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

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July 12, 2011

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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 (R. A. Park et al. 1991).

In an effort to address the potential effects of sea level rise on United States national wildlife refuges, the U. S. Fish and Wildlife Service contracted the application of the SLAMM model for many coastal Region 4 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.

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). The first phase of this work was completed using SLAMM 5, while the second phase simulations were run with SLAMM 6.

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 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 will be used in USFWS simulations, but only where adequate data exist for parameterization.
- Salinity Model: Multiple time-variable freshwater flows may be specified. Salinity is estimated and mapped at MLLW, MHHW, and MTL. Habitat switching may be specified as a function of salinity. This optional sub-model is not utilized in 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

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

The latest literature (Chen et al. 2006; Monaghan et al. 2006) indicates that the eustatic SLR 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 SLR 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 1).

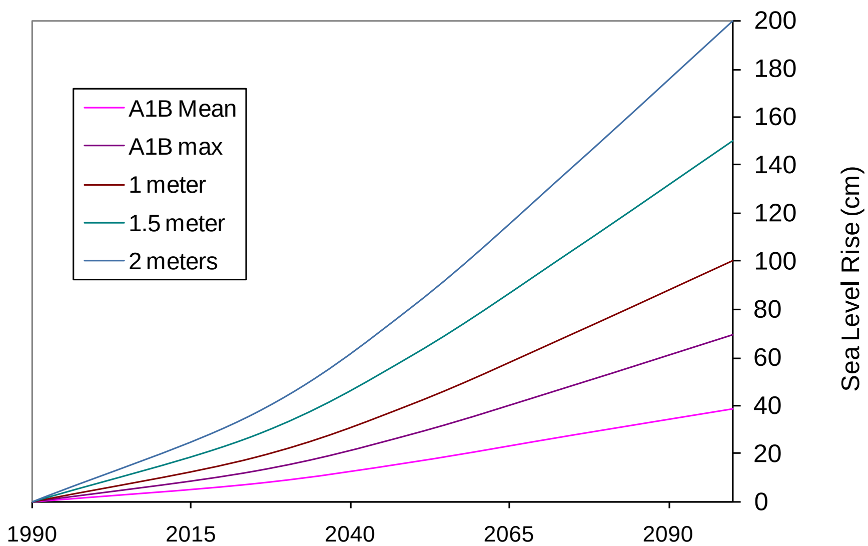


Figure 1: **Summary of SLR scenarios utilized**

Methods and Data Sources

The wetlands layer for the study area (Figure 2) was derived from two layers produced by the National Wetlands Inventory (NWI): a 2000 photo date for the north part of the bay and a 1978 photo for the very south tip of the refuge, south of Ragged Island (Subsite 2 in Figure 5). Converting the NWI survey into 6 m cells indicated that the approximately 16,000 acre refuge (approved acquisition boundary including water) is composed of the following categories:

	Land cover type	Area (acres)	Percentage (%)
	Estuarine Open Water	6137	38
	Irregularly Flooded Marsh	4621	28
	Undeveloped Dry Land	1907	12
	Tidal Swamp	1112	7
	Swamp	817	5
	Inland Fresh Marsh	781	5
	Inland Open Water	345	2
	Developed Dry Land	232	1
	Tidal Fresh Marsh	109	1
	Ocean Beach	60	< 1
	Transitional Marsh	60	< 1
	Cypress Swamp	53	< 1
	Open Ocean	12	< 1
	Estuarine Beach	8	< 1
	Total (incl. water)	**16253**	**100**

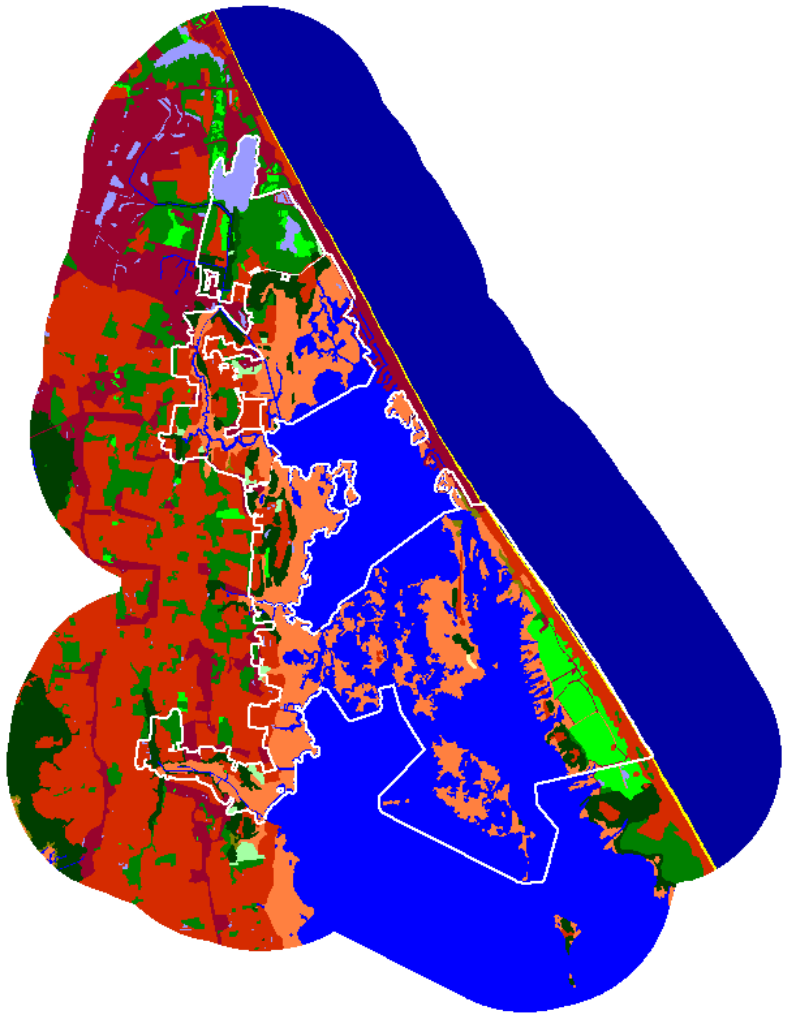


Figure 2. SLAMM study area. The white line indicates Back Bay NWR

The digital elevation map used in this simulation was derived from a 2004 LiDAR data set of the Virginia Beach area and is represented in Figure 3.

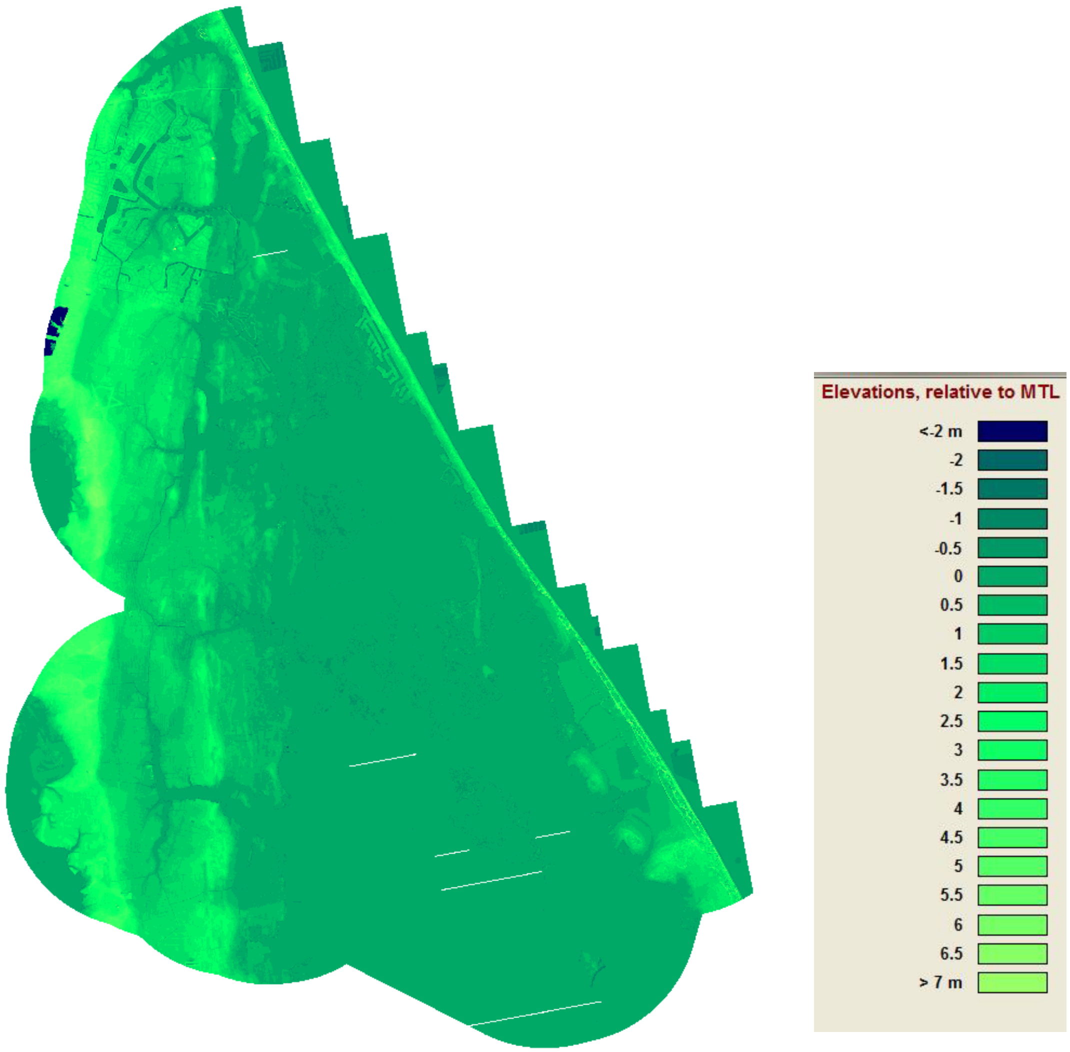


Figure 3. Shade-relief elevation map of study area (white lines are missing elevation data)

In the south of the refuge, between the ocean and the bay, a series of dikes have been built to protect the habitat of migrating and wintering waterfowl (Figure 4). Inundation of lands behind these dikes (and also the protective sand dunes and higher dry lands) was modeled using the connectivity feature of the SLAMM model.

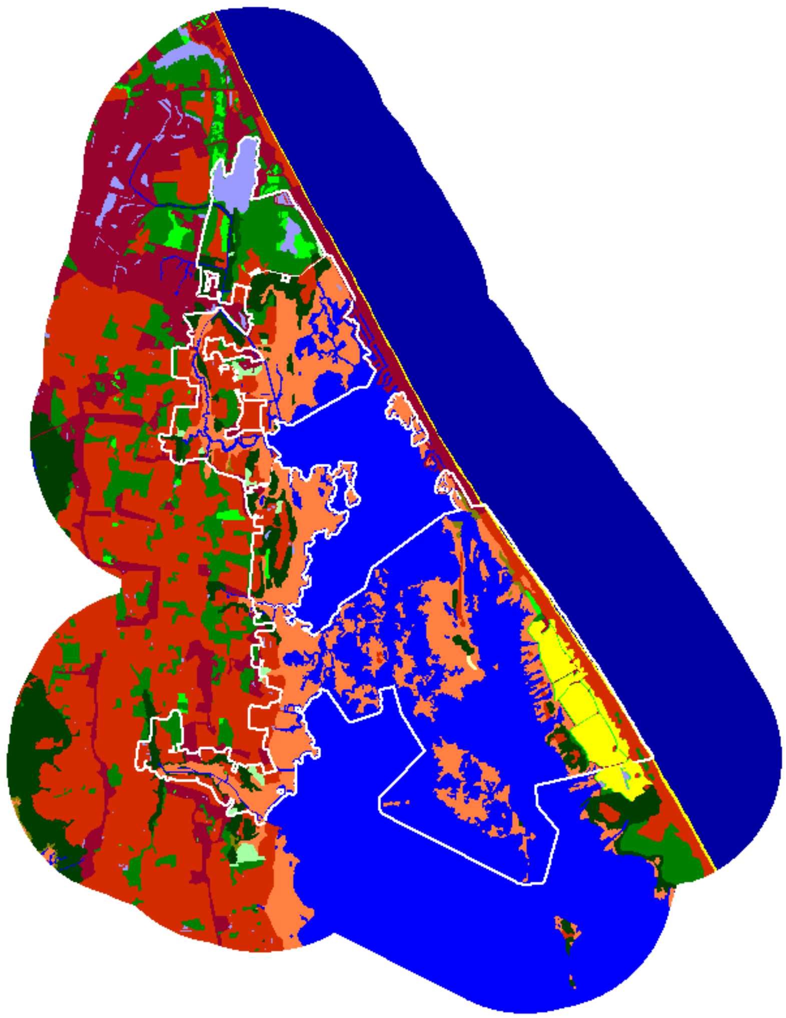


Figure 4. Yellow area represents the dike system in the Back Bay NWR

The historic trend for SLR was estimated at 3.29 mm/yr by taking the average value recorded at the closest gauge stations, Portsmouth, VA, ID 8638660 (3.76 mm/yr), north of the refuge and Oregon Inlet marina, ID 8652587 (2.82 mm/yr), south of the refuge. This measured rate is higher than the global average for the last 100 years (approximately 1.5-2.0 mm/yr) potentially reflecting land subsidence at this site (or other factors causing local SLR to slightly outpace global SLR).

The great diurnal tide range (GT) at this site was estimated from multiple tide stations. For the open ocean, GT was chosen as 1.168 m as measured at the Sandbridge, VA, ID 8639428 gauge station; for the bay it was chosen to be 0.133 m, the average between the GT at Mann Harbor, NC, ID 8652247 (0.123 m) and Manteo, NC, ID 8652232 (0.142 m). These values are in agreement with data available contour maps of the area which indicate a GT of 1.1 m for the ocean and 0.15 m for the bay. Communication with refuge staff indicate that tides within the refuge itself are driven by wind rather than lunar tides.

The elevation at which estuarine water is predicted to regularly inundate the land was estimated based on a frequency of inundation analysis using two years data from the gauge stations Duck, NC, ID 8651370 in the open ocean and Rudee Inlet, VA, ID 8639207, north of Back Bay. For this application, the dry land boundary was defined as the elevation above which inundation is predicted less than once per thirty days. Based on this analysis this elevation was set to be 1.69 Half Tide Units (HTU) SLAMM mean high high water (MHHW). This matches the lower range of LiDAR data for the elevation ranges of non saline-inundated categories (e.g. dry land, inland fresh marsh, non-tidal swamp) reasonably well.

Due to its location approximately 60 miles north of the Oregon Inlet, the estuarine open water in Back Bay NWR is not lunar-tidal and is extremely low in salinity (0-3 ppt, Gallegos, 2011). Water levels within the refuge can range from zero to three feet higher than the ocean water on the other side of the barrier island (Gallegos, 2011). Despite these facts, the LiDAR elevation data within the model conform closely to the SLAMM conceptual model. For example, the mean elevation of the irregularly-flooded marsh in the refuge is only 0.2 m above the oceanic mean tide level. Therefore an increase in oceanic mean tide level would be predicted to have effects on this refuge.

Within this modeling analysis it is assumed that water in the refuge will rise on a one to one basis along with sea-level rise. The reasons for this assumption are as follows.

- Salinity is non-zero suggesting at least episodic influence from ocean water within the refuge.
- Under higher SLR scenarios, the barrier island will be overtopped providing a one-to-one relationship between sea-level and refuge water level. Based on an examination of model results it appears that portions of the barrier island will be regularly breached following one meter of oceanic SLR.

However, given the relative spatial isolation of the refuge from the ocean waters, the assumption of a one to one SLR relationship adds some uncertainty to the timing of model results, particularly for lower SLR scenarios.

Both regularly-flooded and irregularly-flooded marshes were parameterized using the nearest-available accretion data (Cedar Island, NC) with accretion rates set to 3.7 mm/year (Cahoon et al. 1995). Tidal fresh marsh accretion values were set to 5.9 mm/year based upon an average of fresh marsh accretion rates within the region ((Reed et al. n.d.), n=8)

The MTL to NAVD88 correction was applied using the data from the Oregon Inlet Marina, VA, ID 8638660 as no other data are available for this study area, and estimated as -3 cm. Elevation data within the site are therefore being expressed relative to mean tide level at the Oregon Inlet and SLR effects being calculated on that basis.

Modeled USFWS refuge boundaries for Back Bay 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 6 m by 6 m cells. Note that the SLAMM model will track partial conversion of cells based on elevation and slope.

Based on the different observed tidal ranges and dates of the available wetland coverage surveys, three simulation subsites were identified (Figure 5).

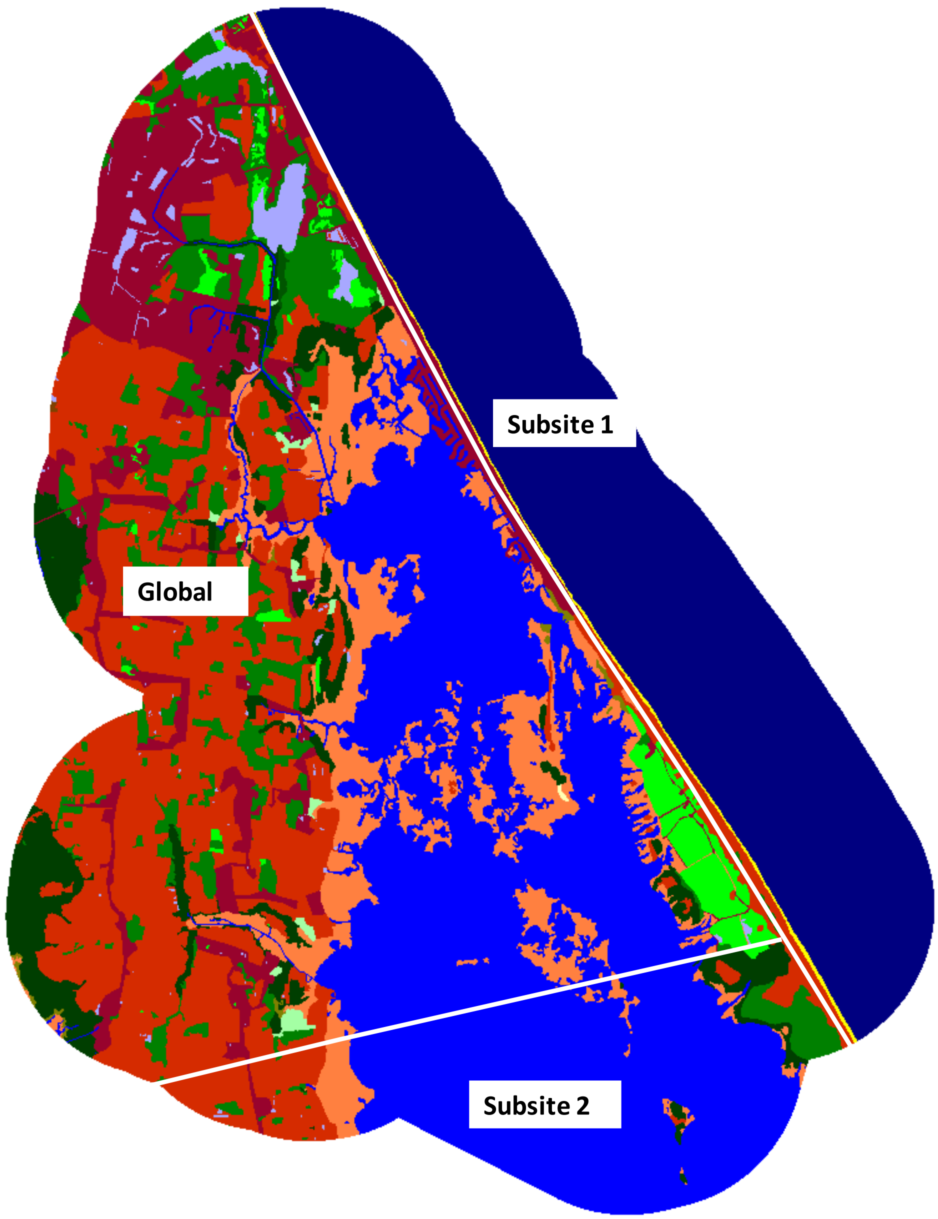


Figure 5. Subsites of the study area for Back Bay NWR

Table 1 summarizes SLAMM input parameters for each subsite. The "Global" subsite includes all the study area that is not within any other subsites boundaries, here all the northern inland part of the study area.

Table 1. Summary of SLAMM input parameters for Back NWR

Parameter	Global	SubSite 1	SubSite 2
Description	Inside Bay	Open Ocean	NWI 1978
NWI Photo Date (YYYY)	2000	2000	1978
DEM Date (YYYY)	2004	2004	2004
Direction Offshore [n,s,e,w]	East	East	East
Historic Trend (mm/yr)	3.29	3.29	3.29
MTL-NAVD88 (m)	-0.03	-0.03	-0.03
GT Great Diurnal Tide Range (m)	0.133	1.168	0.133
Salt Elev. (m above MTL)	0.225	1.974	0.225
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)	3.7	3.7	3.7
Irreg.-Flood Marsh Accr (mm/yr)	3.7	3.7	3.7
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)	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)	11	11	11
Use Elev Pre-processor [True,False]	FALSE	FALSE	FALSE

Results

This simulation of the Back Bay NWR predicts that the refuge will be severely impacted for all SLR scenarios and wetland classes. Table 2 presents the predicted loss of each wetland category by 2100 for each of the five SLR scenarios examined.

Table 2. Predicted loss of land categories by 2100 given simulated scenarios of eustatic SLR

Land cover category	**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	59%	88%	96%	98%	99%
Undeveloped Dry Land	55%	72%	82%	90%	94%
Tidal Swamp	72%	87%	94%	99%	100%
Swamp	76%	86%	94%	99%	99%
Inland Fresh Marsh	5%	9%	13%	15%	15%
Developed Dry Land	47%	64%	75%	88%	96%
Tidal Fresh Marsh	9%	47%	76%	96%	99%
Ocean Beach	-243% (*)	-289% (*)	-319% (*)	-269% (*)	-213% (*)
Cypress Swamp	98%	100%	100%	100%	100%
Estuarine Beach	-53% (*)	-91% (*)	-93% (*)	-11% (*)	-4% (*)

* A negative loss indicates a gain

By 2100, open water that today covers approximately 38% of the refuge is predicted to cover a minimum of 49% of the refuge (given the lowest SLR scenario evaluated or 0.39 m). Open water increases to 79% of the refuge for the 2-m SLR scenario.

Some inland-fresh marsh is predicted to be resilient to all SLR scenarios; this category is predicted to sustain a maximum loss of only 15% given the highest SLR scenario. However this result assumes that fresh marshes on the south-east part of the refuge are permanently protected by the dike system built in the area.

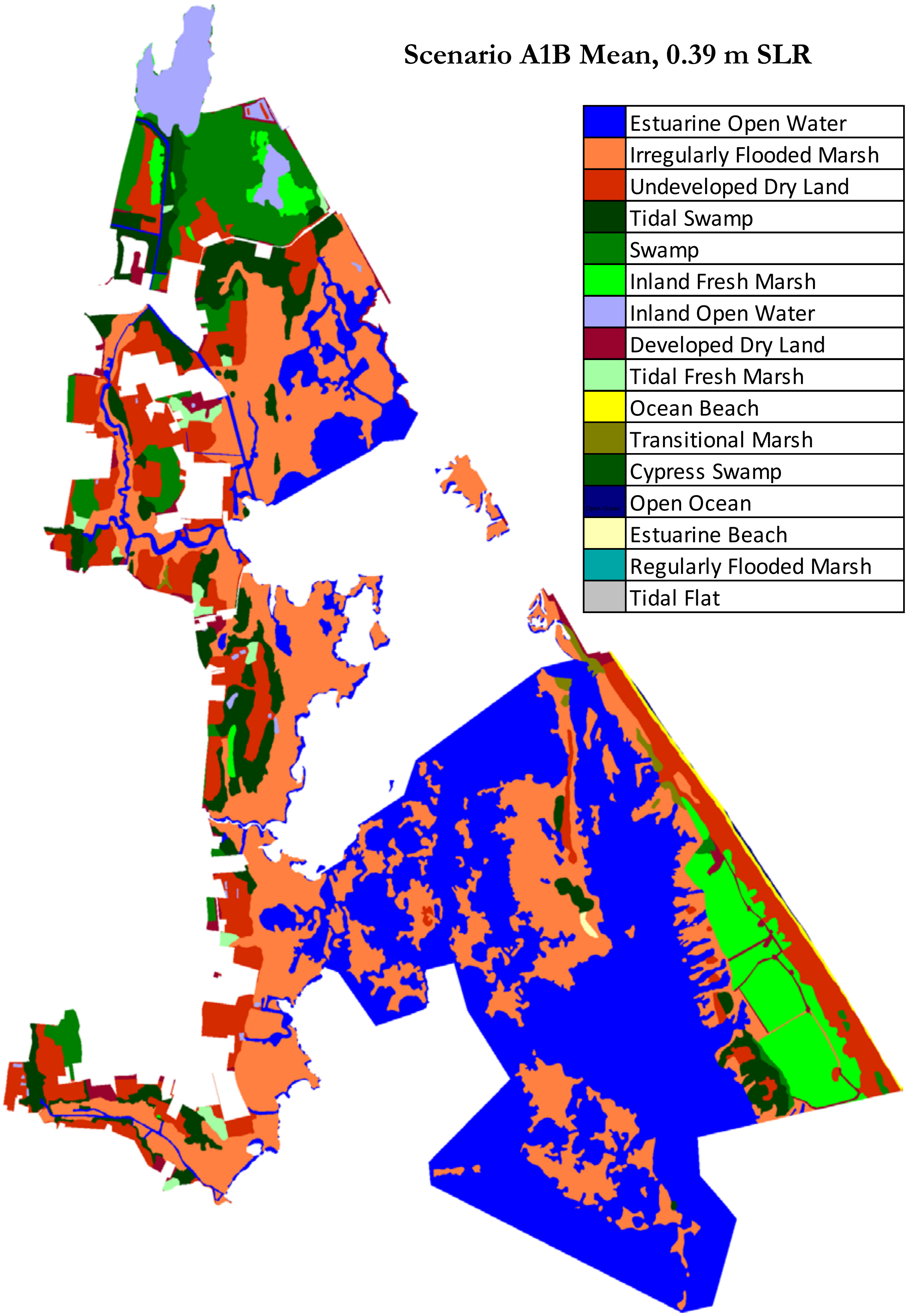
At 1 m of SLR by 2100 96% of refuge irregularly-flooded marsh, 82% of the undeveloped dry land and 94% of swamp are predicted to be lost. These land-cover types comprise the majority of the refuge wetlands today and are predicted to be lost at even greater rates in the higher SLR scenarios, with an almost complete loss at 2 m SLR by 2100. It is also worth noting that at least 50% and up to 96% of the refuge's developed-dry land is predicted to be lost by 2100.

When inundated, irregularly-flooded marsh is initially predicted to convert to regularly-flooded marsh. However, as sea level continues to rise, regularly-flooded marsh then converts to tidal flats. Under the highest SLR scenarios, at around 2050-2075, tidal flats are also completely predicted to convert to open water.

