Application of the Sea-Level Affecting Marshes Model (SLAMM 6) to Edwin B. Forsythe 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 plan for and potentially mitigate the effects of sea-level rise on the U.S. National Wildlife Refuge System (Refuge System), the U. S. Fish and Wildlife Service (FWS) uses a variety of analytical approaches, most notably the SLAMM model. FWS conducts some SLAMM analysis in-house and, more commonly, contracts the application of the SLAMM model. In most cases Refuge System SLAMM analyses are designed to assist in the development of comprehensive conservation plans (CCPs), land acquisition plans, habitat management plans, and other land and resource management plans.

Model Summary

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

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

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

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

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

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

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

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

All model results are subject to uncertainty due to limitations in input data, incomplete knowledge about factors that control the behavior of the system being modeled, and simplifications of the system (Council for Regulatory Environmental Modeling 2008). Site-specific factors that increase or decrease model uncertainty may be covered in the *Discussion* section of this report.

Sea-Level Rise Scenarios

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

In this model application, the A1B scenario mean and maximum predictions are applied. Important assumptions were made in this scenario: reduction in the dispersion of income levels across economies (i.e. economic convergence), capacity building, increased cultural and social interactions among nations, and a substantial reduction in regional differences in per capita income, primarily from the economic growth of nations with increasing income (Nakicenovic et al. 2000). In addition, the A1 family of scenarios assumes that the future world includes rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Given today's global economic and political climate, as well as environmental and ecological constraints, these may not be feasible assumptions for the future.

In particular, the A1B scenario assumes that energy sources will be balanced across all sources, with an increase in use of renewable energy sources coupled with a reduced reliance on fossil fuels (Nakicenovic et al. 2000). Given this A1B scenario, the IPCC WGI Fourth Assessment Report (IPCC 2007) suggests a likely range of 0.21 m to 0.48 m of SLR by 2090-2099 "excluding future rapid dynamical changes in ice flow." The IPCC-produced A1B-mean scenario that was run as a part of this project falls near the middle of this estimated range, predicting 0.39 m of global SLR by 2100. A1B-maximum predicts 0.69 m of global SLR by 2100. However, other scientists using the same set of economic growth scenarios have produced much higher estimates of SLR as discussed below.

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

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

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

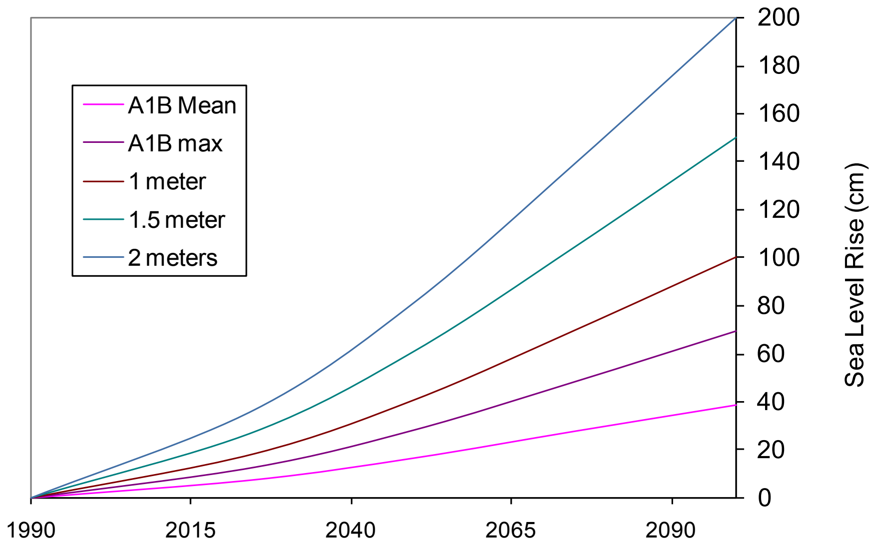


Figure 1. Summary of SLR scenarios utilized.

Data Sources and Methods

Wetland layer. Figure 2 shows the most recent available wetland layer obtained from a National Wetlands Inventory (NWI) photo dated 2008. Converting the NWI survey into 10 m x 10 m cells indicated that the approximately 72,000 acre Edwin B. Forsythe NWR (approved acquisition boundary including water) is composed of the following categories:

Land cover type		Area (acres)	Percentage (%)
	Irregularly-flooded Marsh	31298	43
	Estuarine Open Water	15630	22
	Swamp	11805	16
	Undeveloped Dry Land	7532	10
	Regularly-flooded Marsh	2057	3
	Inland Open Water	838	1
	Developed Dry Land	746	1
	Transitional Salt Marsh	717	<1
	Tidal Flat	534	<1
	Estuarine Beach	326	<1
	Inland Fresh Marsh	253	<1
	Ocean Beach	221	<1
	Open Ocean	180	<1
	Inland Shore	124	<1
	Riverine Tidal	1	<1
	Total (incl. water)	**72263**	**100**

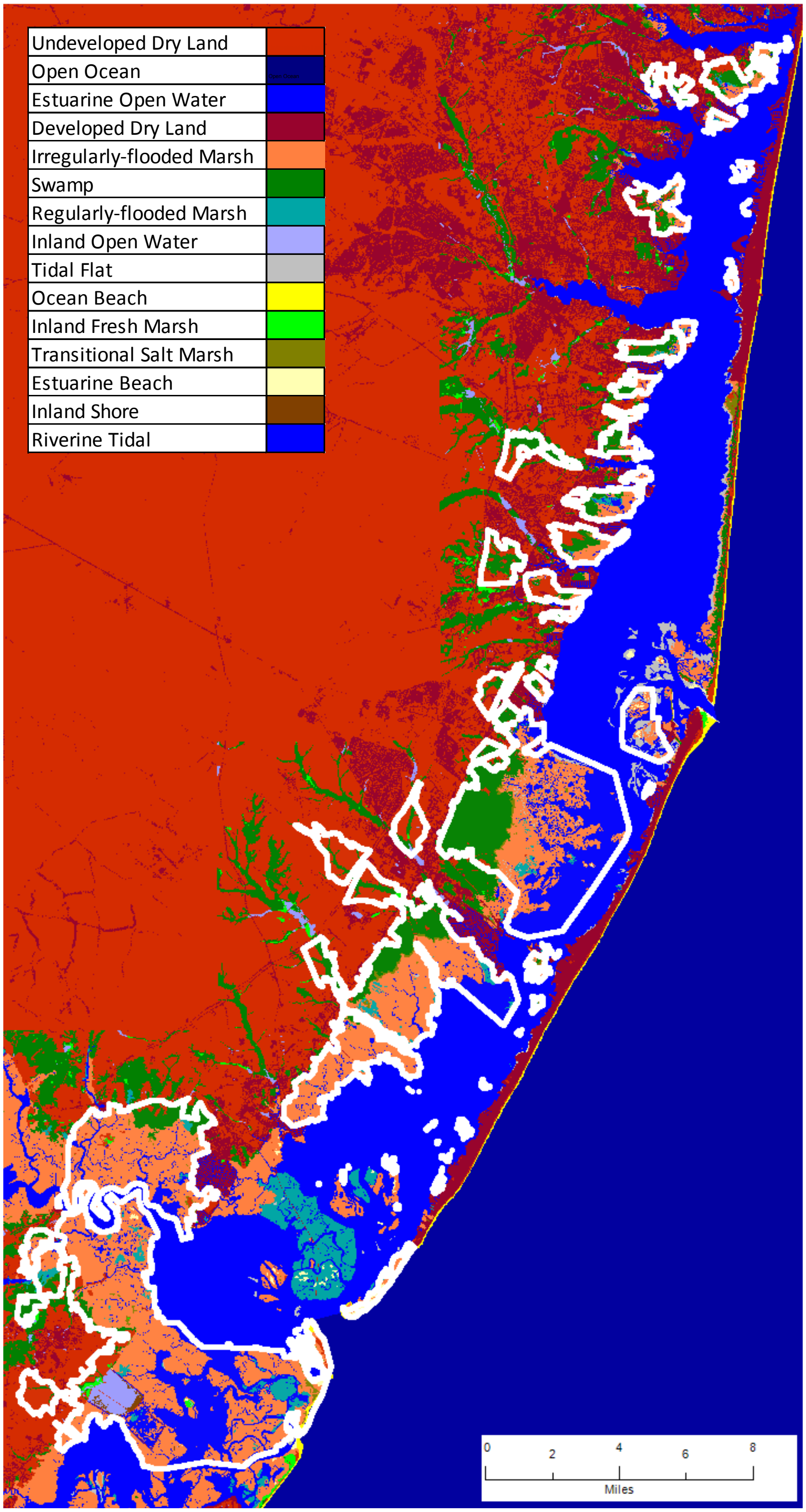


Figure 2. 2008 NWI coverage of the study area. Refuge boundaries are indicated in white.

Elevation Data. The refuge area is LiDAR data obtained from NED collected in 2011, except for a small area inland in the south section of the refuge that is covered by 2001 LiDAR, see Figure 3.

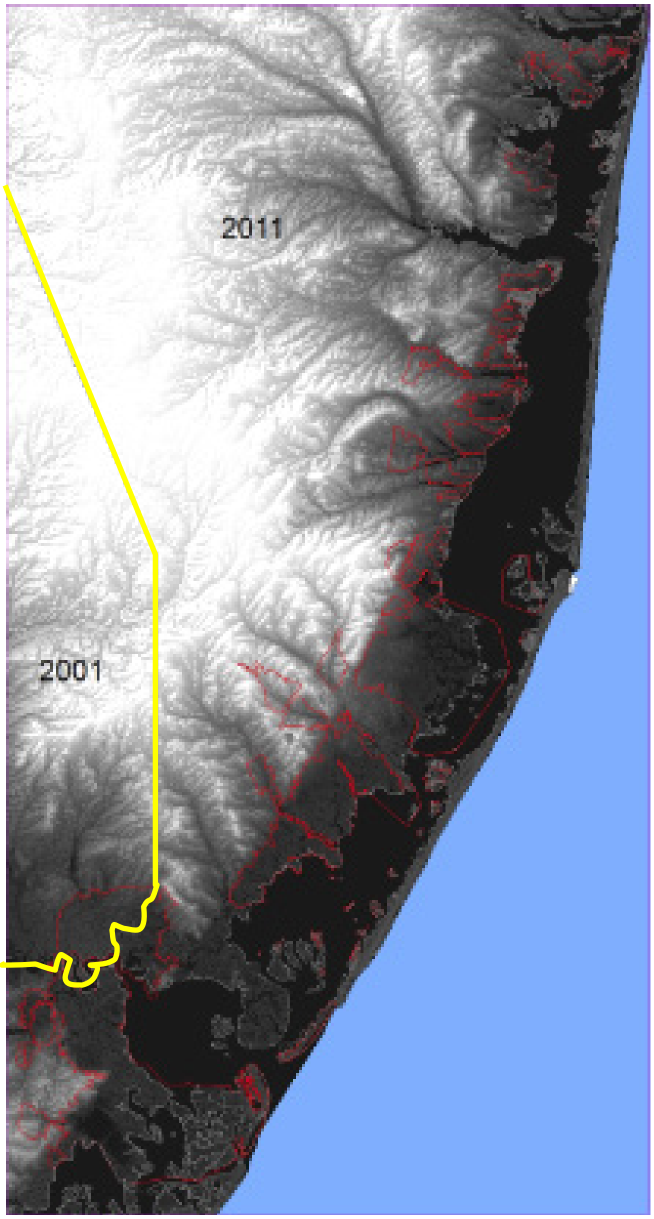


Figure 3. Location of LiDAR. Approved acquisition boundaries shown in red.

Dikes and Impoundments. Within the National Wetland Inventory, there are no wetlands designated as diked or impounded in the Refuge. However, Paul Castelli, the wildlife biologist at the refuge, has confirmed that there are few areas in the refuge that are impounded, in particular the area around refuge headquarters in the south and a small area close to Barnegat, shown in Figure 4. In addition, there is an impounded area near Forked River, although the flood gate is washed out and tides can go in and out. It is the intention of the refuge managers to recommend complete removal of that dike, therefore this area has not been modeled as protected by dikes.

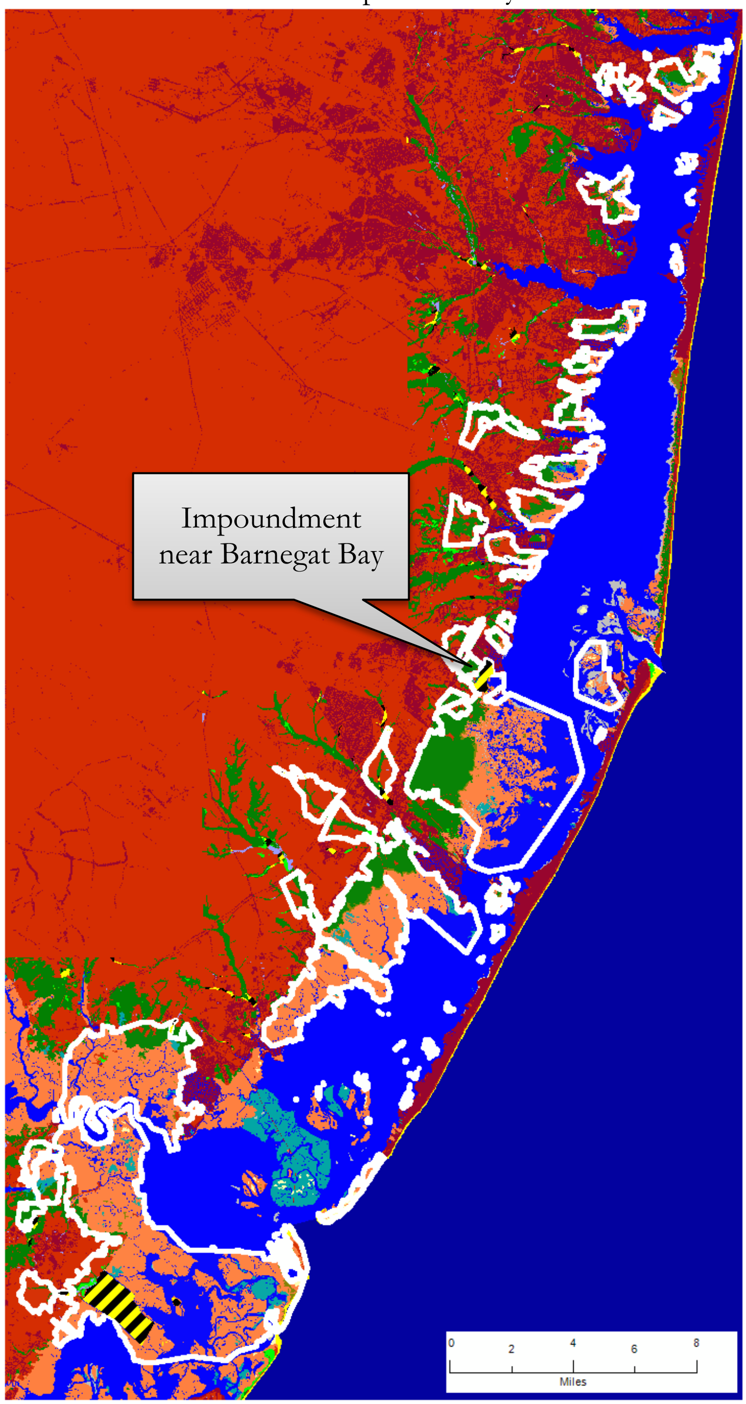


Figure 4. In black and yellow stripes, dikes and impoundments at Forsythe NWR.

Model Timesteps. Model forecast data was output for years 2025, 2050, 2075 and 2100 with the initial condition date set to 2008, the most recent wetland data available.

Historic sea-level rise rates. The historic trend for relative sea-level rise is estimated at 3.95 mm/year based on long term trends measured at nearby NOAA gauges, Atlantic City, NJ (station #8534720, period of record: 1911-2006) and Sandy Hook St., NJ (station #8531680, 1932-2006), as shown in Figure 5, Figure 6, Figure 7. This historical trend is higher than the global average for the last 100 years (approximately 1.7 mm/year), perhaps indicating some subsidence in this area.

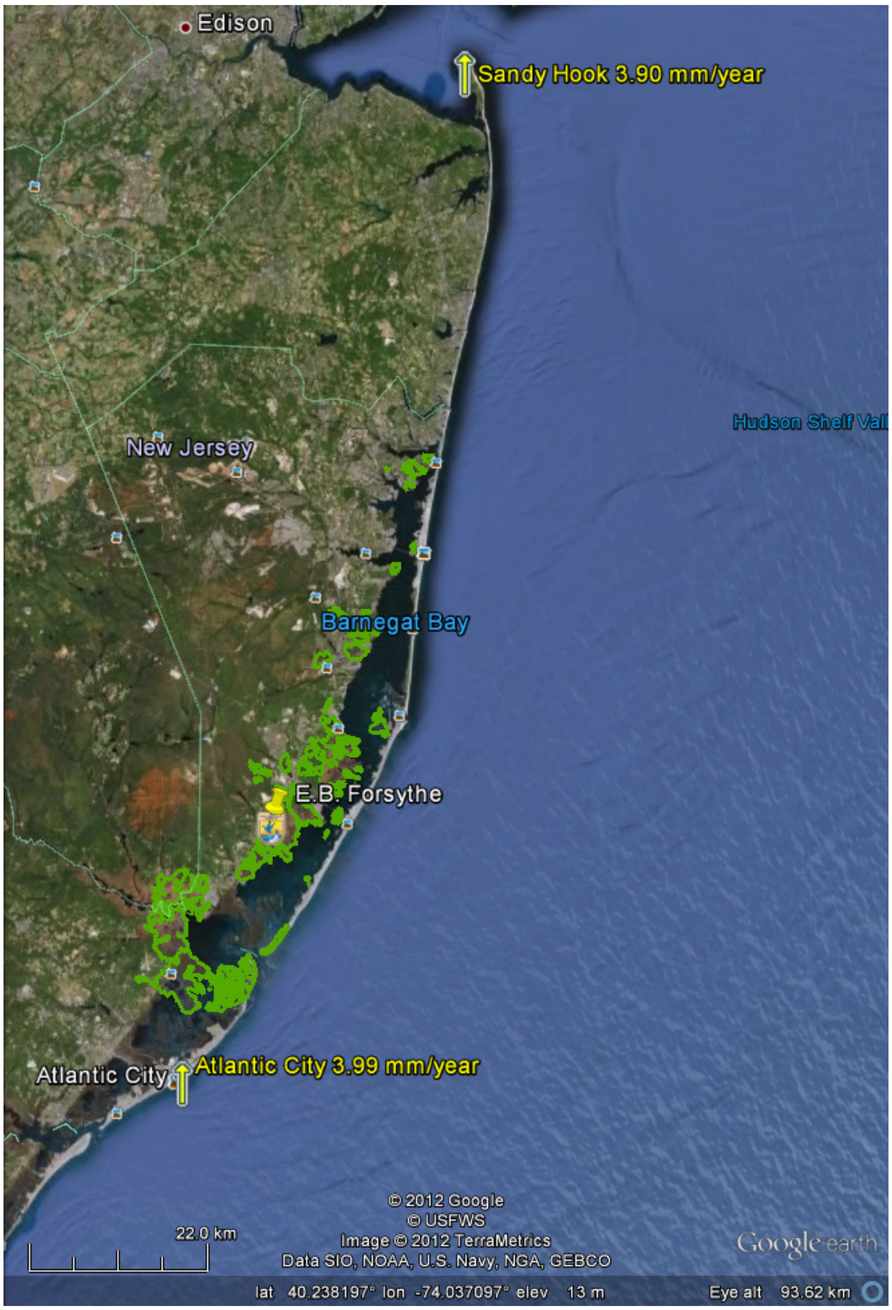


Figure 5. Historic average sea-level trends in the area around Edwin B. Forsythe NWR.

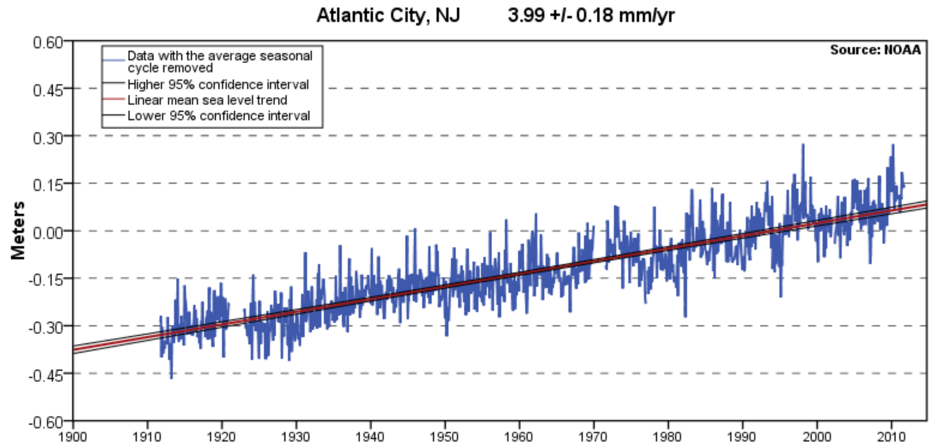


Figure 6. Recorded historic sea level at Atlantic City, NJ.

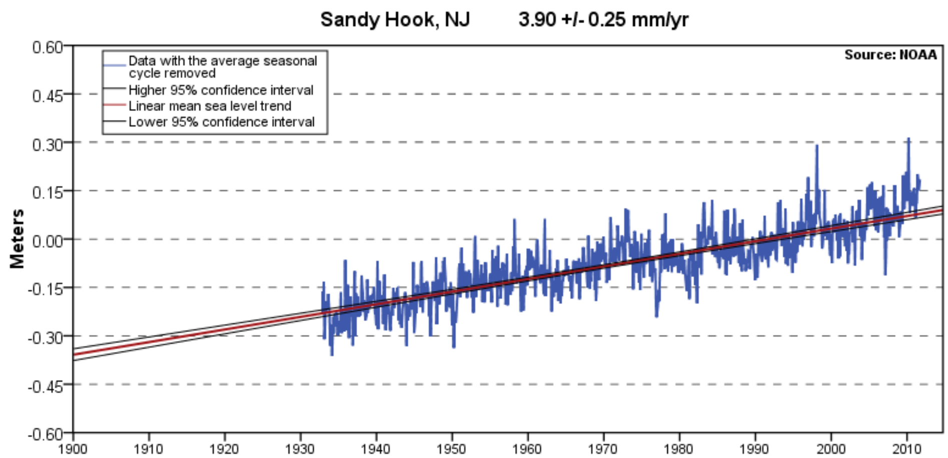


Figure 7. Recorded historic sea level at Sandy Hook, NJ.

Tide Ranges. The great diurnal range (GT) was estimated using the data from the NOAA gauge stations present in the area (shown in red in Figure 8) and several NOAA tide tables (shown in blue in Figure 8). Spatial variability in the tide range over the study area is shown in Figure 8. Several input subsites were defined reflecting these varying tidal ranges. For the ocean side the GT was set to 1.42 m, while four input subsites were created behind the barrier island with GT ranging between 0.19 m and 1.10 m going from north to south.

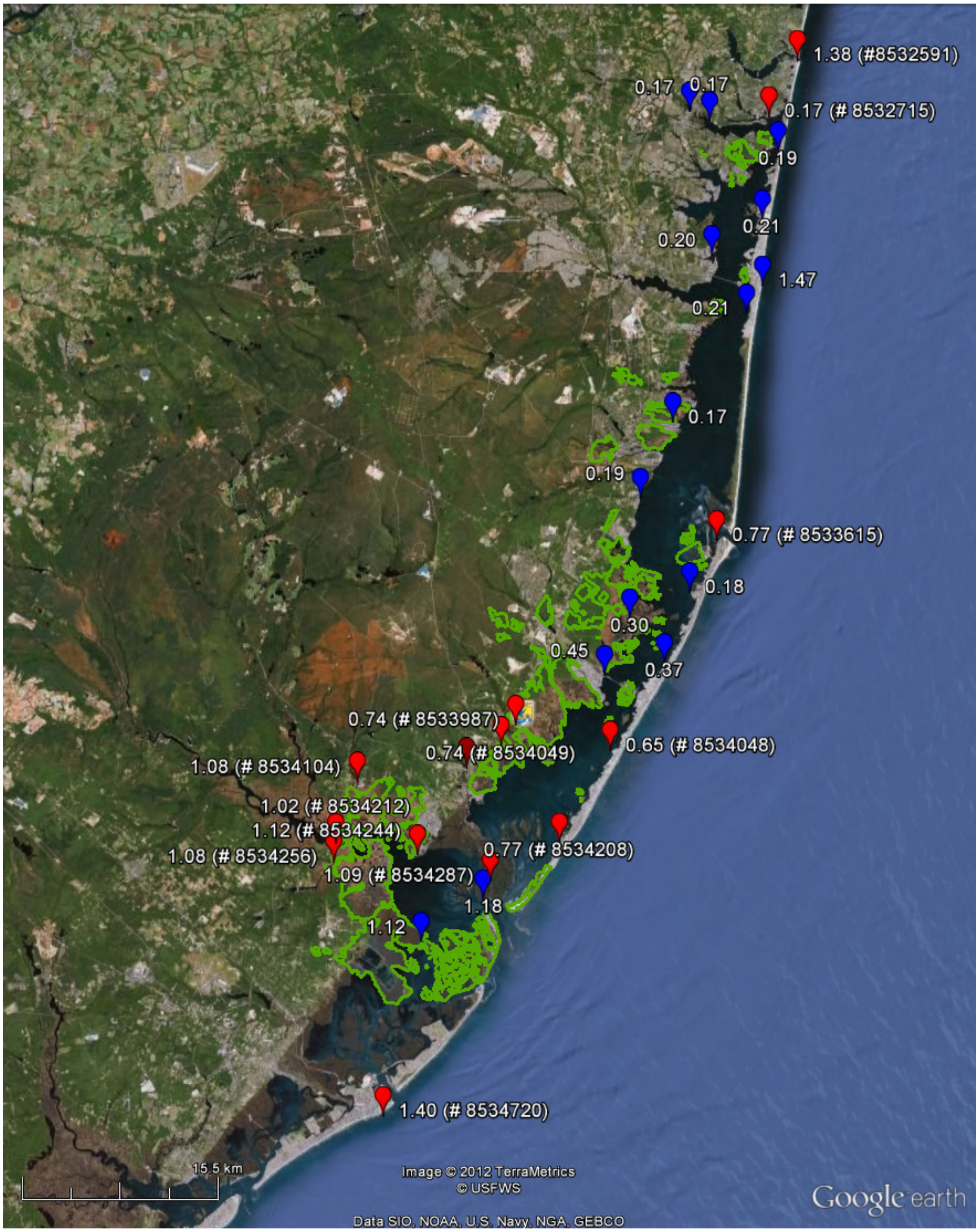


Figure 8. Great diurnal tide ranges (GT) in meters observed at the NOAA gauge stations located in the area around Edwin B. Forsythe NWR.

Salt elevation. This parameter within SLAMM designates the boundary between wet lands and dry lands or saline wetlands and fresh water wetlands. For this application, the salt elevation was estimated at 1.5 Half Tide Units (HTU).

Accretion rates. Accretion rates in salt and irregularly-flooded marshes were set to 3.75 mm/year, the mean of two accretion values measured in the refuge (Erwin et al. 2006). For regularly-flooded marsh the accretion rate was set to 2.5 mm/yr. This value was derived from the analysis of sediment accumulation of soil cores within the refuge property (Velinsky et al. 2011). For other marshes the accretion values were set to the SLAMM defaults.

Erosion rates. Erosion rates for marshes, swamps, and tidal flats were set to SLAMM defaults of 1.8 m/yr, 1 m/yr and 0.5 mm/yr, respectively. Horizontal erosion of marshes and swamps occurs only at the wetland-to-open-water interface and only when adequate open water (fetch) exists for wave setup.

Elevation correction. The MTL-NAVD88 correction was determined using the available data at some of the NOAA gauge stations in the area as shown in Figure 9. The spatial variability of these corrections is accounted for in each input subsite.

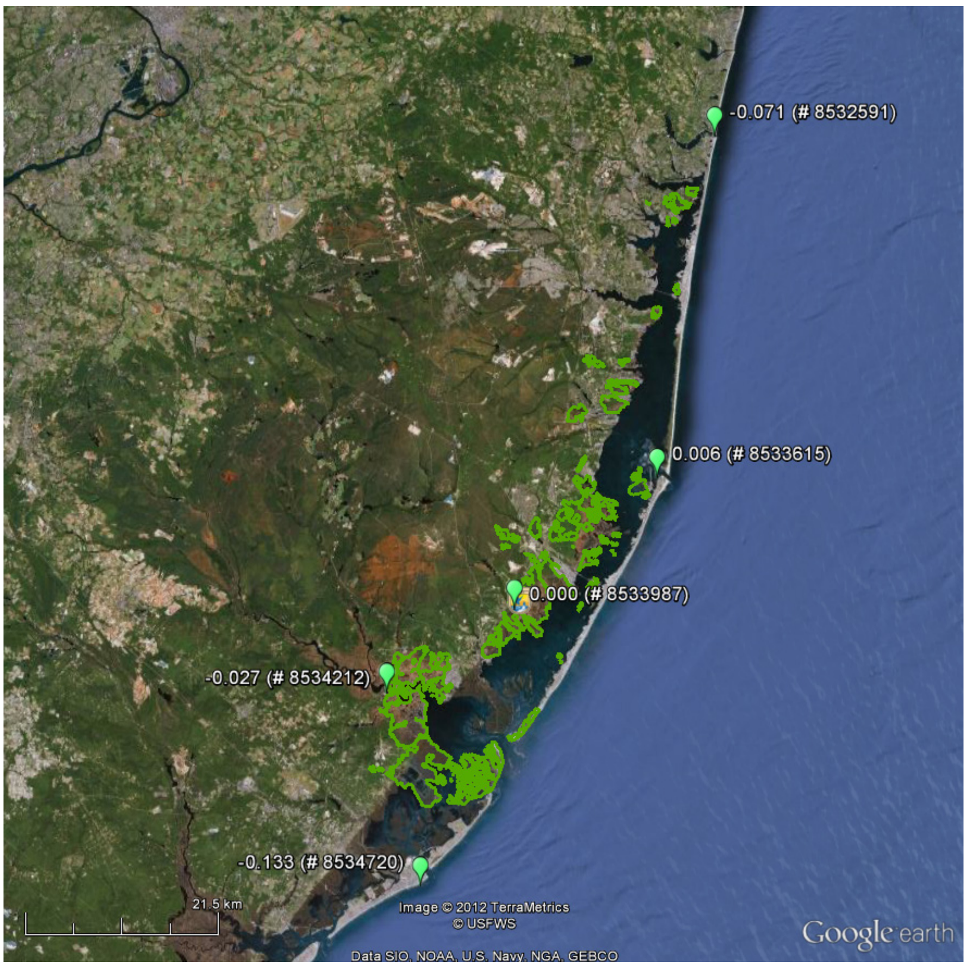


Figure 9. Spatial variability of MTL to NAVD88 correction
in the area around Edwin B. Forsythe NWR.

