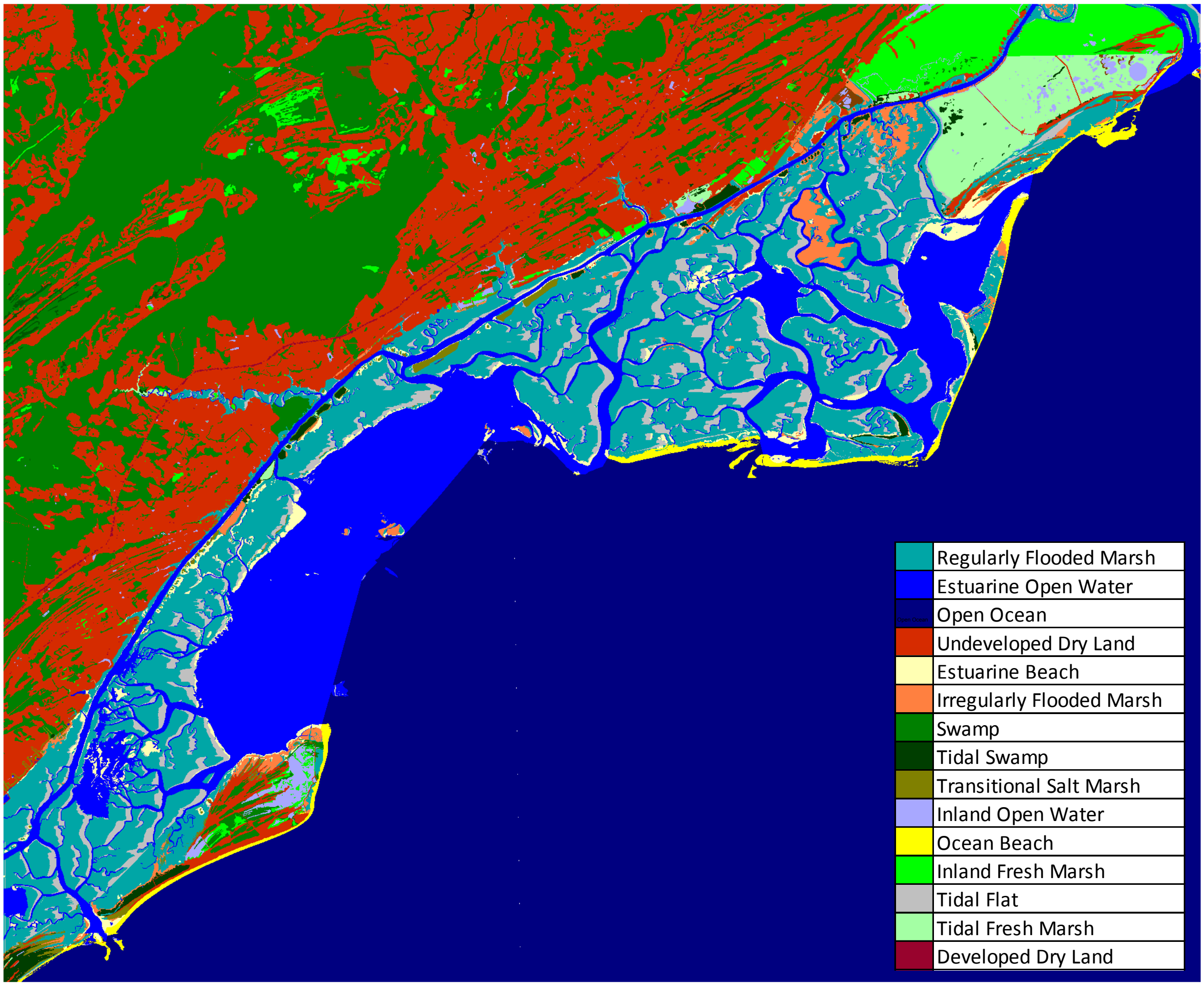
Cape Romain NWR, 2075, 1.5 m SLR by 2100.