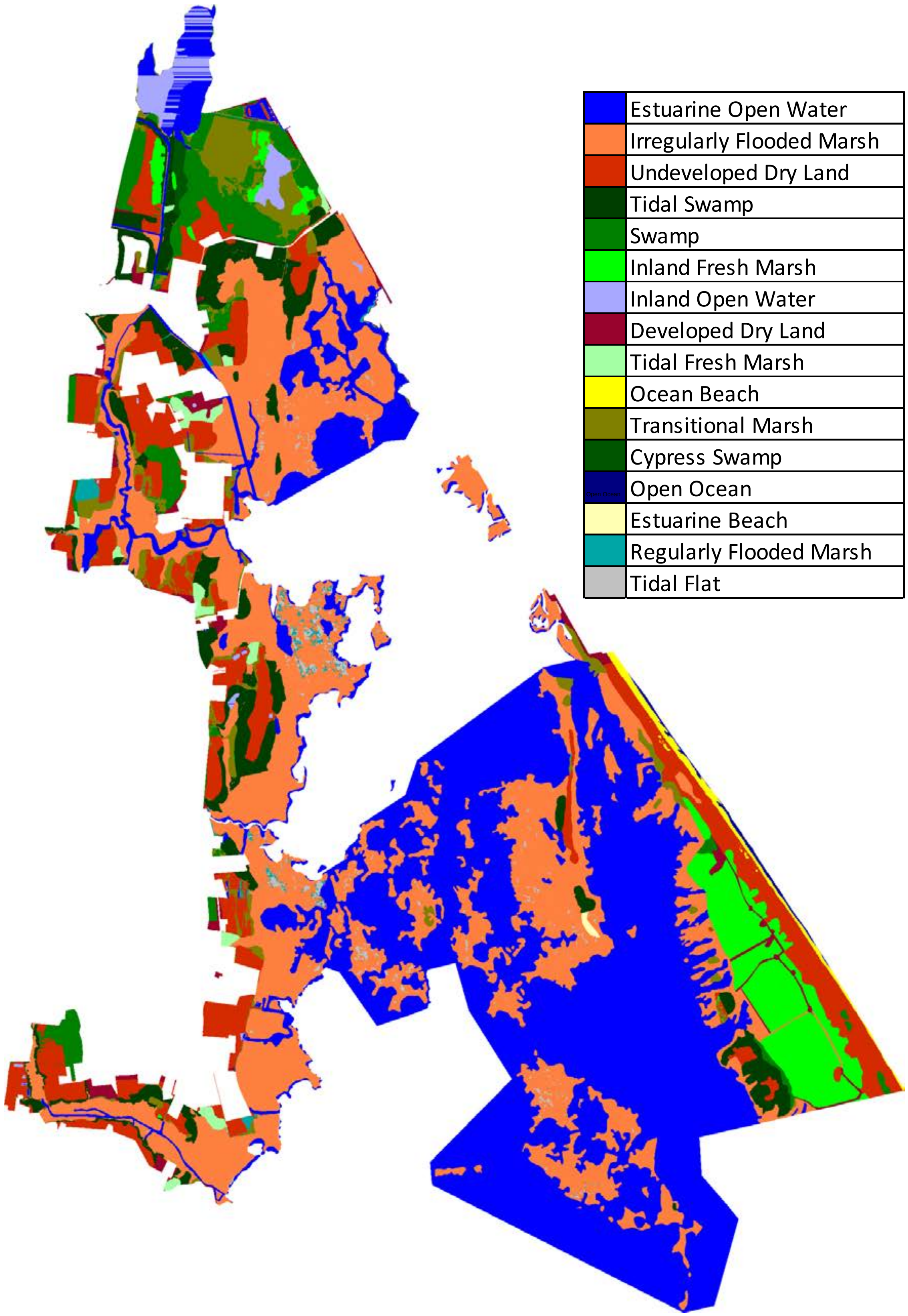
Back Bay NWR
IPCC Scenario A1B-Mean, 0.39 m SLR eustatic by 2100

Results in Acres

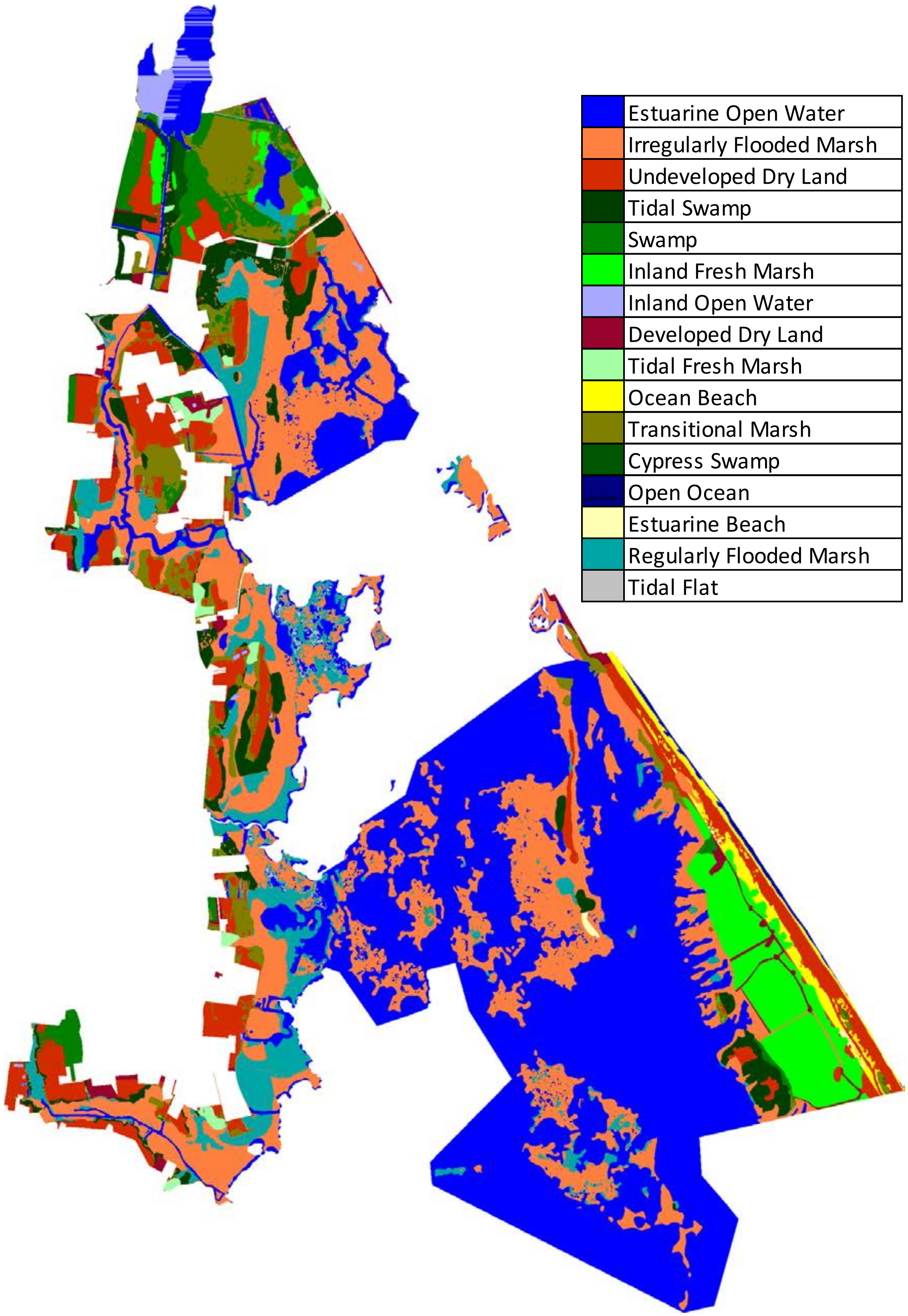
		Initial	2025	2050	2075	2100
	Estuarine Open Water	6137	6340	6572	6762	8051
	Irregularly Flooded Marsh	4621	4632	3814	2342	1897
	Undeveloped Dry Land	1907	1632	1330	1064	852
	Tidal Swamp	1112	860	682	466	307
	Swamp	817	568	418	305	198
	Inland Fresh Marsh	781	739	739	739	739
	Inland Open Water	345	183	107	81	62
	Developed Dry Land	232	196	178	154	123
	Tidal Fresh Marsh	109	100	100	100	100
	Ocean Beach	60	88	192	200	206
	Transitional Marsh	60	558	791	944	808
	Cypress Swamp	53	32	31	30	1
	Open Ocean	12	16	17	18	20
	Estuarine Beach	8	11	18	16	12
	Regularly Flooded Marsh	0	156	1168	1924	1156
	Tidal Flat	0	142	96	1109	1722
	Total (incl. water)	**16253**	**16253**	**16253**	**16253**	**16253**



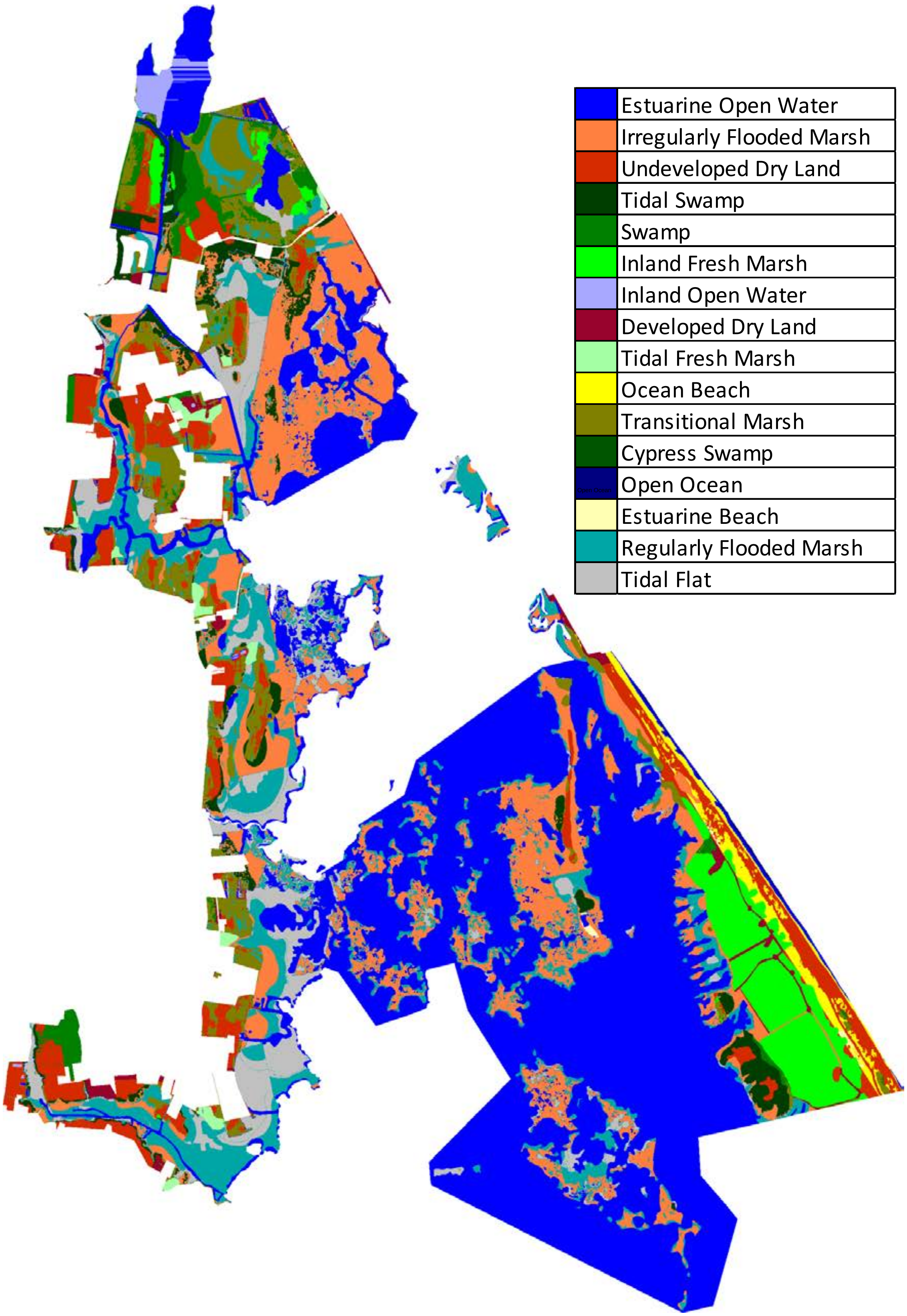
Back Bay NWR, Initial Condition



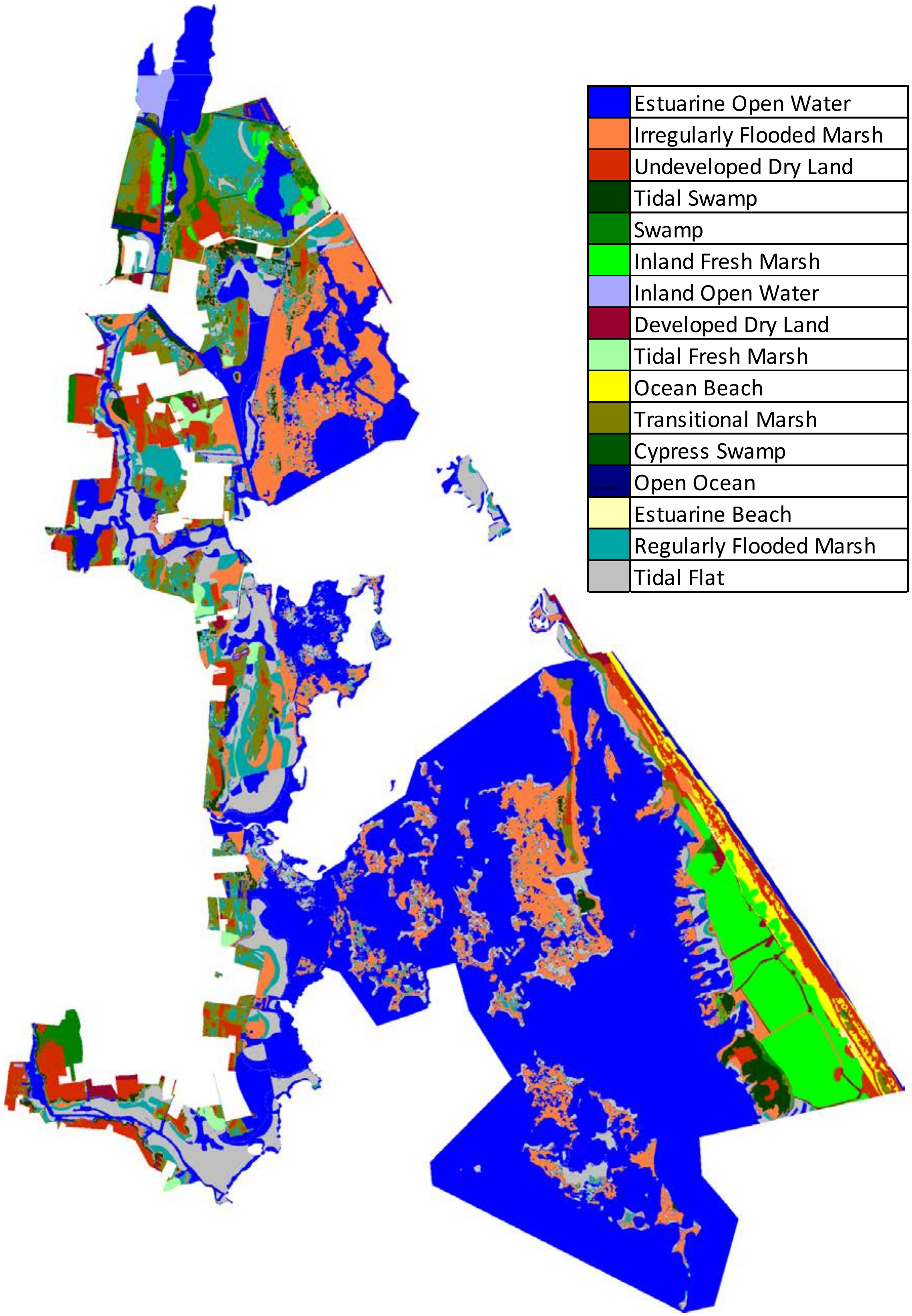
Back Bay NWR, 2025, Scenario A1B Mean, 0.39 m SLR



Back Bay NWR, 2050, Scenario A1B Mean, 0.39 m SLR



Back Bay NWR, 2075, Scenario A1B Mean, 0.39 m SLR

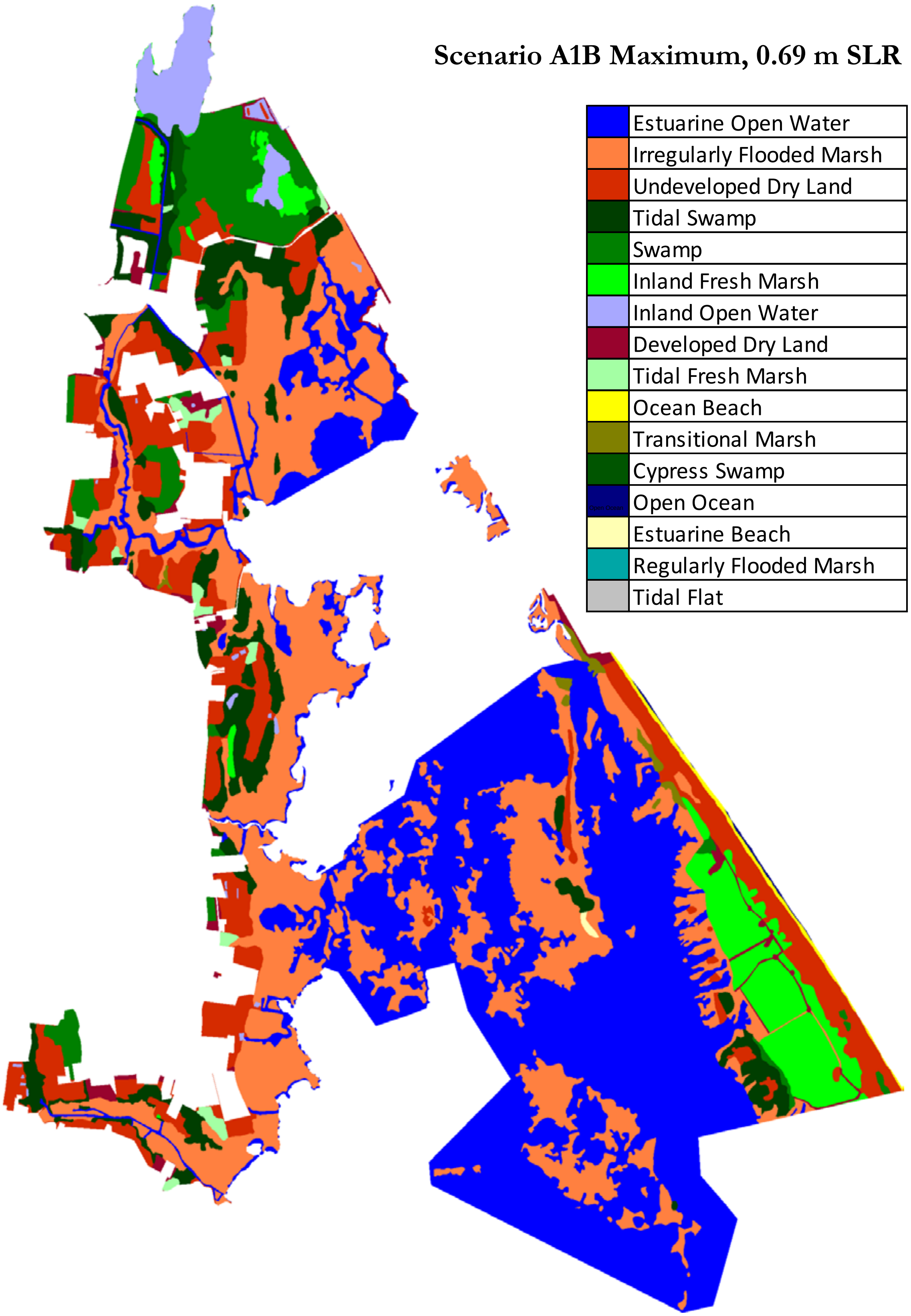


Back Bay NWR, 2100, Scenario A1B Mean, 0.39 m SLR

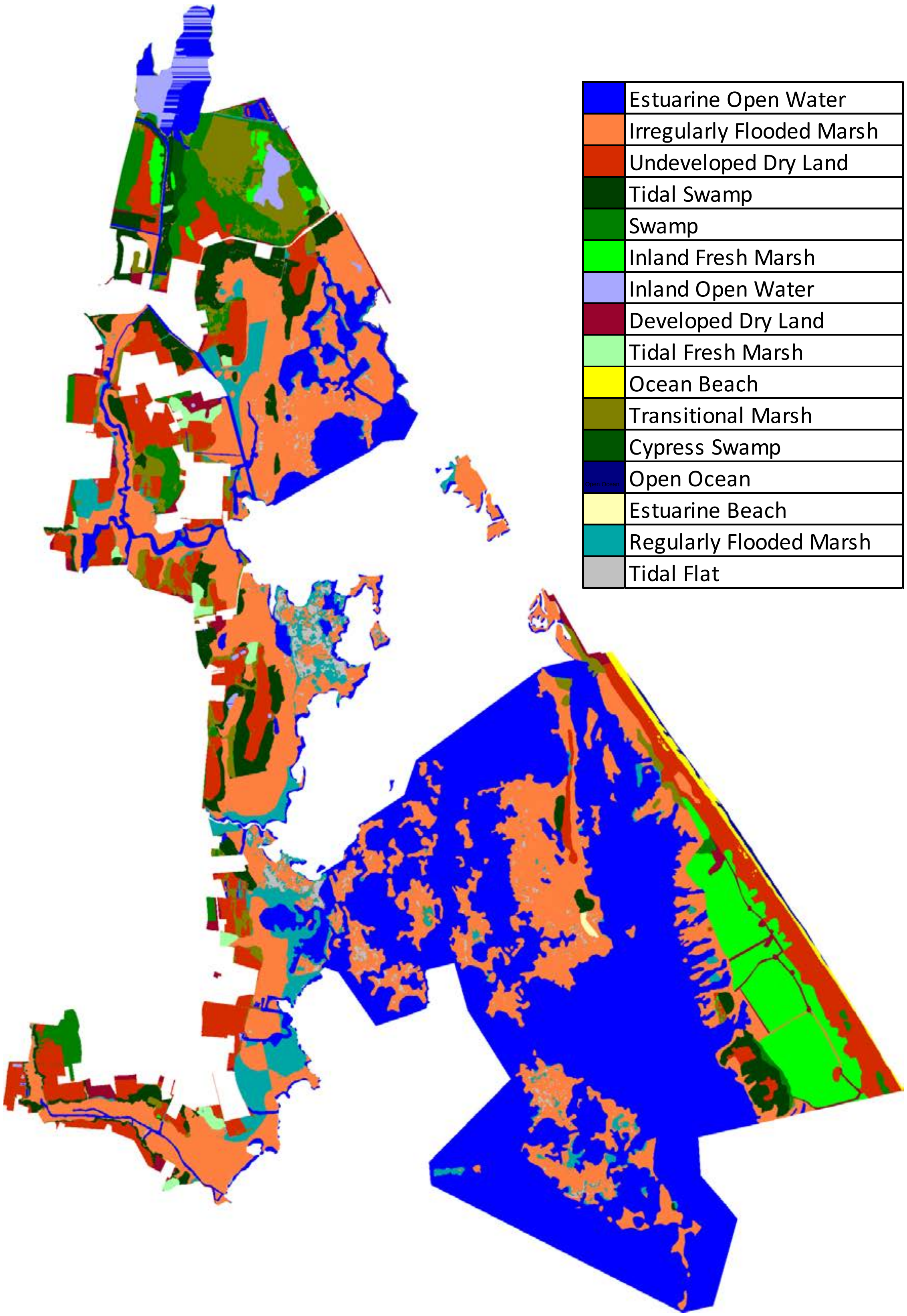
Back Bay NWR
IPCC Scenario A1B-Max, 0.69 m SLR eustatic by 2100

Results in Acres

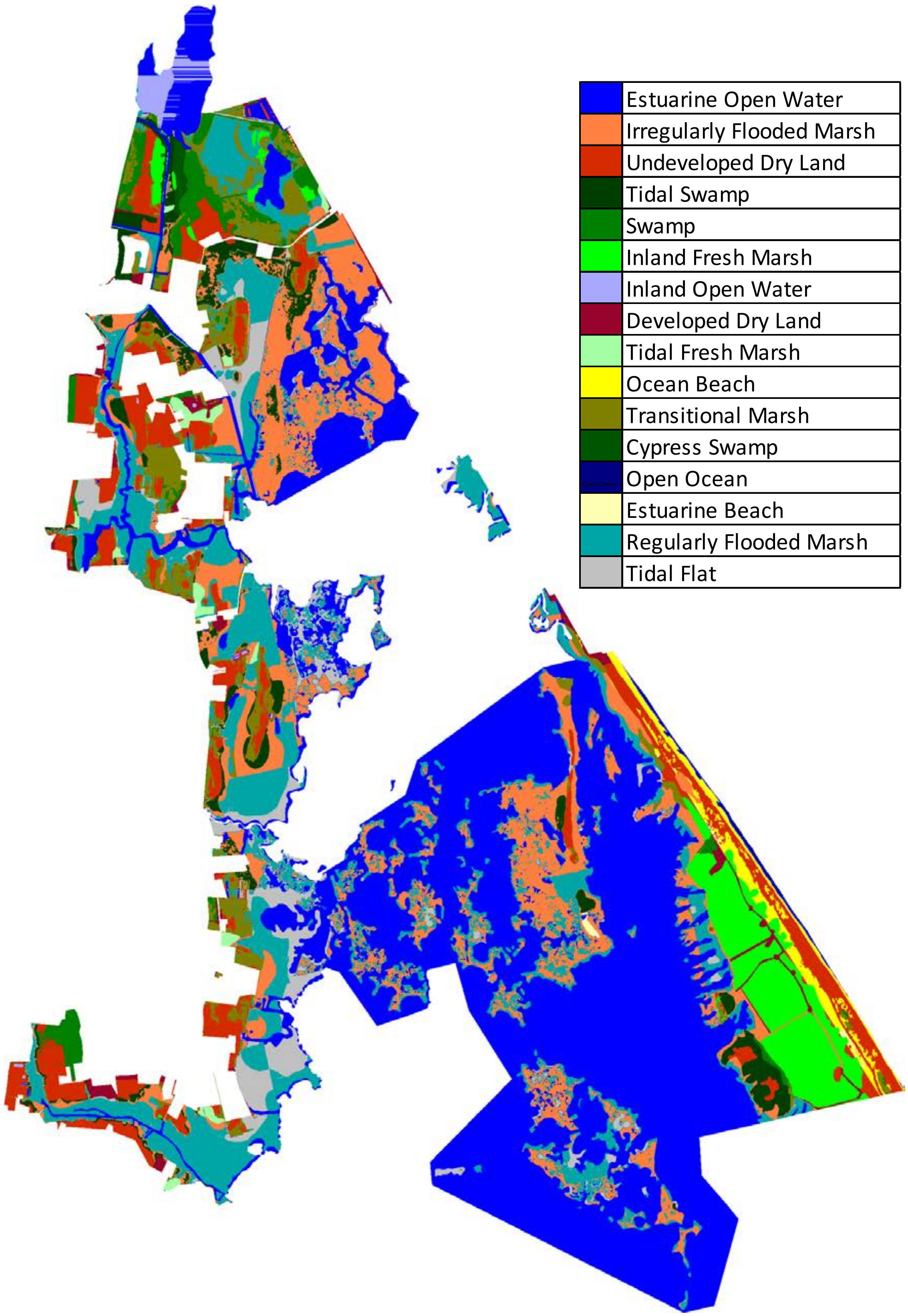
		Initial	2025	2050	2075	2100
	Estuarine Open Water	6137	6345	6710	7678	10231
	Irregularly Flooded Marsh	4621	4050	2106	1245	574
	Undeveloped Dry Land	1907	1582	1148	802	534
	Tidal Swamp	1112	790	507	248	142
	Swamp	817	525	339	171	112
	Inland Fresh Marsh	781	731	724	713	707
	Inland Open Water	345	183	93	65	58
	Developed Dry Land	232	192	161	109	83
	Tidal Fresh Marsh	109	100	89	77	57
	Ocean Beach	60	90	208	223	233
	Transitional Marsh	60	583	745	631	340
	Cypress Swamp	53	31	30	1	0
	Open Ocean	12	17	17	21	50
	Estuarine Beach	8	11	19	14	15
	Regularly Flooded Marsh	0	804	2615	1803	1400
	Tidal Flat	0	222	742	2451	1714
	Total (incl. water)	**16253**	**16253**	**16253**	**16253**	**16253**



