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

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Introduction

Tidal marshes are among the most susceptible ecosystems to climate change, especially accelerated sea level rise (SLR). The International 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 could be 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 brackish 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 most 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, J.K., R.A. Park, and P.W. Mausel. 1992; Park, R.A., J.K. Lee, and D. Canning 1993; Galbraith, H., R. Jones, R.A. Park, J.S. Clough, S. Herrod-Julius, B. Harrington, and G. Page. 2002; National Wildlife Federation et al., 2006; Glick, Clough, 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 width are assumed to undergo overwash during each 25-year time-step due to 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 or can be specified to respond to feedbacks such as frequency of inundation.

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 confirm the SLAMM conceptual model at each site.
- 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, Park, Fuller, 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 (CREM 2008). Site-specific factors that increase or decrease model uncertainty may be covered in the *Discussion* section of this report.

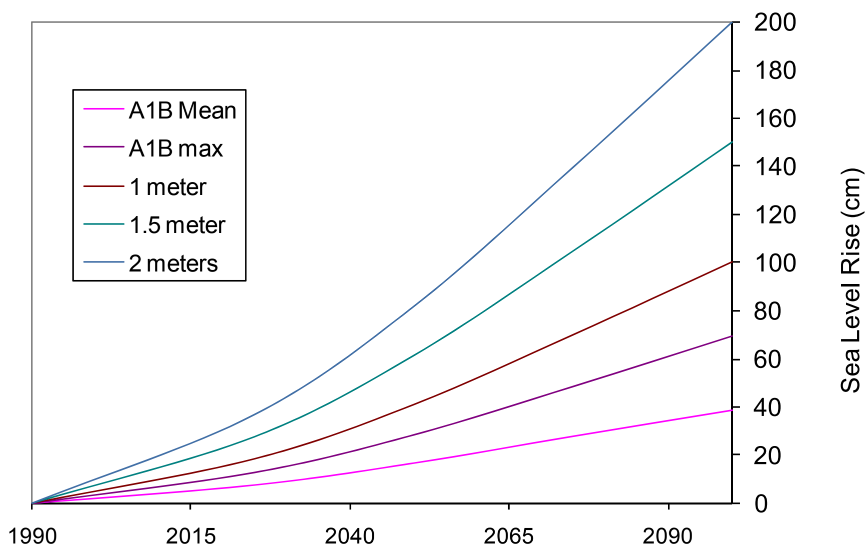
Sea Level Rise Scenarios

SLAMM 6 was run using scenario A1B from the Special Report on Emissions Scenarios (SRES) – mean and maximum estimates. The A1 scenario assumes that the future world includes very 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 (IPC, 2007) suggests a likely range of 0.21 to 0.48 meters of sea level rise by 2090-2099 "excluding future rapid dynamical changes in ice flow." The A1B-mean scenario that was run as a part of this project falls near the middle of this estimated range, predicting 0.40 meters of global sea level rise 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 might be 50 to 140 cm. This work was recently updated and the ranges were increased to 75 to 190 cm (Vermeer and Rahmstorf, 2009). Pfeffer et al. (2008) suggests that 2 meters by 2100 is at the upper end of plausible scenarios due to physical limitations on glaciological conditions. A recent US intergovernmental report states "Although no ice-sheet model is currently capable of capturing the glacier speedups in Antarctica or Greenland that have been observed over the last decade, including these processes in models will very likely show that IPCC AR4 projected sea level rises for the end of the 21st century are too low." (US Climate Change Science Program, 2008) 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, with low probability of the rise being within Intergovernmental Panel on Climate Change (IPCC) confidence limits."

To allow for flexibility when interpreting the results, SLAMM was also run assuming 1 meter, 1½ meters, and 2 meters of eustatic sea-level rise by the year 2100. The A1B- maximum scenario was scaled up to produce these bounding scenarios (Figure 1).

Figure 1: Summary of SLR Scenarios Utilized



Methods and Data Sources

The digital elevation map used in this simulation was supplied by Oregon DOGAMI (Department of Geology and Mineral Industries) and is based on high-resolution LiDAR with a 2008 photo date (Figure 1).

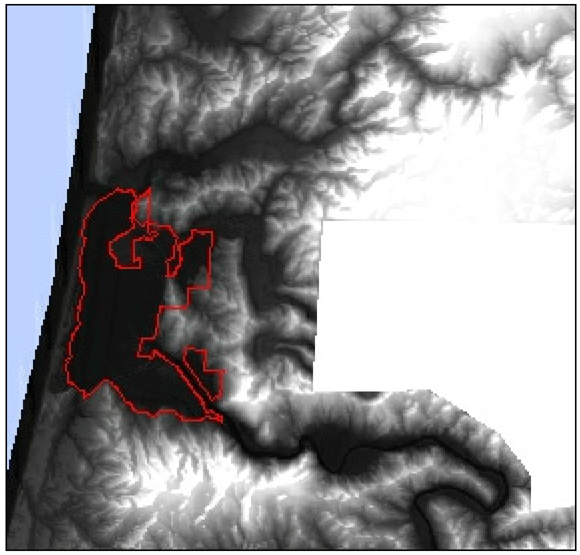


Figure 1: Extent of LiDAR coverage over the refuge.

