Application of the Sea-Level Affecting Marshes Model (SLAMM 6) to Wassaw 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 time the SLAMM model has been applied to this refuge. The first study was performed with SLAMM version 5, did not include LiDAR data for elevations, and the maximum SLR scenarios considered was 1 m by 2100.

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.

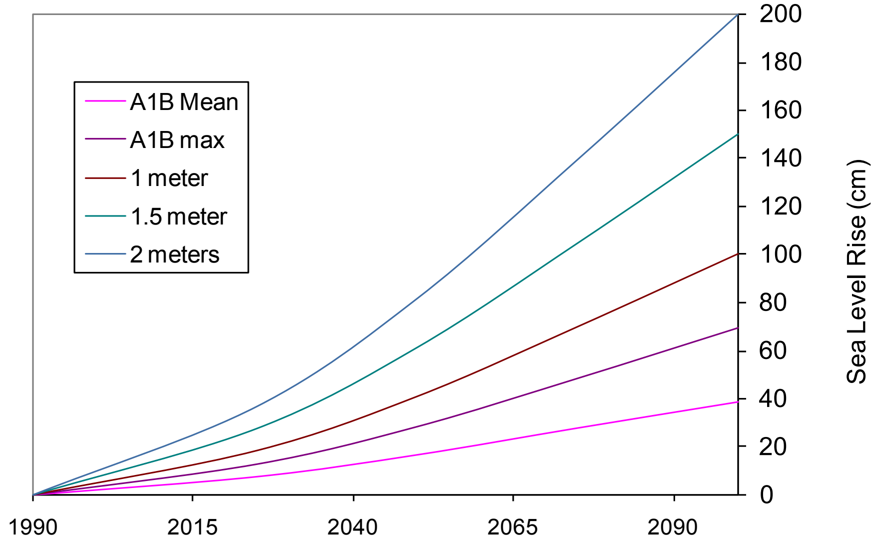


Figure 1. Summary of SLR scenarios utilized.

Data Sources and Methods

Wetland layer. Figure 2 shows the most recent available wetland layer obtained from a National Wetlands Inventory (NWI) photo dated 2007. Converting the NWI survey into 5 m x 5 m cells indicated that the approximately 10,500 acre Wassaw NWR (approved acquisition boundary including water) is composed of the following categories:

Land cover type		Area (acres)	Percentage (%)
	Regularly-flooded Marsh	6736	64
	Undeveloped Dry Land	1800	17
	Estuarine Open Water	1504	14
	Transitional Salt Marsh	209	2
	Irregularly-flooded Marsh	124	1
	Estuarine Beach	78	<1
	Ocean Beach	21	<1
	Swamp	16	<1
	Inland Fresh Marsh	16	<1
	Developed Dry Land	6	<1
	Open Ocean	5	<1
	Inland Open Water	2	<1
	Total (incl. water)	**10519**	**100**

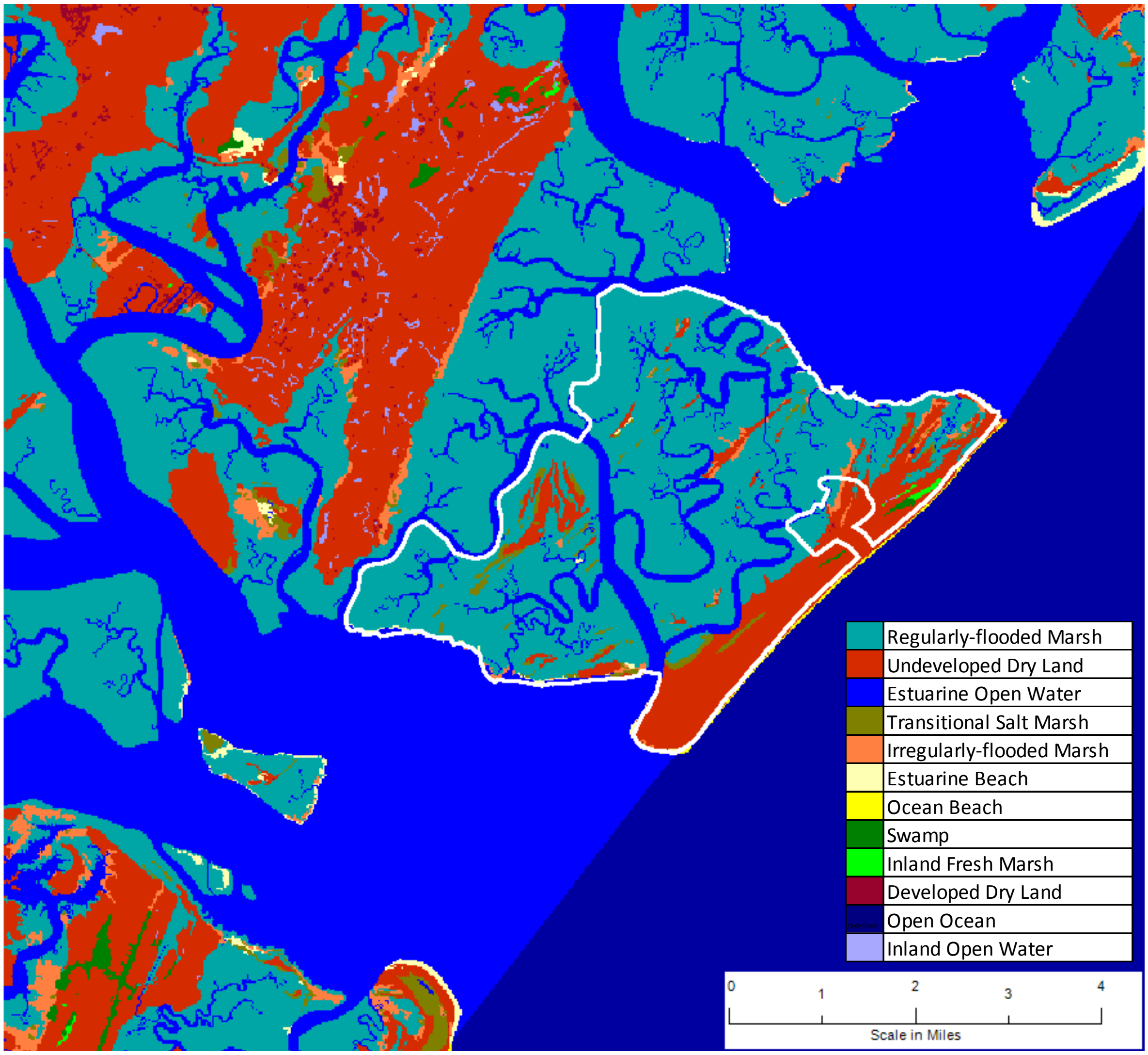


Figure 2. 2007 NWI coverage of the study area. Refuge boundaries are indicated in white.

Elevation Data. The layer covering the study area was based on 2009 bare-earth Georgia Chatham County LiDAR data .

Dikes and Impoundments. According to the National Wetland Inventory, there are no areas 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 2007, the most recent wetland data available.

Historic sea-level rise rates. The historic trend for relative sea-level rise rate was 2.98 mm/yr. This was recorded at the at the closest NOAA gauge to the refuge, Fort Pulaski, Georgia (#8670870). This rate is higher than the global (eustatic) SLR for the last 100 years (approximately 1.7 mm/yr), perhaps indicating some subsidence in this region.

Tide Ranges. The great diurnal range (GT) was estimated using the data from the NOAA gauge station #8670870 present in the area (shown in red in Figure 3) and several NOAA tide tables (shown in blue in Figure 3). Since the tide tables only provide data for the mean tidal range (MN), the GT was derived by multiplying the mean range by a correction factor of 1.09, which is the ratio GT/MN observed at the NOAA gauge station #8670870. Spatial variability in the tide range over the study area is shown in Figure 3. Different input subsites were defined reflecting these varying tidal ranges. For the refuge and coastal area the GT was set to 2.31 m.

Figure 3. Spatial variability of the great diurnal range (GT) estimates.

Salt elevation. This parameter within SLAMM designates the boundary between wet and dry lands or saline wetlands and fresh water wetlands. Based on historical inundation record at the NOAA gauge station #8670870, salt elevation was estimated at 1.2 Half Tide Units (HTU) for all input subsites, corresponding to 1.39 m above MTL in the area within the refuge.

Accretion rates. Accretion rates for regularly-flooded marshes were set to 1.9 mm/yr, irregularly-flooded marshes to 4.3 mm/yr and tidal fresh marshes to 4.8 mm/yr based on data from 36 cores gathered in the surrounding area (Craft, personal communication). Lacking site-specific information, accretion rates of other wetland types were set to the SLAMM default values.

Erosion rates. Erosion rates for marshes, swamps, and tidal flats were set to the SLAMM defaults of 2 m/yr, 1 m/yr and 0.2 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 ranged from -0.055 to -0.003 m, as shown in Figure 4, and were applied on a subsite-by-subsite basis.

Figure 4. Spatial variability of MTL to NAVD88 correction estimates.

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

Input subsites and parameter summary. Based on spatial variability of the tide ranges and elevation corrections, the study area was subdivided in the subsites illustrated in Figure 5.

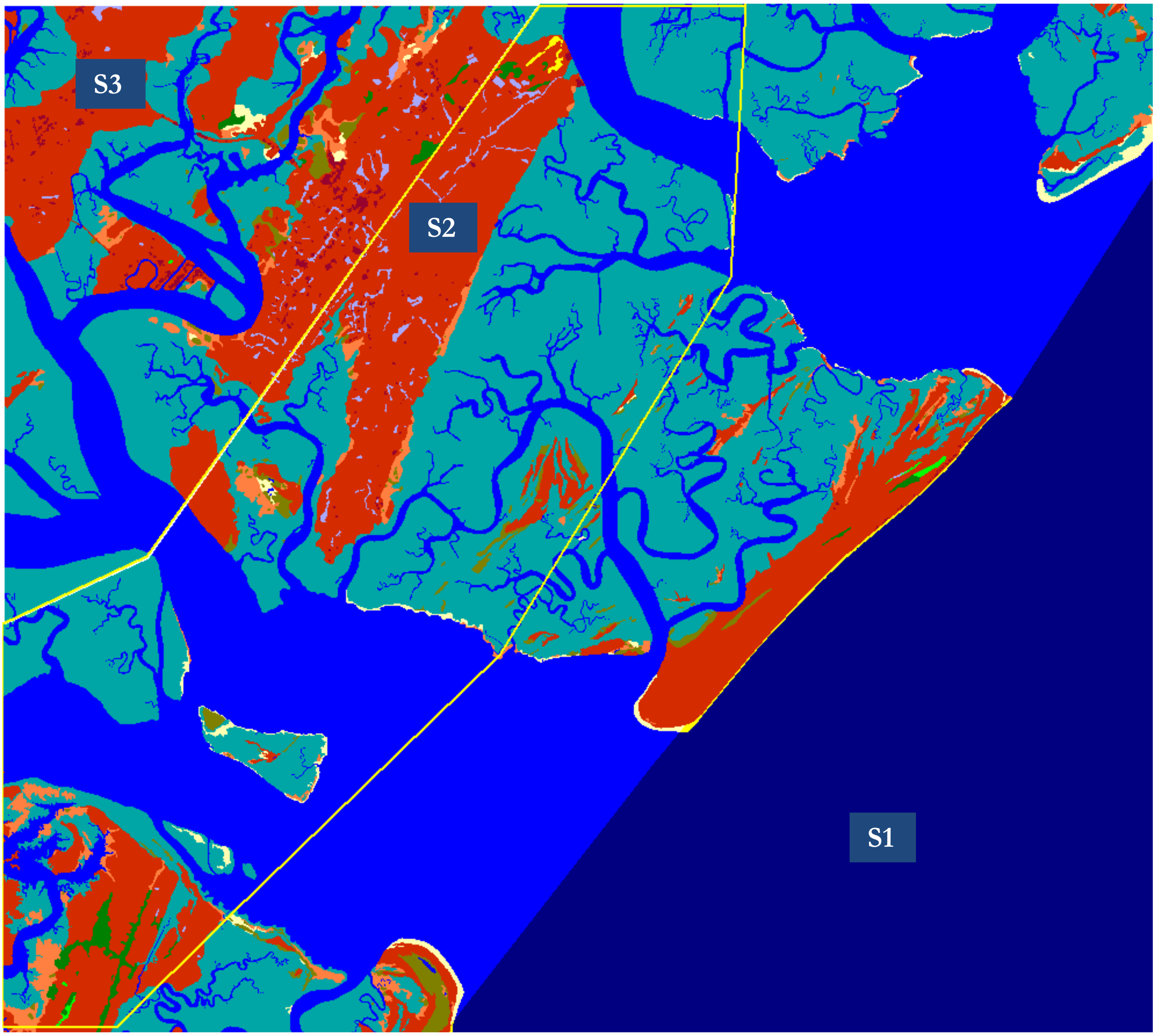


Figure 5. Input subsites (S1-S3) for model application.

Table 1 summarizes all SLAMM input parameters for the input subsites. Values for parameters without specific local information were kept at the model default value.

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

Parameter	S1	S2	S3
NWI Photo Date (YYYY)	2007	2007	2007
DEM Date (YYYY)	2009	2009	2009
Direction Offshore [n,s,e,w]	East	East	East
Historic Trend (mm/yr)	2.98	2.98	2.98
MTL-NAVD88 (m)	-0.049	-0.031	-0.003
GT Great Diurnal Tide Range (m)	2.31	2.31	2.48
Salt Elev. (m above MTL)	1.39	1.39	1.49
Marsh Erosion (horz. m /yr)	2	2	2
Swamp Erosion (horz. m /yr)	1	1	1
T.Flat Erosion (horz. m /yr)	0.2	0.2	0.2
Reg.-Flood Marsh Accr (mm/yr)	1.9	1.9	1.9
Irreg.-Flood Marsh Accr (mm/yr)	4.3	4.3	4.3
Tidal-Fresh Marsh Accr (mm/yr)	4.8	4.8	4.9
Inland-Fresh Marsh Accr (mm/yr)	4	4	4
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)	25	25	25
Use Elev Pre-processor [True,False]	FALSE	FALSE	FALSE

Calibration of Initial Conditions

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

For this refuge, at “time zero” the model converts several areas around the streams and canals from regularly-flooded marsh to tidal flat, as shown in Figure 6 and noted by black arrows in Figure 7, because of their low elevations with respect to the tidal frame of the area.

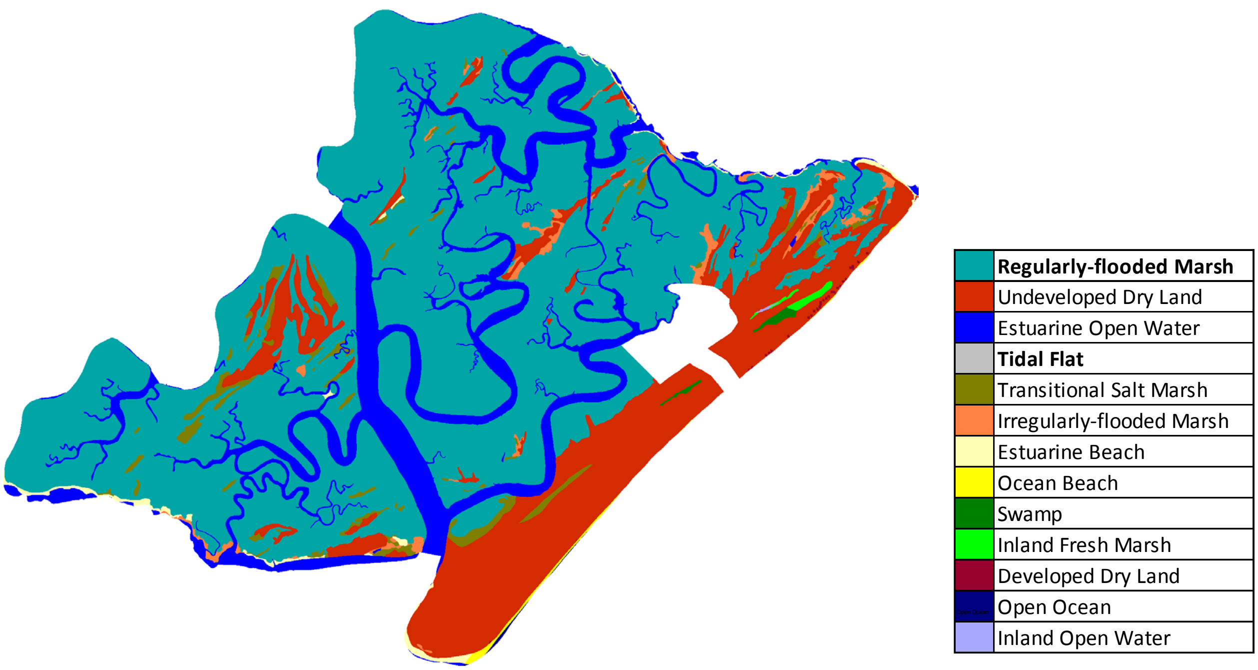


Figure 6. Initial wetland coverage of the refuge as provided by the NWI image.

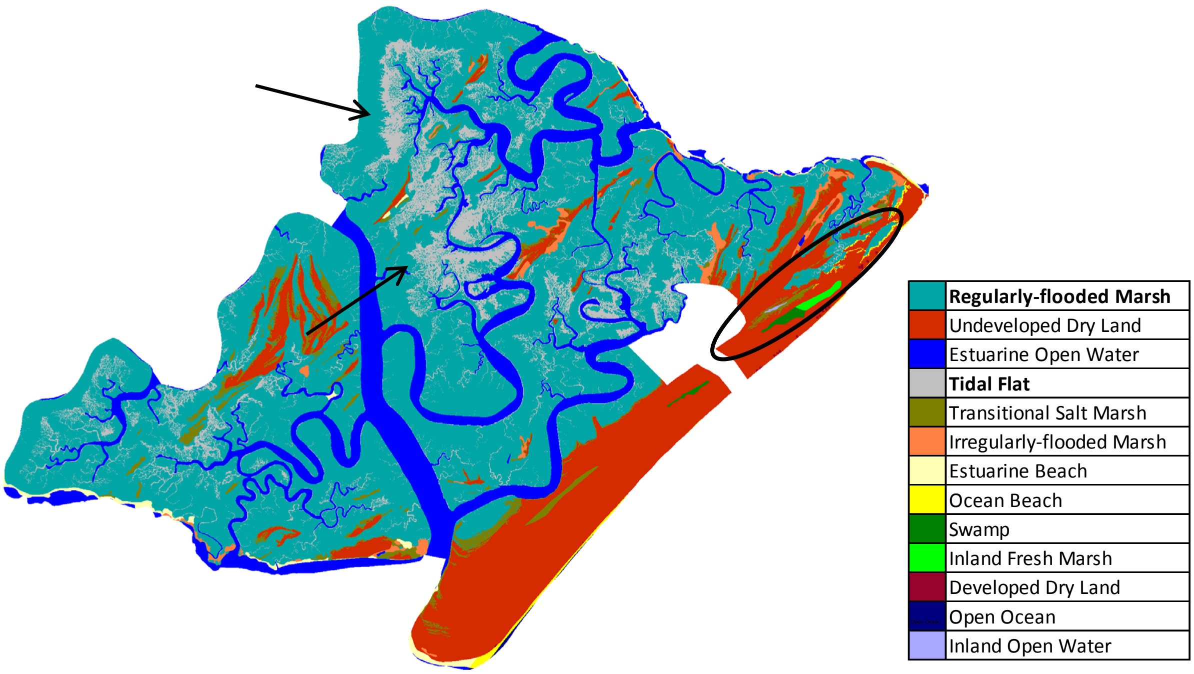


Figure 7. 2007 wetland coverage after SLAMM time zero step.

Despite these changes, this was considered an appropriate model calibration because aerial photos of the area, shown in Figure 8, and conversations with the refuge staff, confirmed that these areas are indeed estuarine, unconsolidated regularly flooded shores, probably mud, rather than regularly-flooded marsh.

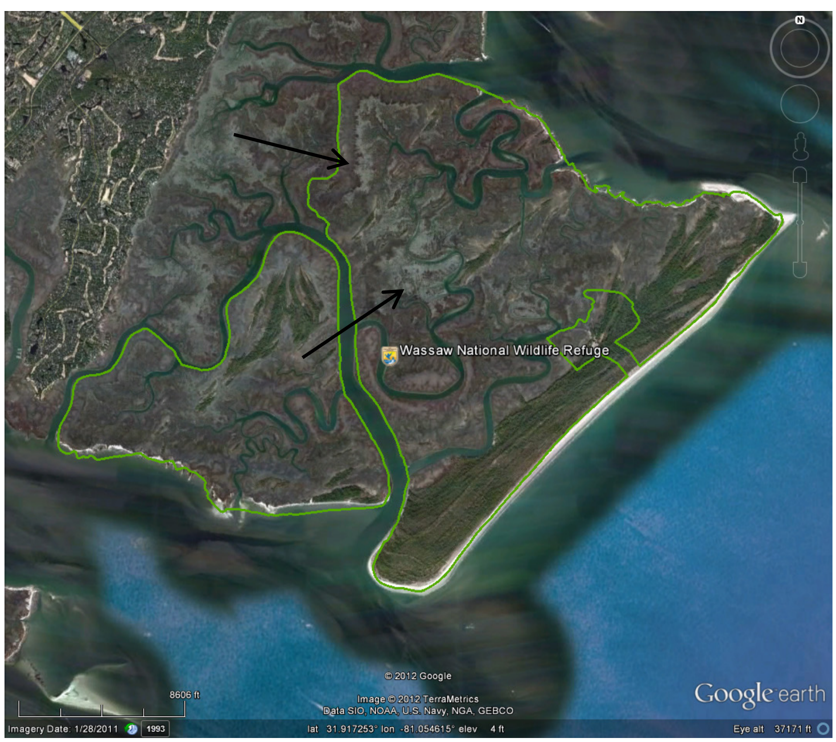


Figure 8. Aerial photo of the refuge.

Another "time-zero" consideration pertains to the ponds in the northeast corner of the refuge. This area is noted by the black oval in Figure 7. These ponds were estimated to be regularly flooded by saline water given current land elevations and oceanic tide levels. However, communication with the refuge staff confirmed that these ponds are brackish, ephemeral ponds in nature and are often filled by rain water only. Given that there are no inland tidal measurements available there is uncertainty as to how the tide range changes when moving inland from the coast. To better calibrate the model to the observed wetland layer of this area, the tide range was reduced by one third when going inland along the Mill Creek. This resulted in minimal "time-zero" changes. However, as there is only a thin ridge of dry land protecting these ponds from inundation from the north, the SLAMM connectivity module predicts that these ponds will become saline given only minimal increases in sea levels.

The initial NWI classification of the Beach Pond as regularly flooded marsh has not been modified as inland fresh because under all SLR scenarios this pond becomes impacted by salt-water intrusion regardless of the initial habitat classification. It should also be noted, that given the overall low elevations in this part of the refuge, DEM measurement errors can have great impacts on predicted saline flooding.

Based on previous 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 2007".

