Application of the Sea-Level Affecting Marshes Model (SLAMM 6) to Mashpee 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.

This is the second application of SLAMM to Mashpee NWR. The first application of SLAMM to the refuge, carried out in 2009, did not include LiDAR-derived elevation data and elevations were dirved from a 1974 contour map. The current application uses a bare-earth LiDAR elevation data obtained in 2010 and a wetland layer derived from aerial photos taken in 1999.

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.

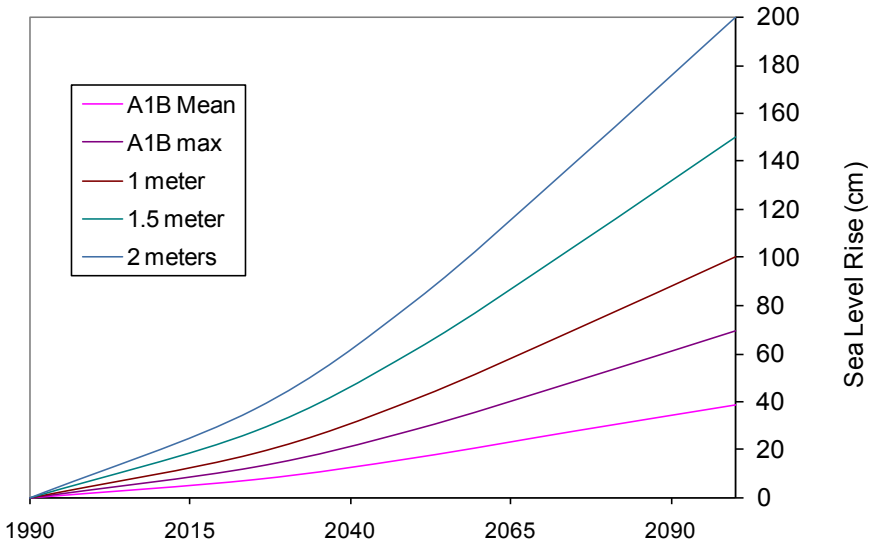


Figure 1. Summary of SLR scenarios utilized.

Data Sources and Methods

Wetland layer. Figure 2 shows the most recent available wetland layer derived for a NWI survey dated 1999. Converting the surveys into 10 m x 10 m cells indicated that the approximately 6,500 acre Mashpee NWR (approved acquisition boundary including water) is composed of the following categories:

Land cover type		Area (acres)	Percentage (%)
	Undeveloped Dry Land	5349	83
	Developed Dry Land	372	6
	Swamp	305	5
	Irregularly-flooded Marsh	161	2
	Estuarine Open Water	157	2
	Inland Open Water	47	<1
	Tidal Swamp	31	<1
	Inland Fresh Marsh	24	<1
	Tidal Fresh Marsh	1	<1
	Estuarine Beach	1	<1
	Total (incl. water)	**6448**	**100**

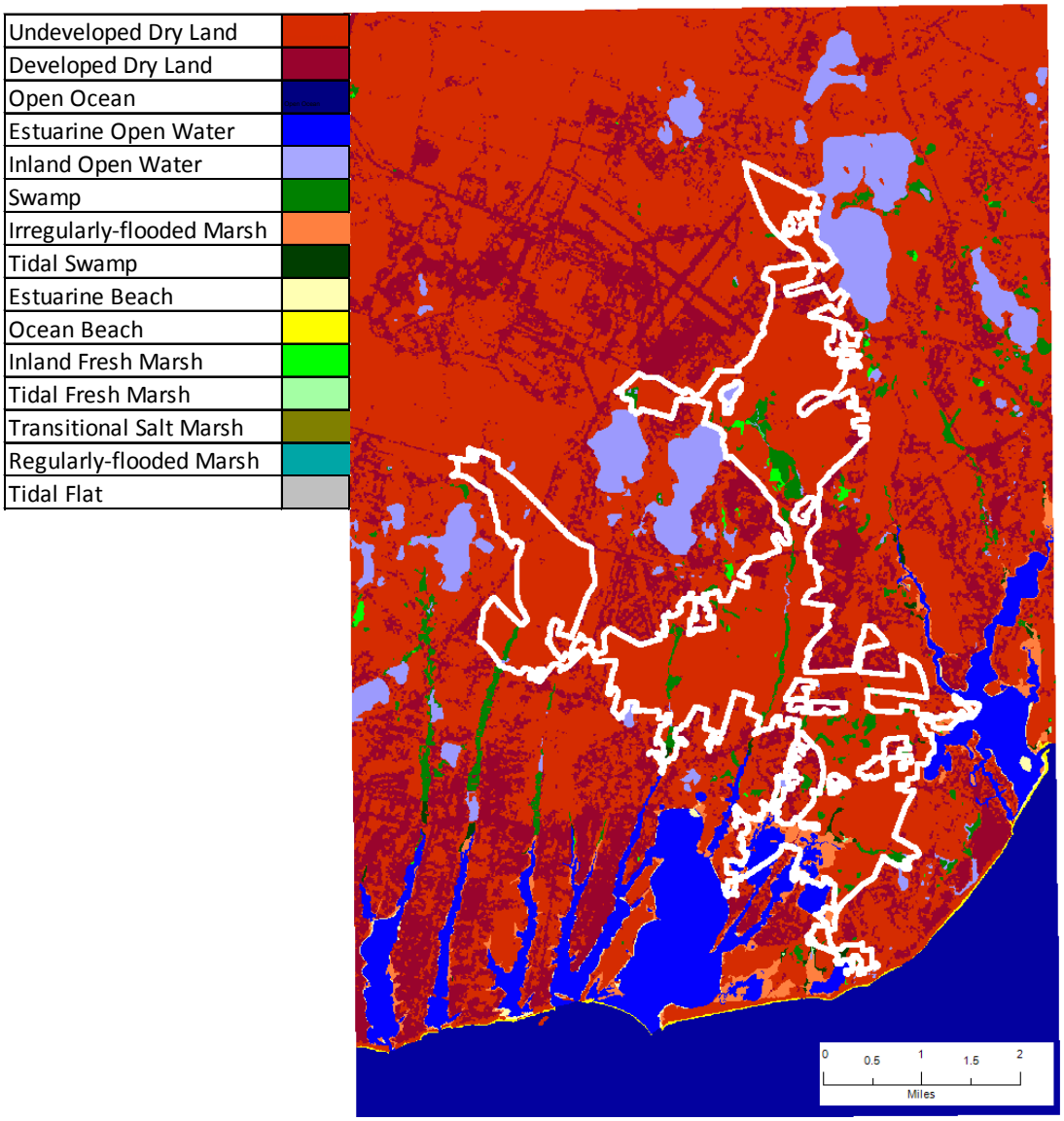


Figure 2. NWI coverage of the study area. Approved refuge boundaries are indicated in white.

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

Dikes and Impoundments. According to the National Wetland Inventory, most of the areas protected by dikes or impoundments are outside the refuge, as shown in Figure 3. In addition, 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 in the National Wetland Inventory. 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.

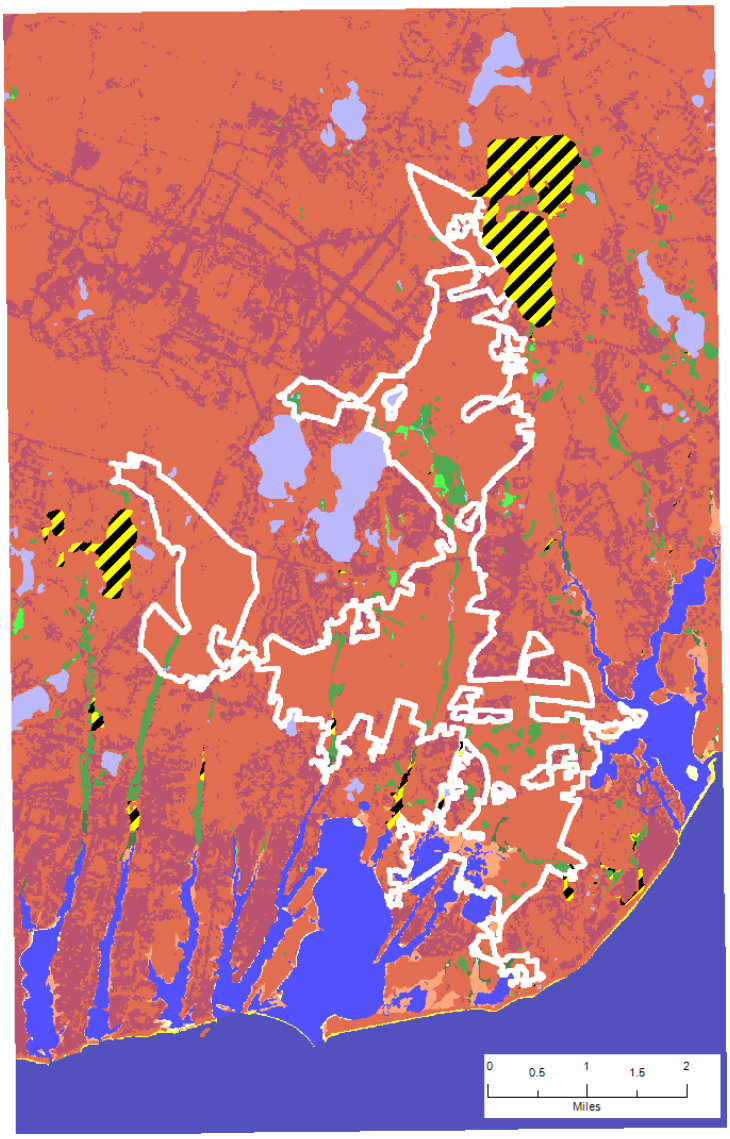


Figure 3. Dikes and impoundments within the study area marked in yellow and black stripes.

Historic sea level rise rates. The historic trend for relative sea level rise rate applied is 2.77 mm/yr, the average value measured Wood Hole, MA (NOAA gauge # 8447930). This rate is somewhat higher than the global (eustatic) SLR for the last 100 years (approximately 1.7 mm/yr), potentially indicating minor subsidence in the region or some other factor causing SLR to be higher than the global average.

Tide Ranges. The great diurnal range (GT) was estimated at 0.91 m using the information from a gauge station at Hambin Pond used for a nitrogen study in the area (Howes et al. 2006).

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), corresponding to 0.61 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 1999, 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 -0.1 m based on the datum measured at the NOAA gauge station in Wood Hole, MA (#84477930).

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

Input subsites and parameter summary. Table 1 summarizes all SLAMM input parameters for the study area. Values for parameters with no specific local information were kept at the model default value.

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

Parameter	Global
NWI Photo Date (YYYY)	1999
DEM Date (YYYY)	2010
Direction Offshore [n,s,e,w]	South
Historic Trend (mm/yr)	2.77
MTL-NAVD88 (m)	-0.1
GT Great Diurnal Tide Range (m)	0.9155
Salt Elev. (m above MTL)	0.61
Marsh Erosion (horz. m /yr)	1.8
Swamp Erosion (horz. m /yr)	1
T.Flat Erosion (horz. m /yr)	0.5
Reg.-Flood Marsh Accr (mm/yr)	3.78
Irreg.-Flood Marsh Accr (mm/yr)	3.78
Tidal-Fresh Marsh Accr (mm/yr)	5.9
Inland-Fresh Marsh Accr (mm/yr)	5.9
Tidal Swamp Accr (mm/yr)	1.1
Swamp Accretion (mm/yr)	0.3
Beach Sed. Rate (mm/yr)	0.5
Freq. Overwash (years)	50
Use Elev Pre-processor [True,False]	FALSE

Calibration of the 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" many of the irregularly-flooded marshes present in Hamblin and Jehu Pond seem to be more consistent with a regularly-flooded marsh type and transitional marsh. Refuge staff confirmed that these areas are flooded regularly.

Based on these results, predicted gains and losses of wetland categories are made with respect to the initial coverage predicted by SLAMM at time zero. These results are summarized in the following table as "SLAMM 1999".

Land cover type		Areas (acres)	
		NWI 1999	**SLAMM Prediction for 1999**
	Undeveloped Dry Land	5349	5343
	Developed Dry Land	372	372
	Swamp	305	303
	Irregularly-flooded Marsh	**161**	**93**
	Estuarine Open Water	157	157
	Inland Open Water	47	47
	Tidal Swamp	31	26
	Inland Fresh Marsh	24	24
	Tidal Fresh Marsh	1	1
	Estuarine Beach	1	1
	Transitional Salt Marsh	**0**	**8**
	Regularly-flooded Marsh	**0**	**74**
	Total (incl. water)	**6448**	**6448**

Results

Percentage losses by 2100 for each land-cover type given different SLR scenarios are presented in Table 2 As discussed above, land-cover losses are calculated in comparison to the "time zero" or "SLAMM 1999" wetland coverage.

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

Land cover category	SLAMM 1999 coverage (acres)	Land cover loss by 2100 for different SLR scenarios				
		0.39 m	0.69 m	1 m	1.5 m	2 m
Undeveloped Dry Land	5343	0%	1%	1%	1%	2%
Developed Dry Land	372	0%	0%	1%	1%	1%
Swamp	303	3%	8%	12%	18%	27%
Irregularly-flooded Marsh	93	28%	71%	87%	95%	95%
Inland Open Water	47	15%	19%	26%	36%	38%
Tidal Swamp	26	34%	52%	62%	74%	85%
Inland Fresh Marsh	24	0%	0%	0%	0%	1%
Regularly-flooded Marsh	74	-25%	18%	29%	23%	15%

Dry lands of the refuge have high elevations and the effects of potential sea-level increases are minimal. The wetlands of the refuge are however greatly affected by long term sea level rise. Irregularly-flooded marsh is fairly resilient up to 0.39 m SLR by 2100 but for higher rates, it significantly reduces its coverage within the refuge. A similar fate is predicted for tidal swamp. Regularly-flooded marsh is predicted to increase at the lowest SLR rate. However, as SLR rates continue to increase this wetland habitat is also predicted to reduce its coverage.

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 as sea level rises, from the current coverage of 3% of the refuge area up to more than 6% coverage under the 2 m SLR by 2100 scenario. Gains in tidal flat and transitional salt marsh are also projected.

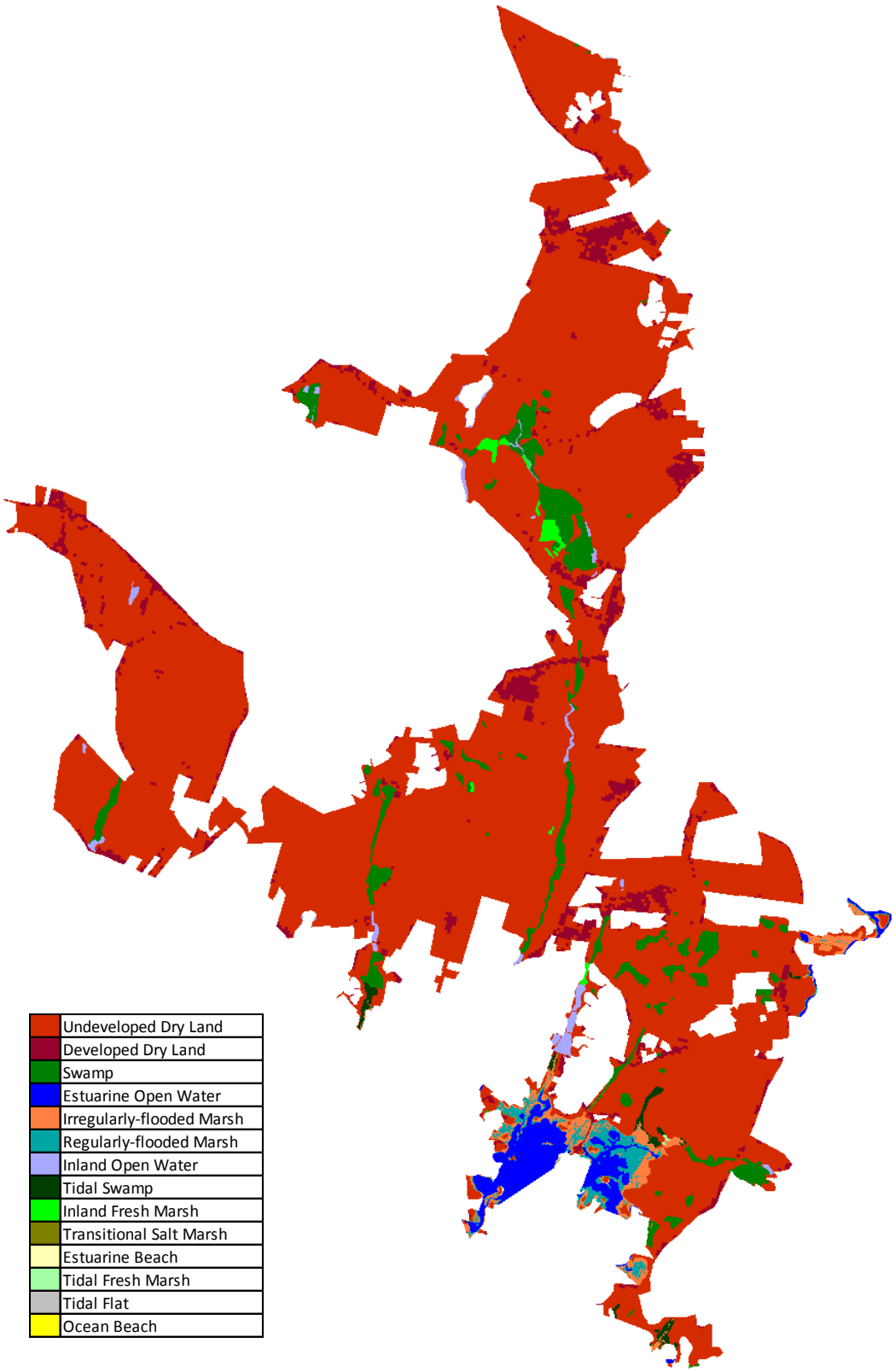
Table 3. Predicted land cover gains by 2100 given simulated scenarios of eustatic SLR at Mashpee NWR.

Land cover category	SLAMM 1999 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	204	214	250	320	381	398
Beach	1	2	3	4	4	6
Tidal Flat	0	16	79	57	37	49
Transitional Salt Marsh	8	21	27	33	44	69

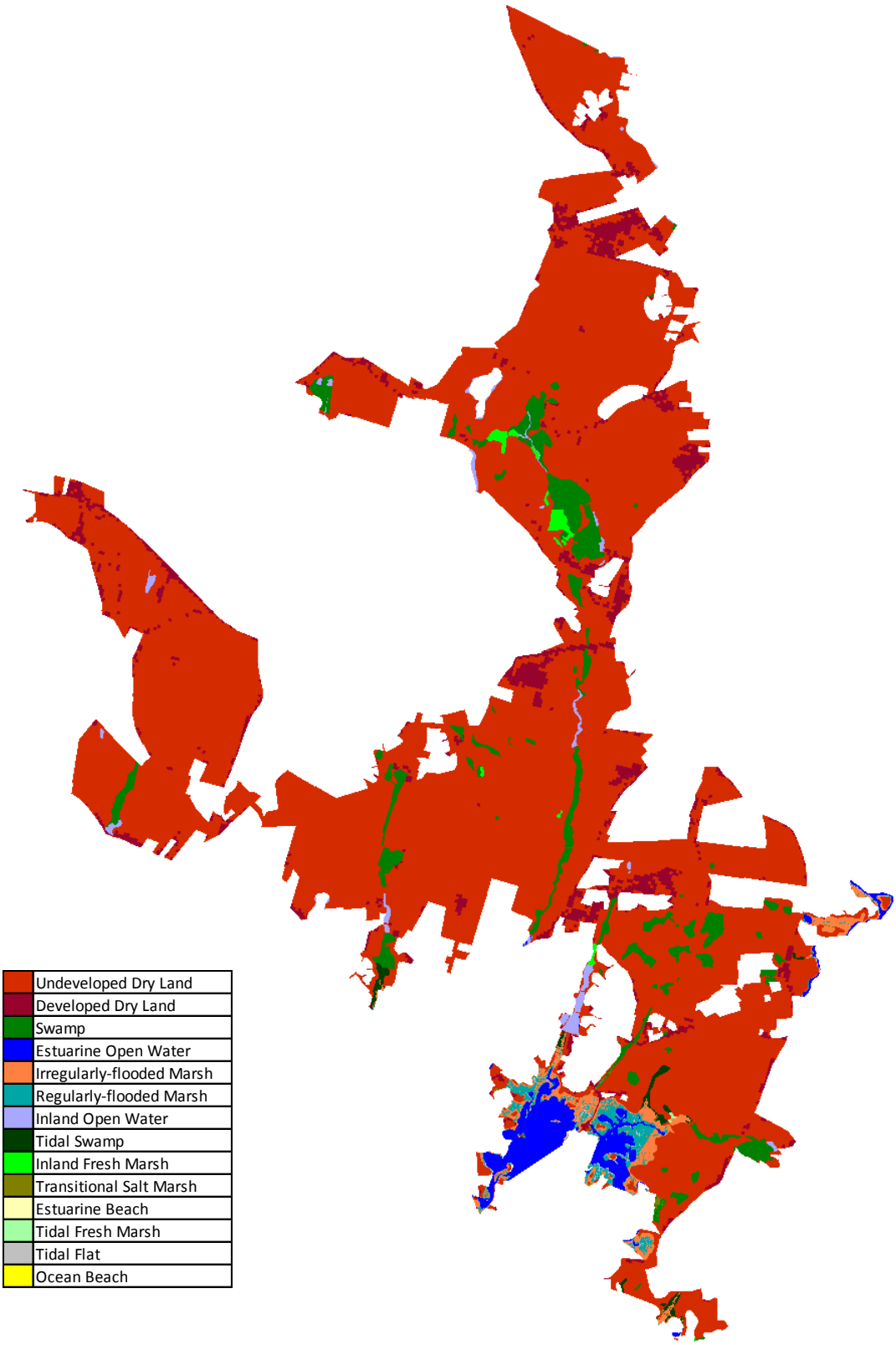
Mashpee NWR
IPCC Scenario A1B-Mean, 0.39 m SLR eustatic by 2100

Results in Acres

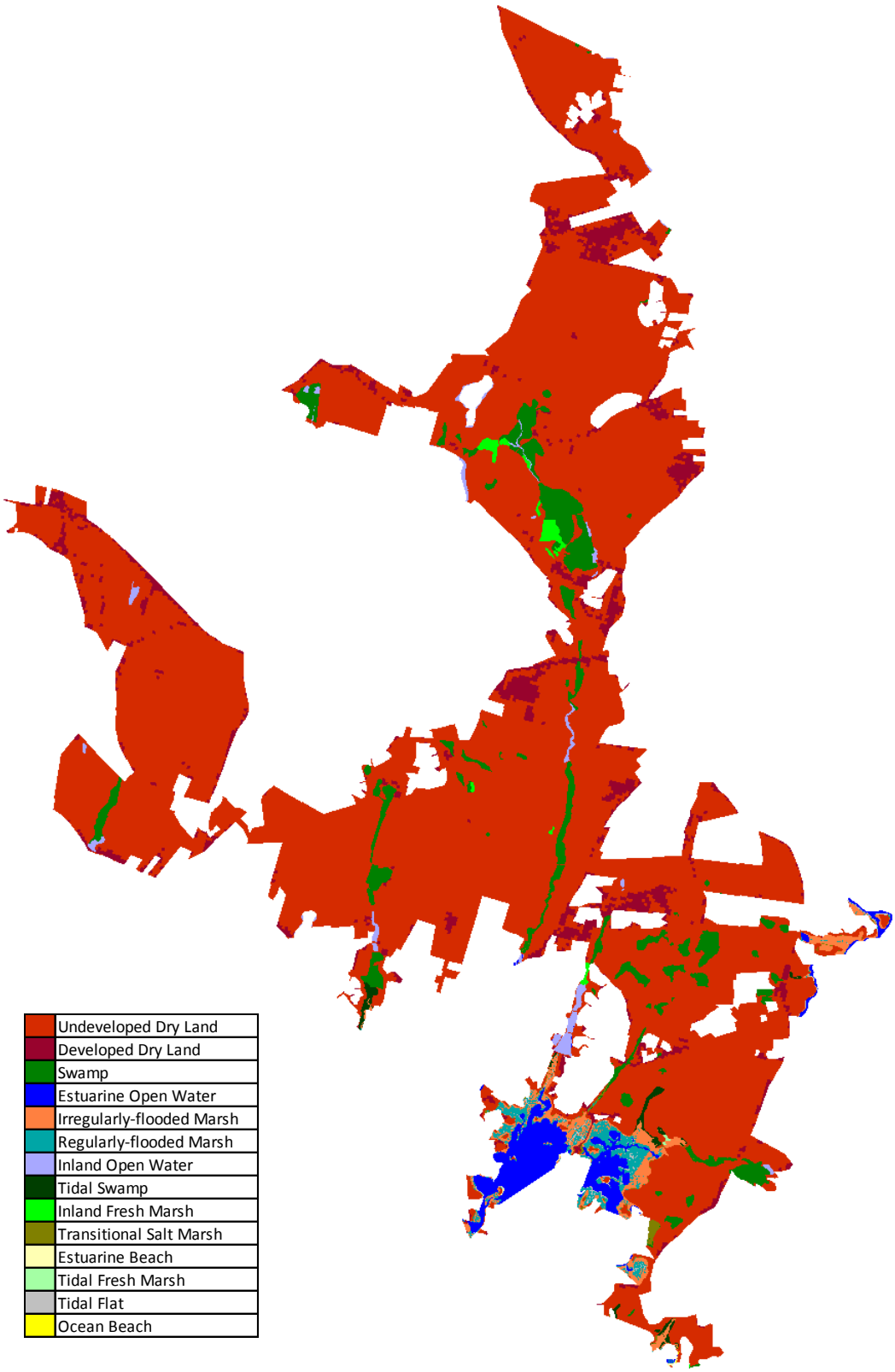
		SLAMM 1999	2025	2050	2075	2100
	Undeveloped Dry Land	5343	5341	5338	5334	5329
	Developed Dry Land	372	372	371	371	371
	Swamp	303	302	299	297	295
	Estuarine Open Water	157	160	161	163	174
	Irregularly-flooded Marsh	93	94	93	77	67
	Regularly-flooded Marsh	74	68	69	83	93
	Inland Open Water	47	46	46	46	40
	Tidal Swamp	26	24	21	19	17
	Inland Fresh Marsh	24	24	24	24	24
	Transitional Salt Marsh	8	7	12	17	21
	Estuarine Beach	1	1	2	1	1
	Tidal Fresh Marsh	1	1	1	1	1
	Tidal Flat	0	9	10	13	16
	Ocean Beach	0	0	0	1	1
	Total (incl. water)	**6448**	**6448**	**6448**	**6448**	**6448**



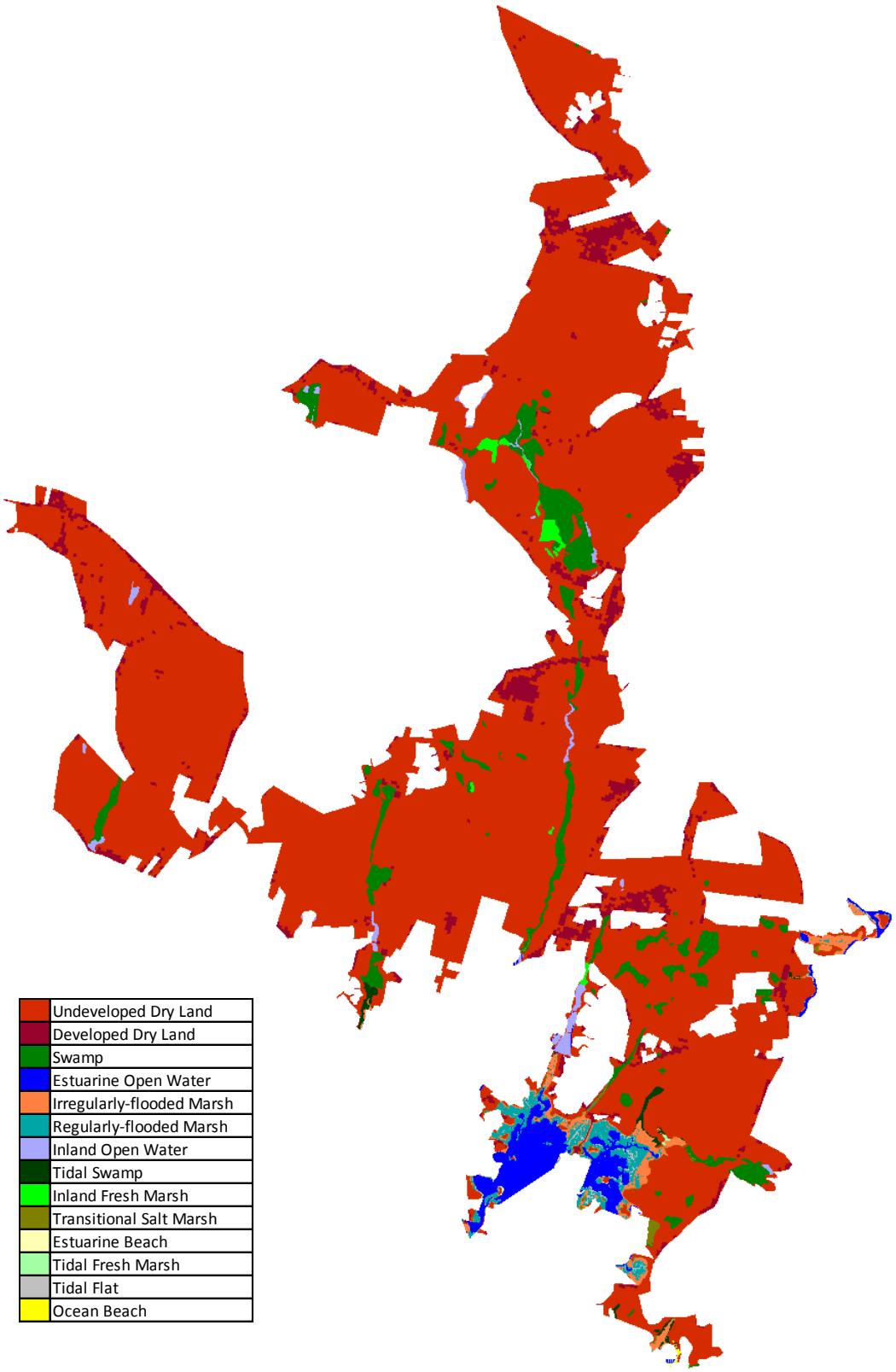
Mashpee NWR, SLAMM 1999.