The wetlands layer for the study area was produced by the Oregon Wetlands Program and is based on a 1995 photo date. Within the refuge, ambiguous NWI code "E2USN" was assigned as tidal flat (rather than estuarine beach), based on the satellite imagery shown in Figure 2.

Figure 2: Areas designated as tidal flat.

Based on communication with Khem So (from the USFWS Oregon Coastal NWR Complex), an area behind the Siletz River Highway has uncertain tidal range due to the effects of a partly functional tidegate at this location Lacking local tidal data describing the spatial extent of tidal muting this region was designated as "protected by dikes" (Figure 3 and Figure 4).

Figure 3: Tidally muted area being Siletz River Highway. See for **Figure 4** area context.

Converting the NWI survey into 15 meter cells indicates that the approximately two thousand acre refuge (approved acquisition boundary including water) is composed of the following categories:

Tidal Flat	35.7%
Undev. Dry Land	19.8%
Saltmarsh	14.0%
Estuarine Open Water	13.0%
Brackish Marsh	11.7%
Inland Fresh Marsh	3.1%

The layer indicating lands protected by dikes or levees was derived using information from the Oregon Wetlands Program (along with the addition of the diked location behind the Siletz River highway). Figure 4 shows the assumed dike coverage for this study area.

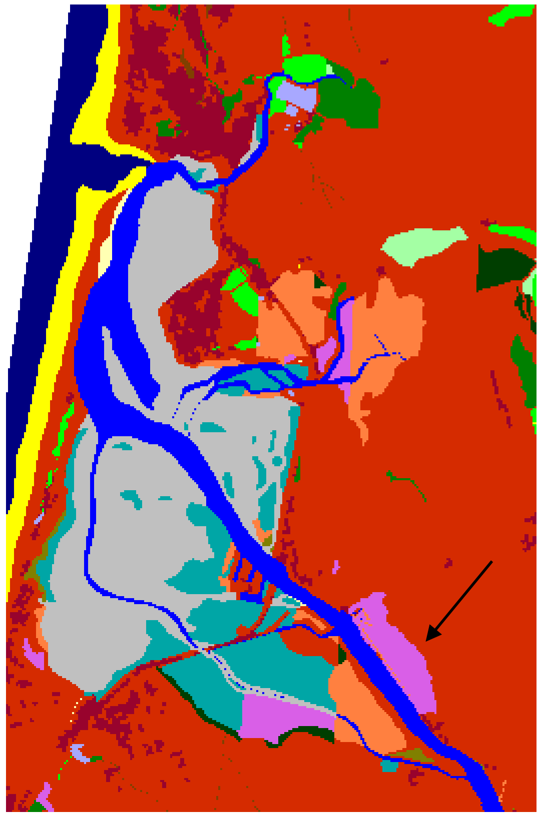


Figure 4: Dike layer in purple. Diked location behind Siletz River Highway denoted by arrow.

The historic trend for sea level rise was estimated at 2.72 mm/year using the nearest NOAA gage with SLR data (9435380, South Beach, OR). This rate of sea level rise is higher than the global average for the last 100 years (approximately 1.7 mm/year). This estimated difference between local and global SLR is assumed to remain constant into future SLR projections.

The tide range was estimated at 1.89 meters (great diurnal range or GT) using NOAA tide table entry for Kernville, Siletz River.

Marsh accretion was set to 3 mm/year based on an accretion study performed in Salmon River (Thom, 1992). No site-specific accretion data were available for this site, but this value is consistent with the regional average of 3.8 mm/year for the Pacific Northwest as described by Thom (1992).

Direct erosion of marshes was assumed to be negligible for this site. SLAMM assumes marsh erosion only when adequate oceanic fetch exists to allow for wave setup. The protected location of this refuge, therefore, precludes model predictions of marsh erosion. Additionally, marsh erosion at this site may be assumed to be minimal due to the depositional nature of the Siletz River Estuary (due to logging activities in the nearby watersheds, Pakenham, 2009).

The MTL to NAVD88 correction was derived using the NOAA VDATUM product. The value of 1.14 meter was used based on the average values from several locations ranging from 1.12 meters to around 1.16.

Modeled U.S. Fish and Wildlife Service 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 15 meter by 15 meter cells. Note that the SLAMM model will also track partial conversion of cells based on elevation and slope.

Erin Stockenberg and Khem So, both of Oregon USFWS, each helped us in our data and parameterization search.