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

Parameter summary. Based on spatial variability of the tide ranges and elevation corrections, the study area was subdivided in the subsites illustrated in Figure 10.

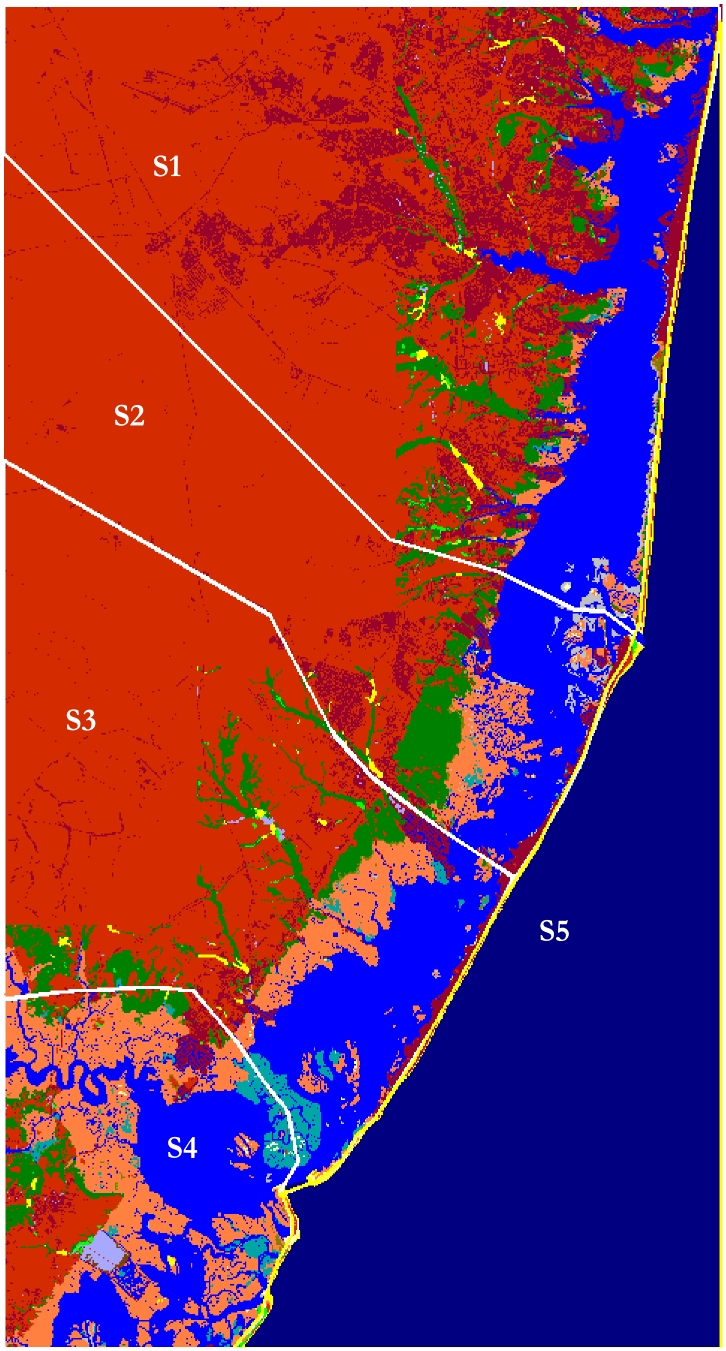


Figure 10. Input subsites (S1-S5) for model application.

The parameters assigned to each subsite are presented in Table 1. Values for parameters with no specific local information were kept at the model default value. 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 1. Summary of SLAMM input parameters for Edwin B. Forsythe NWR.

Parameter	S1	S2	S3	S4	S5
NWI Photo Date (YYYY)	2008	2008	2008	2008	2008
DEM Date (YYYY)	2011	2011	2011	2011	2011
Direction Offshore [n,s,e,w]	East	East	East	East	East
Historic Trend (mm/yr)	3.95	3.95	3.95	3.95	3.95
MTL-NAVD88 (m)	-0.03	0.01	0.00	-0.03	-0.07
GT Great Diurnal Tide Range (m)	0.19	0.33	0.75	1.10	1.42
Salt Elev. (m above MTL)	0.14	0.25	0.56	0.83	1.07
Marsh Erosion (horz. m /yr)	1.8	1.8	1.8	1.8	1.8
Swamp Erosion (horz. m /yr)	1	1	1	1	1
T.Flat Erosion (horz. m /yr)	0.5	0.5	0.5	0.5	0.5
Reg.-Flood Marsh Accr (mm/yr)	3.75	3.75	3.75	3.75	3.75
Irreg.-Flood Marsh Accr (mm/yr)	2.5	2.5	2.5	2.5	2.5
Tidal-Fresh Marsh Accr (mm/yr)	5.9	5.9	5.9	5.9	5.9
Inland-Fresh Marsh Accr (mm/yr)	4	4	4	4	4
Tidal Swamp Accr (mm/yr)	1.1	1.1	1.1	1.1	1.1
Swamp Accretion (mm/yr)	0.3	0.3	0.3	0.3	0.3
Beach Sed. Rate (mm/yr)	0.5	0.5	0.5	0.5	0.5
Freq. Overwash (years)	35	35	35	35	35
Use Elev Pre-processor [True,False]	FALSE	FALSE	FALSE	FALSE	FALSE

Results

Table 2 presents the predicted losses for each land cover type by 2100 within the approved acquisition boundary of Edwin B. Forsythe NWR for each of the five SLR scenarios examined. For this simulation the land-cover losses are calculated in comparison to the 2008 NWI wetland layer.

Table 2. Predicted loss rates of land categories by 2100 given simulated scenarios of eustatic SLR at Edwin B. Forsythe NWR.

Land cover category	Initial coverage (acres)	Land cover loss by 2100 for different SLR scenarios				
		0.39 m	0.69 m	1 m	1.5 m	2 m
Irregularly-flooded Marsh	31298	66%	97%	99%	99%	99%
Swamp	11805	14%	23%	32%	44%	54%
Undeveloped Dry Land	7532	5%	7%	8%	12%	16%
Developed Dry Land	746	8%	11%	15%	23%	30%
Estuarine Beach	326	4%	9%	21%	45%	62%
Inland Fresh Marsh	253	12%	48%	51%	55%	61%

Results of SLAMM simulations suggest Edwin B. Forsythe NWR will be severely affected by increases in sea level under all SLR scenarios. LiDAR data show that irregularly-flooded marsh in this refuge has relatively low elevations and is on the verge of converting to regularly-flooded saltmarsh. Therefore this marsh is predicted to increasingly lose coverage given greater acceleration in SLR as vertical marsh accretion is not capable of keeping pace. At SLR scenarios of 0.69 m and greater by 2100, simulations suggested near complete loss of irregularly-flooded marsh habitat. Under the most conservative SLR scenarios, irregularly-flooded marshes are converted mostly to regularly-flooded marsh. However, as the rate of SLR increases, regularly-flooded marsh is predicted to lose significant acreage, as shown in Table 3 below. Similarly, swamp areas are predicted to be slowly inundated with an overall loss of more than 50% under the 2 m SLR scenario. Undeveloped and developed dry land is also expected to be inundated, but to a much lesser extent.

Major land cover gains are summarized in Table 3. Except for the most conservative SLR scenario, open water is predicted to increasingly inundate refuge areas that are currently covered by wetland, passing from 23% coverage today to more than 70% for the 2 m SLR by 2100 scenario. Simulations project a large amount of tidal flat to be formed for SLR scenarios under 1.5 m by 2100 when regularly-flooded marsh drops below mean-tide level. For higher SLR rates, gains are less pronounced as inundation of the newly-formed tidal flats is predicted.

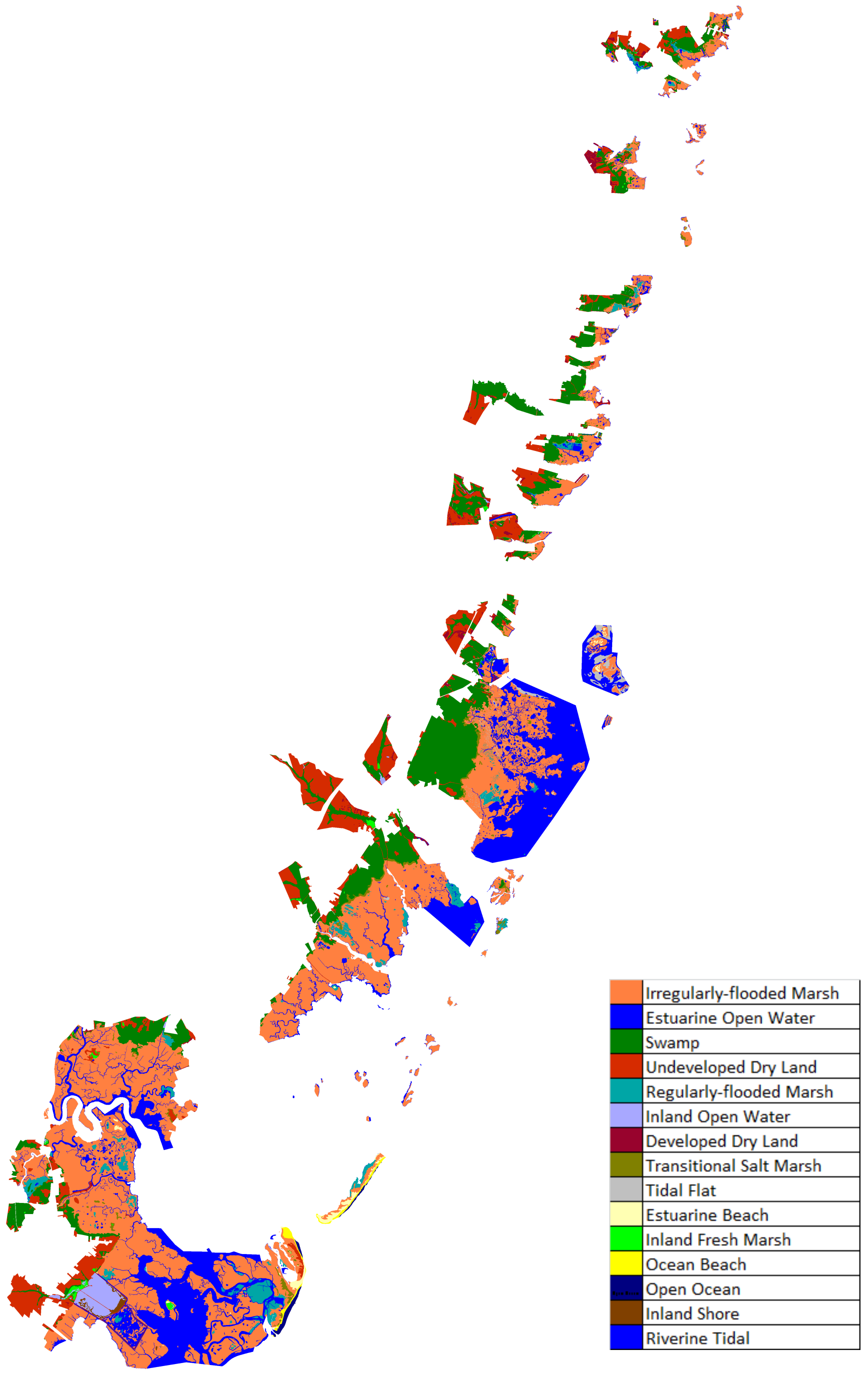
Table 3. Predicted land cover by 2100 given simulated scenarios of eustatic SLR at Edwin B. Forsythe NWR.

Land cover category	Initial coverage (acres)	Land cover by 2100 for different SLR scenarios (acres)				
		0.39 m	0.69 m	1 m	1.5 m	2 m
Open water	16649	19690	24129	33145	48570	51475
Regularly-flooded Marsh	2057	17627	12188	3057	2440	2631
Tidal Flat	534	3770	15875	17719	4590	2888
Transitional Salt Marsh	717	1447	1508	1592	1829	2168

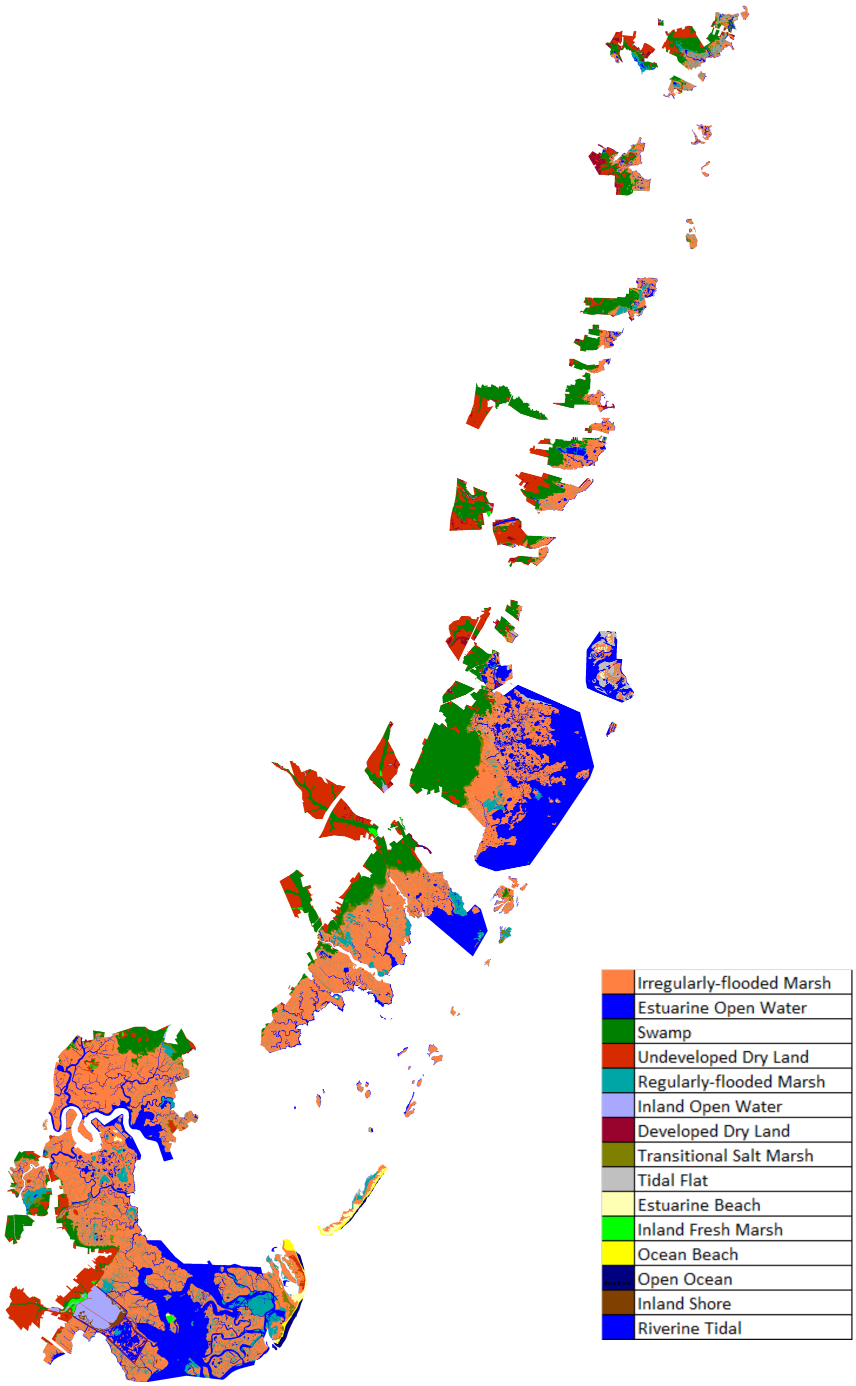
Edwin B. Forsythe NWR
IPCC Scenario A1B-Mean, 0.39 m SLR eustatic by 2100

Results in Acres

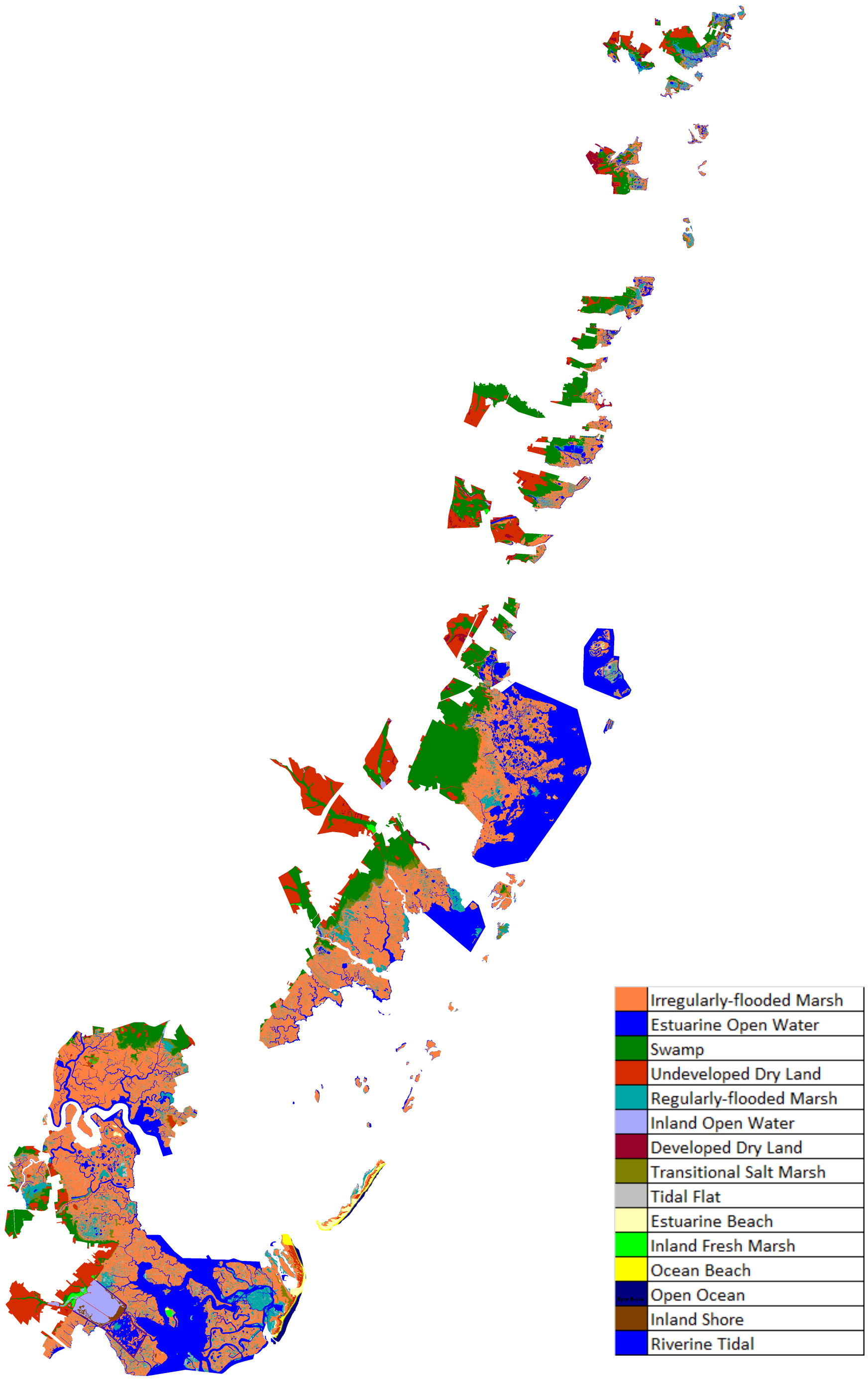
		Initial	2025	2050	2075	2100
	Irregularly-flooded Marsh	31298	28490	26533	20008	10686
	Estuarine Open Water	15630	15677	16267	16663	17818
	Swamp	11805	11685	11389	10859	10205
	Undeveloped Dry Land	7532	7320	7274	7261	7186
	Regularly-flooded Marsh	2057	4213	5343	10521	17627
	Inland Open Water	838	832	831	829	826
	Developed Dry Land	746	725	716	703	688
	Transitional Salt Marsh	717	980	1246	1473	1447
	Tidal Flat	534	1145	1384	2295	3770
	Estuarine Beach	326	326	298	333	314
	Inland Fresh Marsh	253	237	233	227	222
	Ocean Beach	221	214	203	304	309
	Open Ocean	180	294	420	661	1046
	Inland Shore	124	124	124	124	118
	Riverine Tidal	1	1	1	1	1
	Total (incl. water)	**72263**	**72263**	**72263**	**72263**	**72263**



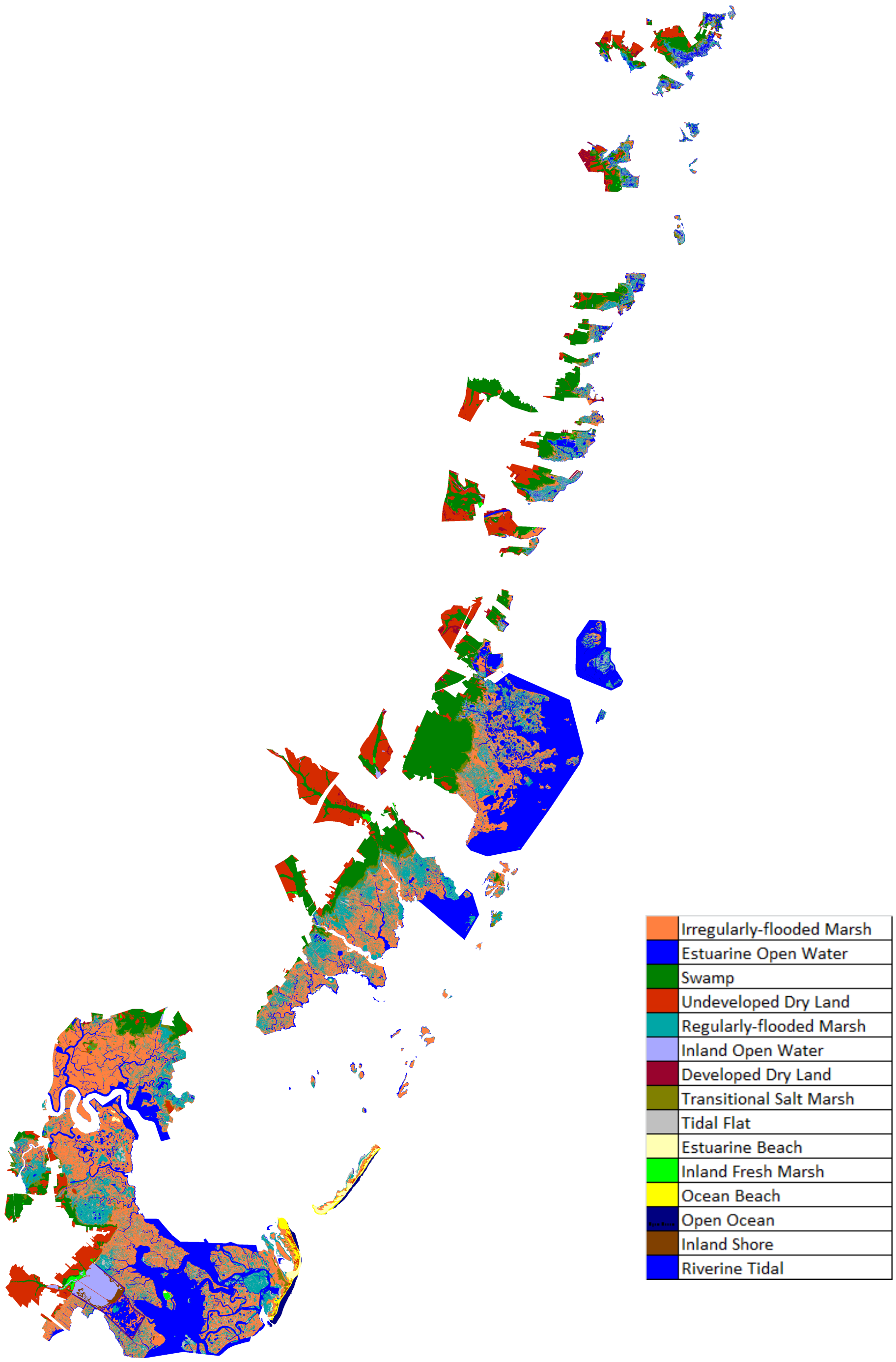
Edwin B. Forsythe NWR, Initial Condition.



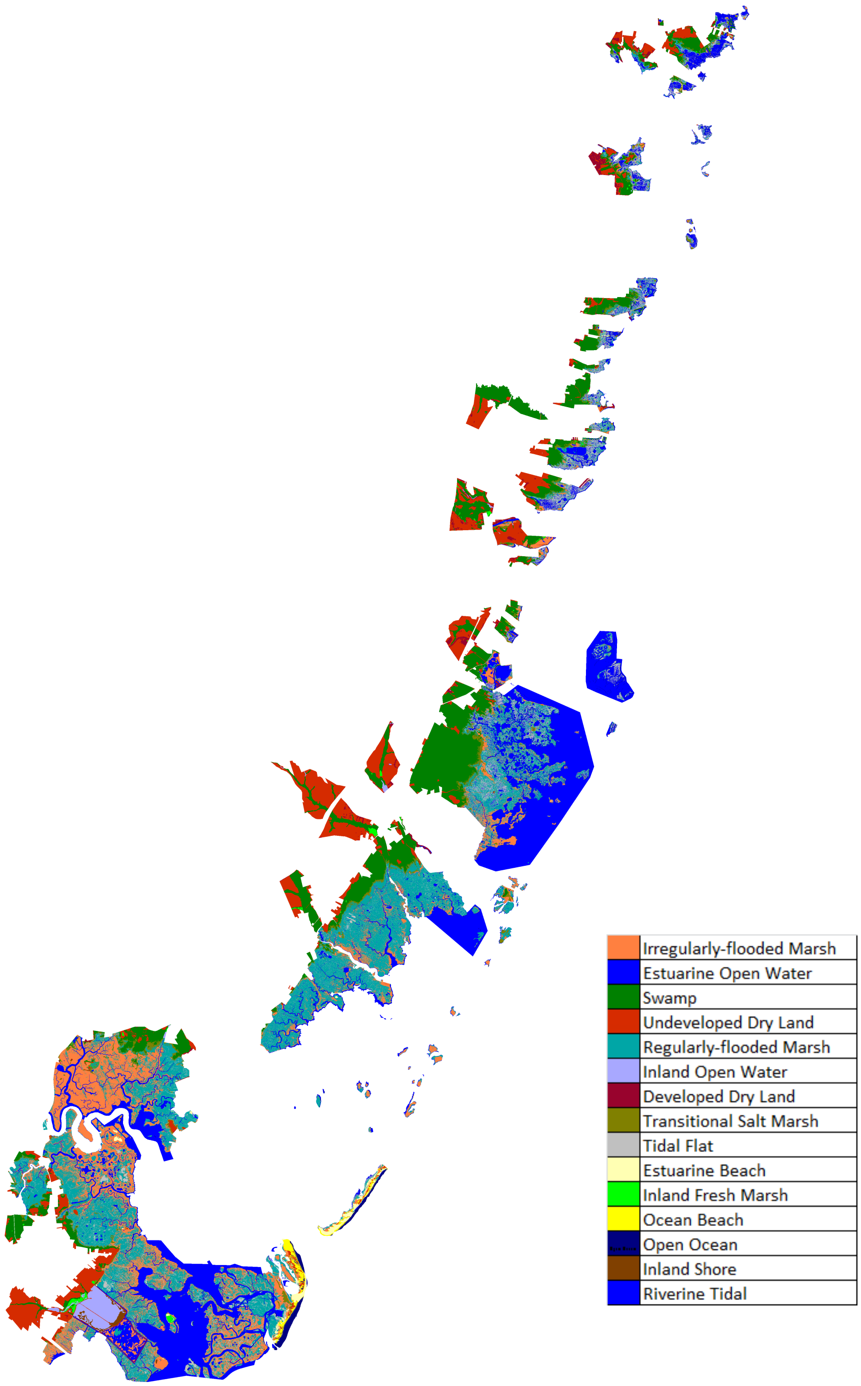
Edwin B. Forsythe NWR, 2025, Scenario A1B Mean, 0.39 m SLR by 2100.



Edwin B. Forsythe NWR, 2050, Scenario A1B Mean, 0.39 m SLR by 2100.



Edwin B. Forsythe NWR, 2075, Scenario A1B Mean, 0.39 m SLR by 2100.