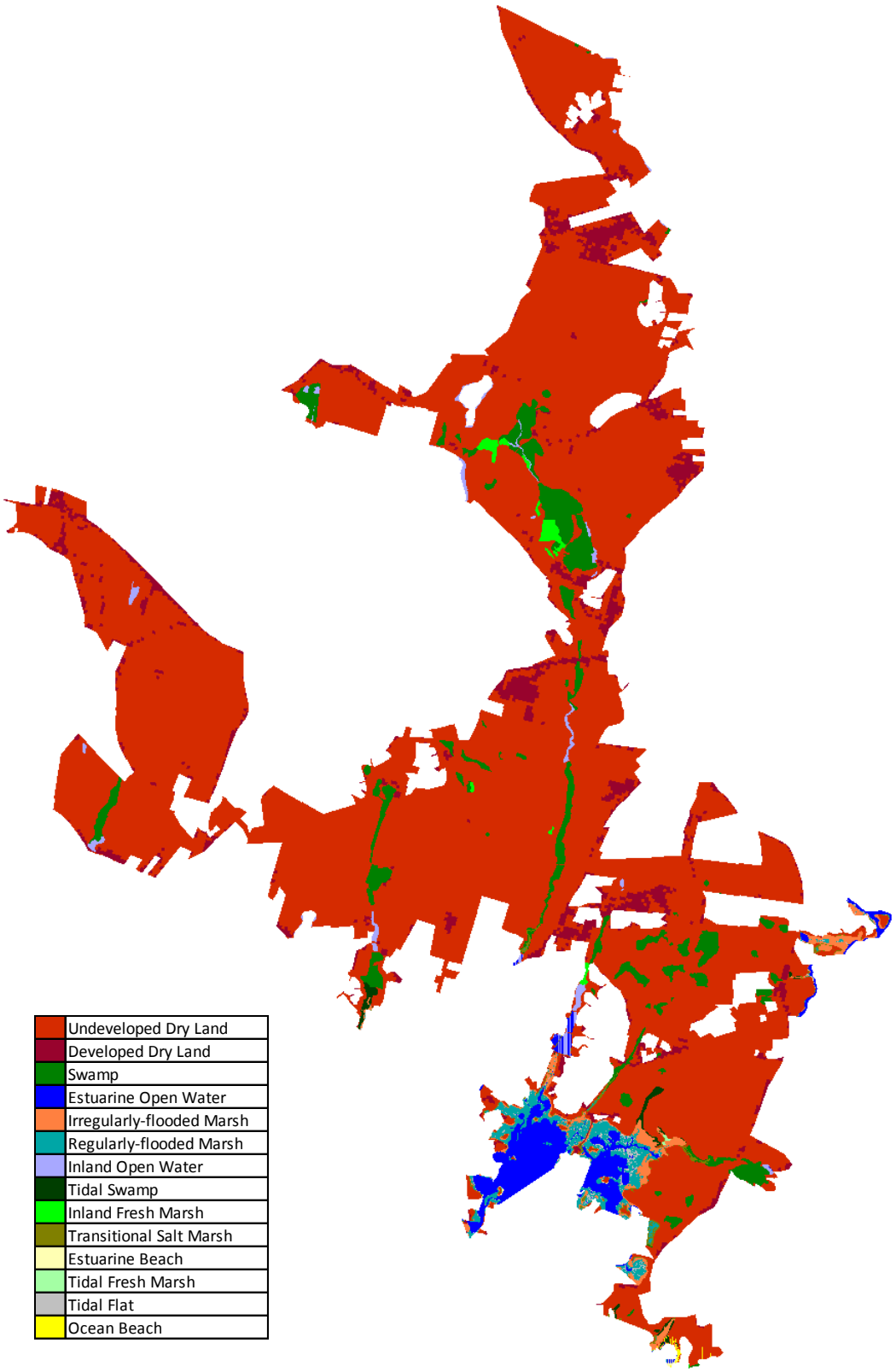
Mashpee NWR, 2025, Scenario A1B Mean, 0.39 m SLR



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



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

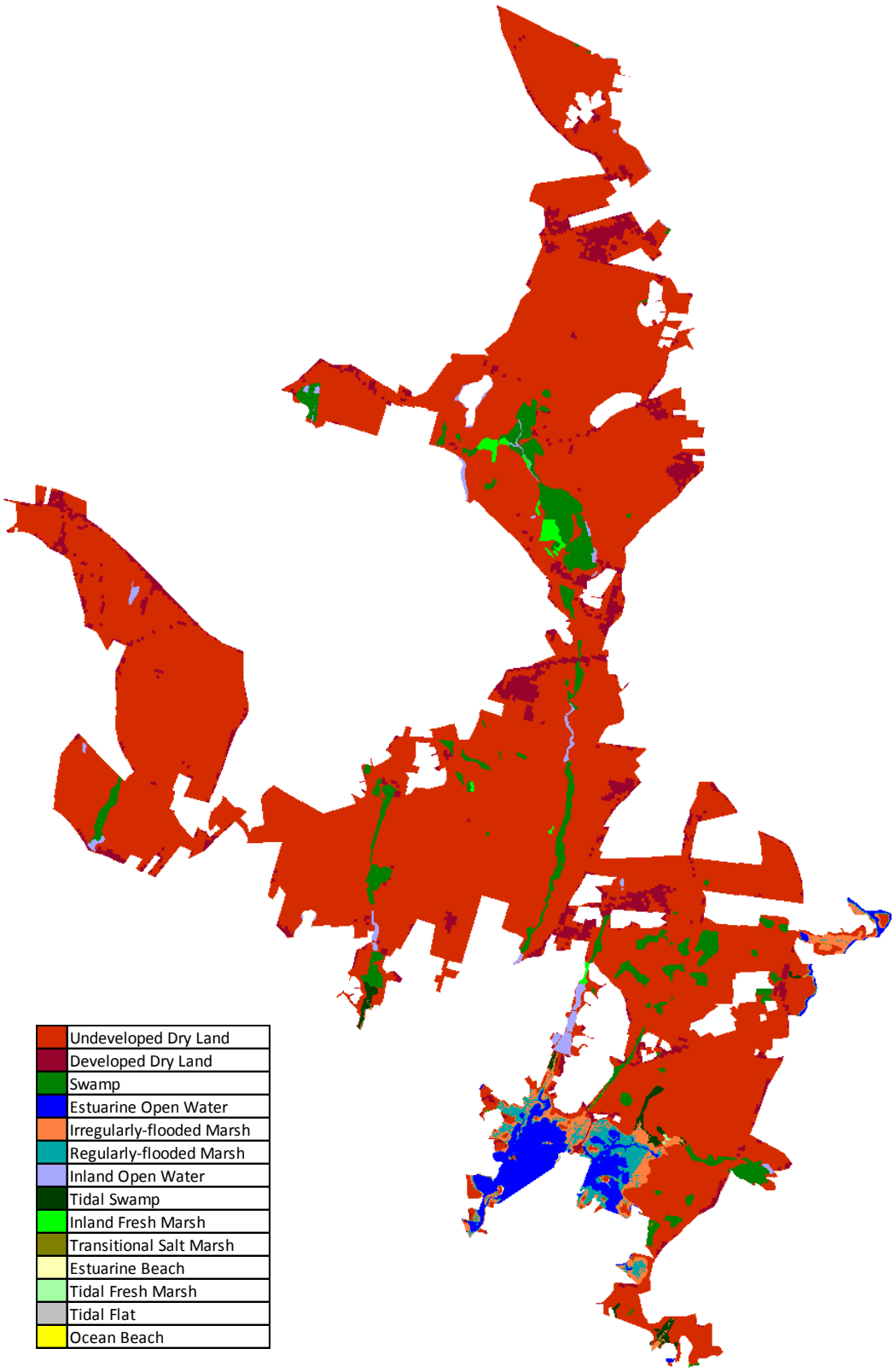


Mashpee NWR, 2100, Scenario A1B Mean, 0.39 m SLR by 2100.

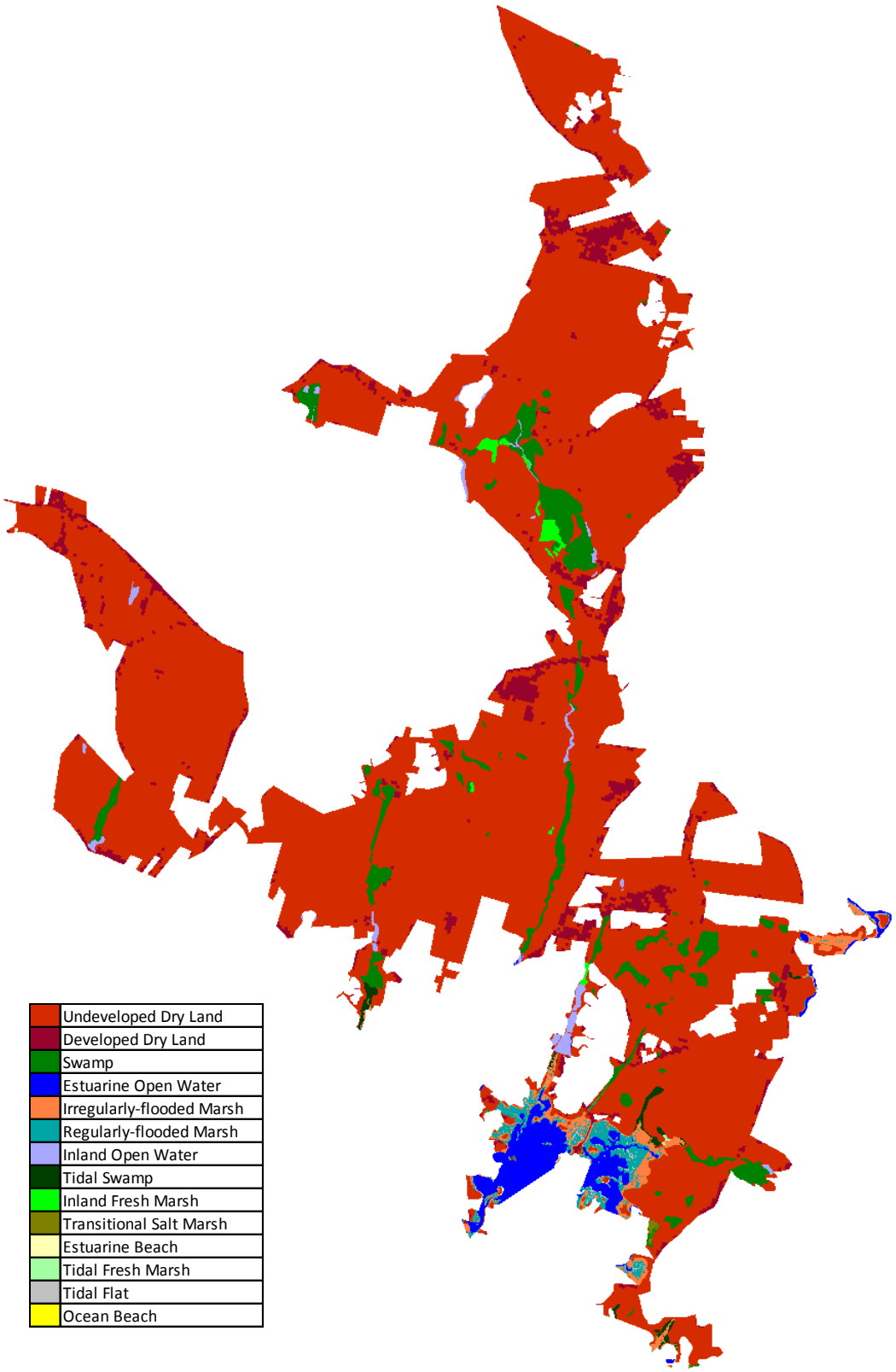
Mashpee NWR
IPCC Scenario A1B-Max, 0.69 m SLR eustatic by 2100

Results in Acres

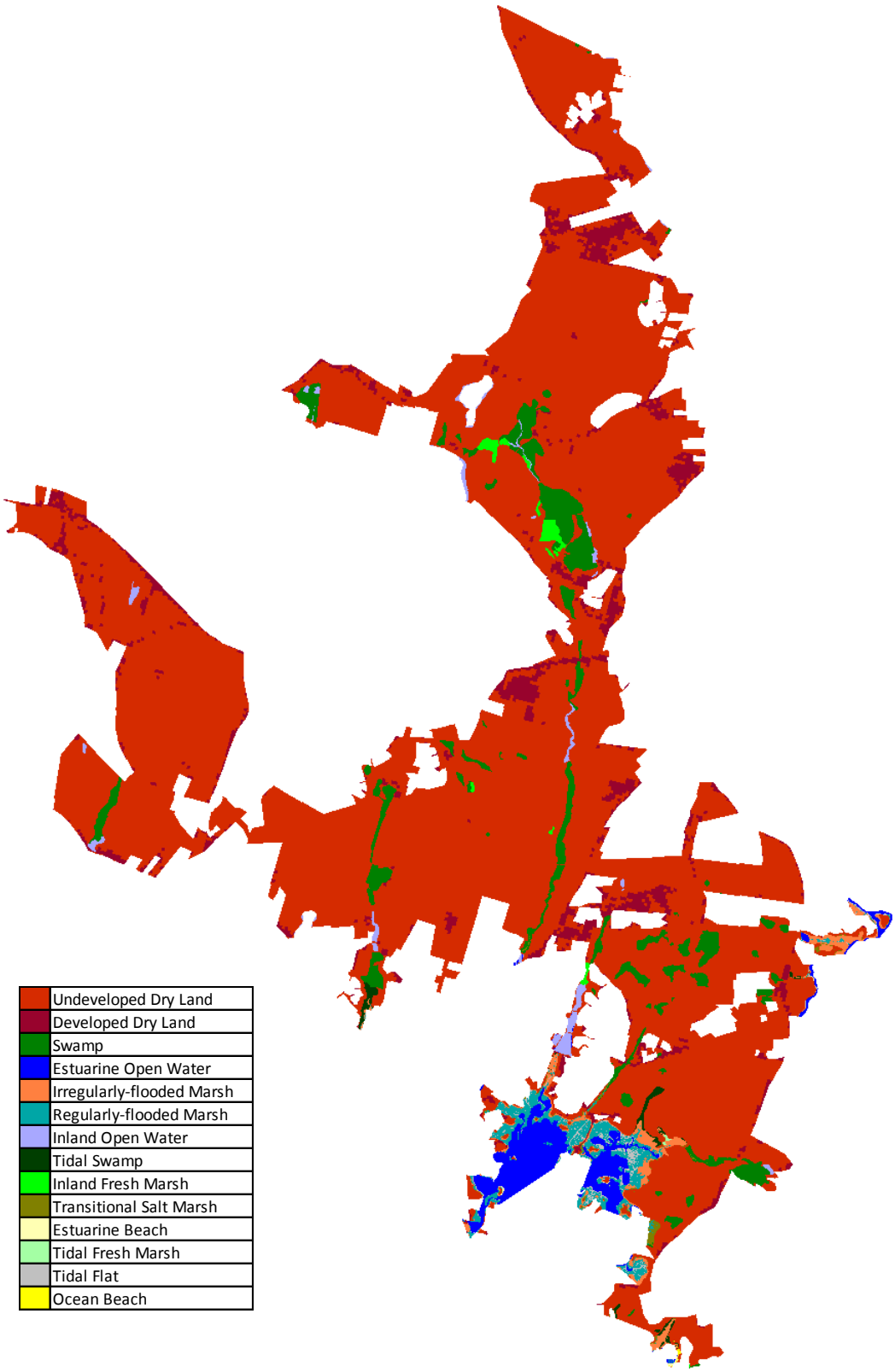
		SLAMM 1999	2025	2050	2075	2100
	Undeveloped Dry Land	5343	5340	5335	5326	5315
	Developed Dry Land	372	372	371	371	370
	Swamp	303	301	298	293	279
	Estuarine Open Water	157	160	165	184	212
	Irregularly-flooded Marsh	93	85	61	43	27
	Regularly-flooded Marsh	74	76	91	67	61
	Inland Open Water	47	46	46	41	38
	Tidal Swamp	26	22	19	16	12
	Inland Fresh Marsh	24	24	24	24	24
	Transitional Salt Marsh	8	9	13	16	27
	Estuarine Beach	1	2	2	1	1
	Tidal Fresh Marsh	1	1	1	0	0
	Tidal Flat	0	11	23	62	79
	Ocean Beach	0	0	1	1	2
	Total (incl. water)	**6448**	**6448**	**6448**	**6448**	**6448**



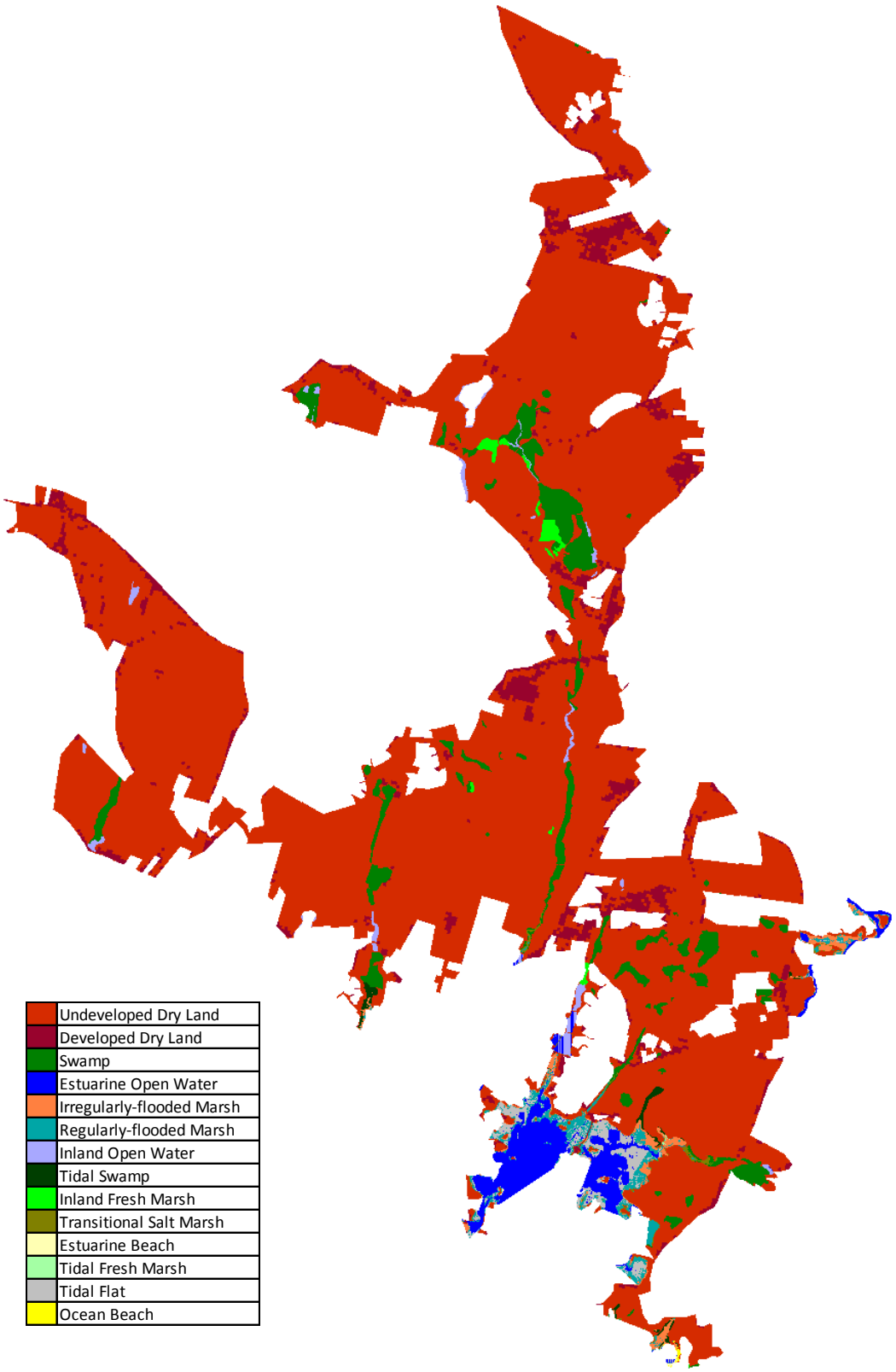
Mashpee NWR, SLAMM 1999.



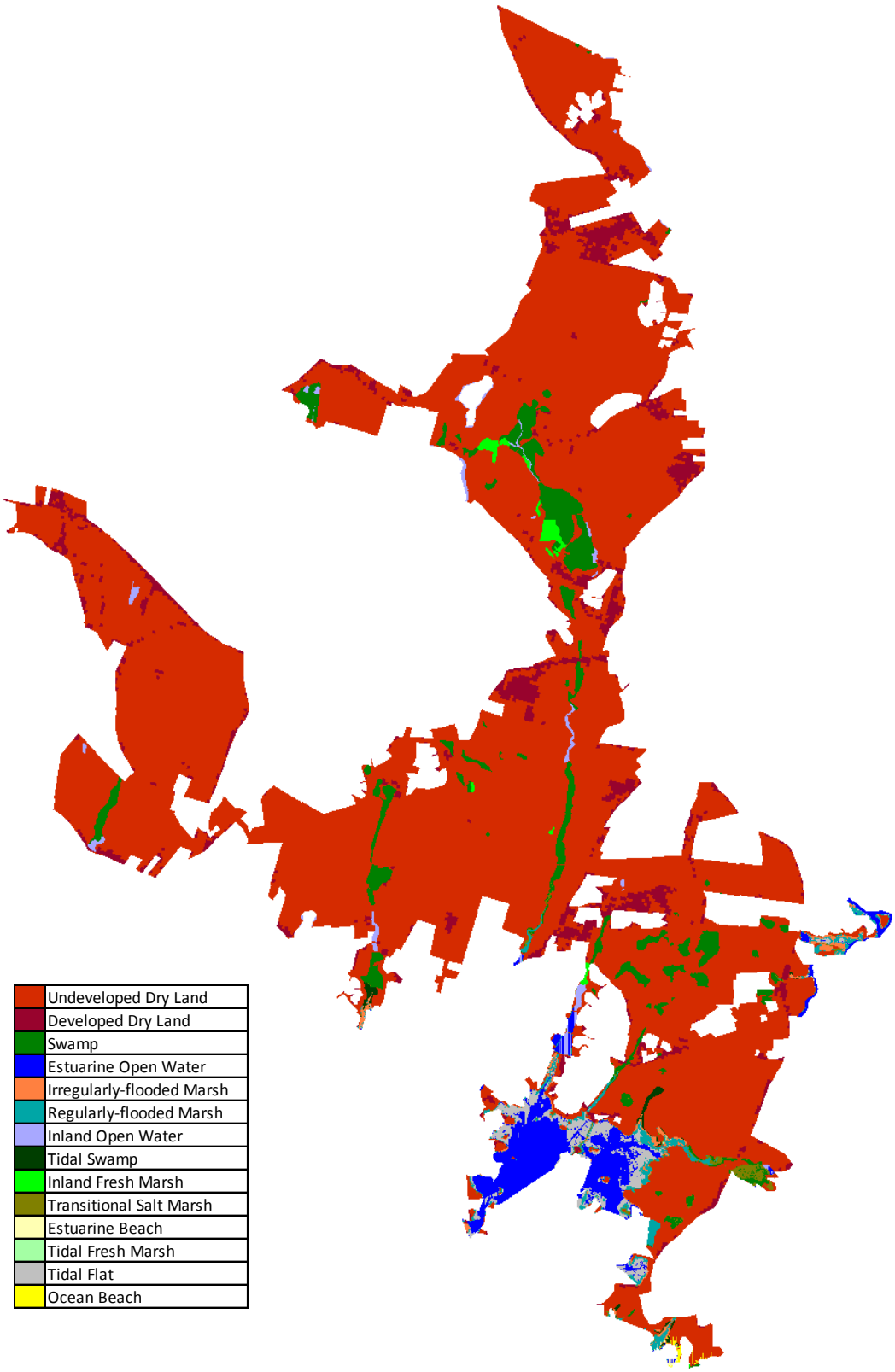
Mashpee NWR, 2025, Scenario A1B Maximum, 0.69 m SLR by 2100.