Land cover type		Area (acres)		2007 Percentage (%)
		NWI	SLAMM 2007	
	Regularly-flooded Marsh	**6736**	**5864**	56
	Undeveloped Dry Land	1800	1625	15
	Estuarine Open Water	1504	1504	14
	Tidal Flat	**0**	**929**	9
	Transitional Salt Marsh	209	323	3
	Irregularly-flooded Marsh	124	117	1
	Estuarine Beach	78	79	<1
	Ocean Beach	21	35	<1
	Swamp	16	16	<1
	Inland Fresh Marsh	16	13	<1
	Developed Dry Land	6	6	<1
	Open Ocean	5	5	<1
	Inland Open Water	2	2	<1
	Total (incl. water)	**10519**	**10519**	**100**

Results

Initial land cover in acres, and predicted wetland losses by 2100 under different SLR scenarios are presented in Table 2. As discussed above, land-cover losses are calculated in comparison to the "time zero" or "SLAMM 2007" wetland coverage.

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

Land cover category	SLAMM 2007 (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	5864	8%	34%	72%	85%	92%
Undeveloped Dry Land	1625	30%	53%	72%	86%	92%
Transitional Salt Marsh	323	-62%([1])	6%	41%	54%	65%
Irregularly-flooded Marsh	117	3%	28%	65%	98%	100%

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

Depending on the scenario examined, the wetlands of Wassaw NWR are predicted to show variable impacts from SLR. Under the scenario of 0.39 m SLR by 2100 regularly- and irregularly-flooded marshes are projected to undergo limited losses. At higher SLR rates, losses for regularly-flooded and irregularly-flooded marsh and undeveloped dry land are always greater than 30% and extend to nearly total loss of these habitat types at 2 m SLR by 2100. Transitional salt marsh is predicted to make moderate gains at the lowest SLR scenario due to the conversion of dry lands but at higher SLR rates, this marsh is also predicted to significantly lose coverage.

Major land cover gains are summarized in Table 3. Open water, which initially covers 15% of the refuge area, is predicted to progressively increase in coverage as SLR accelerates, reaching almost 60% of the refuge area under the 2 m SLR by 2100 scenario. Tidal flats are predicted to progressively increase in coverage due to the conversion of regularly-flooded marsh to tidal flat. However, for the highest SLR rate the gains are less pronounced as water completely inundates the majority of the tidal flats.

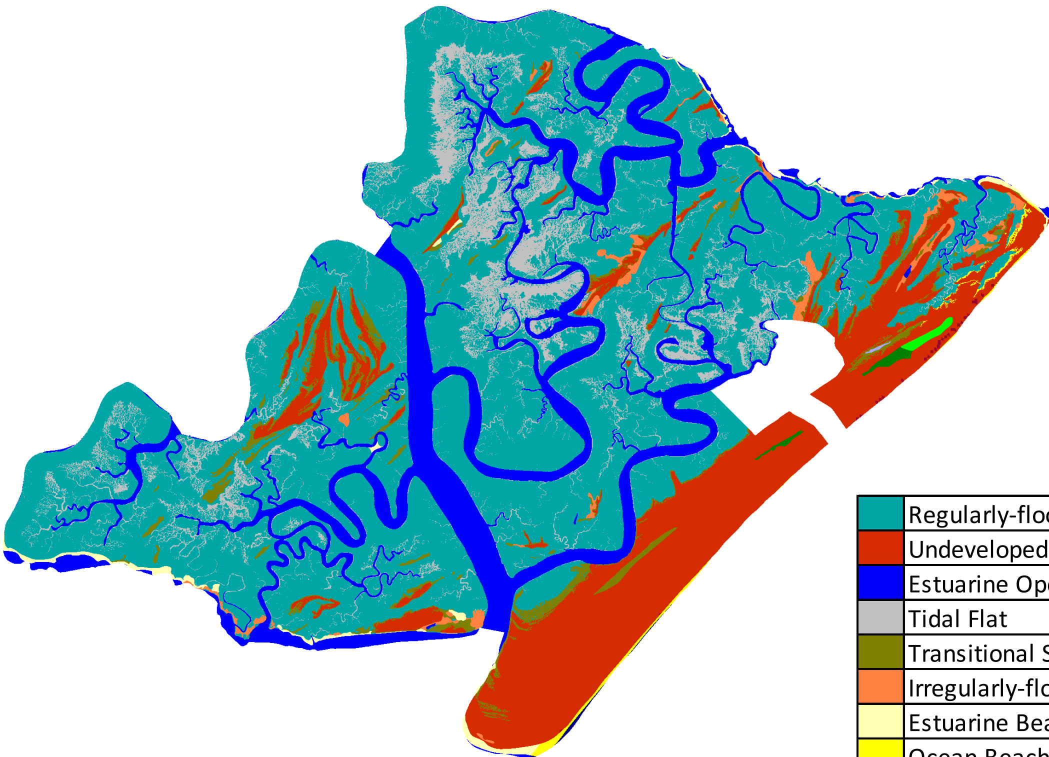
Table 3. Predicted land cover gains by 2100 given simulated scenarios of eustatic SLR at Wassaw NWR.

Land cover category	SLAMM 2007 (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	1511	1771	2037	2418	3164	6022
Tidal Flat	929	1320	3006	5143	5411	3099
Beach	114	255	454	603	691	692

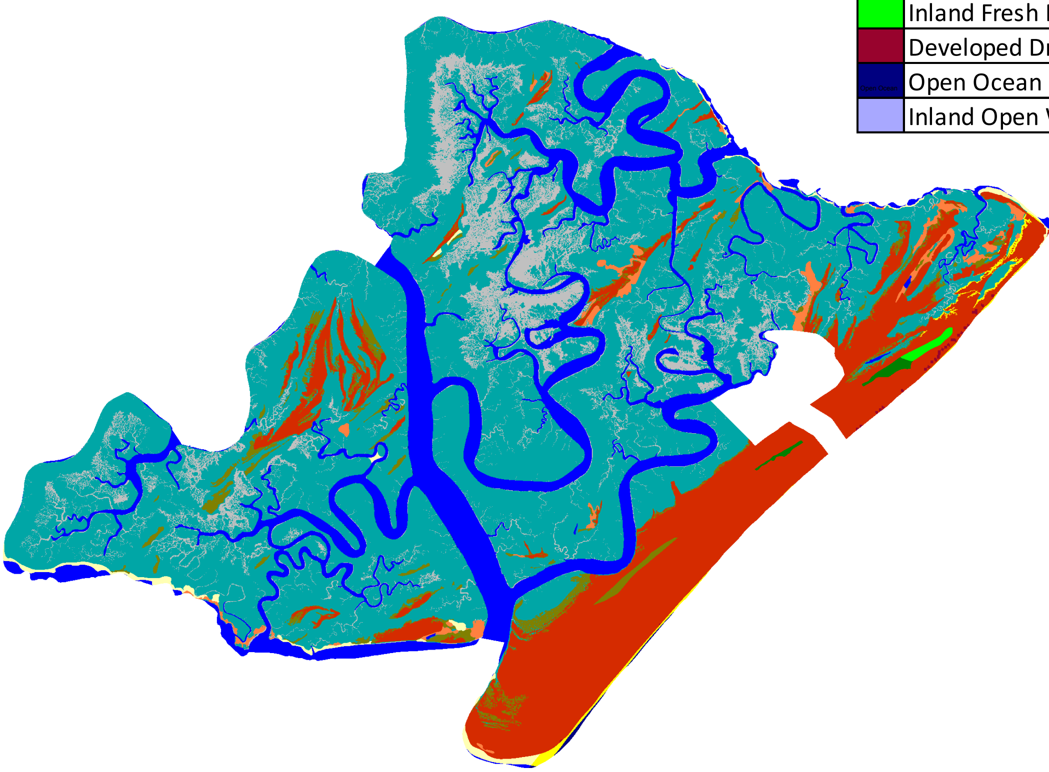
Wassaw NWR
IPCC Scenario A1B-Mean, 0.39 m eustatic SLR by 2100

Results in Acres

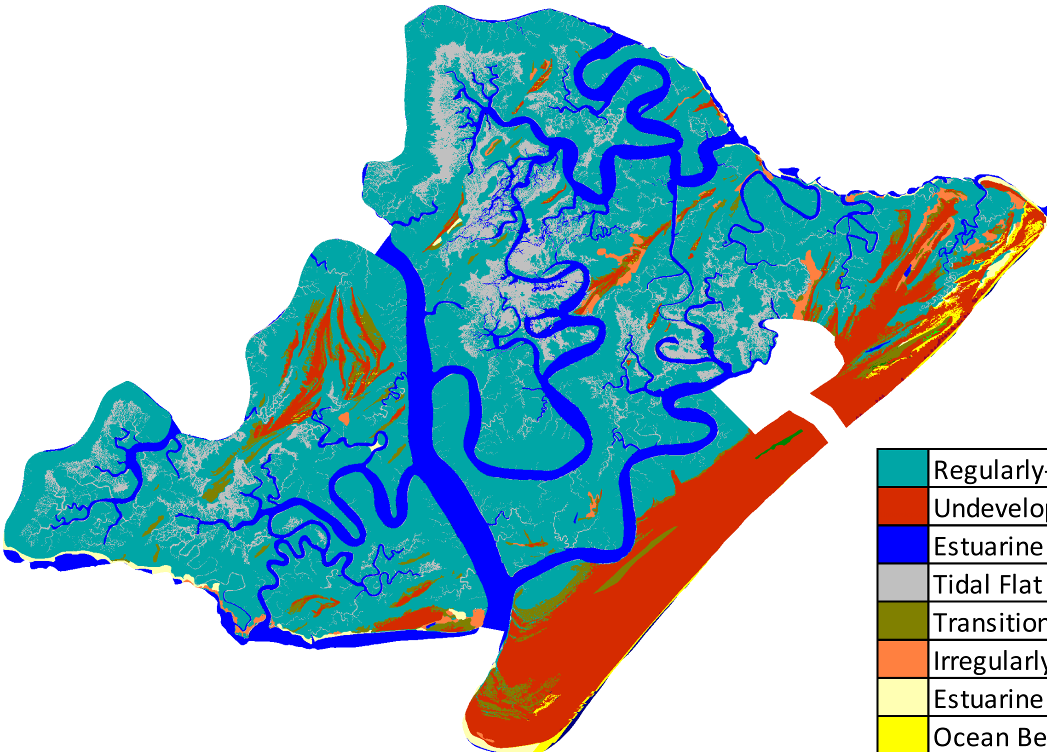
		SLAMM 2007	2025	2050	2075	2100
	Regularly-flooded Marsh	5864	5894	5772	5608	5396
	Undeveloped Dry Land	1625	1580	1451	1289	1134
	Estuarine Open Water	1504	1524	1560	1610	1689
	Tidal Flat	929	951	1035	1169	1320
	Transitional Salt Marsh	323	287	395	459	523
	Irregularly-flooded Marsh	117	116	116	115	114
	Estuarine Beach	79	77	76	85	88
	Ocean Beach	35	38	70	123	167
	Swamp	16	16	6	5	1
	Inland Fresh Marsh	13	13	1	1	1
	Developed Dry Land	6	6	6	5	5
	Open Ocean	5	17	30	48	82
	Inland Open Water	2	0	0	0	0
	Total (incl. water)	**10519**	**10519**	**10519**	**10519**	**10519**



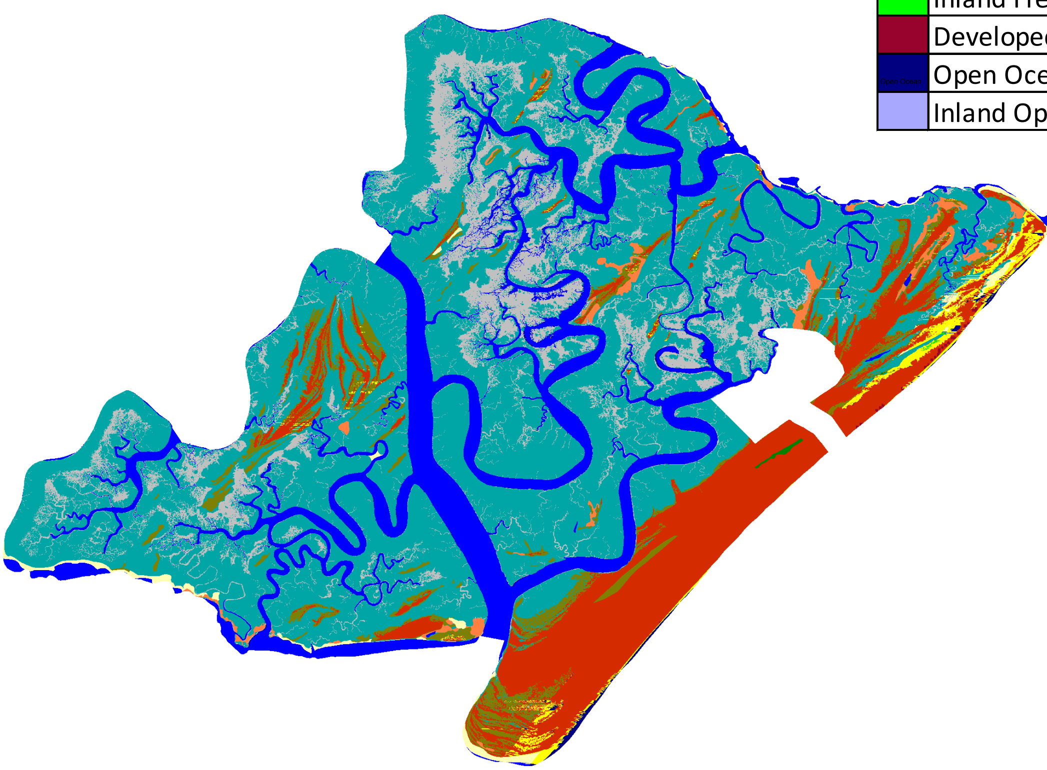
Wassaw NWR, SLAMM 2007.



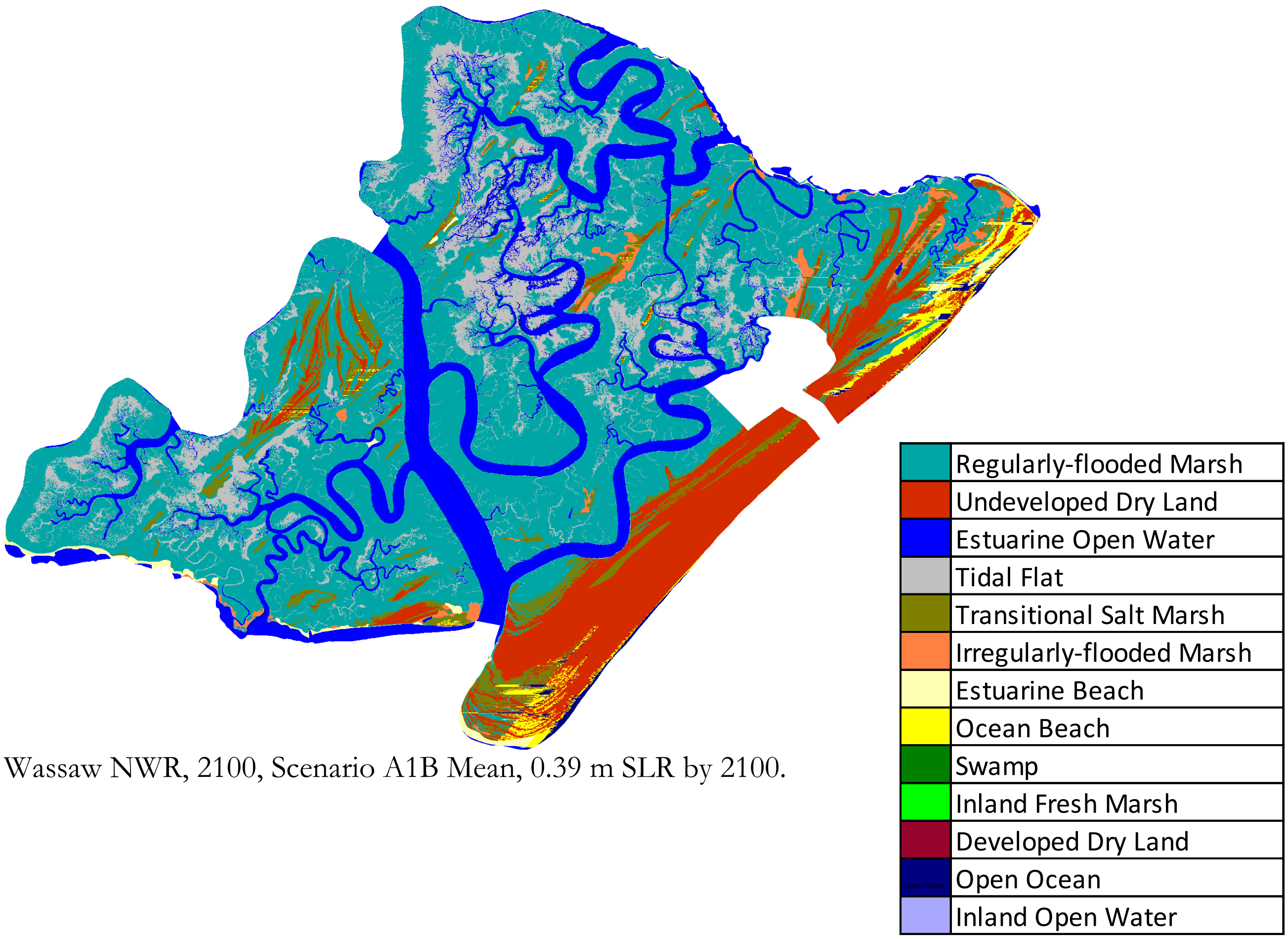
Wassaw NWR, 2025, Scenario A1B Mean, 0.39 m SLR



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



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

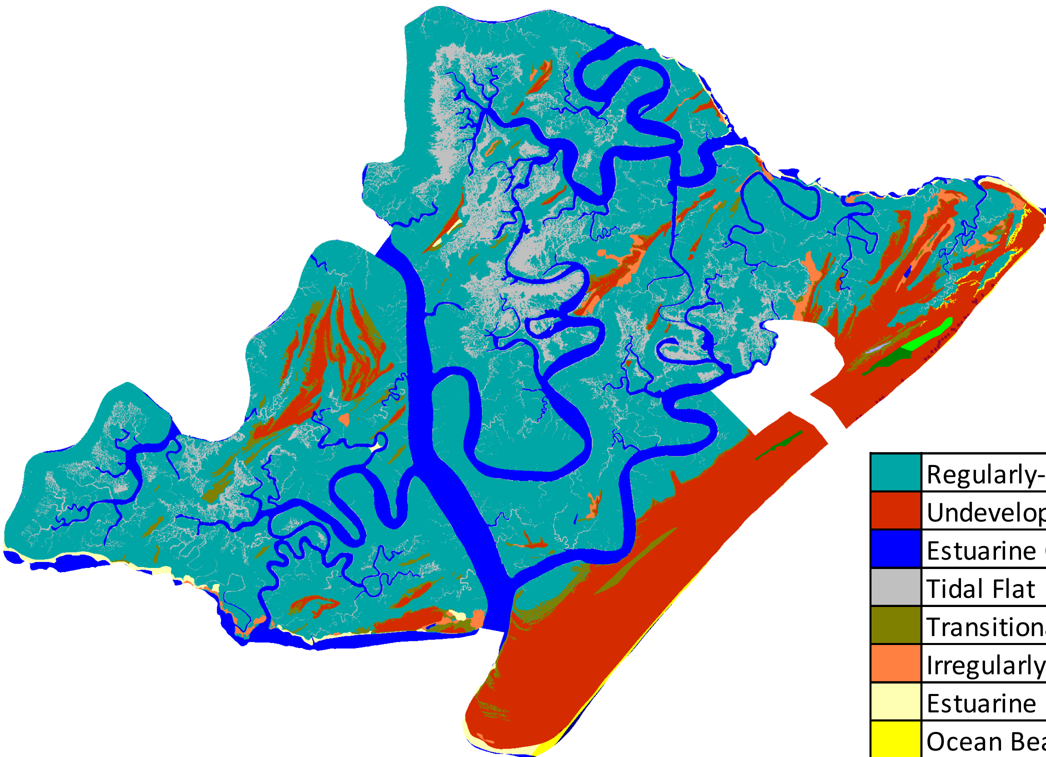


Wassaw NWR, 2100, Scenario A1B Mean, 0.39 m SLR by 2100.

