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

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September 20, 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 (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 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 meters 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 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 meters of sea level rise 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 meters of global sea level rise by 2100. A1B-maximum predicts 0.69 meters of global SLR by 2100.

The latest literature (Chen et al. 2006; Monaghan et al. 2006) indicates that the eustatic rise in sea levels 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 meters 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 sea level rises 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 meter, 1½ meters, and 2 meters of eustatic sea-level rise by the year 2100. The A1B- maximum scenario was scaled up to produce these bounding scenarios (Figure 1).

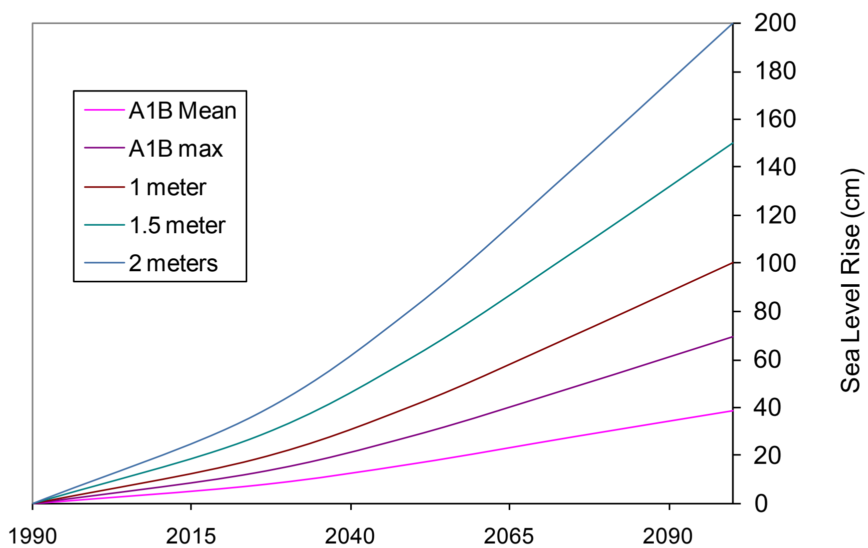


Figure 1: Summary of SLR scenarios utilized

Methods and Data Sources

Two sets of LiDAR data were used:

- 2002 NASA/USGS Airborne LiDAR collected as part of the Assessment of Coastal Erosion (ALACE) Project for California, Oregon, and Washington Coastlines.
- 2002 LiDAR data collected by the US Army Corps of Engineers - Coastal Hydraulics Laboratory.

Where LiDAR data was not available, elevation from the 1972 1/3-Arc Second National Elevation Dataset (10 meter resolution contour data) were used. As shown in Figure 2, only a few areas of the refuge were not covered by LiDAR data. In areas lacking LiDAR data the elevation pre-processor module of SLAMM was used to assign elevations for wetlands as a function of the local tide range. For a more in-depth description of the elevation preprocessor, see the SLAMM 6 technical documentation (Clough et al. 2010). This process causes additional uncertainty in model results as covered in the *Discussion* section below.

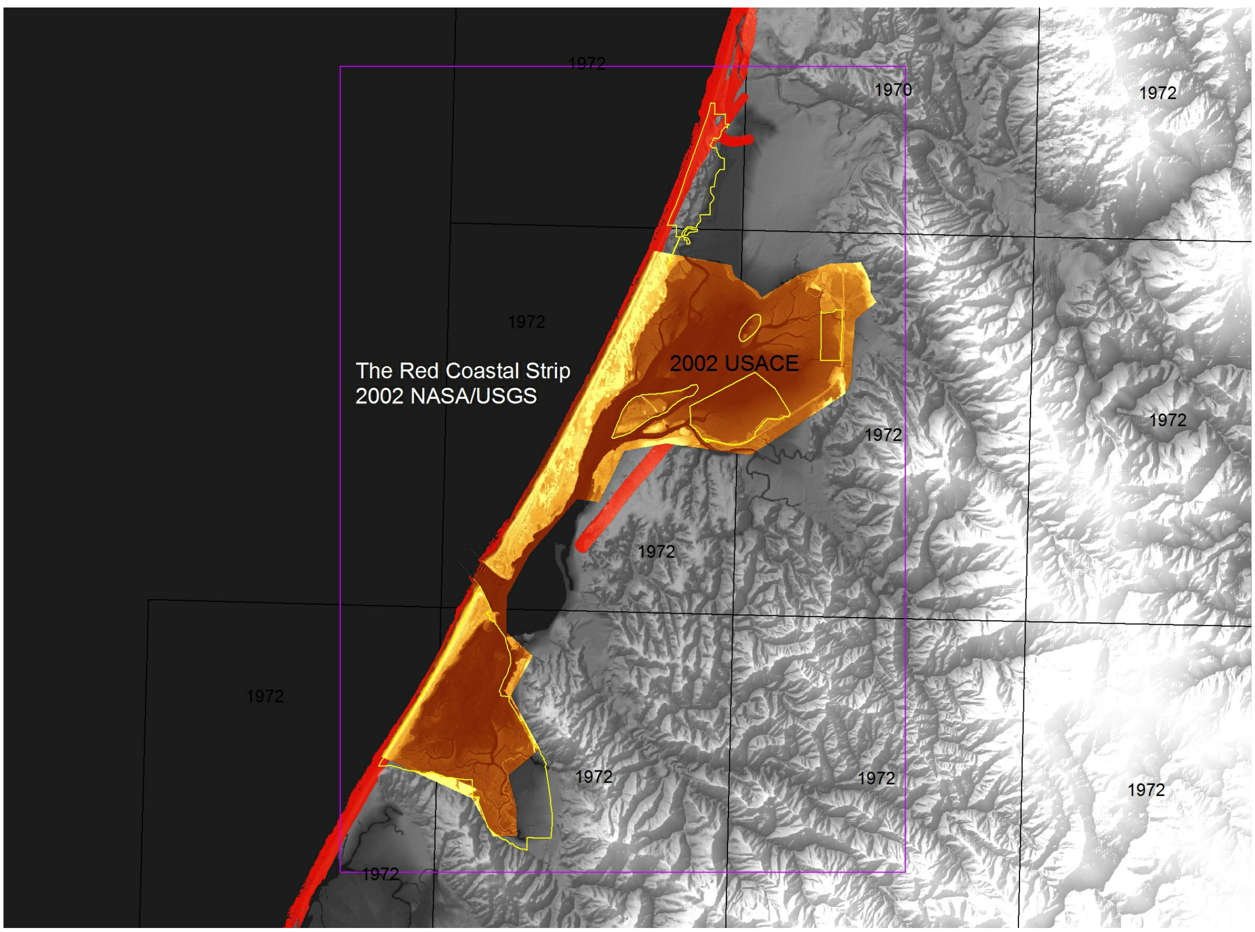


Figure 2. Elevation data used for SLAMM analysis of Humboldt Bay NWR. Refuge boundaries are shown by yellow lines

The National Wetlands Inventory for the study area was updated based on 2009 photography. Some areas, primarily outside of the refuge, were based on 1983 data. Converting the NWI survey into 10 meter cells indicated that the approximately 9,880 acres of the refuge included in this study (approved acquisition boundary including water) are composed of the following categories:

Table 1. Wetland coverage in Humboldt Bay NWR according to the 1983/2009 NWI layer

Land cover type		Area (acres)	Percentage (%)
	Tidal Flat	3,116	32
	Estuarine Open Water	3,052	31
	Undeveloped Dry Land	1,387	14
	Inland Fresh Marsh	1,148	12
	Regularly Flooded Marsh	493	5
	Swamp	213	2
	Irregularly Flooded Marsh	158	2
	Developed Dry Land	95	1
	Ocean Beach	65	1
	Estuarine Beach	50	1
	Inland Open Water	38	< 1
	Tidal Creek	28	< 1
	Inland Shore	28	< 1
	Transitional Salt Marsh	8	< 1
	Total (incl. water)	**9,879**	**100**

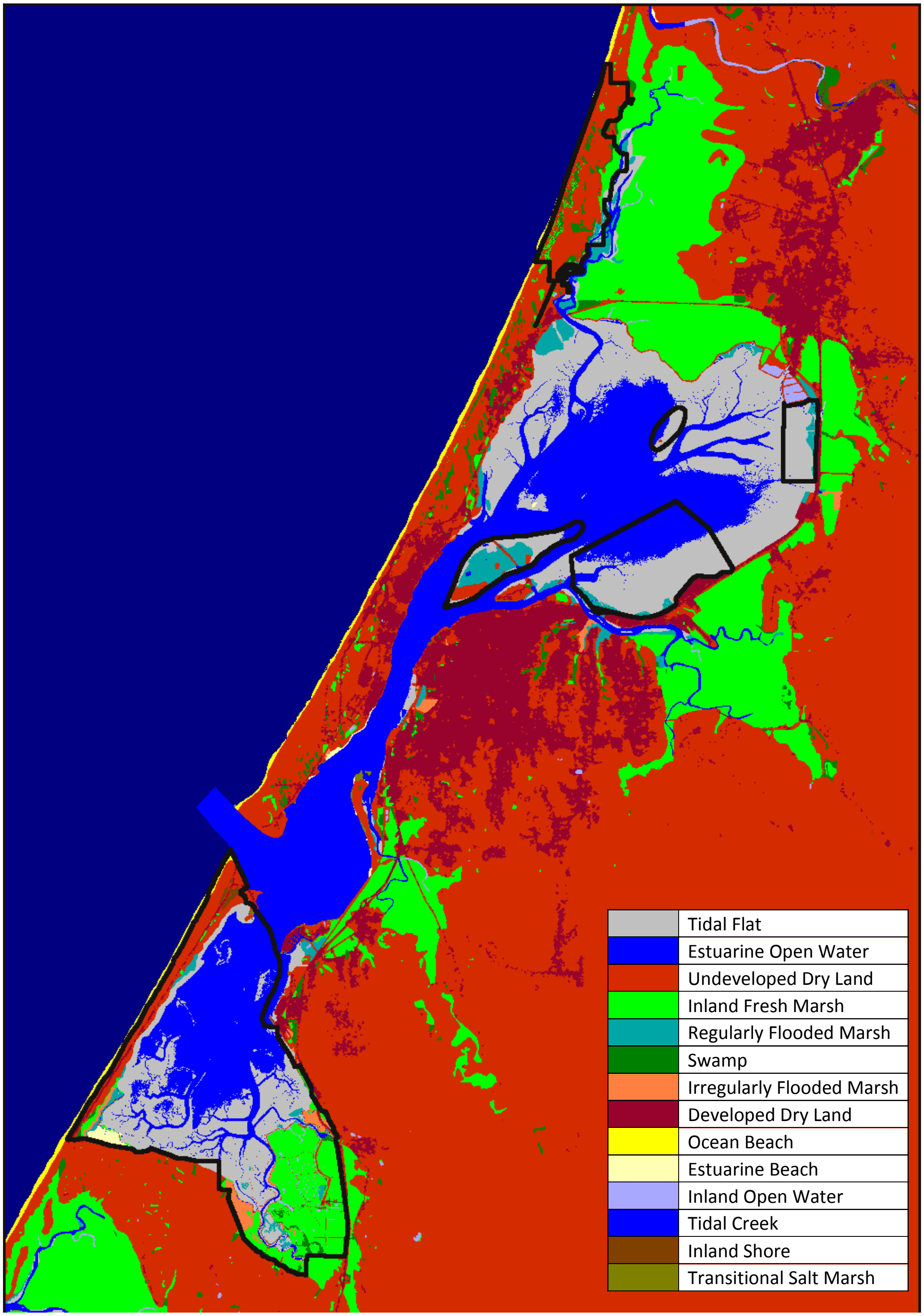


Figure 3. NWI Wetland Layer used for Humboldt Bay NWR, with refuge boundary shown in black.

According to the National Wetland Inventory, there are diked areas within the Humboldt Bay NWR study area. Based on several discussions with refuge staff, it was understood that there are dikes and tide gates in the southeastern portion of the refuge (Hookton Slough). Staff communication suggested that these dikes were failing and that tide-gates in the region were leaking. This complicates the hydrodynamic setup in the southernmost portion of the refuge. SLAMM either assumes that regions are fully diked (and that the dikes will be maintained until land elevations are 2 meters below mean tide level), or it assumes that dikes are not present. Therefore this simulation was run twice, once including the diked areas and a second time with the dikes removed to predict the effect of these dikes being removed. See *Results* section for more details. The location of diked lands is shown in Figure 4.

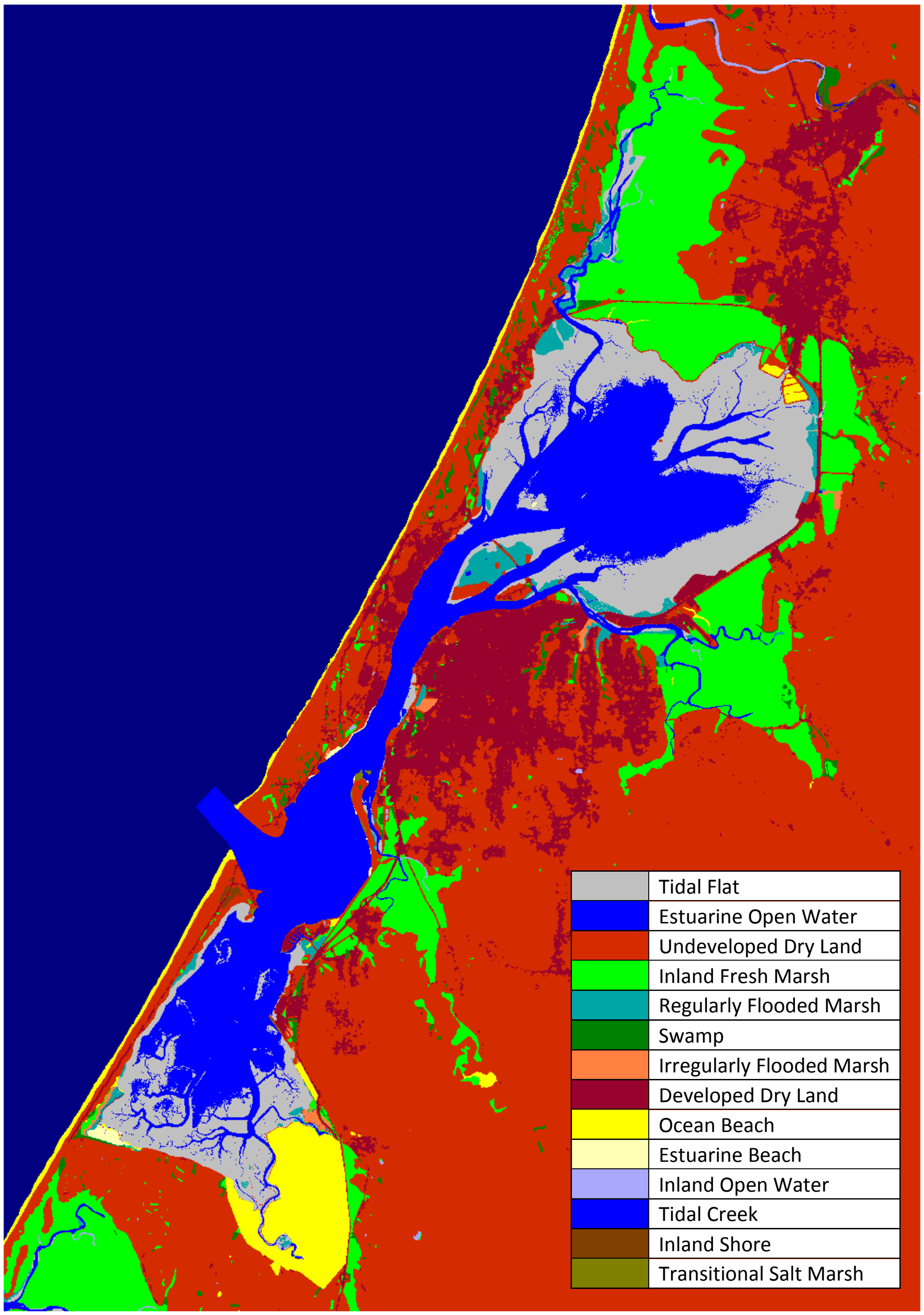


Figure 4. Location of dikes (yellow) in Humboldt Bay NWR study area

Several NOAA tidal gauge stations are located in Humboldt Bay, as presented in Figure 5 and Table 2.

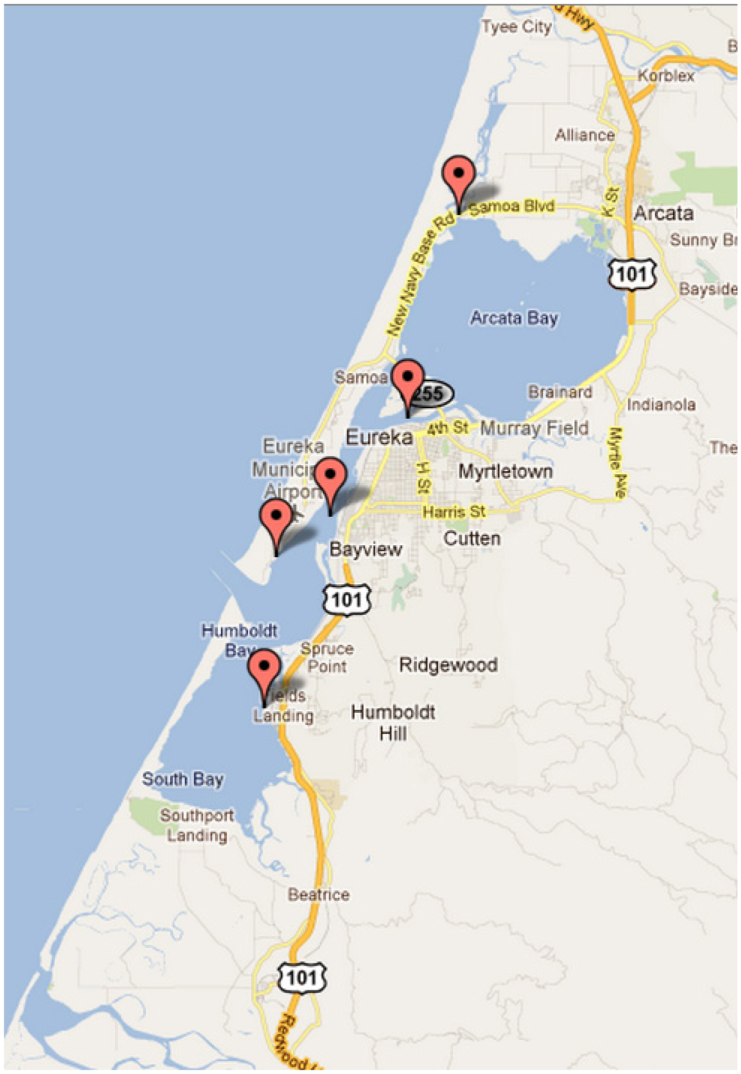


Figure 5. Location of NOAA tide stations in the study area

Table 2. Tide ranges applied to Humboldt Bay subsites

NOAA Gauge #	Location	GT (m)	Subsite Where Applied
9418865	Mad River Slough, Arcata Bay	2.33	1
9418801	Eureka	2.17	1 & 3
9418778	Bucksport, Humboldt Bay	2.13	3
9418767	North Spit, Humboldt Bay	2.09	3
9418723	Fields Landing, Humboldt Bay	2.06	2

The historic trend for sea level rise in the Humboldt Bay area was estimated to be 4.73 mm/year, which was measured at North Spit, CA NOAA gauge #9418767. This rate is more than twice the global average for the last 100 years (approximately 1.5-2.0 mm/year). Within SLAMM relative sea level change is estimated as the sum of the historic eustatic trend, the site-specific rate of change of elevation due to subsidence or other factors, and the accelerated rise depending on the scenario chosen (IPCC 2001; Titus et al. 1991).

Three values of great diurnal tide range (GT) were determined from the data in Table 2 and applied to Humboldt Bay NWR. The northern portion of the refuge, including Arcata Bay (subsite 1 shown in Figure 6) was assigned a GT of 2.25 m. South Bay (subsite 2) was assigned a GT of 2.06 m, and the remaining study area (subsite 3) was assigned a GT of 2.13 reflecting the average of the stations in the center of the study area shown in Figure 6.

The "salt elevation" parameter within SLAMM designates the boundary between coastal wetlands and dry lands or fresh water wetlands. An estimate of this elevation may be derived by examining historical tide gauge data to determine how frequently different elevations are flooded with ocean water. For this application, the salt boundary was defined as 1.5 Half-Tide Units (HTU), leading to the salt elevations for each subsite shown in Table 3.

Table 3. Salt elevations applied

Subsite	GT (m)	Salt Elevation (m)
1	2.25	1.7
2	2.13	1.6
3	2.06	1.6

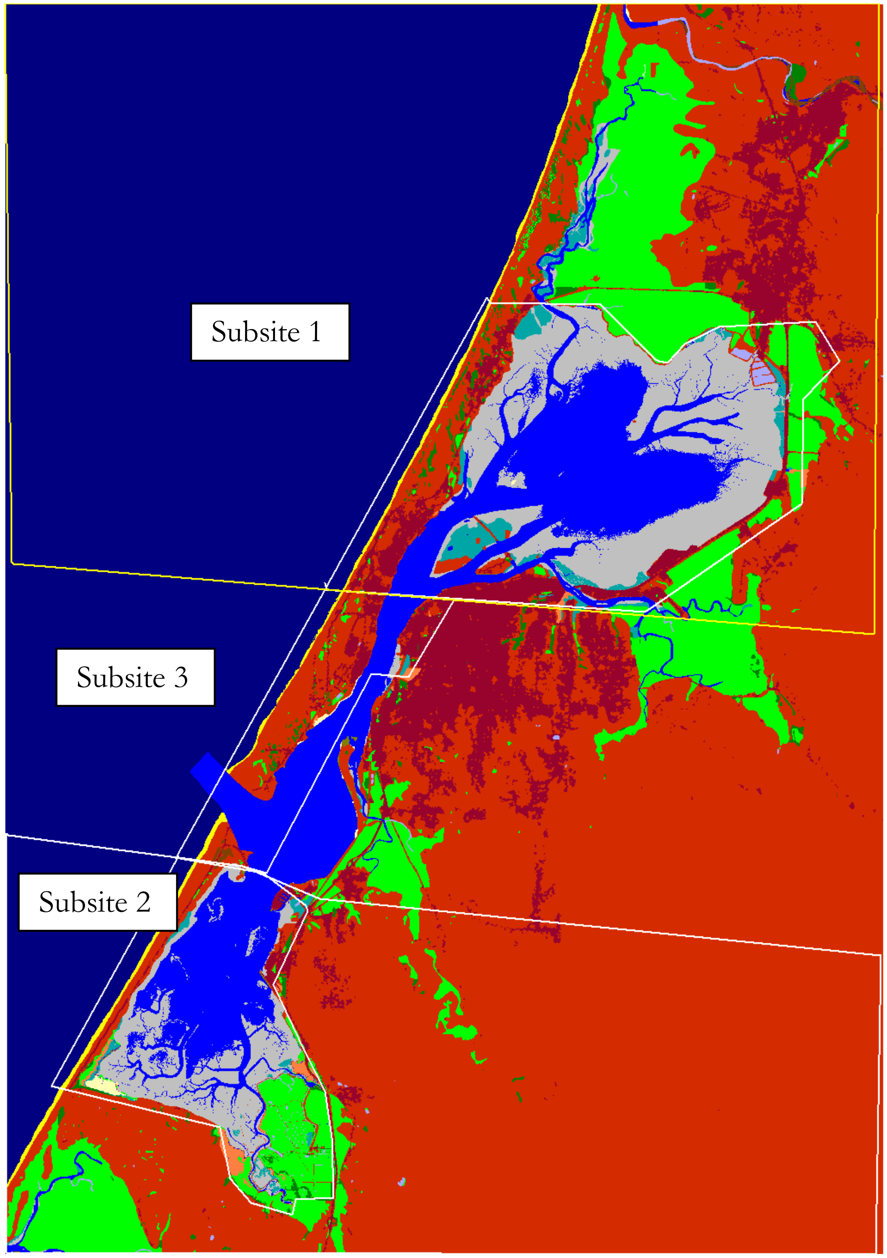


Figure 6. Subsites within the Humboldt Bay NWR study area

Because no site-specific data were available, accretion rates applied were derived from rates measured in South San Francisco Bay (Patrick and DeLaune 1990). An average accretion rate of 6.5 mm/year was determined using the average accretion measurements from Bird Island (5 mm/yr) and Baumberg (8 mm/yr) in the study of Patrick and DeLaune (1990).

The MTL to NAVD88 correction was assigned for each subsite based on information from NOAA tide gauges. For subsite 1 the correction value of 0.953 m was applied based on the datum from the NOAA gauge 9418865 at Mad River Slough, Arcata Bay. The correction value applied to subsite 2 was 0.941 m derived from NOAA gauge 941872, Fields Landing. For subsite 3 a correction of 1.025 m was applied based on data from NOAA gauge 9418767, North Spit.

The cell-size used for this analysis was 10 meter by 10 meter cells. Note that SLAMM will also track partial conversion of cells based on elevation and slope.

Table 4 presents all the input parameters applied to the subsites shown in Figure 6. Additional subsites were identified based on the different dates of LiDAR and NWI updates. However, physical parameters were assigned according to Table 4.

Table 4. Summary of SLAMM parameters applied to Humboldt Bay NWR

Description	SubSite 1	SubSite 2	SubSite 3
NWI Photo Date	2009, 1983	2009, 1983	2009, 1983
Direction Offshore [n,s,e,w]	West	West	West
Historic Trend (mm/yr)	4.73	4.73	4.73
MTL-NAVD88 (m)	0.953	0.941	1.025
GT Great Diurnal Tide Range (m)	2.25	2.06	2.13
Salt Elev. (m above MTL)	1.7	1.6	1.6
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)	6.5	6.5	6.5
Irreg.-Flood Marsh Accr (mm/yr)	6.5	6.5	6.5
Tidal-Fresh Marsh Accr (mm/yr)	6.5	6.5	6.5
Inland-Fresh Marsh Accr (mm/yr)	6.5	6.5	6.5
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)	0	0	0
Use Elev Pre-processor [True,False]	TRUE	TRUE	TRUE

Results

SLAMM simulations predict that Humboldt Bay NWR will be impacted by all SLR scenarios tested. Overall results (including the maintenance of existing dikes) are summarized in Table 5.

Tidal flat comprises the most acreage of any land-cover category within the refuge and SLAMM predicts increasing losses of tidal flat with increasing SLR up to 1.5 m by 2100, culminating in a maximum loss of 92% under this SLR scenario.

Because the primary SLAMM simulation assumed that the Hookton Slough will remain diked, SLR impacts on inland fresh marsh are predicted to be minimal (maximum loss is 22% under 2 m SLR). In these simulations, Hookton Slough was protected from salt water intrusion until 2100 at all but the 1.5 and 2 m SLR scenarios.

Table 5. Predicted Change Rates of Land Categories by 2100 Given Simulated Scenarios of Eustatic Sea Level Rise.

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**
Tidal Flat	33	56	84	92	86
Undeveloped Dry Land	10	15	20	26	31
Inland Fresh Marsh	1	3	5	10	22
Regularly Flooded Marsh	-12([1])	-5	-1	-4	37
Swamp	4	8	14	23	29
Irregularly Flooded Marsh	13	17	21	28	72
Developed Dry Land	26	31	39	52	63
Ocean Beach	-16	-59	-122	-214	-285
Estuarine Beach	-17	-32	-42	9	-7

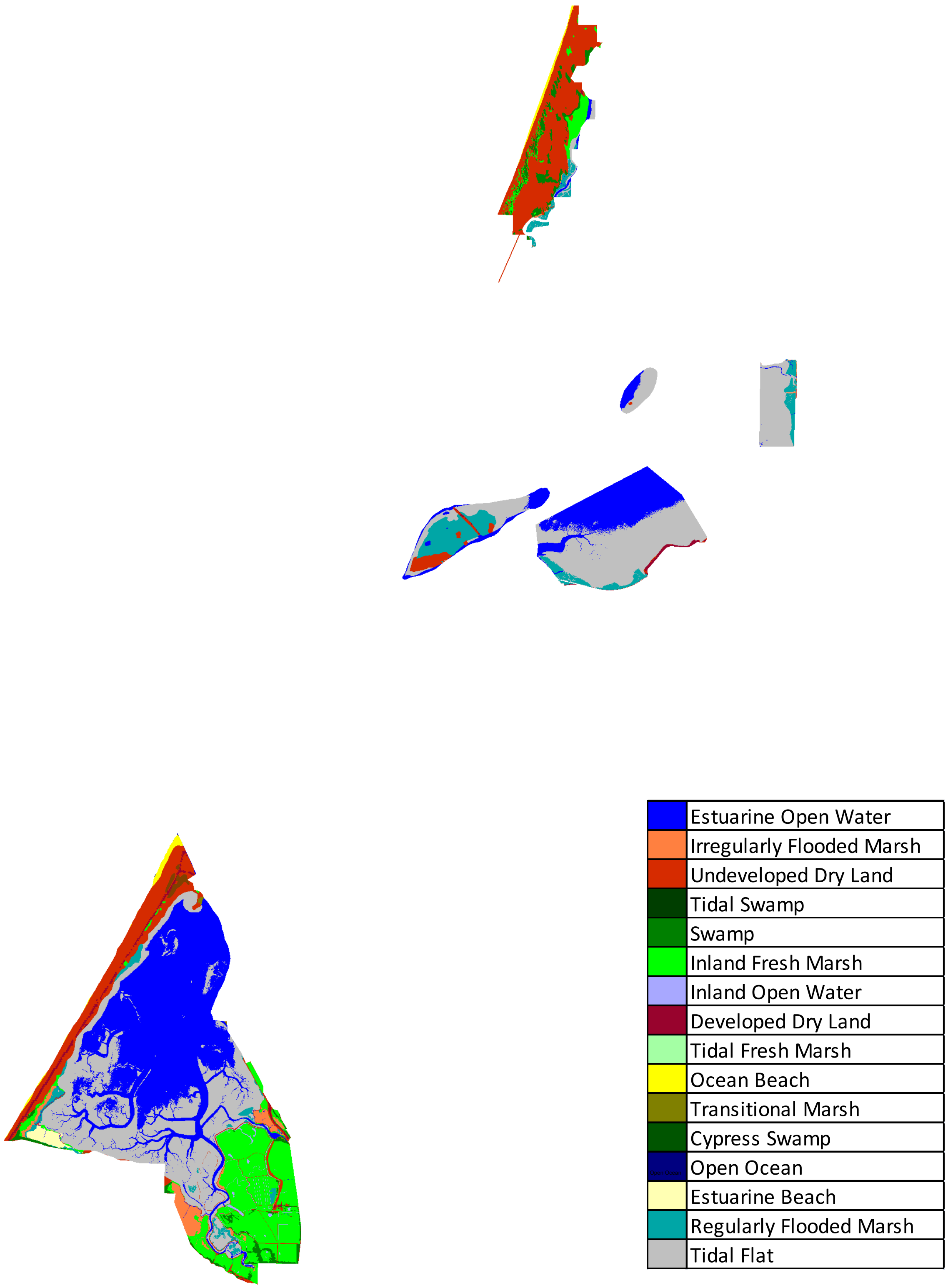
([1]) A *negative value indicates a gain with respect to initial coverage*

As noted above, the simulation was also run assuming no dikes at Hookton Slough. This was not the primary simulation run for this site because assuming the area is not diked results in an immediate wide-scale conversion of the inland-fresh marsh at this location—a prediction that does not match current NWI maps. Furthermore, to be consistent with other USFWS refuge analyses, dikes that currently protect wetlands are assumed to be maintained. A short section discussing *No Dikes Results* can found after the maps presenting the primary model results.