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



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

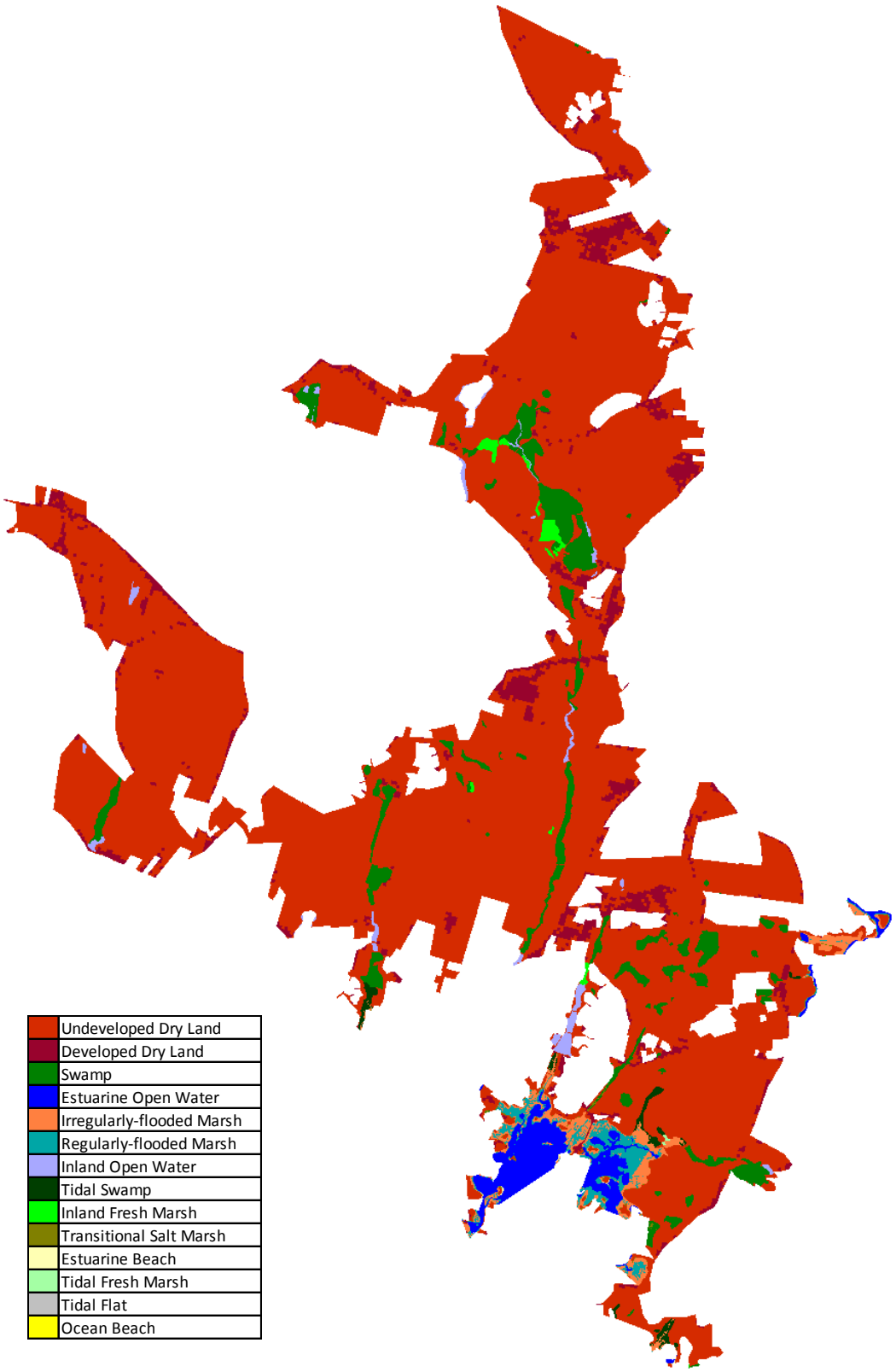


Mashpee NWR, 2100, Scenario A1B Maximum, 0.69 m SLR by 2100.

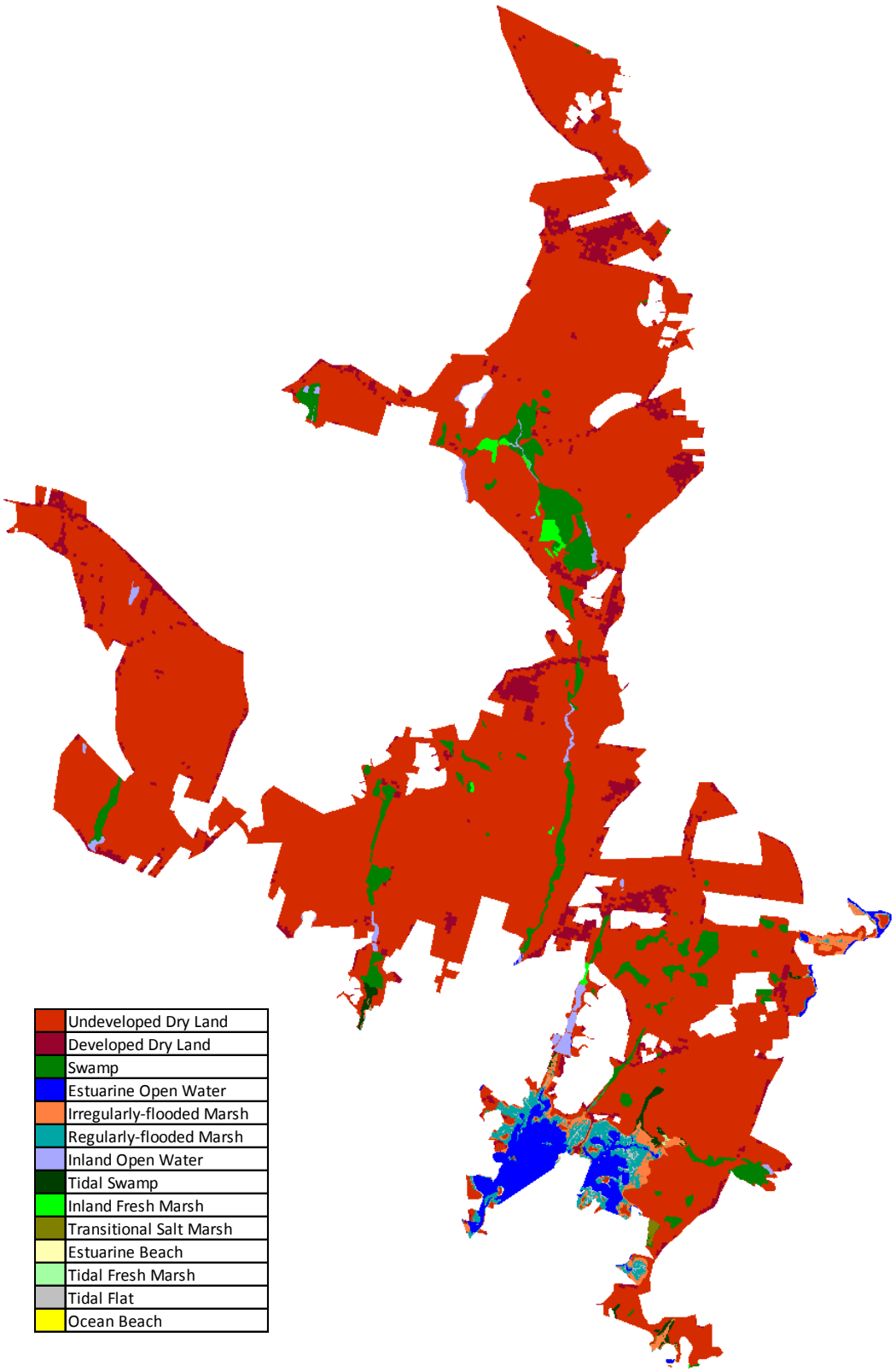
Mashpee NWR
1 m eustatic SLR by 2100

Results in Acres

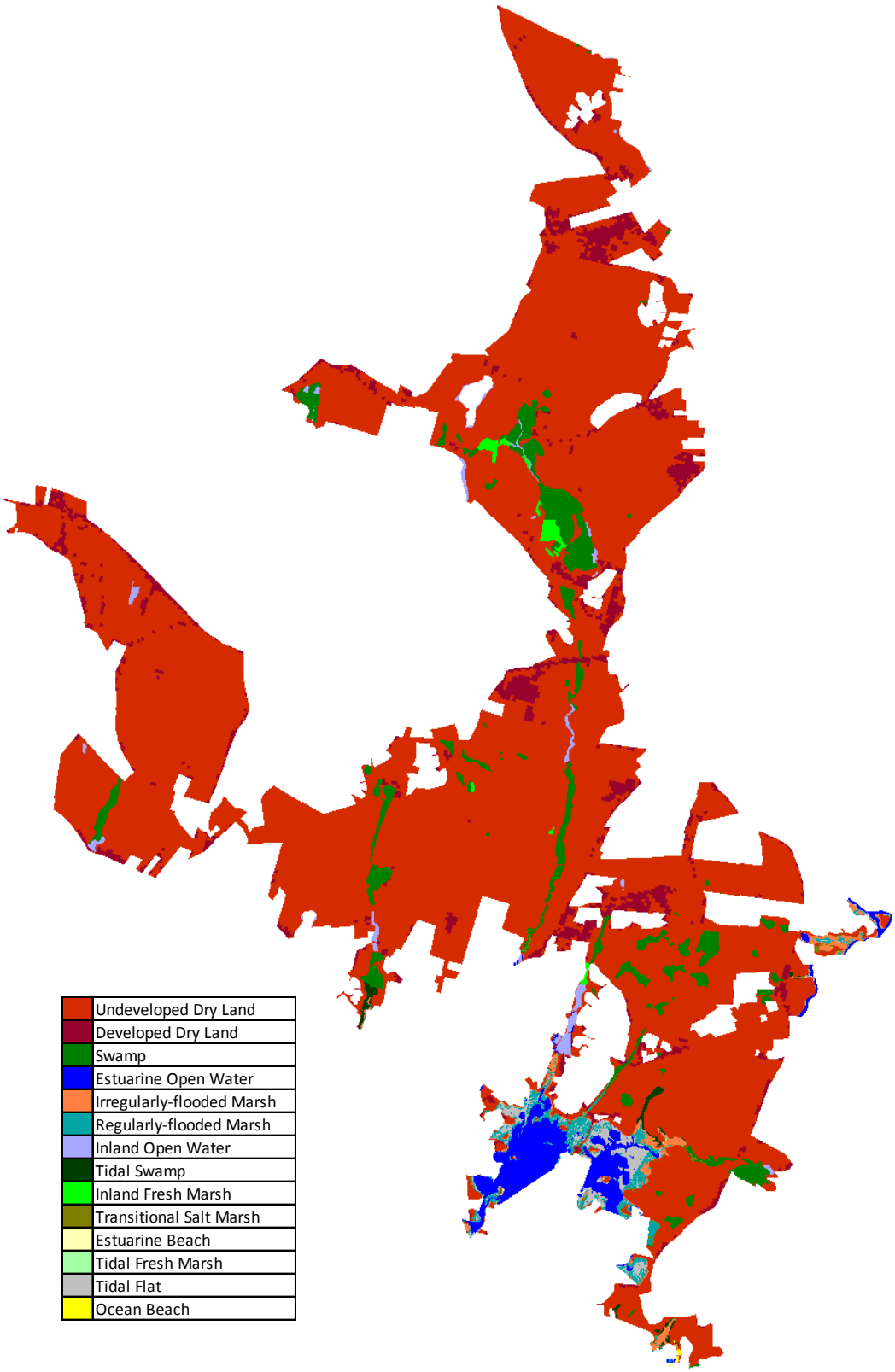
		SLAMM 1999	2025	2050	2075	2100
	Undeveloped Dry Land	5343	5339	5331	5317	5300
	Developed Dry Land	372	372	371	370	369
	Swamp	303	299	296	282	266
	Estuarine Open Water	157	161	175	209	285
	Irregularly-flooded Marsh	93	70	45	22	12
	Regularly-flooded Marsh	74	87	70	51	53
	Inland Open Water	47	46	45	39	34
	Tidal Swamp	26	21	17	13	10
	Inland Fresh Marsh	24	24	24	24	24
	Transitional Salt Marsh	8	10	12	28	33
	Estuarine Beach	1	2	1	1	1
	Tidal Fresh Marsh	1	1	0	0	0
	Tidal Flat	0	16	58	90	57
	Ocean Beach	0	0	1	2	3
	Total (incl. water)	**6448**	**6448**	**6448**	**6448**	**6448**



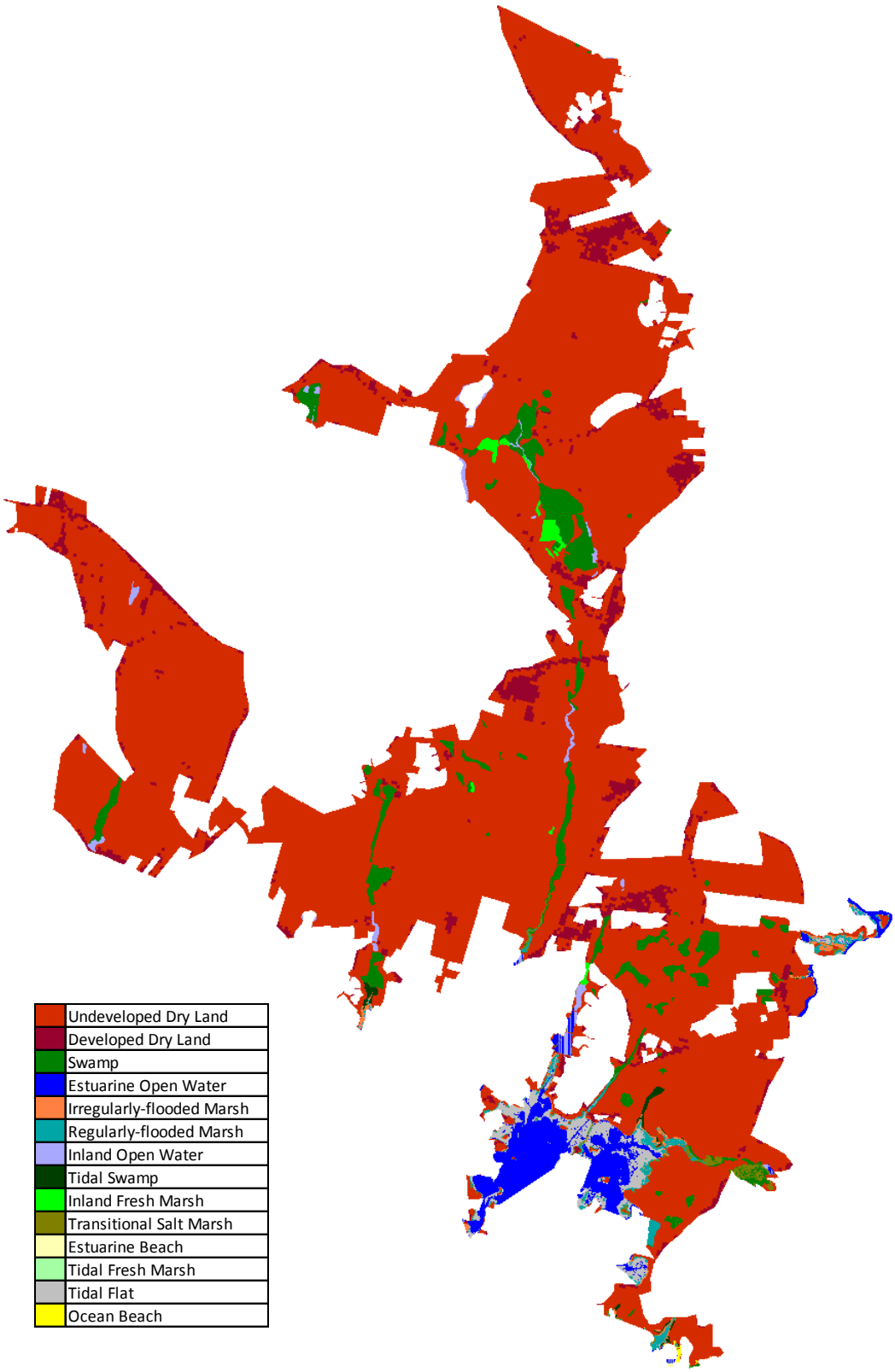
Mashpee NWR, SLAMM 1999.



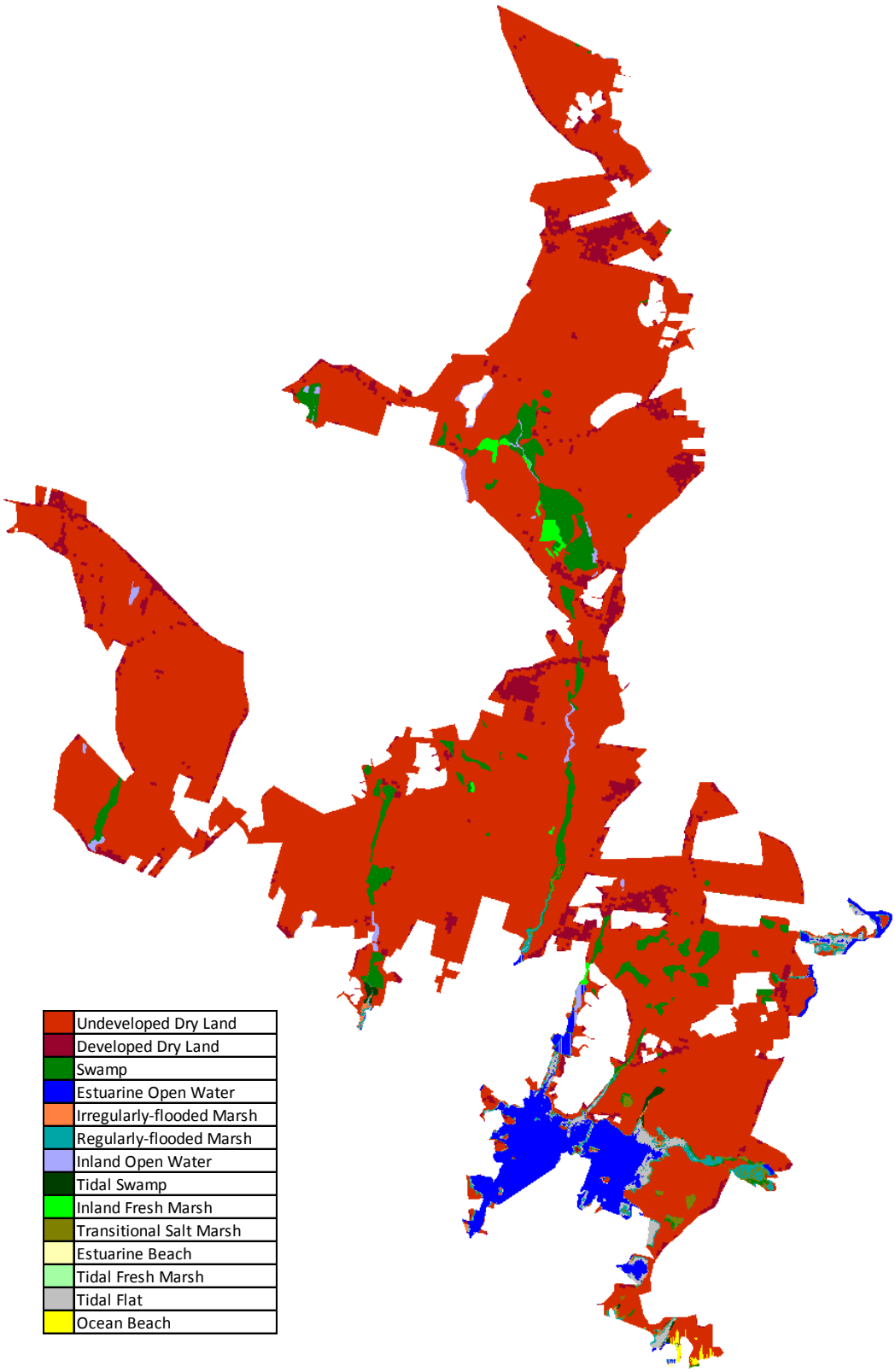
Mashpee NWR, 2025, 1 m SLR by 2100.



Mashpee NWR, 2050, 1 m SLR by 2100.



Mashpee NWR, 2075, 1 m SLR by 2100.

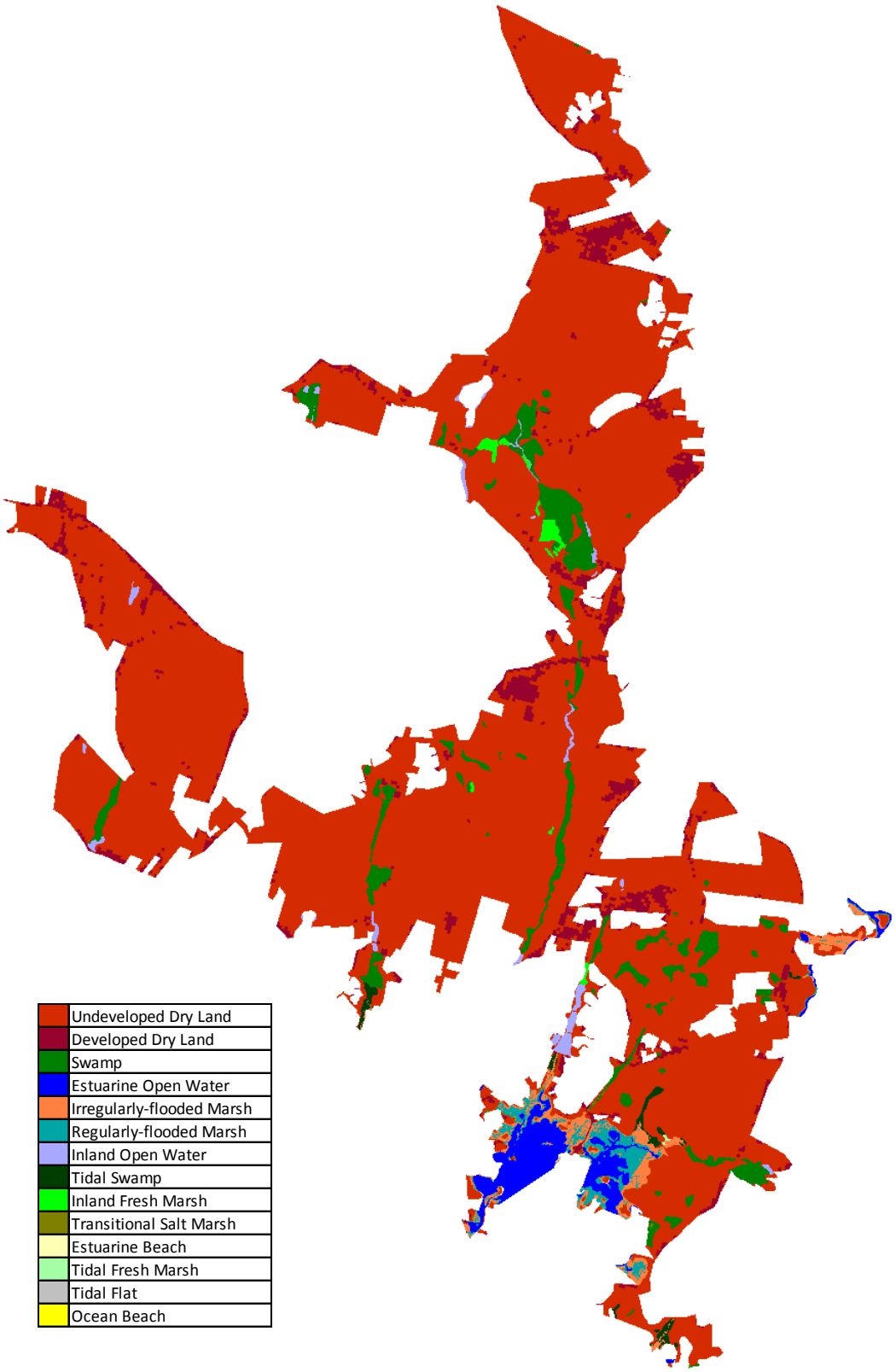


Mashpee NWR, 2100, 1 m SLR by 2100.

