

Application of the Sea-Level Affecting Marshes Model (SLAMM 6) to Protection Island 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 (R. A. 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).

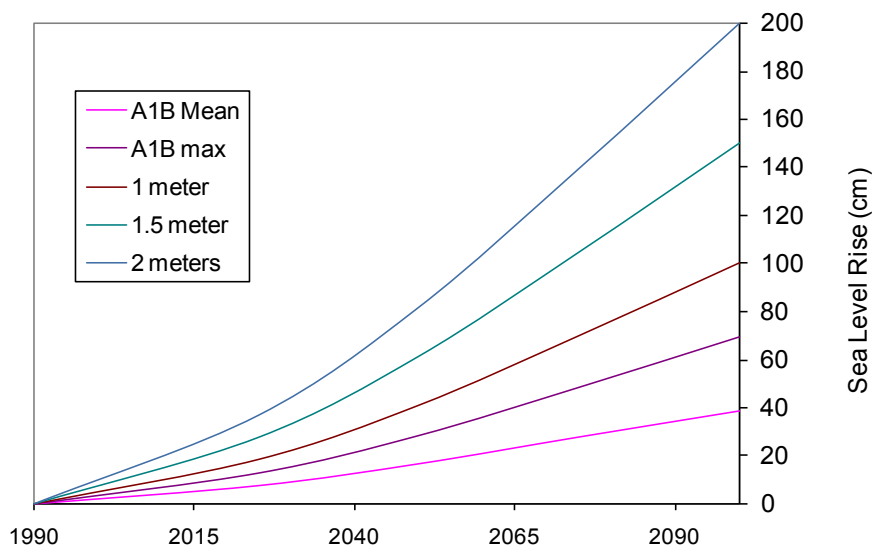


Figure 1. Summary of SLR scenarios utilized

Data Sources and Methods

Wetland layer. Figure 2 shows the most recent wetland layer obtained from a National Wetlands Inventory (NWI) photo, dated 1980. The approved acquisition boundary includes all 363 acres of undeveloped dry land that make up the island itself. A few small buildings are present in the island but they were not categorized as developed dry land. No other significant wetland categories are present within the refuge. Approximately 122 acres of tidal flats surround the island.

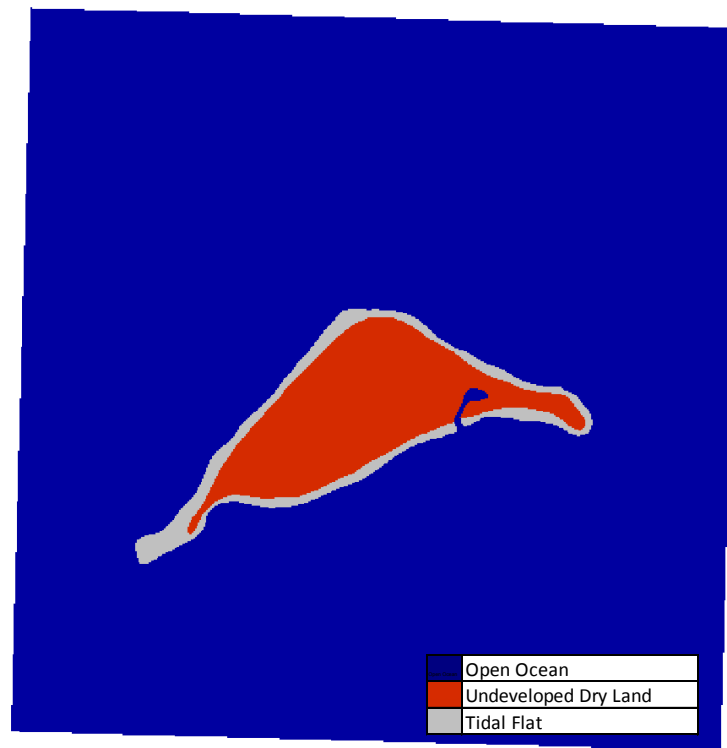


Figure 2. 1980 NWI coverage of the study area.

Elevation Data. The only available elevations for the refuge are from the National Elevation Dataset (NED); this location is not currently covered by LiDAR. Because LiDAR data were not available for this site, the elevation pre-processor module of SLAMM was used to assign elevations for wetlands as a function of the local tide range. For a more in-depth description of the elevation preprocessor, see the SLAMM 6 technical documentation (Clough et al. 2010). This process causes additional uncertainty in model results as covered in the *Discussion* section below.

Model Timesteps. Model forecast outputs were chosen at years 2025, 2050, 2075 and 2100 with the initial condition date set to 1980 (the most recent wetland data available).

Dikes and Impoundments. According to the NWI, there are no dikes or impoundments.

Historic sea level rise rates. The historic trend for relative sea level rise was estimated at 1.1 mm/yr using the average of the two nearest NOAA gages with long-term SLR data (9444900, Port Townsend, WA; 9444090, Port Angeles, WA). The rate of sea level rise for this refuge is lower than the global (eustatic) SLR for the last 100 years (approximately 1.7 mm/year). This estimate is in agreement with

several studies that show the surrounding region subject to mild vertical uplift, with higher rates of uplift occurring in lands west of the refuge (Verdonck 2006, Mitchell et al. 1994).

Tide Ranges. The great diurnal range or GT was estimated at 2.38 m by taking the average of the tide data observed at Port Townsend (2.60 m) and Port Angeles (2.15 m).

Salt elevation. This parameter within SLAMM designates the boundary between wet lands and dry lands or saline wetlands and fresh water wetlands. For this application, salt elevation was estimated at 1.5 Half Tide Units (HTU), equivalent to 1.79 m above MTL.

Accretion rates. Salt marsh vertical accretion rates of 3.6 mm/yr were estimated 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, based on measurement from the Altamaha River in Georgia (Personal Communication, Dr. Christopher Craft). 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. 1999, 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 1.16 m was derived using the datum recorded at the nearby NOAA gauge station # 9444090 in Port Angeles, WA.

Refuge boundaries. Modeled USFWS refuge boundaries for Washington 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 cells.

Input subsites and parameter summary. Figure 3 illustrates the three different simulation input subsites that were identified based on the offshore direction. This distinction improves the elevation estimates by the SLAMM preprocessor. Table 1 summarizes all SLAMM input parameters for the study area.