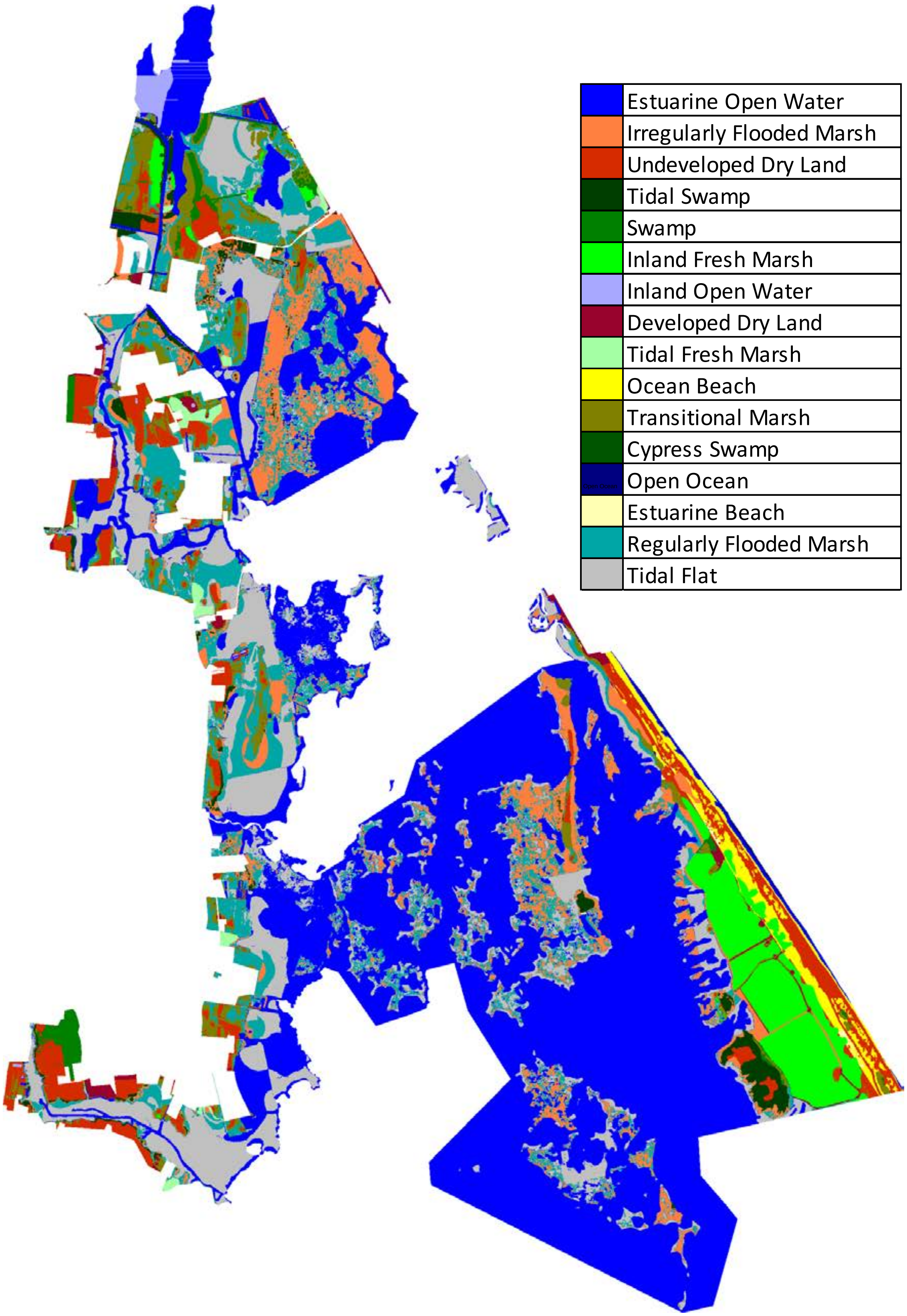
Back Bay NWR, Initial Condition



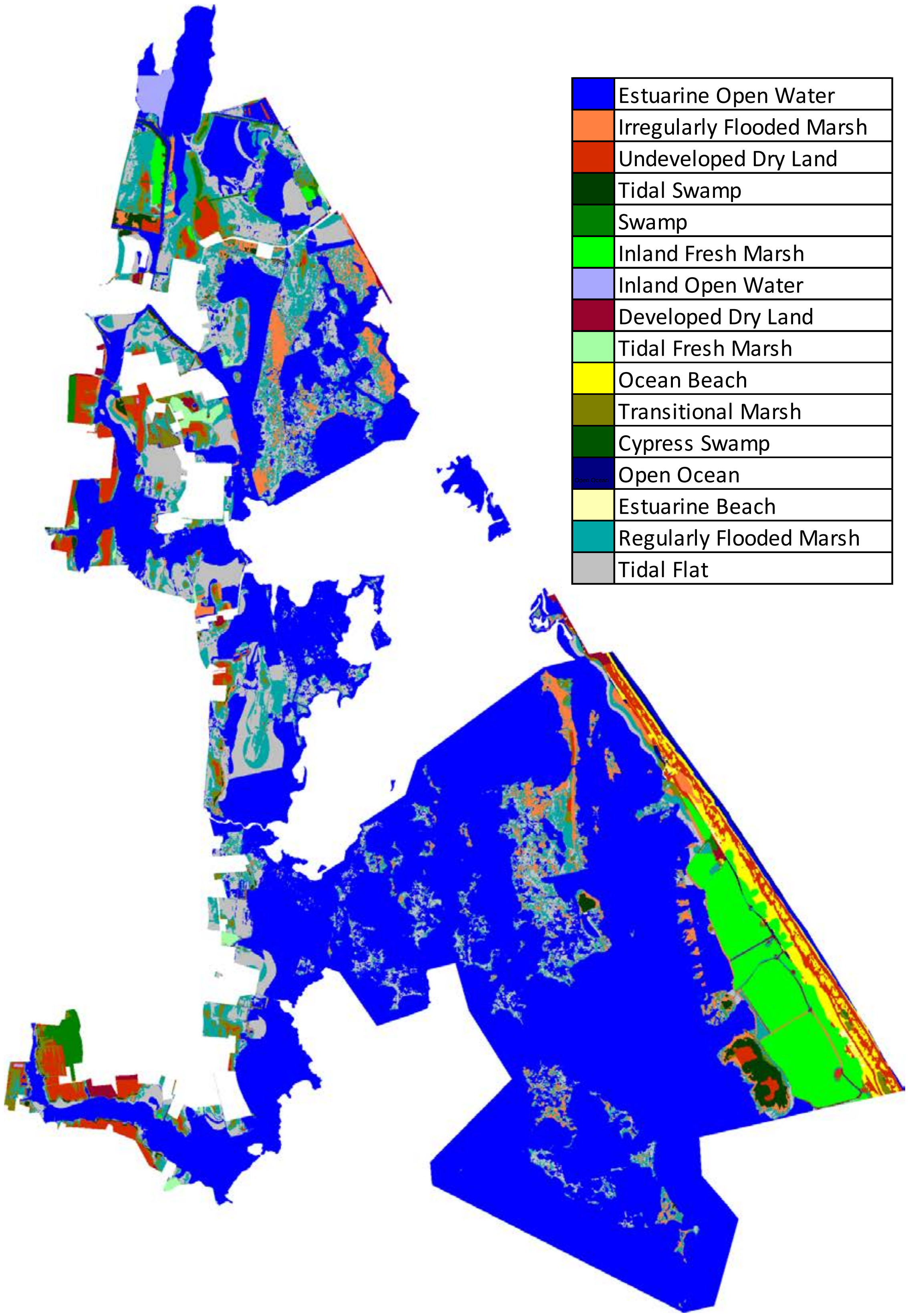
Back Bay NWR, 2025, Scenario A1B Maximum, 0.69 m SLR



Back Bay NWR, 2050, Scenario A1B Maximum, 0.69 m SLR



Back Bay NWR, 2075, Scenario A1B Maximum, 0.69 m SLR

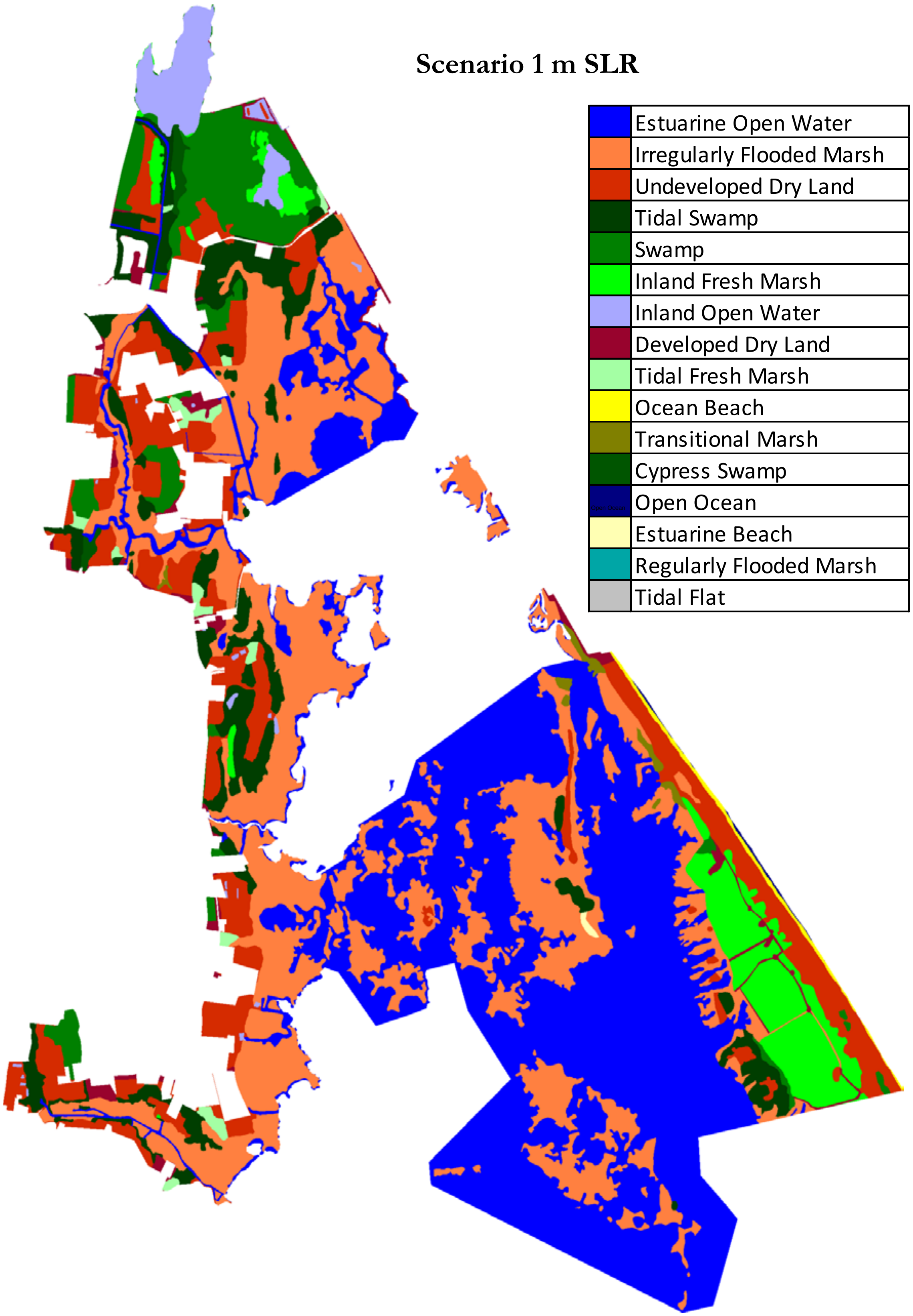


Back Bay NWR, 2100, Scenario A1B Maximum, 0.69 m SLR

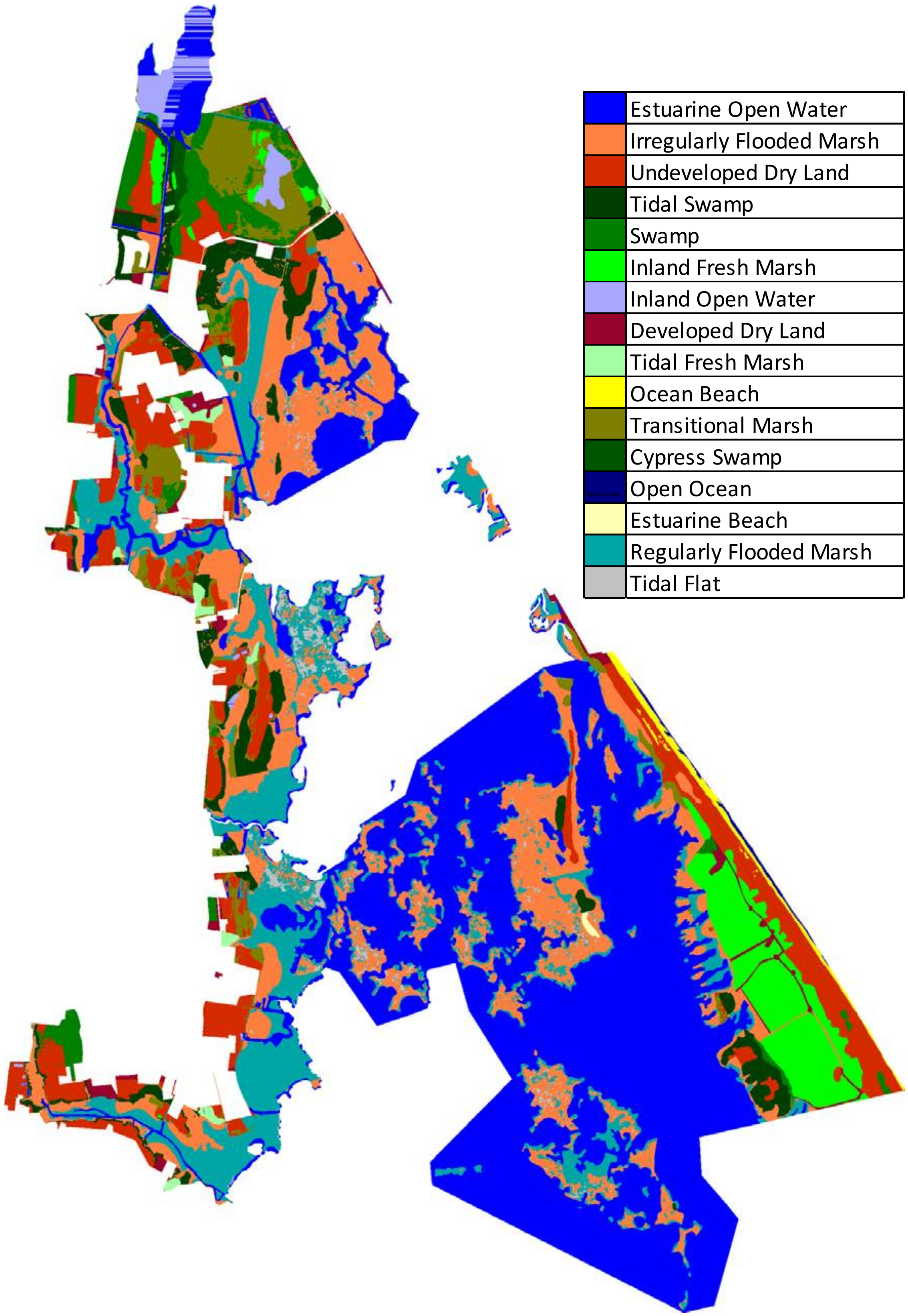
Back Bay NWR
1 m eustatic SLR by 2100

Results in Acres

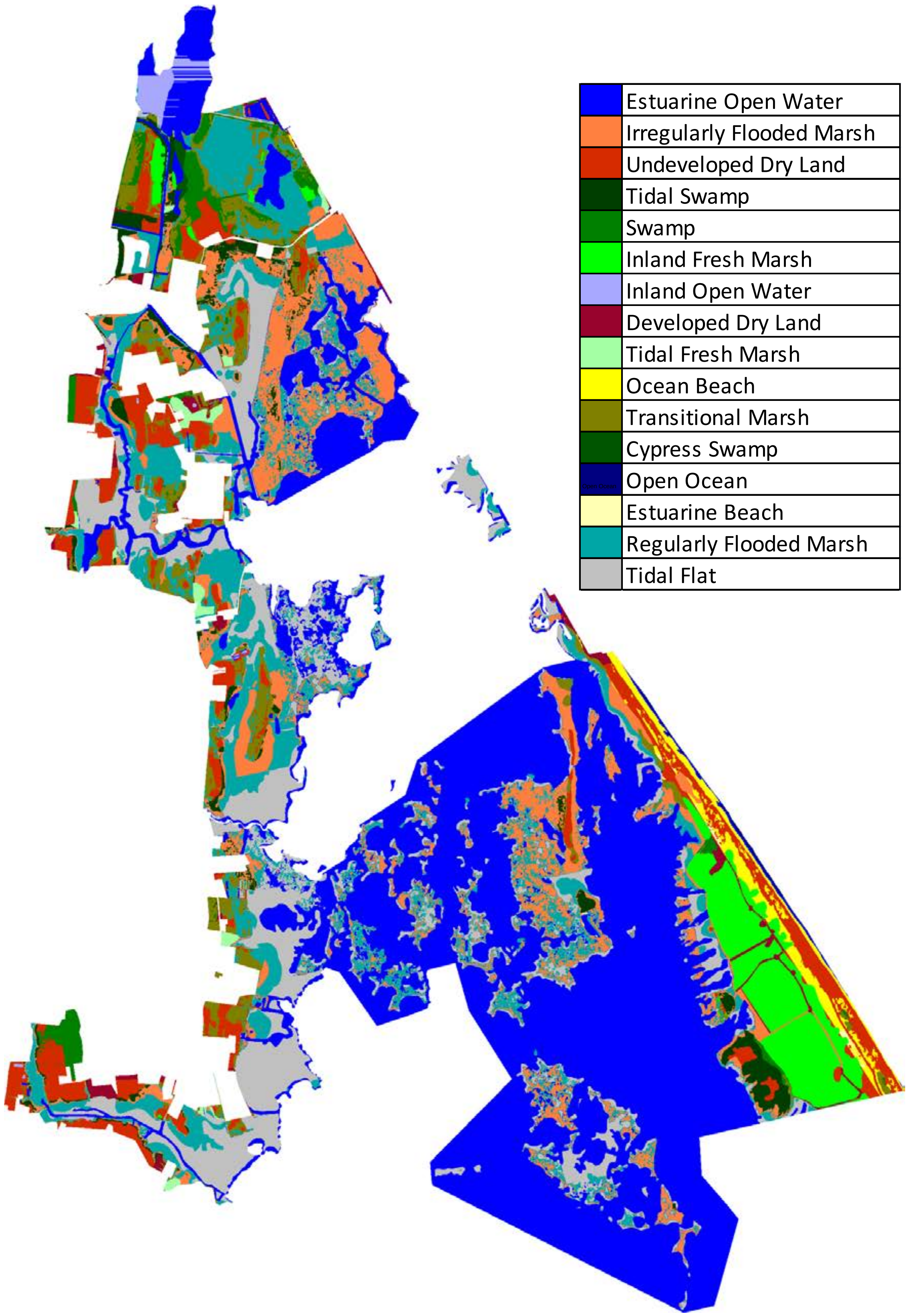
		Initial	2025	2050	2075	2100
	Estuarine Open Water	6137	6348	6831	9089	11301
	Irregularly Flooded Marsh	4621	2723	1567	566	166
	Undeveloped Dry Land	1907	1524	979	580	334
	Tidal Swamp	1112	729	344	152	70
	Swamp	817	462	260	119	49
	Inland Fresh Marsh	781	726	713	699	676
	Inland Open Water	345	182	86	59	57
	Developed Dry Land	232	188	142	87	59
	Tidal Fresh Marsh	109	92	77	40	26
	Ocean Beach	60	94	220	242	251
	Transitional Marsh	60	665	700	563	330
	Cypress Swamp	53	31	16	0	0
	Open Ocean	12	17	18	52	75
	Estuarine Beach	8	10	13	15	15
	Regularly Flooded Marsh	0	2241	2181	1887	1039
	Tidal Flat	0	223	2106	2101	1804
	Total (incl. water)	**16253**	**16253**	**16253**	**16253**	**16253**