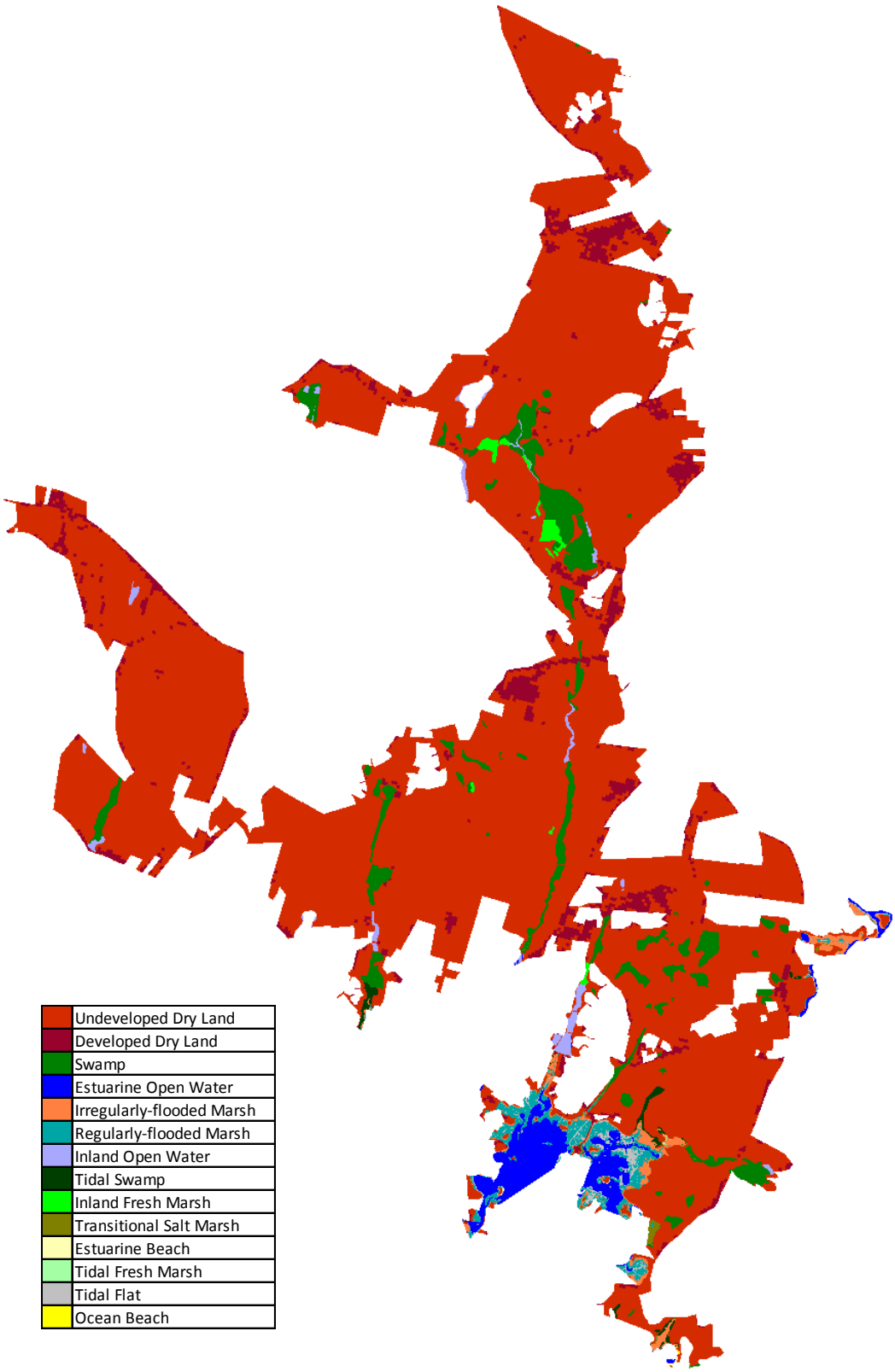
Mashpee NWR
1.5 m eustatic SLR by 2100

Results in Acres

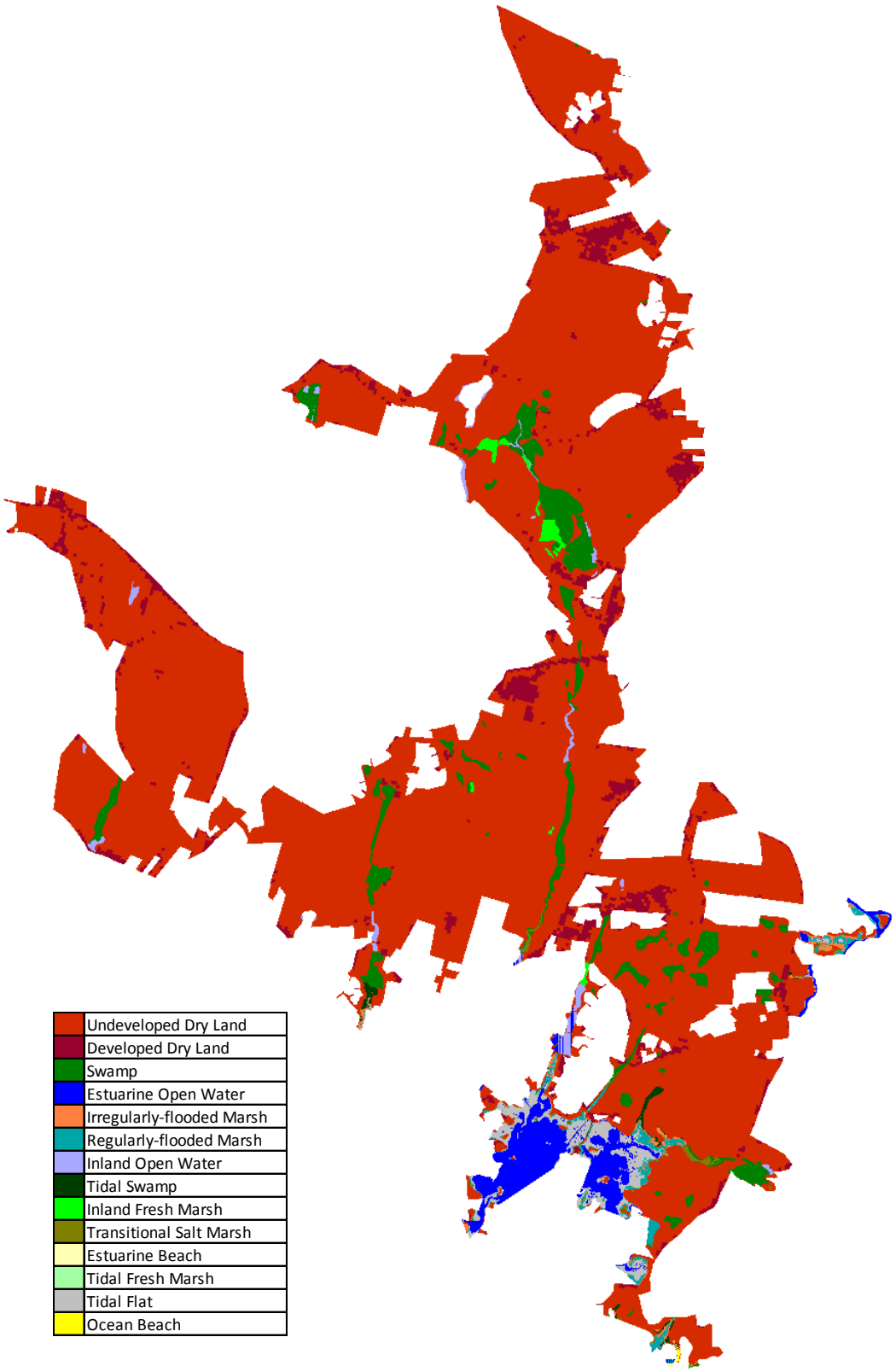
		SLAMM 1999	2025	2050	2075	2100
	Undeveloped Dry Land	5343	5337	5324	5300	5273
	Developed Dry Land	372	371	371	369	368
	Swamp	303	299	291	266	249
	Estuarine Open Water	157	164	191	290	350
	Irregularly-flooded Marsh	93	56	24	10	5
	Regularly-flooded Marsh	74	89	52	40	57
	Inland Open Water	47	46	42	37	30
	Tidal Swamp	26	20	14	9	7
	Inland Fresh Marsh	24	24	24	24	24
	Transitional Salt Marsh	8	11	21	50	44
	Estuarine Beach	1	2	1	1	0
	Tidal Fresh Marsh	1	0	0	0	0
	Tidal Flat	0	28	92	48	37
	Ocean Beach	0	0	1	3	4
	Total (incl. water)	**6448**	**6448**	**6448**	**6448**	**6448**



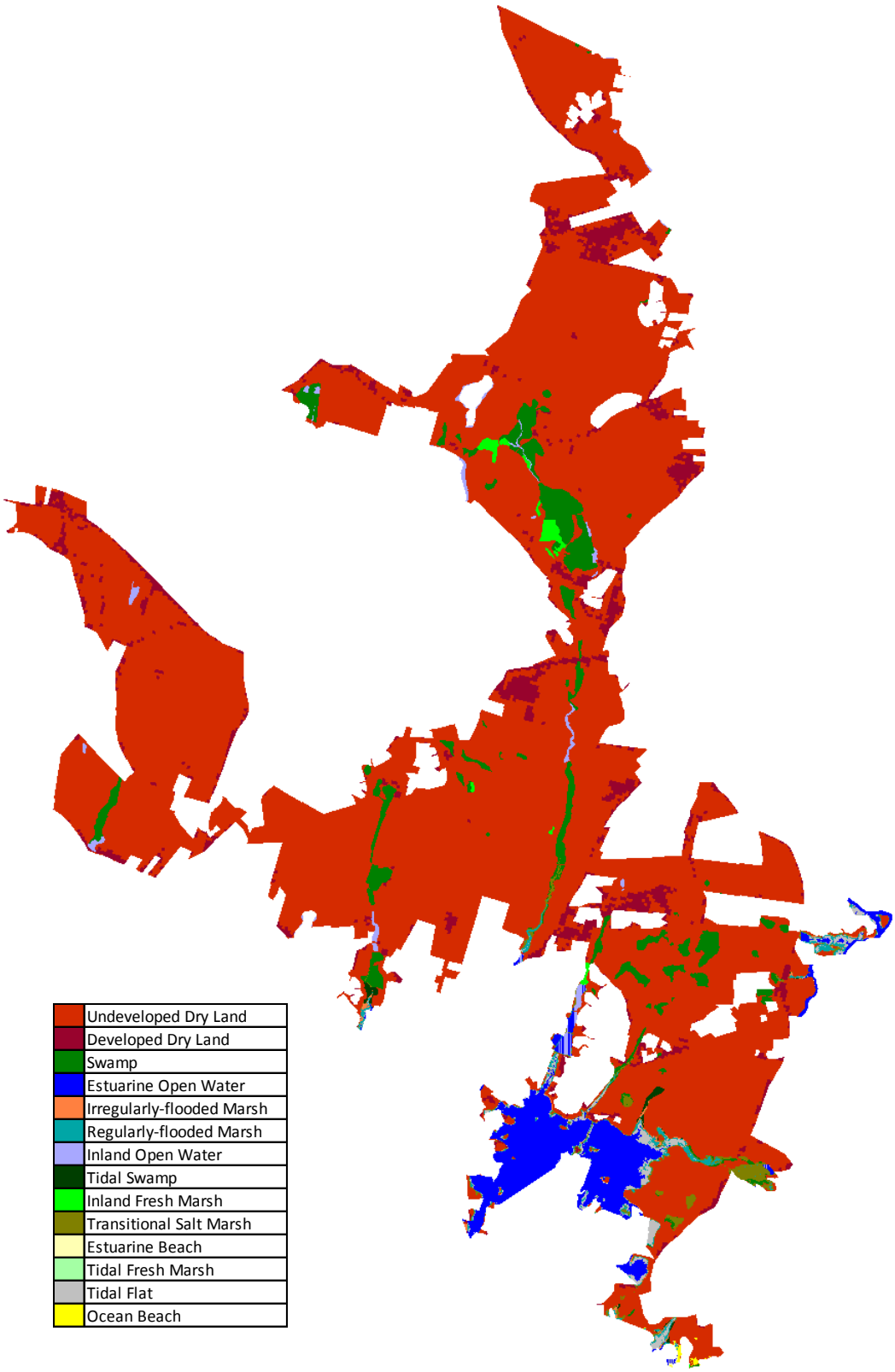
Mashpee NWR, SLAMM 1999.



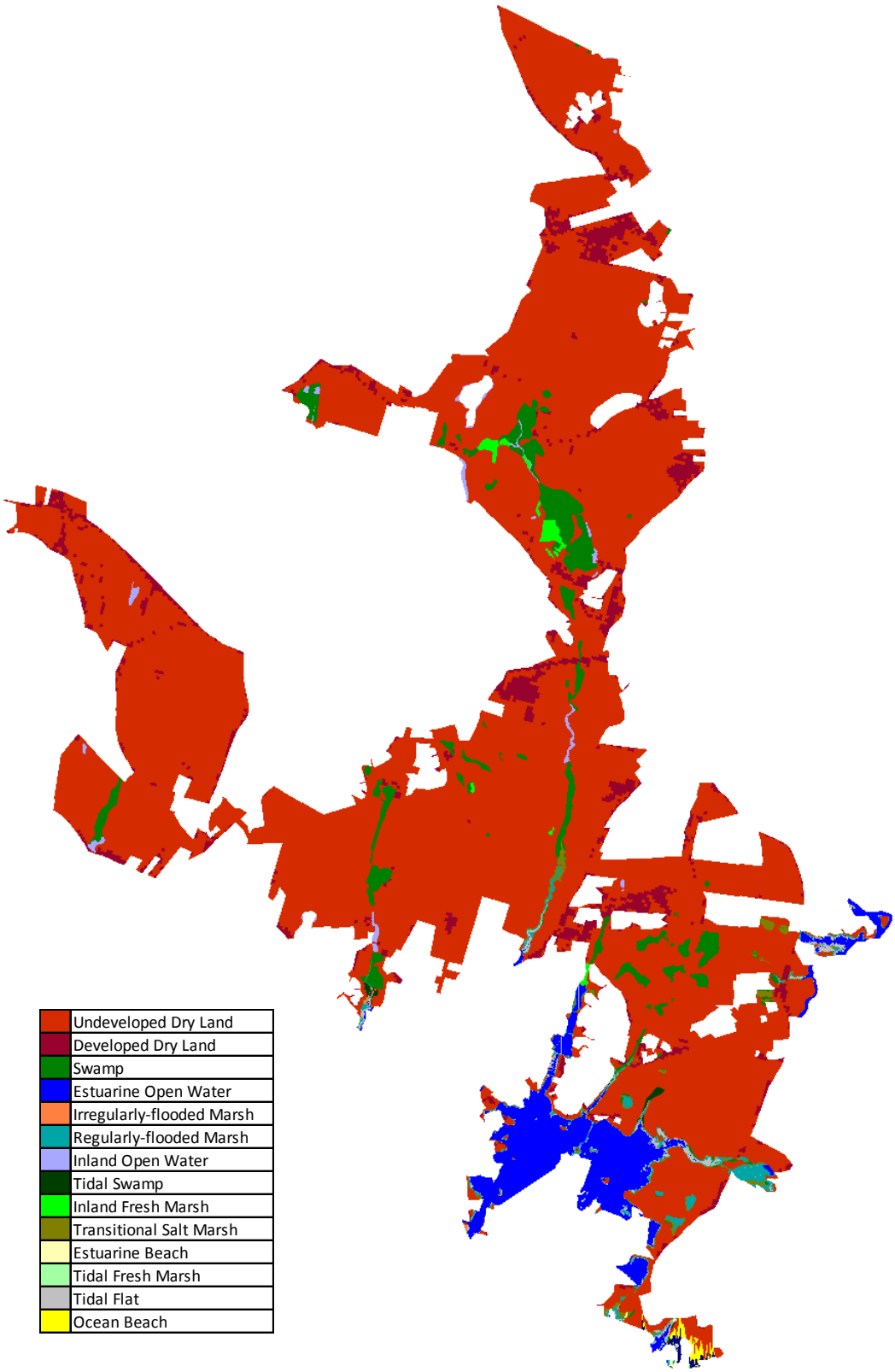
Mashpee NWR, 2025, 1.5 m SLR by 2100.



Mashpee NWR, 2050, 1.5 m SLR by 2100.



Mashpee NWR, 2075, 1.5 m SLR by 2100.

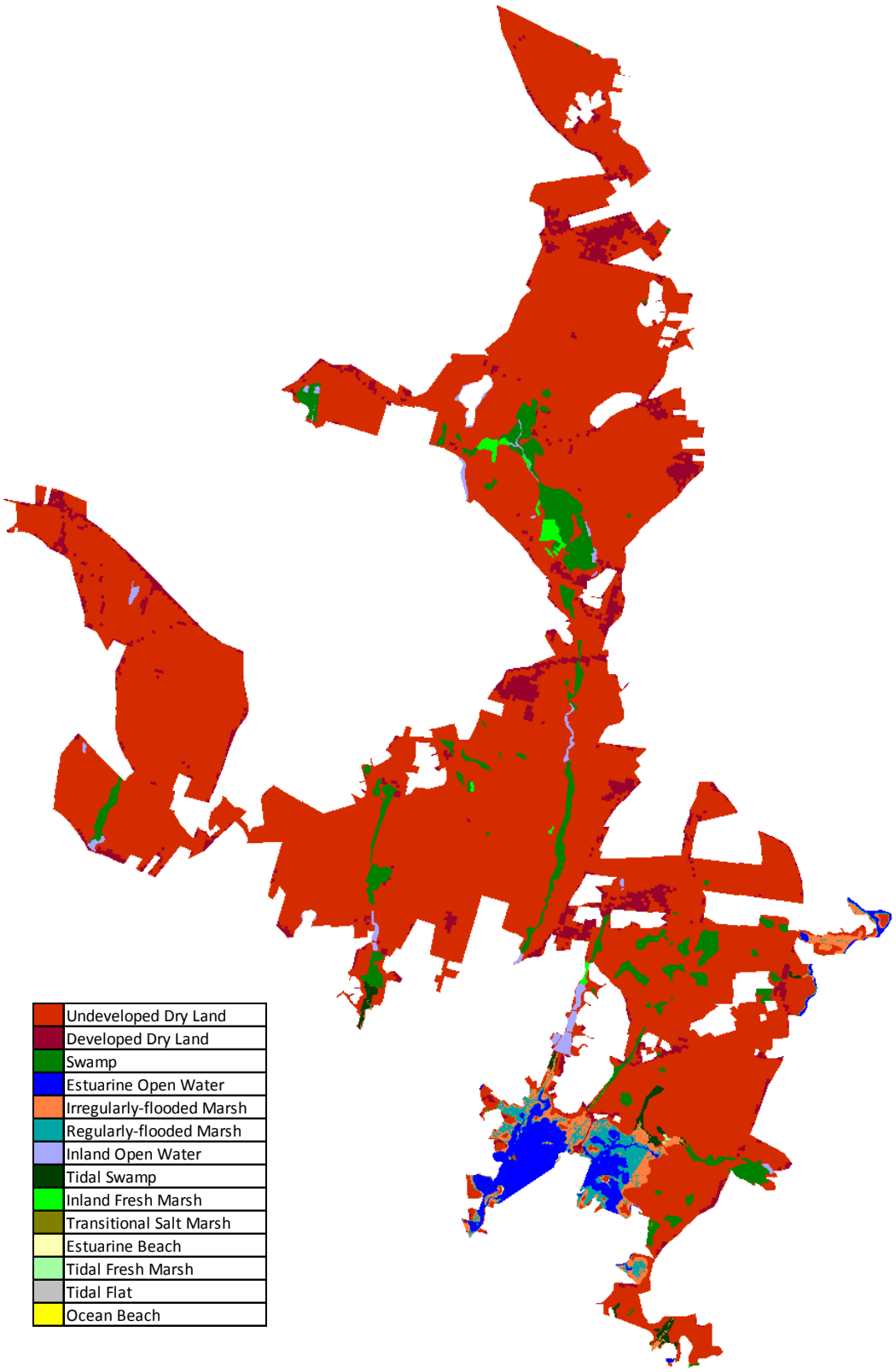


Mashpee NWR, 2100, 1.5 m SLR by 2100.

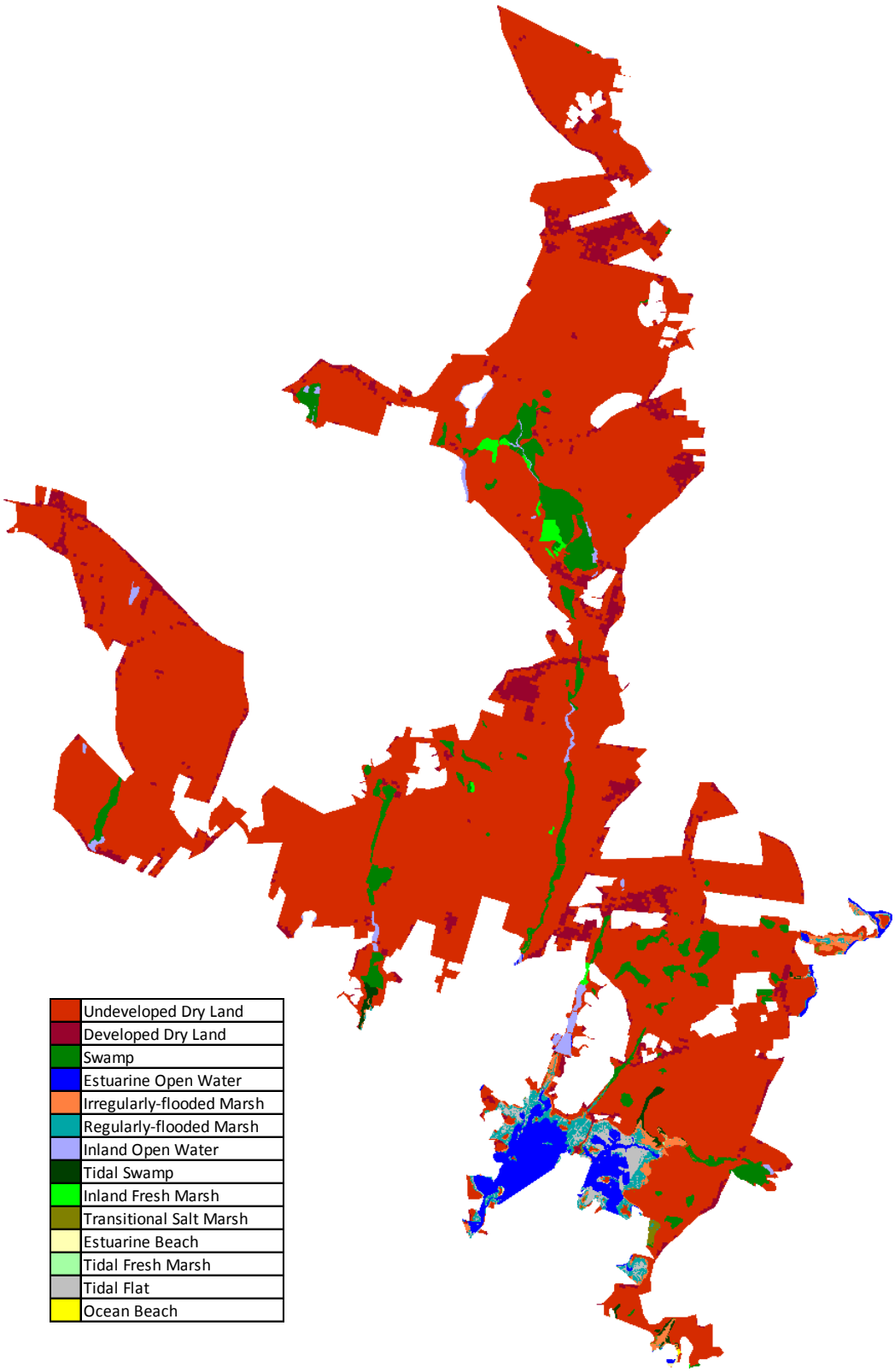
Mashpee NWR
2 m eustatic SLR by 2100

Results in Acres

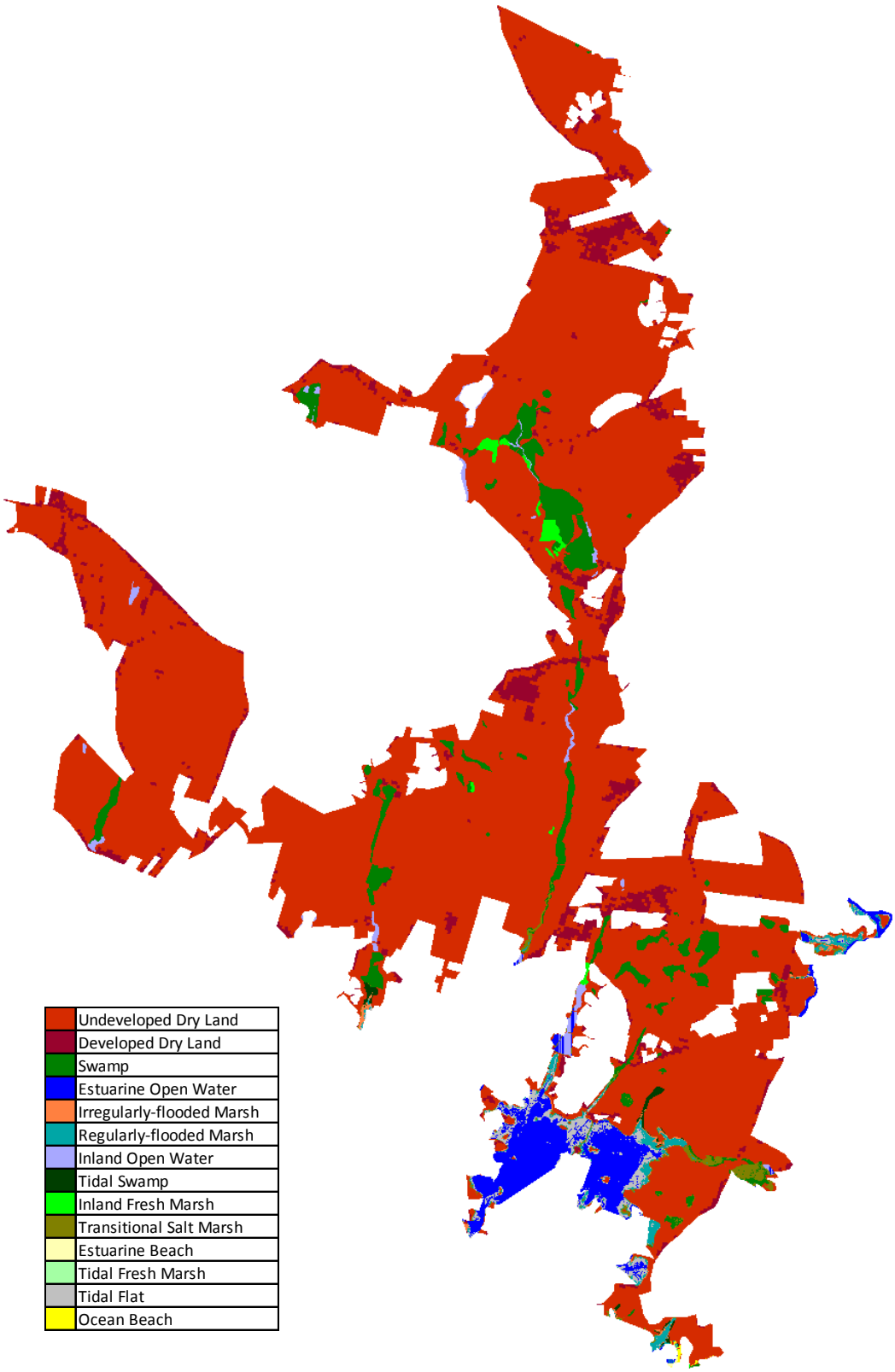
		SLAMM 1999	2025	2050	2075	2100
	Undeveloped Dry Land	5343	5335	5315	5282	5241
	Developed Dry Land	372	371	370	368	367
	Swamp	303	298	278	252	222
	Estuarine Open Water	157	168	233	308	366
	Irregularly-flooded Marsh	93	47	15	7	5
	Regularly-flooded Marsh	74	72	53	53	63
	Inland Open Water	47	46	41	34	29
	Tidal Swamp	26	18	12	7	4
	Inland Fresh Marsh	24	24	24	24	23
	Transitional Salt Marsh	8	13	41	58	69
	Estuarine Beach	1	2	1	0	1
	Tidal Fresh Marsh	1	0	0	0	0
	Tidal Flat	0	53	64	49	49
	Ocean Beach	0	0	2	4	5
	Total (incl. water)	**6448**	**6448**	**6448**	**6448**	**6448**



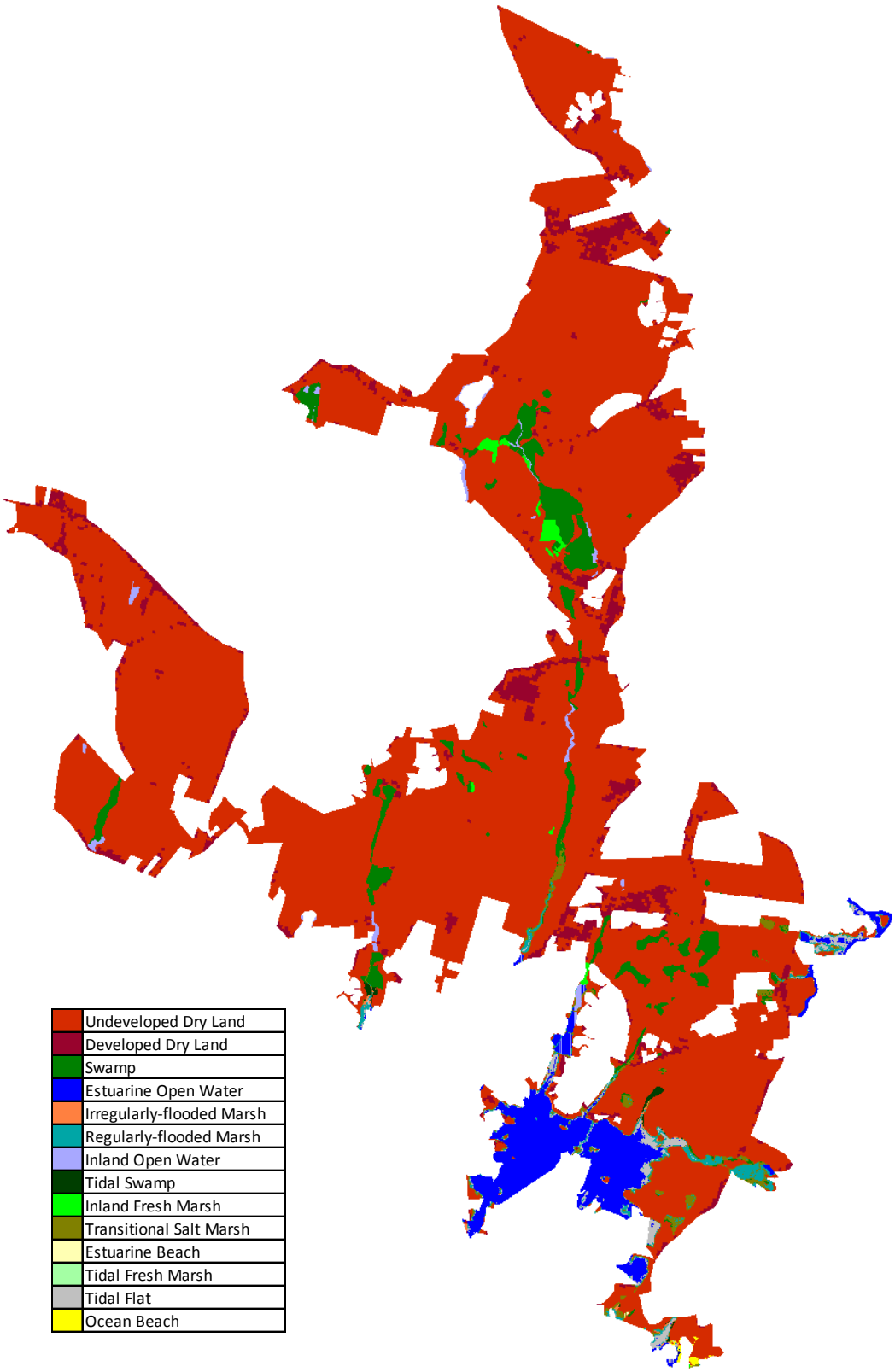
Mashpee NWR, SLAMM 1999.