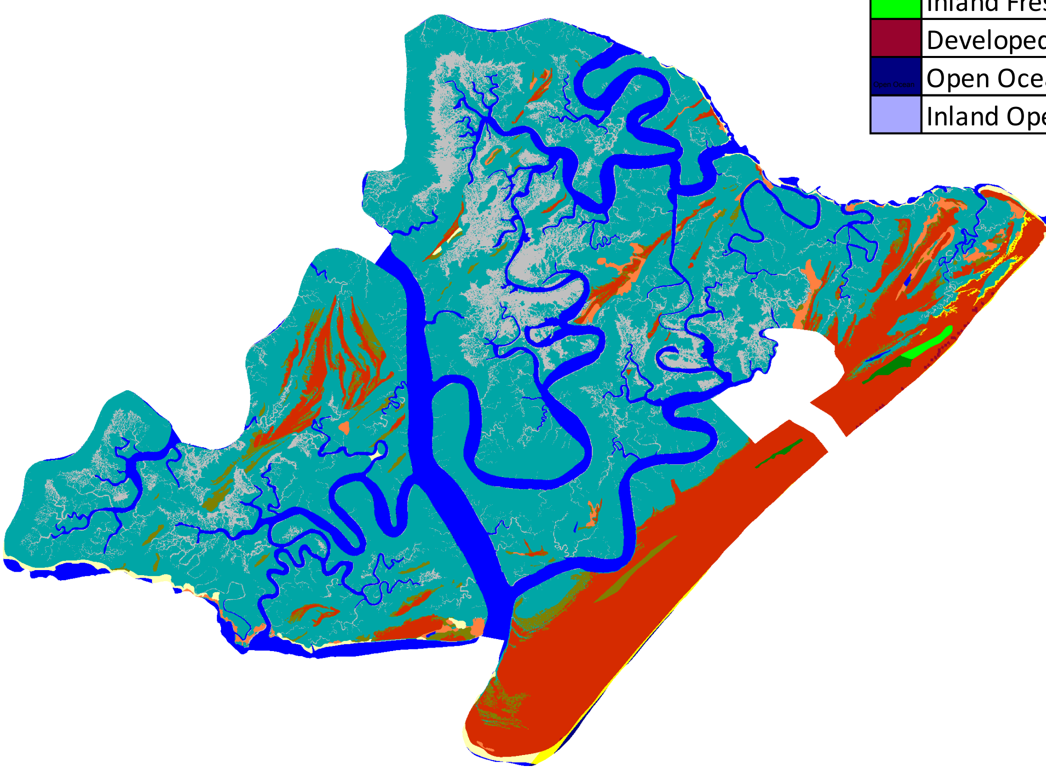
Wassaw NWR
IPCC Scenario A1B-Max, 0.69 m eustatic SLR by 2100

Results in Acres

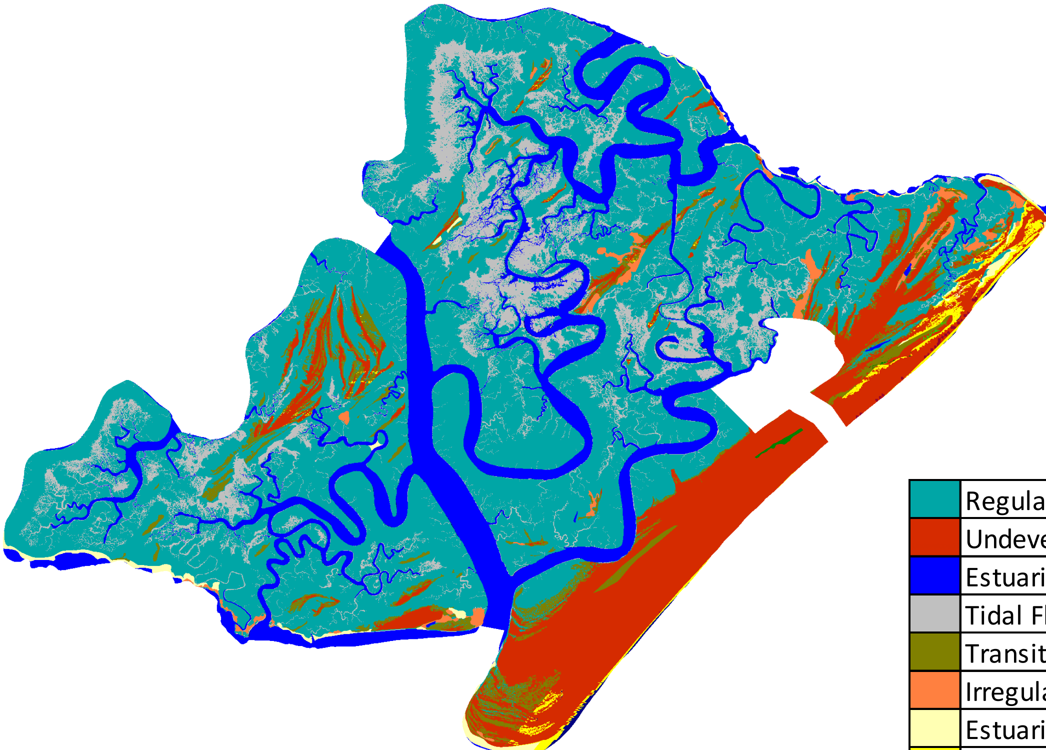
		SLAMM 2007	2025	2050	2075	2100
	Regularly-flooded Marsh	5864	5861	5643	5223	3875
	Undeveloped Dry Land	1625	1559	1346	1104	756
	Estuarine Open Water	1504	1529	1593	1722	1896
	Tidal Flat	929	988	1183	1650	3006
	Transitional Salt Marsh	323	296	428	389	304
	Irregularly-flooded Marsh	117	116	114	106	85
	Estuarine Beach	79	77	77	86	91
	Ocean Beach	35	39	91	170	363
	Swamp	16	16	6	0	0
	Inland Fresh Marsh	13	13	1	0	0
	Developed Dry Land	6	6	6	5	3
	Open Ocean	5	18	32	63	140
	Inland Open Water	2	0	0	0	0
	Total (incl. water)	**10519**	**10519**	**10519**	**10519**	**10519**



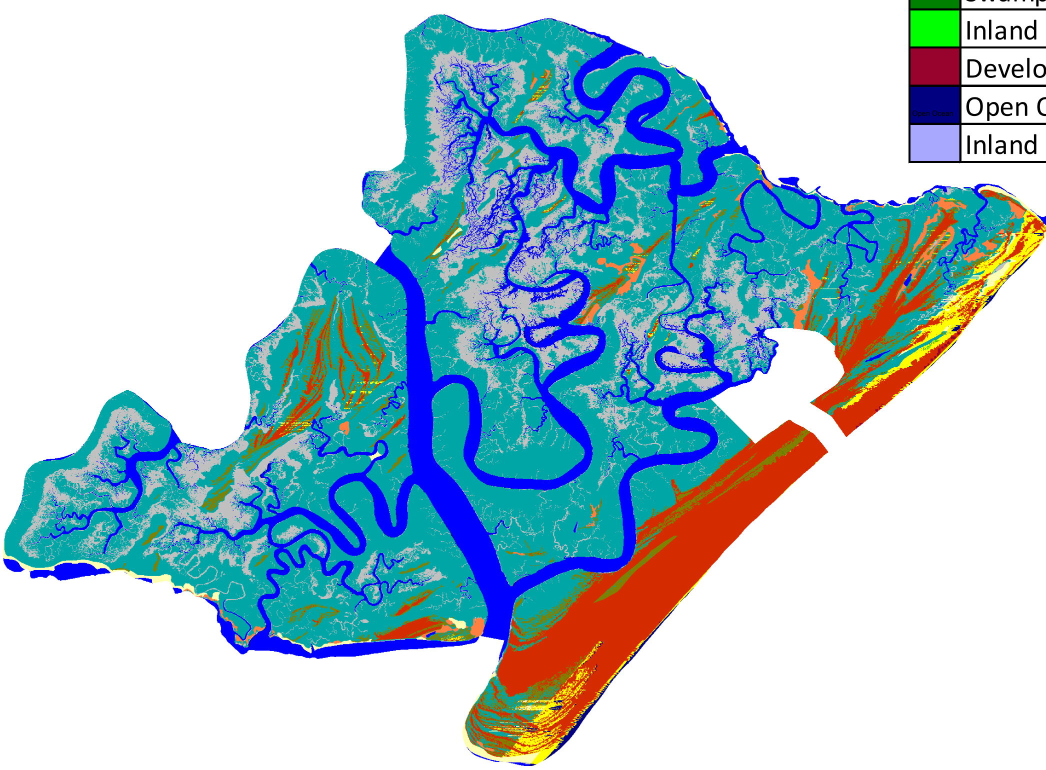
Wassaw NWR, SLAMM 2007.



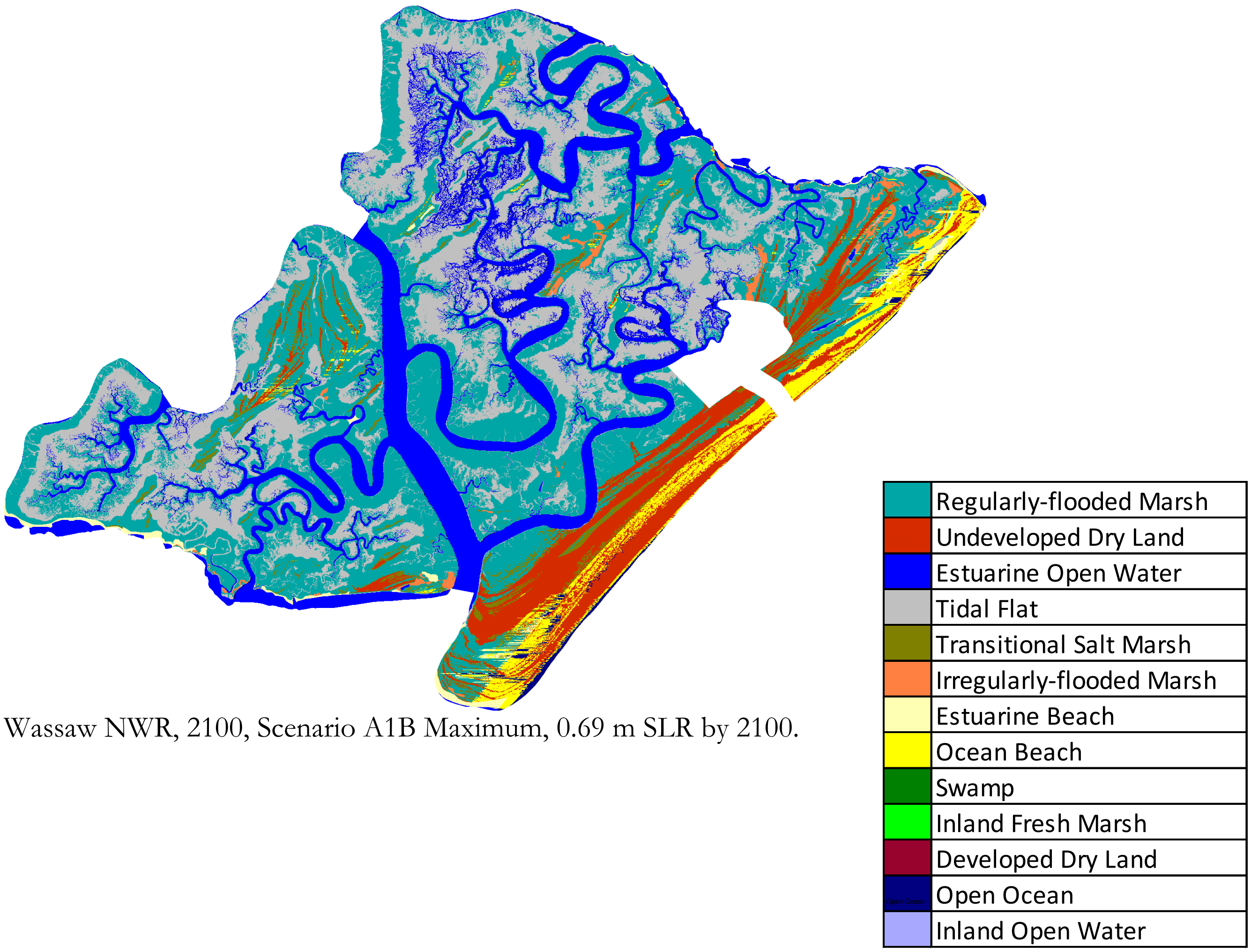
Wassaw NWR, 2025, Scenario A1B Maximum, 0.69 m SLR by 2100.



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



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

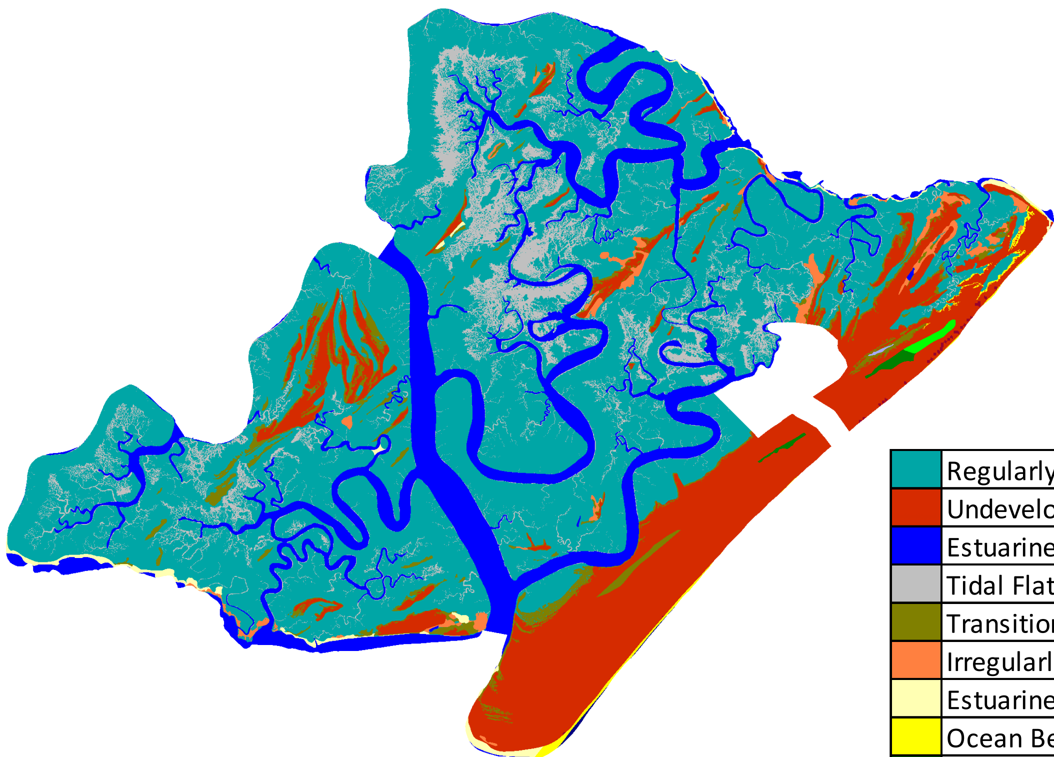


Wassaw NWR, 2100, Scenario A1B Maximum, 0.69 m SLR by 2100.

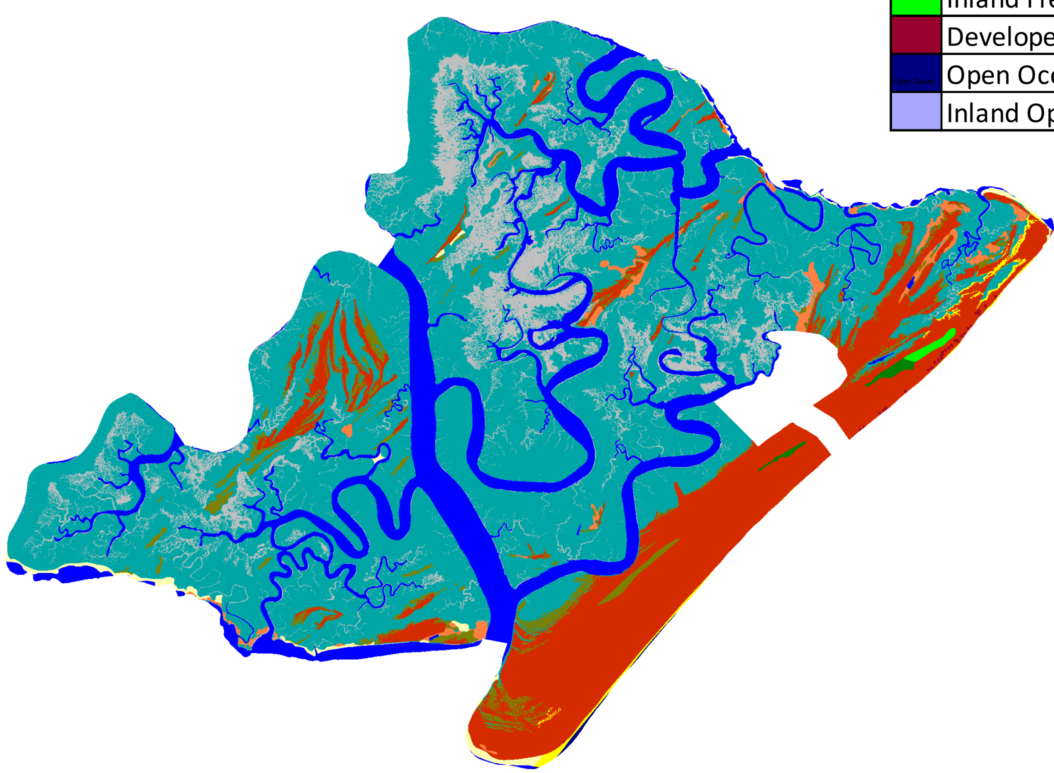
Wassaw NWR
1 m eustatic SLR by 2100

Results in Acres

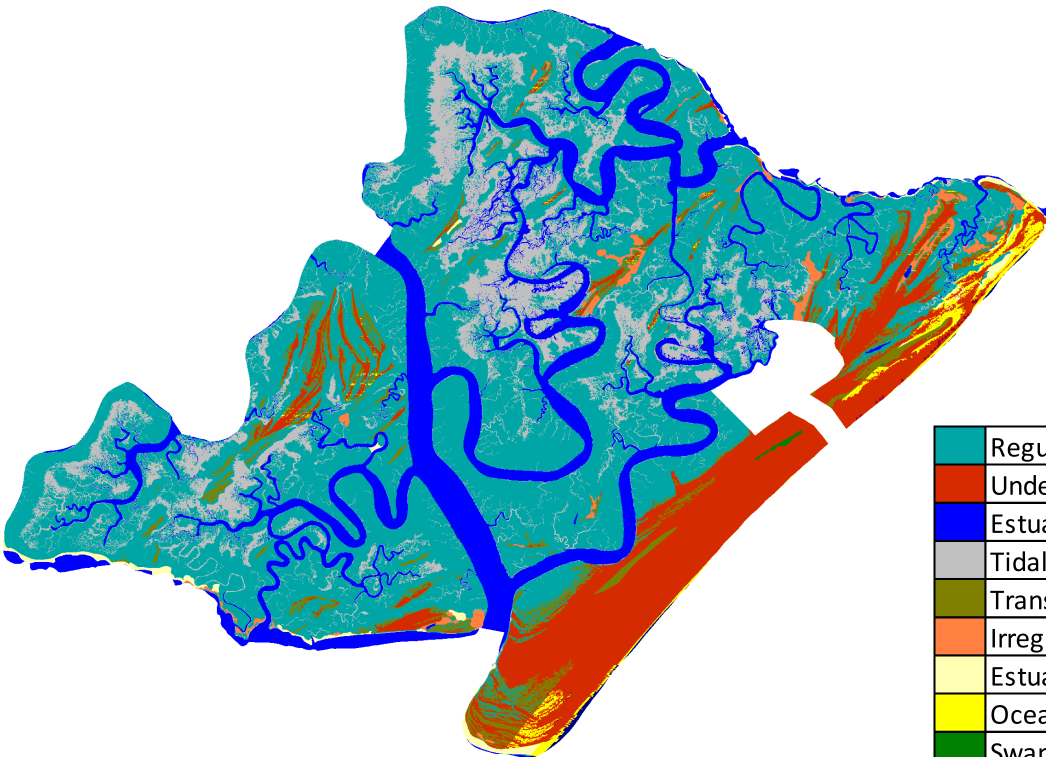
		SLAMM 2007	2025	2050	2075	2100
	Regularly-flooded Marsh	5864	5827	5472	3955	1658
	Undeveloped Dry Land	1625	1530	1250	823	463
	Estuarine Open Water	1504	1537	1642	1860	2196
	Tidal Flat	929	1029	1393	3003	5143
	Transitional Salt Marsh	323	308	419	307	190
	Irregularly-flooded Marsh	117	116	109	75	42
	Estuarine Beach	79	77	77	86	93
	Ocean Beach	35	42	111	321	510
	Swamp	16	16	5	0	0
	Inland Fresh Marsh	13	13	1	0	0
	Developed Dry Land	6	6	6	3	1
	Open Ocean	5	18	34	84	223
	Inland Open Water	2	0	0	0	0
	Total (incl. water)	**10519**	**10519**	**10519**	**10519**	**10519**



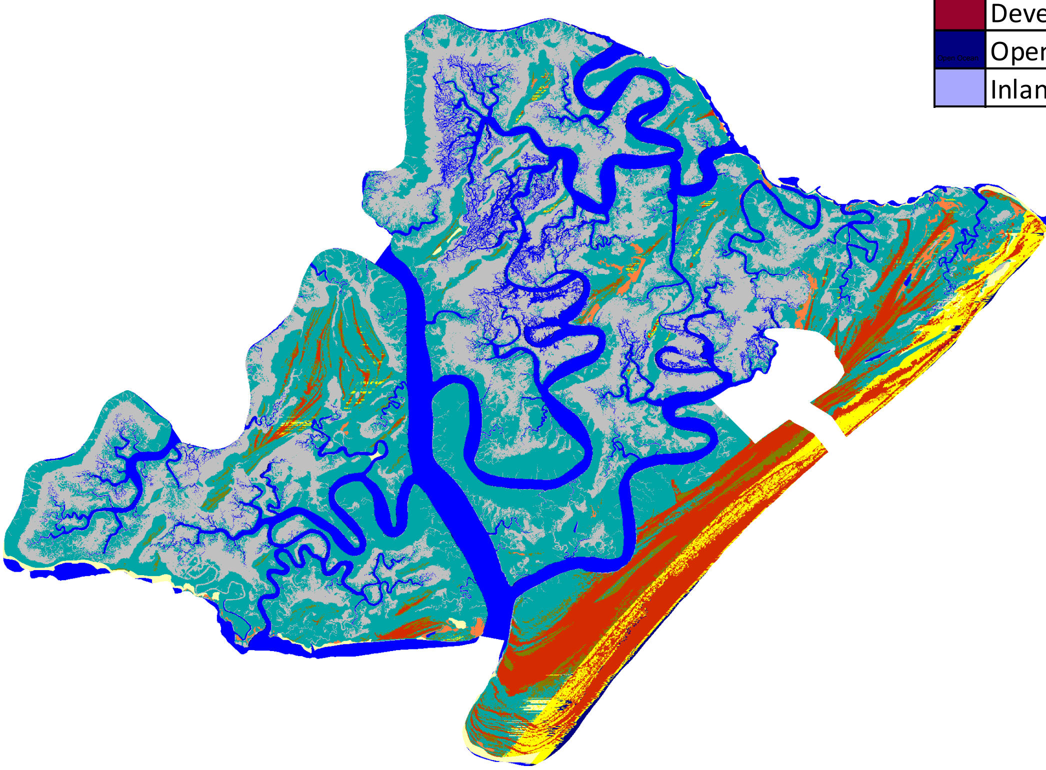
Wassaw NWR, SLAMM 2007.



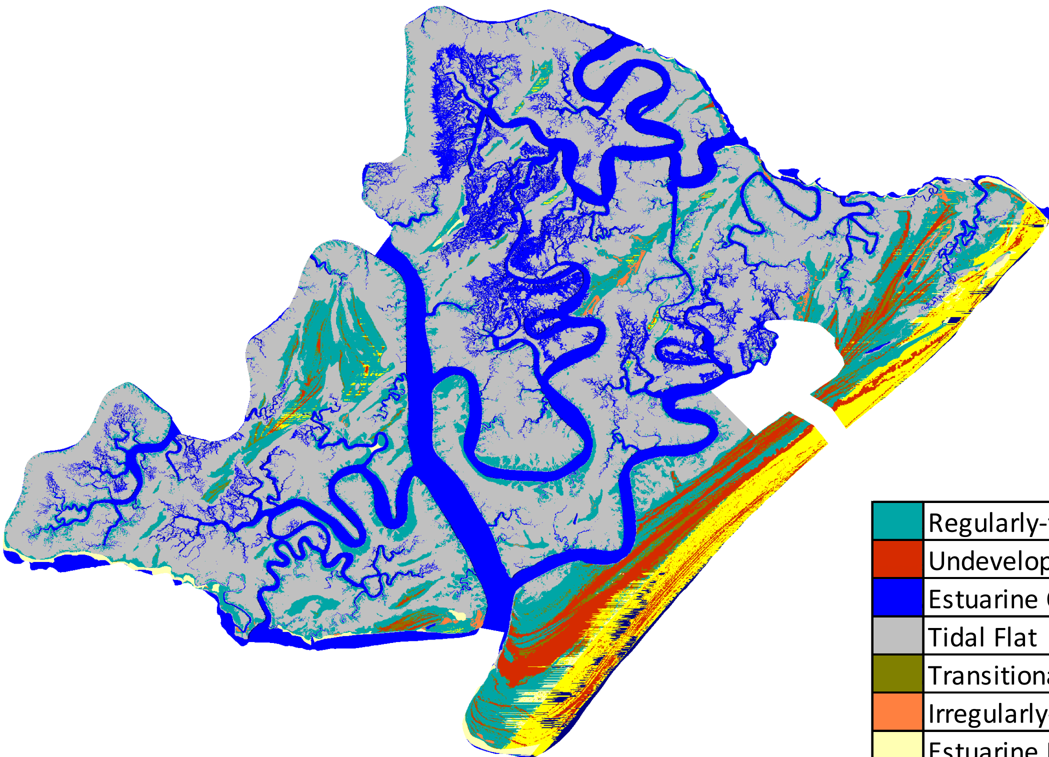
Wassaw NWR, 2025, 1 m SLR by 2100.