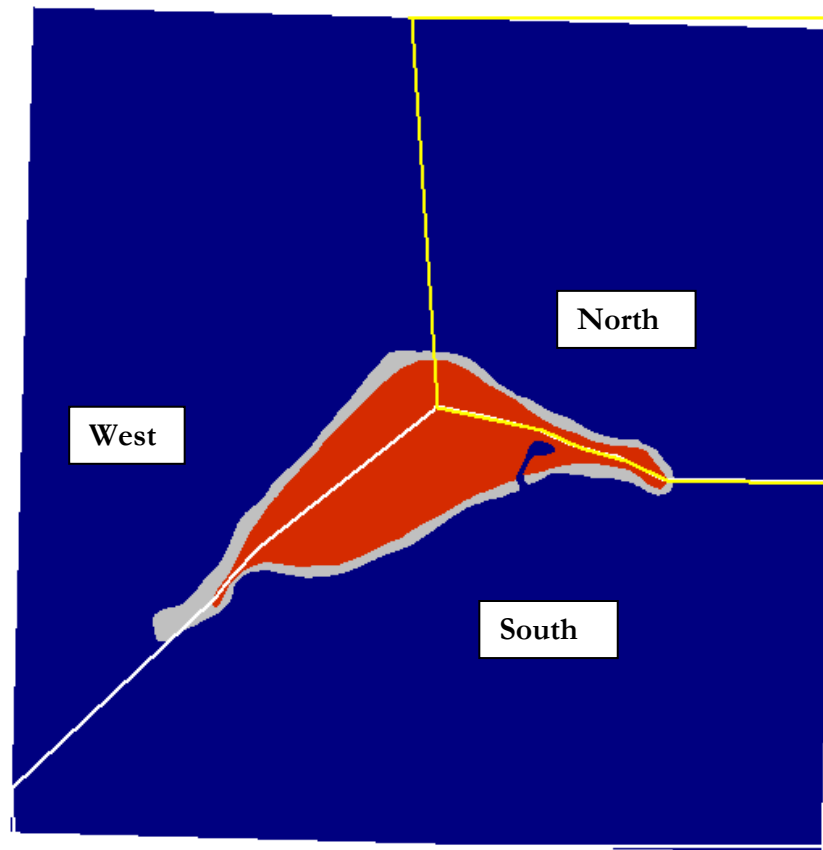


Figure 3. Input subsites applied for model application.

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Table 1. Summary of SLAMM input parameters for Protection Island NWR

Description	Protection Island
NWI Photo Date (YYYY)	1980
DEM Date (YYYY)	1981
Direction Offshore [n,s,e,w]	N/S/W
Historic Trend (mm/yr)	1.085
MTL-NAVD88 (m)	1.16
GT Great Diurnal Tide Range (m)	2.38
Salt Elev. (m above MTL)	1.78
Marsh Erosion (horz. m /yr)	2
Swamp Erosion (horz. m /yr)	1
T.Flat Erosion (horz. m /yr)	0.2
Reg.-Flood Marsh Accr (mm/yr)	3.6
Irreg.-Flood Marsh Accr (mm/yr)	3.75
Tidal-Fresh Marsh Accr (mm/yr)	4
Inland-Fresh Marsh Accr (mm/yr)	4
Mangrove Accr (mm/yr)	7
Tidal Swamp Accr (mm/yr)	1.1
Swamp Accretion (mm/yr)	0.3
Beach Sed. Rate (mm/yr)	0.5
Freq. Overwash (years)	0
Use Elev Pre-processor [True,False]	TRUE

Results

This simulation of the Protection Island NWR predicts that the wetland covers of refuge will not be significantly impacted by SLR. Table 2 presents the land cover by 2100 of the simulated area for each of the five SLR scenarios examined.

Table 2. Predicted wetland coverage by 2100 given simulated scenarios of eustatic SLR at Protection Island NWR

Land cover category	Initial coverage (acres)	Land cover by 2100 for different SLR scenarios				
		0.39 m	0.69 m	1 m	1.5 m	2 m
Undeveloped Dry Land	363	346	326	305	293	292
Tidal Flat	122	79	58	29	0	0
Ocean Beach	0	16	36	57	69	66
Open Water	0	43	65	94	123	127

A range from 5% to 16% of dry land within the refuge is predicted to be converted to ocean beach and open water for SLR scenarios at and below 1 m by 2100. For higher SLR scenarios, additional losses of dry land are predicted to be quite limited given the high elevations of the remaining refuge land, culminating in a maximum of 20% lost. The tidal flat around the island is predicted to be increasingly converted to open water as sea level continues to rise. A complete loss for this land cover category is predicted for SLR 1.5 m or higher.

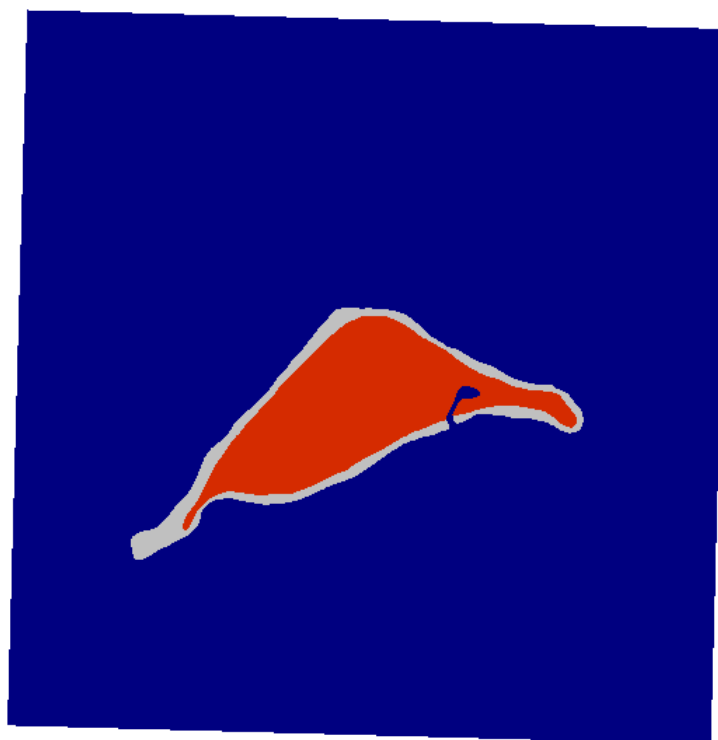
Application of the Sea-Level Affecting Marshes Model (SLAMM 6) to Protection Island NWR

Protection Island NWR

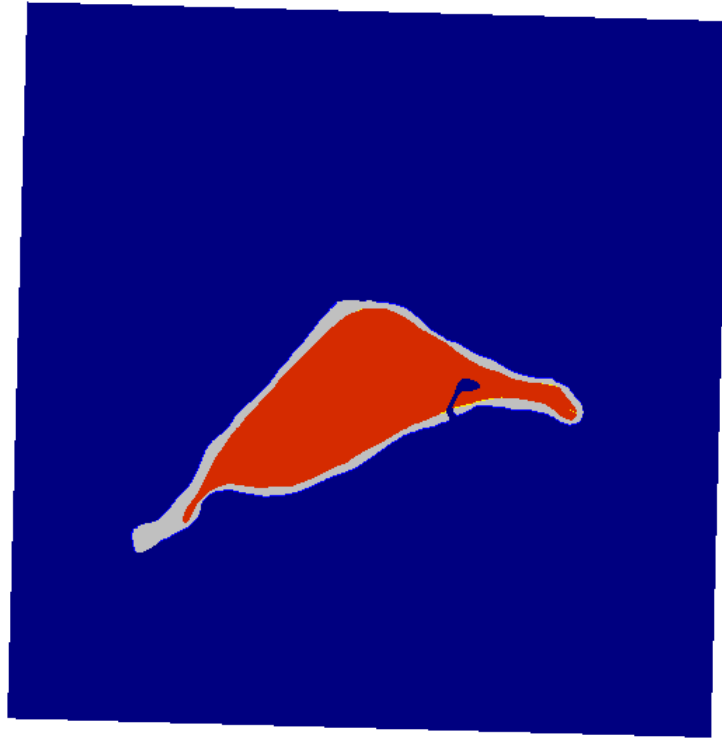
IPCC Scenario A1B-Mean, 0.39 m SLR eustatic by 2100