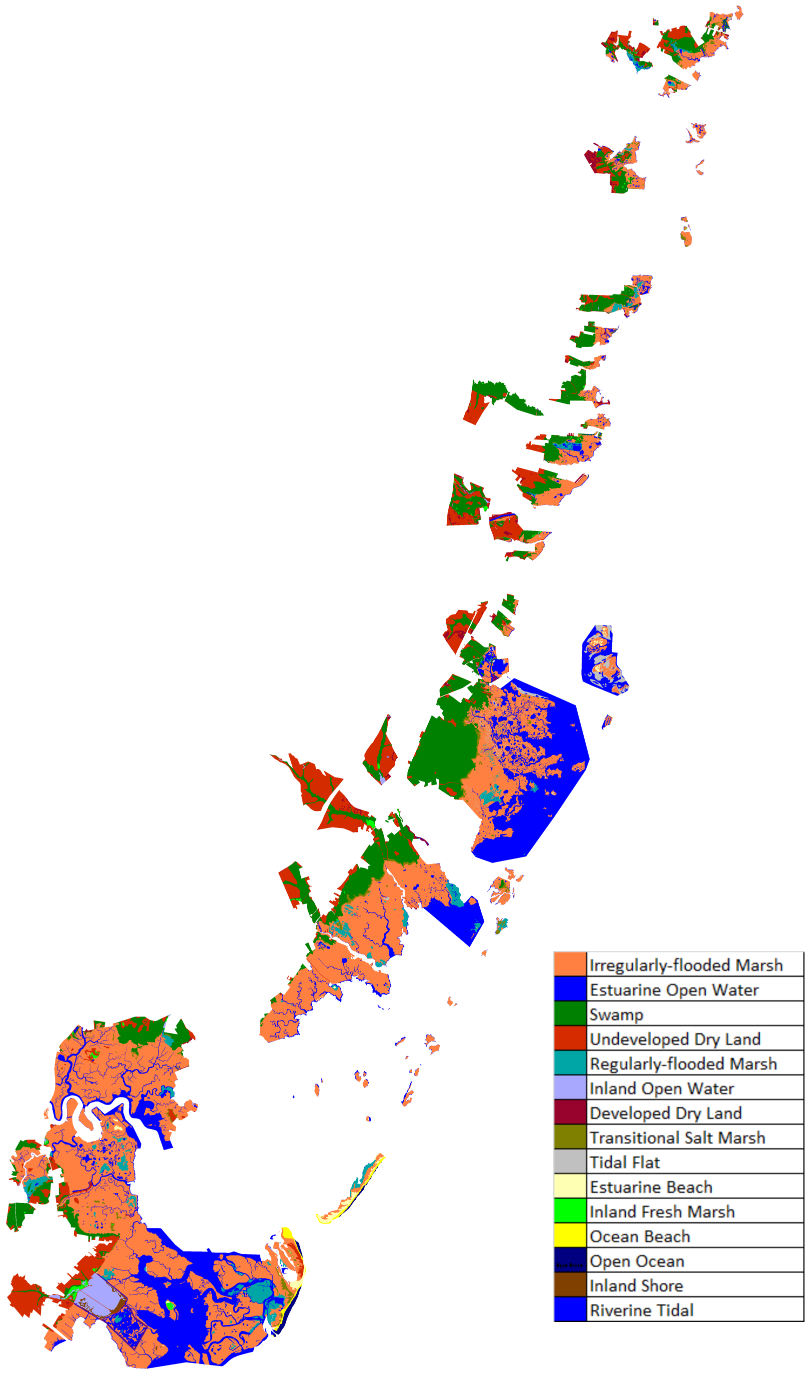


Edwin B. Forsythe NWR, 2100, Scenario A1B Mean, 0.39 m SLR by 2100.

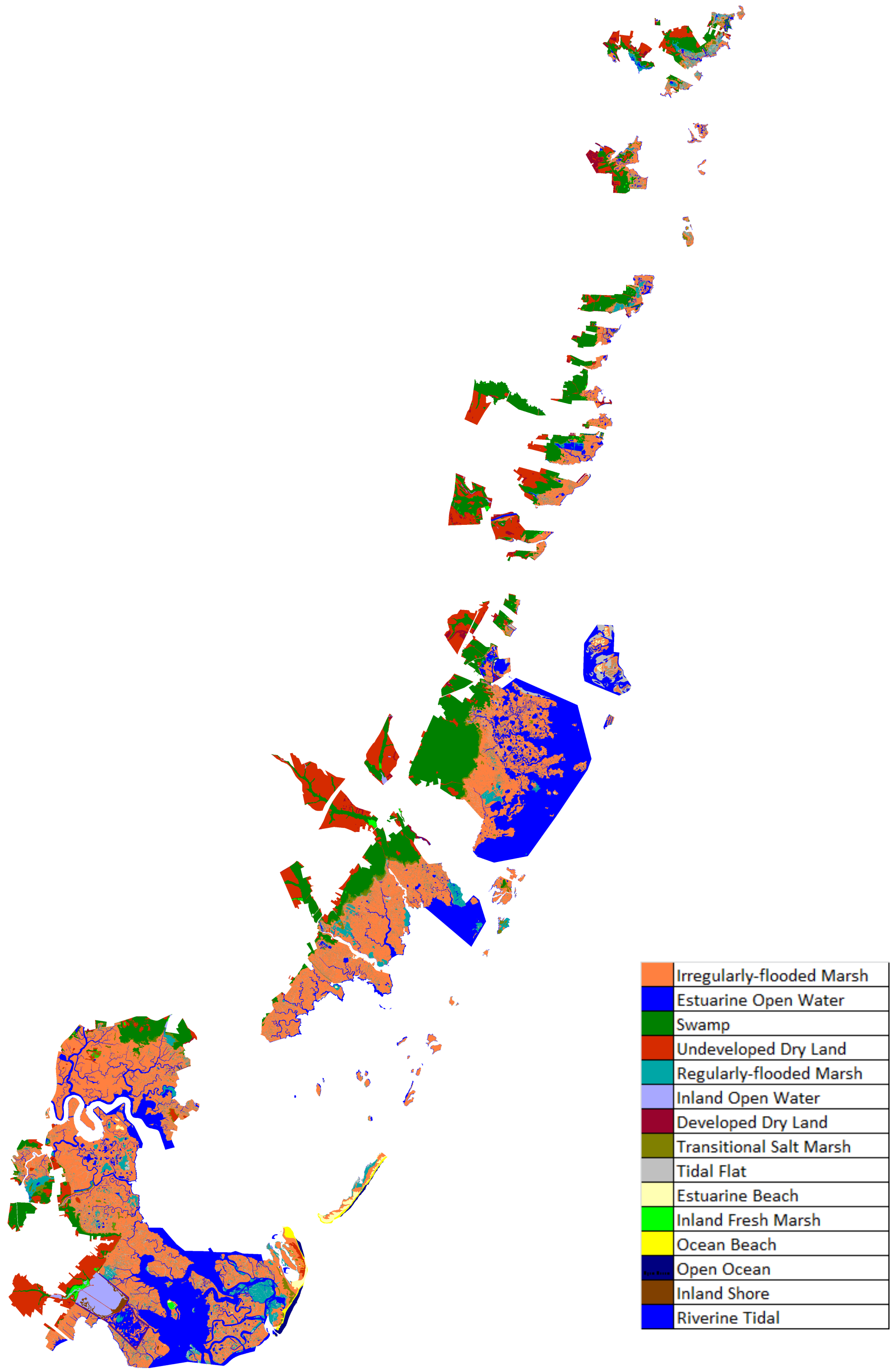
Edwin B. Forsythe NWR
IPCC Scenario A1B-Max, 0.69 m SLR eustatic by 2100

Results in Acres

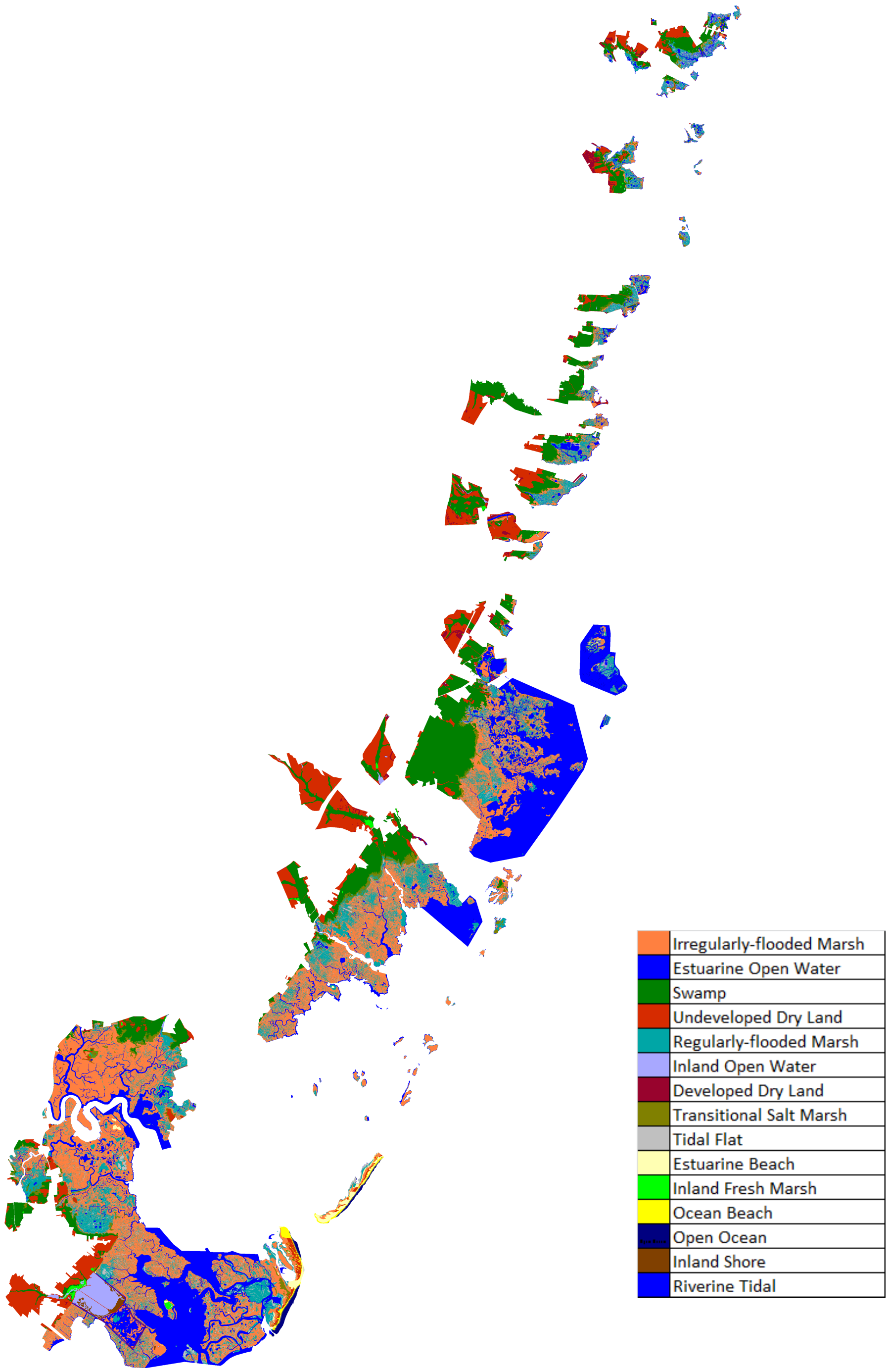
		Initial	2025	2050	2075	2100
	Irregularly-flooded Marsh	31298	28058	21481	5711	1017
	Estuarine Open Water	15630	15685	16455	17458	21284
	Swamp	11805	11641	11127	10111	9058
	Undeveloped Dry Land	7532	7313	7248	7183	7042
	Regularly-flooded Marsh	2057	4247	9597	20699	12188
	Inland Open Water	838	832	830	826	824
	Developed Dry Land	746	723	709	687	661
	Transitional Salt Marsh	717	1017	1354	1551	1508
	Tidal Flat	534	1530	2122	6081	15875
	Estuarine Beach	326	326	292	318	298
	Inland Fresh Marsh	253	236	226	213	133
	Ocean Beach	221	215	211	321	336
	Open Ocean	180	316	486	989	2022
	Inland Shore	124	124	124	115	19
	Riverine Tidal	1	1	1	1	0
	Total (incl. water)	**72263**	**72263**	**72263**	**72263**	**72263**



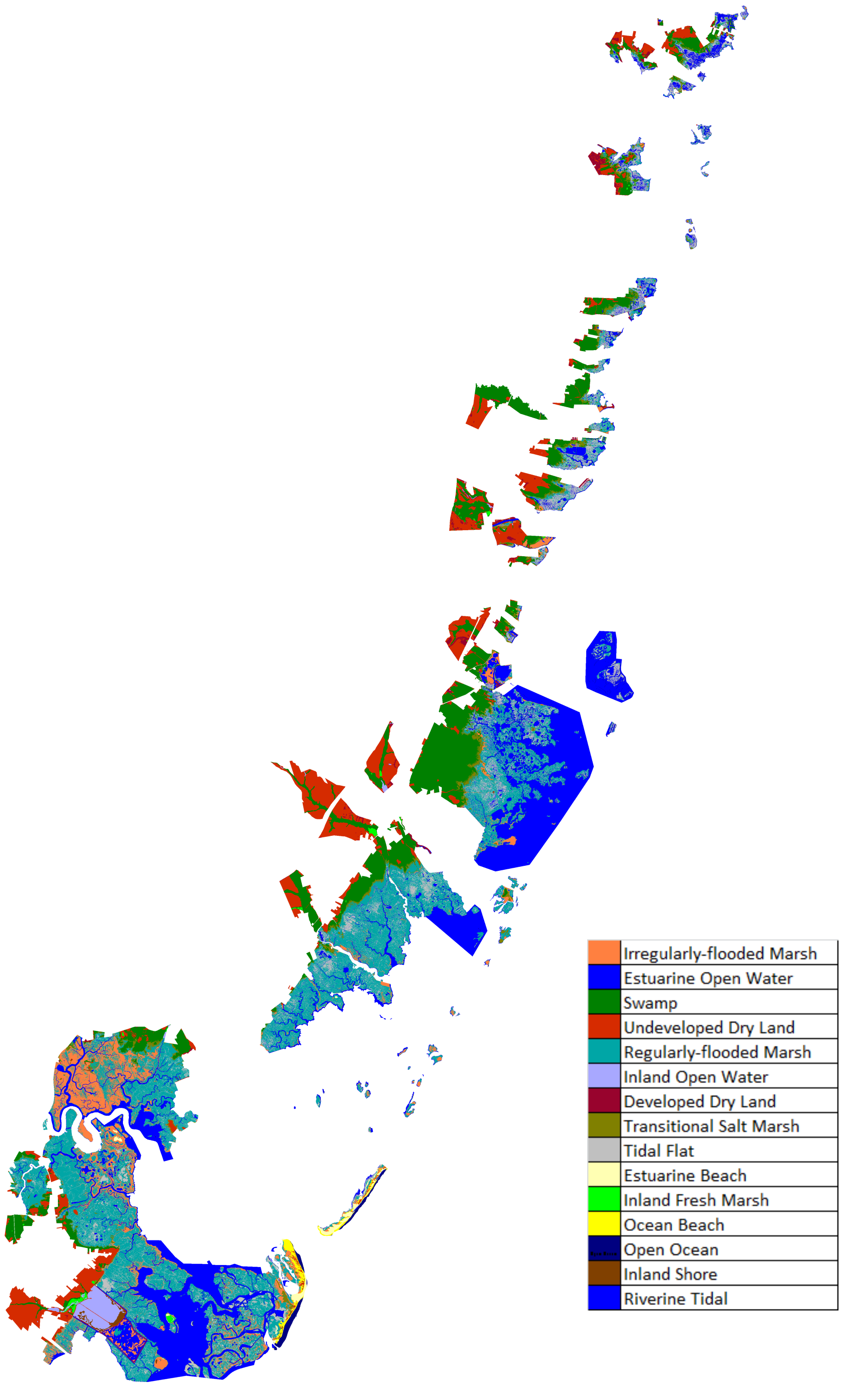
Edwin B. Forsythe NWR, Initial Condition.



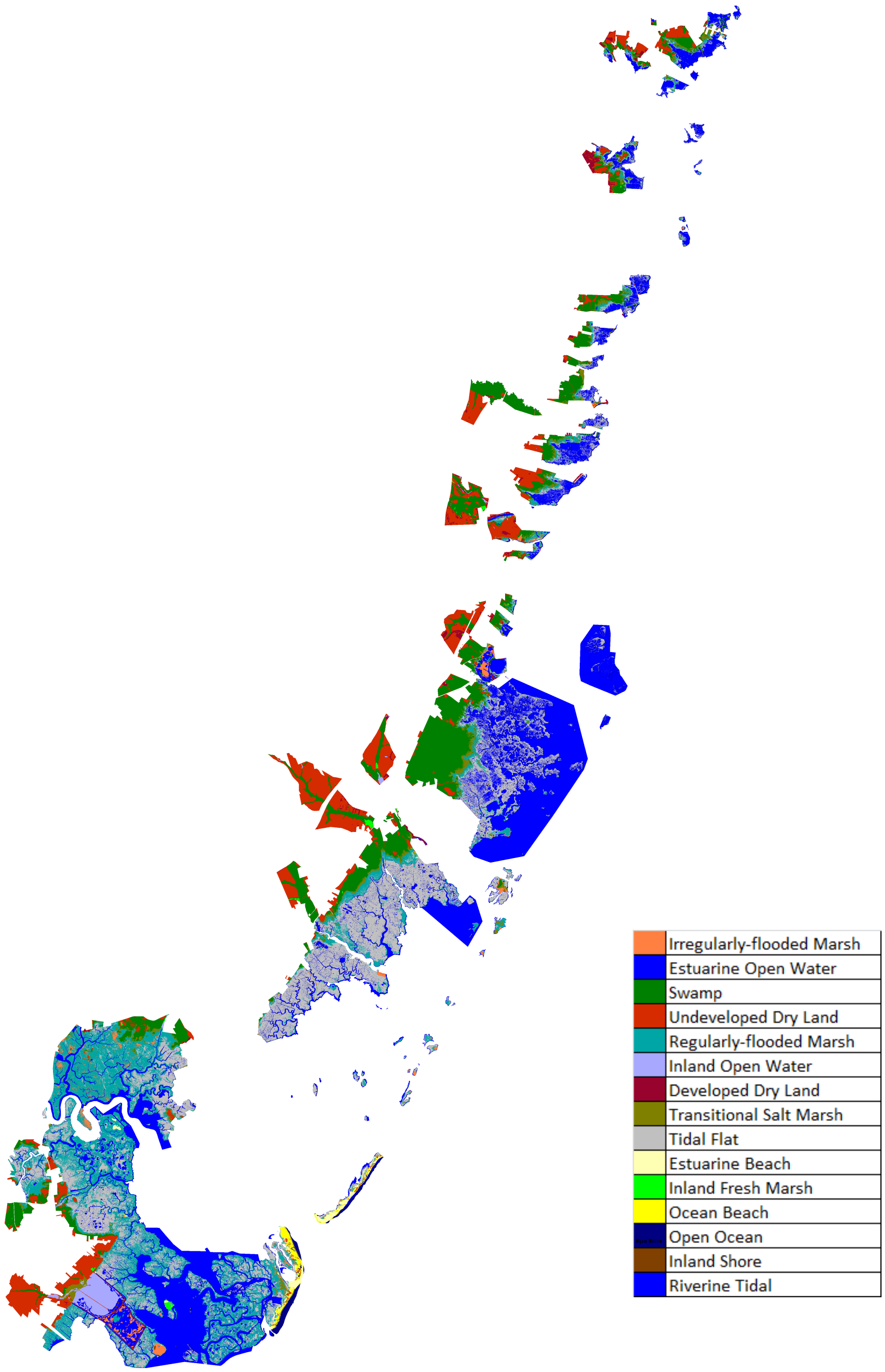
Edwin B. Forsythe NWR, 2025, Scenario A1B Maximum, 0.69 m SLR by 2100.



Edwin B. Forsythe NWR, 2050, Scenario A1B Maximum, 0.69 m SLR by 2100.



Edwin B. Forsythe NWR, 2075, Scenario A1B Maximum, 0.69 m SLR by 2100.

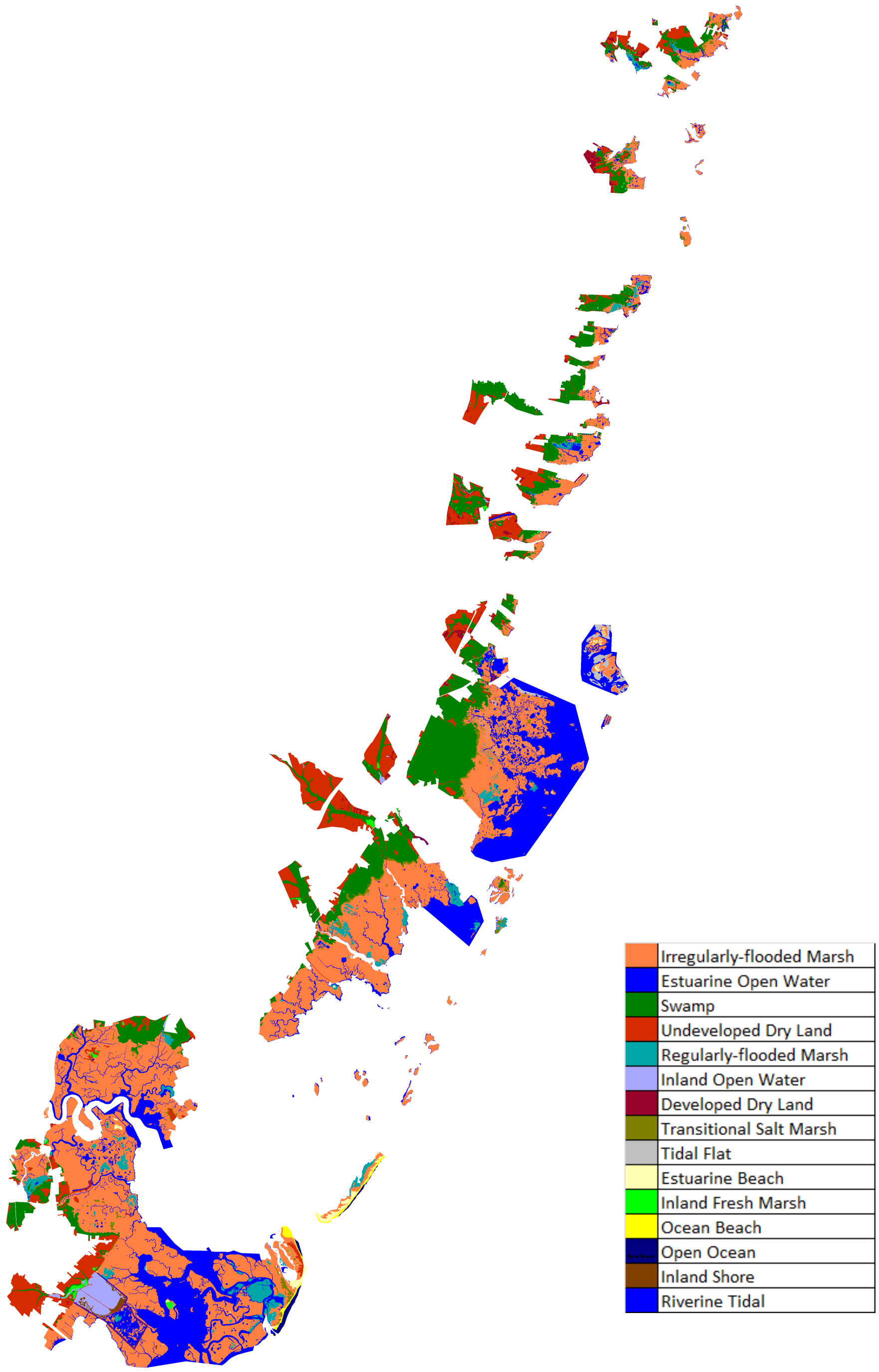


Edwin B. Forsythe NWR, 2100, Scenario A1B Maximum, 0.69 m SLR by 2100.

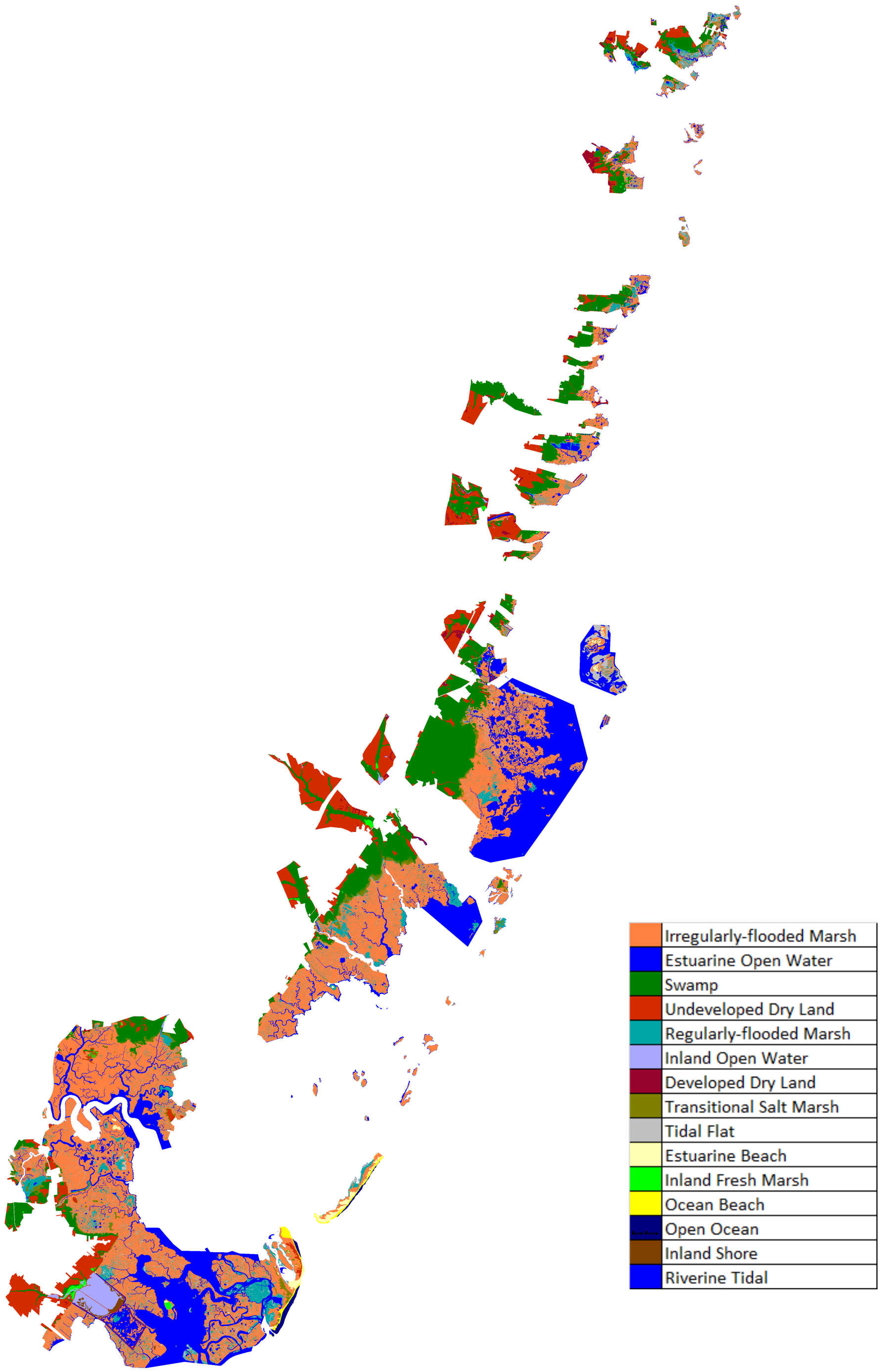
Edwin B. Forsythe NWR
1 m eustatic SLR by 2100

Results in Acres

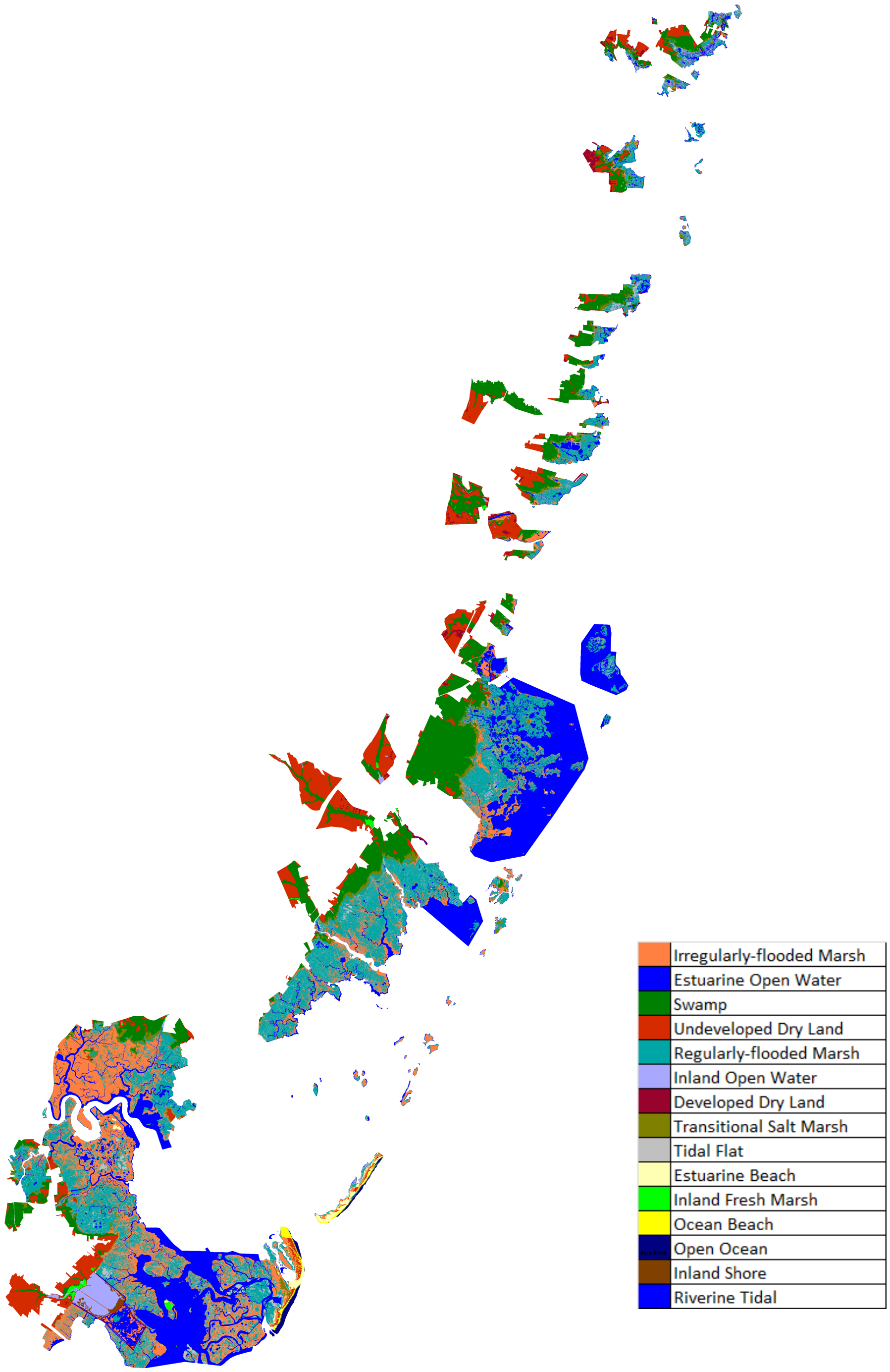
		Initial	2025	2050	2075	2100
	Irregularly-flooded Marsh	31298	27464	12617	1157	469
	Estuarine Open Water	15630	15689	16634	19013	29665
	Swamp	11805	11582	10732	9337	8016
	Undeveloped Dry Land	7532	7305	7216	7079	6907
	Regularly-flooded Marsh	2057	4499	17539	14590	3057
	Inland Open Water	838	832	829	824	797
	Developed Dry Land	746	721	702	669	632
	Transitional Salt Marsh	717	1068	1498	1834	1592
	Tidal Flat	534	1873	3115	15493	17719
	Estuarine Beach	326	325	279	326	257
	Inland Fresh Marsh	253	233	219	132	123
	Ocean Beach	221	216	210	328	339
	Open Ocean	180	332	547	1457	2682
	Inland Shore	124	124	124	22	6
	Riverine Tidal	1	1	1	1	0
	Total (incl. water)	**72263**	**72263**	**72263**	**72263**	**72263**



