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

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Introduction

Tidal marshes are among the most susceptible ecosystems to climate change, especially accelerated sea-level rise (SLR). The Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) suggested that global sea level will increase by approximately 30 cm to 100 cm by 2100 (IPCC 2001). Rahmstorf (2007) suggests that this range may be too conservative and that the feasible range by 2100 is 50 to 140 cm. Rising sea levels may result in tidal marsh submergence (Moorhead and Brinson 1995) and habitat "migration" as salt marshes transgress landward and replace tidal freshwater and irregularly-flooded marsh (Park et al. 1991).

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

Model Summary

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

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

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

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

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

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

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

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

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

Sea-level rise Scenarios

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

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

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

Current 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.

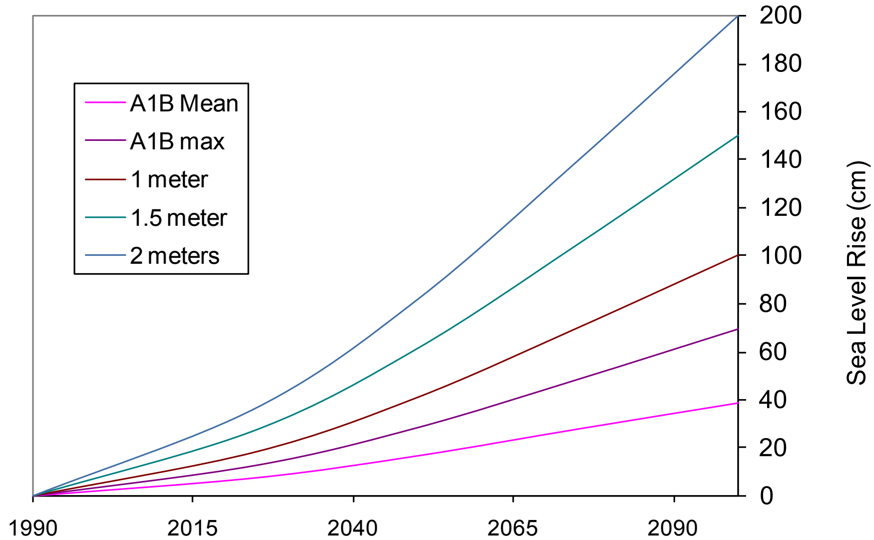


Figure 1. Summary of SLR scenarios utilized.

Data Sources and Methods

Wetland layer. Figure 2 shows the most recent available wetlands layer obtained from a National Wetlands Inventory (NWI) photo dated 2009. Converting the NWI survey into 10 m x 10 m cells indicates that the 16,641 acre Swanquarter NWR (refuge boundary including water) is composed of the following categories:

Land cover type		Area (acres)	Percentage (%)
	Regularly-flooded Marsh	6079	37
	Irregularly-flooded Marsh	3299	20
	Tidal Swamp	2601	16
	Estuarine Open Water	1742	10
	Estuarine Beach	1447	9
	Transitional Salt Marsh	783	5
	Swamp	486	3
	Tidal Fresh Marsh	90	<1
	Inland Fresh Marsh	90	<1
	Undeveloped Dry Land	22	<1
	Inland Open Water	3	<1
	Total (incl. water)	**16641**	**100**

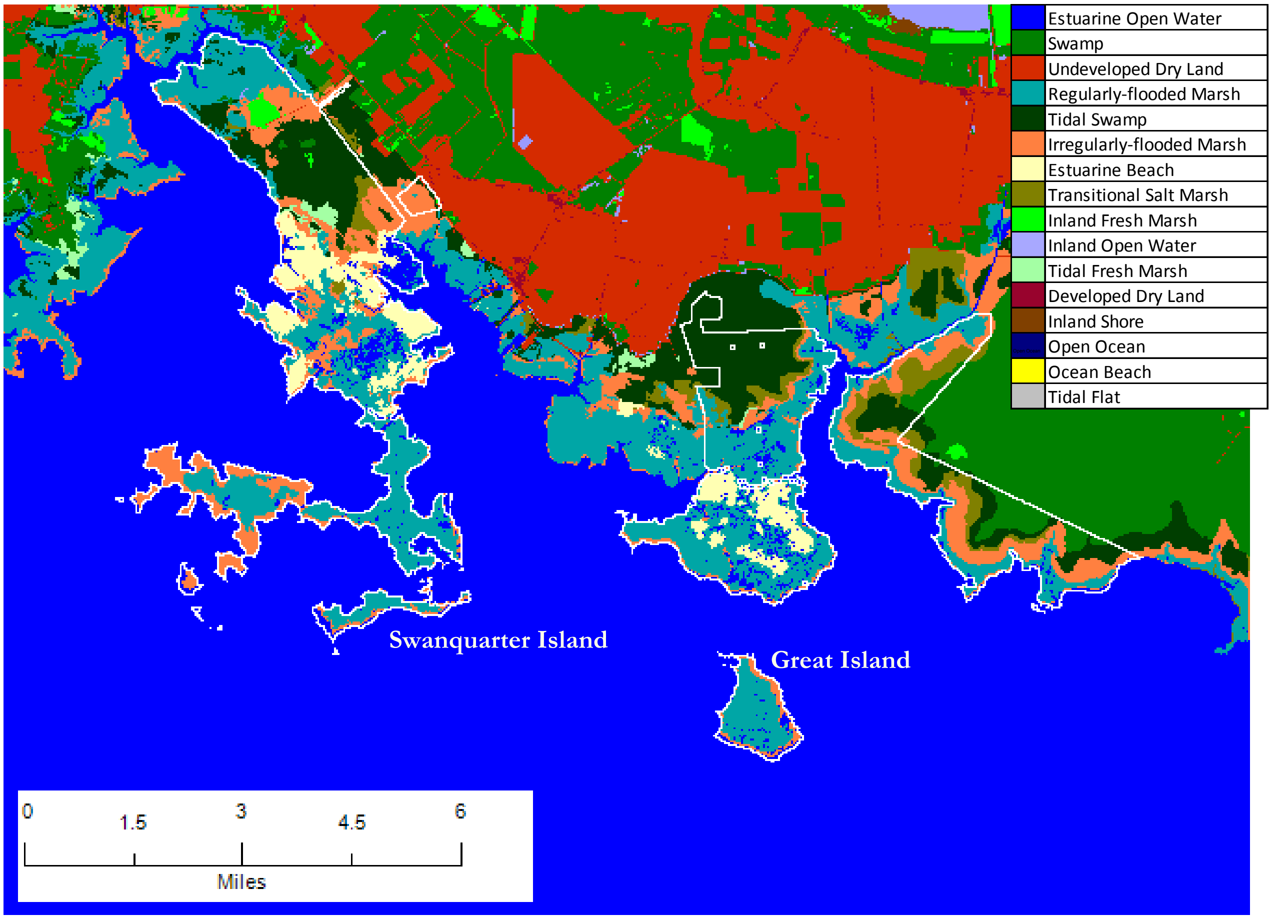


Figure 2. 2009 NWI coverage of the study area. Refuge boundaries are indicated in white.

Elevation Data. The elevation layer was derived from bare-earth LiDAR data collected for Hyde County, North Carolina in 2007. However, Great Island and part of Swanquarter Island are not covered by LiDAR data. Therefore for these areas, the SLAMM elevation preprocessor module was used. This module estimates elevations for wetlands as a function of the local tide range (Clough et al. 2010). Because of this estimation, predicted wetland changes in these islands are more uncertain than for the rest of the refuge.

Dikes and Impoundments. According to the National Wetland Inventory, there are no wetlands protected by dikes or impoundments within the refuge.

Model Timesteps. Model forecast data is output for years 2025, 2050, 2075 and 2100 with the initial condition date set to 2009, the date of the most recent wetland data available.

Historic sea-level rise rates. The historic trend for relative sea-level rise rates have been recorded at the two NOAA gauge stations in the area of the refuge: Oregon Inlet Marina (#8652587) and Beaufort (#8656483), NC. Historic data from these gauges are shown in Figure 3. For this study, the average of 2.66 mm/yr was applied. This rate is 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 slightly higher than the global average.

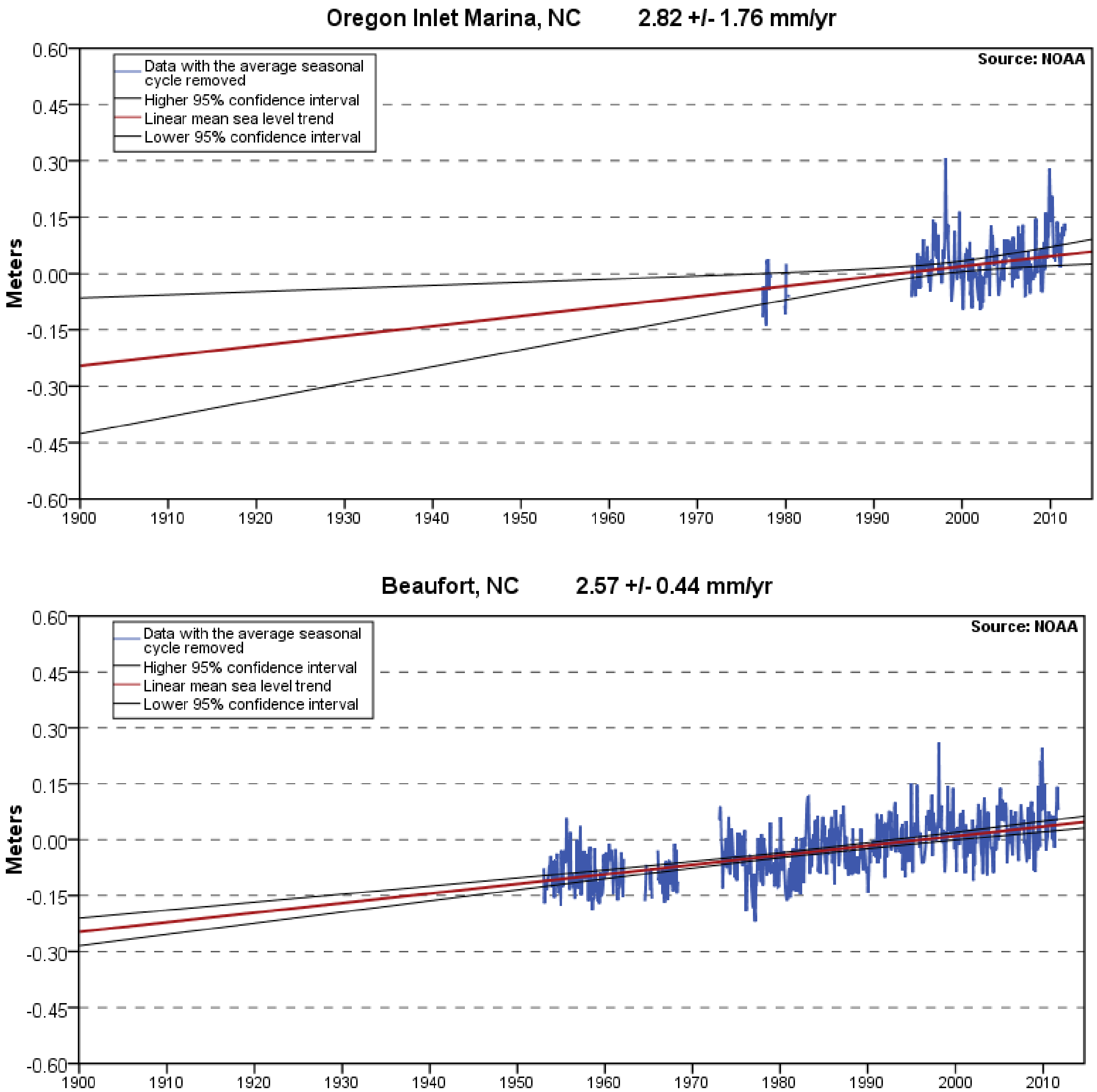


Figure 3. Sea-level rise Trends for the NOAA gauges closest to Swanquarter NWR.

Tide Ranges. The great diurnal tide range applied was 0.127 m which was measured at the NOAA tide gauge at Cedar Island, NC (# 8655151).

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 1.5 Half Tide Units (HTU) for all input subsites.

Accretion rates. Accretion rates for saltmarsh habitat were set to 3.7 mm/yr in Swanquarter NWR based on Cahoon and coworkers (1998) who measured accretion rates of saltmarshes in Cedar Island NWR. Tidal fresh marsh accretion values were set to 5.9 mm/year based upon an average of fresh marsh accretion rates within the region while the estimated accretion rate of 4.1 mm/yr for irregularly-flooded marsh was based on accretion rates measured at other marshes in the east coast of United States (Reed et al. 2008, n=8). Uncertainty remains as to whether saltmarsh accretion rates could increase as a function of SLR due to increased frequency of inundation and sediment dynamics. Accretion rates were kept temporally constant for this analysis.

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

Elevation correction. MTL to NAVD88 corrections determined using NOAA's VDATUM software. An average value of -0.030 m was applied throughout the refuge.

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

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

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

Parameter	Value applied
NWI Photo Date (YYYY)	2010
DEM Date (YYYY)	2007
Direction Offshore [n,s,e,w]	South
Historic Trend (mm/yr)	2.66
MTL-NAVD88 (m)	-0.03
GT Great Diurnal Tide Range (m)	0.127
Salt Elev. (m above MTL)	0.19
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)	3.7
Irreg.-Flood Marsh Accr (mm/yr)	4.1
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)	25
Use Elev Pre-processor [True,False]	FALSE/TRUE([1])

([1]) Preprocessor used for Great Island and part of Swanquarter Island

Results

The initial land cover in acres and wetland percentage losses by 2100 for different SLR scenario are presented in Table 2. Land-cover losses are calculated in comparison to the initial 2010 NWI wetland coverage.

Table 2. Predicted loss rates of land categories by 2100 given simulated scenarios of eustatic SLR at Swanquarter 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
Regularly-flooded Marsh	6079	6%	20%	54%	72%	91%
Irregularly-flooded Marsh	3299	0%	26%	62%	97%	99%
Tidal Swamp	2601	50%	84%	96%	100%	100%
Estuarine Beach	1447	23%	79%	98%	100%	100%
Transitional Salt Marsh	783	-32%([1])	13%	41%	91%	100%
Swamp	486	61%	75%	89%	100%	100%
Tidal Fresh Marsh	90	5%	39%	84%	99%	100%
Inland Fresh Marsh	90	27%	71%	94%	100%	100%
Undeveloped Dry Land	22	75%	96%	100%	100%	100%

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

Simulation results show that the refuge is predicted to be greatly affected by SLR across all studied scenarios. At 1 m SLR by 2100, 60% of regularly- and irregularly-flooded marshes are predicted to convert to tidal flat and open water. At higher SLR scenarios irregularly-flooded marshes are almost predicted to be completely lost.

Similar or even more pronounced trends are observed for all other wetland categories. Swamps are predicted to be the most vulnerable categories under the lowest predicted rate of SLR. Transitional salt marsh is predicted to have some gains under lower SLR scenarios as dry lands and swamps are converted. However, as sea-level rise rates increase, this marsh type is also predicted to progressively lose coverage until its complete loss by 2100 under the 2 m SLR scenario. Overall, the majority of the refuge is predicted to be inundated given 1 m SLR by 2100.

Predicted land cover gains are summarized in Table 3. Open water, which initially covers about 11% of the refuge, is predicted to increase coverage as sea level rises, reaching 73% coverage under the 2 m SLR scenario by 2100. Tidal flat, which is currently not present in the refuge, is predicted to gradually occupy areas that were previously covered by salt marshes, though there is uncertainty as to whether these marshes might convert directly to open water when permanently inundated. Combined, open water and tidal flat are predicted to cover almost 90% of the refuge area under 1.5 m SLR by 2100 scenario and reach almost 97% at 2 m SLR by 2100.

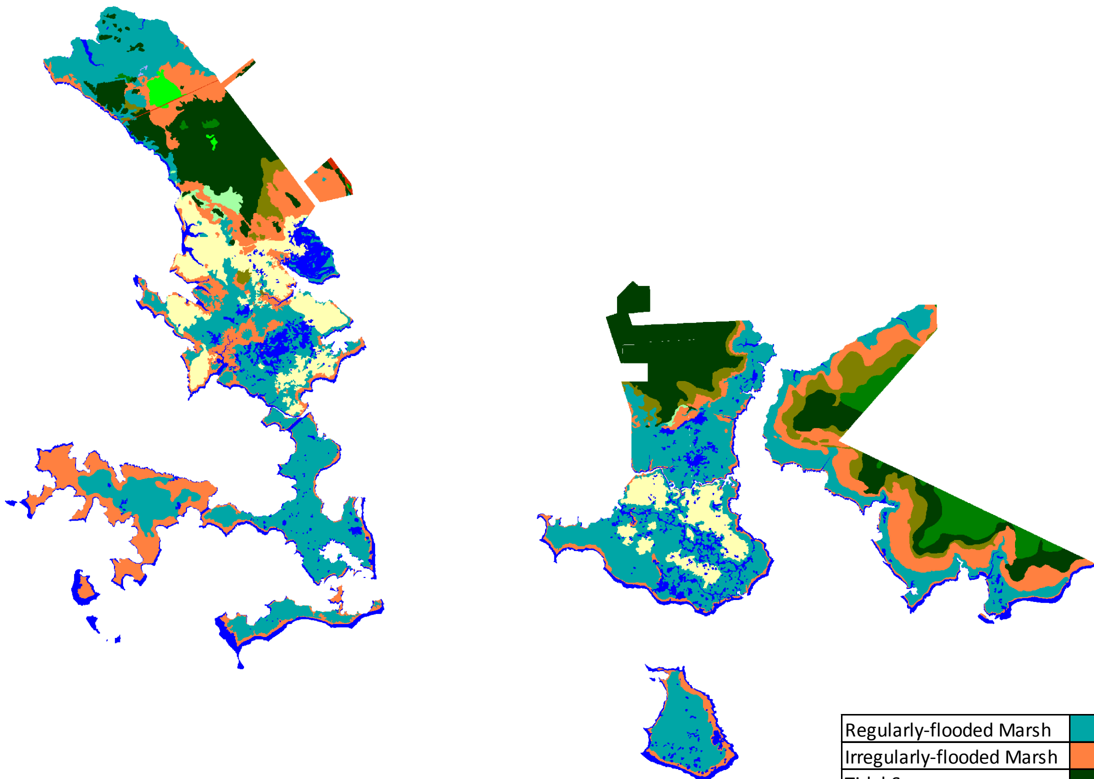
Table 3. Predicted land cover gains by 2100 given simulated scenarios of eustatic SLR at Swanquarter NWR.

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	1745	3216	5386	8109	11132	12095
Tidal Flat	0	612	2371	3808	3653	3968

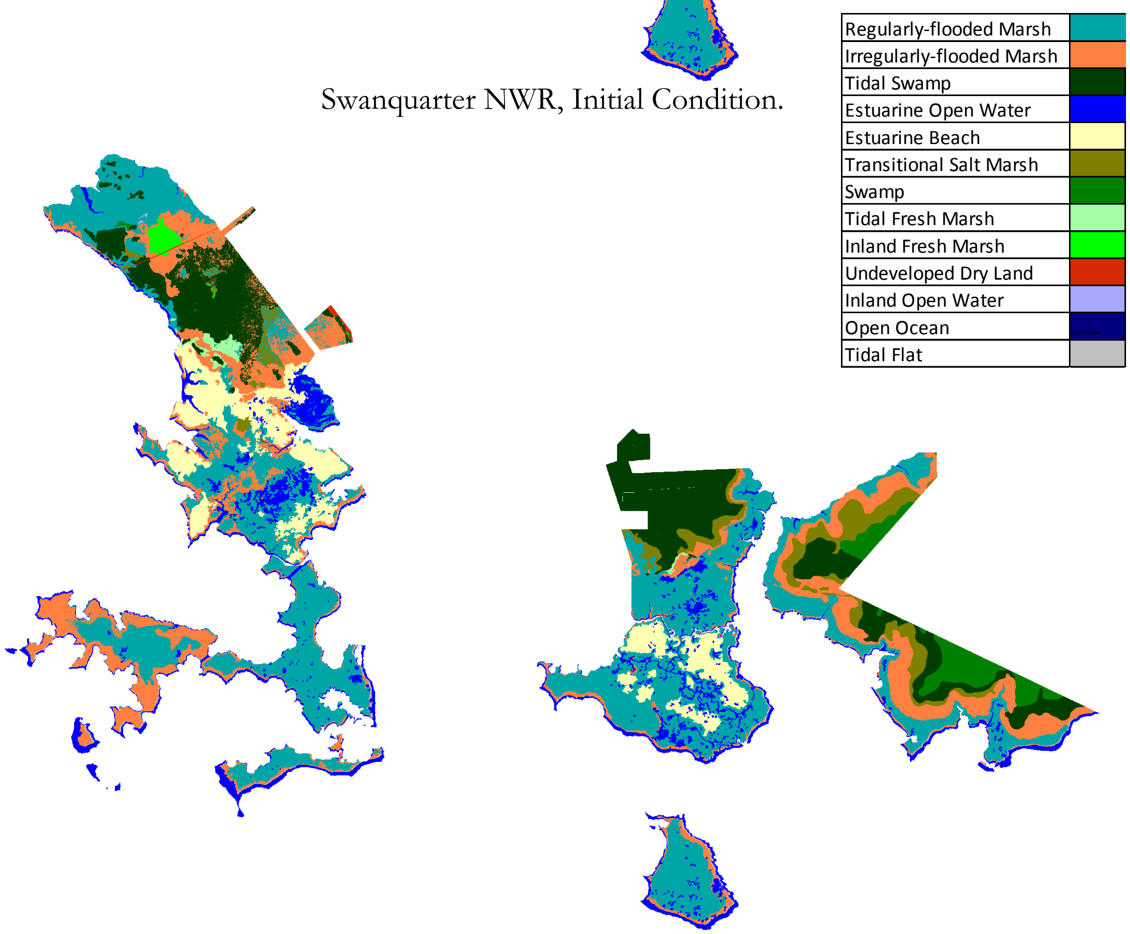
Swanquarter NWR
IPCC Scenario A1B-Mean, 0.39 m SLR eustatic by 2100

Results in Acres

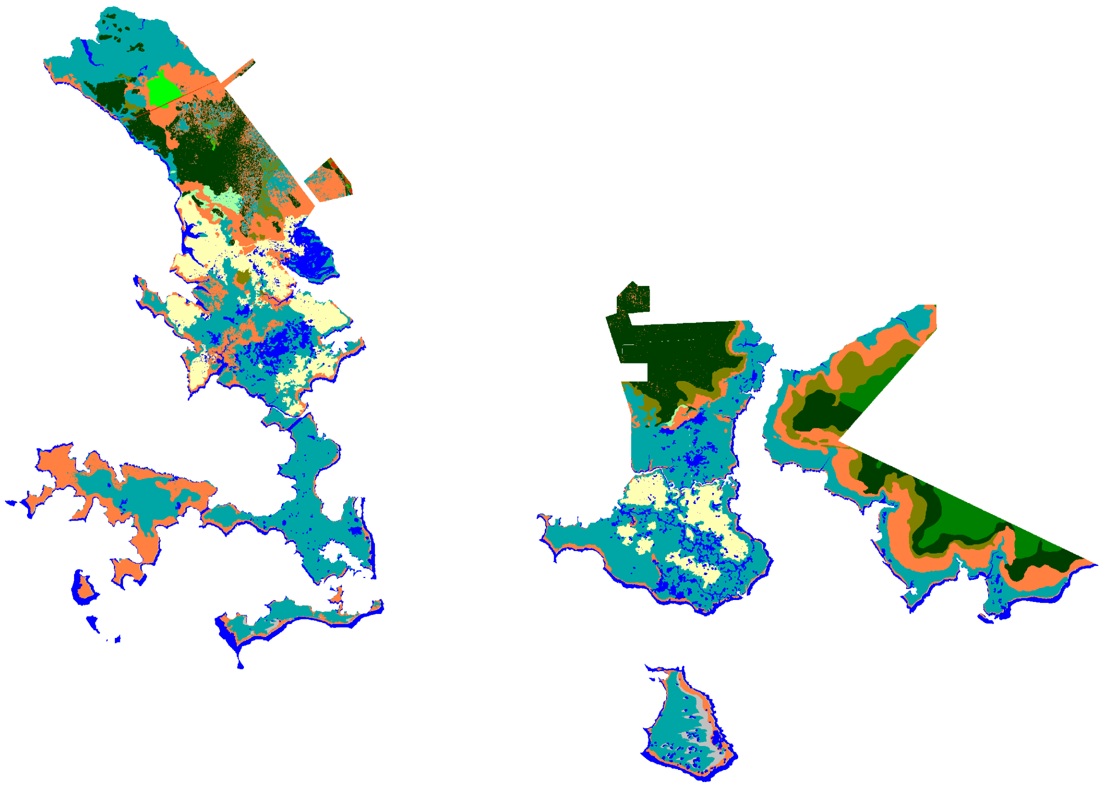
		Initial	2025	2050	2075	2100
	Regularly-flooded Marsh	6079	6245	6162	5722	5715
	Irregularly-flooded Marsh	3299	3119	3266	3329	3297
	Tidal Swamp	2601	2518	2291	1869	1312
	Estuarine Open Water	1742	1752	1821	2073	3069
	Estuarine Beach	1447	1445	1403	1318	1108
	Transitional Salt Marsh	783	760	769	787	1033
	Swamp	486	470	465	454	190
	Tidal Fresh Marsh	90	86	86	86	86
	Inland Fresh Marsh	90	85	85	67	66
	Undeveloped Dry Land	22	21	16	9	6
	Inland Open Water	3	3	0	0	0
	Open Ocean	0	10	70	124	147
	Tidal Flat	0	128	208	803	612
	Total (incl. water)	**16641**	**16641**	**16641**	**16641**	**16641**