Results in Acres

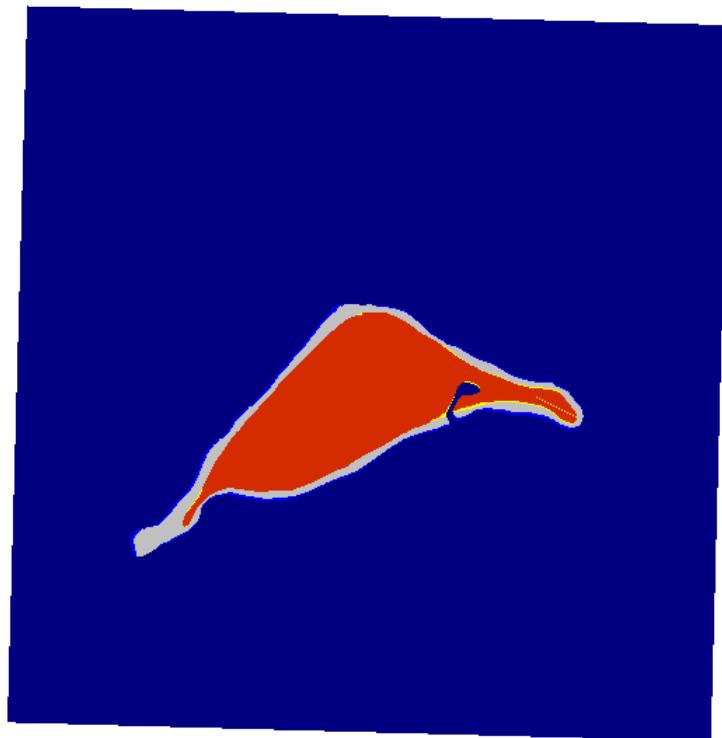
		Initial	2025	2050	2075	2100
	Undeveloped Dry Land	363	361	357	352	346
	Tidal Flat	122	107	99	89	79
	Estuarine Open Water	0	15	23	33	43
	Ocean Beach	0	2	5	11	16
	Total	485	485	485	484	484



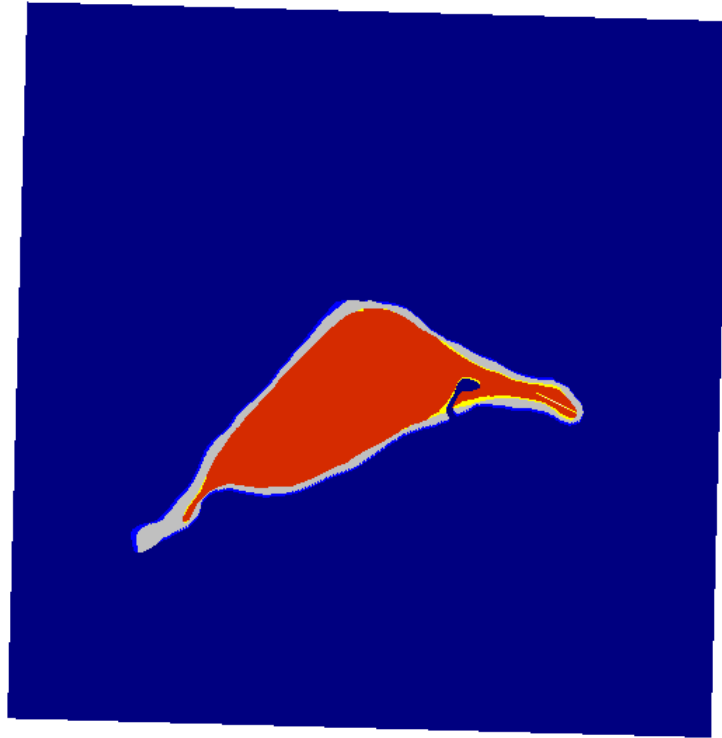
Protection Island NWR, Initial Condition



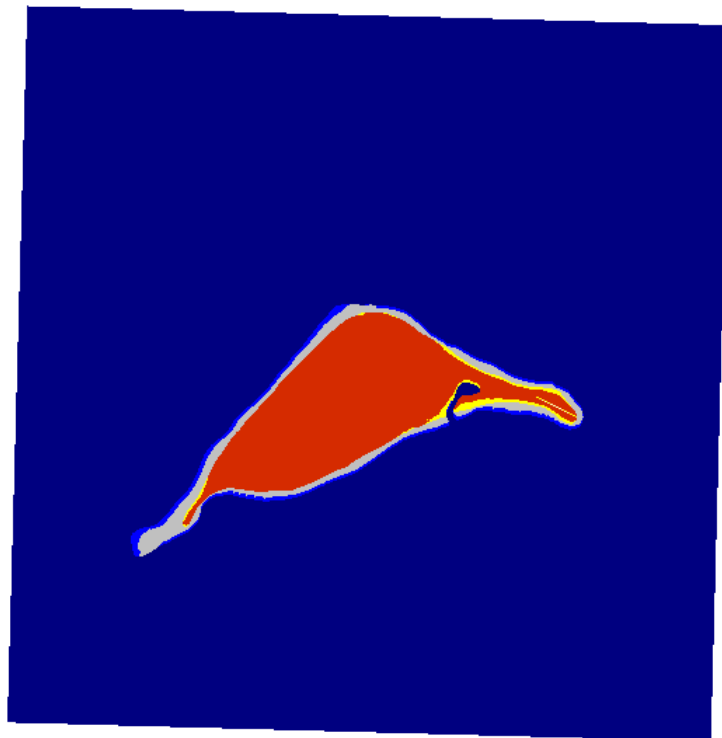
Protection Island NWR, 2025, Scenario A1B Mean, 0.39 m SLR



Protection Island NWR, 2050, Scenario A1B Mean, 0.39 m SLR



Protection Island NWR, 2075, Scenario A1B Mean, 0.39 m SLR







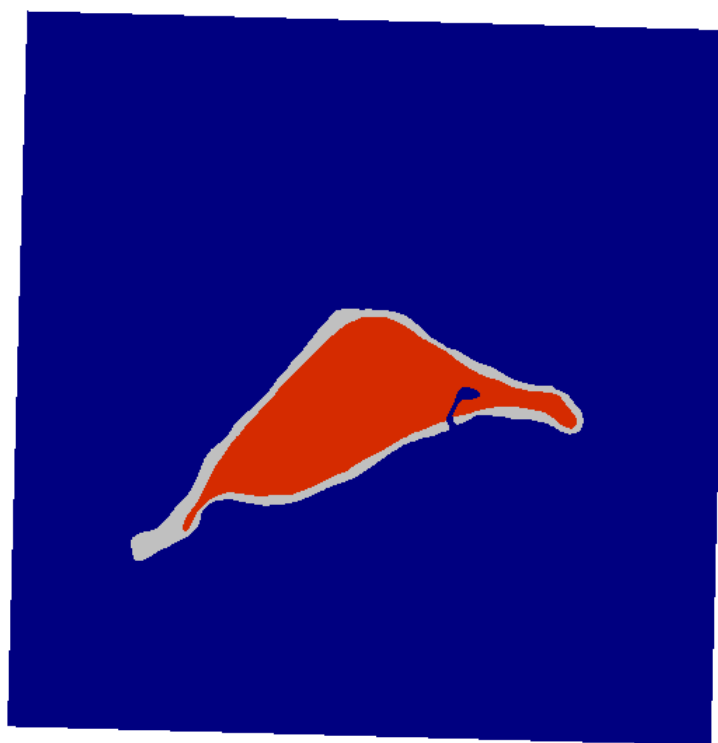
Protection Island NWR, 2100, Scenario A1B Mean, 0.39 m SLR