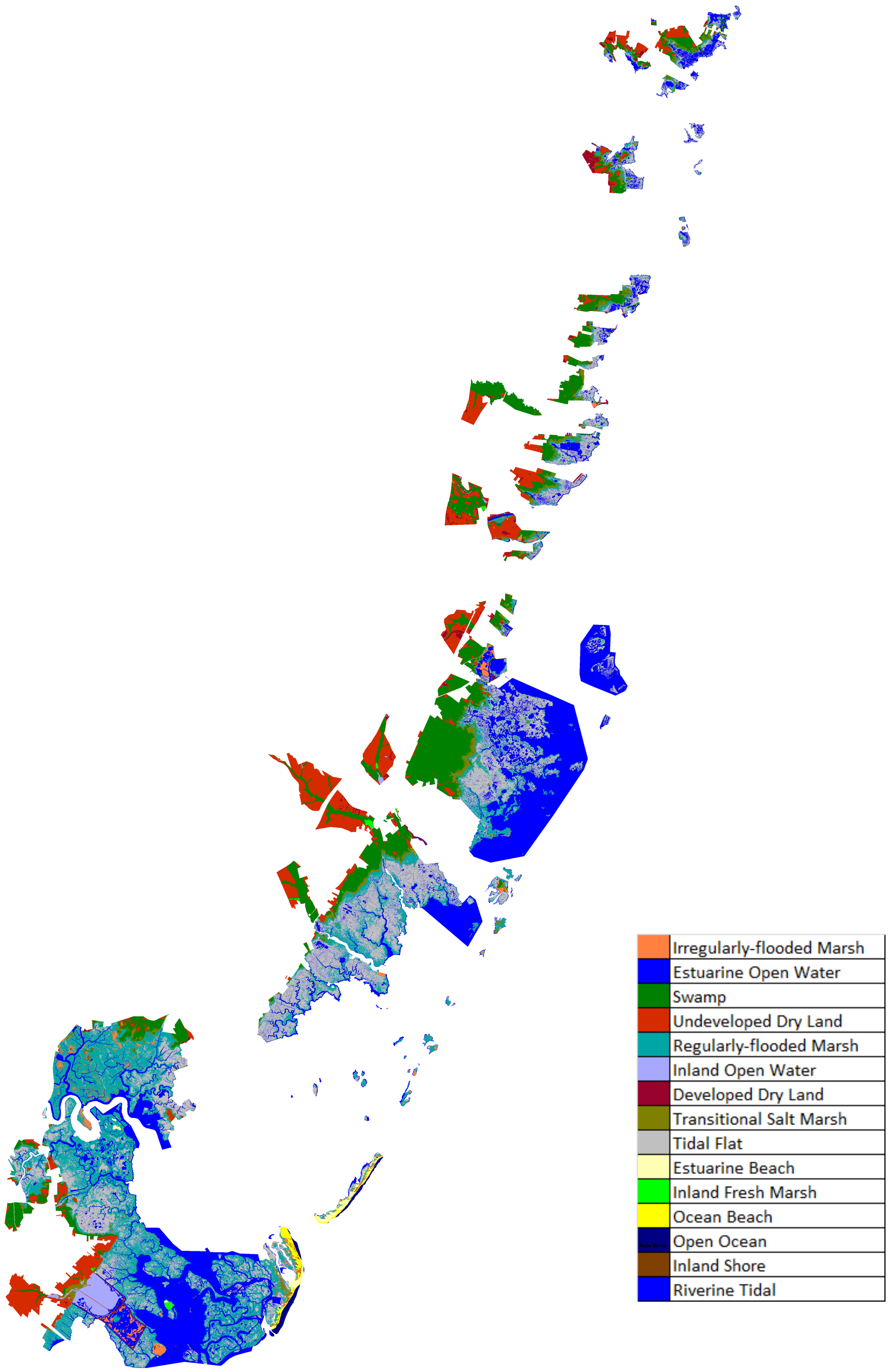
Edwin B. Forsythe NWR, Initial Condition.



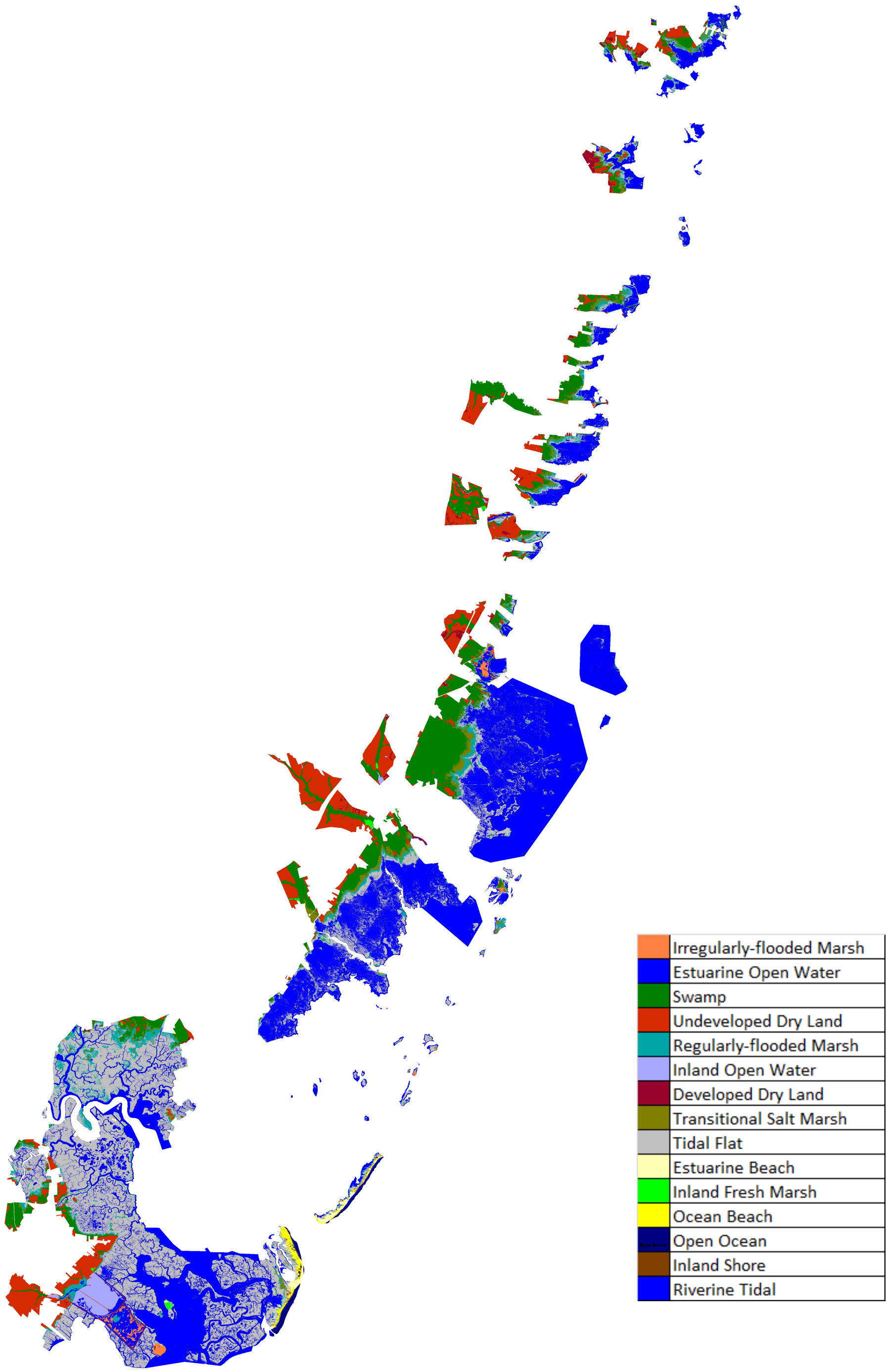
Edwin B. Forsythe NWR, 2025, 1 m SLR by 2100.



Edwin B. Forsythe NWR, 2050, 1 m SLR by 2100.



Edwin B. Forsythe NWR, 2075, 1 m SLR by 2100.

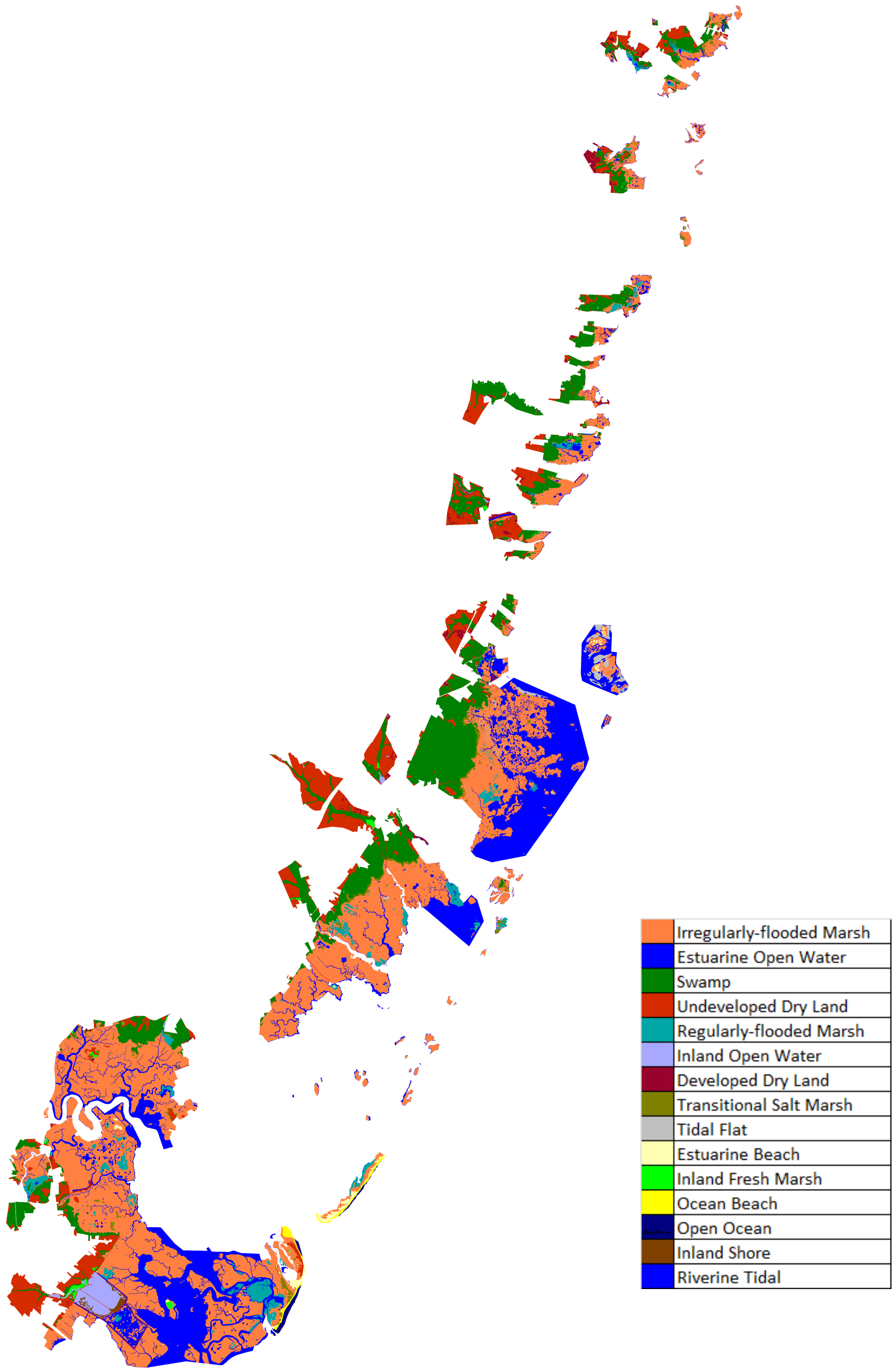


Edwin B. Forsythe NWR, 2100, 1 m SLR by 2100.

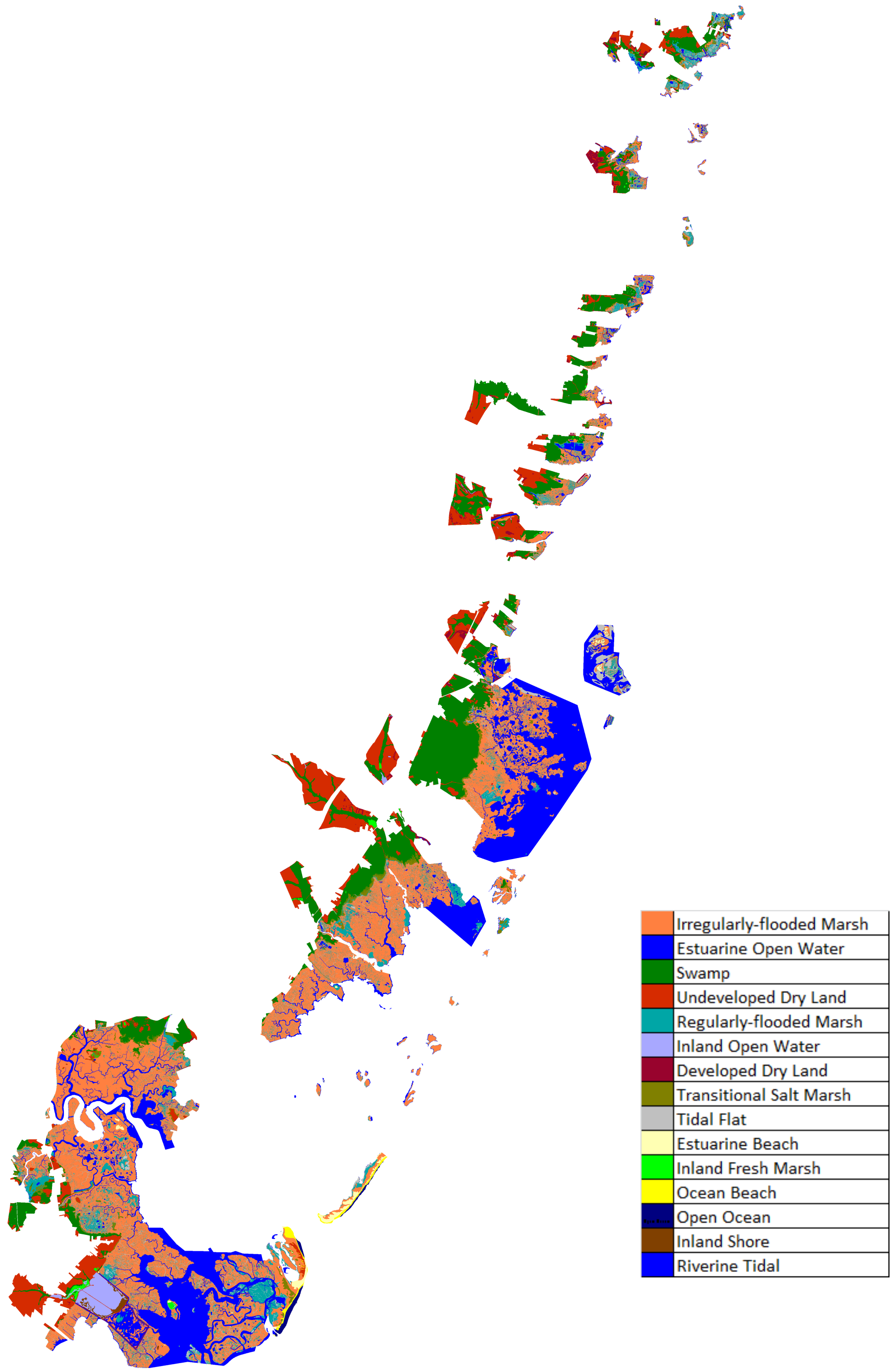
Edwin B. Forsythe NWR
1.5 m eustatic SLR by 2100

Results in Acres

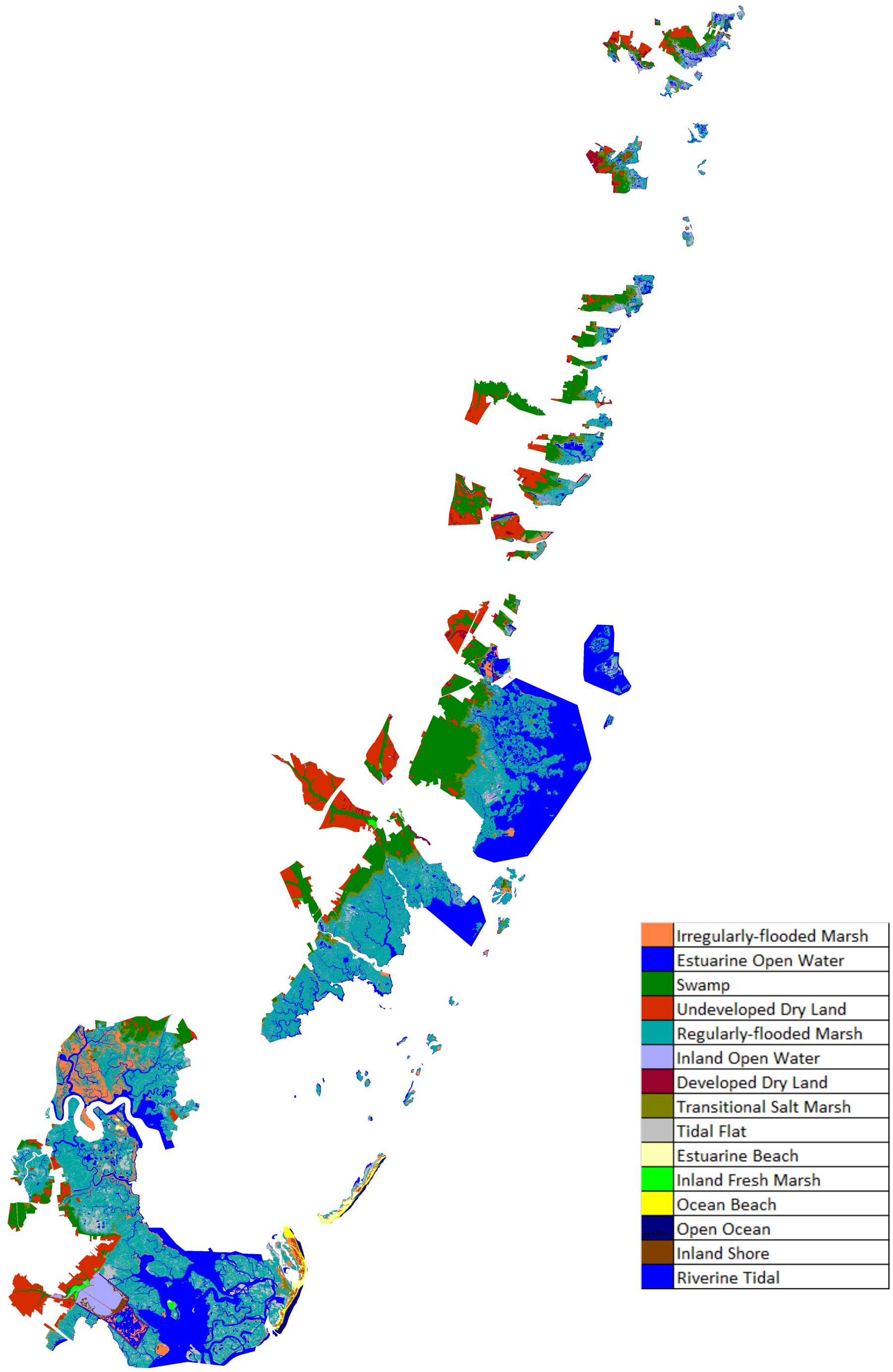
		Initial	2025	2050	2075	2100
	Irregularly-flooded Marsh	31298	26075	3451	474	357
	Estuarine Open Water	15630	15717	17153	21706	45358
	Swamp	11805	11478	10091	8180	6657
	Undeveloped Dry Land	7532	7292	7159	6943	6665
	Regularly-flooded Marsh	2057	5558	24441	4837	2440
	Inland Open Water	838	831	826	824	795
	Developed Dry Land	746	718	687	638	577
	Transitional Salt Marsh	717	1142	1848	2323	1829
	Tidal Flat	534	2211	5145	23557	4590
	Estuarine Beach	326	320	270	325	180
	Inland Fresh Marsh	253	229	207	122	113
	Ocean Beach	221	219	221	292	280
	Open Ocean	180	348	647	2035	2417
	Inland Shore	124	124	116	6	5
	Riverine Tidal	1	1	1	0	0
	Total (incl. water)	**72263**	**72263**	**72263**	**72263**	**72263**



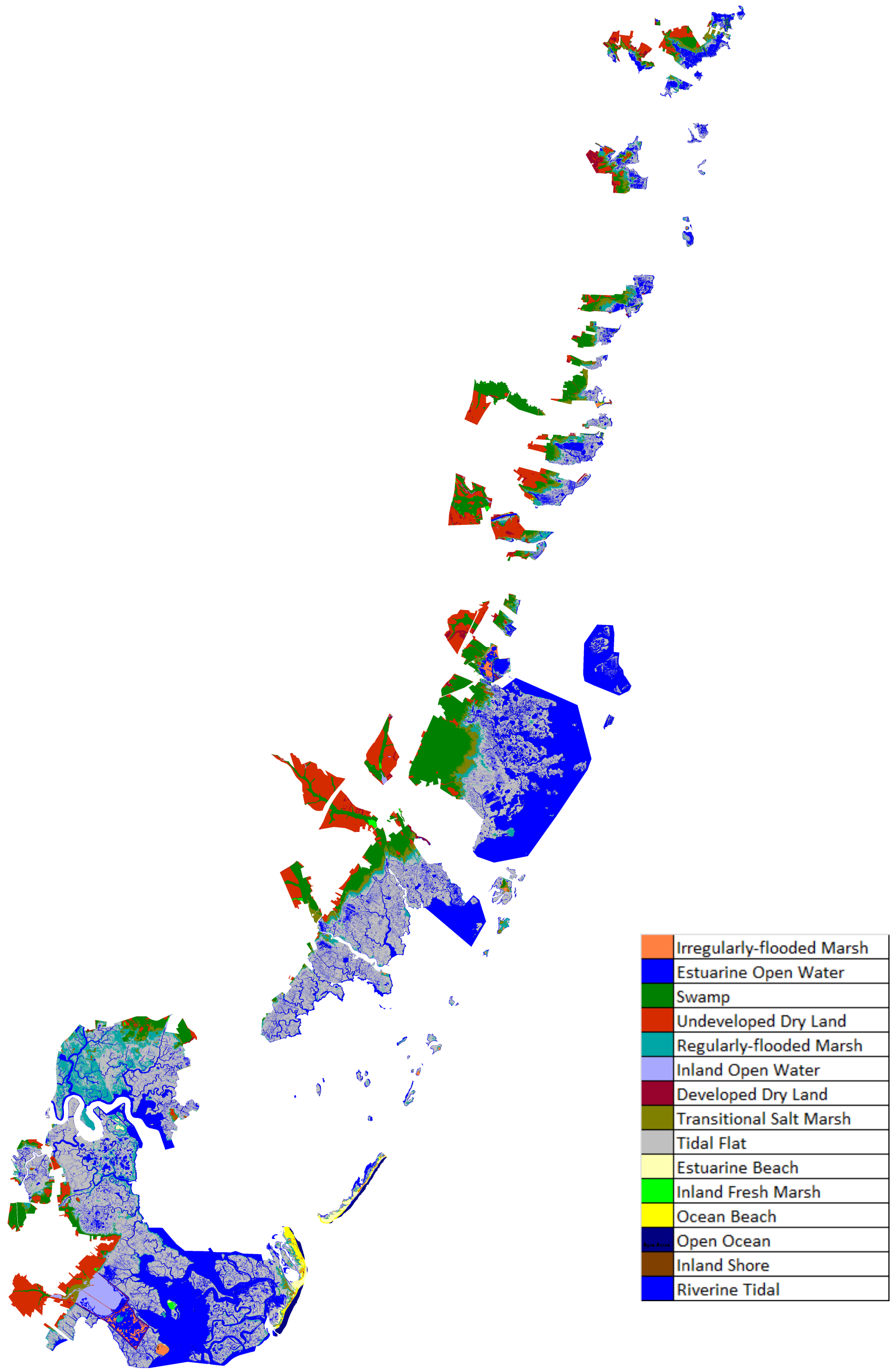
Edwin B. Forsythe NWR, Initial Condition.



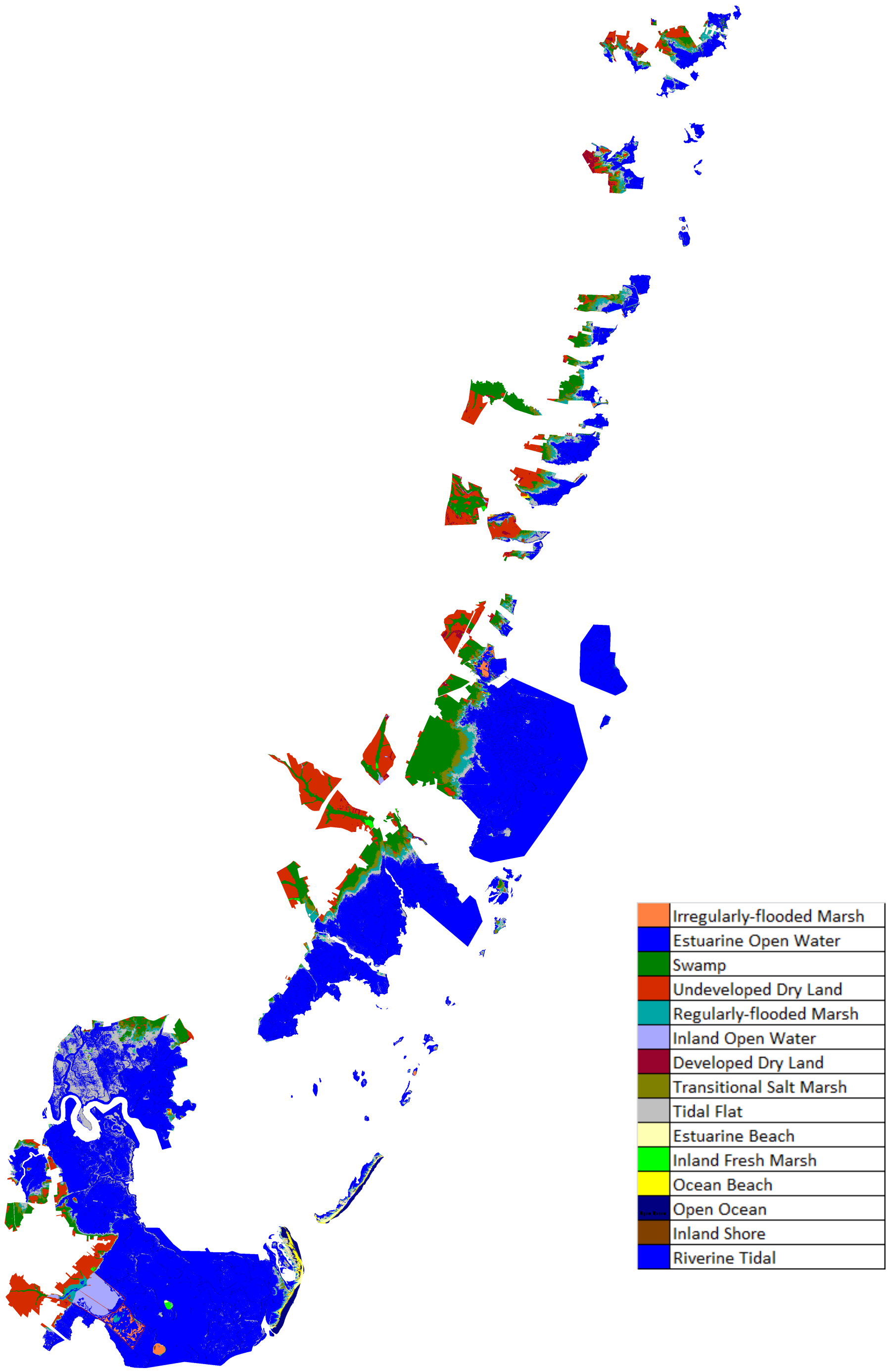
Edwin B. Forsythe NWR, 2025, 1.5 m SLR by 2100.