Wassaw NWR, 2050, 1 m SLR by 2100.



Wassaw NWR, 2075, 1 m SLR by 2100.

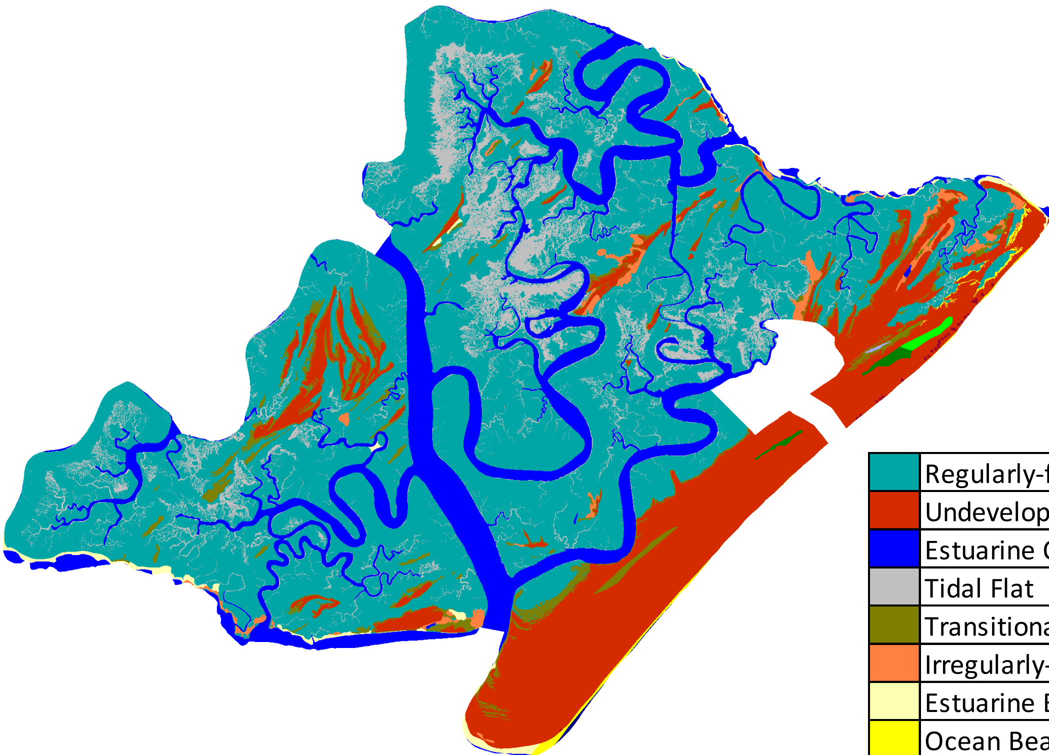


Wassaw NWR, 2100, 1 m SLR by 2100.

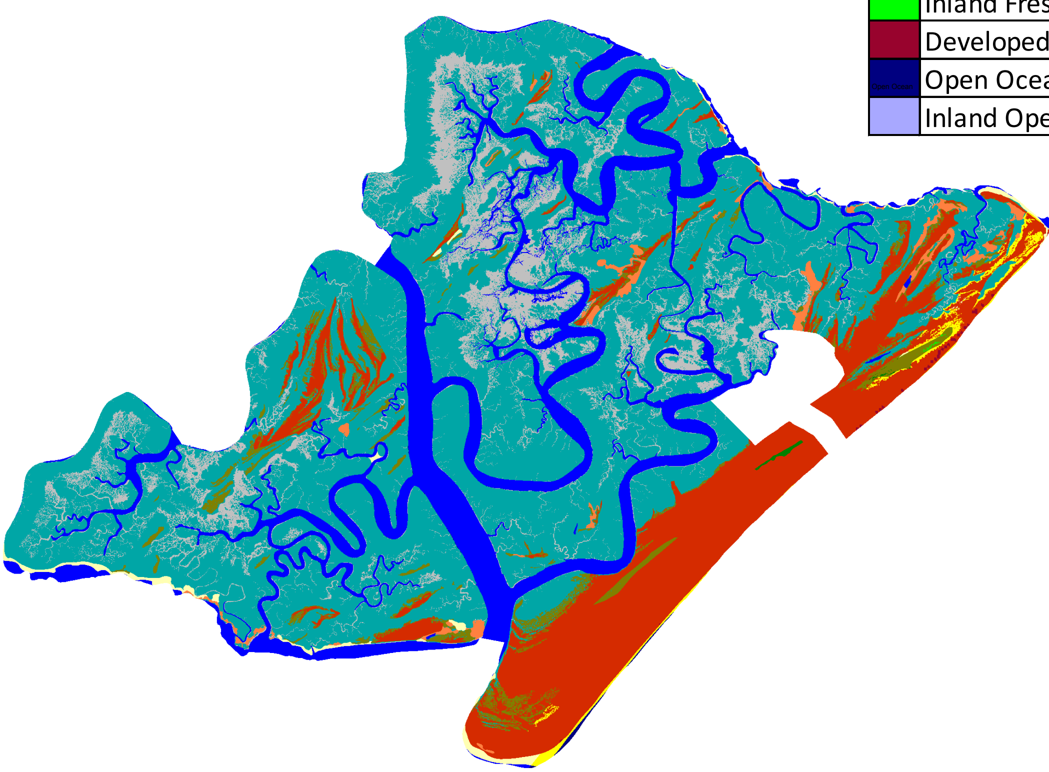
Wassaw NWR
1.5 m eustatic SLR by 2100

Results in Acres

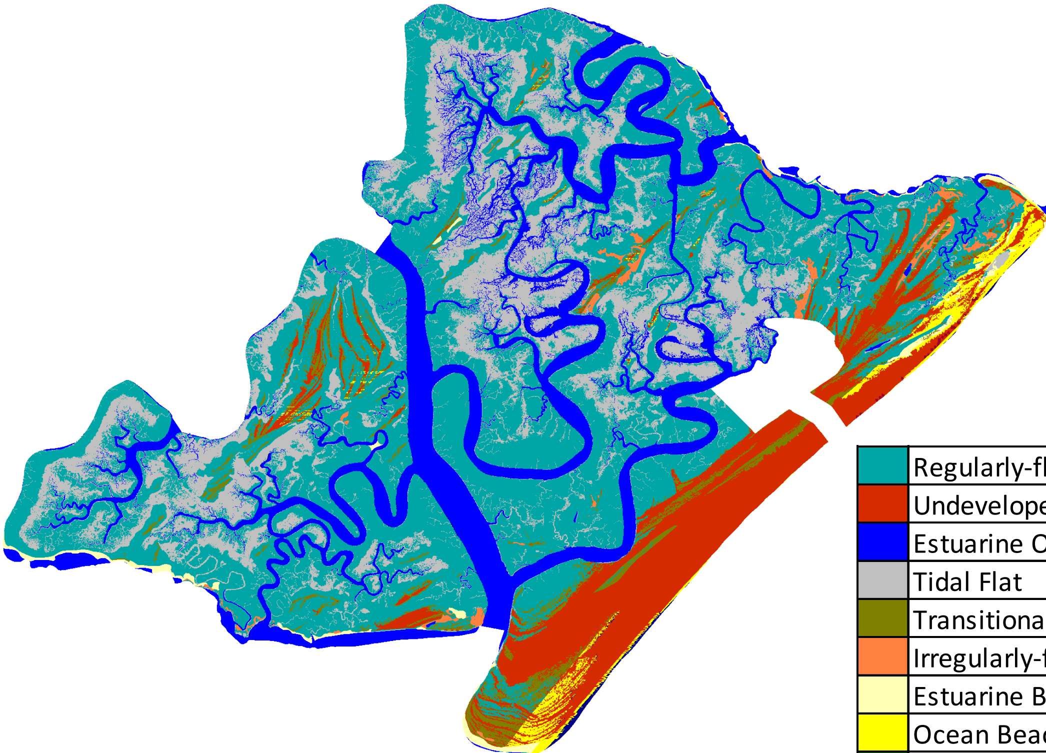
		SLAMM 2007	2025	2050	2075	2100
	Regularly-flooded Marsh	5864	5768	4857	1483	882
	Undeveloped Dry Land	1625	1468	1087	492	220
	Estuarine Open Water	1504	1555	1746	2182	2855
	Tidal Flat	929	1095	2089	5331	5411
	Transitional Salt Marsh	323	344	376	284	149
	Irregularly-flooded Marsh	117	114	86	30	2
	Estuarine Beach	79	78	77	93	100
	Ocean Beach	35	66	153	481	591
	Swamp	16	6	0	0	0
	Inland Fresh Marsh	13	1	0	0	0
	Developed Dry Land	6	6	5	1	0
	Open Ocean	5	19	41	142	309
	Inland Open Water	2	0	0	0	0
	Total (incl. water)	**10519**	**10519**	**10519**	**10519**	**10519**



Wassaw NWR, SLAMM 2007.



Wassaw NWR, 2025, 1.5 m SLR by 2100.



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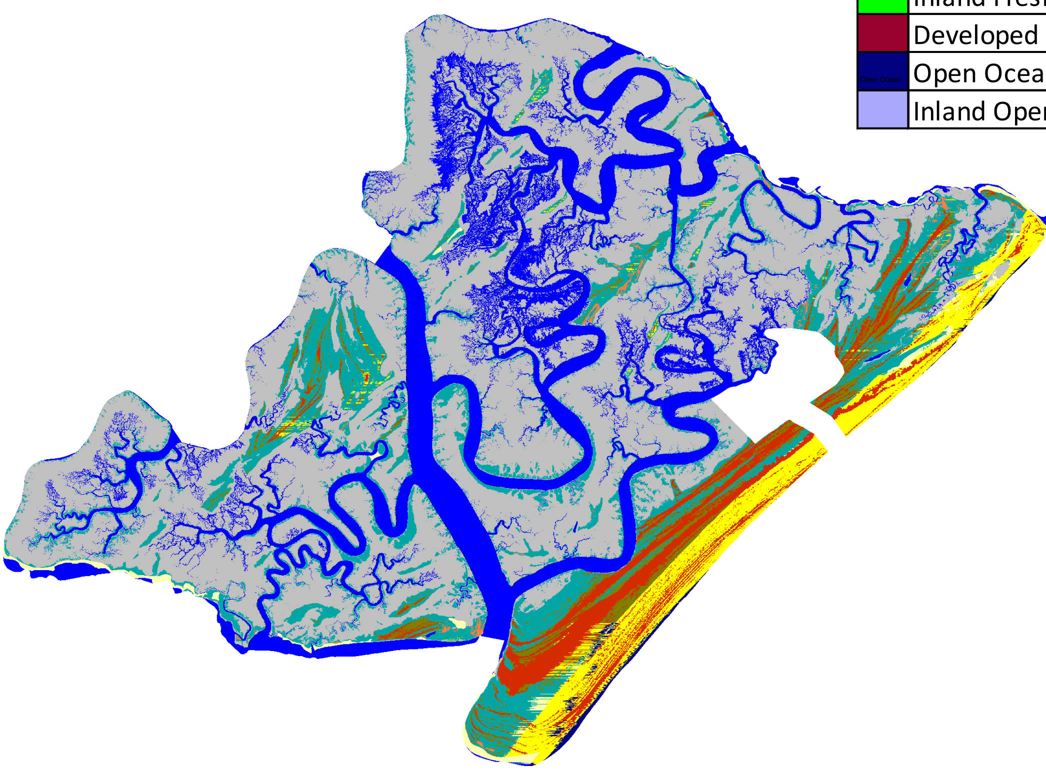

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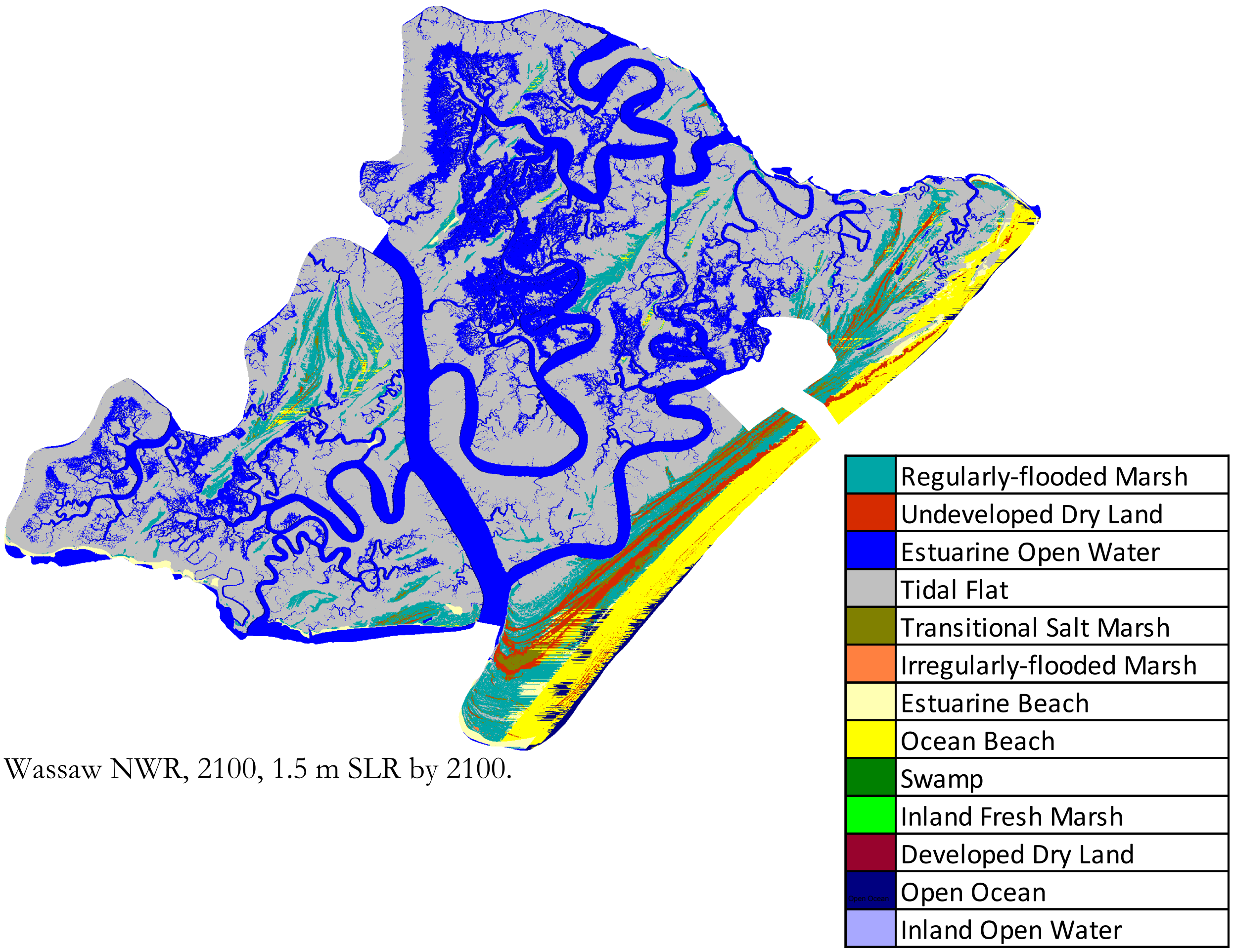
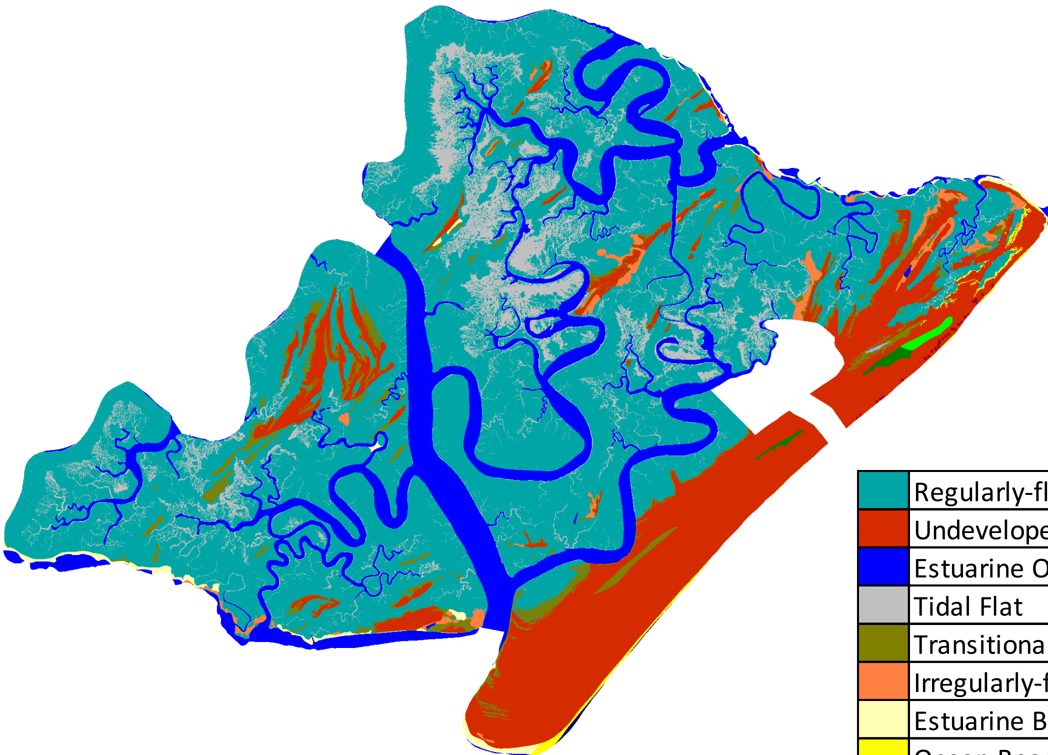


Wassaw NWR, 2100, 1.5 m SLR by 2100.

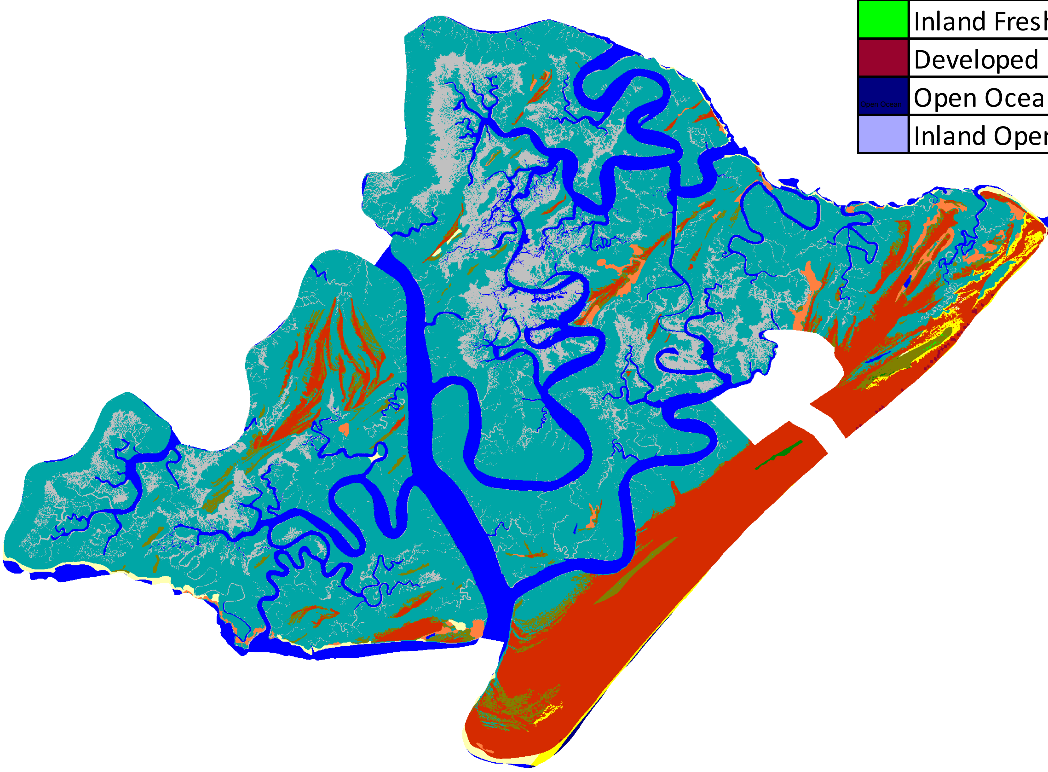
Wassaw NWR
2 m eustatic SLR by 2100

Results in Acres

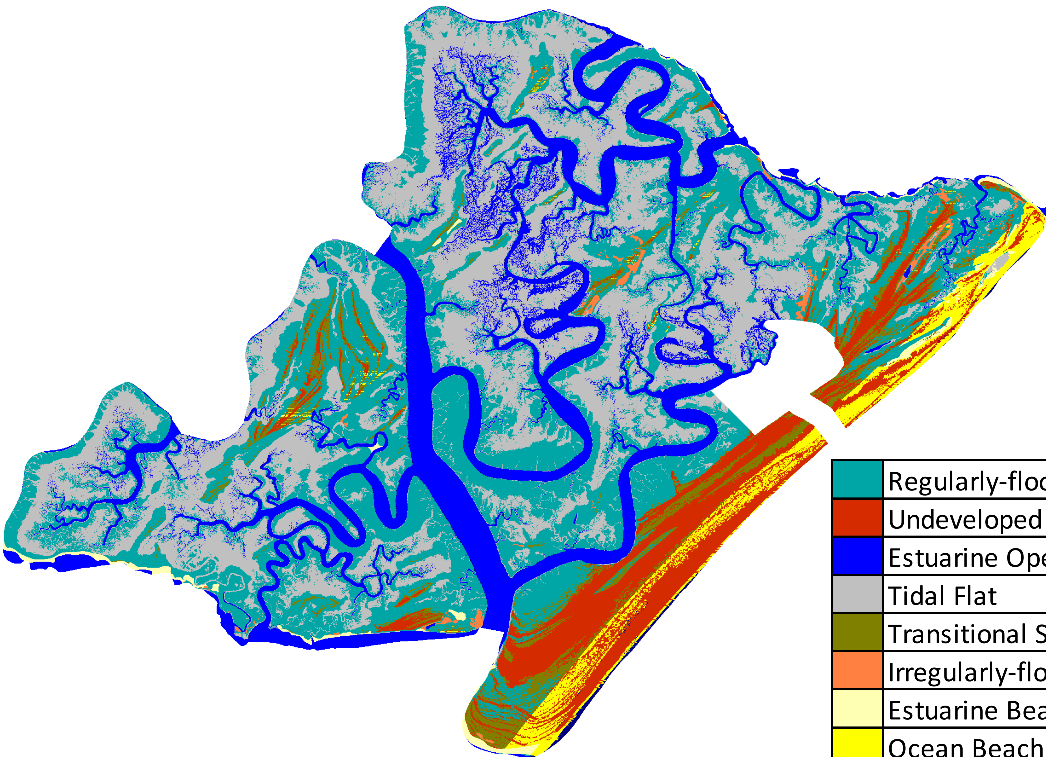
		SLAMM 2007	2025	2050	2075	2100
	Regularly-flooded Marsh	5864	5702	3433	871	461
	Undeveloped Dry Land	1625	1427	832	309	132
	Estuarine Open Water	1504	1571	1870	2593	5718
	Tidal Flat	929	1174	3478	5652	3099
	Transitional Salt Marsh	323	351	416	259	113
	Irregularly-flooded Marsh	117	112	58	4	0
	Estuarine Beach	79	78	77	92	93
	Ocean Beach	35	71	299	561	599
	Swamp	16	6	0	0	0
	Inland Fresh Marsh	13	1	0	0	0
	Developed Dry Land	6	6	4	0	0
	Open Ocean	5	19	53	177	303
	Inland Open Water	2	0	0	0	0
	Total (incl. water)	**10519**	**10519**	**10519**	**10519**	**10519**



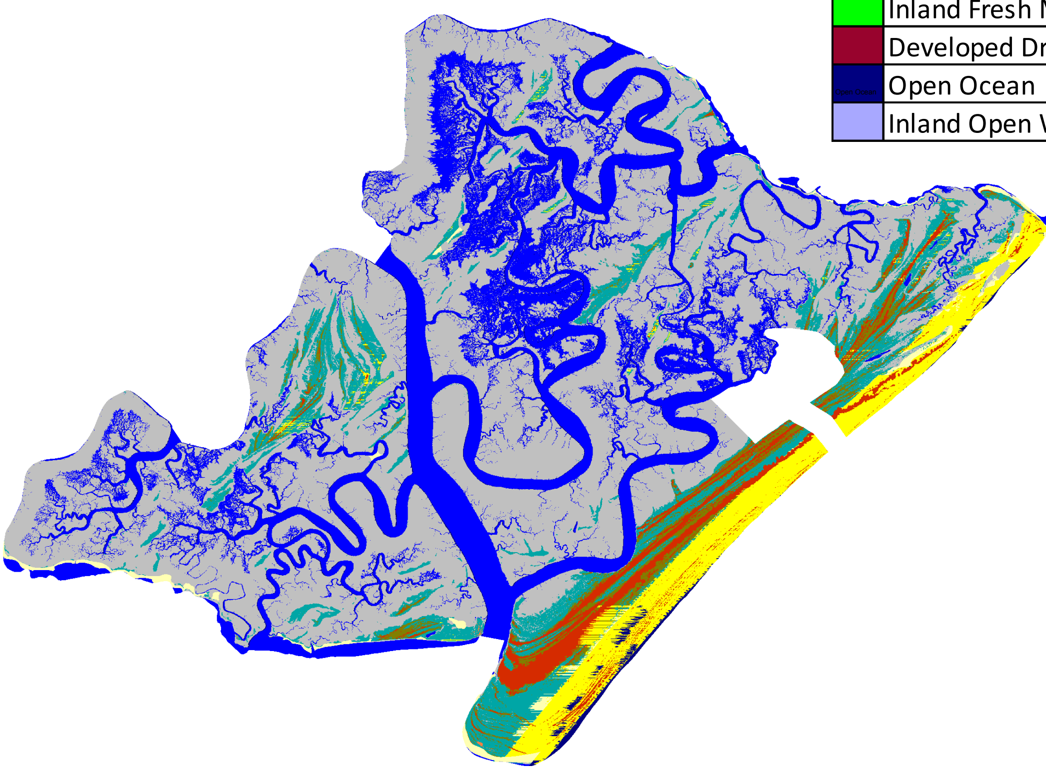
Wassaw NWR, SLAMM 2007.