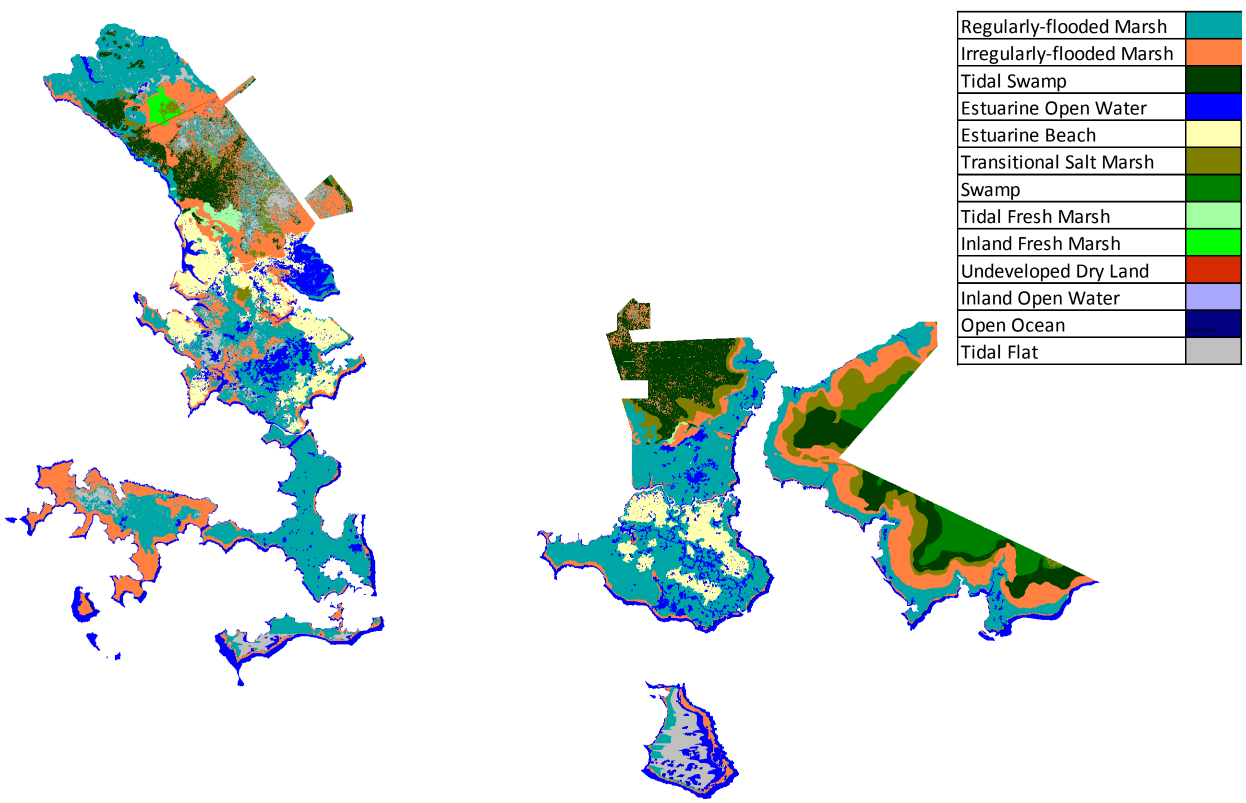
Swanquarter NWR, Initial Condition.



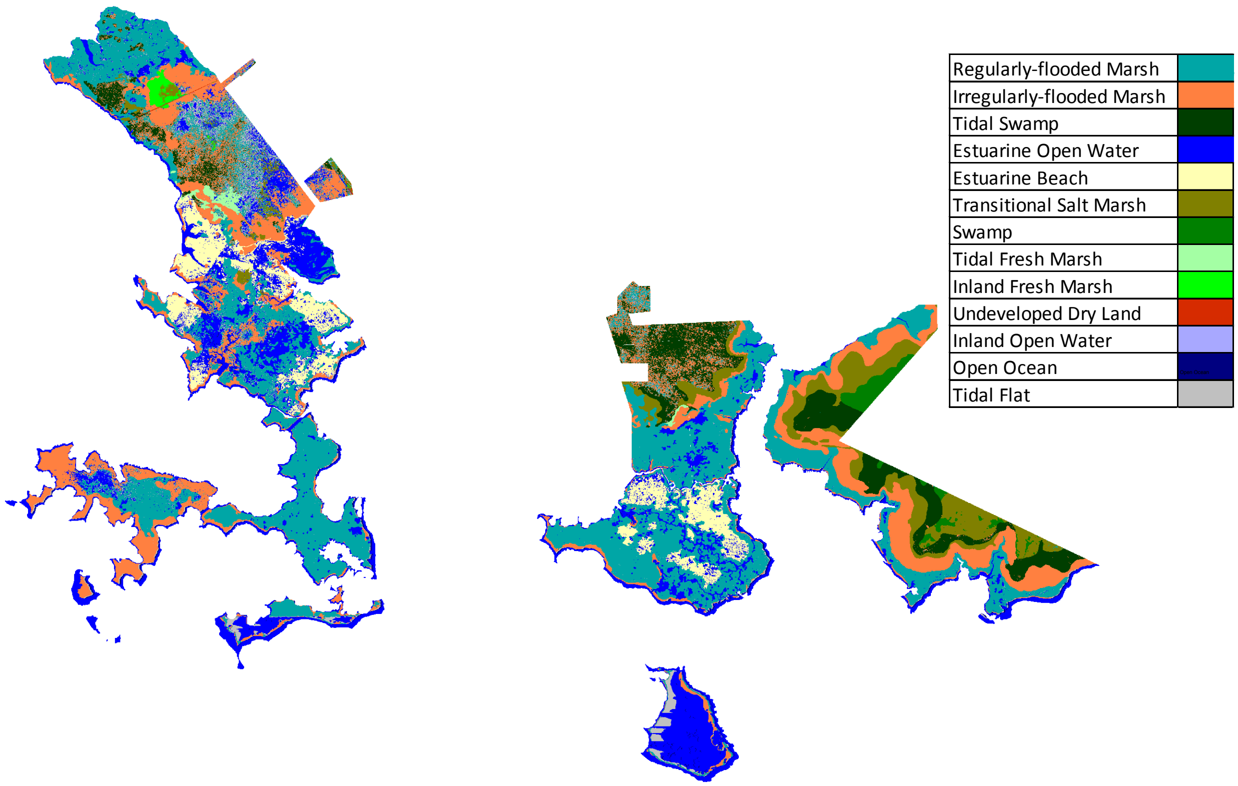
Swanquarter NWR, 2025, Scenario A1B Mean, 0.39 m SLR by 2100.



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



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

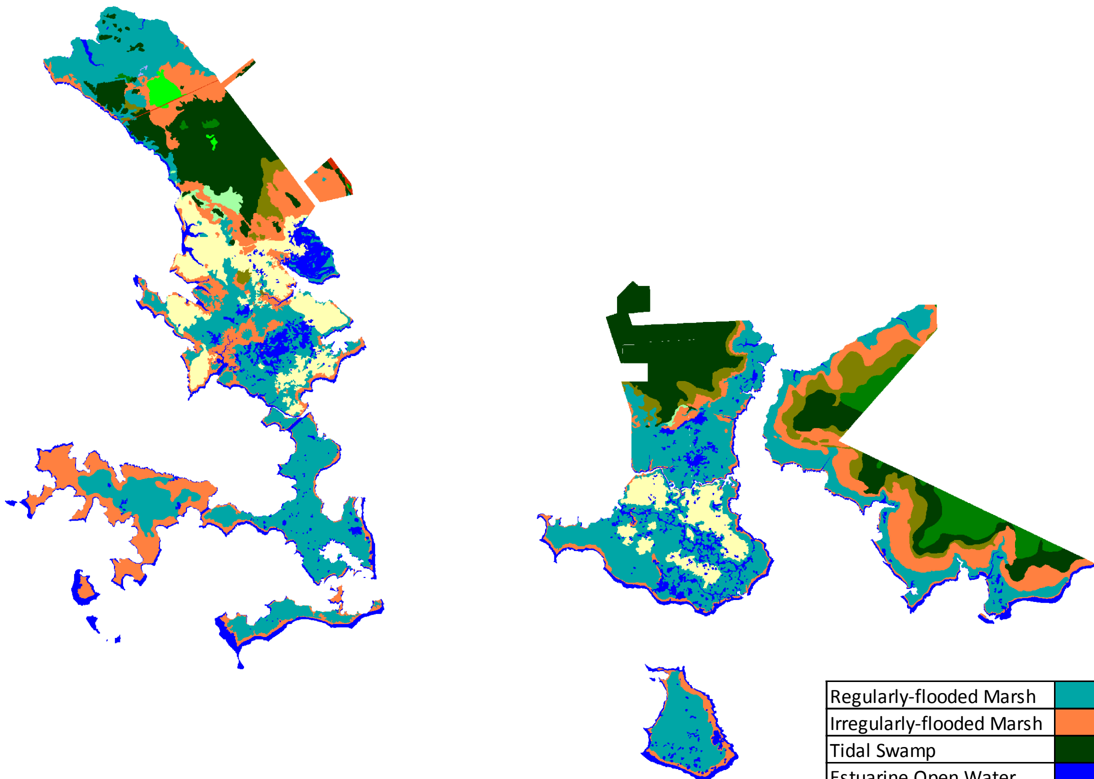


Swanquarter NWR, 2100, Scenario A1B Mean, 0.39 m SLR by 2100.

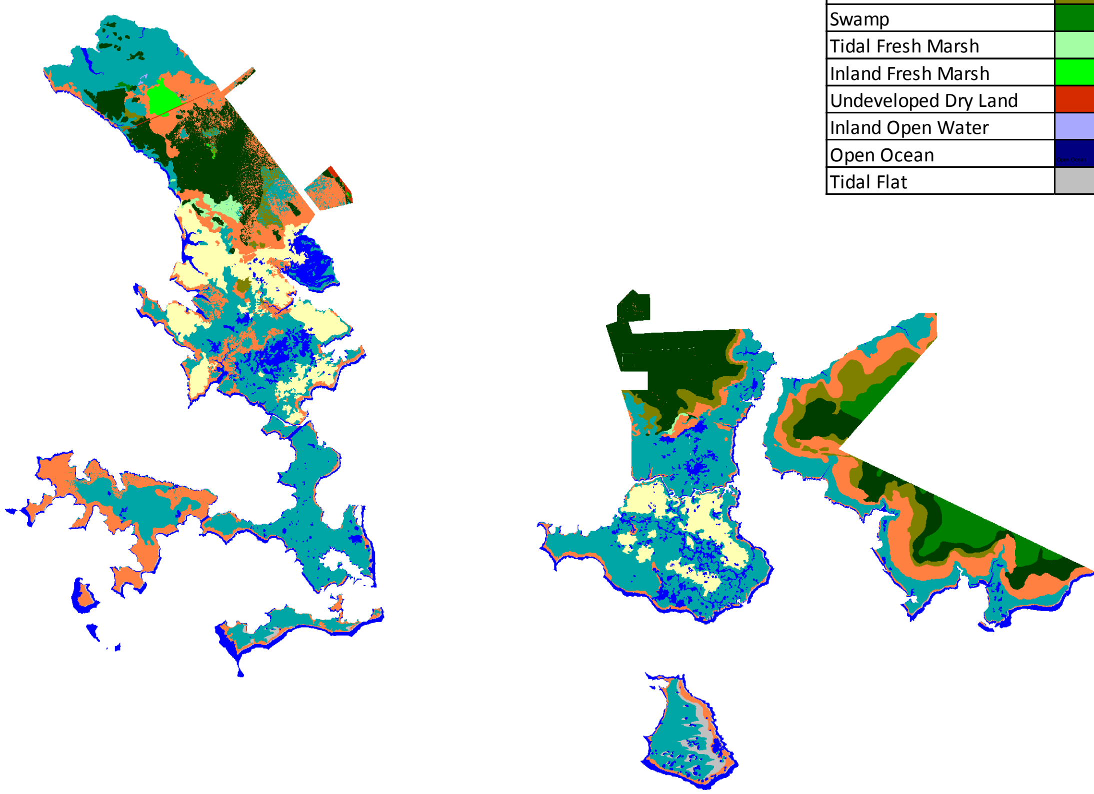
Swanquarter NWR
IPCC Scenario A1B-Max, 0.69 m SLR eustatic by 2100

Results in Acres

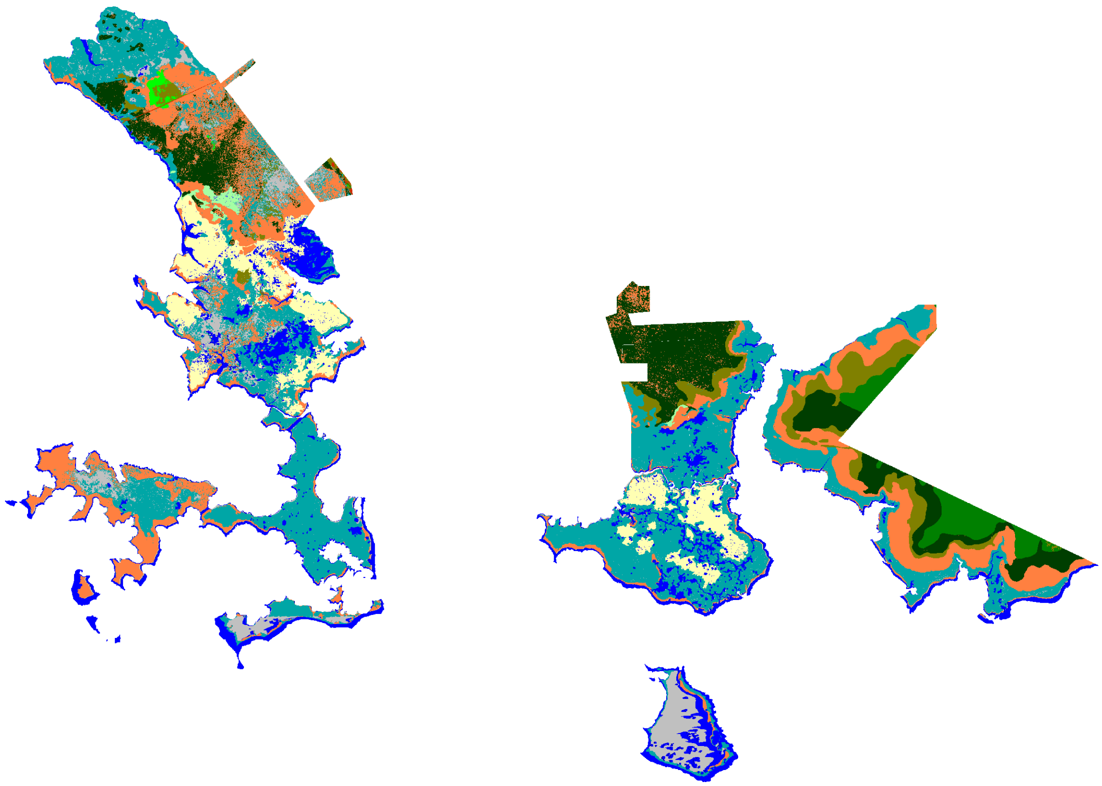
		Initial	2025	2050	2075	2100
	Regularly-flooded Marsh	6079	6122	5617	5490	4844
	Irregularly-flooded Marsh	3299	3137	3213	3324	2434
	Tidal Swamp	2601	2456	1957	969	414
	Estuarine Open Water	1742	1766	2062	3405	5122
	Estuarine Beach	1447	1442	1351	958	310
	Transitional Salt Marsh	783	755	778	1003	678
	Swamp	486	470	458	156	122
	Tidal Fresh Marsh	90	86	83	73	55
	Inland Fresh Marsh	90	85	48	35	26
	Undeveloped Dry Land	22	21	11	4	1
	Inland Open Water	3	3	0	0	0
	Open Ocean	0	16	79	147	264
	Tidal Flat	0	283	983	1078	2371
	Total (incl. water)	**16641**	**16641**	**16641**	**16641**	**16641**



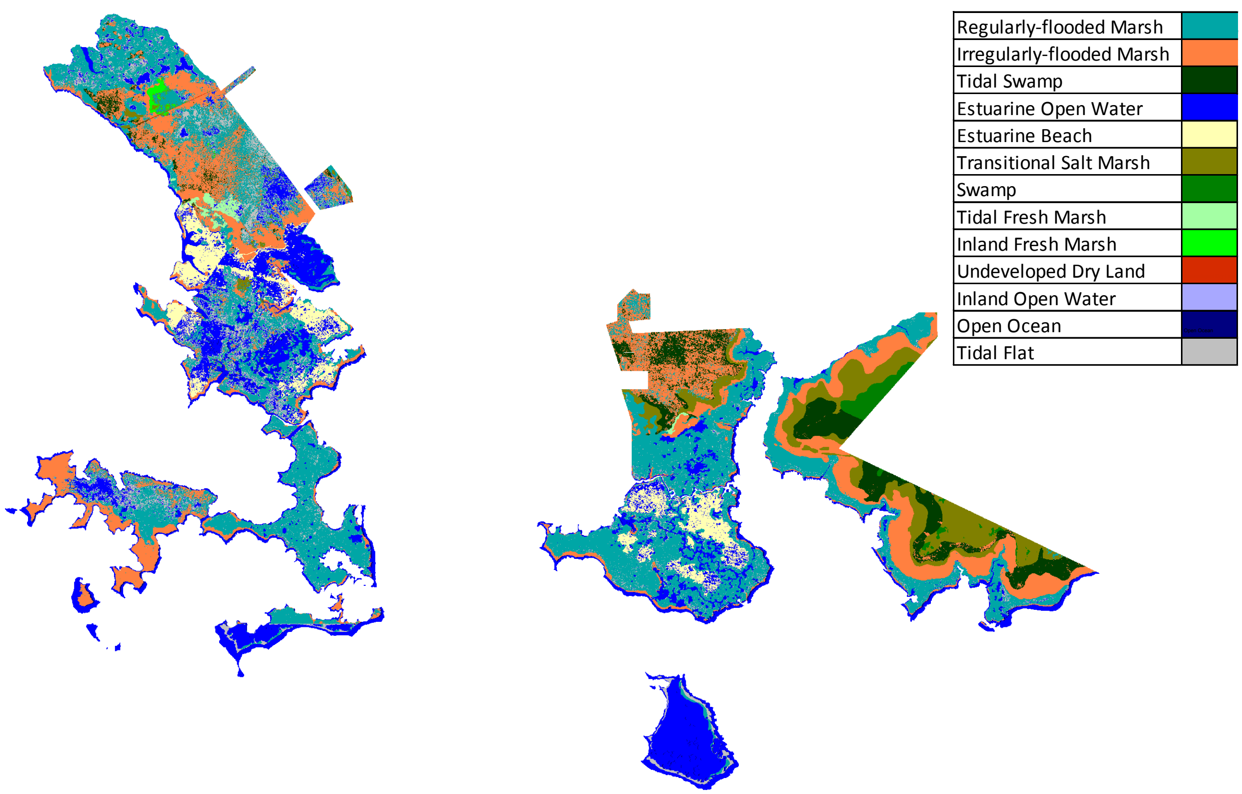
Swanquarter NWR, Initial Condition.



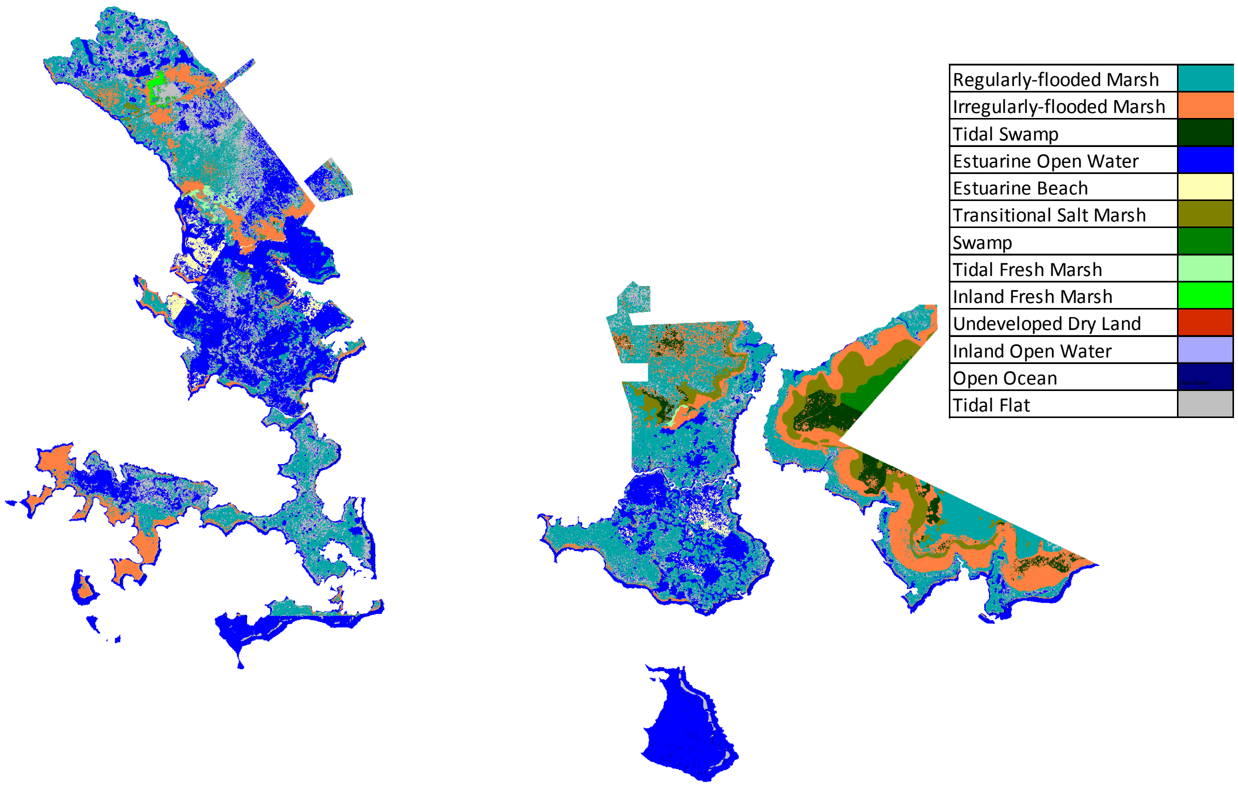
Swanquarter NWR, 2025, Scenario A1B Maximum, 0.69 m SLR by 2100.