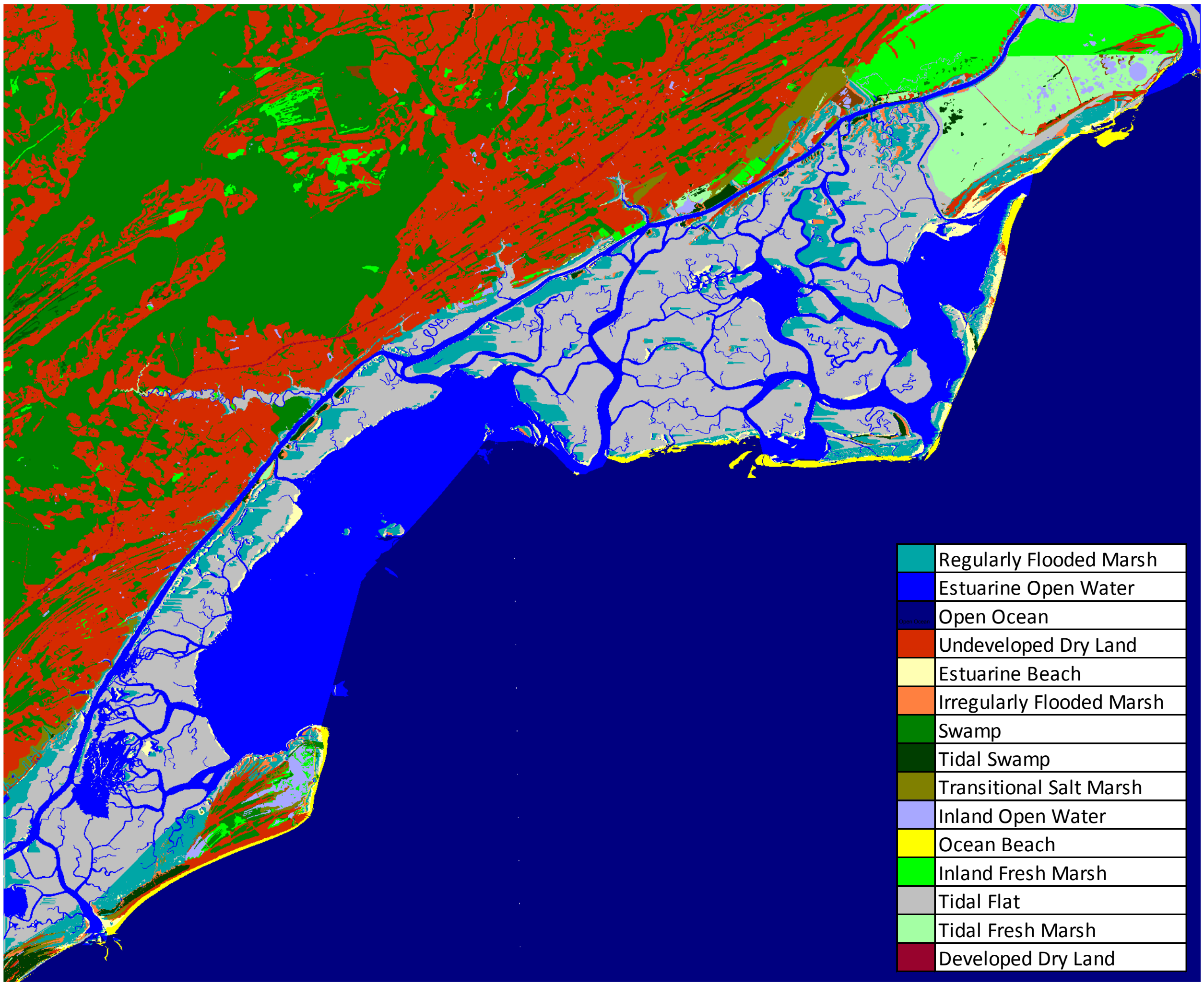
Cape Romain NWR, 2100, 1.5 m SLR by 2100.