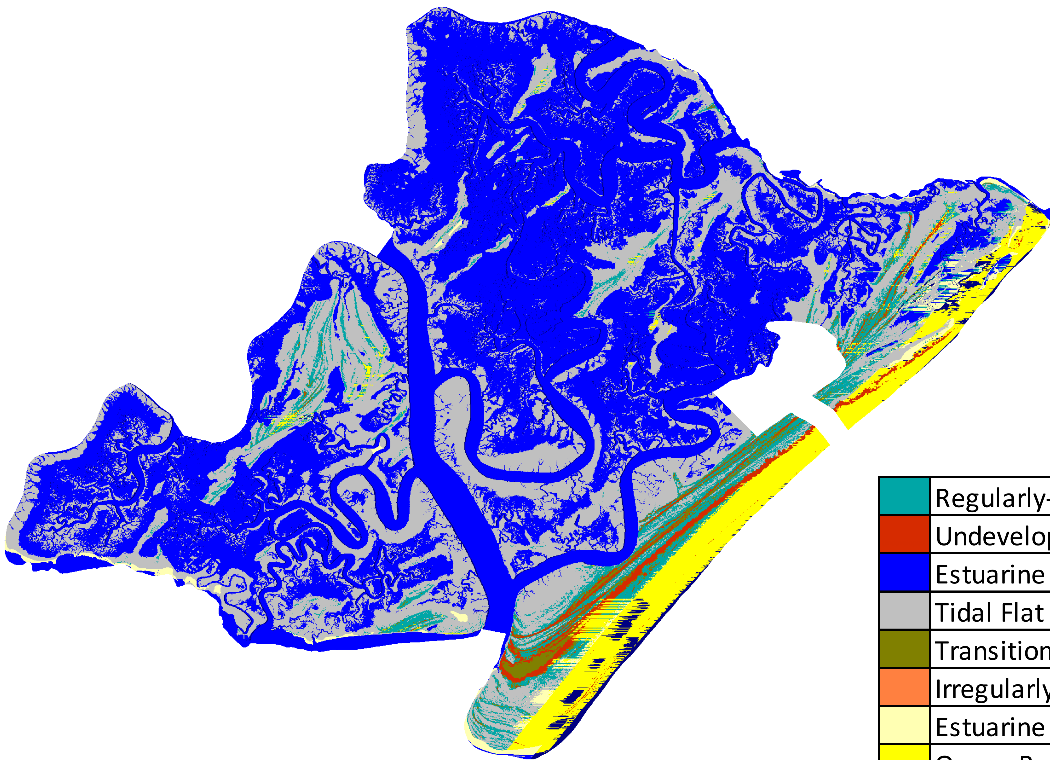
Wassaw NWR, 2025, 2 m SLR by 2100.



Wassaw NWR, 2050, 2 m SLR by 2100.



Wassaw NWR, 2075, 2 m SLR by 2100.



Wassaw NWR, 2100, 2 m SLR by 2100.

Discussion

SLAMM predictions for Wassaw NWR indicate that the refuge is sensitive to SLR under all but the most conservative of SLR scenarios examined. Regularly-flooded marsh losses are predicted to exceed 30% given a SLR rate of 0.69 m by 2100. The maximum predicted loss rate for these salt marshes is 92% (given 2 m eustatic SLR by 2100). Similarly, irregularly-flooded mash is predicted to be progressively lost given increasing SLR rates. On the contrary, open water and tidal flats are predicted to gradually take over the entire area of the refuge. Qualitatively, the results of this study are comparable to the previous SLAMM analysis of the refuge conducted in 2008.

It is worth noting that in this application, the SLAMM conceptual model, along with the inclusion of high resolution elevation data, has identified areas in the refuge where the NWI classification may be refined for this site. This is particularly true with respect to the demarcation between regularly-flooded marsh and tidal flats (see the discussion on "time-zero" above). This has several interesting implications. First, it validates the conceptual model used to make SLR predictions and shows how SLAMM could potentially be used to cross check available NWI layers. Second, it illustrates how the use of high-resolution elevation data considerably improves wetland characterization and model predictions.

While data-layer updates have considerably improved the SLAMM projections reported here, input layers, parameter inputs, 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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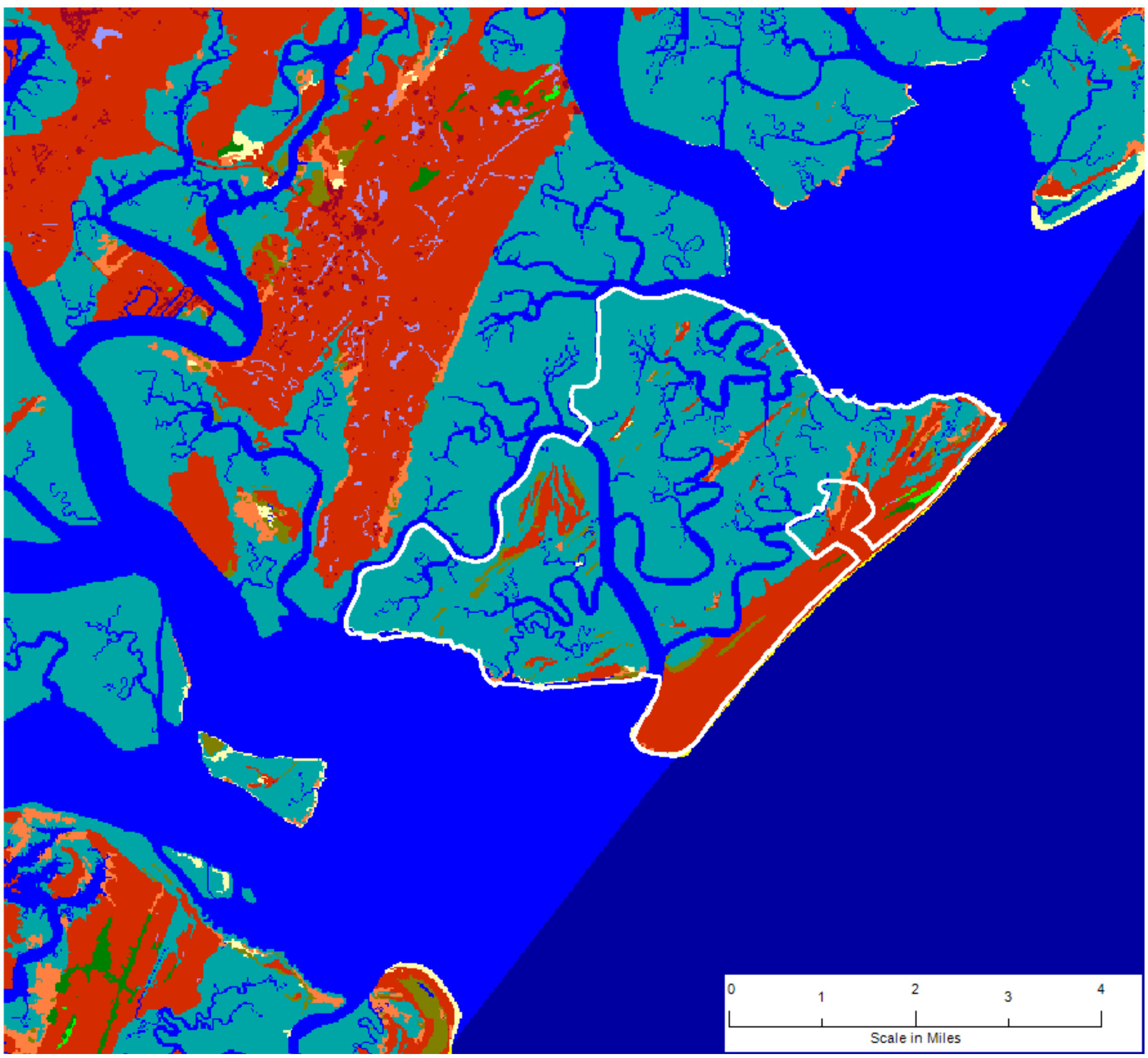
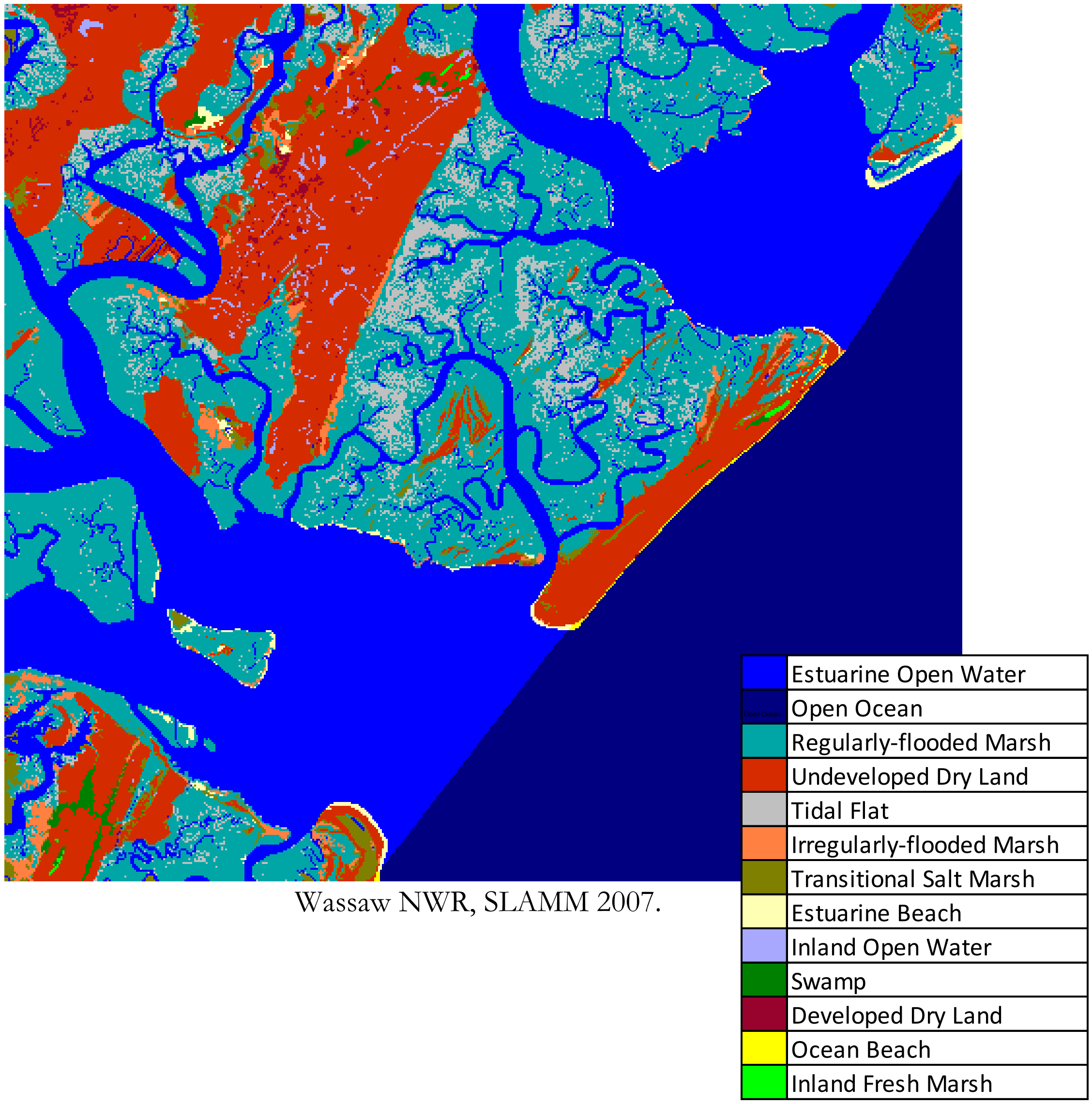
Appendix A: Contextual Results

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:

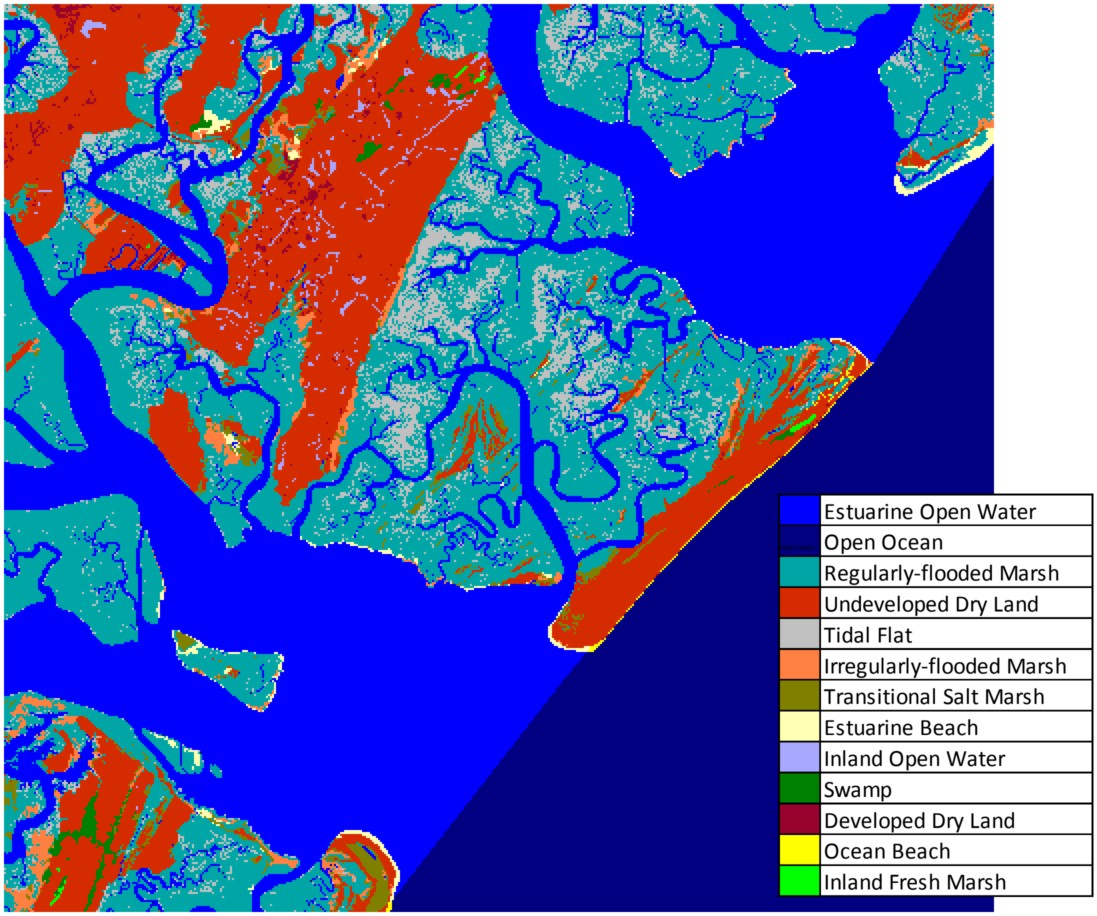
- Results were critically examined within USFWS refuges but not as closely examined for the larger region.
- Site-specific parameters for the model were derived for USFWS refuges whenever possible and may not be regionally applicable.
- Especially in areas where dikes are present, an effort was made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



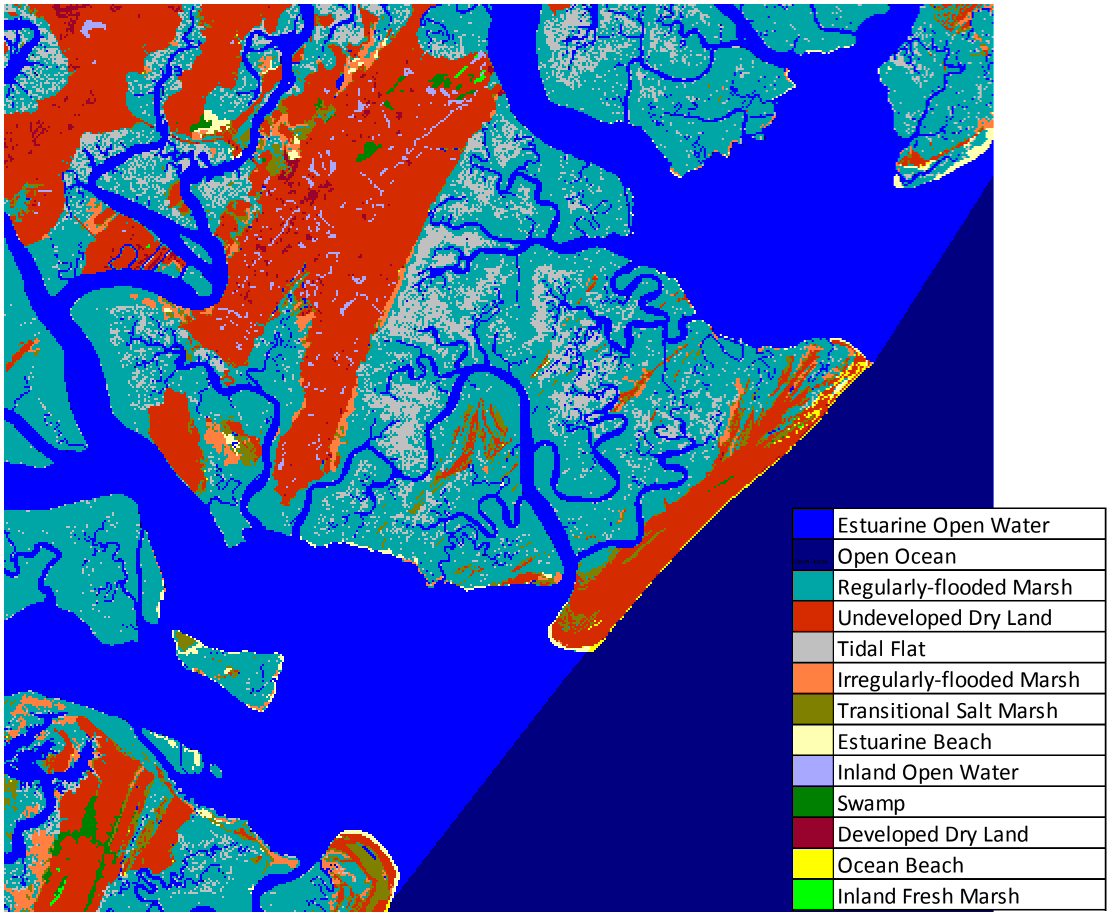
Wassaw National Wildlife Refuge within simulation context (white).



Wassaw NWR, SLAMM 2007.



