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

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

August 2, 2012

warren pinnacle consulting, inc.

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

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

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.

This is the second application of SLAMM to Monomoy NWR. The first application of SLAMM to the refuge, carried out in 2009, included LiDAR-derived elevation data only for the eastern coast of the refuge. The current application uses a bare-earth LiDAR elevation data obtained in 2010 and a wetland layer derived from aerial photos taken in 2010.

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.

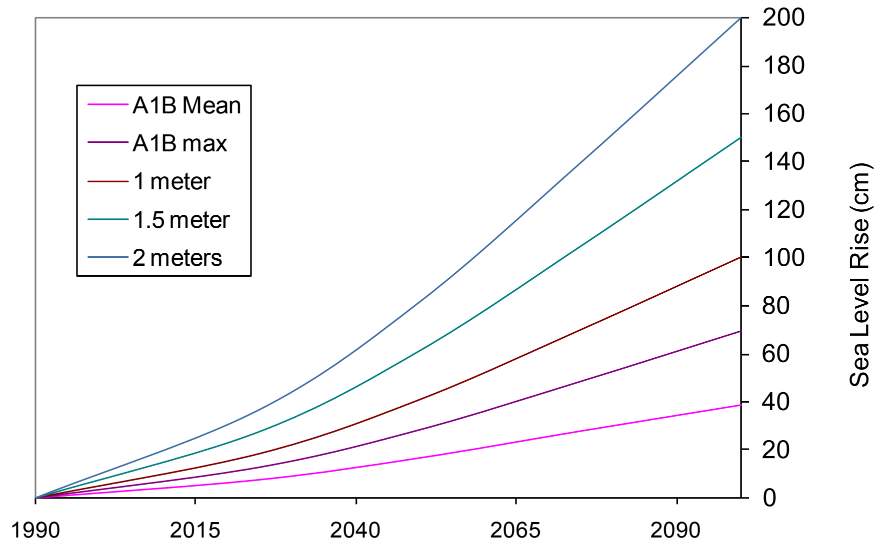


Figure 1. Summary of SLR scenarios utilized.

Data Sources and Methods

Wetland layer. Figure 2 shows the most recent available wetland layer. The coverage of the study area is a combination of a NWI survey dated 2008 and a 2010 GIS layer produced by the refuge staff that covers the entire refuge area.

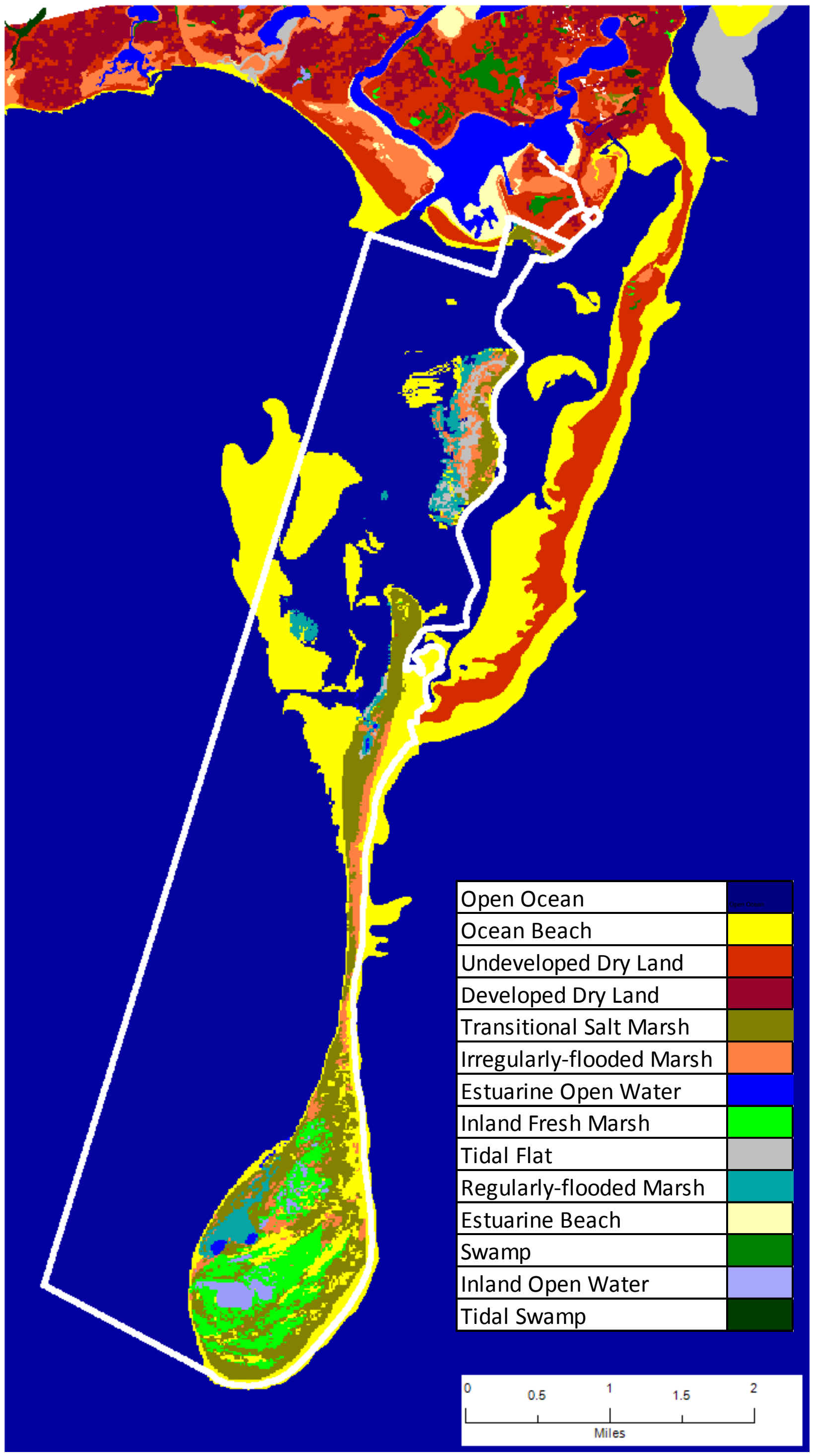


Figure 2. NWI coverage of the study area. Approved refuge boundaries are indicated in white.

The following table was used to cross-walk the refuge wetlands into SLAMM:

Wetland Category Description	Code	SLAMM Category	Code
Anderson Level II Code 12 - Commercial and Services	12	Developed Dry land	1
Anderson 7 (Barren Land) 73 Sandy areas other than beaches	773	Undeveloped dry land	2
Dune Blowout	A.1855	Ocean Beach	12
Water-lily Aquatic Wetland	CEGL002386	Inland Fresh Marsh	5
Overwash Dune Grassland	CEGL004097	Irregularly-flooded marsh	20
Eastern Reed Marsh	CEGL004141	Inland Fresh Marsh	5
North Atlantic Low Salt Marsh	CEGL004192	Regularly-flooded marsh	8
Salt Panne (Salicornia Type)	CEGL004308	Tidal flat	11
North Atlantic Upper Ocean Beach	CEGL004400	Ocean beach	12
North Atlantic High Salt Marsh	CEGL006006	Irregularly-flooded marsh	20
Northern Interdunal Cranberry Swale	CEGL006141	Irregularly-flooded marsh	20
Northern Beach-heather Dune Shrubland	CEGL006143	Transitional Salt Marsh	7
Eastern Cattail Marsh	CEGL006153	Inland Fresh Marsh	5
Northern Atlantic Coast Beaked Ditch-grass Bed	CEGL006167	Regularly-flooded marsh	8
Northern Beachgrass Dune	CEGL006274	Ocean beach	12
Bulrush Deepwater Marsh	CEGL006275	Inland Fresh Marsh	5
Northern Bayberry Dune Shrubland	CEGL006295	Transitional Salt Marsh	7
Coastal Pitch Pine / Scrub Oak Barrens	CEGL006315	Undeveloped Dry Land	2
Northeastern Atlantic Brackish Interdunal Swal	CEGL006342	Irregularly-flooded marsh	20
Salt Flat	CEGL006369	Tidal Flat	11
Tall Maritime Shrubland	CEGL006379	Undeveloped Dry Land	2
Coastal Salt Pond Marsh	CEGL006398	Irregularly Flooded Marsh	20
Bayberry Shrub Wetland	CEGL006444	Inland Fresh Marsh	5
Coastal Freshwater Marsh	CEGL006935	Inland Fresh Marsh	5
Estuarine, Nearshore, Intertidal, Aquatic Bed, Algal	E(A)2AB1	Tidal Flat	11
Estuarine, Nearshore, Intertidal, Aquatic Bed, Rooted Vascular	E(A)2AB3	Tidal Flat	11
Estuarine, Nearshore, Subtidal, Unconsolidated Substrate, Sand	E(A)2US2	Estuarine Beach	10
Marine, Nearshore, Subtidal, Unconsolidated Substrate, Sand	M(A)1US2	Open Ocean	19
Marine, Nearshore, Intertidal, Unconsolidated Substrate, Sand	M(A)2US2	Ocean Beach	12
Palustrine, Emergent	PEM1	Inland Fresh Marsh	5
Palustrine, Unconsolidated Bottom	PUB	Inland Open Water	15
North Atlantic Eel-grass BedMarine, Nearshore, Subtidal, Unconsolidated Substrate, Sand	M(A)1US2	Open Ocean	19
North Atlantic Eel-grass Bed	M(A)2US2	Ocean Beach	12

This "crosswalk" was created by Warren Pinnacle Consulting staff and vetted by refuge staff prior to use.

Converting the surveys into 5 m x 5 m cells indicated that the approximately 7,500 acre Monomoy NWR (approved acquisition boundary including water) is composed of the following categories:

Land cover type		Area (acres)	Percentage (%)
	Open Ocean	5,072	68
	Ocean Beach	967	13
	Transitional Salt Marsh	691	9
	Inland Fresh Marsh	291	4
	Irregularly-flooded Marsh	187	2
	Regularly-flooded Marsh	149	2
	Inland Open Water	61	<1
	Tidal Flat	57	<1
	Undeveloped Dry Land	15	<1
	Estuarine Open Water	14	<1
	Developed Dry Land	3	<1
	Total (incl. water)	**7,507**	**100**

Elevation Data. The elevation layer covering the refuge area was based on a bare-earth LiDAR data layer collected in 2010 by USACE.

Dikes and Impoundments. According to the National Wetland Inventory, there are no areas protected by dikes or impoundments within the refuge. In this simulation, the connectivity algorithm was also used in this simulation to capture the effects of any natural or man-made impoundments that may not have been marked as diked. The connectivity module of SLAMM ensures that dry land only converts to wetland if there is an unimpeded path from open water to the dry land in question.

Historic sea level rise rates. The historic trend for relative sea level rise rate applied was 3.43 mm/yr., the average value measured at Nantucket Island, MA (NOAA gauge # 8449130). This rate is higher than the global (eustatic) SLR for the last 100 years (approximately 1.7 mm/yr.), indicating that SLR is higher than the global average in this region. This differential is maintained through model forecasts.

Tide Ranges. The great diurnal range (GT) was estimated at 1.4 m using the data from the NOAA gauge station at Chatham, MA (# 84477505).

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 1.33 Half Tide Units (HTU) for all input subsites, corresponding to 0.93 m above MTL in the area within the refuge.

Accretion rates. Accretion rates in salt and brackish marshes were set to 3.78 mm/year, and the rates in tidal fresh marshes to 5.9 mm/year based on measurements from Nauset Marsh, MA (C.T. Roman et al. 1997). Lacking site specific information, accretion rates of other wetland types were set to SLAMM default value.

Model Timesteps. Model forecast data is output for years 2025, 2050, 2075 and 2100 with the initial condition date set to 2010, the most recent wetland data available.

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

Elevation correction. MTL to NAVD88 correction was set to -0.137 m based on the datum measured at the NOAA gauge station in Chatham, MA (#84477505).

Refuge boundaries. Modeled USFWS refuge boundaries for Massachusetts 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 5 m.

Input subsites and parameter summary. The study area was subdivided in the subsites illustrated in Figure 4 to account for the different directions of the ocean.

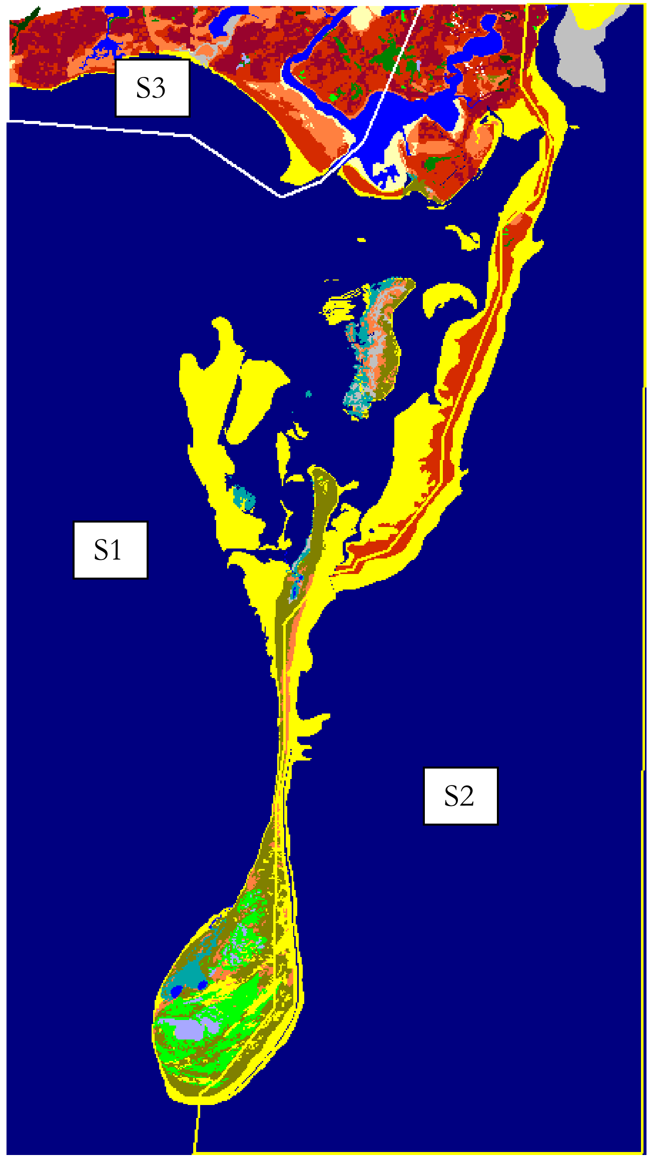


Figure 3. Input subsites for model application.

Table 1 summarizes all SLAMM input parameters for the input subsites. Values for parameters with no specific local information were kept at the model default value.

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

Parameter	S1	S2	S3
NWI Photo Date (YYYY)	2010	2010	2010
DEM Date (YYYY)	2010	2010	2010
Direction Offshore [n,s,e,w]	West	East	South
Historic Trend (mm/yr)	3.43	3.43	3.43
MTL-NAVD88 (m)	-0.137	-0.137	-0.137
GT Great Diurnal Tide Range (m)	1.4	1.4	1.4
Salt Elev. (m above MTL)	0.93	0.93	0.93
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)	3.78	3.78	3.78
Irreg.-Flood Marsh Accr (mm/yr)	3.78	3.78	3.78
Tidal-Fresh Marsh Accr (mm/yr)	5.9	5.9	5.9
Inland-Fresh Marsh Accr (mm/yr)	5.9	5.9	5.9
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)	0	0	0
Use Elev Pre-processor [True,False]	FALSE	FALSE	FALSE

Calibration of initial conditions

Initially, SLAMM simulates a "time zero" step, in which the consistency of model assumptions for wetland elevations is validated with respect to available wetland coverage information, elevation data and tidal frames. Due to simplifications within the SLAMM conceptual model, DEM and wetland layer uncertainty, or other local factors, some cells may fall below their lowest allowable elevation category and would be immediately converted by the model to a different land cover category (e.g. an area categorized in the wetland layer as swamp where water has a tidal regime according to its elevation and tidal information will be converted to a tidal marsh). These cells represent outliers on the distribution of elevations for a given land-cover type. Generally, a threshold tolerance of up to 5% change is allowed for in major land cover categories in SLAMM analyses.

For this refuge, at "time zero" no significant conversions are observed within the refuge area, indicating that the improved elevation information from LiDAR, the wetland coverage provided the refuge combined with the tidal information make the model consistent with the current wetland status of the refuge.

Results

Percentage losses by 2100 for each land-cover type given different SLR scenarios are presented in Table 2. Land-cover losses are calculated in comparison to the initial 2010 wetland coverage and sorted by decreasing initial land cover.

Table 2. Predicted loss rates of land categories by 2100 given simulated scenarios of eustatic SLR at Monomoy 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
Ocean Beach	967	16%	34%	52%	62%	65%
Transitional Salt Marsh	691	5%	0%	12%	41%	62%
Inland Fresh Marsh	291	1%	40%	68%	86%	94%
Irregularly-flooded Marsh	187	11%	33%	43%	53%	63%
Inland Open Water	61	3%	53%	53%	54%	54%
Undeveloped Dry Land	15	24%	43%	60%	78%	83%

Wetlands covering Monomoy NWR are predicted to be fairly resilient to the effects of SLR under the A1B Mean SLR scenario (0.39 m by 2100). However, under the 0.69 m by 2100 scenario (and above) important losses of inland fresh marsh, irregularly-flooded marsh, ocean beach, and undeveloped dry land occur. The inland fresh marsh habitat appears to be the most endangered wetland type, with 94% of these wetlands predicted lost at 2.0 m of SLR by 2100 and higher.

Losses of wetland habitats of one type may be balanced with gains in other habitat categories. Major land cover gains are summarized in Table 3. Open water is predicted to progressively increase coverage of the refuge as sea level rises, from the current coverage of 69% up to more than 80% coverage of the refuge area under the 2 m SLR by 2100 scenario. Large gains in tidal flat and regularly-flooded marsh, are also projected.

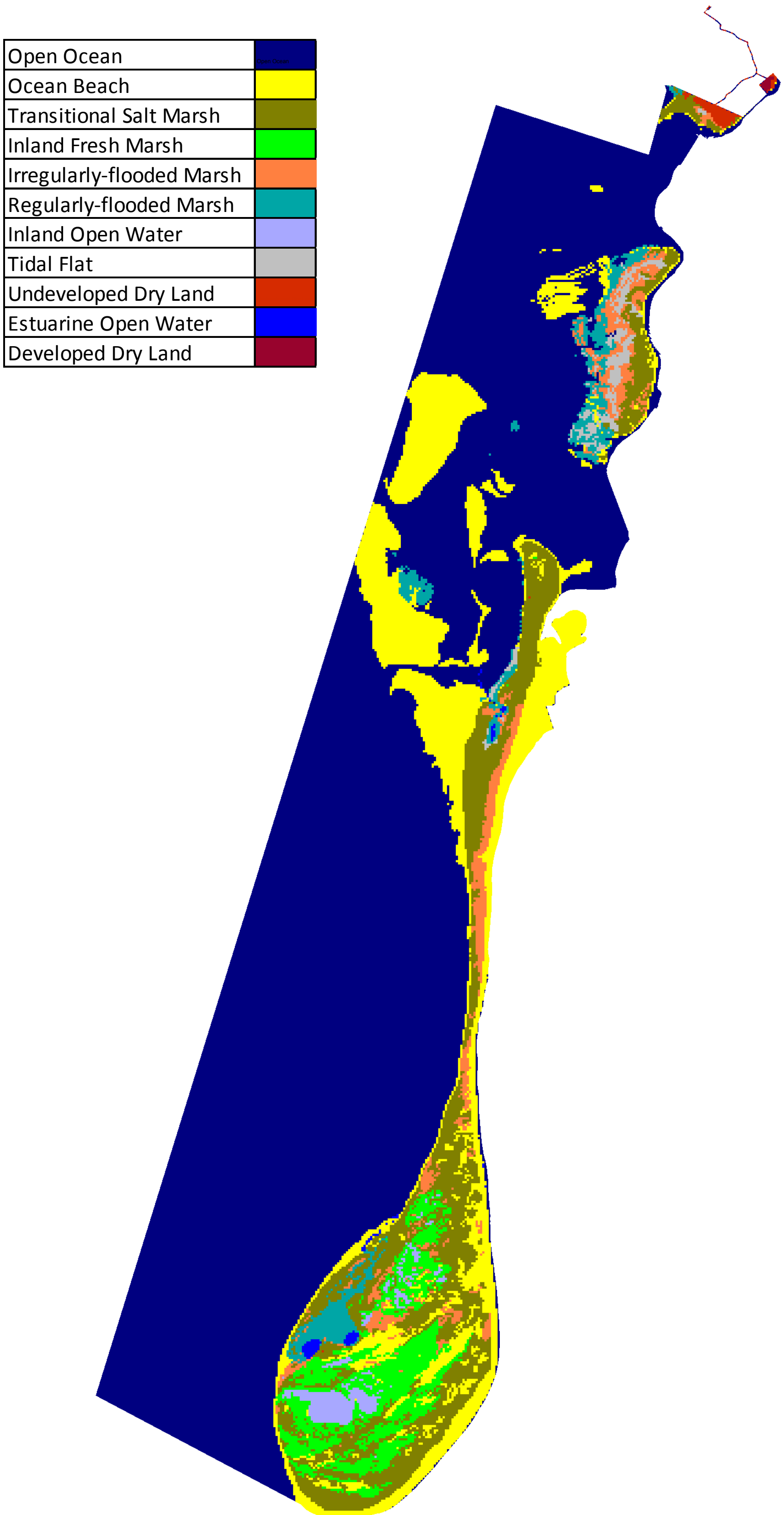
Table 3. Predicted land cover gains by 2100 given simulated scenarios of eustatic SLR at Monomoy NWR.

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	5086	5249	5464	5651	5888	6093
Tidal Flat	57	62	113	236	300	343
Regularly-flooded Marsh	149	195	259	309	380	348

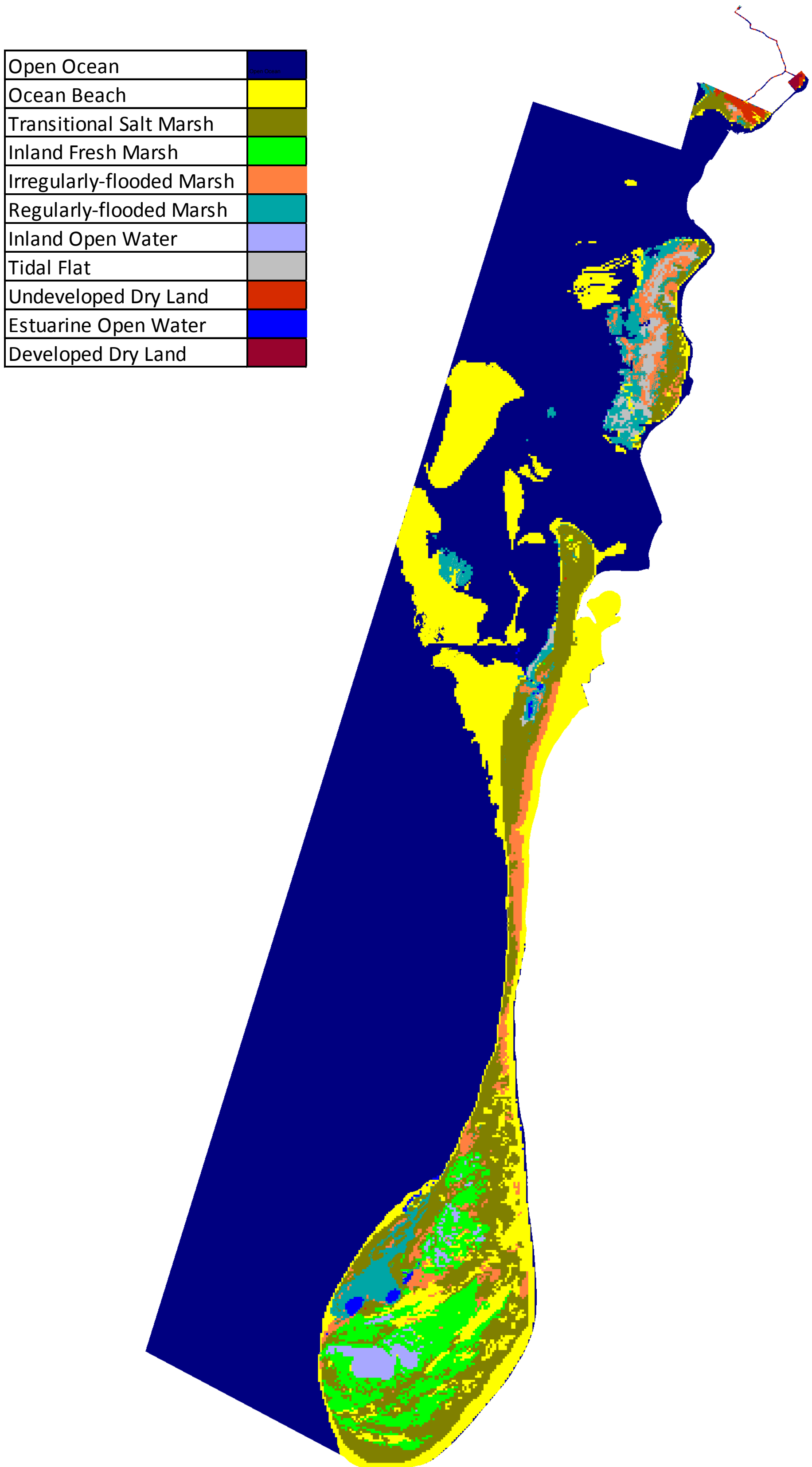
Monomoy NWR
IPCC Scenario A1B-Mean, 0.39 m SLR eustatic by 2100