Protection Island NWR

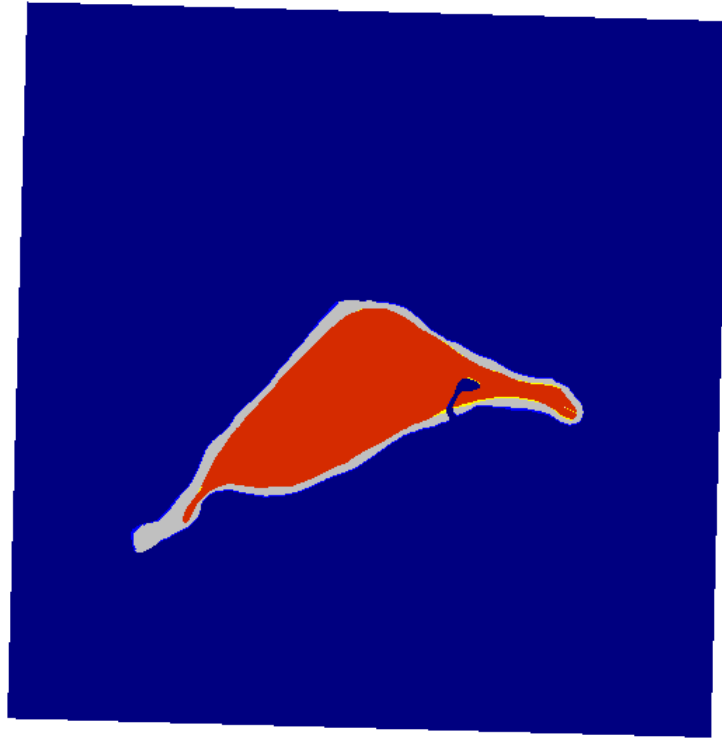
IPCC Scenario A1B-Max, 0.69 m SLR eustatic by 2100

Results in Acres

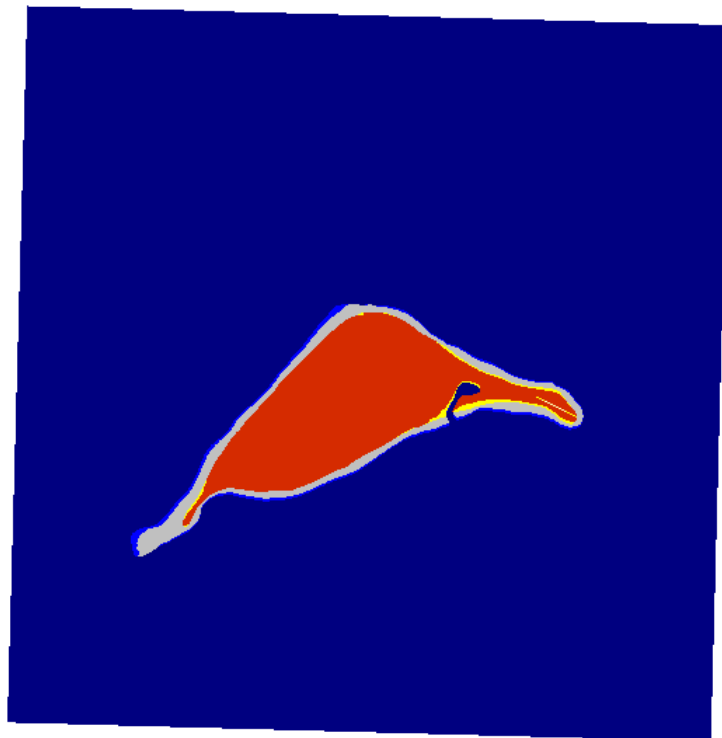
		Initial	2025	2050	2075	2100
	Undeveloped Dry Land	363	359	350	340	326
	Tidal Flat	122	104	92	76	58
	Estuarine Open Water	0	19	31	47	65
	Ocean Beach	0	4	12	22	36
	Total	485	485	485	485	485



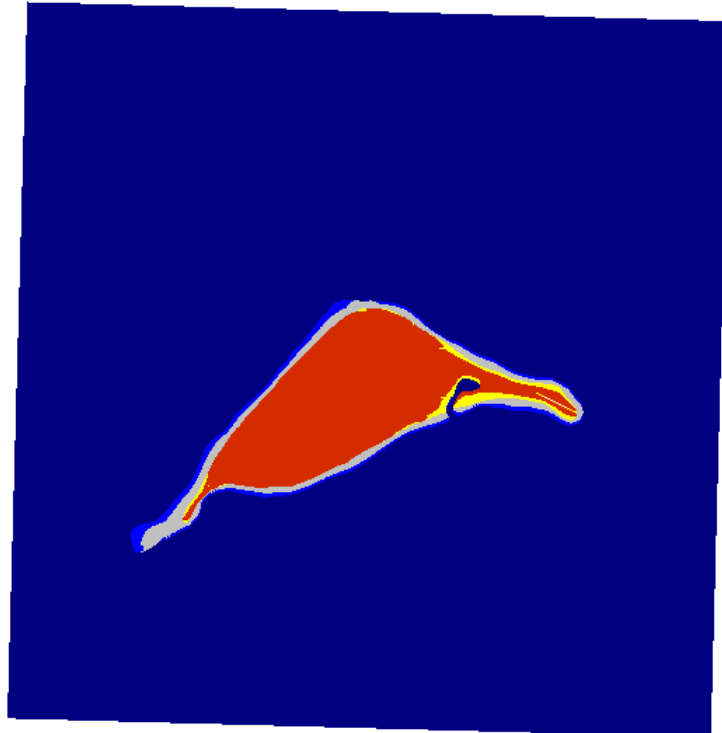
Protection Island NWR, Initial Condition



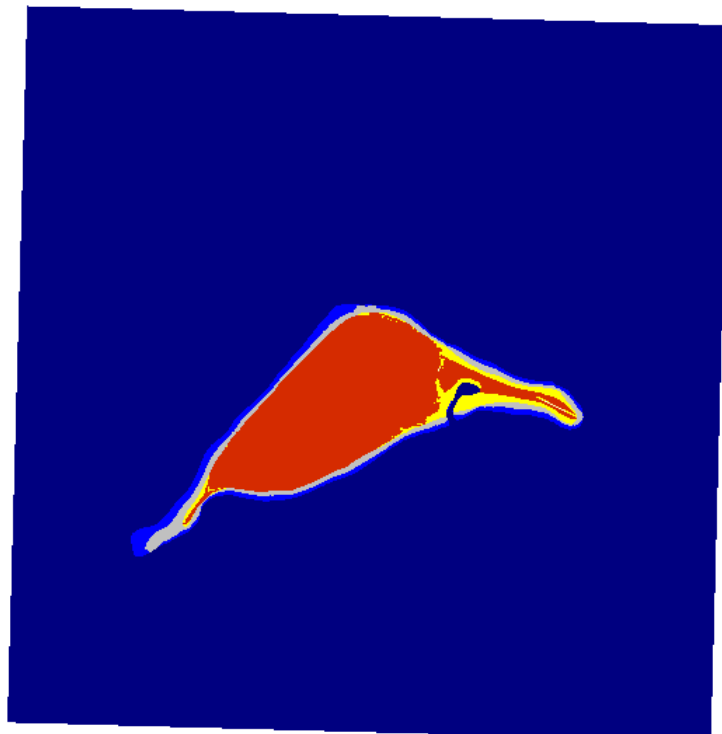
Protection Island NWR, 2025, Scenario A1B Maximum, 0.69 m SLR