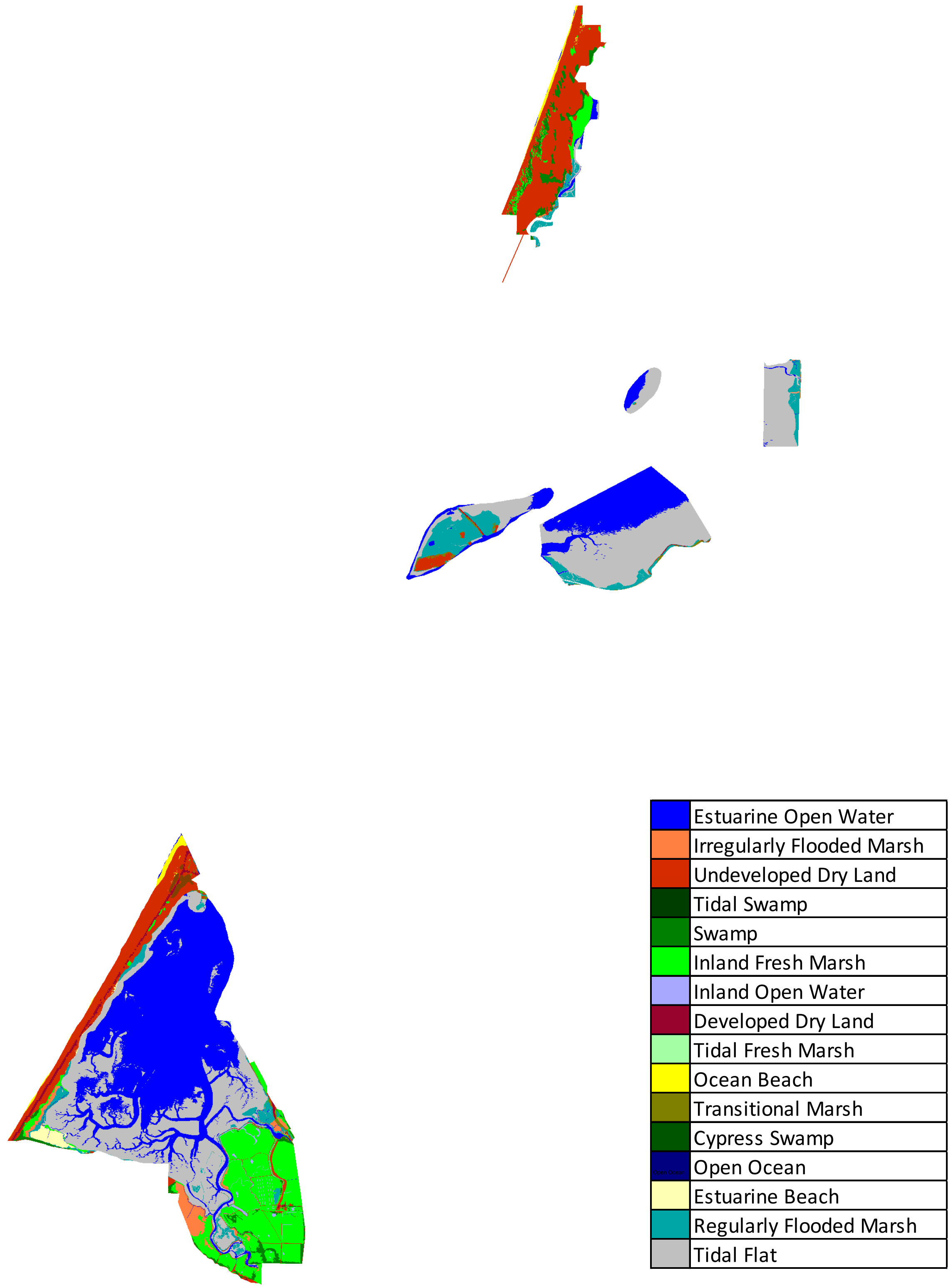
Humboldt Bay NWR
IPCC Scenario A1B-Mean, 0.39 m SLR eustatic by 2100

Results in Acres

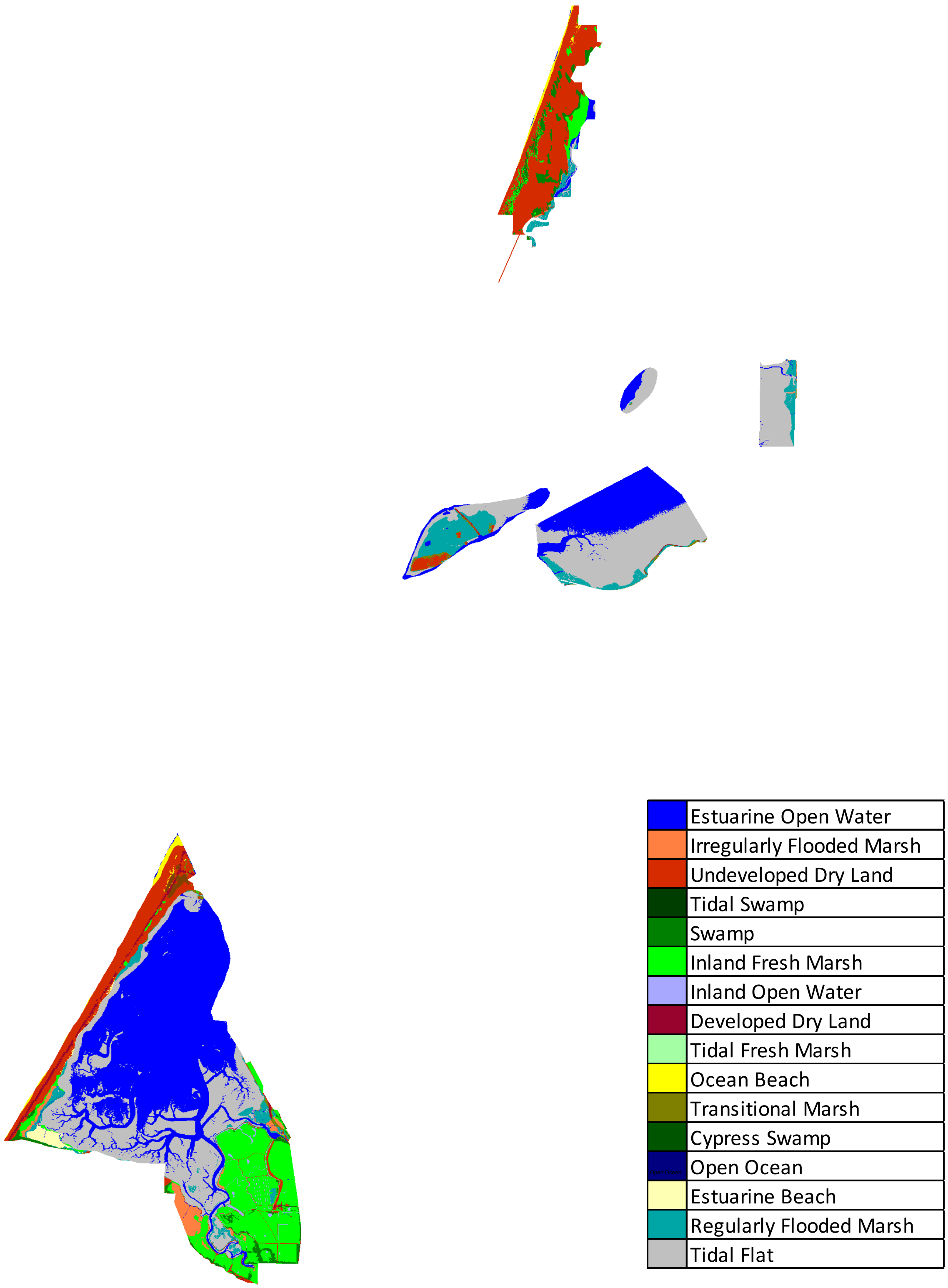
		Initial	2025	2050	2075	2100
	Tidal Flat	3116	2897	2677	2396	2084
	Estuarine Open Water	3052	3285	3518	3806	4129
	Undeveloped Dry Land	1387	1317	1300	1276	1246
	Inland Fresh Marsh	1148	1136	1136	1136	1136
	Regularly Flooded Marsh	493	564	553	553	552
	Swamp	213	211	210	208	204
	Irregularly Flooded Marsh	158	138	138	138	138
	Developed Dry Land	95	74	73	72	70
	Ocean Beach	65	66	70	71	76
	Estuarine Beach	50	53	54	56	59
	Inland Open Water	38	38	38	38	38
	Tidal Creek	28	28	28	28	28
	Inland Shore	28	28	28	28	28
	Transitional Salt Marsh	8	44	56	72	92
	Total (incl. water)	**9879**	**9879**	**9879**	**9879**	**9879**



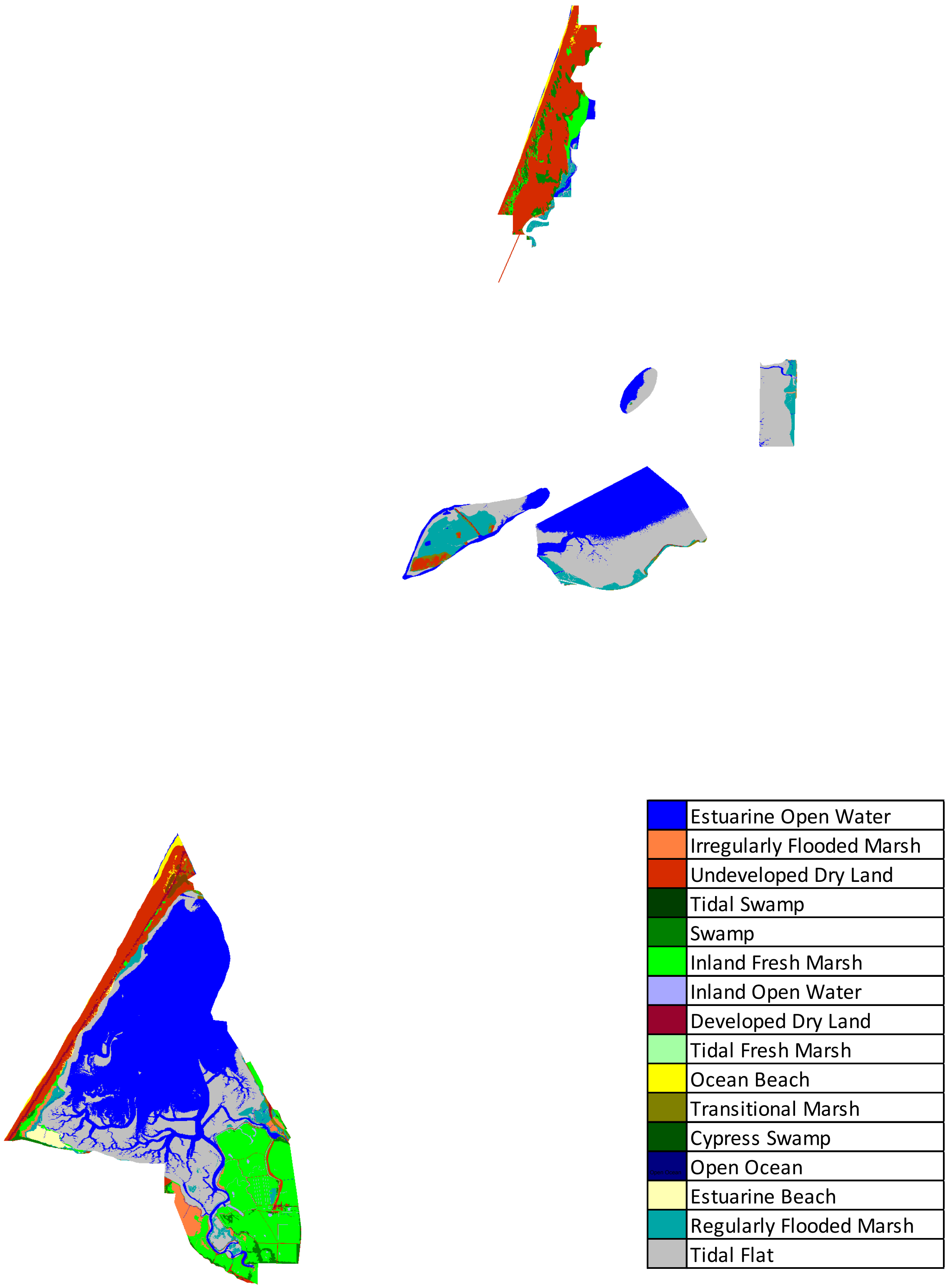
Humboldt Bay NWR, Initial Condition



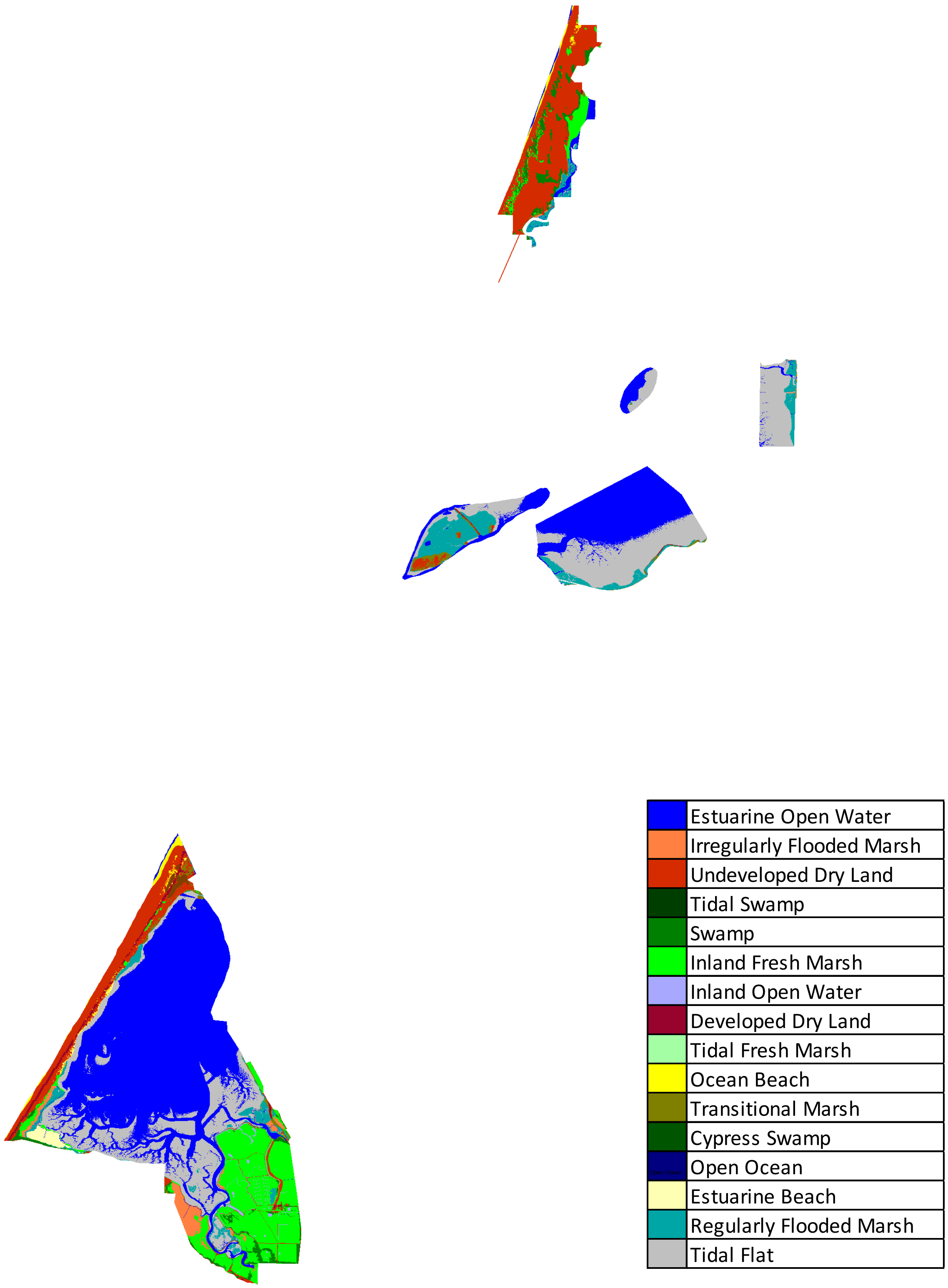
Humboldt Bay NWR, 2025, Scenario A1B Mean



Humboldt Bay NWR, 2050, Scenario A1B Mean



Humboldt Bay NWR, 2075, Scenario A1B Mean

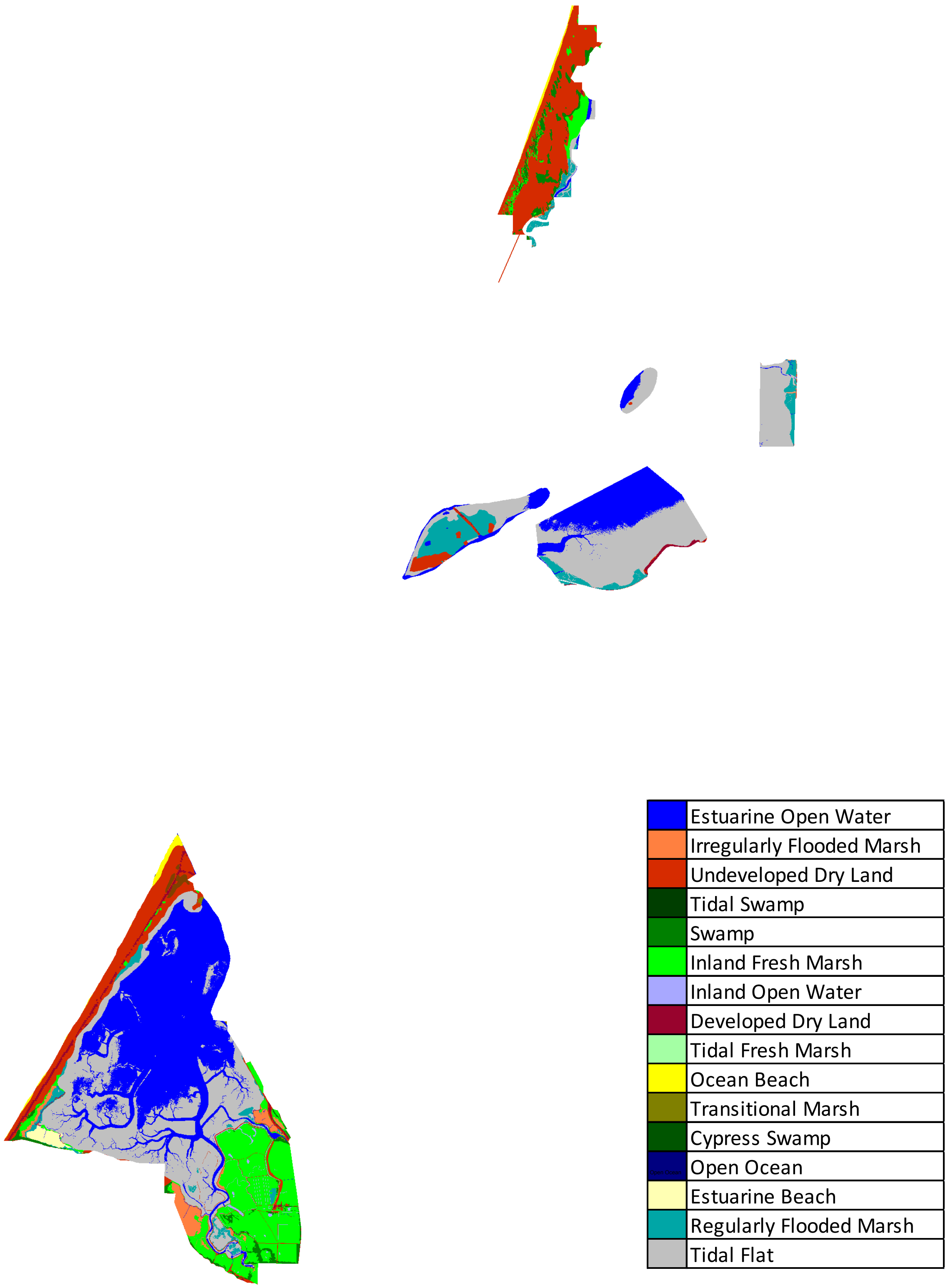


Humboldt Bay NWR, 2100, Scenario A1B Mean

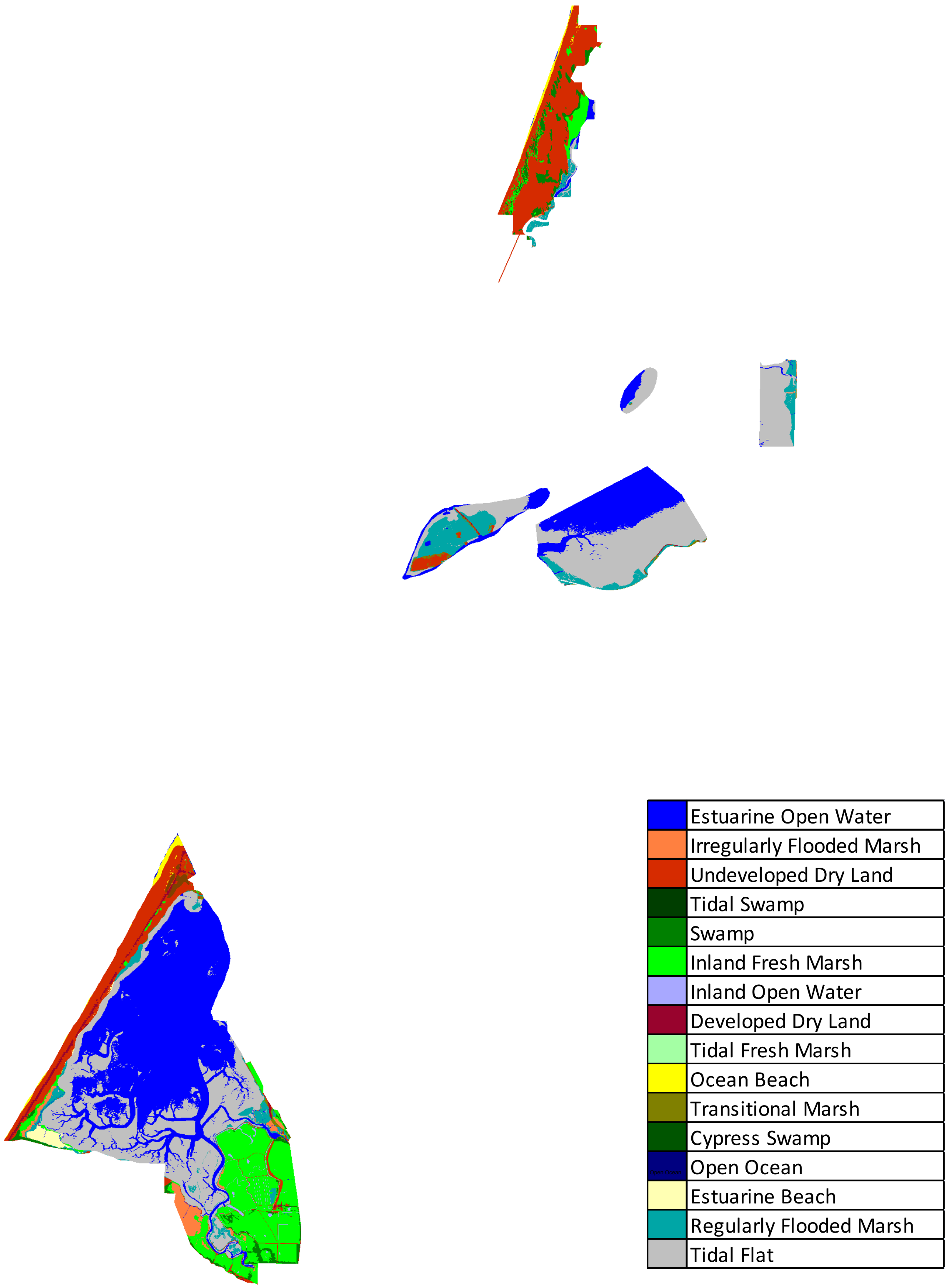
Humboldt Bay NWR
IPCC Scenario A1B-Max, 0.69 m SLR eustatic by 2100

Results in Acres

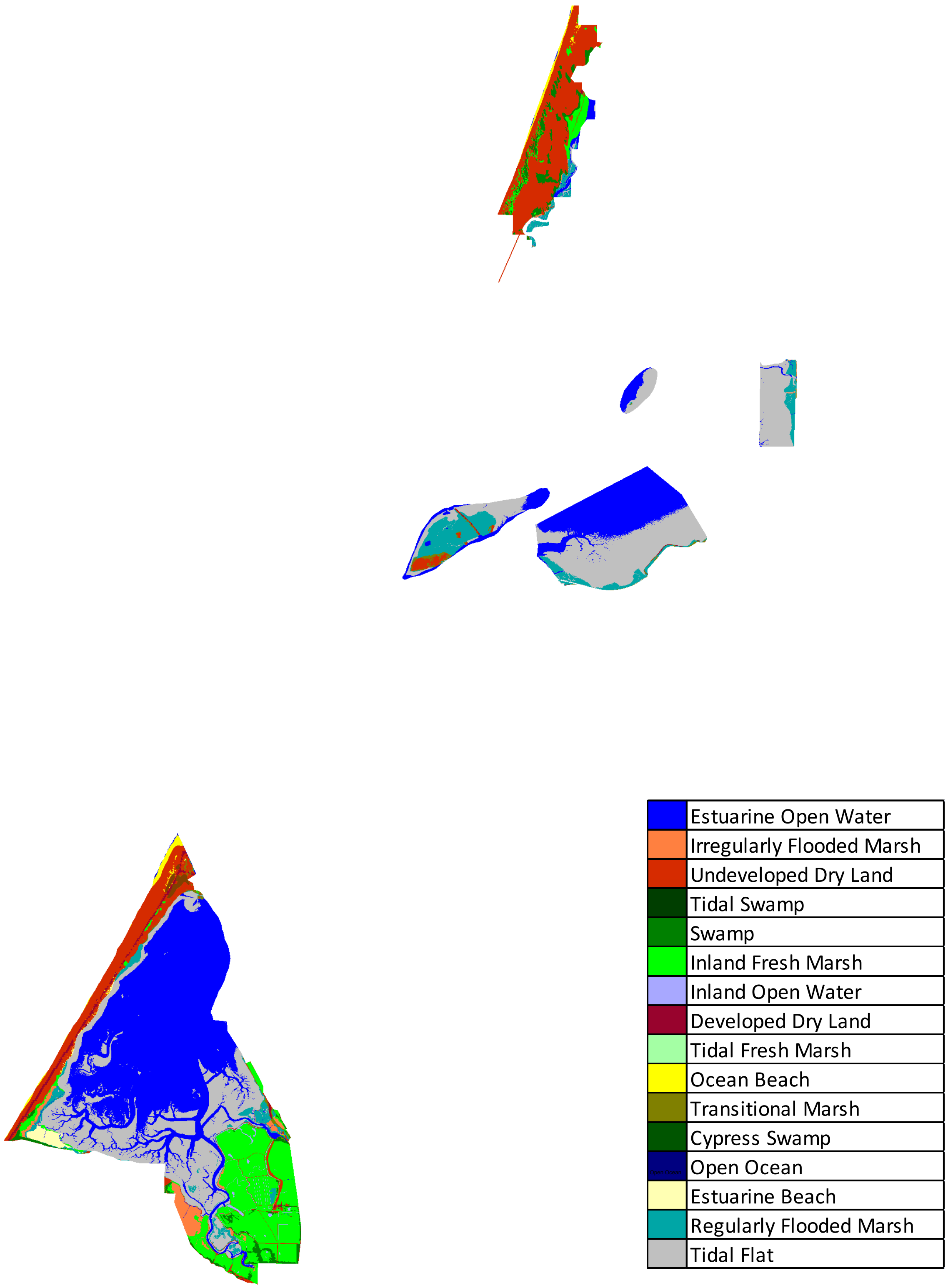
		Initial	2025	2050	2075	2100
	Tidal Flat	3116	2825	2544	2105	1380
	Estuarine Open Water	3052	3357	3661	4127	4895
	Undeveloped Dry Land	1387	1312	1287	1242	1180
	Inland Fresh Marsh	1148	1136	1132	1123	1113
	Regularly Flooded Marsh	493	566	551	543	519
	Swamp	213	211	209	204	196
	Irregularly Flooded Marsh	158	138	137	134	130
	Developed Dry Land	95	74	73	70	65
	Ocean Beach	65	67	74	83	104
	Estuarine Beach	50	53	56	61	66
	Inland Open Water	38	38	38	38	38
	Tidal Creek	28	28	28	28	28
	Inland Shore	28	28	28	28	28
	Transitional Salt Marsh	8	45	62	94	135
	Total (incl. water)	**9879**	**9879**	**9879**	**9879**	**9879**