Results in Acres

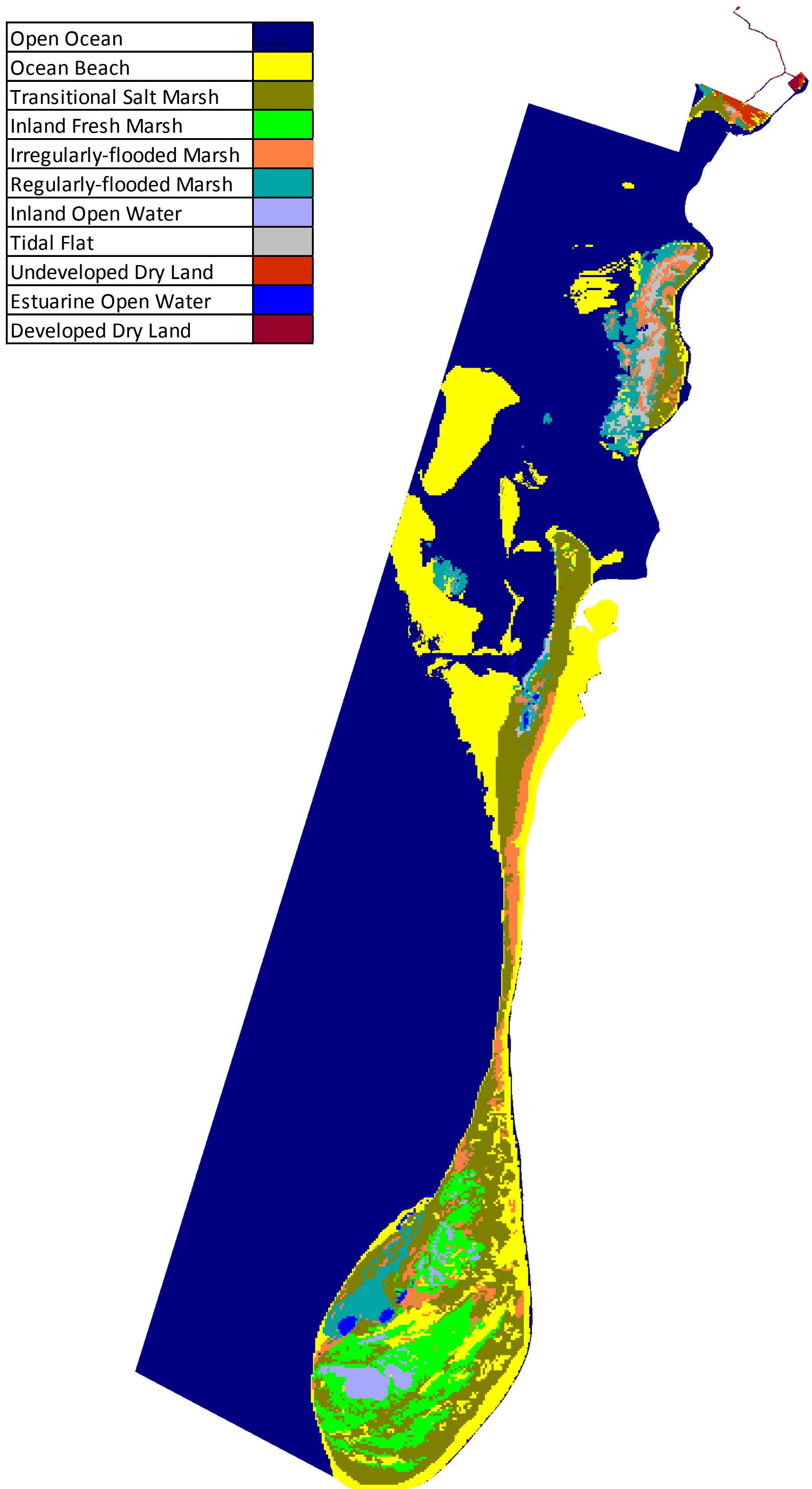
		Initial	2025	2050	2075	2100
	Open Ocean	5072	5090	5115	5159	5228
	Ocean Beach	967	950	926	882	814
	Transitional Salt Marsh	691	667	665	660	655
	Inland Fresh Marsh	291	290	290	290	290
	Irregularly-flooded Marsh	187	180	178	173	167
	Regularly-flooded Marsh	149	179	182	188	195
	Inland Open Water	61	60	60	60	60
	Tidal Flat	57	59	58	61	62
	Undeveloped Dry Land	15	14	13	12	11
	Estuarine Open Water	14	16	18	19	22
	Developed Dry Land	3	3	3	3	3
	Total (incl. water)	**7507**	**7507**	**7507**	**7507**	**7507**



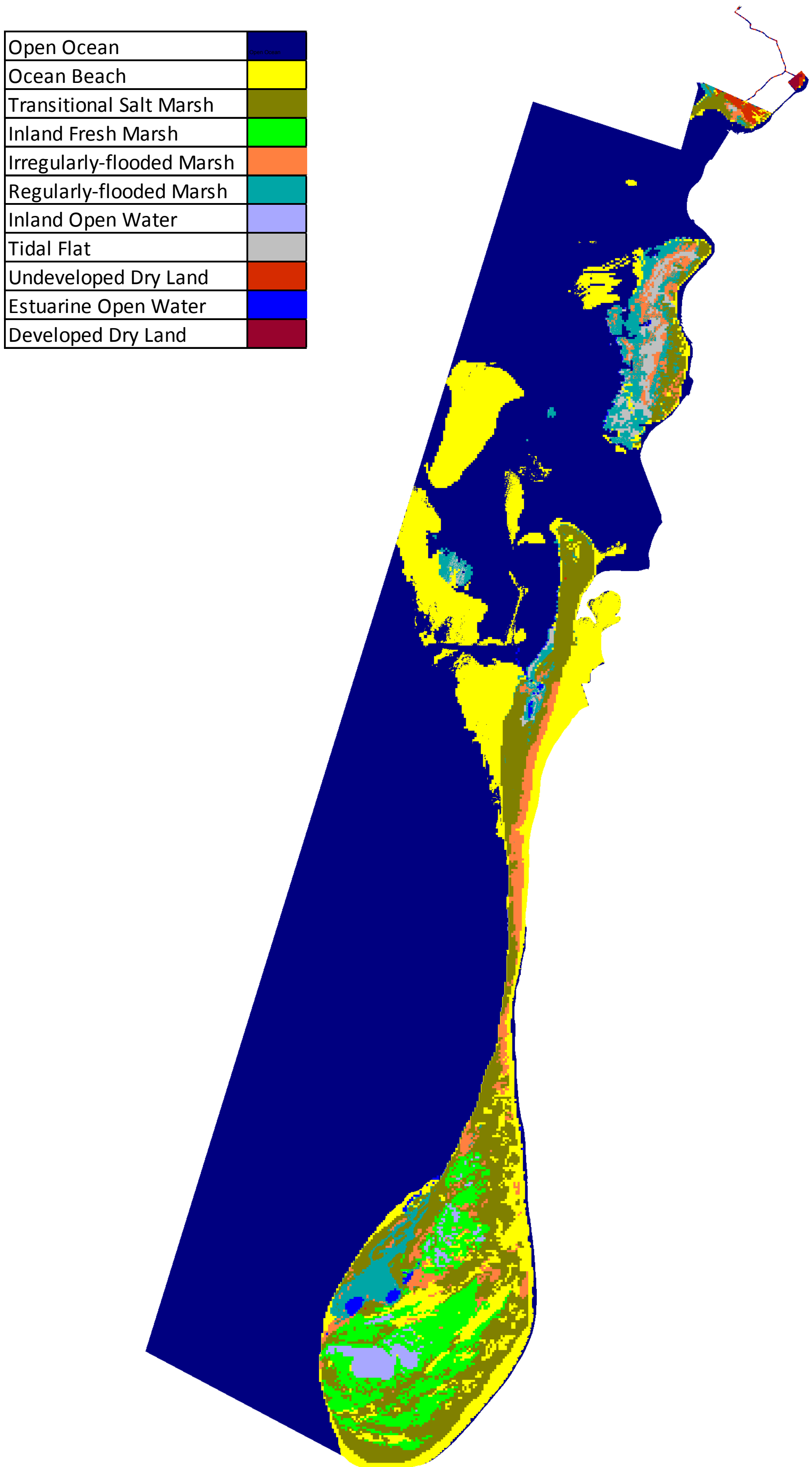
Monomoy NWR, Initial Condition.



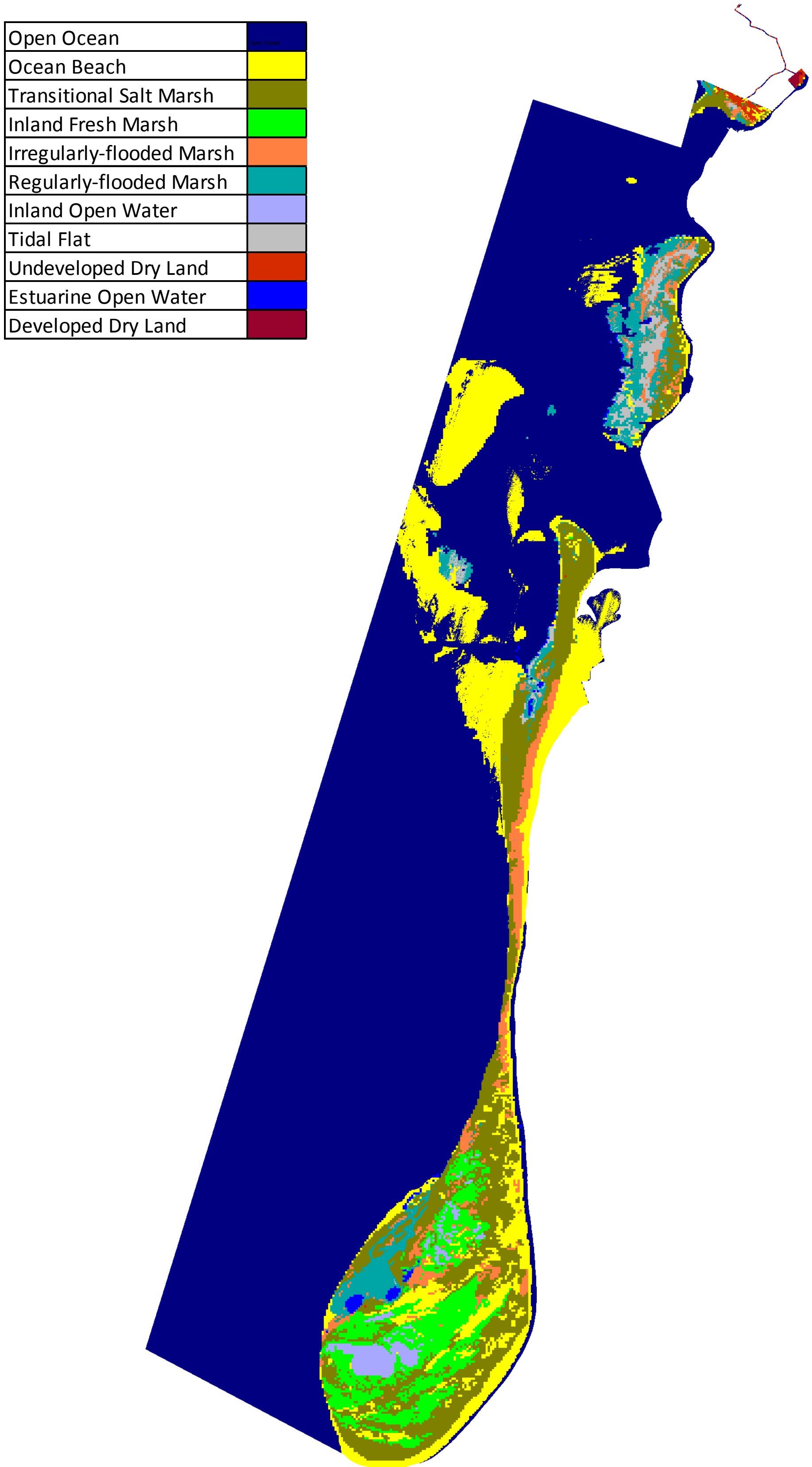
Monomoy NWR, 2025, Scenario A1B Mean, 0.39 m SLR



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



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

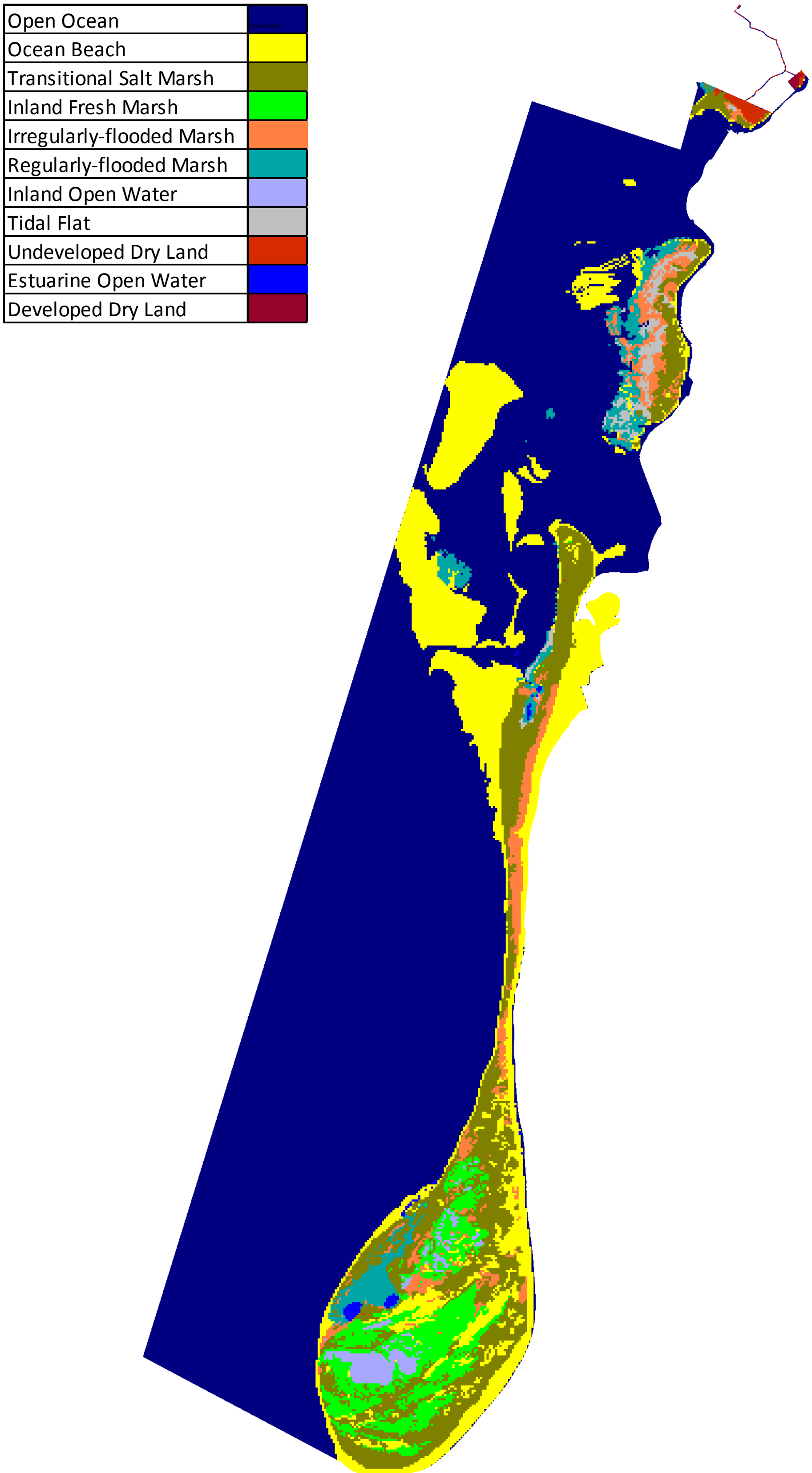


Monomoy NWR, 2100, Scenario A1B Mean, 0.39 m SLR by 2100.

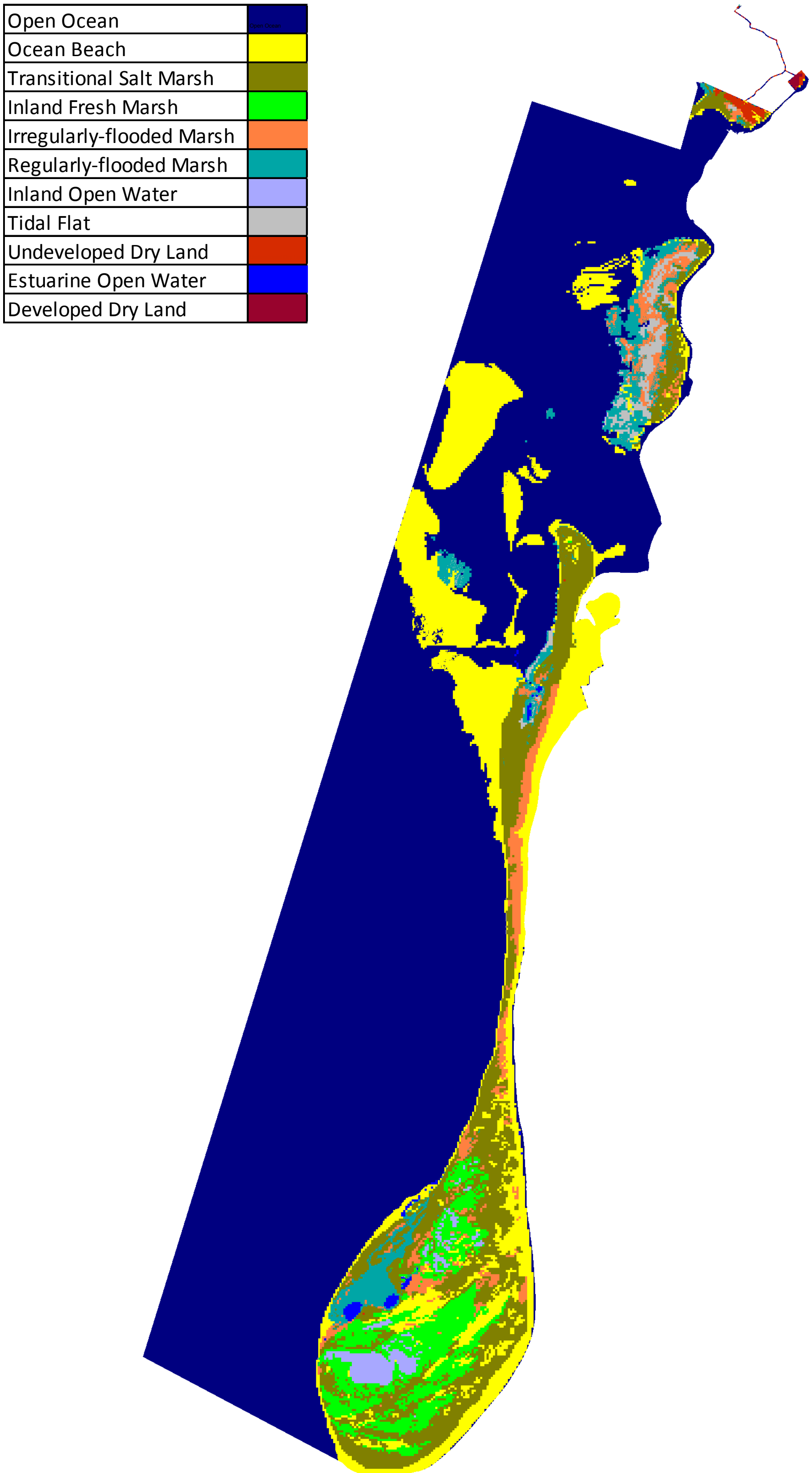
Monomoy NWR
IPCC Scenario A1B-Max, 0.69 m SLR eustatic by 2100

Results in Acres

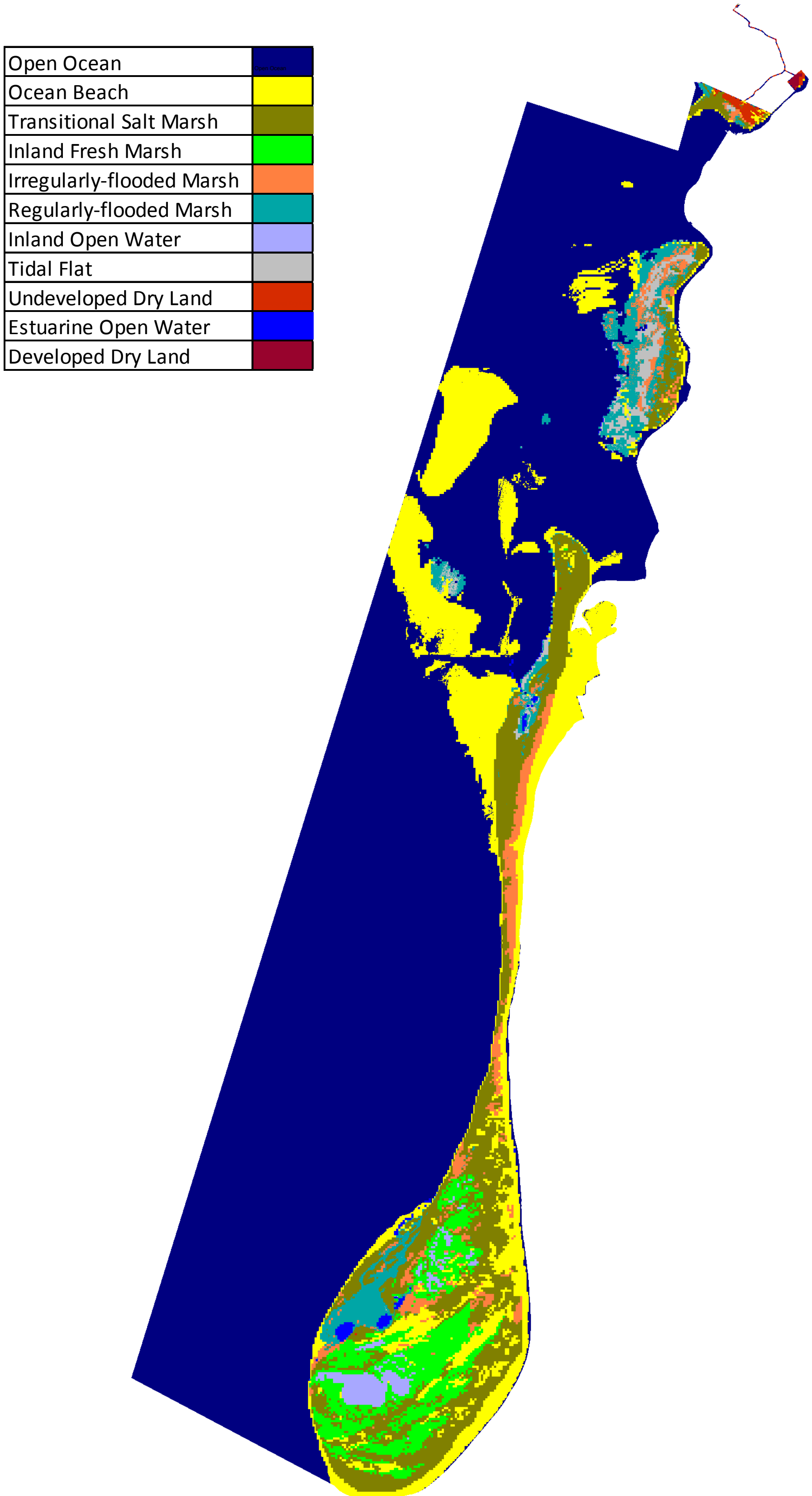
		Initial	2025	2050	2075	2100
	Open Ocean	5072	5091	5125	5229	5407
	Ocean Beach	967	949	916	813	637
	Transitional Salt Marsh	691	665	655	683	694
	Inland Fresh Marsh	291	290	289	245	174
	Irregularly-flooded Marsh	187	179	167	144	125
	Regularly-flooded Marsh	149	181	196	218	259
	Inland Open Water	61	60	60	49	29
	Tidal Flat	57	60	64	79	113
	Undeveloped Dry Land	15	14	13	11	8
	Estuarine Open Water	14	16	19	31	57
	Developed Dry Land	3	3	3	3	3
	Total (incl. water)	**7507**	**7507**	**7507**	**7507**	**7507**



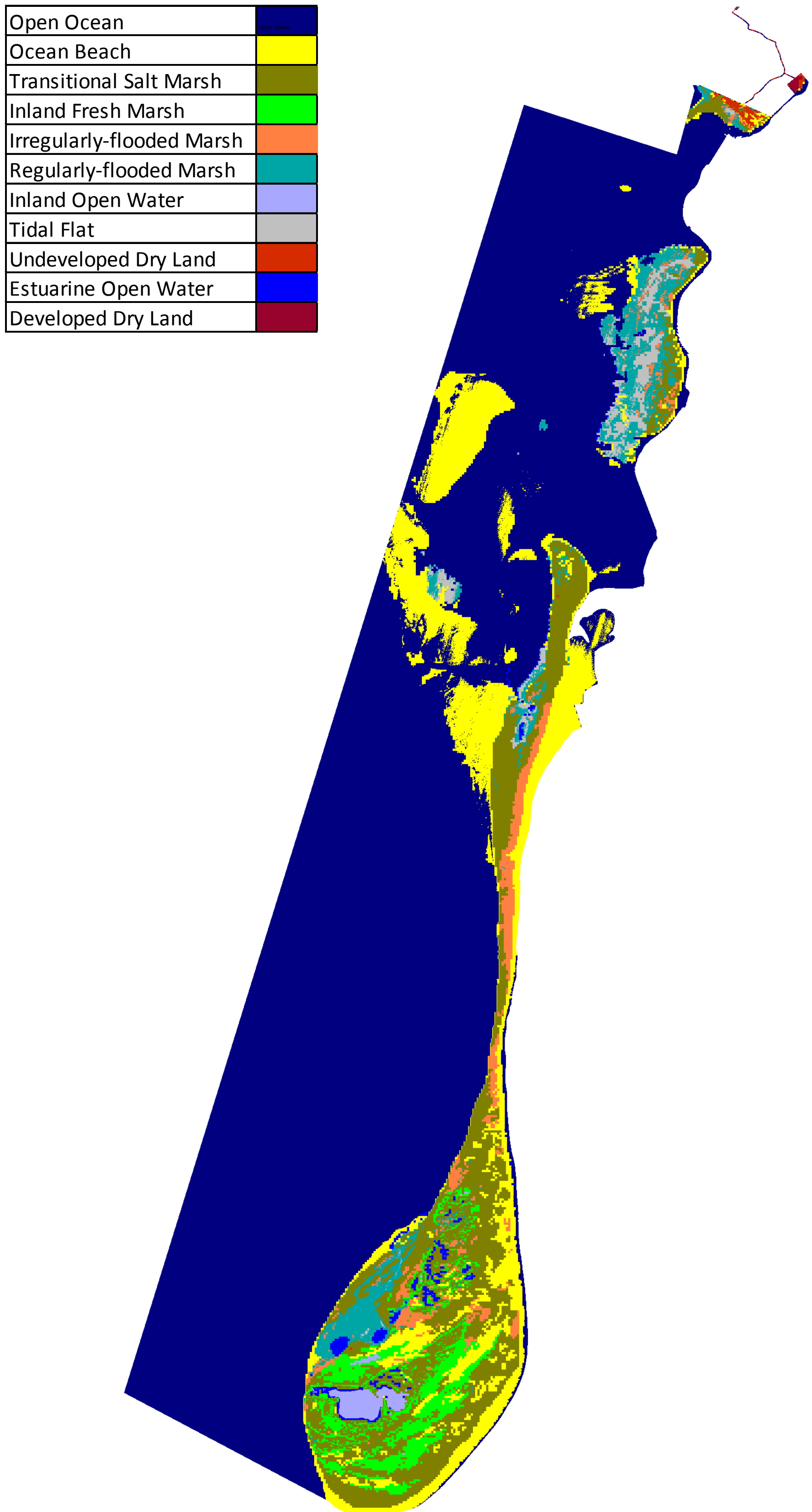
Monomoy NWR, Initial Condition.