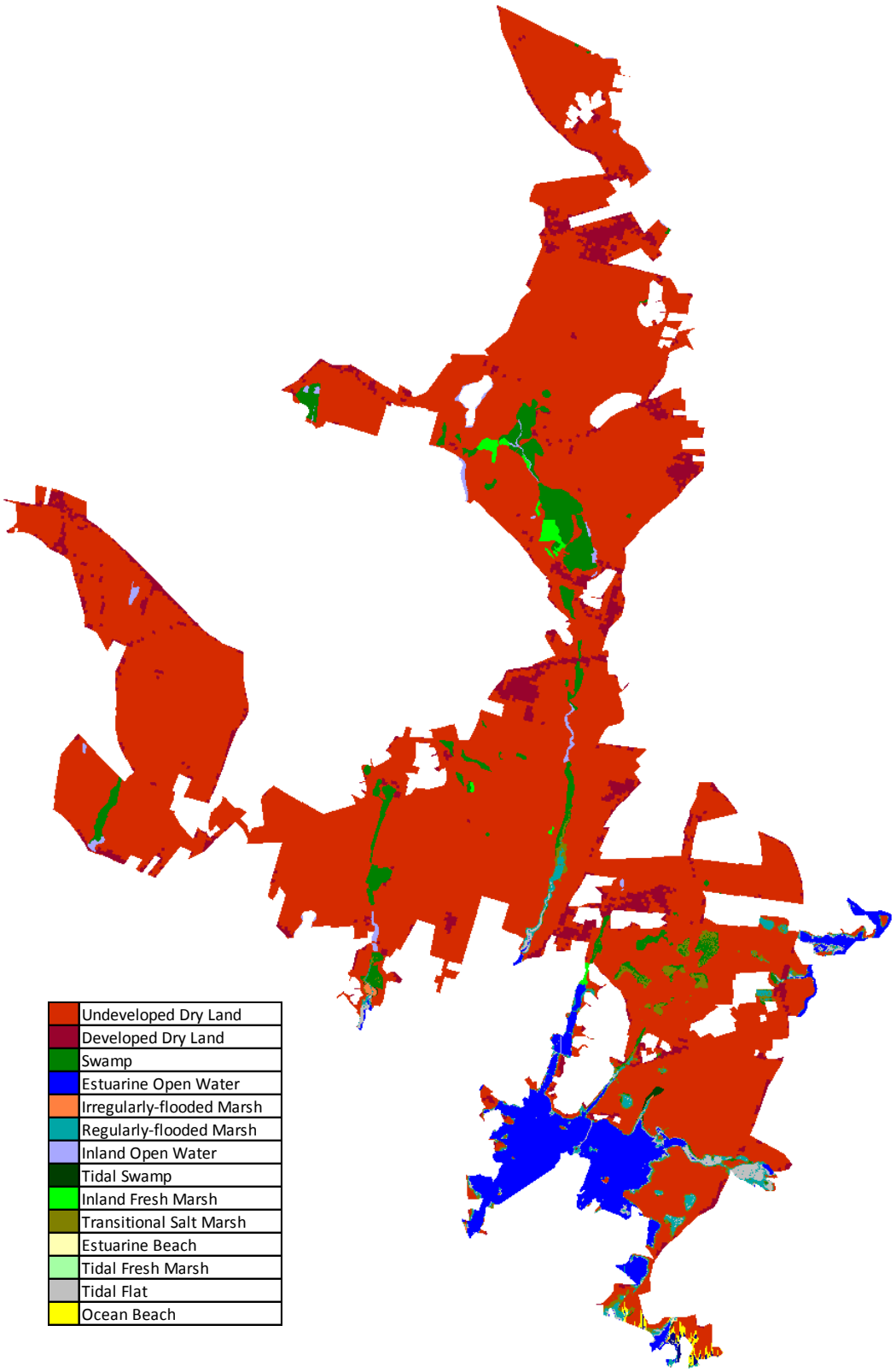
Mashpee NWR, 2025, 2 m SLR by 2100.



Mashpee NWR, 2050, 2 m SLR by 2100.



Mashpee NWR, 2075, 2 m SLR by 2100.



Mashpee NWR, 2100, 2 m SLR by 2100.

Discussion

As almost 90% of Mashpee NWR is comprised of high elevation dry land, SLAMM predictions suggest that refuge coverage is relatively resilient to sea-level rise. However, existing wetlands are predicted to be greatly affected for SLR scenarios above 0.39 m by 2100. Although these wetlands cover a relatively small portion of the refuge, around 8%, the predicted inundation and conversions suggest a potential loss of the wetland-habitat richness currently covering the refuge.

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 and nine times as many cells were used in the new analysis. More importantly, this analysis used much more precise elevation information based on new LiDAR data. The new analysis predicts loss trends that are similar to the previous analysis. However, some wetlands are lower in the tidal frame than previously estimated and this makes them more subject to inundation. "Swamp" and "tidal swamp" are examples of categories predicted to be more vulnerable than in the previous analysis.

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.

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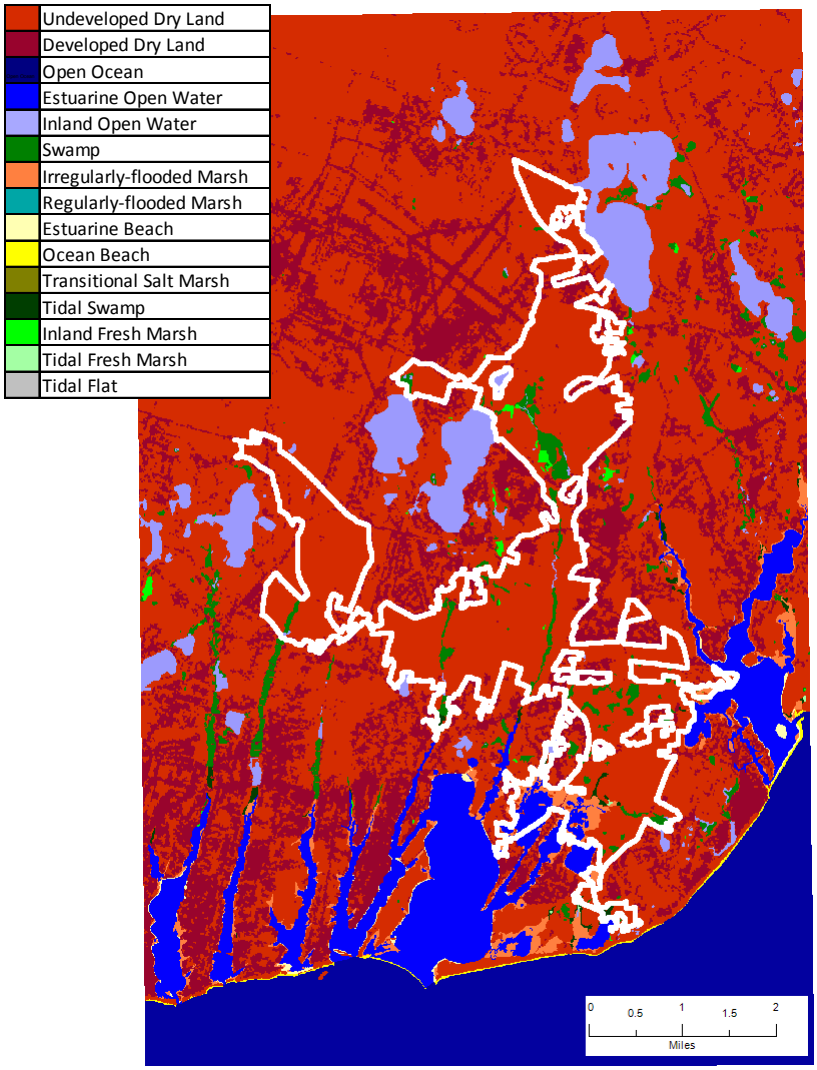
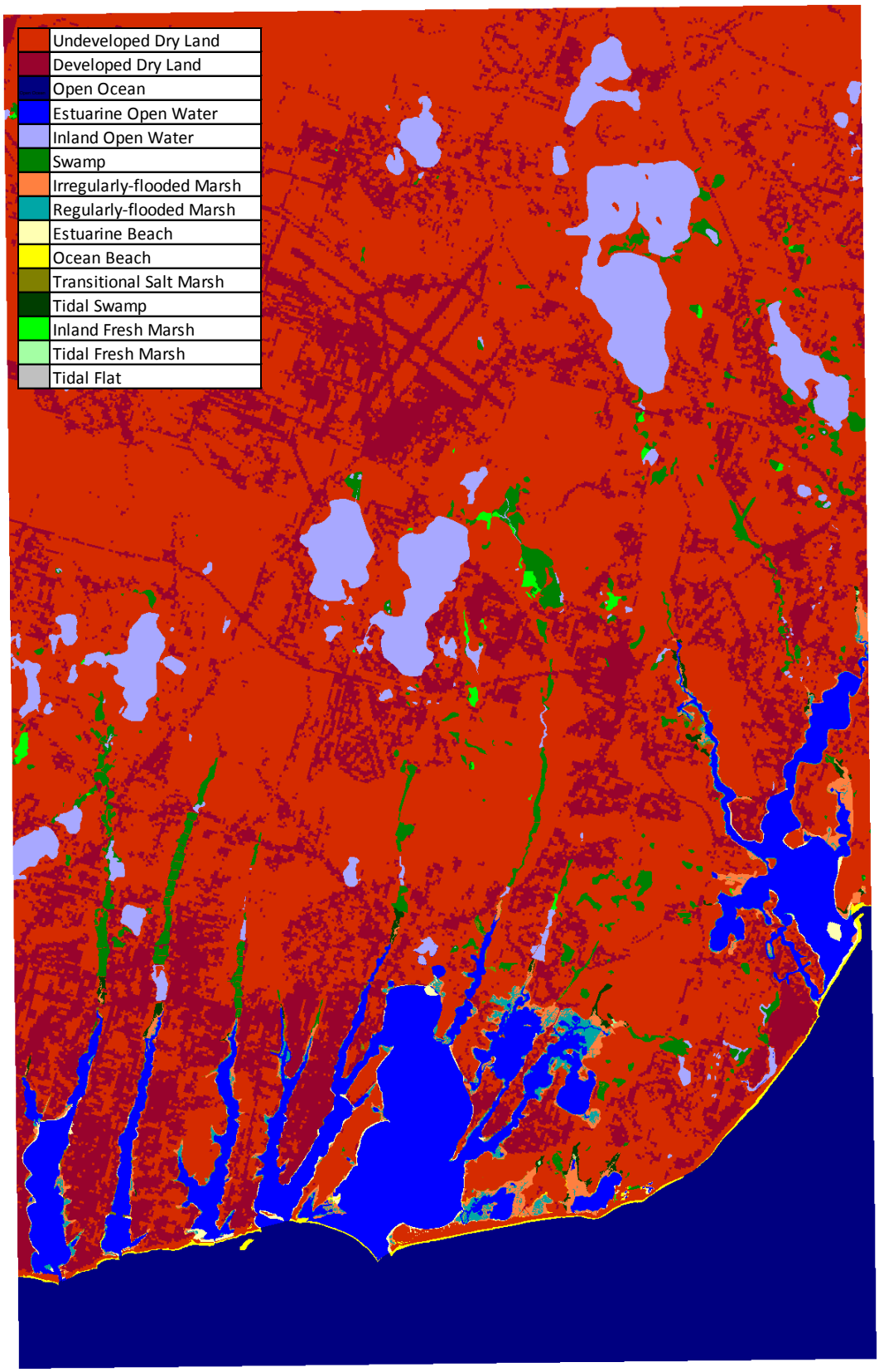
Appendix A: Contextual Results

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. 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.



Mashpee National Wildlife Refuge within simulation context (black).



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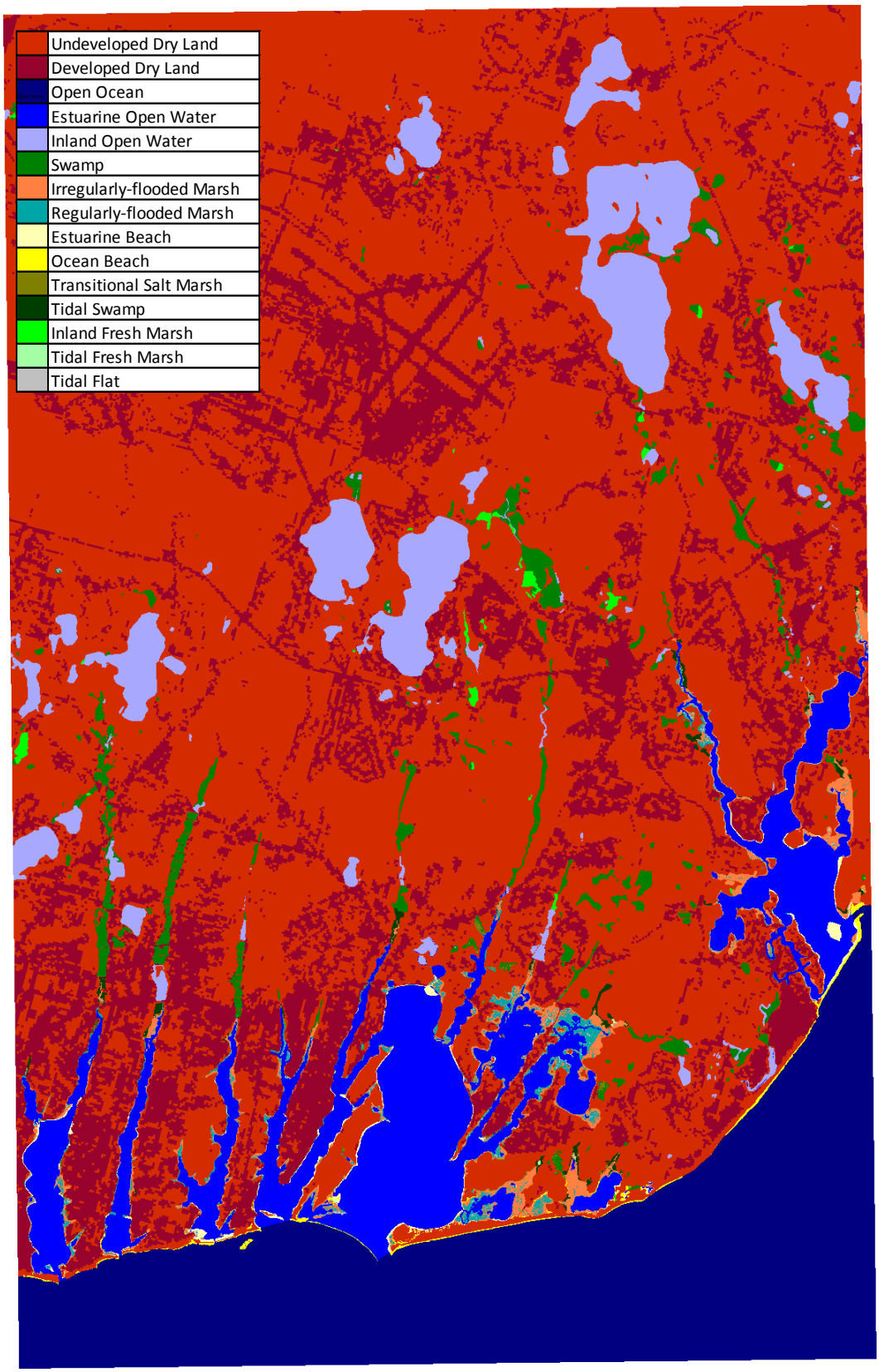
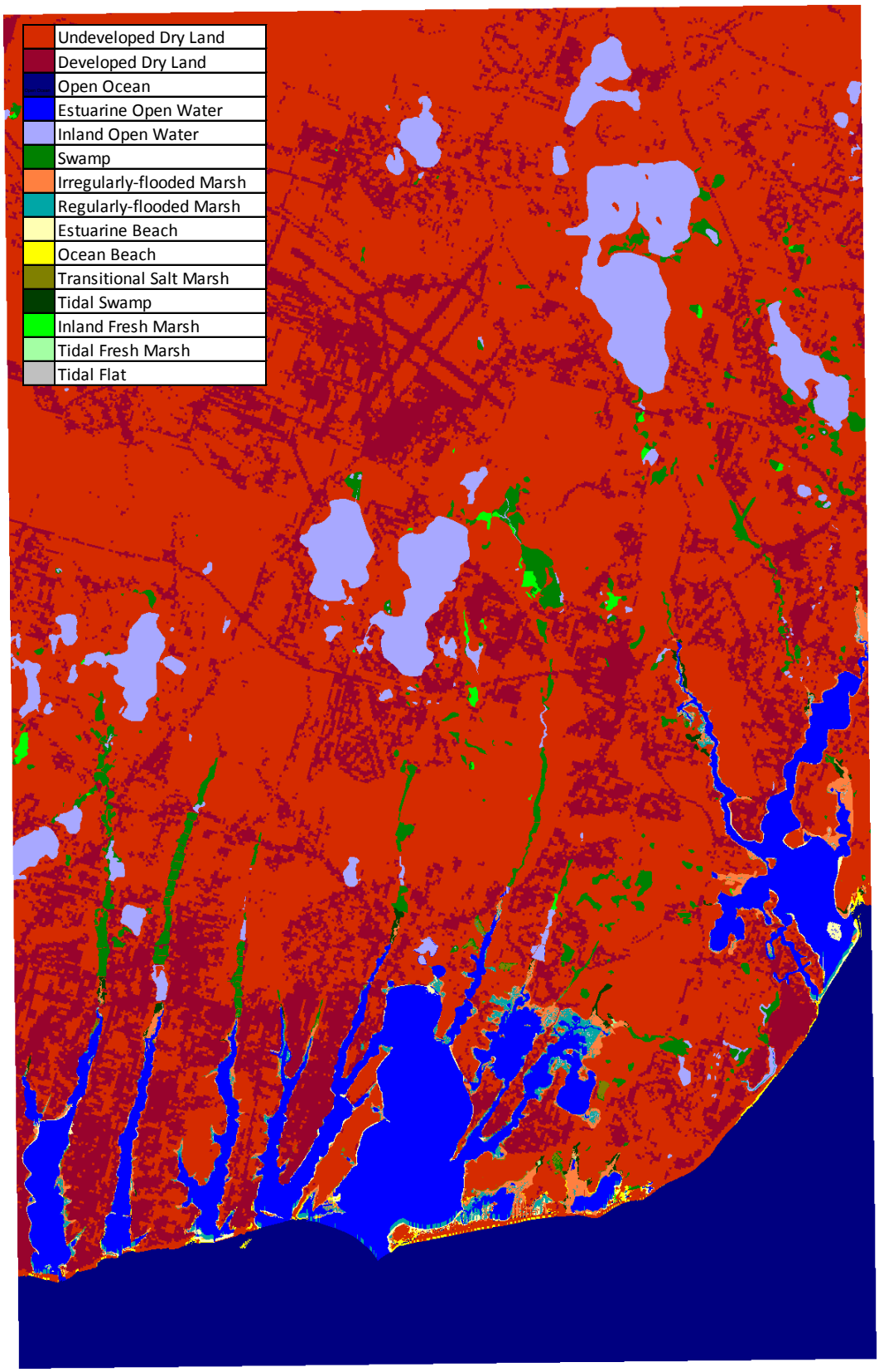


Mashpee NWR, 2025, Scenario A1B Mean, 0.39 m SLR by 2100.