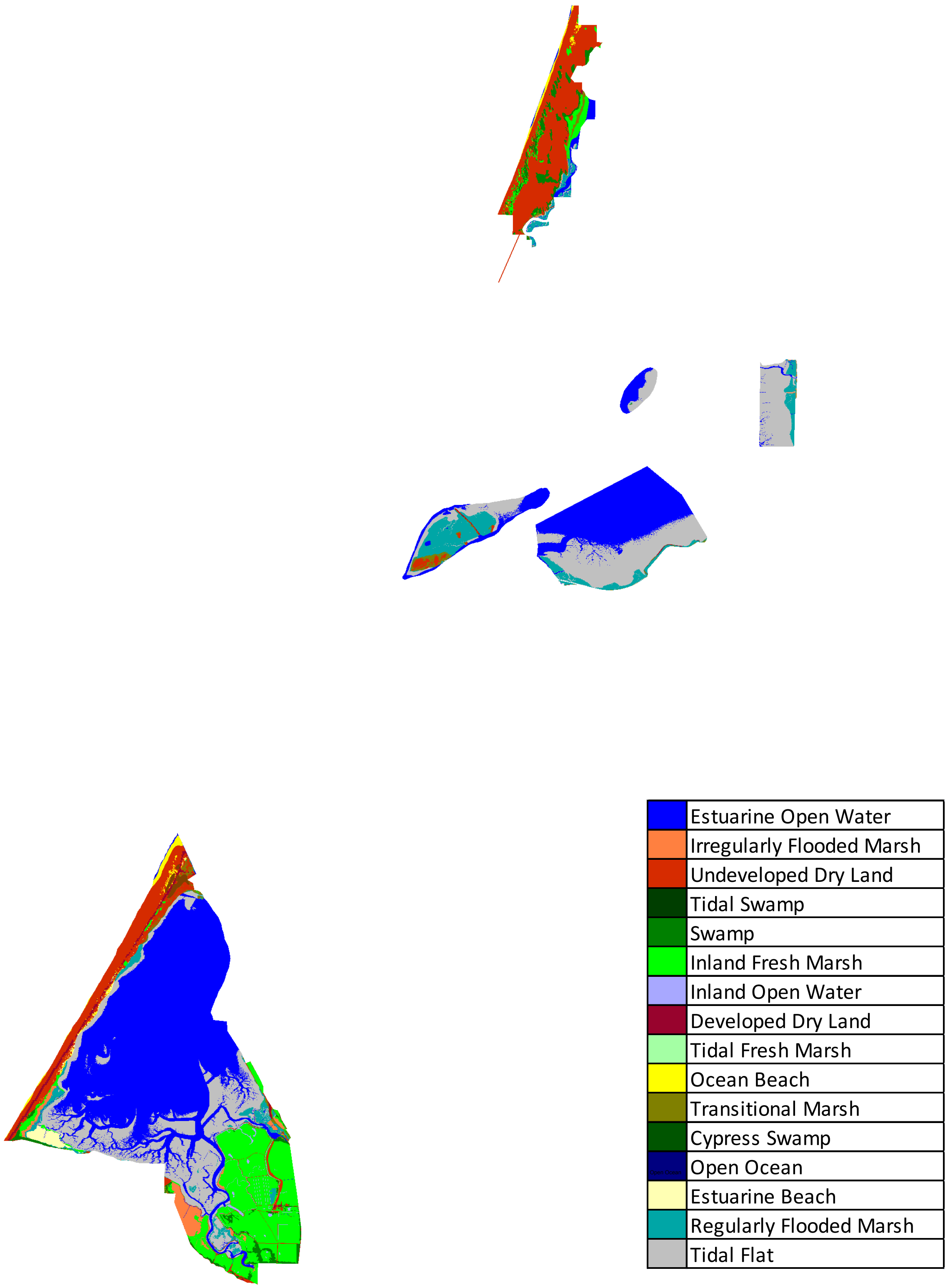
Humboldt Bay NWR, Initial Condition



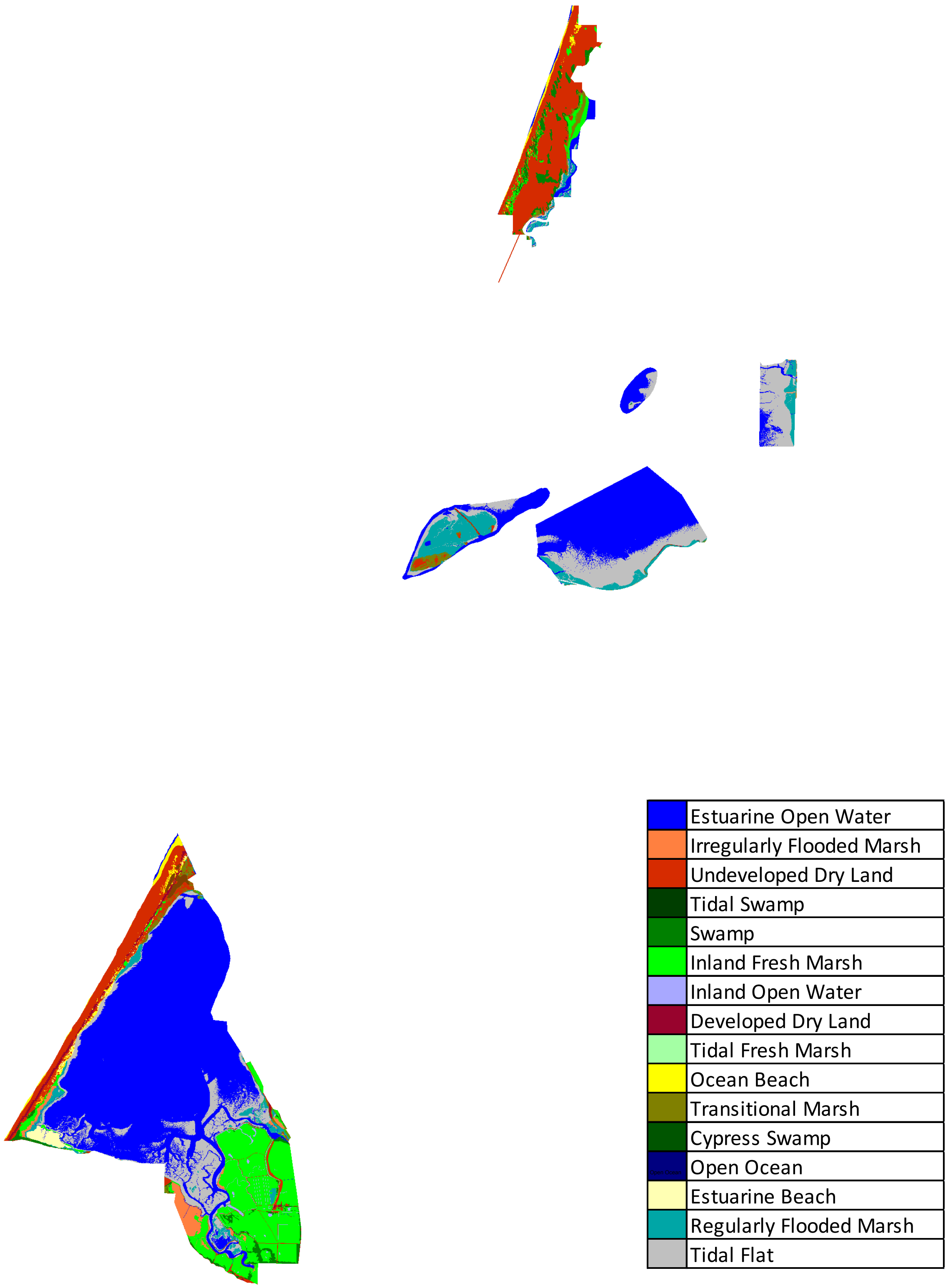
Humboldt Bay NWR, 2025, Scenario A1B Maximum



Humboldt Bay NWR, 2050, Scenario A1B Maximum



Humboldt Bay NWR, 2075, Scenario A1B Maximum

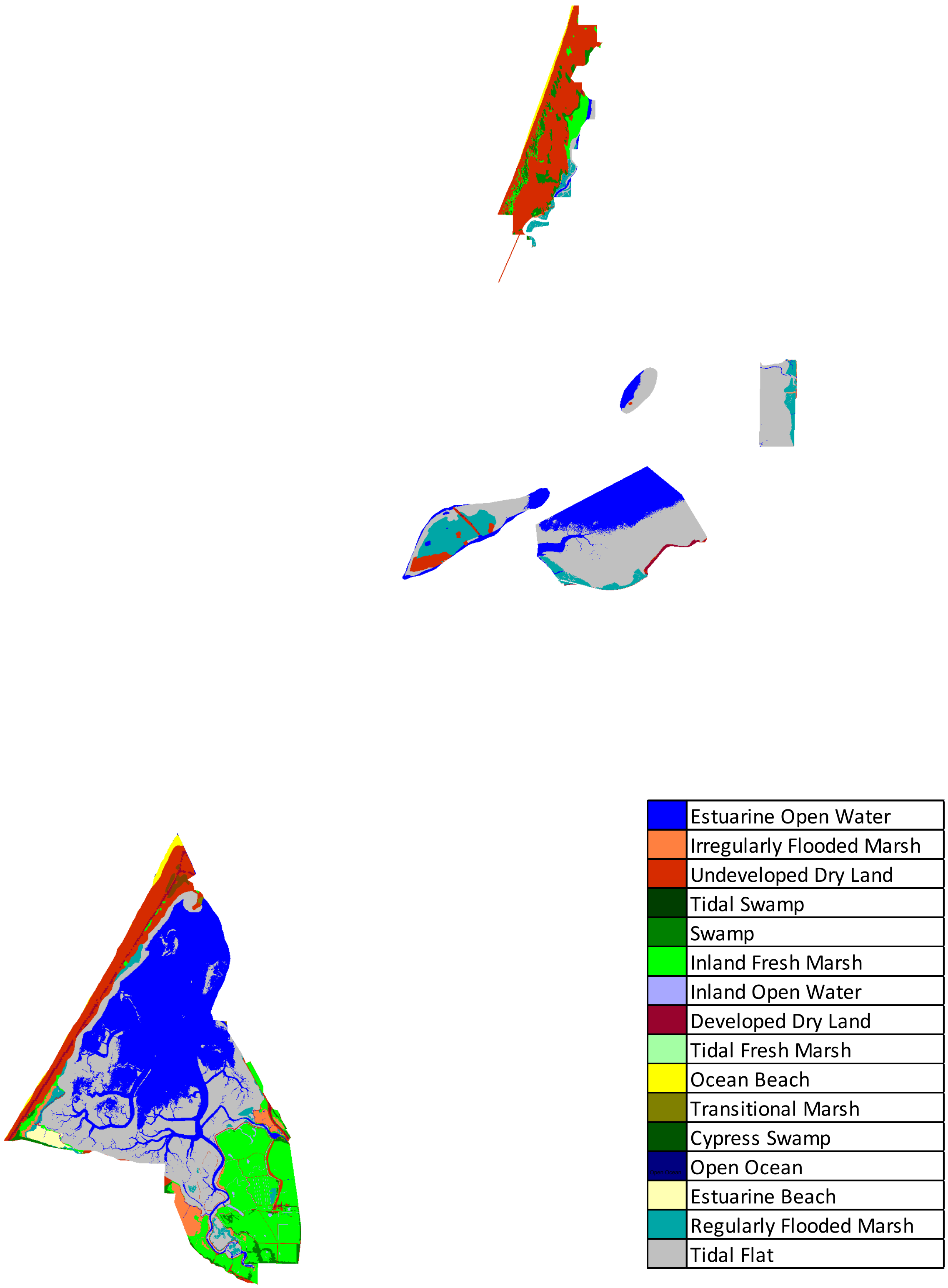


Humboldt Bay NWR, 2100, Scenario A1B Maximum

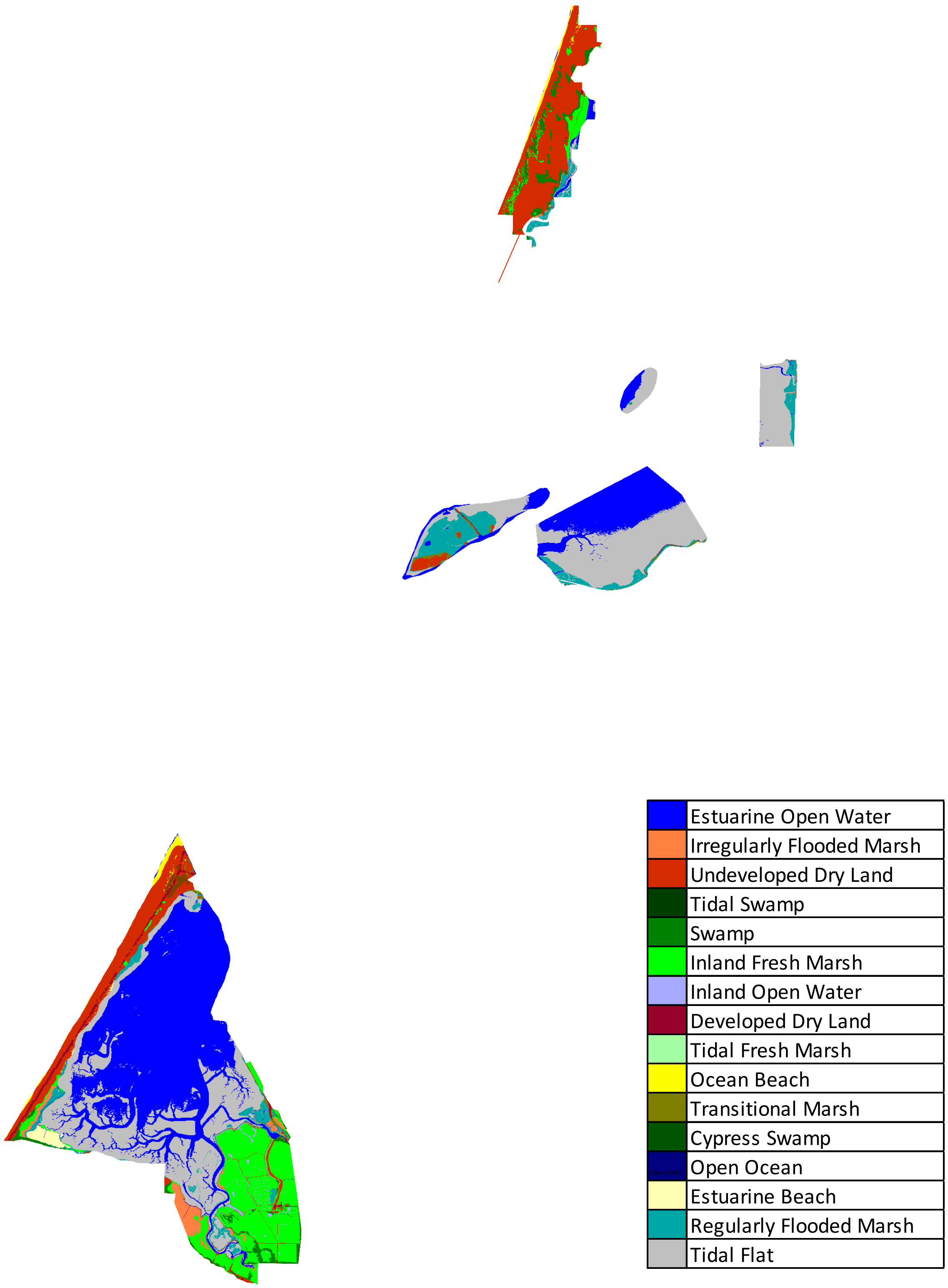
Humboldt Bay NWR
1 m eustatic SLR by 2100

Results in Acres

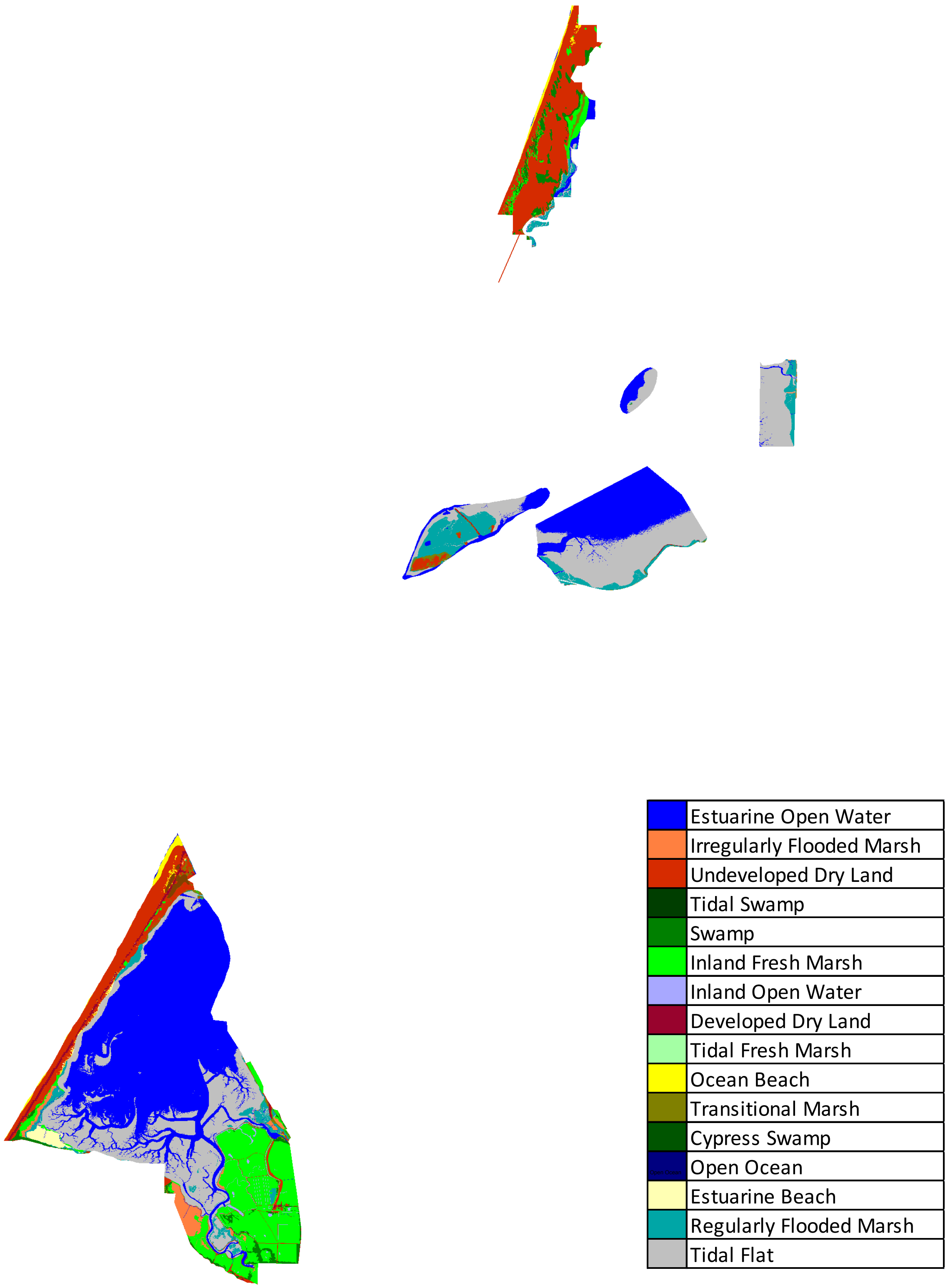
		Initial	2025	2050	2075	2100
	Tidal Flat	3116	2753	2393	1654	504
	Estuarine Open Water	3052	3432	3829	4631	5839
	Undeveloped Dry Land	1387	1307	1269	1198	1110
	Inland Fresh Marsh	1148	1133	1122	1106	1086
	Regularly Flooded Marsh	493	567	545	508	497
	Swamp	213	210	207	199	184
	Irregularly Flooded Marsh	158	138	134	129	125
	Developed Dry Land	95	74	71	67	58
	Ocean Beach	65	68	78	100	144
	Estuarine Beach	50	54	59	68	71
	Inland Open Water	38	38	38	38	38
	Tidal Creek	28	28	28	28	28
	Inland Shore	28	28	28	28	28
	Transitional Salt Marsh	8	48	76	127	167
	Total (incl. water)	**9879**	**9879**	**9879**	**9879**	**9879**