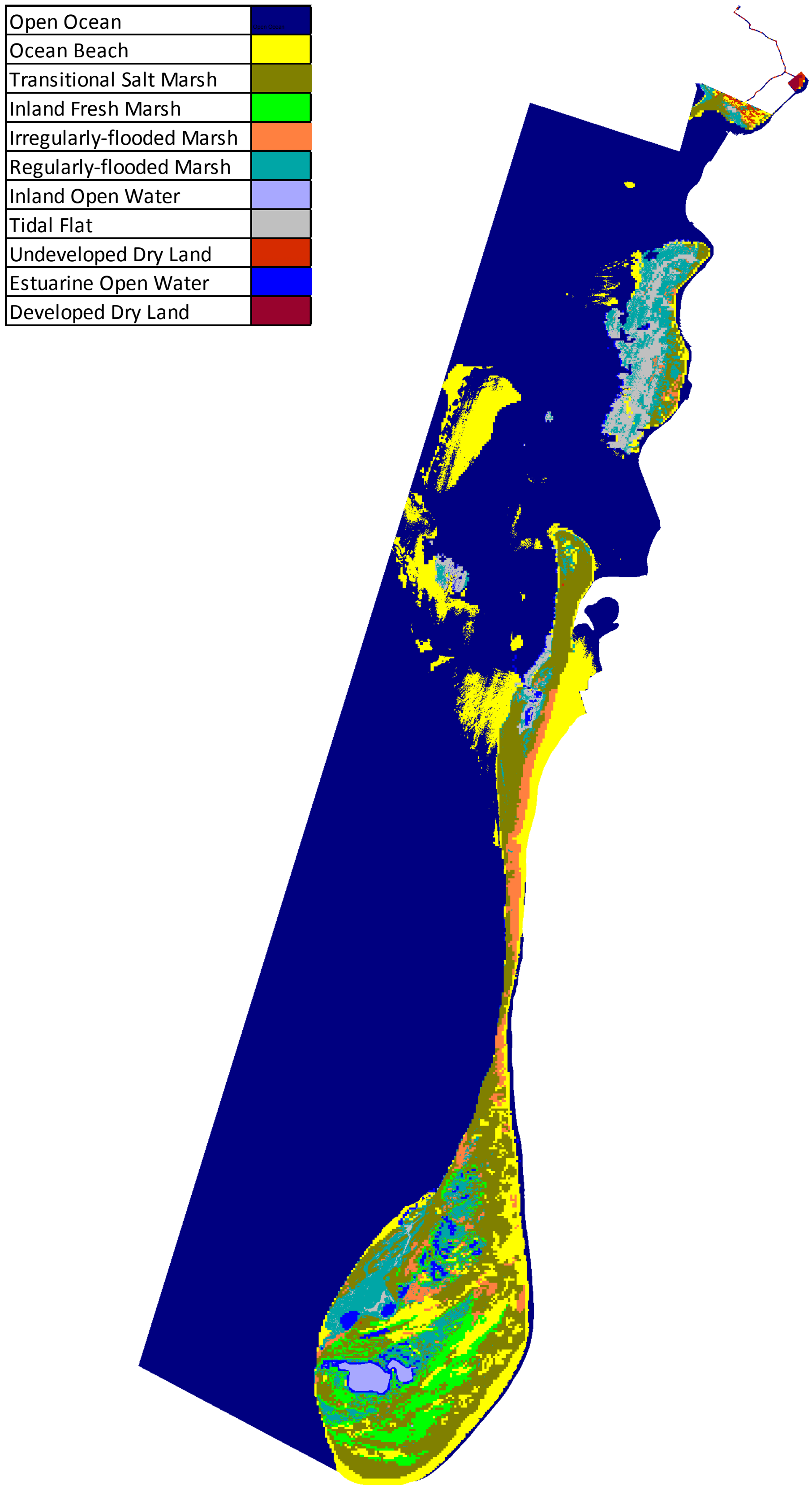
Monomoy NWR, 2025, Scenario A1B Maximum, 0.69 m SLR by 2100.



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



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

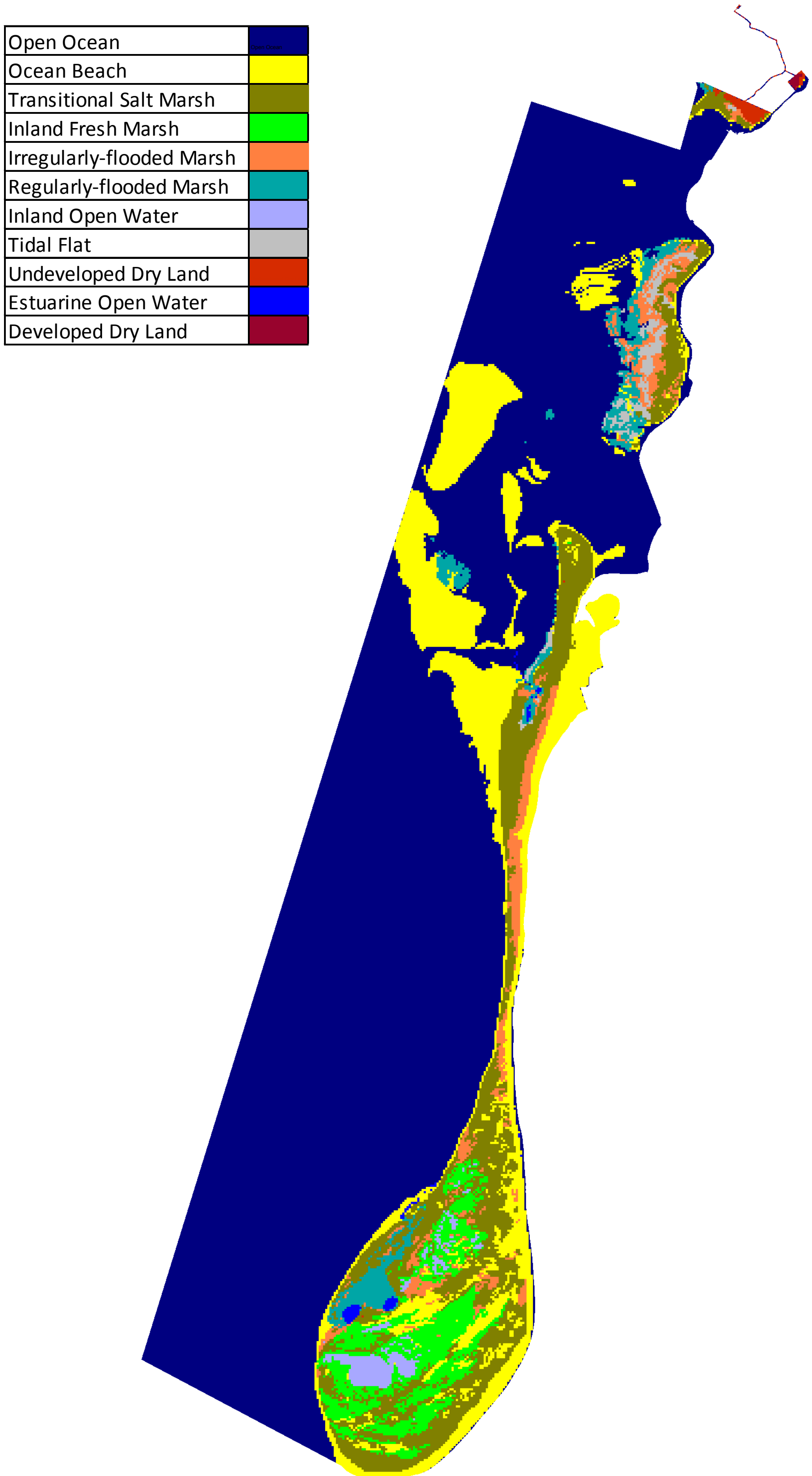


Monomoy NWR, 2100, Scenario A1B Maximum, 0.69 m SLR by 2100.

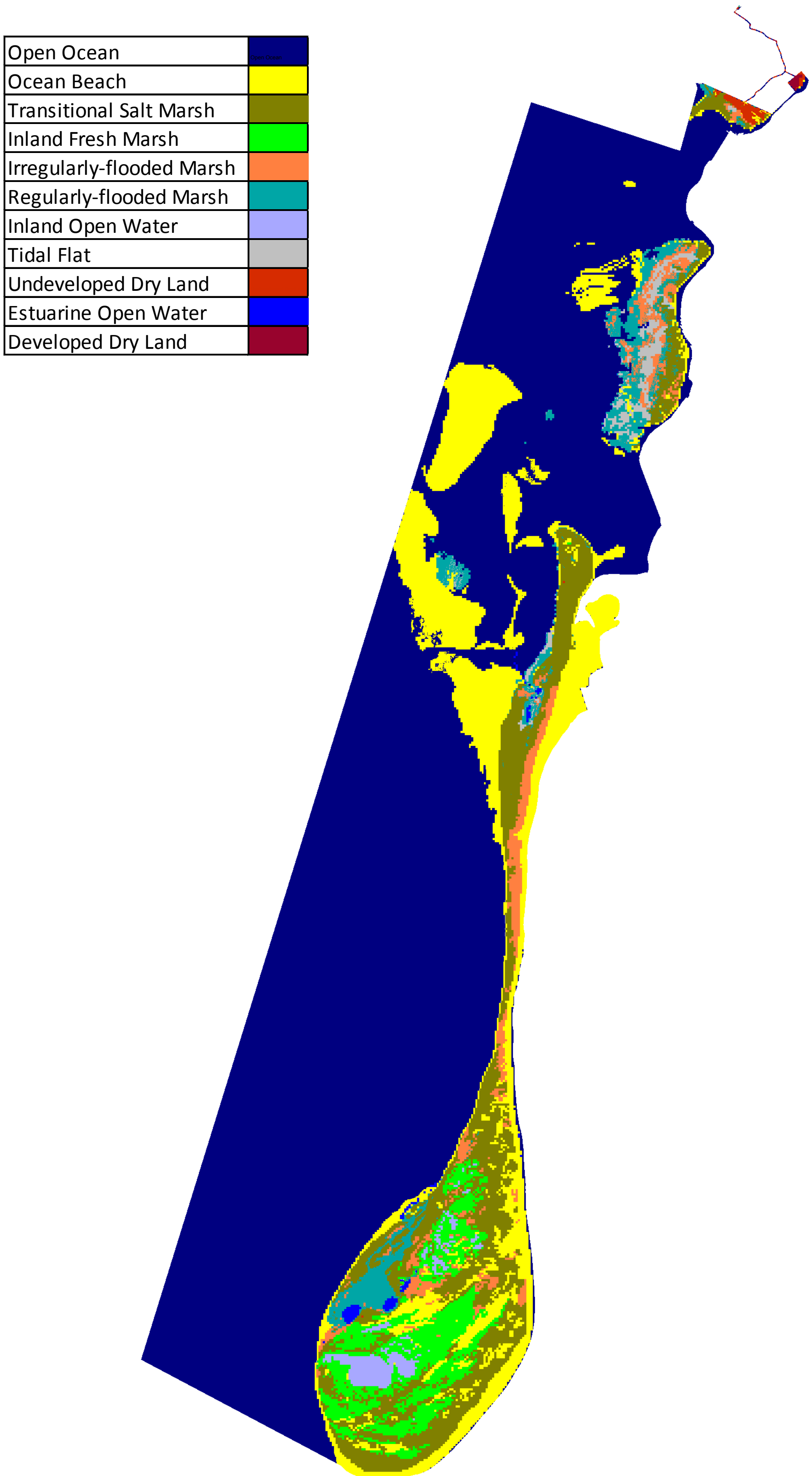
Monomoy NWR
1 m eustatic SLR by 2100

Results in Acres

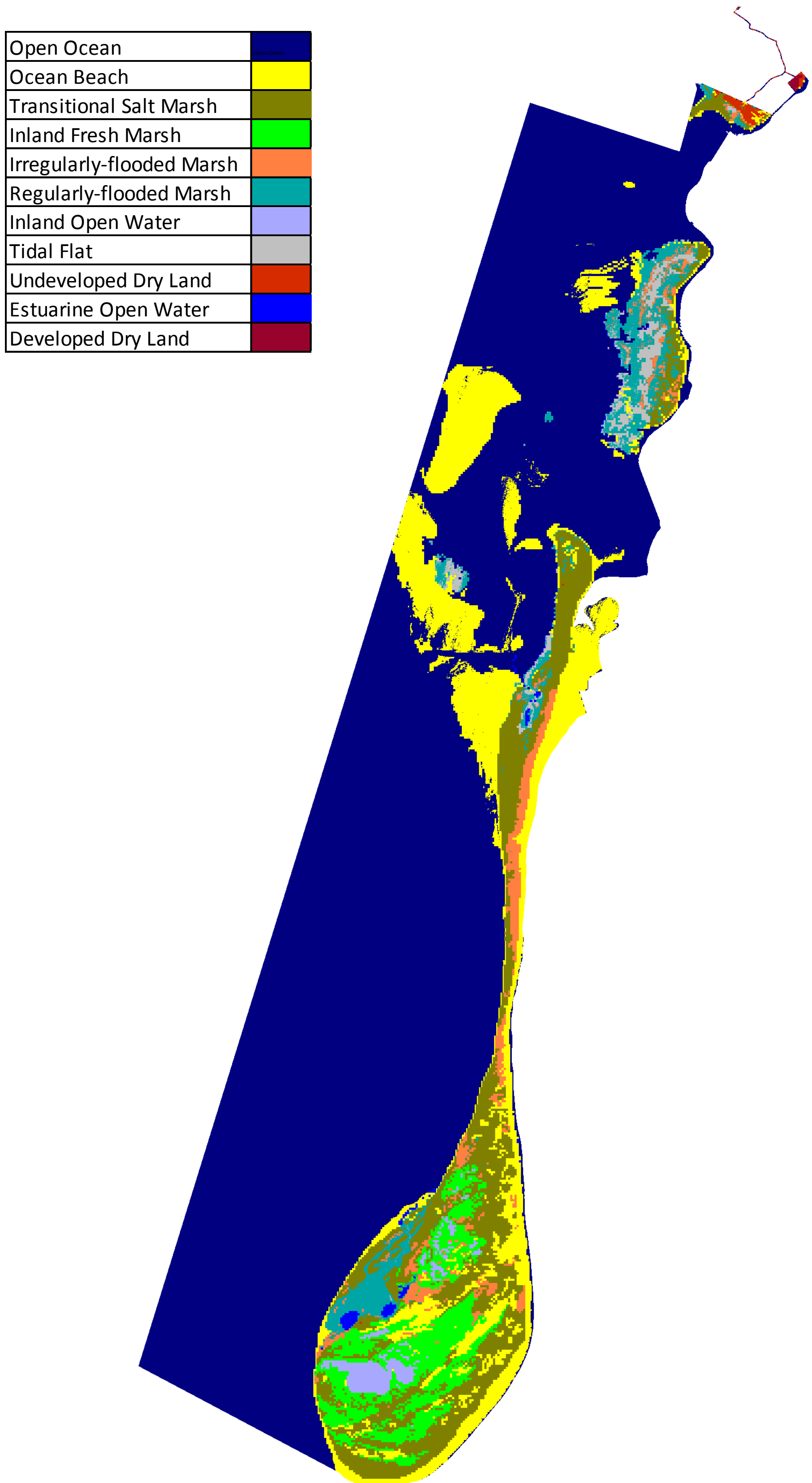
		Initial	2025	2050	2075	2100
	Open Ocean	5072	5093	5148	5356	5581
	Ocean Beach	967	947	893	688	466
	Transitional Salt Marsh	691	662	644	734	607
	Inland Fresh Marsh	291	290	289	162	94
	Irregularly-flooded Marsh	187	176	151	122	107
	Regularly-flooded Marsh	149	185	212	220	309
	Inland Open Water	61	60	60	33	29
	Tidal Flat	57	61	74	130	236
	Undeveloped Dry Land	15	13	12	9	6
	Estuarine Open Water	14	16	19	50	70
	Developed Dry Land	3	3	3	3	3
	Total (incl. water)	**7507**	**7507**	**7507**	**7507**	**7507**



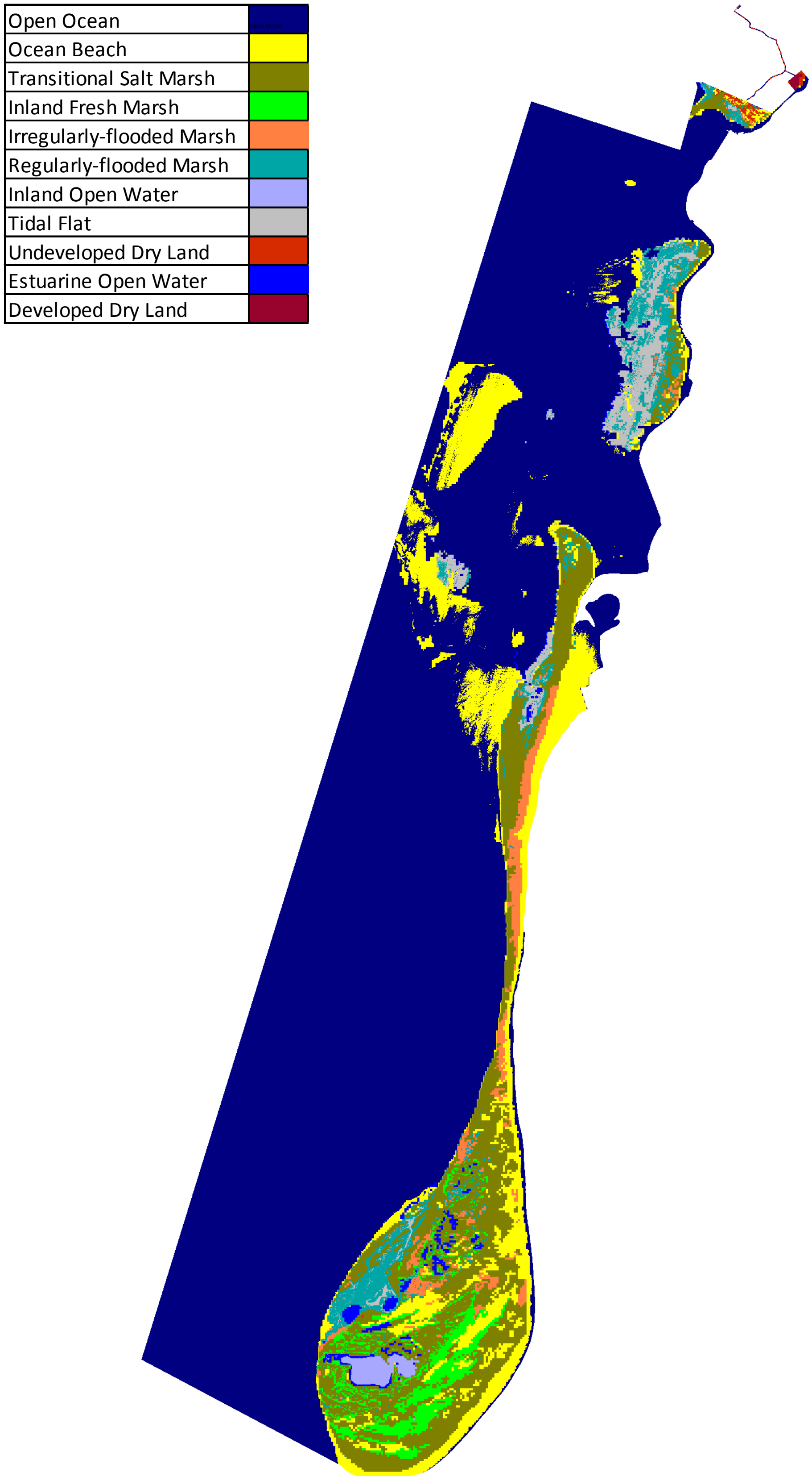
Monomoy NWR, Initial Condition.



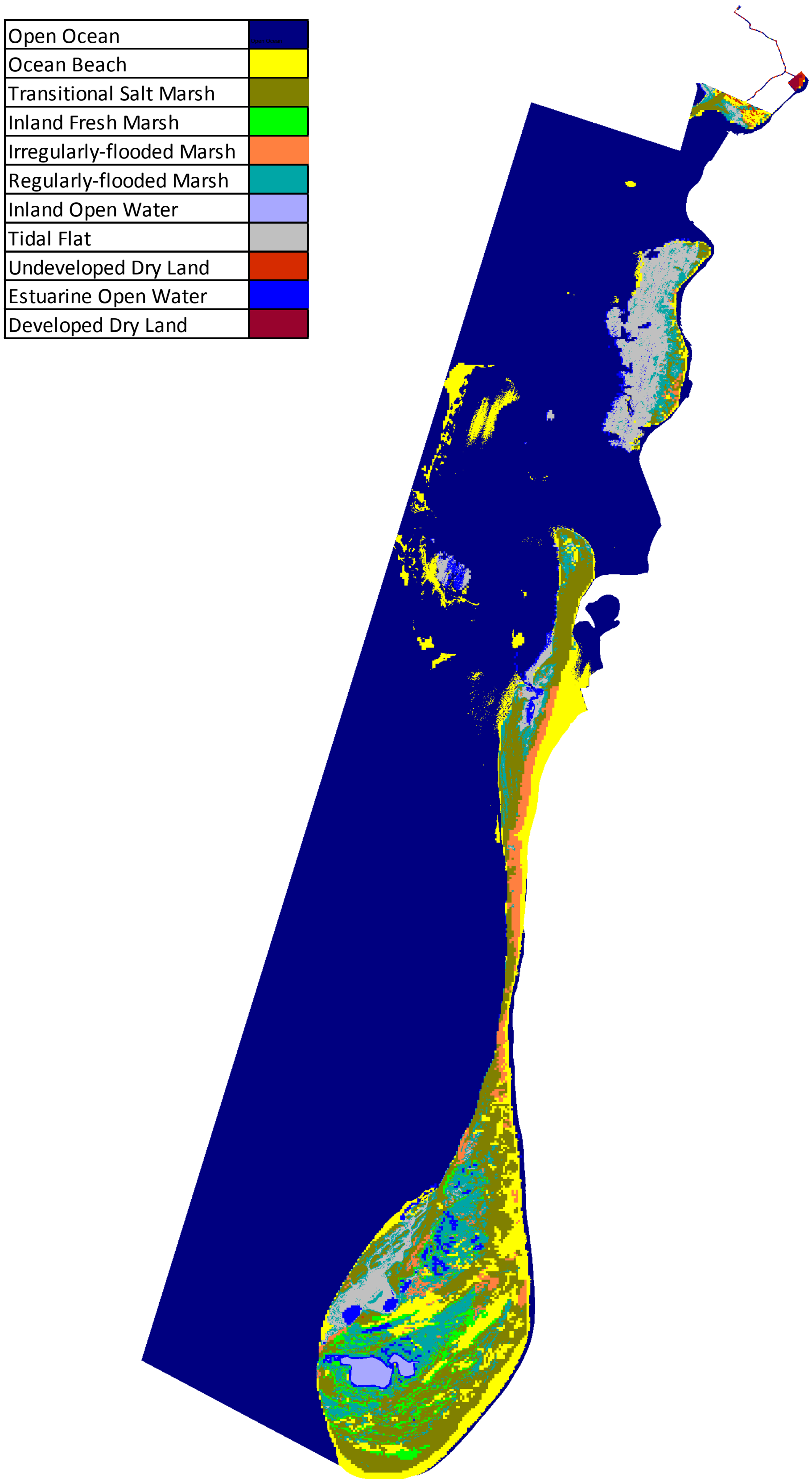
Monomoy NWR, 2025, 1 m SLR by 2100.



Monomoy NWR, 2050, 1 m SLR by 2100.



Monomoy NWR, 2075, 1 m SLR by 2100.

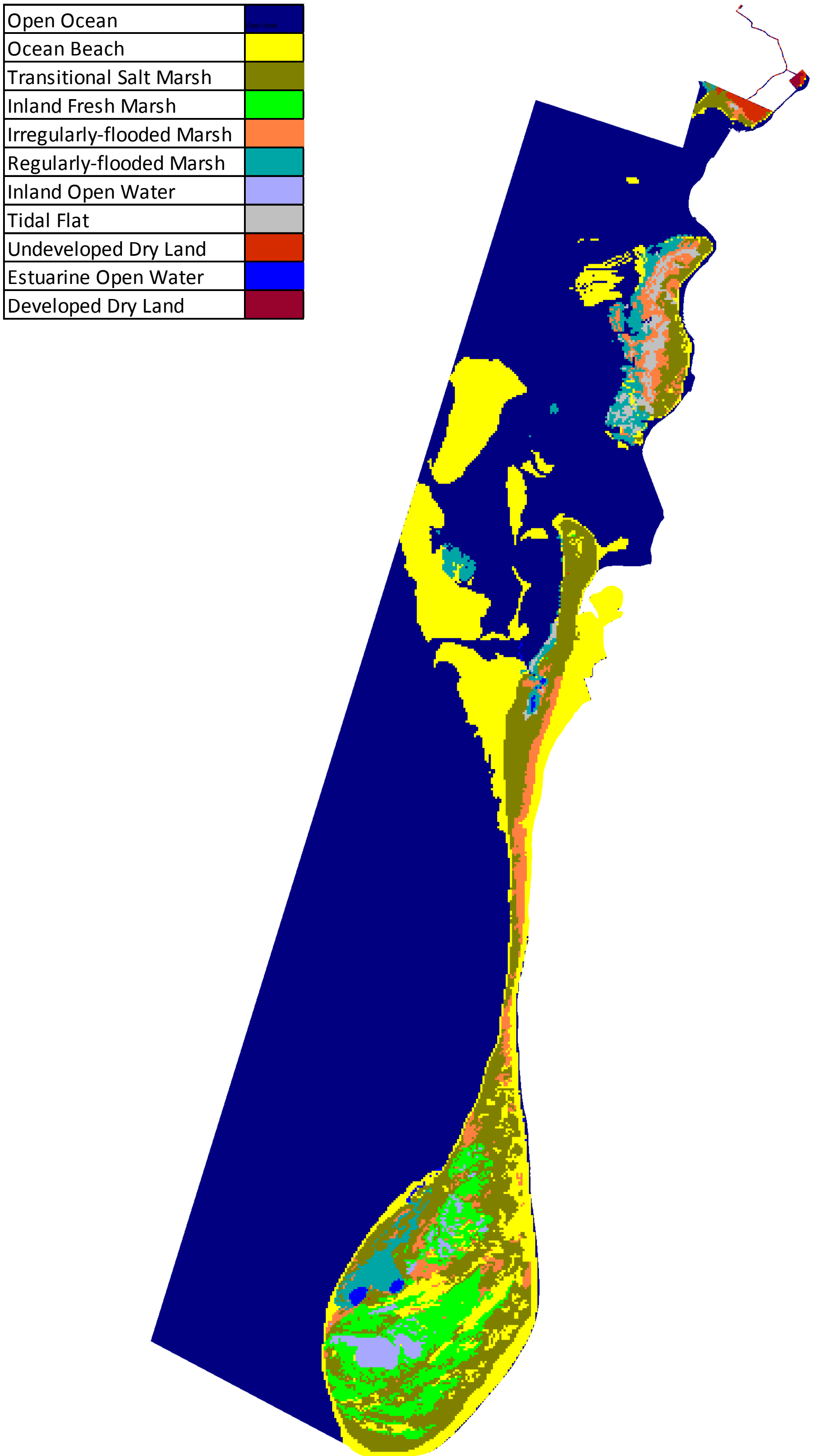


Monomoy NWR, 2100, 1 m SLR by 2100.