Edwin B. Forsythe NWR, 2050, 1.5 m SLR by 2100.



Edwin B. Forsythe NWR, 2075, 1.5 m SLR by 2100.

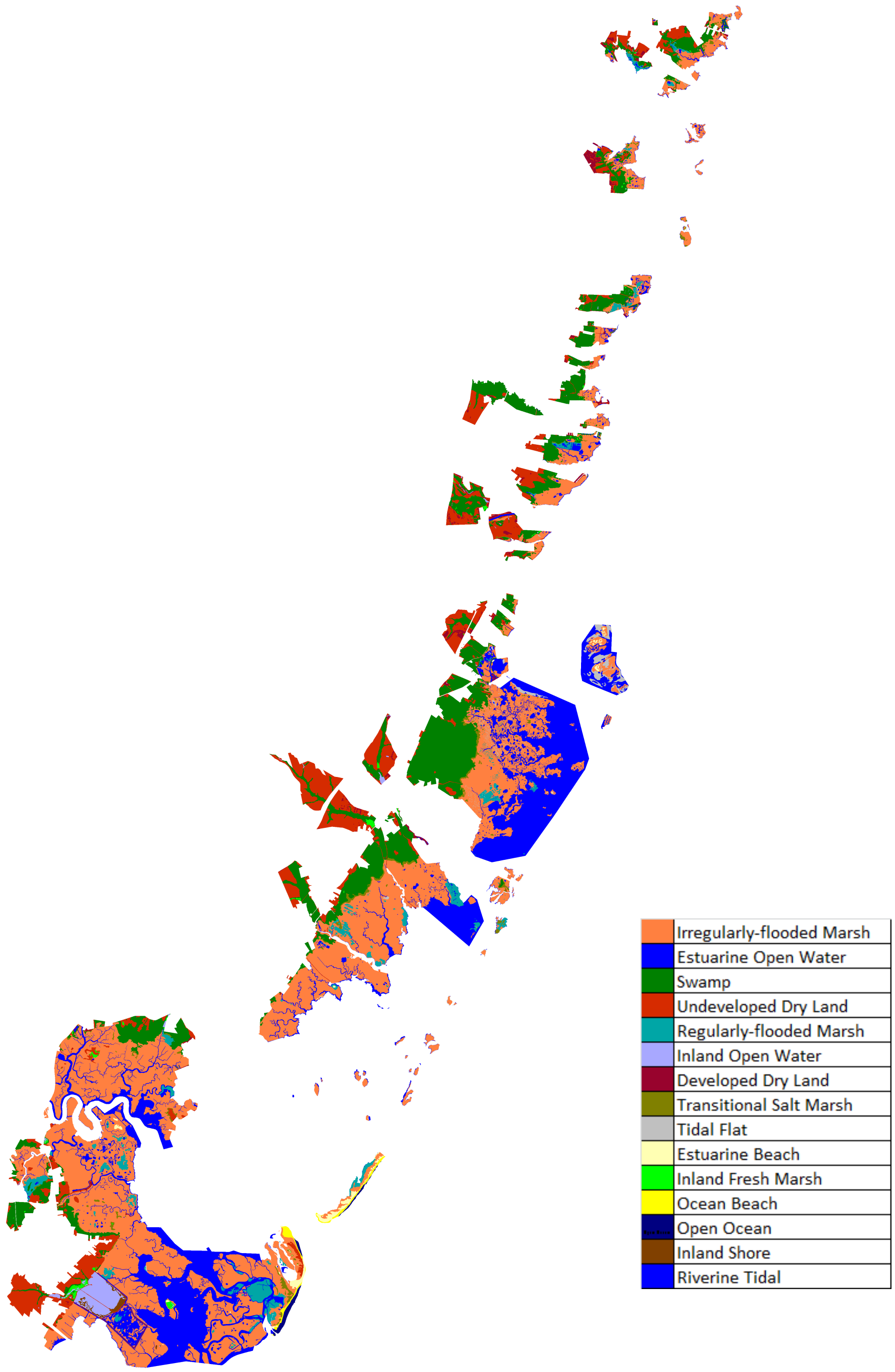


Edwin B. Forsythe NWR, 2100, 1.5 m SLR by 2100.

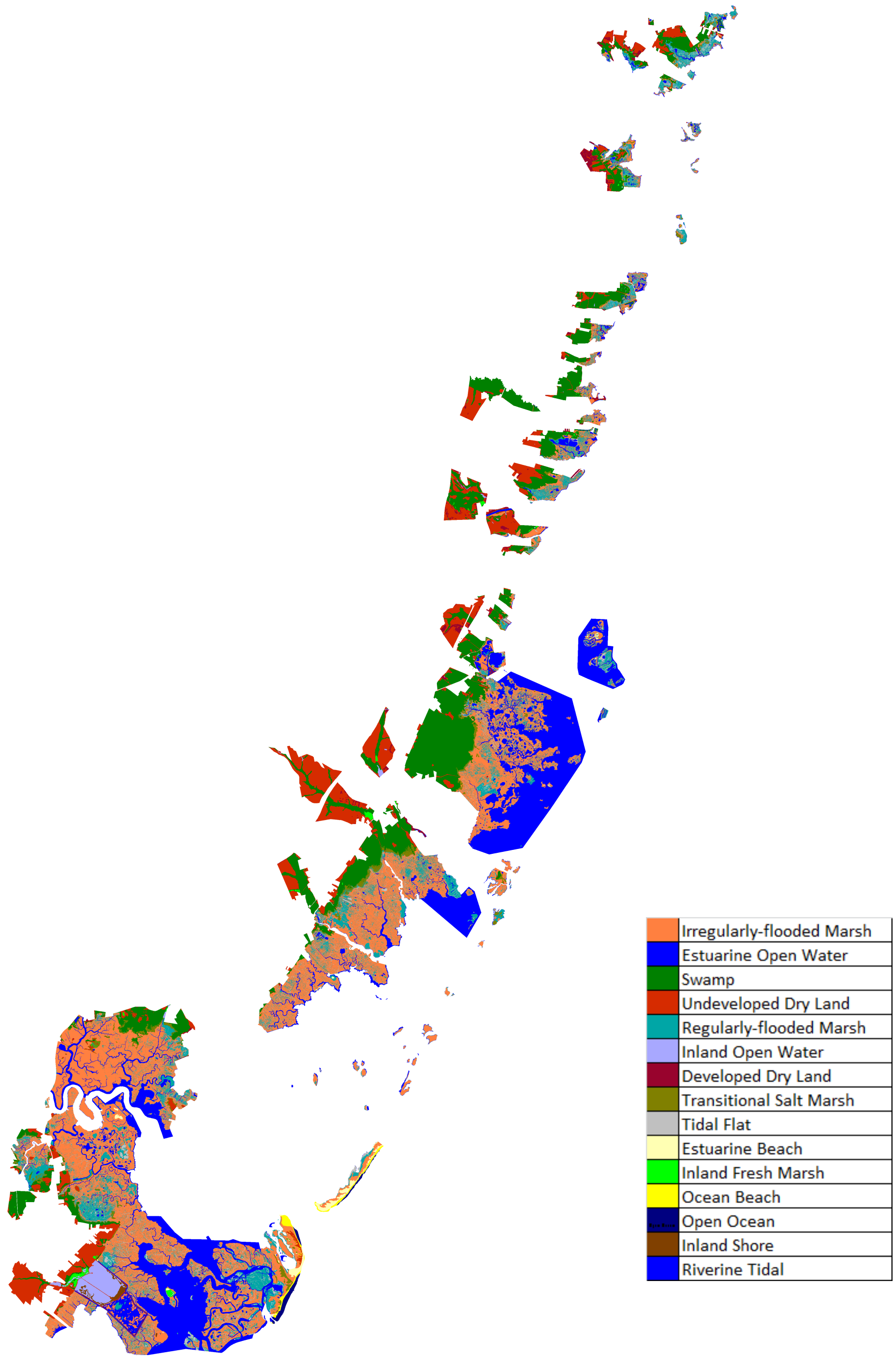
Edwin B. Forsythe NWR
2 m eustatic SLR by 2100

Results in Acres

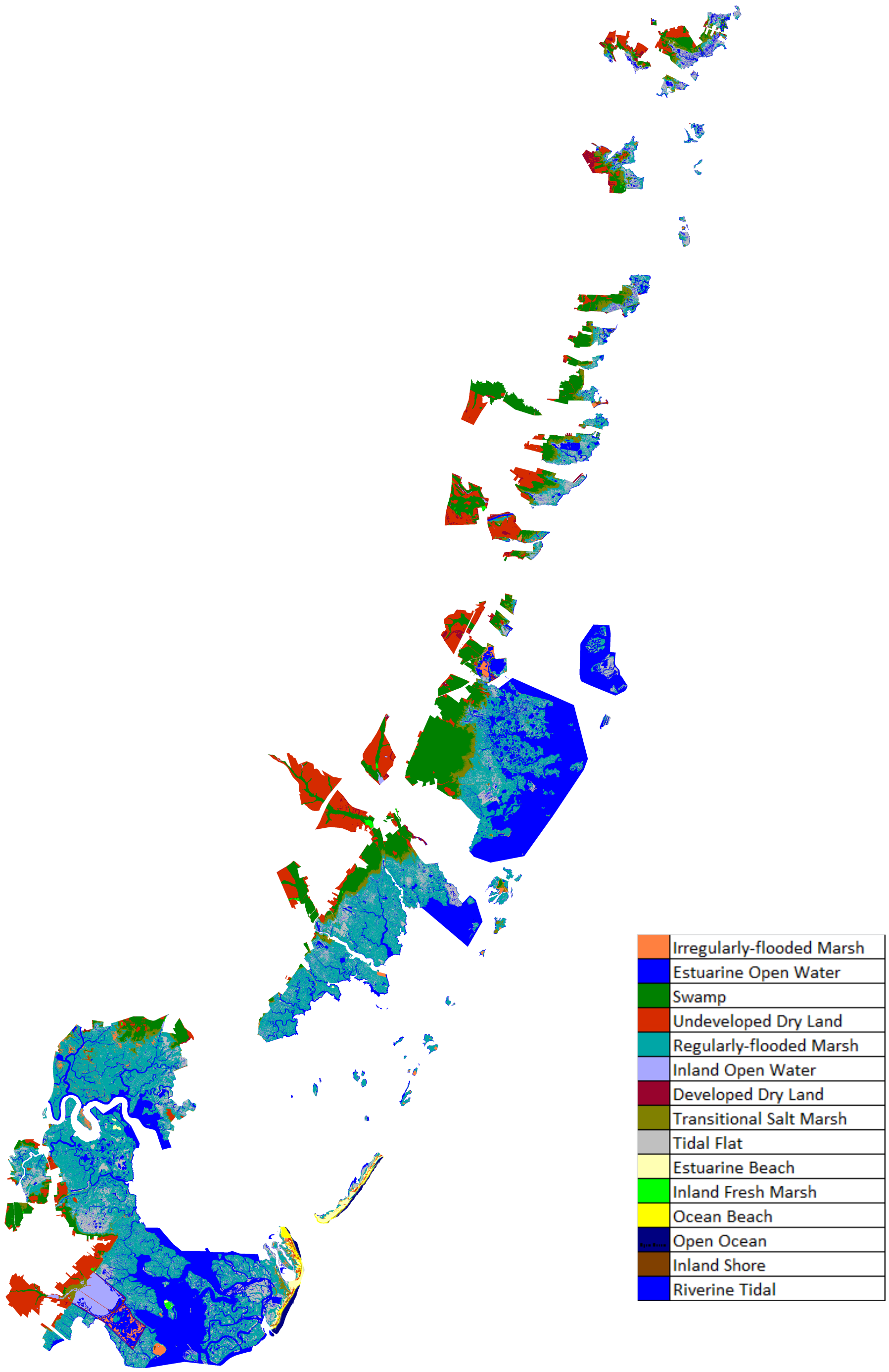
		Initial	2025	2050	2075	2100
	Irregularly-flooded Marsh	31298	23854	1040	379	296
	Estuarine Open Water	15630	16093	18172	25304	48135
	Swamp	11805	11371	9421	7213	5464
	Undeveloped Dry Land	7532	7279	7080	6792	6356
	Regularly-flooded Marsh	2057	7507	24266	3005	2631
	Inland Open Water	838	831	826	796	795
	Developed Dry Land	746	716	672	603	520
	Transitional Salt Marsh	717	1198	2453	2574	2168
	Tidal Flat	534	2197	6971	22646	2888
	Estuarine Beach	326	298	265	255	123
	Inland Fresh Marsh	253	226	130	118	100
	Ocean Beach	221	222	229	250	237
	Open Ocean	180	345	715	2323	2546
	Inland Shore	124	124	23	5	4
	Riverine Tidal	1	1	1	0	0
	Total (incl. water)	**72263**	**72263**	**72263**	**72263**	**72263**



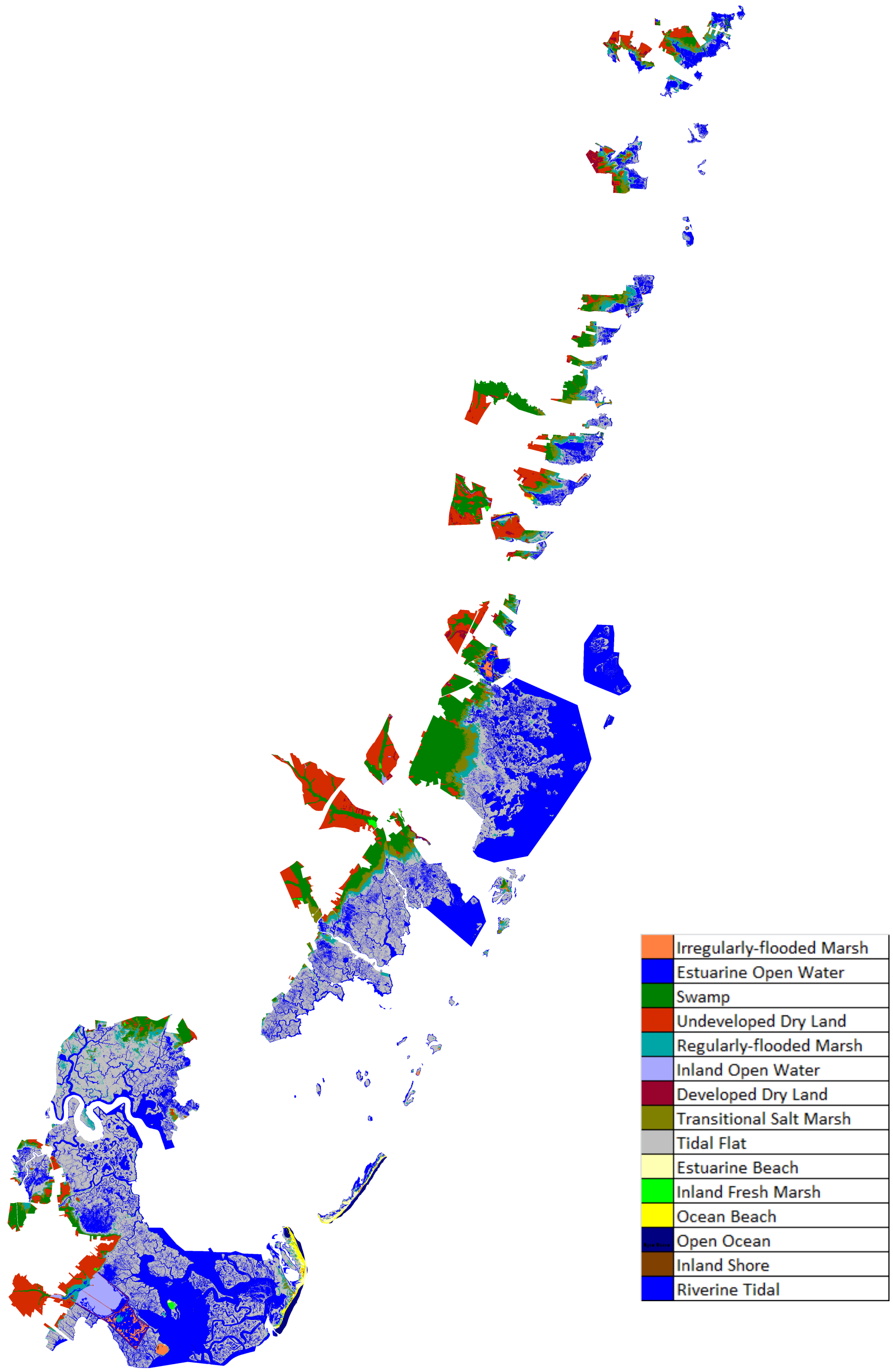
Edwin B. Forsythe NWR, Initial Condition.



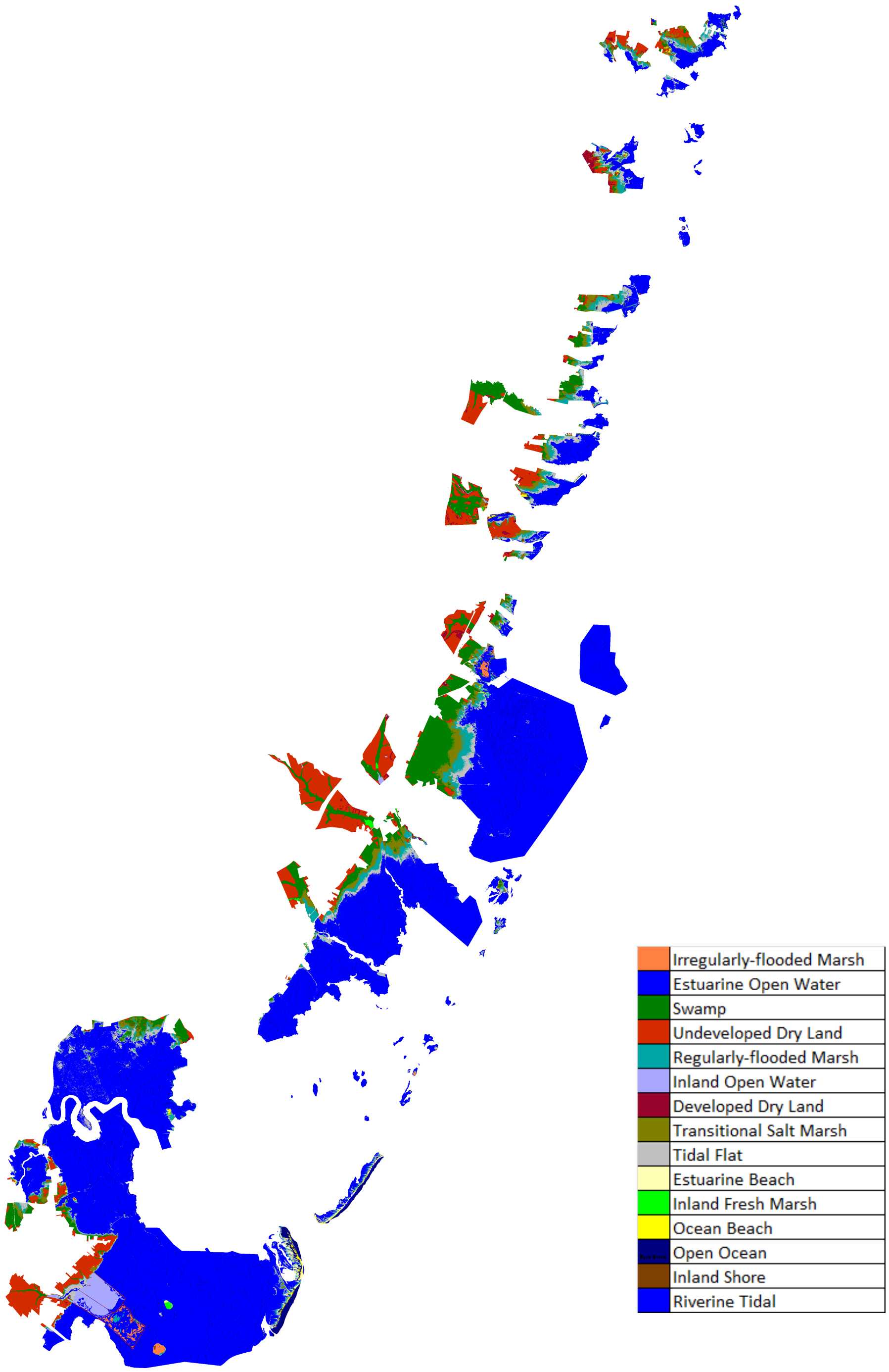
Edwin B. Forsythe NWR, 2025, 2 m SLR by 2100.



Edwin B. Forsythe NWR, 2050, 2 m SLR by 2100.



Edwin B. Forsythe NWR, 2075, 2 m SLR by 2100.



Edwin B. Forsythe NWR, 2100, 2 m SLR by 2100.

Discussion

SLAMM simulations indicate that future SLR, coupled with low elevations, may cause severe land loss in Edwin B. Forsythe NWR. For SLR under 0.69 m by 2100, significant losses of irregularly-flooded marsh is balanced by gains of regularly-flooded marsh. However, for higher rates of SLR, marshes do not appear to be capable of keeping pace with the rate of sea-level increase and are therefore predicted to be converted to open water or tidal flat. Swamp appears to be slightly more resilient to SLR. However, this marsh type is also predicted to lose significant coverage within the refuge, up to a 54% loss for the 2 m SLR by 2100 scenario.

Compared to a previous SLAMM analysis of the refuge, this new study employed LiDAR-derived elevation data for the entire study area. As a result, this more-detailed description of wetland elevations shows that there are more areas lying low in the tidal frame. Therefore, wetlands overall are predicted to be more vulnerable to inundation than previously estimated.

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

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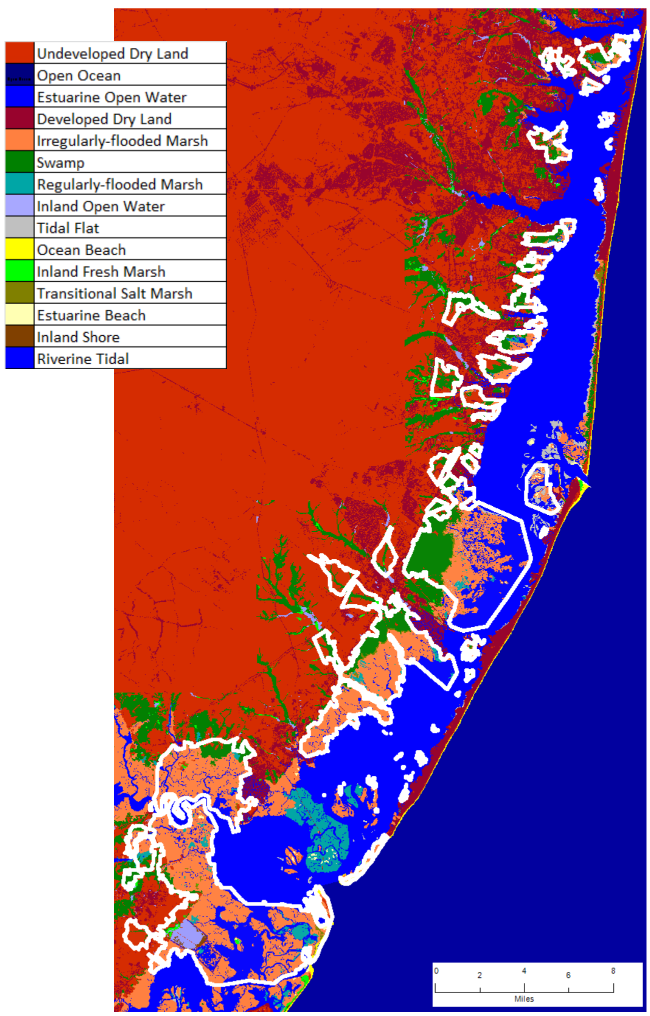
Appendix A: Contextual Results

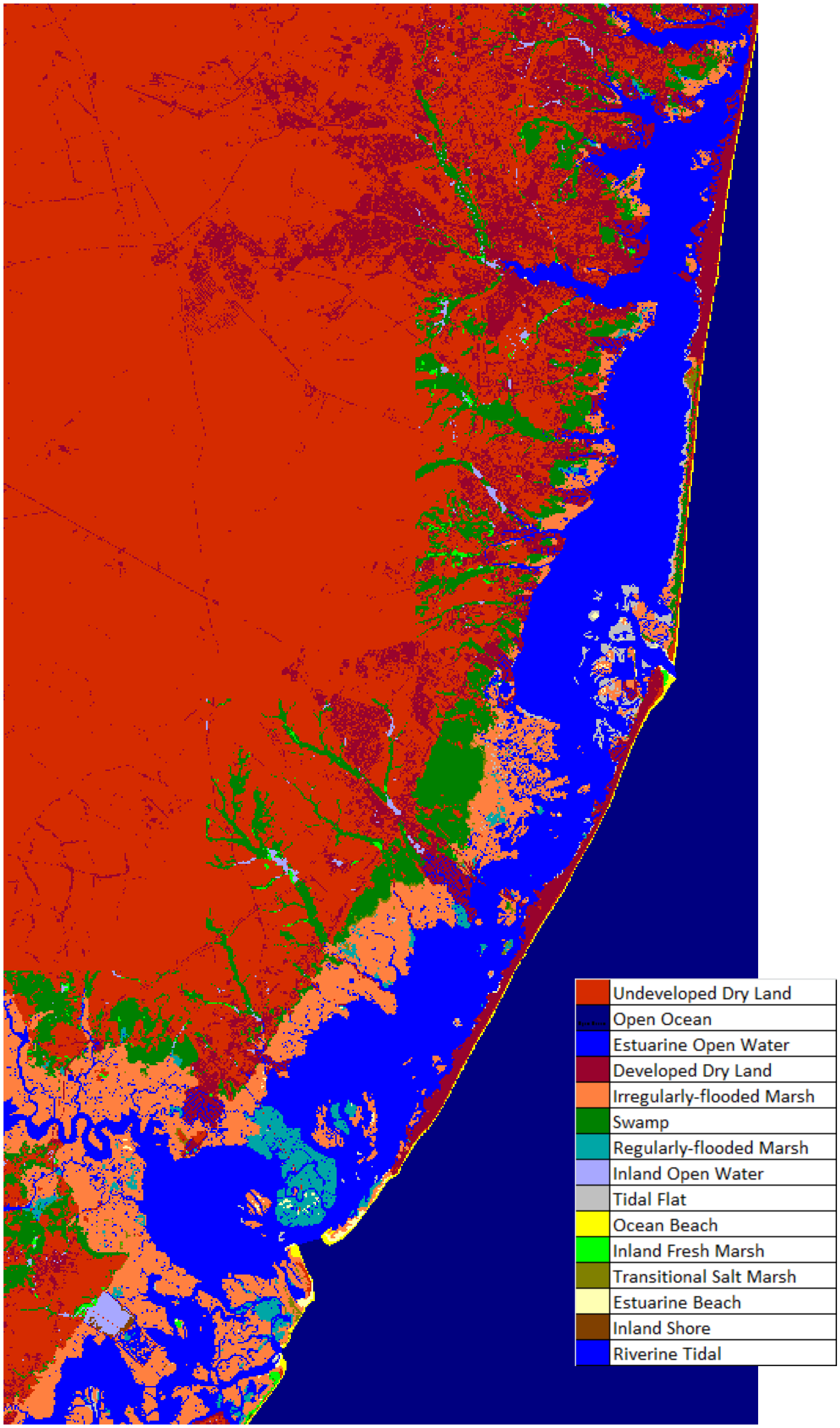
The SLAMM model takes into account the context of the surrounding lands or open water when calculating effects. For example, erosion rates are calculated based on the maximum fetch (wave action) which is estimated by assessing contiguous open water to a given marsh cell. Another example is that inundated dry lands will convert to marshes or ocean beach depending on their proximity to open ocean (Clough et al. 2010).