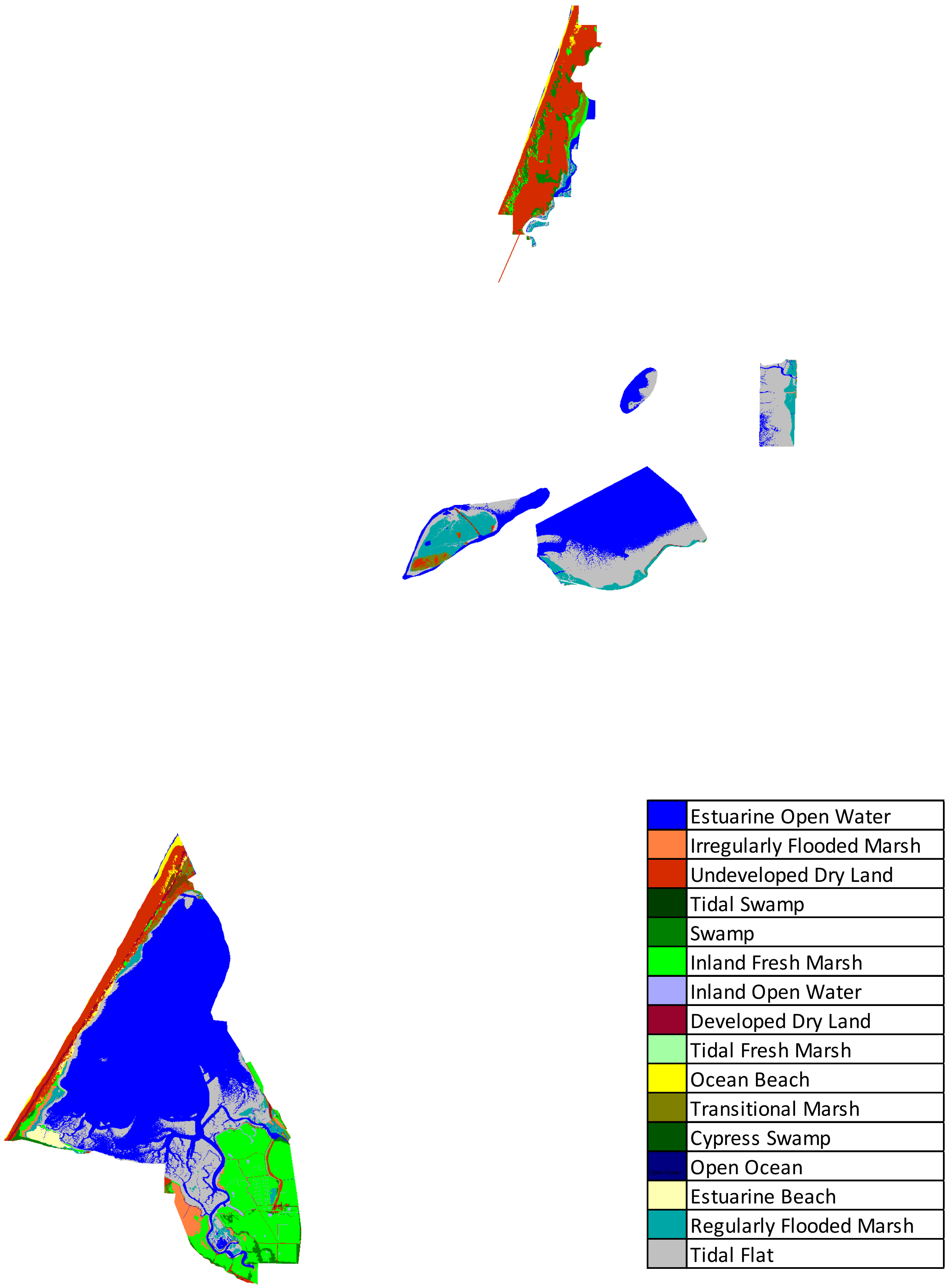
Humboldt Bay NWR, Initial Condition



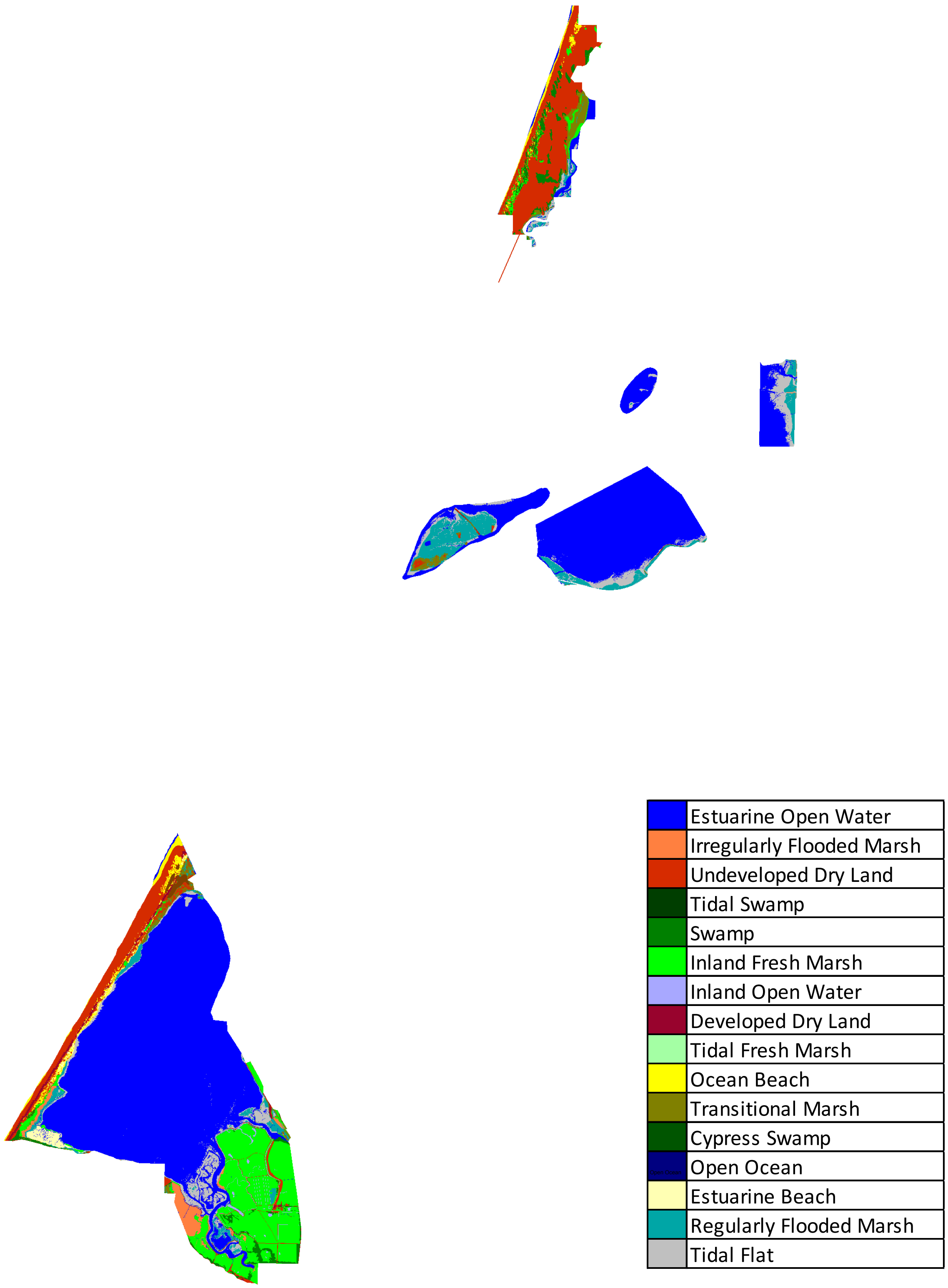
Humboldt Bay NWR, 2025, 1 m



Humboldt Bay NWR, 2050, 1 m



Humboldt Bay NWR, 2075, 1 m

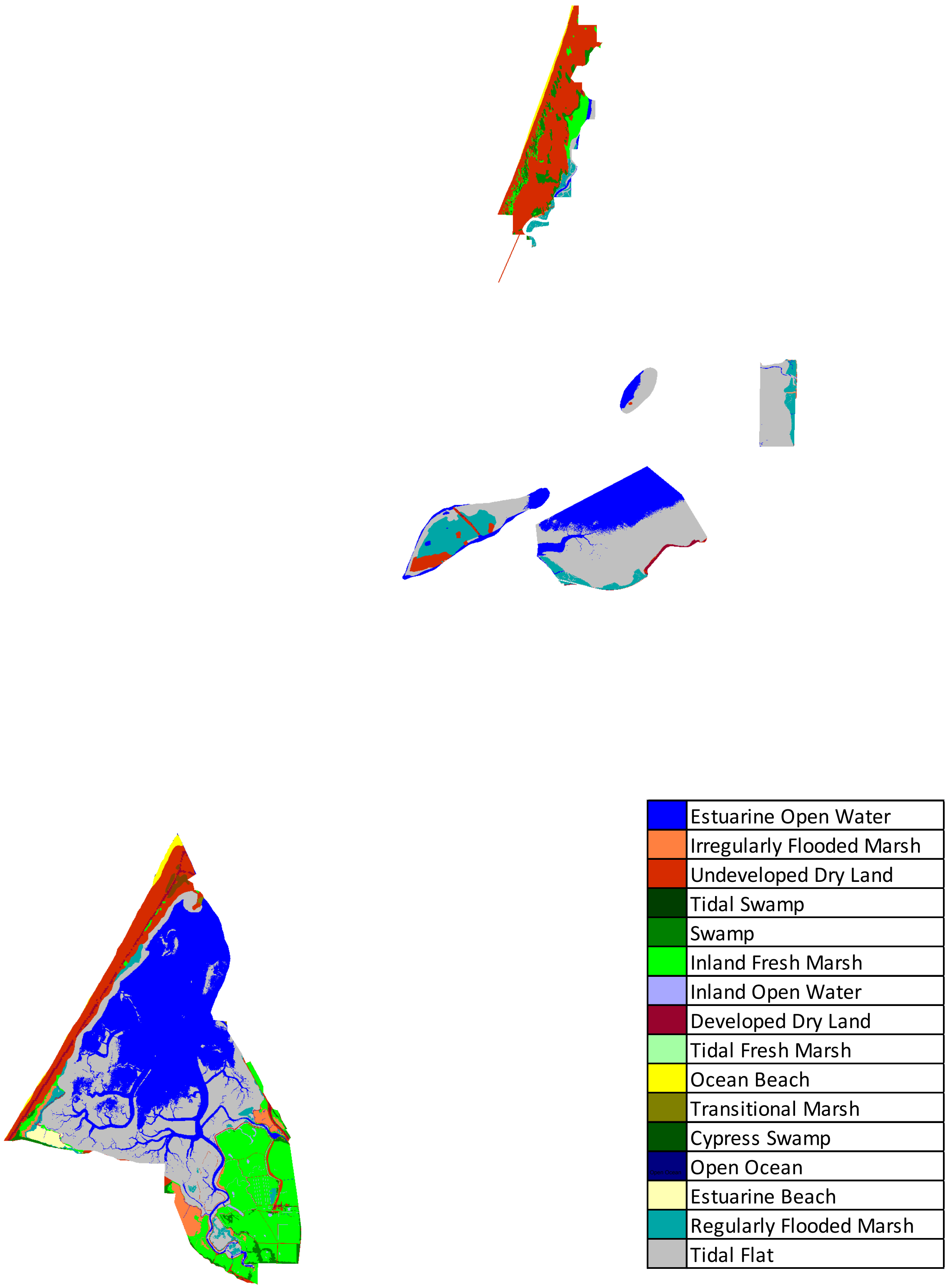


Humboldt Bay NWR, 2100, 1 m

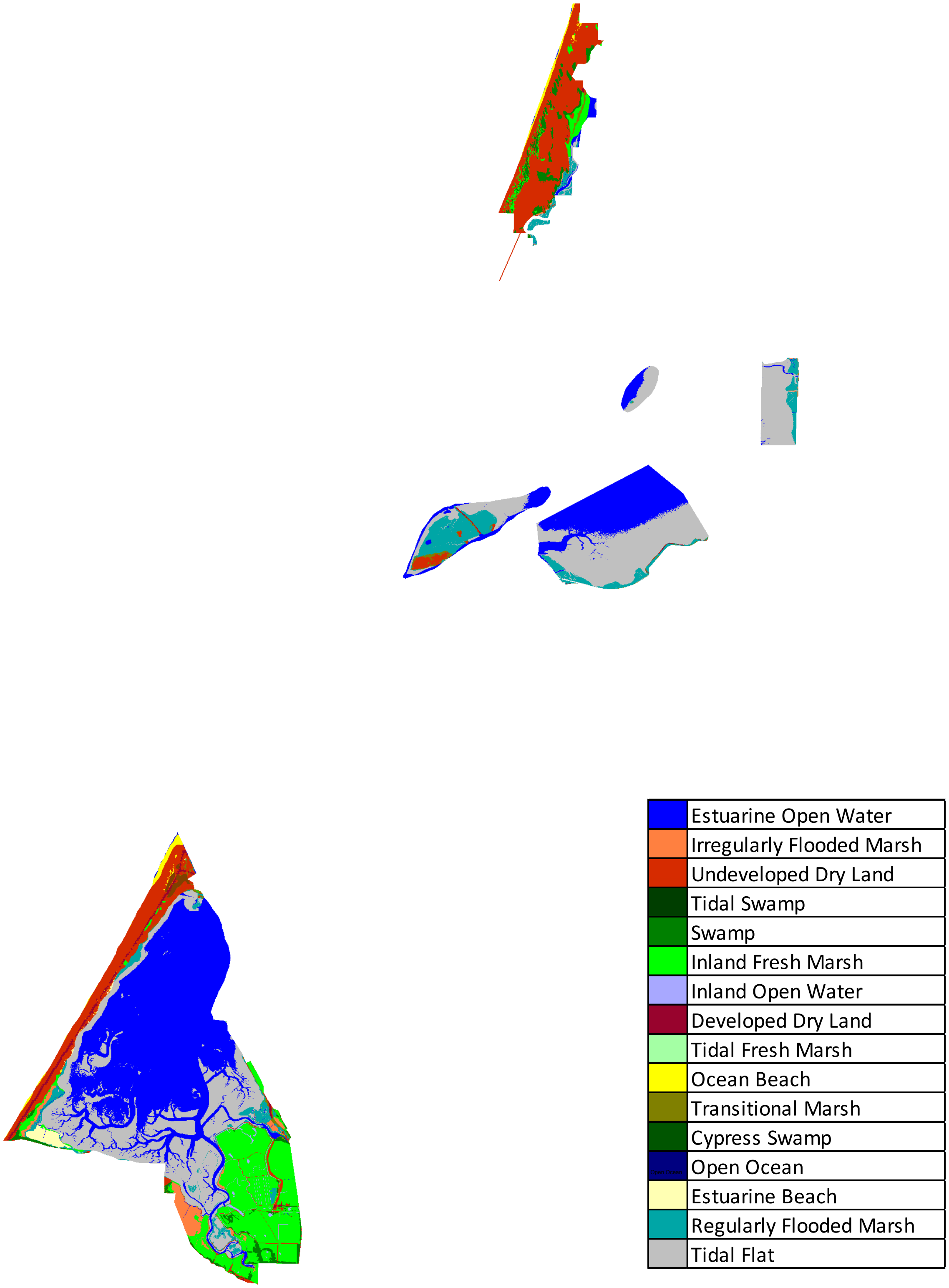
Humboldt Bay NWR
1.5 m eustatic SLR by
2100

Results in Acres

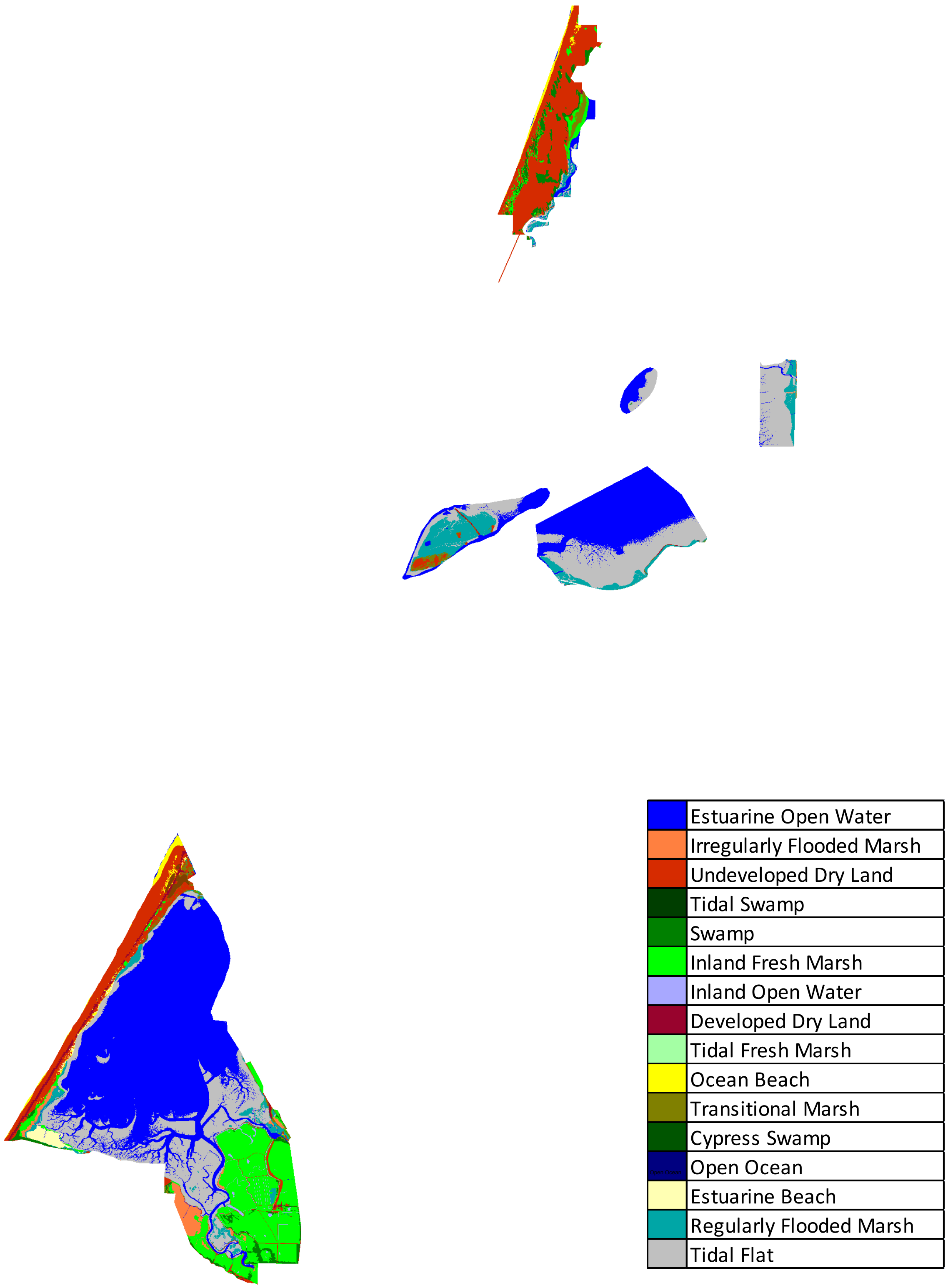
		Initial	2025	2050	2075	2100
	Tidal Flat	3116	2648	2102	601	237
	Estuarine Open Water	3052	3544	4168	5752	6291
	Undeveloped Dry Land	1387	1298	1233	1117	1022
	Inland Fresh Marsh	1148	1126	1107	1078	1028
	Regularly Flooded Marsh	493	567	513	501	515
	Swamp	213	210	203	187	165
	Irregularly Flooded Marsh	158	137	130	124	114
	Developed Dry Land	95	73	69	59	45
	Ocean Beach	65	71	90	143	204
	Estuarine Beach	50	55	65	76	46
	Inland Open Water	38	38	38	38	38
	Tidal Creek	28	28	28	28	28
	Inland Shore	28	28	28	28	28
	Transitional Salt Marsh	8	56	105	148	119
	Total (incl. water)	**9879**	**9879**	**9879**	**9879**	**9879**



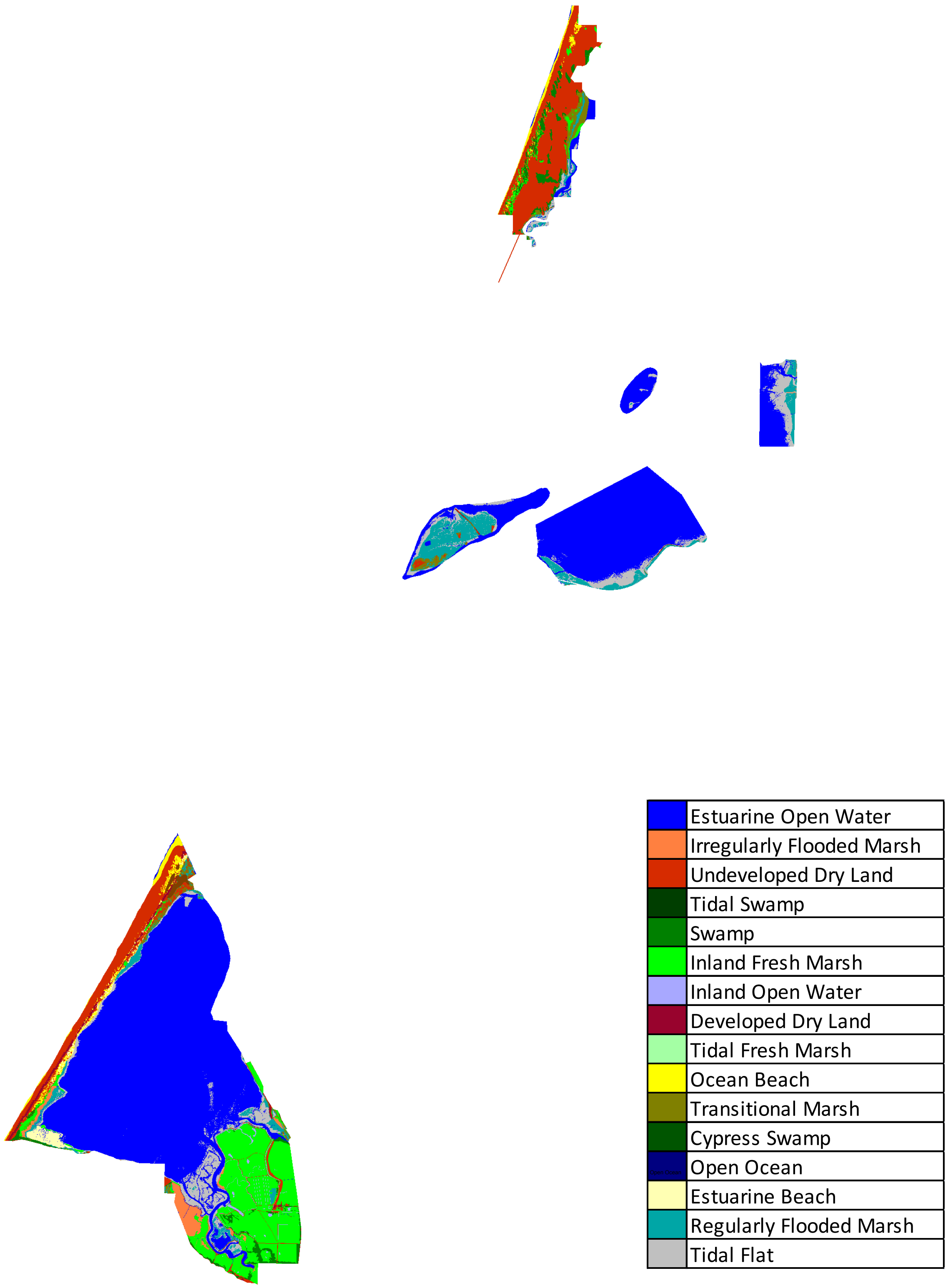
Humboldt Bay NWR, Initial Condition



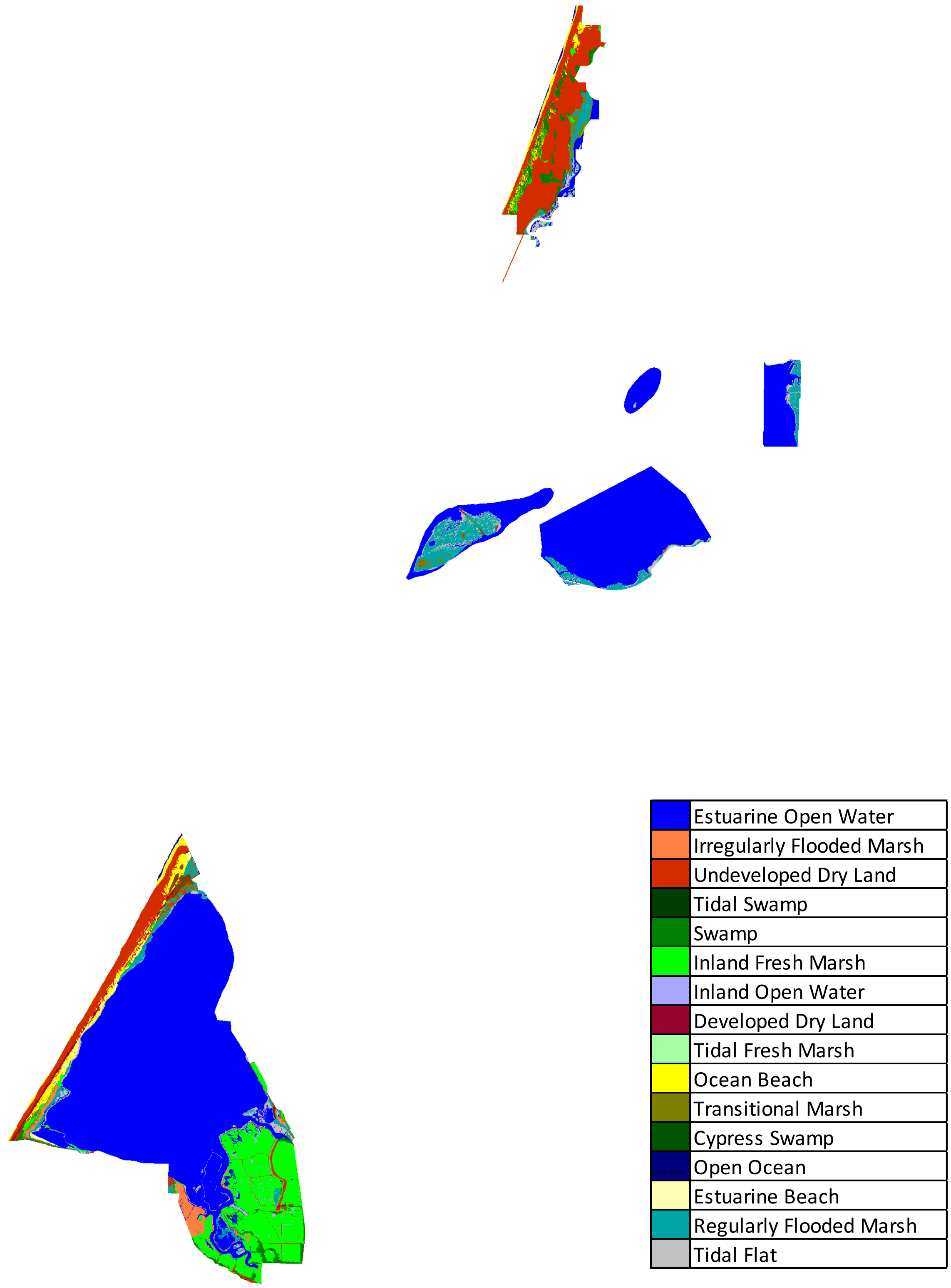
Humboldt Bay NWR, 2025, 1.5 m



Humboldt Bay NWR, 2050, 1.5 m



Humboldt Bay NWR, 2075, 1.5 m

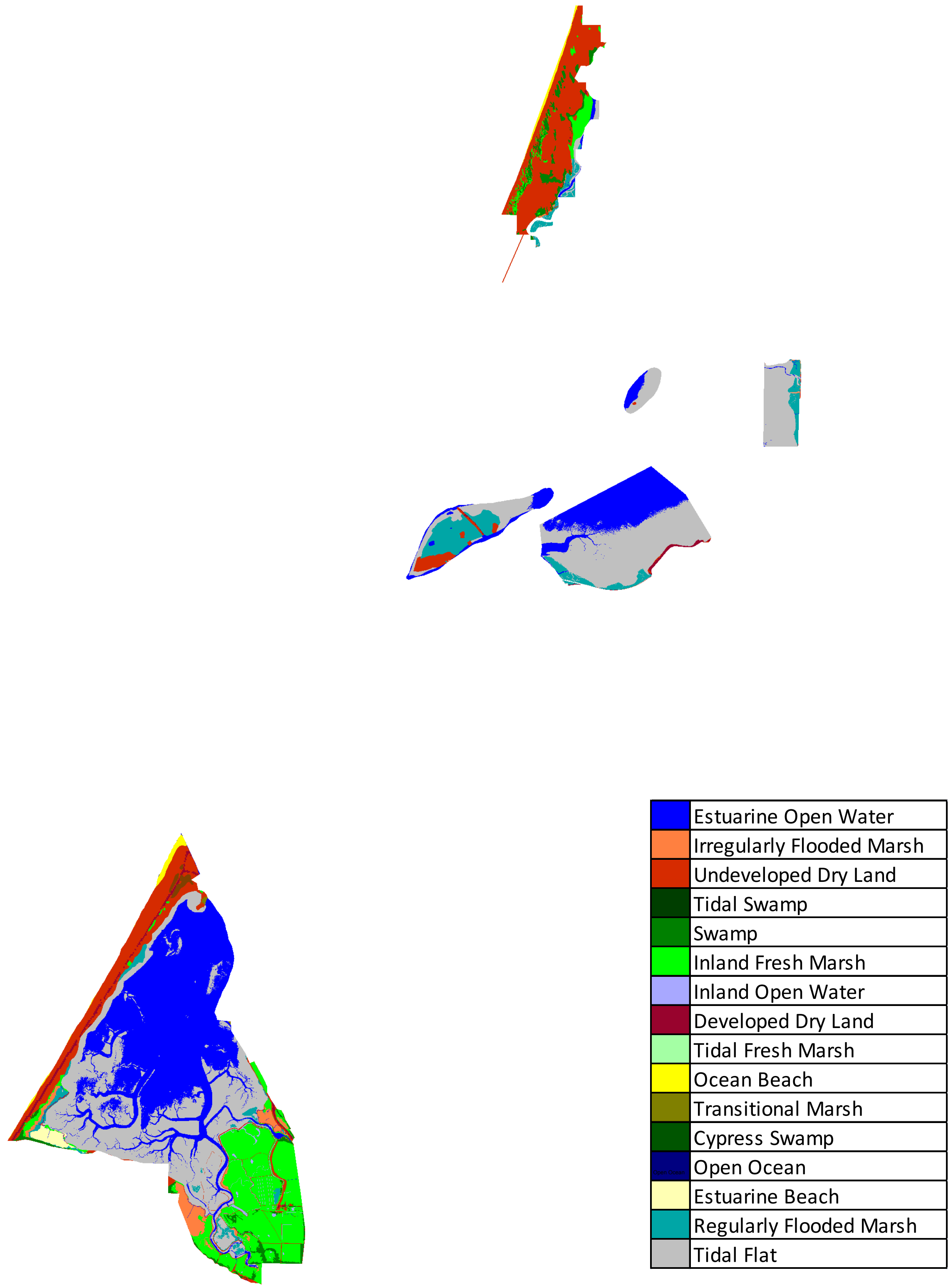


Humboldt Bay NWR, 2100, 1.5 m

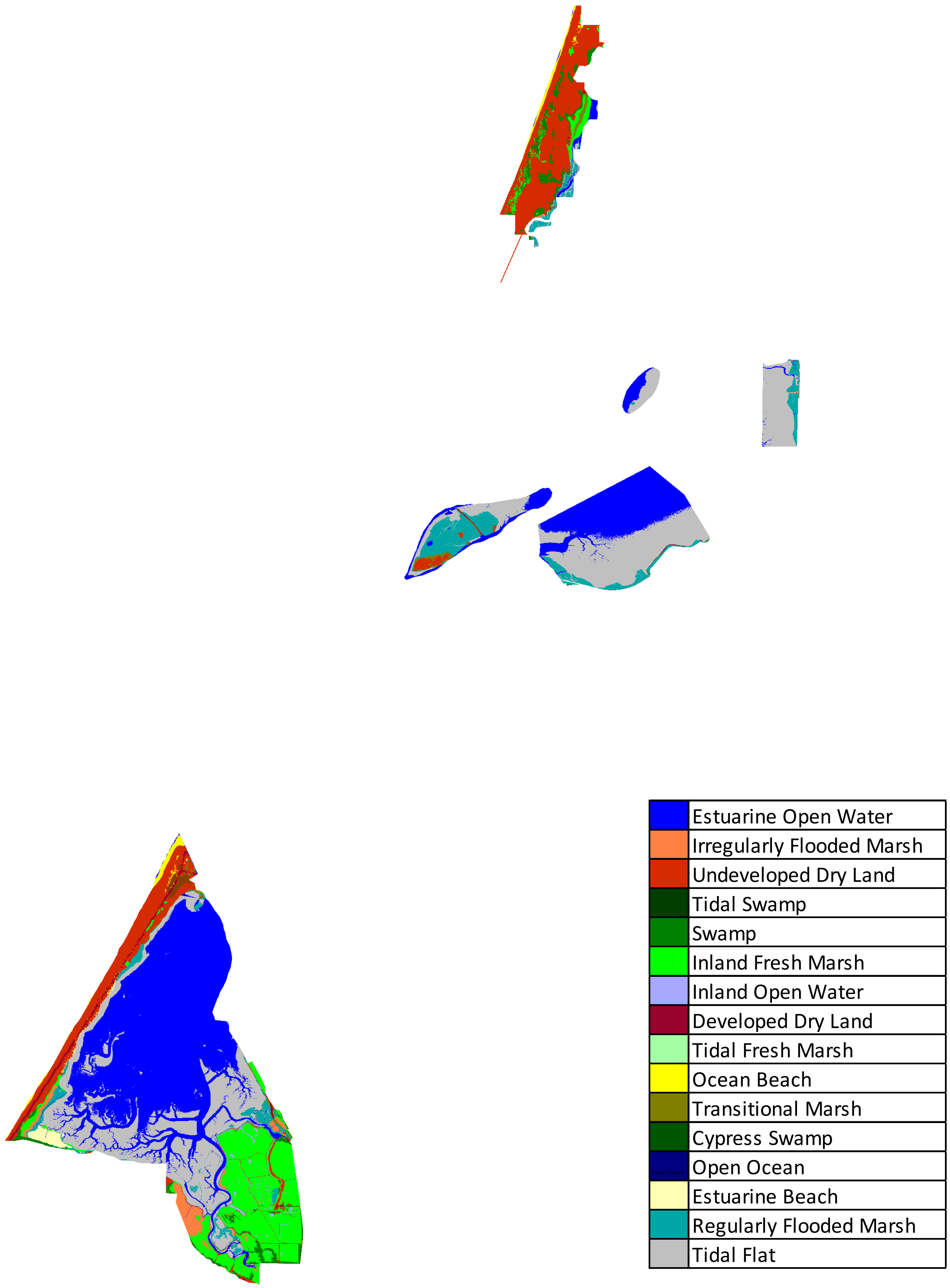
Humboldt Bay NWR
2 m eustatic SLR by 2100

Results in Acres

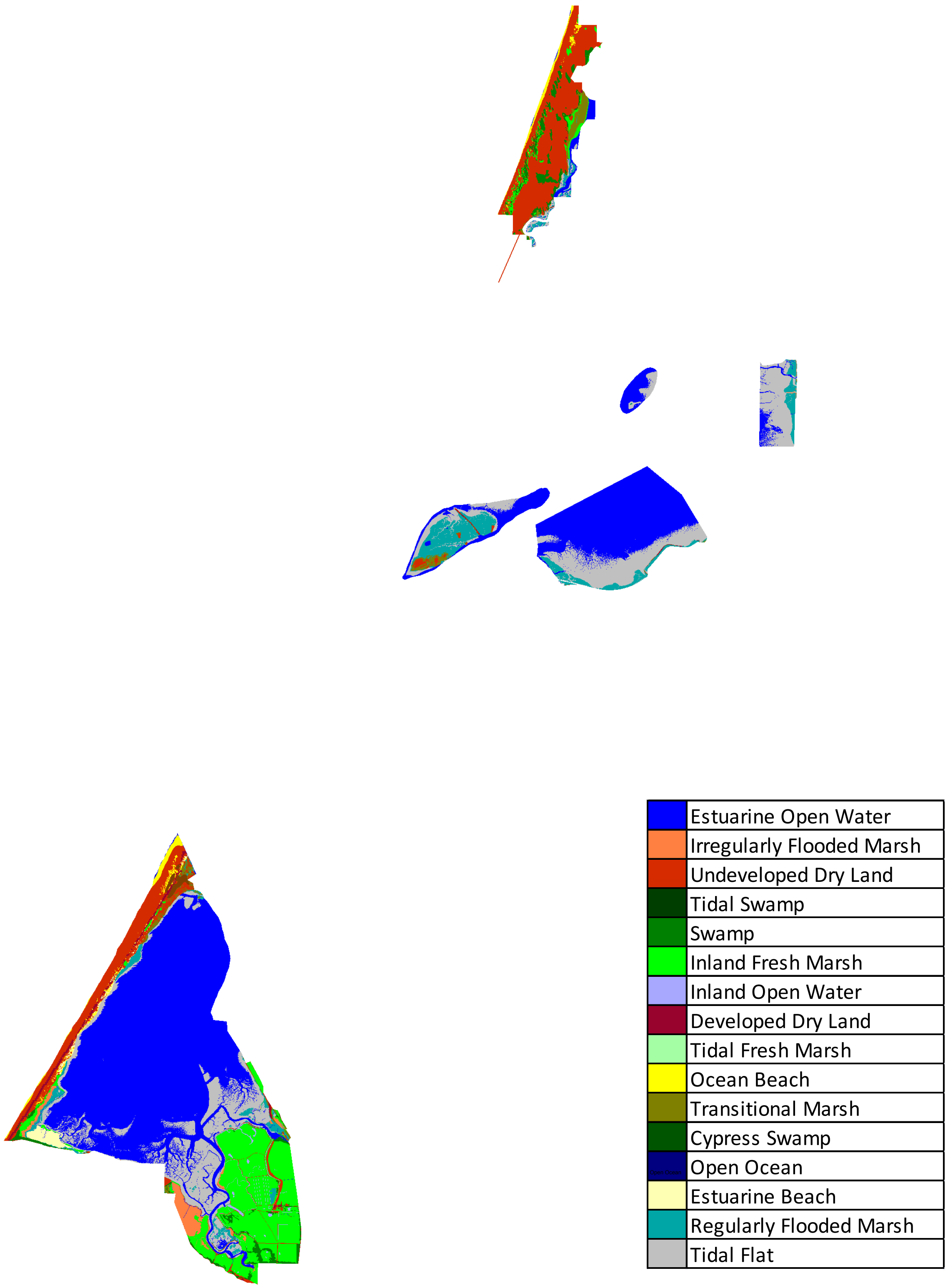
		Initial	2025	2050	2075	2100
	Tidal Flat	3116	2545	1591	294	432
	Estuarine Open Water	3052	3655	4719	6183	6587
	Undeveloped Dry Land	1387	1287	1190	1053	954
	Inland Fresh Marsh	1148	1120	1090	1051	892
	Regularly Flooded Marsh	493	565	492	499	313
	Swamp	213	209	198	174	151
	Irregularly Flooded Marsh	158	136	127	118	44
	Developed Dry Land	95	73	66	50	35
	Ocean Beach	65	74	106	186	251
	Estuarine Beach	50	57	72	51	53
	Inland Open Water	38	38	38	38	38
	Tidal Creek	28	28	28	28	28
	Inland Shore	28	28	28	28	28
	Transitional Salt Marsh	8	65	133	127	73
	Total (incl. water)	**9879**	**9879**	**9879**	**9879**	**9879**