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



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

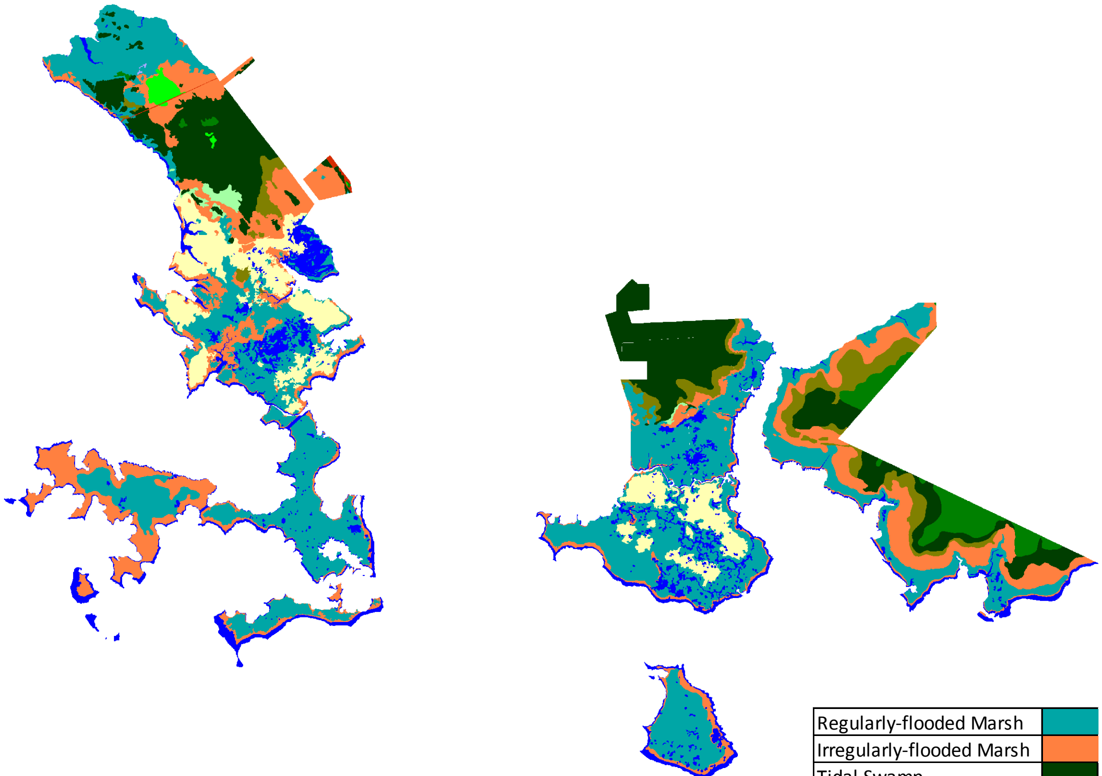


Swanquarter NWR, 2100, Scenario A1B Maximum, 0.69 m SLR by 2100.

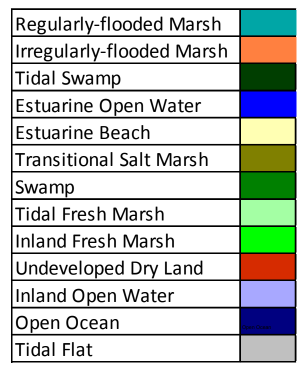
Swanquarter NWR
1 m eustatic SLR by 2100

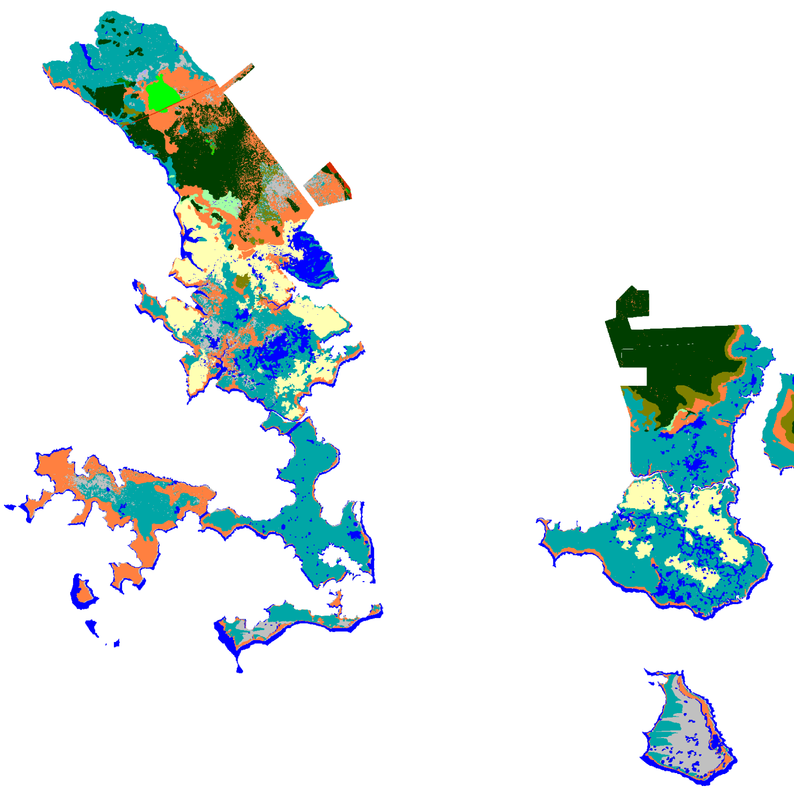
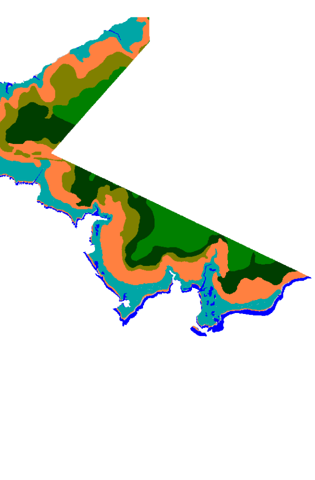
Results in Acres

		Initial	2025	2050	2075	2100
	Regularly-flooded Marsh	6079	5631	5507	4354	2816
	Irregularly-flooded Marsh	3299	3105	3345	2749	1252
	Tidal Swamp	2601	2397	1474	461	96
	Estuarine Open Water	1742	1801	2769	4481	7734
	Estuarine Beach	1447	1428	1232	402	24
	Transitional Salt Marsh	783	744	774	939	464
	Swamp	486	469	448	129	53
	Tidal Fresh Marsh	90	84	70	34	14
	Inland Fresh Marsh	90	85	33	18	5
	Undeveloped Dry Land	22	20	7	1	0
	Inland Open Water	3	3	0	0	0
	Open Ocean	0	26	87	199	375
	Tidal Flat	0	848	893	2876	3808
	Total (incl. water)	**16641**	**16641**	**16641**	**16641**	**16641**

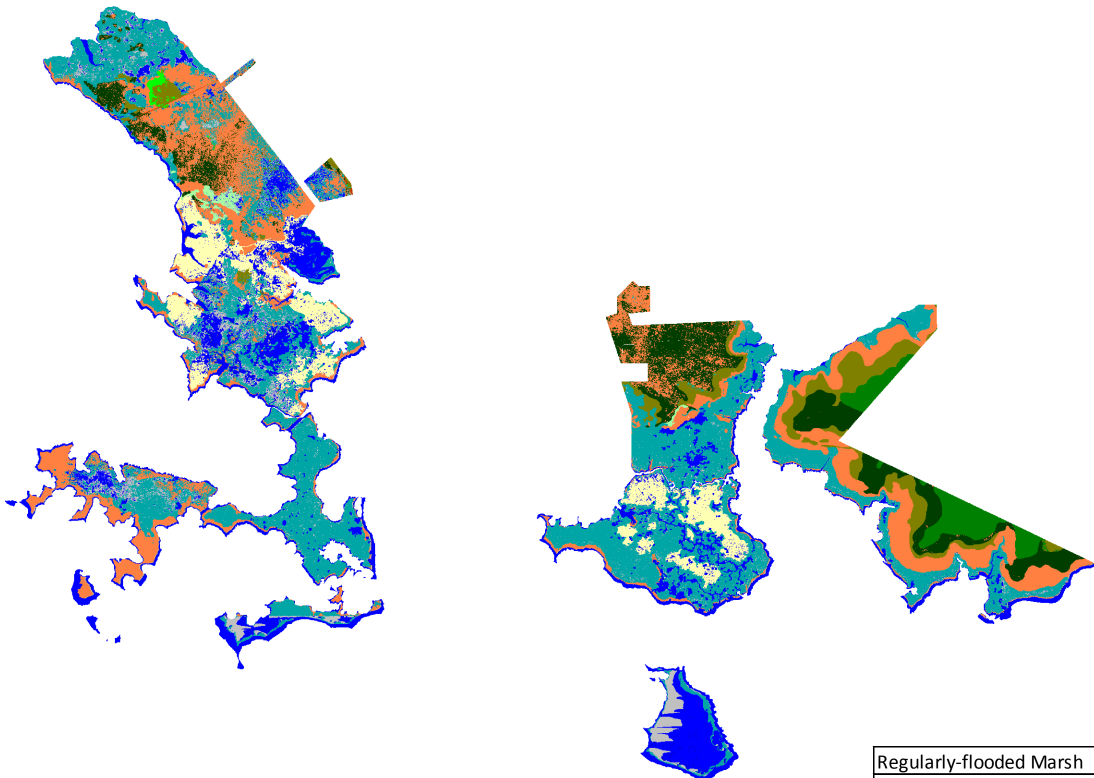


Swanquarter NWR, Initial Condition.

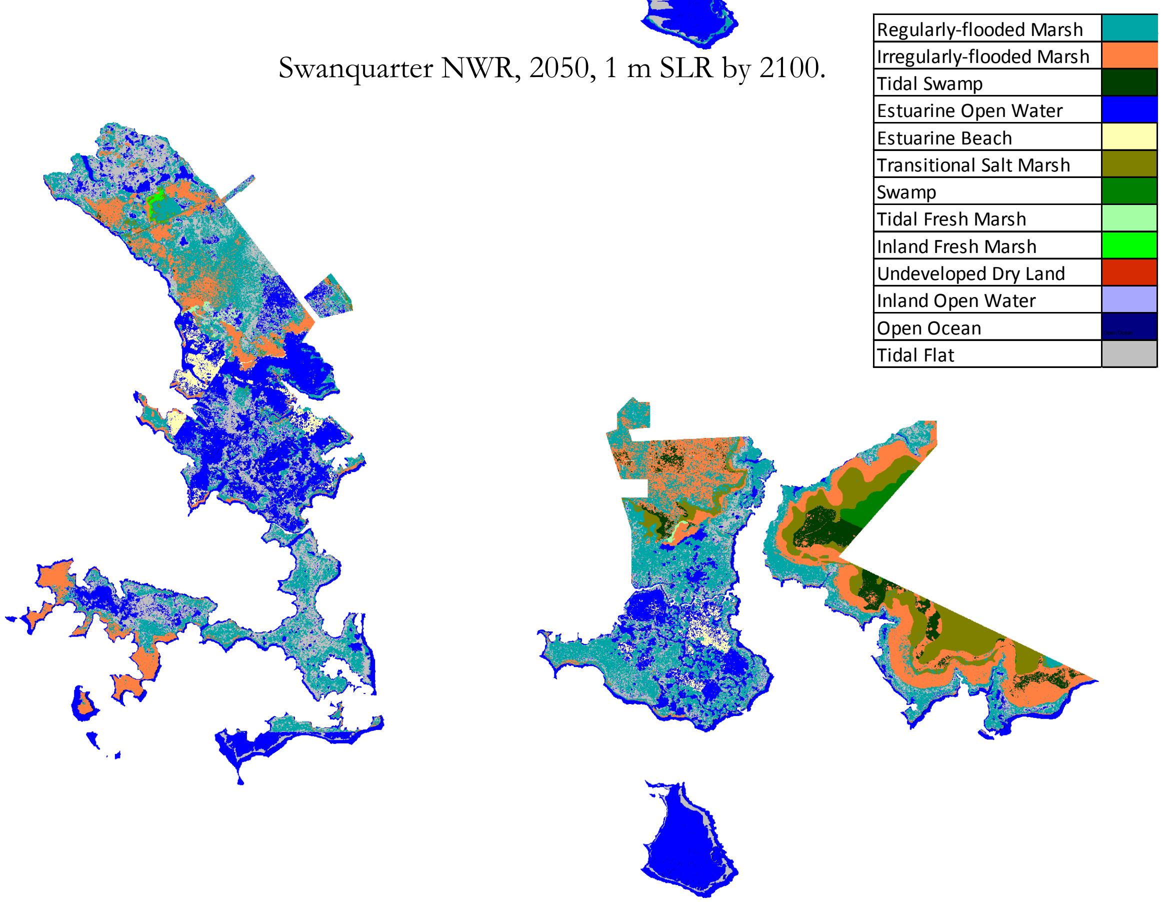


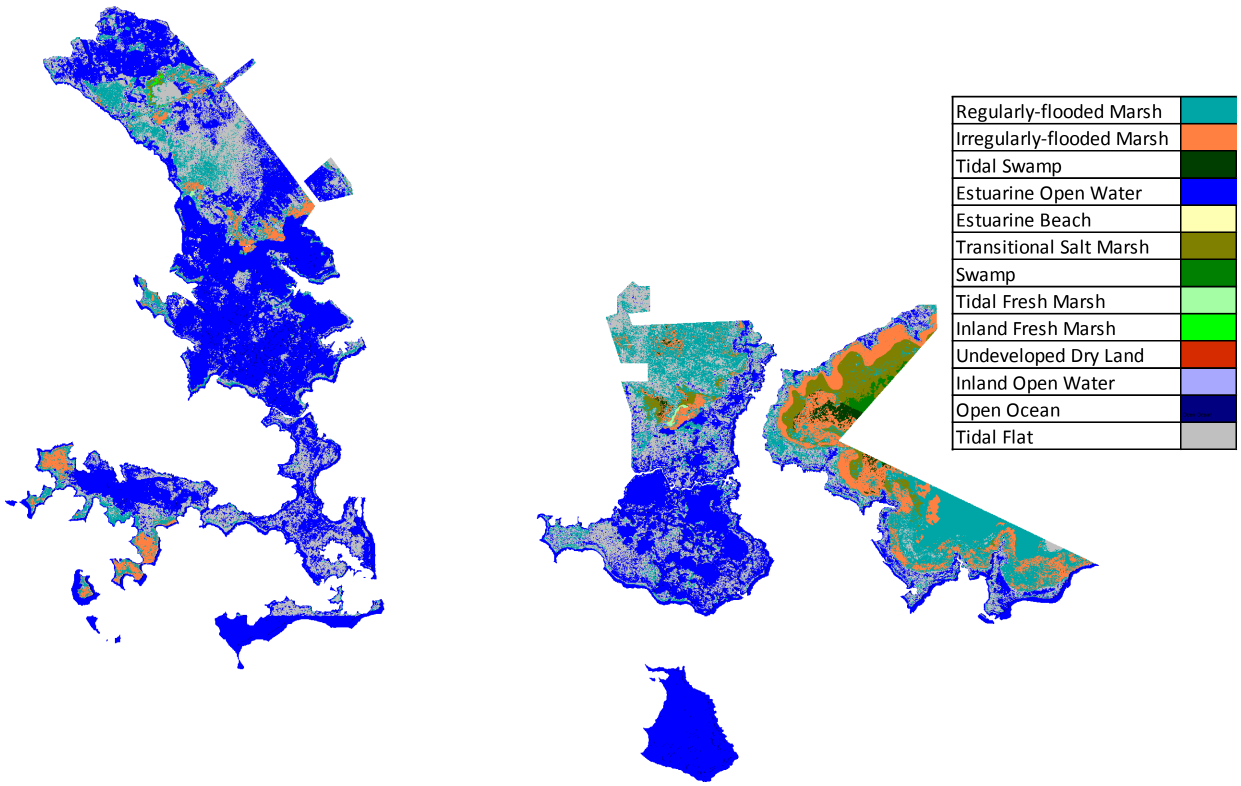
Swanquarter NWR, 2025, 1 m SLR by 2100.



Swanquarter NWR, 2050, 1 m SLR by 2100.



Swanquarter NWR, 2075, 1 m SLR by 2100.

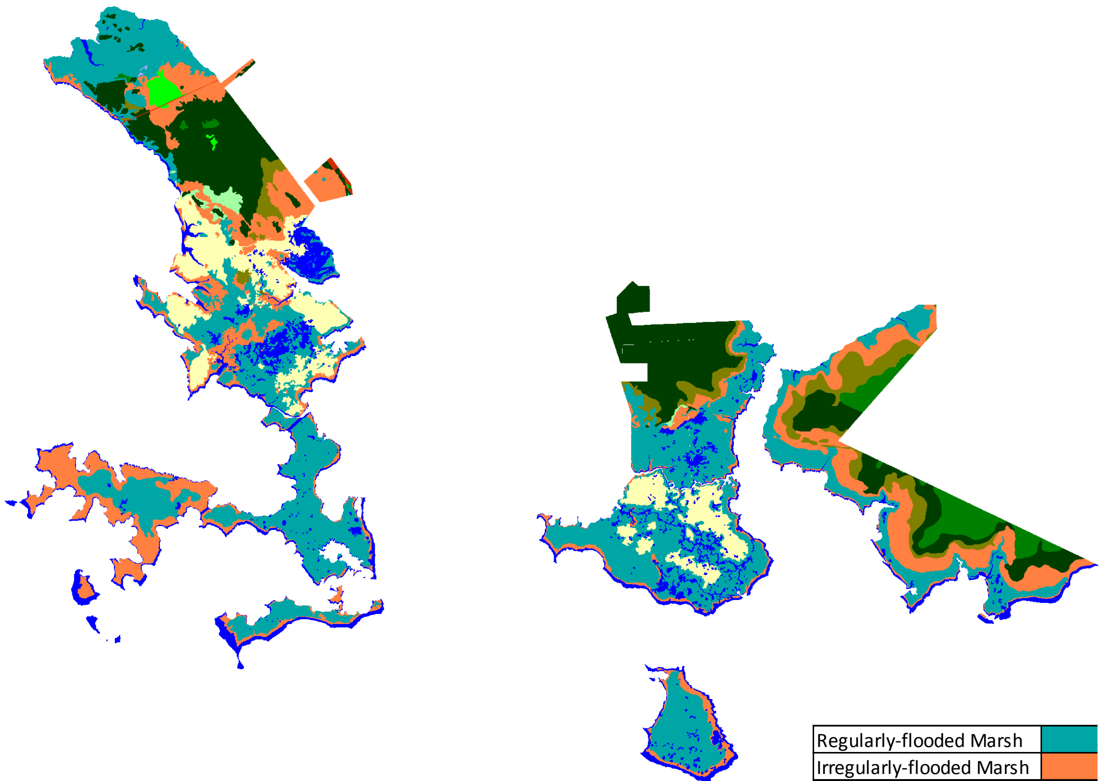


Swanquarter NWR, 2100, 1 m SLR by 2100.

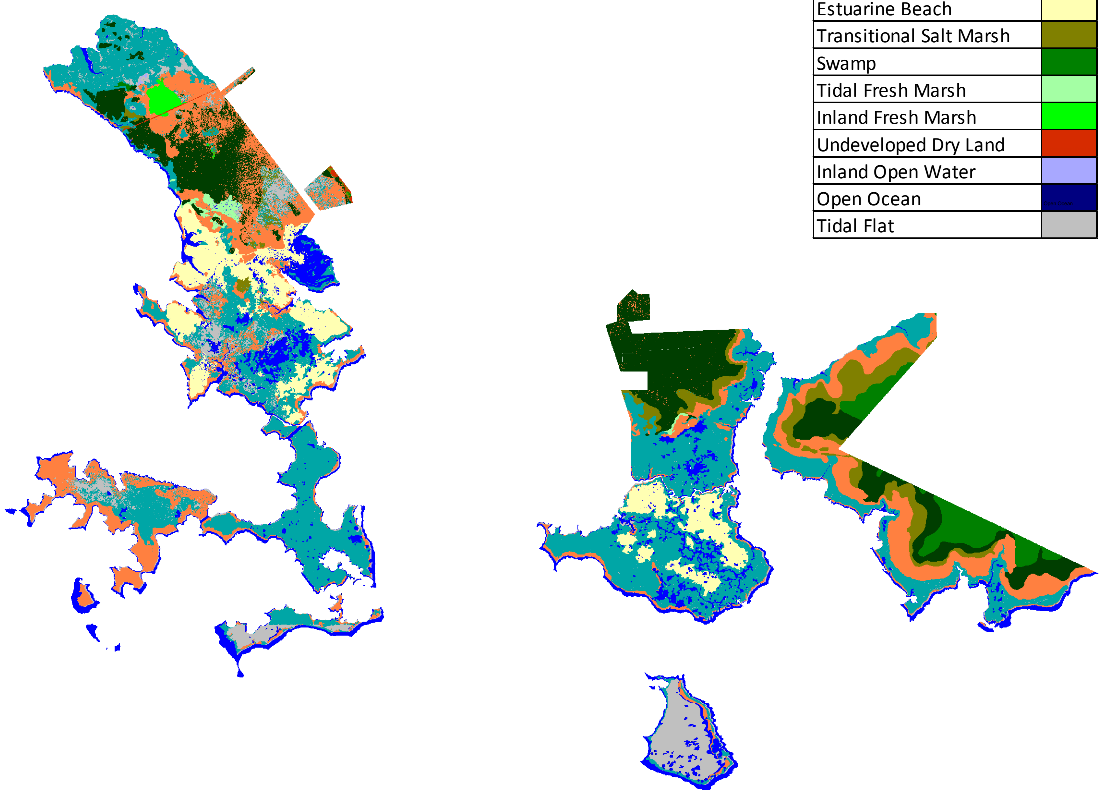
Swanquarter NWR
1.5 m eustatic SLR by 2100

Results in Acres

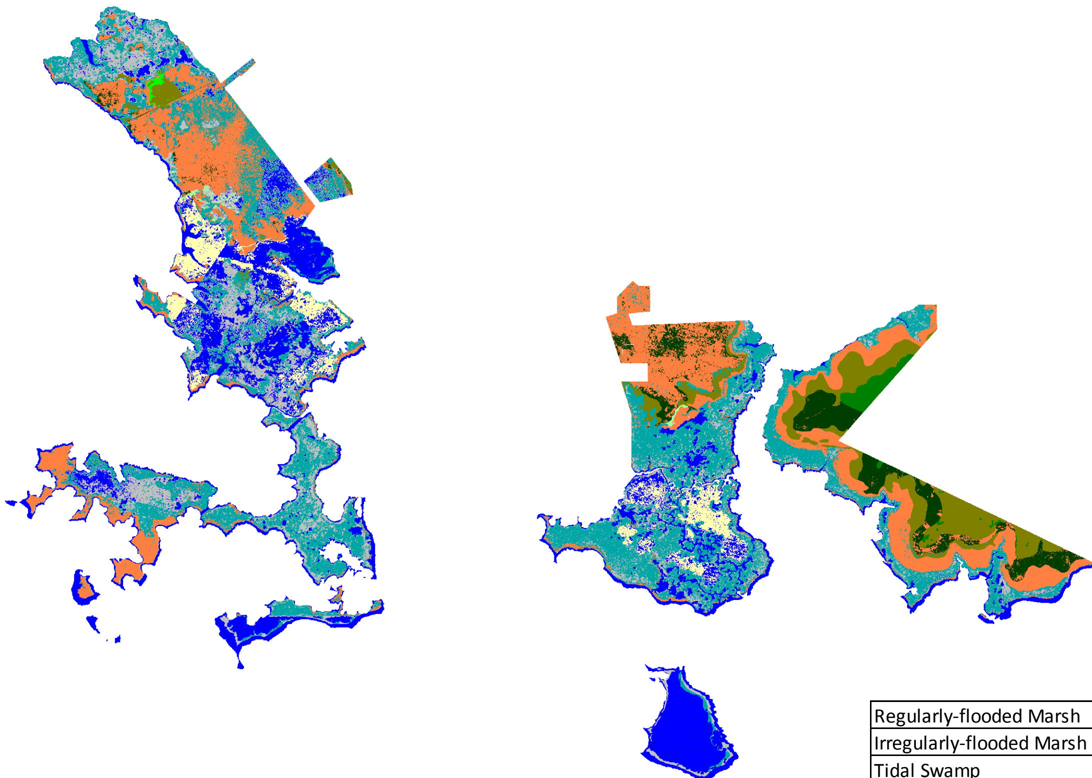
		Initial	2025	2050	2075	2100
	Regularly-flooded Marsh	6079	5523	4591	3725	1681
	Irregularly-flooded Marsh	3299	3066	3421	1306	100
	Tidal Swamp	2601	2277	786	96	5
	Estuarine Open Water	1742	1849	3464	6456	10766
	Estuarine Beach	1447	1407	846	29	0
	Transitional Salt Marsh	783	730	1034	390	70
	Swamp	486	469	146	65	0
	Tidal Fresh Marsh	90	79	36	9	1
	Inland Fresh Marsh	90	84	19	1	0
	Undeveloped Dry Land	22	17	4	0	0
	Inland Open Water	3	3	0	0	0
	Open Ocean	0	26	119	283	366
	Tidal Flat	0	1111	2177	4281	3653
	Total (incl. water)	**16641**	**16641**	**16641**	**16641**	**16641**

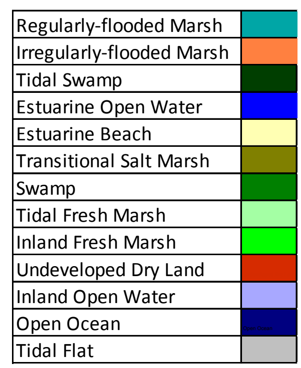


Swanquarter NWR, Initial Condition.