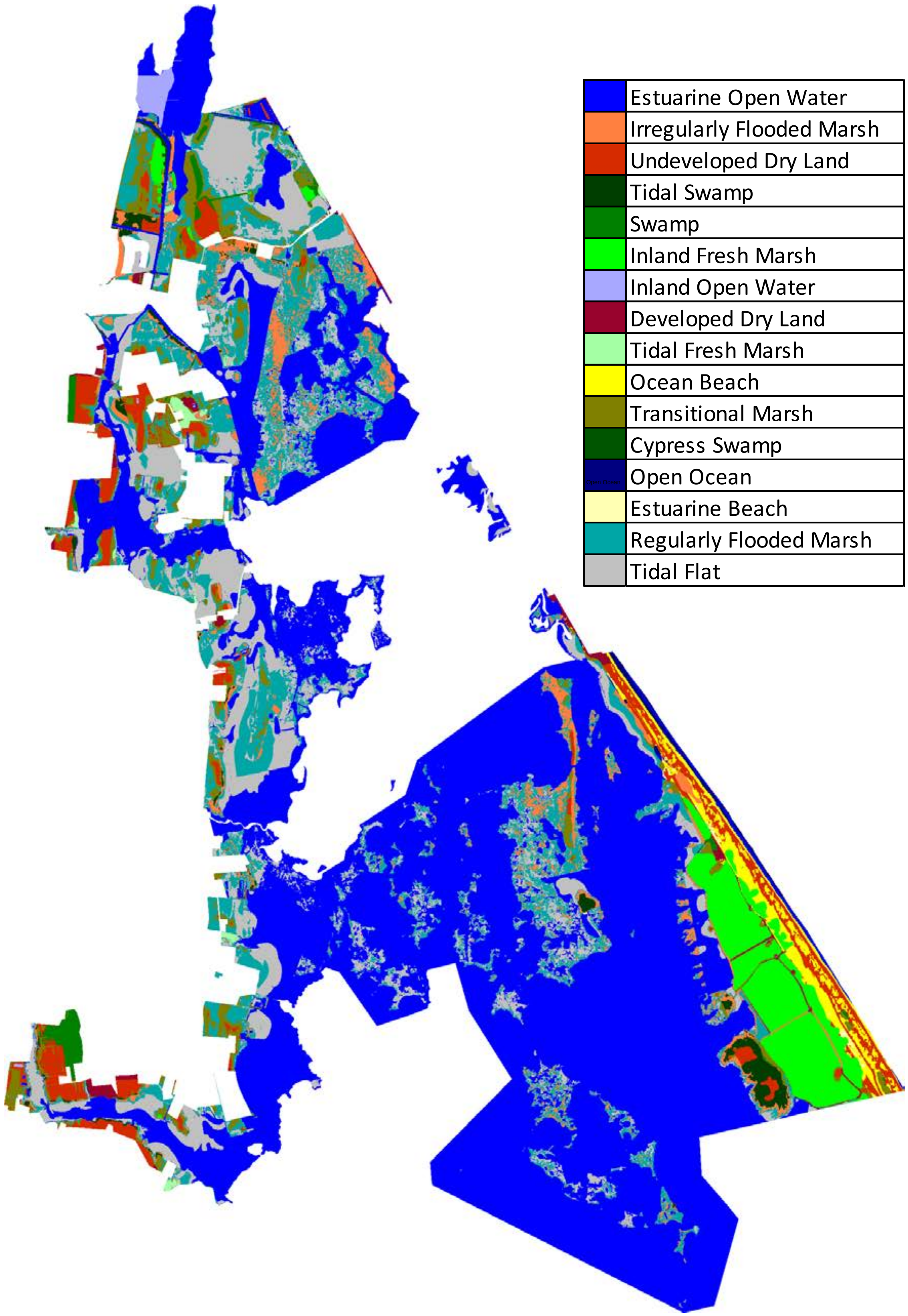
Back Bay NWR, Initial Condition



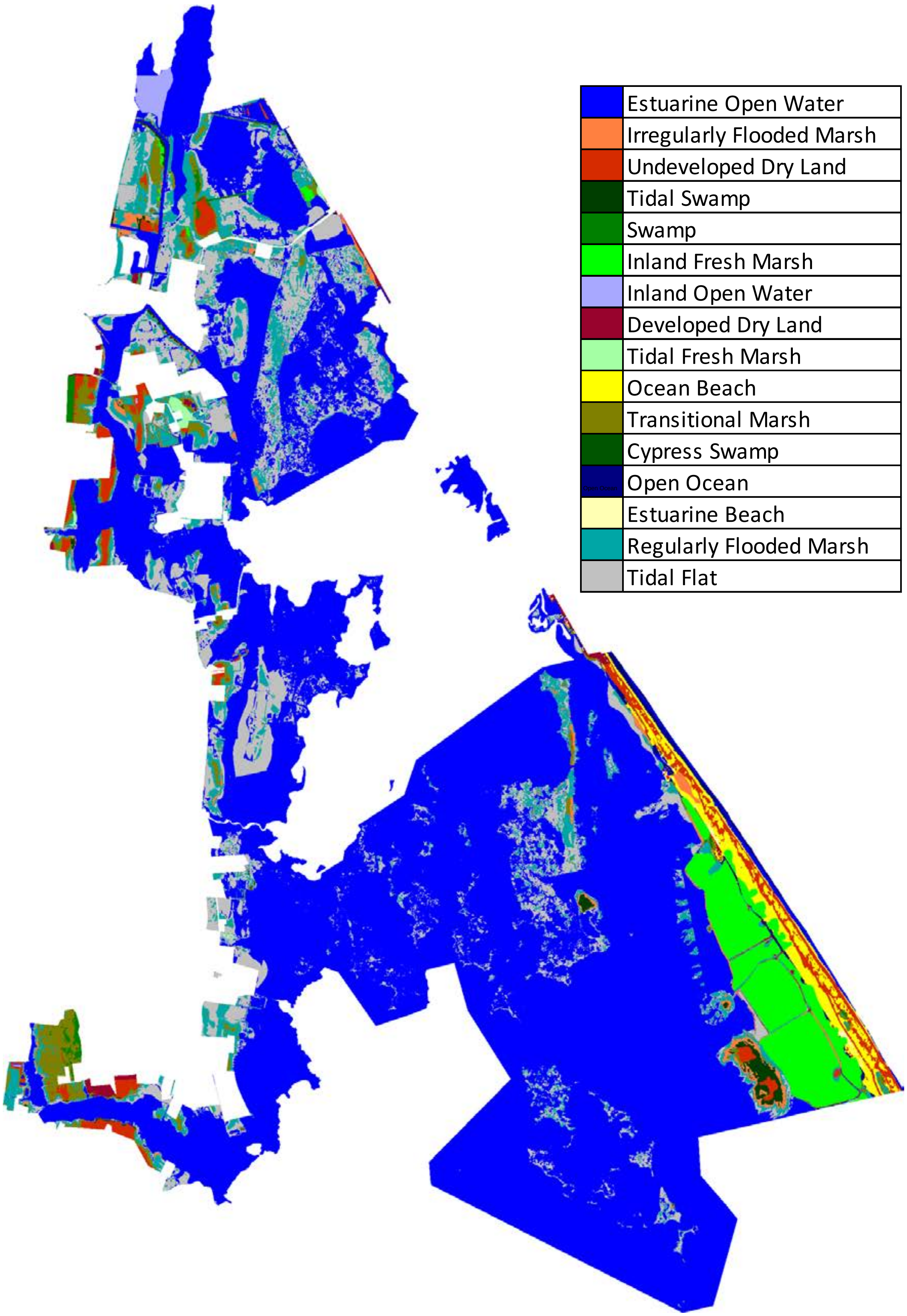
Back Bay NWR, 2025, 1 m SLR



Back Bay NWR, 2050, 1 m SLR



Back Bay NWR, 2075, 1 m SLR

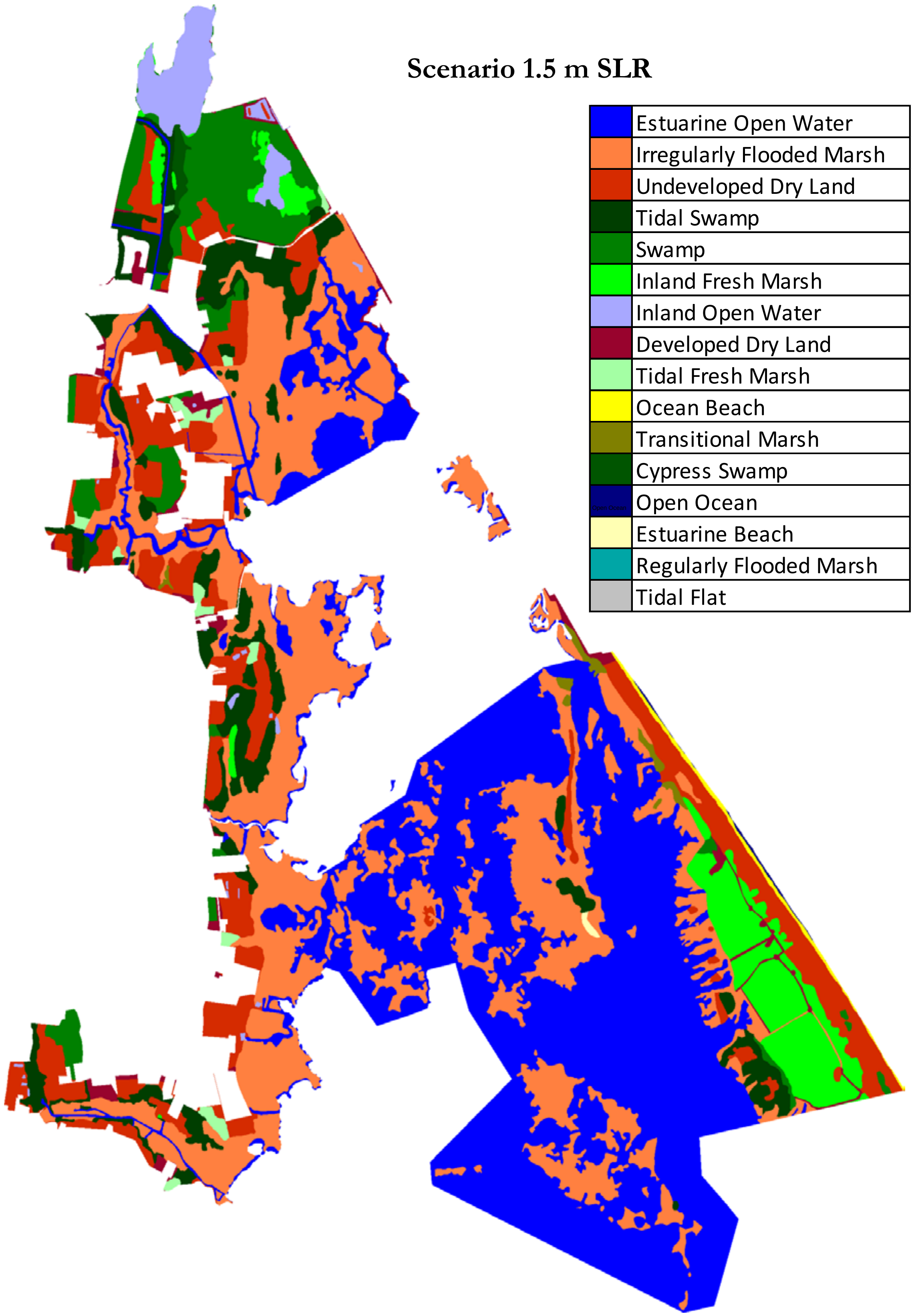


Back Bay NWR, 2100, 1 m SLR

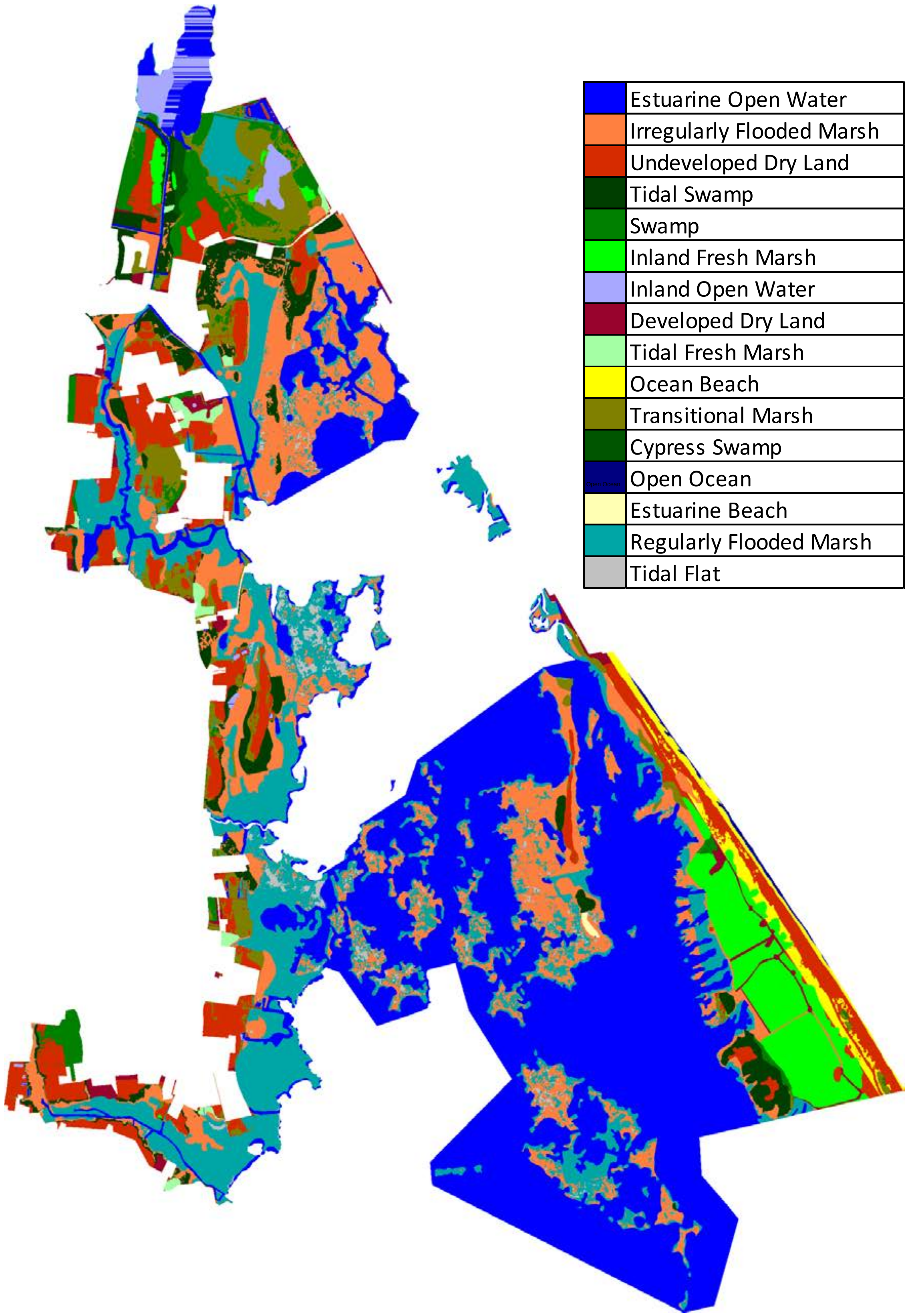
Back Bay NWR
1.5 m eustatic SLR by 2100

Results in Acres

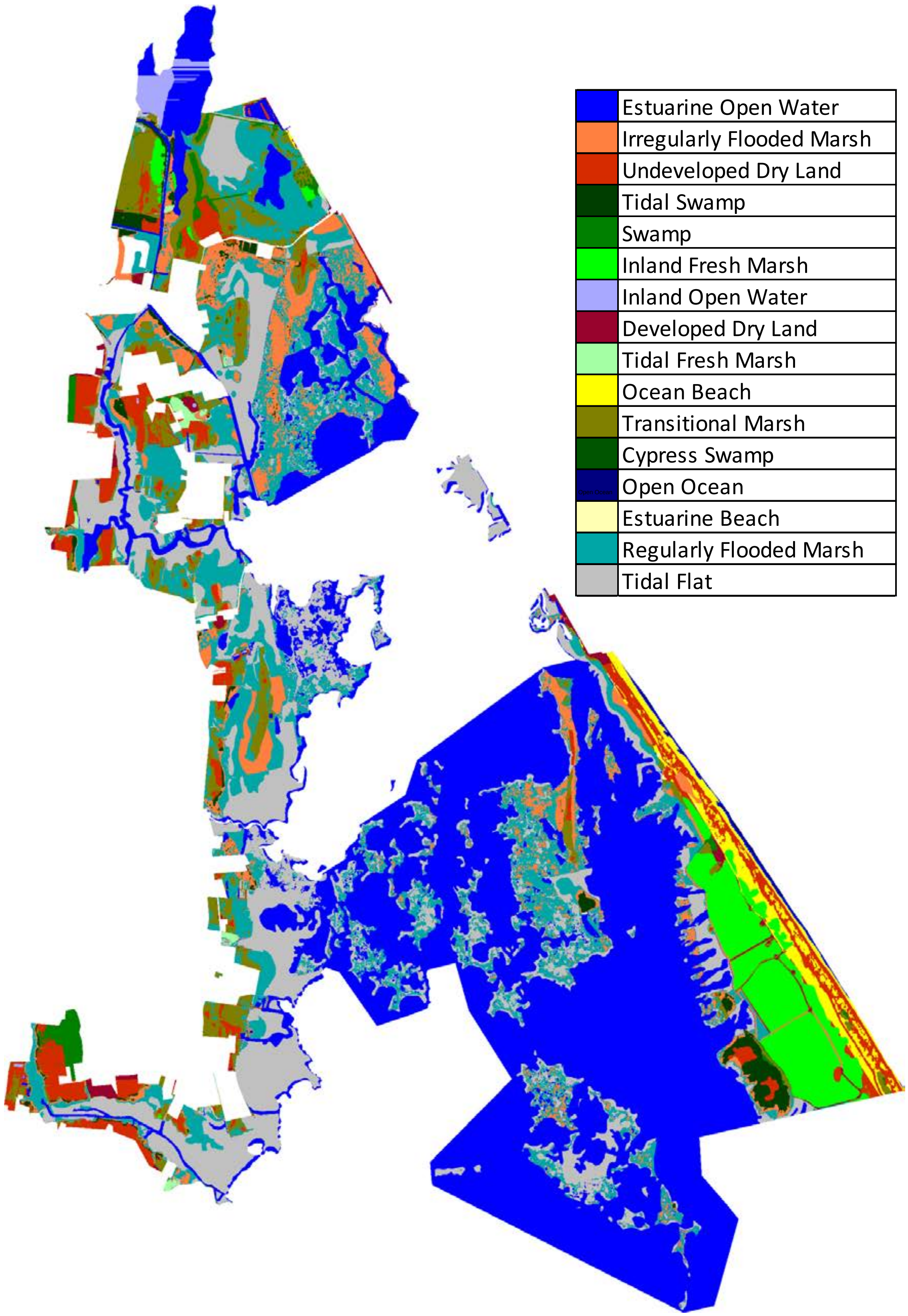
		Initial	2025	2050	2075	2100
	Estuarine Open Water	6137	6350	6894	9858	12288
	Irregularly Flooded Marsh	4621	2270	916	197	70
	Undeveloped Dry Land	1907	1311	729	344	188
	Tidal Swamp	1112	617	206	70	14
	Swamp	817	402	151	52	9
	Inland Fresh Marsh	781	715	700	674	667
	Inland Open Water	345	181	76	57	56
	Developed Dry Land	232	175	102	61	27
	Tidal Fresh Marsh	109	79	41	18	5
	Ocean Beach	60	214	269	279	221
	Transitional Marsh	60	681	873	492	199
	Cypress Swamp	53	31	0	0	0
	Open Ocean	12	17	22	68	151
	Estuarine Beach	8	10	6	9	9
	Regularly Flooded Marsh	0	2970	2436	1723	675
	Tidal Flat	0	230	2832	2350	1673
	Total (incl. water)	**16253**	**16253**	**16253**	**16253**	**16253**