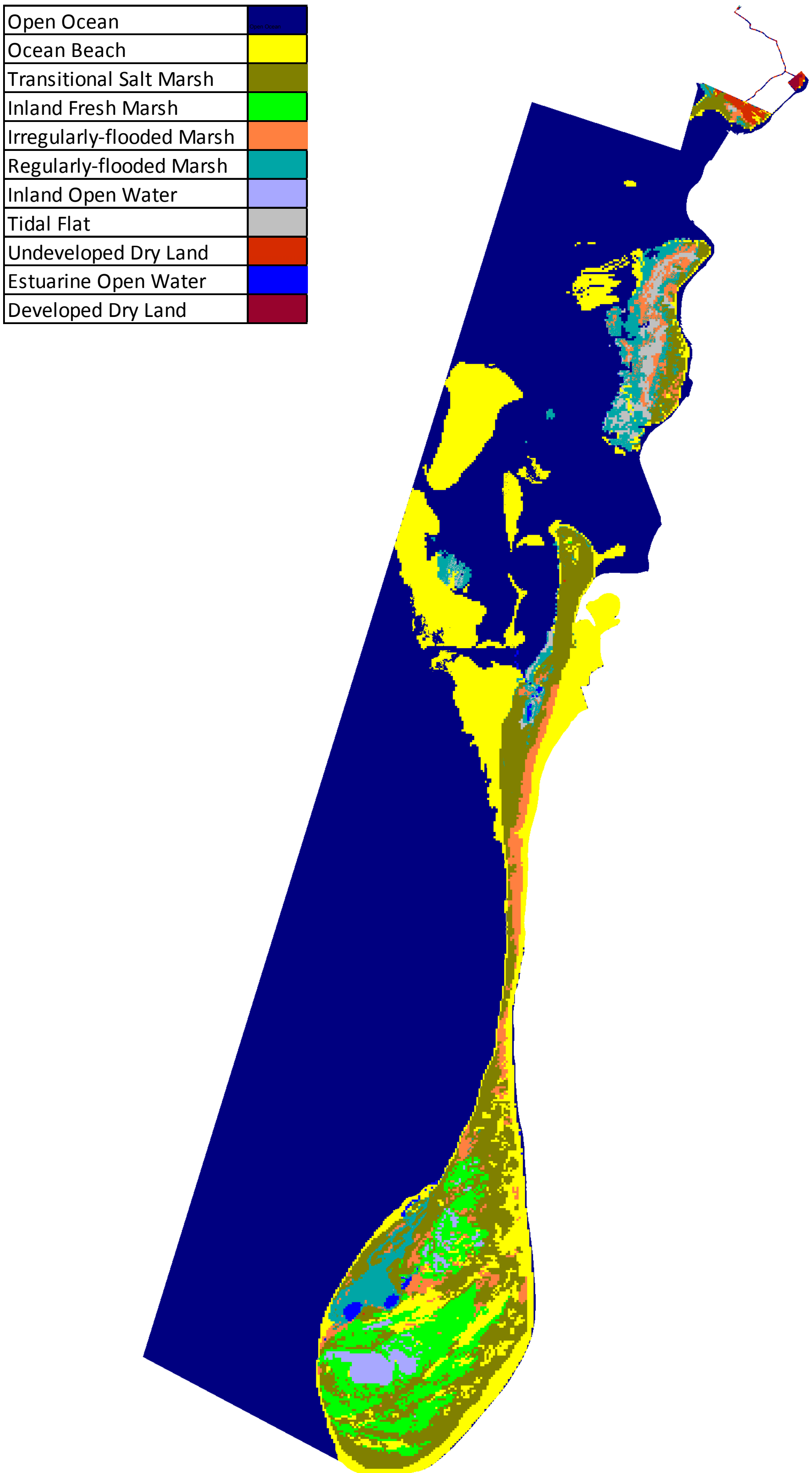
Monomoy NWR
1.5 m eustatic SLR by 2100

Results in Acres

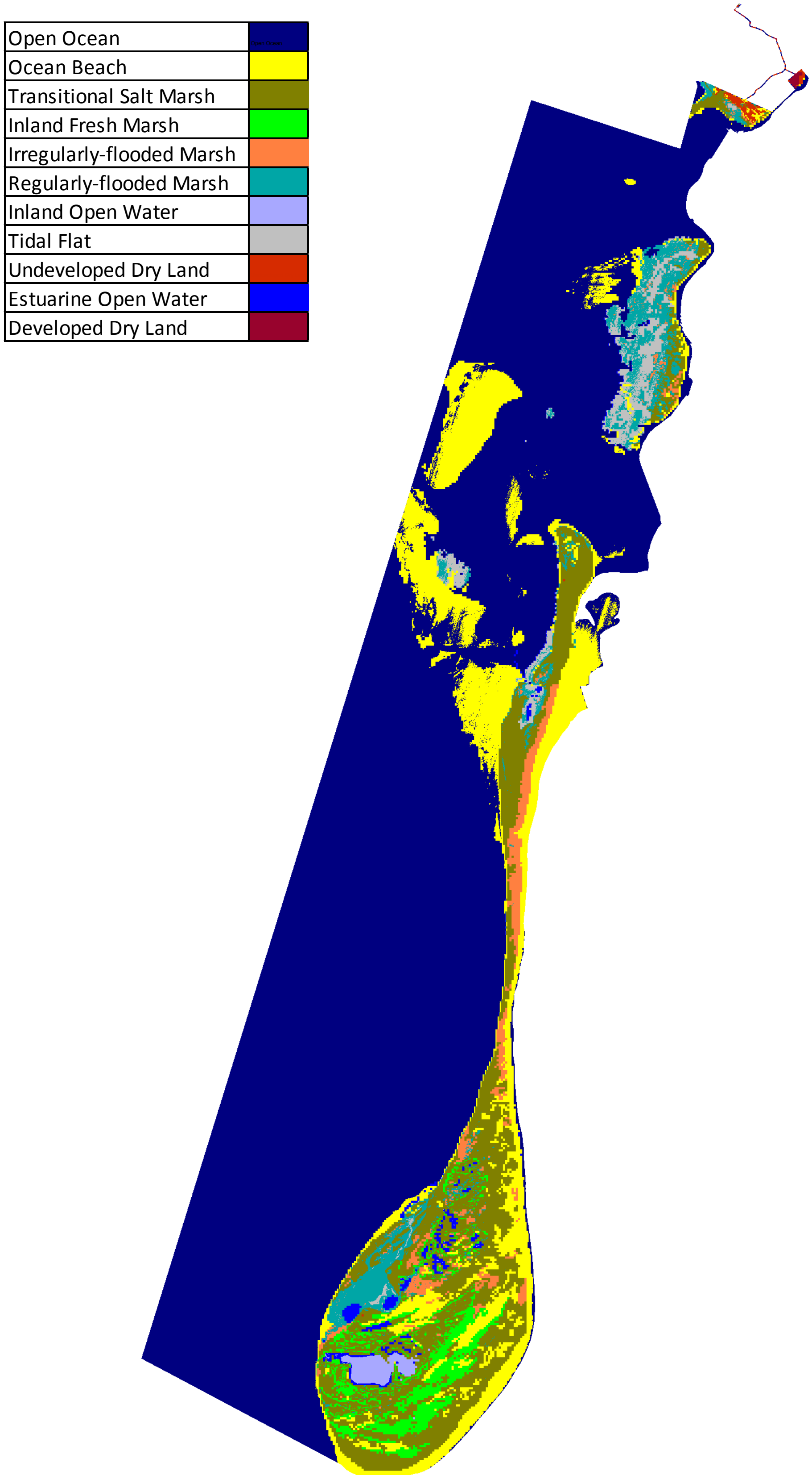
		Initial	2025	2050	2075	2100
	Open Ocean	5072	5098	5223	5548	5680
	Ocean Beach	967	943	820	498	369
	Transitional Salt Marsh	691	658	735	616	405
	Inland Fresh Marsh	291	290	175	76	41
	Irregularly-flooded Marsh	187	171	128	104	88
	Regularly-flooded Marsh	149	192	225	298	380
	Inland Open Water	61	60	34	29	29
	Tidal Flat	57	64	107	262	300
	Undeveloped Dry Land	15	13	11	6	3
	Estuarine Open Water	14	17	47	67	209
	Developed Dry Land	3	3	3	3	3
	Total (incl. water)	**7507**	**7507**	**7507**	**7507**	**7507**



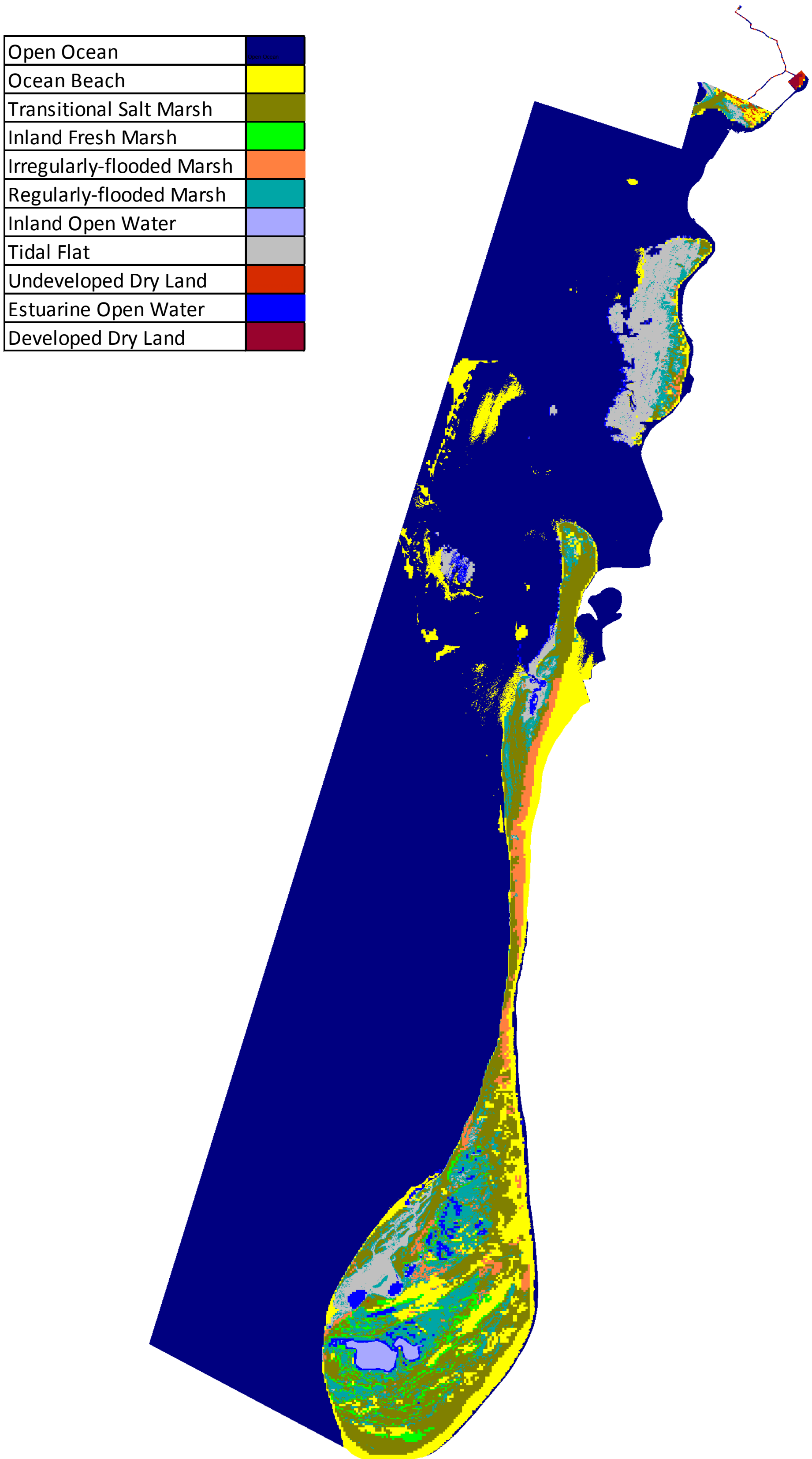
Monomoy NWR, Initial Condition.



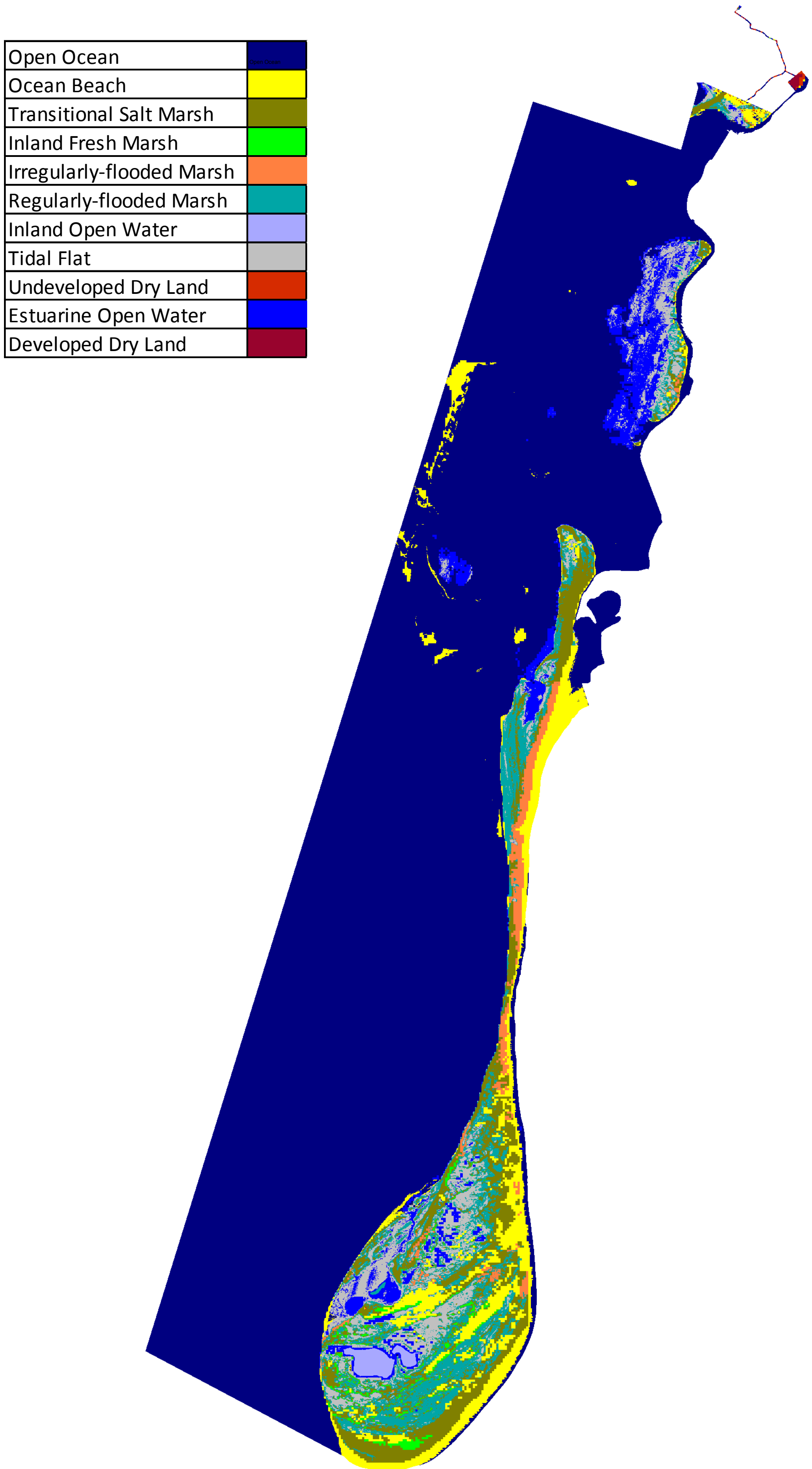
Monomoy NWR, 2025, 1.5 m SLR by 2100.



Monomoy NWR, 2050, 1.5 m SLR by 2100.



Monomoy NWR, 2075, 1.5 m SLR by 2100.

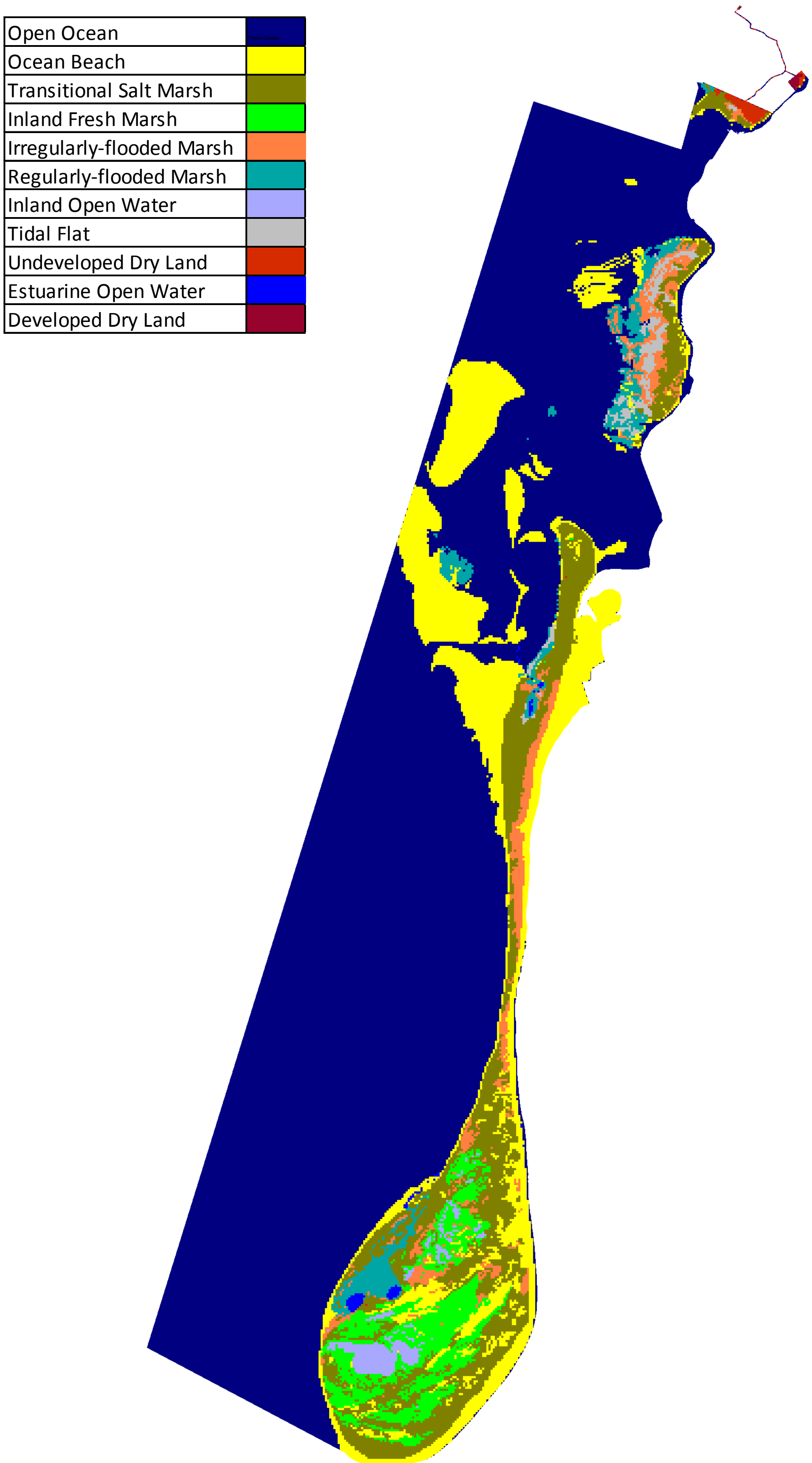


Monomoy NWR, 2100, 1.5 m SLR by 2100.

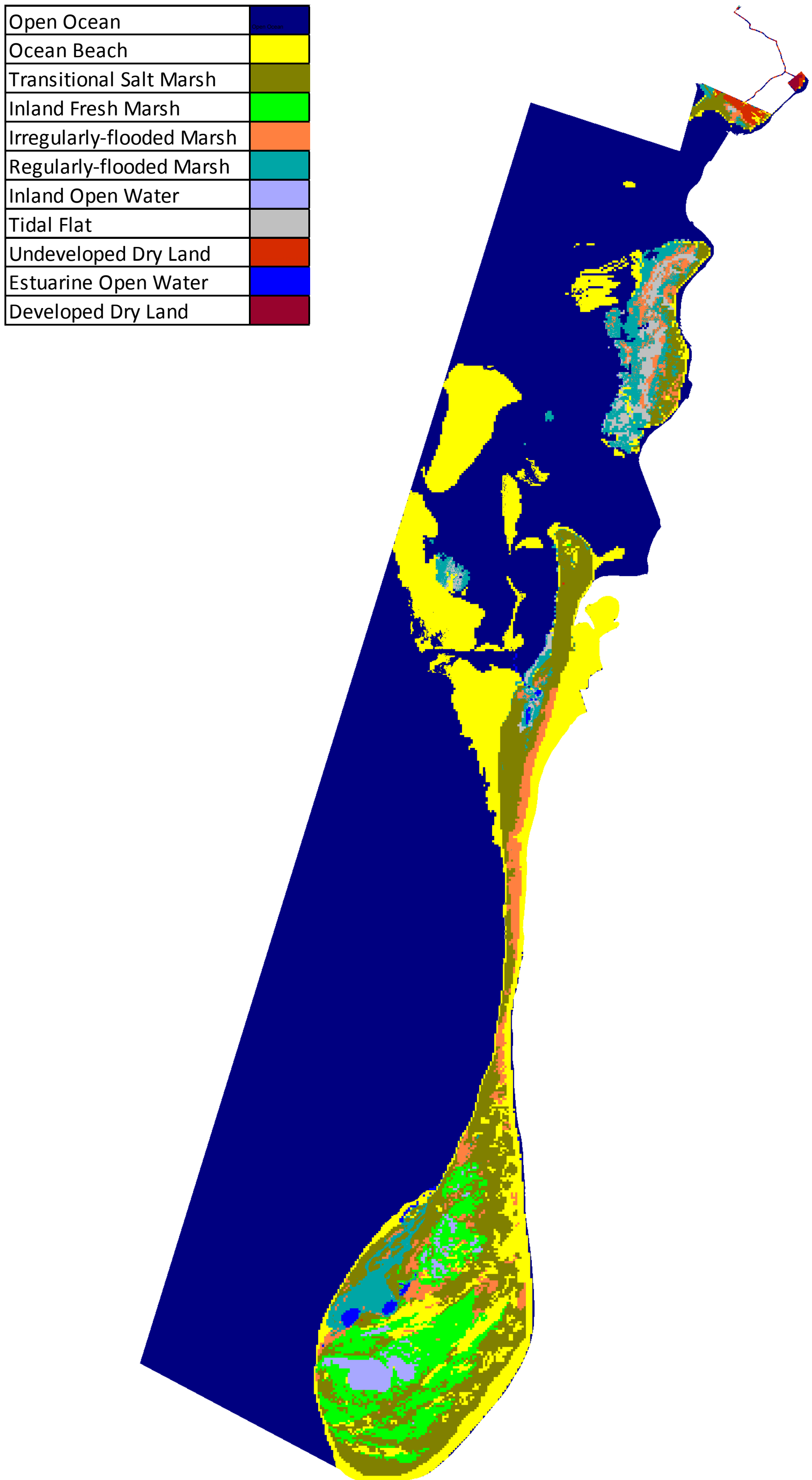
Monomoy NWR
2 m eustatic SLR by 2100

Results in Acres

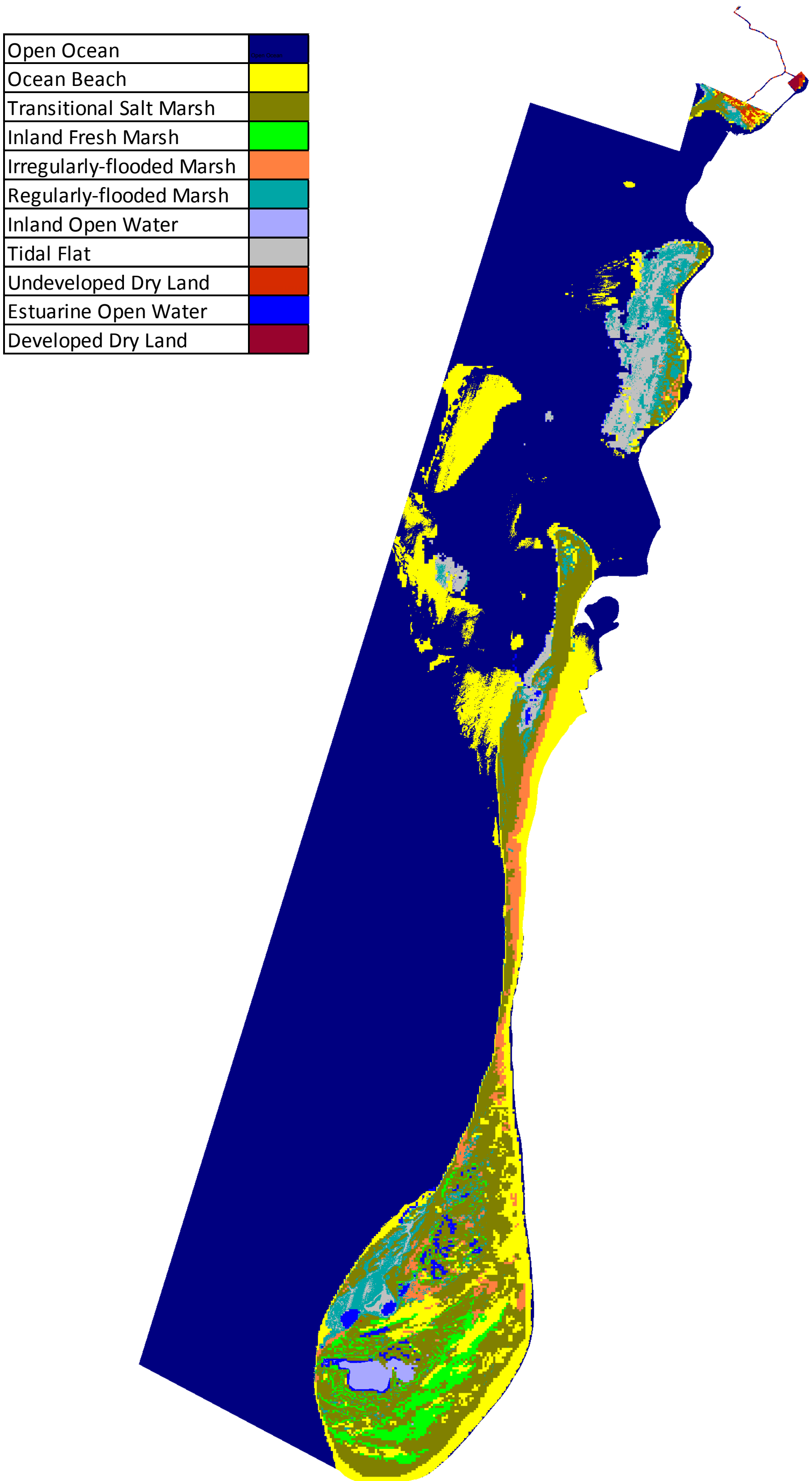
		Initial	2025	2050	2075	2100
	Open Ocean	5072	5102	5332	5647	5712
	Ocean Beach	967	939	711	401	338
	Transitional Salt Marsh	691	654	739	500	265
	Inland Fresh Marsh	291	289	142	44	17
	Irregularly-flooded Marsh	187	165	116	92	70
	Regularly-flooded Marsh	149	198	208	398	348
	Inland Open Water	61	60	33	29	29
	Tidal Flat	57	67	164	242	343
	Undeveloped Dry Land	15	13	9	4	3
	Estuarine Open Water	14	17	49	148	381
	Developed Dry Land	3	3	3	3	3
	Total (incl. water)	**7507**	**7507**	**7507**	**7507**	**7507**