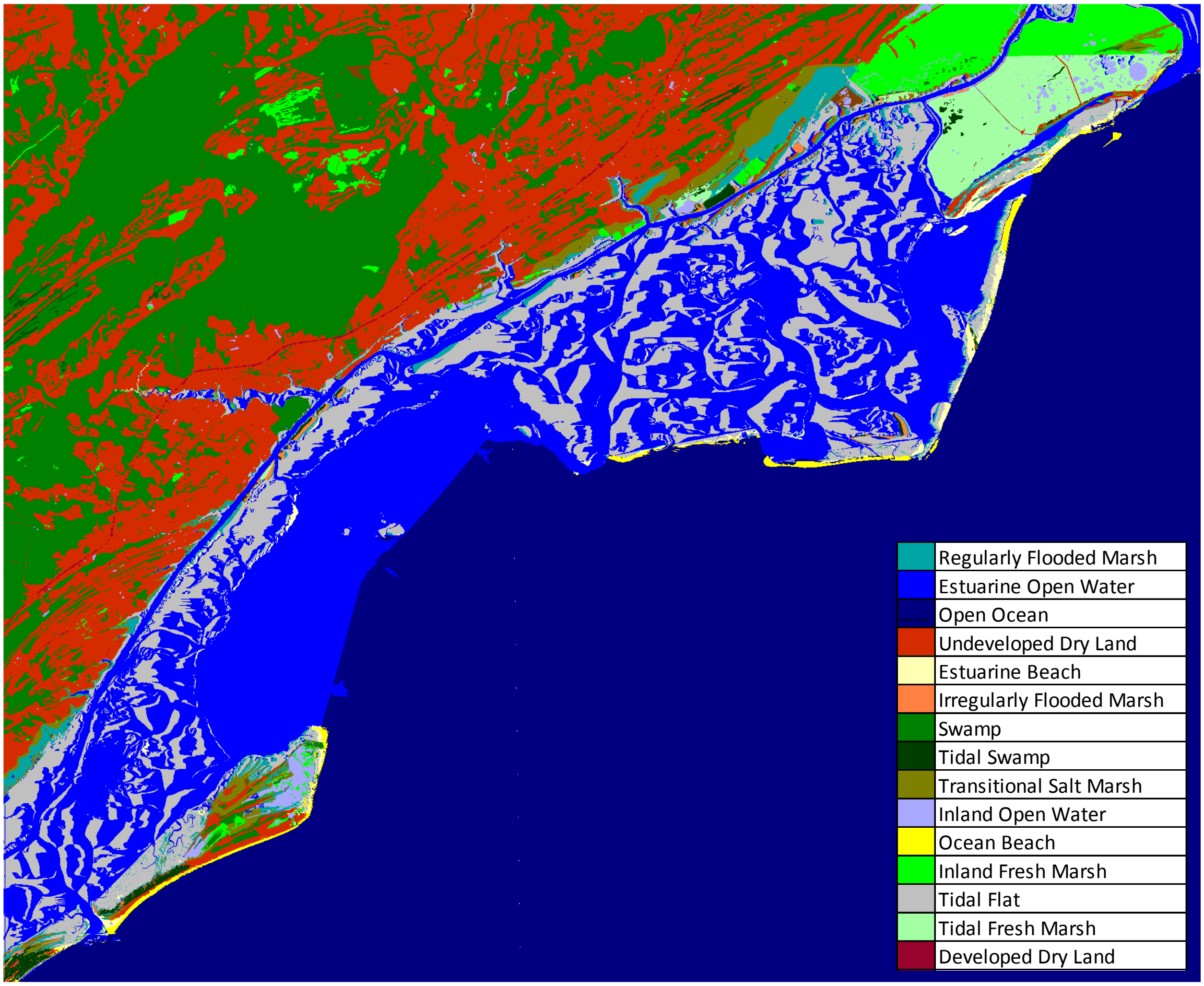
Cape Romain NWR, Initial Condition.



