Application of the Sea-Level Affecting Marshes Model (SLAMM 6) to Julia Butler Hansen 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 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 Region 1 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).

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 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

SLAMM 6 was run using 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 m of SLR 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 m of global SLR by 2100. A1B-maximum predicts 0.69 m 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 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.

To allow for flexibility when interpreting the results, SLAMM was also run assuming 1 m, 1.5 m, and 2 m of eustatic SLR by the year 2100. The A1B- maximum scenario was scaled up to produce these bounding scenarios (Figure 1).

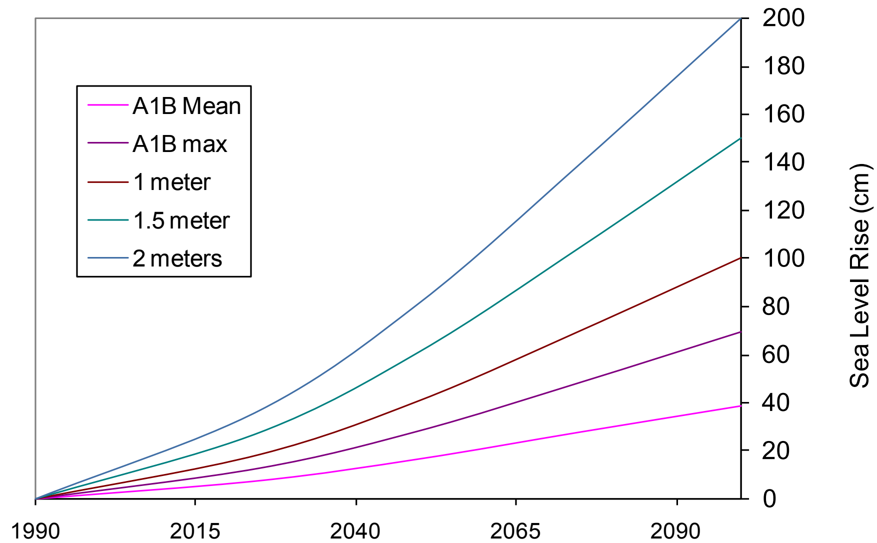


Figure 1. Summary of SLR scenarios utilized

Data Sources and Methods

Wetland layer. Figure 2 shows the most recent wetland layer available for the study area obtained by combining National Wetlands Inventory (NWI) photos dated 1981, the Oregon wetland database with dates ranging 1993-2009 and a recent layer covering the entire refuge area produced by the Lower Columbia River Estuary Partnership (LCREP) between 2007-2010. The crosswalk from the wetland classes identified by LCREP to SLAMM is summarized in Table 1.

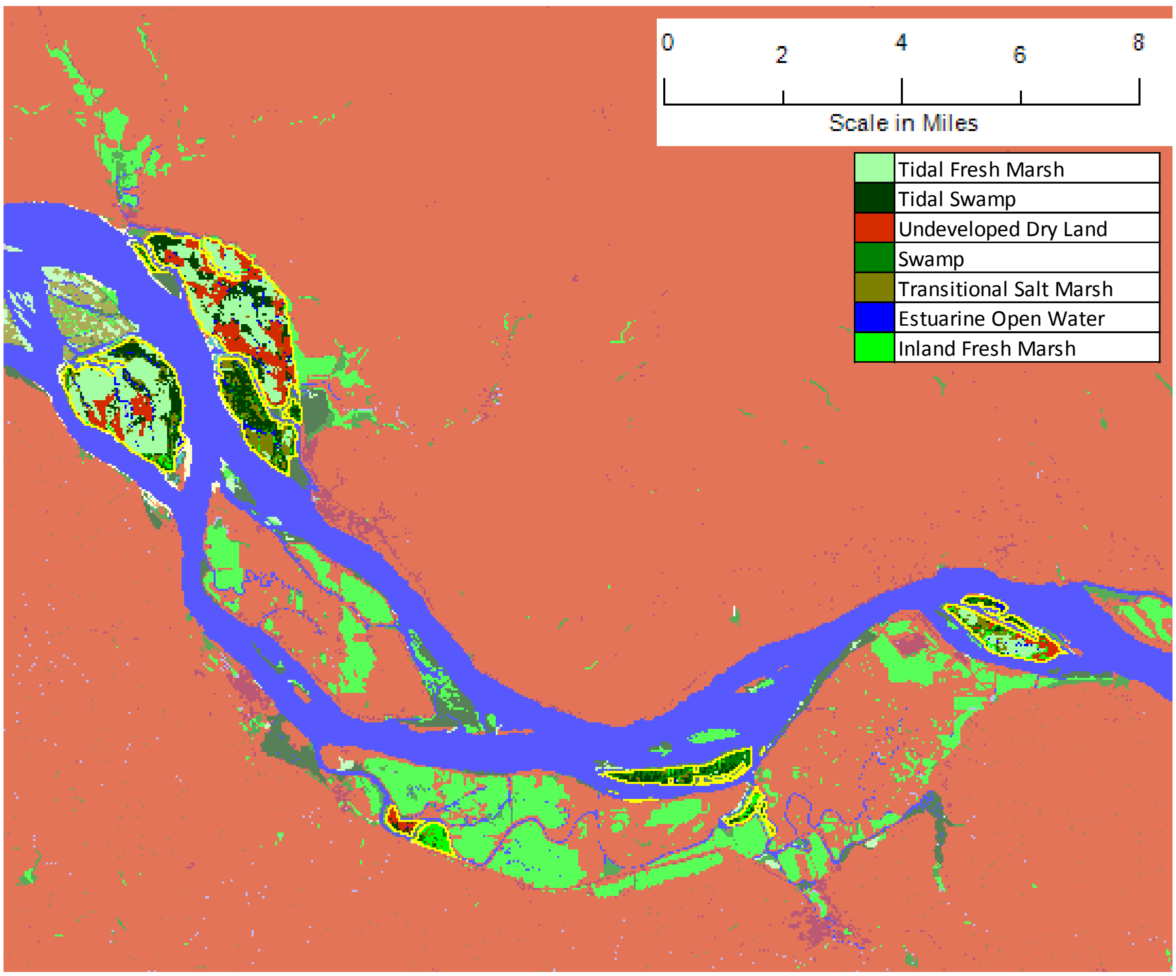


Figure 2. Wetland coverage of the study area. Refuge boundaries are indicated in yellow

Table 1. Wetland codes crosswalk from LCREP to SLAMM for Julia Butler Hansen NWR

LCREP	SLAMM
coniferous upland forest	Undeveloped dry land
deciduous upland forest	Undeveloped dry land
coniferous wetland forest - non-tidal	Swamp
coniferous wetland forest - tidally influenced	Tidal swamp
coniferous wetland forest - tidally impaired	Tidal swamp
deciduous wetland forest - non-tidal	Swamp
deciduous wetland forest - tidally influenced	Tidal swamp
deciduous wetland forest - tidally impaired	Tidal swamp
upland shrub-scrub	Undeveloped dry land
wetland shrub-scrub - non-tidal	Inland fresh marsh
wetland shrub-scrub - tidally influenced	Transitional marsh
wetland shrub-scrub - tidally impaired	Transitional marsh
upland herbaceous	Undeveloped dry land
wetland herbaceous - non-tidal	Inland fresh marsh
wetland herbaceous - tidally influenced	Tidal fresh marsh
wetland herbaceous - tidally impaired	Tidal fresh marsh
aquatic bed	Estuarine water
agriculture	Undeveloped dry land
tree farms	Undeveloped dry land
bare	Undeveloped dry land
mud	Tidal flat
sand	Estuarine beach
rock	Rocky intertidal
urban, impervious surface	Developed dry land
urban, open space developed	Developed dry land
water	Estuarine water

Converting the land-cover survey into 30 m cells indicated that the approximately 6,800 acre Julia Butler Hansen NWR (approved acquisition boundary including water) is composed of the following categories:

	Land cover type	Area (acres)	Percentage (%)
	Tidal Fresh Marsh	2096	31
	Tidal Swamp	1449	21
	Undeveloped Dry Land	1161	17
	Swamp	781	12
	Transitional Salt Marsh	606	9
	Estuarine Open Water	331	5
	Inland Fresh Marsh	315	5
	Developed Dry Land	12	<1
	Riverine Tidal	12	<1
	Estuarine Beach	10	<1
	Tidal Flat	7	<1
	Regularly Flooded Marsh	1	<1
	Total (incl. water)	**6781**	**100**

Elevation Data. The digital elevation map used in this simulation, shown in Figure 3, is a bare-earth dataset that was derived primarily by combining data from the Puget Sound LiDAR Consortium dated 2005 and a NOAA LiDAR dated 2009.

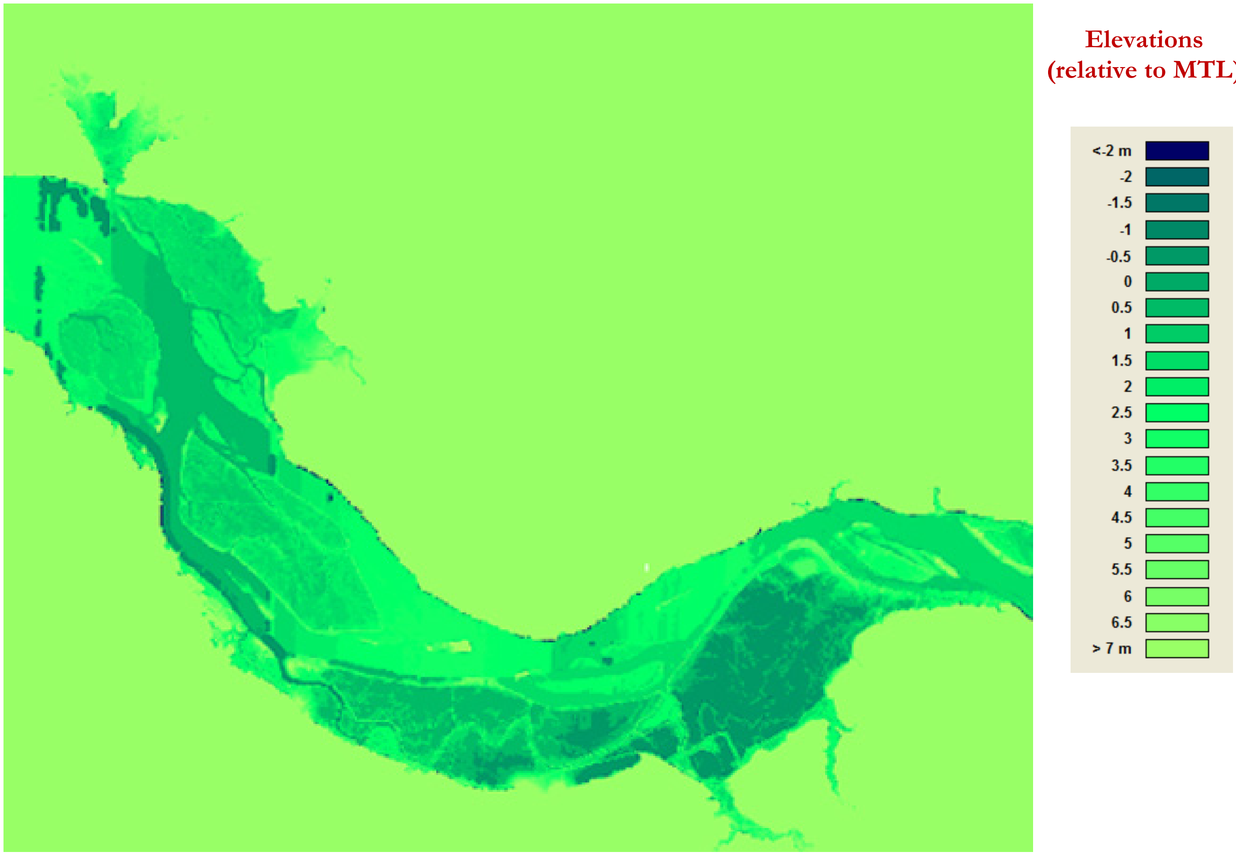


Figure 3. Shade-relief elevation map of the study area.

Model Timesteps. Model forecast outputs were chosen at years 2025, 2050, 2075 and 2100 with the initial condition date set to 1981 (the most recent wetland data available for the refuge).

Dikes and Impoundments. Areas in the study area protected by dikes were derived from a combination of data sources. Diked and impounded areas are listed within the National Wetland Inventory, but this coverage is often incomplete. Therefore this map was combined with one provided by the refuge staff showing that Tenasillahe Island and the mainland of the refuge are protected by dikes, as illustrated in Figure 4. SLAMM assumes that this dike system will prevent water from entering the protected areas for all SLR scenarios examined.

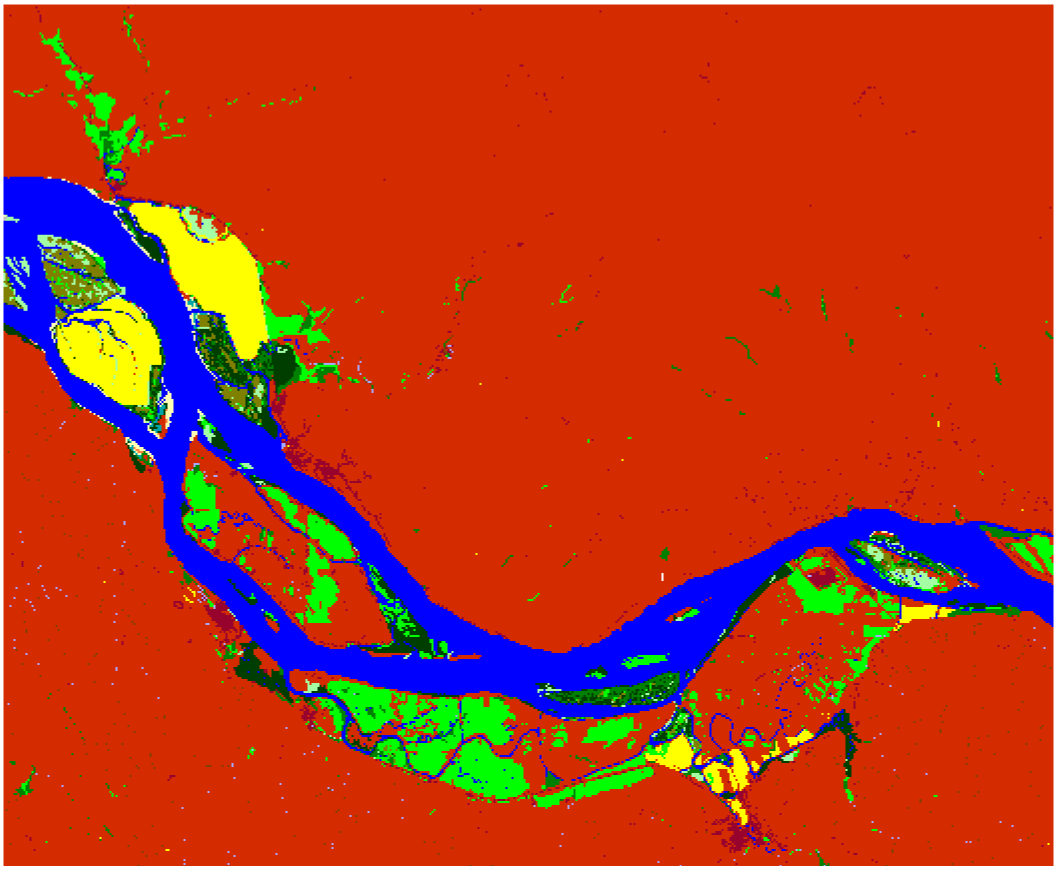


Figure 4. In yellow the refuge area protected by dikes

Historic sea level rise rates. The historic SLR trend recorded at the nearby NOAA gauge station of Astoria, OR (ID 9439040) is on average -0.31 mm/yr. This negative rate is an outlier compared to other regional NOAA gauges (Toke Point 1.6mm/year, Seattle 2.06 mm/year, Garibaldi, 1.98 mm/year). Since the Astoria value is likely due to a localized uplift (Burgette et al. 2009; Canning 2007), a historic SLR rate of 2 mm/yr. was used in this model application, corresponding roughly to the average regional SLR trend. This value is also quite similar to the global average of SLR recorded for the last 100 years (approximately 1.7 mm/year, IPCC 2007a), and as a result, predicted local SLR will closely match future global scenarios. However, the potential for localized regions of uplift or subsidence are consequently ignored within this analysis.

Tide Ranges. Figure 5 shows the locations of the three NOAA tide gauge stations closest to the study area used to define the tide ranges for this site.

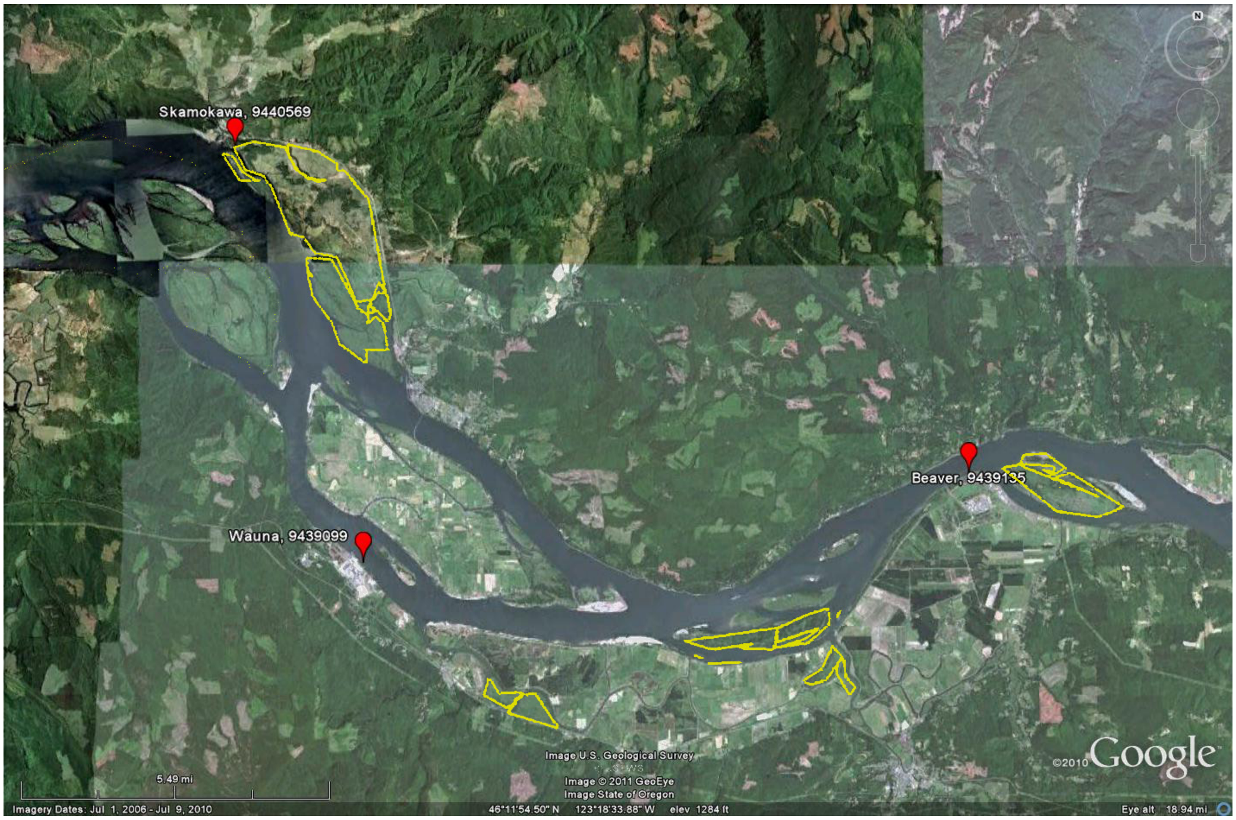


Figure 5. Location of NOAA tides gages used for Julia Butler Hansen NWR

The great diurnal tide range, summarized in Table 2, varies from 2.31 m closer to the mouth of the Columbia River to 1.73 upriver. The observed gradient of decreasing tidal range from south to north was applied to this SLAMM simulation.

Table 2. NOAA tide gauges and values.

Station ID	Site Name	Tide Range (m)	Salt Elevation (m)
9440569	Skamokawa, WA	2.31	1.76
9439099	Wauna, OR	2.15	1.64
9439135	Beaver, OR	1.73	1.32

Observed data from gauge stations along the Columbia River were used to model tidal ranges for the surrounding region.

Salt elevation. This parameter within SLAMM designates the boundary between wet lands and dry lands or saline wetlands and fresh water wetlands. As such, this value may be best derived by examining historical tide gage data. For this application, the salt boundary was defined as the elevation above which inundation is predicted less than once per thirty days using data from the gauge station at Skamokawa, WA (ID 9440569) and Wauna, OR (ID 9439099). The salt elevations calculated from these two sites are very similar, approximately 1.5 Half Tide Units (HTU). Applying this estimated value to all the available gauge stations defines salt elevations that range between 1.32 m above MTL at Beaver, to 1.76 m above MTL at Skamokawa.

Accretion rates. Salt marsh vertical accretion rates of 3.6 mm/yr were from a regional average based on (Thom 1992) who measured accretion rates of regularly flooded (salt) marshes in the Pacific Northwest. Model accretion rates for irregularly flooded (brackish) marsh were set to 3.75 mm/yr and the tidal fresh marsh to 4 mm/yr, using SLAMM defaults in the absence of site-specific data. These values fall within the range of Pacific Northwest accretion measurements by (Thom 1992). These rates also fall near the average values of a comprehensive literature review of accretion rates (Cahoon et al. 1995).

Erosion rates. Erosion rates for the tidal flat were set to 0.2 m/yr, roughly based on a regional map of shoreline erosion (Keuler 1988). Erosion rates for marshes and swamps were set to SLAMM defaults of 2 m/yr and 1 m/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. The MTL to NAVD88 correction of -0.286 m was derived from Skamokawa gauge station that has this datum available and verified with other locations going upstream the river using NOAA VDATUM software..

Refuge boundaries. Modeled USFWS refuge boundaries for Oregon are based on Approved Acquisition Boundaries as published on the FWS National Wildlife Refuge Data and Metadata website. The cell-size used for this analysis was 30 m by 30 m cells.

Input subsites and parameter summary. Based on the spatial tidal differences (see Table 2), 4 different simulation input subsites were identified as illustrated in Figure 6. Table 3 summarizes all SLAMM input parameters for each subsite of the study area. Values for parameters with no specific local information were kept at their default value.

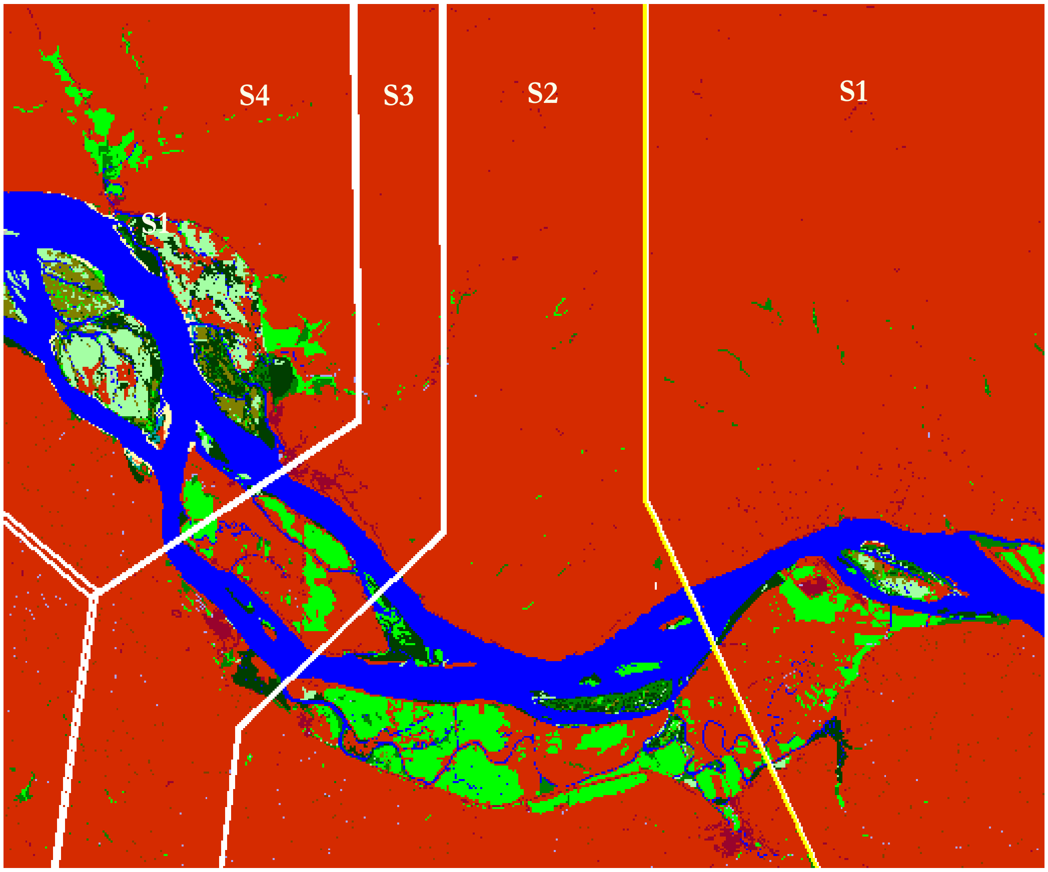


Figure 6. Input subsites for model application.

Table 3. Summary of SLAMM input parameters for Julia Butler Hansen NWR

Parameter	SubSite 1	SubSite 2	SubSite 3	SubSite 4
Description	Crims Island	Wallace Island	Puget Island	Tenasillahe Island
NWI Photo Date (YYYY)	1981	1981	1981	1981
DEM Date (YYYY)	2005	2005	2005	2005
Direction Offshore [n,s,e,w]	West	West	West	West
Historic Trend (mm/yr)	2	2	2	2
MTL-NAVD88 (m)	1.9228	1.7999	1.6601	1.578
GT Great Diurnal Tide Range (m)	1.73	1.94	2.15	2.31
Salt Elev. (m above MTL)	1.3	1.46	1.61	1.73
Marsh Erosion (horz. m /yr)	2	2	2	2
Swamp Erosion (horz. m /yr)	1	1	1	1
T.Flat Erosion (horz. m /yr)	0.2	0.2	0.2	0.2
Reg.-Flood Marsh Accr (mm/yr)	3.6	3.6	3.6	3.6
Irreg.-Flood Marsh Accr (mm/yr)	3.75	3.75	3.75	3.75
Tidal-Fresh Marsh Accr (mm/yr)	4	4	4	4
Inland-Fresh Marsh Accr (mm/yr)	4	4	4	4
Mangrove Accr (mm/yr)	7	7	7	7
Tidal Swamp Accr (mm/yr)	1.1	1.1	1.1	1.1
Swamp Accretion (mm/yr)	0.3	0.3	0.3	0.3
Beach Sed. Rate (mm/yr)	0.5	0.5	0.5	0.5
Freq. Overwash (years)	0	0	0	0
Use Elev Pre-processor [True,False]	FALSE	FALSE	FALSE	FALSE

Initial model calibration. Initially, SLAMM simulates a "time zero" step, in which the conceptual model validates the consistency between wetland information, elevation and tidal data. Due to local factors, DEM and NWI uncertainty, and simplifications within the SLAMM conceptual model, some cells inevitably 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. These threshold values are site specific and they can be calibrated by analyzing the elevation distribution statistics associated to each land cover category.