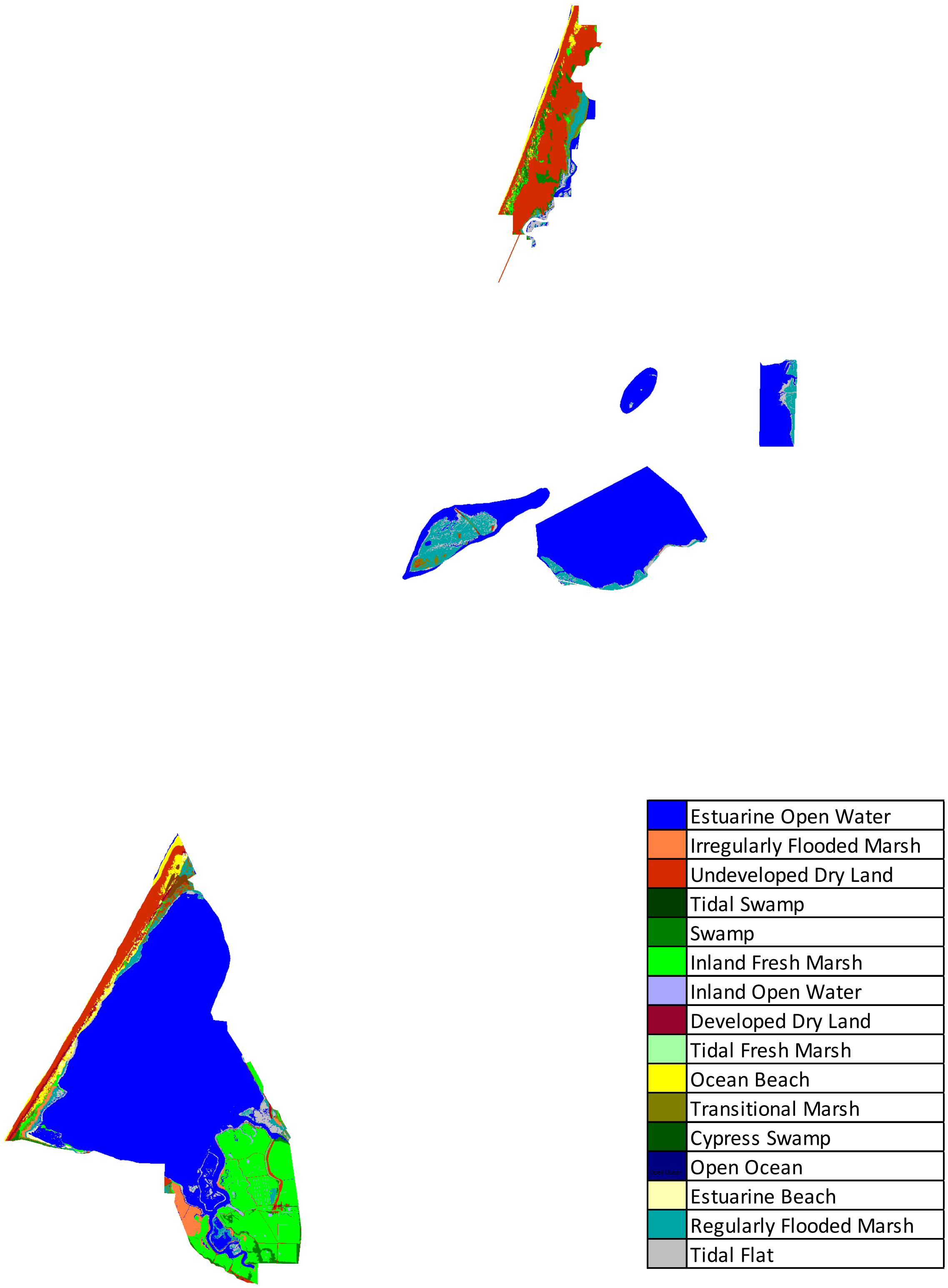
Humboldt Bay NWR, Initial Condition



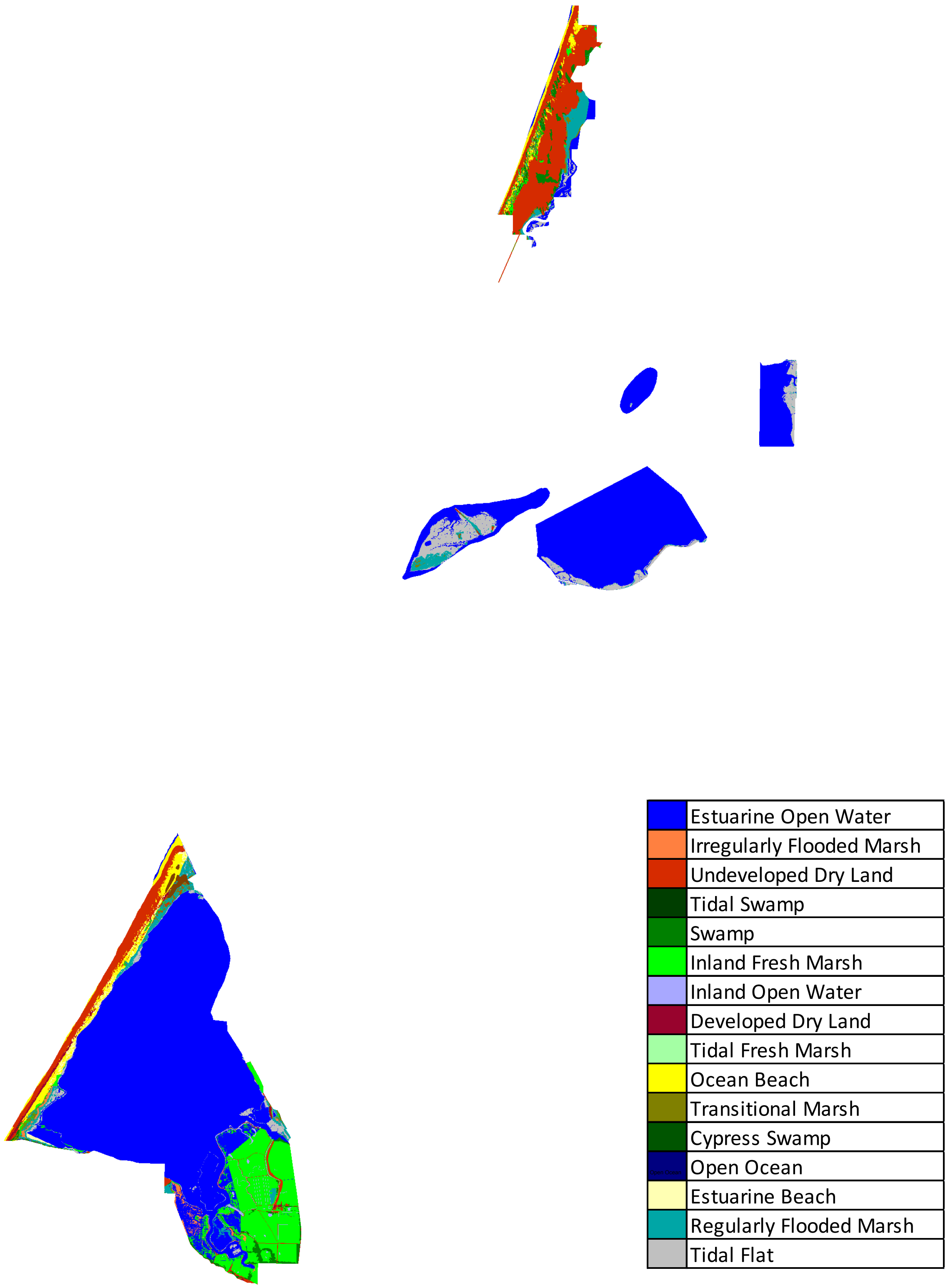
Humboldt Bay NWR, 2025, 2 m



Humboldt Bay NWR, 2050, 2 m



Humboldt Bay NWR, 2075, 2 m



Humboldt Bay NWR, 2100, 2 m

No-Dikes Results

Results of the model run with dikes removed are subject to considerable uncertainty for several reasons:

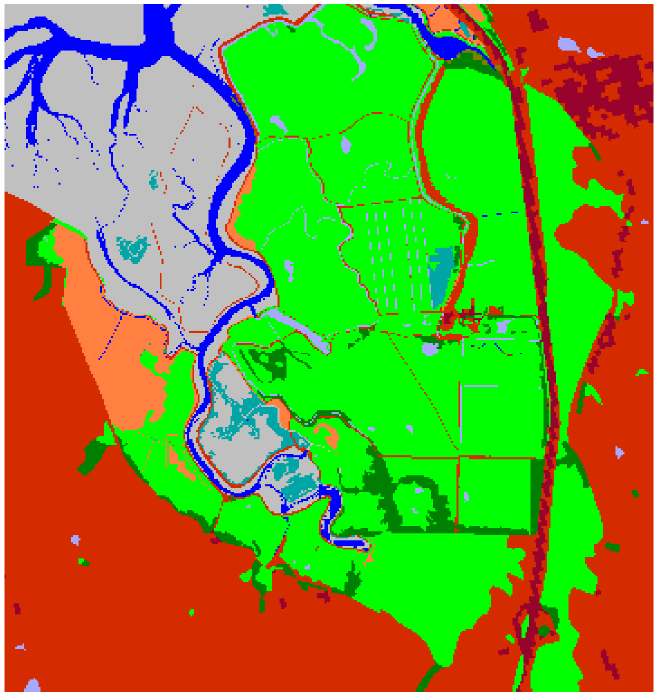
- Much of the elevation data behind the dikes at Hookton Slough are not covered by LiDAR (Figure 2). (These elevations could not be "improved" with the elevation pre-processor because the presence of the dikes complicates the tide-range-to-elevation relationship.)
- When dikes are removed accretion tends to become extremely dynamic due to the reintroduction of sediment to low-elevation wetlands. Such dynamic changes in accretion are not accounted for in this model.

Results of the simulation where dikes were not included, presented in Table 6, differed from those generated when the dikes were included primarily in the inland fresh marsh, regularly-flooded and irregularly-flooded marsh, and swamp categories. Under the 1 m of SLR by 2100 scenario, only five percent of inland fresh marsh was predicted to be lost when dikes were included in the simulation; however 90% was predicted to be lost when dike removal was simulated. Accordingly, a much larger gain in regularly-flooded marsh was predicted when dikes were not included. Swamp and irregularly-flooded marsh were predicted to be lost at much higher rates when dikes were removed. For example, when dikes were included the maximum swamp loss predicted was 29% and the maximum irregularly-flooded marsh loss predicted was 72% (under 2 m SLR by 2100). When dikes were removed the maximum swamp loss predicted was 58% and maximum irregularly-flooded marsh loss predicted was 91% (also in the 2 m SLR by 2100 scenario).

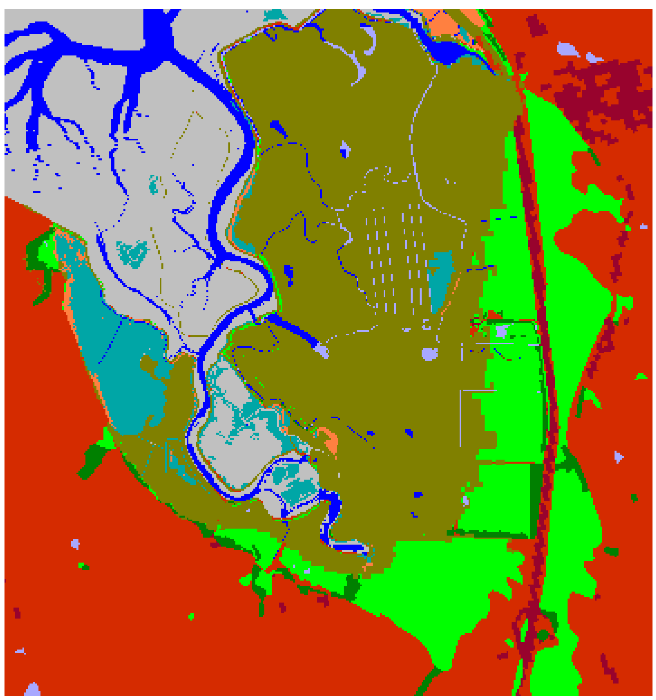
Table 6. Predicted Change Rates of Land Categories by 2100 Given
Simulated Scenarios of Eustatic Sea Level Rise for simulations without dikes included.
Positive values indicate losses, negative values indicate gains.

Land cover category	**Land cover change by 2100 for different SLR scenarios (%)**				
	0.39 m	**0.69 m**	**1 m**	**1.5 m**	**2 m**
Tidal Flat	28	48	70	77	73
Undeveloped Dry Land	14	19	24	30	35
Inland Fresh Marsh	74	84	90	94	97
Regularly Flooded Marsh	-137	-128	-96	-85	-9
Swamp	33	38	45	53	58
Irregularly Flooded Marsh	66	74	78	83	91
Developed Dry Land	28	34	42	55	65

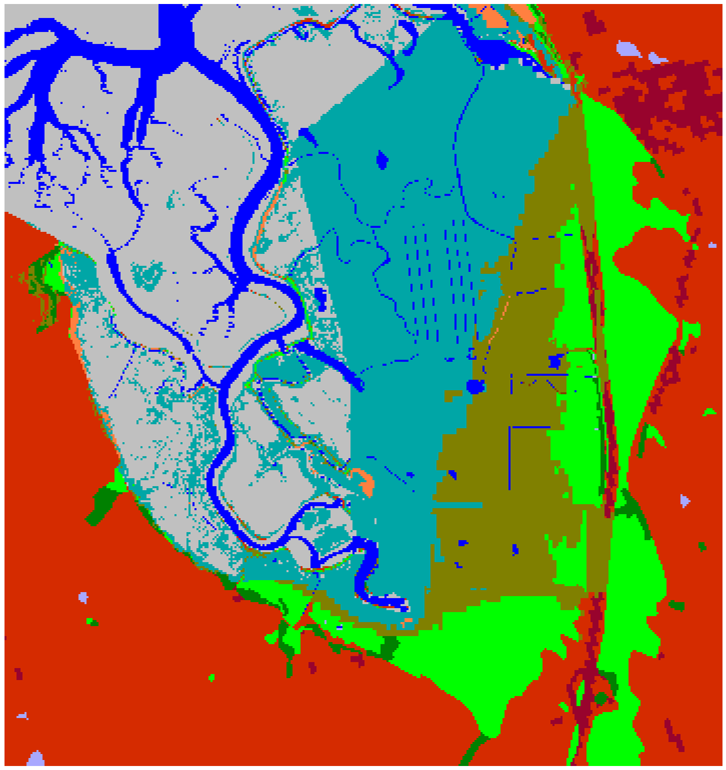
The maps presented below illustrate the potential effects of 1 m of SLR by 2100 on the Hookton Slough area when dikes are not simulated. Important to note is that SLAMM would predict the majority of the inland fresh marsh and regularly flooded marsh to convert to transitional salt marsh and regularly flooded, respectively, based on their current location in the tidal frame. By 2100 the majority of the area is predicted to convert to tidal flat. In addition, without human intervention, Highway 101 is predicted to convert to marsh.



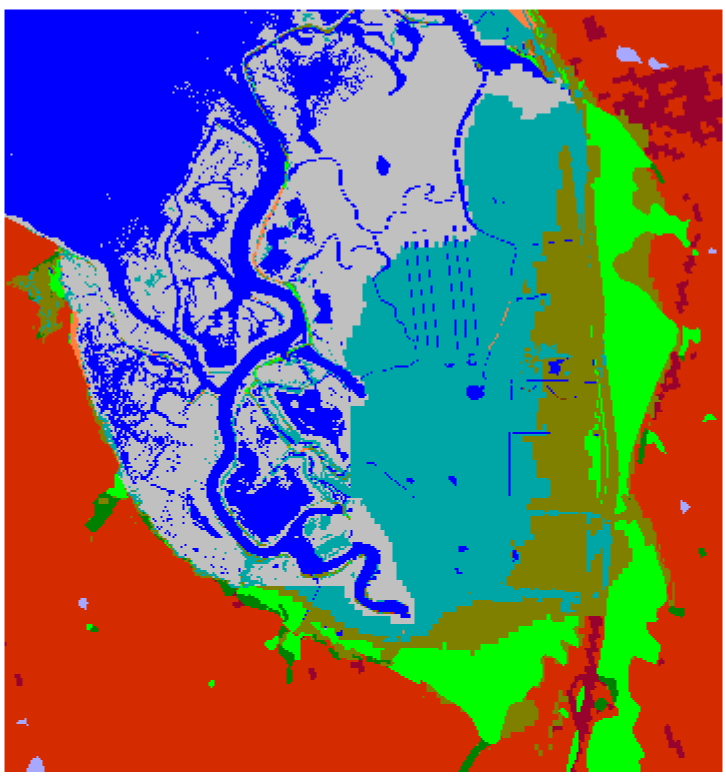
Hookton Slough, Initial Condition



Hookton Slough, “time-zero” with no dikes
(SLAMM model assumptions applied regarding wetland types given current elevations)



Hookton Slough, 2050, 1 m scenario



Hookton Slough, 2100, 1 m scenario

Discussion

The application of SLAMM to Humboldt Bay NWR indicates the effects of sea-level rise on this refuge will be significant. Tidal flat comprises the most acreage of any land-cover category within the refuge, and is predicted to be lost at a high rate, culminating in a maximum predicted loss of 92% at 1.5 m SLR by 2100. Less loss of tidal flat is predicted at the 2 m SLR by 2100 scenario since there is tidal flat created due to increased inundation of marsh under this scenario.

An important source of model uncertainty is the accretion rate for vegetation. The accretion rate for marshes in Humboldt Bay NWR was assumed to be 6 mm/yr based on a study of salt marshes in San Francisco Bay by Patrick and DeLaune (1990). Based on conversations with refuge staff, it is known that Humboldt Bay receives a high amount of sediment and therefore marshes in this area may have high accretion rates. However, there are no data to provide quantitative estimates of accretion in Humboldt Bay NWR at this time. Based on discussion with staff at the refuge, these data are currently being collected.

The best available elevation data for this site were derived from LiDAR data collected in 2002. However, LiDAR data did not cover the Hookton and White Slough areas of the refuge at the time of this study, resulting in the use of data from 10-meter contours created in 1972. The SLAMM pre-processor was utilized to estimate elevation ranges for all of the non-diked wetlands as a function of tide range and known relationships between wetland types and tide ranges when LiDAR data was unavailable. The pre-processor assumes wetland elevations to be uniformly distributed over their feasible vertical elevation ranges or "tidal frames"—an assumption that may not reflect reality. If wetlands elevations are actually clustered high in the tidal frame they would be less vulnerable to SLR. On the contrary, if in reality wetlands are towards the bottom, they are more vulnerable than what is predicted by the simulation results.

Tidal flat results are an especially uncertain portion of SLAMM model results. The effects of storms, spatially variable erosion and accretion rates, uncertainty about the nature of substrate below existing marshes, and uncertainty about the initial tidal-flat to open-water boundary make a precise accounting of tidal-flat fate difficult to achieve.

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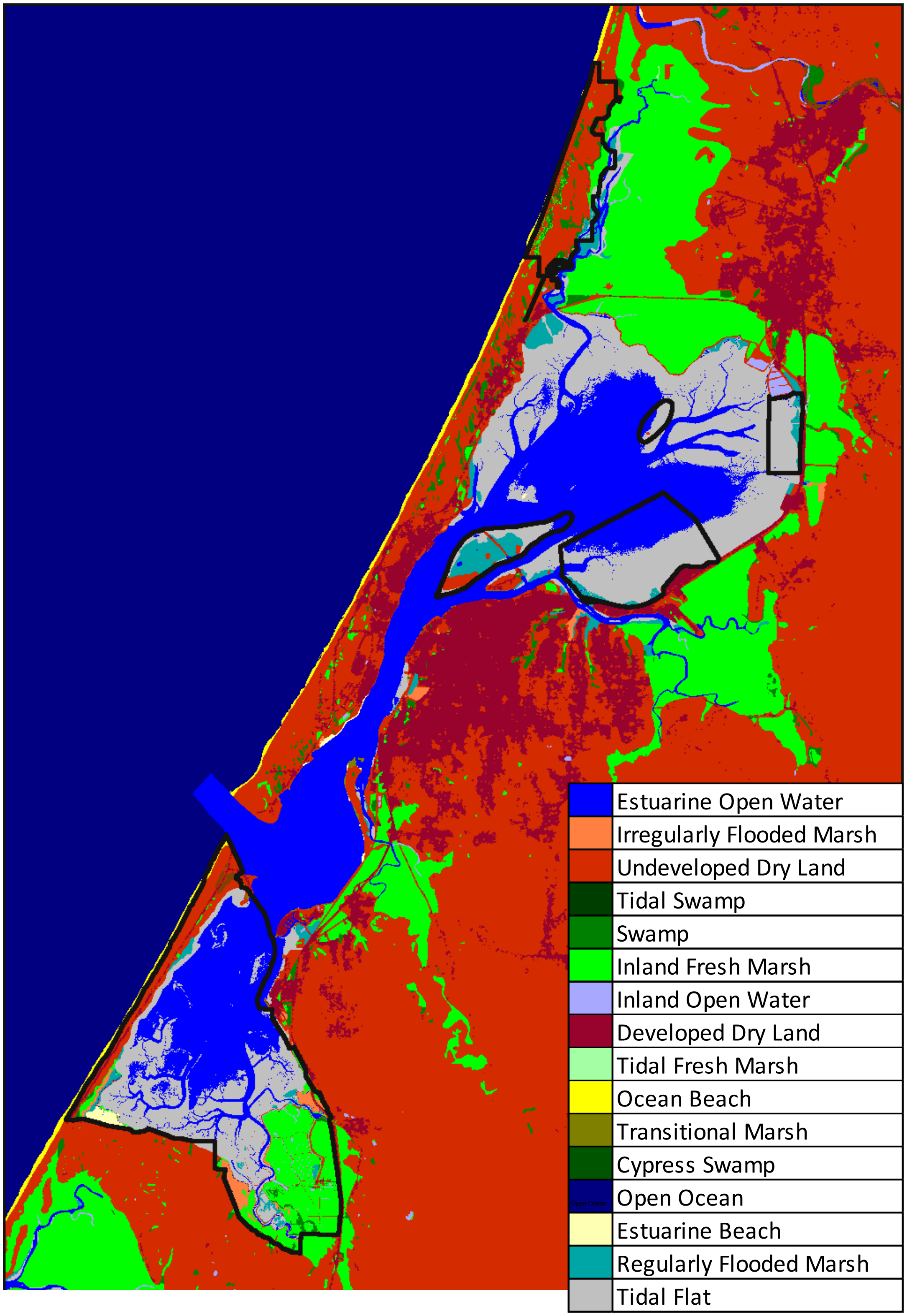
Appendix A: Contextual Results

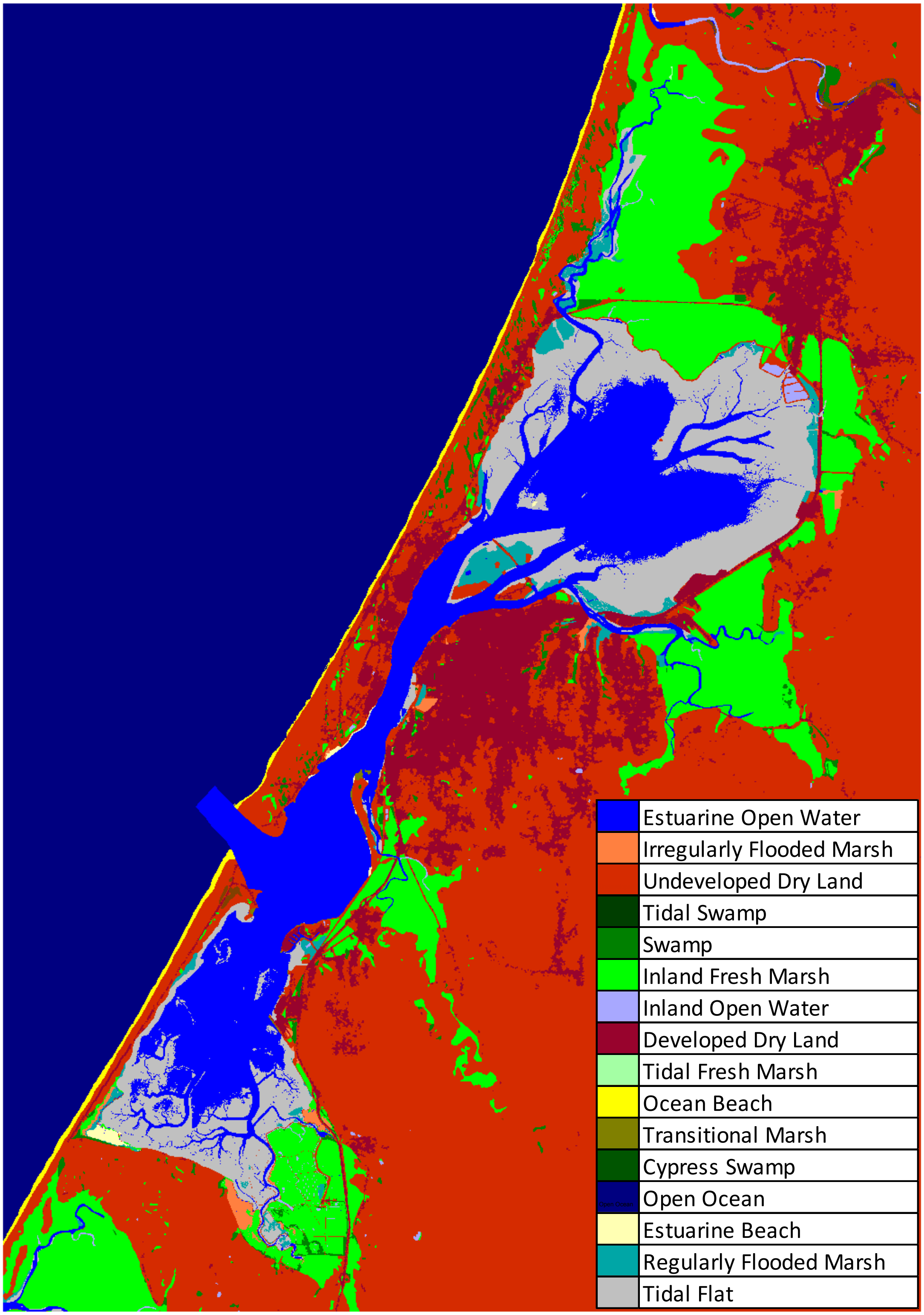
The SLAMM model does take into account the context of the surrounding lands or open water when calculating effects. For example, erosion rates are calculated based on the maximum fetch (wave action) which is estimated by assessing contiguous open water to a given marsh cell. Another example is that inundated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

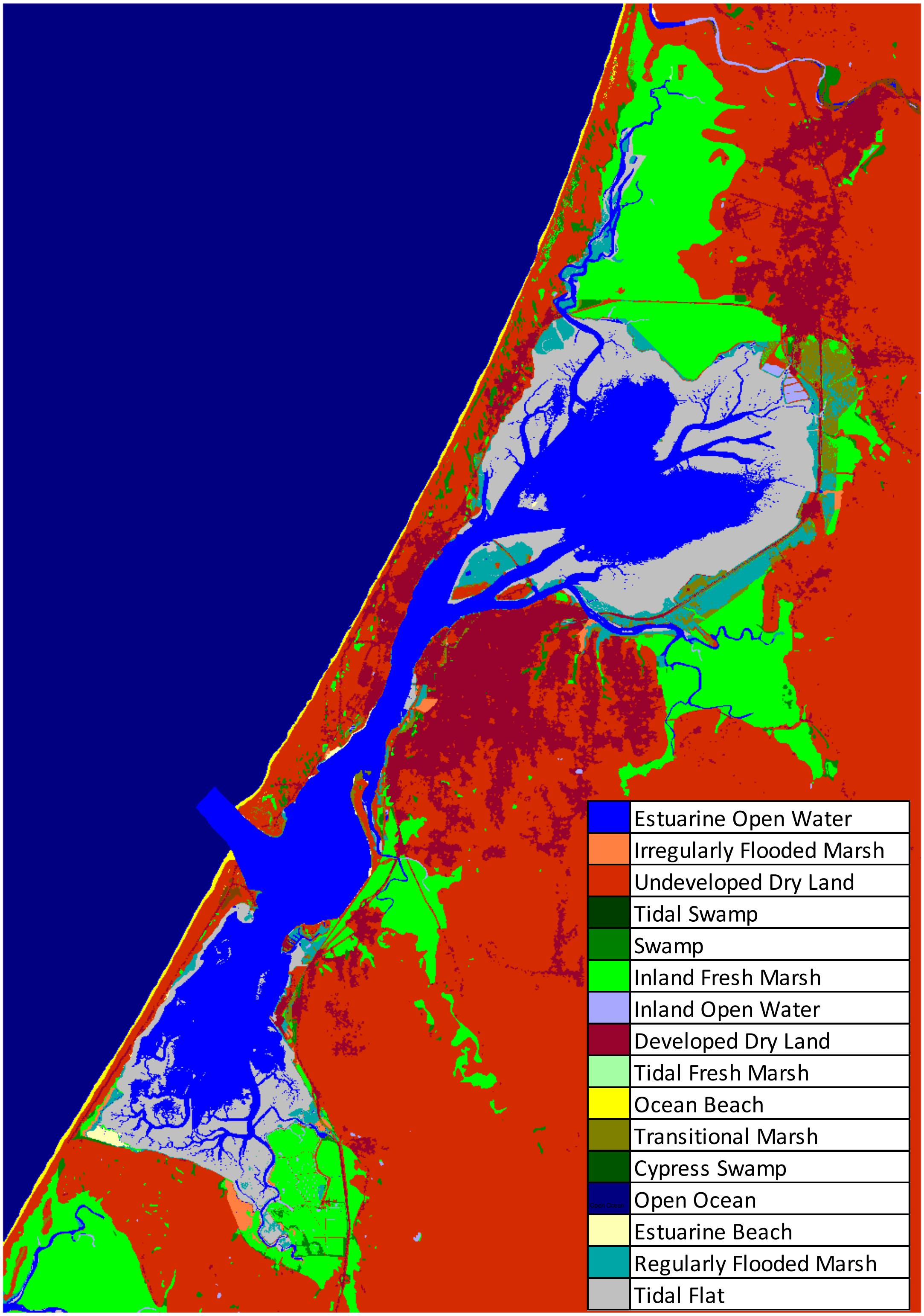
- Results were closely examined (quality assurance) within USFWS refuges but not closely examined for the larger region.
- Site-specific parameters for the model were derived for USFWS refuges whenever possible and may not be regionally applicable.
- Especially in areas where dikes are present, an effort was made to assess the probable location and effects of dikes for USFWS refuges, but this effort was not made for surrounding areas
- The inland-fresh marsh surrounding Hookton Slough was designated as diked.
- The effect of partially breached dikes, tide gates, or roadways leading to muted tidal regimes within the contextual area was not included.