Protection Island NWR, 2050, Scenario A1B Maximum, 0.69 m SLR







Protection Island NWR, 2075, Scenario A1B Maximum, 0.69 m SLR

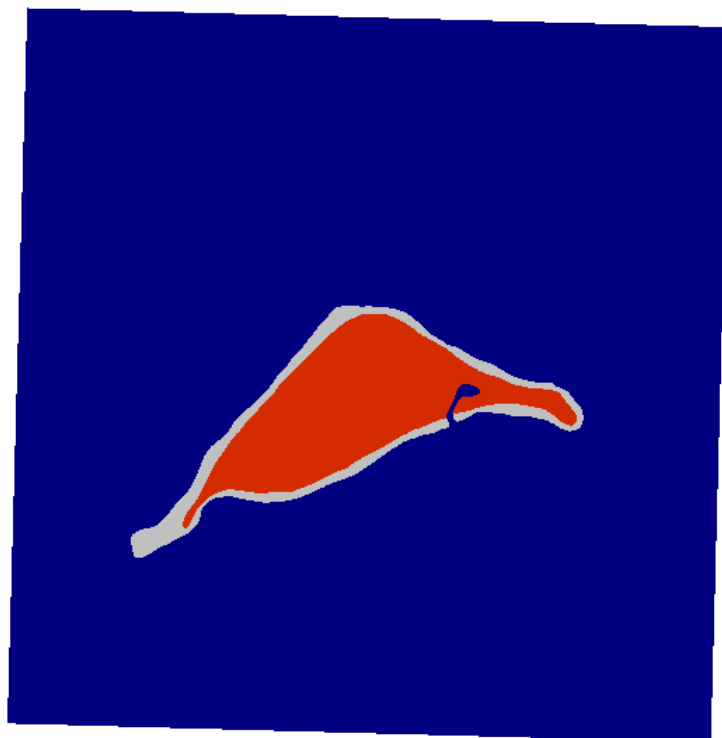


Protection Island NWR, 2100, Scenario A1B Maximum, 0.69 m SLR

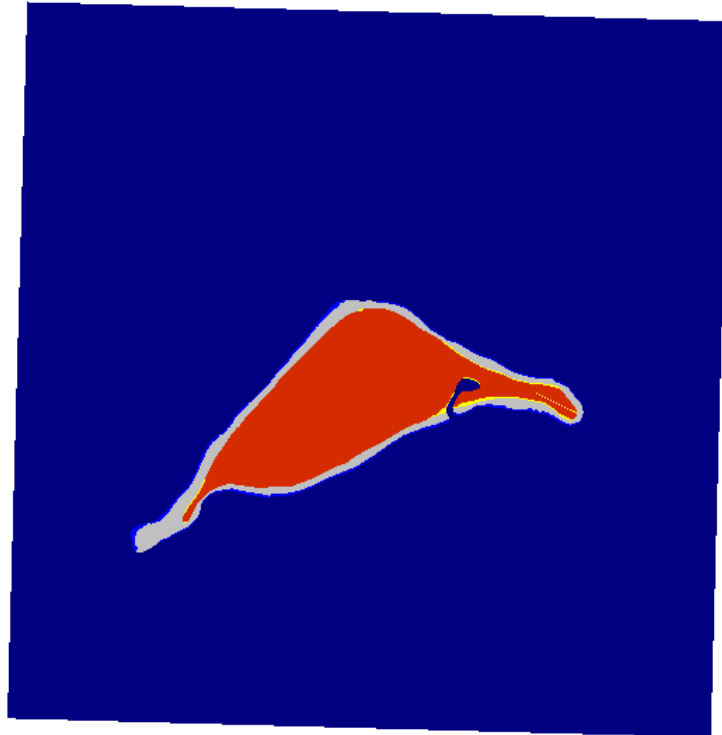
Protection Island NWR
1 m eustatic SLR by 2100

Results in Acres

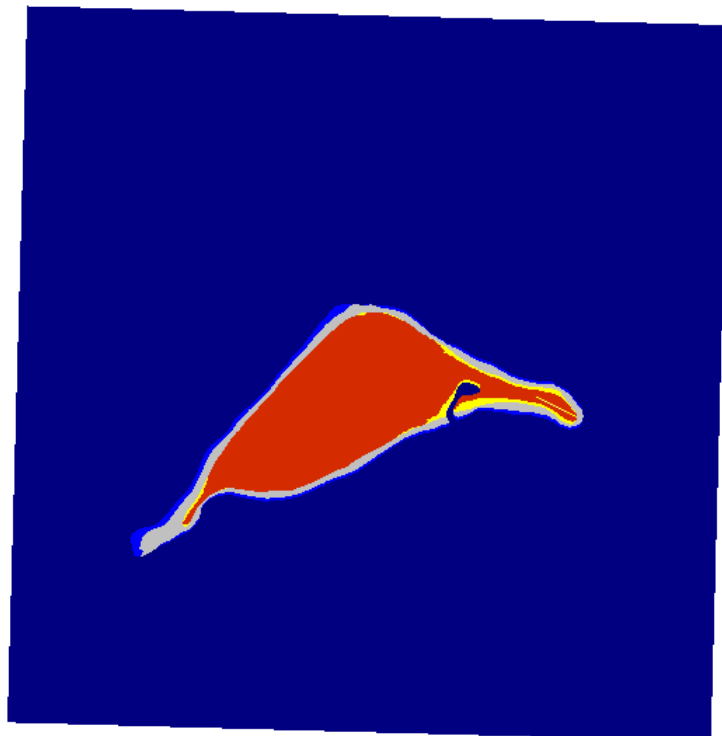
		Initial	2025	2050	2075	2100
	Undeveloped Dry Land	363	355	343	325	305
	Tidal Flat	122	99	82	57	29
	Estuarine Open Water	0	23	41	66	94
	Ocean Beach	0	7	19	37	57
	Total	485	485	485	485	485



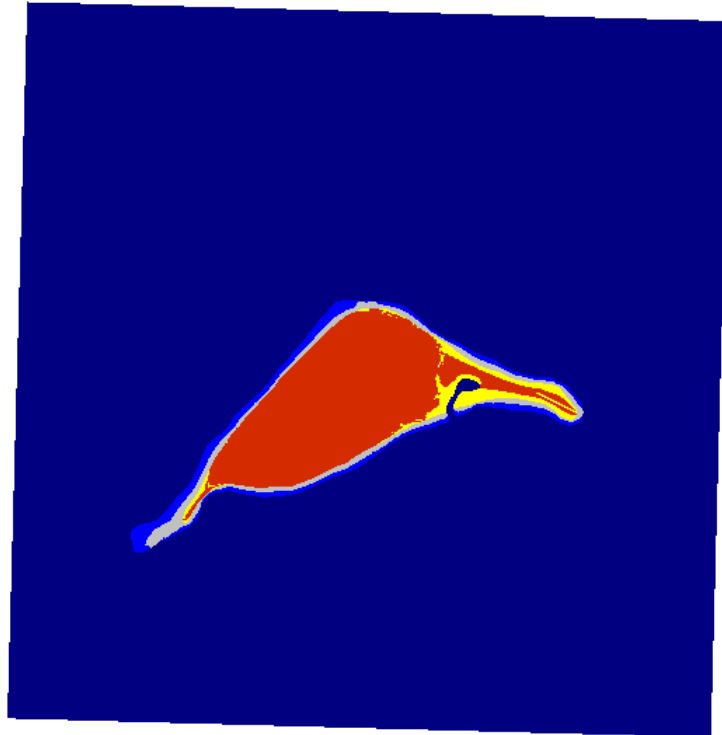
Protection Island NWR, Initial Condition