In this study, in order for the SLAMM model to initially reproduce a similar wetland land cover to the available wetland survey, the minimum elevations for some wetland categories were set to the values shown in Table 4. These adjustments to the conceptual model were necessary to prevent SLAMM from predicting immediate inundation of these areas and reflect local dynamic wetland regimes that in riverine environments. Within SLAMM, Tidal Swamp and Tidal Fresh Marsh lower-boundary elevations are assumed to be highly dependent on freshwater flow and therefore are generally set based on site-specific data.

Table 4. Modifications of SLAMM conceptual model

Wetland category	Minimum elevation (HTU)	Observed lowest 5 Pct. (HTU)
Tidal swamp	-0.54	-0.54
Tidal Fresh Marsh	-0.47	-0.47
Inland Fresh Marsh	1.0	-1.0

In the table above "HTU" refers to "half-tide units" with -1.0 reflecting MLLW, 0.0 reflecting MTL, and 1.0 reflecting MHHW.

The apparent inconsistency between the minimum elevation of the inland-fresh marsh and the observed lowest 5% is due to the fact that the minimum elevation for this wetland type was set based on elevations within the refuge only (excluding diked areas). The presence of inland fresh marsh at MLLW (-1.0 HTU) is almost certainly representative of data outside of the study area in which the marshes should either be classified as protected by dikes or should be classified as tidal marshes. No additional effort was put in calibrating the model outside the refuge.

Results

Table 5 summarizes the predicted loss of the major wetland categories by 2100 for each of the five SLR scenarios examined.

Table 5. Predicted loss rates of land categories by 2100 given simulated scenarios of eustatic SLR at Julia Butler Hansen 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
Tidal Fresh Marsh	2096	1%	1%	3%	11%	30%
Tidal Swamp	1449	3%	4%	10%	15%	49%
Undeveloped Dry Land	1161	18%	21%	23%	25%	41%
Swamp	781	84%	88%	91%	94%	95%
Transitional Salt Marsh	606	-54%([1])	21%	53%	63%	73%
Estuarine Open Water	331	-24%	-39%	-51%	-144%	-376%
Inland Fresh Marsh	315	22%	71%	80%	87%	91%
Tidal Flat([2])	7	-107	-267	-349	-567	-1376
Regularly Flooded Marsh([2])	1	-493	-971	-1190	-1045	-255
Irregularly Flooded Marsh([2])	0	-5	-17	-72	-60	-435

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

([2]) For this land cover category, the reported value is the absolute loss/gain in acres with respect to the initial coverage.

Depending on the SLR scenario considered, SLAMM simulations predict that approximately 8% to 44% of the refuge will be covered by open water or tidal flat by 2100 as compared to the 5% coverage of these categories currently observed.

All the dominant wetland categories in the refuge are predicted to sustain losses. Tidal fresh marsh and tidal swamp, which combined initially cover more than 50% of the refuge, are predicted to have similar loss trends. They appear to be resilient up to 1.5 m SLR scenario while losses rates increase significantly for the 2 m LSR scenario, 30% for the tidal fresh marsh and 49% for tidal swamp. The resilience of tidal fresh marsh is mostly due to the fact most that most of the refuge area covered by this wetland type is protected by the dike system that prevents inundation for all SLR scenarios.

On the contrary, predictions for swamp and inland fresh marsh show significant losses, up to more than 95% for the highest SLR scenario.

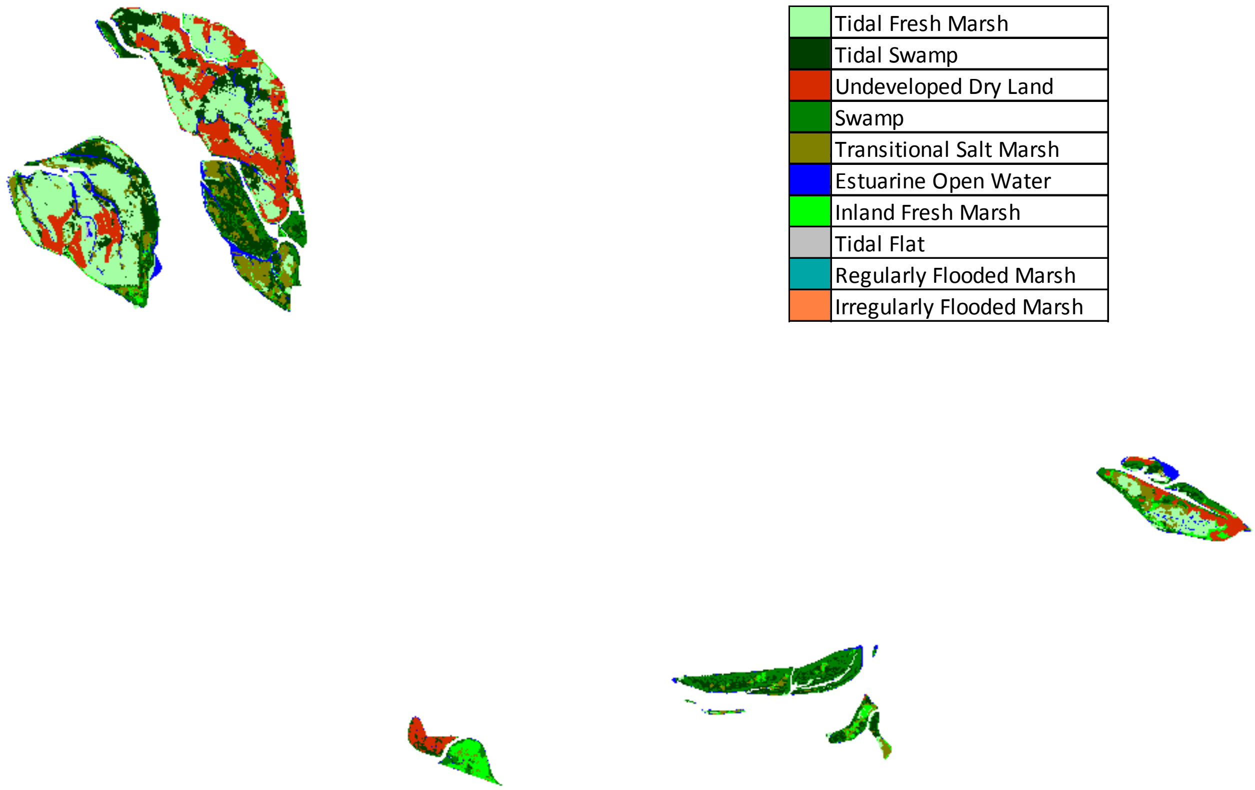
Transitional salt mash is also predicted to increasingly lose coverage, except for the lowest SLR scenario where approximately additional 300 acres are predicted to be added to this land cover category. However, this result may be due to the conversion of some areas in the refuge made initially by SLAMM because of an inconsistency between NWI wetland information, elevation and tide data. However, for higher SLR scenarios, the coverage of this area will be increasingly converted to other wetland categories.

Irregularly and regularly flooded marshes, today almost inexistent in the refuge, are predicted to make significant gains. Irregularly flooded marsh is predicted to increase coverage as sea level becomes higher, reaching a maximum of 435 acres for the 2 m SLR by 2100 scenario. Similarly, the area covered by regular flooded marsh is predicted to significantly increase for SLR scenarios up to 1 m SLR by 2100 where the total coverage is predicted to be approximately 1200 acres. For higher SLR scenarios, gains are predicted to be more modest as increasing land is predicted to be converted to tidal flat rather than marsh.

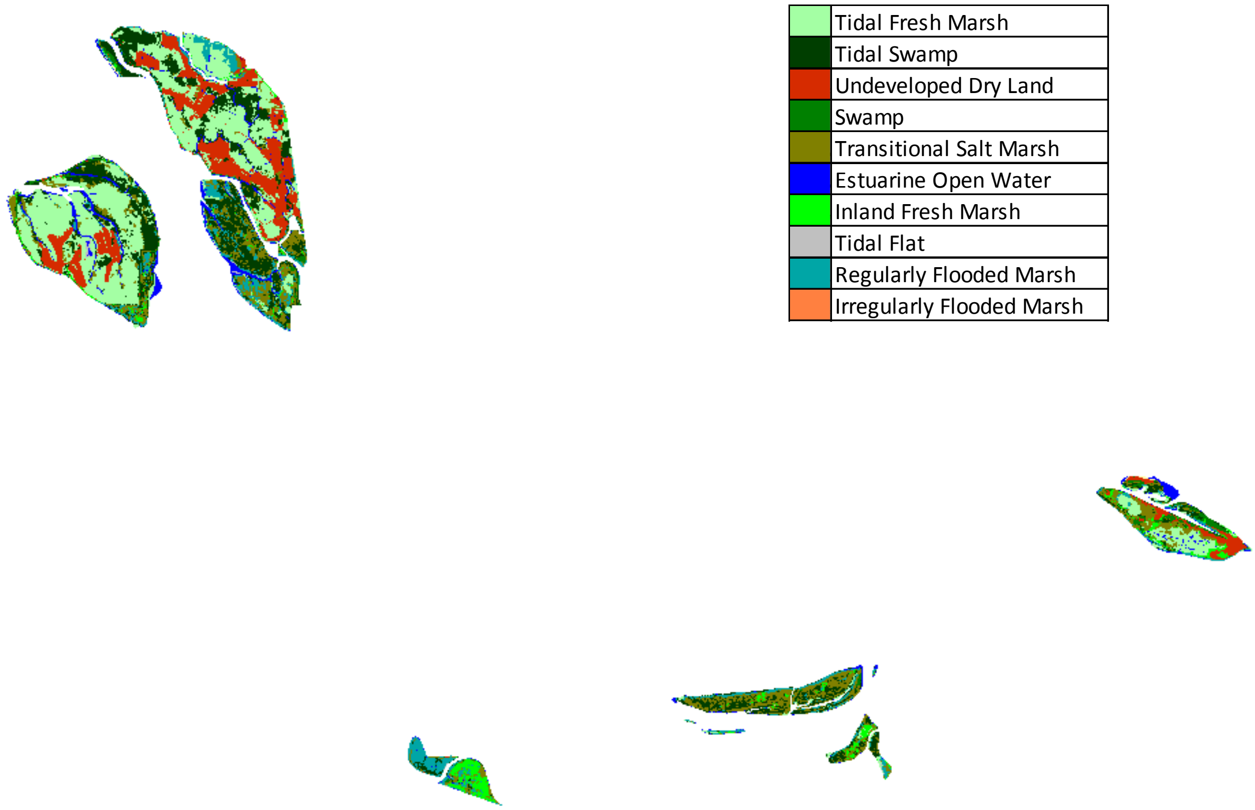
Julia Butler Hansen NWR
IPCC Scenario A1B-Mean, 0.39 m SLR eustatic by 2100

Results in Acres

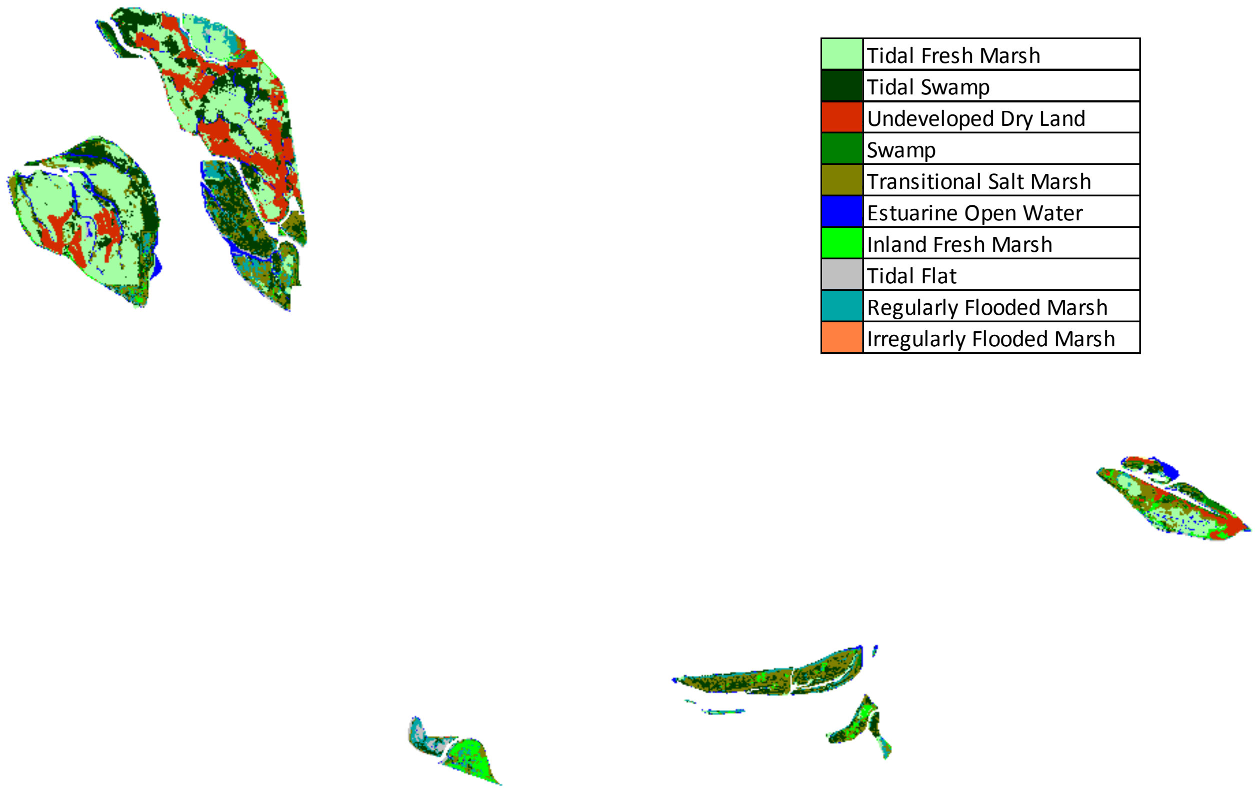
		Initial	2025	2050	2075	2100
	Tidal Fresh Marsh	2096	2084	2084	2084	2084
	Tidal Swamp	1449	1421	1417	1413	1407
	Undeveloped Dry Land	1161	966	961	956	949
	Swamp	781	153	143	133	124
	Transitional Salt Marsh	606	933	943	945	931
	Estuarine Open Water	331	344	351	382	411
	Inland Fresh Marsh	315	249	248	246	245
	Developed Dry Land	12	5	5	5	5
	Riverine Tidal	12	3	2	2	2
	Estuarine Beach	10	10	10	10	10
	Tidal Flat	7	27	147	127	114
	Regularly Flooded Marsh	1	585	465	475	494
	Irregularly Flooded Marsh	0	1	4	3	5
	Total (incl. water)	**6781**	**6781**	**6781**	**6781**	**6781**



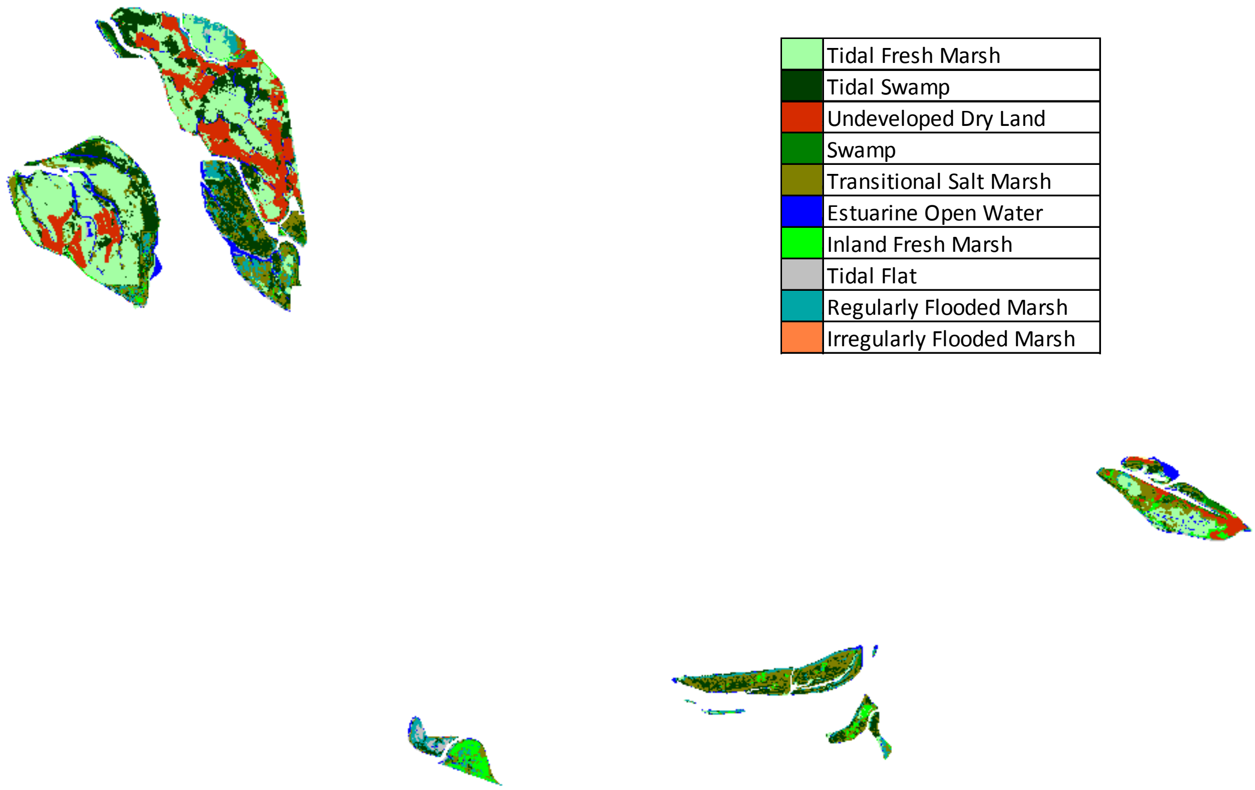
Julia Butler Hansen NWR, Initial Condition



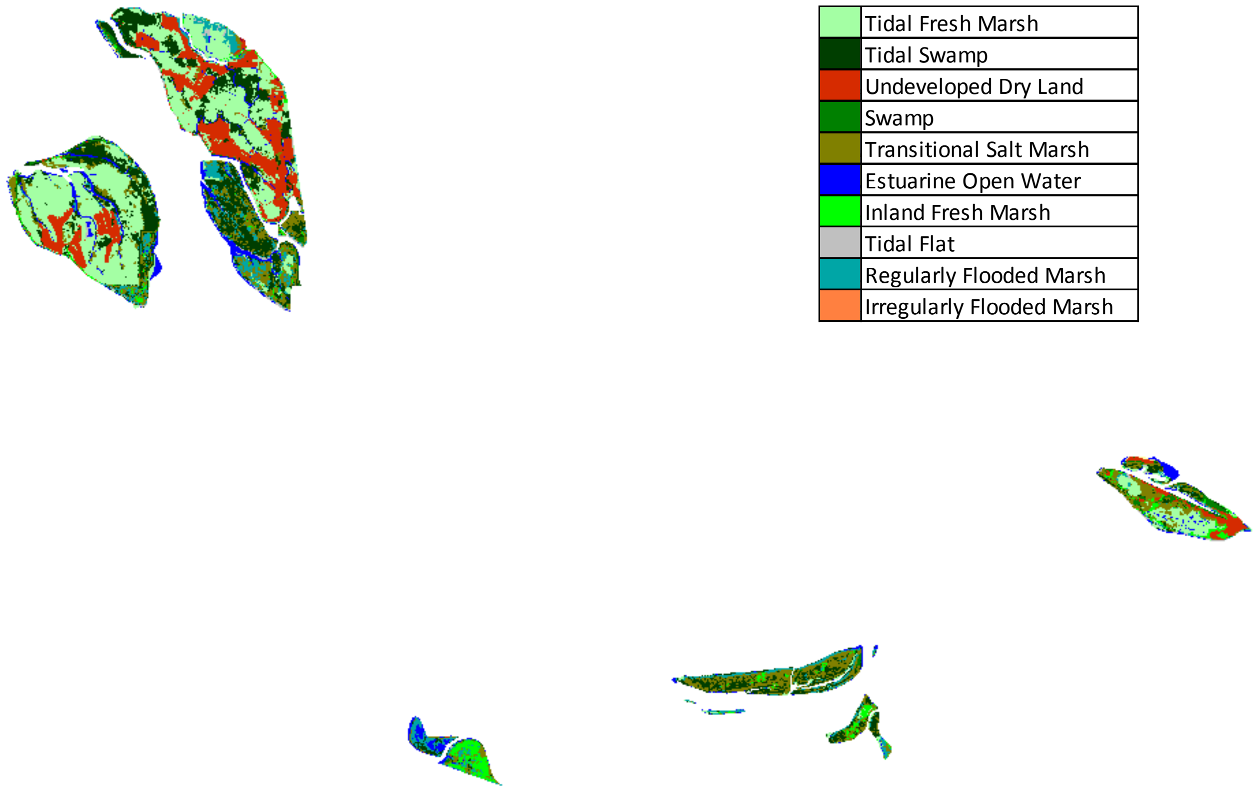
Julia Butler Hansen NWR, 2025, Scenario A1B Mean, 0.39 m SLR



Julia Butler Hansen NWR, 2050, Scenario A1B Mean, 0.39 m SLR



Julia Butler Hansen NWR, 2075, Scenario A1B Mean, 0.39 m SLR

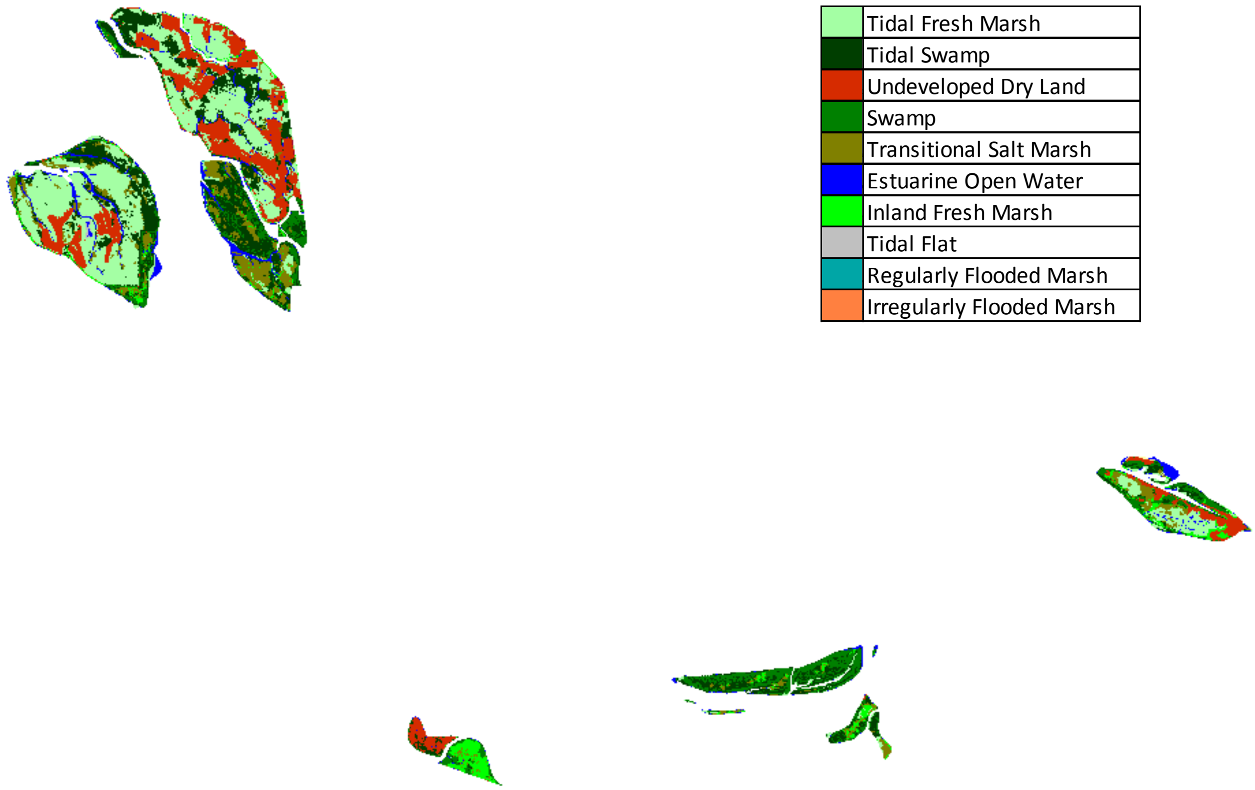


Julia Butler Hansen NWR, 2100, Scenario A1B Mean, 0.39 m SLR

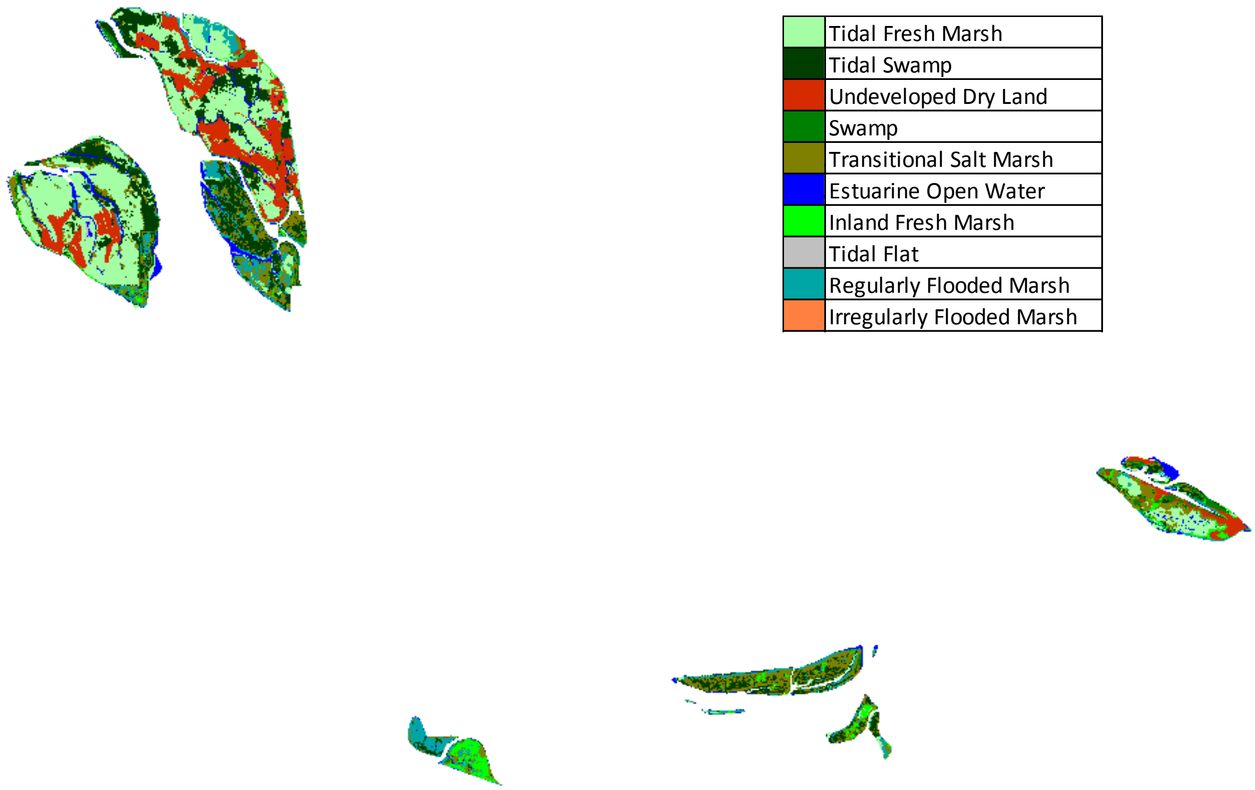
Julia Butler Hansen NWR
IPCC Scenario A1B-Max, 0.69 m SLR eustatic by 2100