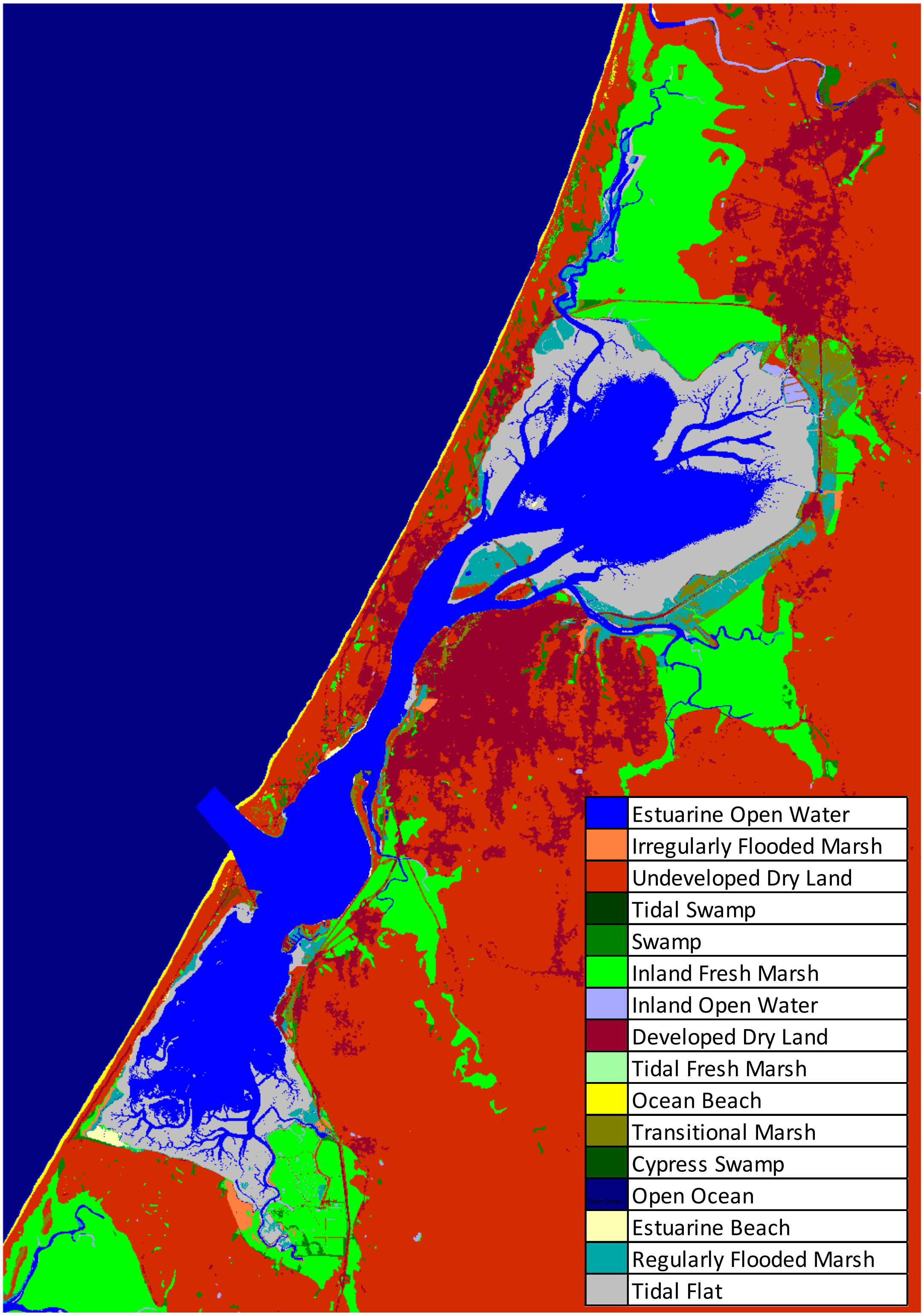
Humboldt Bay NWR within simulation context.



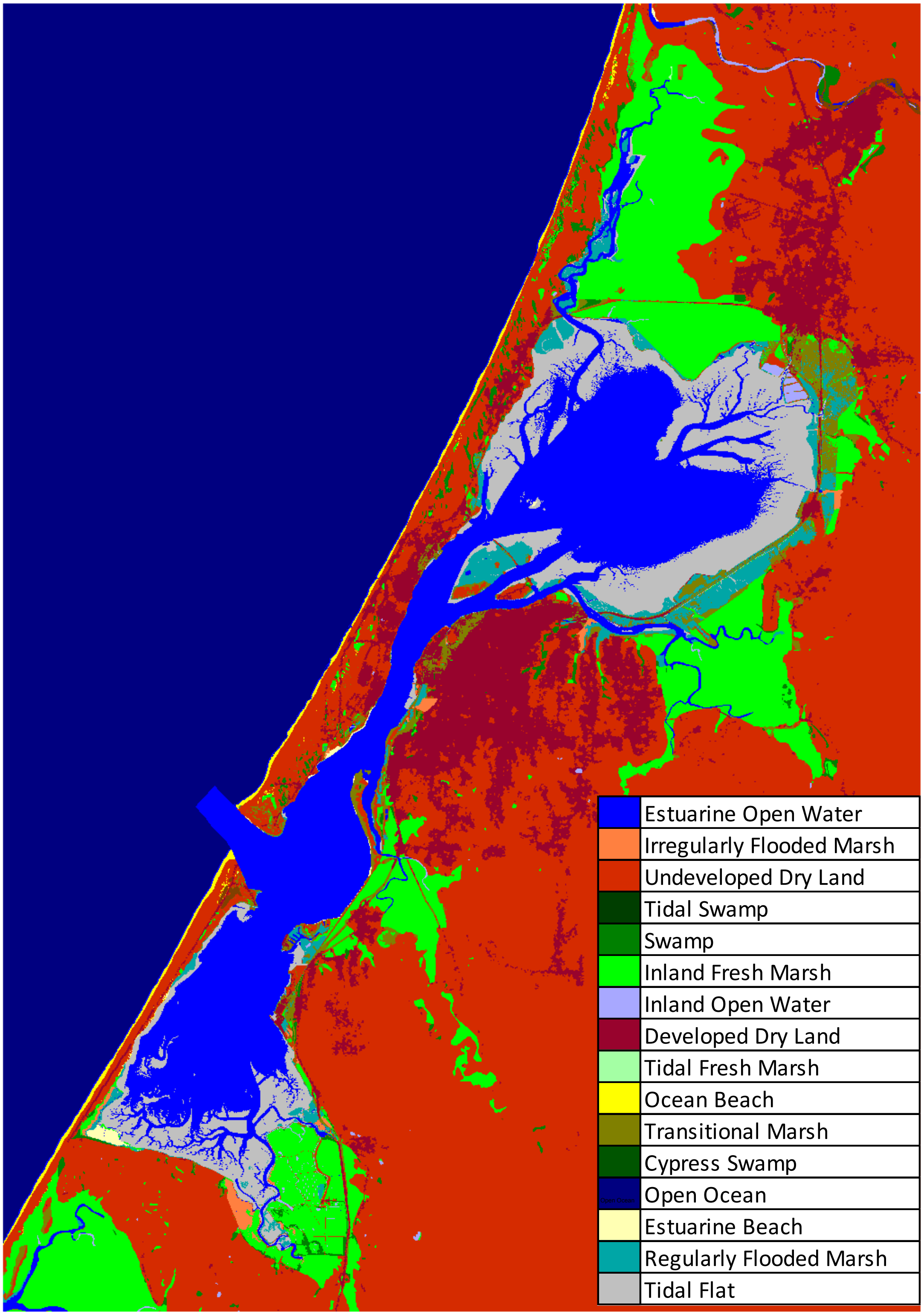
Humboldt Bay context, Initial conditions



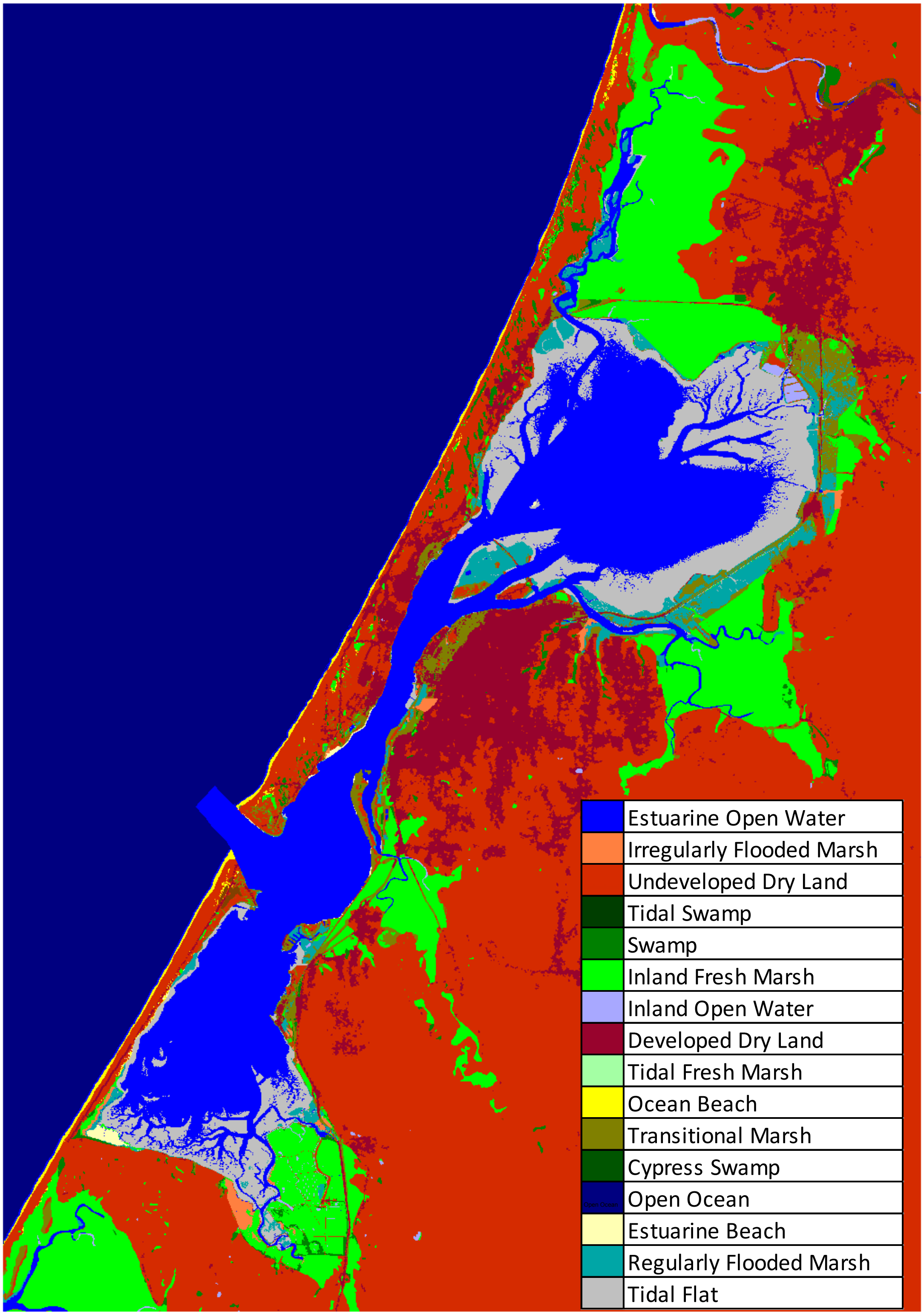
Humboldt Bay context, 2025, Scenario A1B Mean, 0.39 m SLR



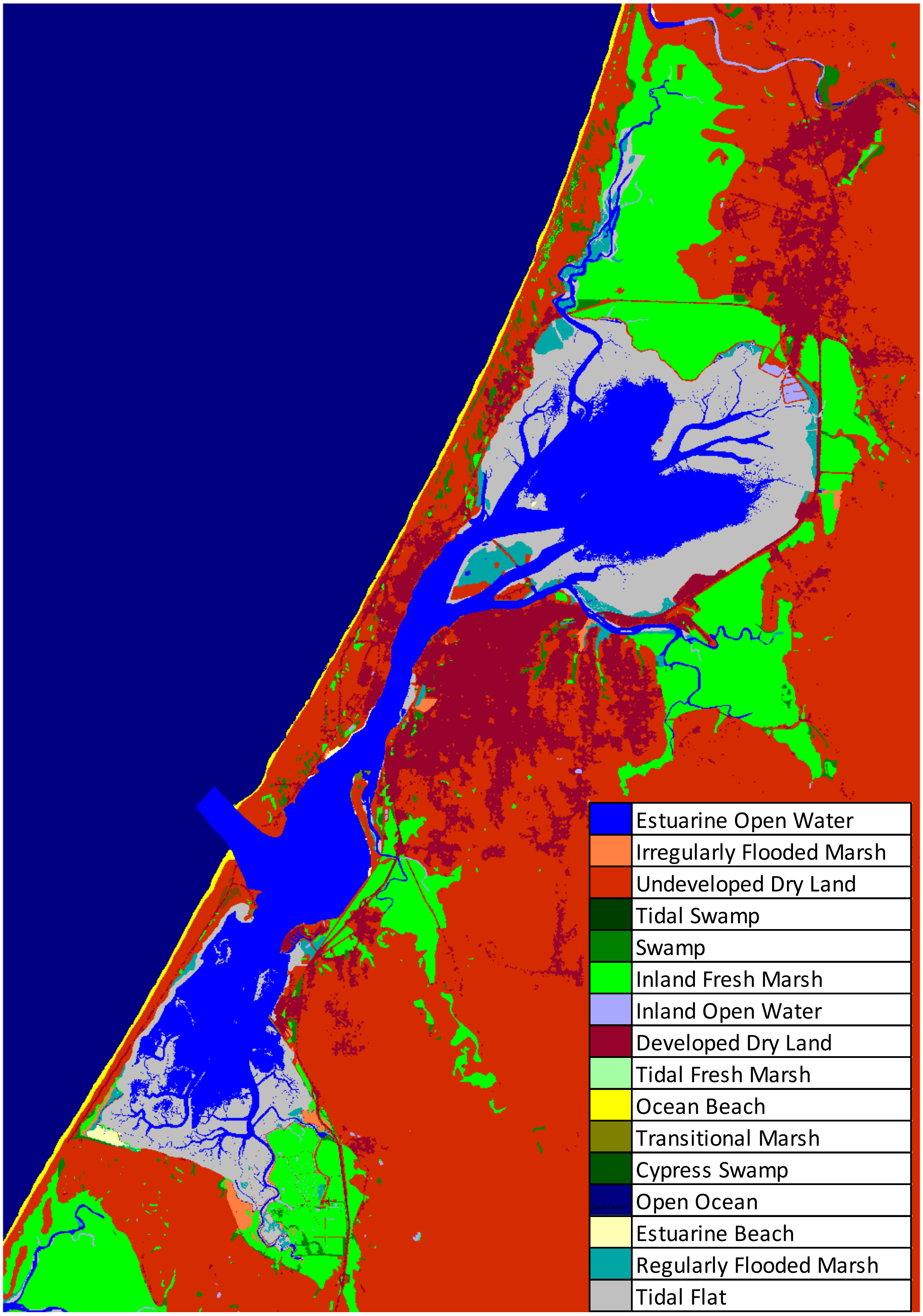
Humboldt Bay context, 2050, Scenario A1B Mean, 0.39 m SLR



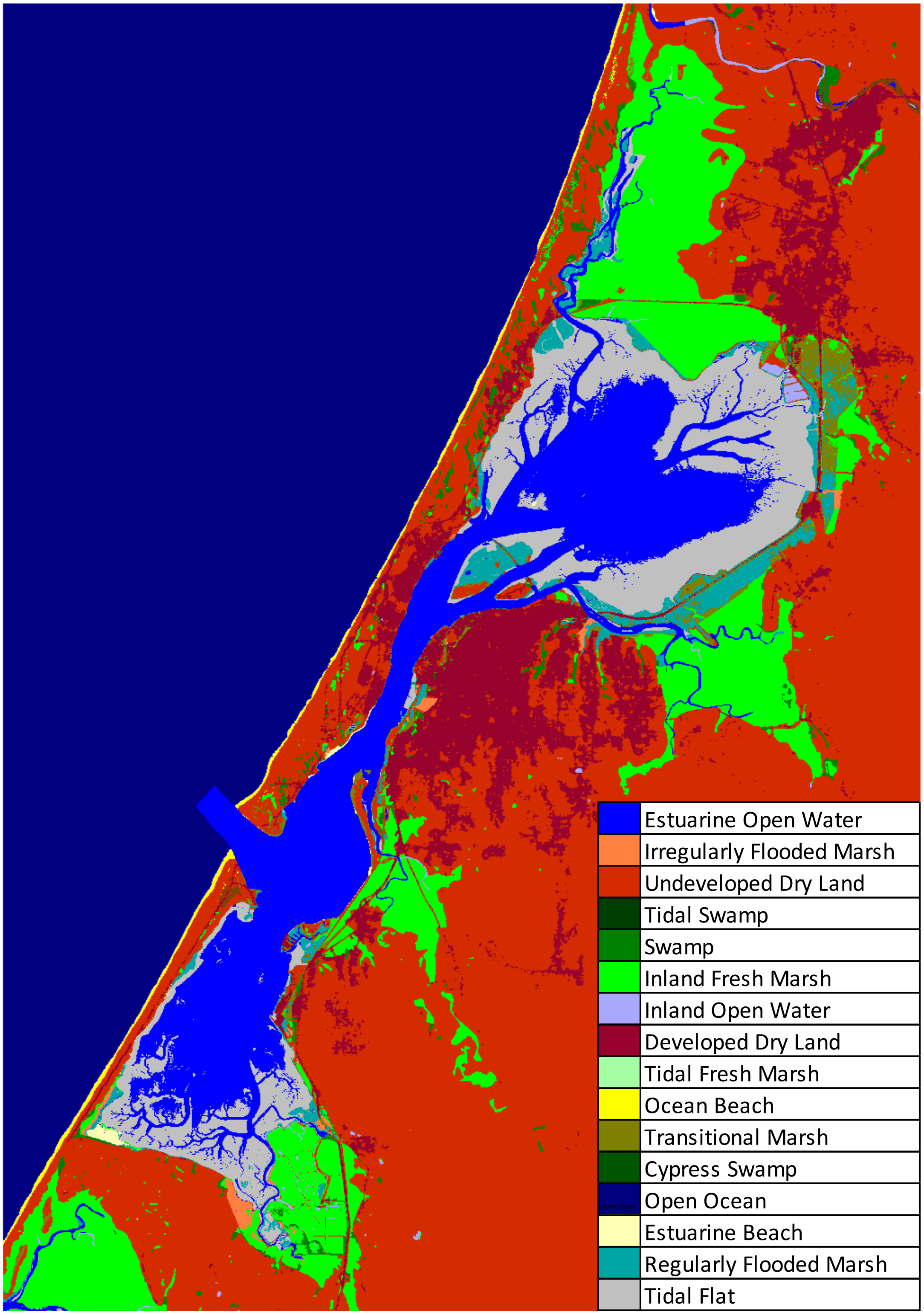
Humboldt Bay context, 2075, Scenario A1B Mean, 0.39 m SLR



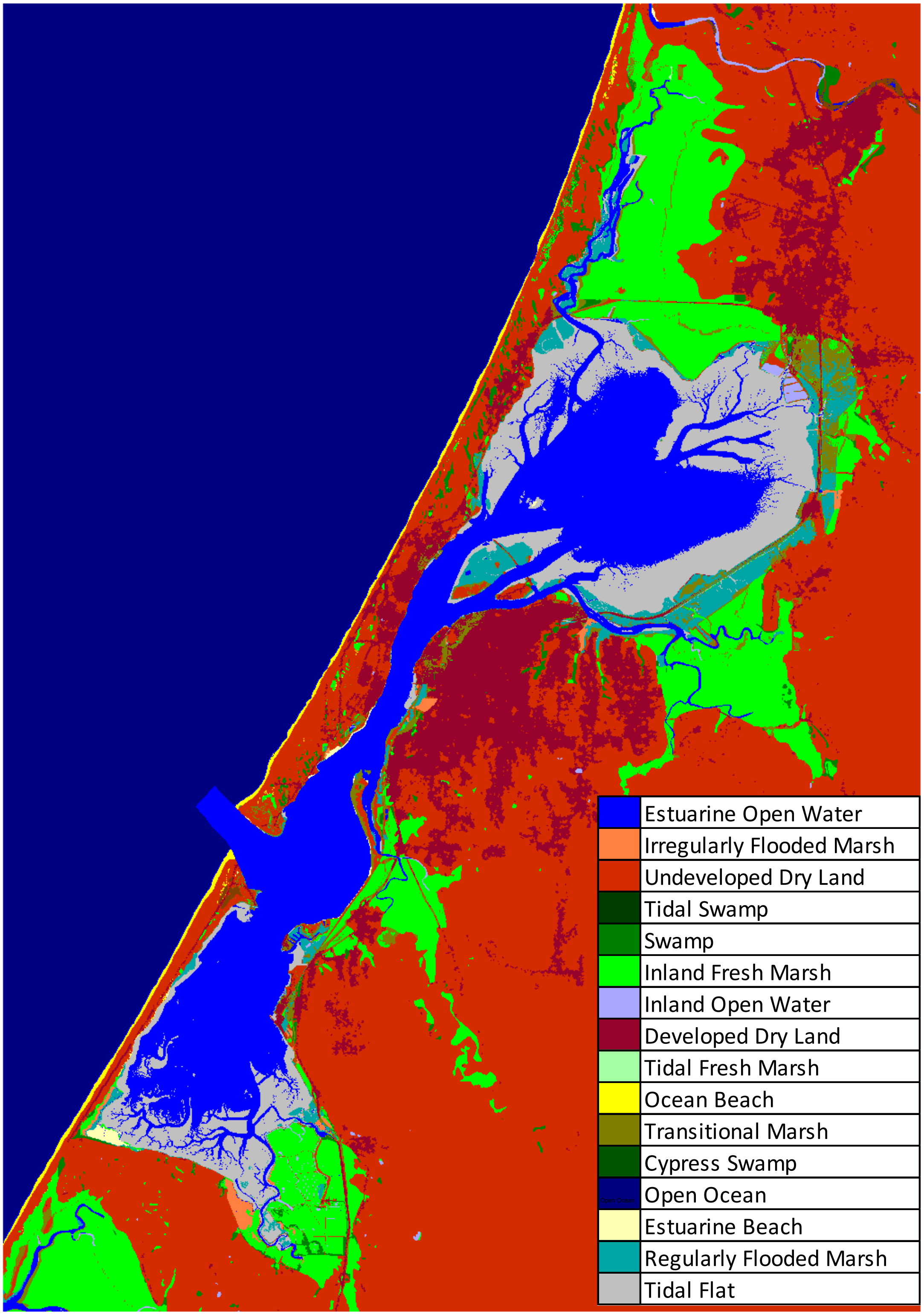
Humboldt Bay context, 2100, Scenario A1B Mean, 0.39 m SLR



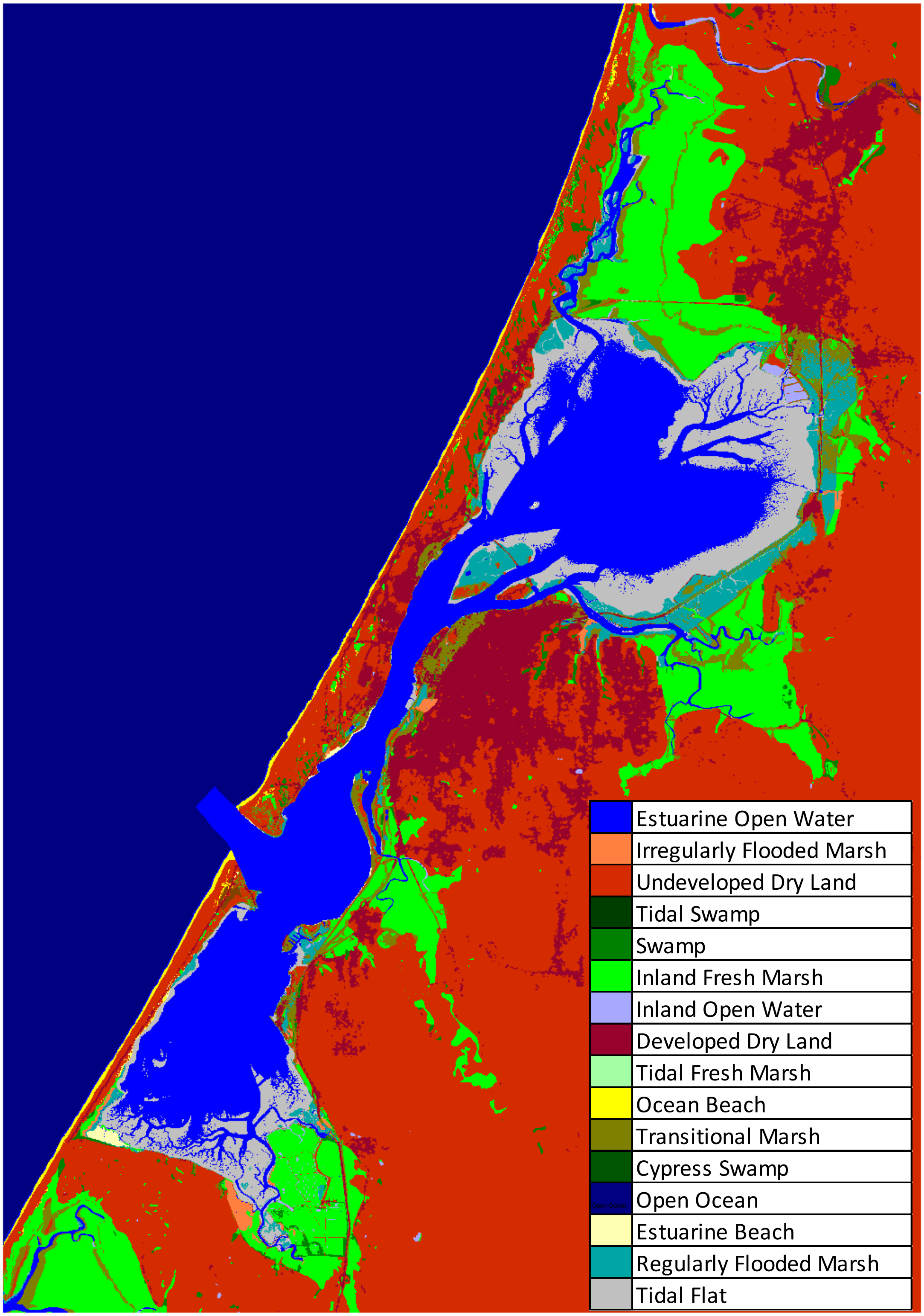
Humboldt Bay context, Initial Condition



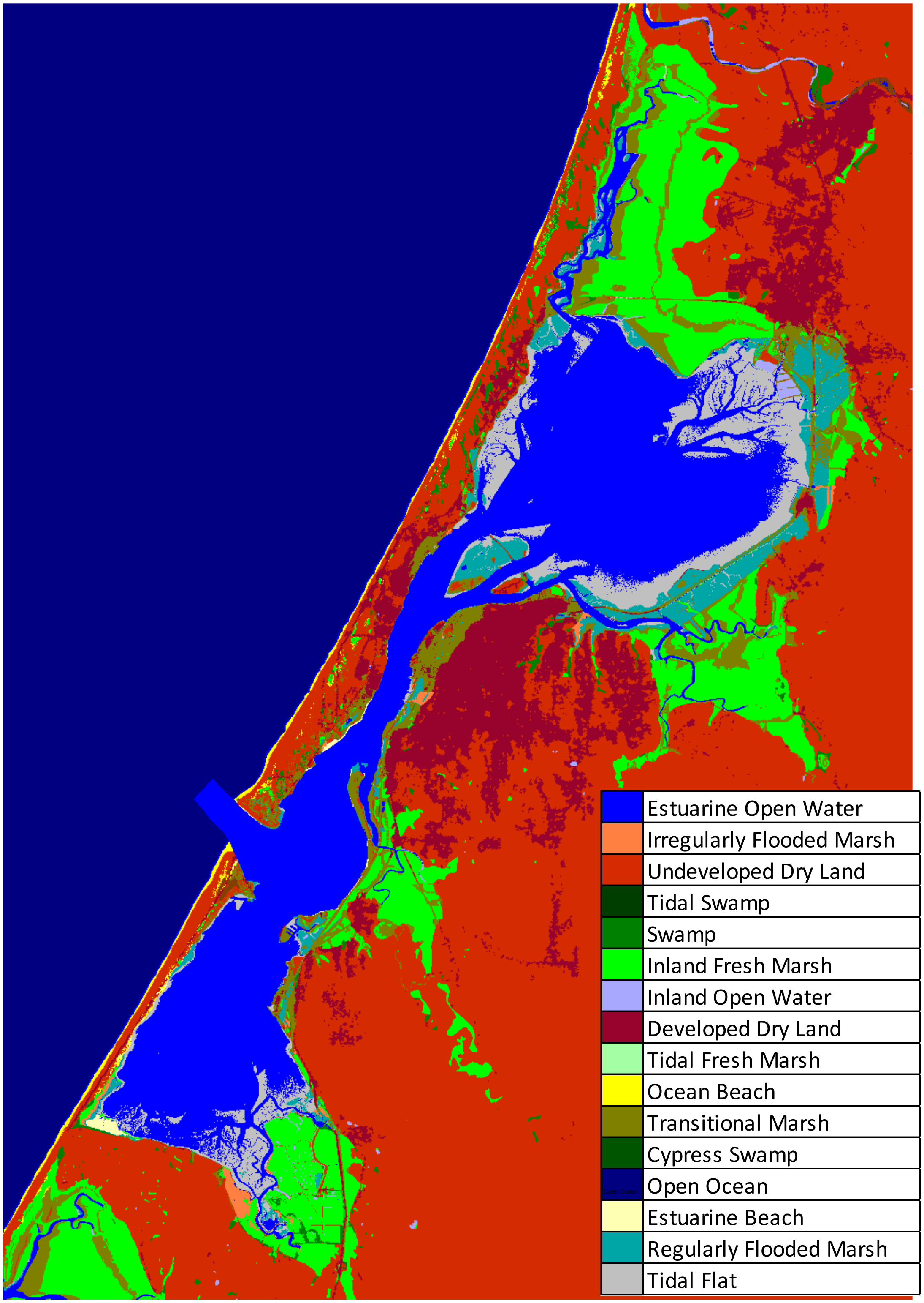
Humboldt Bay context, 2025, Scenario A1B Maximum, 0.69 m SLR