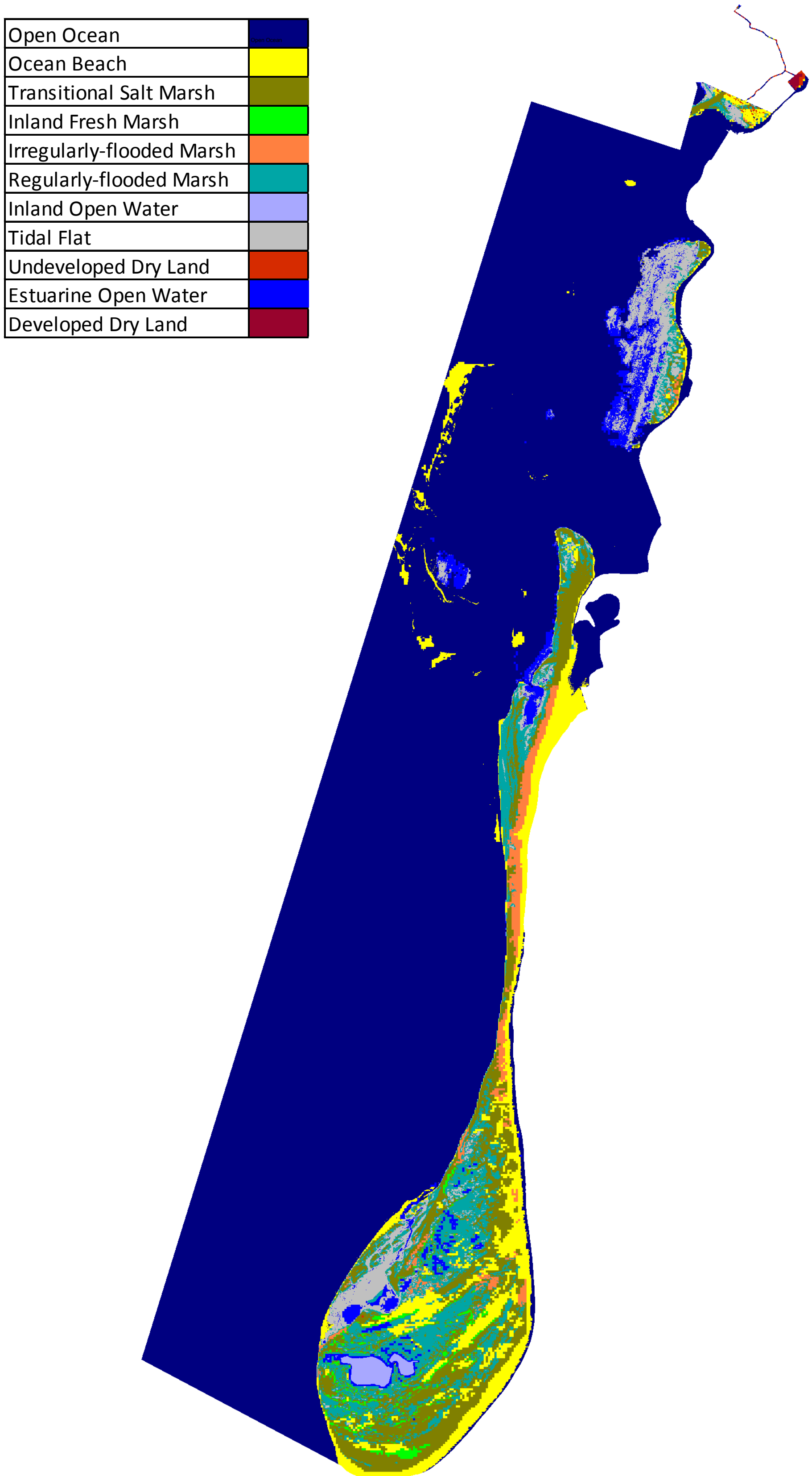
Monomoy NWR, Initial Condition.



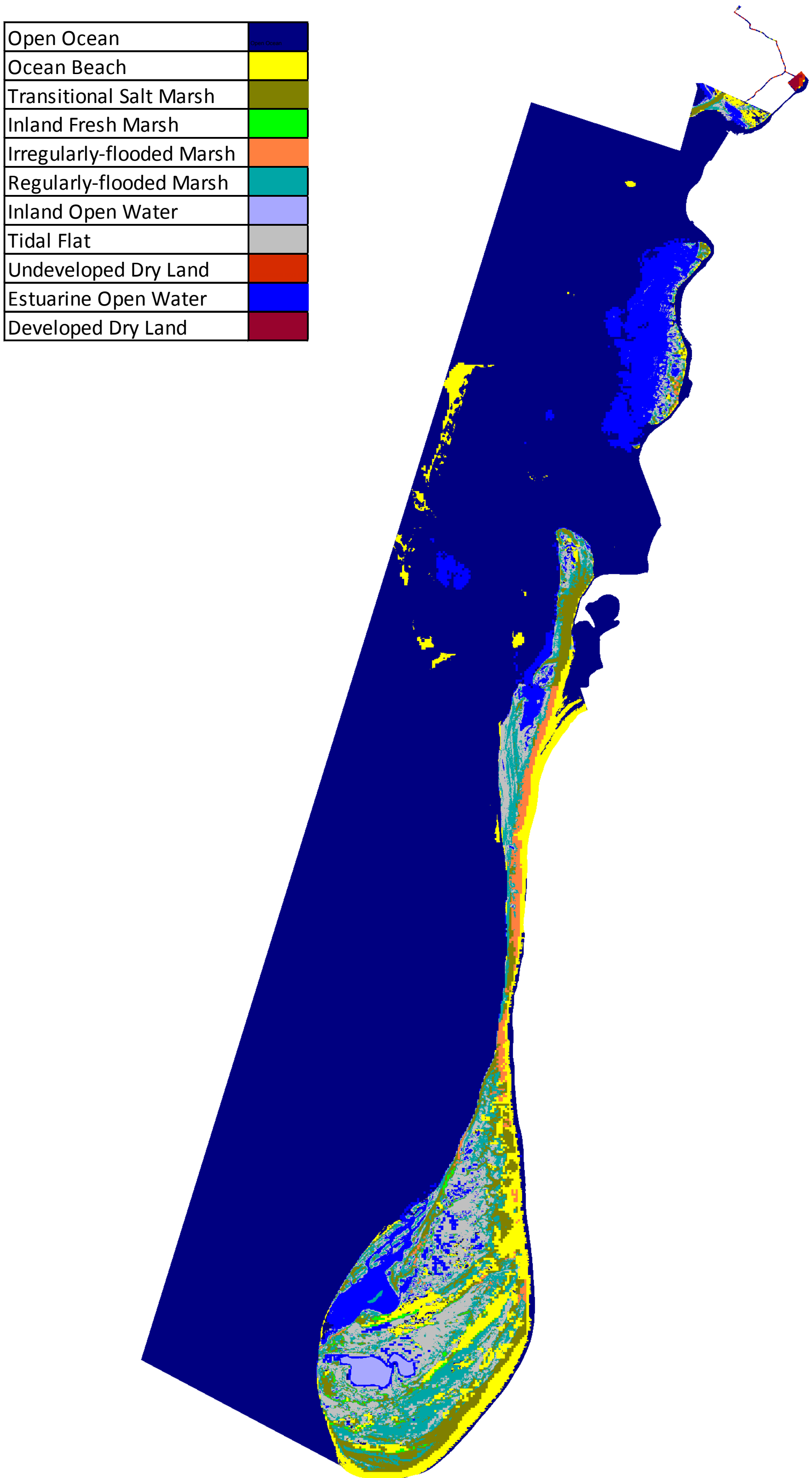
Monomoy NWR, 2025, 2 m SLR by 2100.



Monomoy NWR, 2050, 2 m SLR by 2100.



Monomoy NWR, 2075, 2 m SLR by 2100.



Monomoy NWR, 2100, 2 m SLR by 2100.

Discussion

SLAMM predictions for Monomoy NWR suggest that refuge wetland coverage is relatively resilient to sea-level rise under the 0.39 m by 2100 scenario (the lowest SLR scenario examined), but quite susceptible at higher SLR scenarios. Excluding open water, the overall wetland coverage is predicted to be significantly reduced as sea level rise increases. Up to one third of wetlands are predicted converted to open water under the 2 m SLR by 2100 scenario. Regularly-flooded marsh habitats are predicted to increase coverage.

Compared to the previous SLAMM analysis of the refuge conducted in 2009, several differences must be noted. First, the SLAMM version used for this analysis has changed. More importantly, the combination of more precise elevation information using LiDAR data and the detailed wetland layer provided by the refuge staff make the comparison with previous simulated projections very difficult if not meaningless. One factor that supports the validity of these projections is that by using these high quality data (elevation and wetland coverage) and the available tidal information, the elevation ranges of wetlands in the refuge closely match the SLAMM conceptual model.

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

References

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. (2008). *Application of the Sea-Level Affection Marshes Model (SLAMM 5.0) to St. Marks Wildlife Refuge*. Warren Pinnacle Consulting, Inc.

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.

Kish, S. (2011). "Erosion Data."

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

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

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

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

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

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

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

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

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

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

C.T. Roman, J.A. Peck, J.R. Allen, J.W. King, and P.G. Appleby. (1997). "Accretion of a New England (U.S.A.) salt marsh in response to inlet migration, storms and sea-level rise." *Estuarine, Coastal and Shelf Science*, 45(6), 717–727.

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.

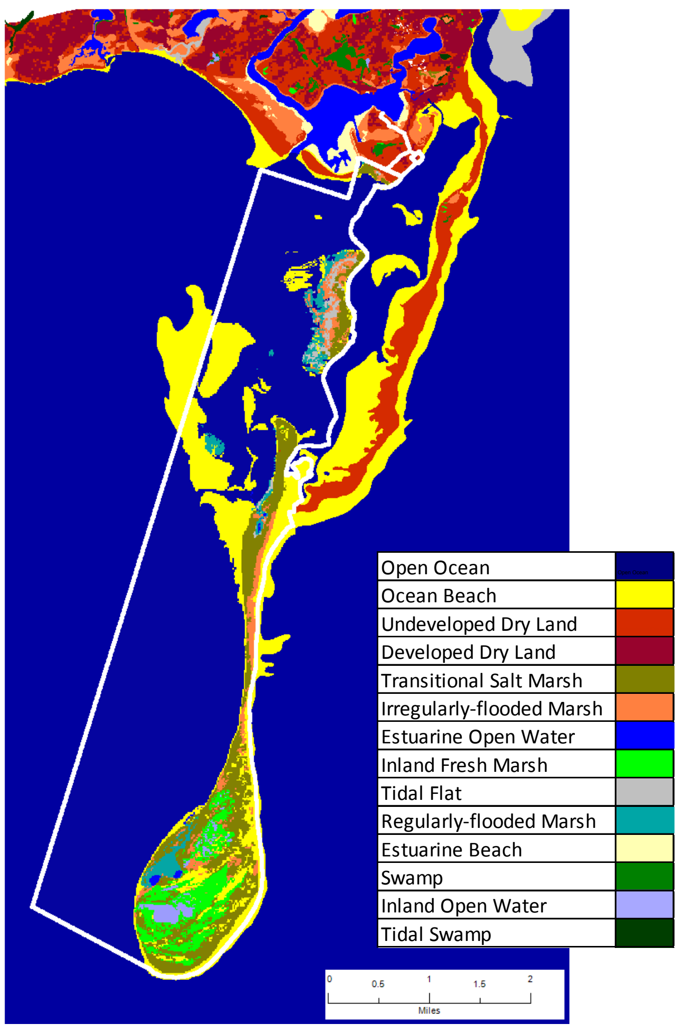
U.S. Department of the Interior Fish and Wildlife Service Southeast Region. (2006). *St. Marks National Wildlife Refuge Comprehensive Conservation Plan*.

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

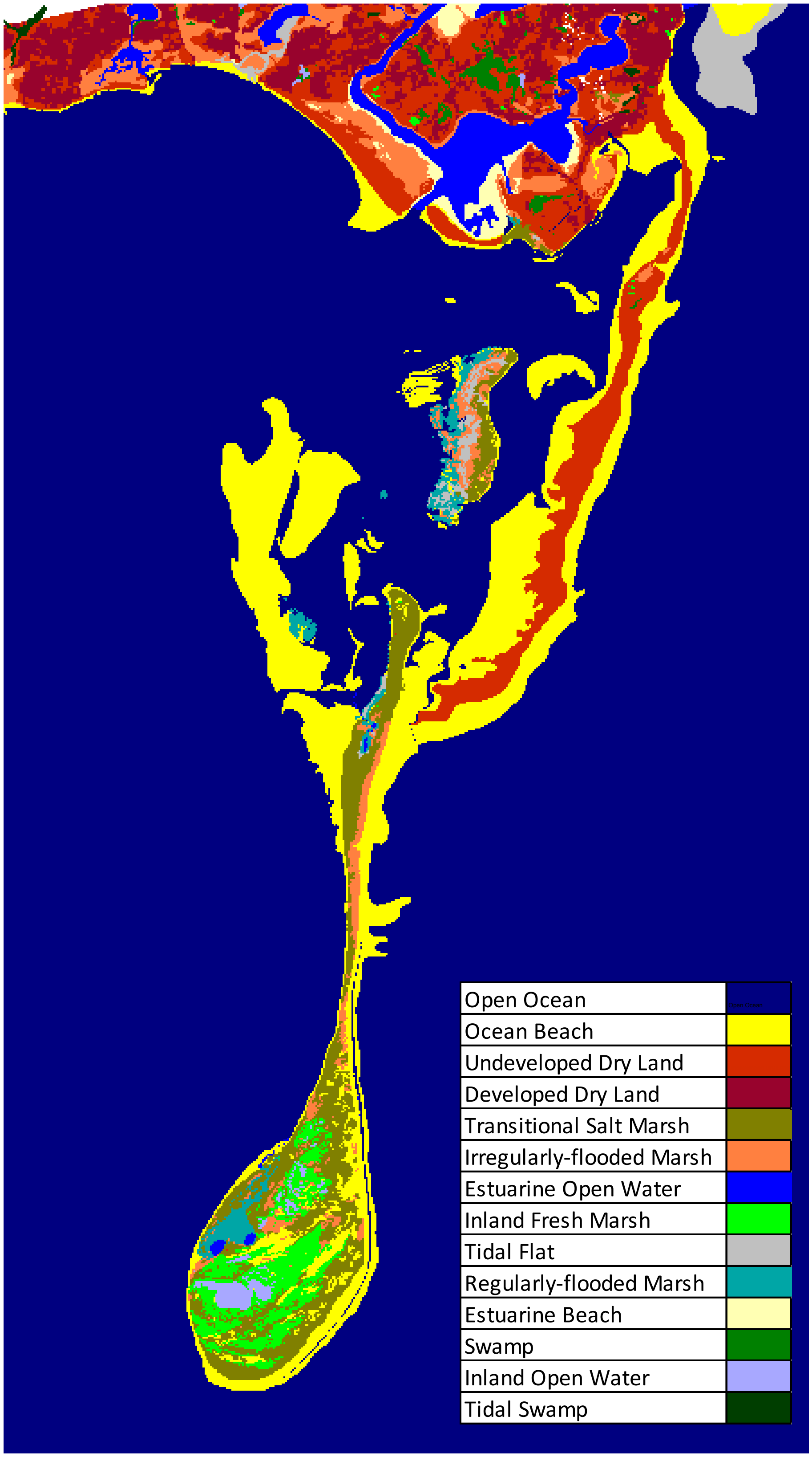
Appendix A: Contextual Results

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:

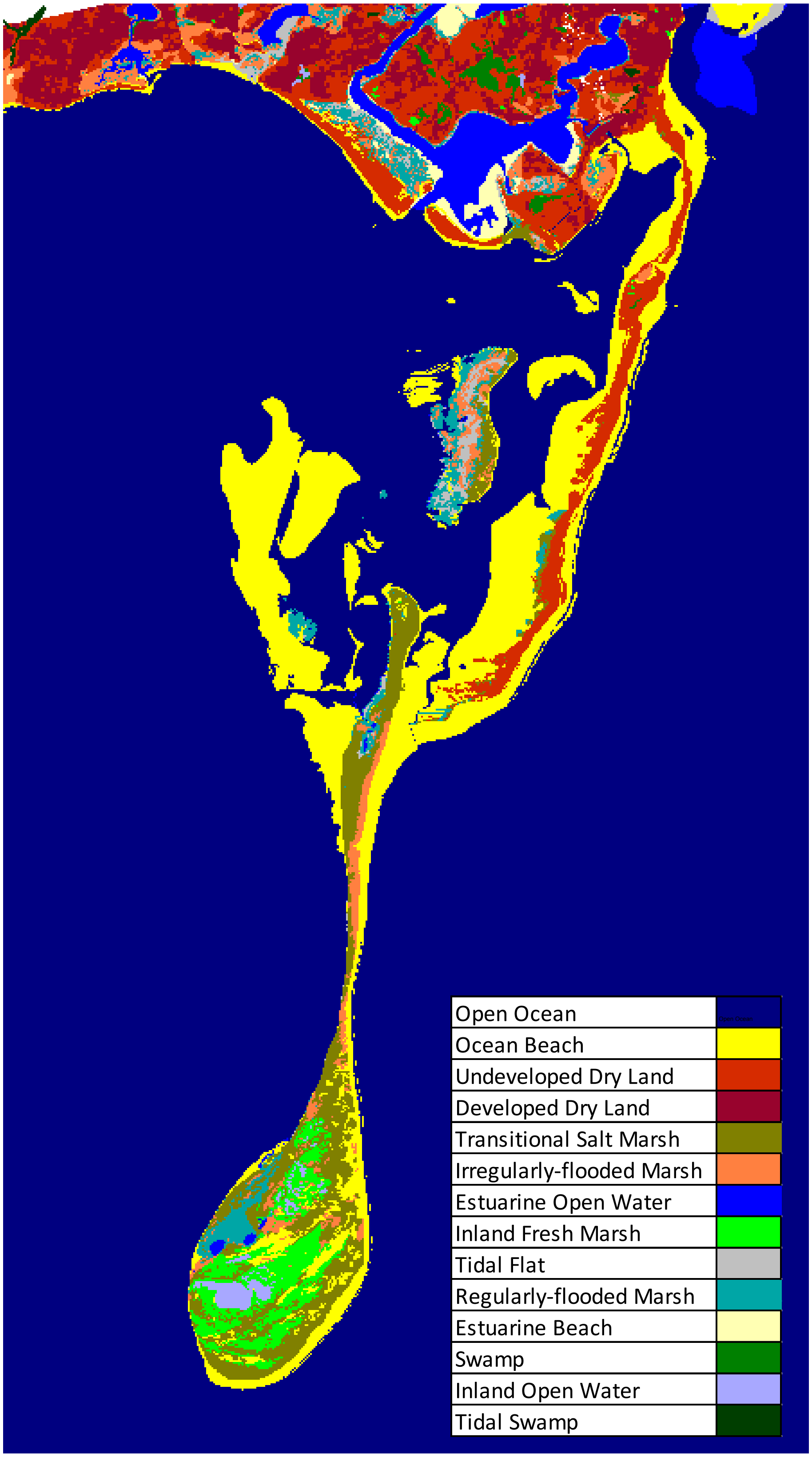
- Results were critically examined within USFWS refuges but not closely examined for the larger region.
- Site-specific parameters for the model were derived for USFWS refuges whenever possible and may not be regionally applicable.
- Especially in areas where dikes are present, an effort was made to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



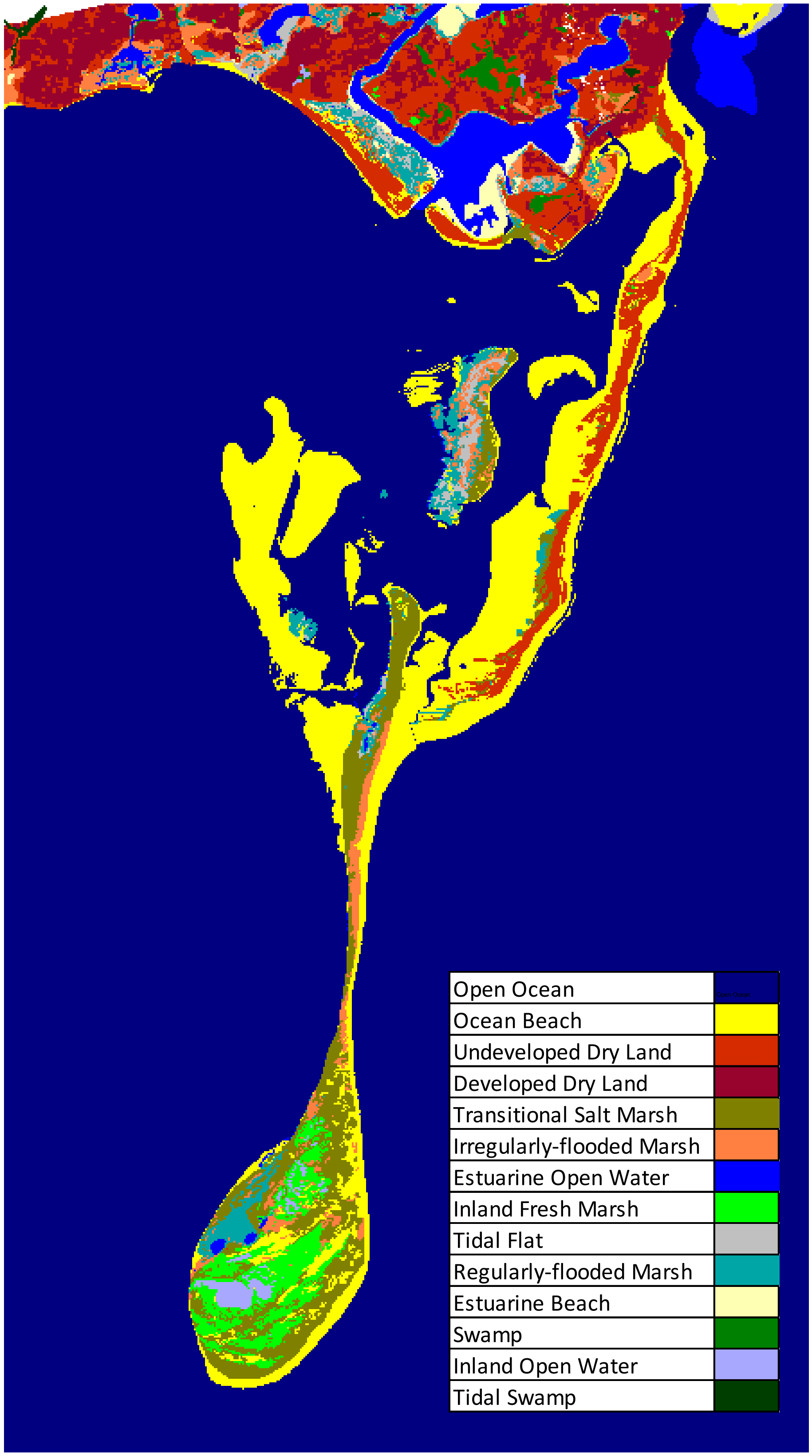
Monomoy National Wildlife Refuge within simulation context (white).



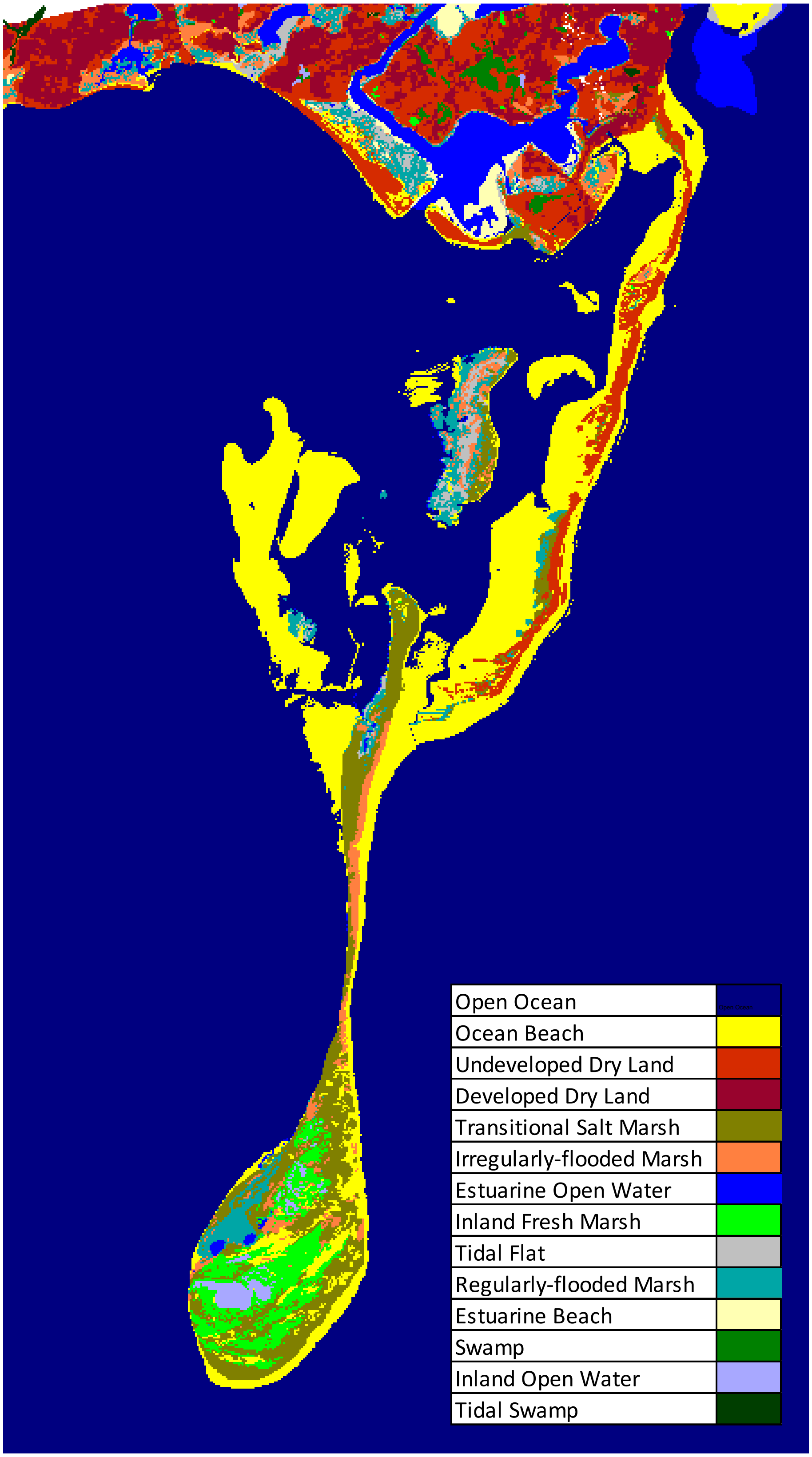
Monomoy NWR, Initial Condition.