Results in Acres

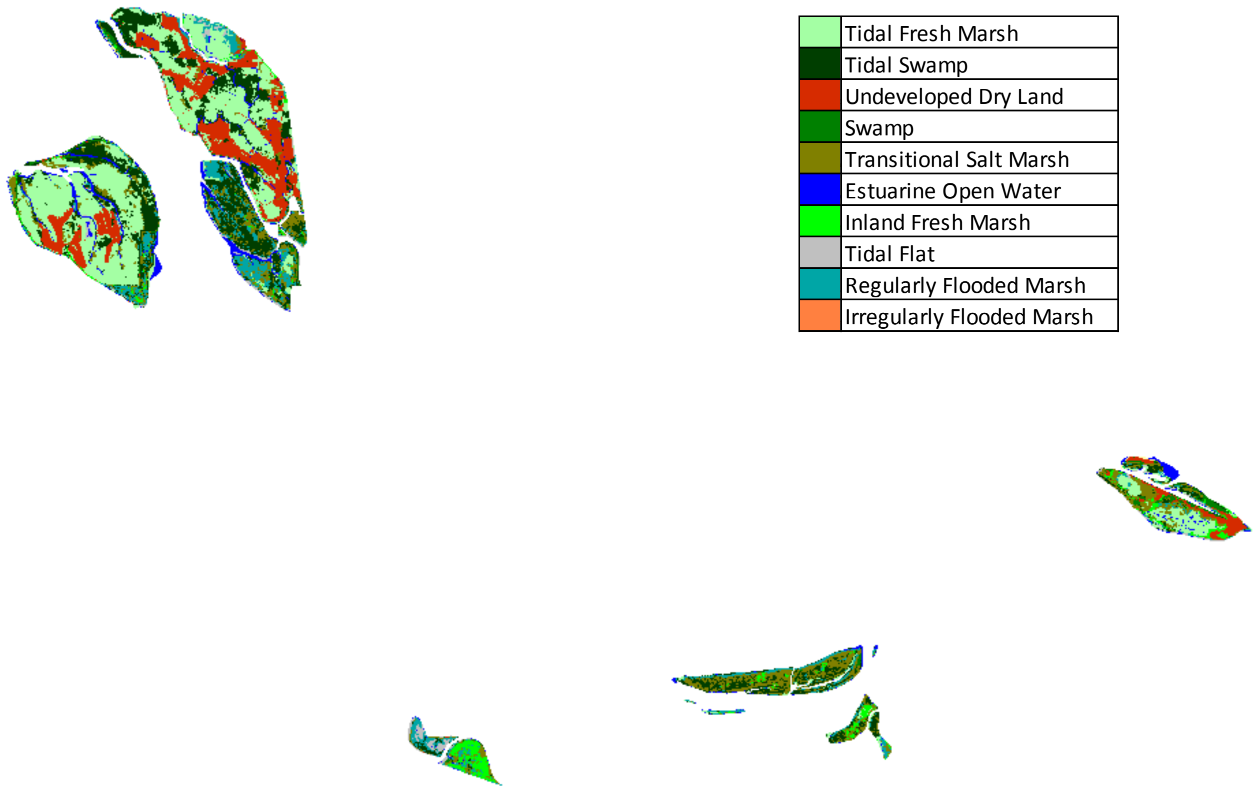
		Initial	2025	2050	2075	2100
	Tidal Fresh Marsh	2096	2083	2081	2077	2072
	Tidal Swamp	1449	1418	1412	1402	1386
	Undeveloped Dry Land	1161	963	956	937	920
	Swamp	781	147	132	116	97
	Transitional Salt Marsh	606	898	823	520	479
	Estuarine Open Water	331	345	356	427	459
	Inland Fresh Marsh	315	245	238	214	92
	Developed Dry Land	12	5	5	5	4
	Riverine Tidal	12	3	2	2	1
	Estuarine Beach	10	10	10	10	10
	Tidal Flat	7	29	199	228	274
	Regularly Flooded Marsh	1	632	561	834	972
	Irregularly Flooded Marsh	0	3	8	9	17
	Total (incl. water)	**6781**	**6781**	**6781**	**6781**	**6781**



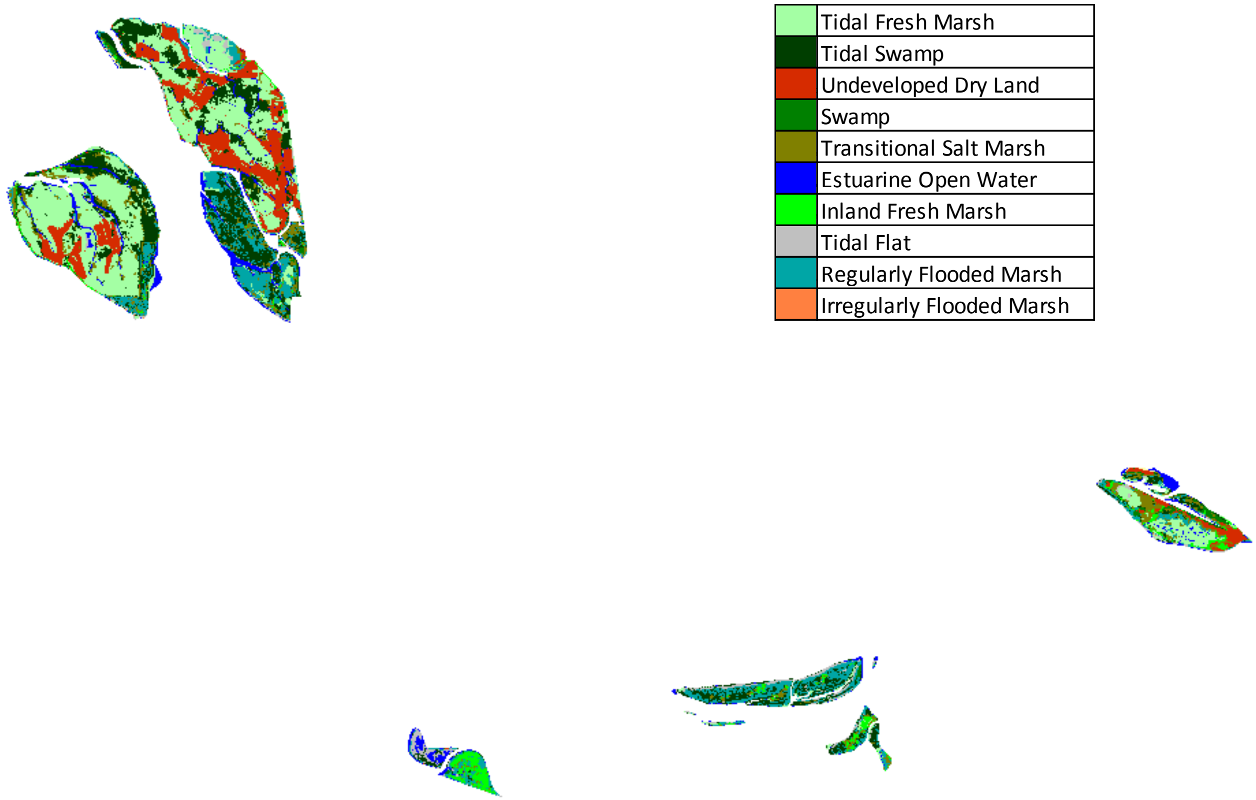
Julia Butler Hansen NWR, Initial Condition



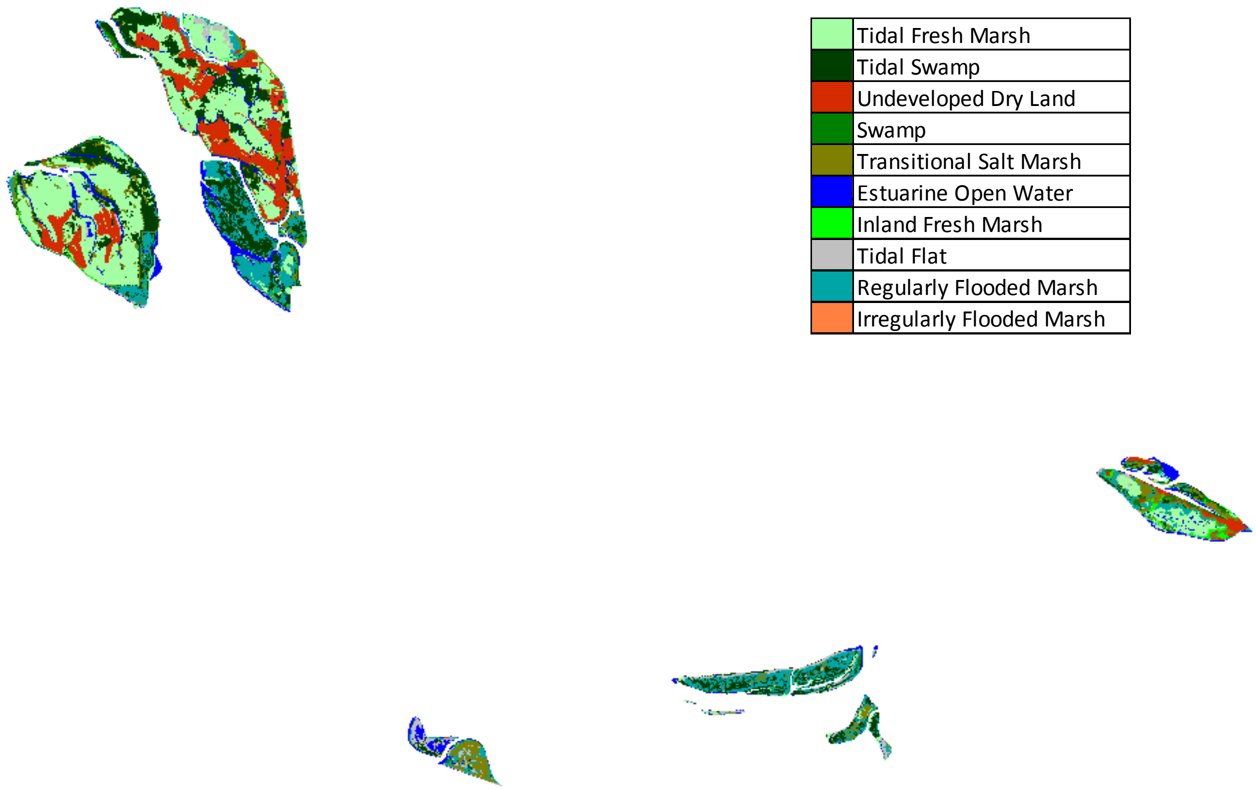
Julia Butler Hansen NWR, 2025, Scenario A1B Maximum, 0.69 m SLR



Julia Butler Hansen NWR, 2050, Scenario A1B Maximum, 0.69 m SLR



Julia Butler Hansen NWR, 2075, Scenario A1B Maximum, 0.69 m SLR

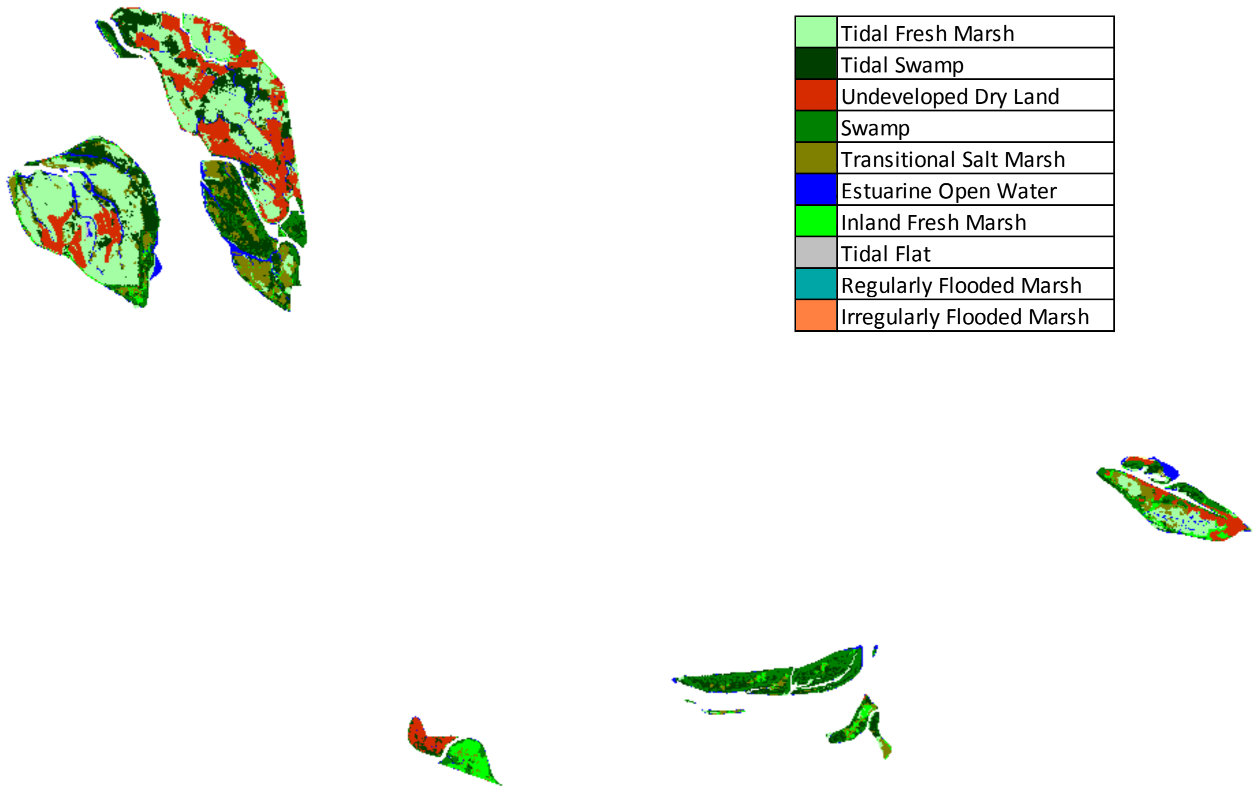


Julia Butler Hansen NWR, 2100, Scenario A1B Maximum, 0.69 m SLR

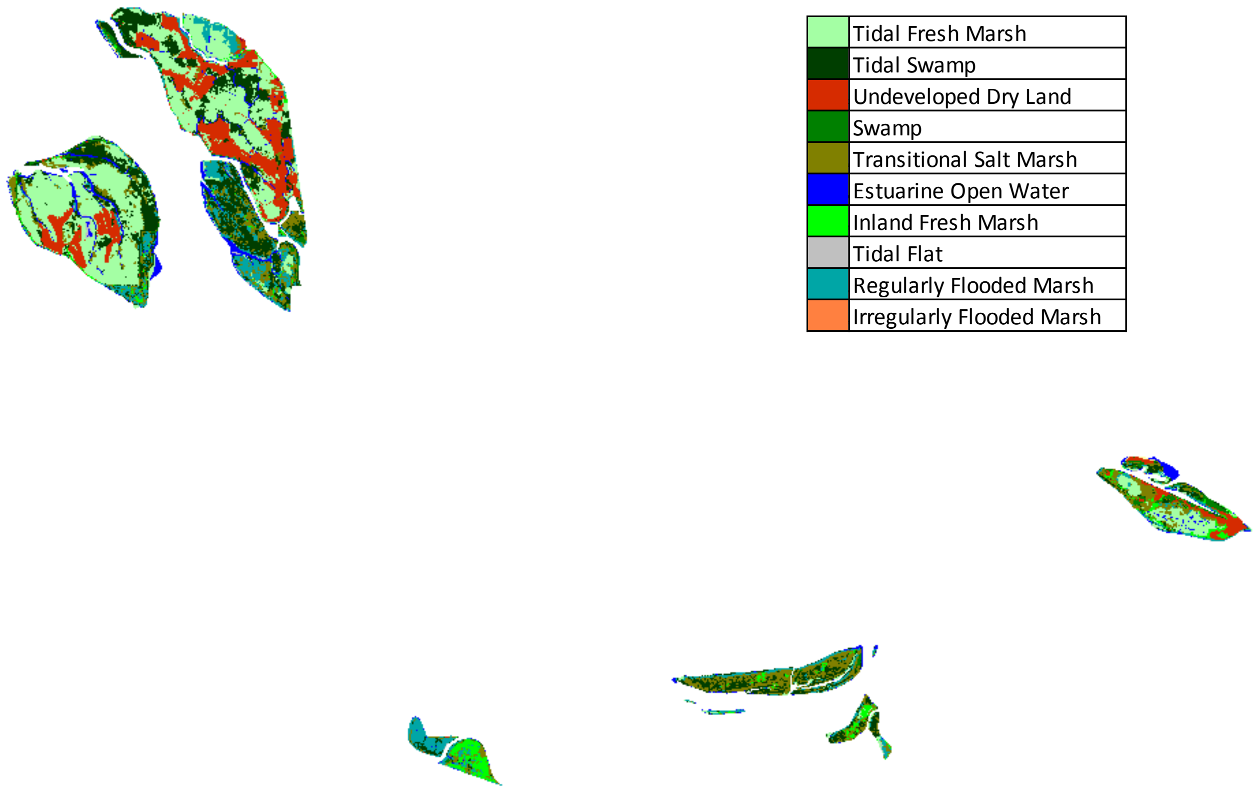
Julia Butler Hansen NWR
1 m eustatic SLR by 2100

Results in Acres

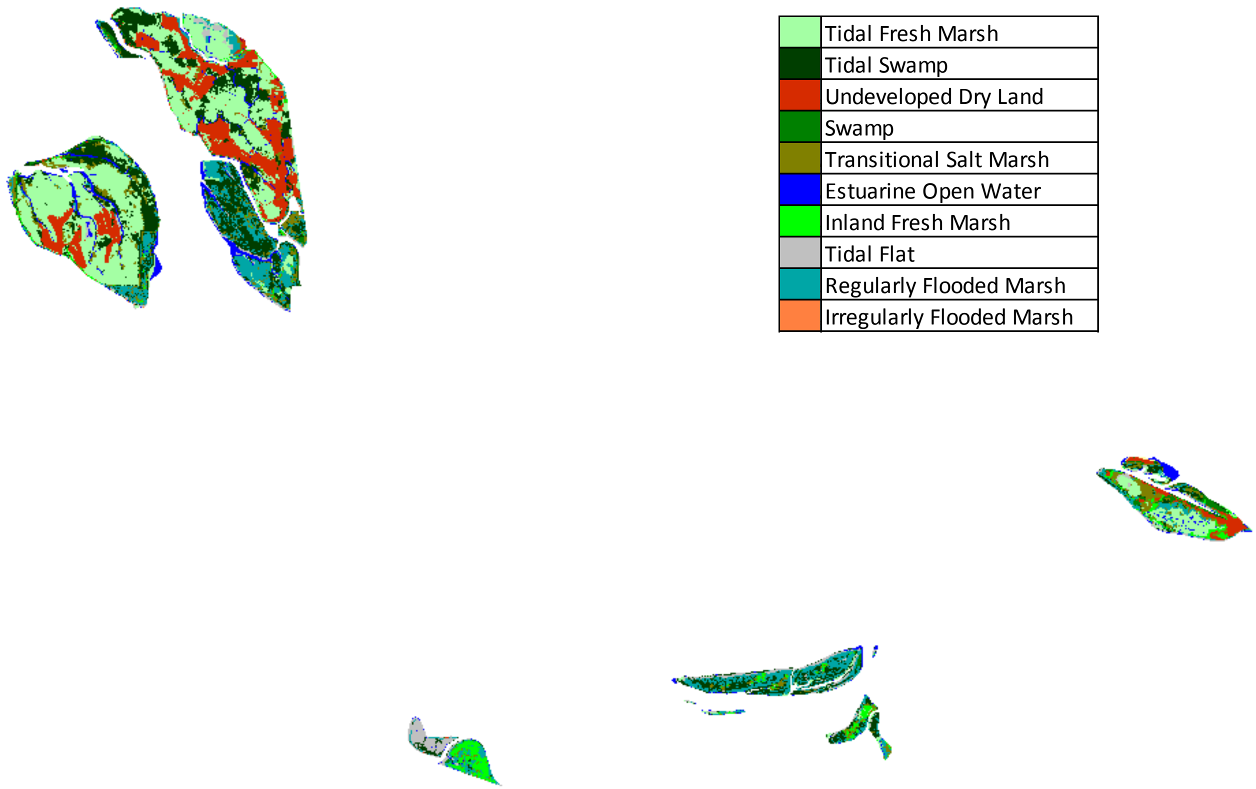
		Initial	2025	2050	2075	2100
	Tidal Fresh Marsh	2096	2081	2076	2066	2028
	Tidal Swamp	1449	1415	1405	1383	1310
	Undeveloped Dry Land	1161	961	944	920	897
	Swamp	781	142	123	96	67
	Transitional Salt Marsh	606	830	495	437	284
	Estuarine Open Water	331	346	361	455	501
	Inland Fresh Marsh	315	239	210	76	63
	Developed Dry Land	12	5	5	4	3
	Riverine Tidal	12	2	2	1	1
	Estuarine Beach	10	10	10	10	7
	Tidal Flat	7	33	298	304	356
	Regularly Flooded Marsh	1	712	842	1006	1191
	Irregularly Flooded Marsh	0	4	11	23	72
	Total (incl. water)	**6781**	**6781**	**6781**	**6781**	**6781**



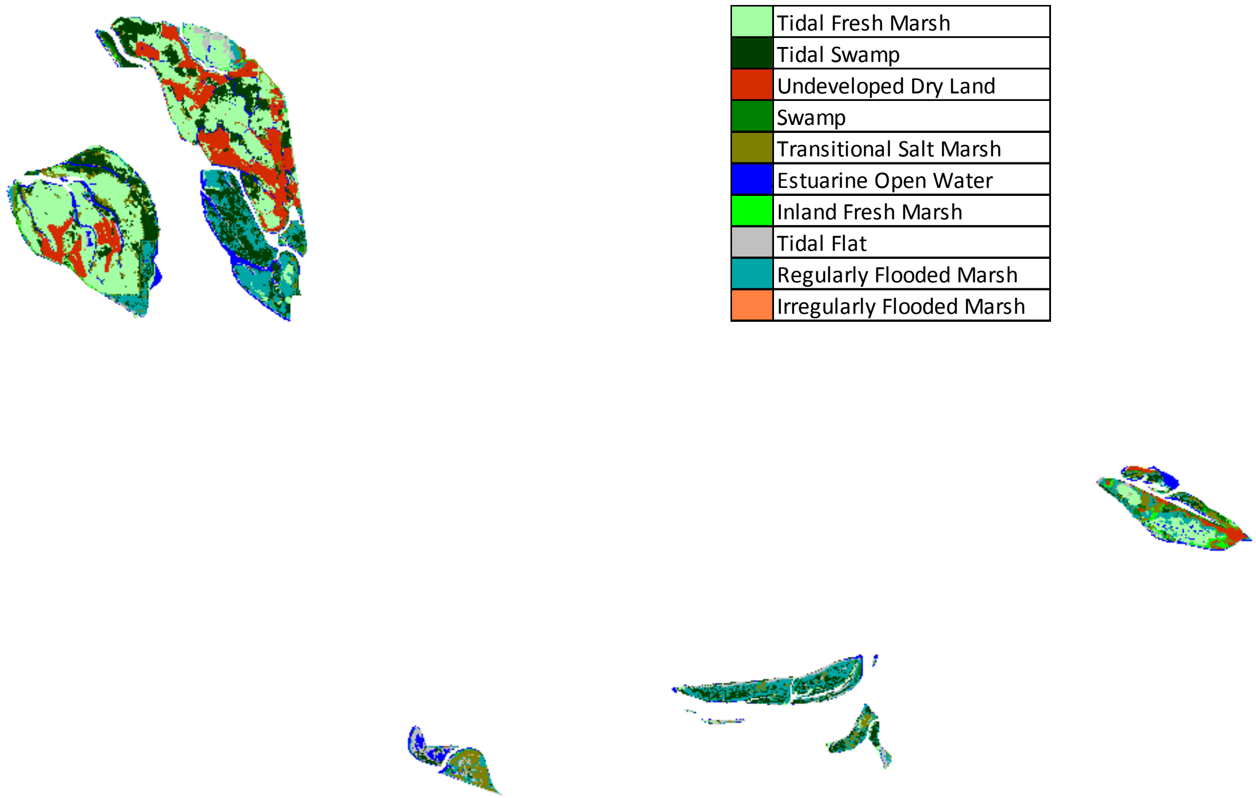
Julia Butler Hansen NWR, Initial Condition