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:

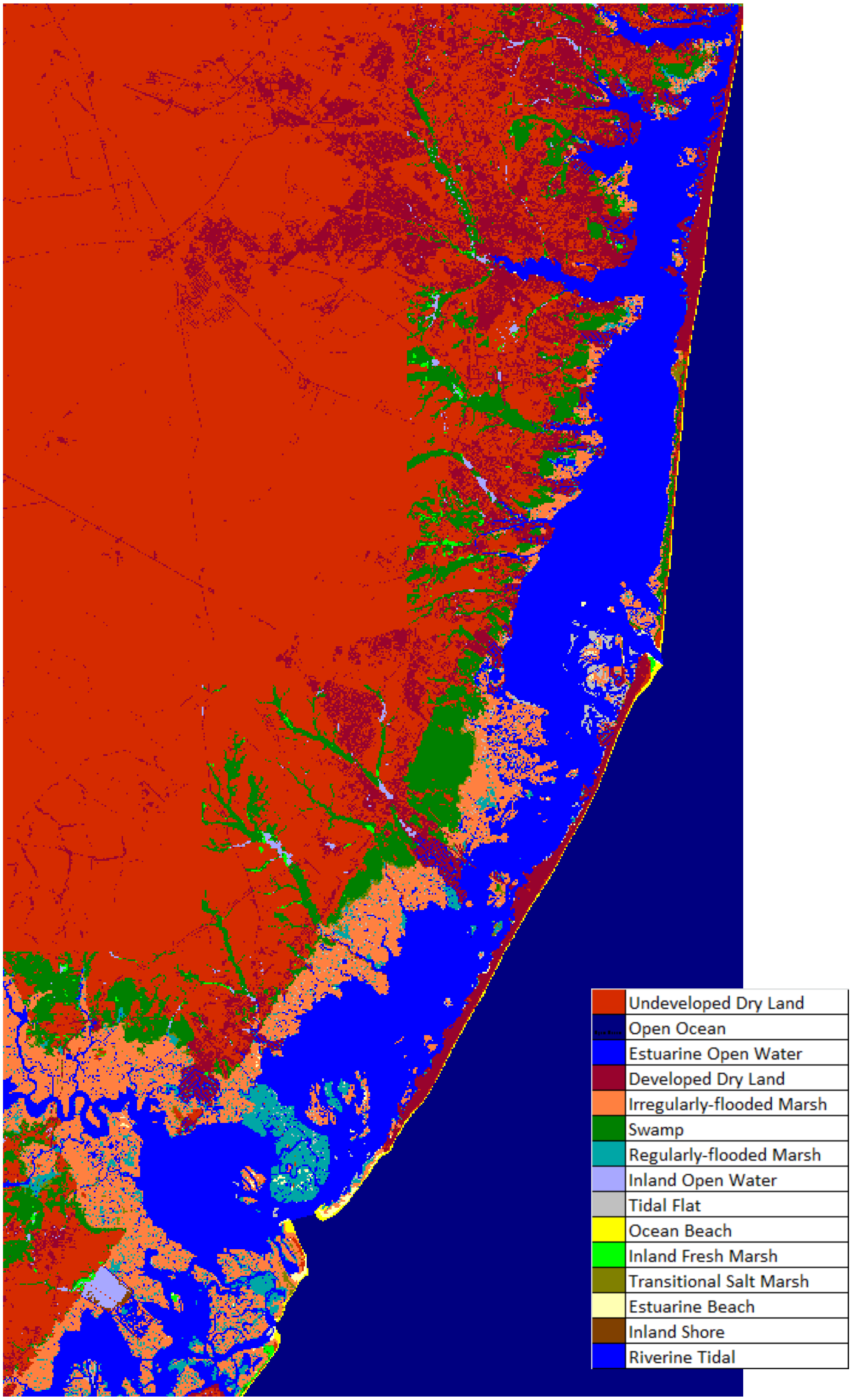
- Results were closely examined within USFWS refuges but not as closely examined for the larger region.
- Site-specific parameters for the model were derived for USFWS refuges whenever possible and may not be regionally applicable.
- Especially in areas where dikes are present, an effort was made to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



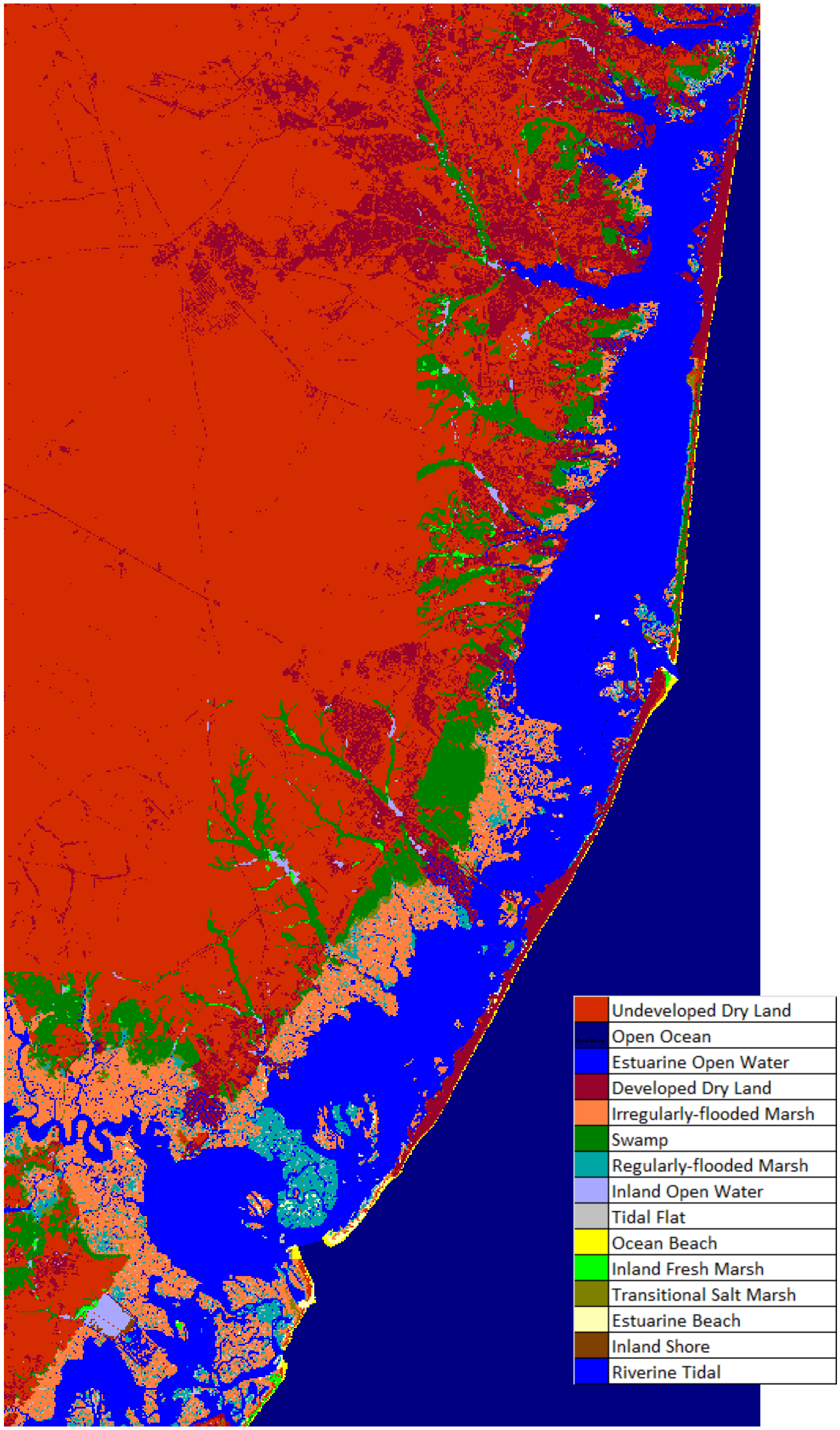
Edwin B. Forsythe National Wildlife Refuge (outlined in white) within simulation context.



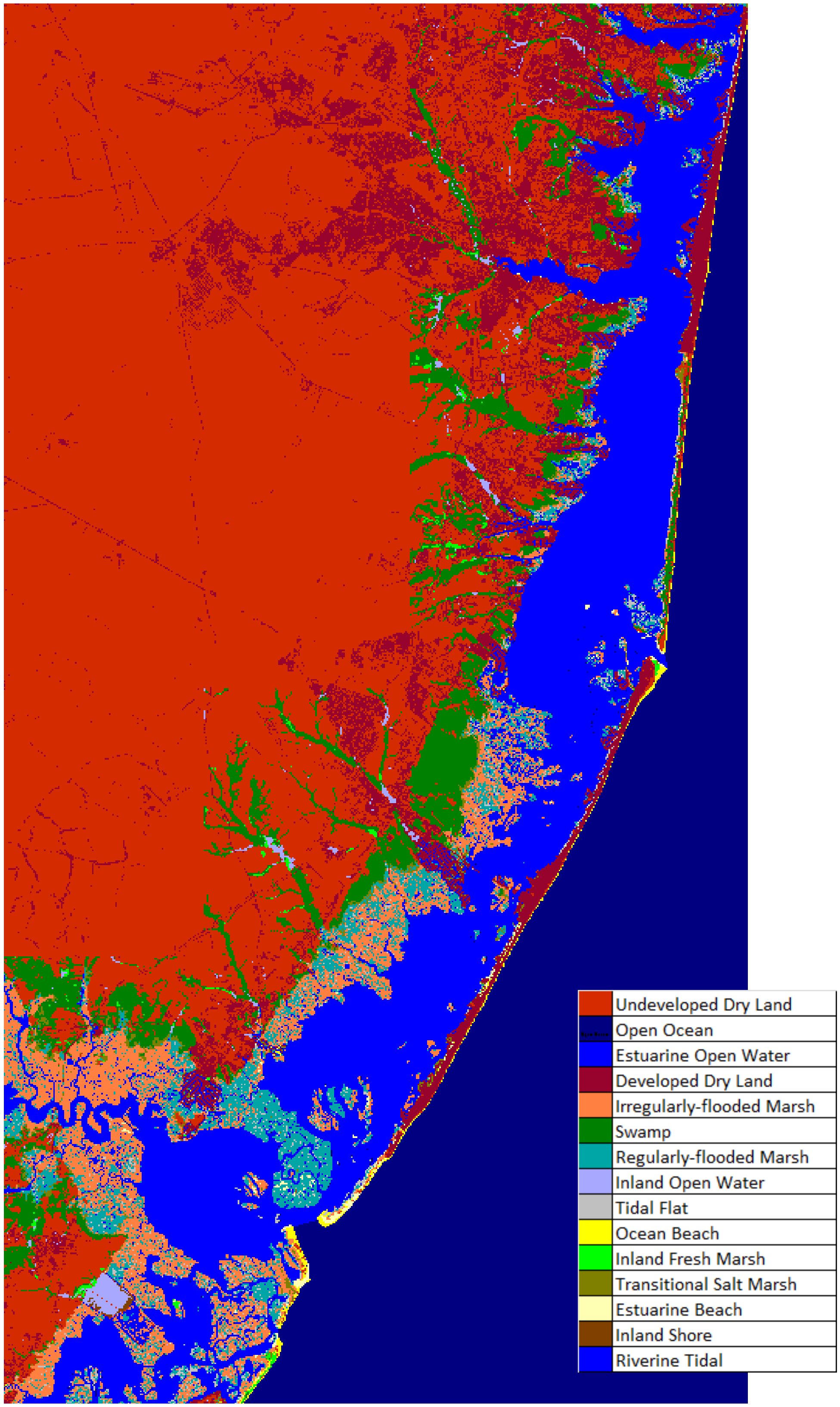
Edwin B. Forsythe NWR, Initial Condition.



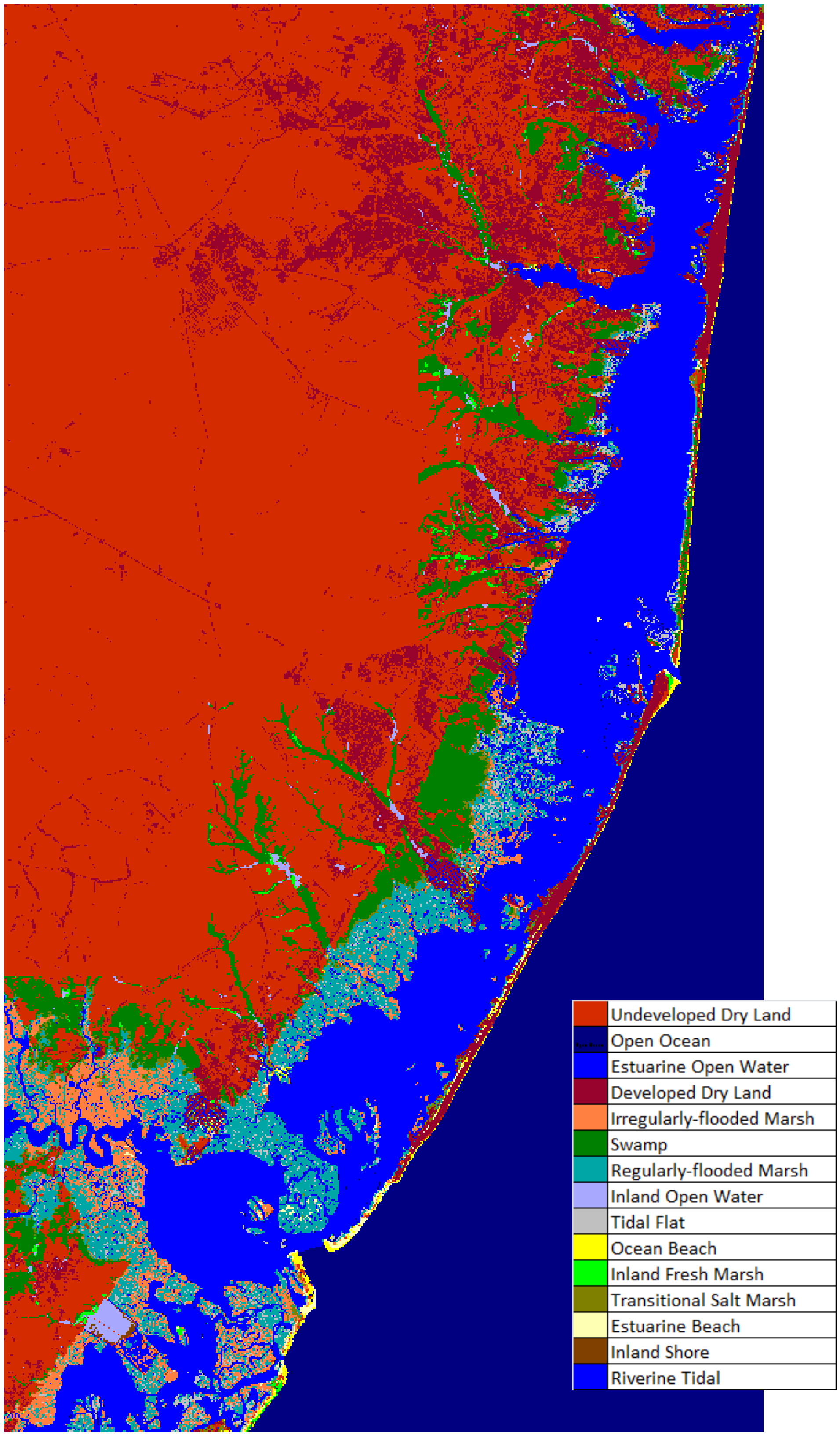
Edwin B. Forsythe NWR, 2025, Scenario A1B Mean, 0.39 m SLR by 2100.



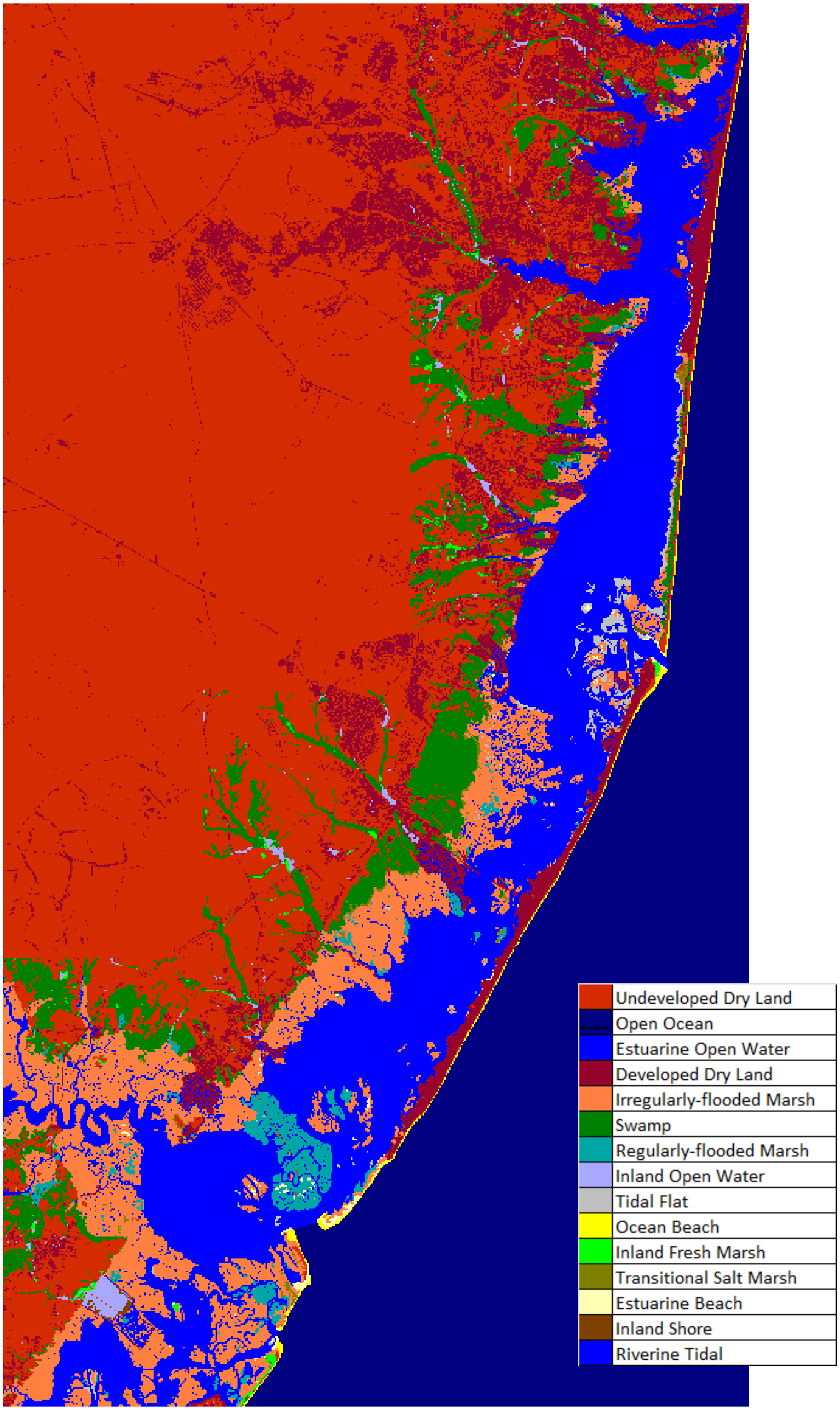
Edwin B. Forsythe NWR, 2050, Scenario A1B Mean, 0.39 m SLR by 2100.



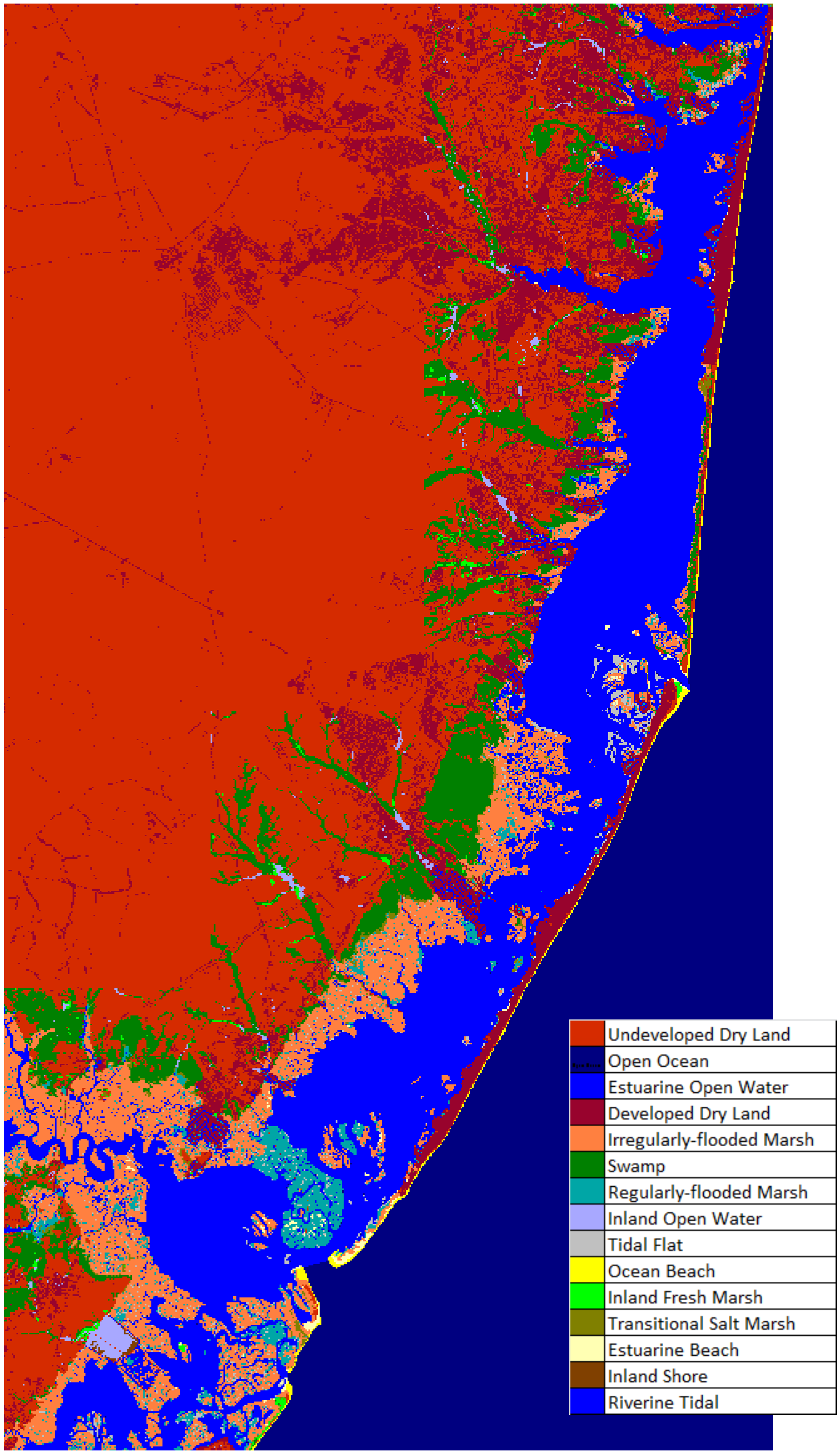
Edwin B. Forsythe NWR, 2075, Scenario A1B Mean, 0.39 m SLR by 2100.



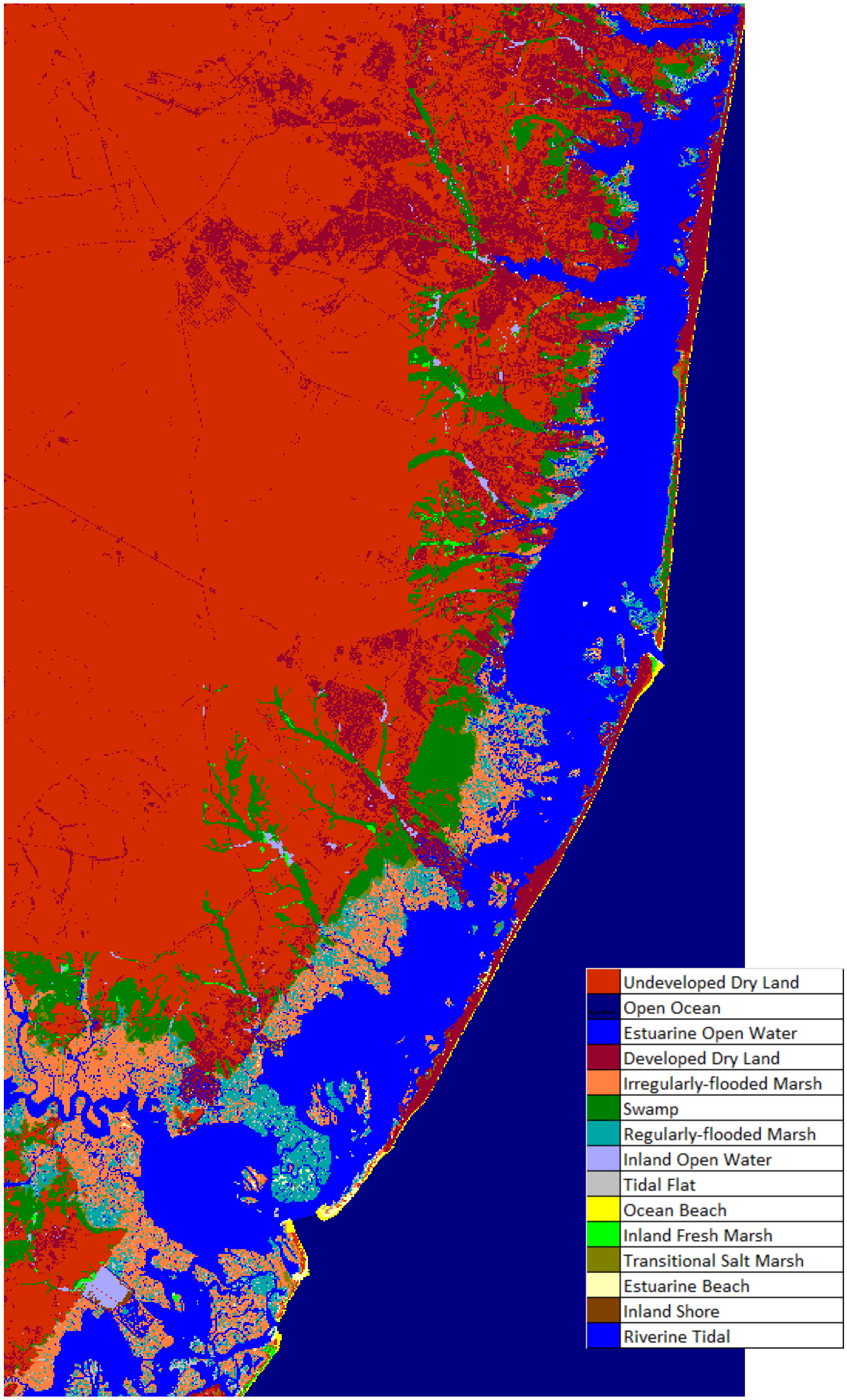
Edwin B. Forsythe NWR, 2100, Scenario A1B Mean, 0.39 m SLR by 2100.



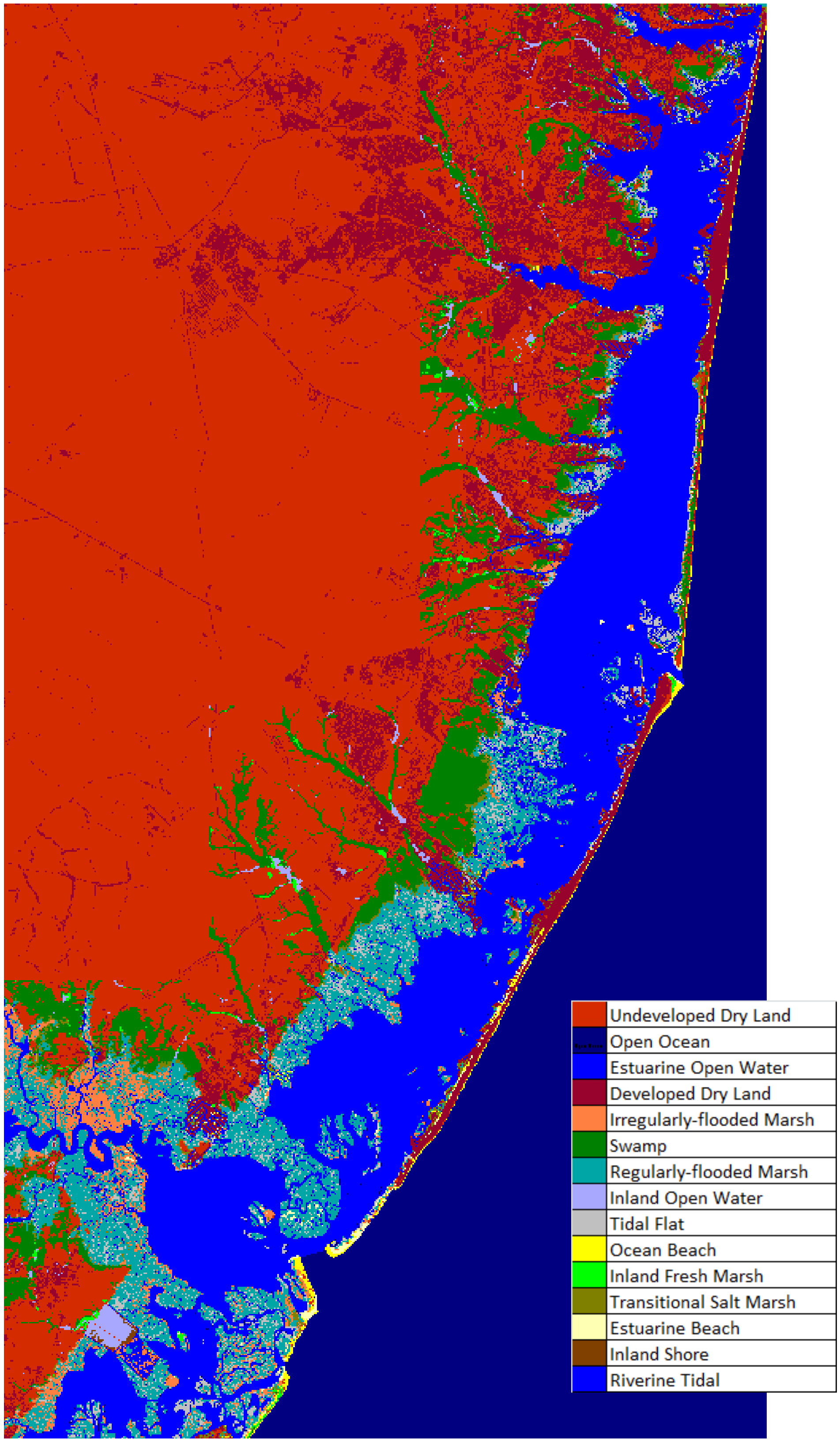
Edwin B. Forsythe NWR, Initial Condition.