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



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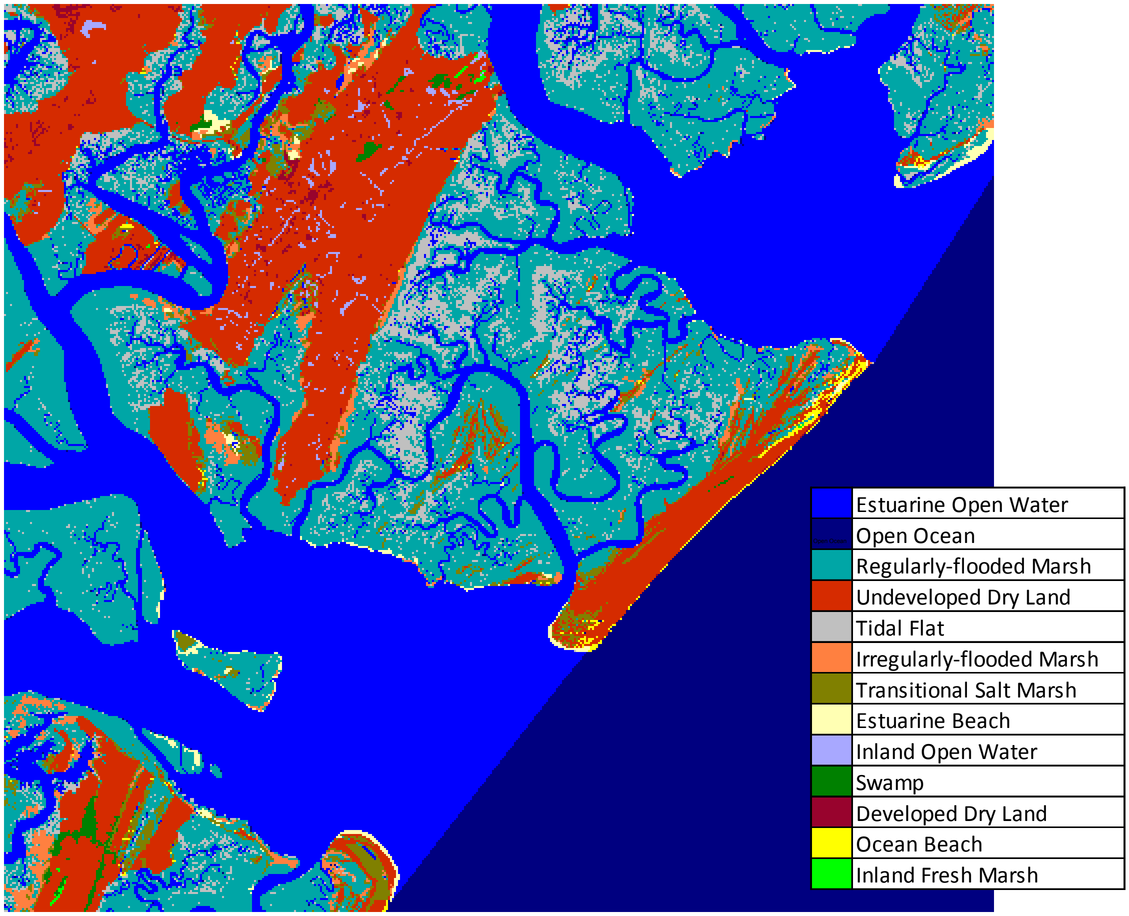
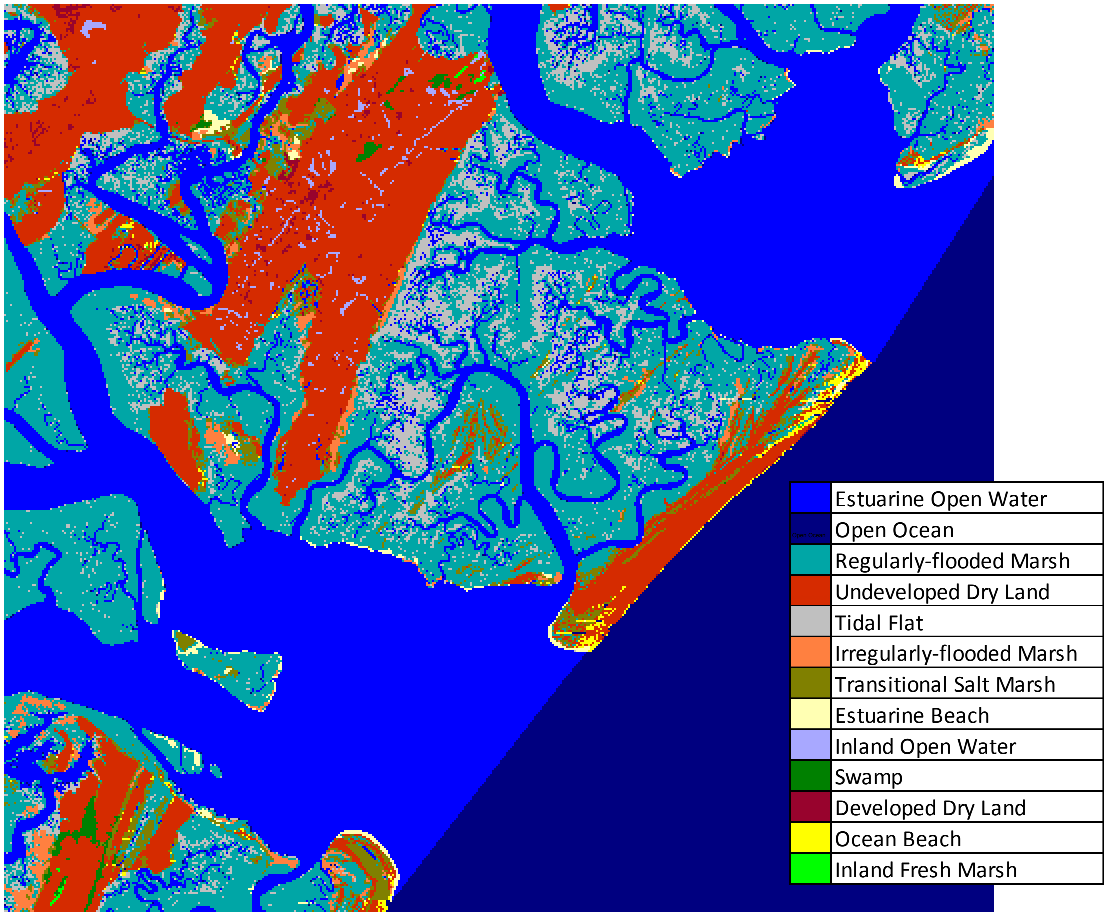
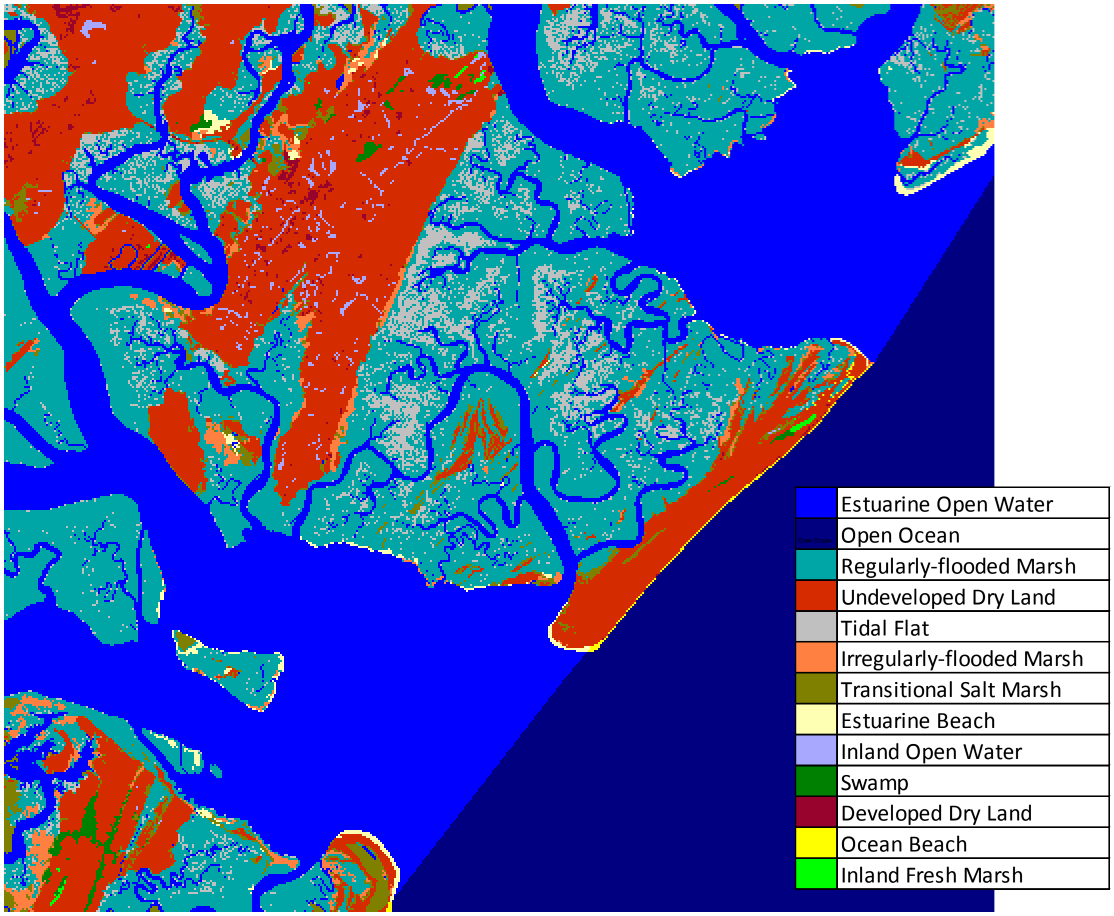


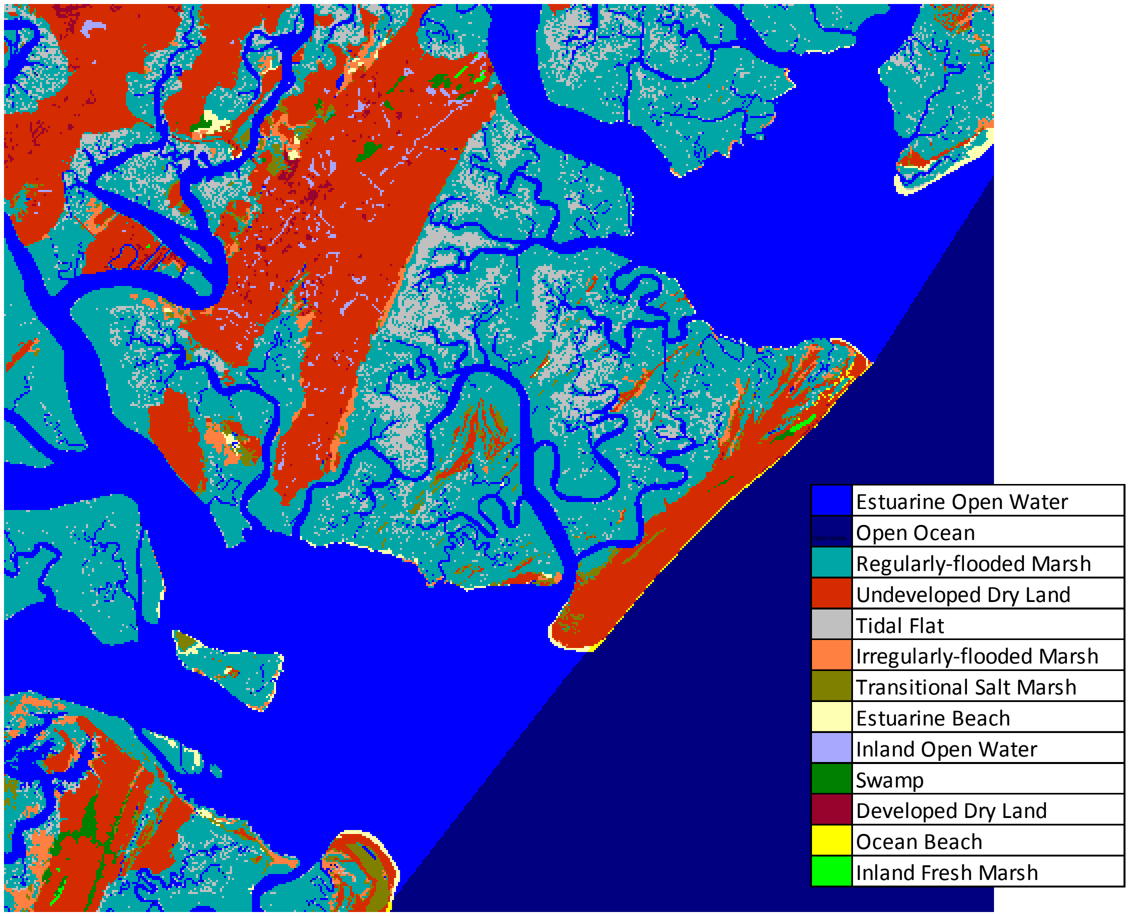
Wassaw NWR, 2075, Scenario A1B Mean, 0.39 m SLR by 2100.



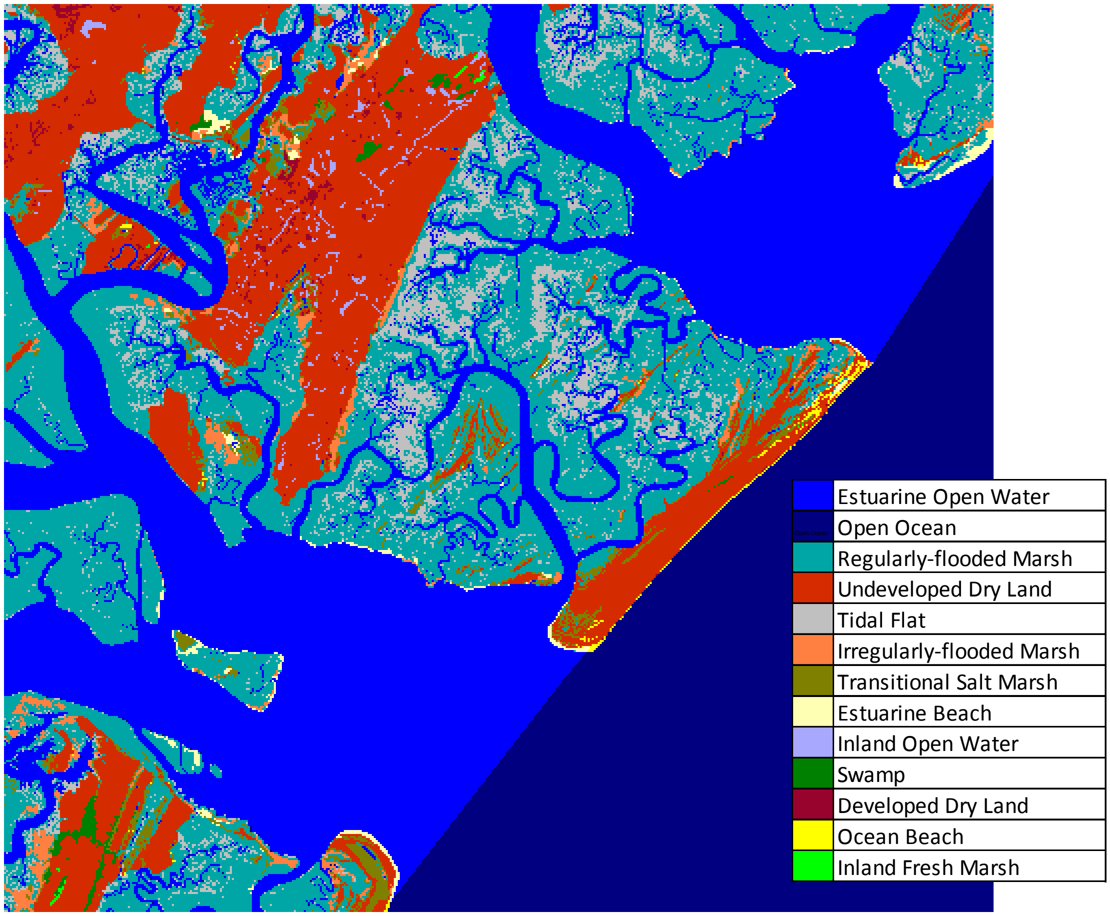
Wassaw NWR, 2100, Scenario A1B Mean, 0.39 m SLR by 2100.



Wassaw NWR, SLAMM 2007.



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



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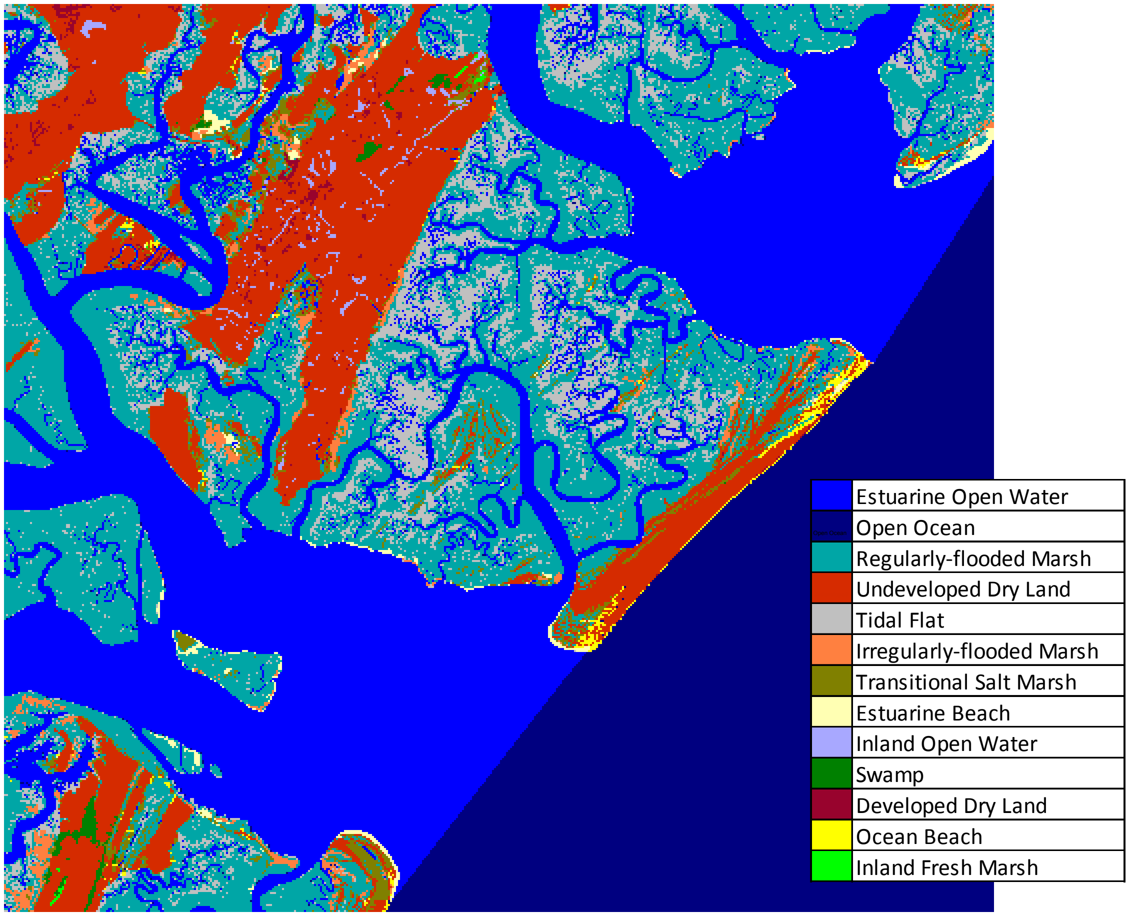
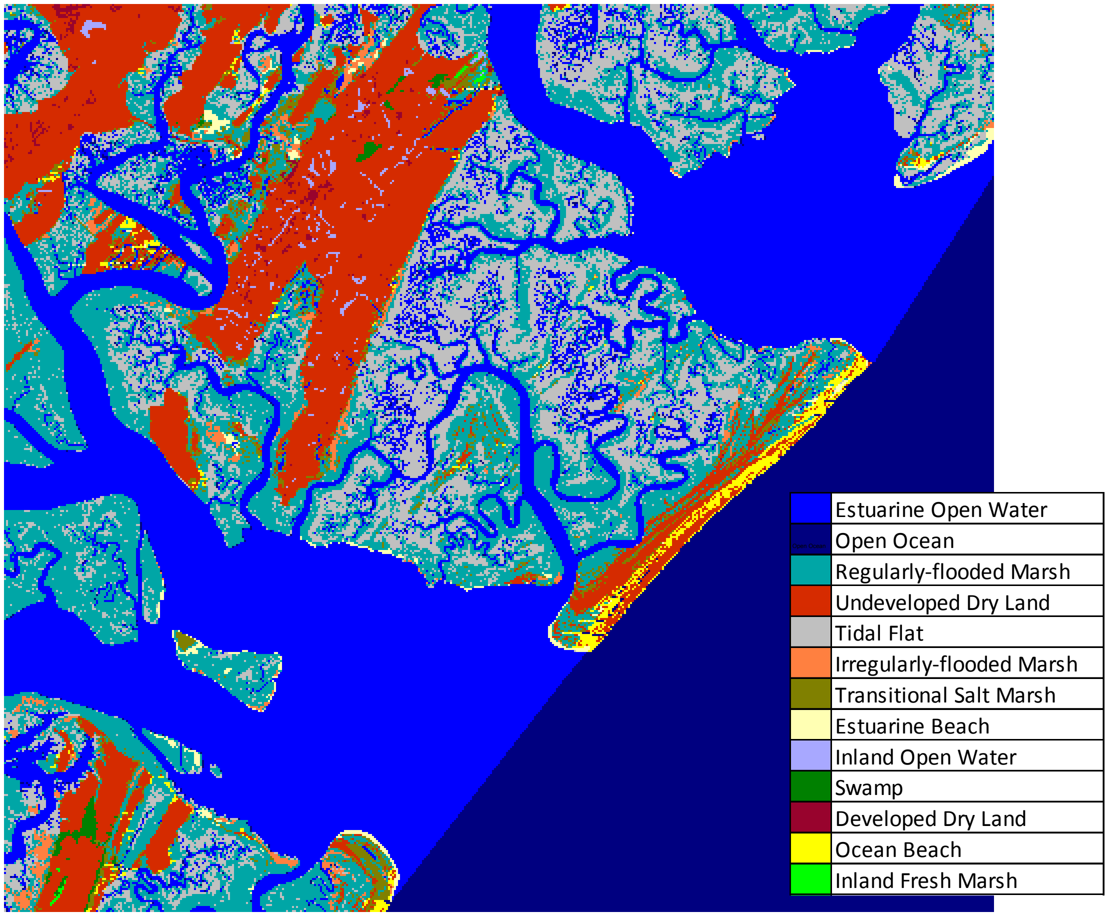


Wassaw NWR, 2075, Scenario A1B Maximum, 0.69 m SLR by 2100.