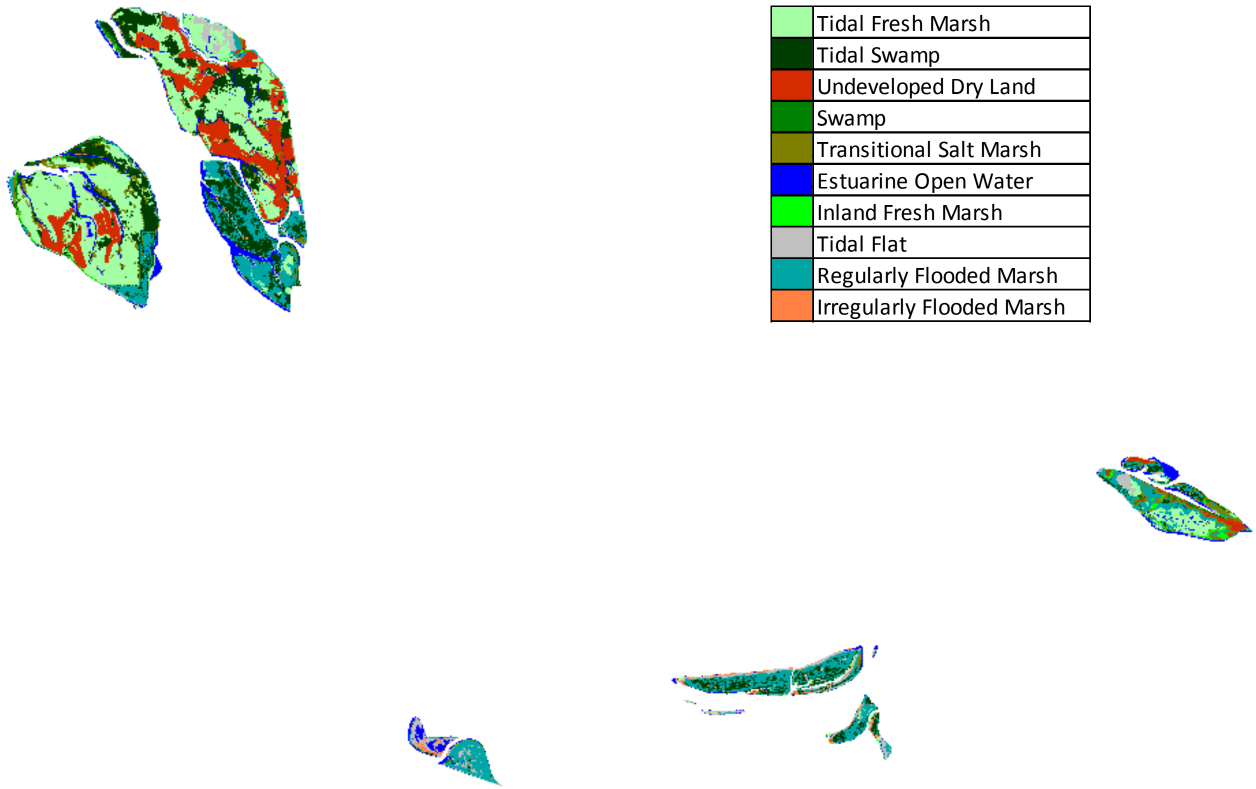
Julia Butler Hansen NWR, 2025, 1 m SLR



Julia Butler Hansen NWR, 2050, 1 m SLR



Julia Butler Hansen NWR, 2075, 1 m SLR

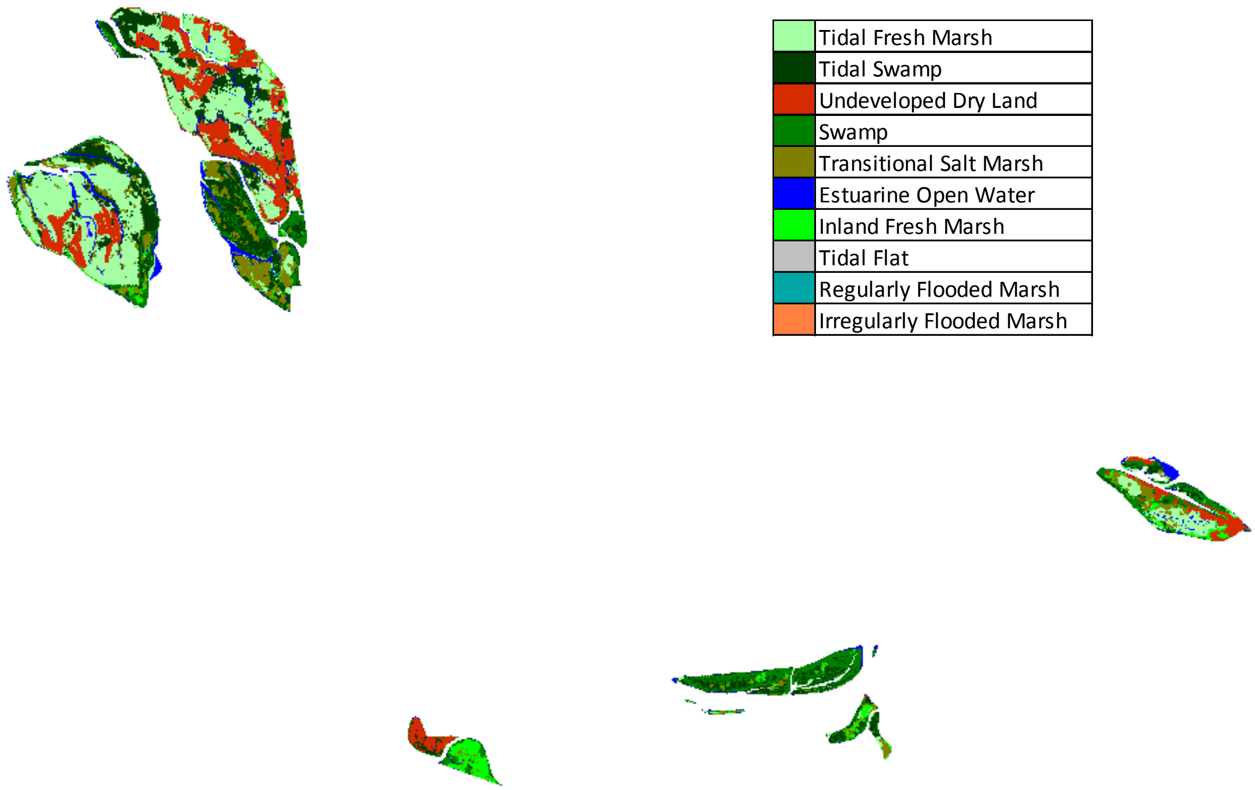


Julia Butler Hansen NWR, 2100, 1 m SLR

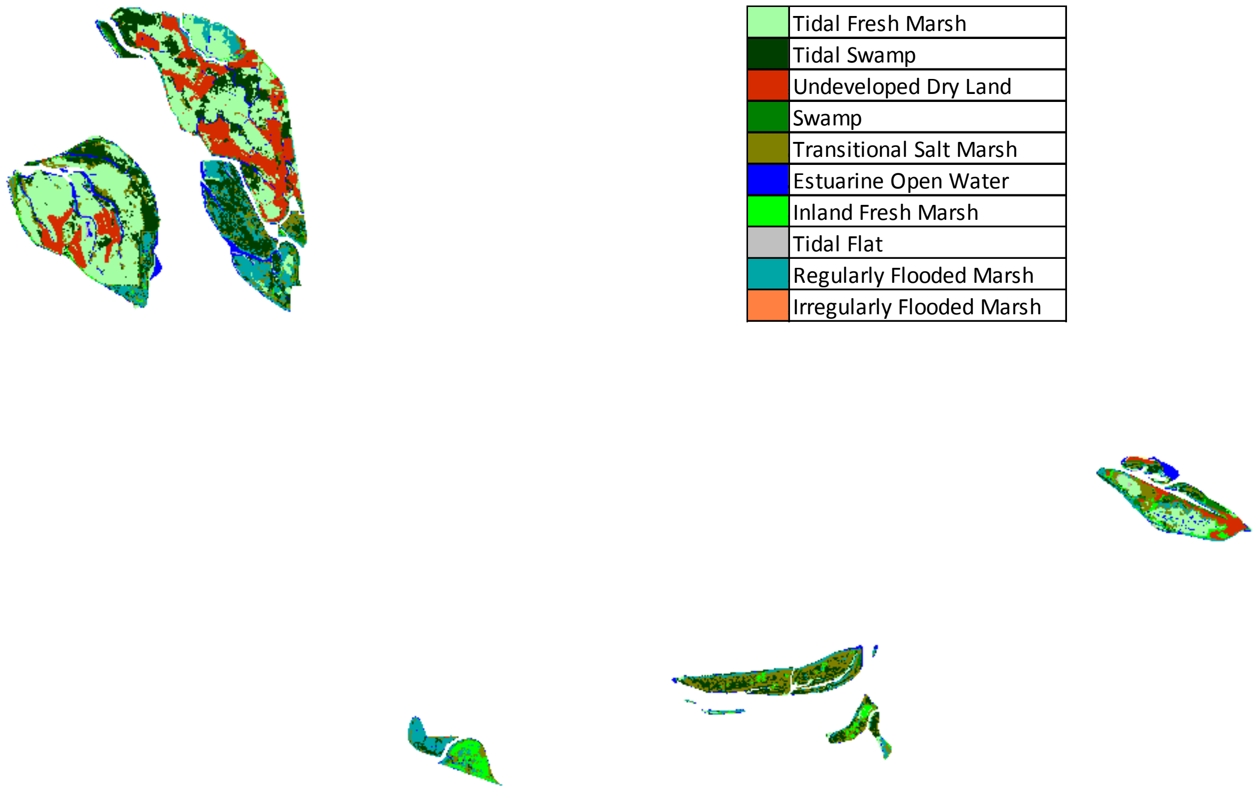
Julia Butler Hansen NWR
1.5 m eustatic SLR by
2100

Results in Acres

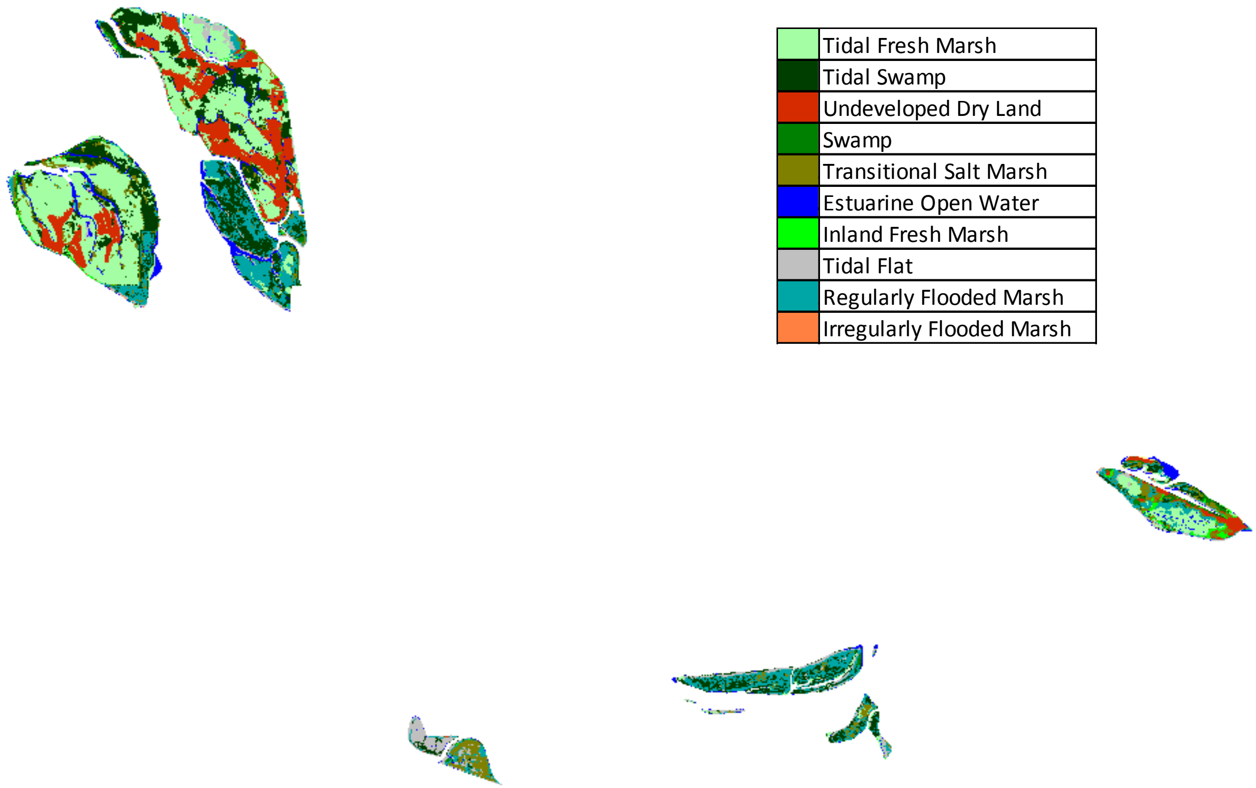
		Initial	2025	2050	2075	2100
	Tidal Fresh Marsh	2096	2077	2066	1996	1875
	Tidal Swamp	1449	1411	1391	1303	1233
	Undeveloped Dry Land	1161	957	927	894	865
	Swamp	781	133	104	65	48
	Transitional Salt Marsh	606	689	435	269	223
	Estuarine Open Water	331	348	370	504	808
	Inland Fresh Marsh	315	222	76	58	40
	Developed Dry Land	12	5	4	3	3
	Riverine Tidal	12	2	1	1	1
	Estuarine Beach	10	10	10	7	5
	Tidal Flat	7	42	388	403	573
	Regularly Flooded Marsh	1	878	989	1191	1046
	Irregularly Flooded Marsh	0	7	21	88	60
	Total (incl. water)	**6781**	**6781**	**6781**	**6781**	**6781**



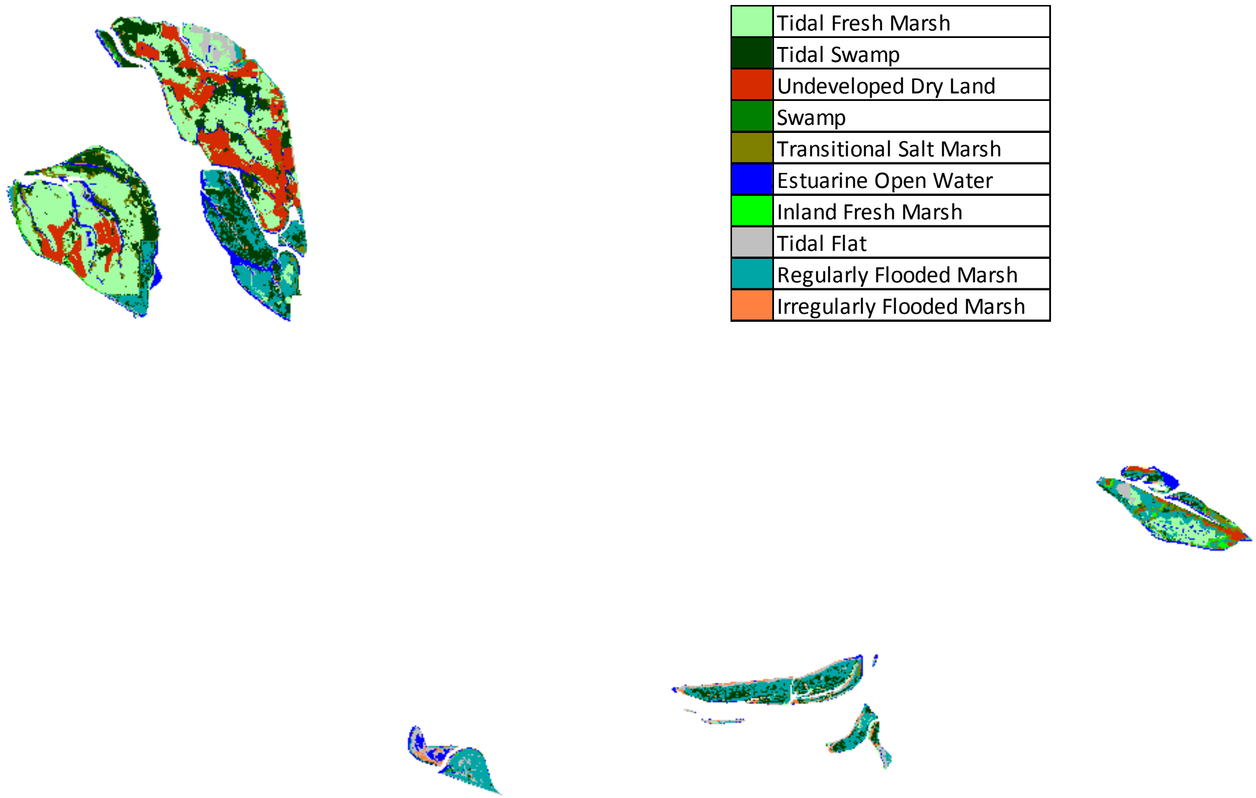
Julia Butler Hansen NWR, Initial Condition



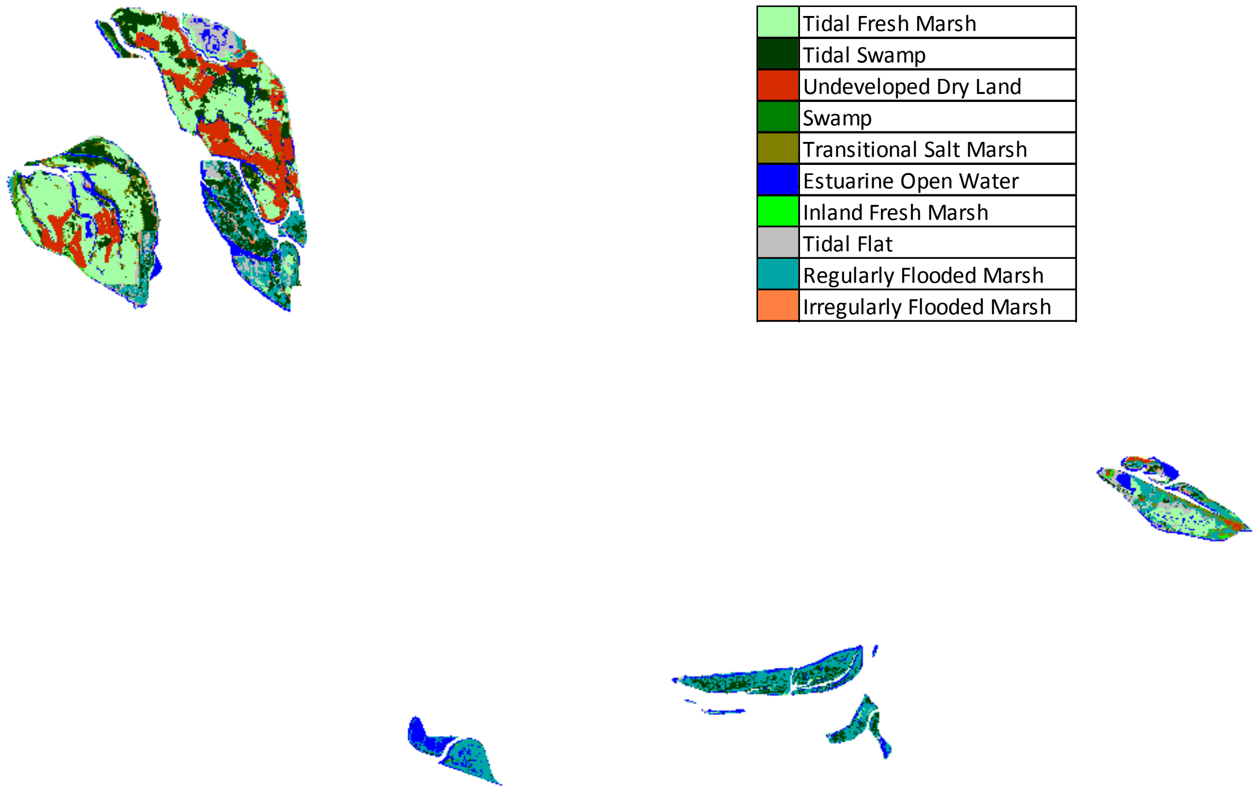
Julia Butler Hansen NWR, 2025, 1.5 m SLR



Julia Butler Hansen NWR, 2050, 1.5 m SLR



Julia Butler Hansen NWR, 2075, 1.5 m SLR

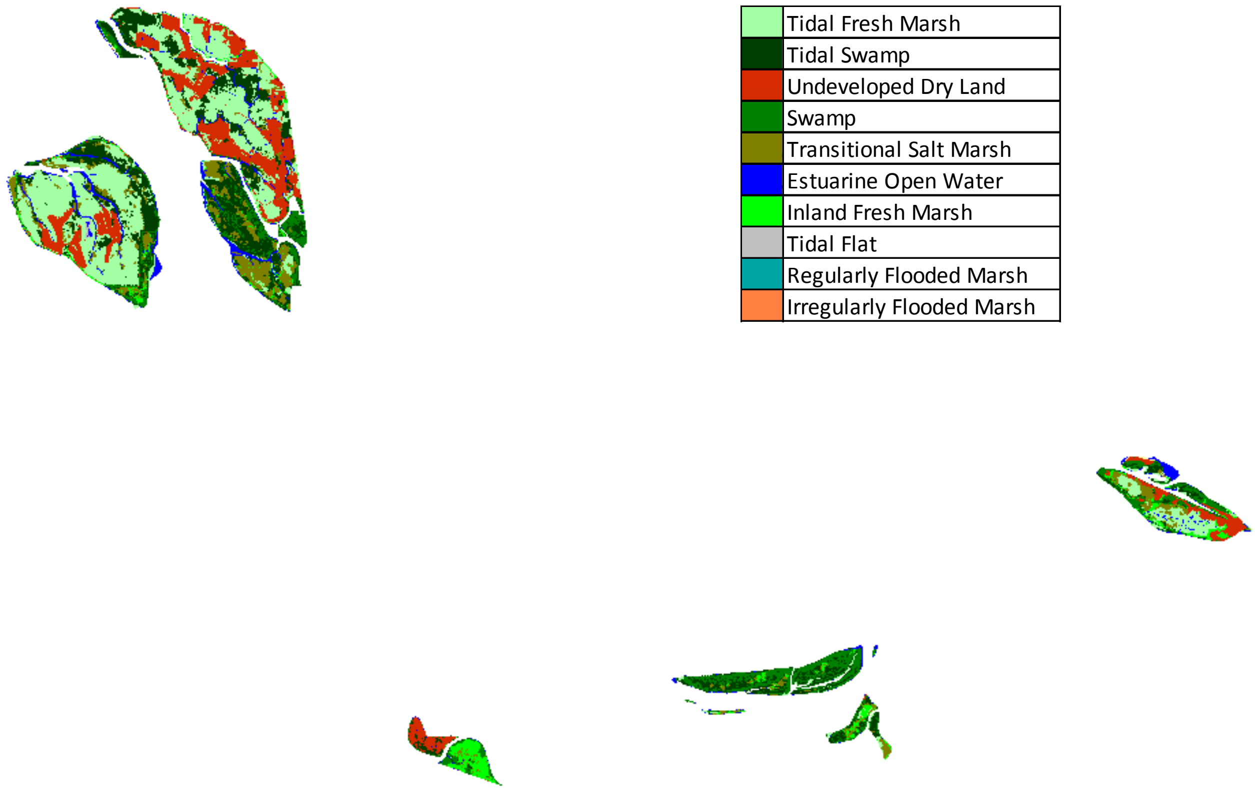


Julia Butler Hansen NWR, 2100, 1.5 m SLR

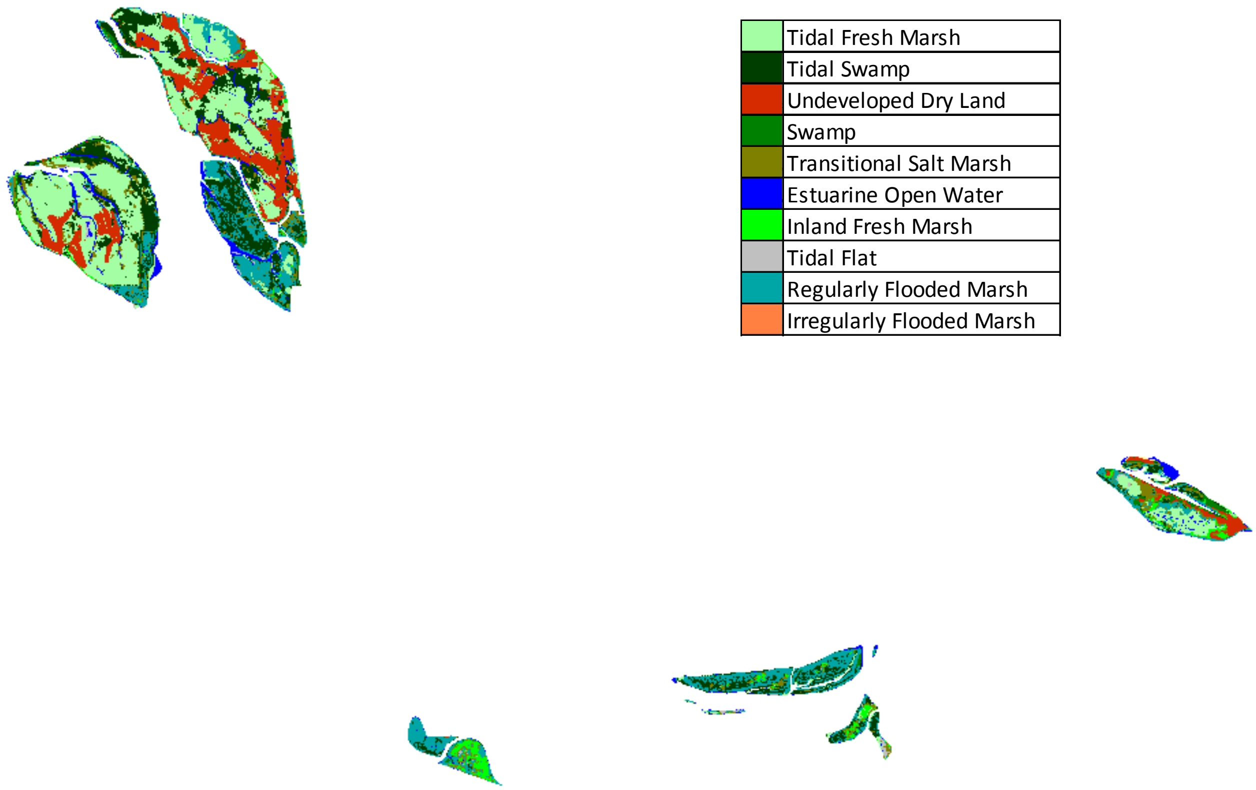
Julia Butler Hansen NWR
2 m eustatic SLR by 2100

Results in Acres

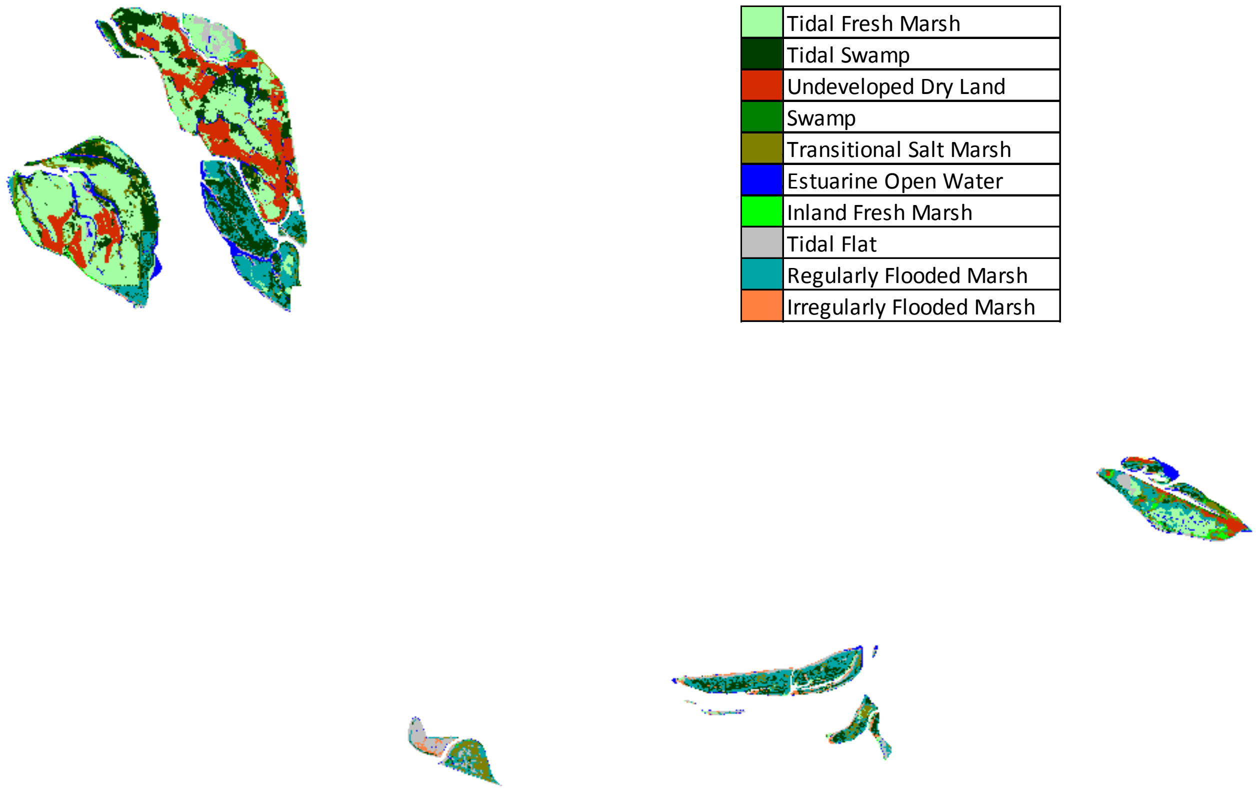
		Initial	2025	2050	2075	2100
	Tidal Fresh Marsh	2096	2074	2028	1882	1468
	Tidal Swamp	1449	1406	1333	1251	737
	Undeveloped Dry Land	1161	948	912	871	690
	Swamp	781	126	83	51	37
	Transitional Salt Marsh	606	437	386	240	164
	Estuarine Open Water	331	351	379	732	1575
	Inland Fresh Marsh	315	189	65	41	29
	Developed Dry Land	12	5	3	3	3
	Riverine Tidal	12	2	1	1	0
	Estuarine Beach	10	10	9	6	5
	Tidal Flat	7	53	457	576	1383
	Regularly Flooded Marsh	1	1170	1051	1050	256
	Irregularly Flooded Marsh	0	10	74	77	435
	Total (incl. water)	**6781**	**6781**	**6781**	**6781**	**6781**