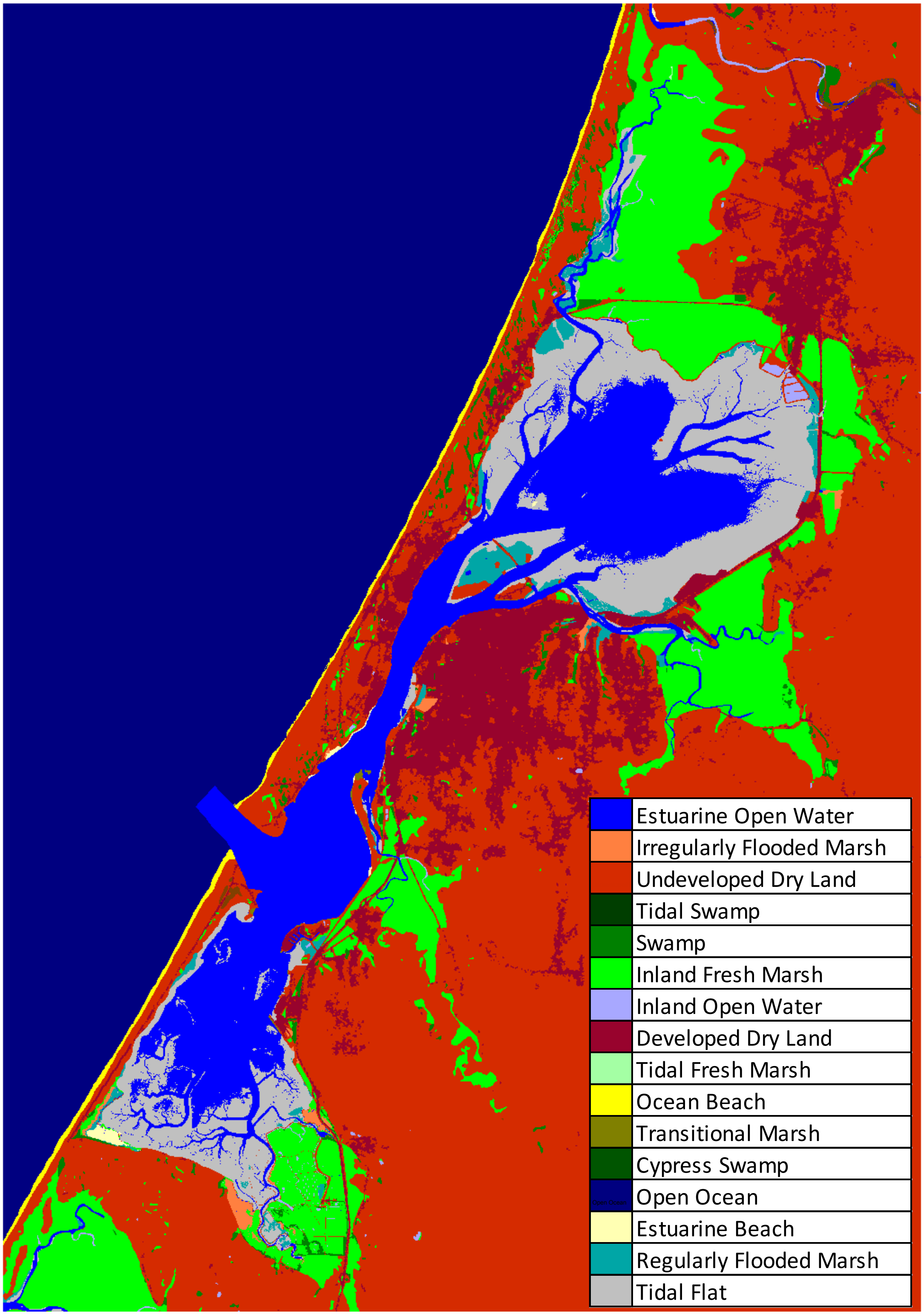
Humboldt Bay context, 2050, Scenario A1B Maximum, 0.69 m SLR



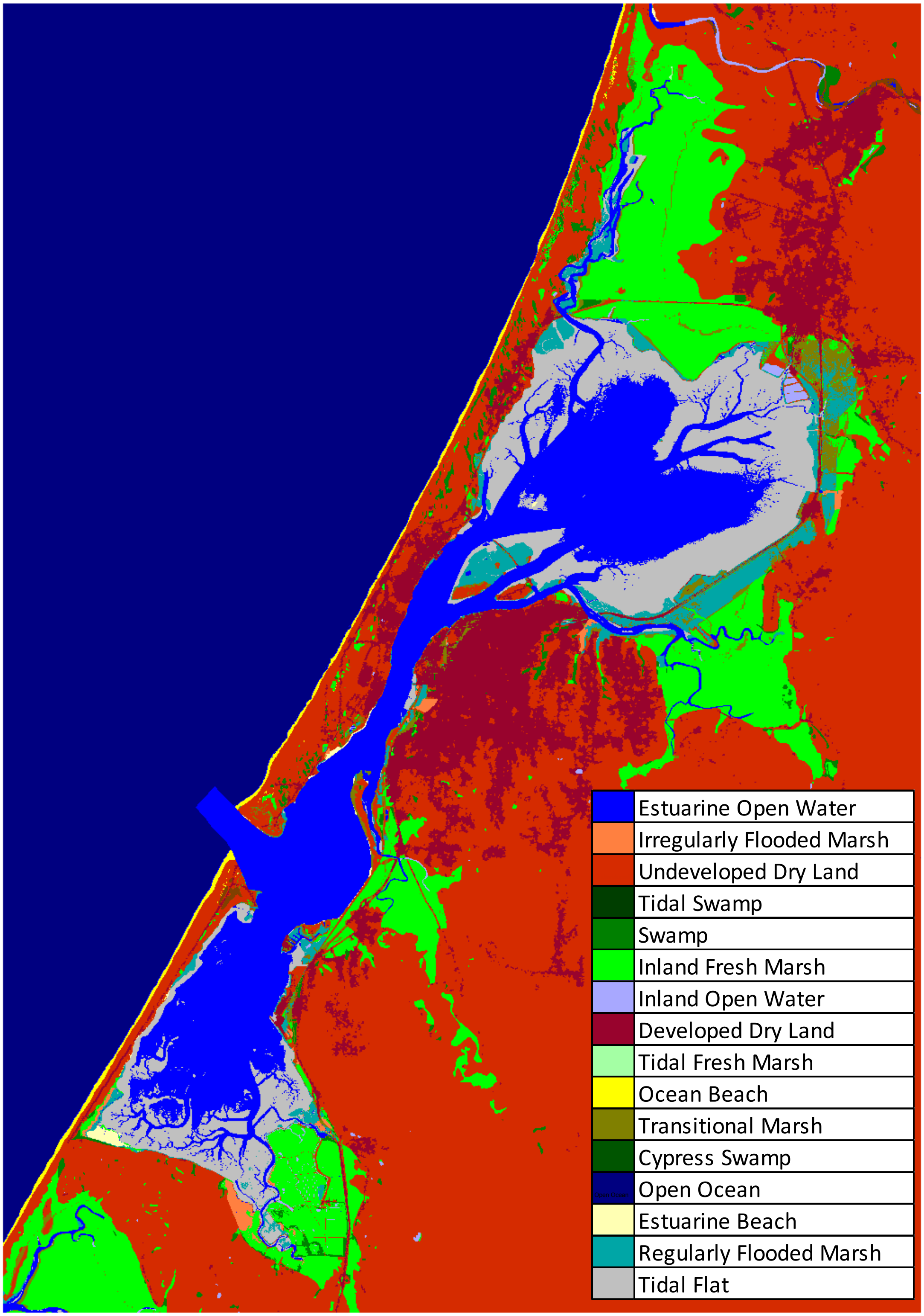
Humboldt Bay context, 2075, Scenario A1B Maximum, 0.69 m SLR



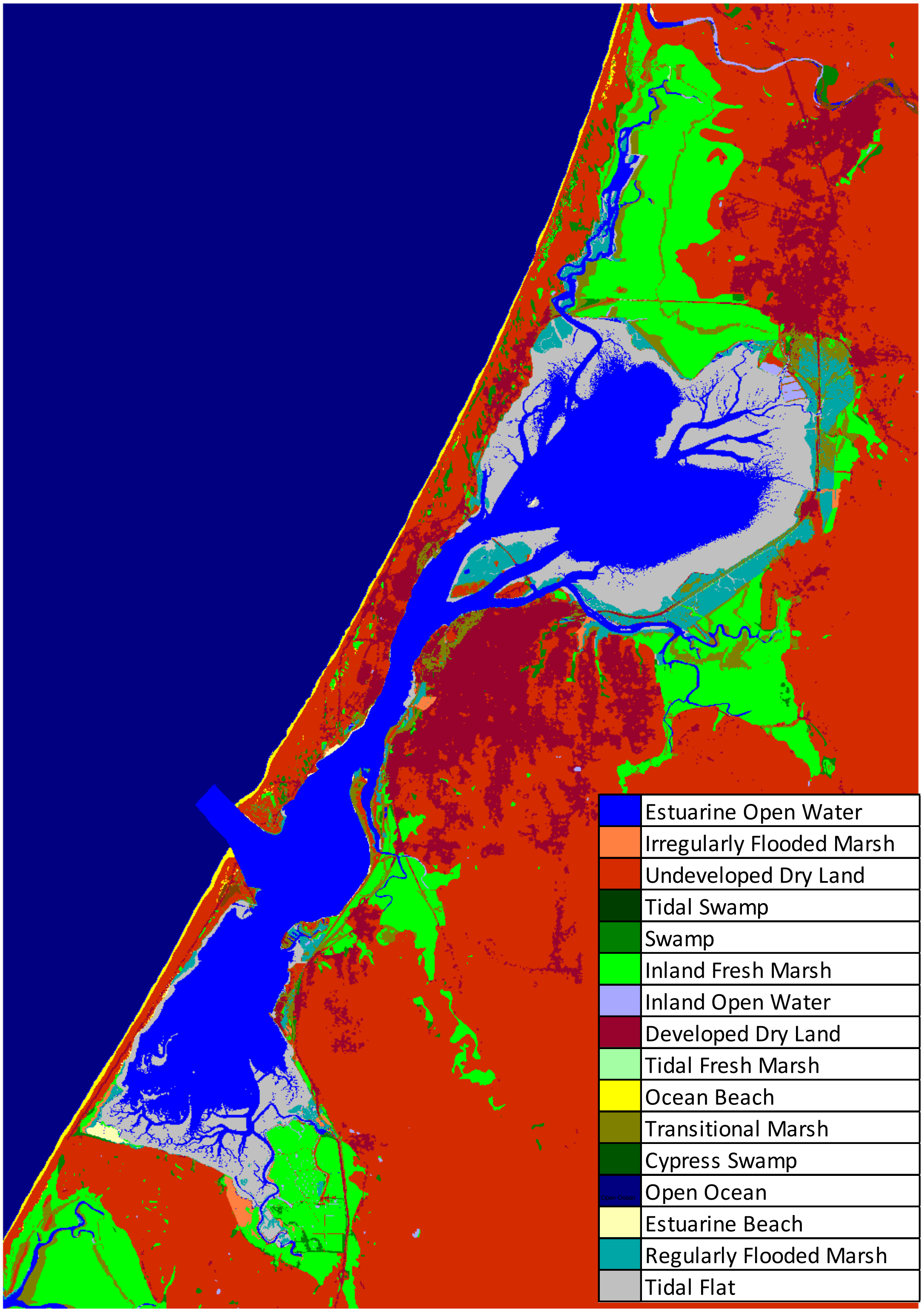
Humboldt Bay context, 2100, Scenario A1B Maximum, 0.69 m SLR