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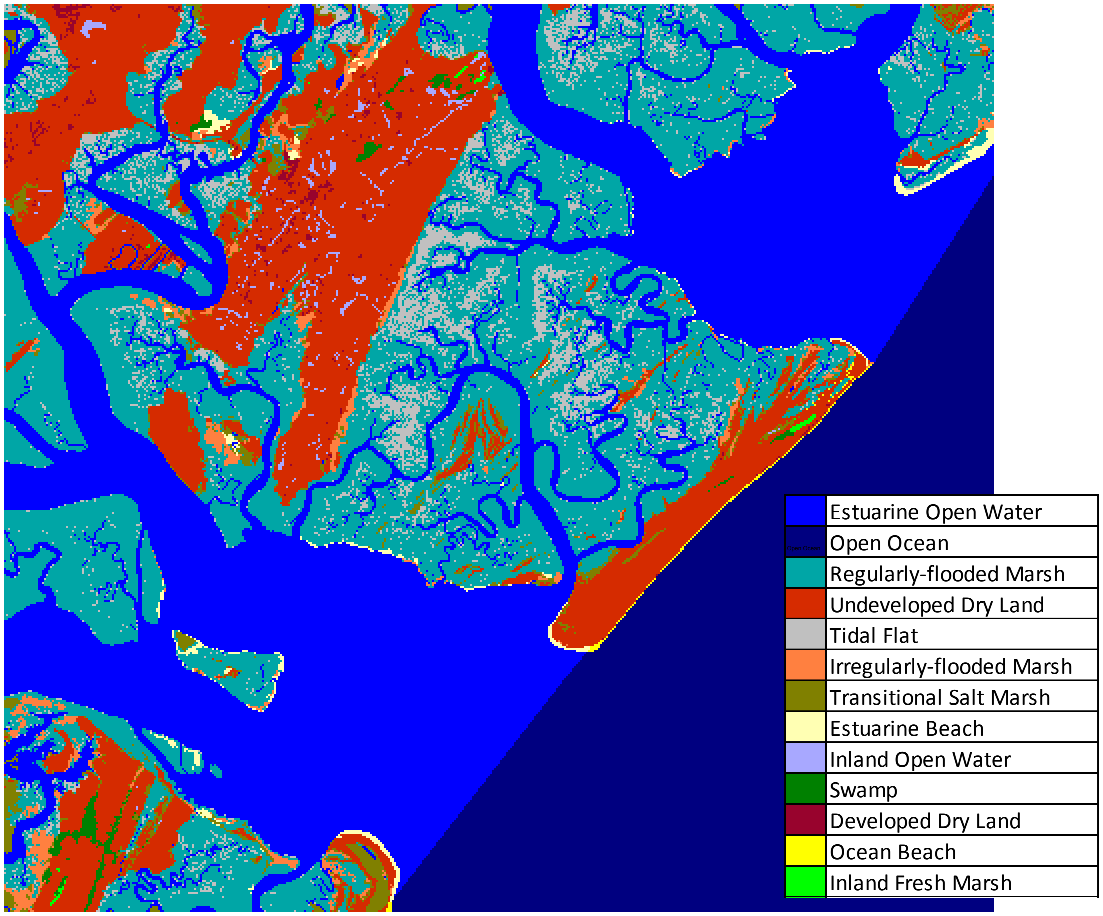

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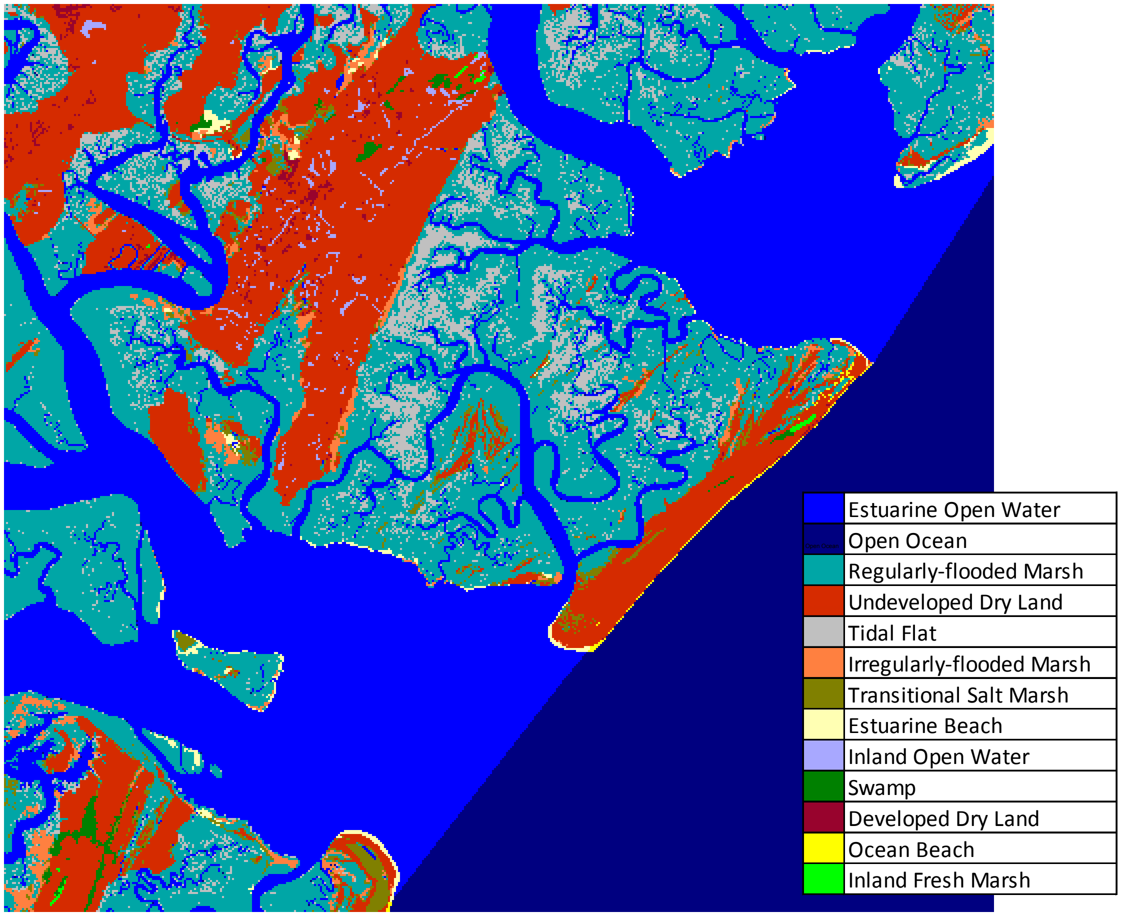
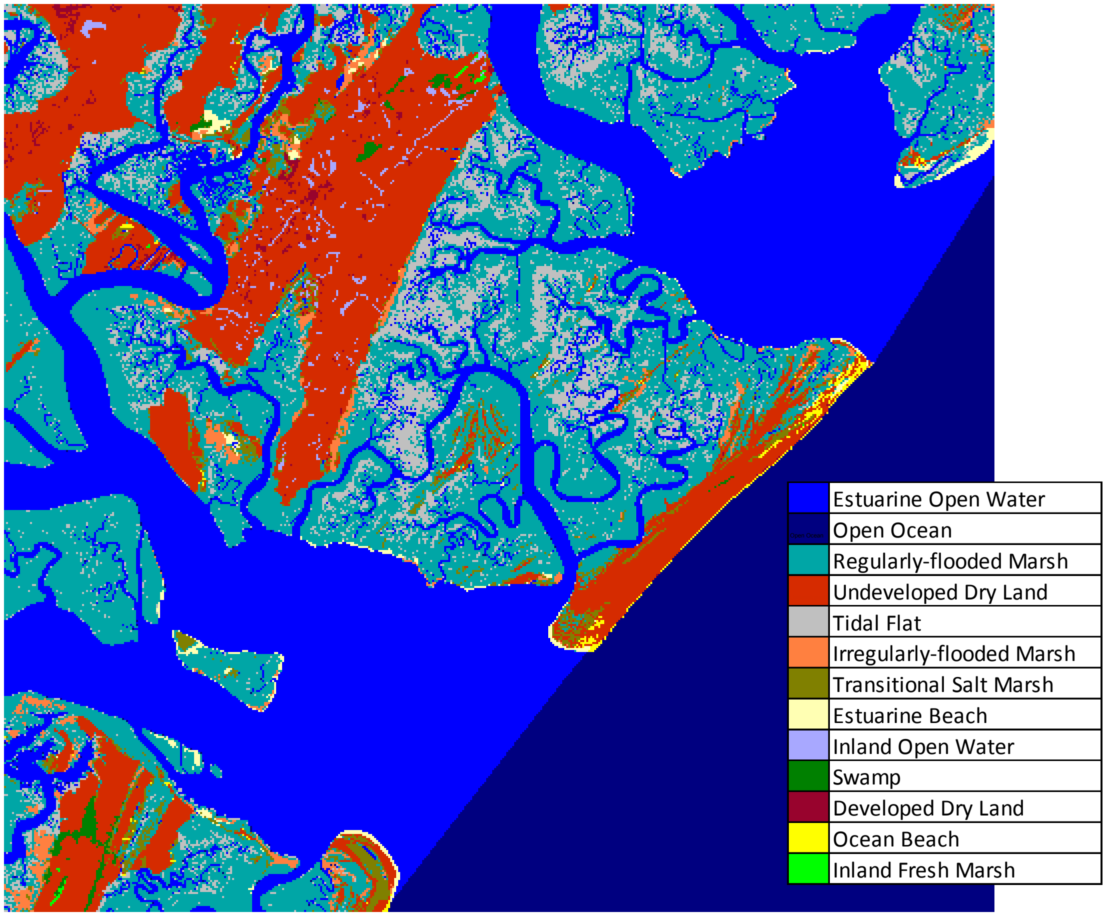


Wassaw NWR, 2025, 1 m SLR by 2100.



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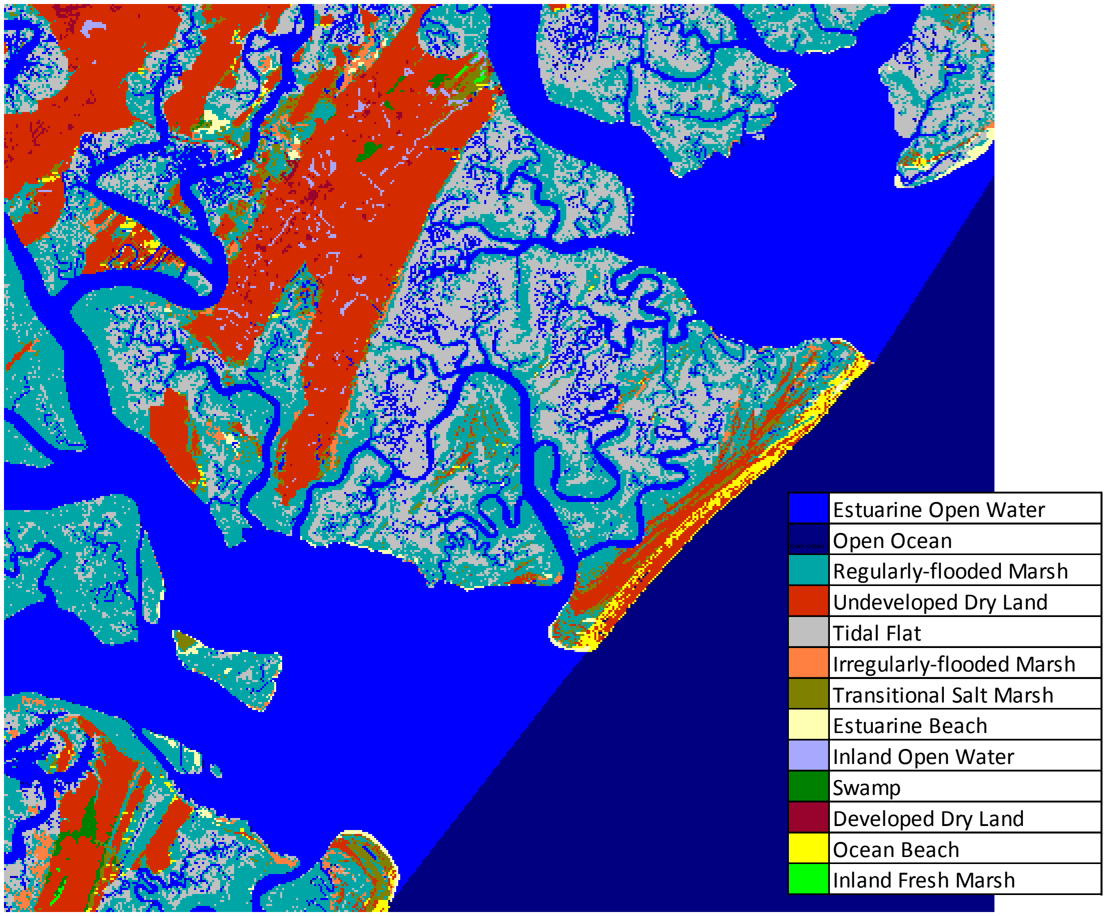

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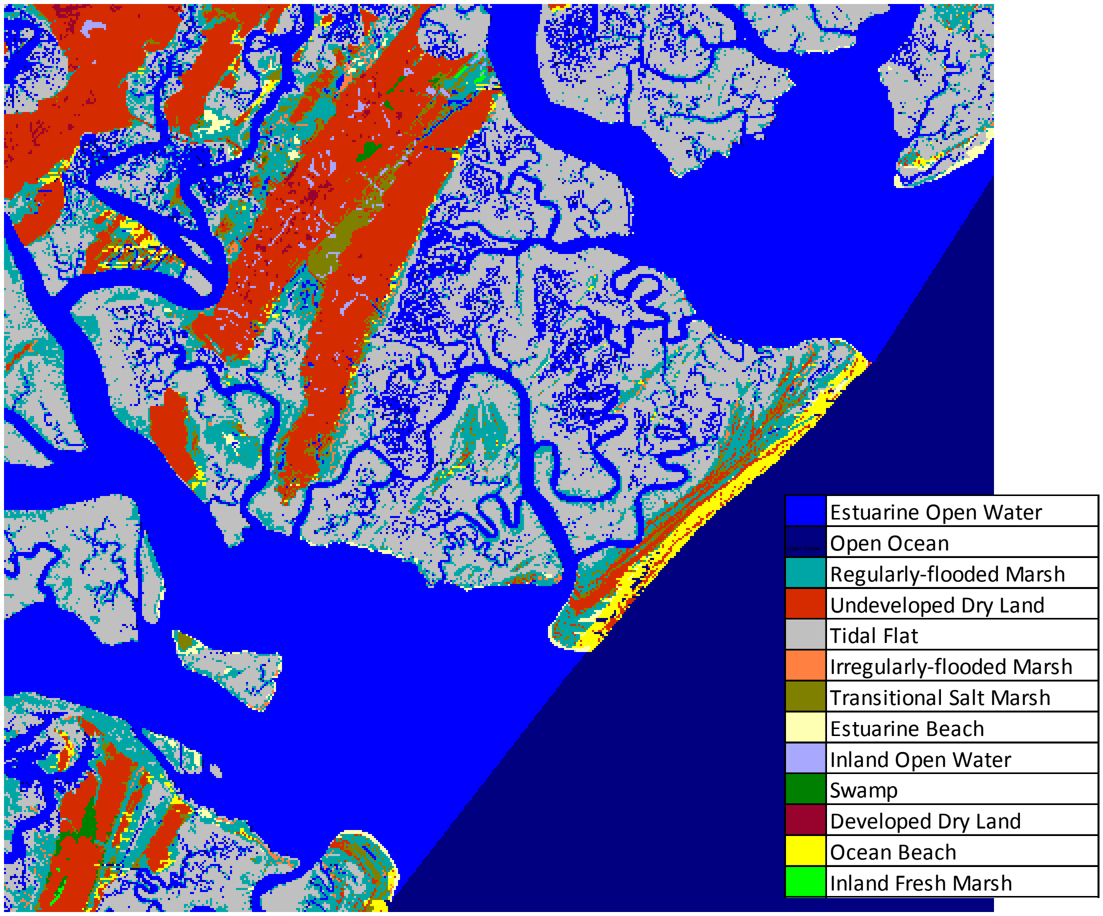

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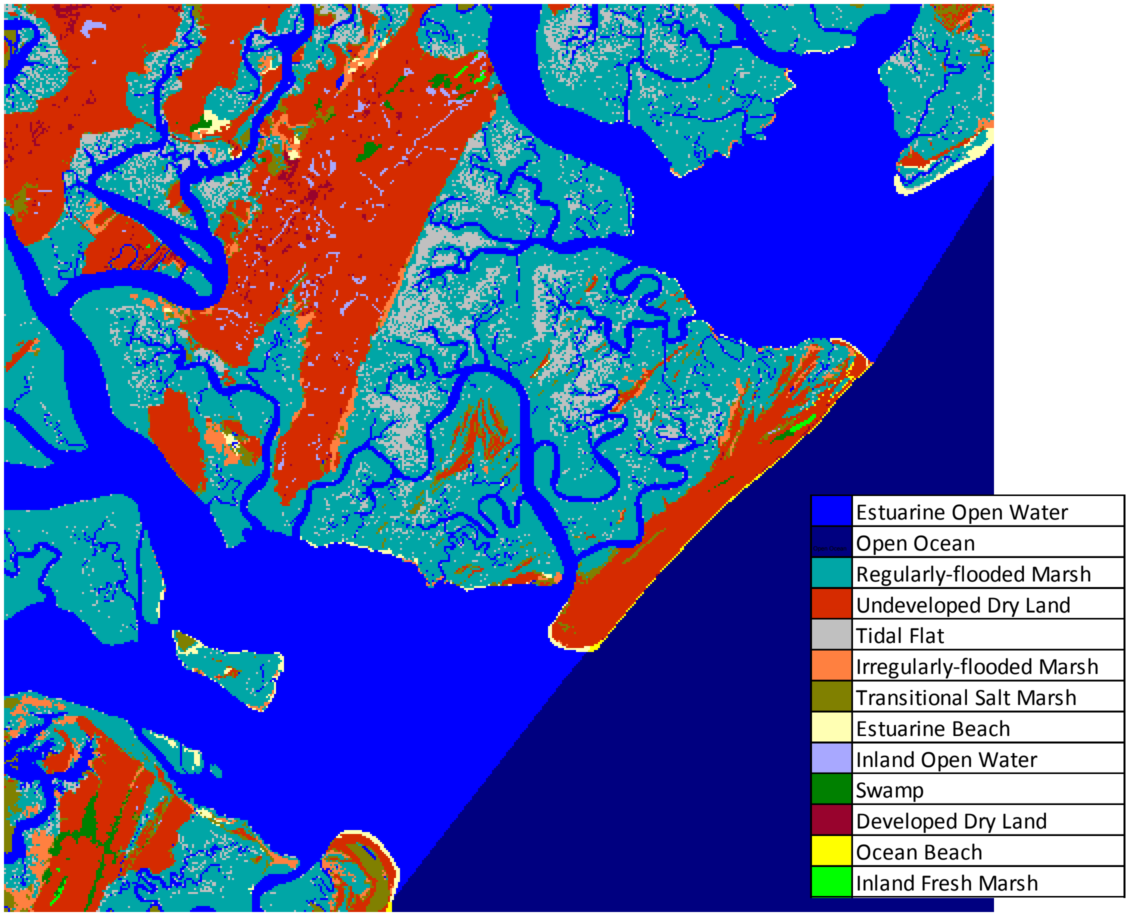

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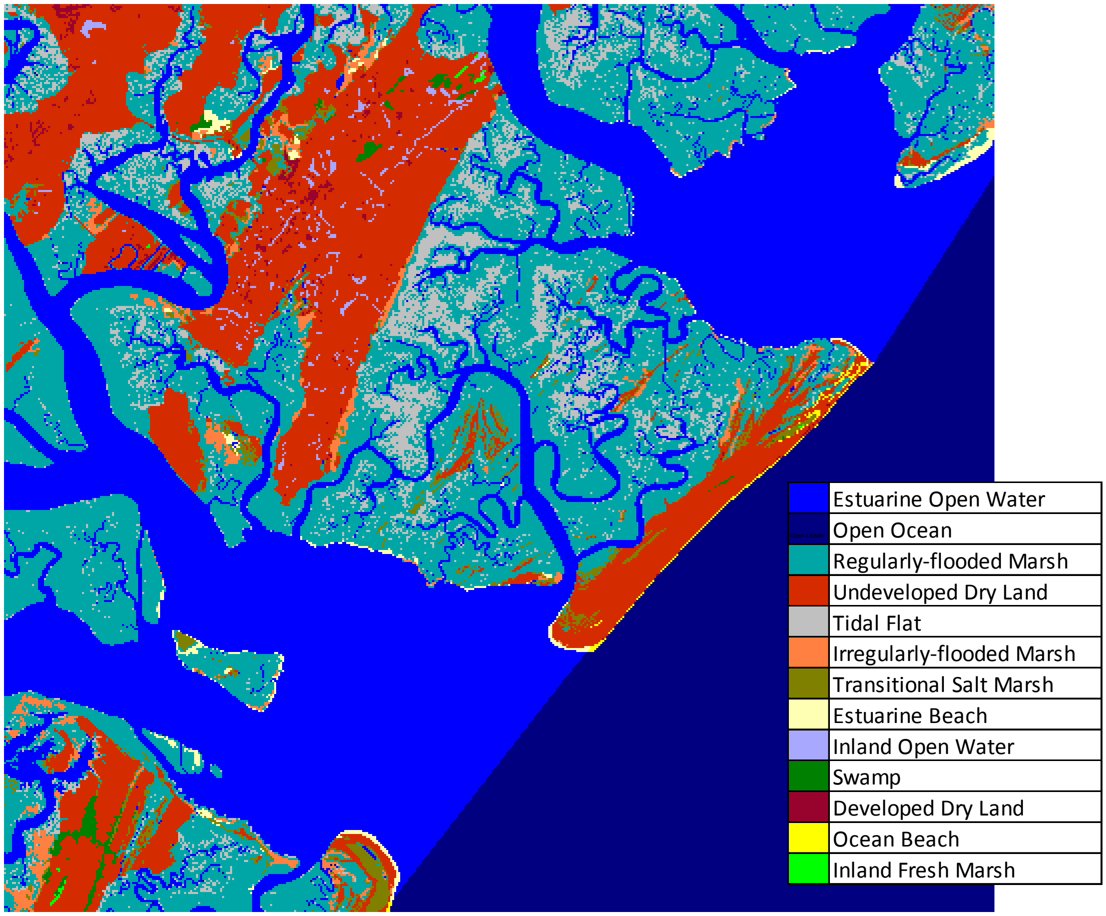

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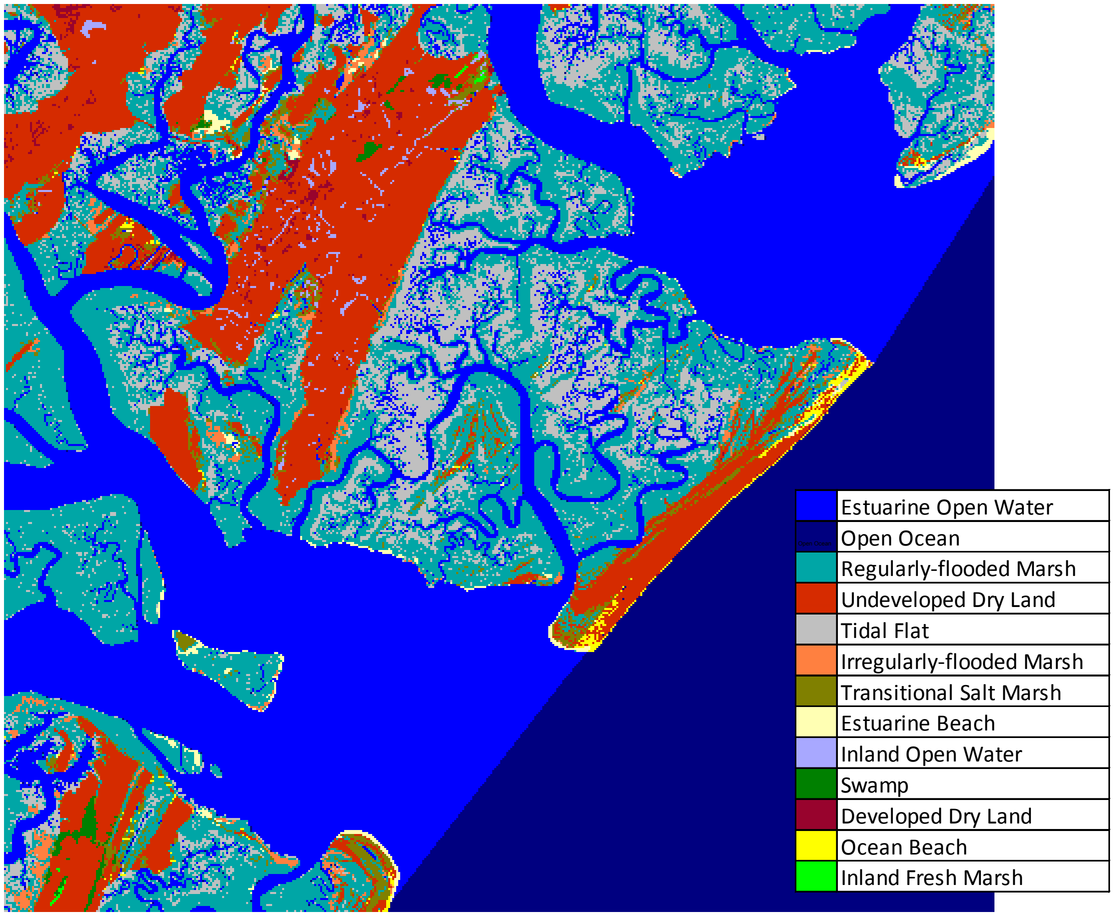