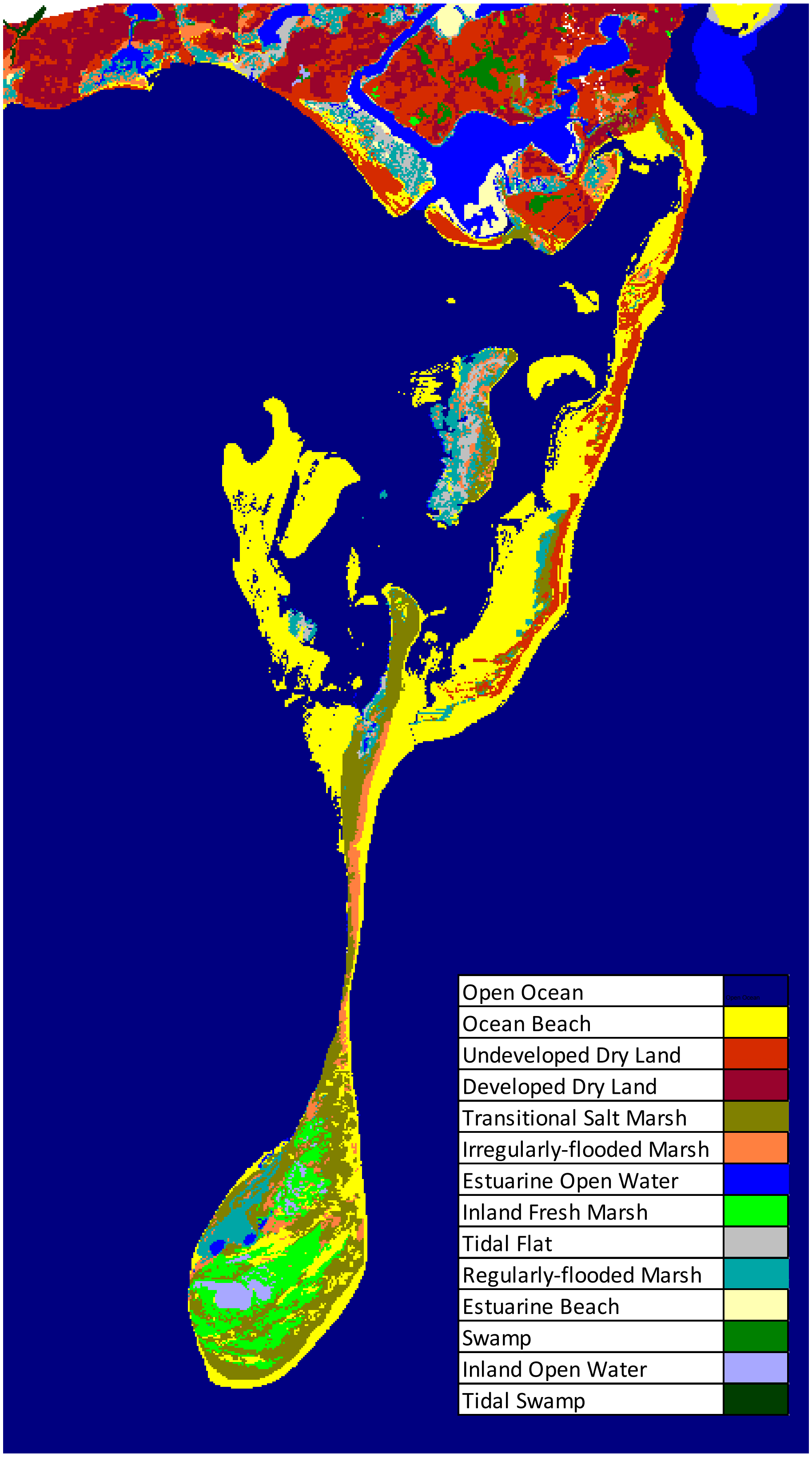
Monomoy NWR, 2025, Scenario A1B Mean, 0.39 m SLR by 2100.



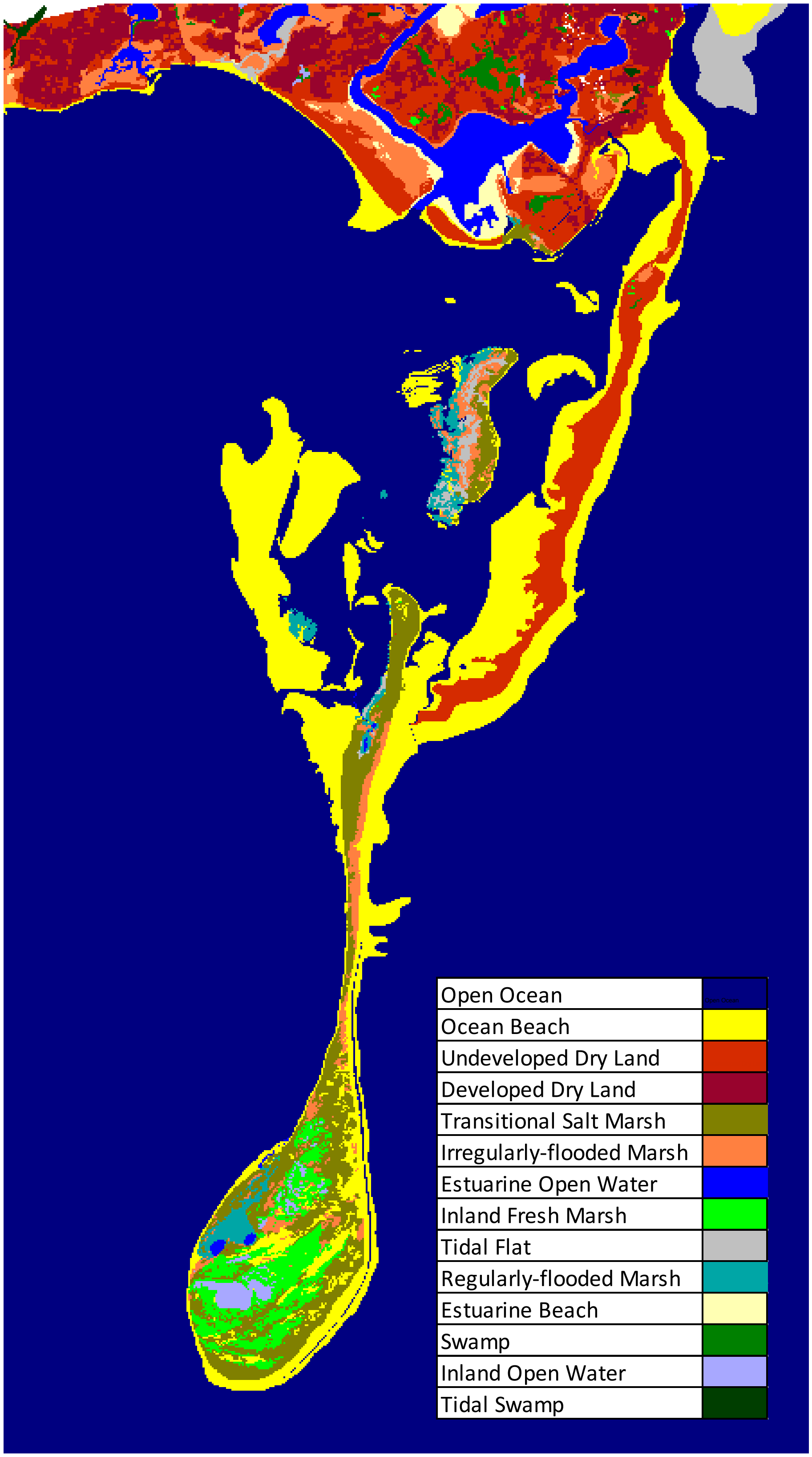
Monomoy NWR, 2050, Scenario A1B Mean, 0.39 m SLR by 2100.



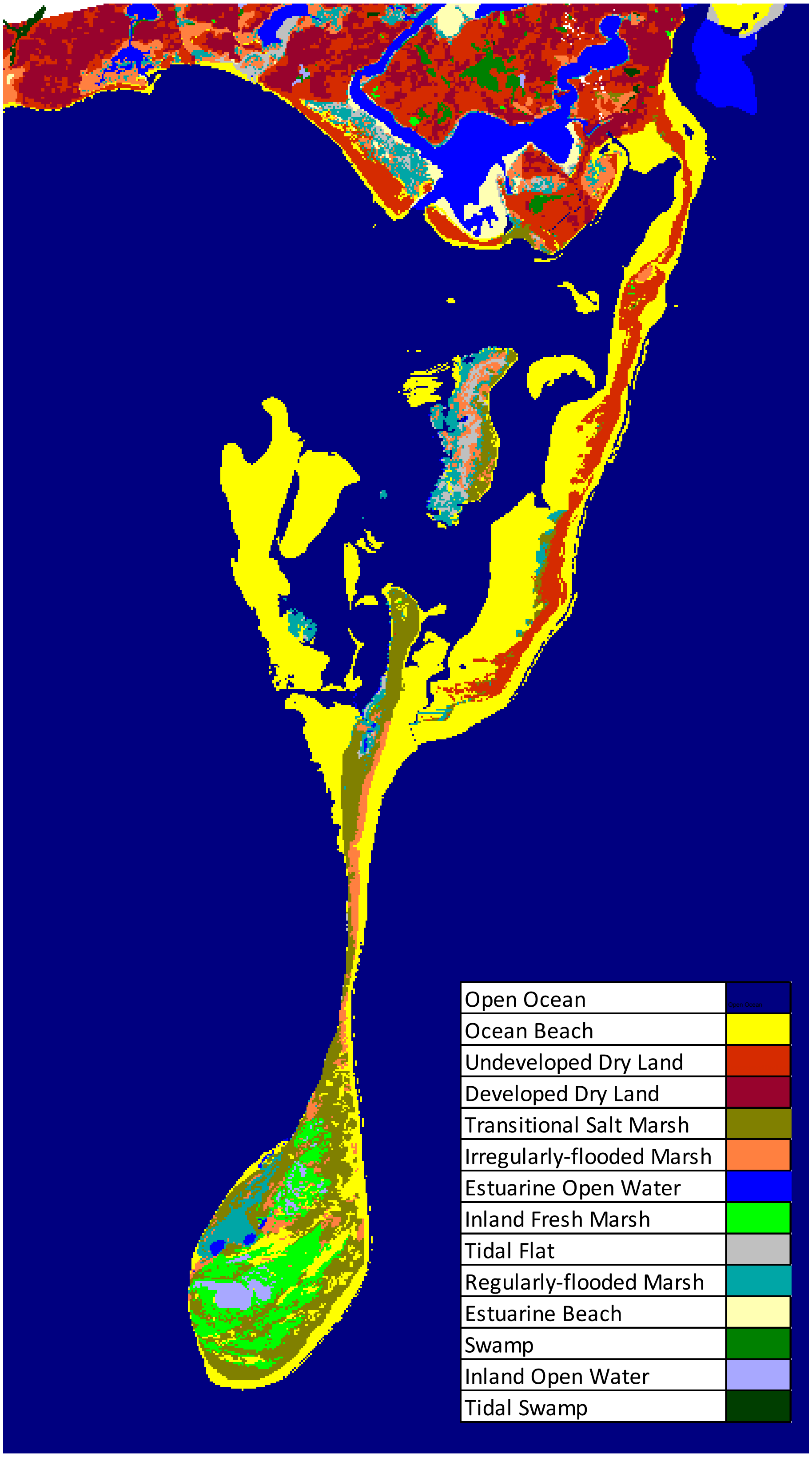
Monomoy NWR, 2075, Scenario A1B Mean, 0.39 m SLR by 2100.



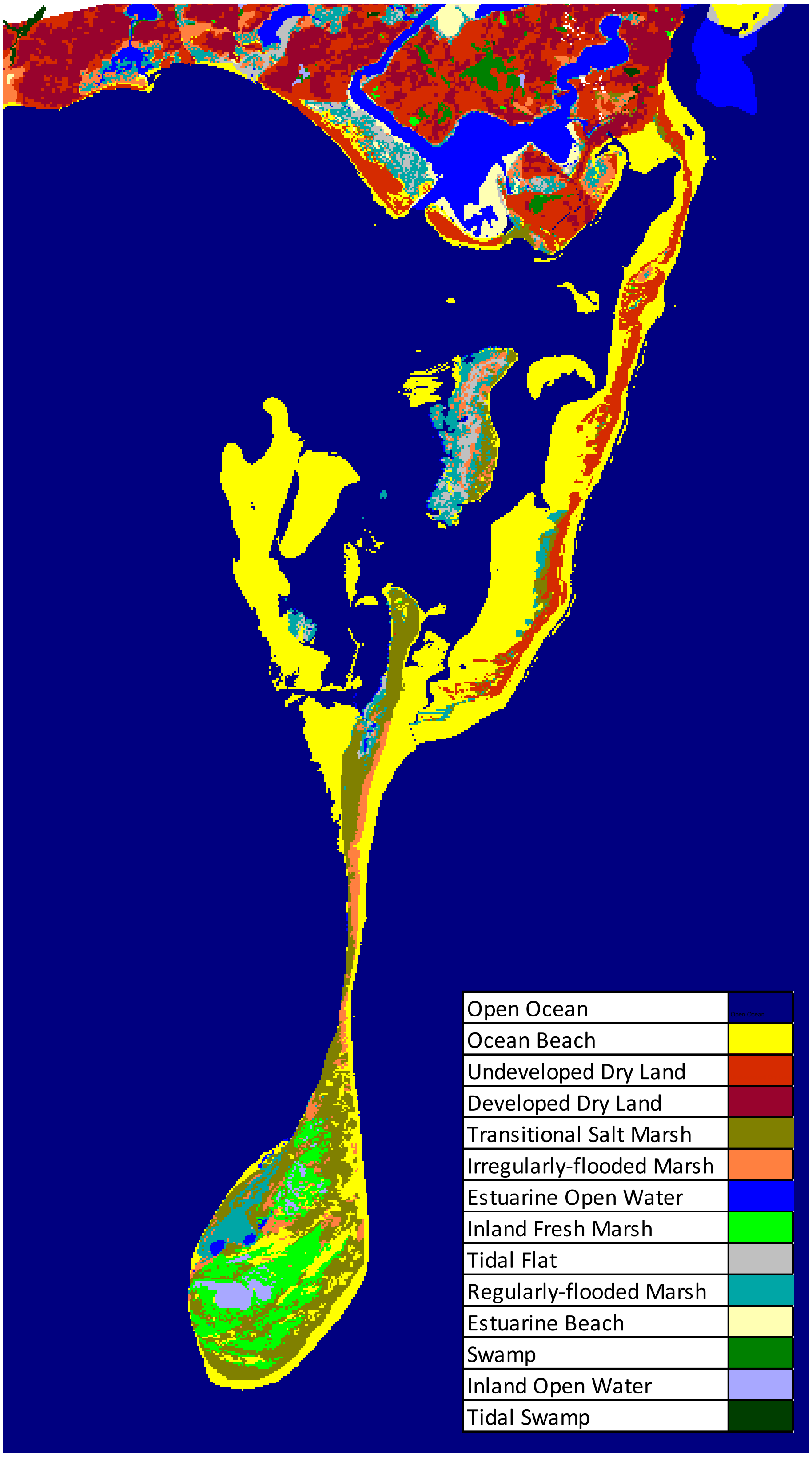
Monomoy NWR, 2100, Scenario A1B Mean, 0.39 m SLR by 2100.



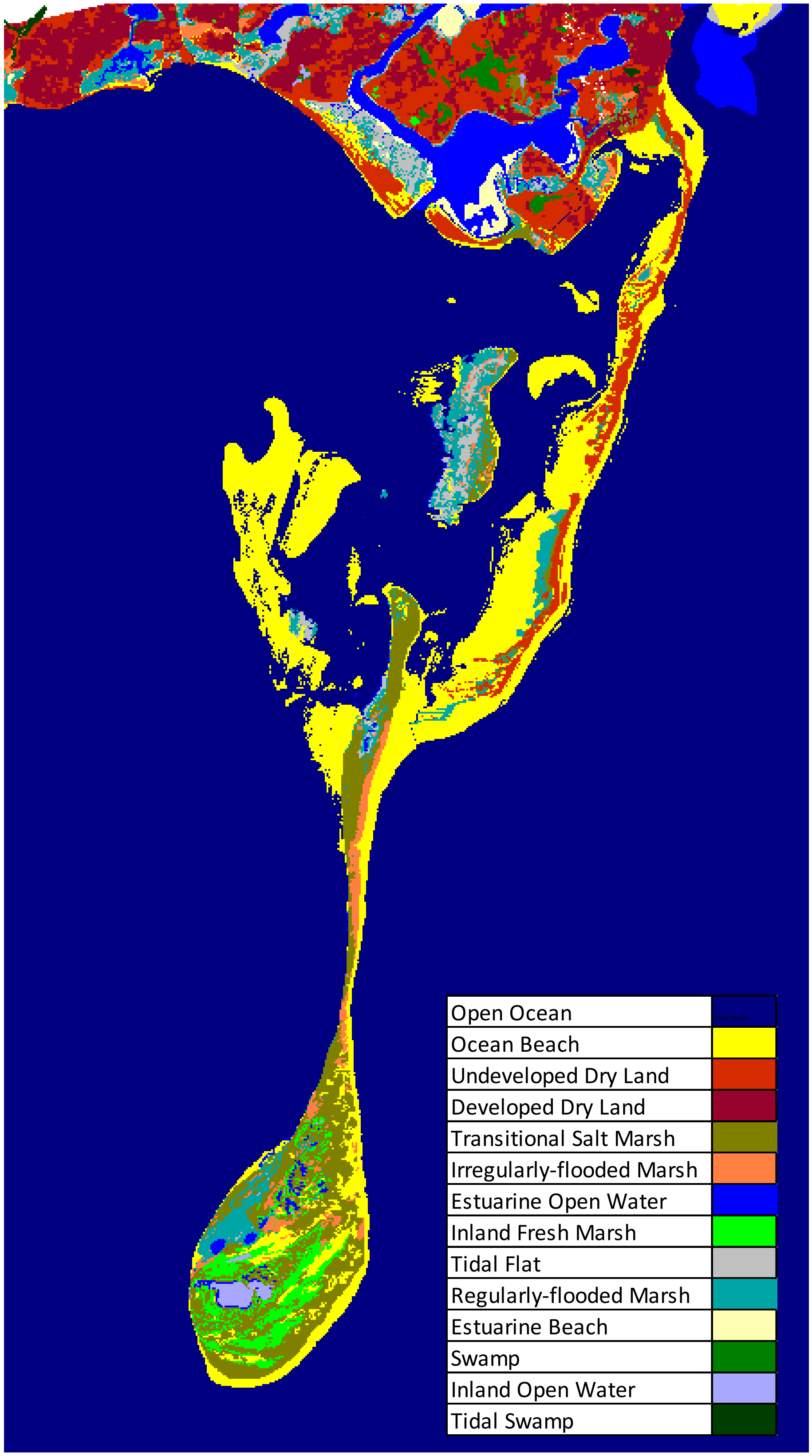
Monomoy NWR, Initial Condition.



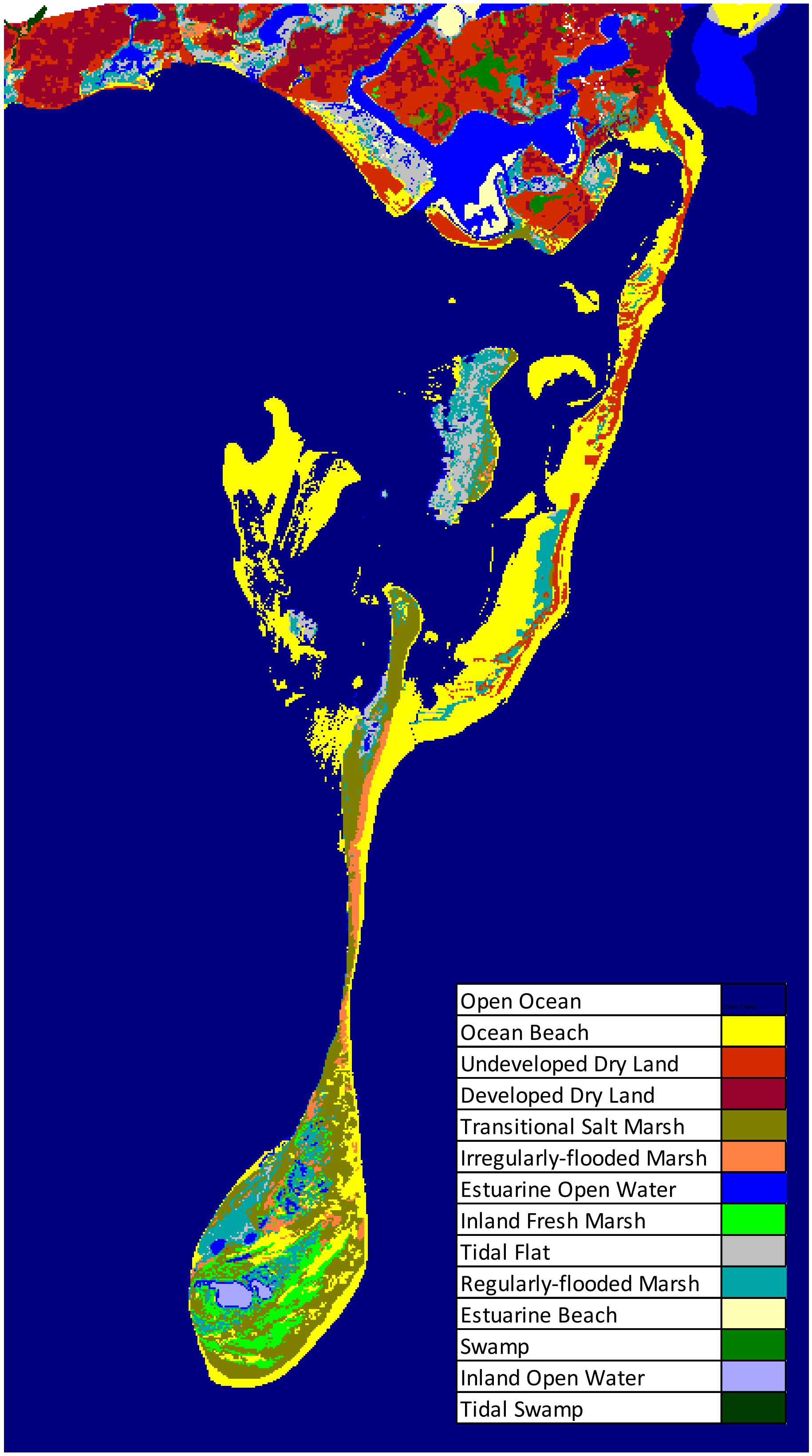
Monomoy NWR, 2025, Scenario A1B Maximum, 0.69 m SLR by 2100.



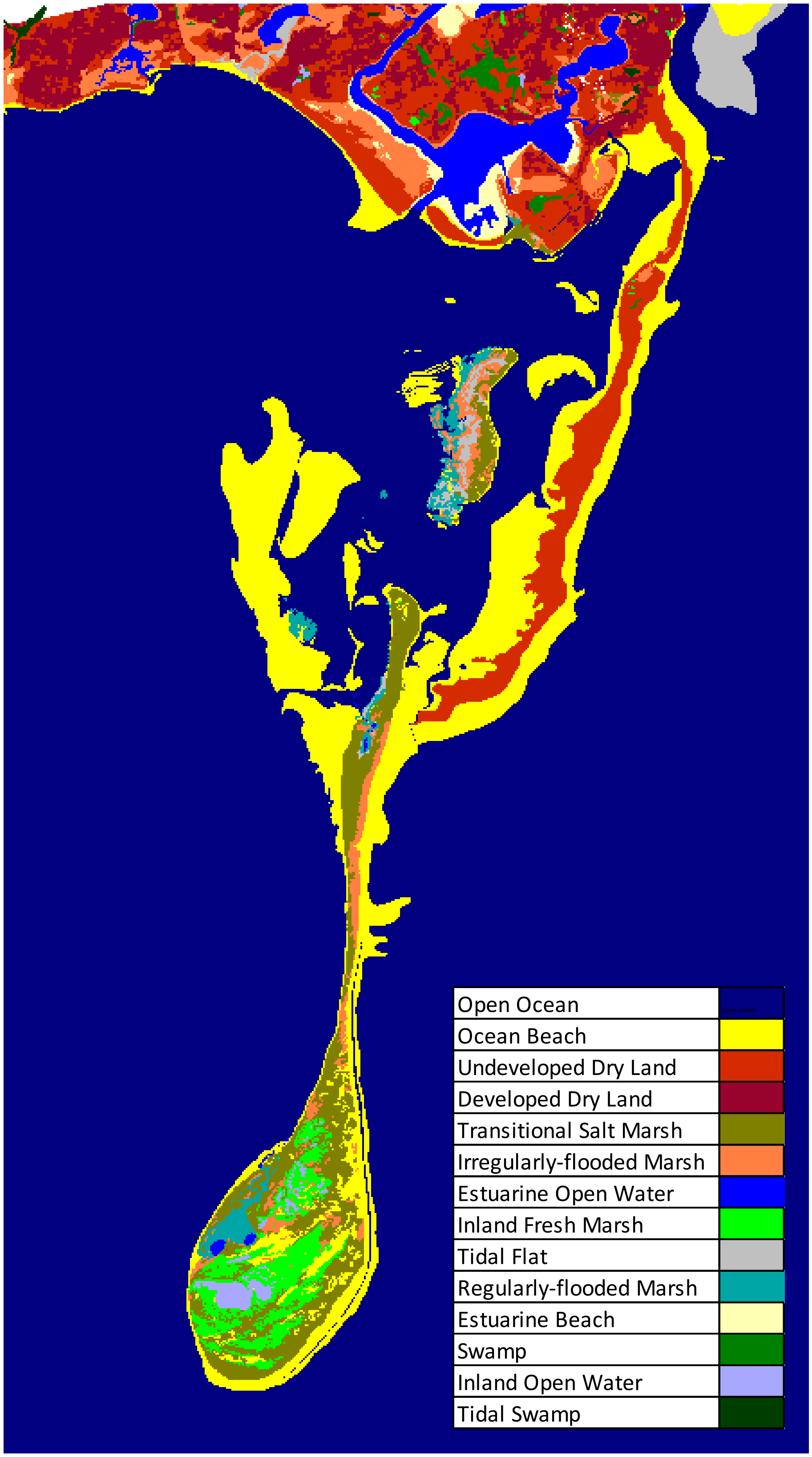
Monomoy NWR, 2050, Scenario A1B Maximum, 0.69 m SLR by 2100.