Swanquarter NWR, 2025, 1.5 m SLR by 2100.





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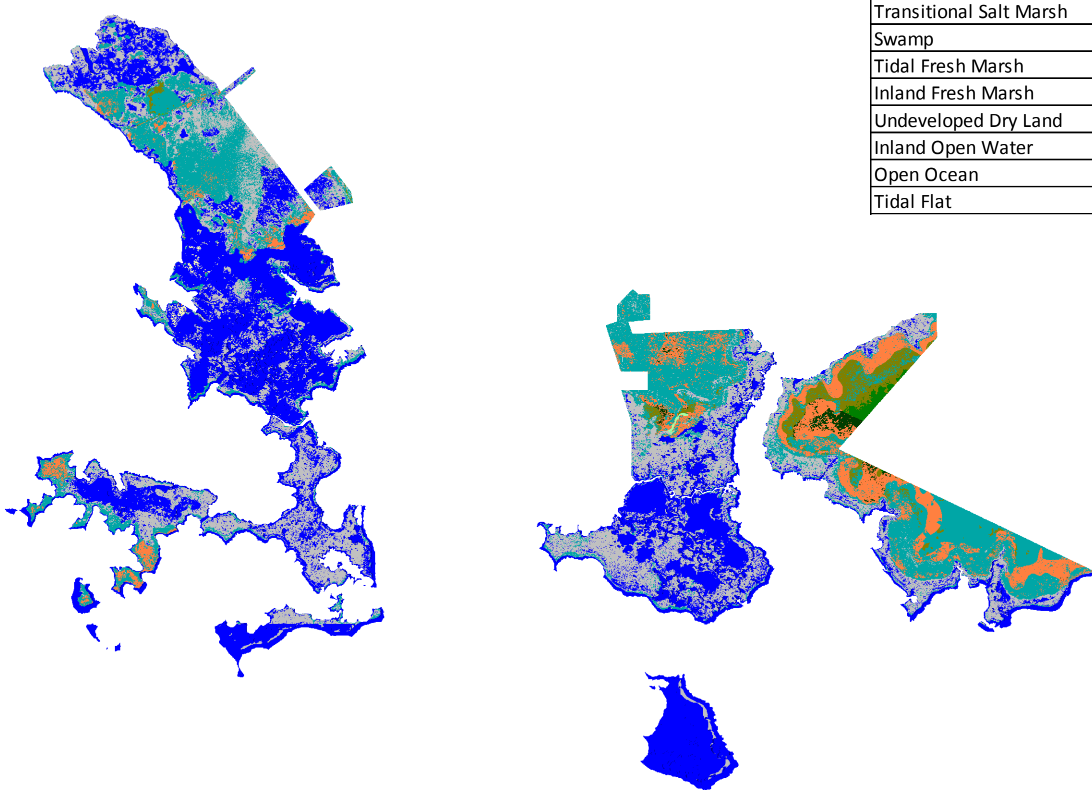
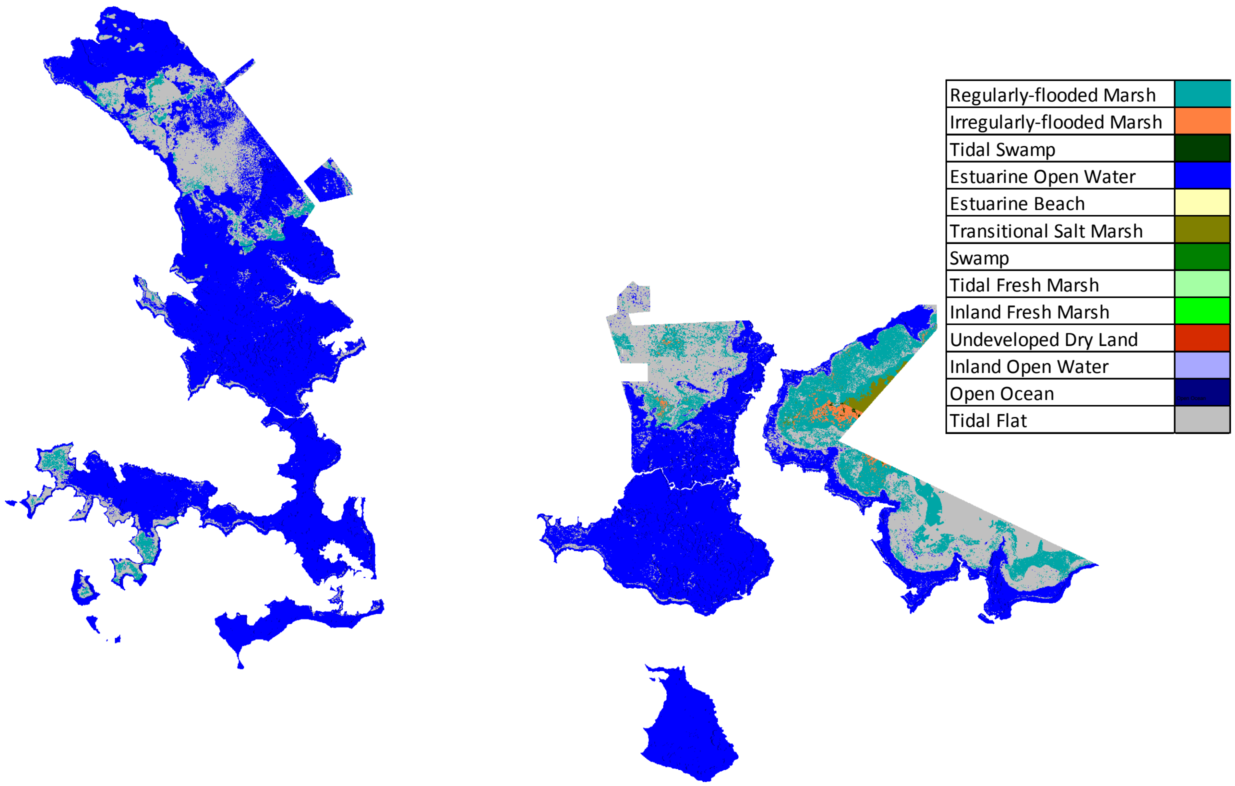


Swanquarter NWR, 2075, 1.5 m SLR by 2100.

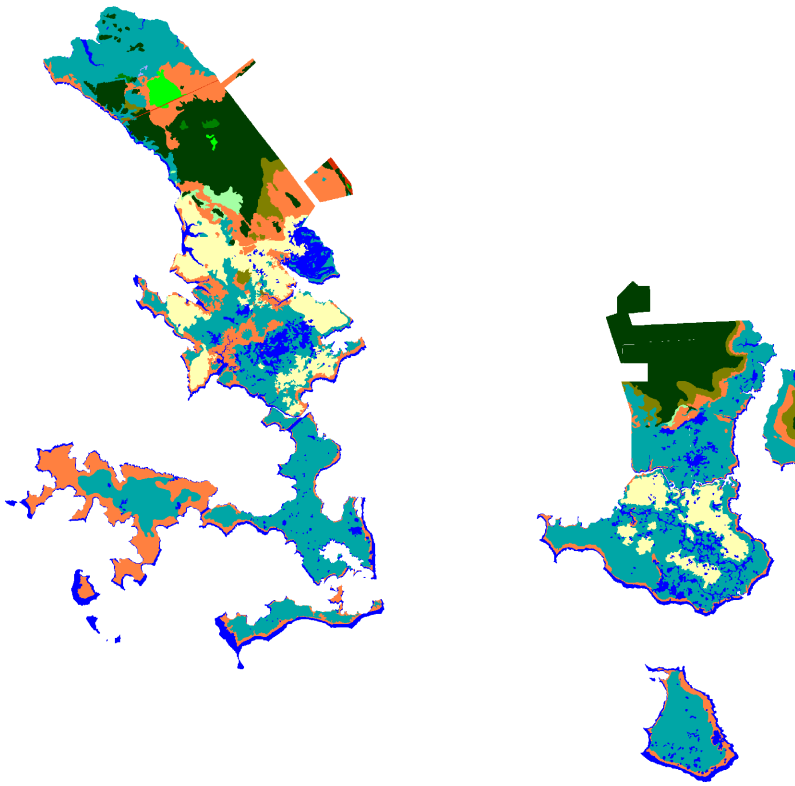


Swanquarter NWR, 2100, 1.5 m SLR by 2100.

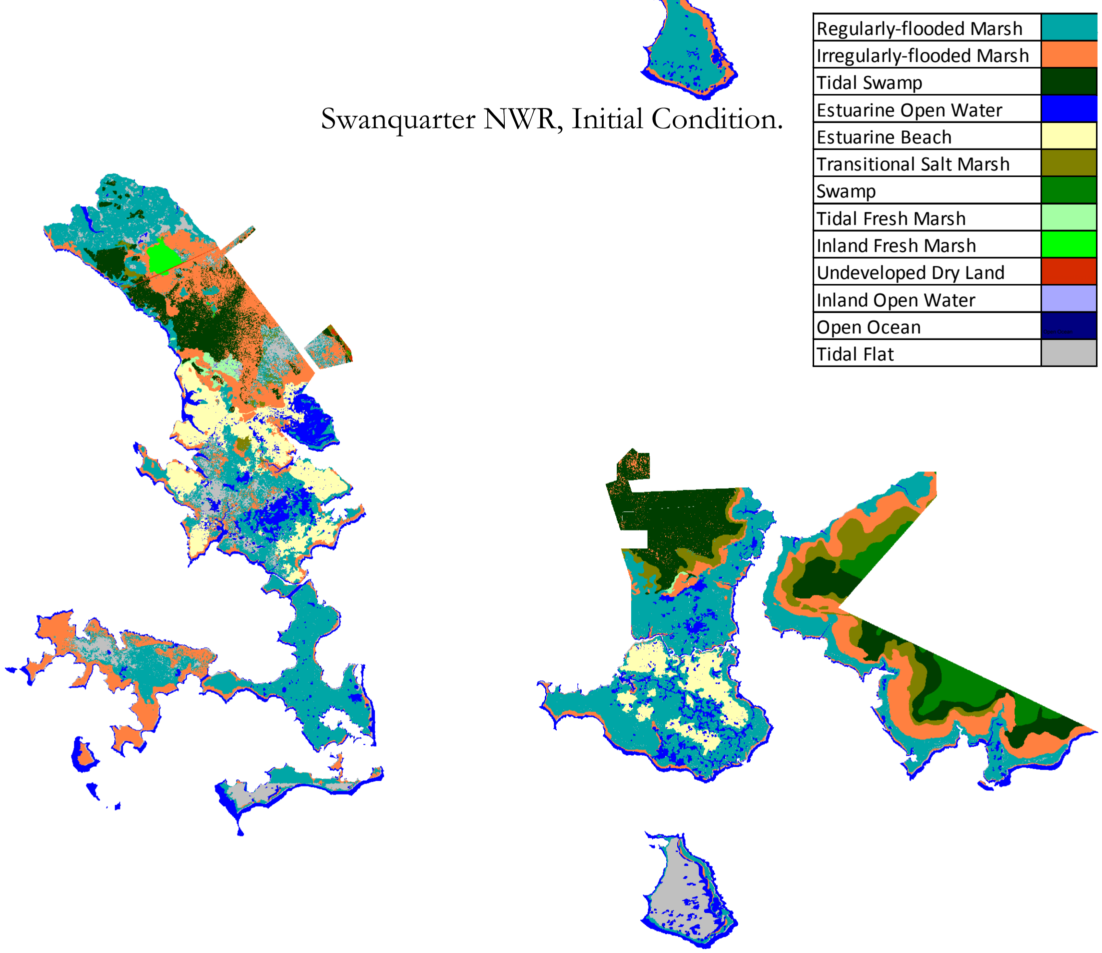
Swanquarter NWR
2 m eustatic SLR by 2100

Results in Acres

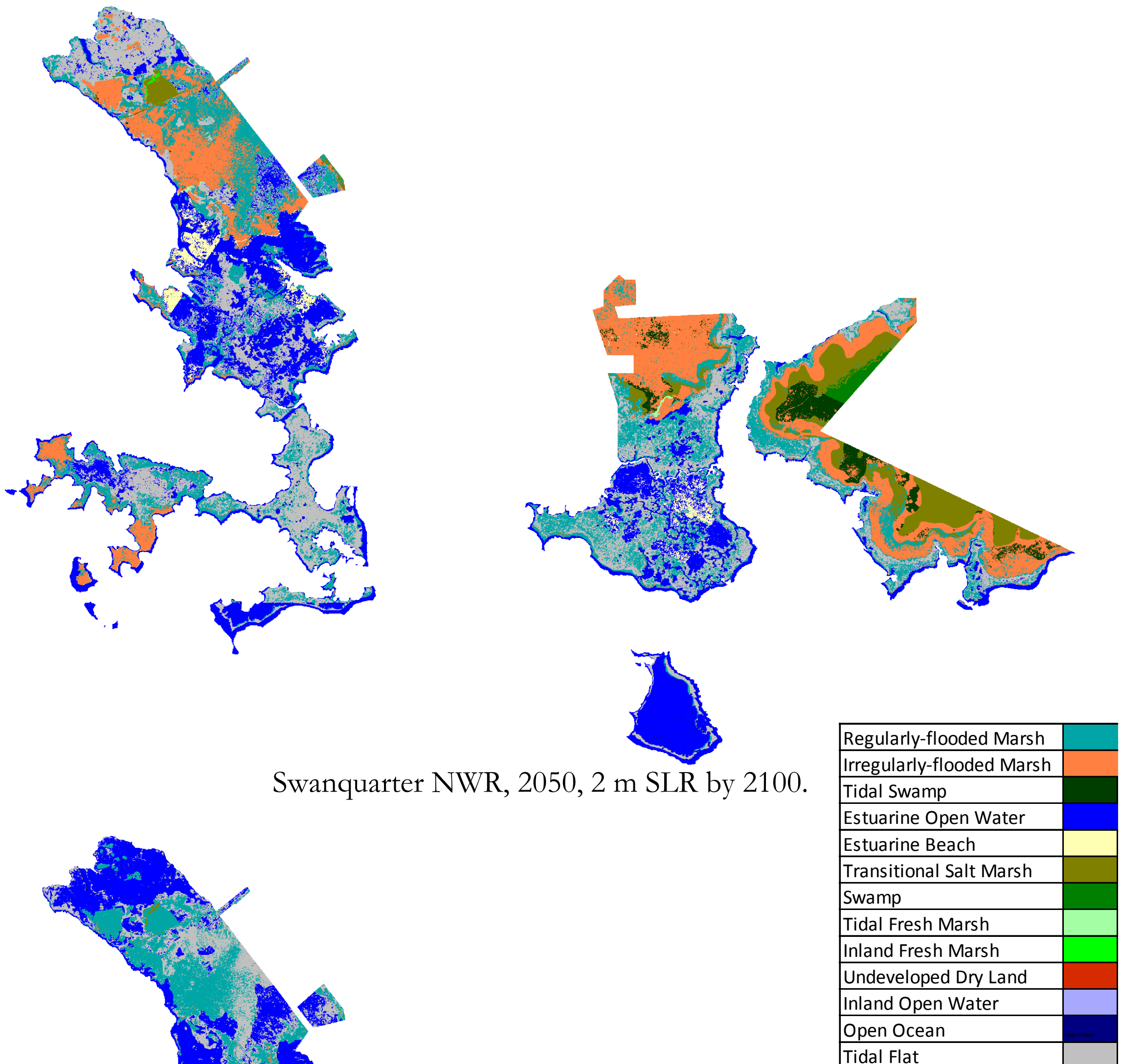
		Initial	2025	2050	2075	2100
	Regularly-flooded Marsh	6079	5537	3463	4014	560
	Irregularly-flooded Marsh	3299	3079	3108	433	18
	Tidal Swamp	2601	2130	413	18	0
	Estuarine Open Water	1742	1897	4107	8414	11754
	Estuarine Beach	1447	1389	380	0	0
	Transitional Salt Marsh	783	721	962	127	1
	Swamp	486	464	102	1	0
	Tidal Fresh Marsh	90	73	16	1	0
	Inland Fresh Marsh	90	83	8	0	0
	Undeveloped Dry Land	22	15	1	0	0
	Inland Open Water	3	0	0	0	0
	Open Ocean	0	29	153	294	341
	Tidal Flat	0	1225	3927	3339	3968
	Total (incl. water)	**16641**	**16641**	**16641**	**16641**	**16641**



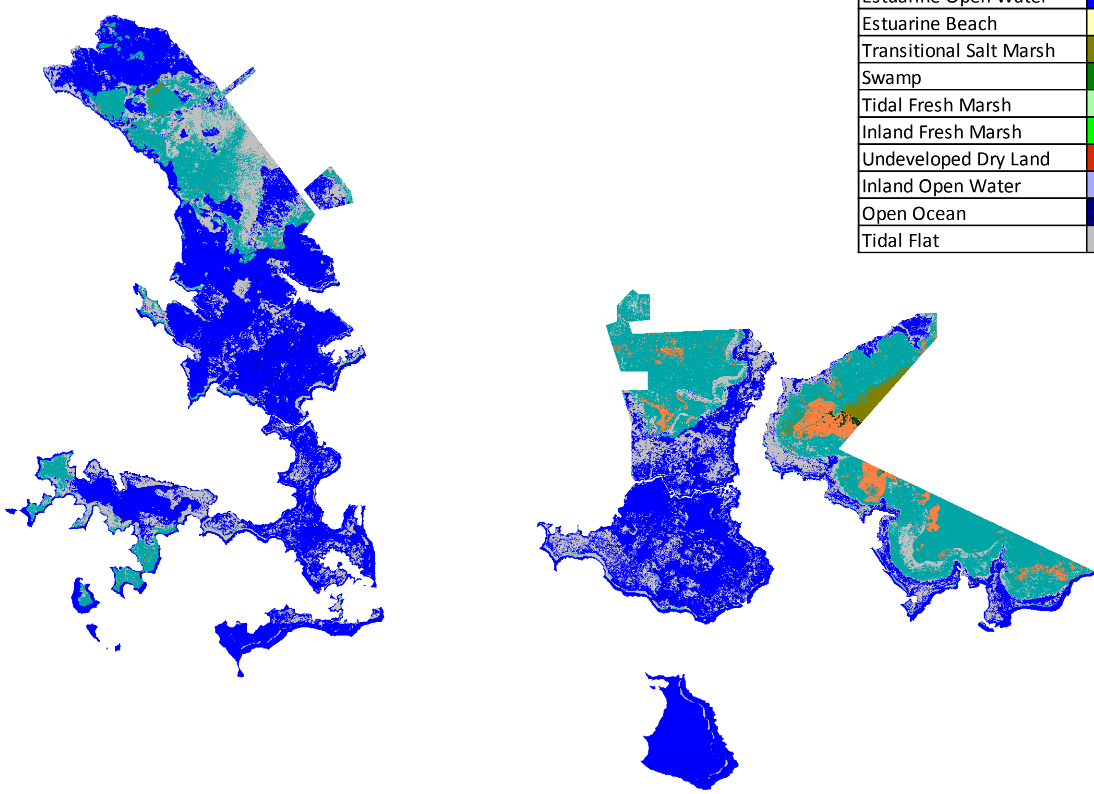
Swanquarter NWR, Initial Condition.



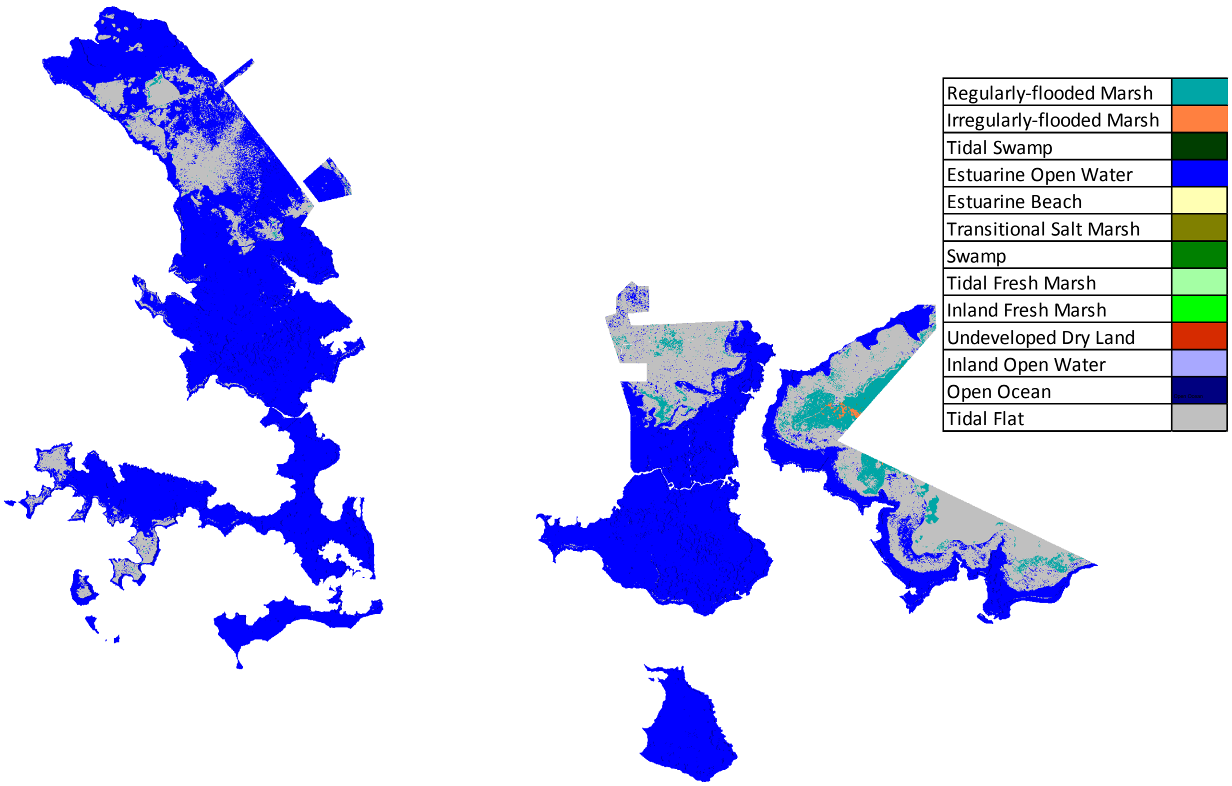
Swanquarter NWR, 2025, 2 m SLR by 2100.