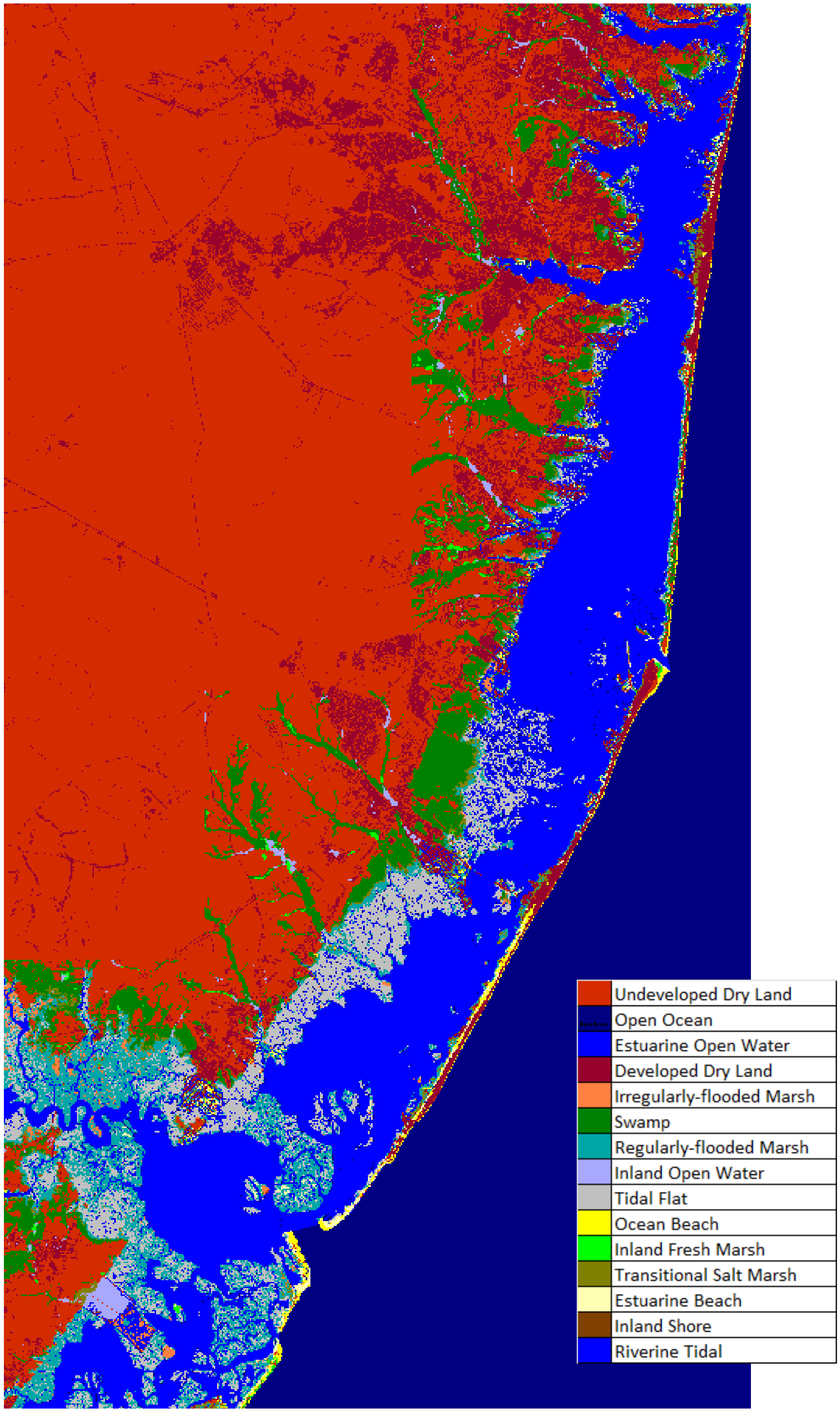
Edwin B. Forsythe NWR, 2025, Scenario A1B Maximum, 0.69 m SLR by 2100.



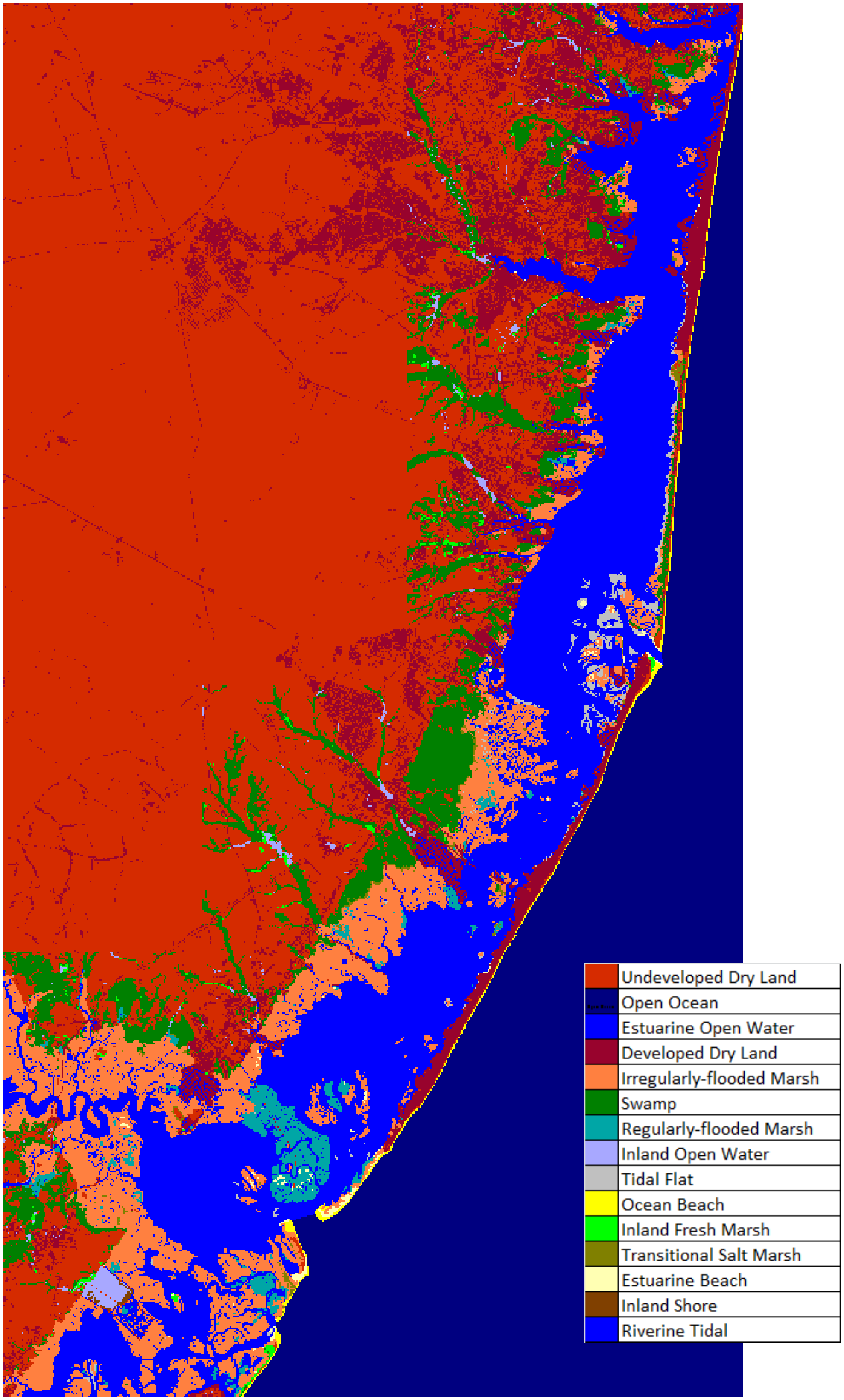
Edwin B. Forsythe NWR, 2050, Scenario A1B Maximum, 0.69 m SLR by 2100.



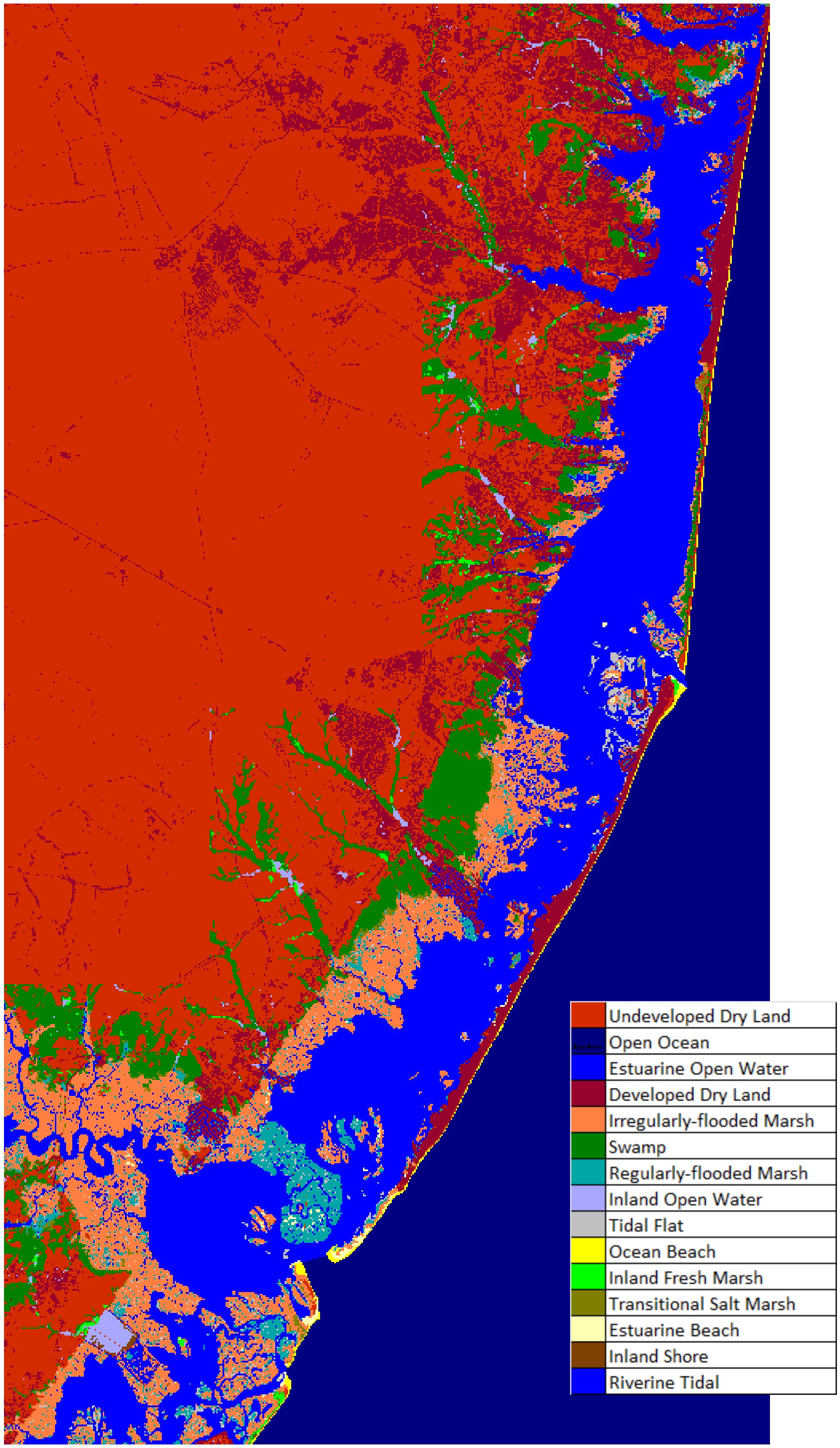
Edwin B. Forsythe NWR, 2075, Scenario A1B Maximum, 0.69 m SLR by 2100.



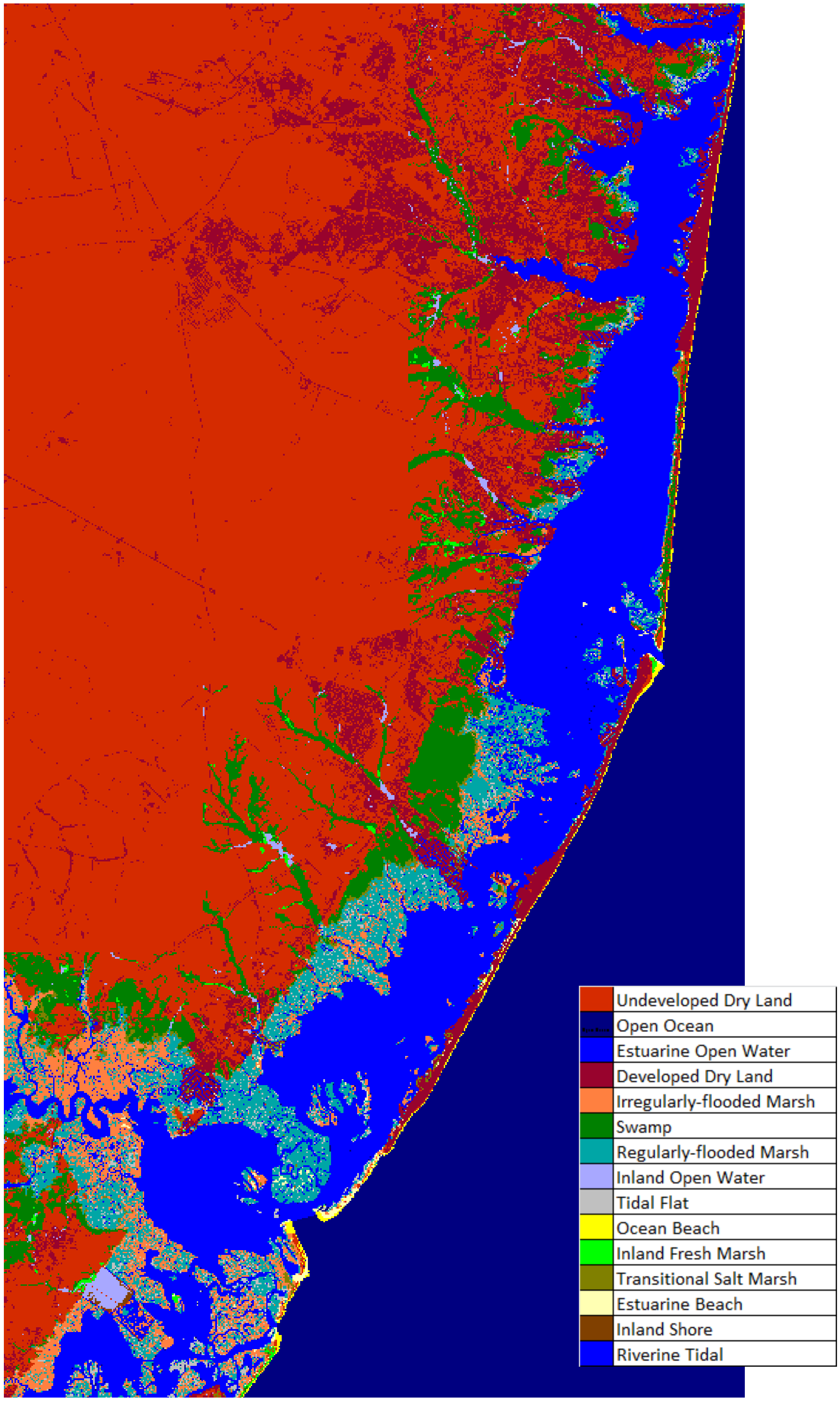
Edwin B. Forsythe NWR, 2100, Scenario A1B Maximum, 0.69 m SLR by 2100.



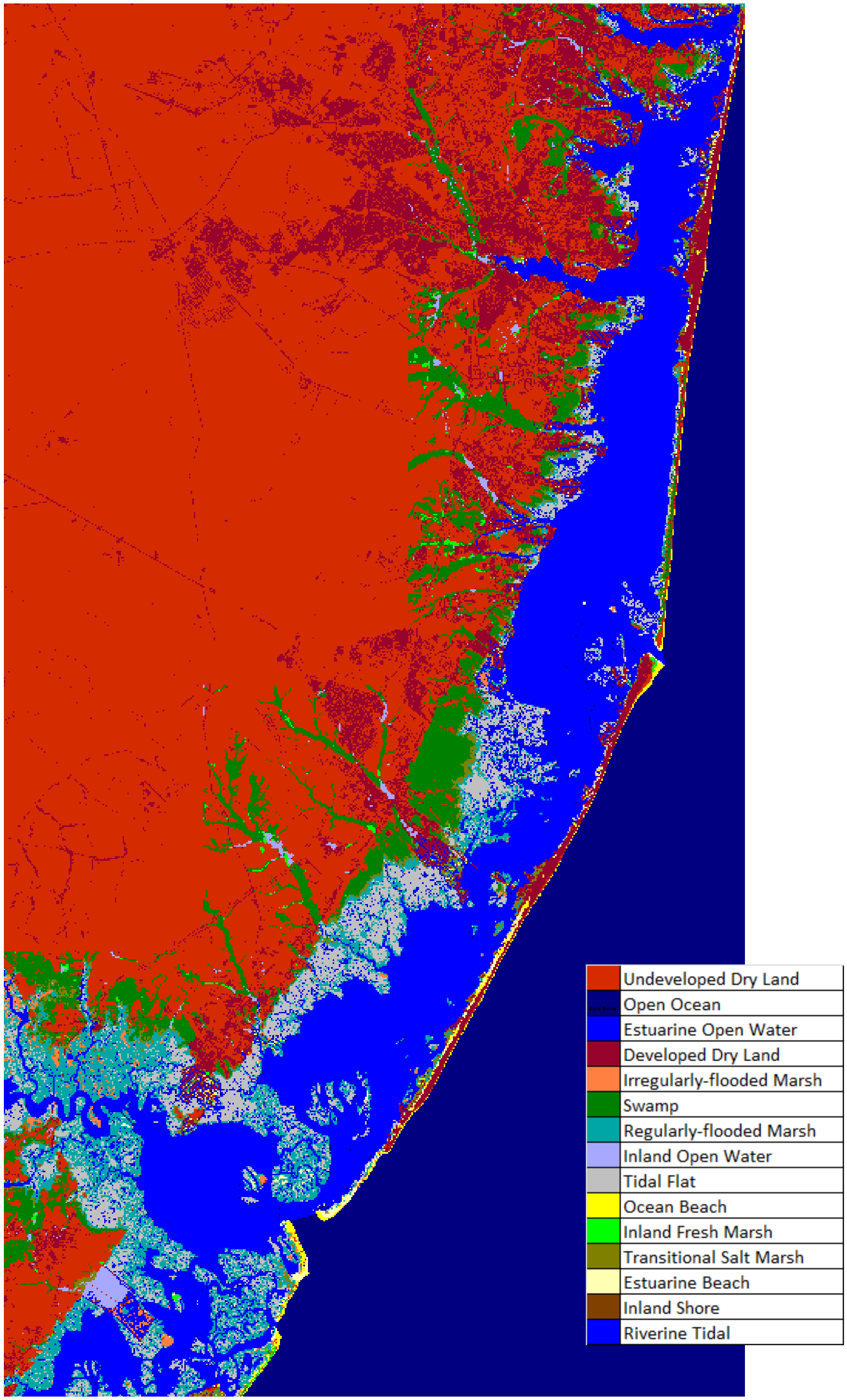
Edwin B. Forsythe NWR, Initial Condition.



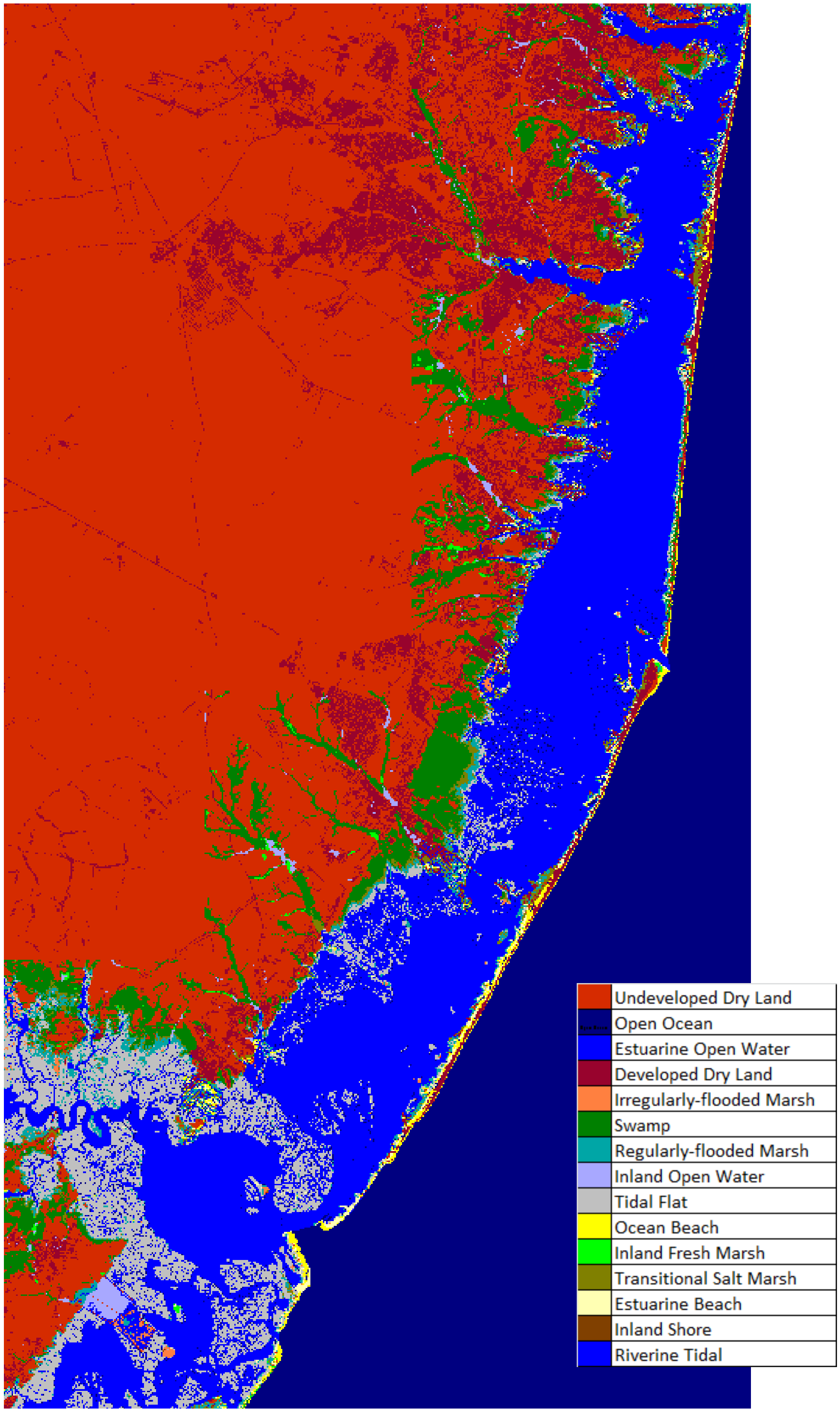
Edwin B. Forsythe NWR, 2025, 1 m SLR by 2100.



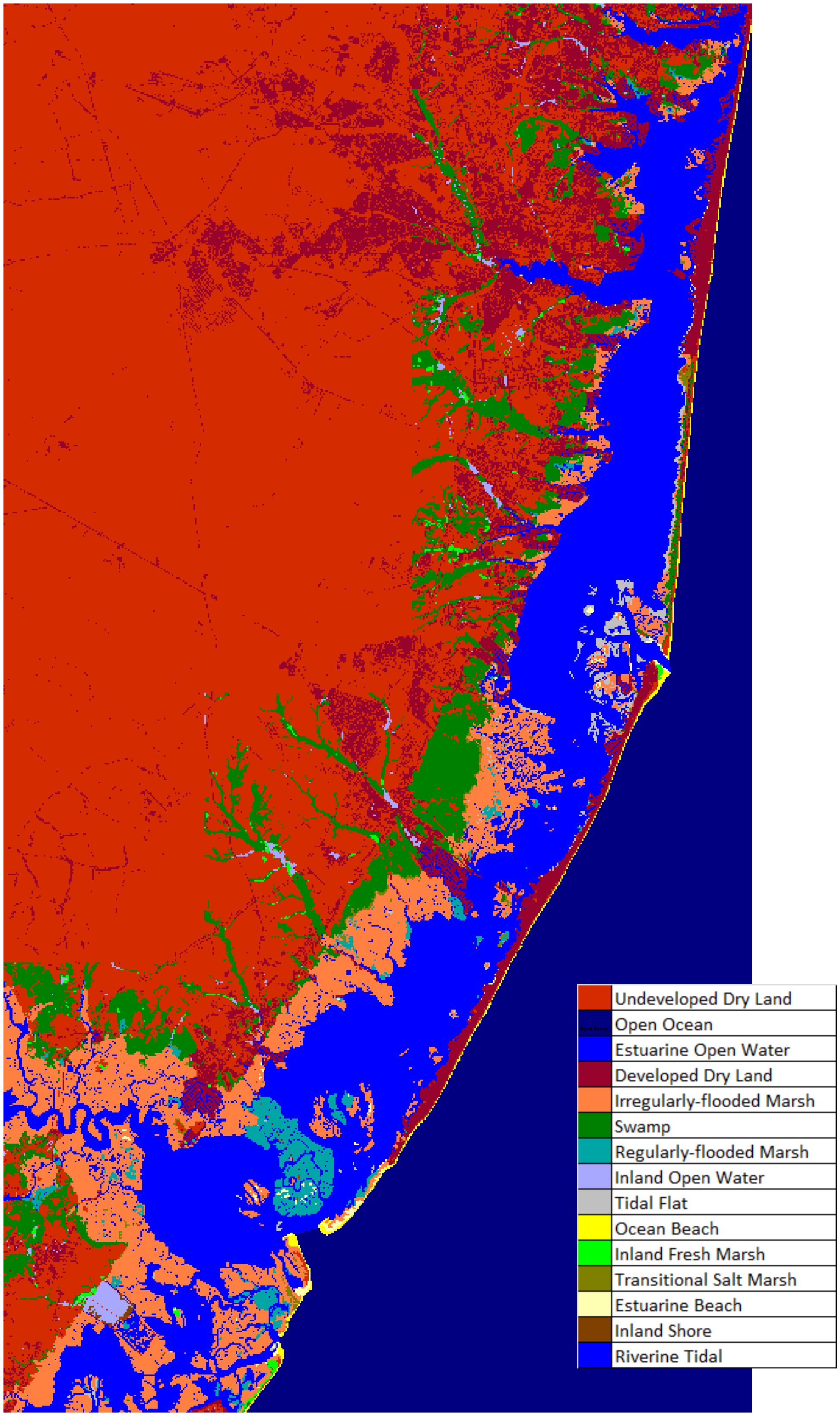
Edwin B. Forsythe NWR, 2050, 1 m SLR by 2100.



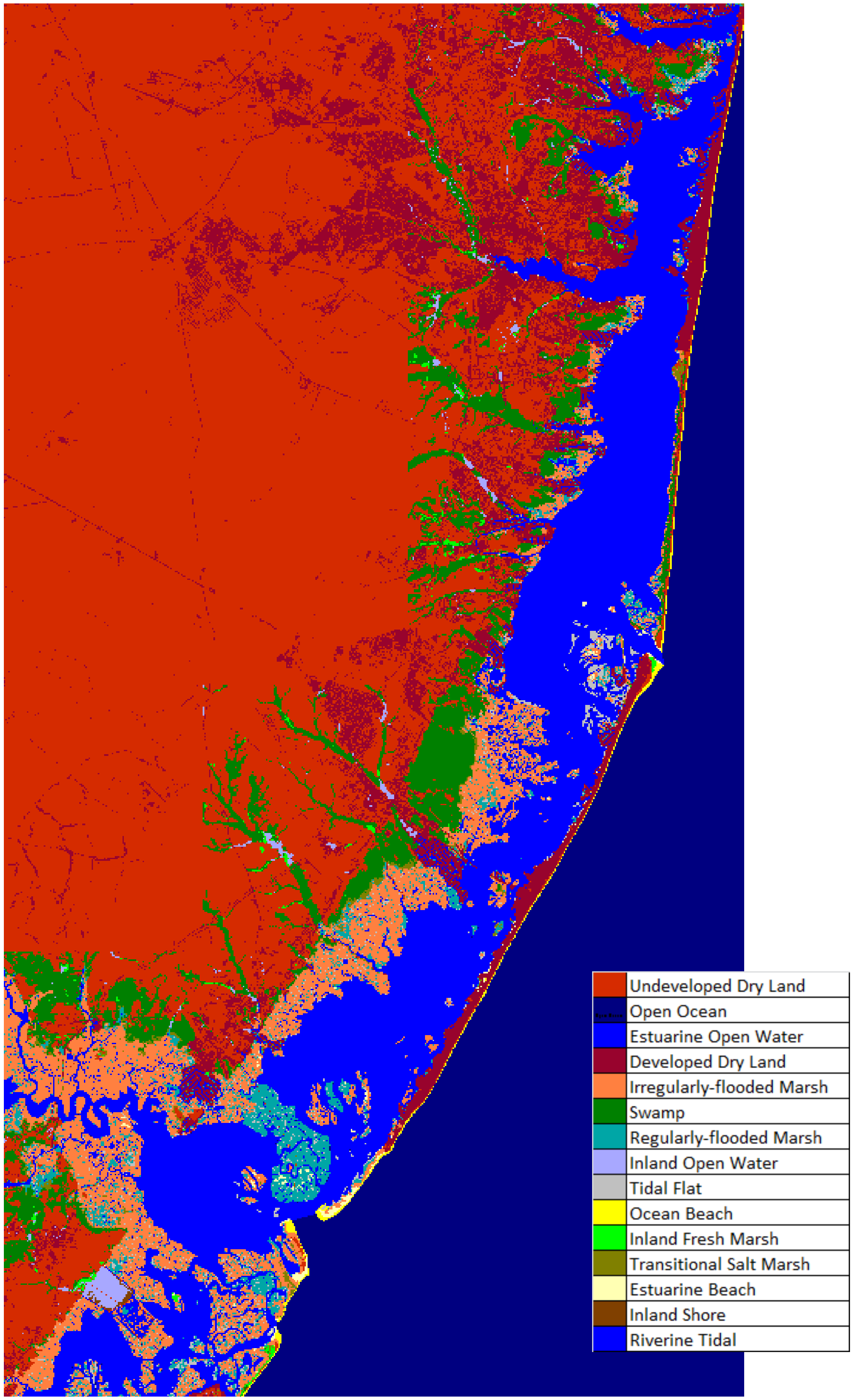
Edwin B. Forsythe NWR, 2075, 1 m SLR by 2100..