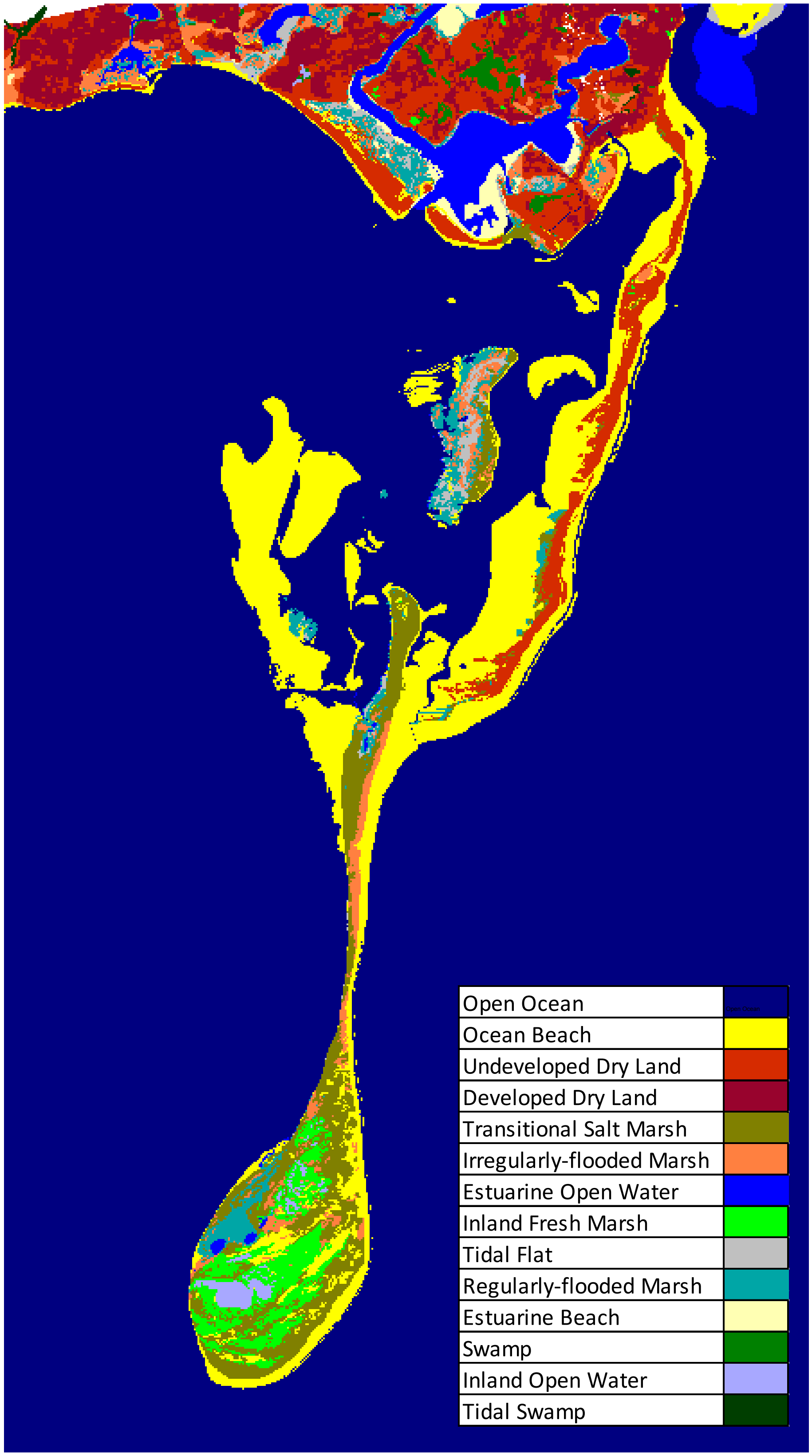
Monomoy NWR, 2075, Scenario A1B Maximum, 0.69 m SLR by 2100.



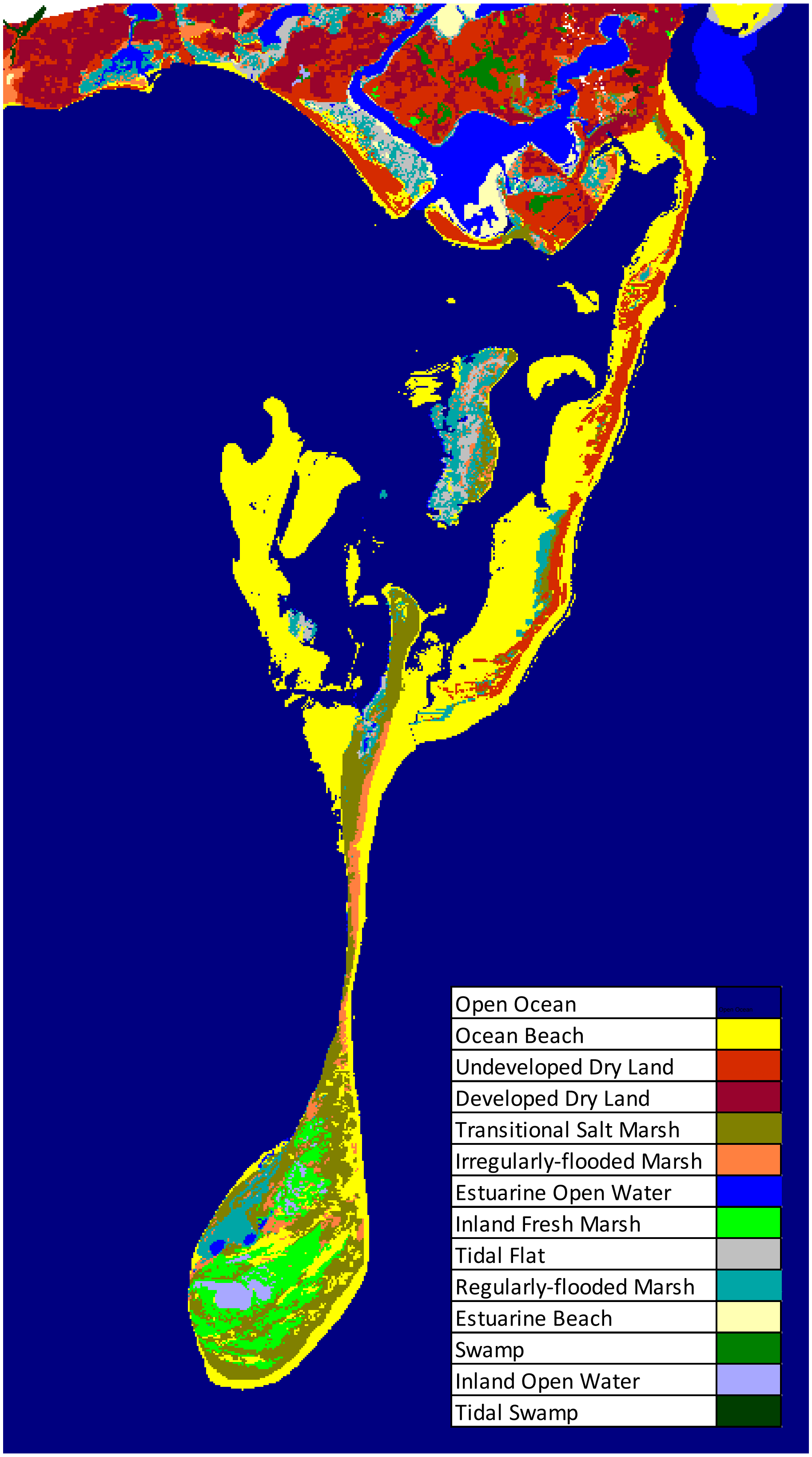
Monomoy NWR, 2100, Scenario A1B Maximum, 0.69 m SLR by 2100.



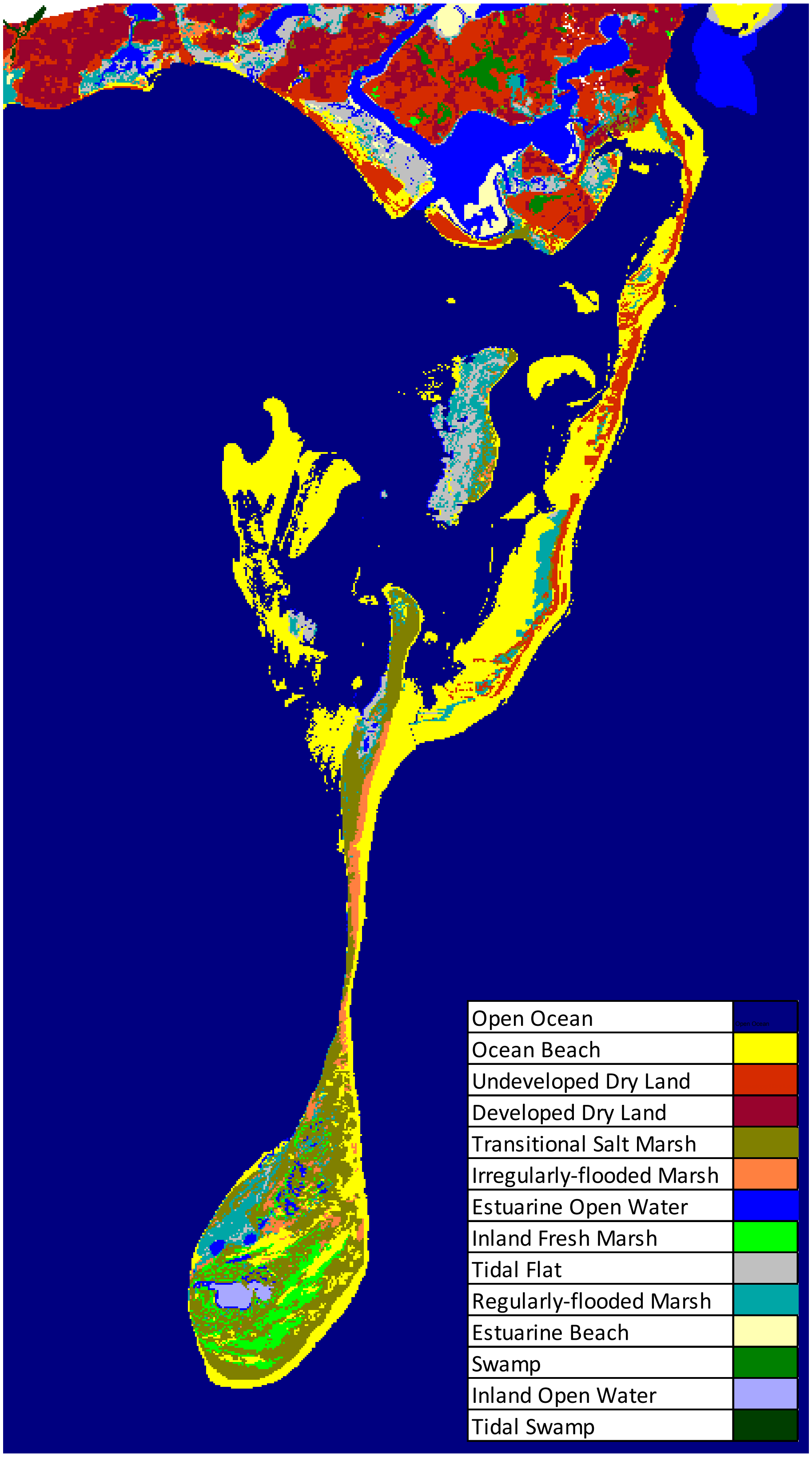
Monomoy NWR, Initial Condition.



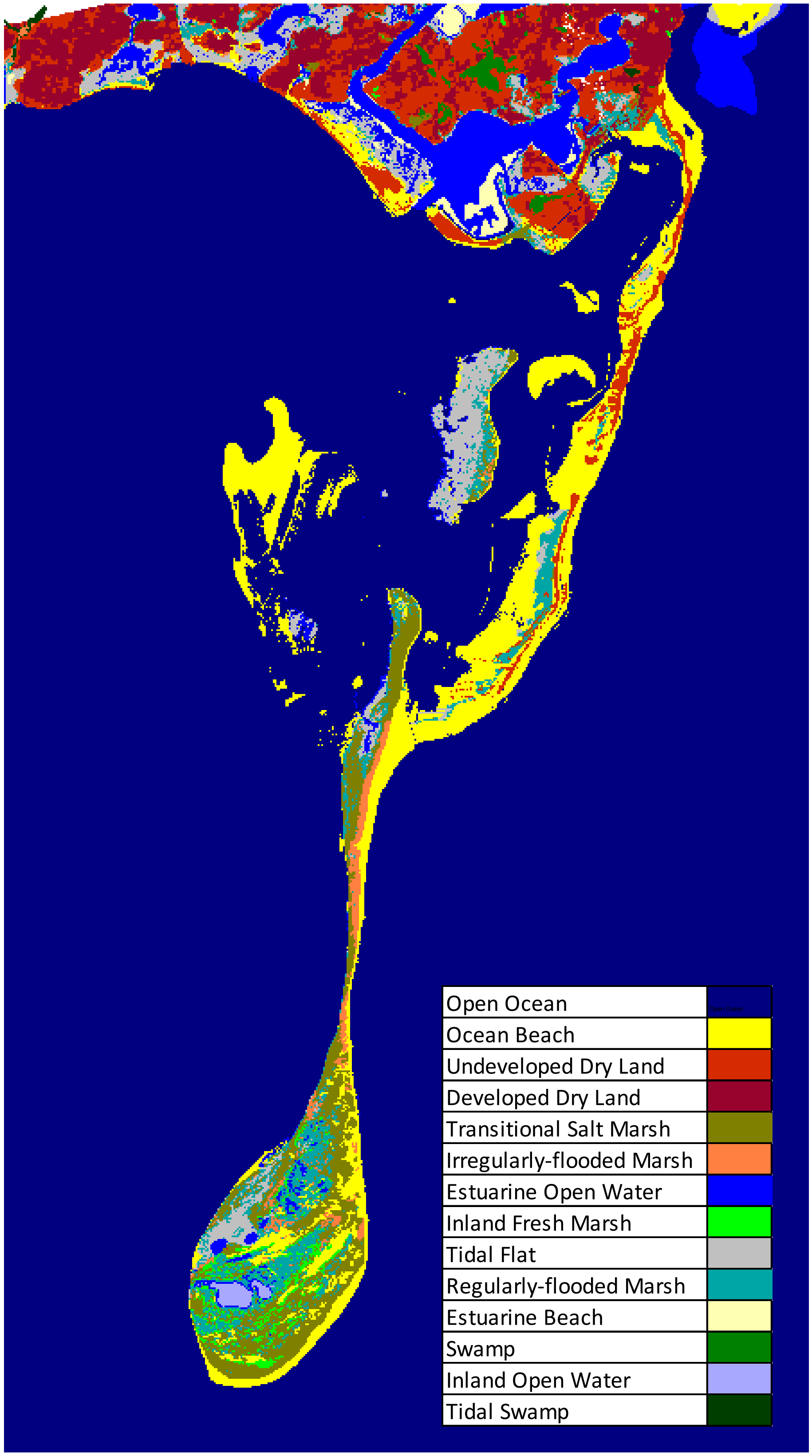
Monomoy NWR, 2025, 1 m SLR by 2100.



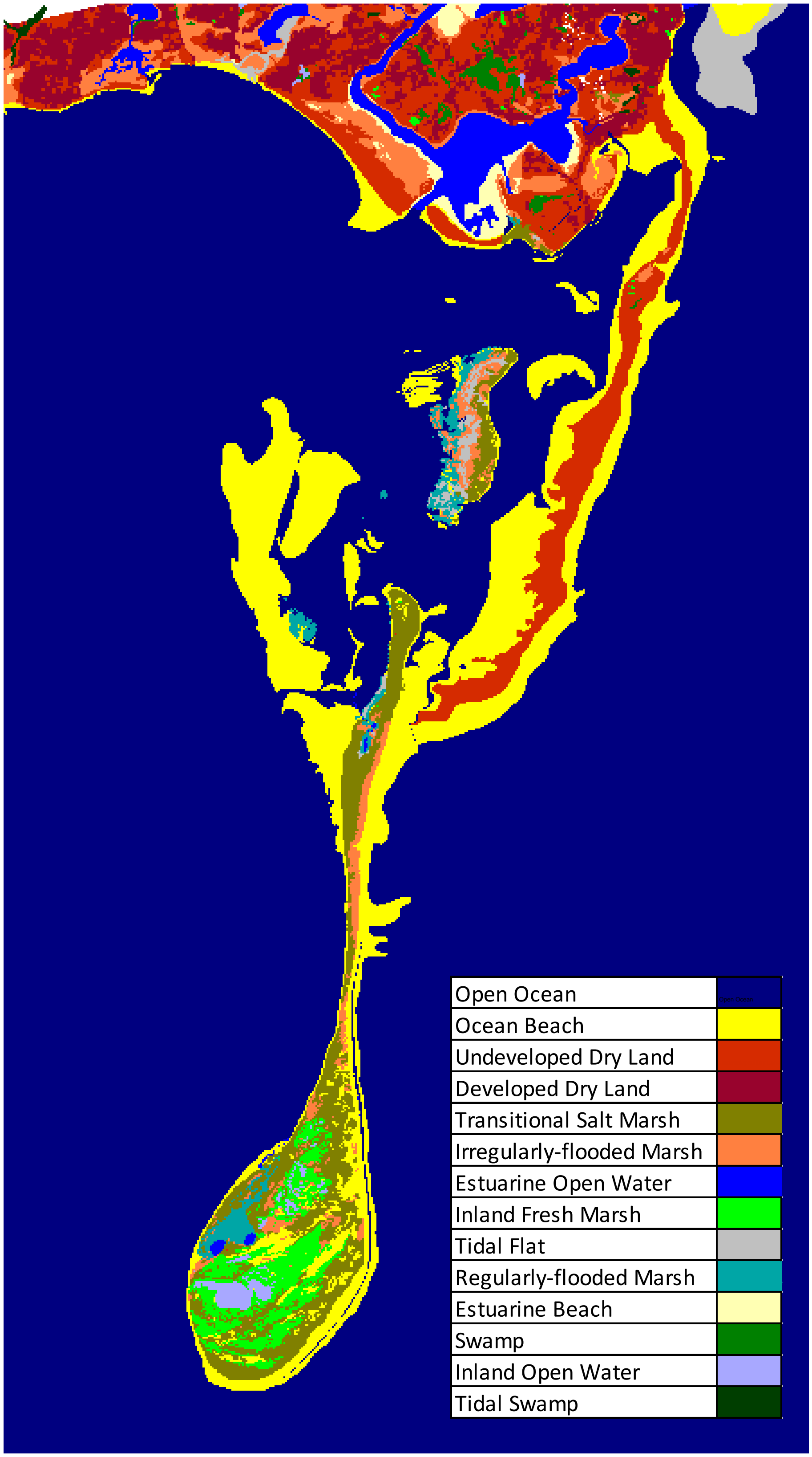
Monomoy NWR, 2050, 1 m SLR by 2100.



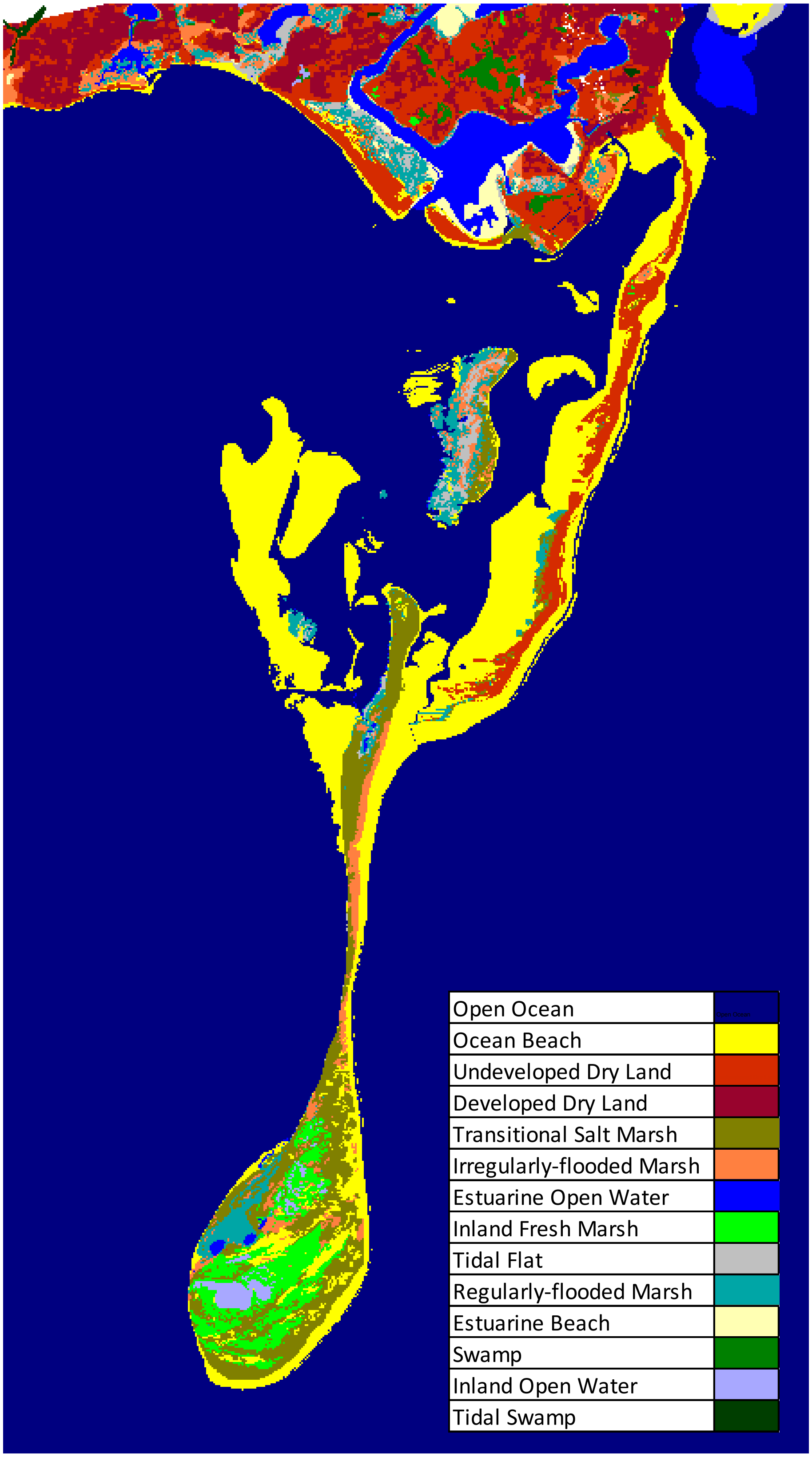
Monomoy NWR, 2075, 1 m SLR by 2100.



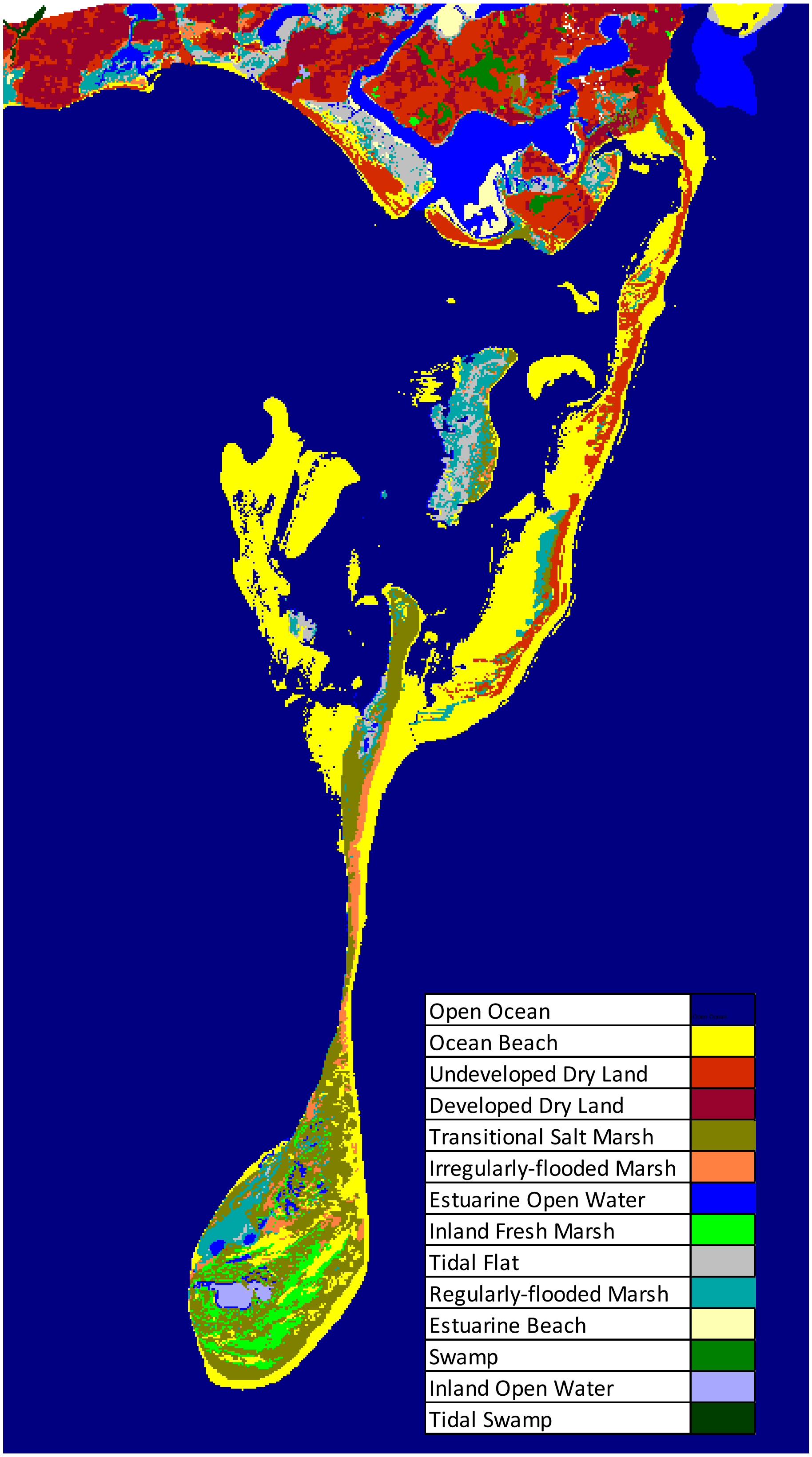
Monomoy NWR, 2100, 1 m SLR by 2100.