Swanquarter NWR, 2050, 2 m SLR by 2100.



Swanquarter NWR, 2075, 2 m SLR by 2100.



Swanquarter NWR, 2100, 2 m SLR by 2100.

Discussion

SLAMM predictions for Swanquarter NWR suggest that the refuge wetland coverage will be substantially altered as a result of sea-level rise. The micro-tidal regime of this refuge causes marshes to be especially susceptible to rising water levels.

Regularly- and irregularly-flooded marshes that currently cover approximately 57% of refuge lands are predicted to be increasingly converted to tidal flat and open water as sea-level rise continues. Almost total loss of these categories is predicted for the 1.5 m SLR by 2100 scenario. Other wetland categories, such as swamps and tidal swamps, appear to be even more fragile, with a complete loss predicted at lower SLR rates. Conversely, open water and tidal flat are predicted to steadily increase their coverage from the 11% of the total refuge area they inhabit today to up to 97% in 2100 under the 2 m SLR.

Comparing the results of this analysis to the previous SLAMM simulation of the refuge, conducted by USFWS in 2008, is difficult since the NWI and elevation maps have changed since that earlier analysis. Qualitatively, prediction results show a similar trend to those obtained previously, showing that the refuge is fragile with respect to SLR. Quantitatively, salt marshes now appear to be slightly more resilient. However, this result may be due to the fact the most of the land cover recently classified as estuarine beach and almost immediately lost to open water or tidal flat, was previously classified as salt marsh and thus resulting in greater percentages of saltmarsh losses.

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

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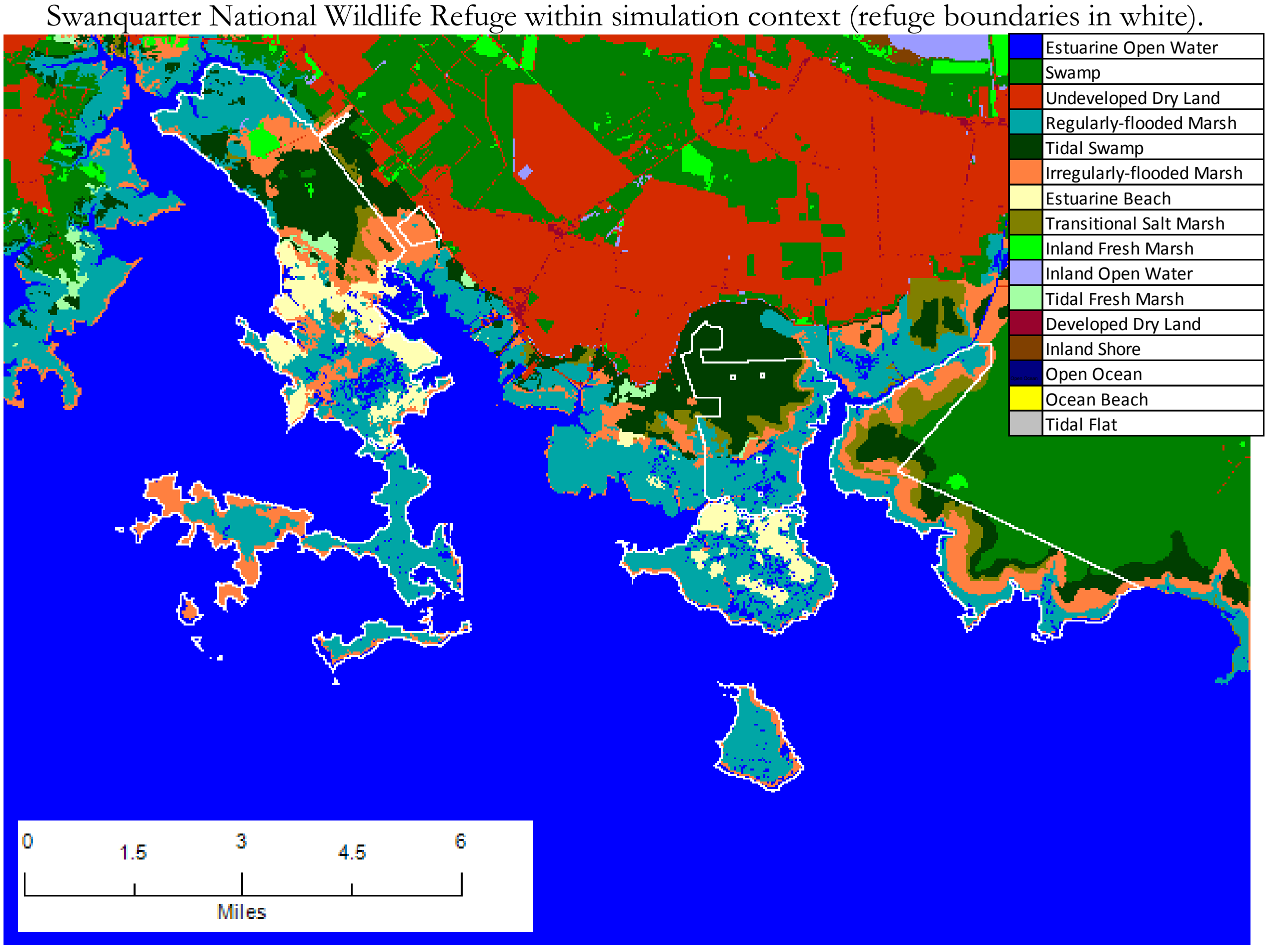
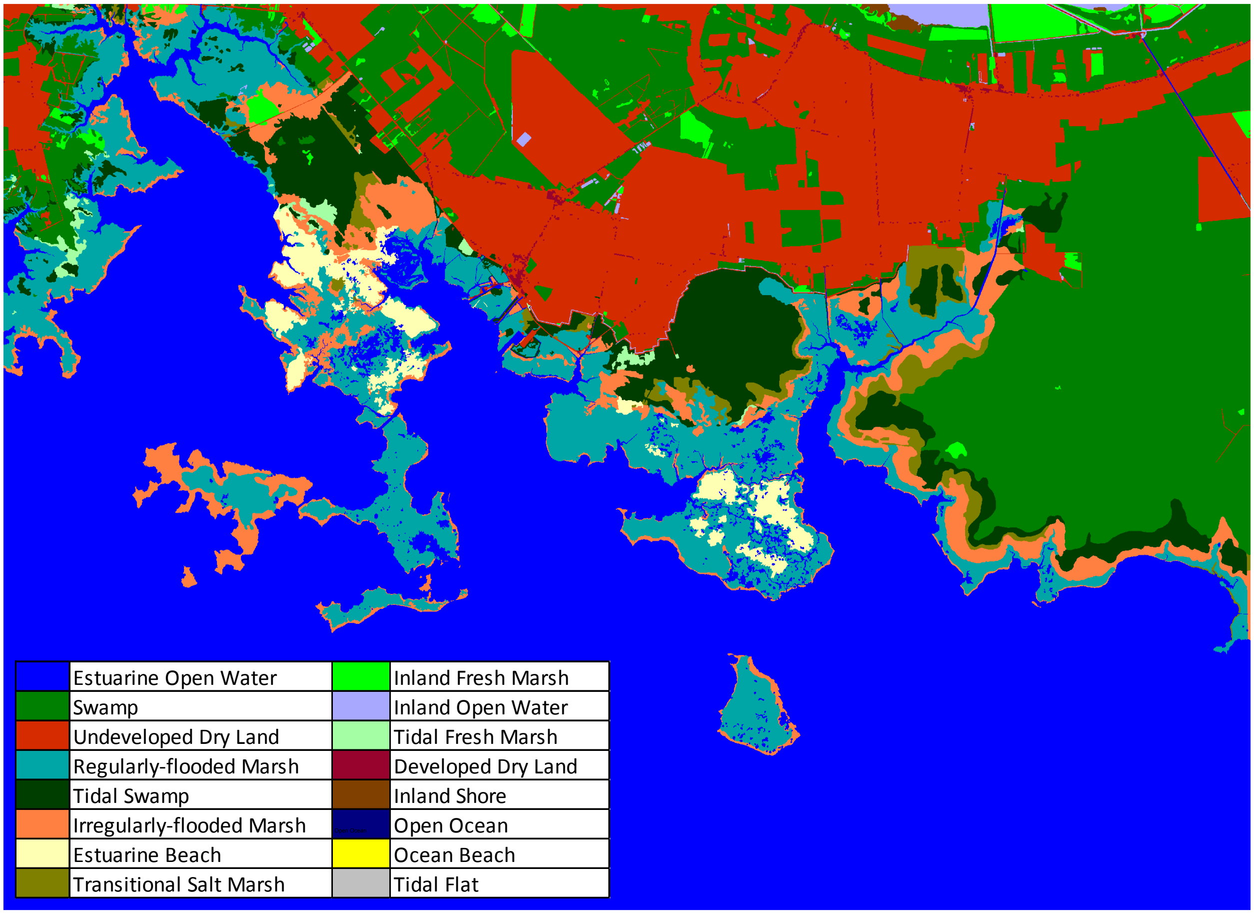
Appendix A: Contextual Results

The SLAMM model 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:

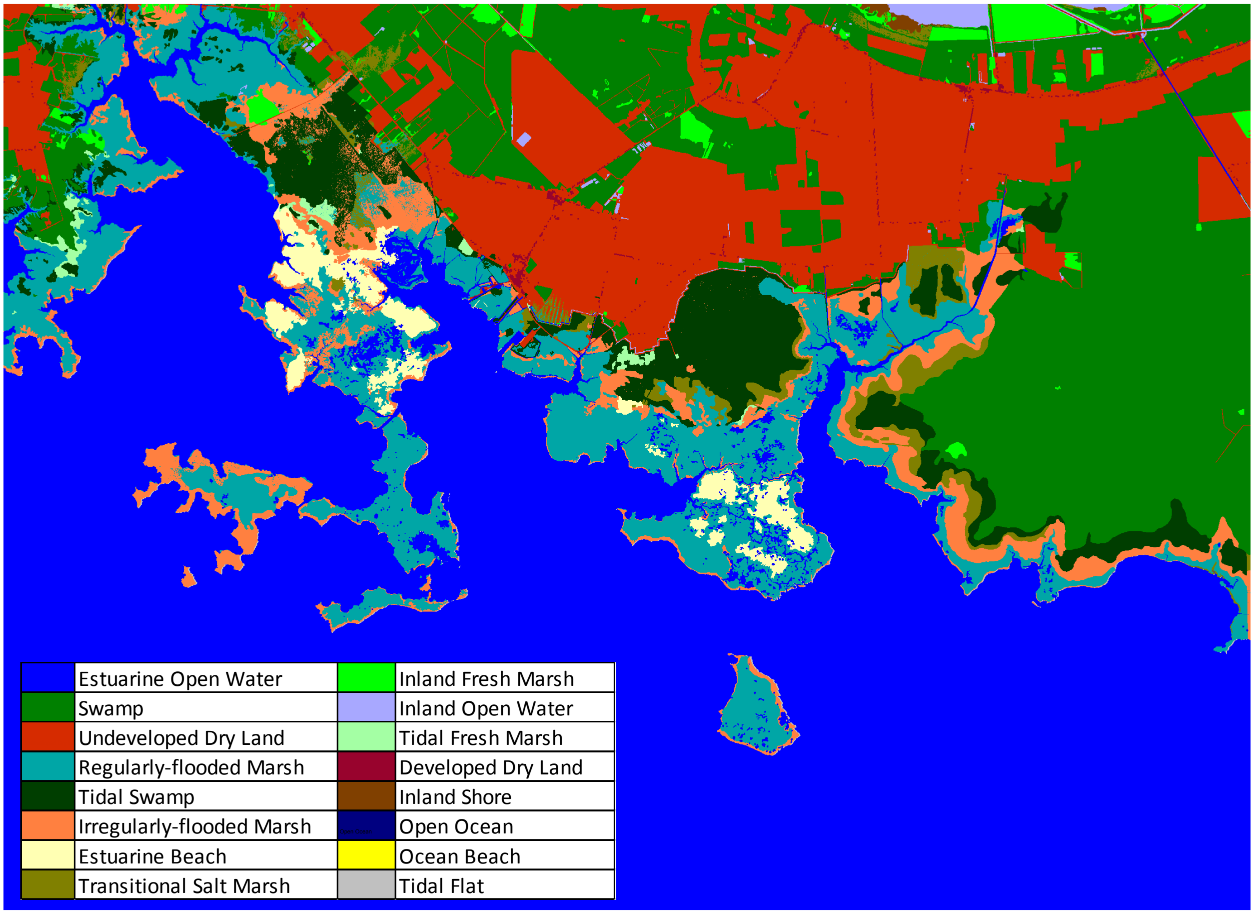
- Results were critically examined within USFWS refuges but not closely examined for the larger region.
- Site-specific parameters for the model were derived for USFWS refuges whenever possible and may not be regionally applicable.
- Especially in areas where dikes are present, an effort was made to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

Swanquarter National Wildlife Refuge within simulation context (refuge boundaries in white).

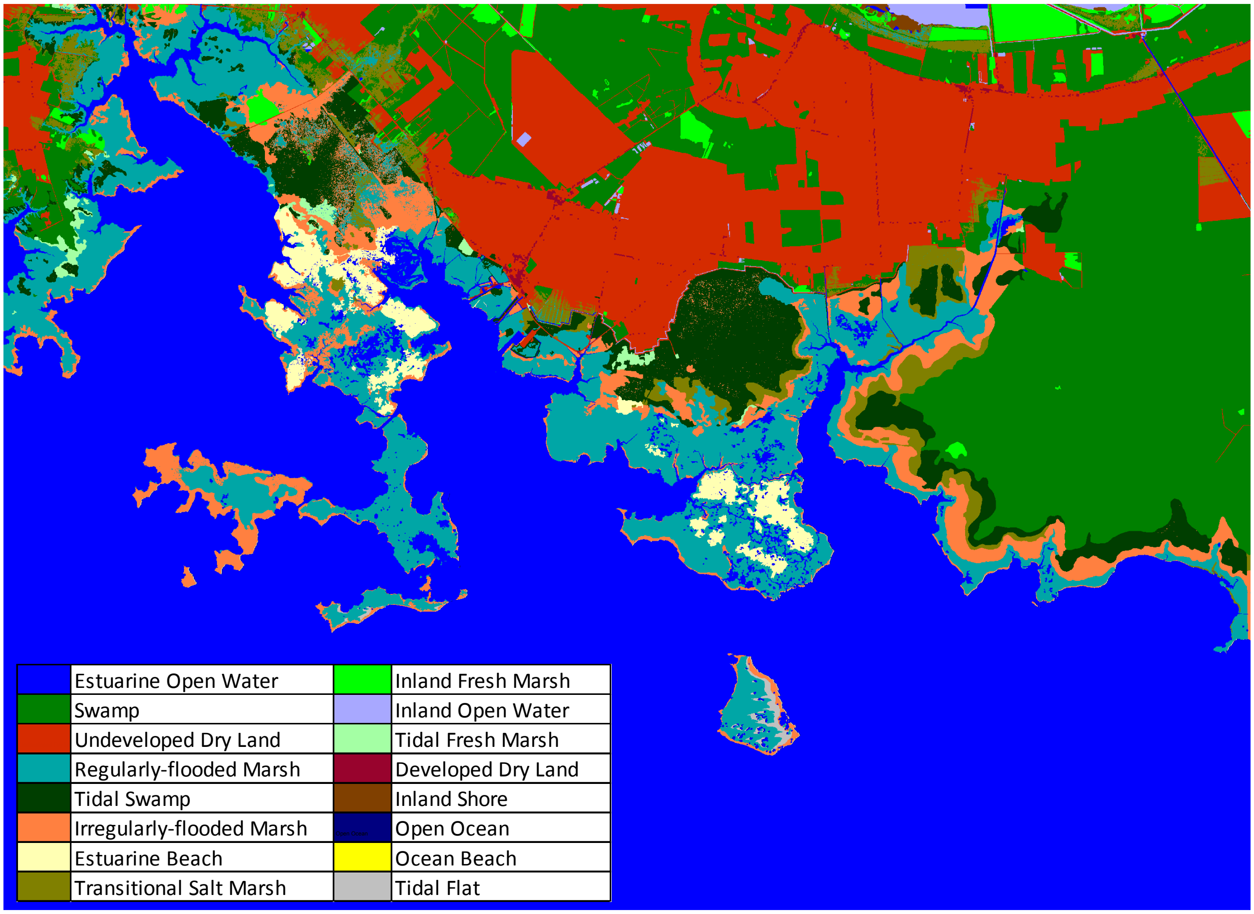




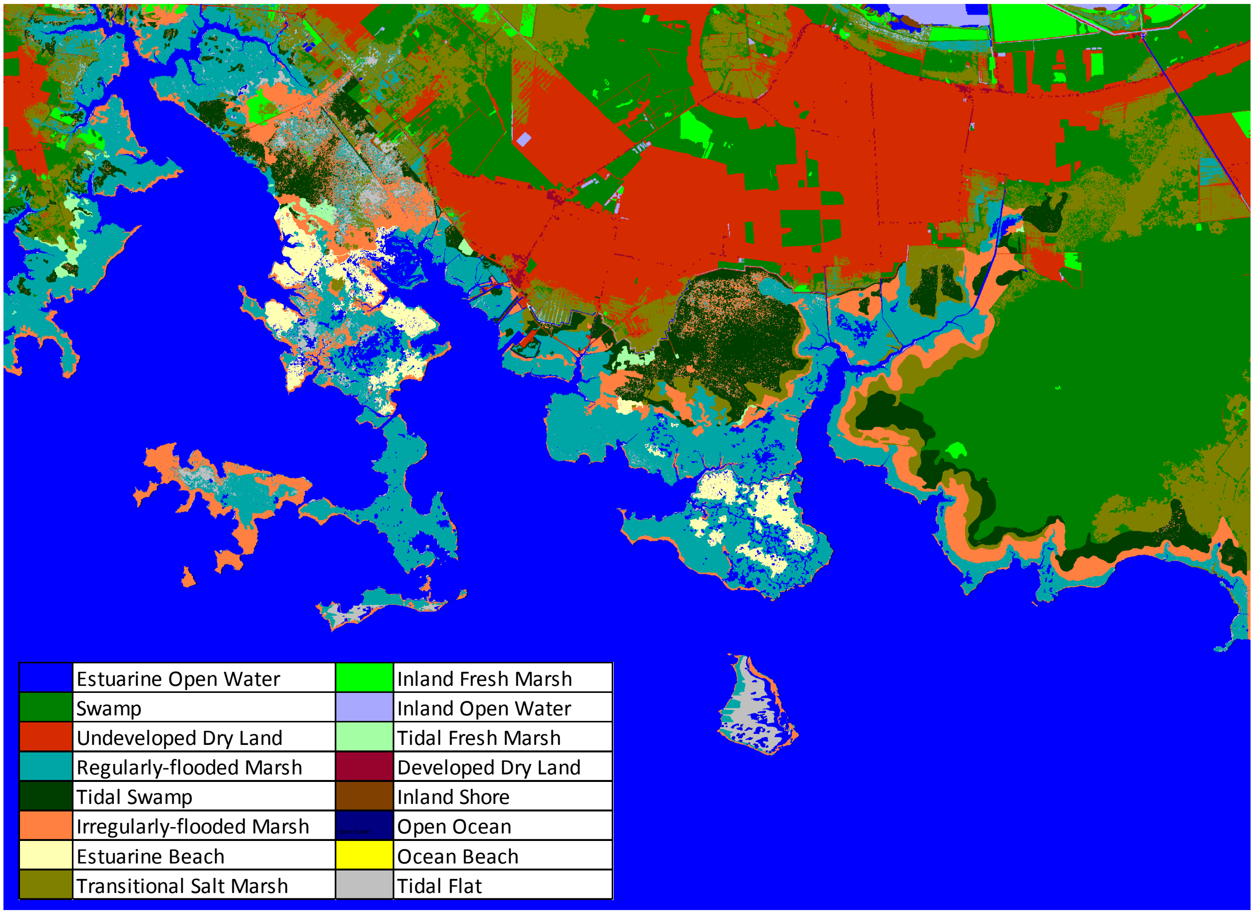
Swanquarter NWR, Initial Condition.



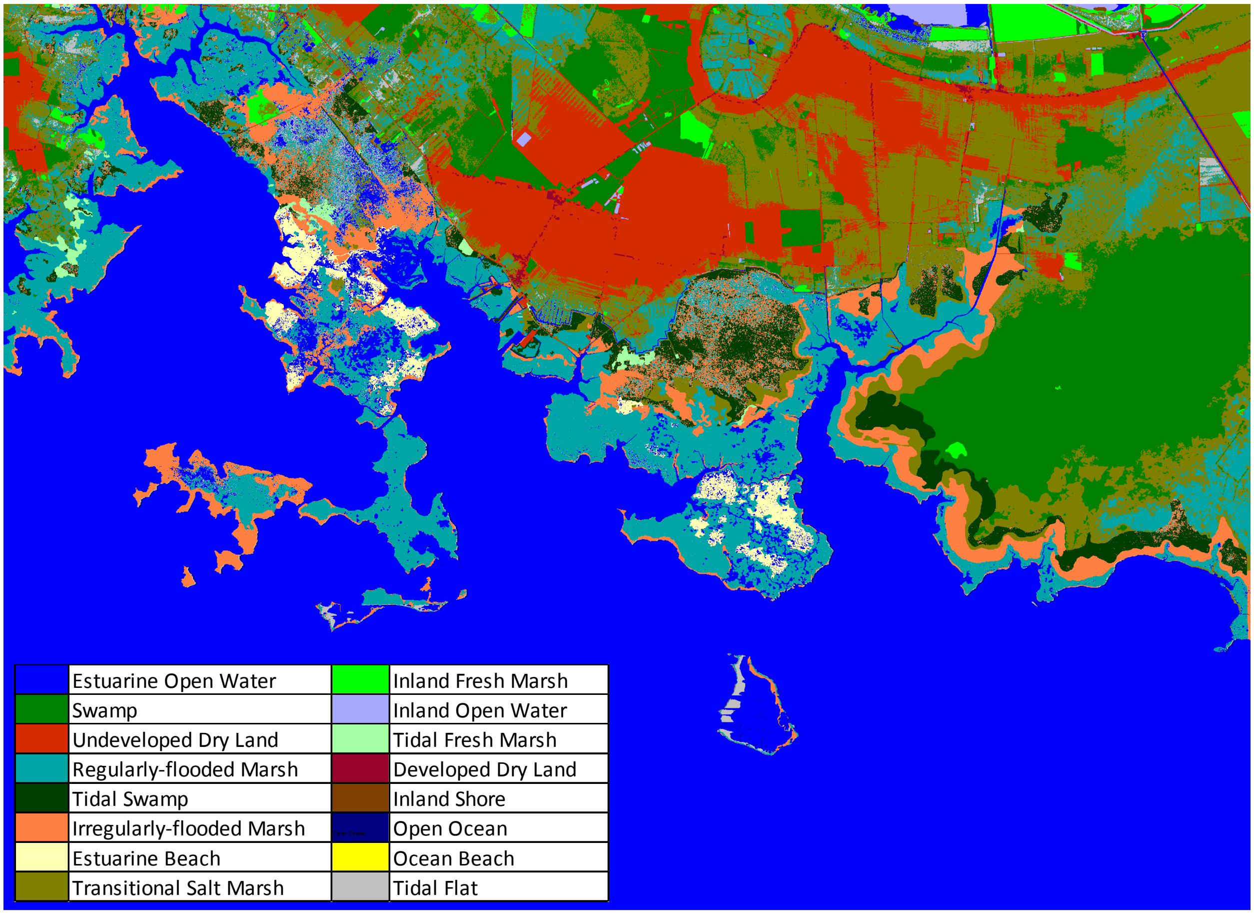
Swanquarter NWR, 2025, Scenario A1B Mean, 0.39 m SLR by 2100.