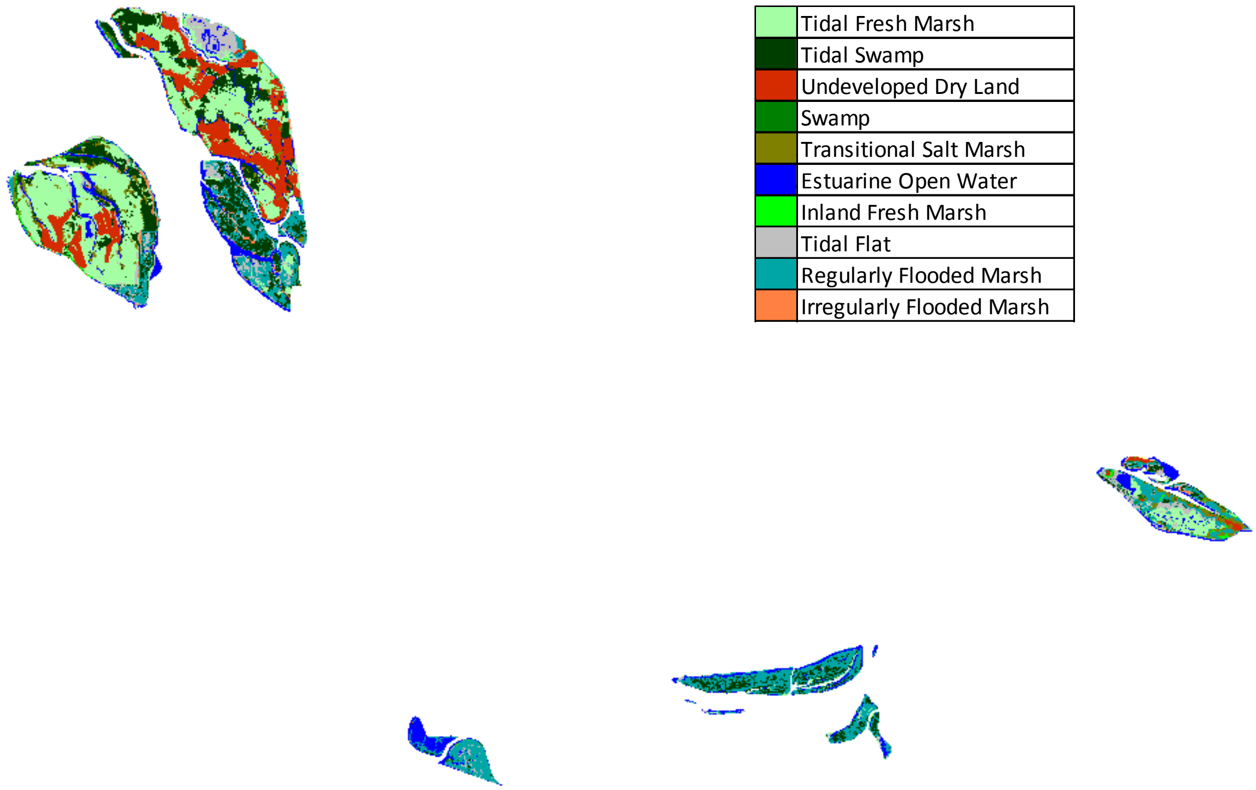
Julia Butler Hansen NWR, Initial Condition



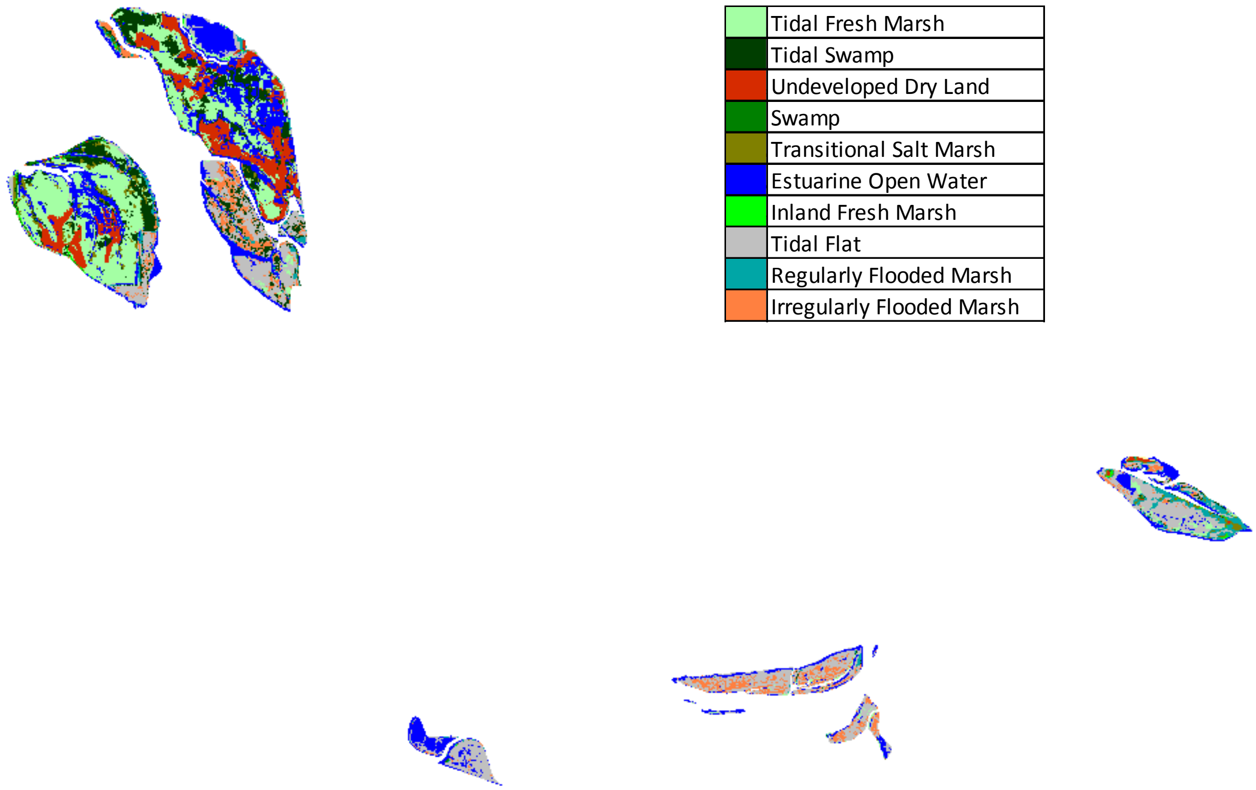
Julia Butler Hansen NWR, 2025, 2 m SLR



Julia Butler Hansen NWR, 2050, 2 m SLR



Julia Butler Hansen NWR, 2075, 2 m SLR



Julia Butler Hansen NWR, 2100, 2 m SLR

Discussion

Model results for Julia Butler Hansen NWR indicate wetlands in the refuge are sensitive to SLR.

A significant part of the refuge is protected by dikes. SLAMM assumes that the dike system is maintained as sea level continues to rise (up to two meters). Therefore all the wetlands within these areas are not predicted to change across any of the SLR scenarios simulated. As a consequence, tidal-fresh marsh and tidal swamp are predicted to be relatively resilient with respect to sea level rise. For the remaining land covered by these wetland types, there seems to be a threshold between 1.5 m and 2 m SLR by 2100 where predictions show a significant increase in loss of these wetlands.

Swamp, transitional salt marsh and inland fresh marsh are predicted to be greatly affected and increasingly converted to other land cover categories as sea level continues to rise. In particular, open water is predicted to gradually inundate areas of the refuge and tidal flats are predicted to be formed. In addition, irregularly and regularly-flooded marsh are also predicted to appear and expand their coverage. At higher sea level-rise scenarios, however, areas with regularly flooded marsh are predicted to eventually be converted to open water or tidal flat.

Several sources of uncertainty are associated with these results. First, the "historic sea level trend" parameter is used to estimate the amount of uplift or subsidence occurring within a site. The Astoria NOAA gauge, the closest gauge to the Julia Butler Hansen NWR, indicates significant uplift. However, the uplift observed at this gauge is likely to be extremely localized and may not be representative of the overall SLR trend in the refuge. Therefore, the rate applied in this model application was 2 mm/yr. The potential for localized uplift zones therefore adds some uncertainty to the results.

Additional sources of uncertainty are the input parameters for accretion rates. Accretion data were taken from the available literature and applied on the entire study area. However, more specific measurements of accretion rates within the refuge could provide better predictions of marsh losses in the future.

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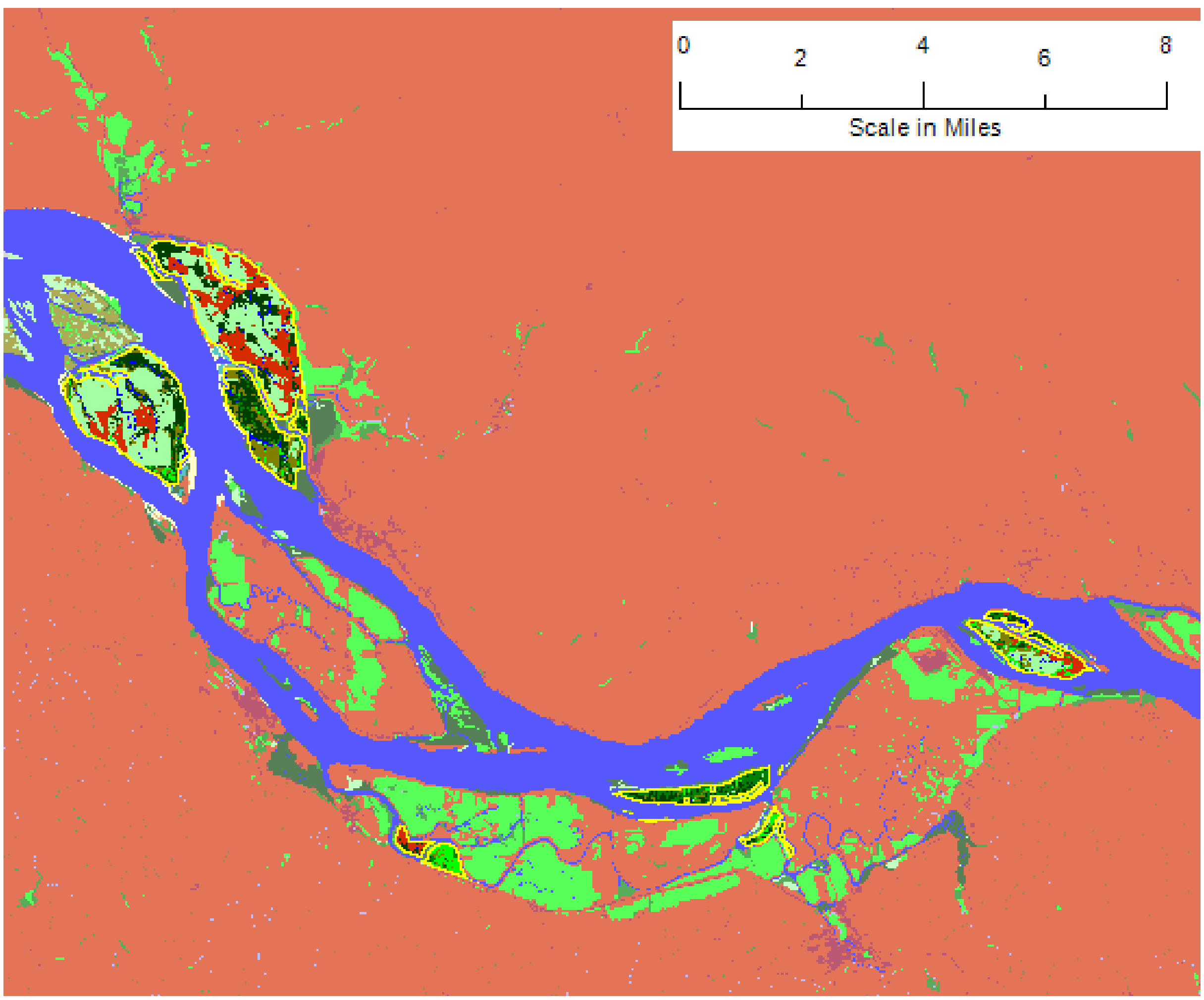
Appendix A: Contextual Results

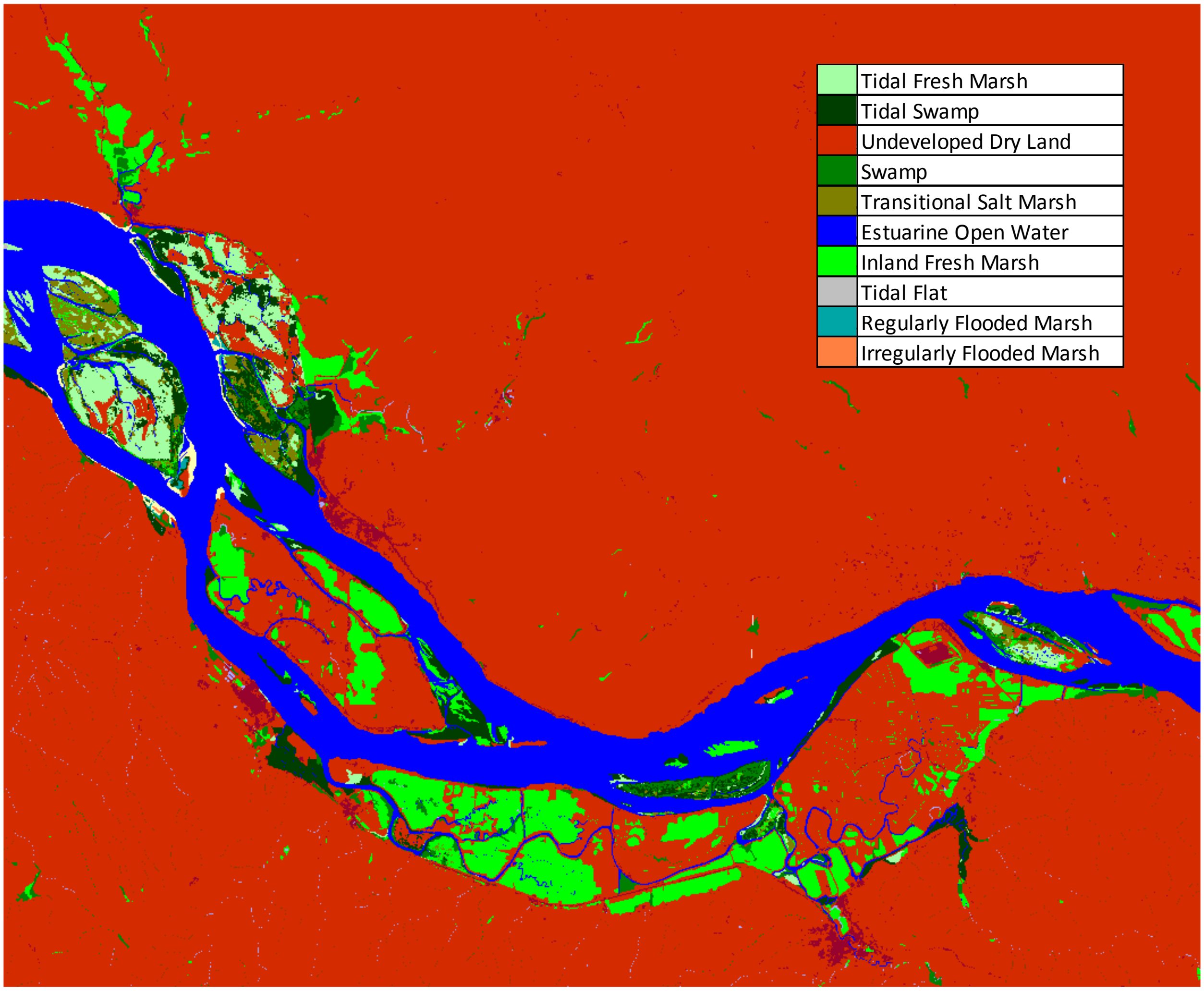
The SLAMM model does take into account the context of the surrounding lands or open water when calculating effects. For example, erosion rates are calculated based on the maximum fetch (wave action) which is estimated by assessing contiguous open water to a given marsh cell. Another example is that inundated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

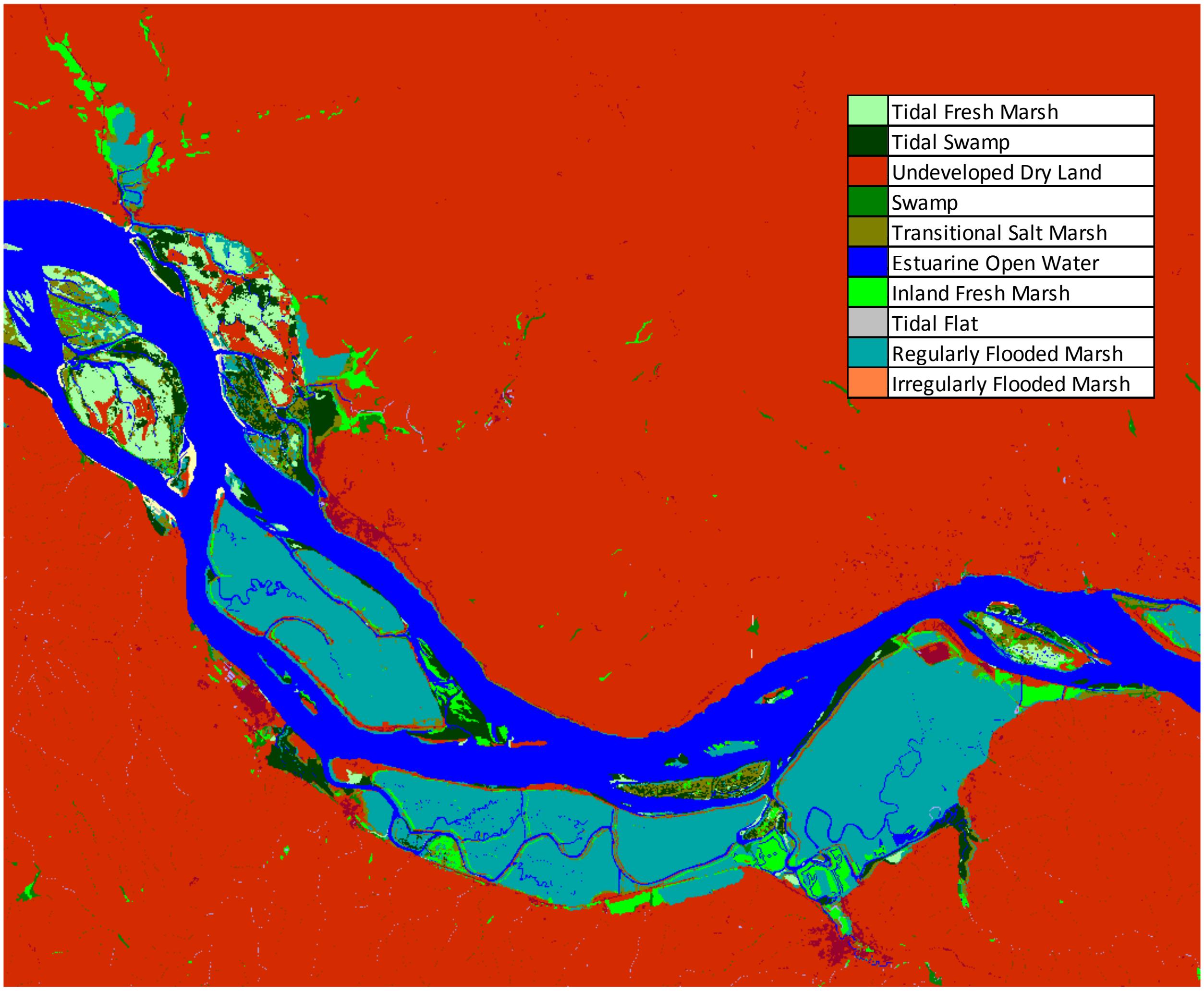
- Results were closely examined (quality assurance) within USFWS refuges but not closely examined for the larger region.
- Site-specific parameters for the model were derived for USFWS refuges whenever possible and may not be regionally applicable.
- Especially in areas where dikes are present, an effort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



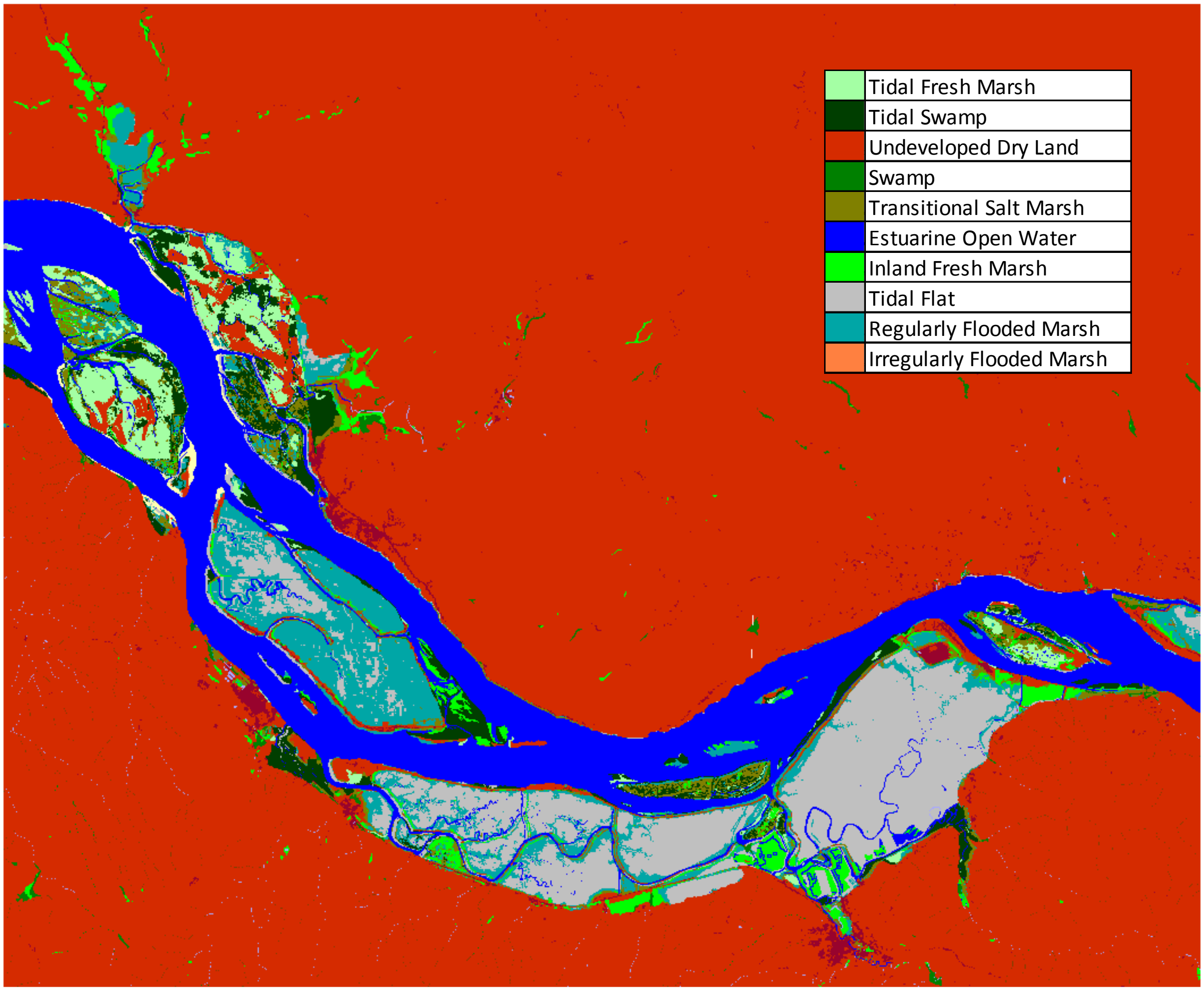
Julia Butler Hansen National Wildlife Refuges within simulation context (yellow).