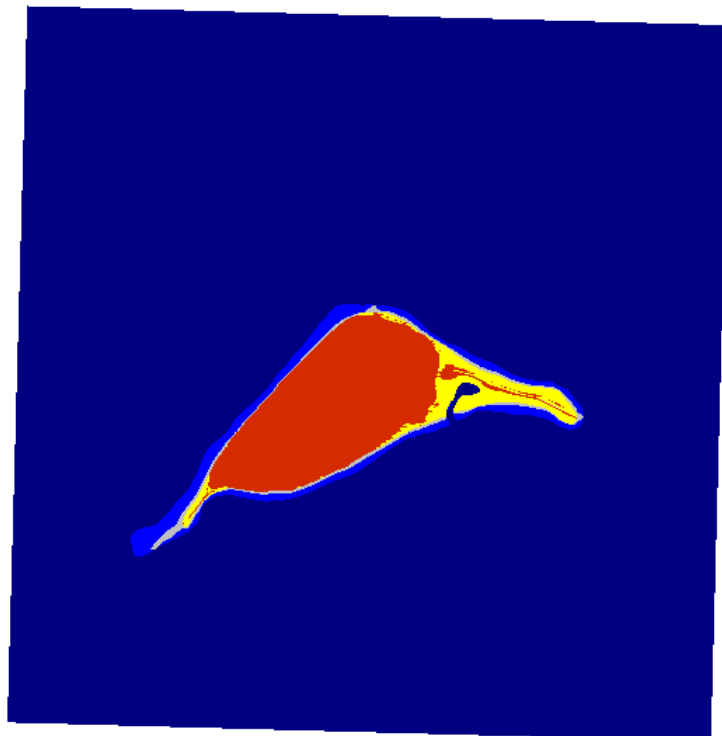
Protection Island NWR, 2025, 1 m SLR



Protection Island NWR, 2050, 1 m SLR







Protection Island NWR, 2075, 1 m SLR

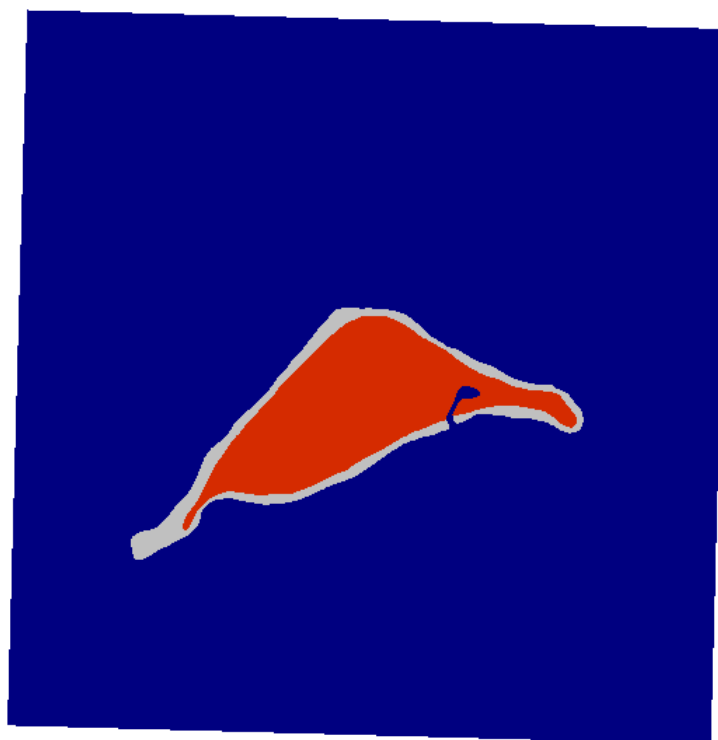


Protection Island NWR, 2100, 1 m SLR

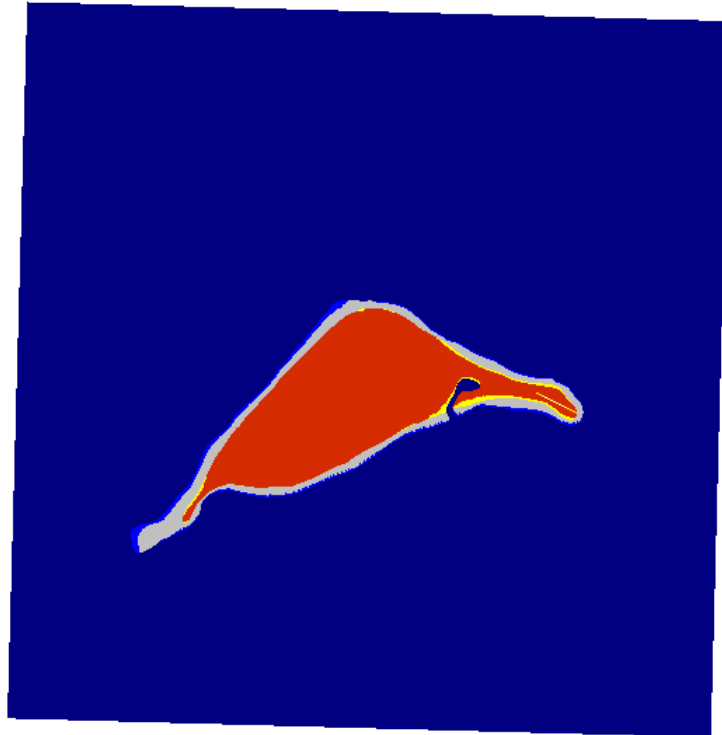
Protection Island NWR
1.5 m eustatic SLR by 2100

Results in Acres

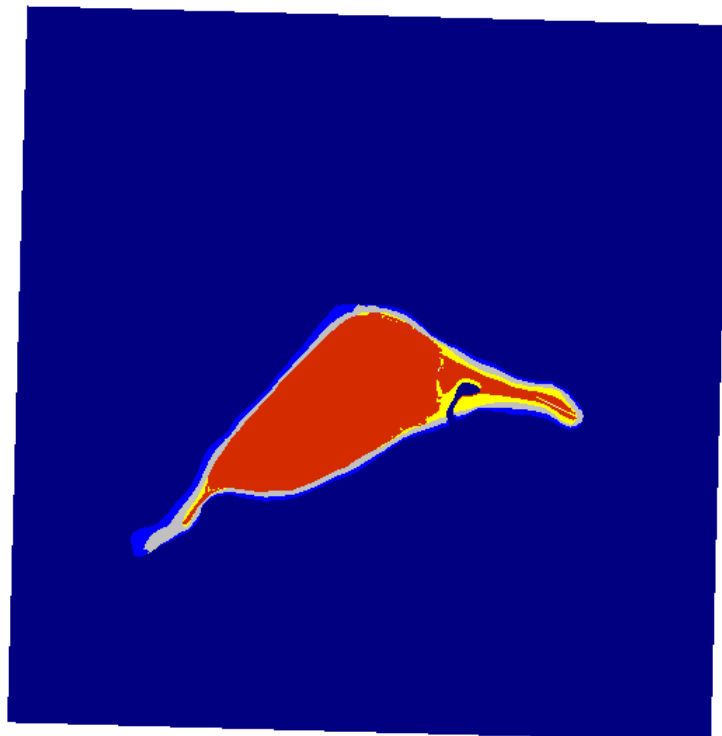
		Initial	2025	2050	2075	2100
	Undeveloped Dry Land	363	350	329	302	293
	Tidal Flat	122	93	64	22	0
	Estuarine Open Water	0	29	59	101	123
	Ocean Beach	0	12	33	60	68
	Total	485	485	485	485	485