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



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



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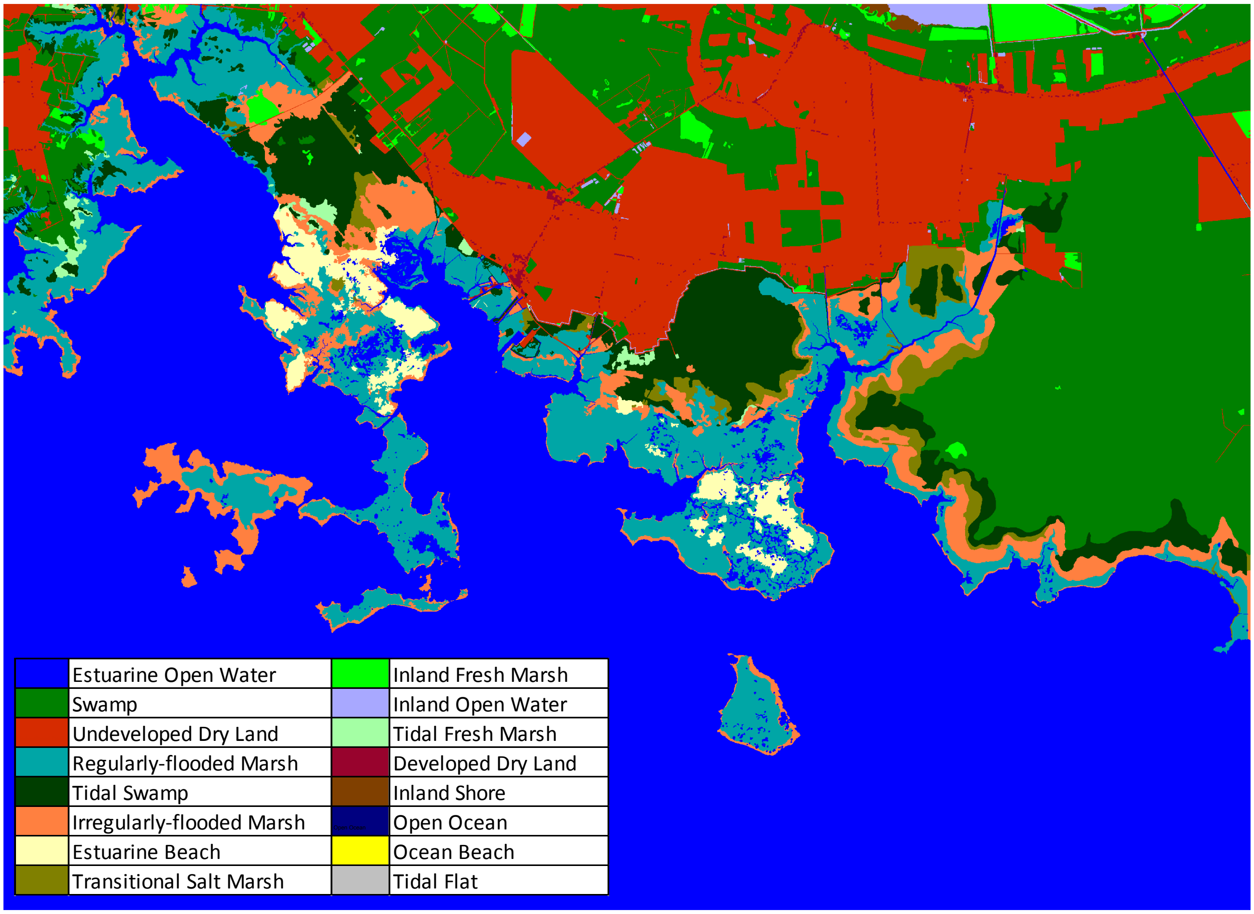

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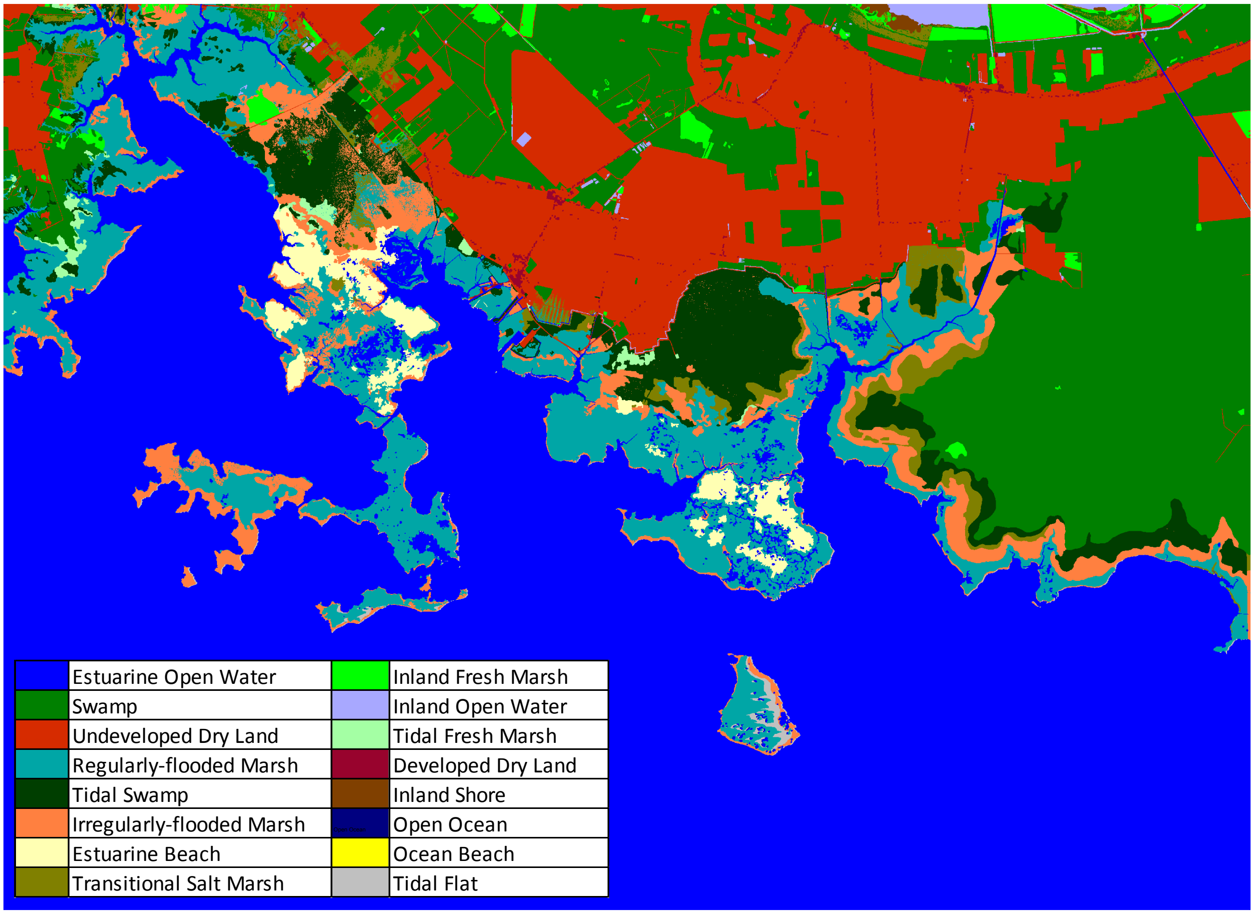
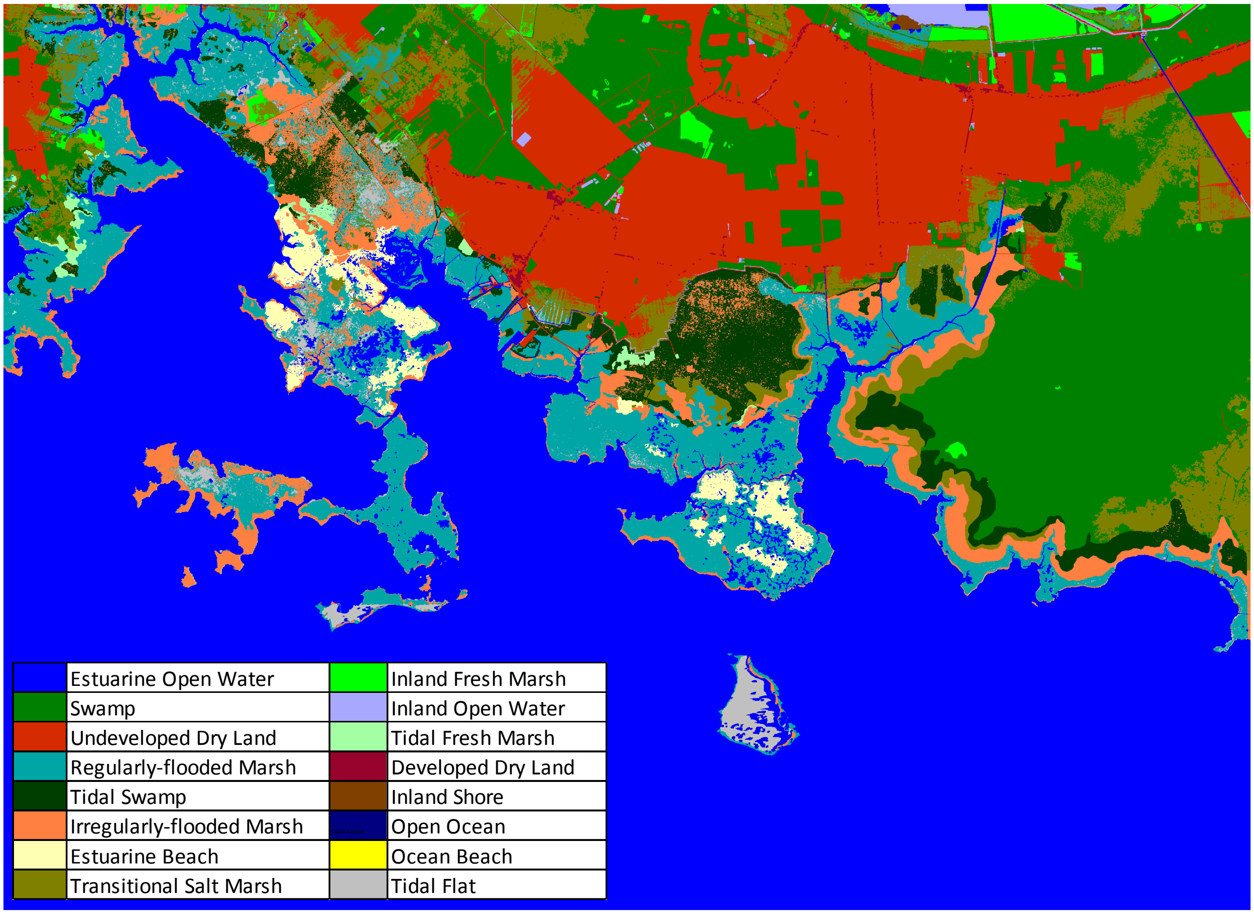


Swanquarter NWR, 2025, Scenario A1B Maximum, 0.69 m SLR by 2100.



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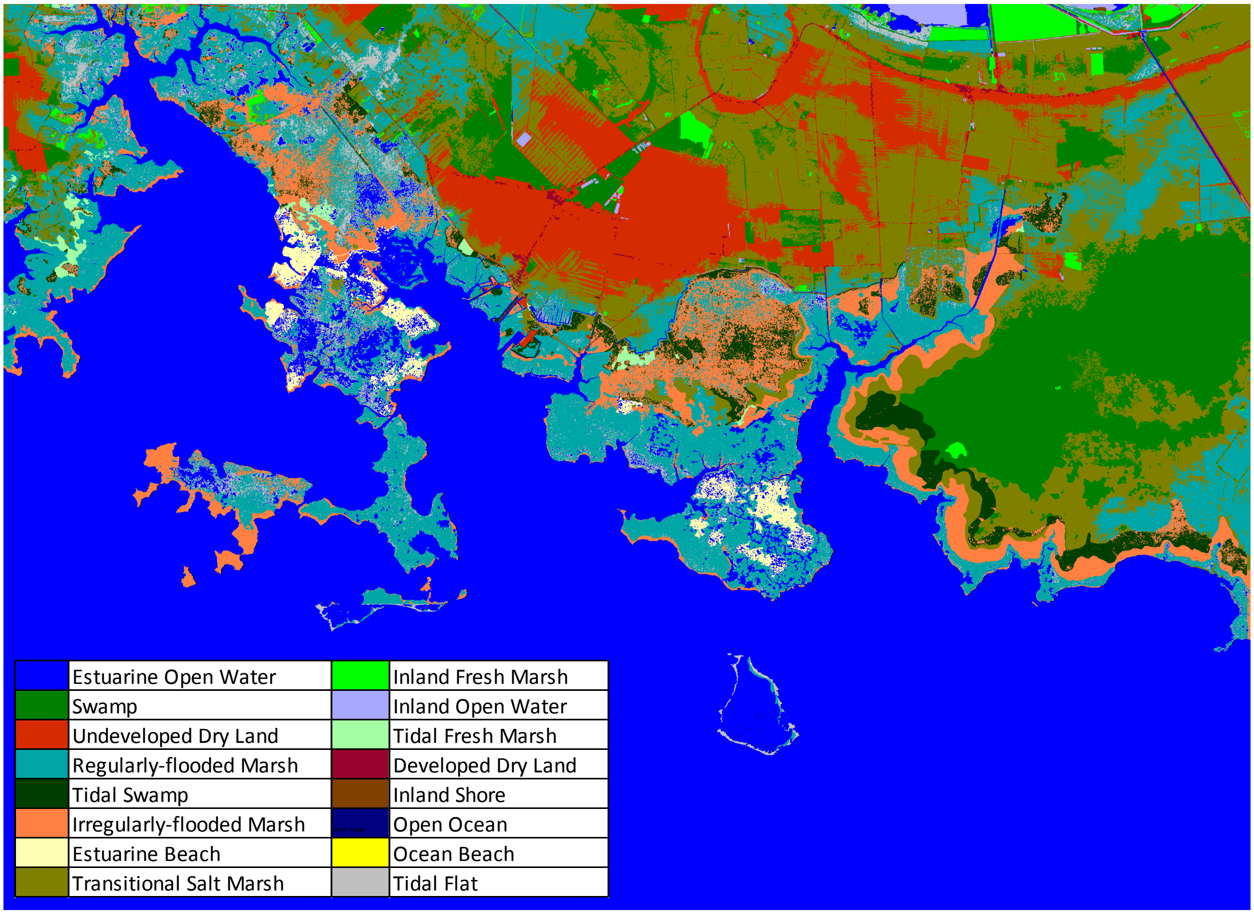

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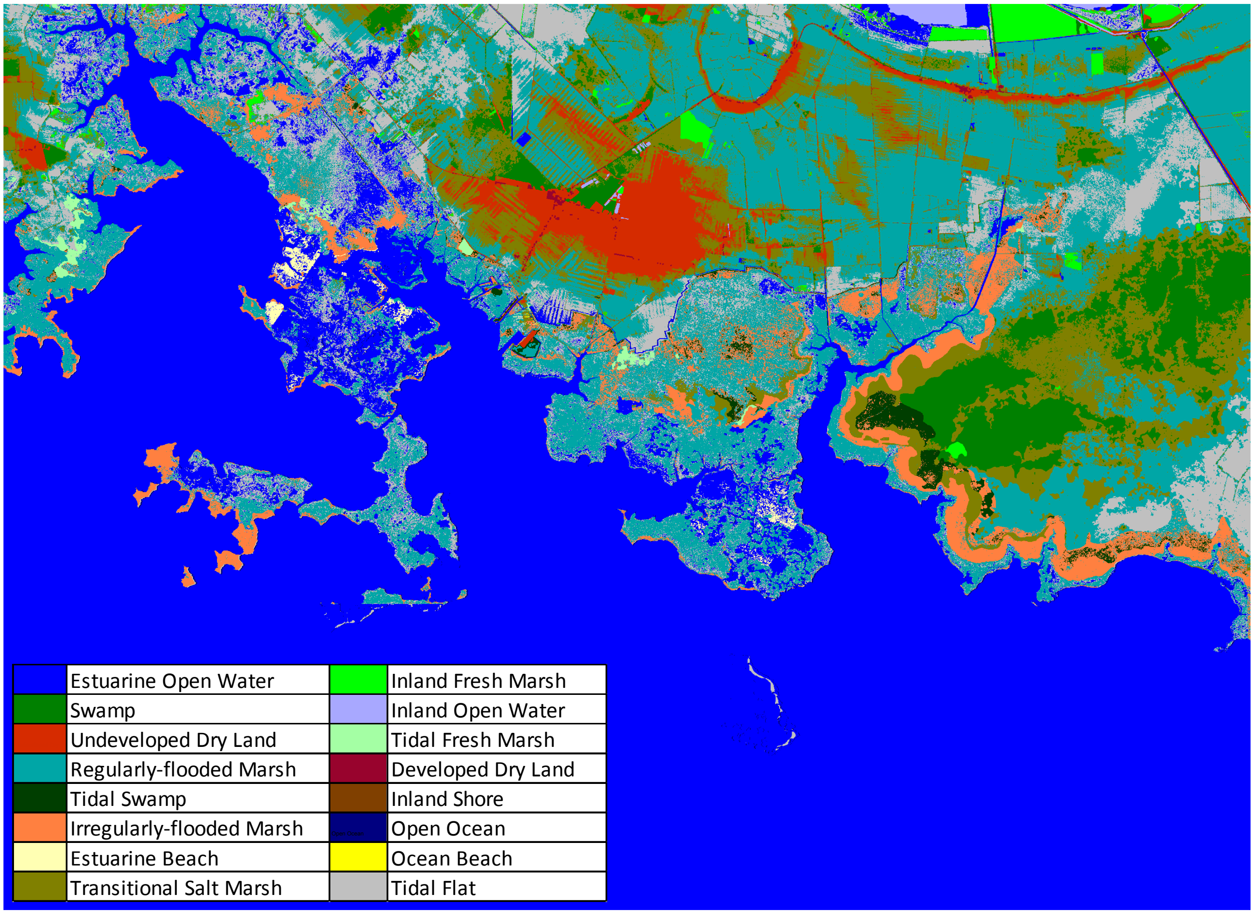

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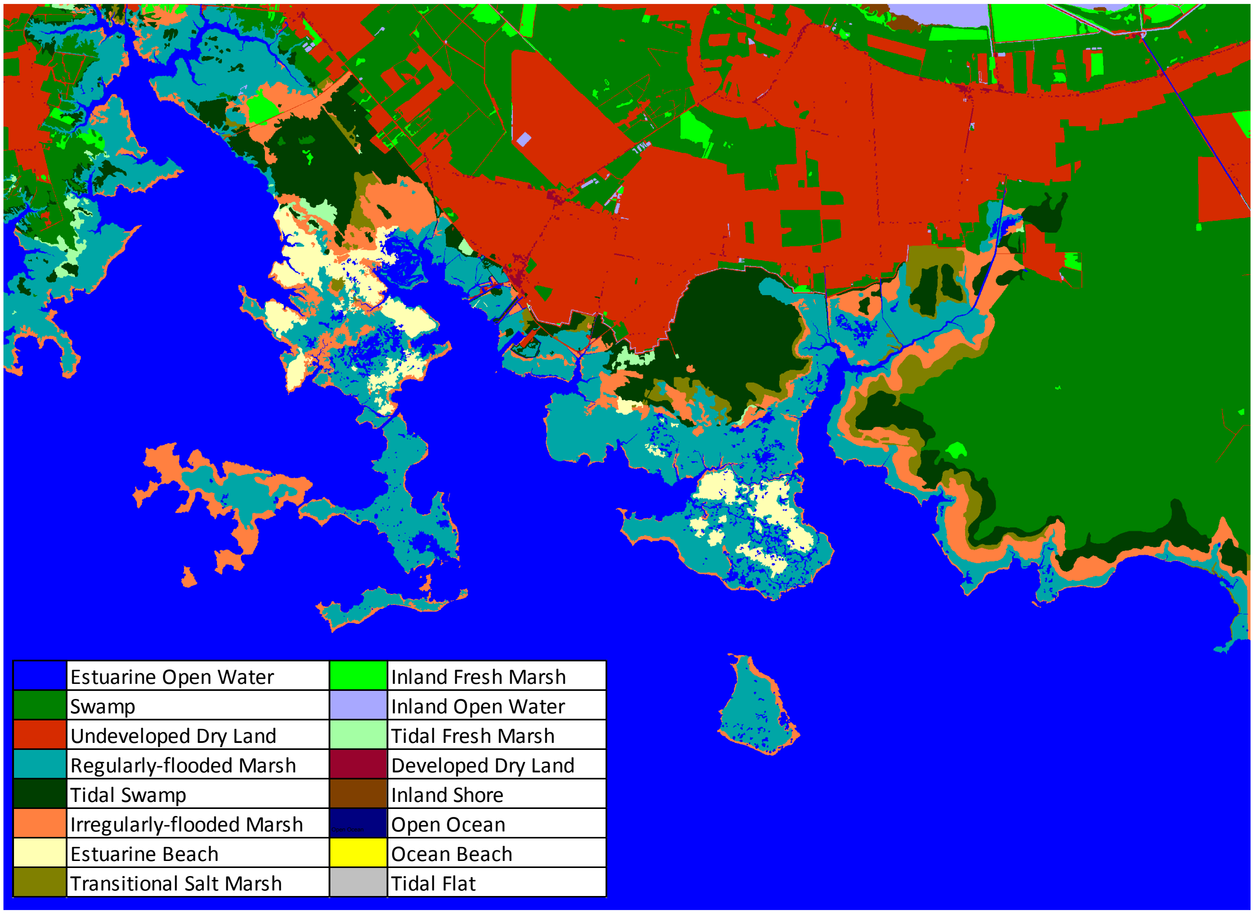
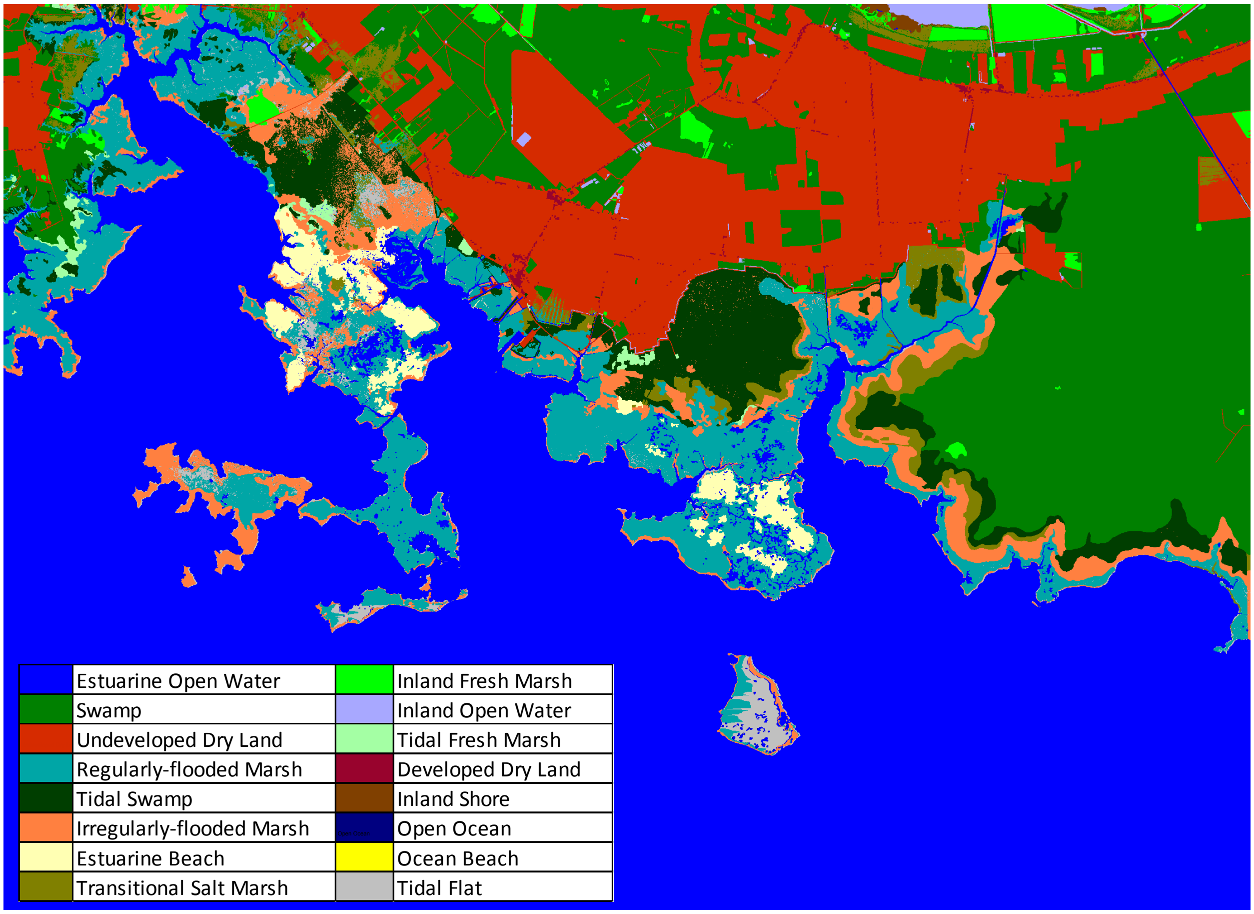
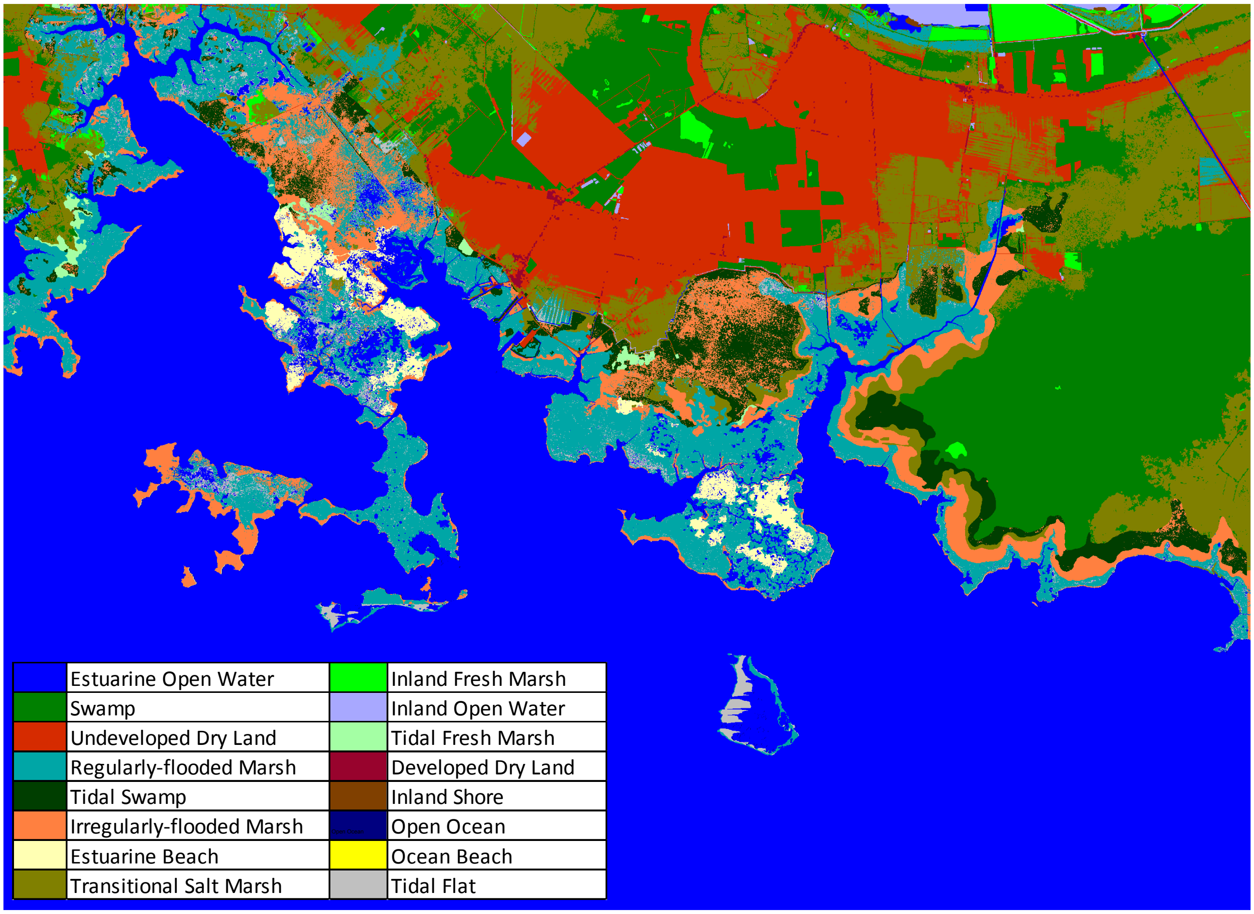