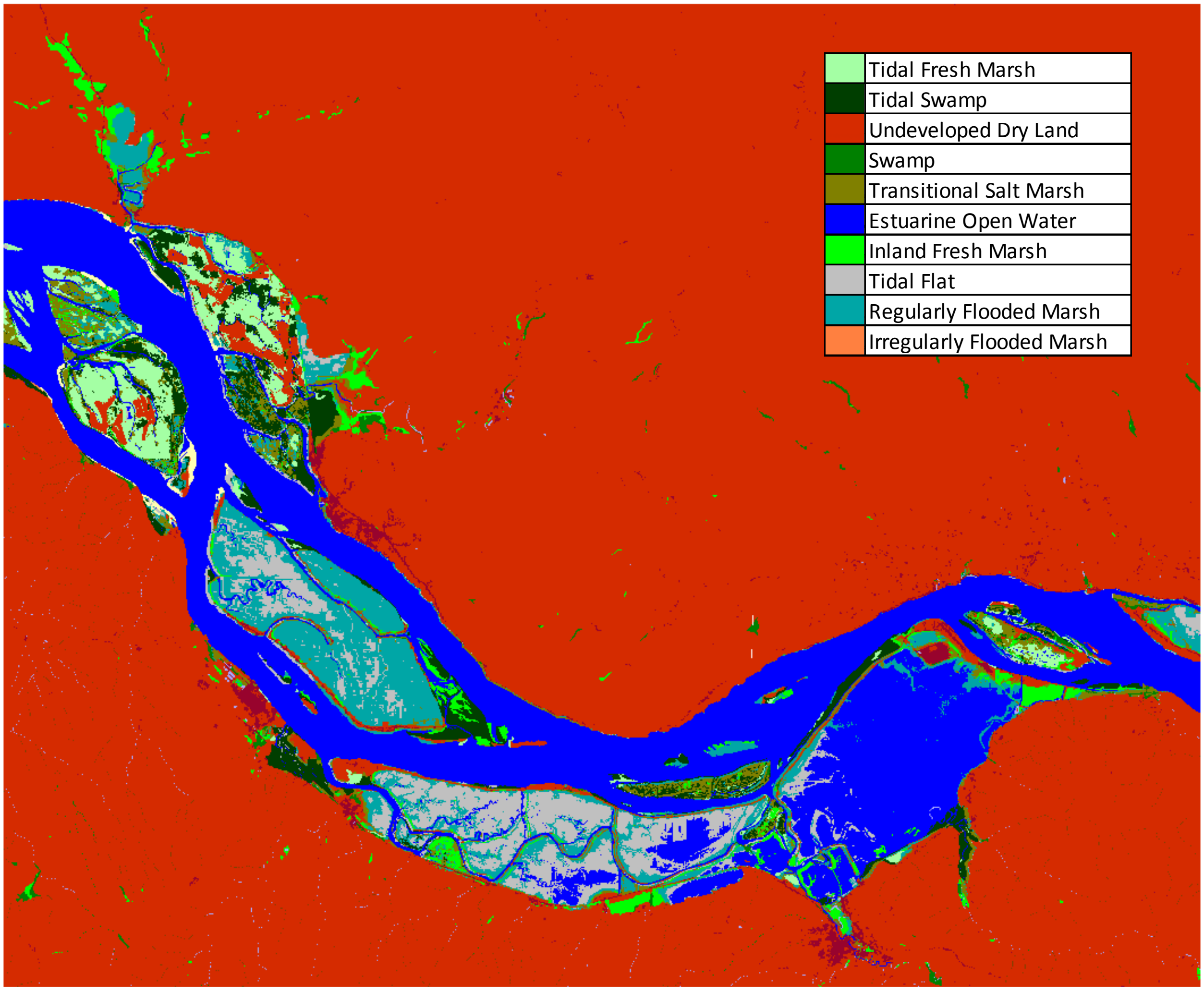
Julia Butler Hansen NWR, Initial Condition



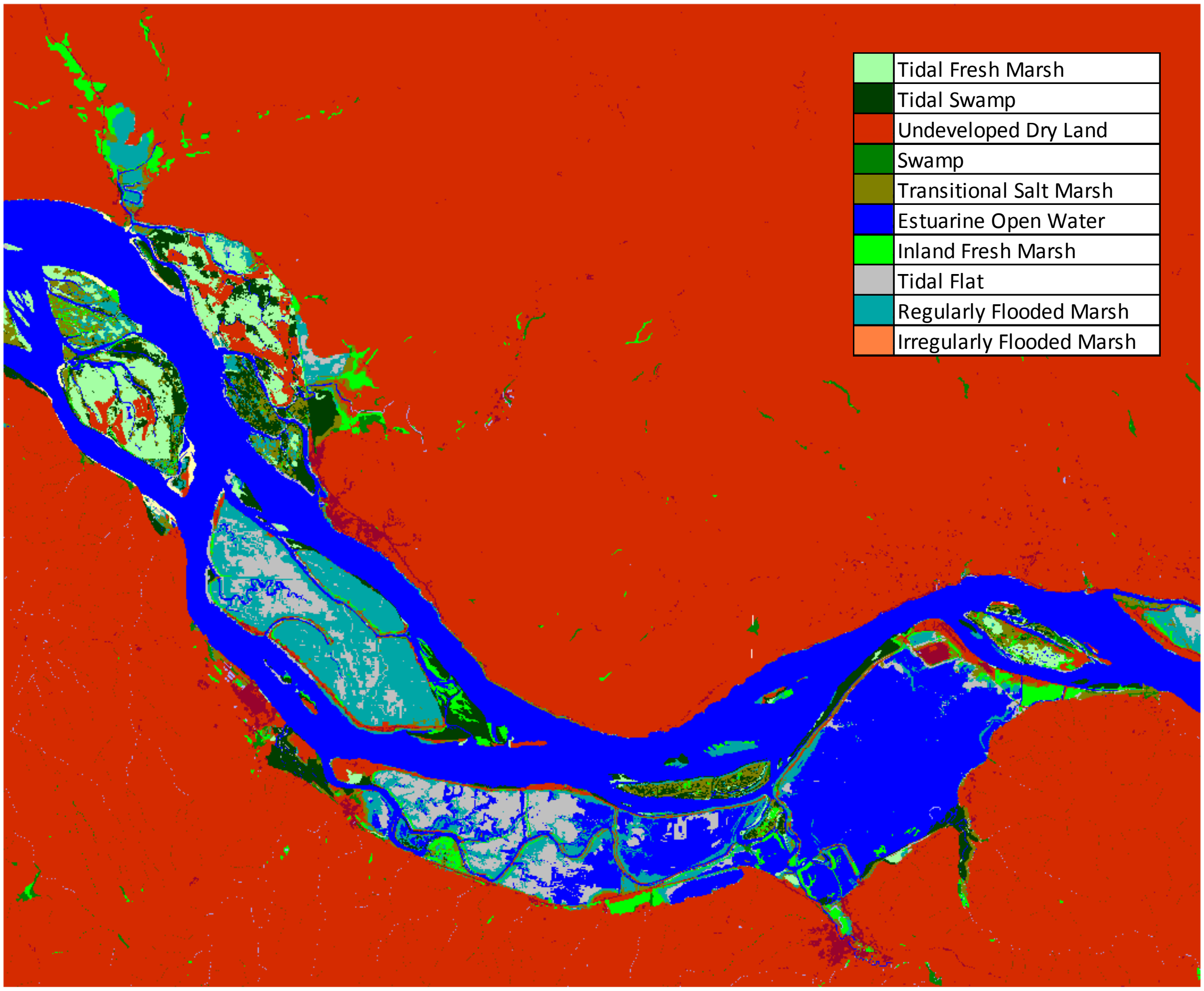
Julia Butler Hansen NWR, 2025, Scenario A1B Mean, 0.39 m SLR



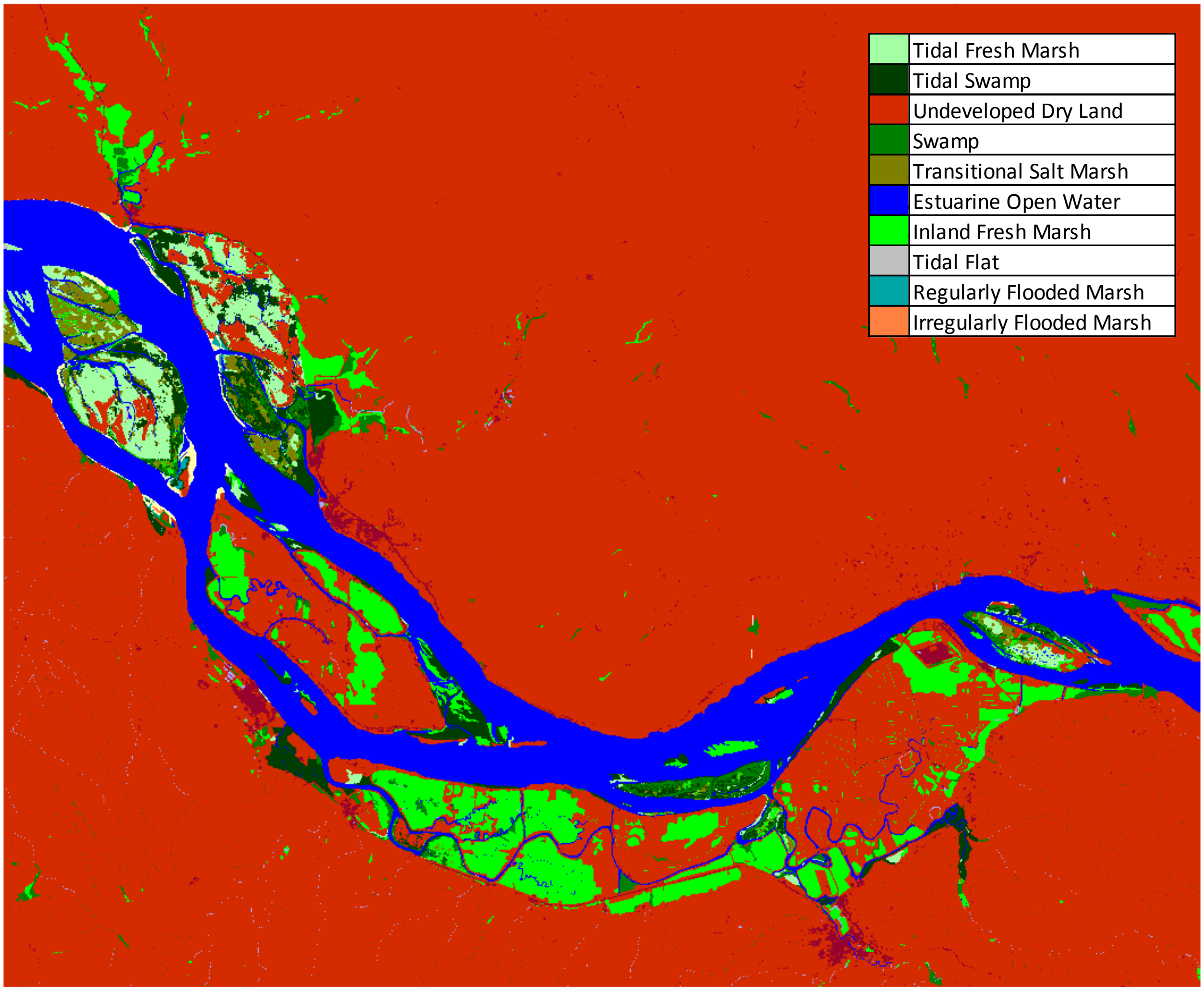
Julia Butler Hansen NWR, 2050, Scenario A1B Mean, 0.39 m SLR



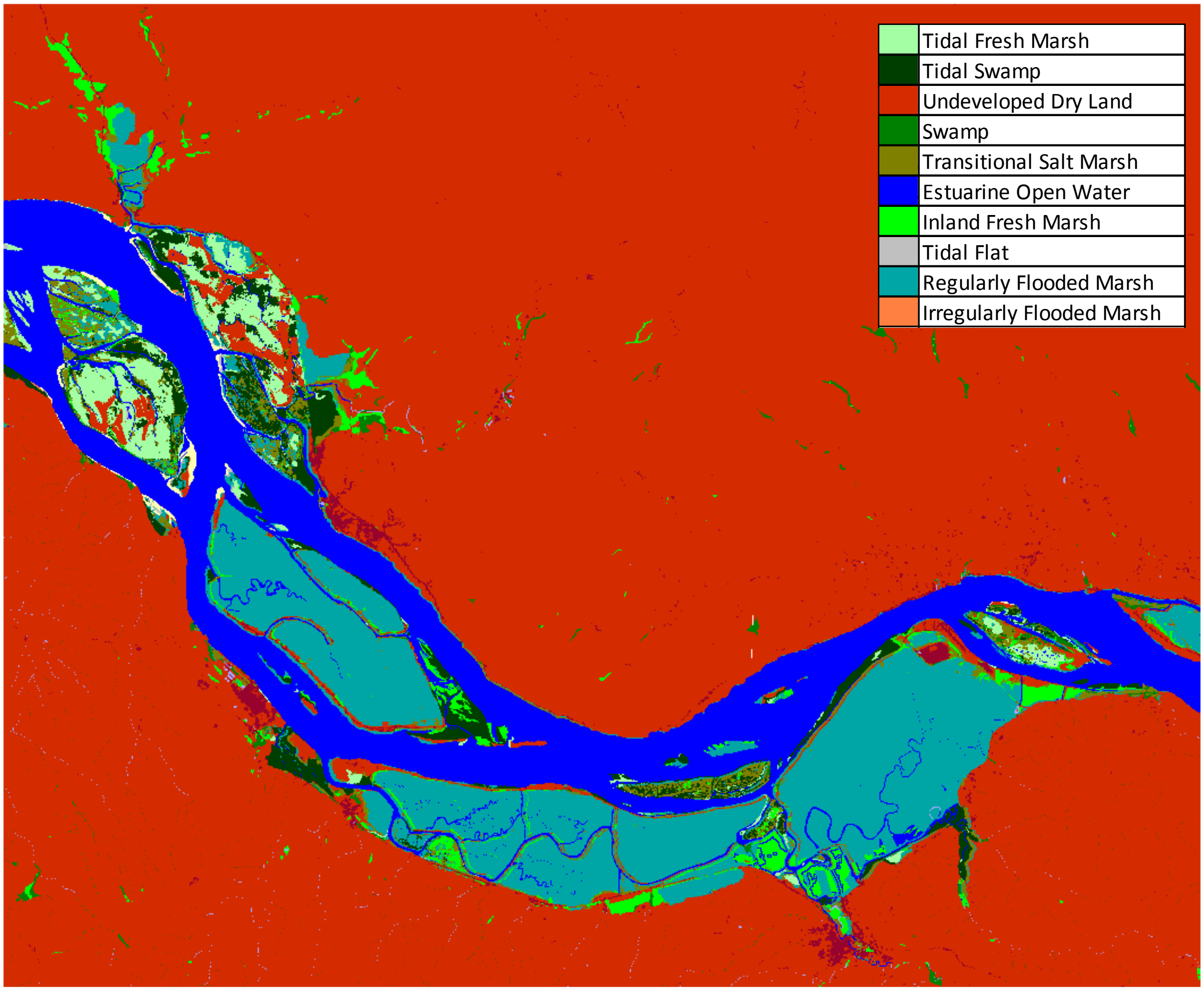
Julia Butler Hansen NWR, 2075, Scenario A1B Mean, 0.39 m SLR



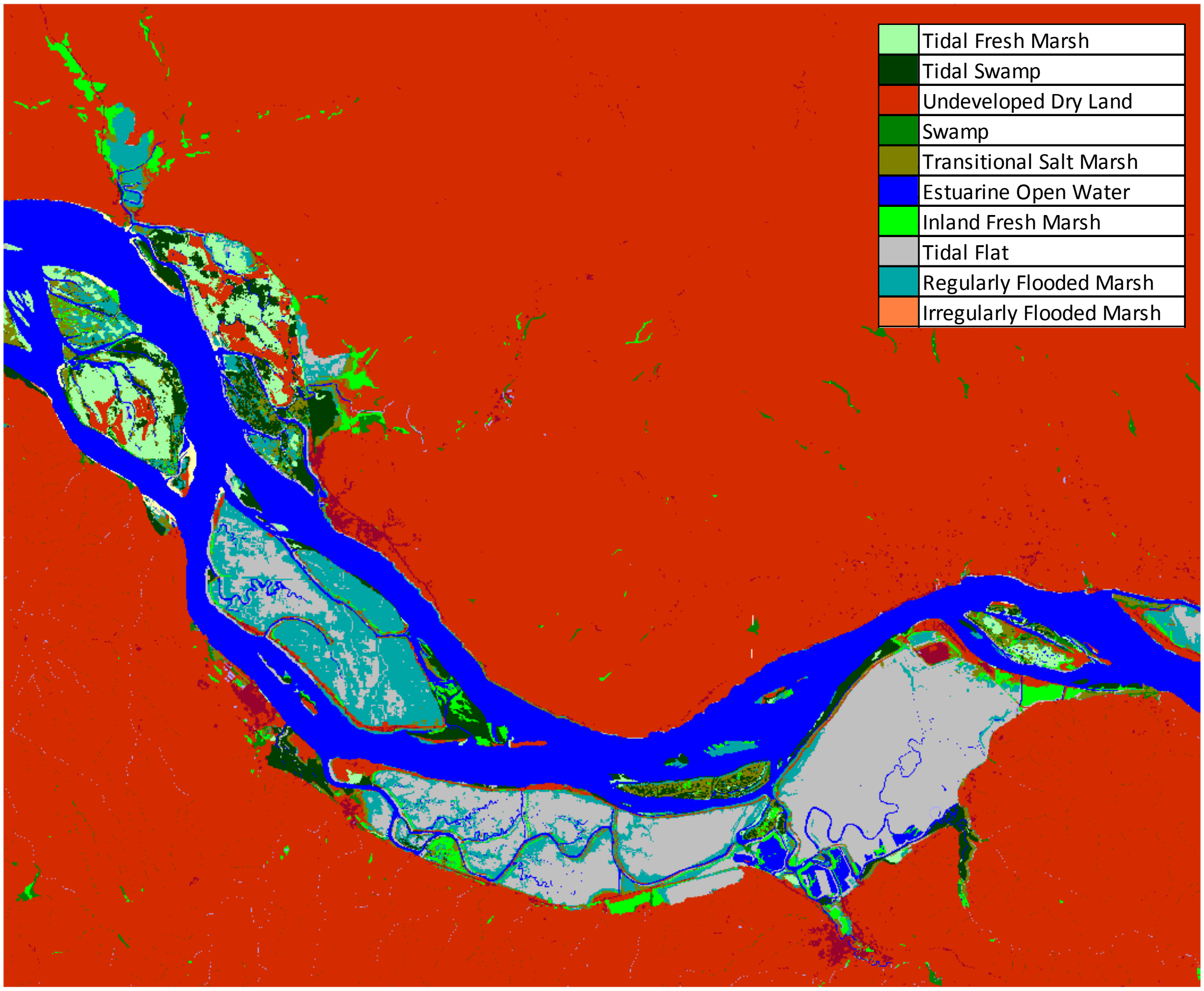
Julia Butler Hansen NWR, 2100, Scenario A1B Mean, 0.39 m SLR



Julia Butler Hansen NWR, Initial Condition



Julia Butler Hansen NWR, 2025, Scenario A1B Maximum, 0.69 m SLR



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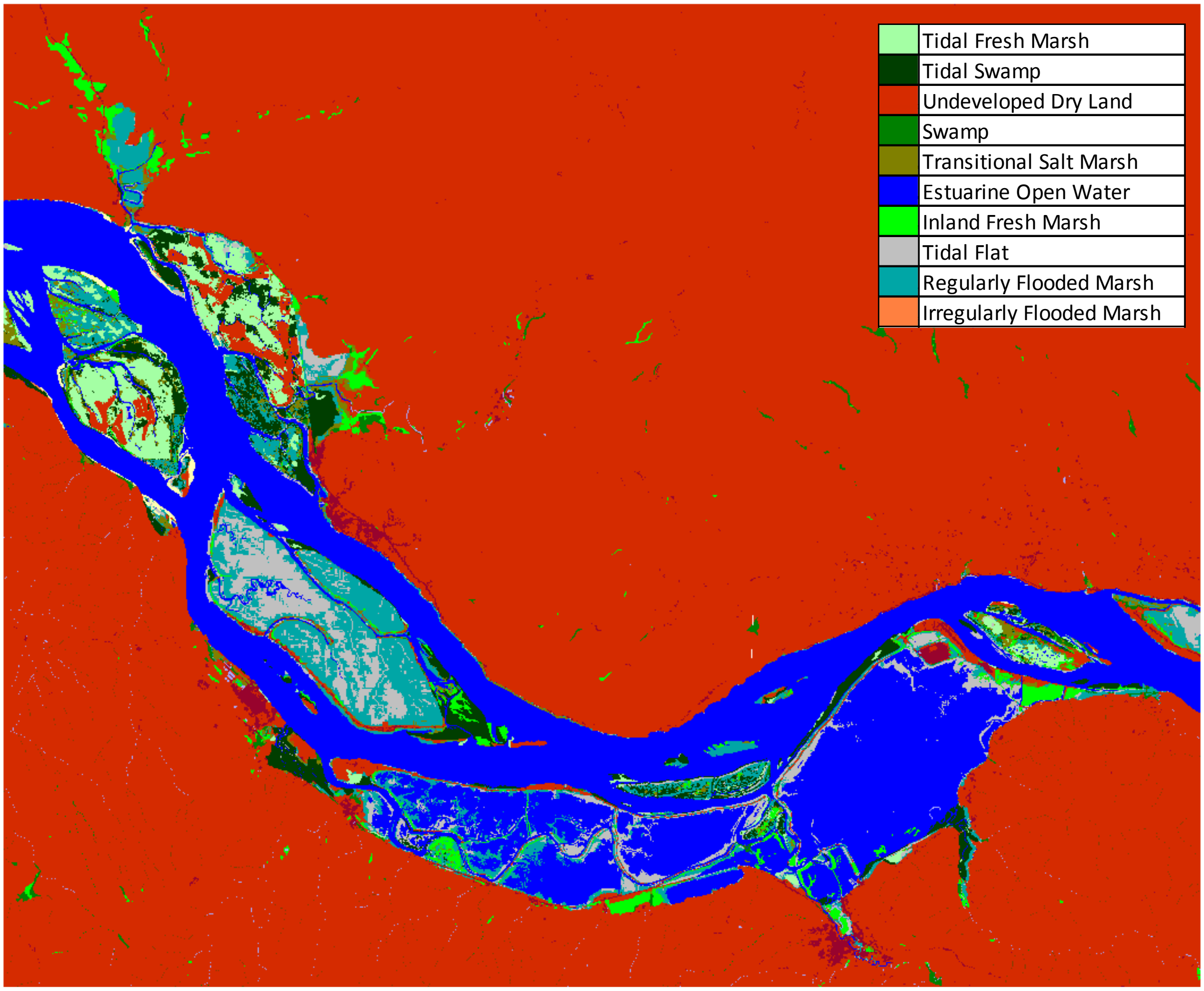

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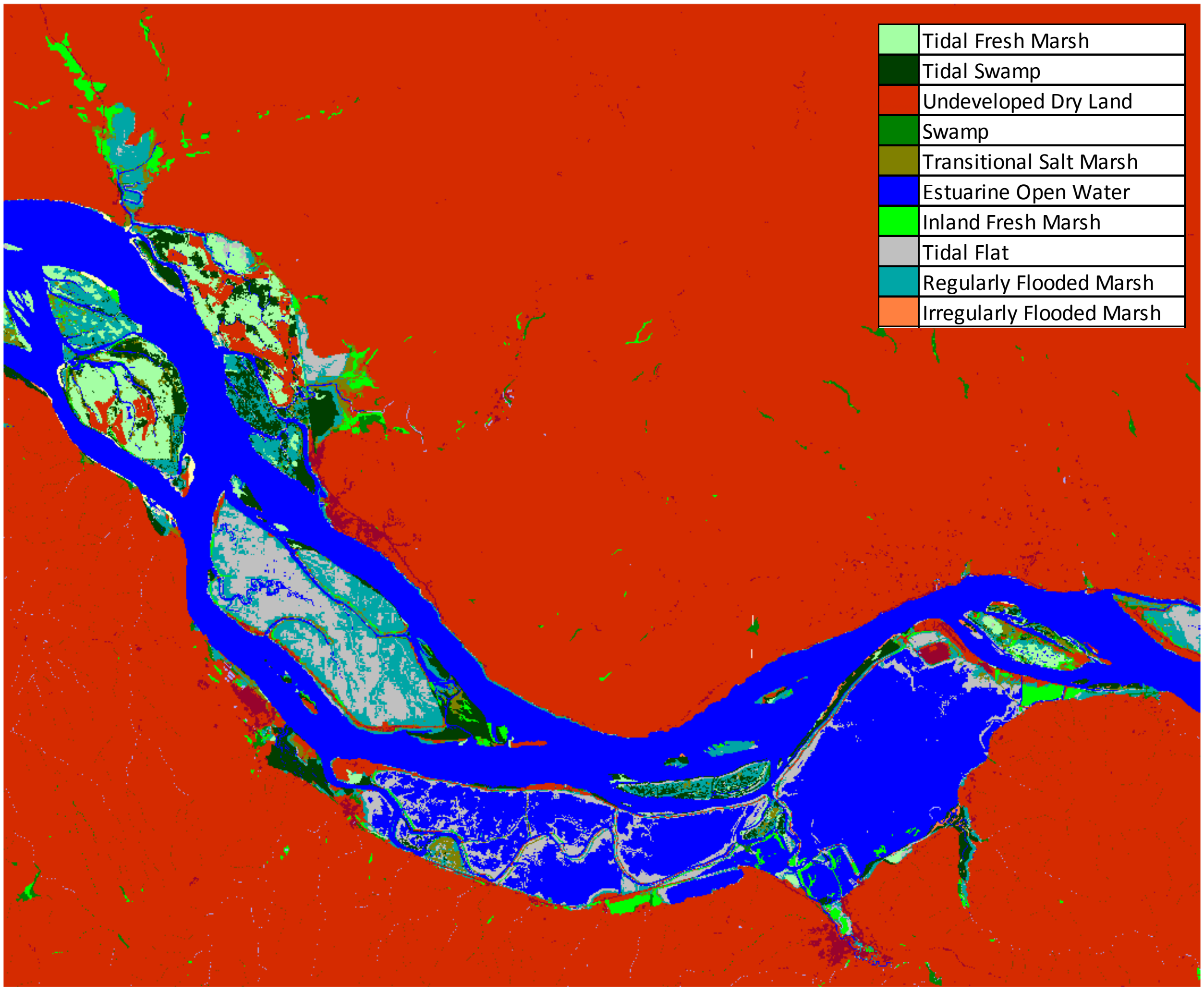
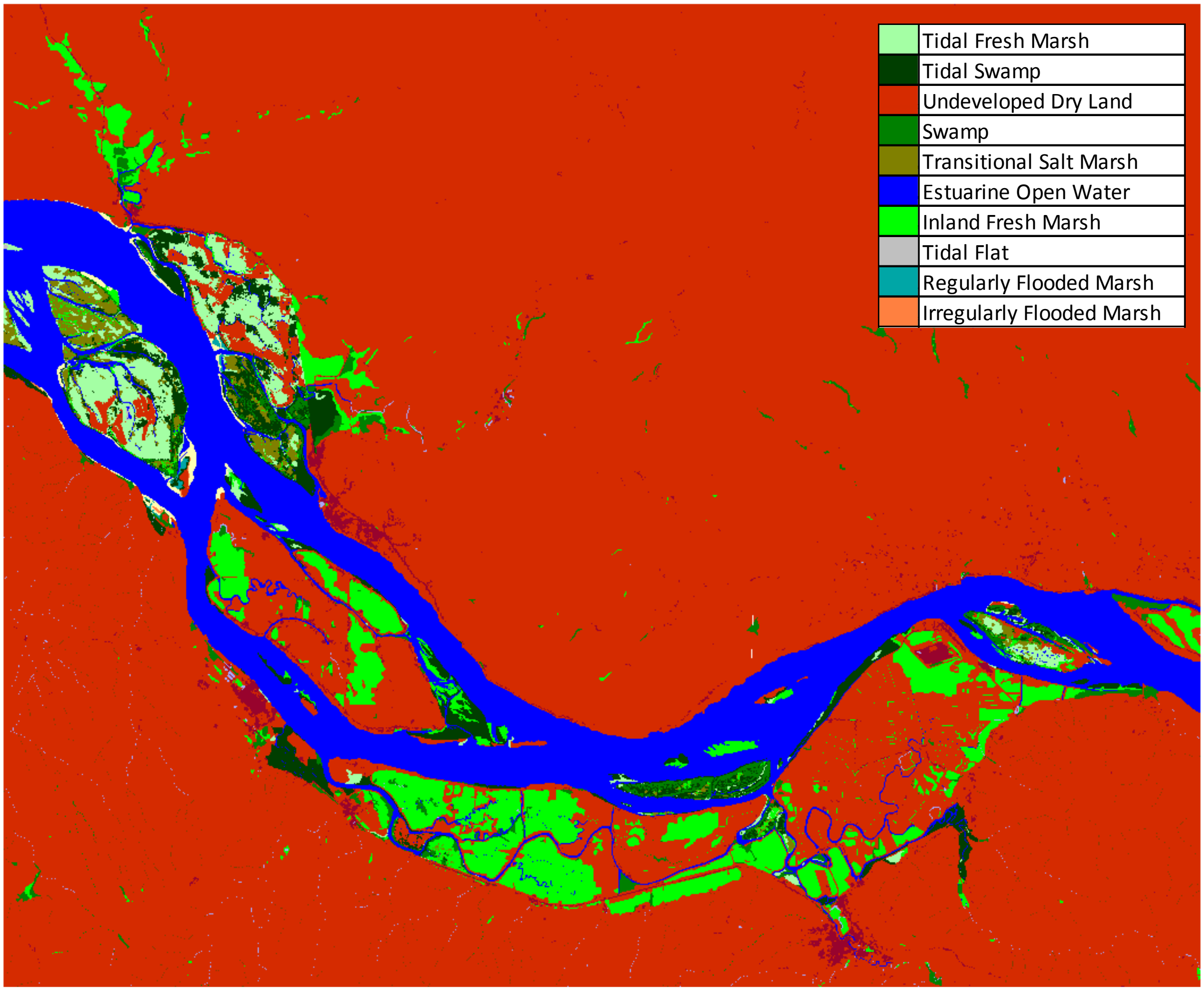
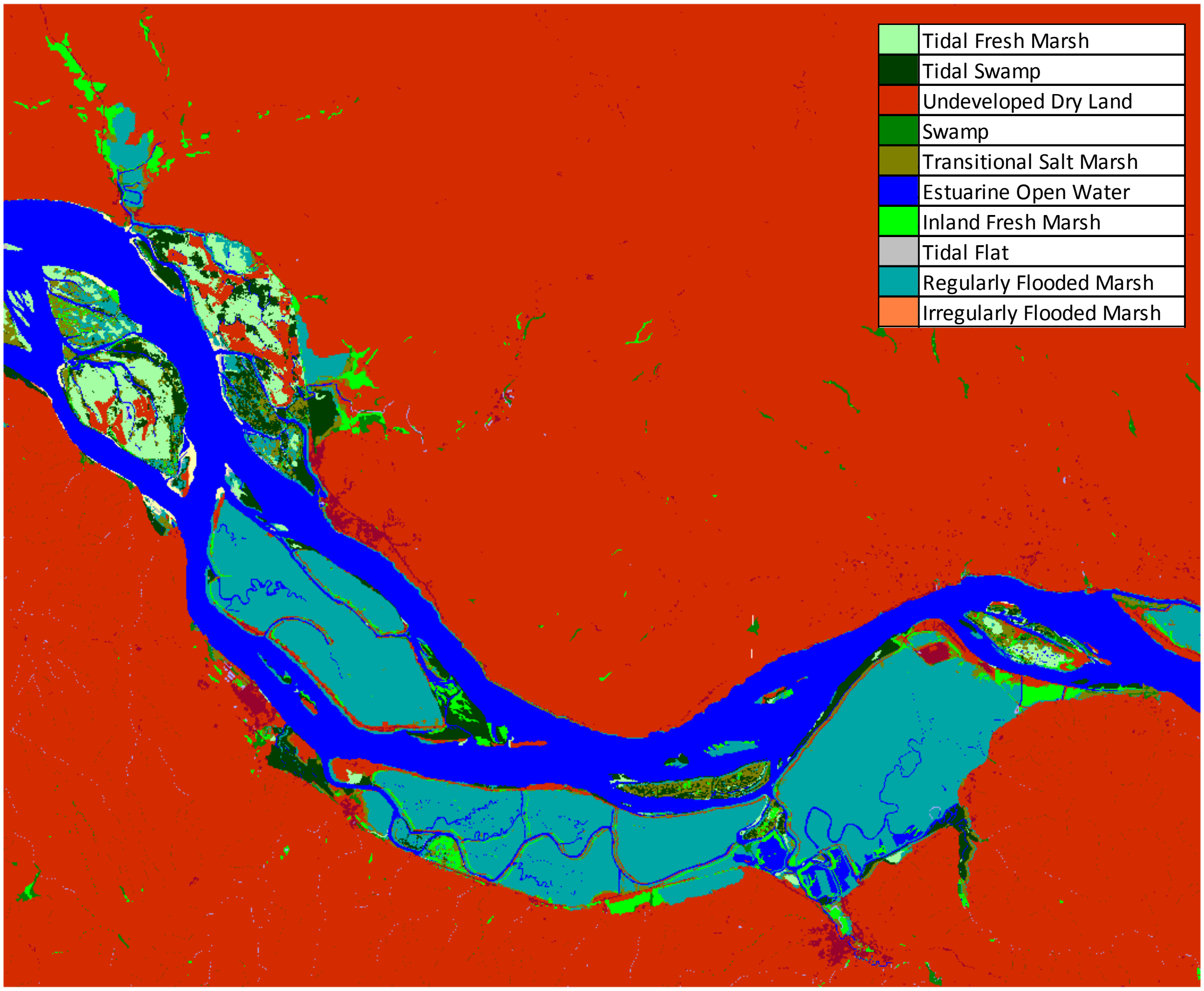