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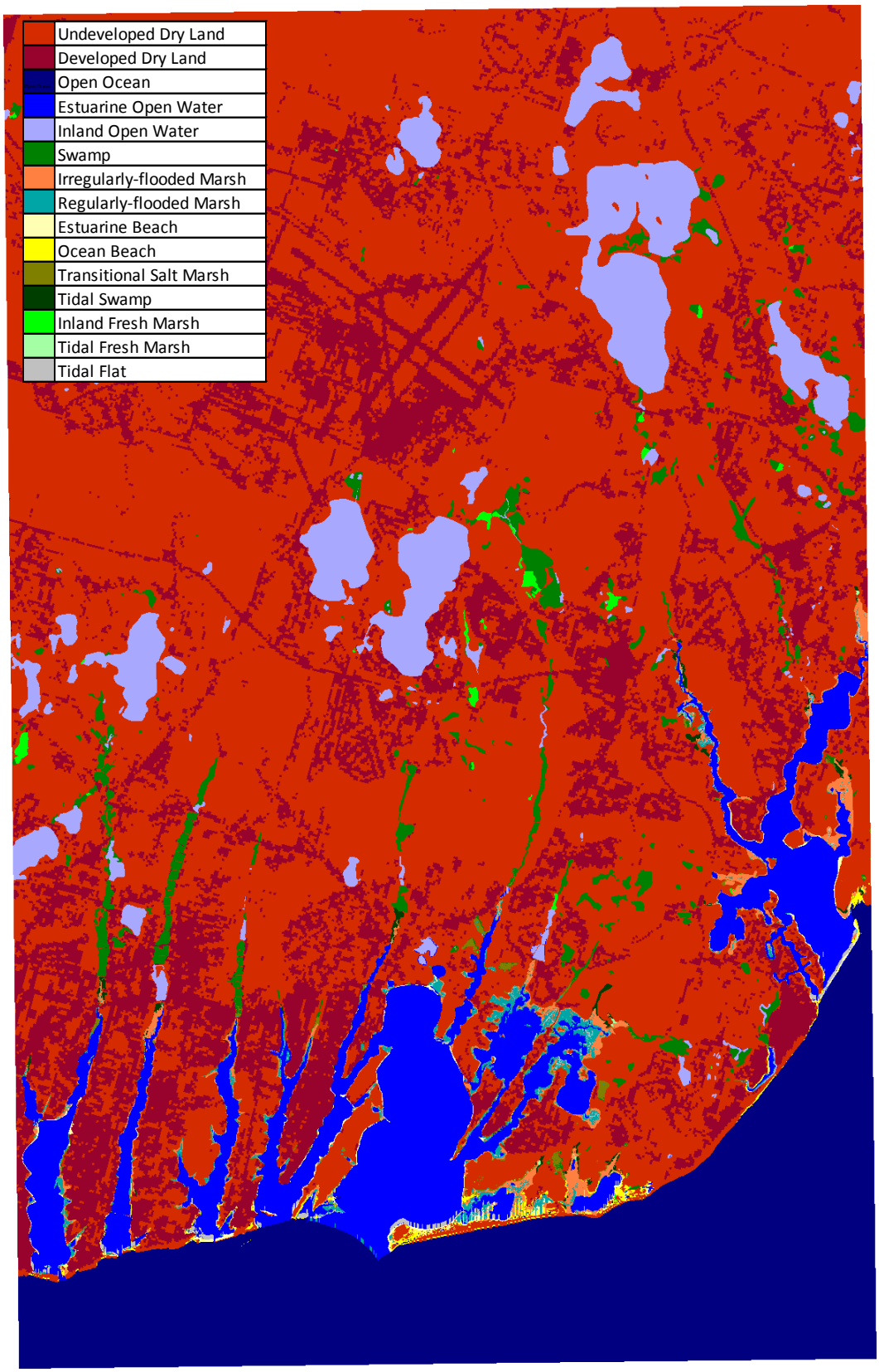

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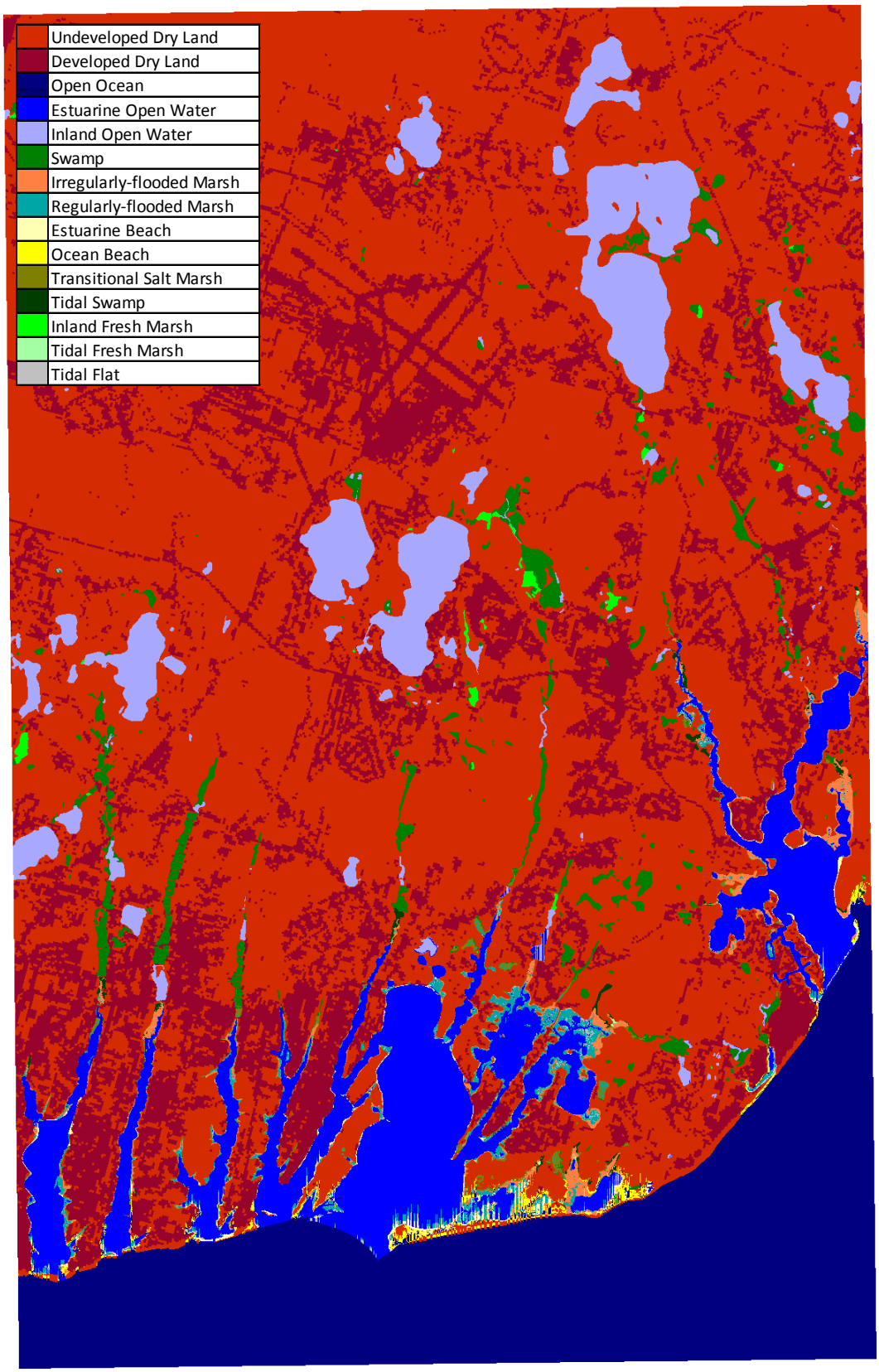
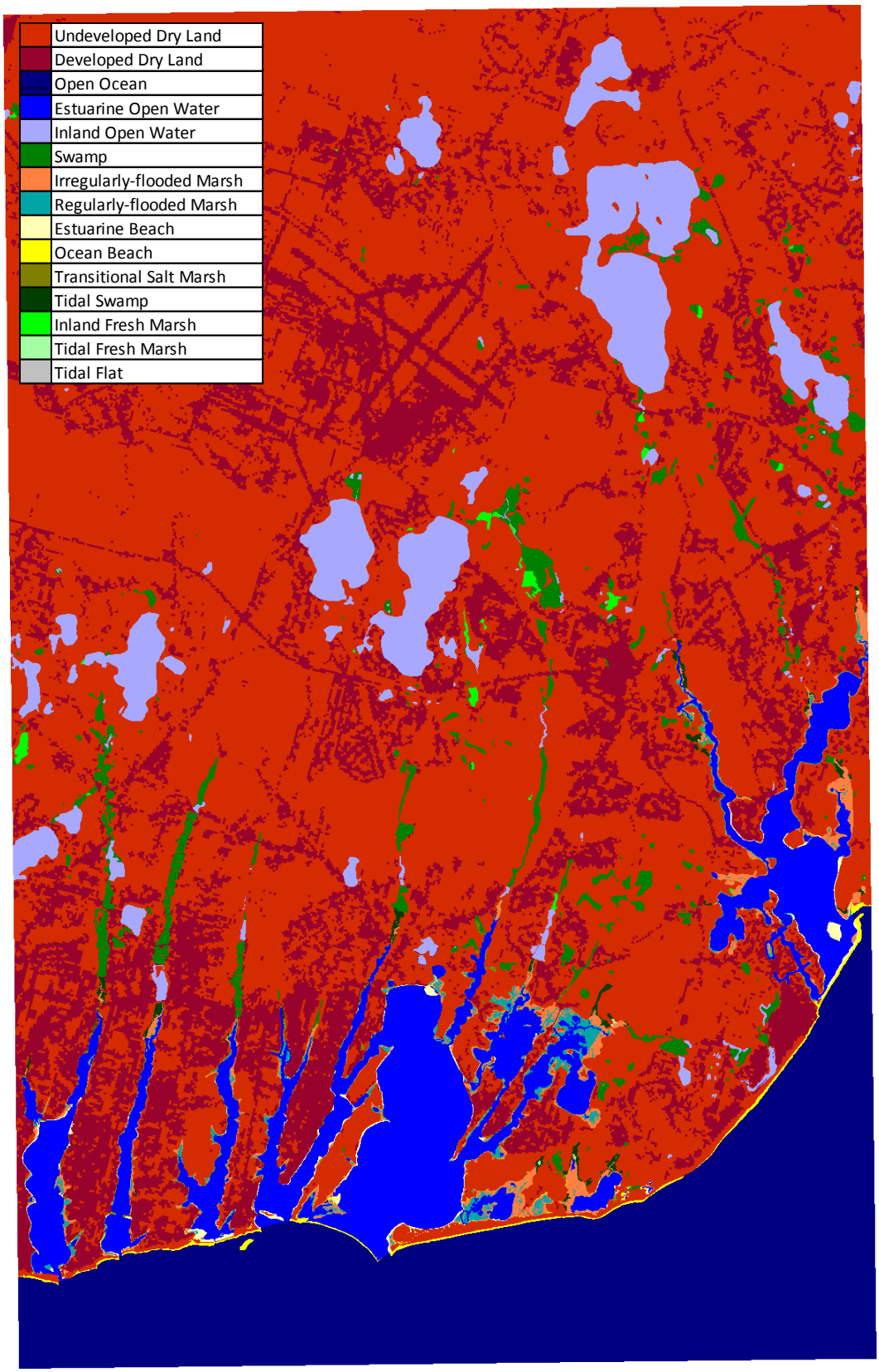


Mashpee NWR, 2100, Scenario A1B Mean, 0.39 m SLR by 2100.



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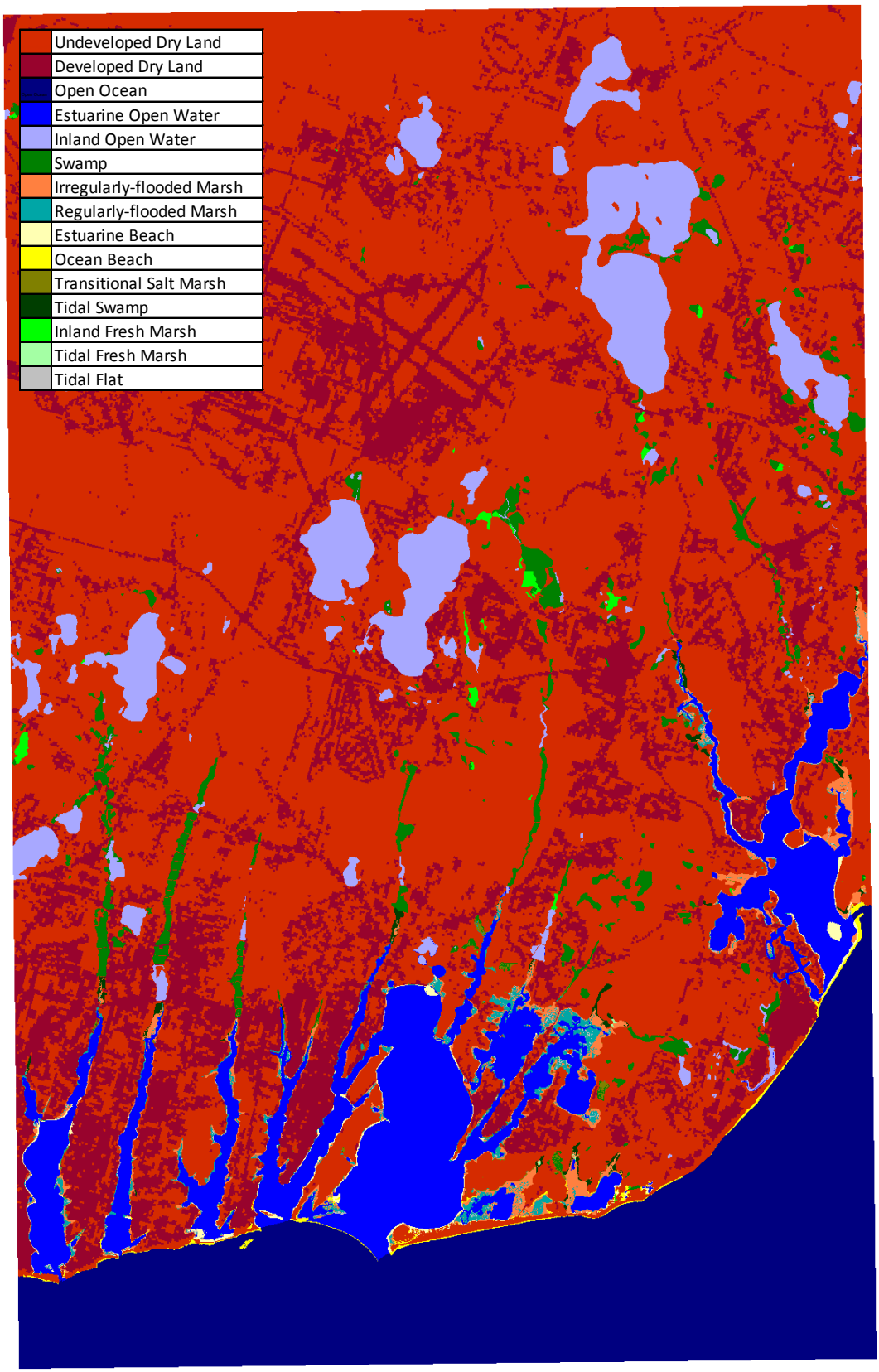
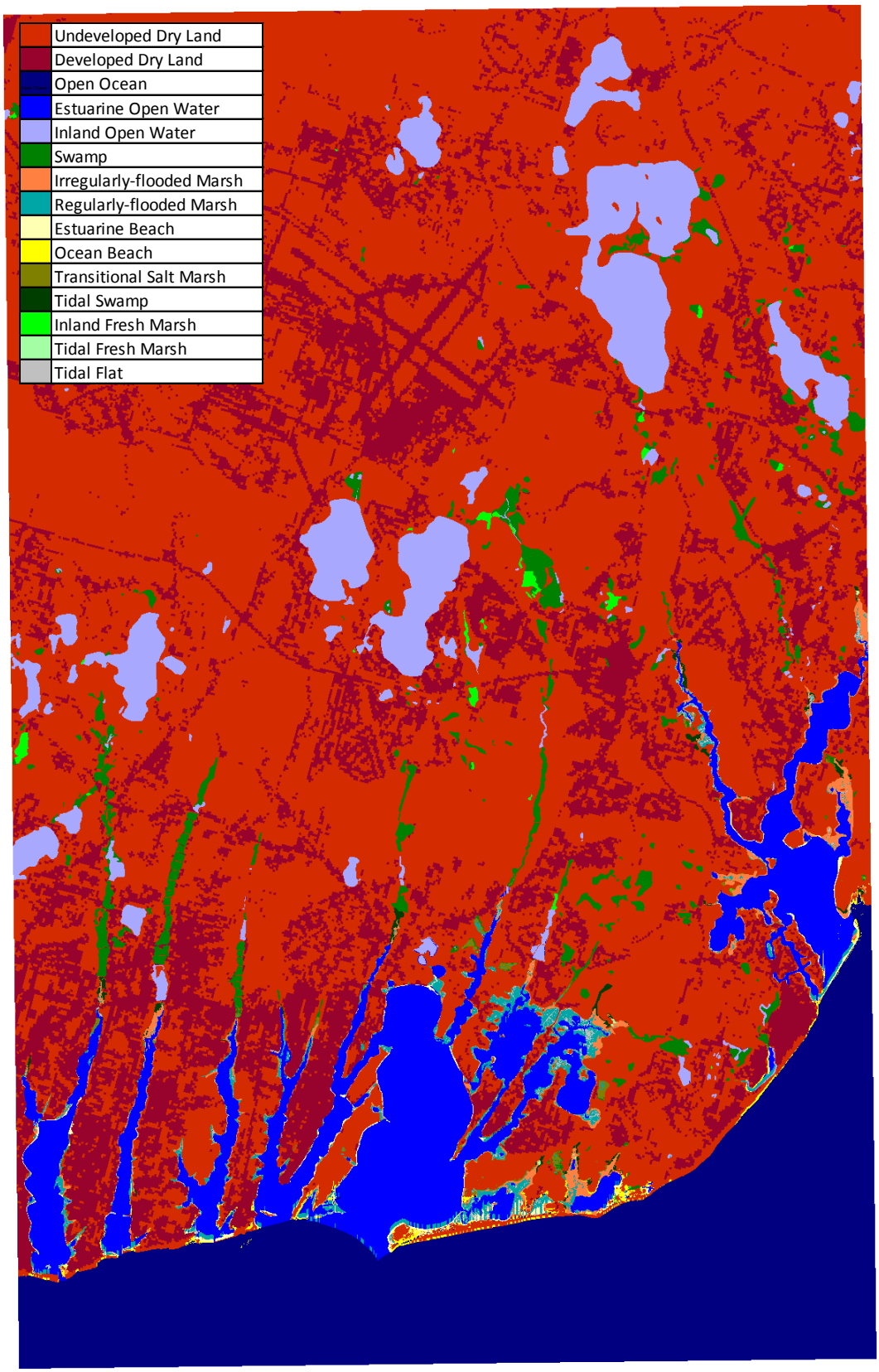
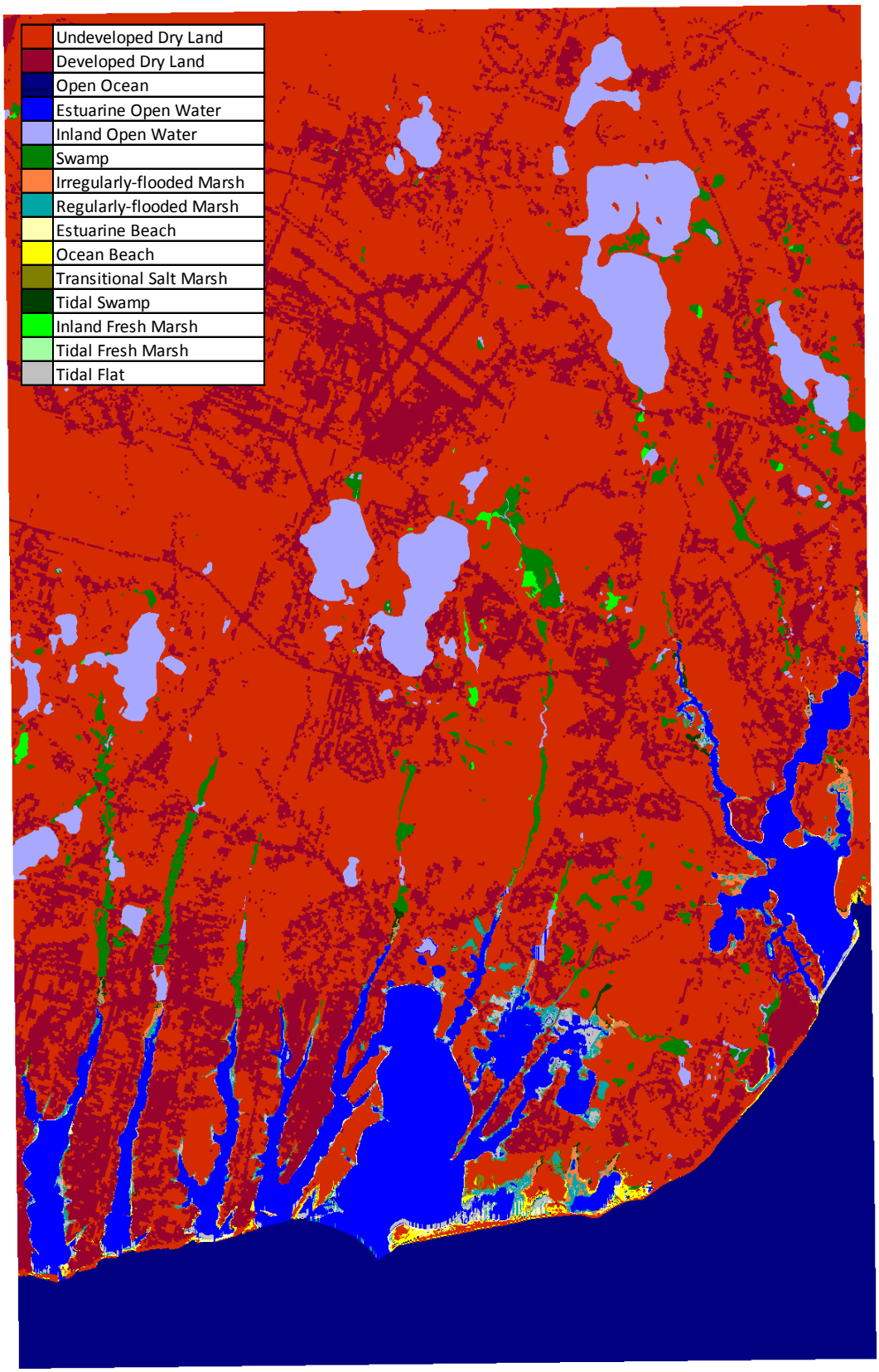


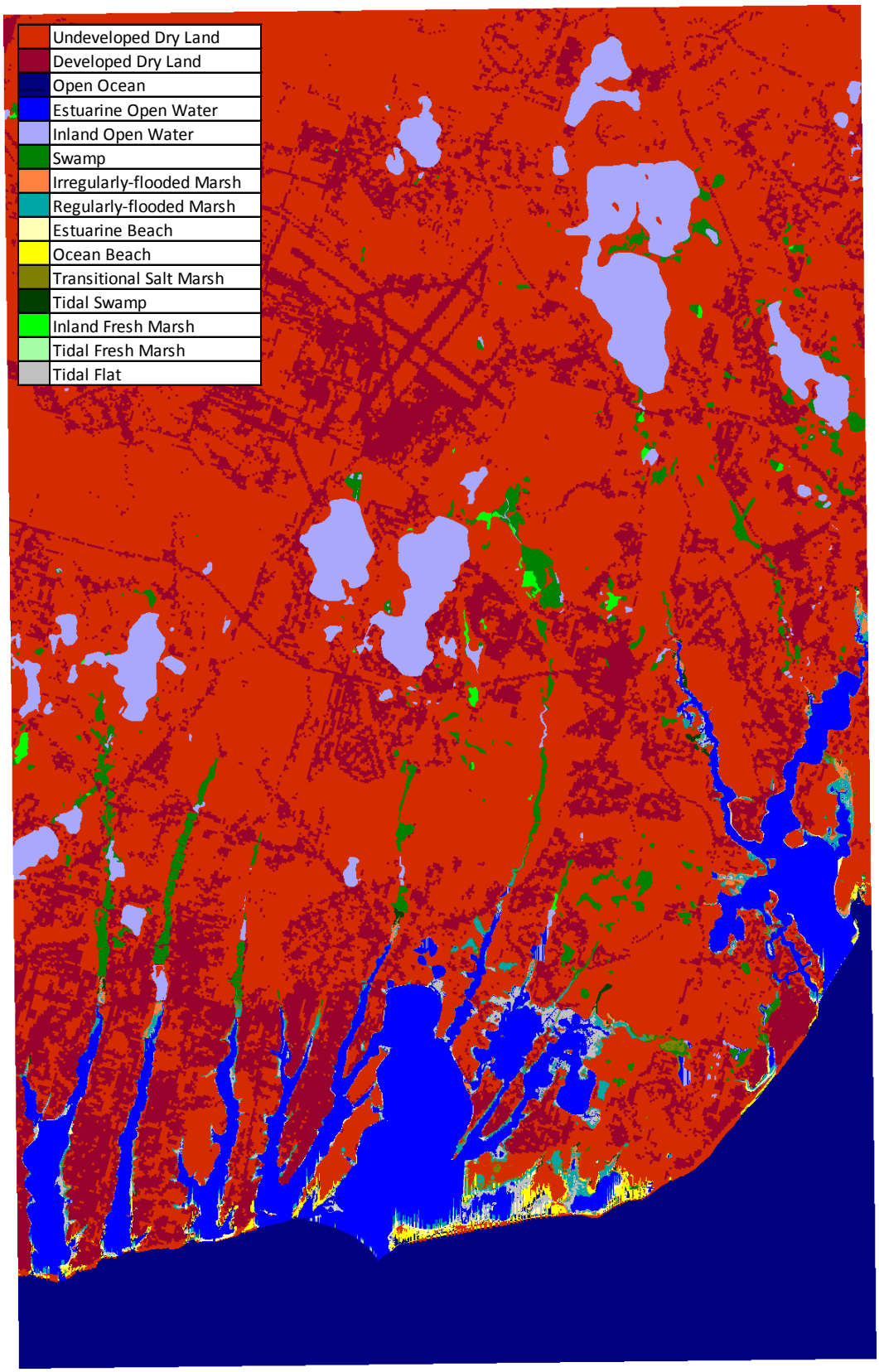
Mashpee NWR, 2025, Scenario A1B Maximum, 0.69 m SLR by 2100.



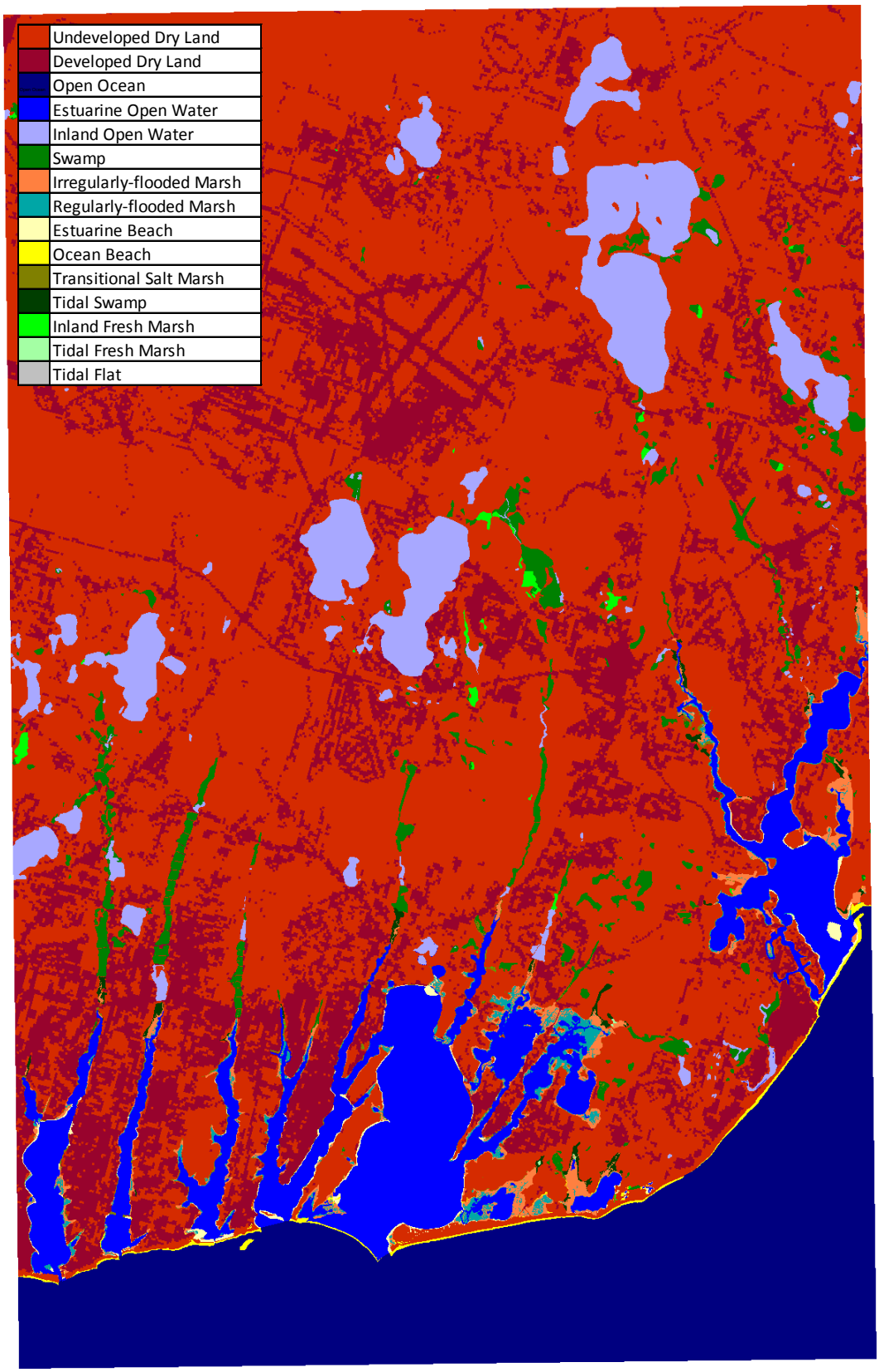
Mashpee NWR, 2050, Scenario A1B Maximum, 0.69 m SLR by 2100.