Swanquarter NWR, Initial Condition.



Swanquarter NWR, 2025, 1 m SLR by 2100.



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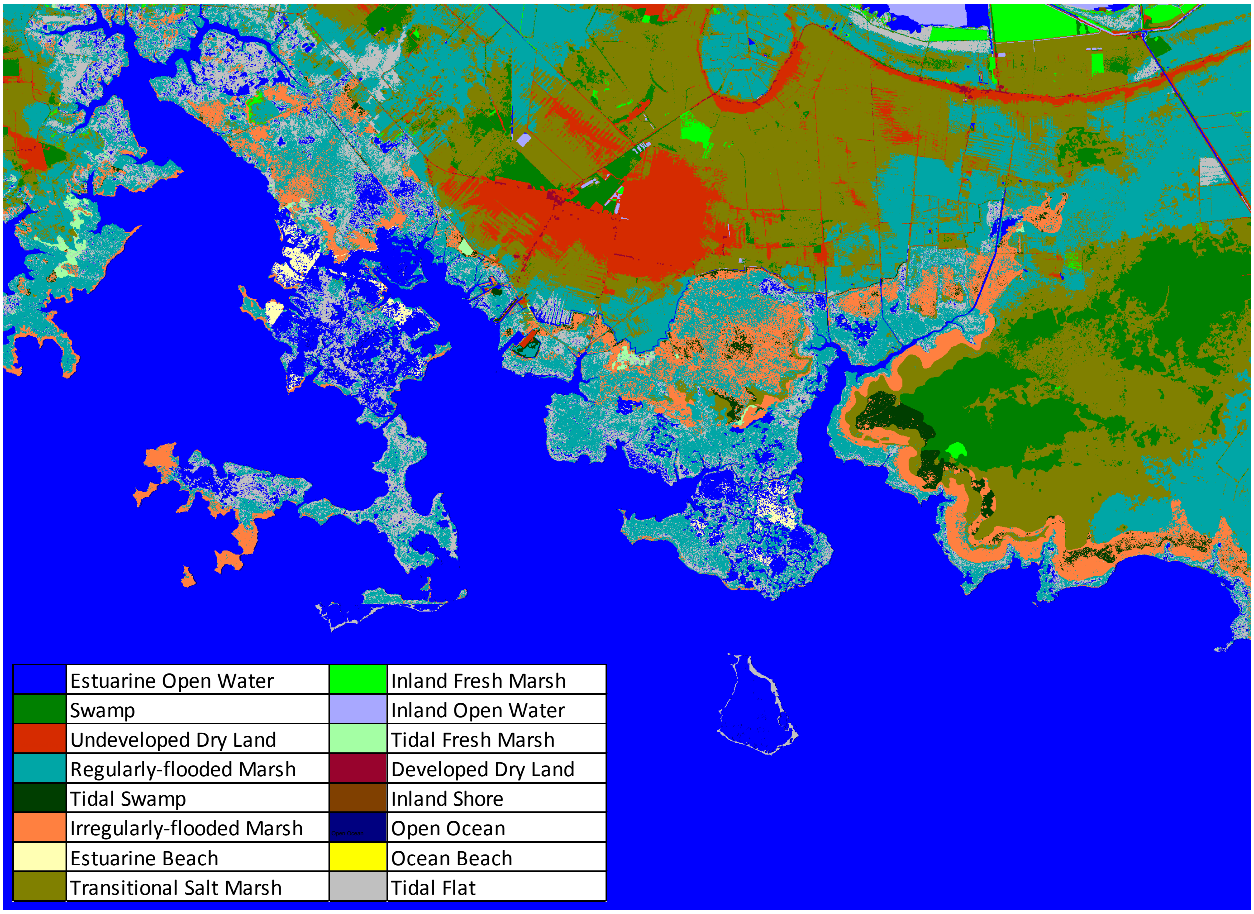

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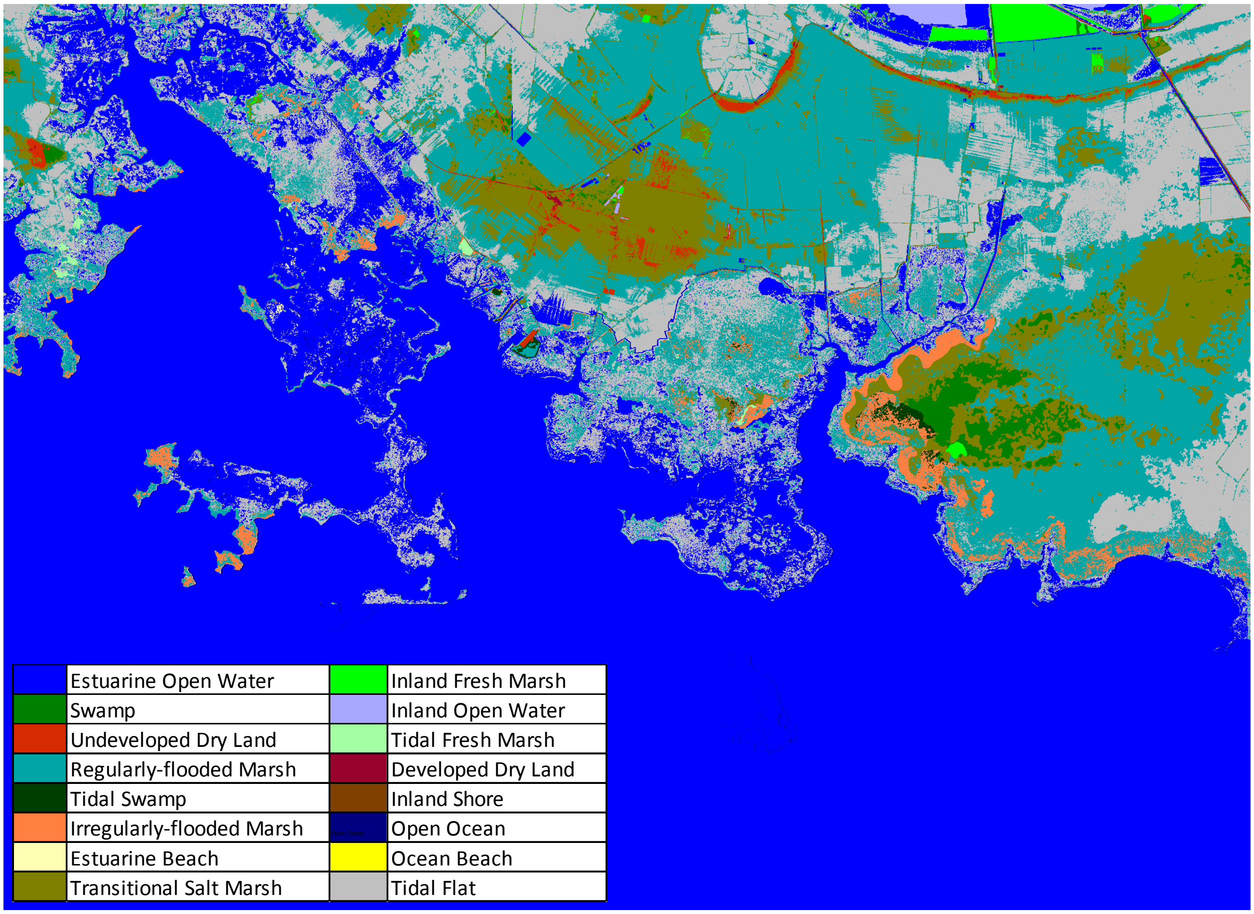

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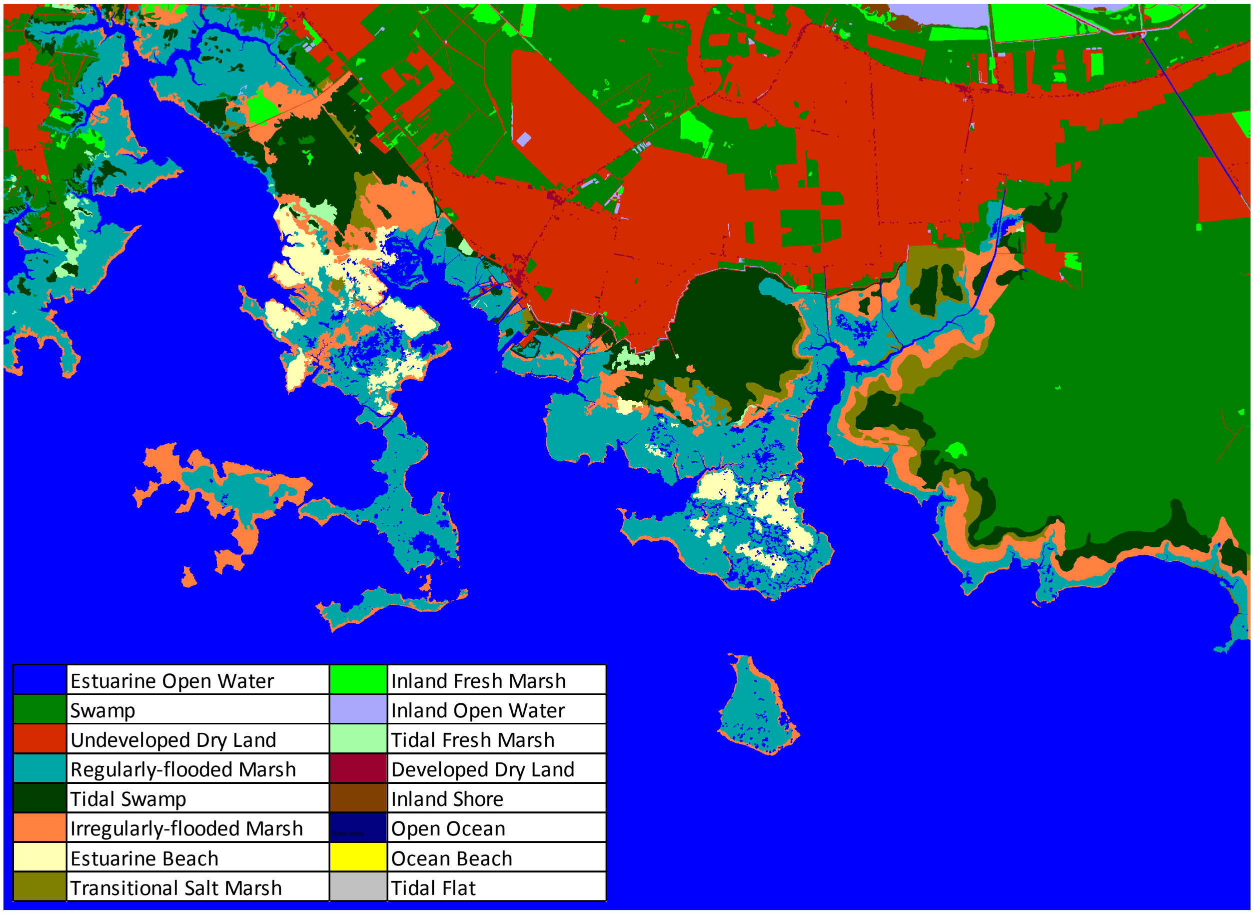

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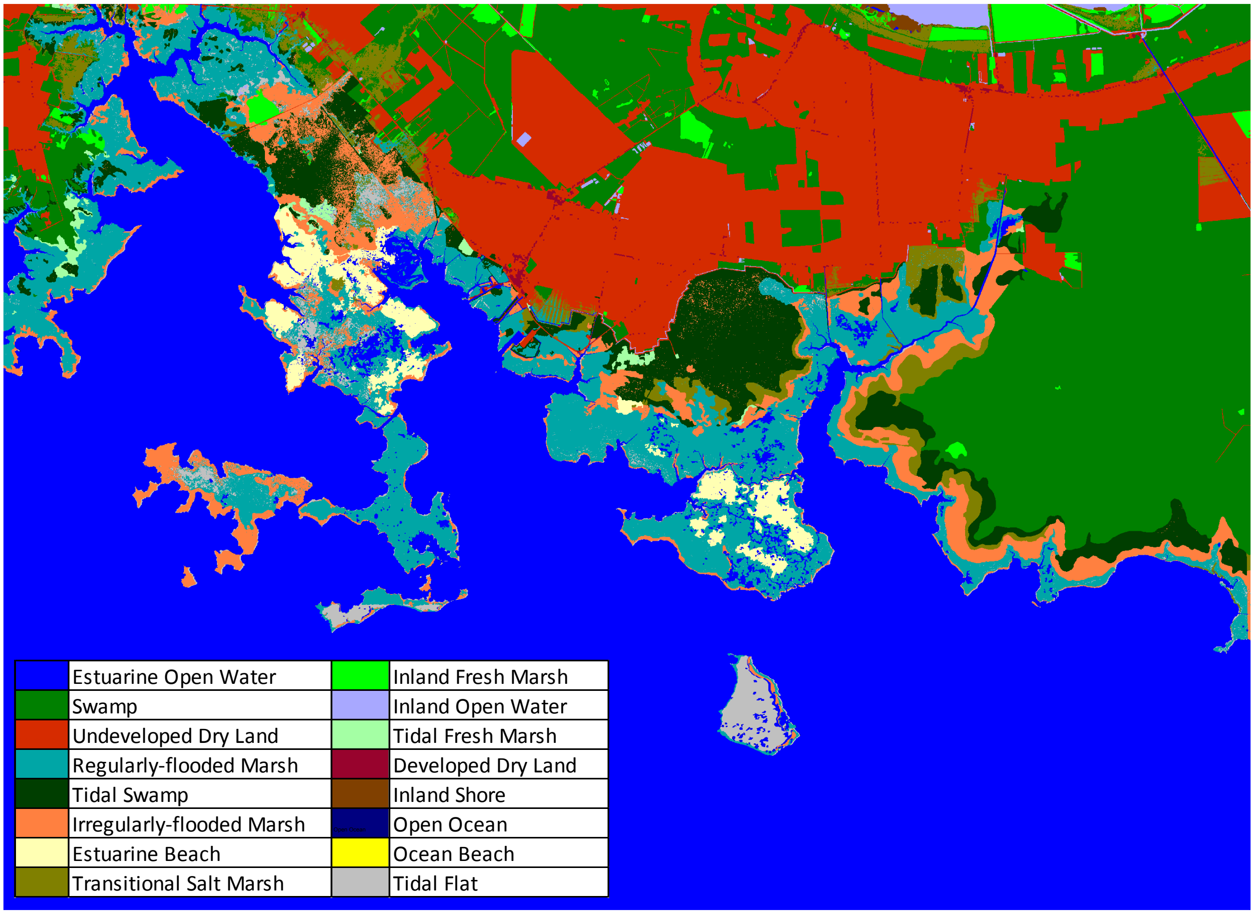

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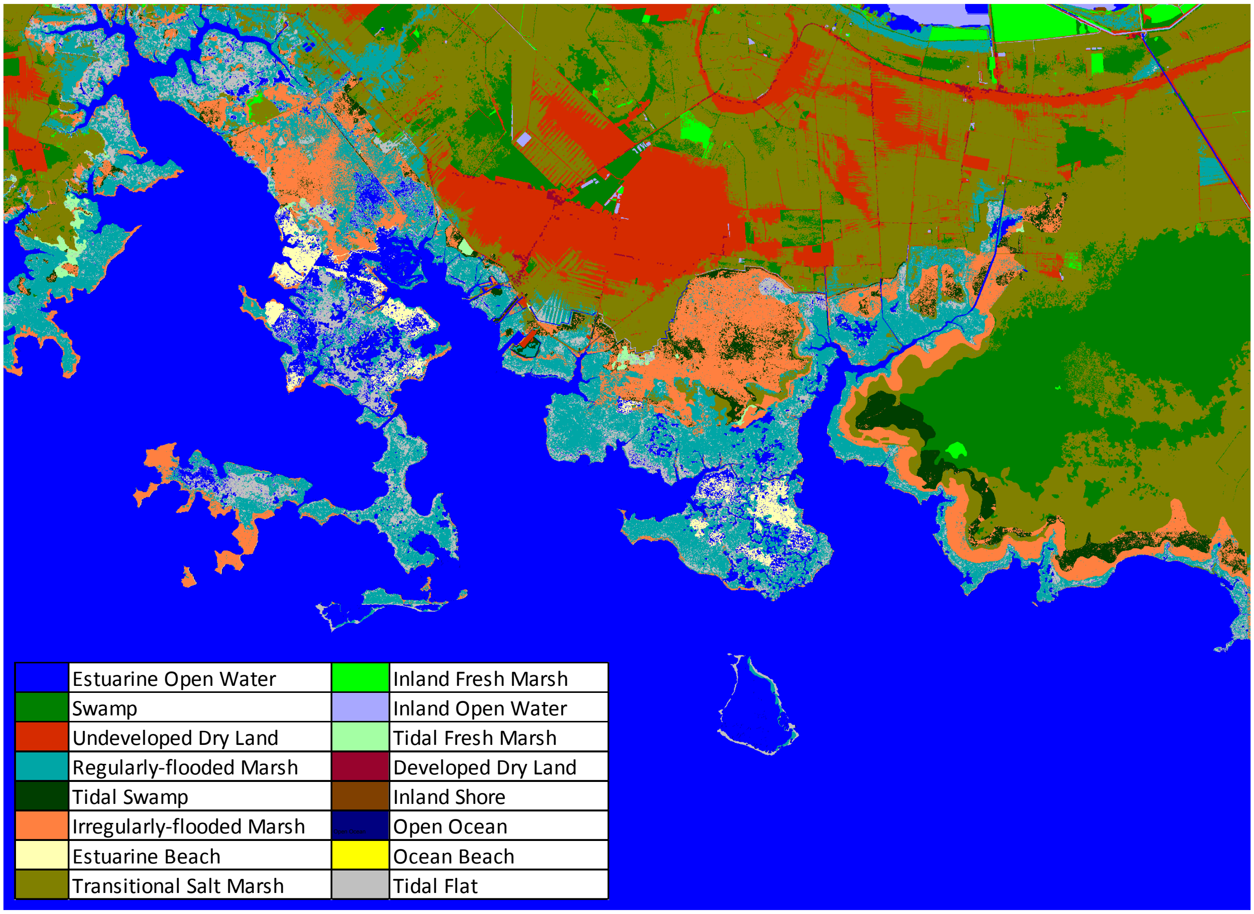