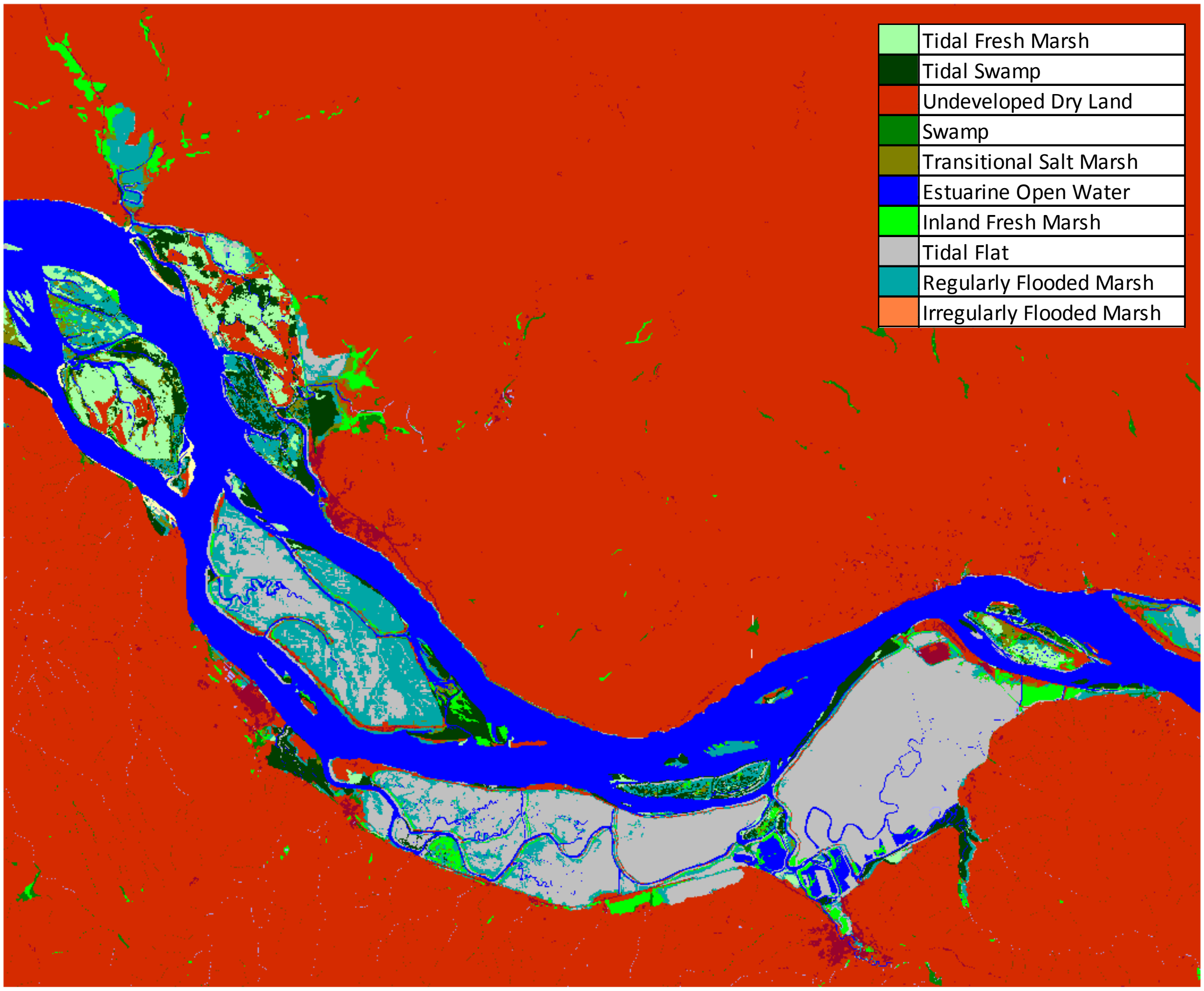
Julia Butler Hansen NWR, 2100, Scenario A1B Maximum, 0.69 m SLR



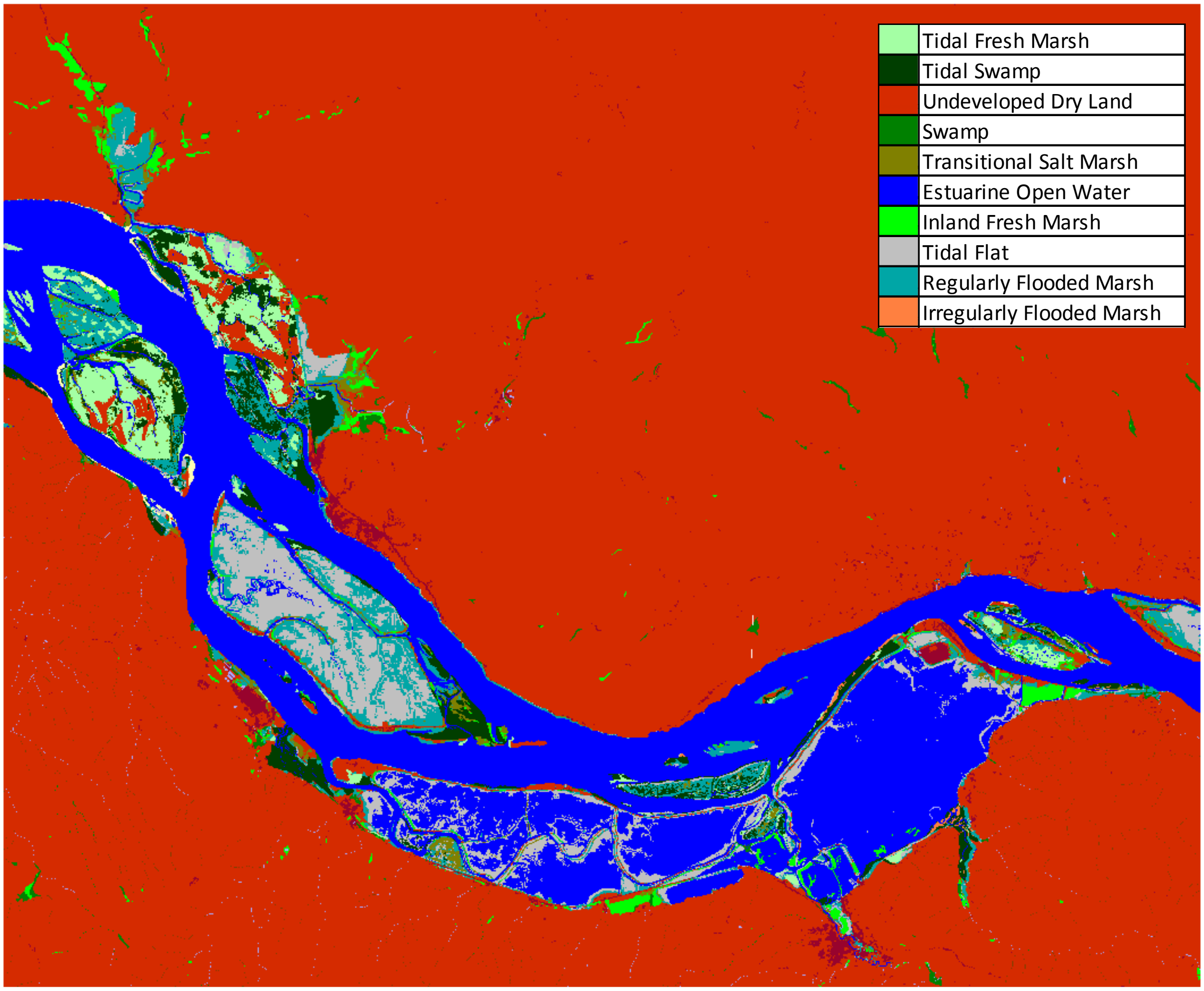
Julia Butler Hansen NWR, Initial Condition



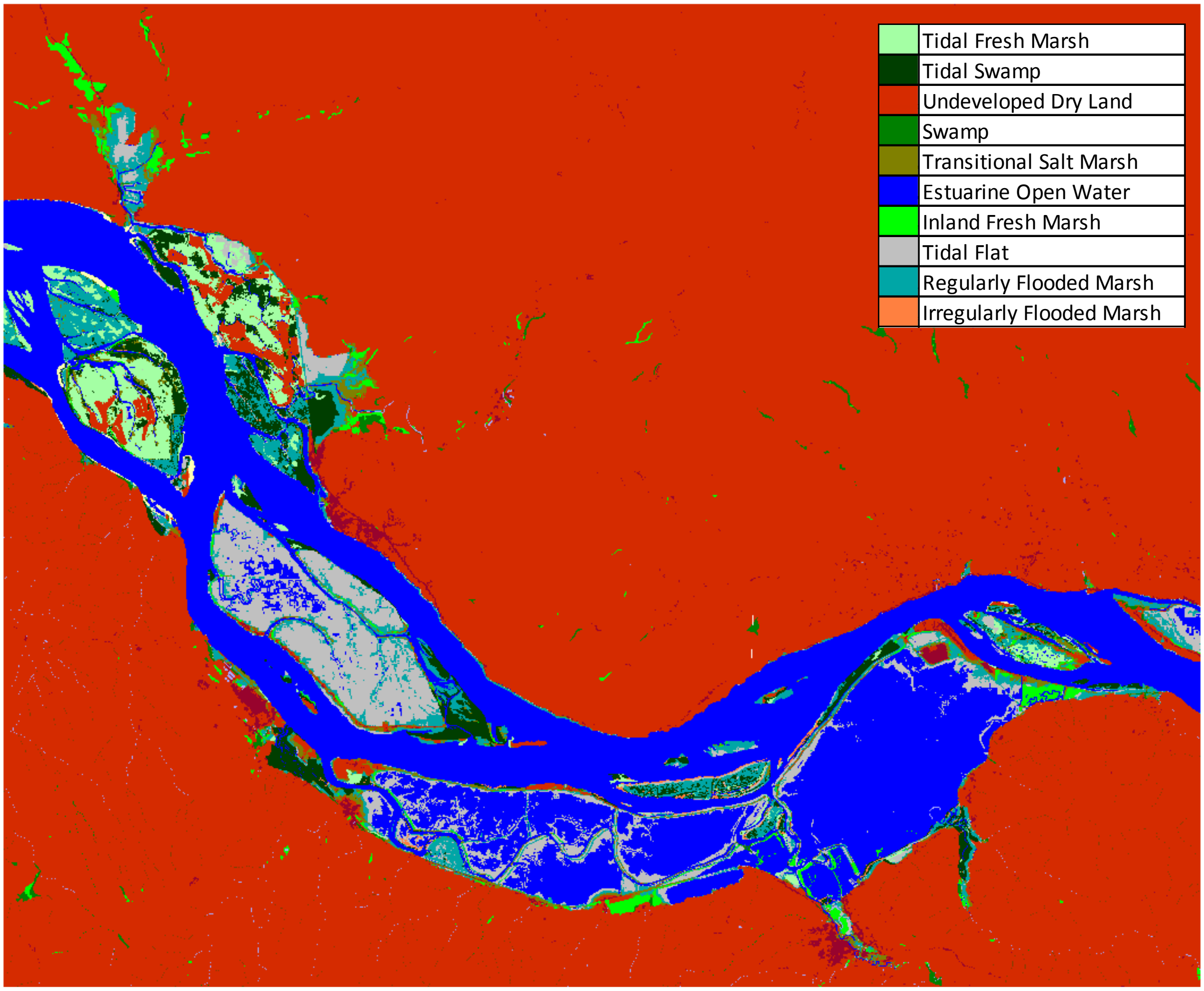
Julia Butler Hansen NWR, 2025, 1 m SLR



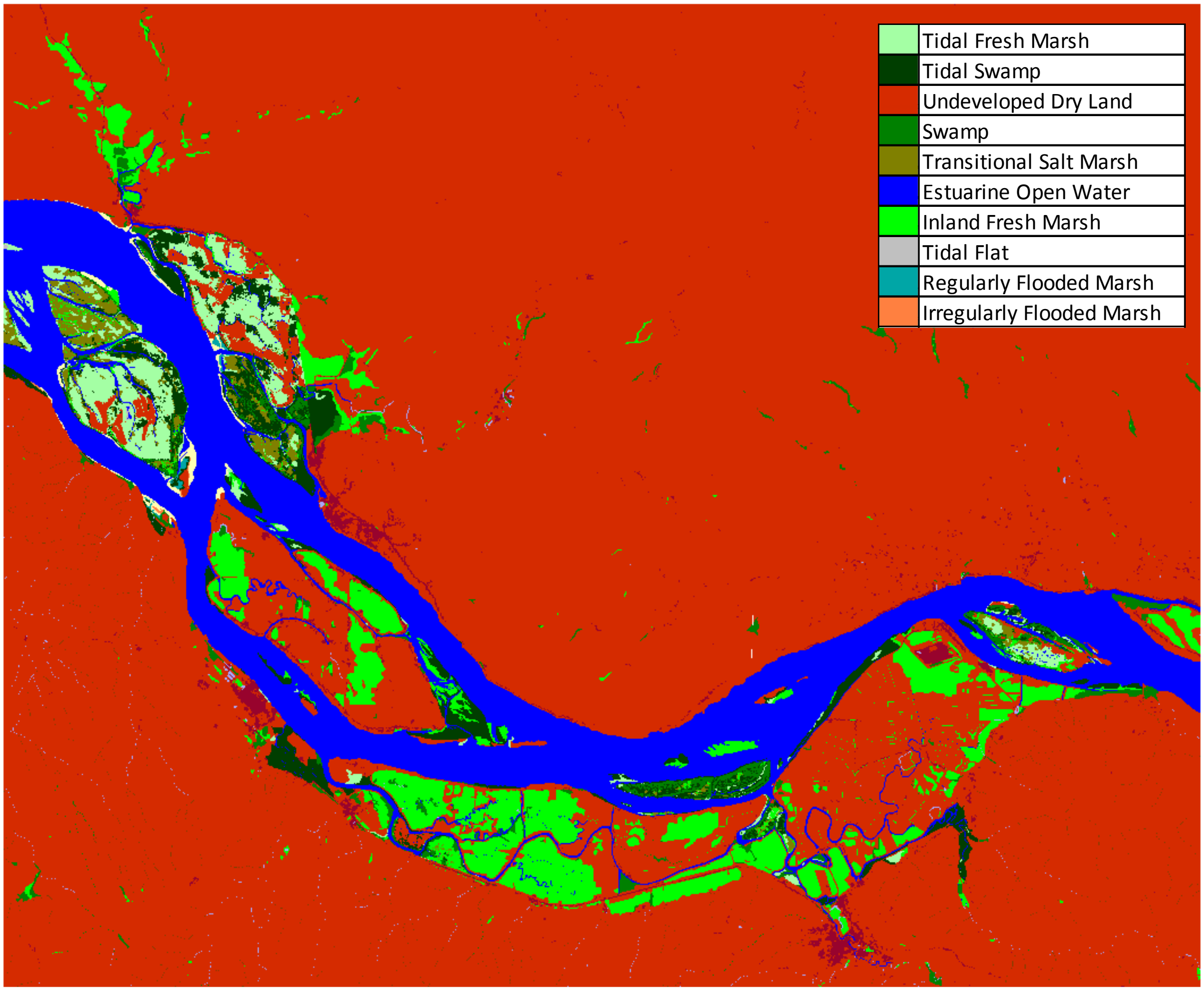
Julia Butler Hansen NWR, 2050, 1 m SLR



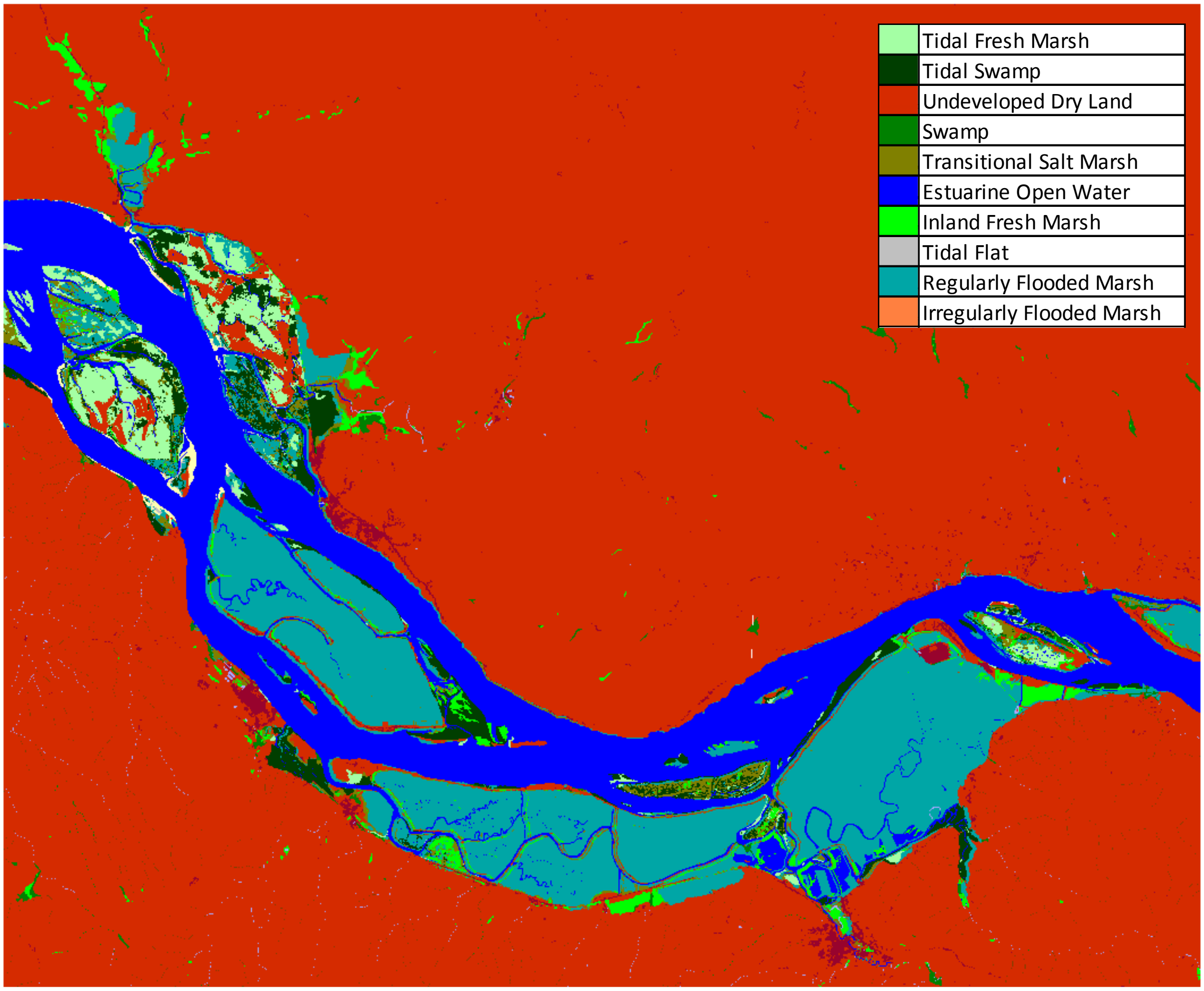
Julia Butler Hansen NWR, 2075, 1 meter



Julia Butler Hansen NWR, 2100, 1 m SLR



Julia Butler Hansen NWR, Initial Condition



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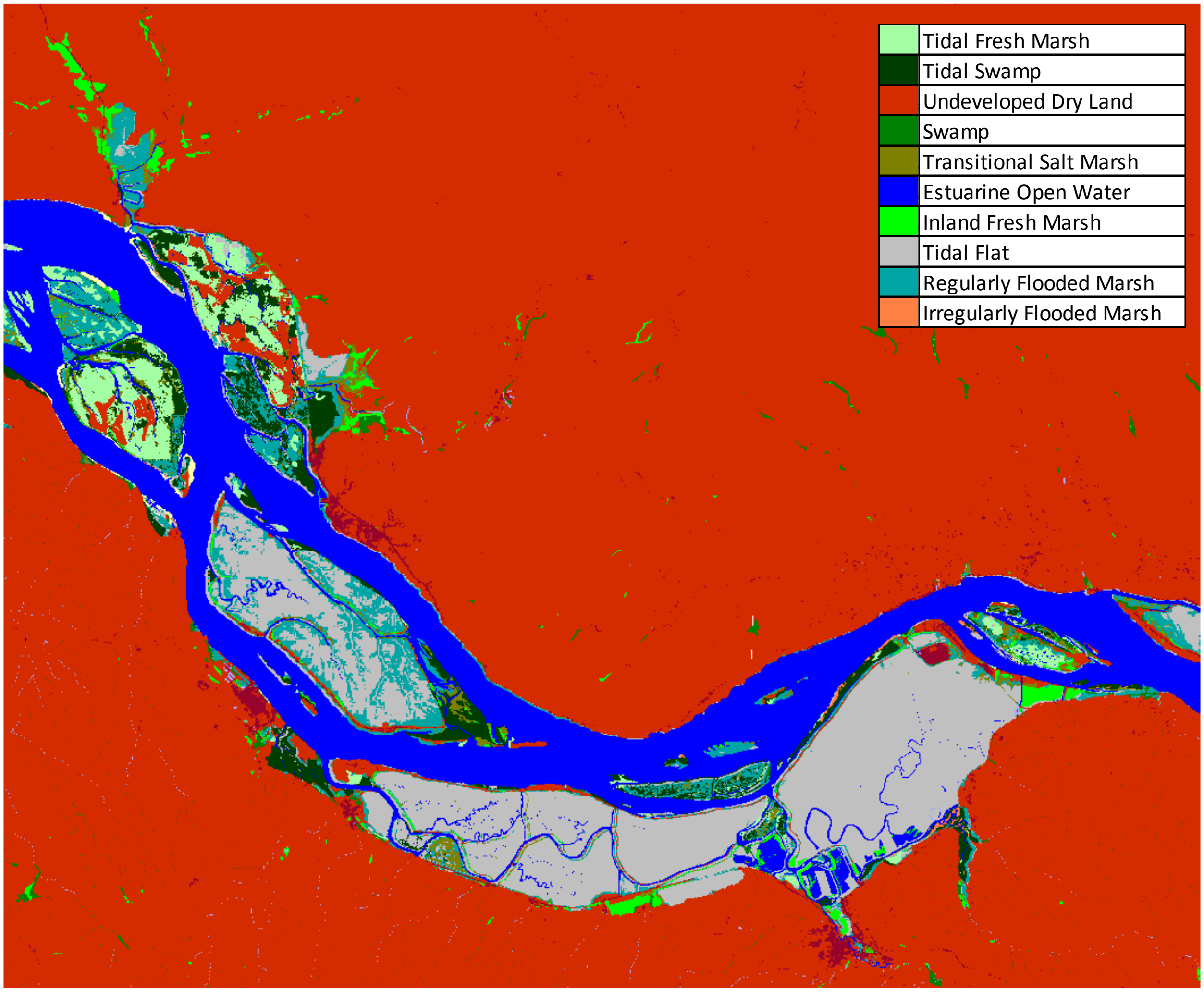