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



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



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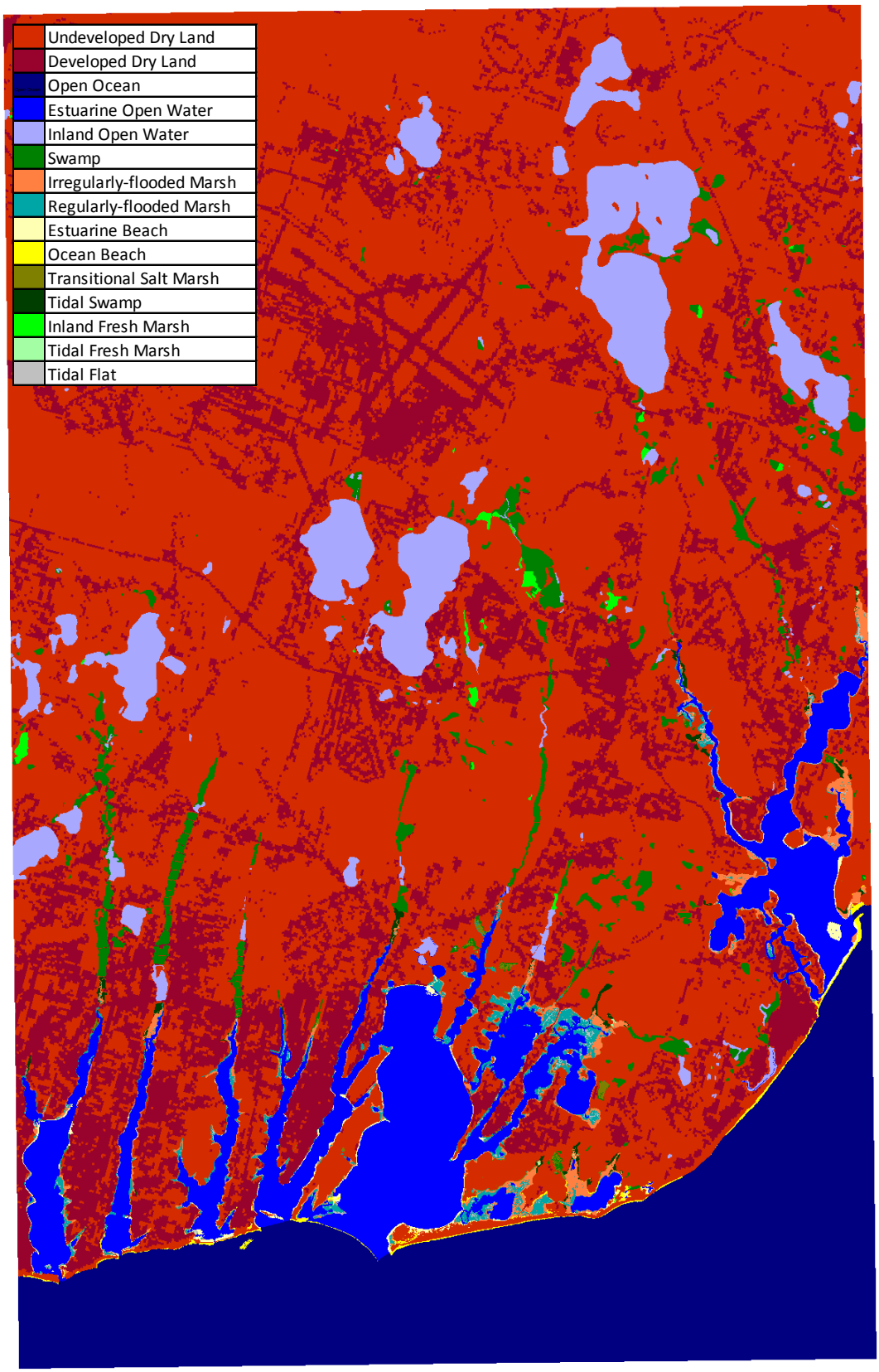

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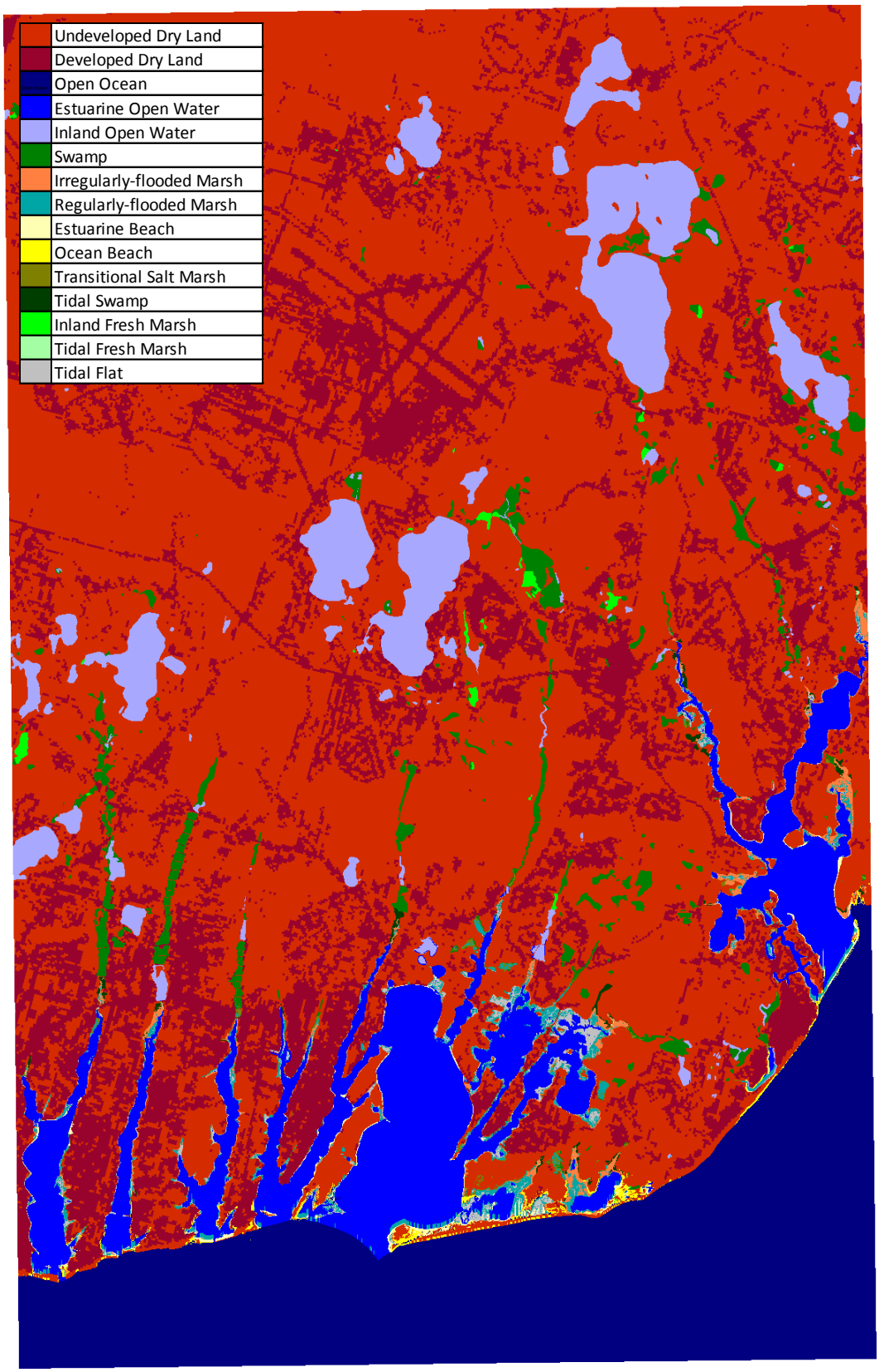

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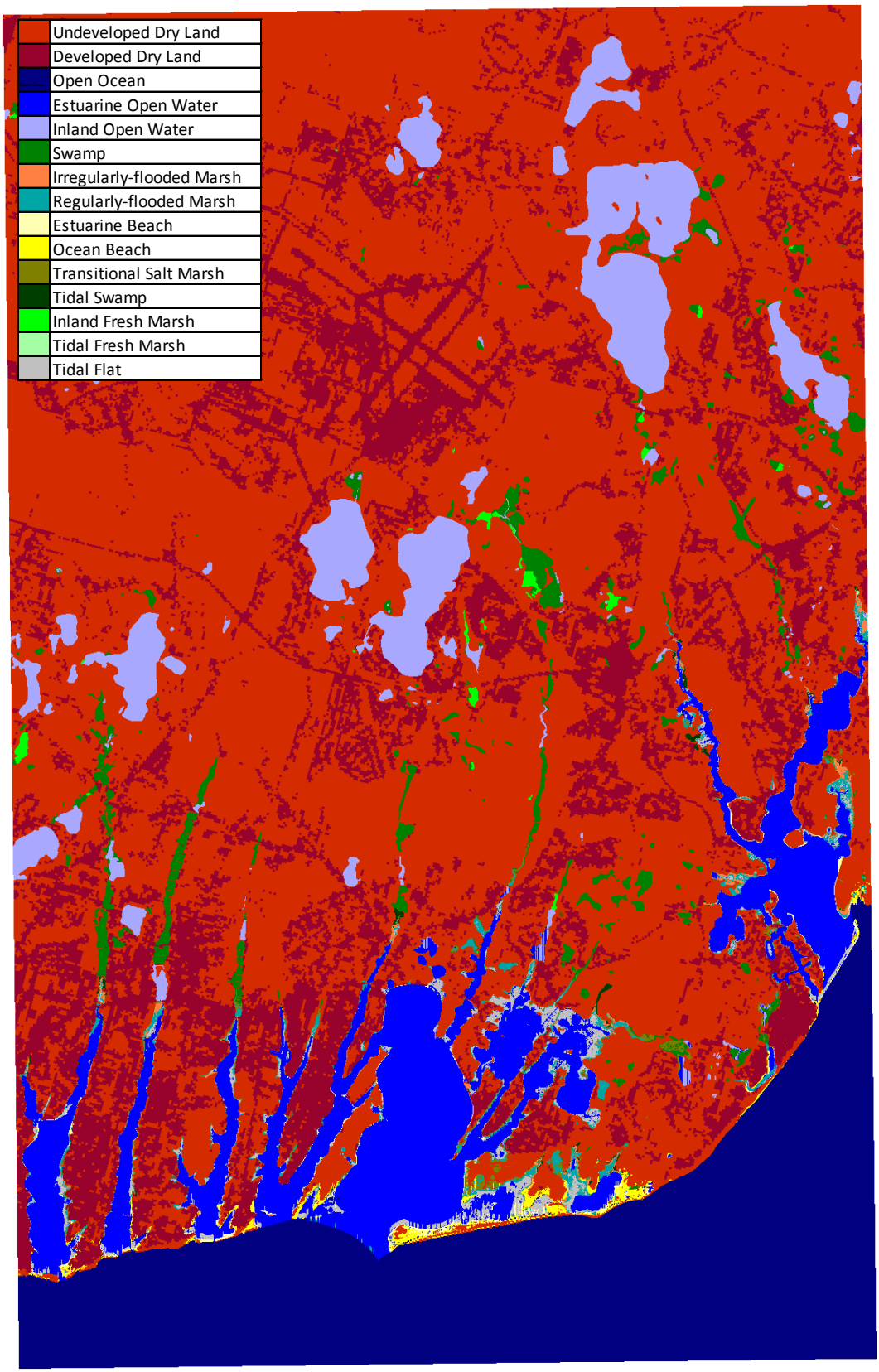

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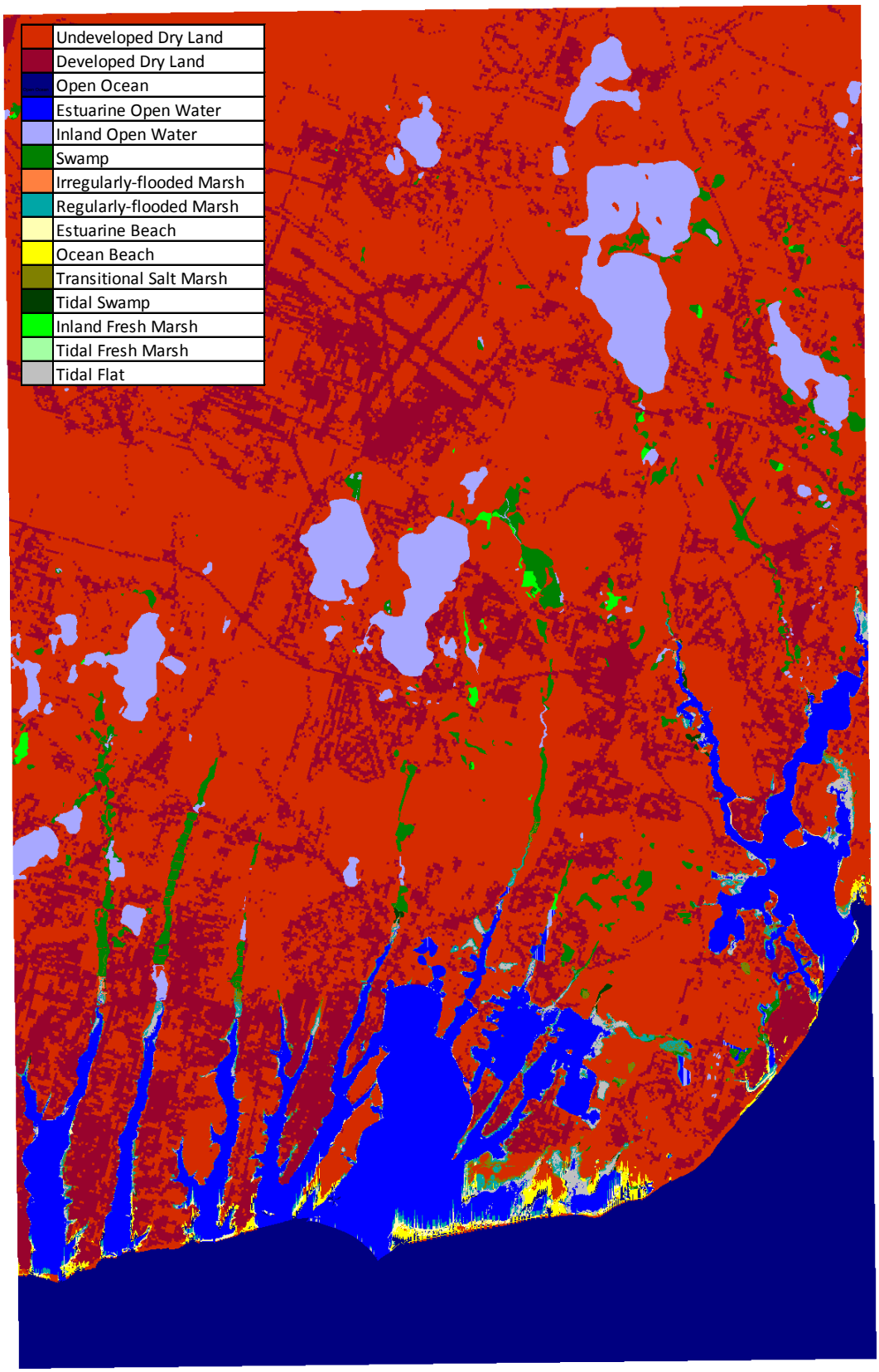

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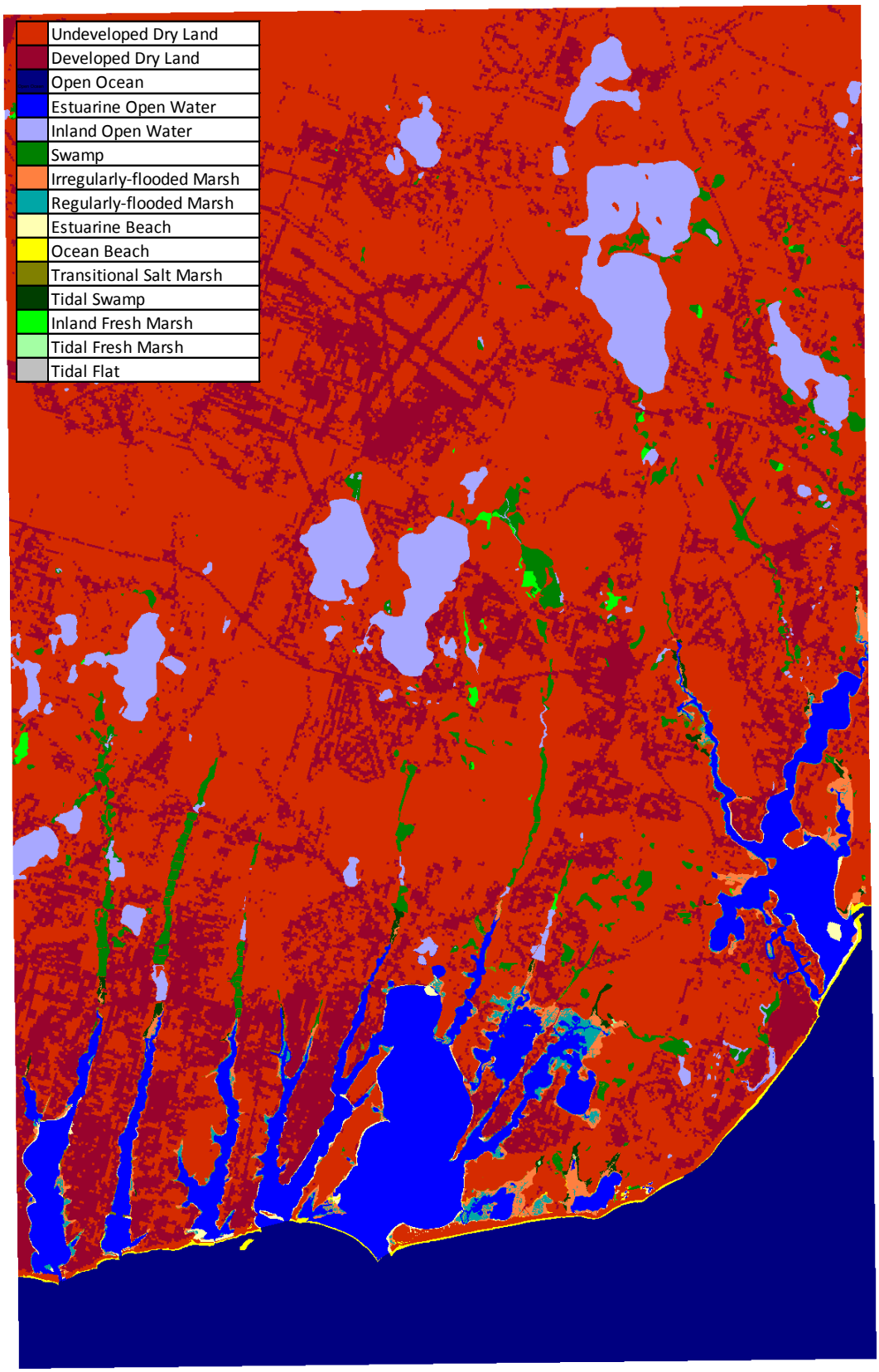

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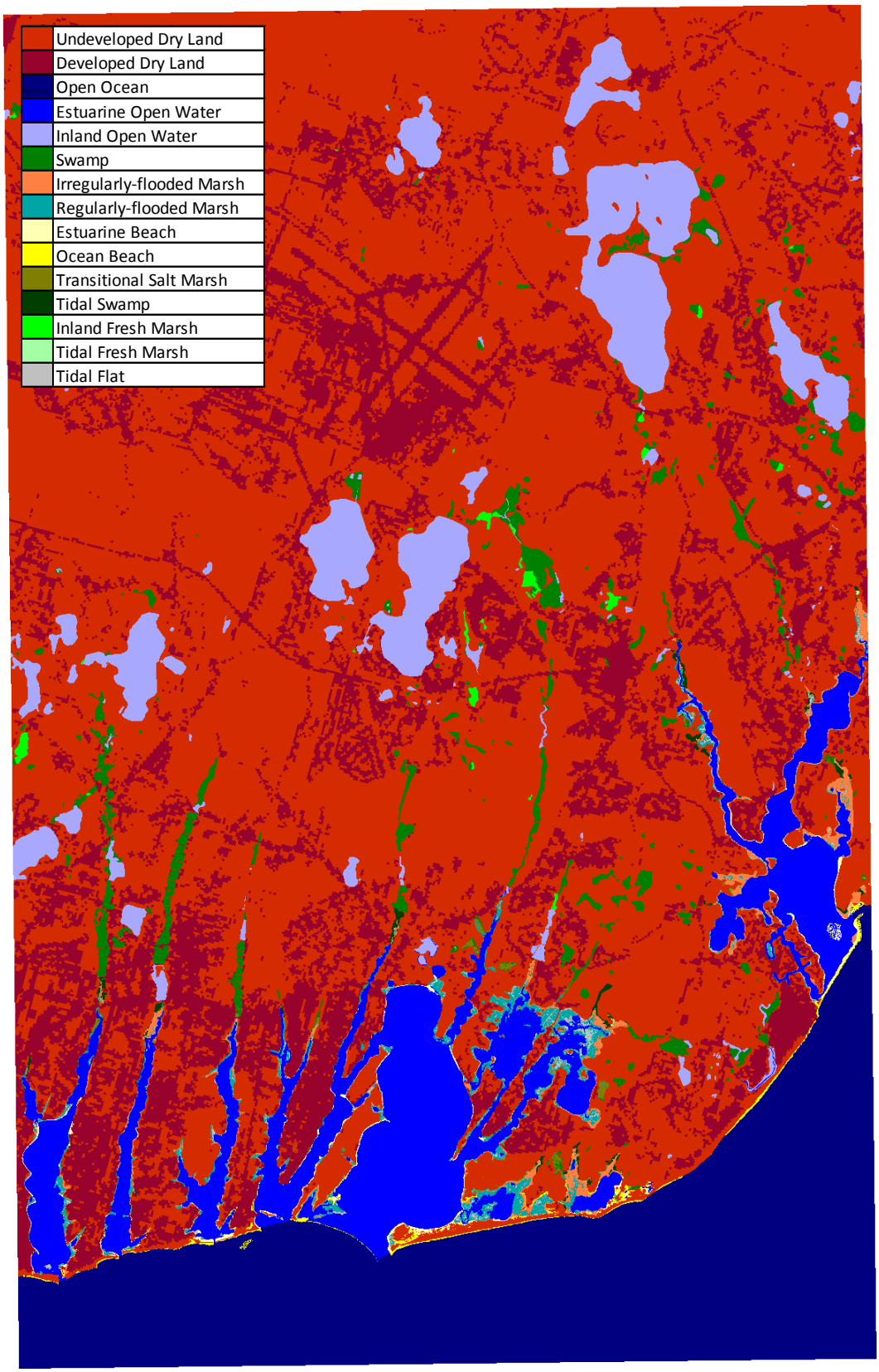

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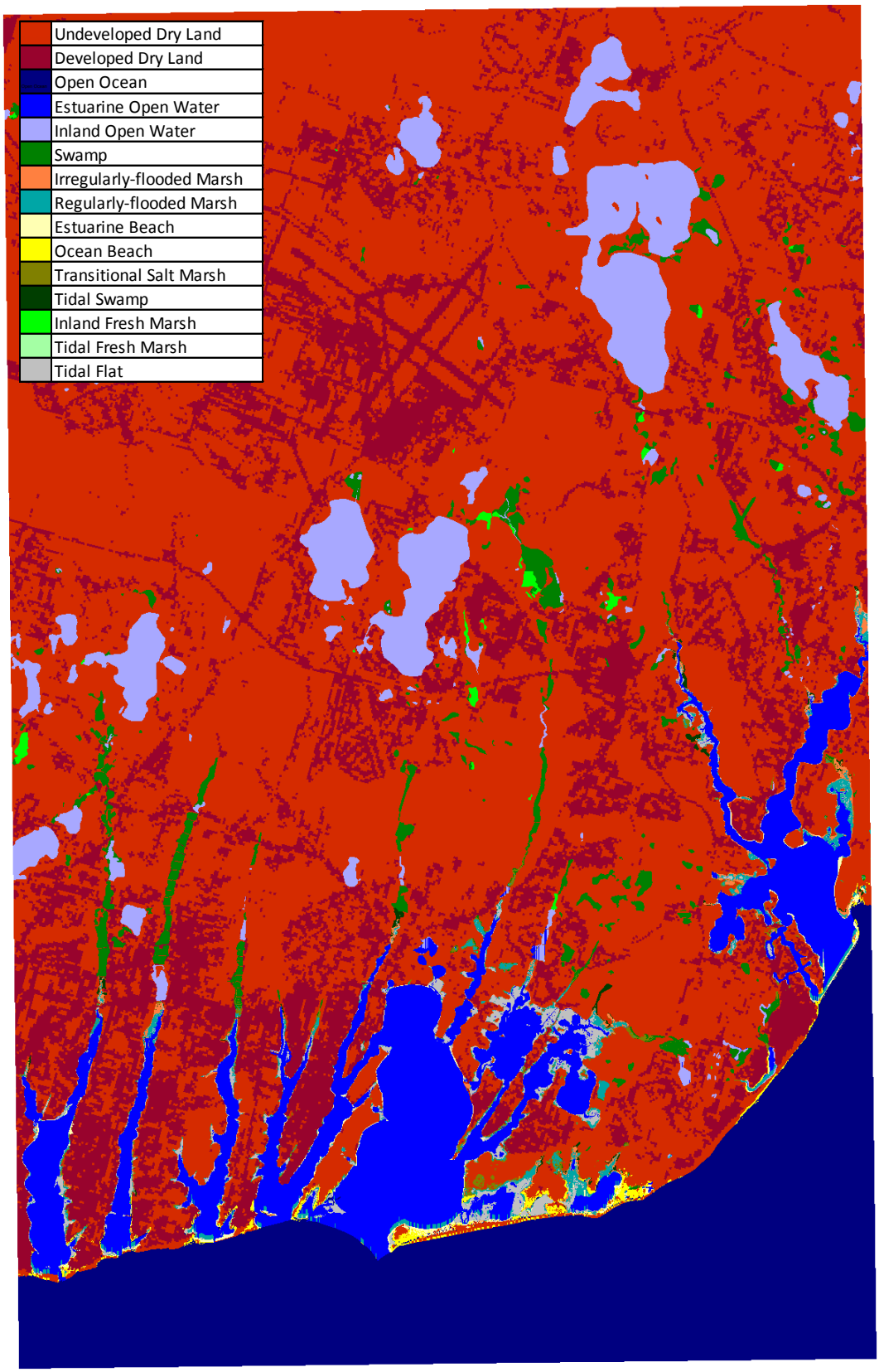