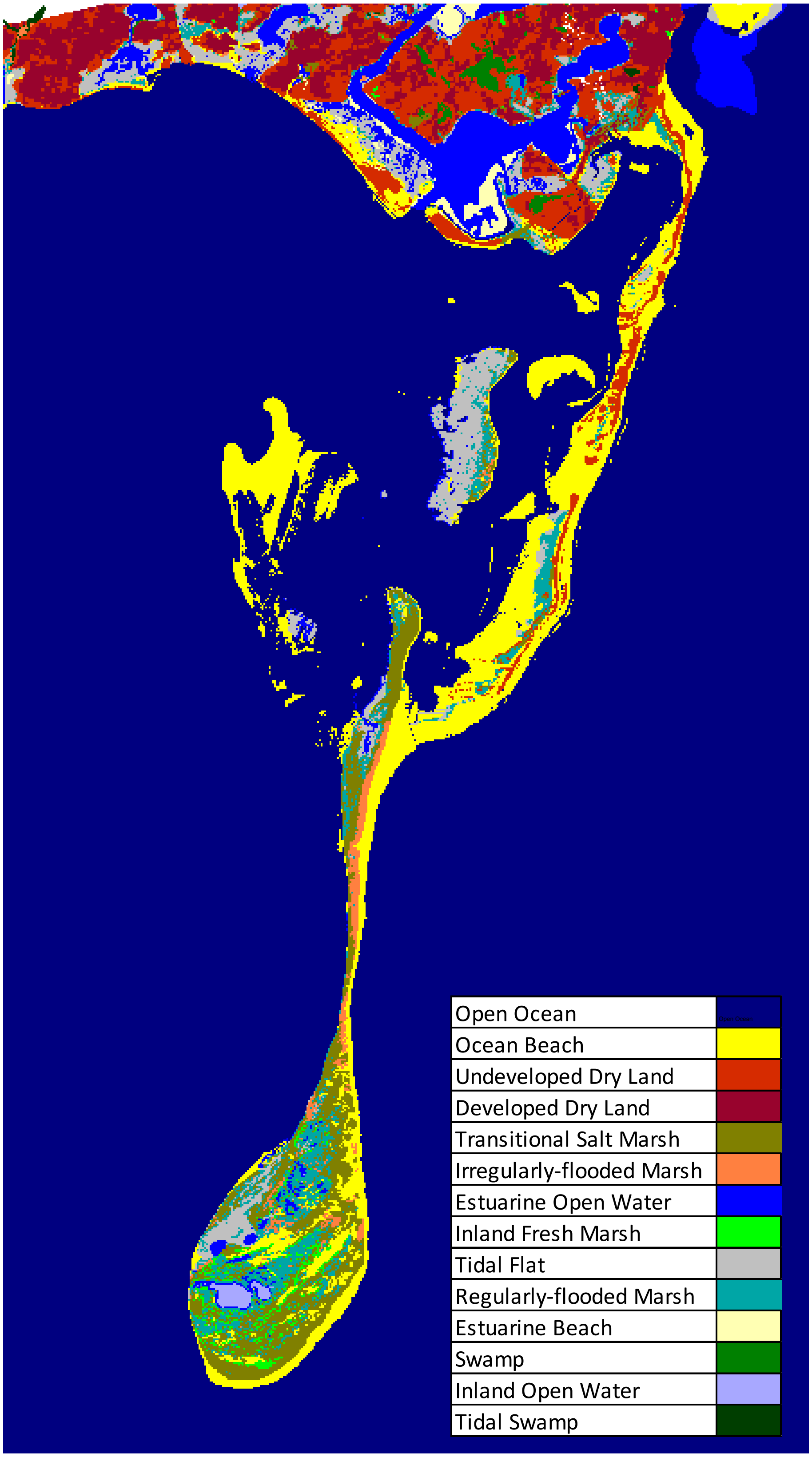
Monomoy NWR, Initial Condition.



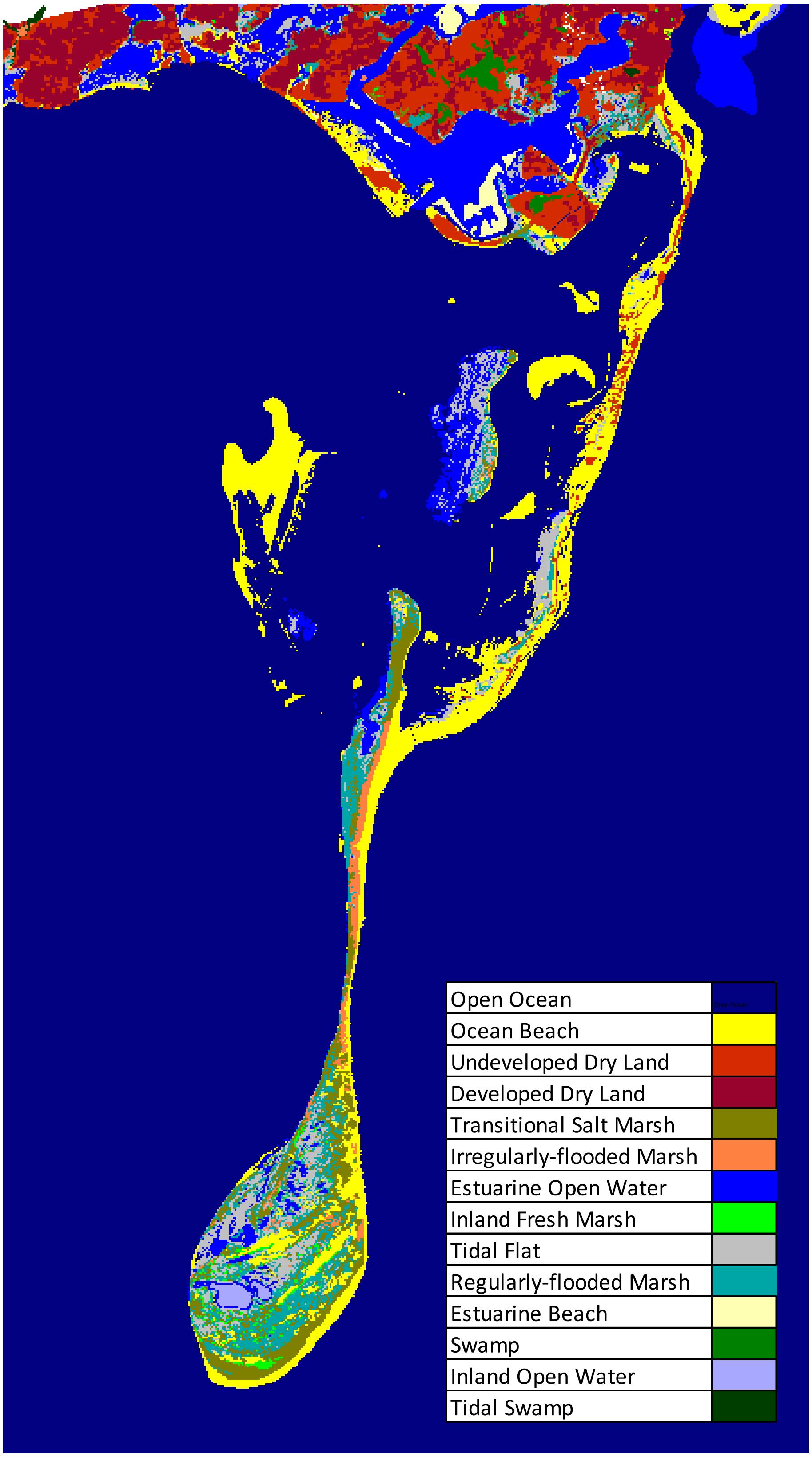
Monomoy NWR, 2025, 1.5 m SLR by 2100.



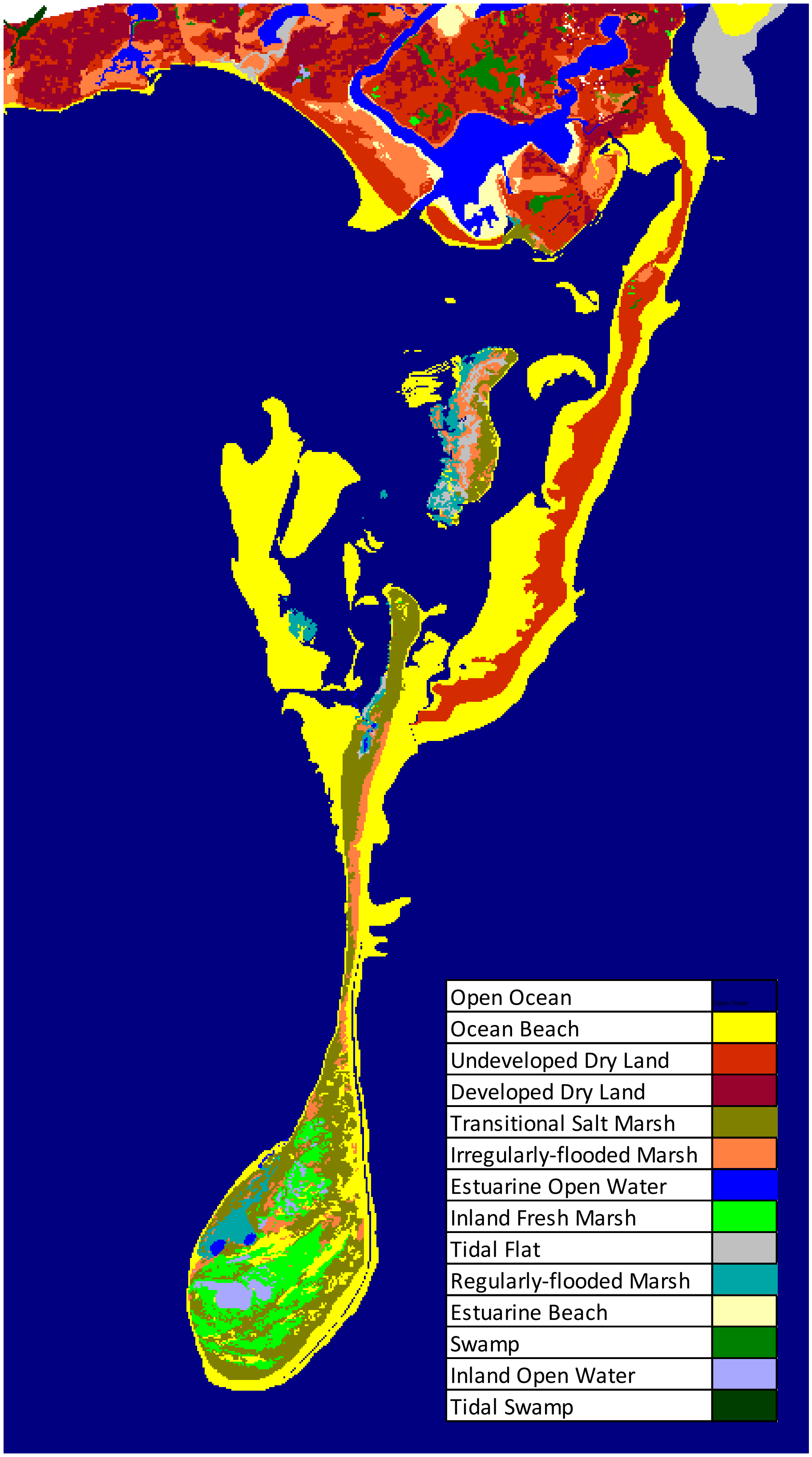
Monomoy NWR, 2050, 1.5 m SLR by 2100.



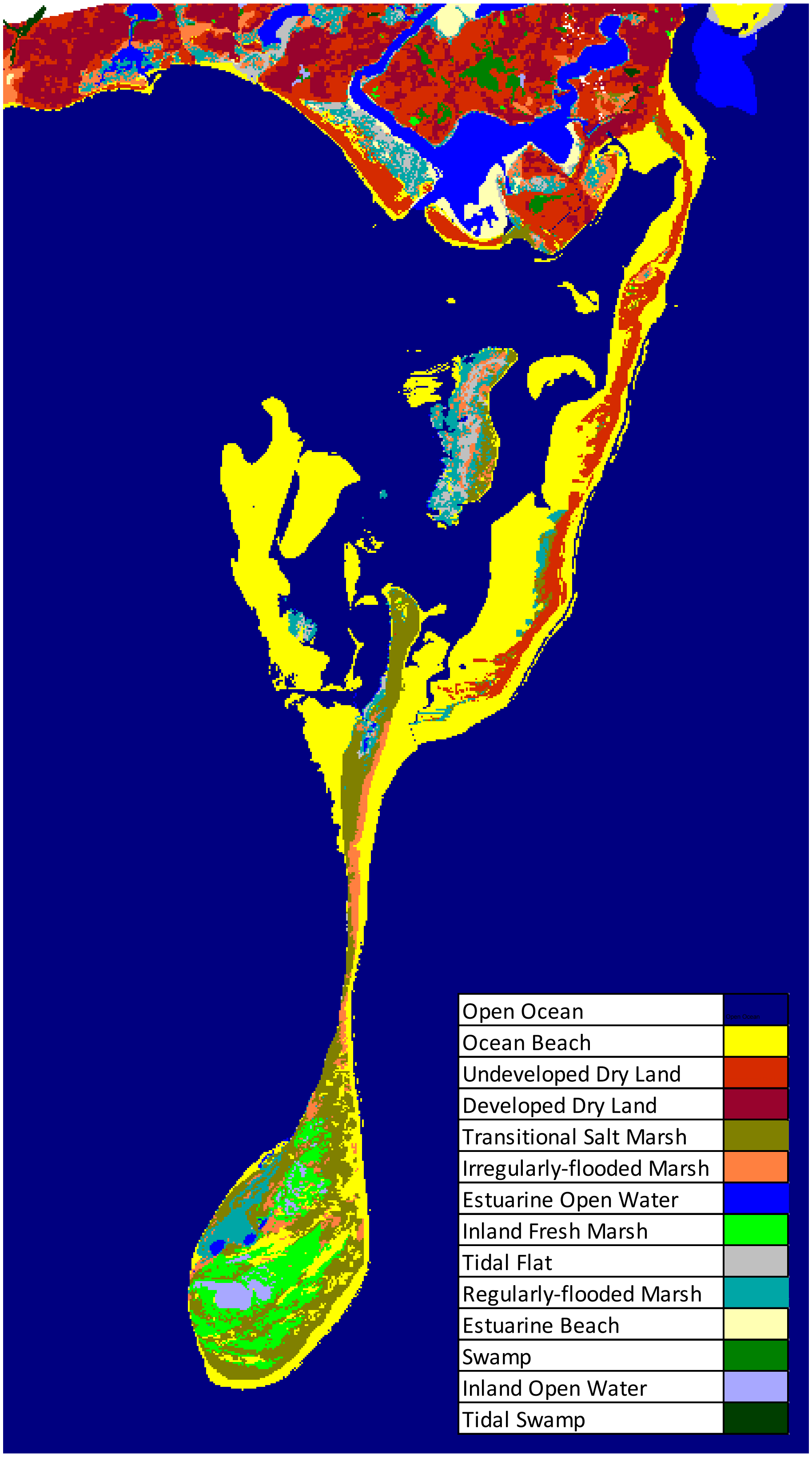
Monomoy NWR, 2075, 1.5 m SLR by 2100.



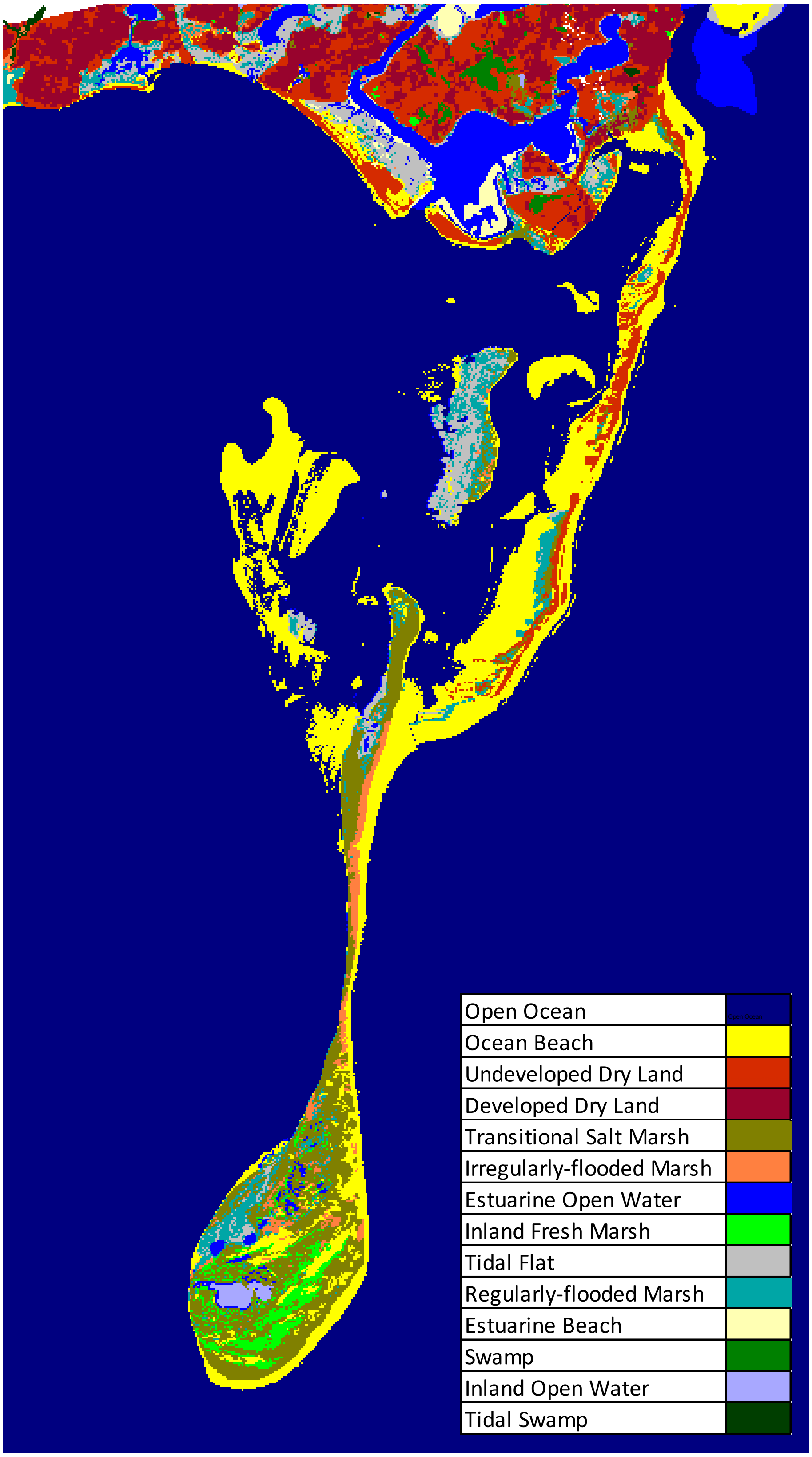
Monomoy NWR, 2100, 1.5 m SLR by 2100.



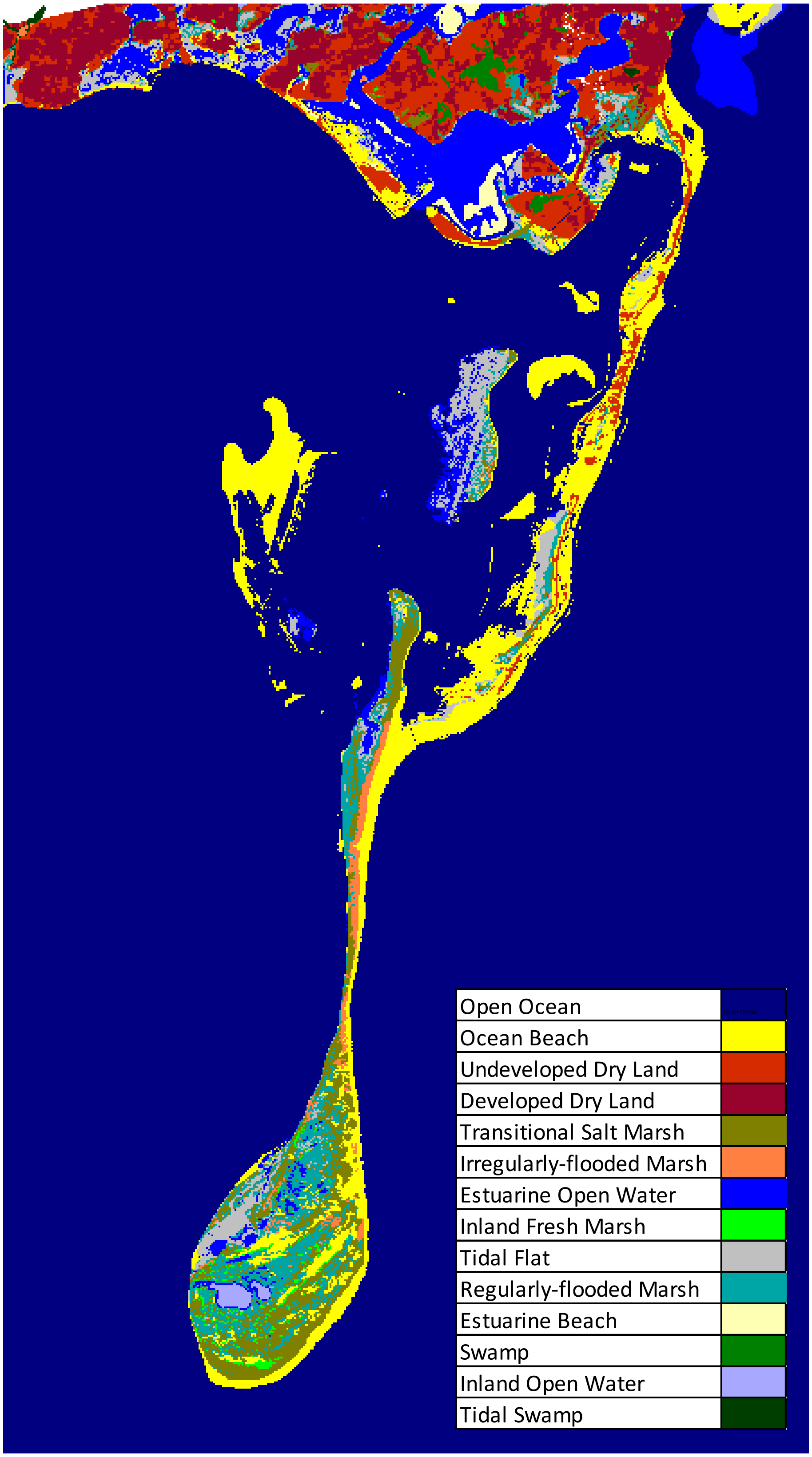
Monomoy NWR, Initial Condition.



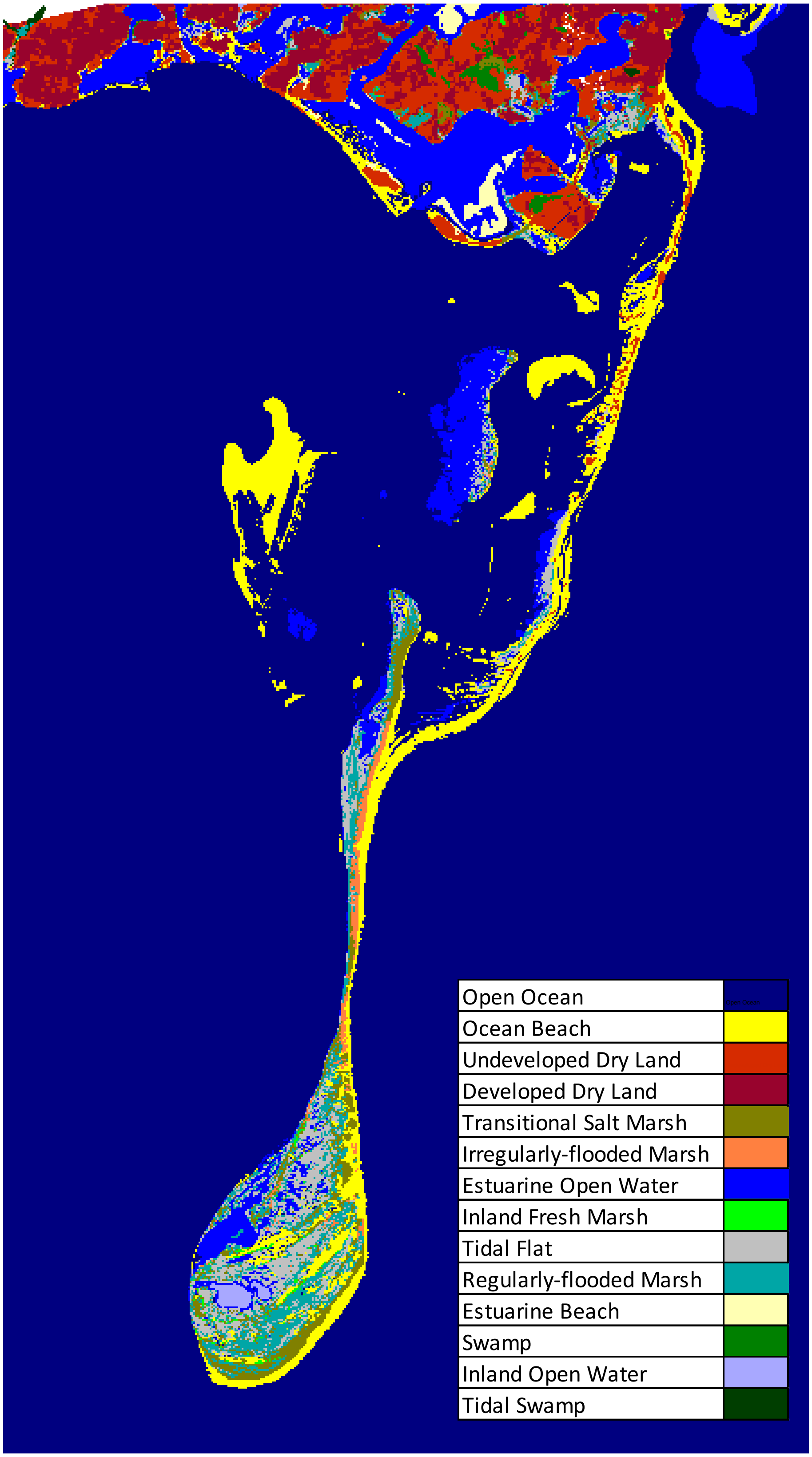
Monomoy NWR, 2025, 2 m SLR by 2100.



Monomoy NWR, 2050, 2 m SLR by 2100.



Monomoy NWR, 2075, 2 m SLR by 2100.



Monomoy NWR, 2100, 2 m SLR by 2100.