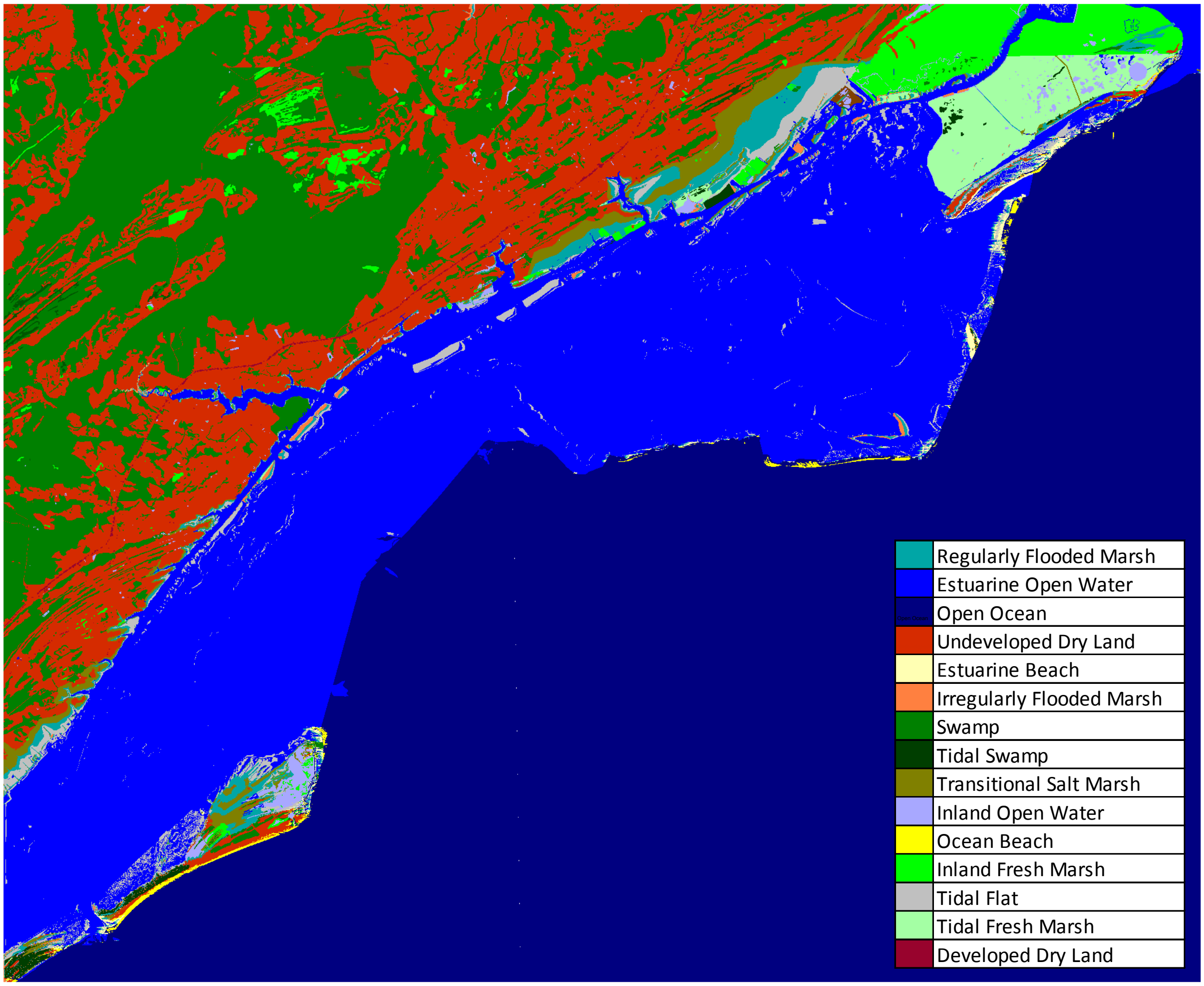
Cape Romain NWR, 2025, 2 m SLR by 2100.



Cape Romain NWR, 2050, 2 m SLR by 2100.



Cape Romain NWR, 2075, 2 m SLR by 2100.



Cape Romain NWR, 2100, 2 m SLR by 2100.