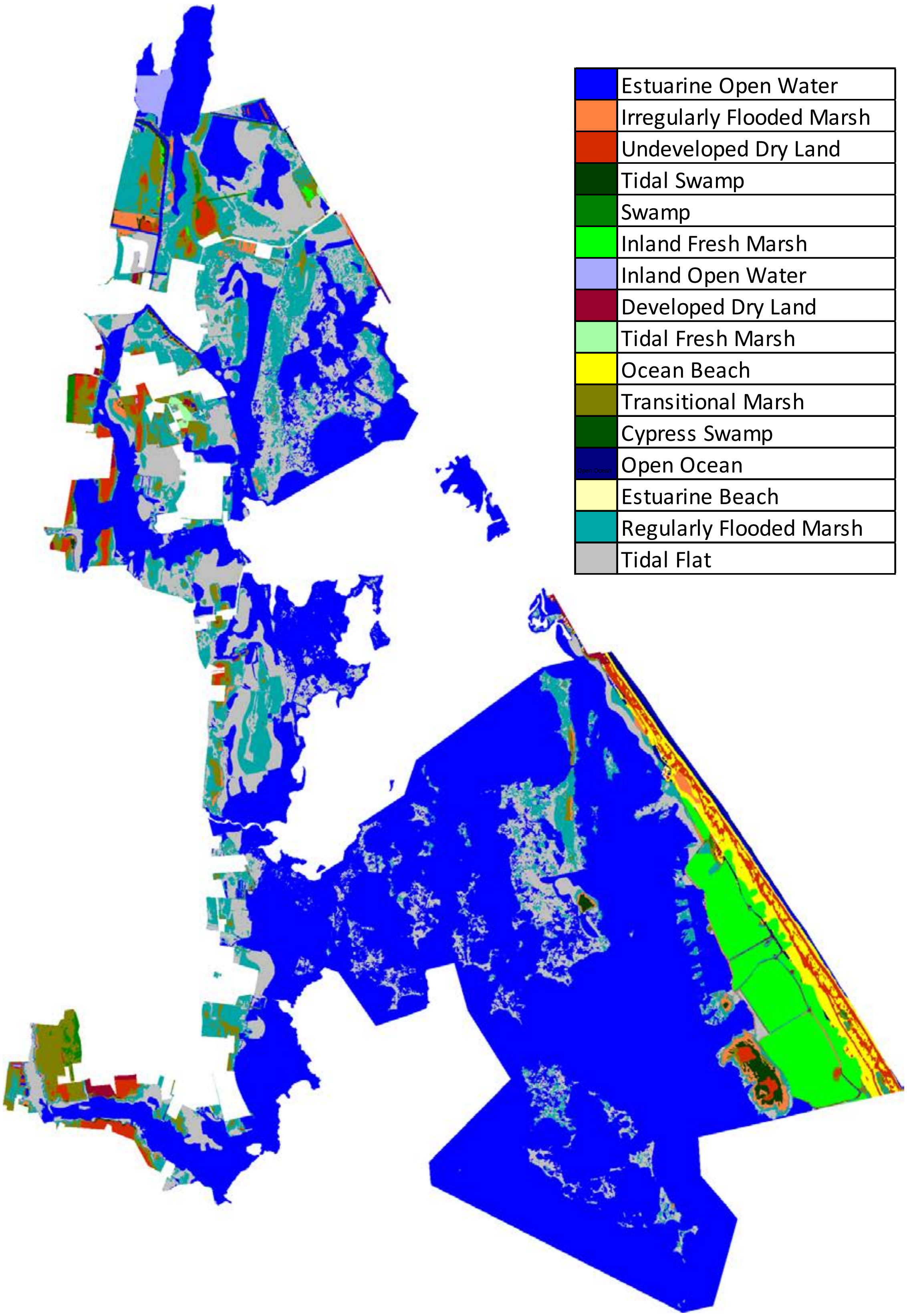
Back Bay NWR, Initial Condition



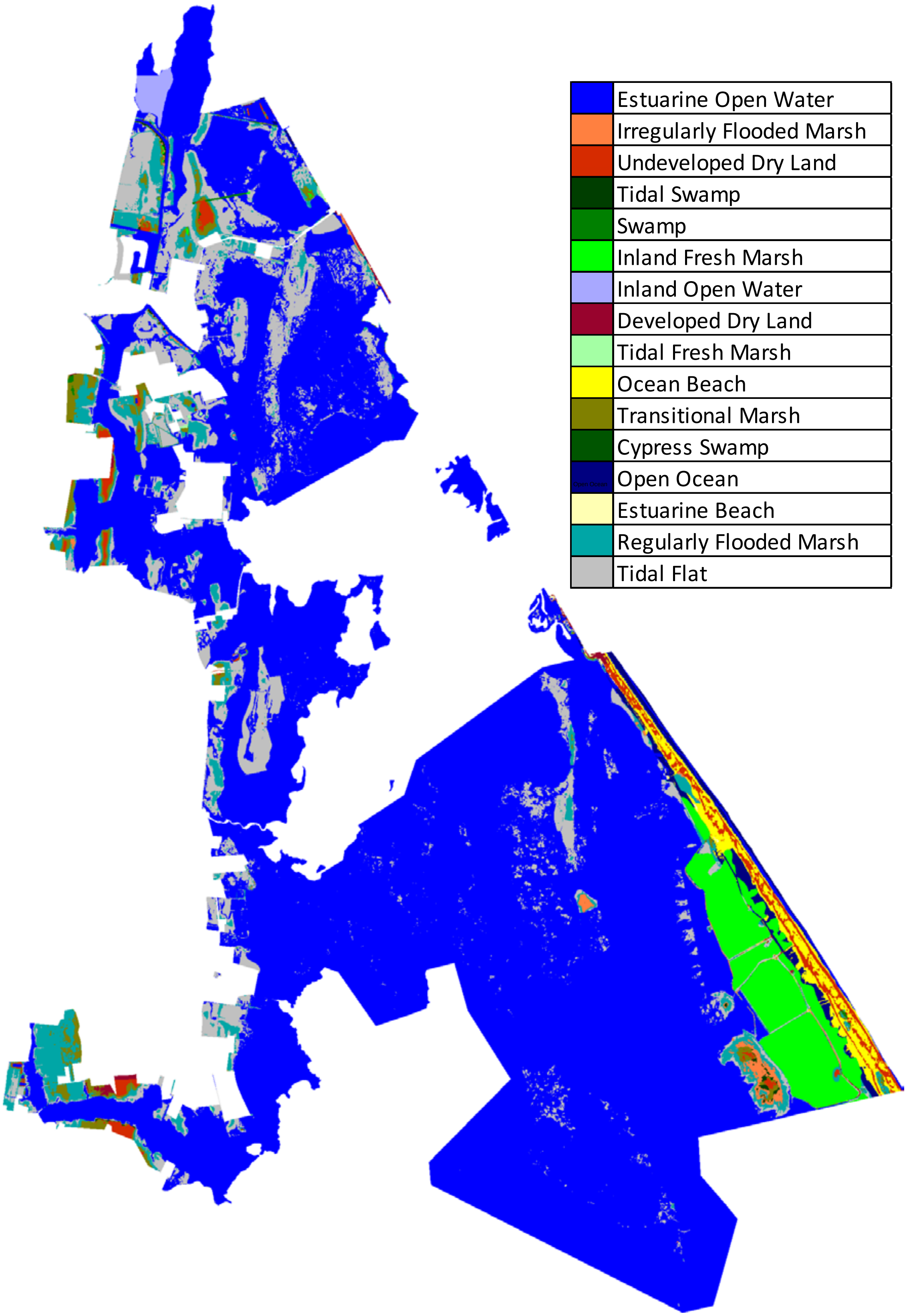
Back Bay NWR, 2025, 1.5 m SLR



Back Bay NWR, 2050, 1.5 m SLR



Back Bay NWR, 2075, 1.5 m SLR

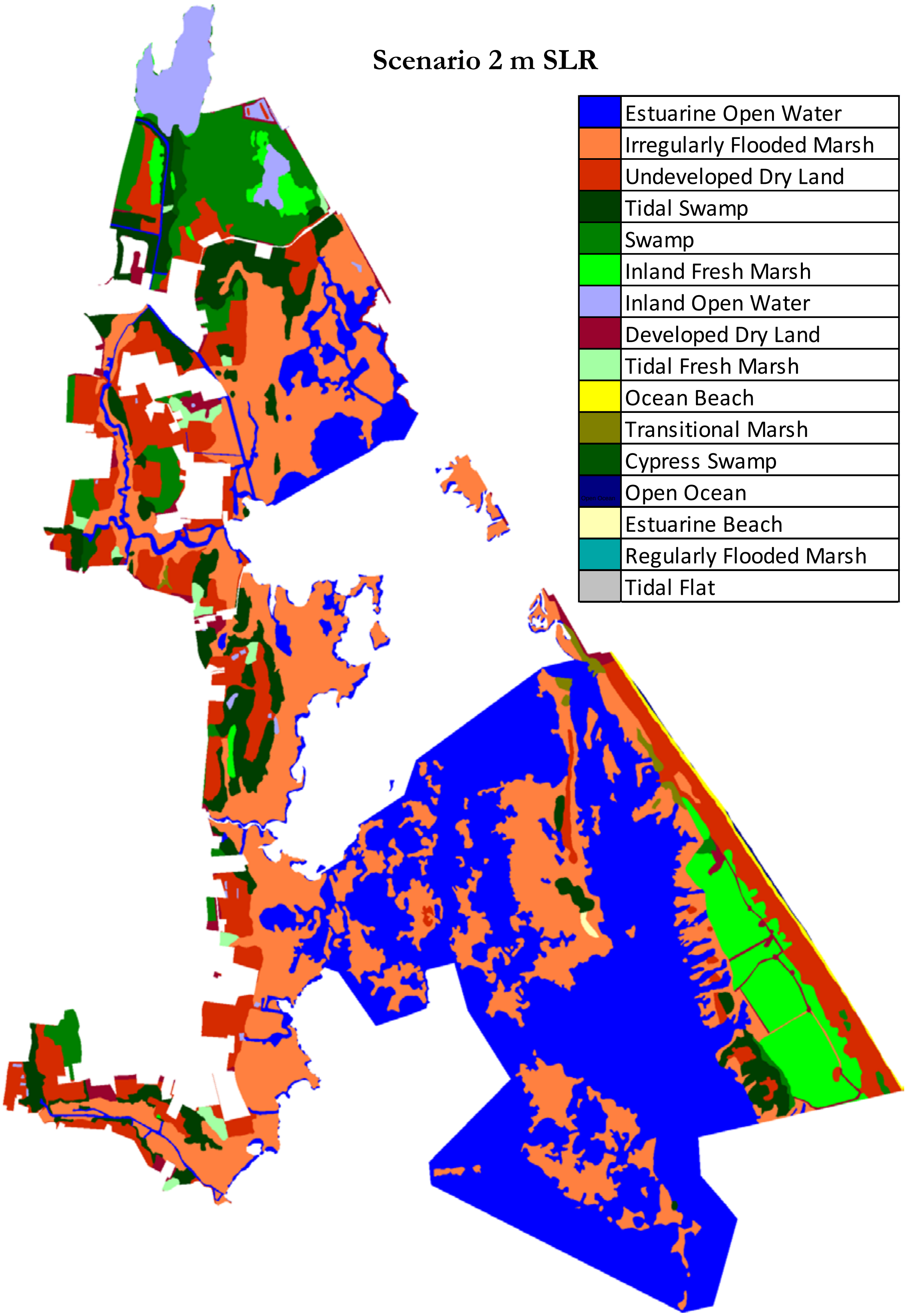


Back Bay NWR, 2100, 1.5 m SLR

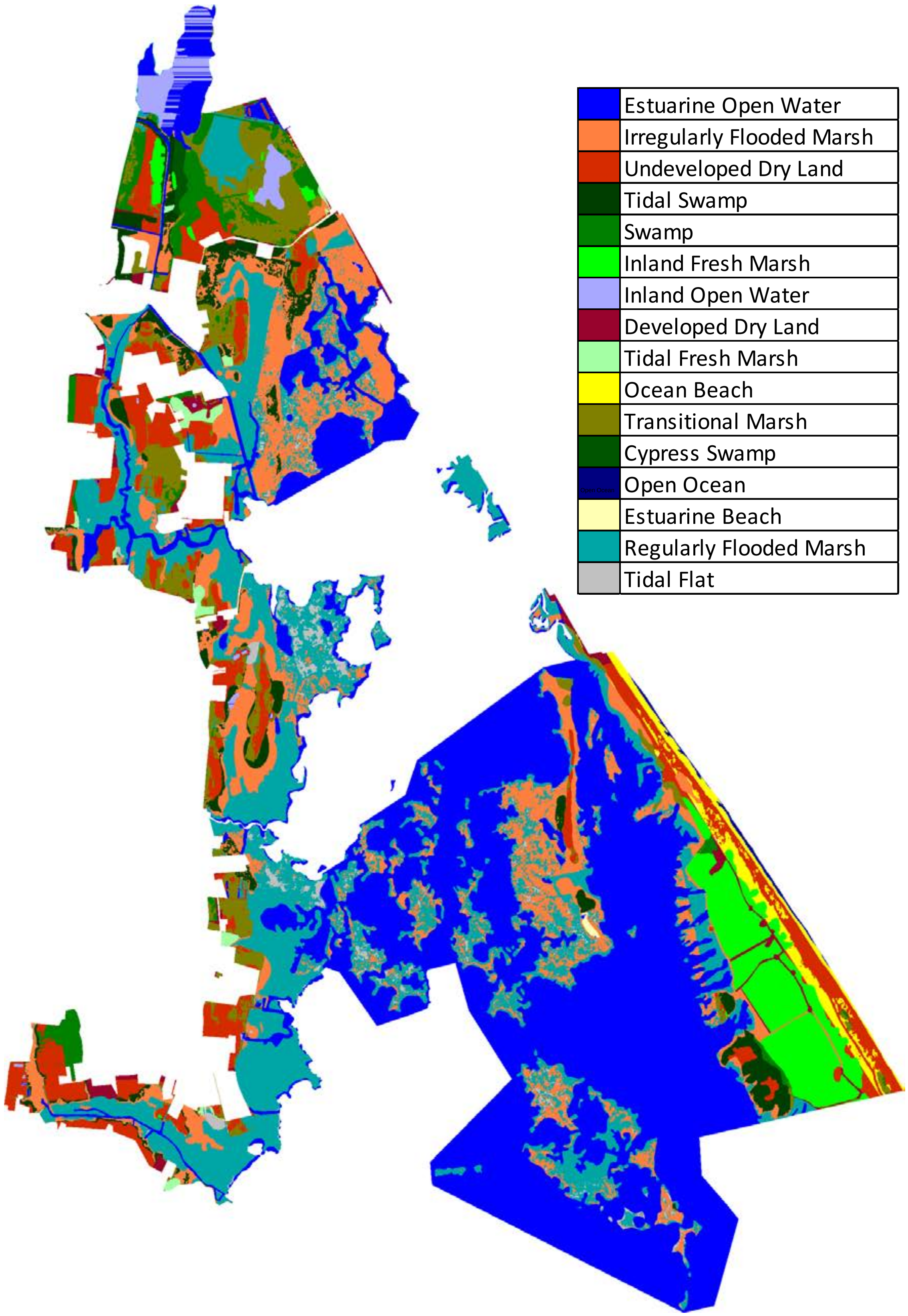
Back Bay NWR
2 m eustatic SLR by 2100

Results in Acres

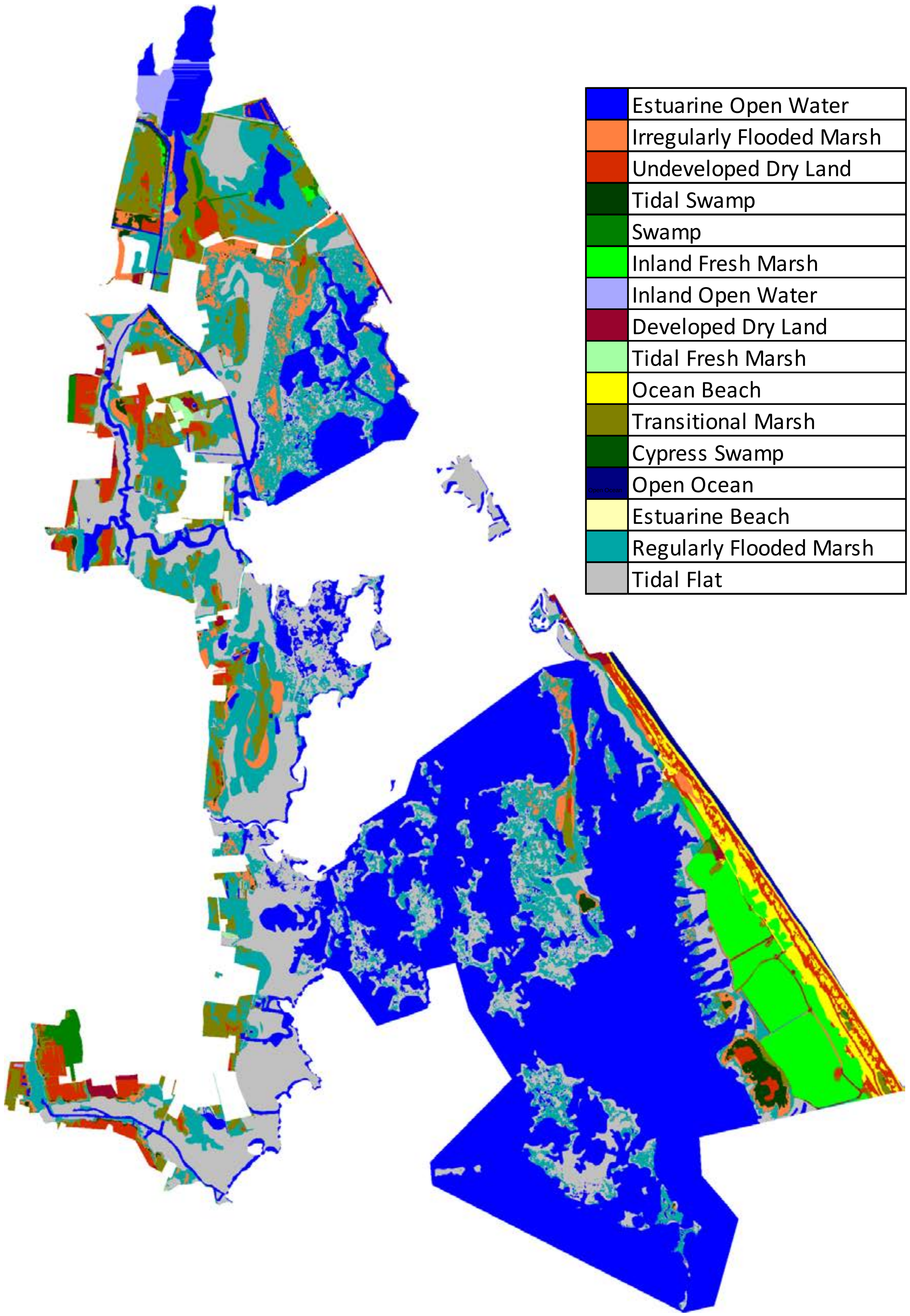
		Initial	2025	2050	2075	2100
	Estuarine Open Water	6137	6355	6939	10303	12900
	Irregularly Flooded Marsh	4621	1988	554	125	30
	Undeveloped Dry Land	1907	1189	556	229	113
	Tidal Swamp	1112	500	132	27	2
	Swamp	817	347	113	14	5
	Inland Fresh Marsh	781	712	677	668	661
	Inland Open Water	345	180	66	56	56
	Developed Dry Land	232	164	85	37	10
	Tidal Fresh Marsh	109	74	27	5	1
	Ocean Beach	60	229	265	268	188
	Transitional Marsh	60	829	911	416	110
	Cypress Swamp	53	31	0	0	0
	Open Ocean	12	17	59	113	227
	Estuarine Beach	8	10	8	11	8
	Regularly Flooded Marsh	0	3375	2618	1442	534
	Tidal Flat	0	253	3243	2540	1409
	Total (incl. water)	**16253**	**16253**	**16253**	**16253**	**16253**



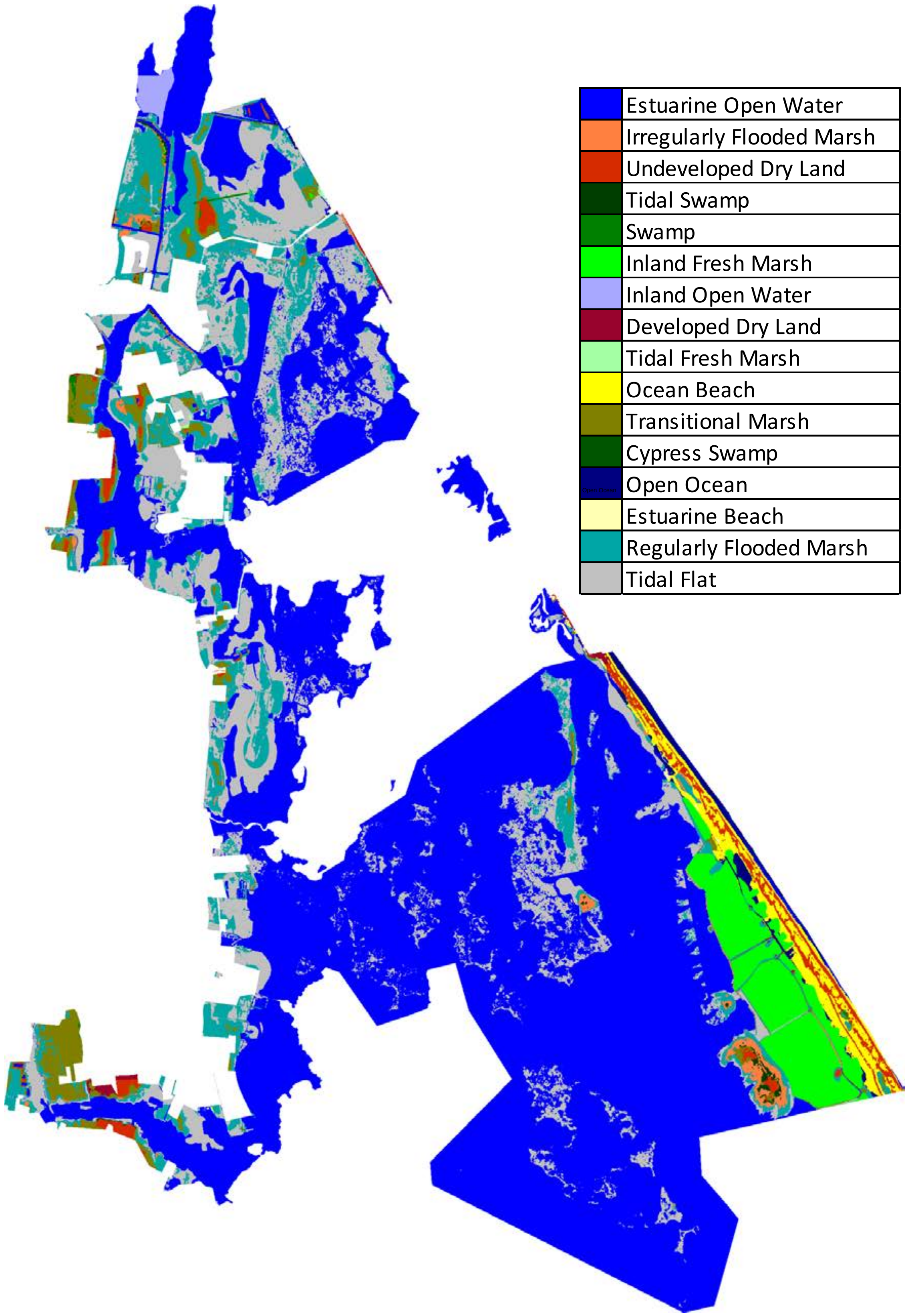
Back Bay NWR, Initial Condition



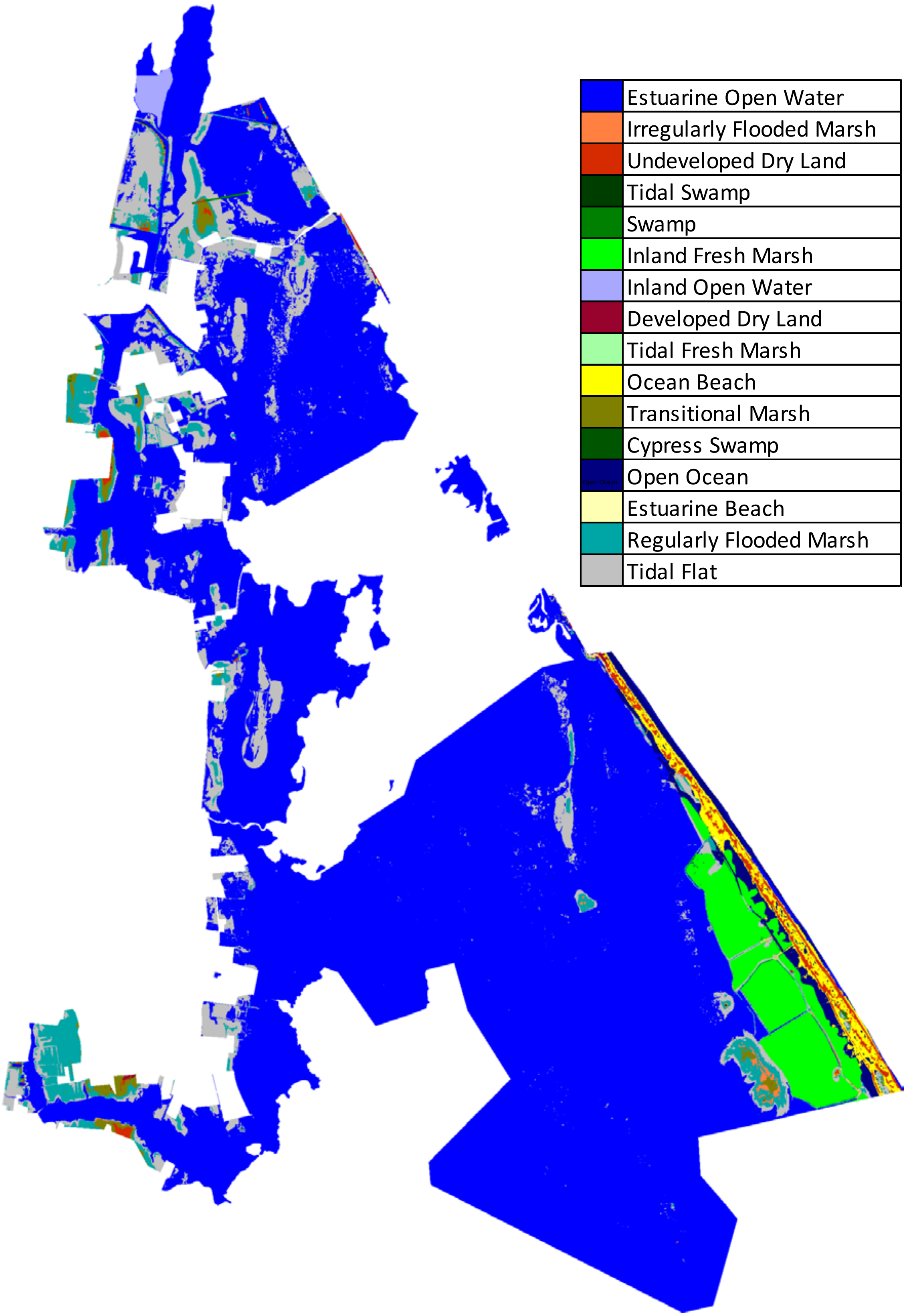
Back Bay NWR, 2025, 2 m SLR



Back Bay NWR, 2050, 2 m SLR



Back Bay NWR, 2075, 2 m SLR



Back NWR, 2100, 2 m SLR

Discussion

Model results for Back Bay NWR indicate that it is vulnerable to sea level rise under all SLR scenarios examined. The microtidal regime of the refuge makes its wetland habitat highly sensitive to SLR.

Excluding open water, irregularly-flooded marsh, swamp and inland-fresh marsh make up more than 90% of wetlands in the refuge today.

- When rates of sea-level rise exceeds predicted accretion rates in this region (true for all SLR scenarios examined), irregularly-flooded marsh are predicted to sustain considerable losses, over 55% 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.
- Similarly, refuge swamps are predicted to experience a minimum of 75% losses by 2100.
- Most of the inland-fresh marshes within the refuge are protected by dikes and therefore this wetland type is highly resilient for all SLR scenarios. This simulation assumes that dikes will be maintained against up to two meters of local SLR.

Local accretion data were not available for this site, and accretion values were estimated using data from the nearby Cedar Island, NC. Local data regarding accretion rates within the refuge itself could provide better predictions of marsh losses in the future.

An examination of SLAMM predictions suggests that the barrier islands within this refuge will be regularly overtopped by ocean water under SLR scenarios of 1 meter or more. SLAMM does not simulate the effects of permanent overwash of the barrier islands protecting the island. Such a change in coastal morphometry would have significant effects on local tide range and salinity.

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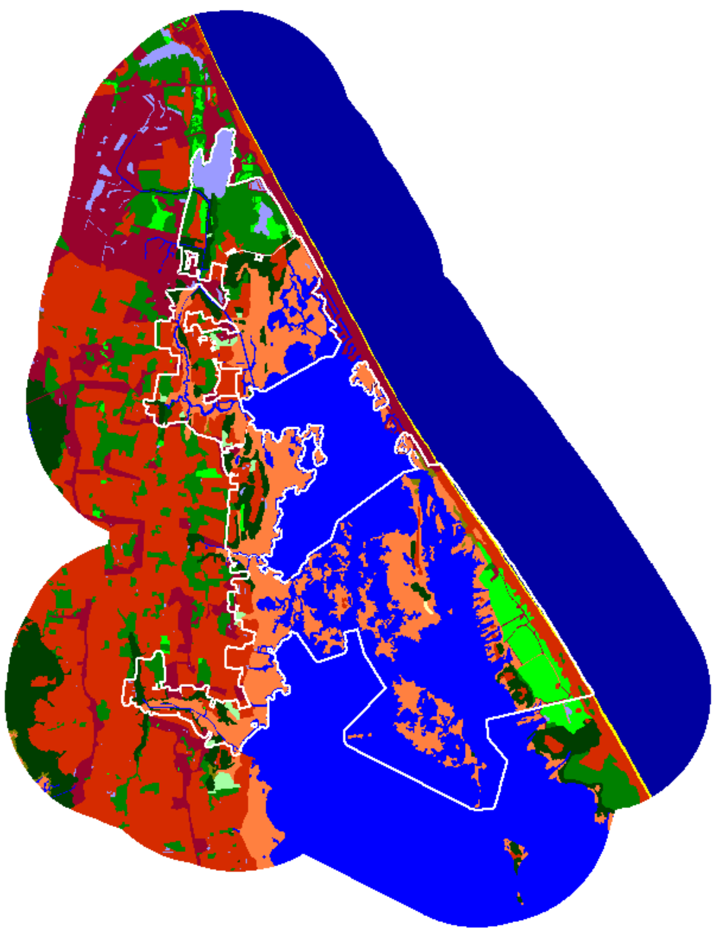
Appendix A: Contextual Results

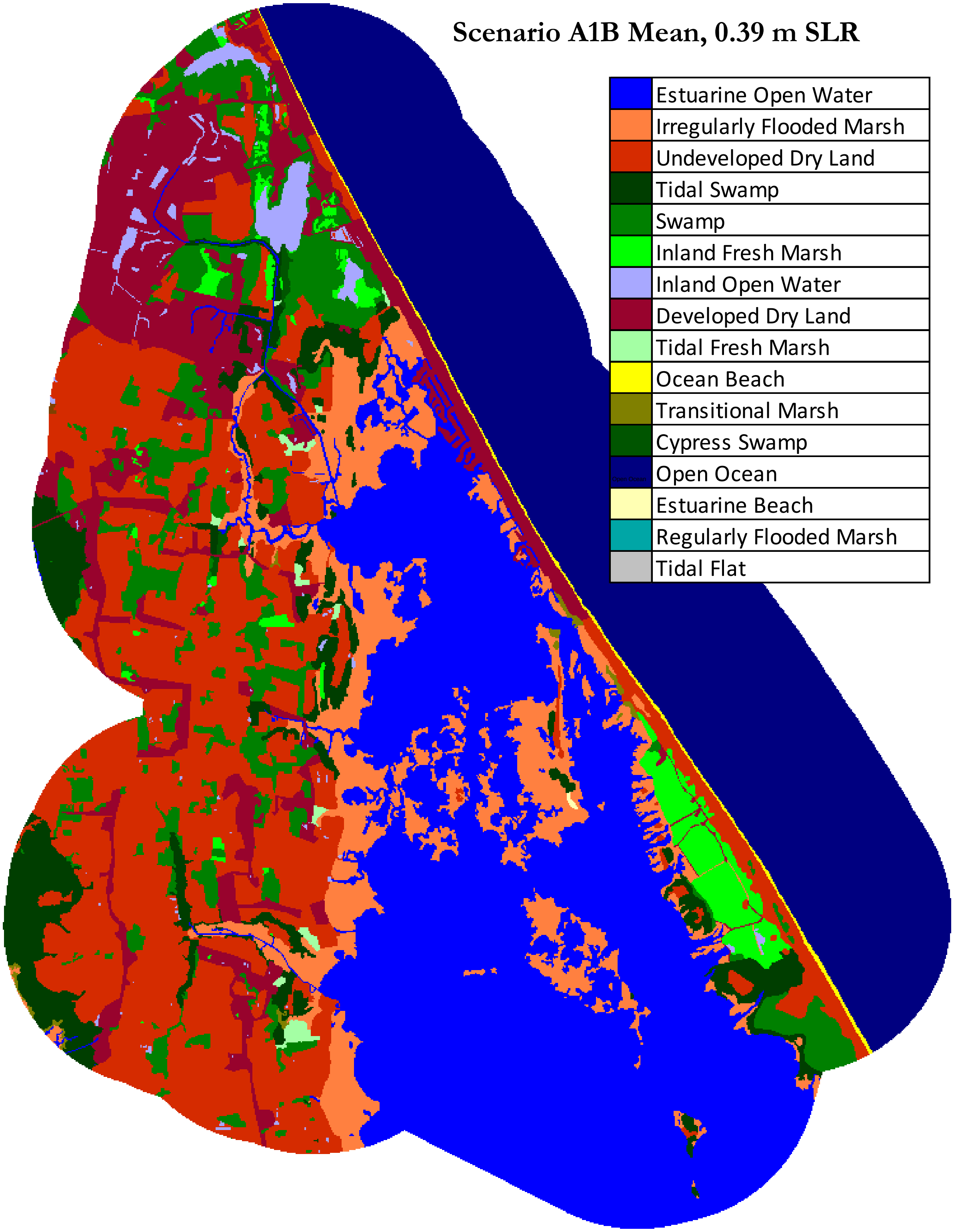
The SLAMM model does take into account the context of the surrounding lands or open water when calculating effects. For example, erosion rates are calculated based on the maximum fetch (wave action) which is estimated by assessing contiguous open water to a given marsh cell. Another example is that inundated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

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

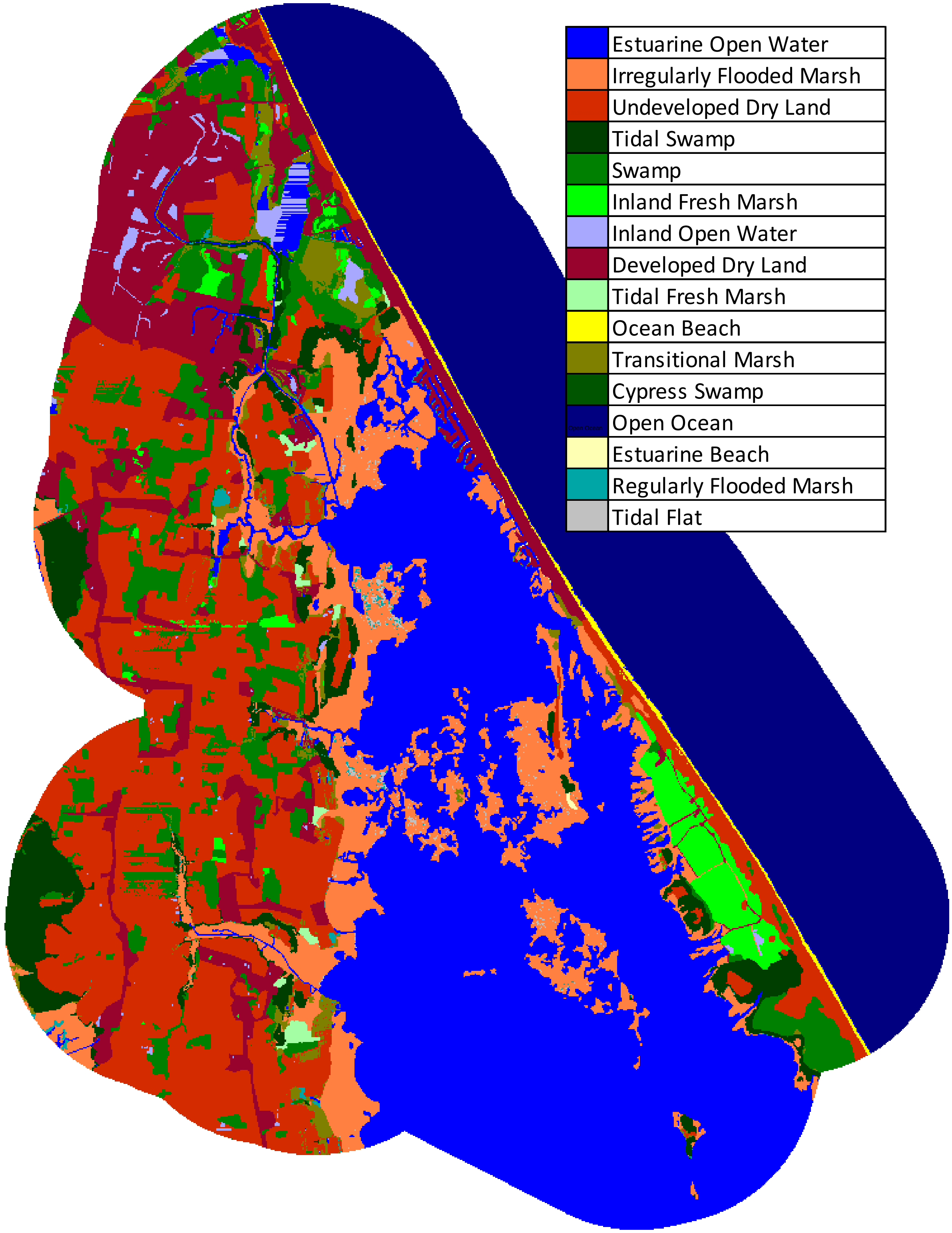
- Results were closely examined (quality assurance) within USFWS refuges but not closely examined for the larger region.
- Site-specific parameters for the model were derived for USFWS refuges whenever possible and may not be regionally applicable.
- Especially in areas where dikes are present, an effort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



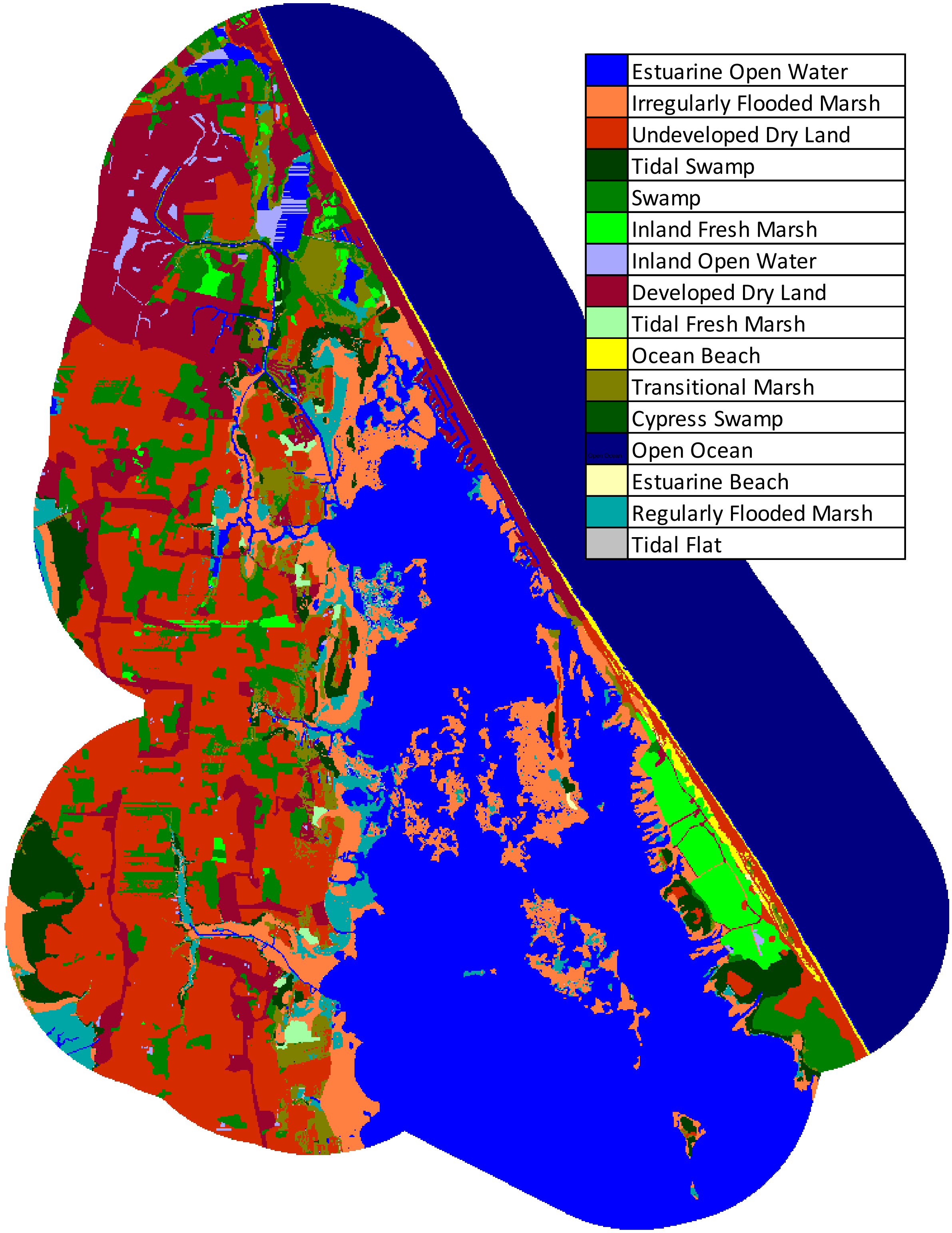
Back Bay NWR within simulation context.