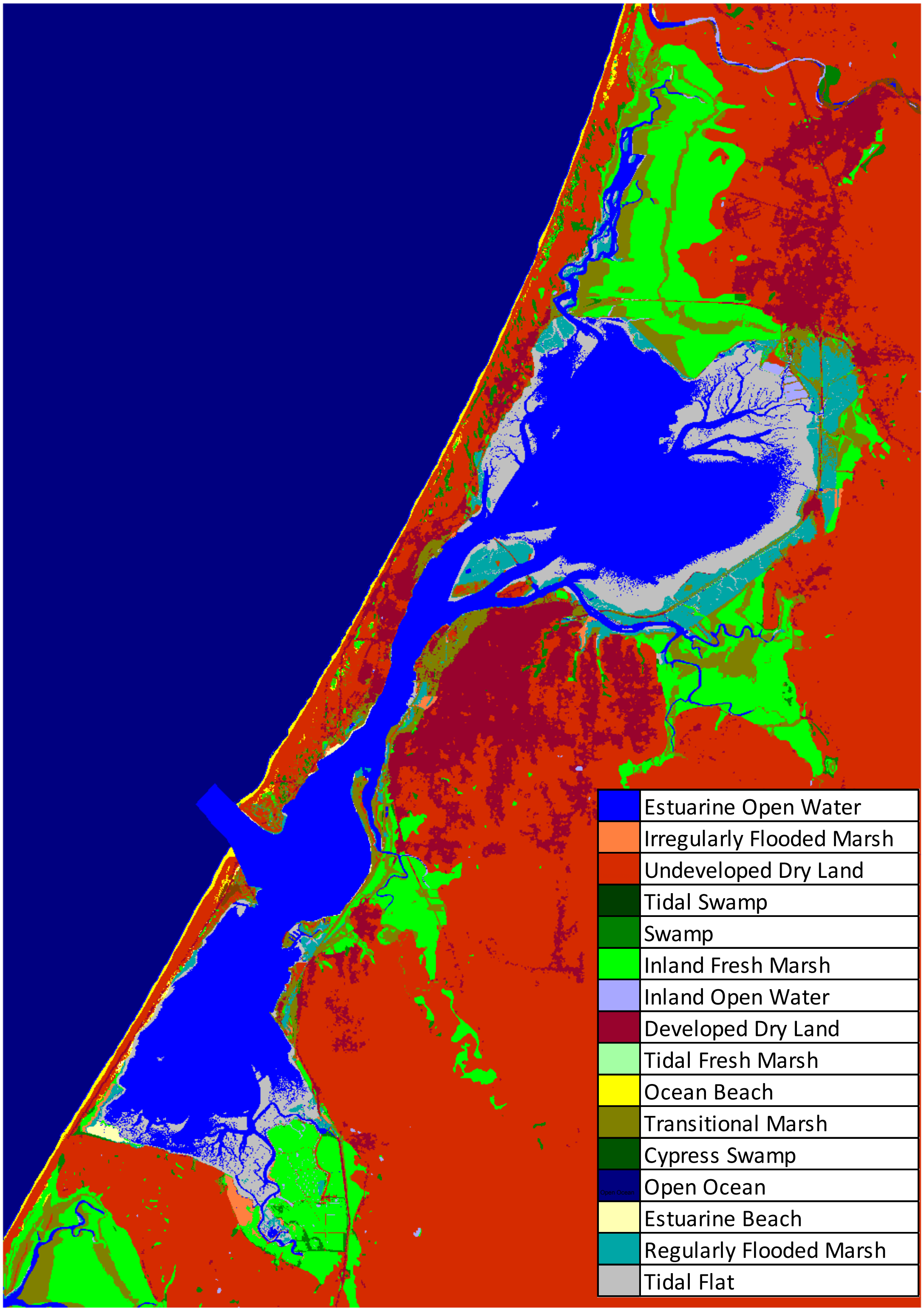
Humboldt Bay context, Initial Condition



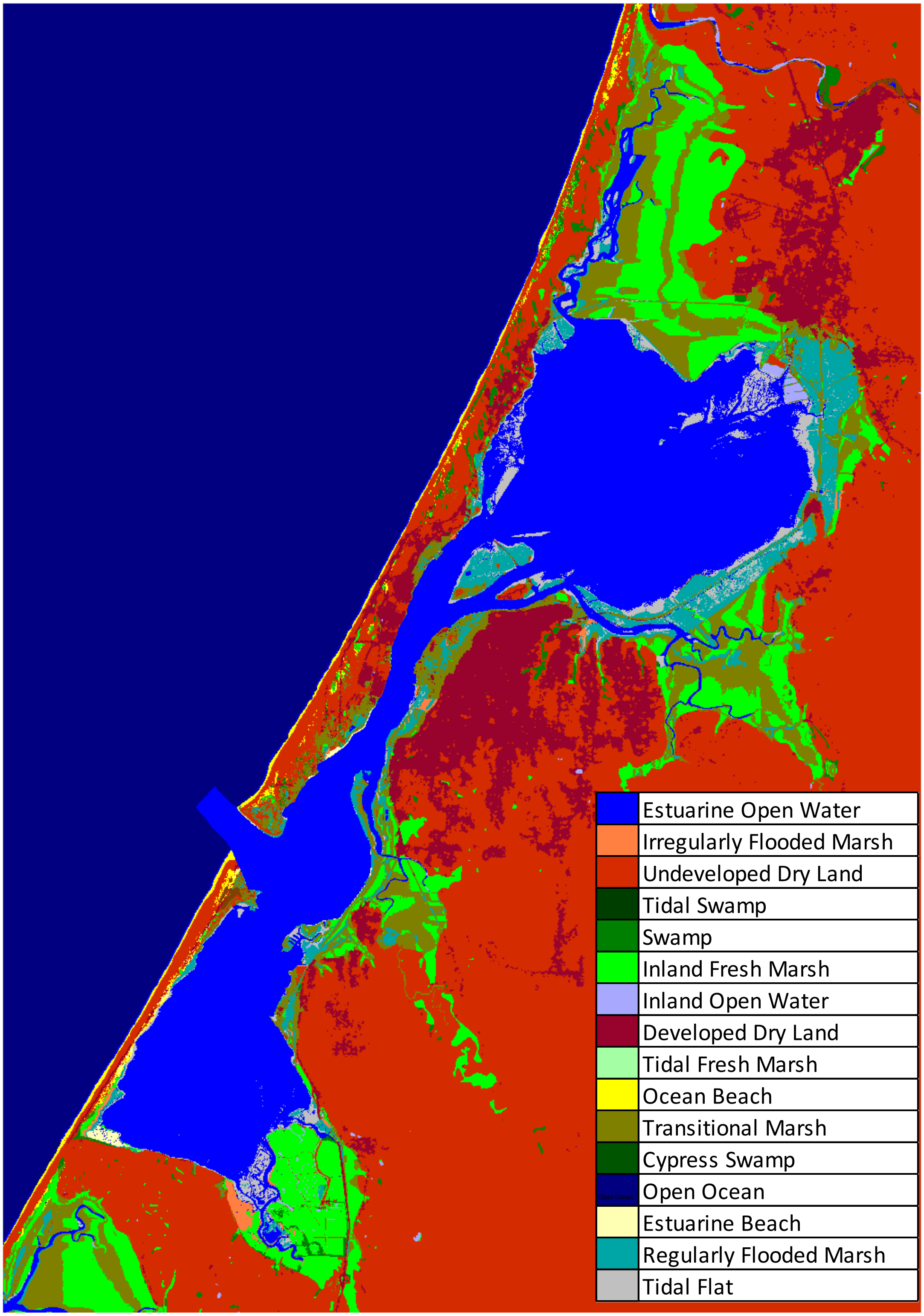
Humboldt Bay context, 2025, 1 m SLR



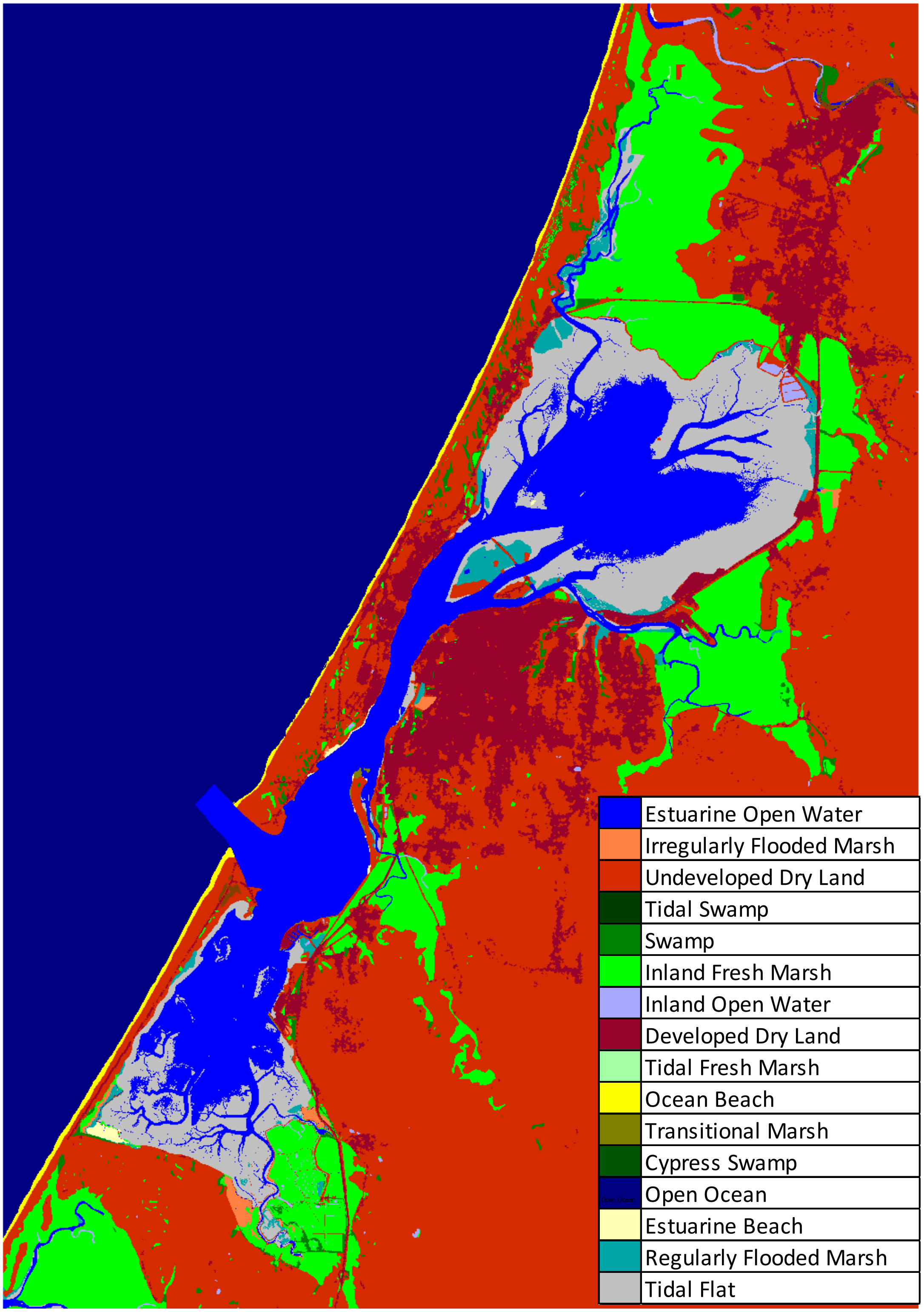
Humboldt Bay context, 2050, 1 m SLR



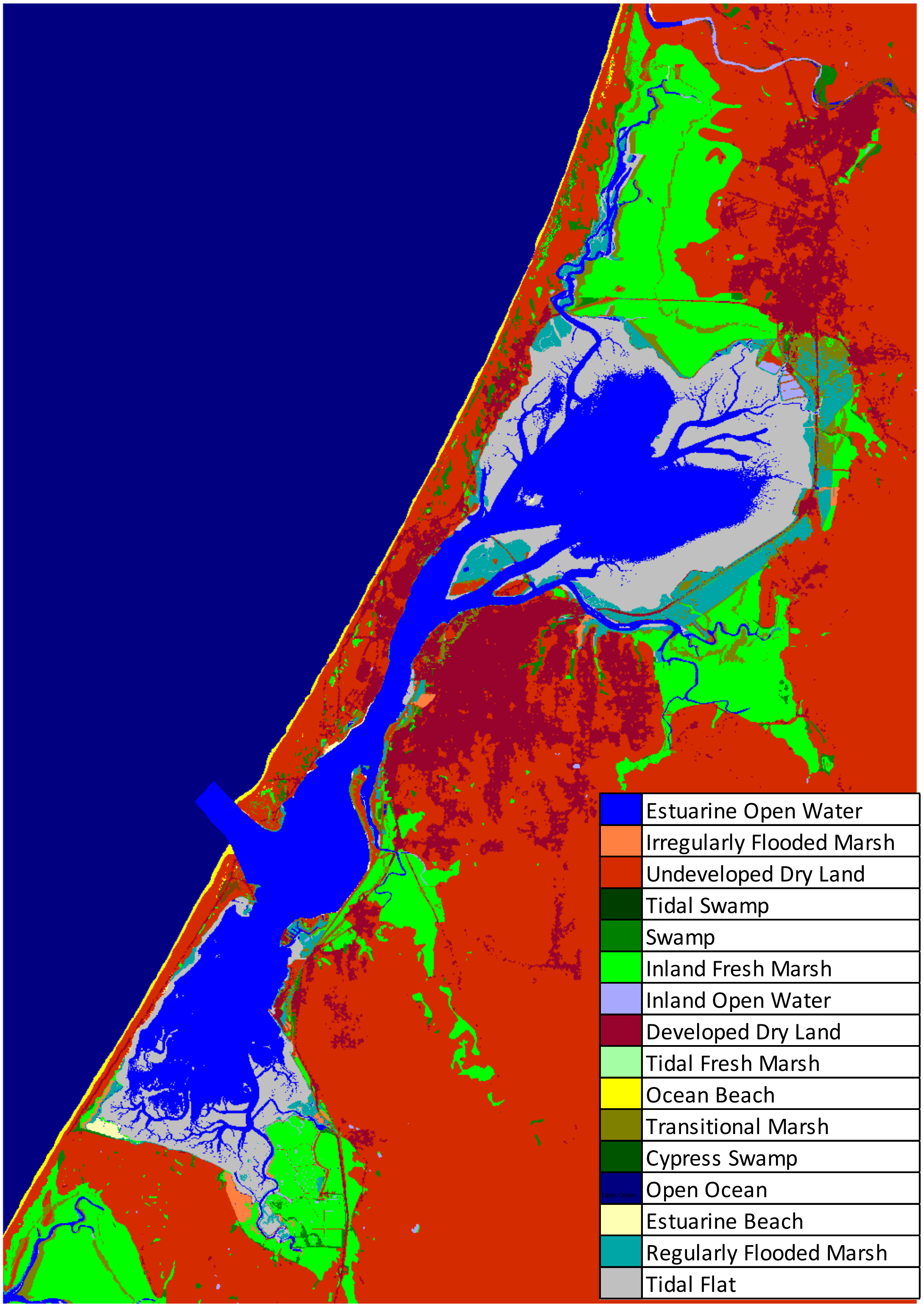
Humboldt Bay context, 2075, 1 m SLR



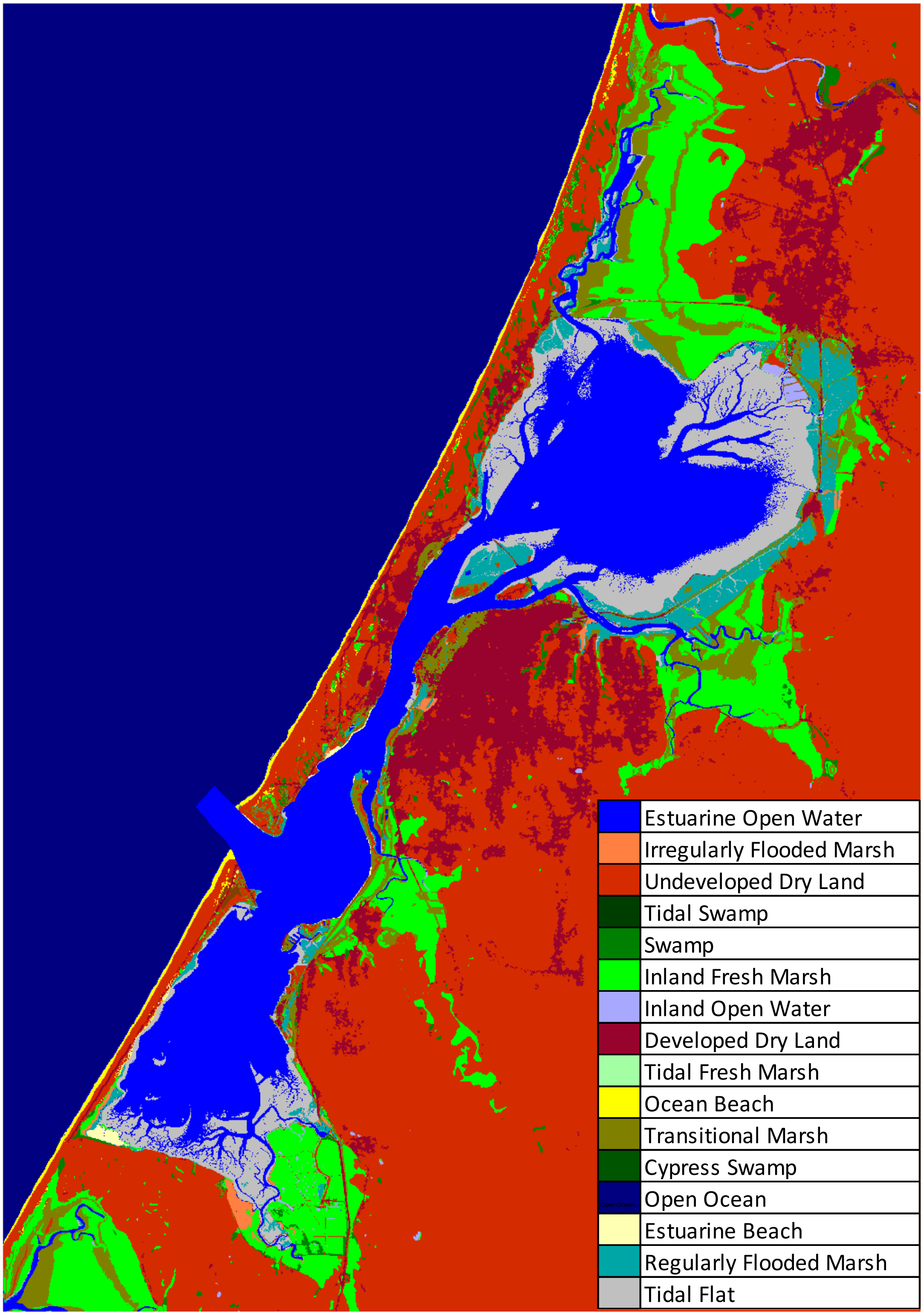
Humboldt Bay context, 2100, 1 m SLR



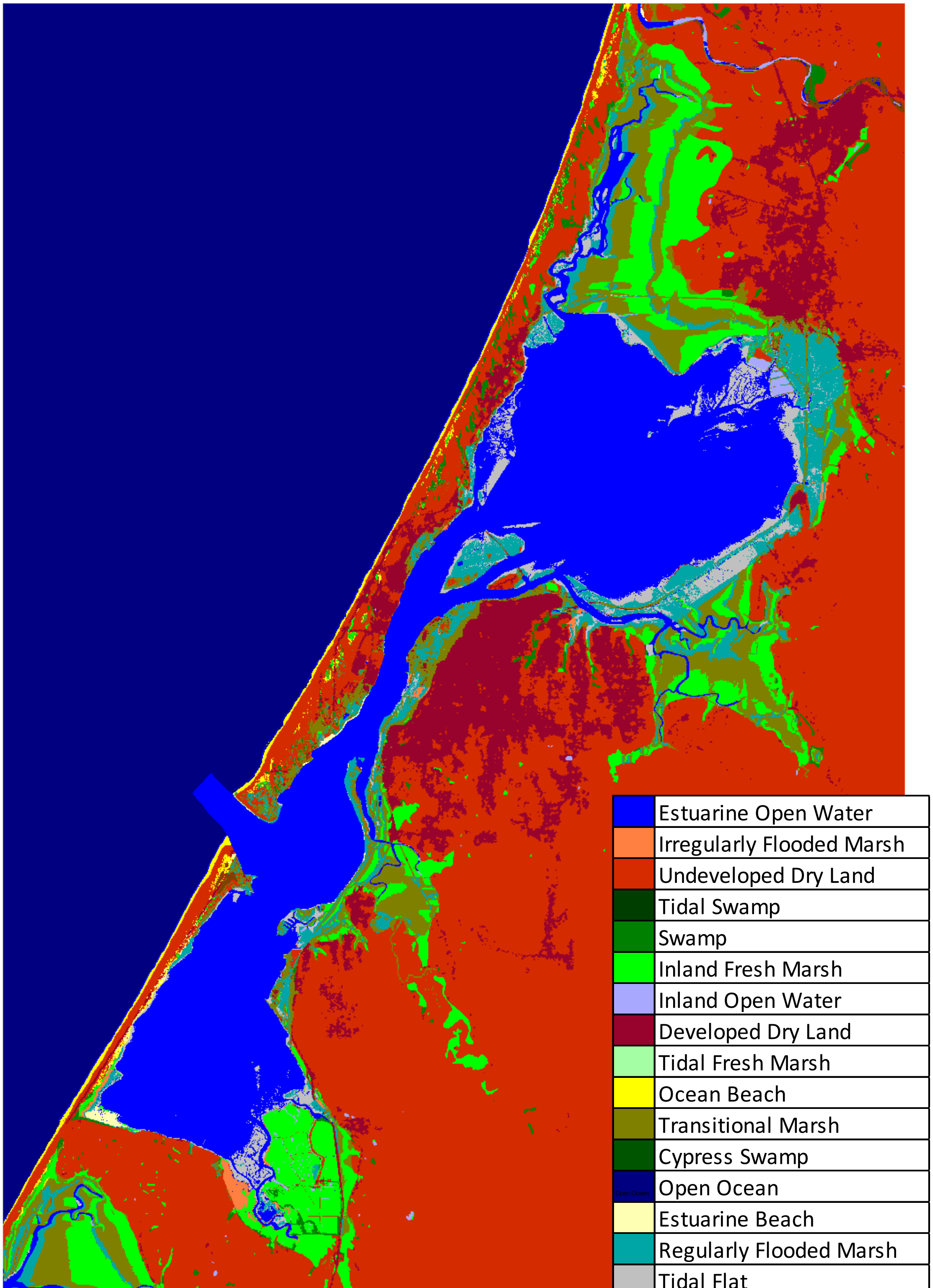
Humboldt Bay context, Initial Condition



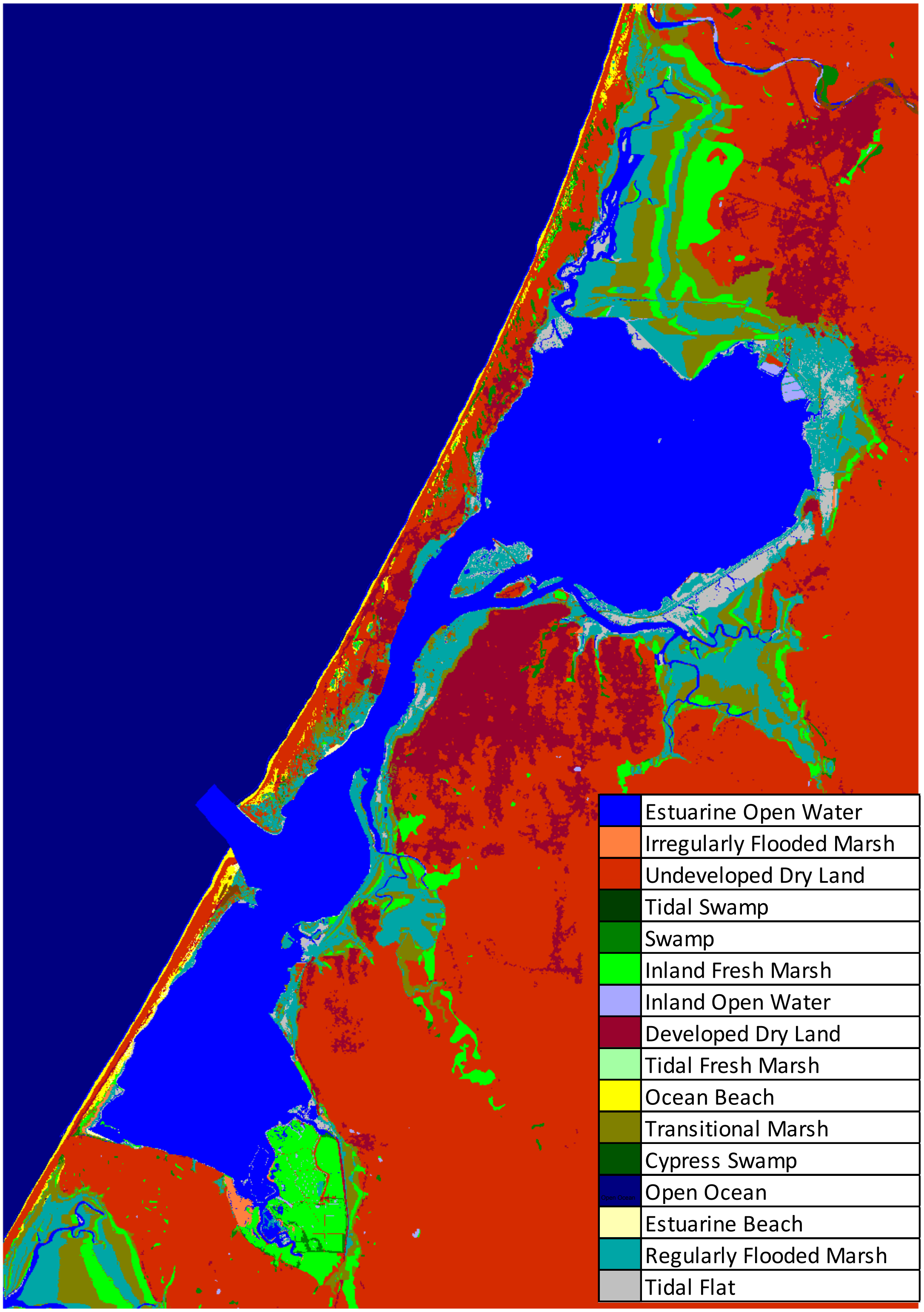
Humboldt Bay context, 2025, 1.5 m SLR



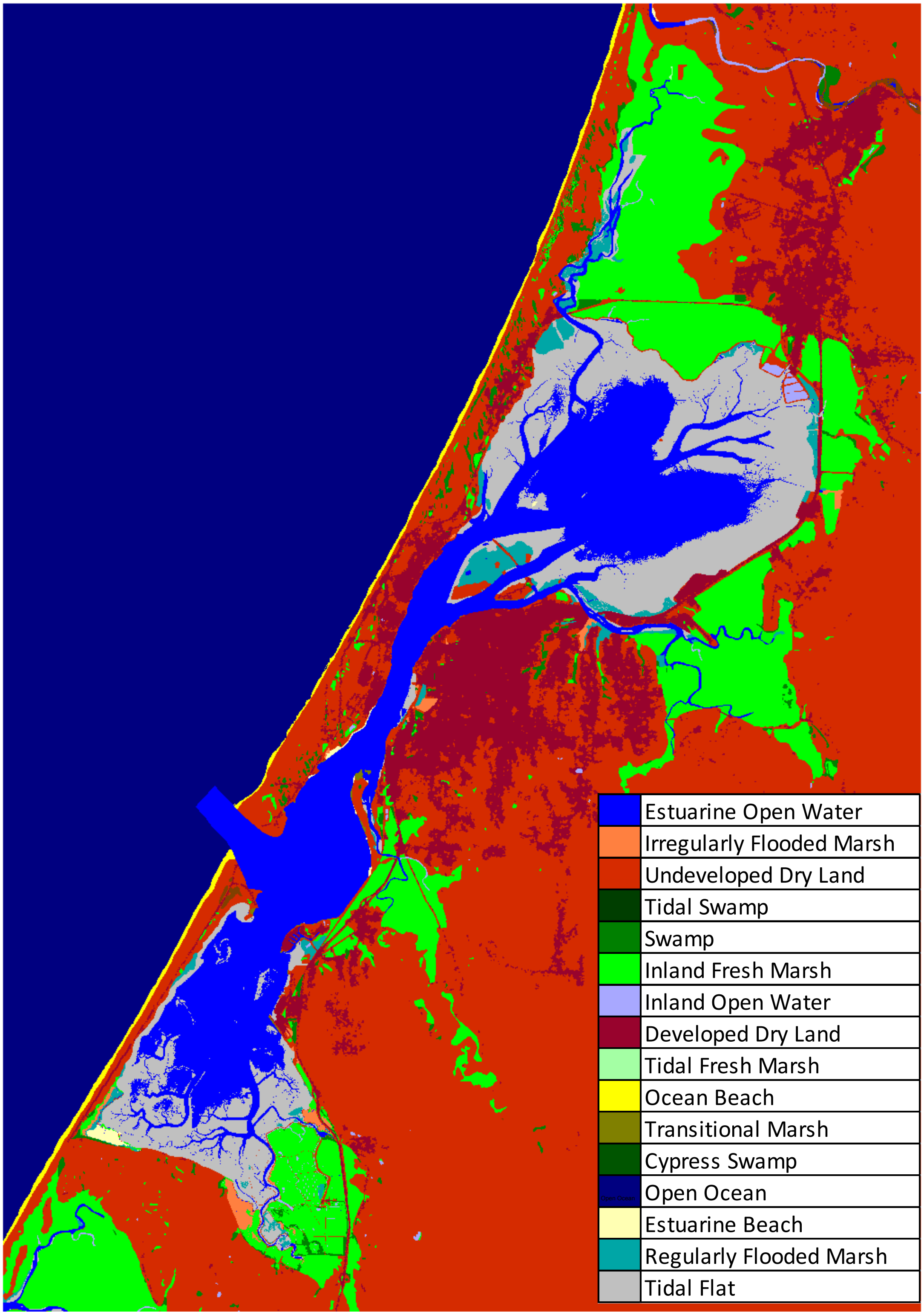
Humboldt Bay context, 2050, 1.5 m SLR



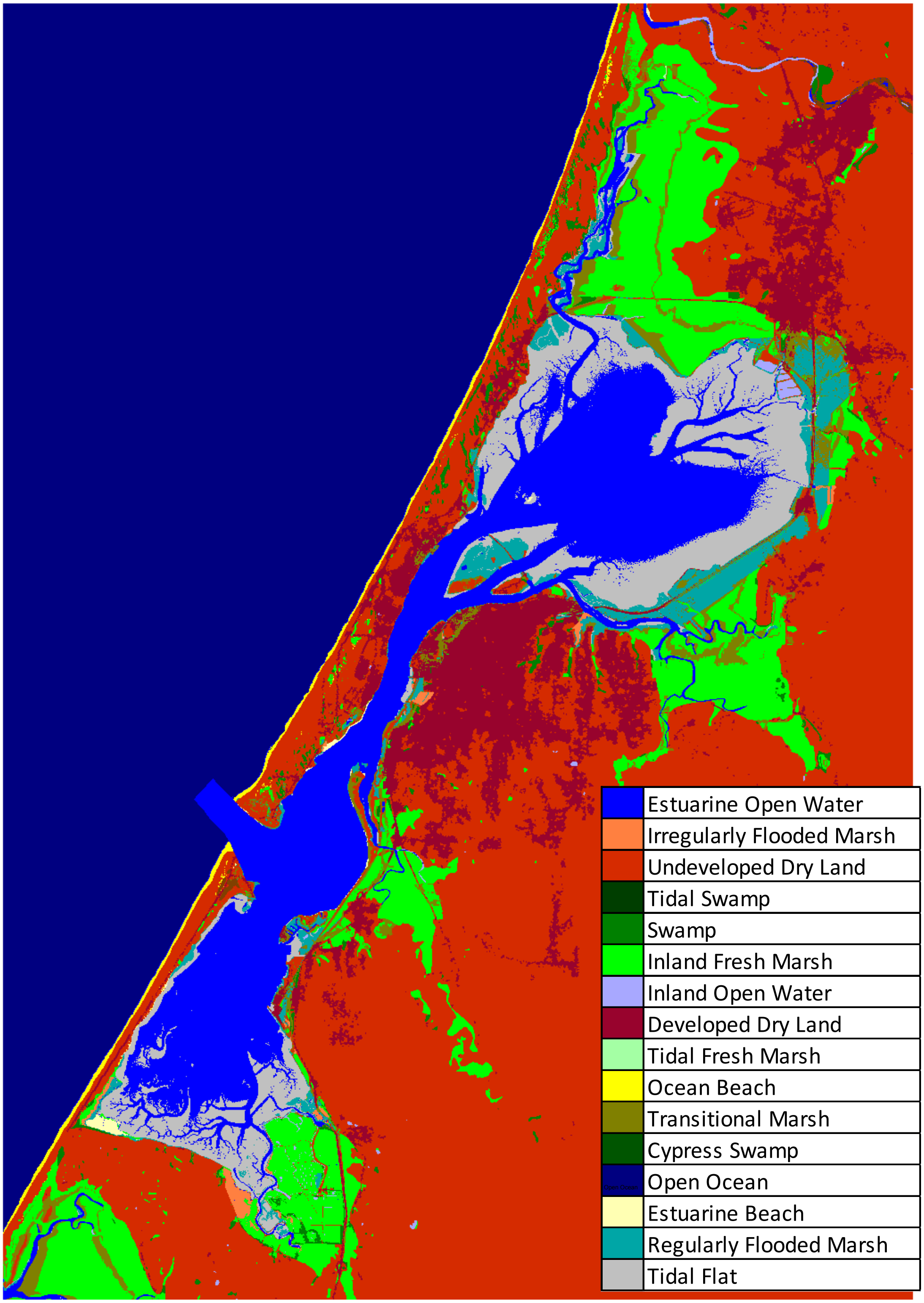
Humboldt Bay context, 2075, 1.5 m SLR



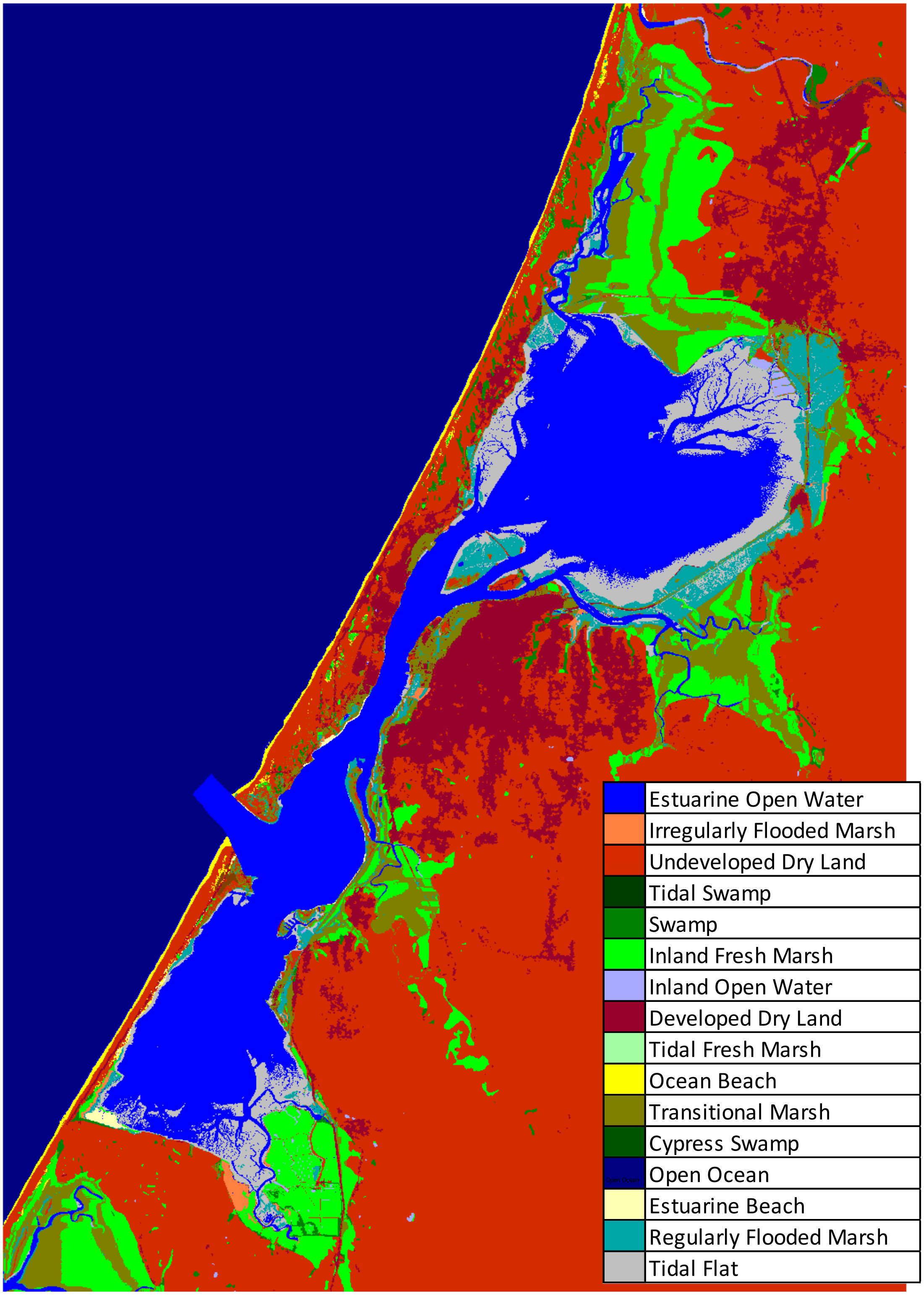
Humboldt Bay context, 2100, 1.5 m SLR



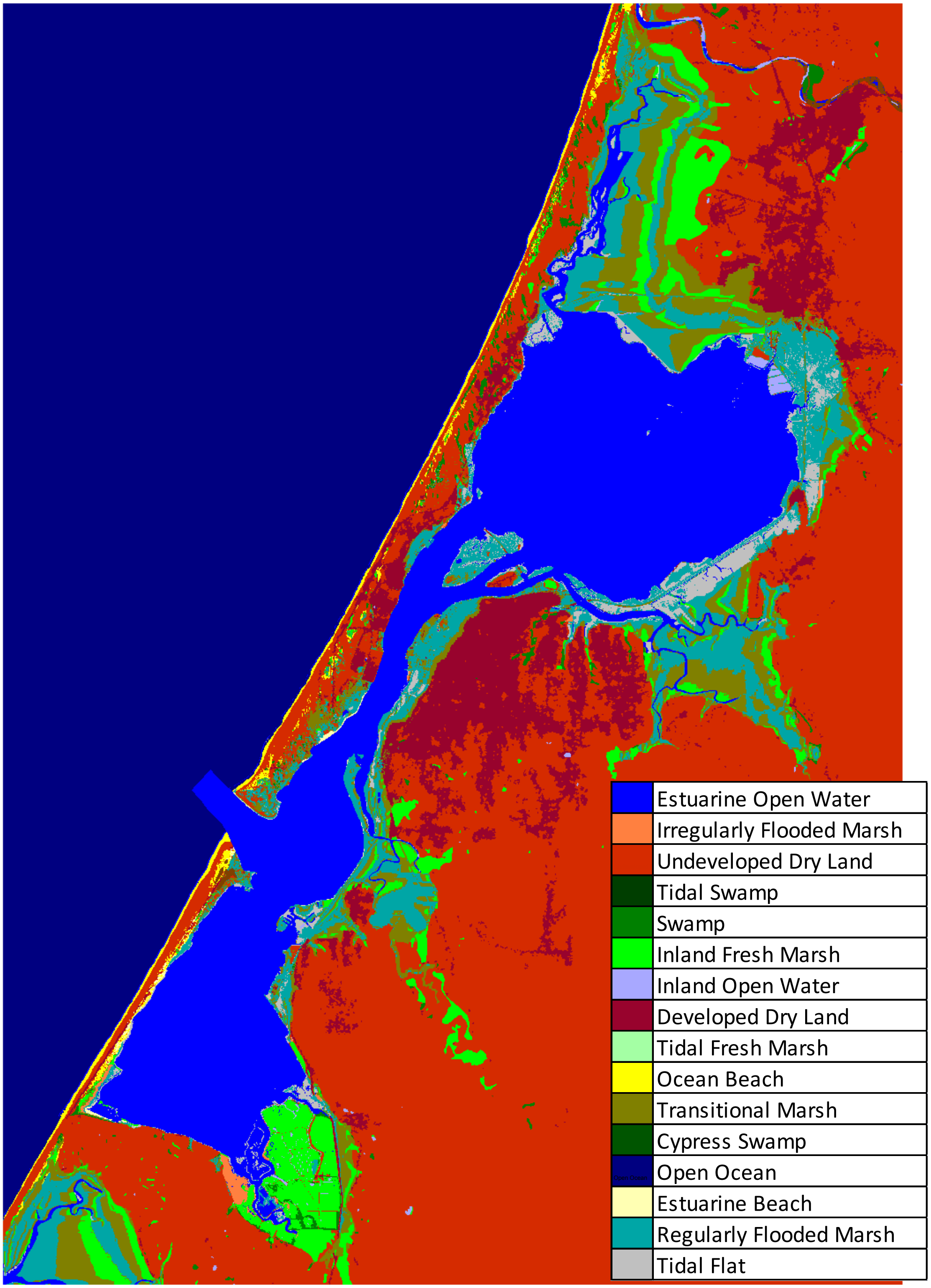
Humboldt Bay context, Initial Condition



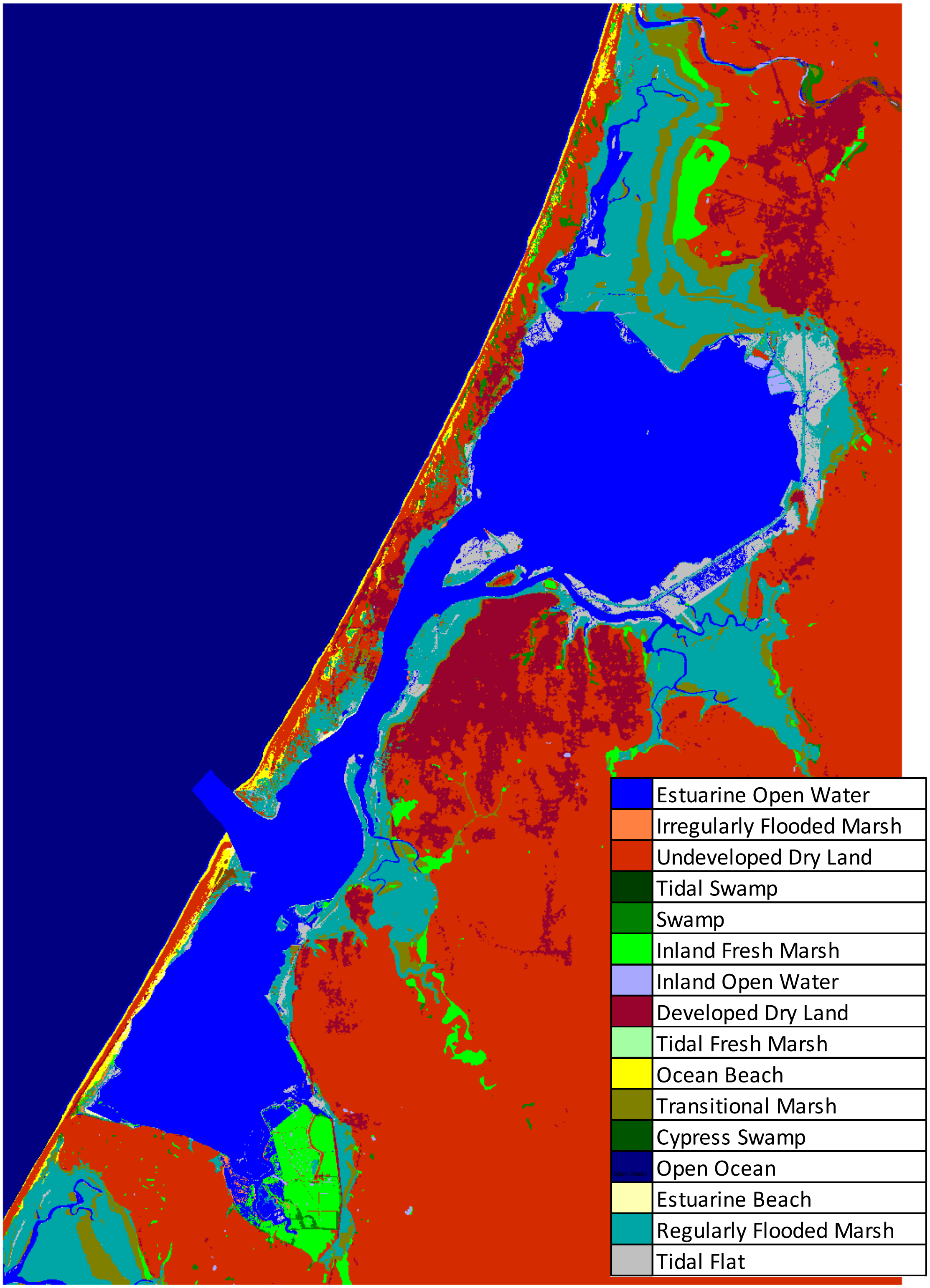
Humboldt Bay context, 2025, 2 m SLR



Humboldt Bay context, 2050, 2 m SLR



Humboldt Bay context, 2075, 2 m SLR



Humboldt Bay context, 2100, 2 m SLR