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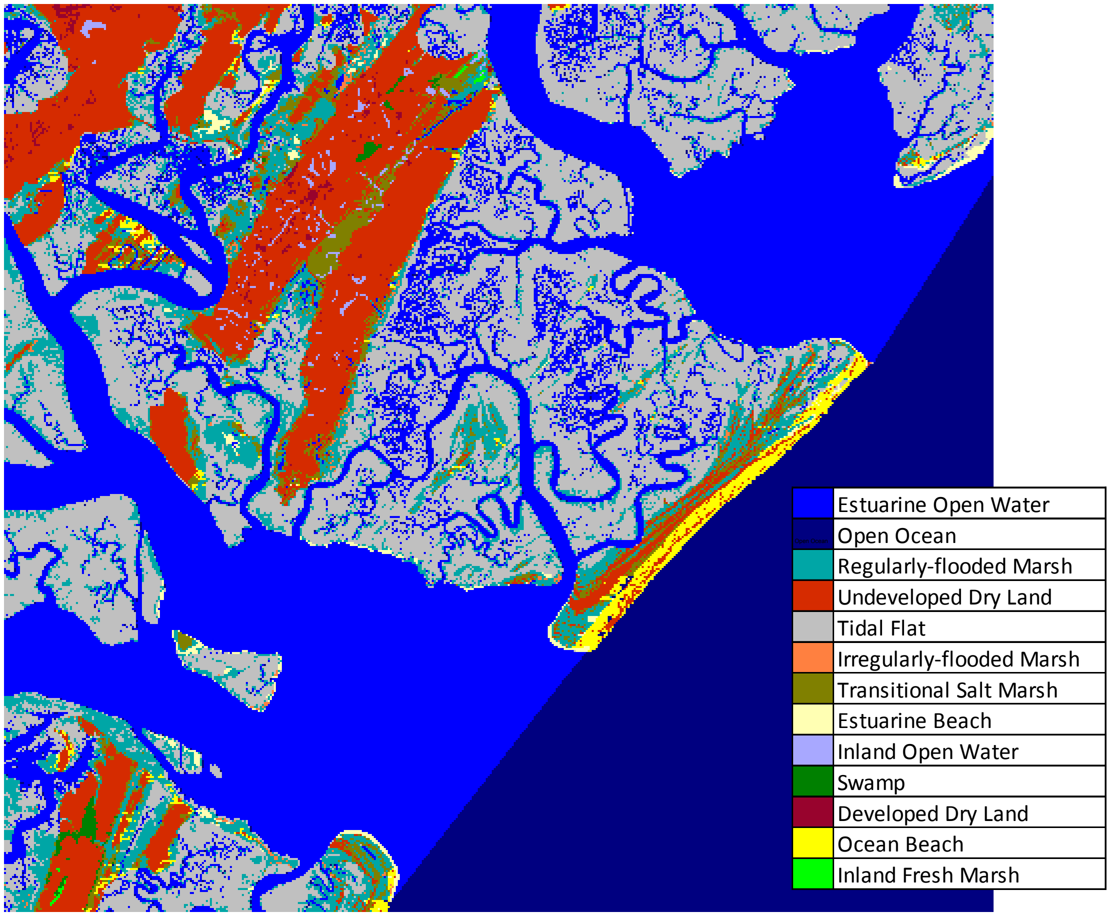
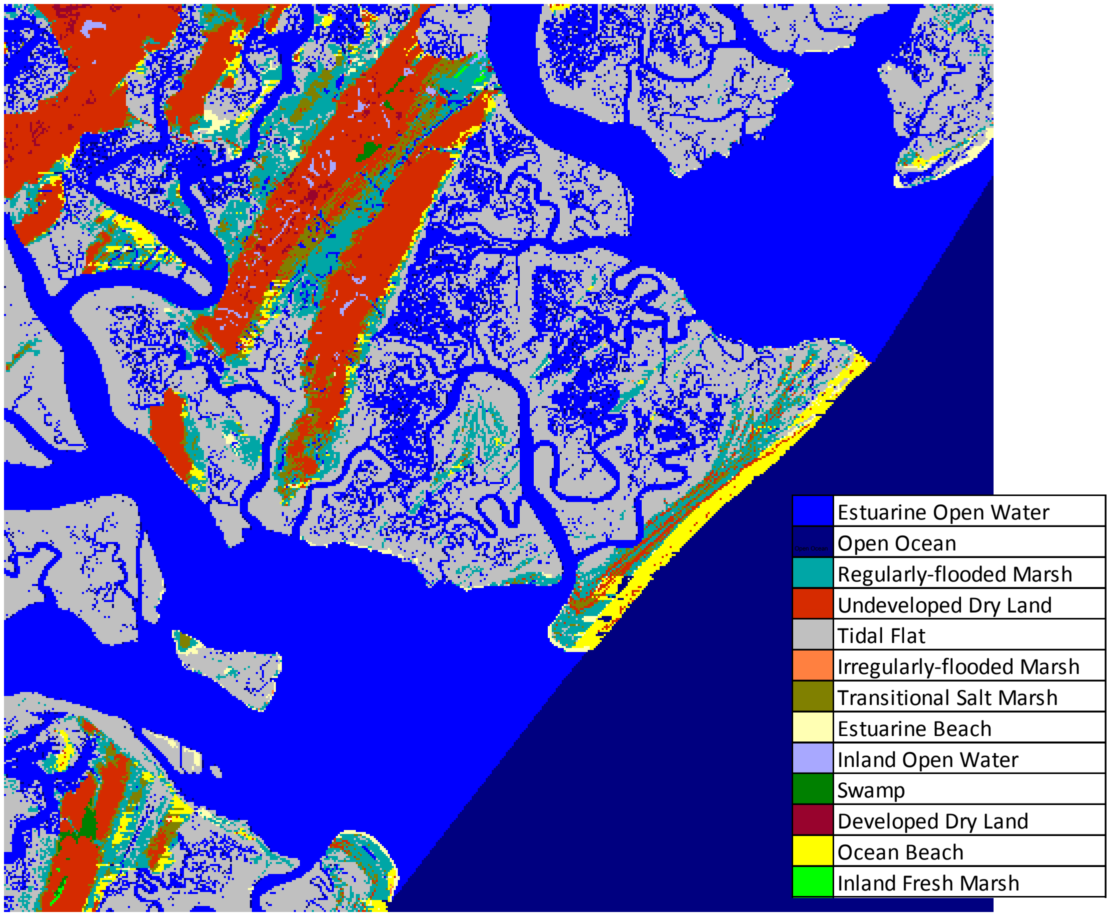
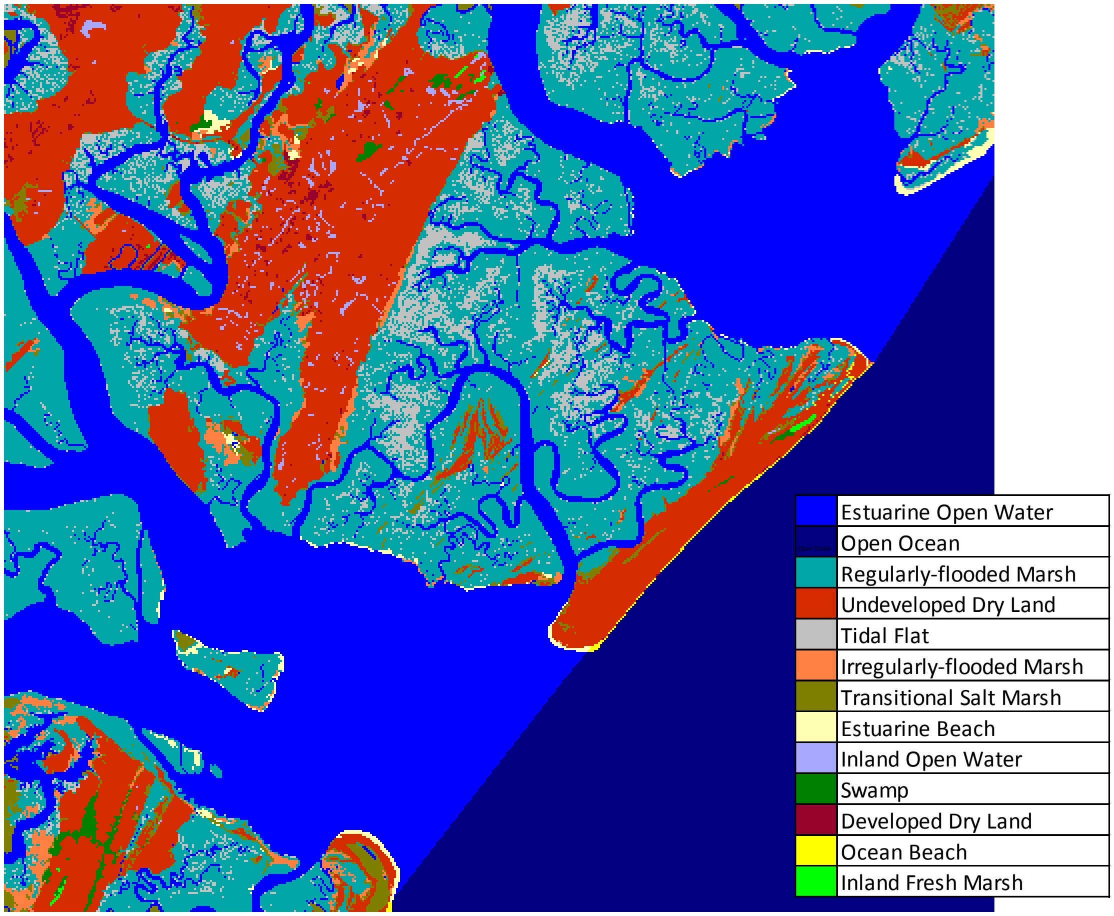


Wassaw NWR, 2075, 1.5 m SLR by 2100.



Wassaw NWR, 2100, 1.5 m SLR by 2100.



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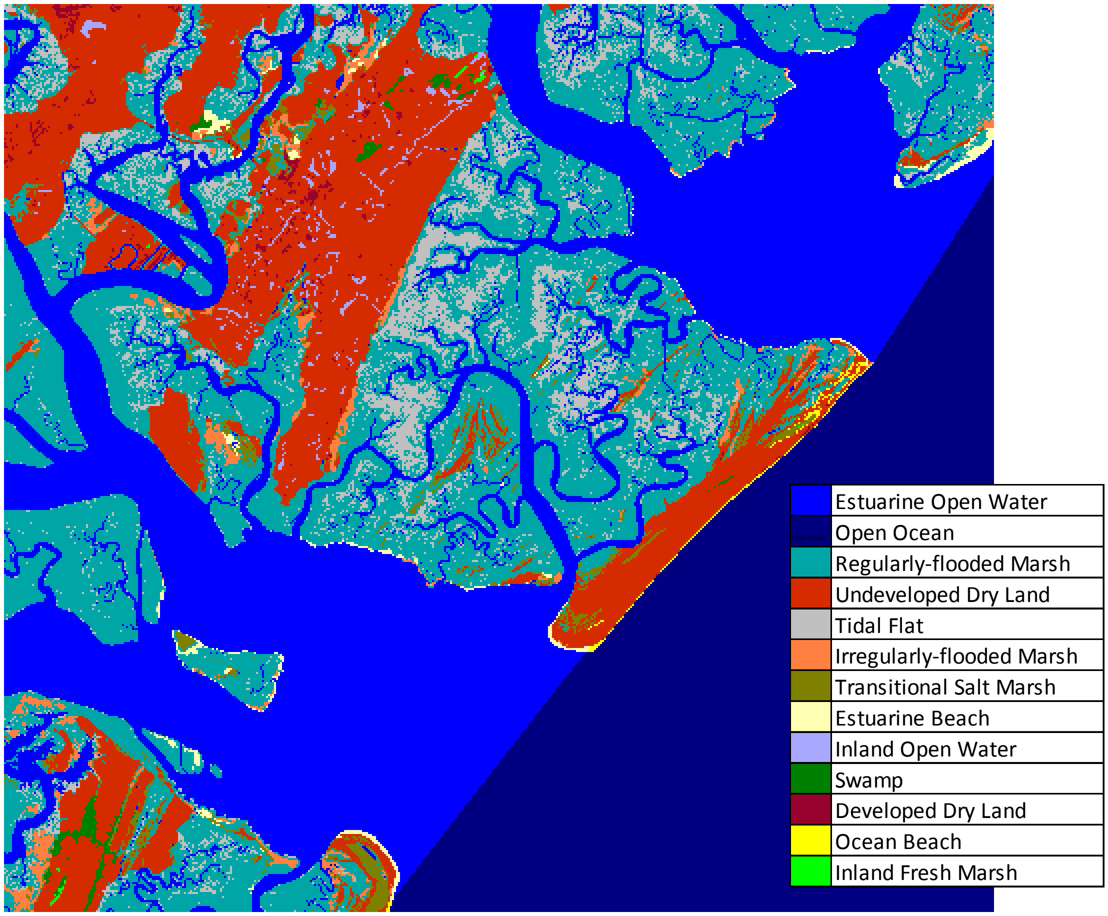
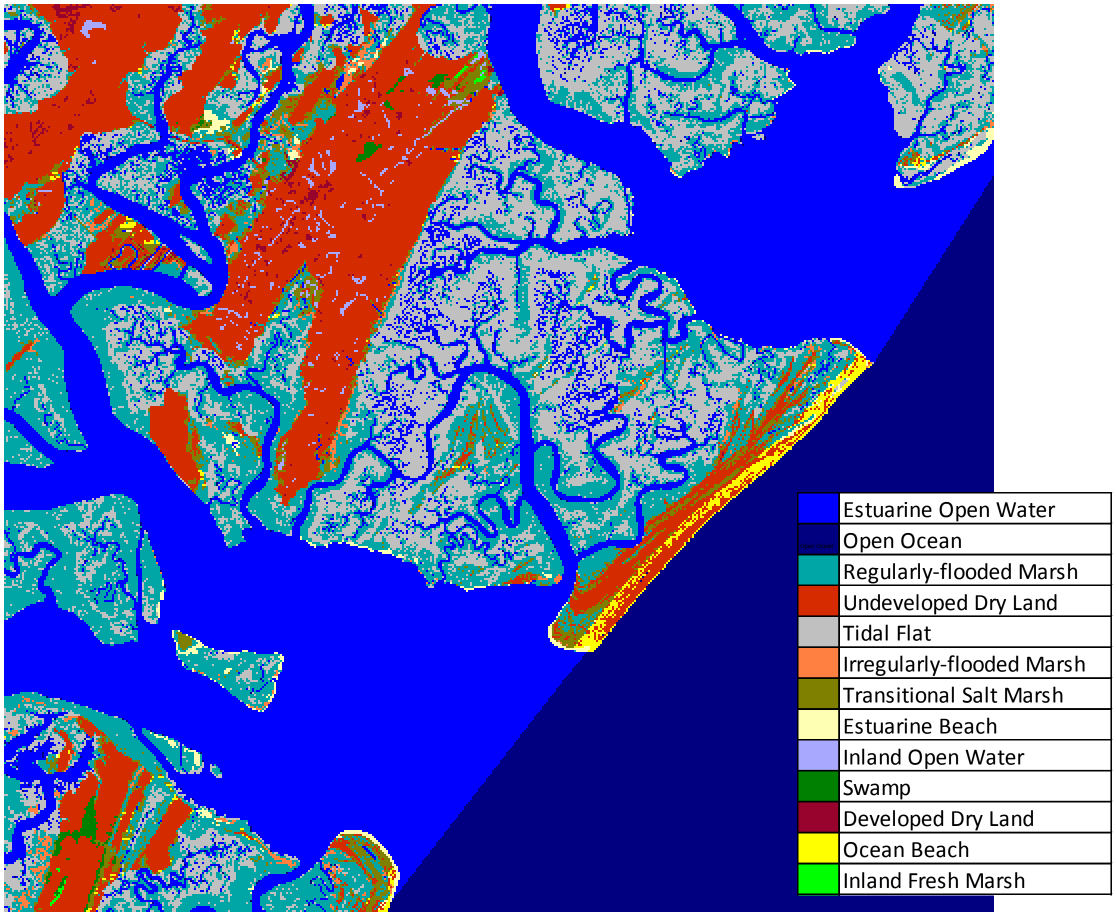
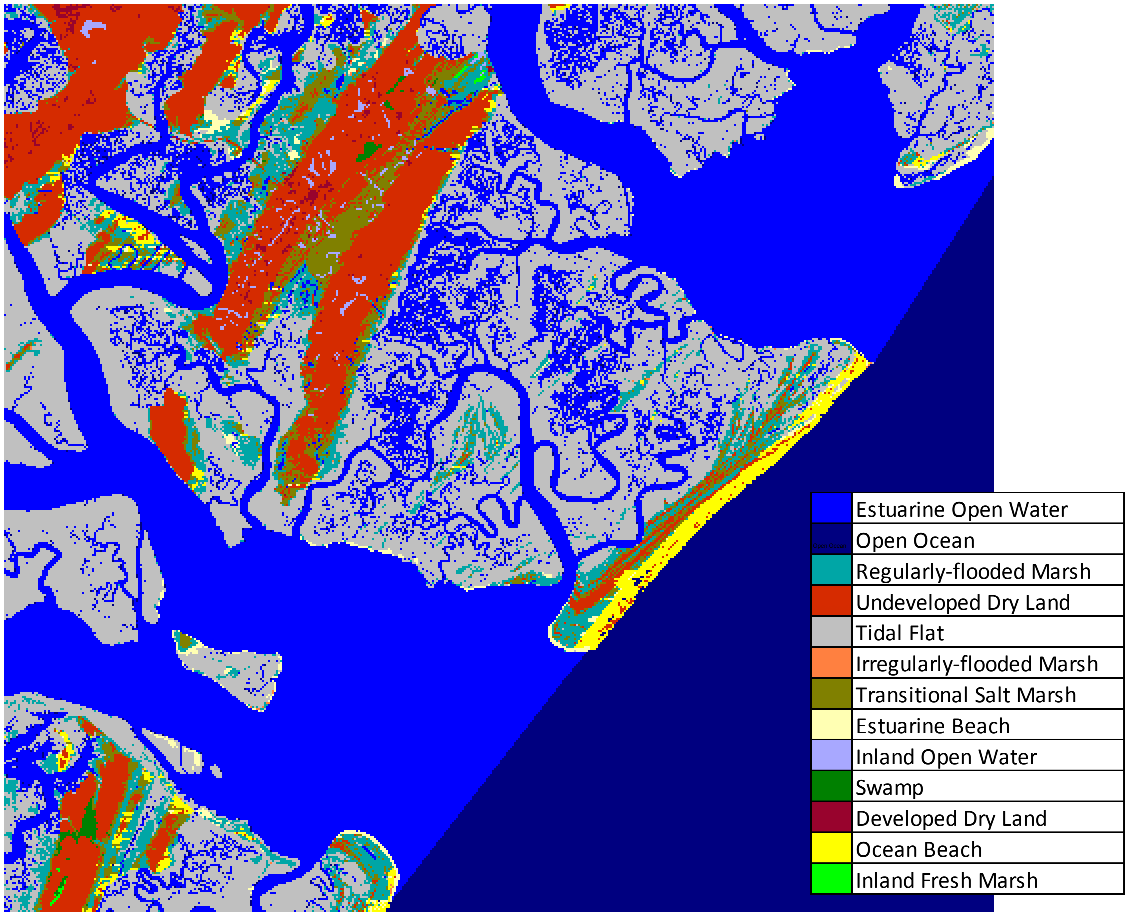


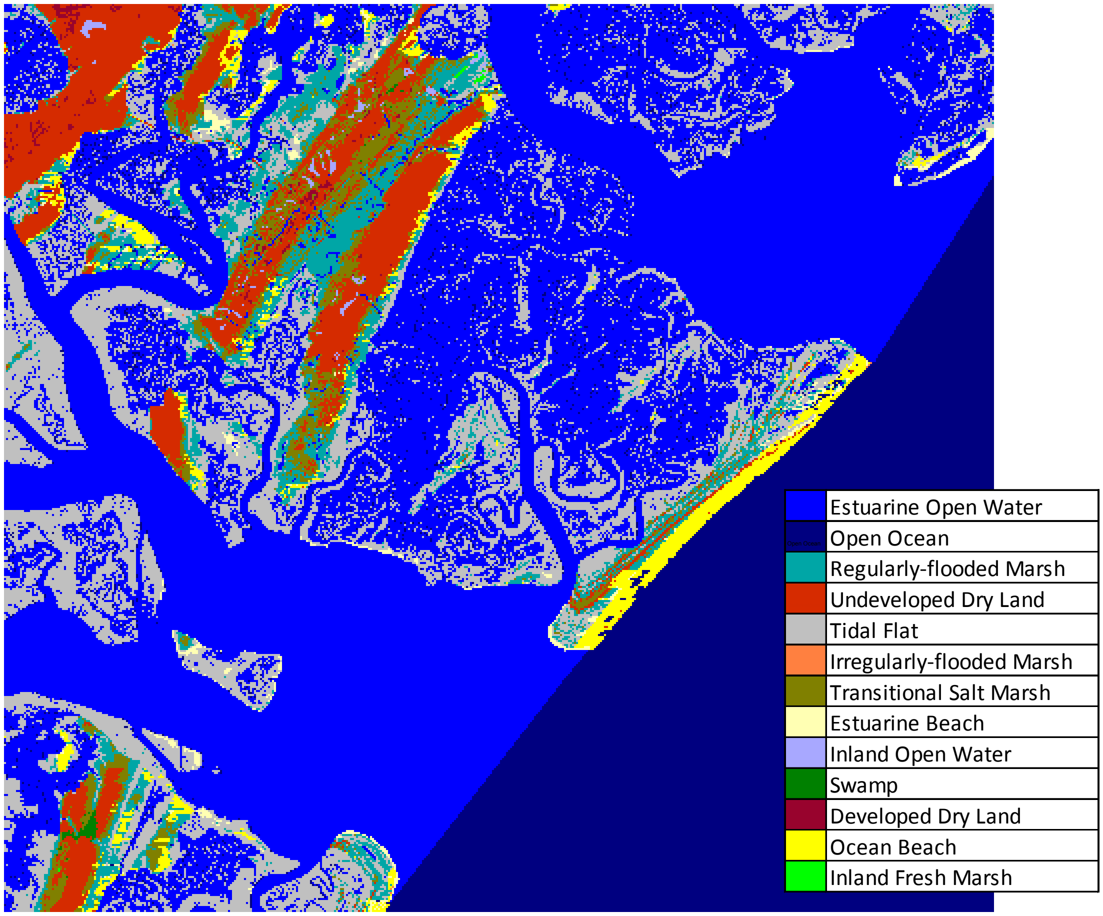
Wassaw NWR, 2025, 2 m SLR by 2100.



Wassaw NWR, 2050, 2 m SLR by 2100.



Wassaw NWR, 2075, 2 m SLR by 2100.



Wassaw NWR, 2100, 2 m SLR by 2100.