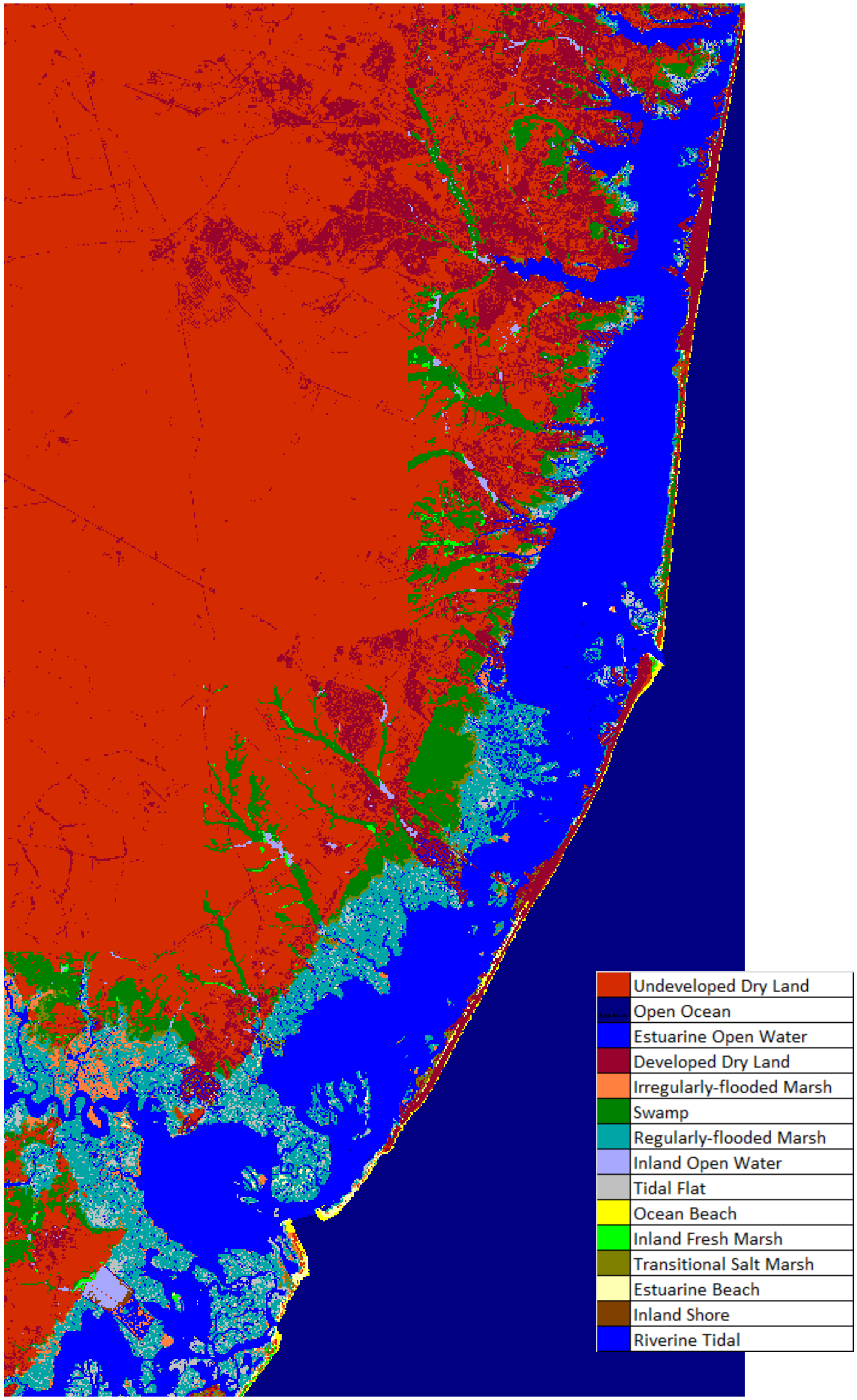
Edwin B. Forsythe NWR, 2100, 1 m SLR by 2100.



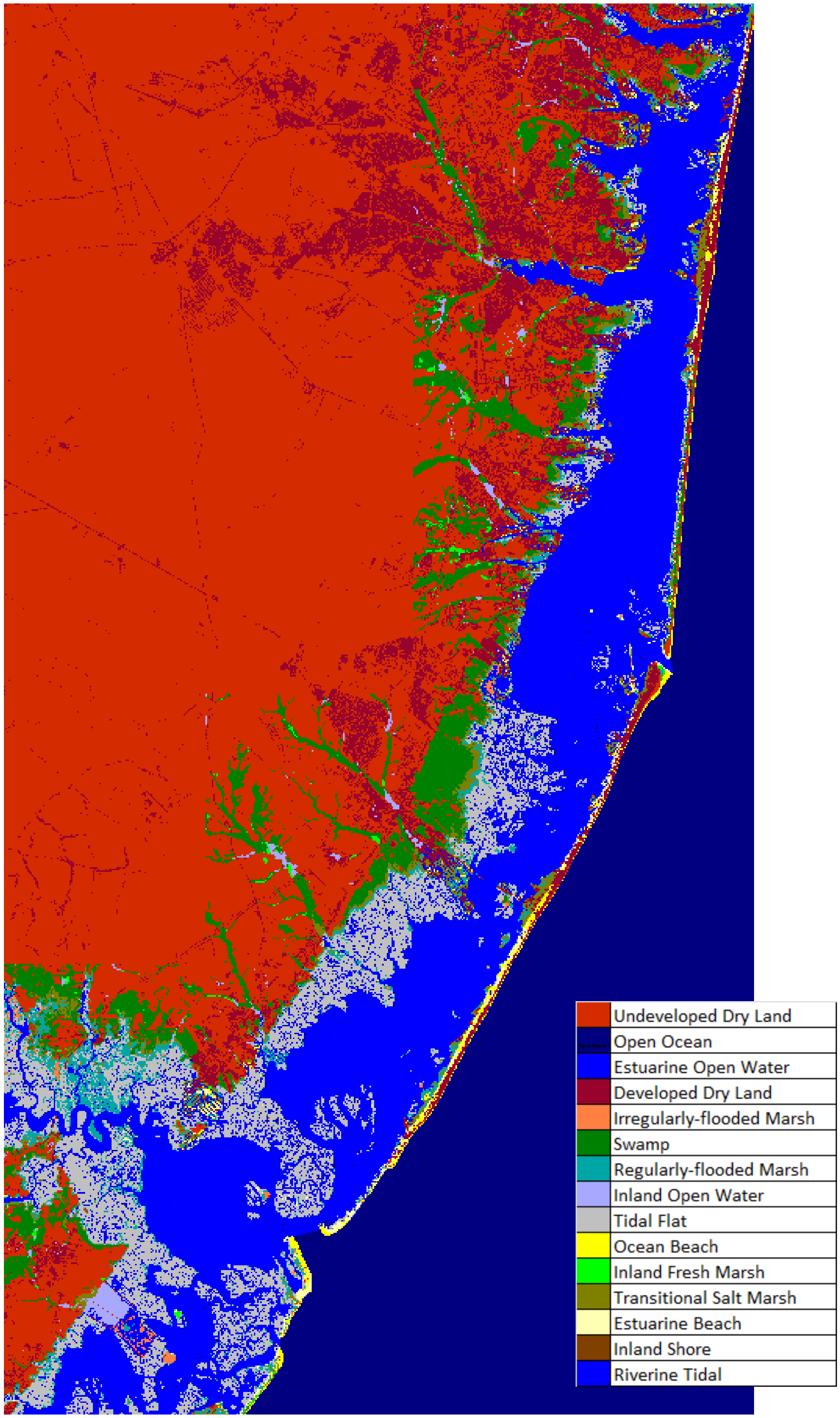
Edwin B. Forsythe NWR, Initial Condition.



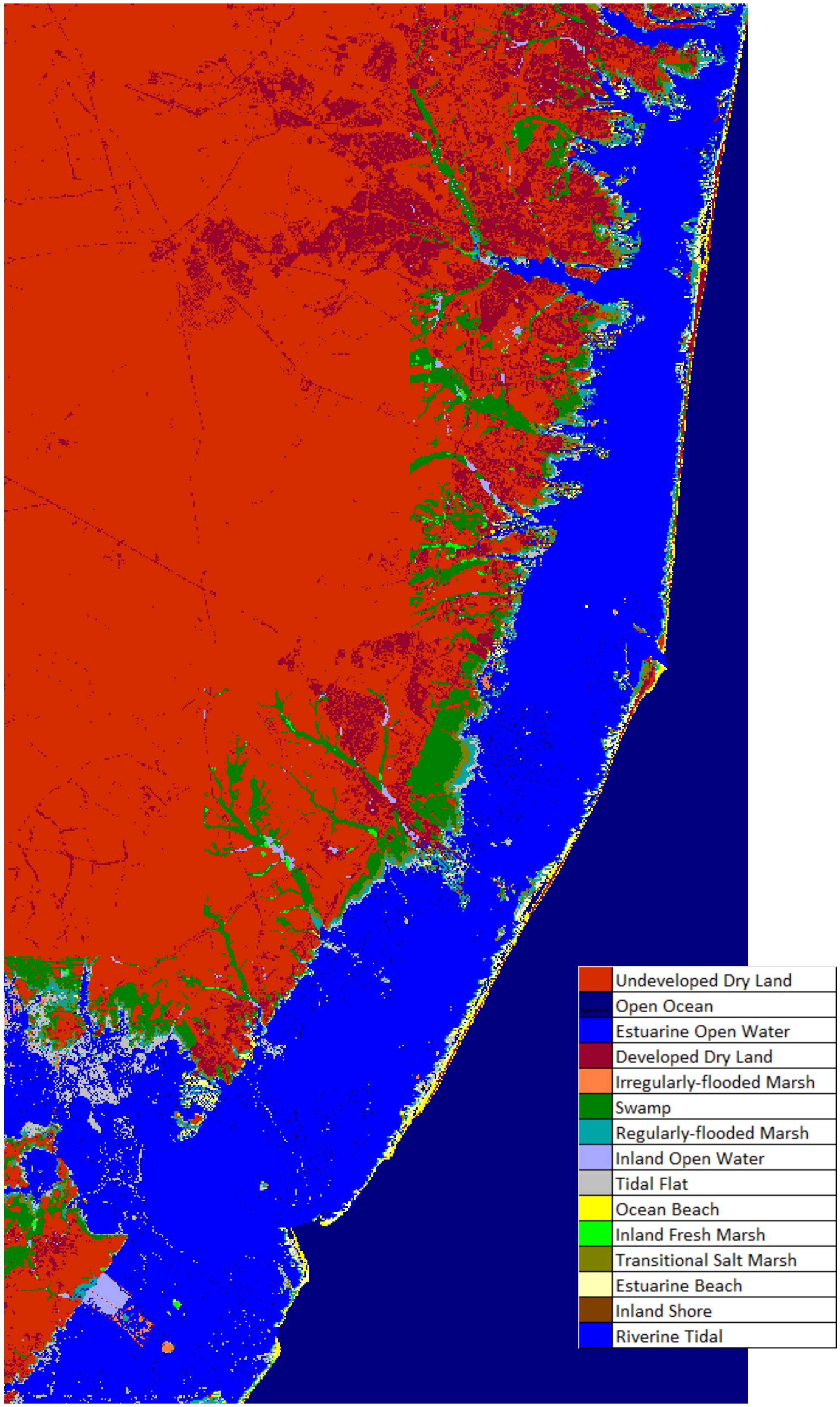
Edwin B. Forsythe NWR, 2025, 1.5 m SLR by 2100.



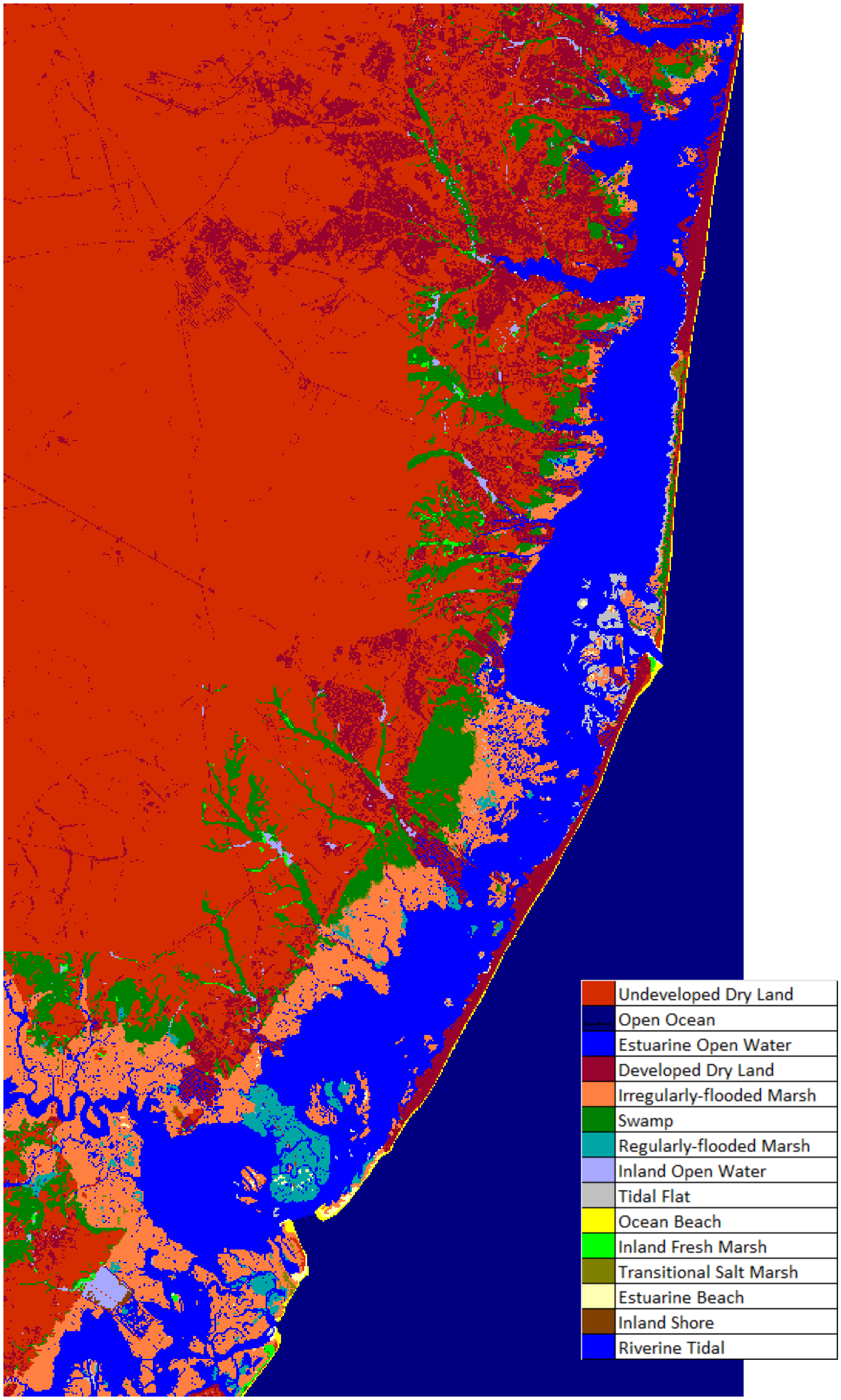
Edwin B. Forsythe NWR, 2050, 1.5 m SLR by 2100.



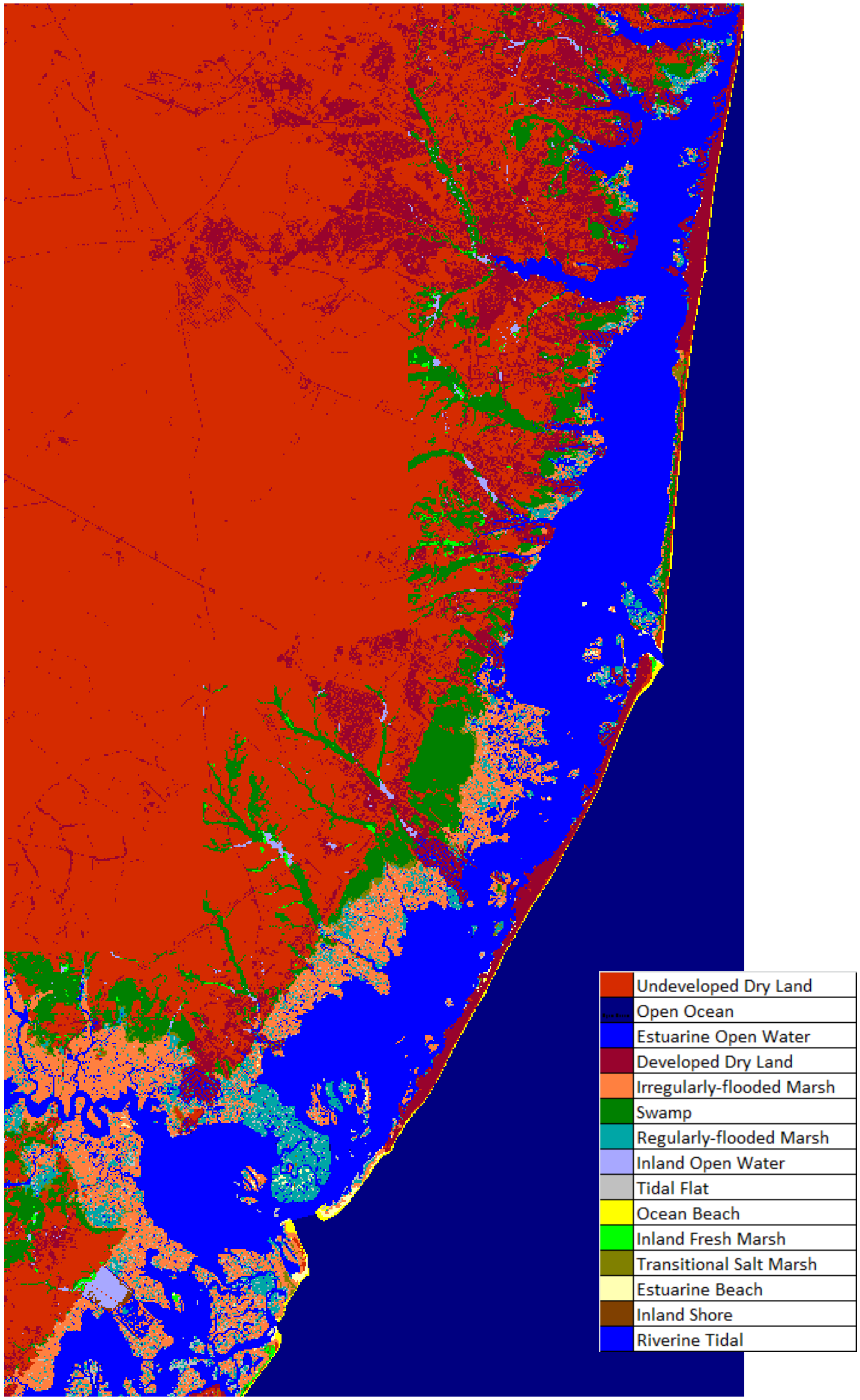
Edwin B. Forsythe NWR, 2075, 1.5 m SLR by 2100.



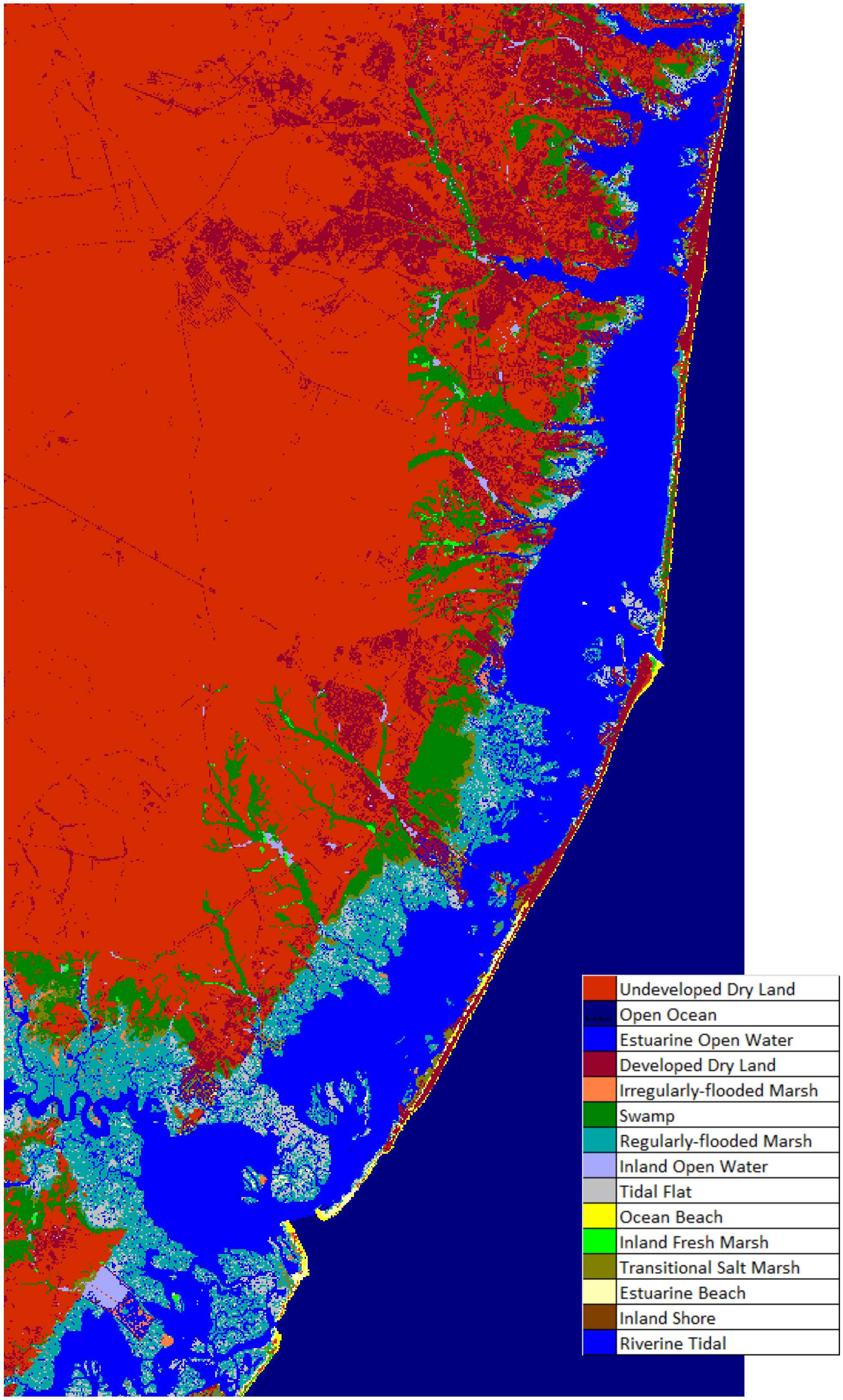
Edwin B. Forsythe NWR, 2100, 1.5 m SLR by 2100.



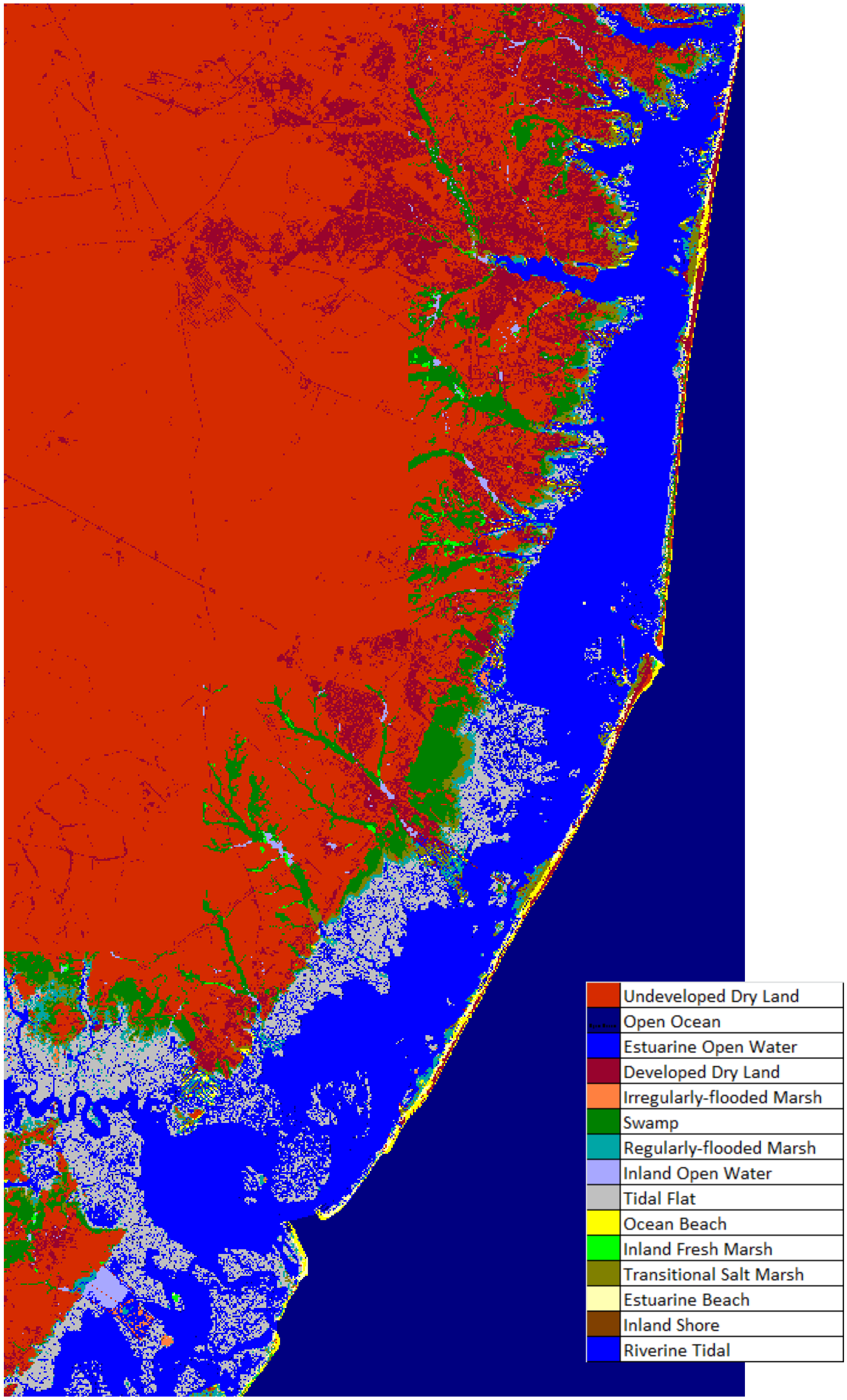
Edwin B. Forsythe NWR, Initial Condition.



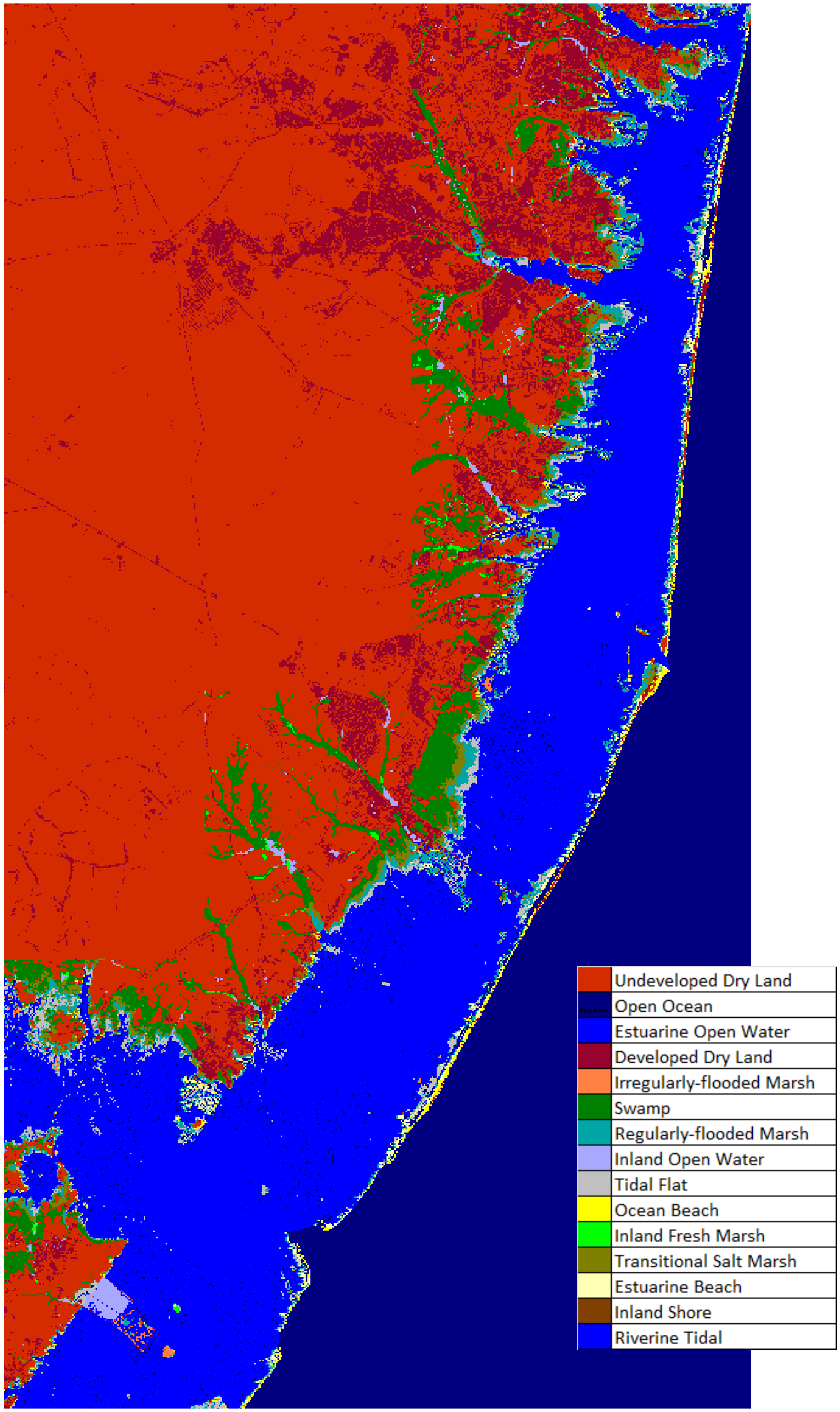
Edwin B. Forsythe NWR, 2025, 2 m SLR by 2100.



Edwin B. Forsythe NWR, 2050, 2 m SLR by 2100.



Edwin B. Forsythe NWR, 2075, 2 m SLR by 2100.



Edwin B. Forsythe NWR, 2100, 2 m SLR by 2100.