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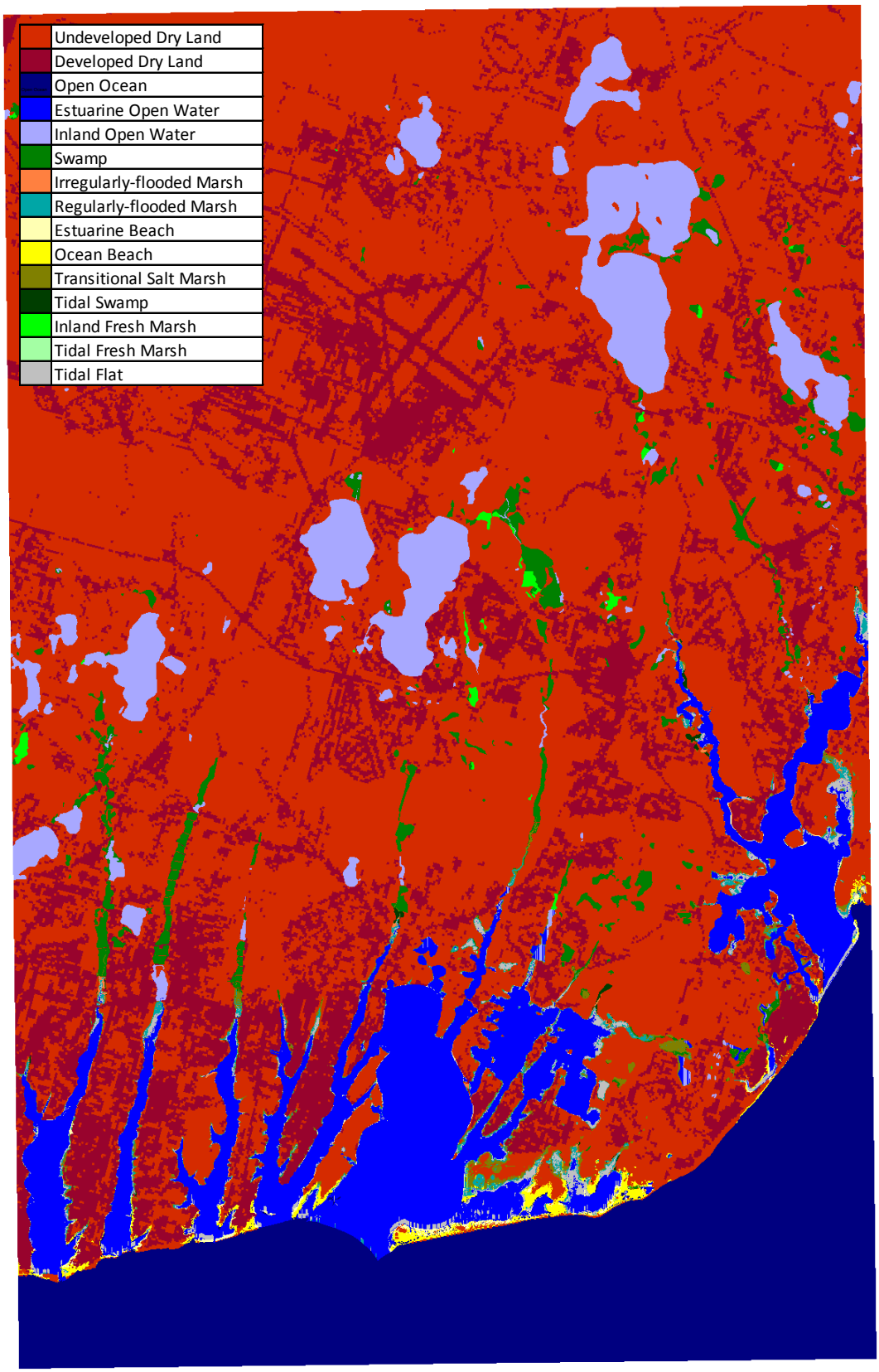

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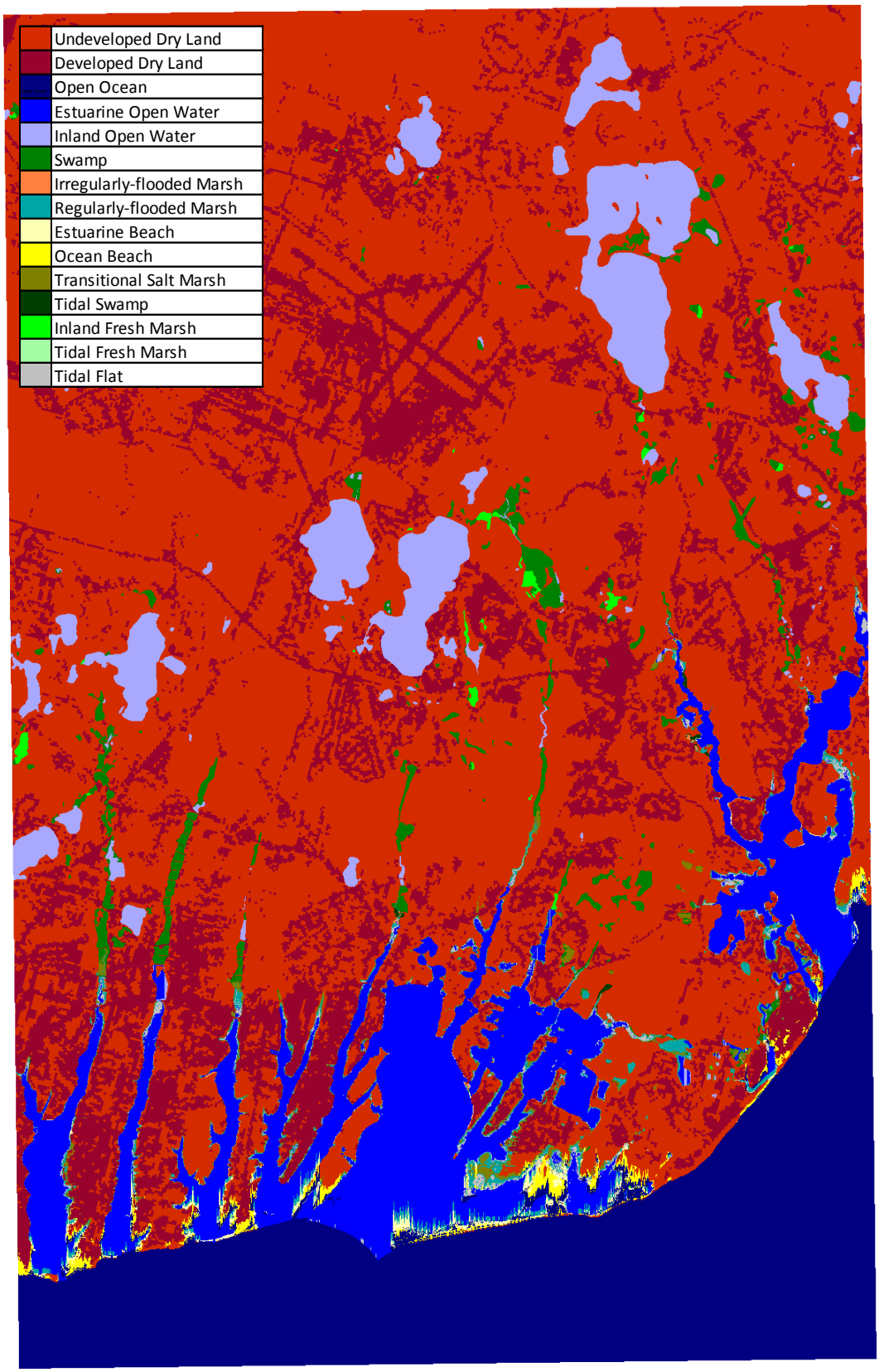
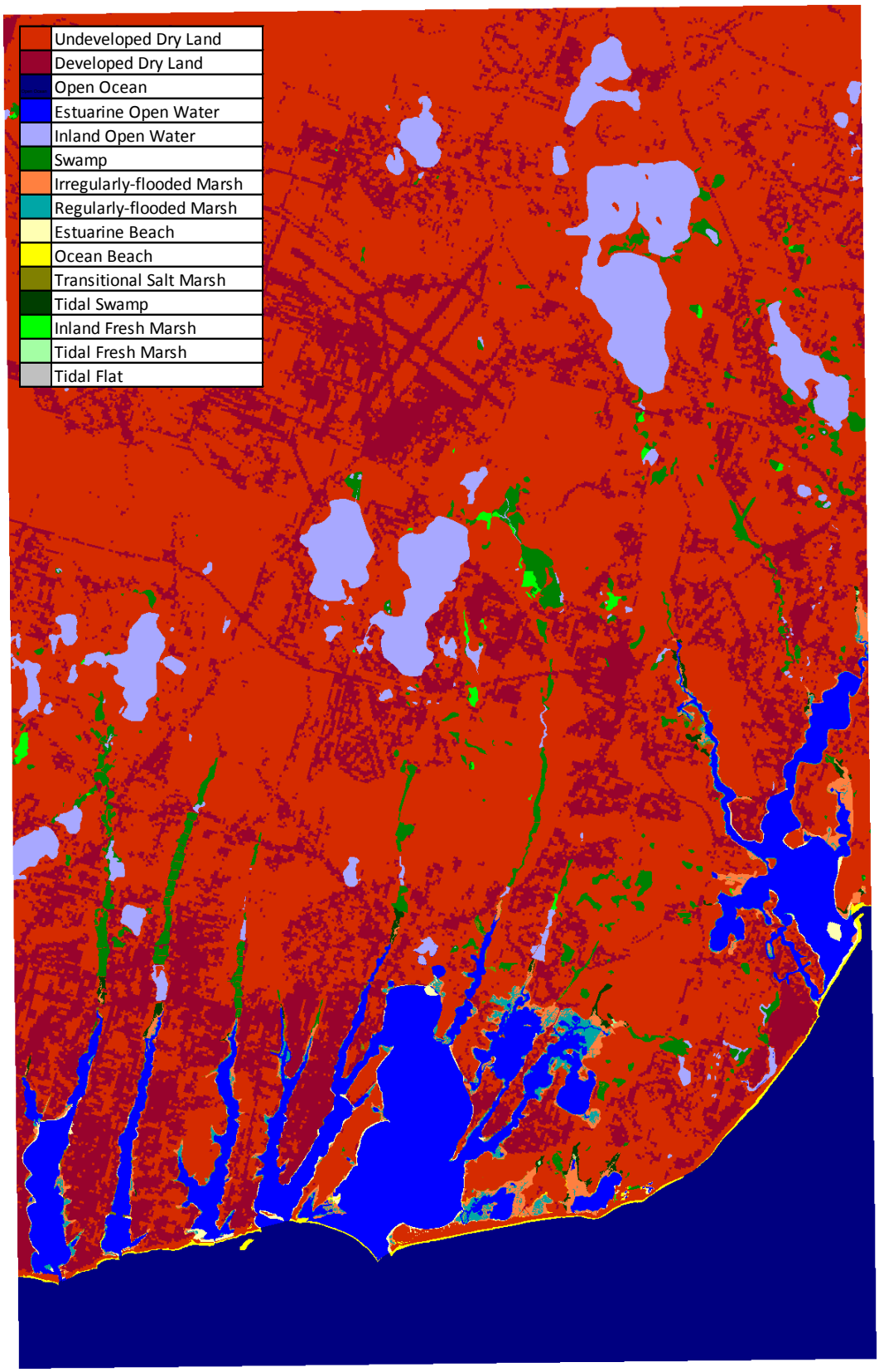
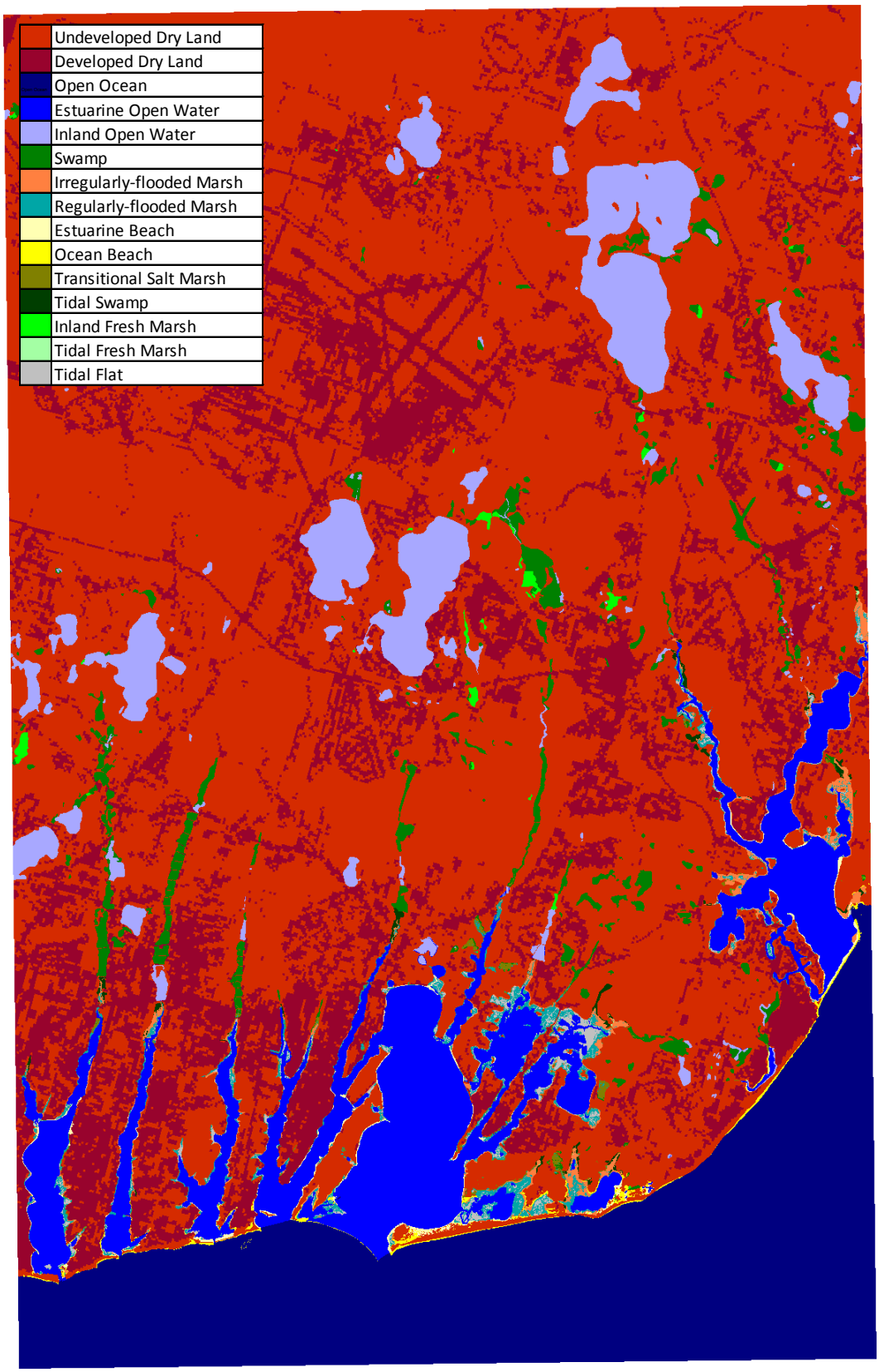


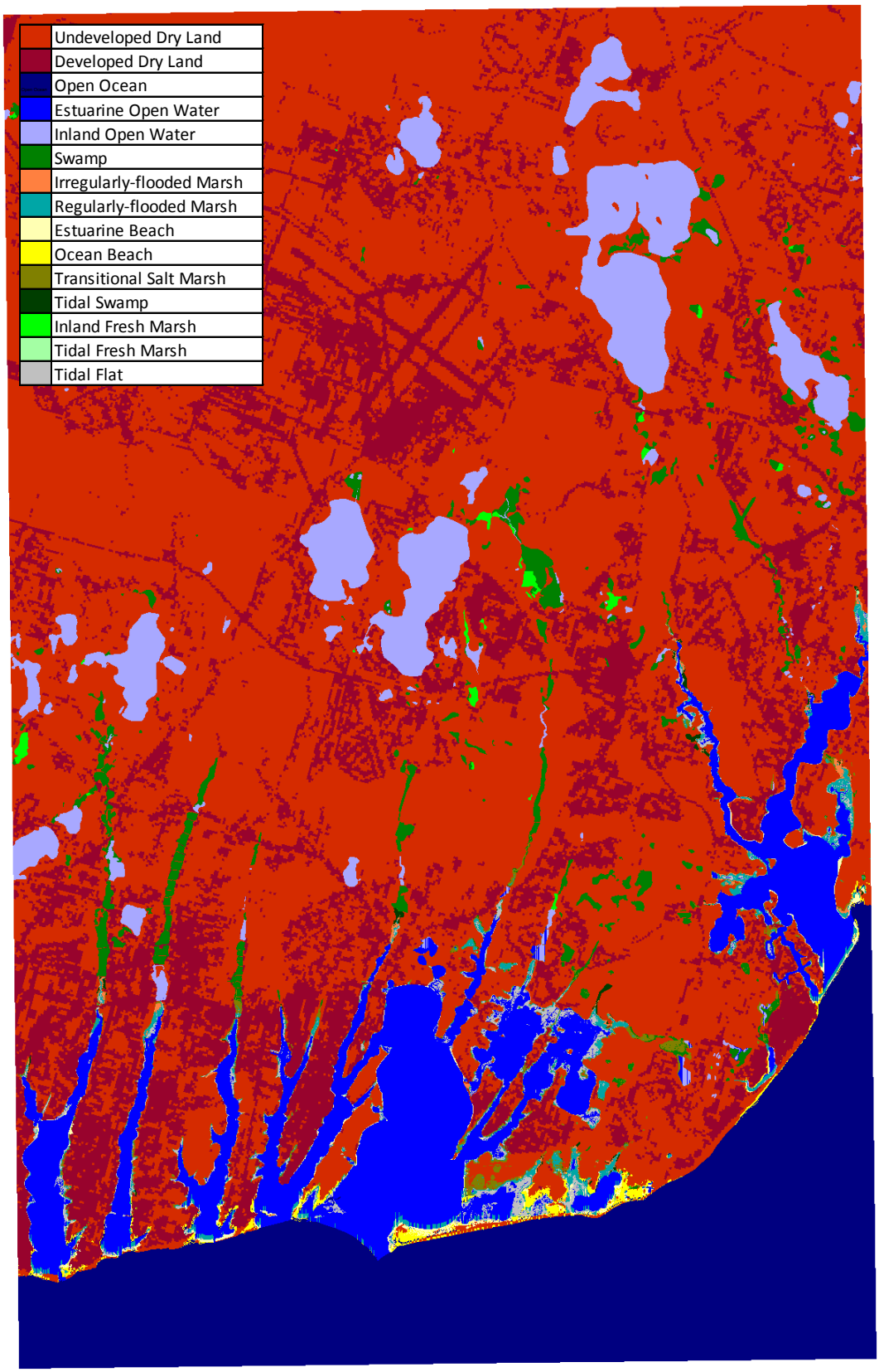
Mashpee NWR, 2100, 1.5 m SLR by 2100.



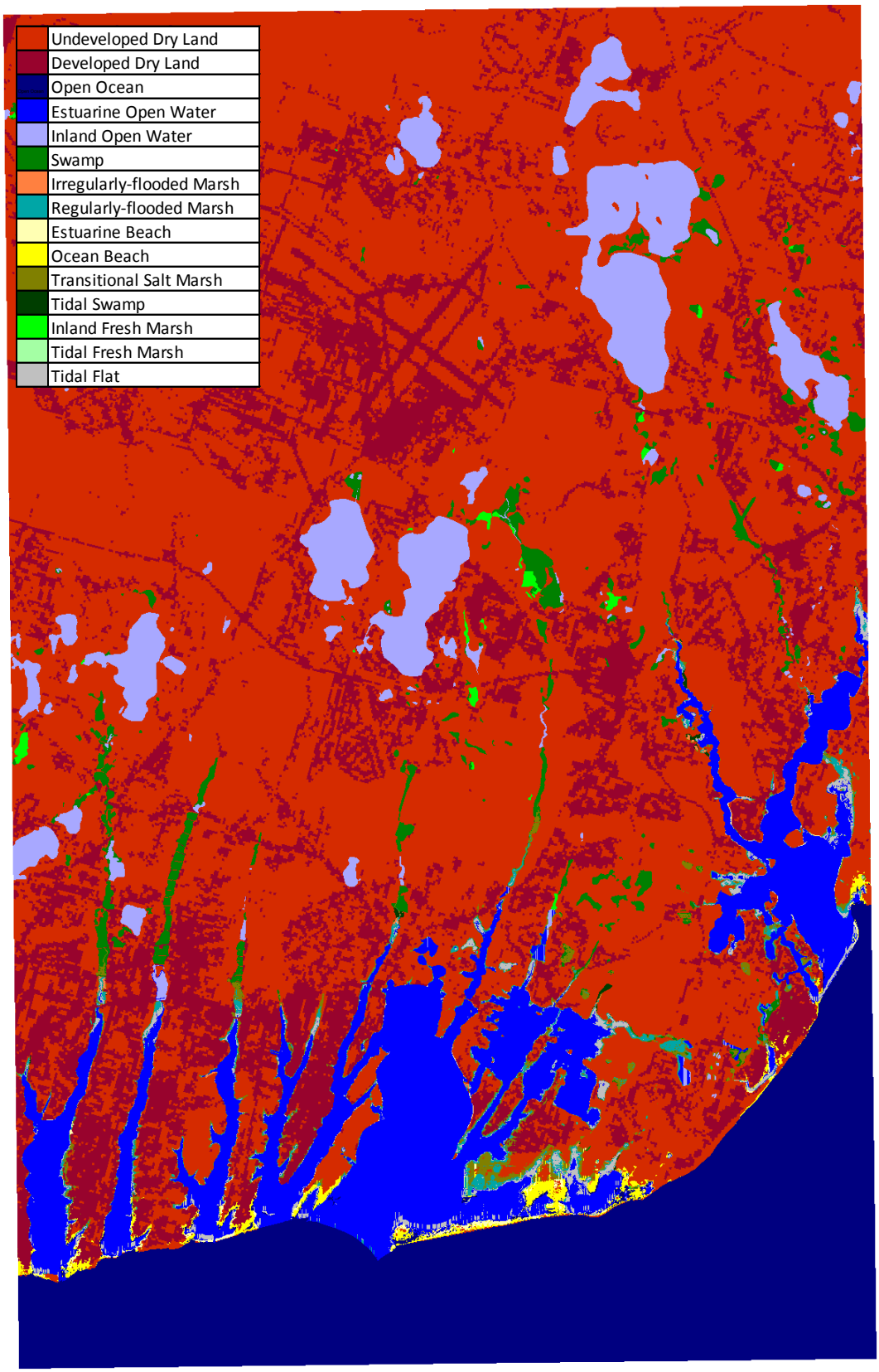
Mashpee NWR, SLAMM 1999.



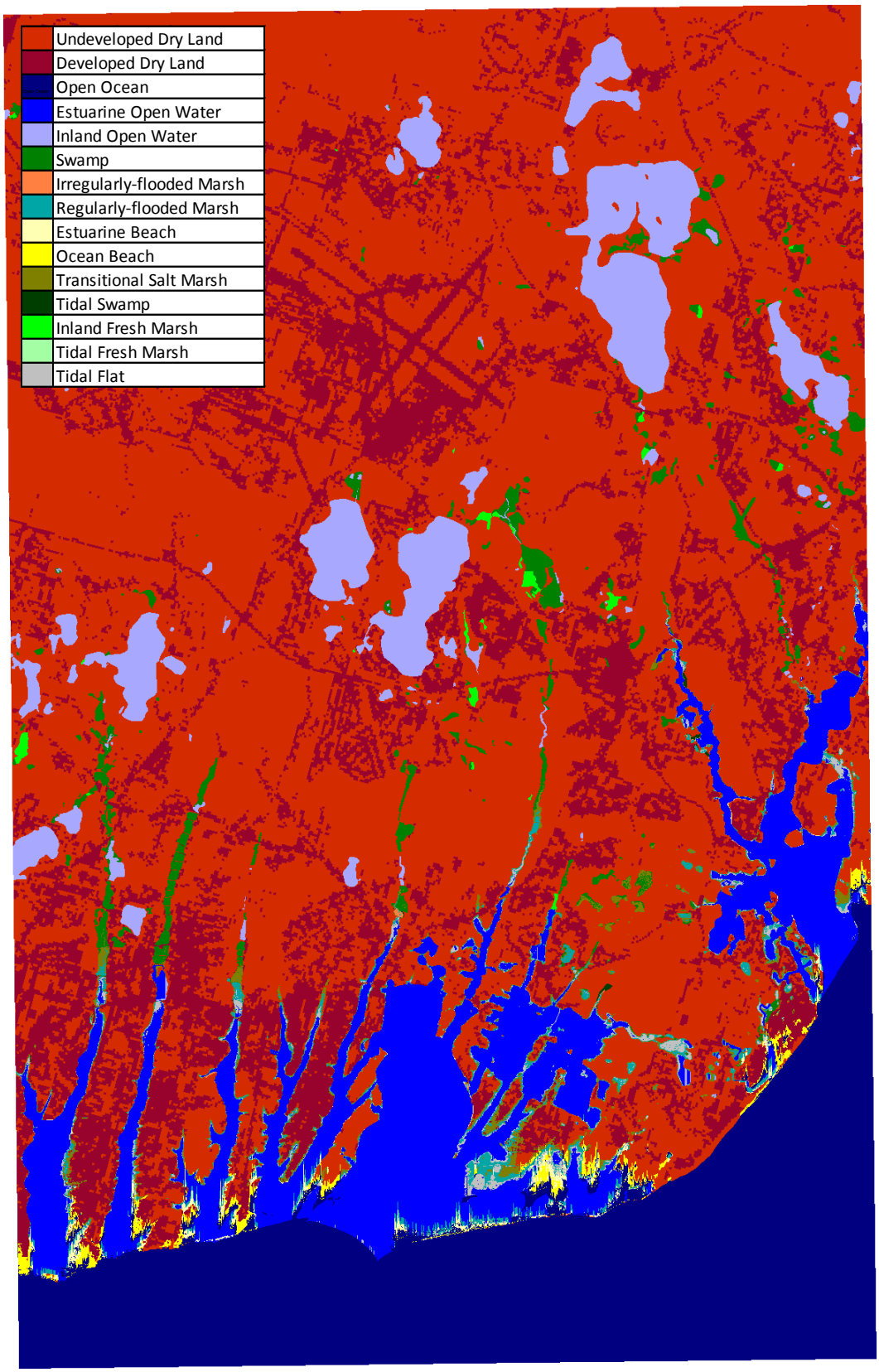
Mashpee NWR, 2025, 2 m SLR by 2100.



Mashpee NWR, 2050, 2 m SLR by 2100.



Mashpee NWR, 2075, 2 m SLR by 2100.



Mashpee NWR, 2100, 2 m SLR by 2100.