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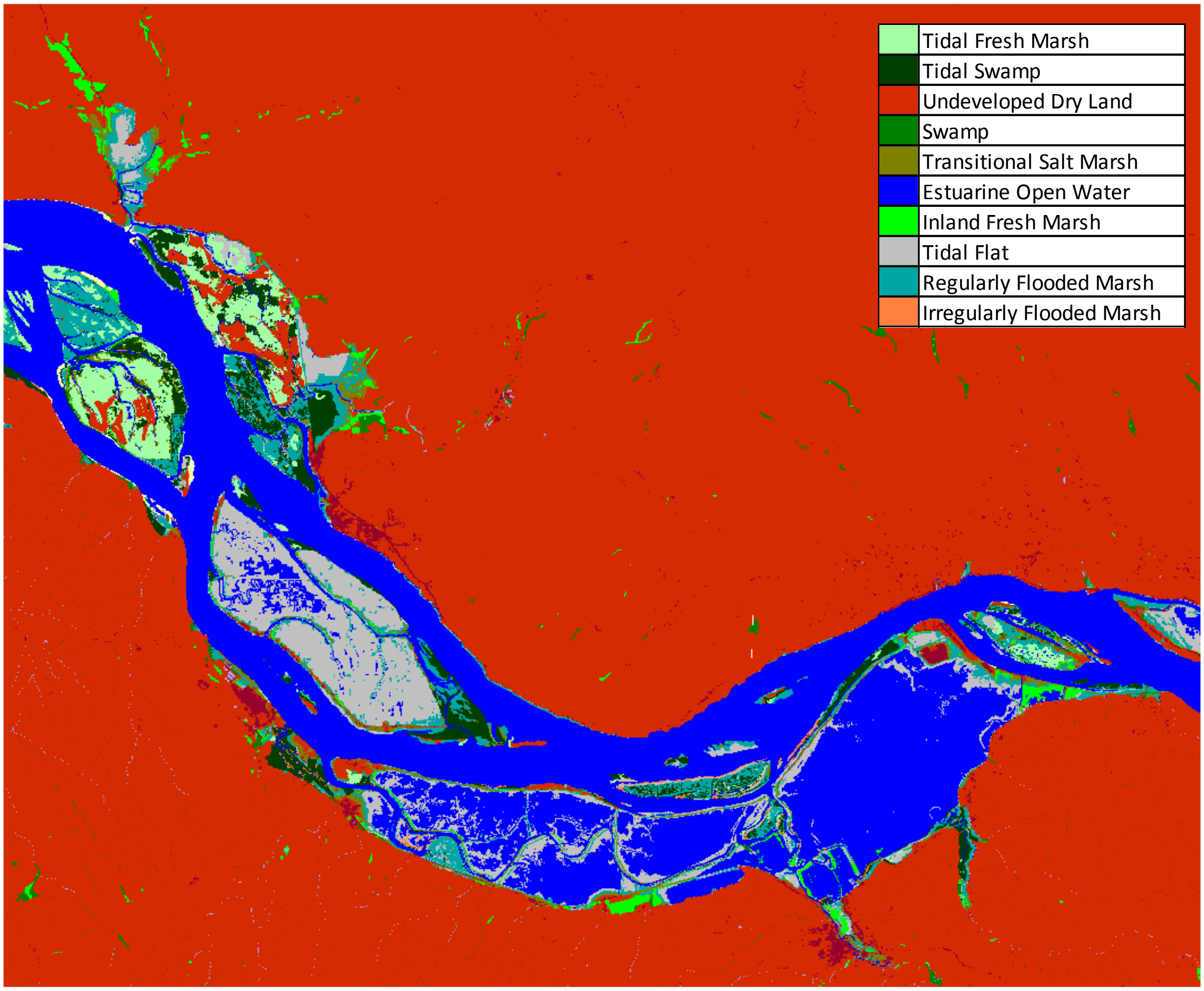

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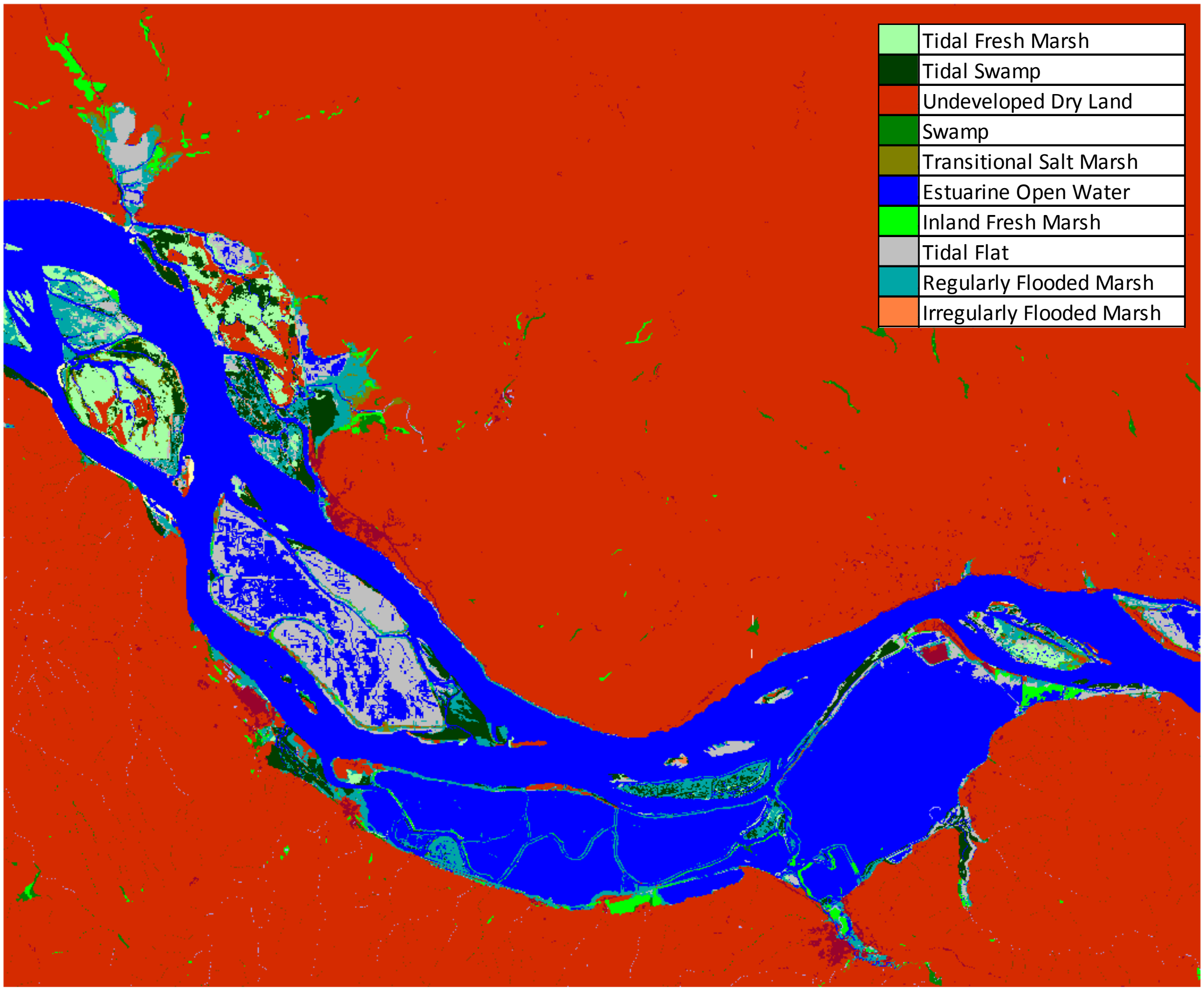
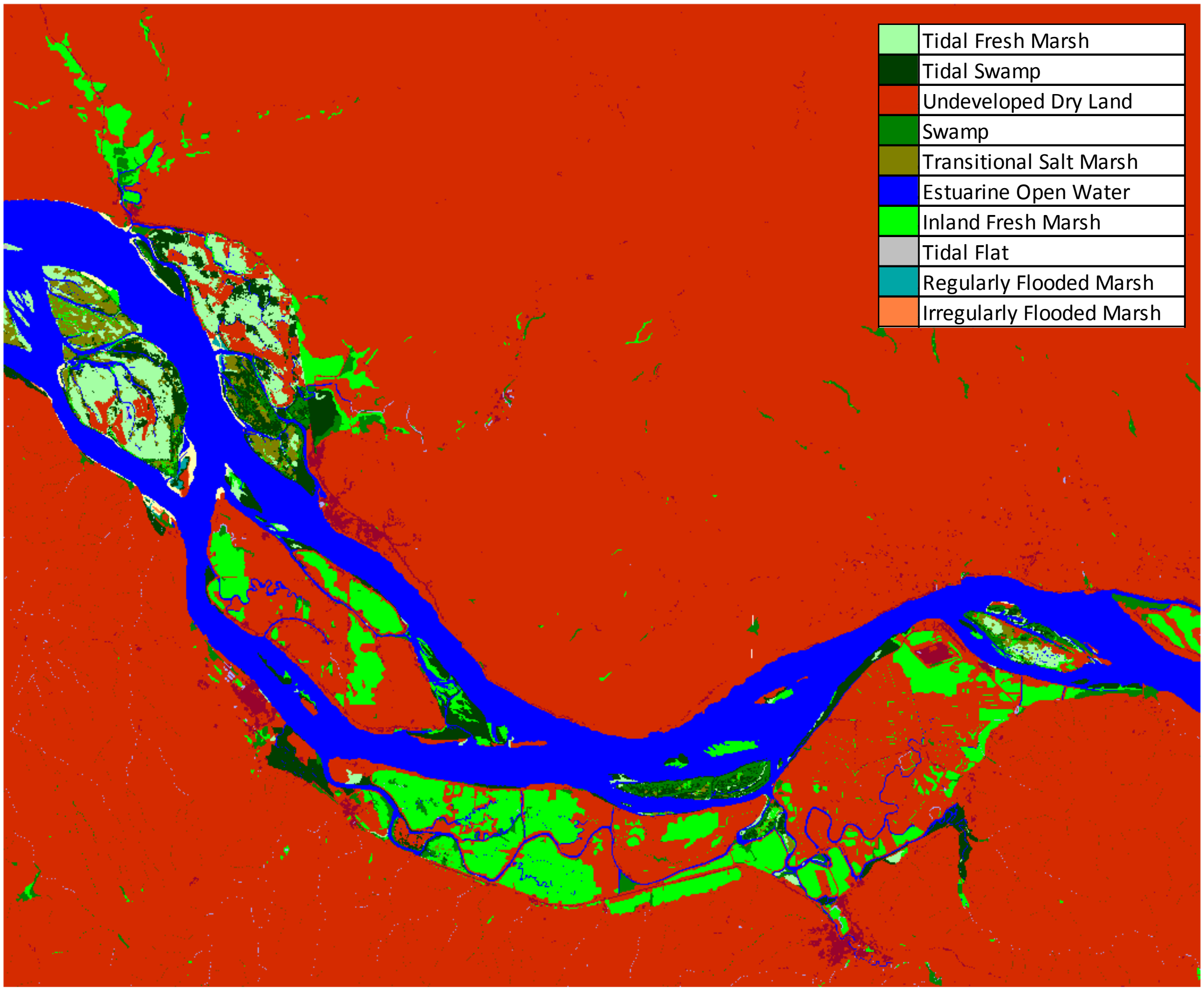
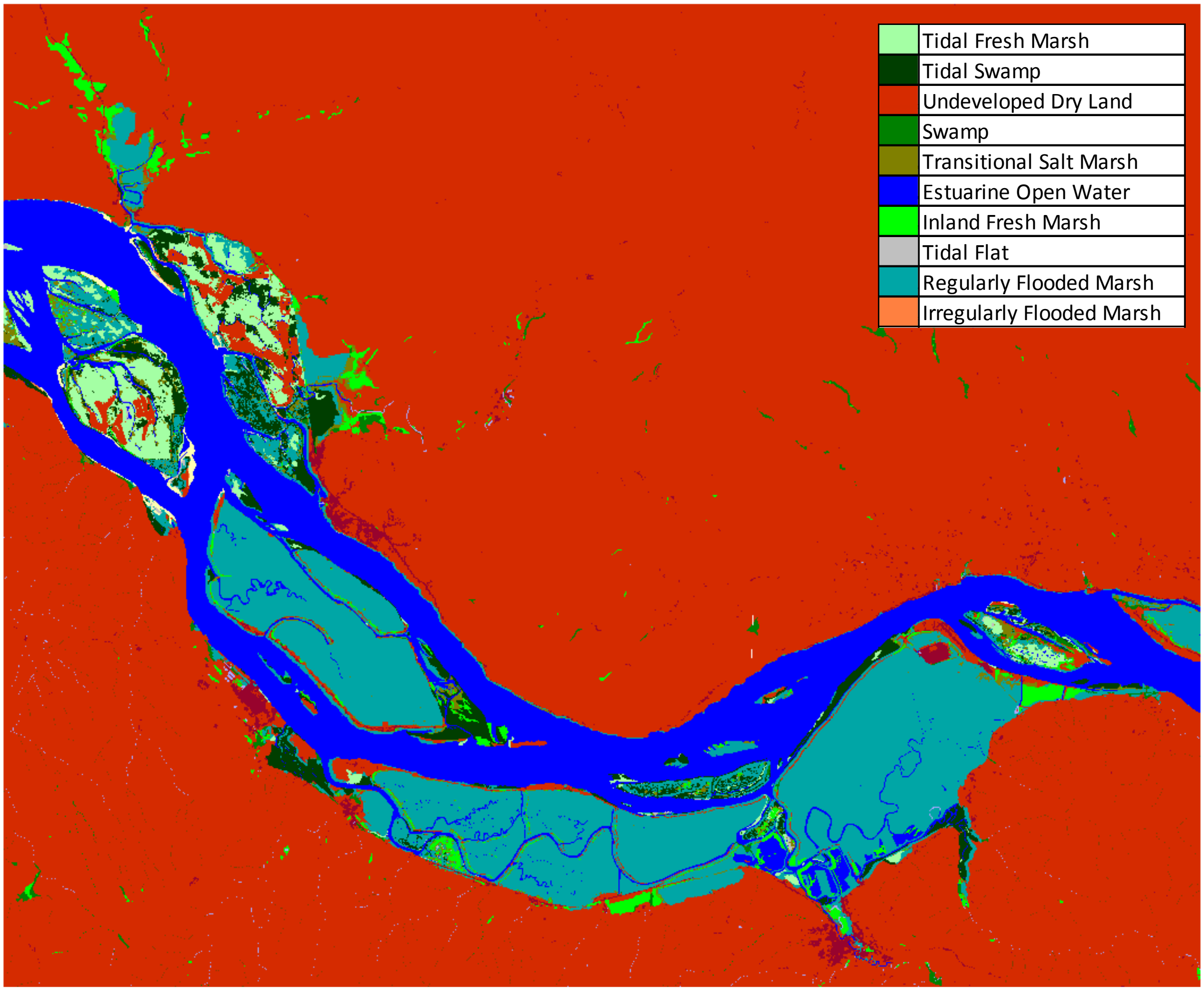


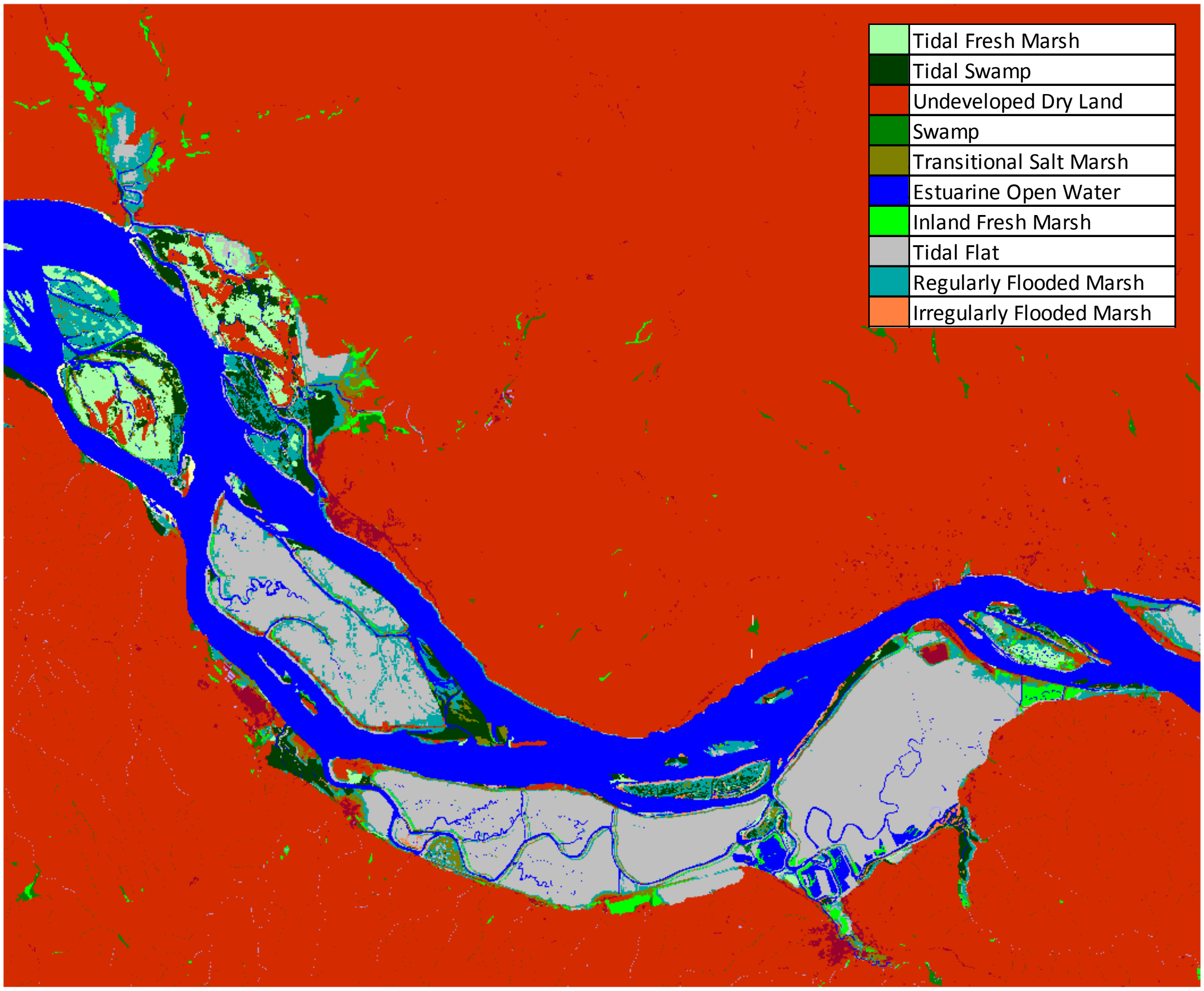
Julia Butler Hansen NWR, 2100, 1.5 m SLR



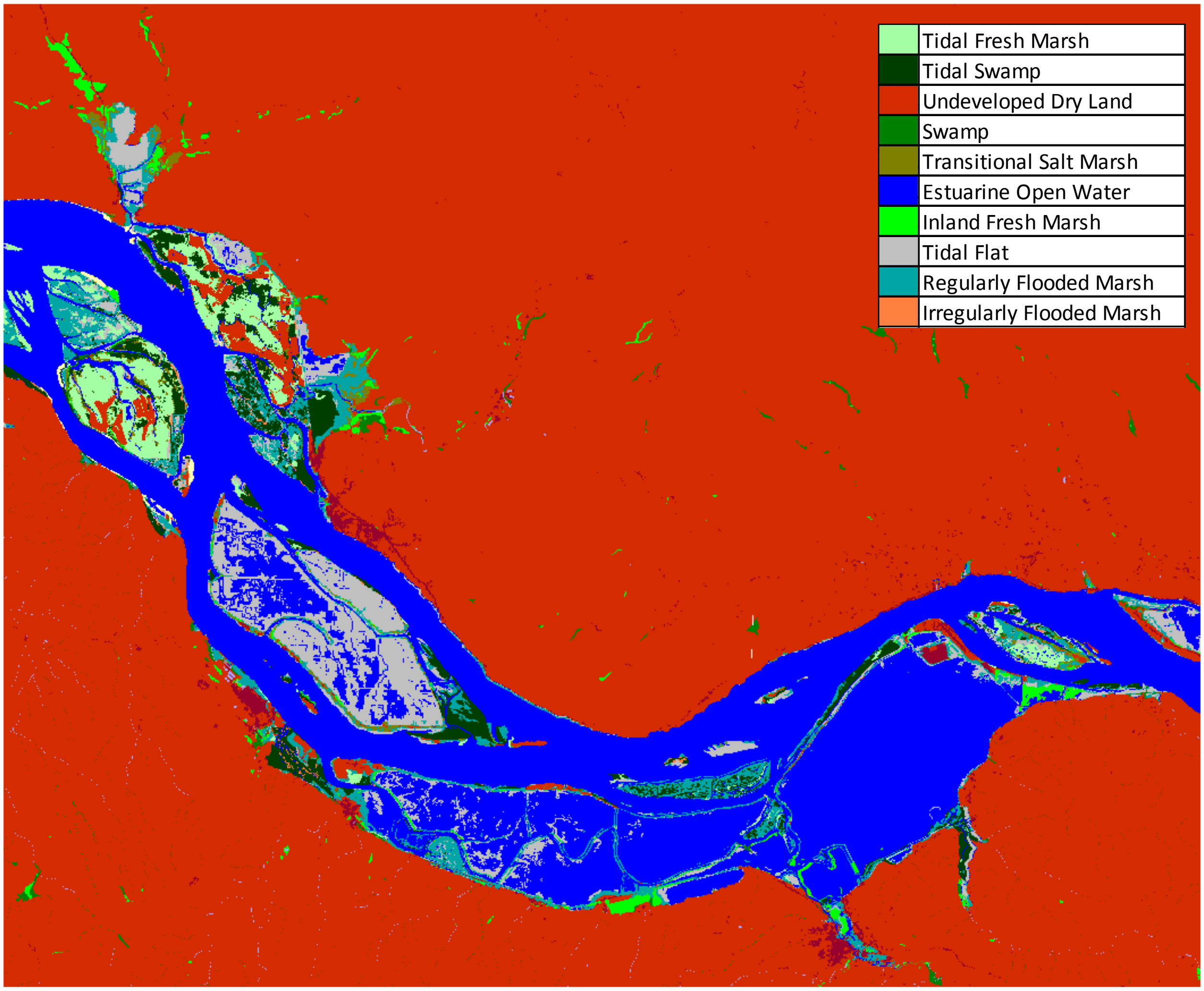
Julia Butler Hansen NWR, Initial Condition



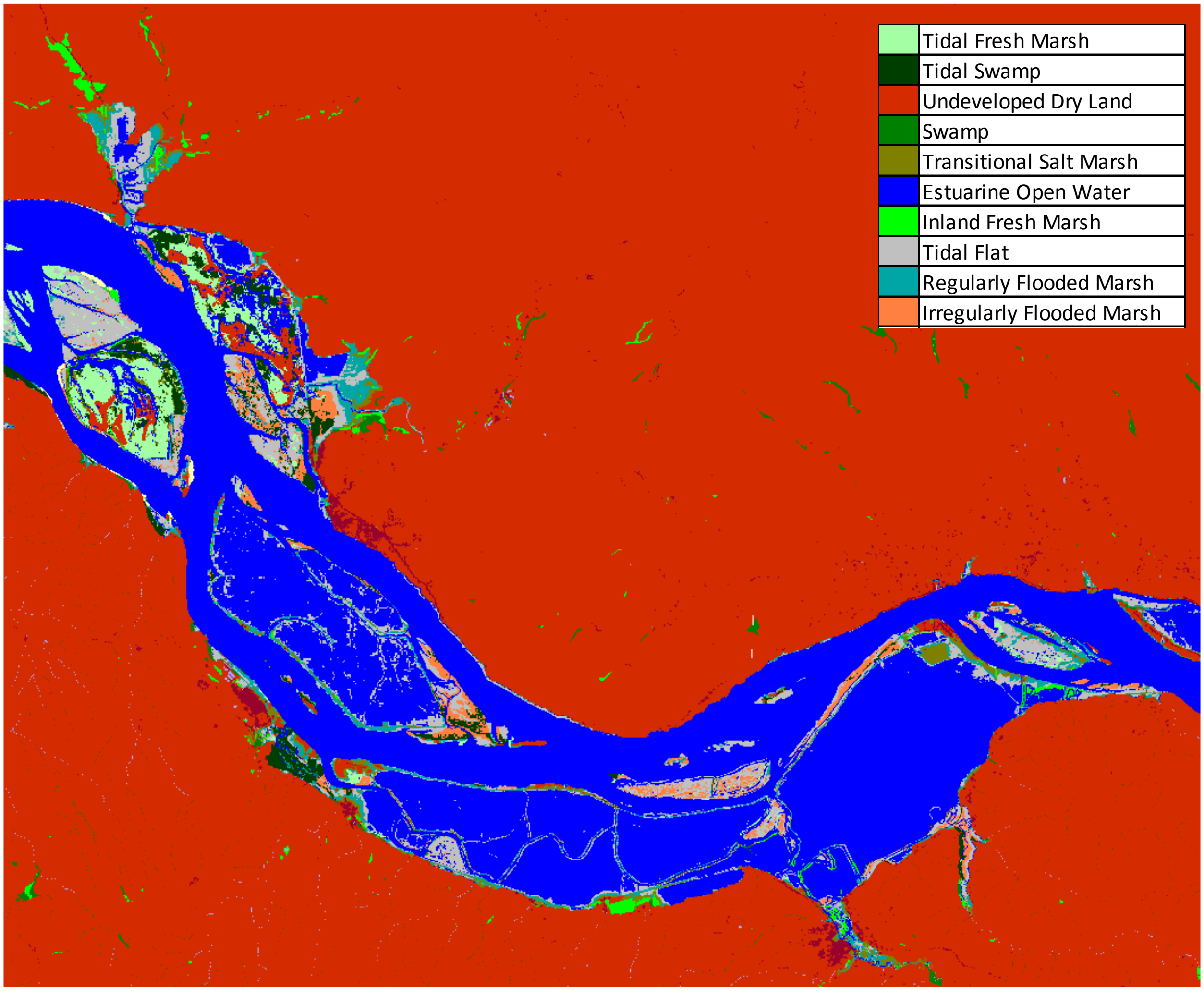
Julia Butler Hansen NWR, 2025, 2 m SLR



Julia Butler Hansen NWR, 2050, 2 m SLR



Julia Butler Hansen NWR, 2075, 2 m SLR



Julia Butler Hansen NWR, 2100, 2 m SLR