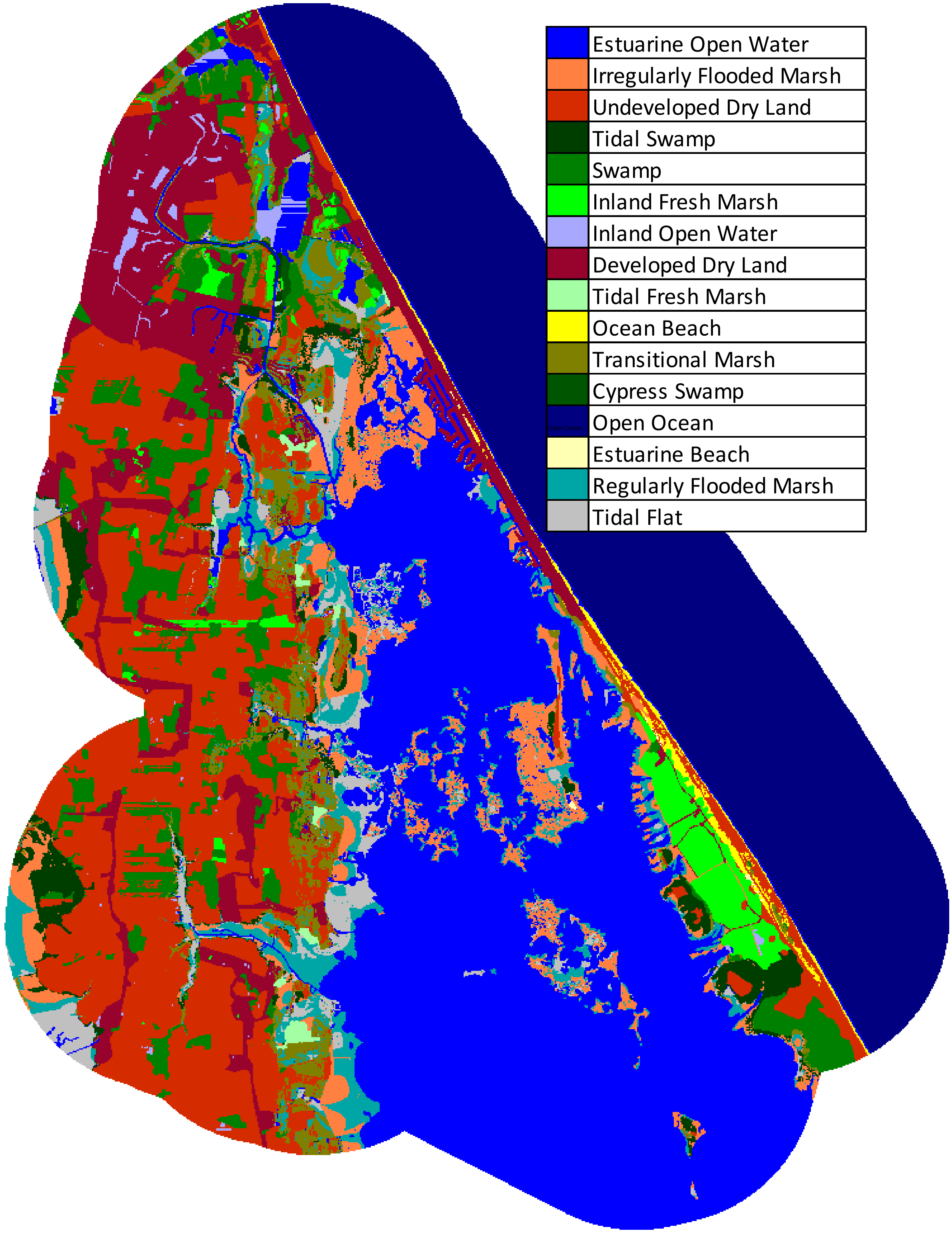
Back Bay context, Initial conditions



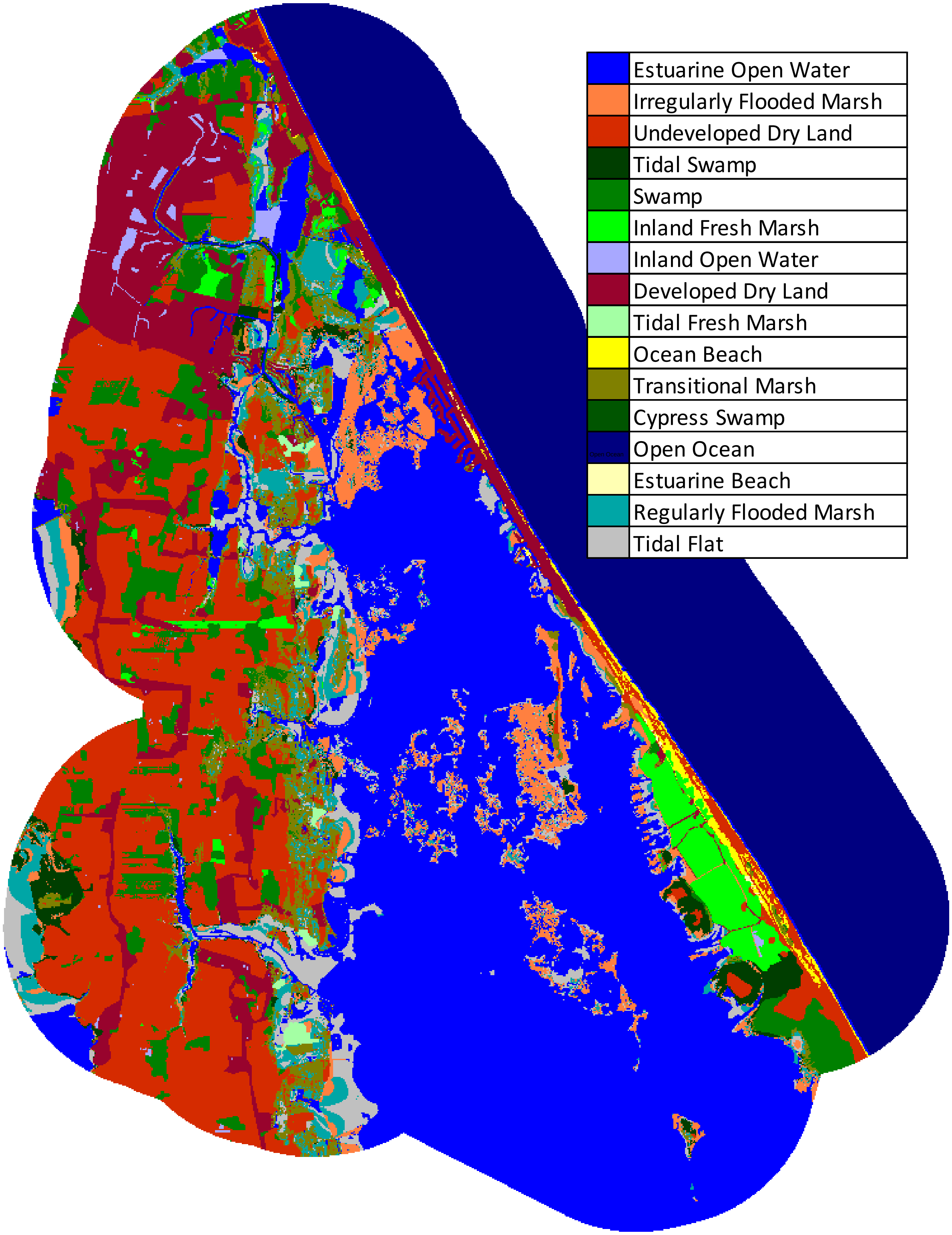
Back Bay context, 2025, Scenario A1B Mean, 0.39 m SLR



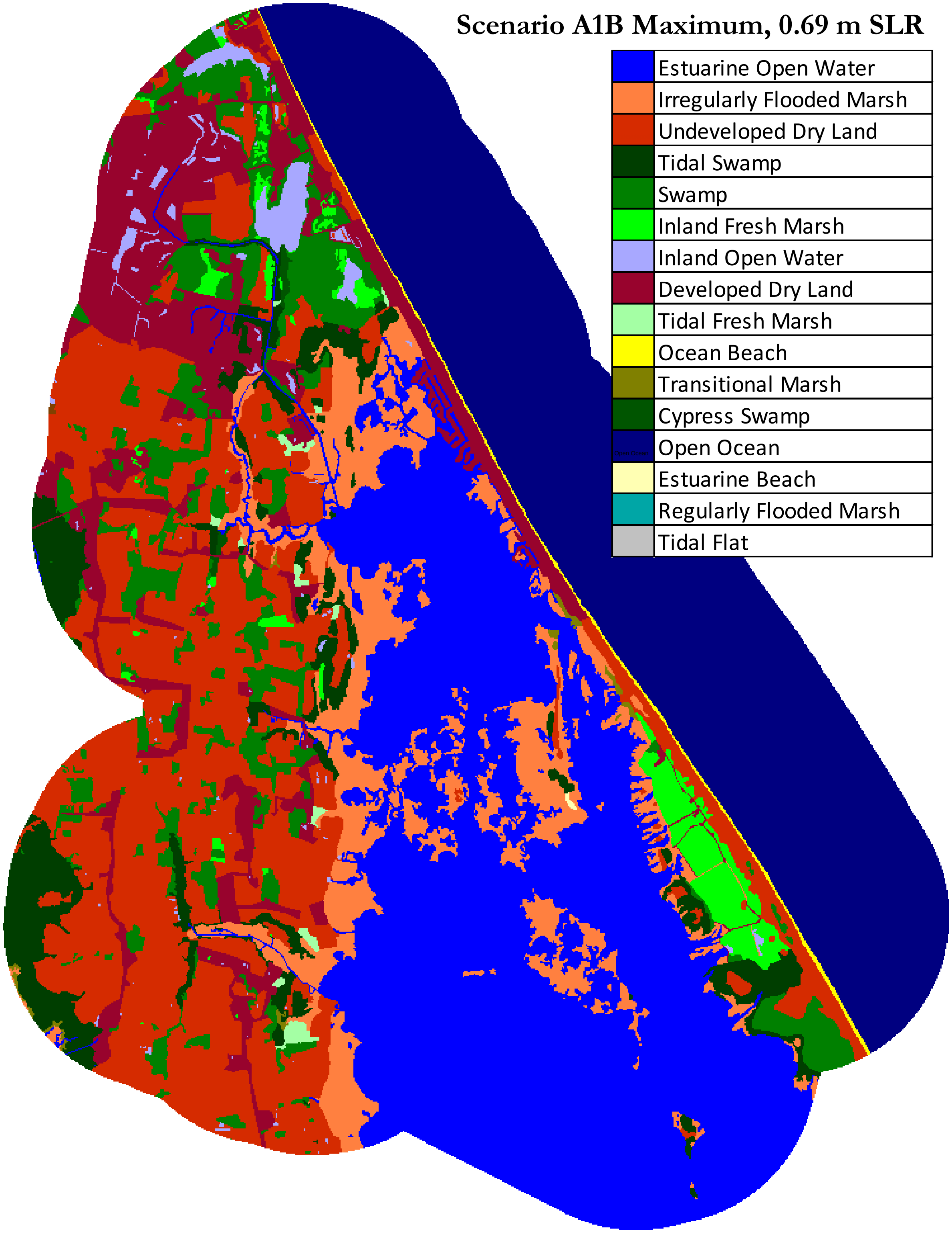
Back Bay context, 2050, Scenario A1B Mean, 0.39 m SLR



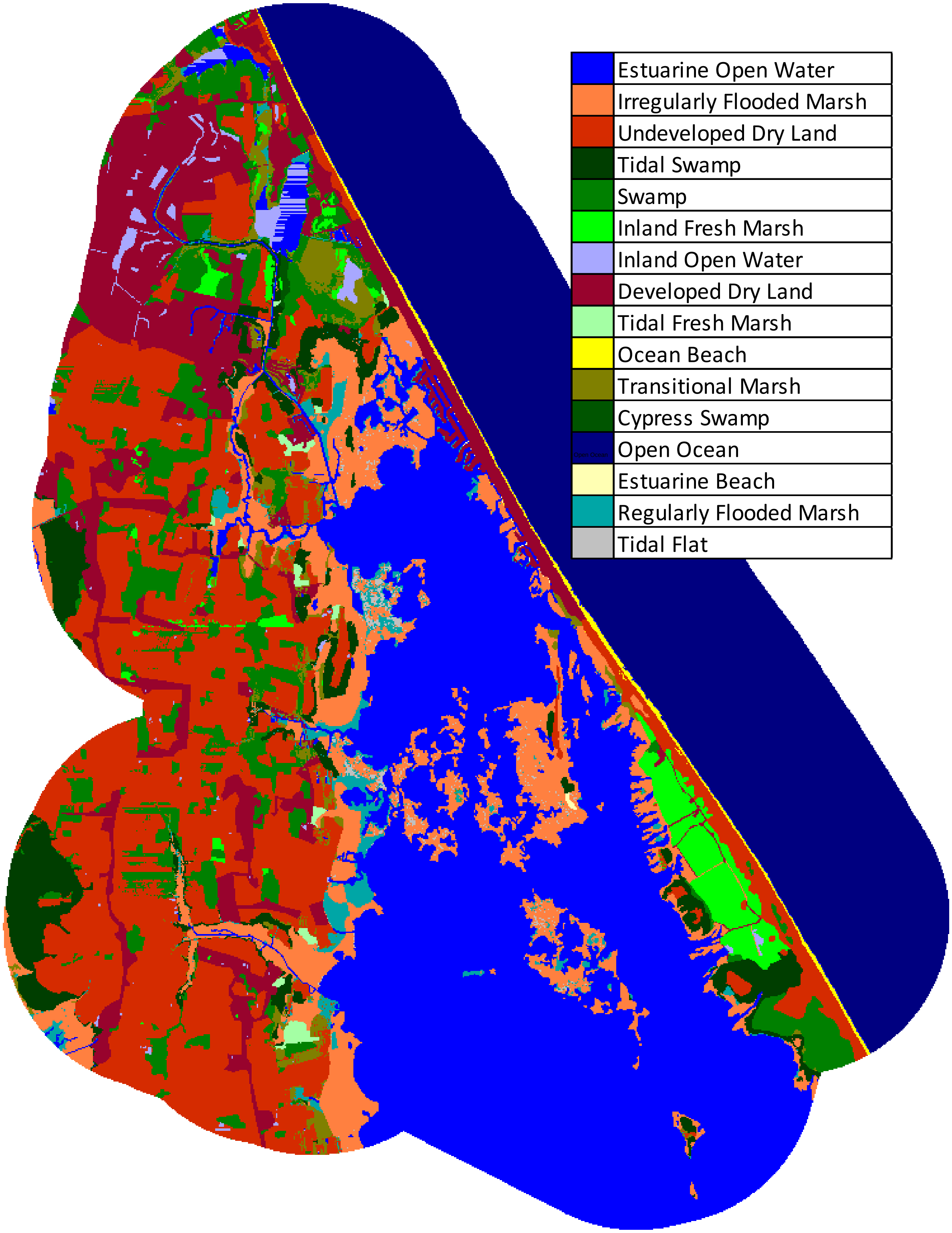
Back Bay context, 2075, Scenario A1B Mean, 0.39 m SLR



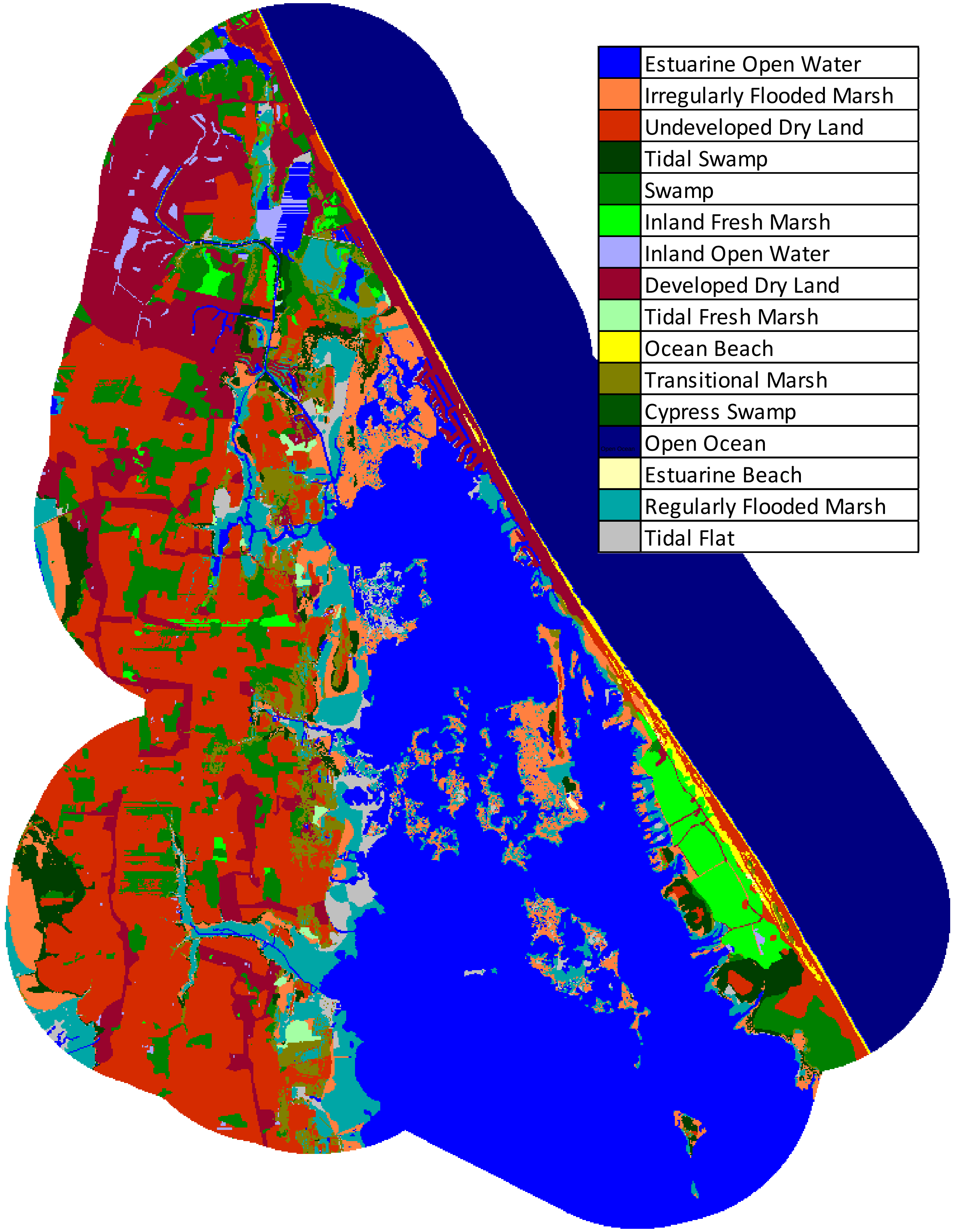
Back Bay context, 2100, Scenario A1B Mean, 0.39 m SLR