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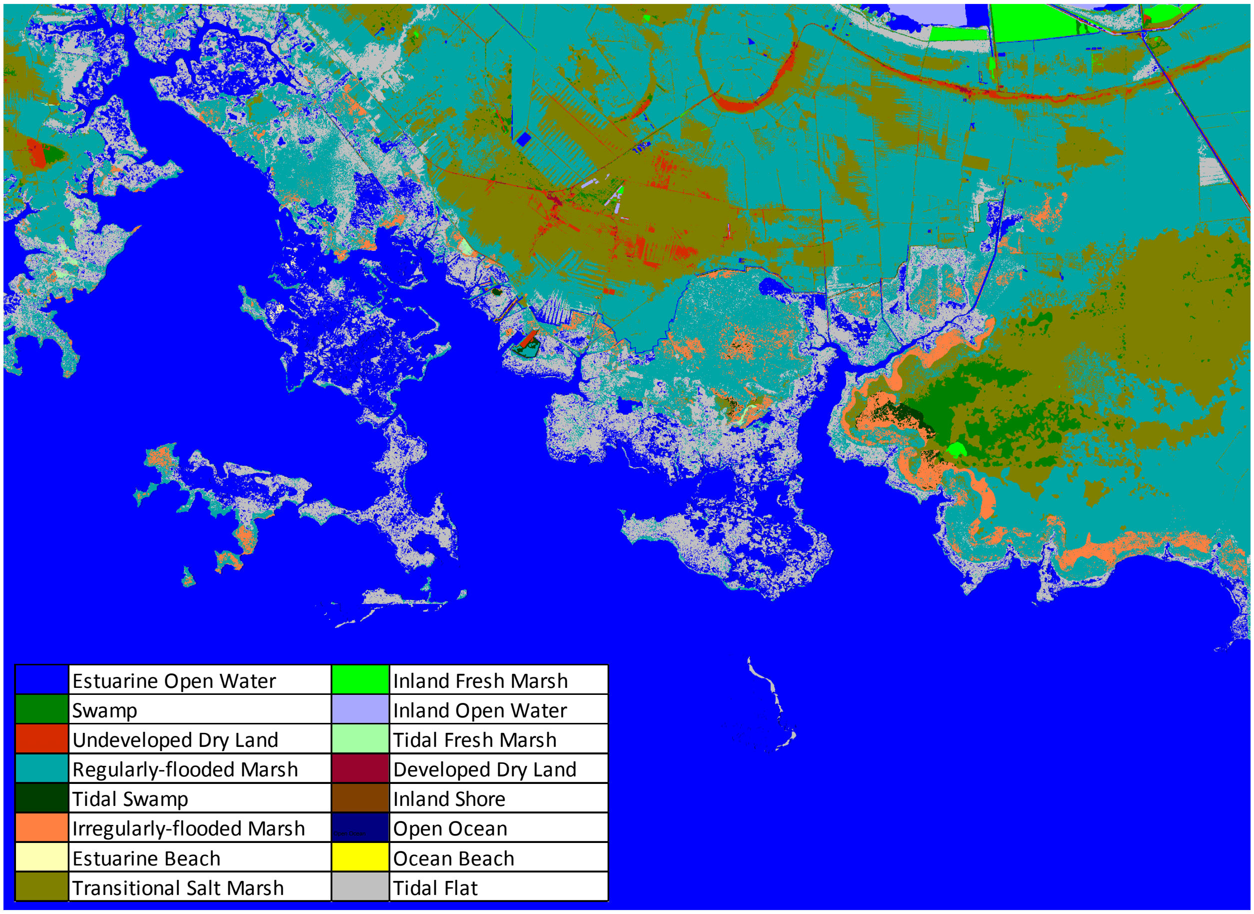

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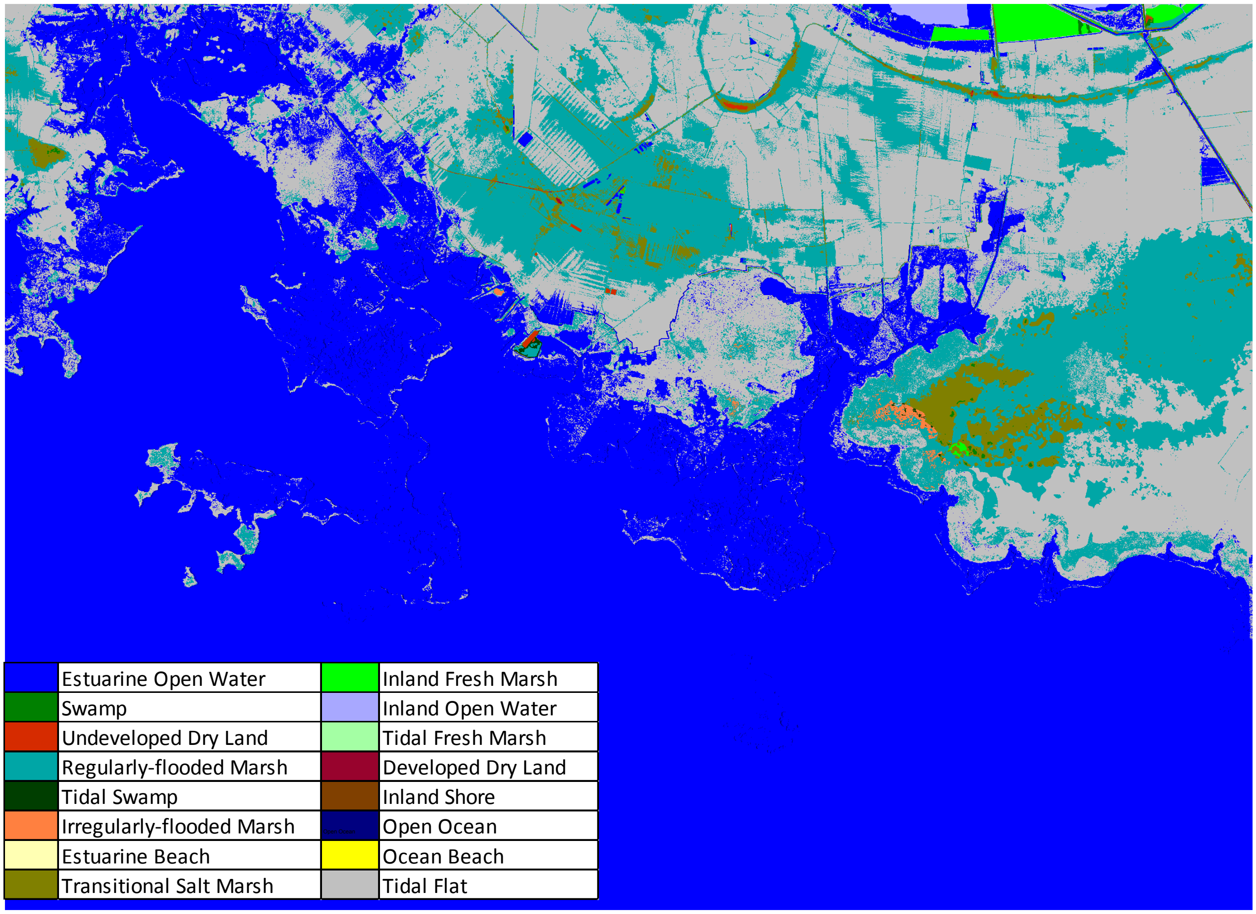

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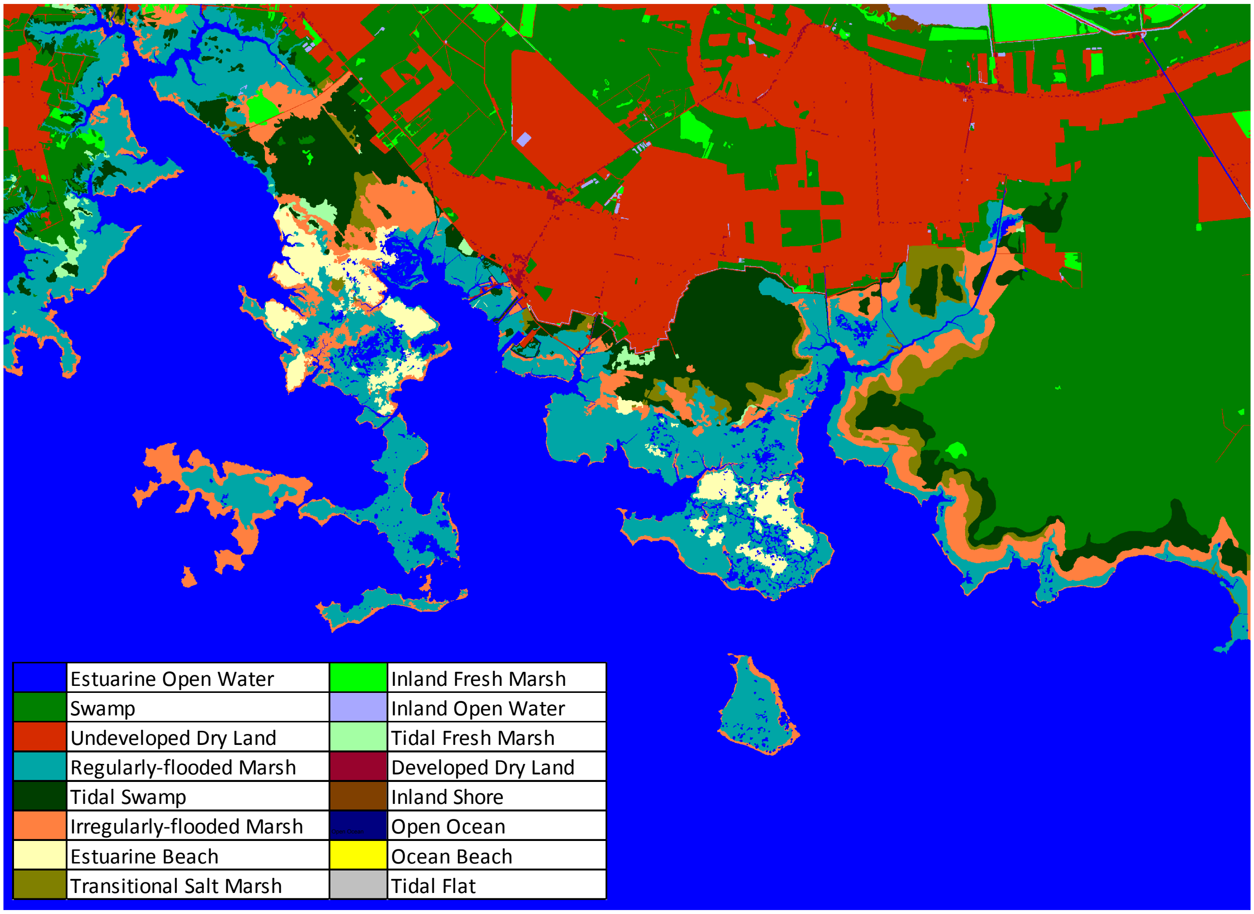
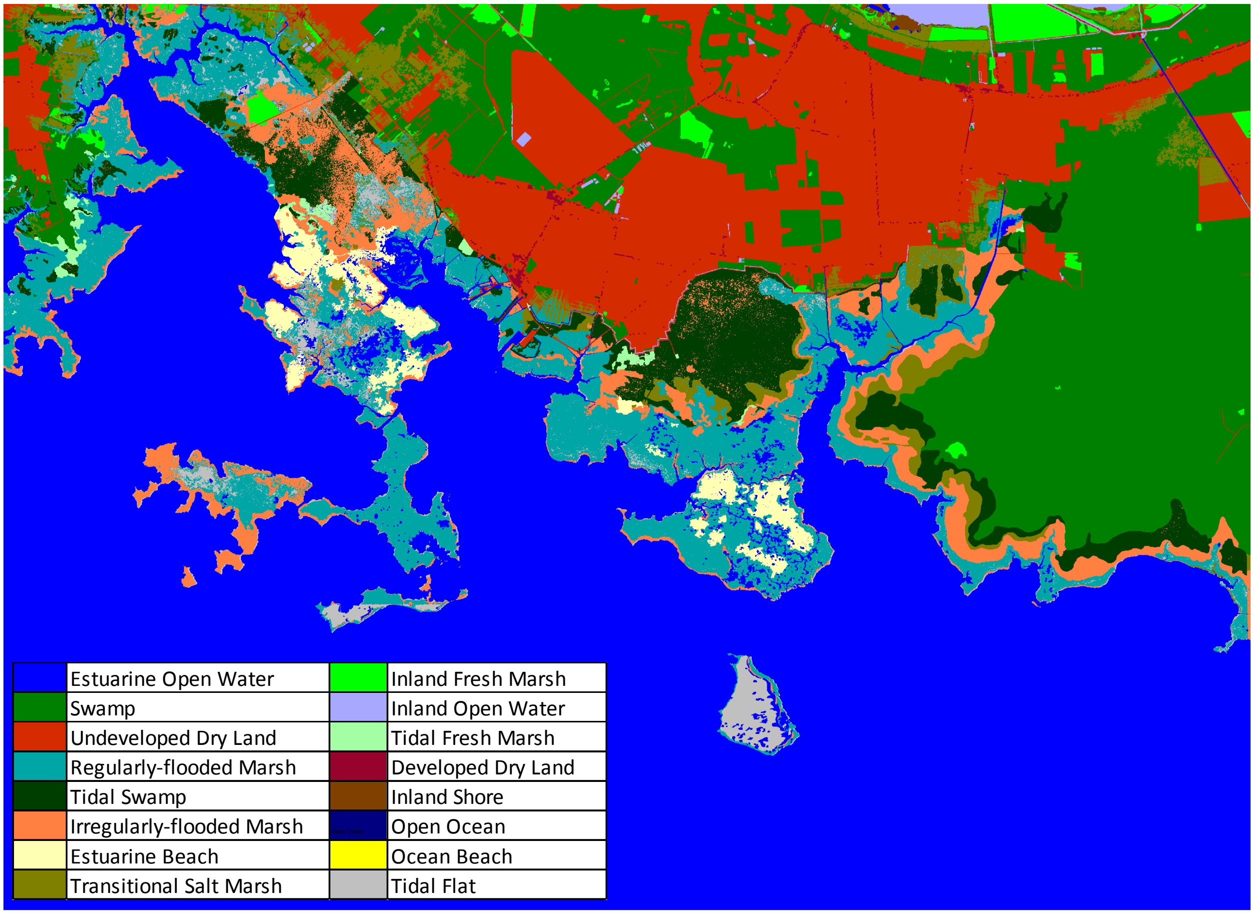


Swanquarter NWR, Initial Condition.



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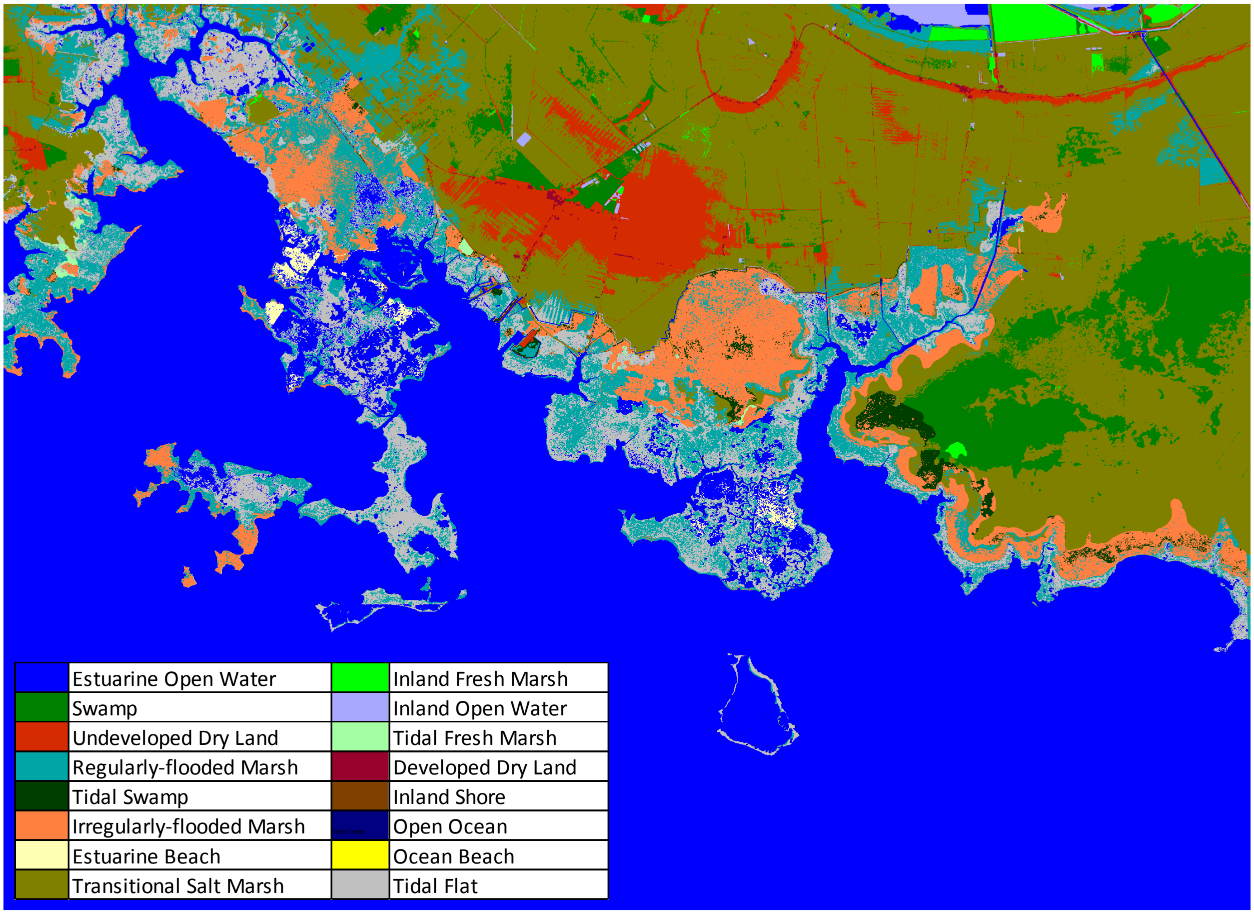

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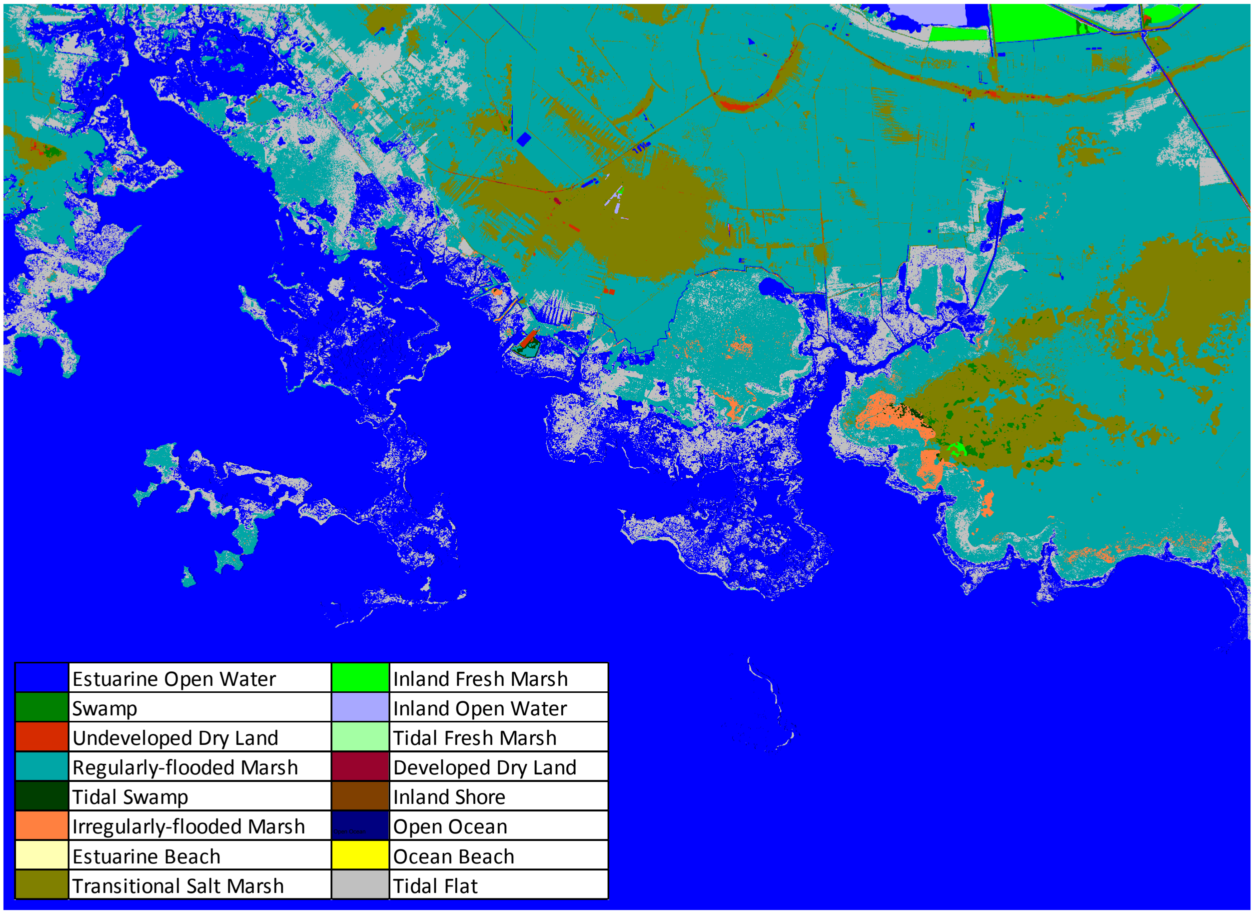

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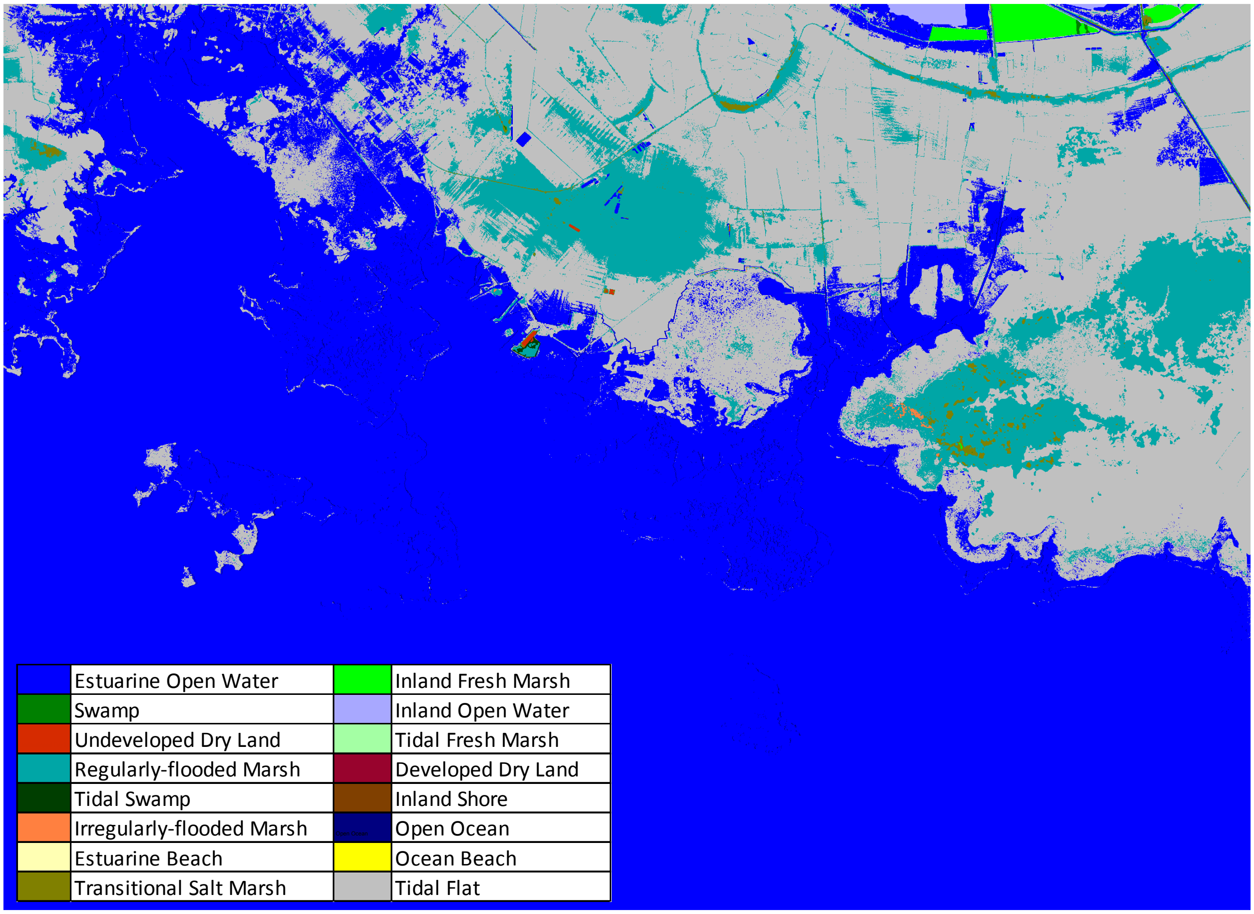

Swanquarter NWR, 2100, 2 m SLR by 2100.