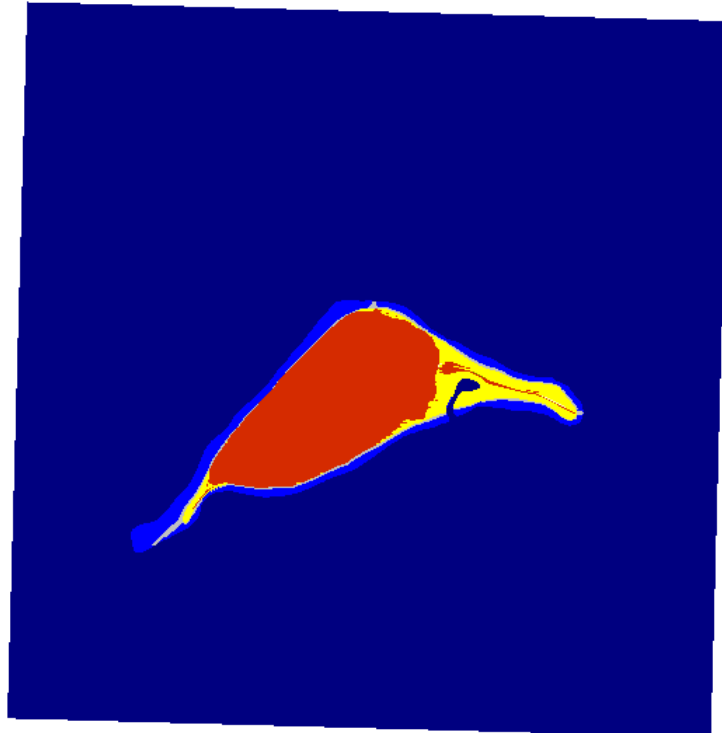
Protection Island NWR, Initial Condition



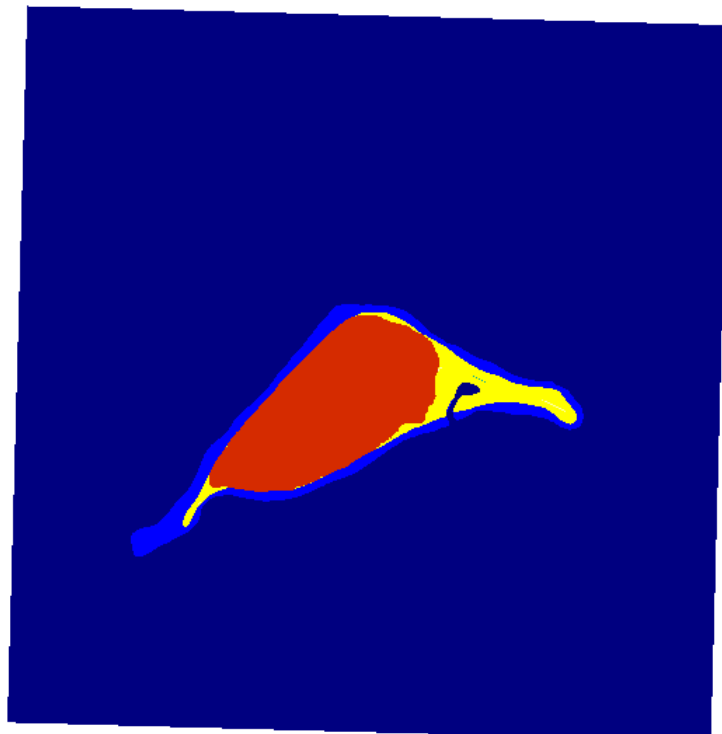
Protection Island NWR, 2025, 1.5 m SLR



Protection Island NWR, 2050, 1.5 m SLR



Protection Island NWR, 2075, 1.5 m SLR

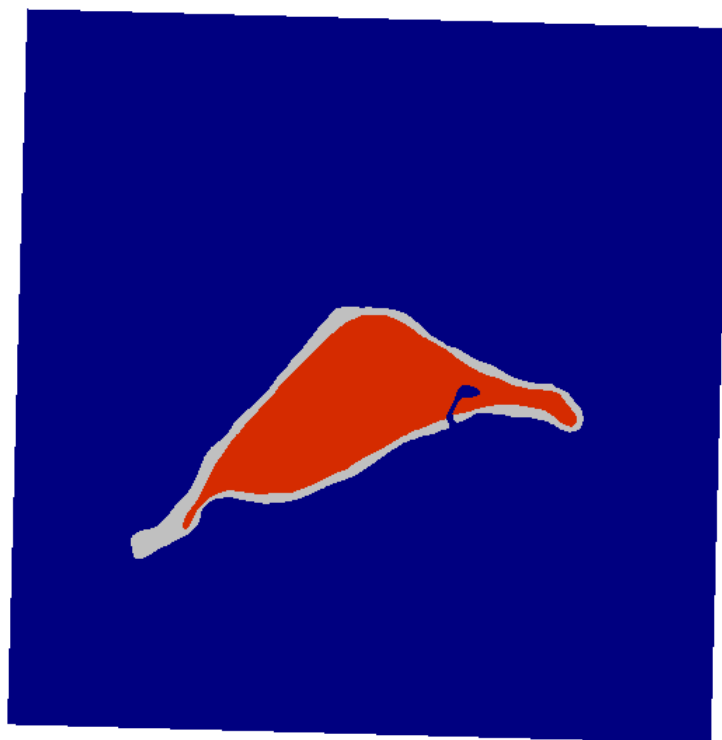


Protection Island NWR, 2100, 1.5 m SLR

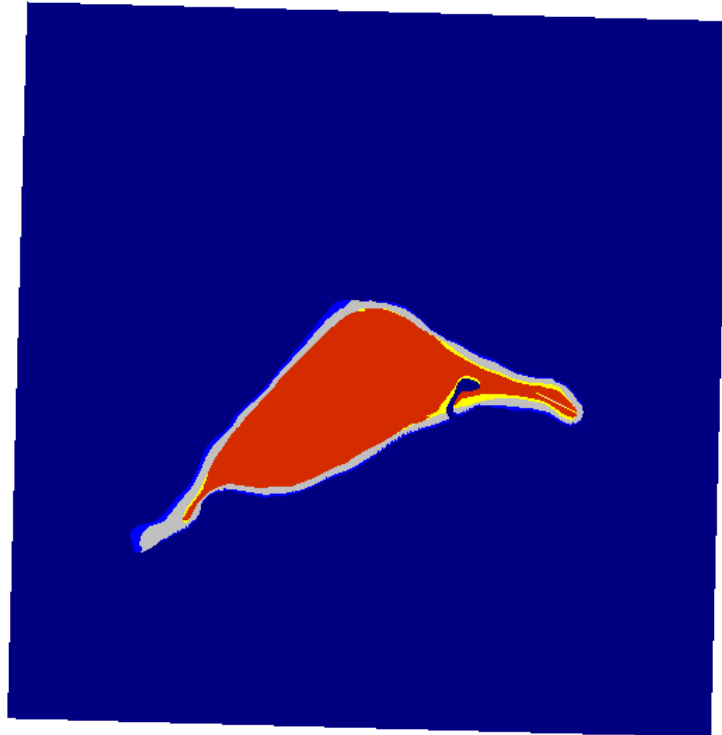
Protection Island NWR
2 m eustatic SLR by 2100