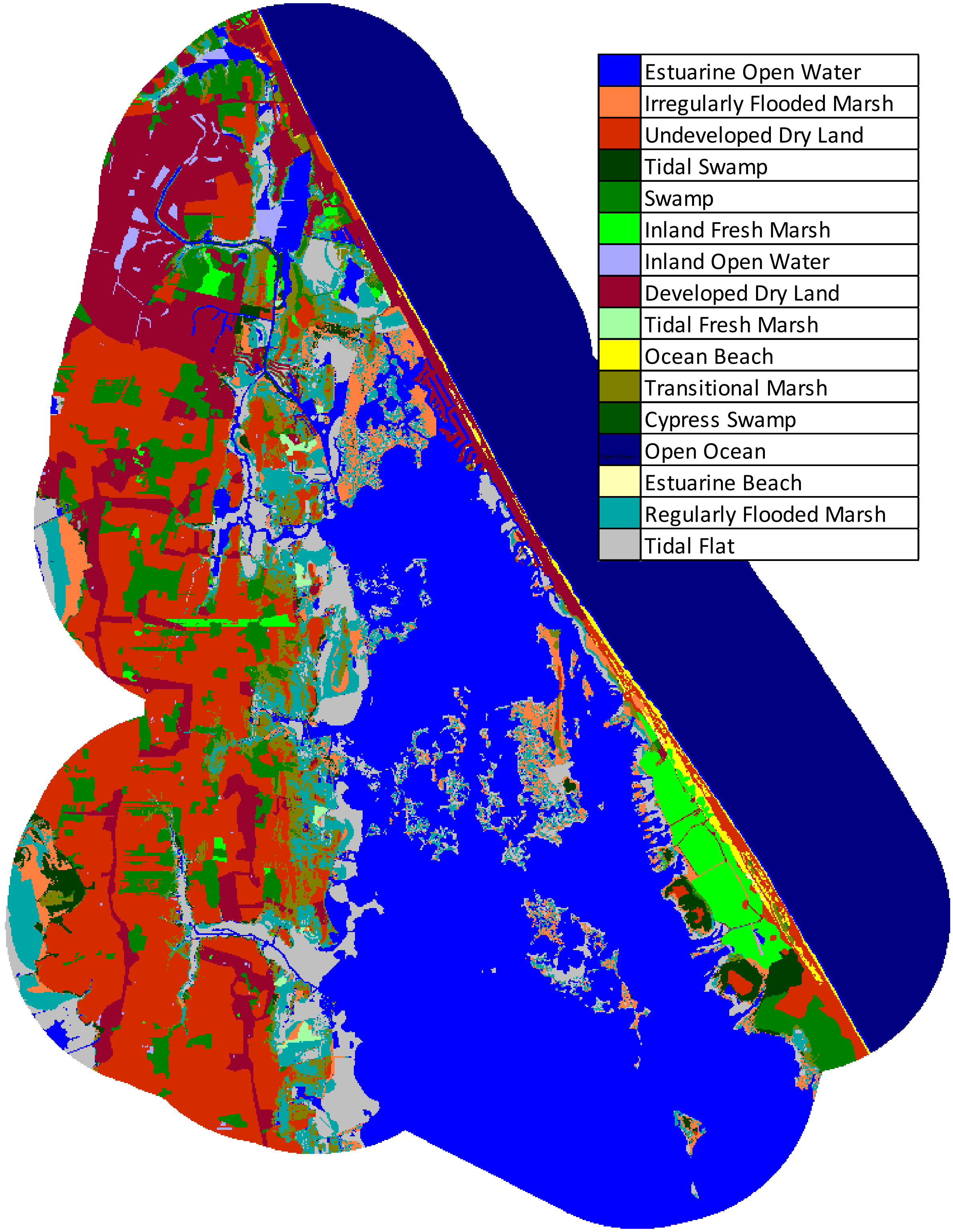
Back Bay context, Initial Condition



Back Bay context, 2025, Scenario A1B Maximum, 0.69 m SLR



Back Bay context, 2050, Scenario A1B Maximum, 0.69 m SLR



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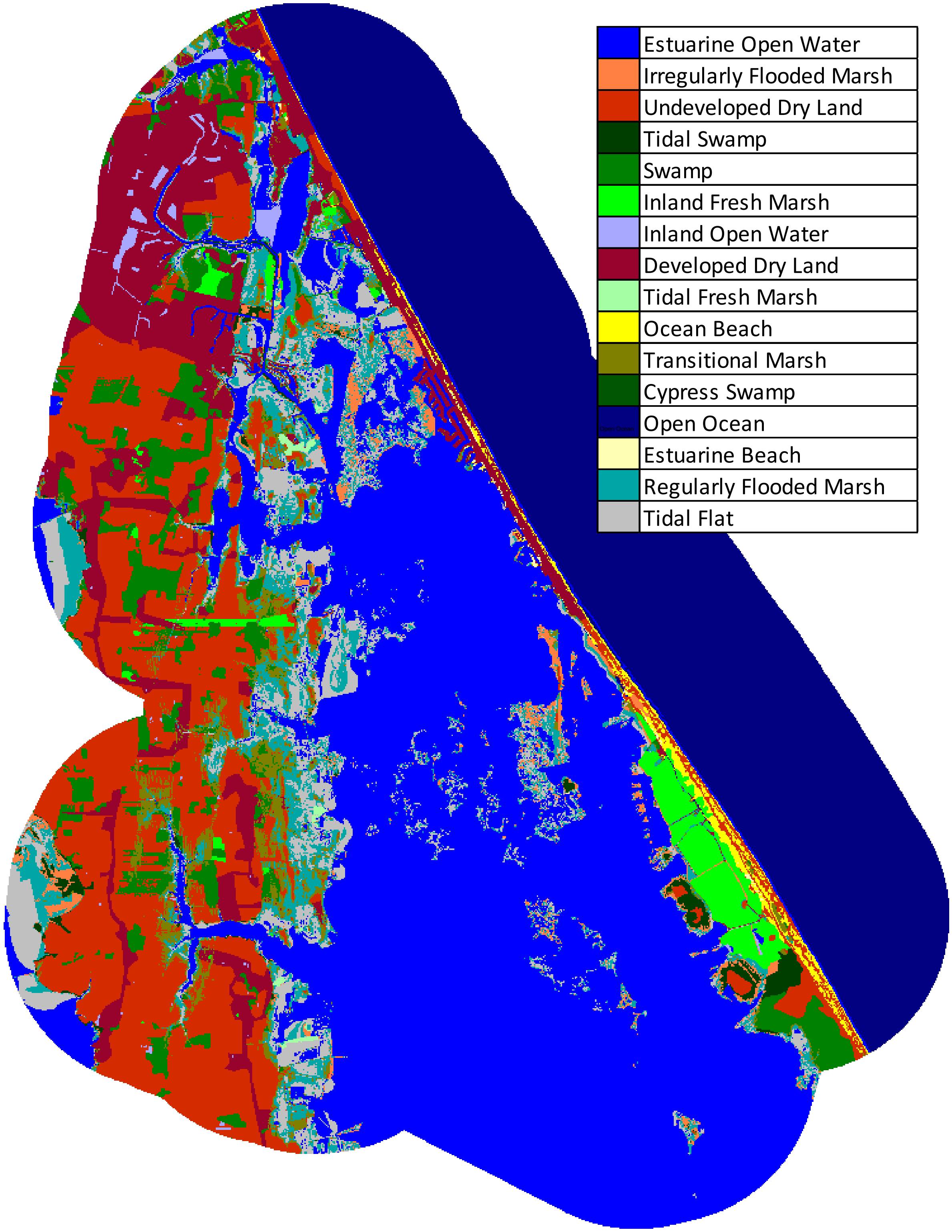
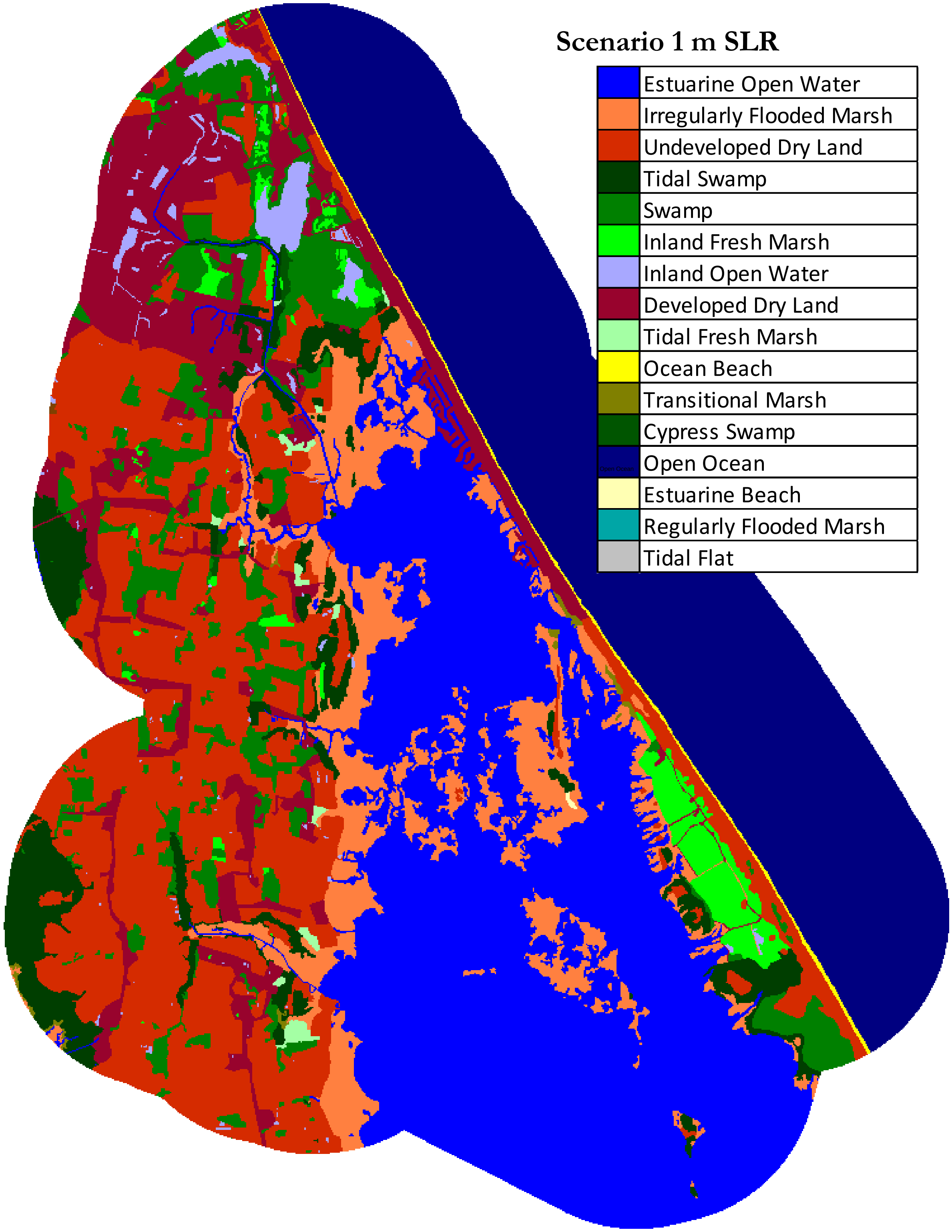
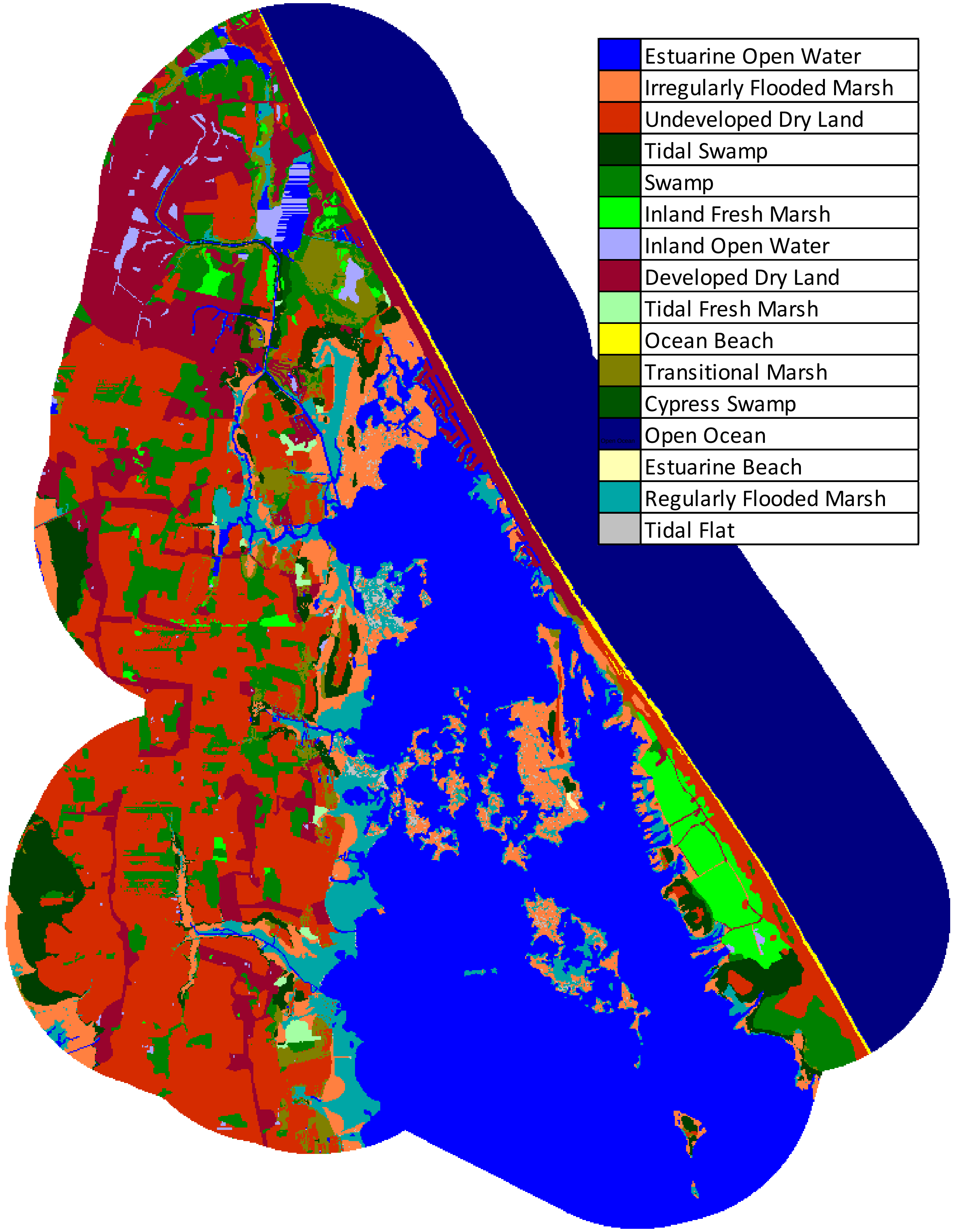


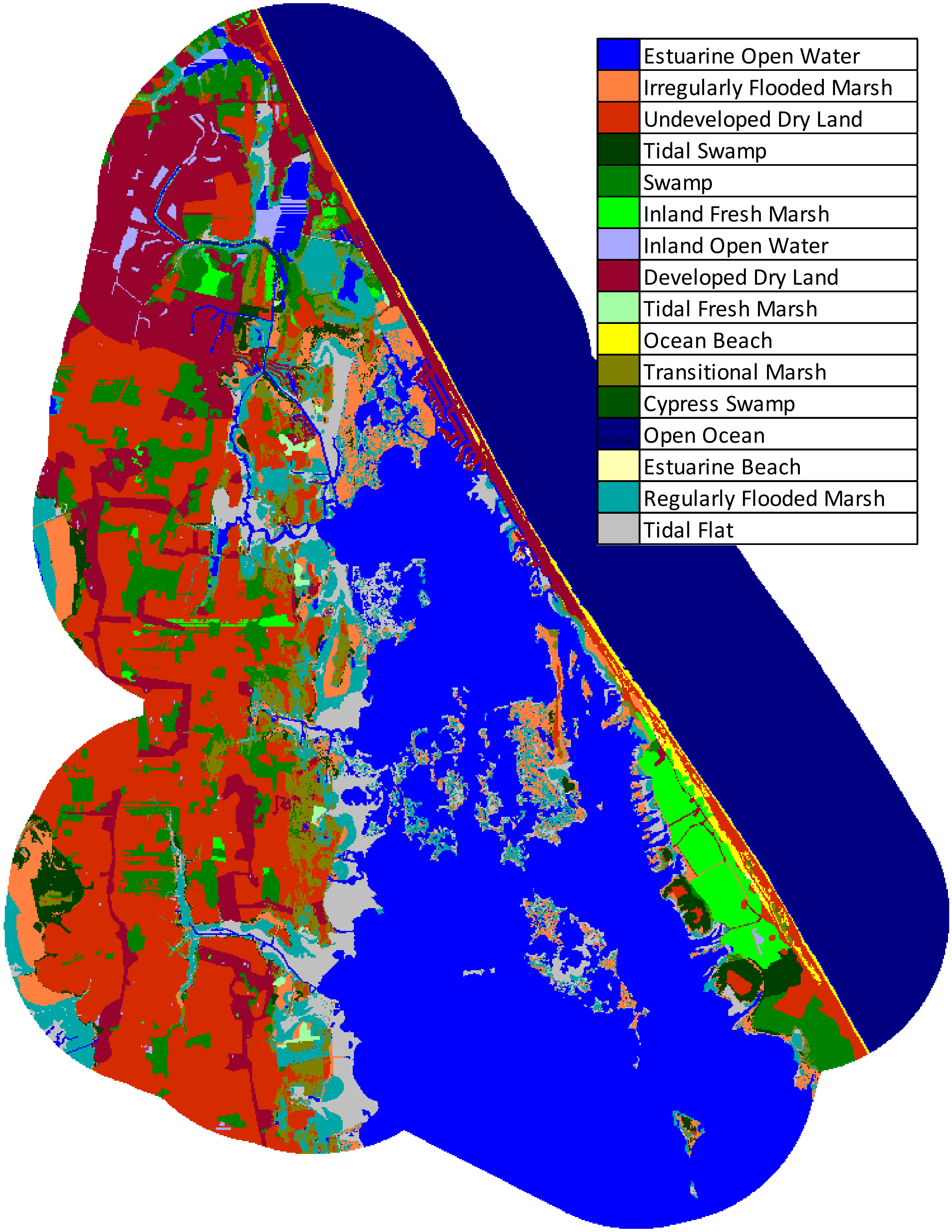
Back Bay context, 2100, Scenario A1B Maximum, 0.69 m SLR



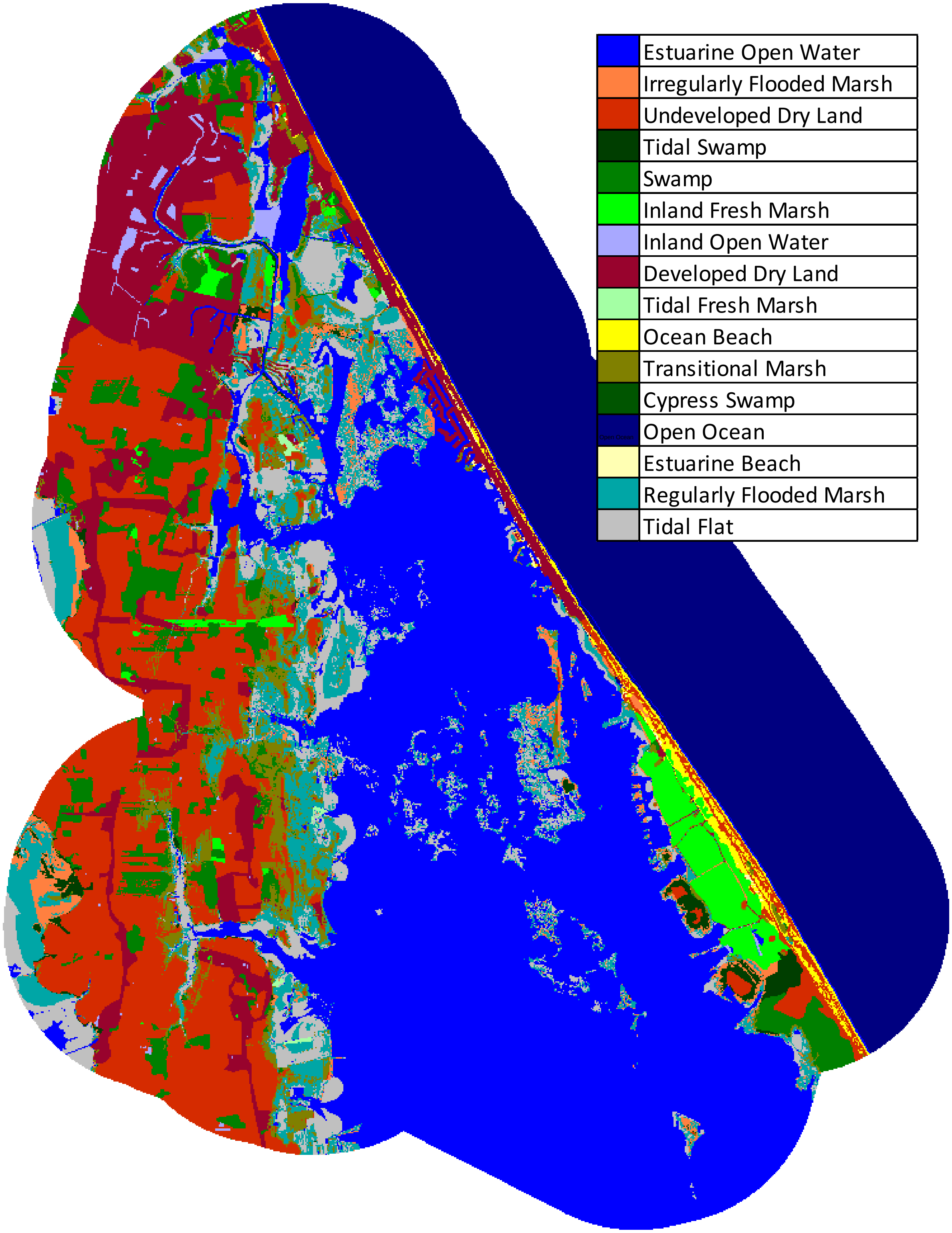
Back Bay context, Initial Condition



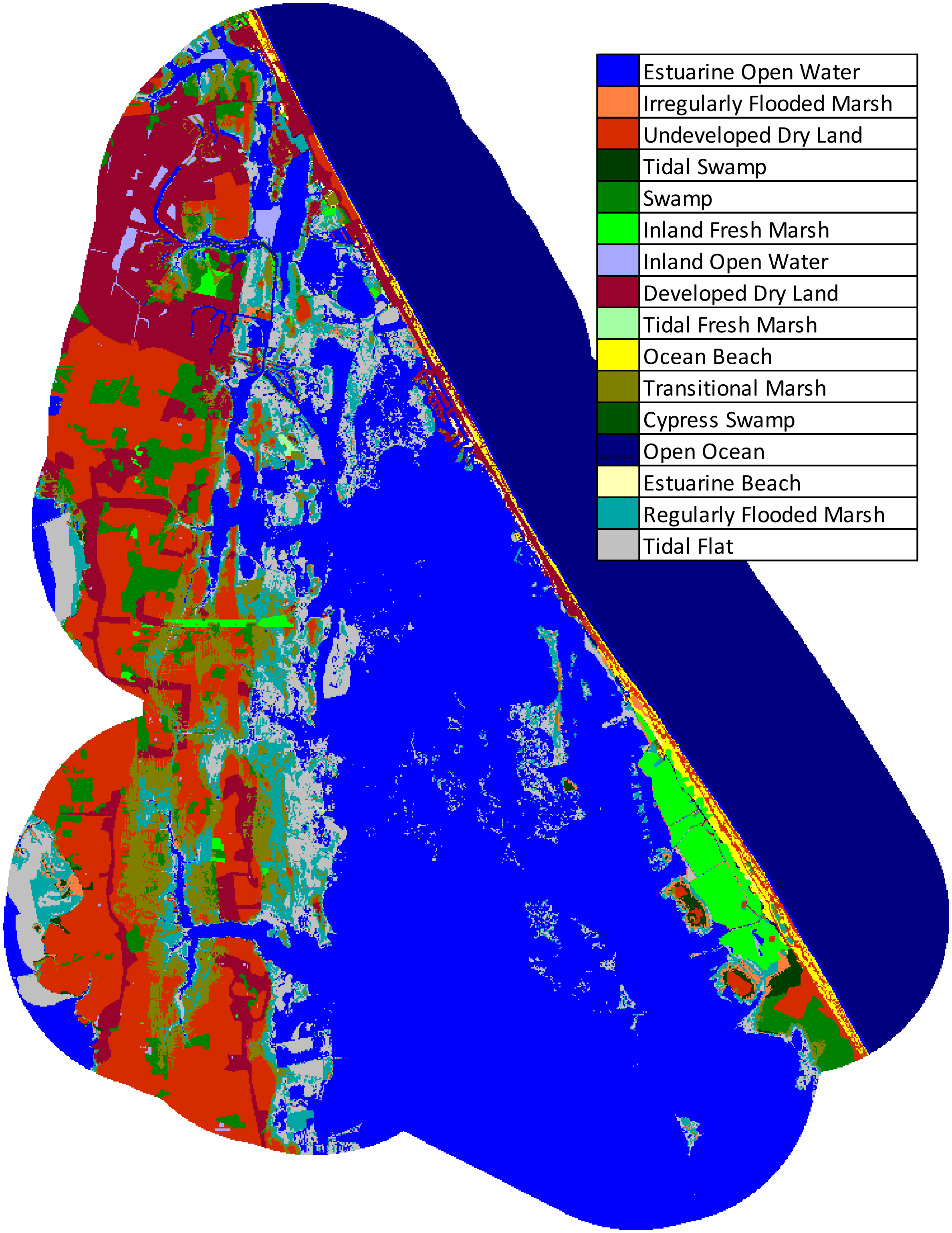
Back Bay context, 2025, 1 m SLR



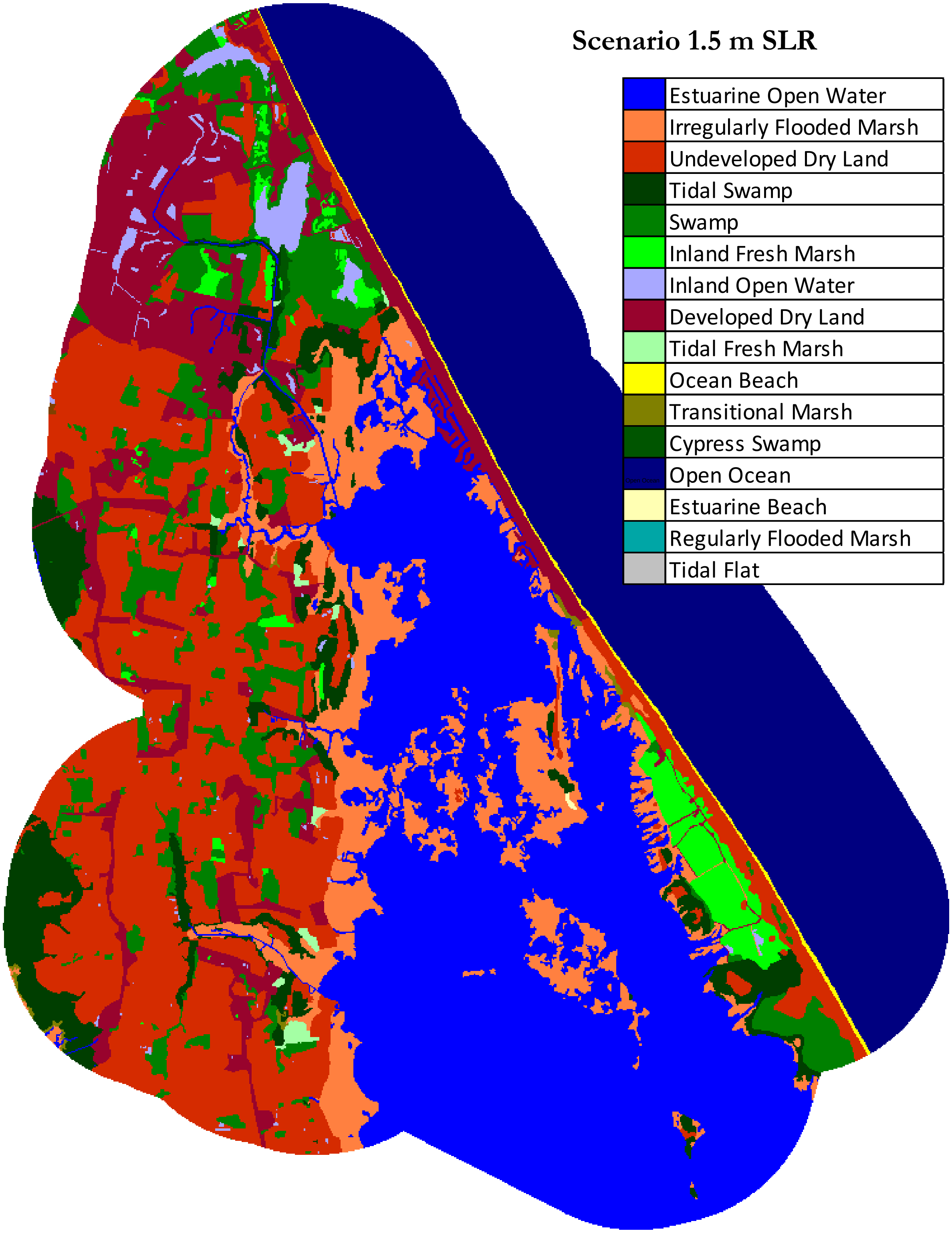
Back Bay context, 2050, 1 m SLR



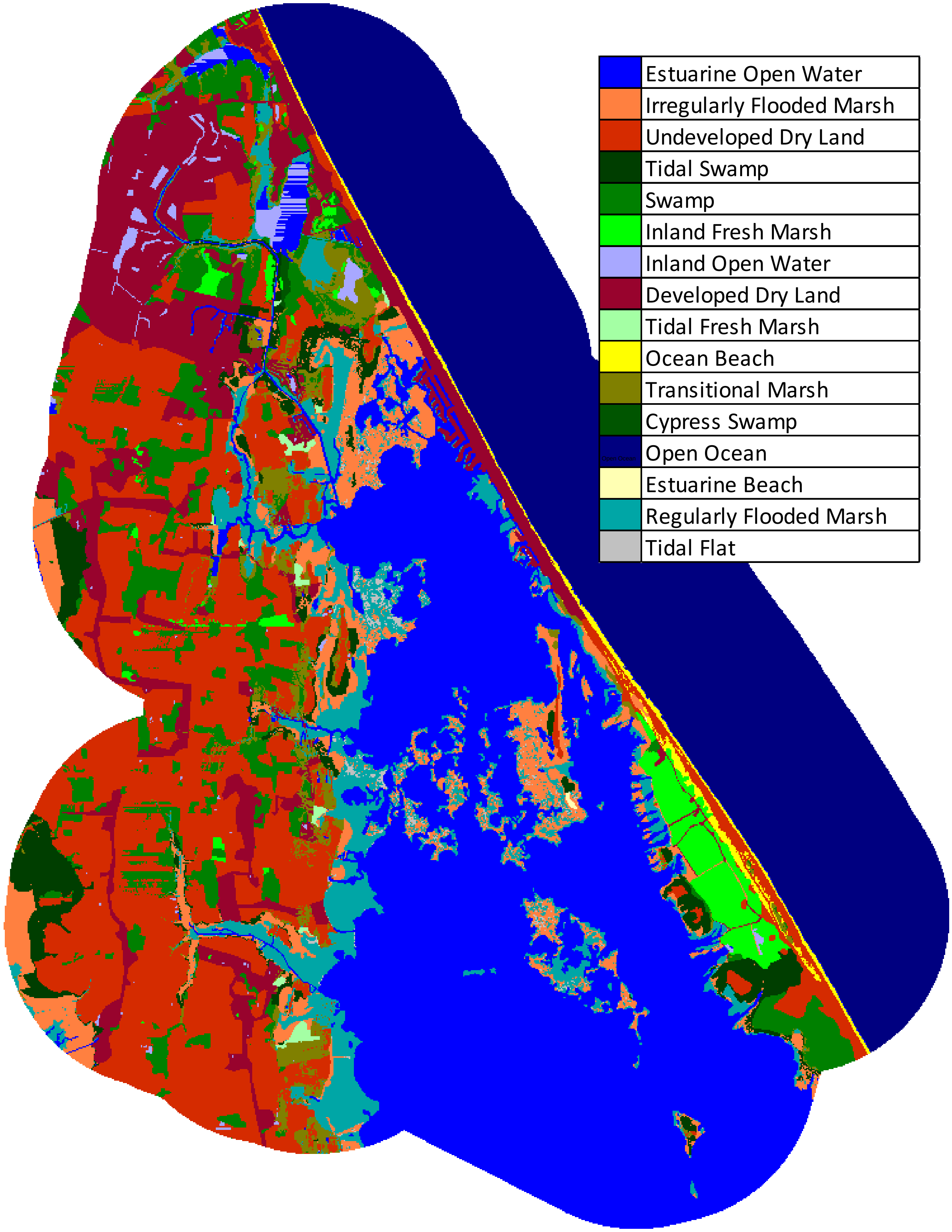
Back Bay context, 2075, 1 m SLR



Back Bay context, 2100, 1 m SLR



Back Bay context, Initial Condition



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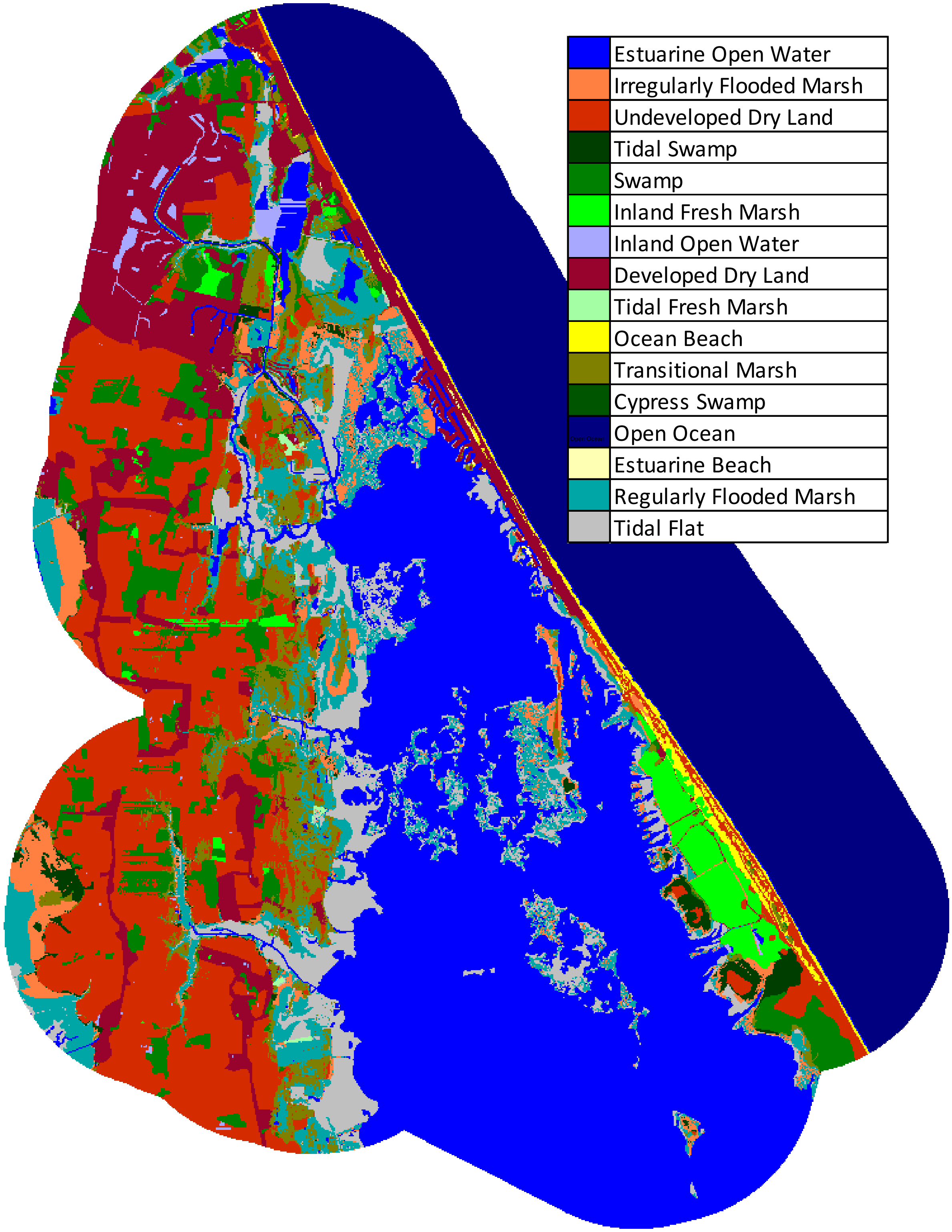