Results in Acres

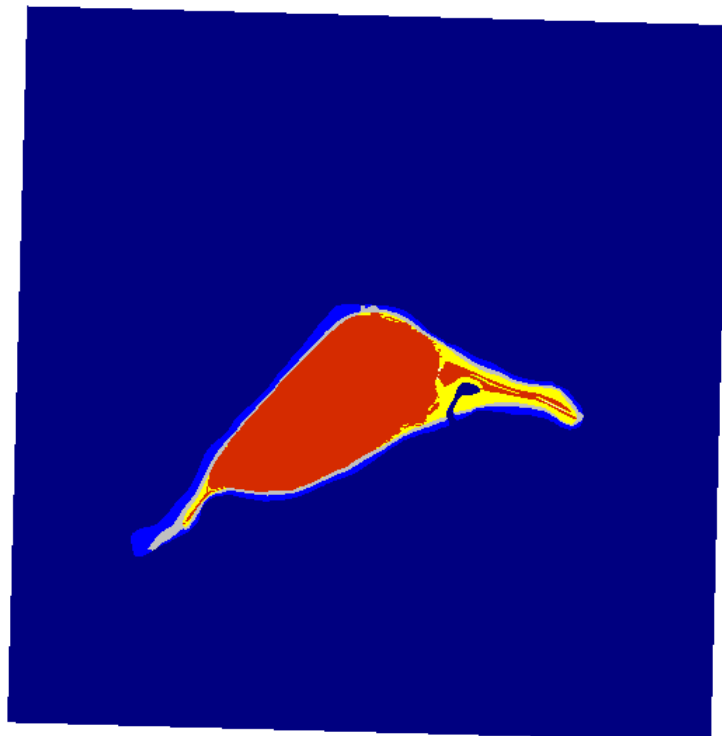
		Initial	2025	2050	2075	2100
	Undeveloped Dry Land	363	345	315	294	291
	Tidal Flat	122	86	43	0	0
	Estuarine Open Water	0	36	79	122	127
	Ocean Beach	0	17	46	68	65
	Total	485	485	485	485	485



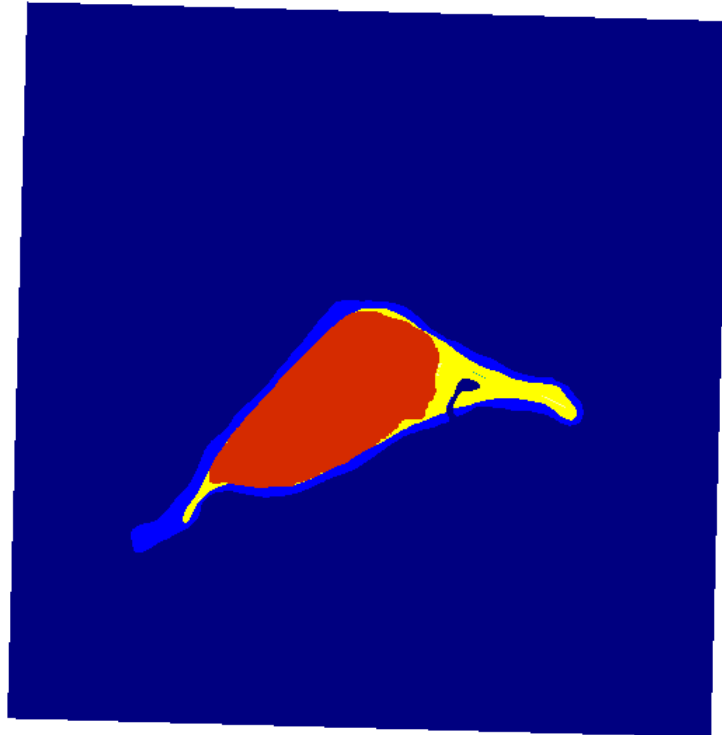
Protection Island NWR, Initial Condition



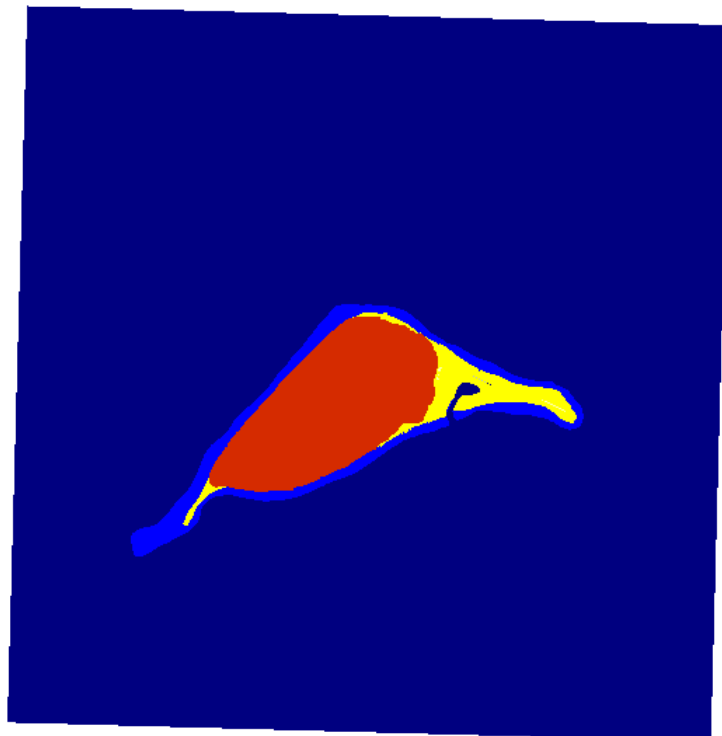
Protection Island NWR, 2025, 2 m SLR



Protection Island NWR, 2050, 2 m SLR



Protection Island NWR, 2075, 2 m SLR



Protection Island NWR, 2100, 2 m SLR

Discussion

Model results for Protection Island NWR indicate that overall the refuge is fairly resilient to the SLR scenarios examined. The majority of the study area is located at elevations that preclude effects from SLR by 2100 (e.g., more than 80% of the island dry land has elevations greater than 2 m).

Some dry lands at lower elevations in the eastern portion of the study area are predicted to be adversely affected by SLR scenarios up to 1 m. These land covers are predicted to be increasingly converted to ocean beach as sea levels continues to rise. The existing tidal flat surrounding the island is also predicted to slowly disappear as result of SLR with a total loss by 2100 for SLR scenarios greater than 1.5 m.

The distinction between beach and tidal flat may be less evident than these simulations suggest. Although the NWI layer does not separately categorize these two land covers, it is reasonable to assume that there is currently some beach habitat between the tidal flat and dry land. Similarly, the predicted beaches formed by 2100 may include some tidal flat habitats.

When considering model uncertainty, it is also important to note that the elevation data used are not LiDAR; therefore additional uncertainty in characterizing these lower-elevation land covers is certainly present.

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