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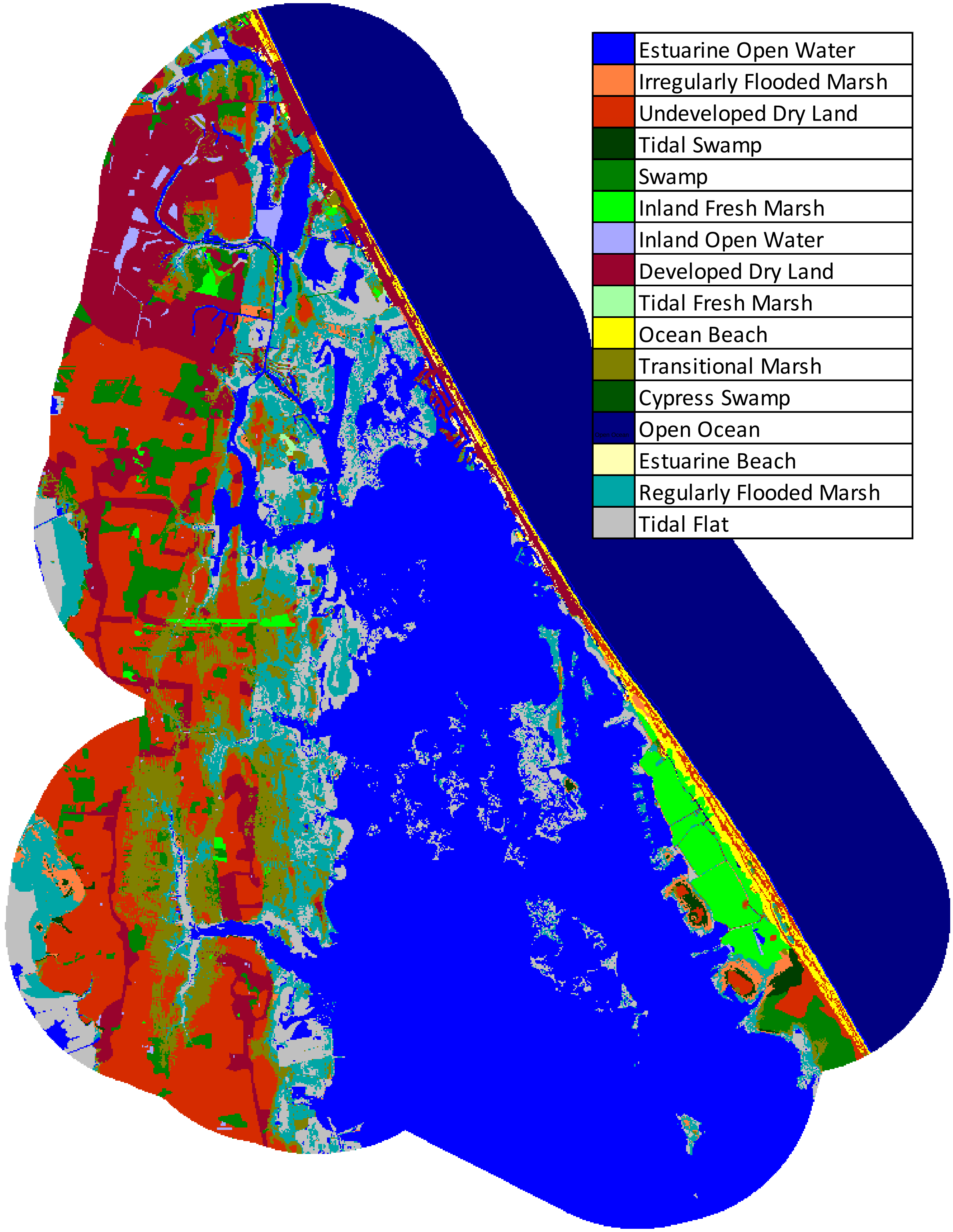

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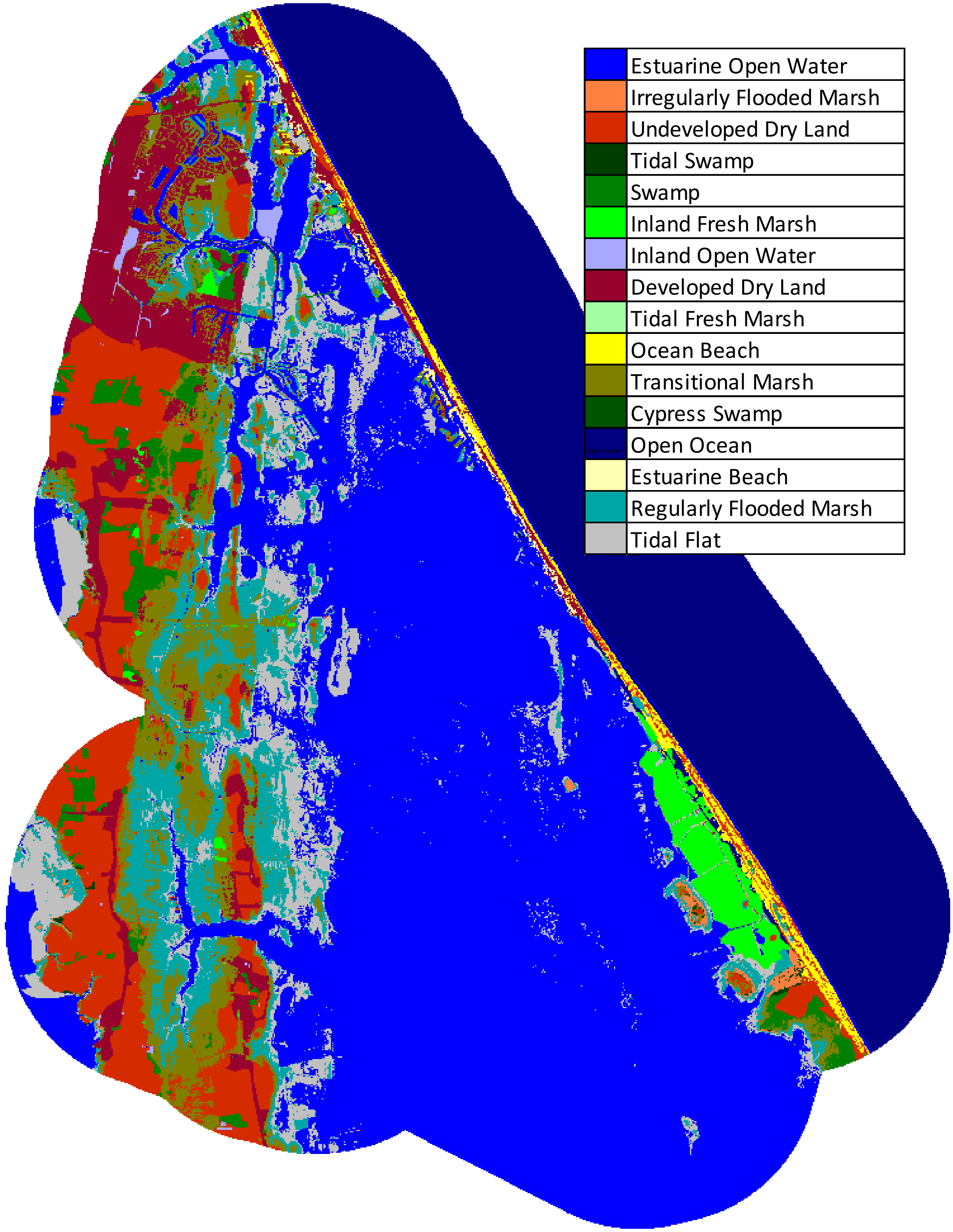
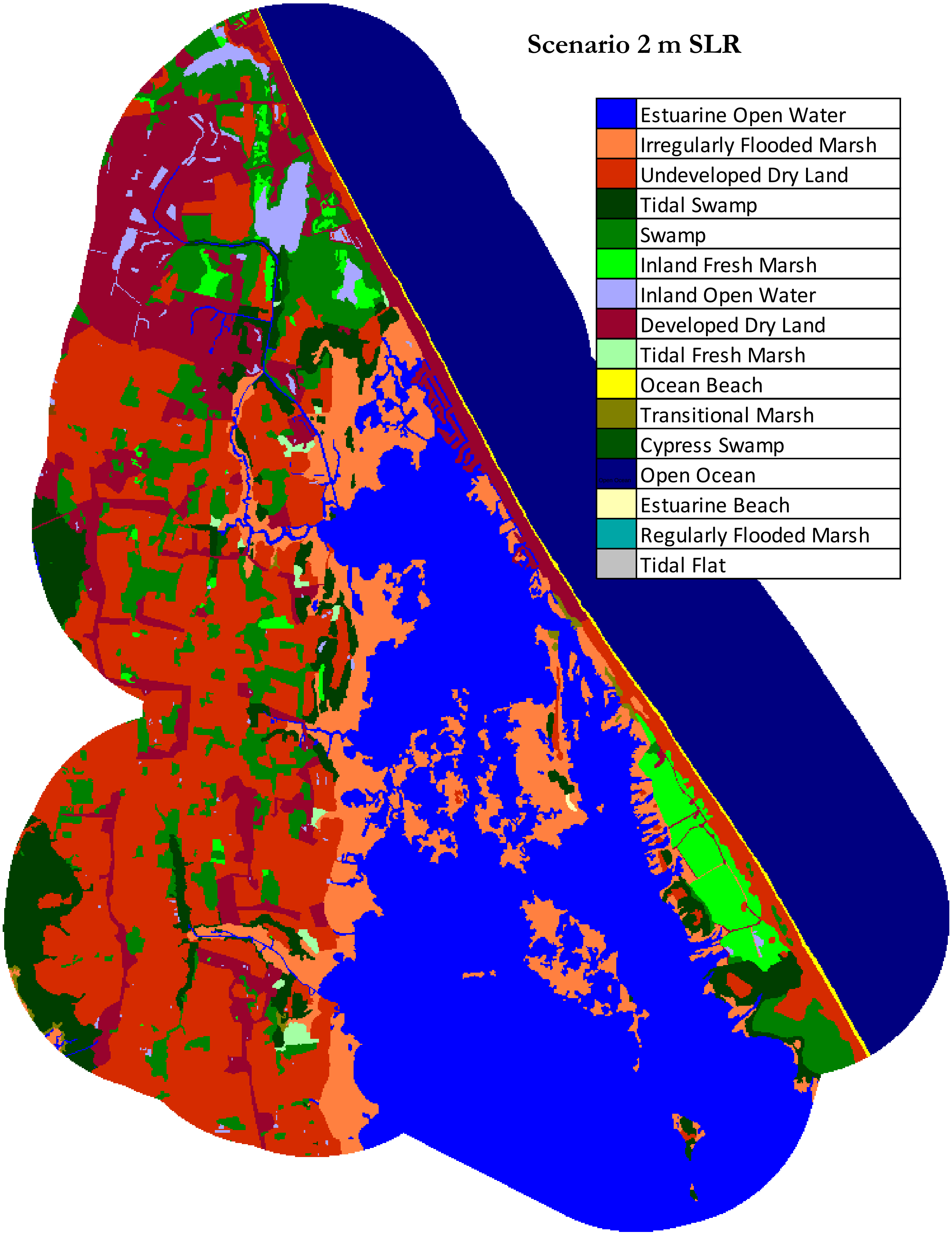
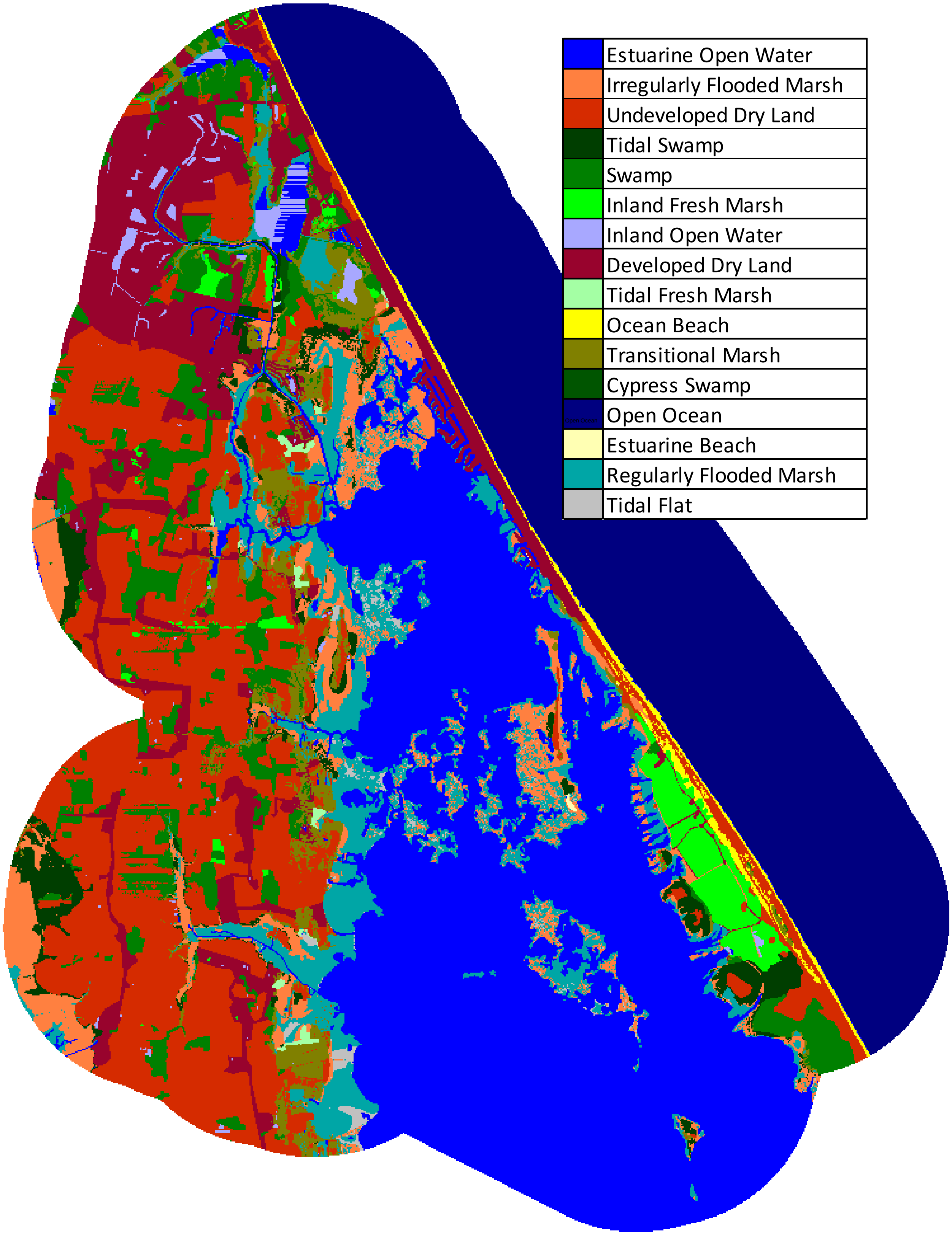


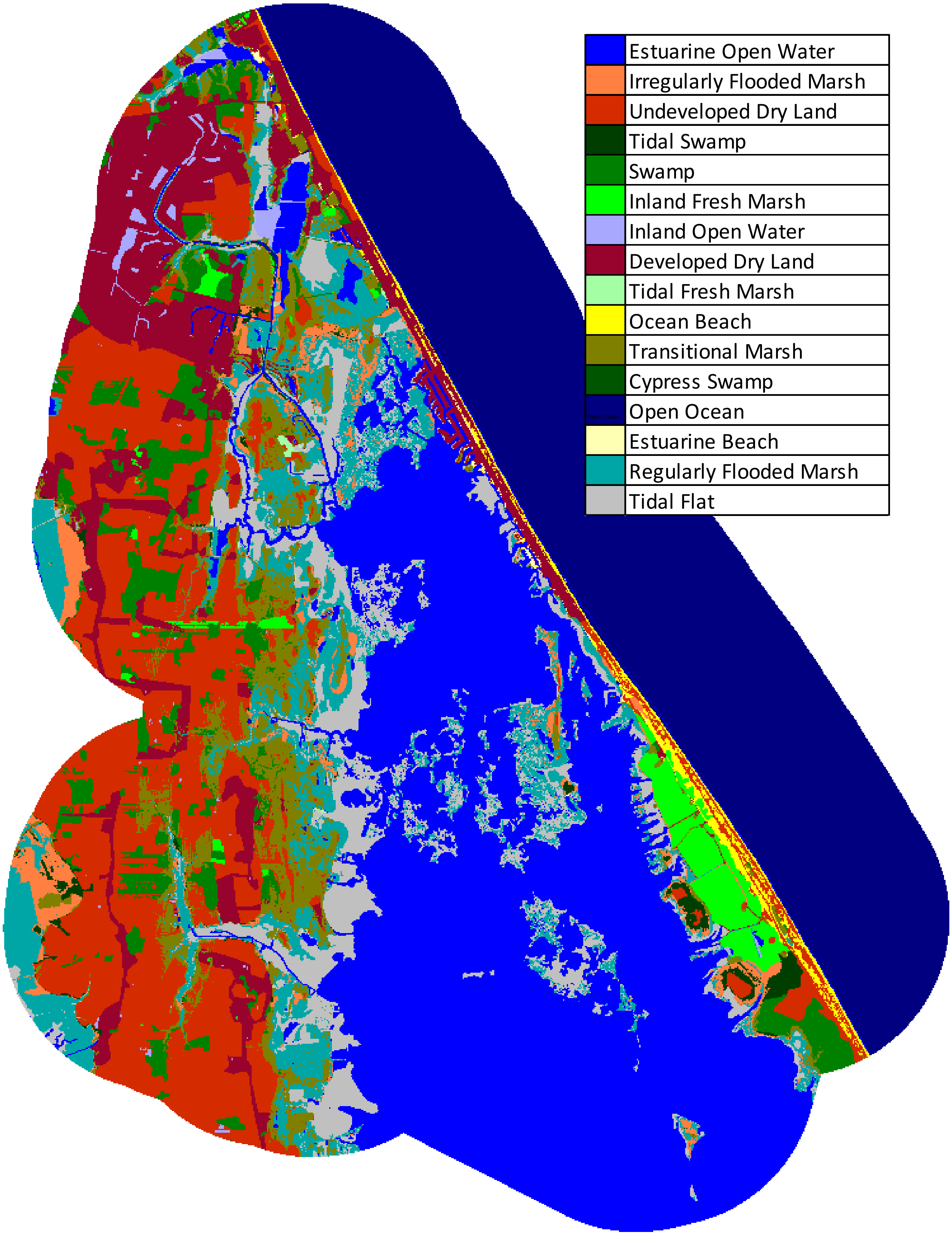
Back Bay context, 2100, 1.5 m SLR



Back Bay context, Initial Condition



Back Bay context, 2025, 2 m SLR



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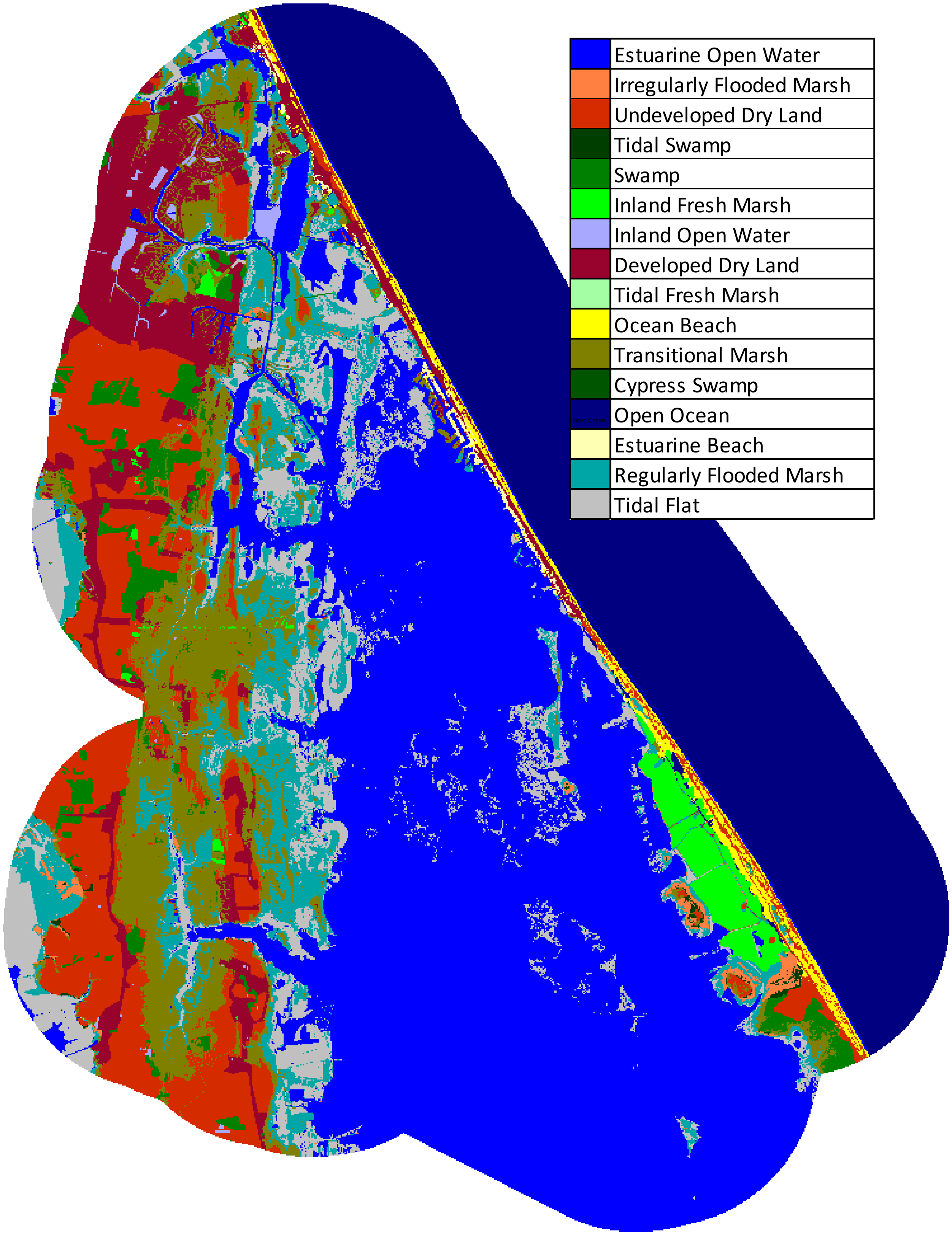
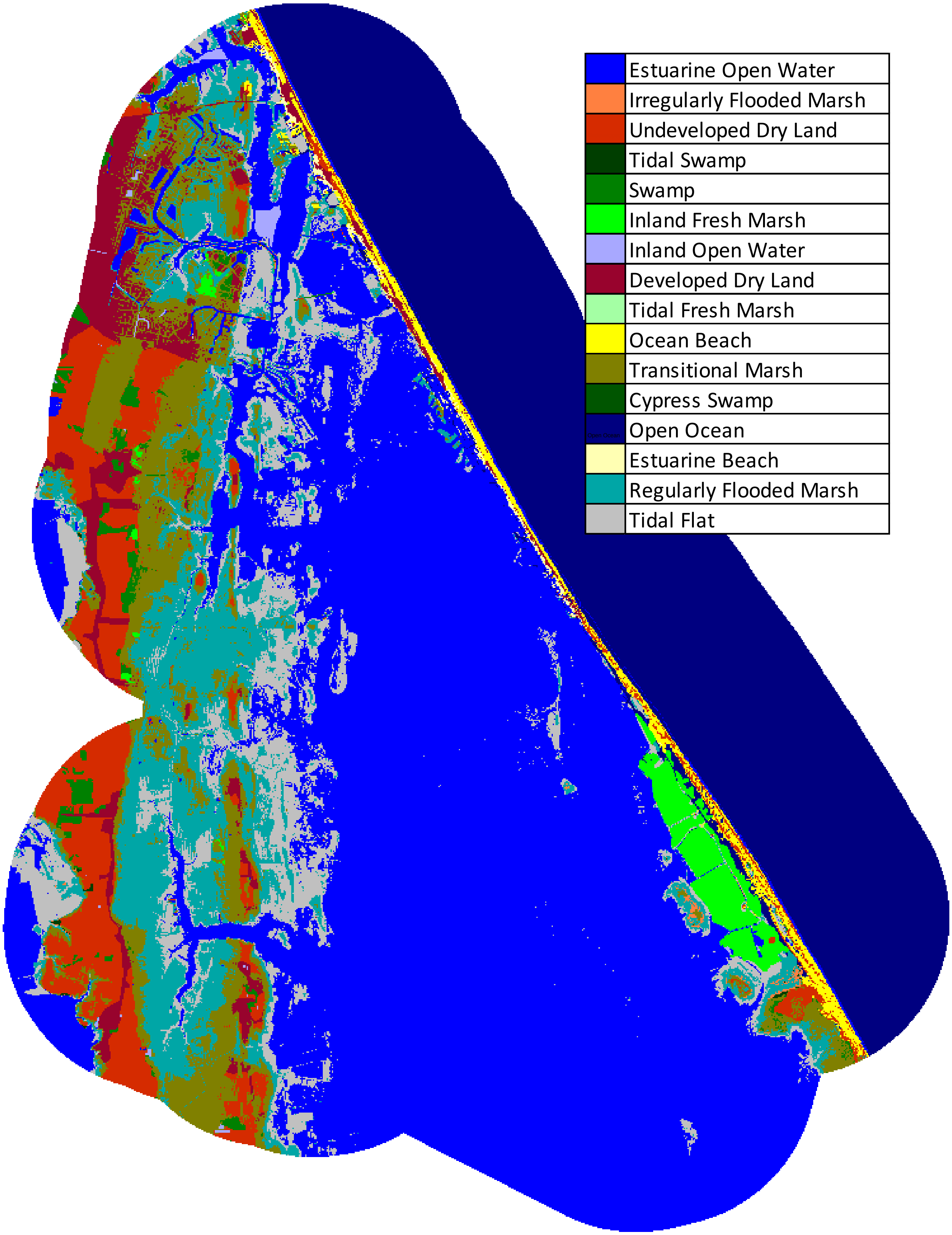


Back Bay context, 2075, 2 m SLR



Back Bay context, 2100, 2 m SLR