SUMMARY OF SLAMM INPUT PARAMETERS FOR SILETZ BAY NWR

Parameter	Global	SubSite 2
Description	Context	Siletz
NWI Photo Date (YYYY)	2000	1995
DEM Date (YYYY)	2008	2008
Direction Offshore [n,s,e,w]	West	West
Historic Trend (mm/yr)	2.72	2.72
MTL-NAVD88 (m)	1.14	1.14
GT Great Diurnal Tide Range (m)	2.165	1.89
Salt Elev. (m above MTL)	1.44	1.257
Marsh Erosion (horz. m /yr)	0	0
Swamp Erosion (horz. m /yr)	0	0
T.Flat Erosion (horz. m /yr)	0	0
Reg. Flood Marsh Accr (mm/yr)	3	3
Irreg. Flood Marsh Accr (mm/yr)	3	3
Tidal Fresh Marsh Accr (mm/yr)	3	3
Beach Sed. Rate (mm/yr)	0.5	0.5
Freq. Overwash (years)	0	0
Use Elev Pre-processor [True,False]	FALSE	FALSE

Results

The SLAMM simulation of Siletz Bay NWR predicts that irregularly flooded (brackish) marsh – which comprises roughly 12% of the refuge – is susceptible to loss in the highest SLR scenarios. Dry land loss rates are predicted to range from 12%-40% by 2100. Loss of refuge tidal flat – which comprises slightly more than one third of the refuge – is only predicted in the most extreme SLR scenario.

SLR by 2100 (m)	0.39	0.69	1	1.5	2
Tidal Flat	0%	0%	-2%	-13%	29%
Undev. Dry Land	12%	20%	26%	34%	40%
Saltmarsh	-4%	-13%	-27%	-63%	40%
Brackish Marsh	-2%	-2%	2%	65%	86%
Inland Fresh Marsh	6%	9%	11%	13%	15%

Predicted Loss Rates of Land Categories by 2100 Given Simulated Scenarios of Eustatic Sea Level Rise

Maps of SLAMM input and output to follow will use the following legend:

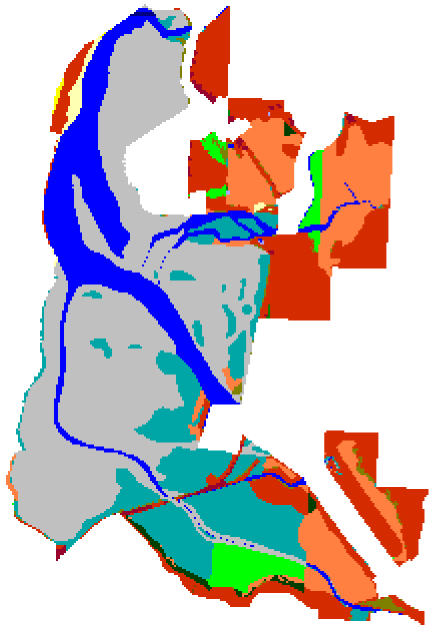
Siletz Raster
IPCC Scenario A1B-Mean, 0.39 M SLR Eustatic by 2100

Results in Acres

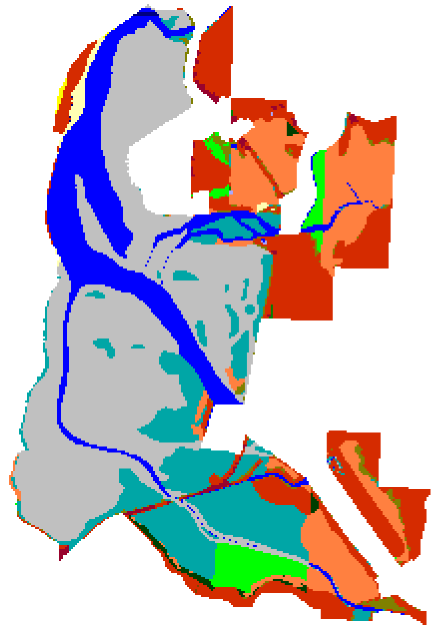
	Initial	2025	2050	2075	2100
Tidal Flat	715.8	716.1	716.4	716.5	716.8
Undev. Dry Land	395.6	377.4	371.5	362.3	348.7
Saltmarsh	280.6	286.4	287.3	289.3	291.8
Estuarine Open Water	261.3	260.4	260.5	260.5	260.5
Brackish Marsh	234.6	235.4	237.3	238.8	239.6
Inland Fresh Marsh	62.4	60.9	60.2	59.2	58.4
Tidal Swamp	18.1	15.9	13.7	11.7	10.5
Dev. Dry Land	15.3	14.3	14.1	14.0	13.8
Estuarine Beach	9.5	12.1	12.1	12.2	12.3
Trans. Salt Marsh	5.1	18.6	24.2	32.8	44.5
Ocean Beach	1.9	2.0	2.0	1.9	2.0
Inland Open Water	1.1	0.6	0.6	0.6	0.6
Swamp	0.7	0.7	0.7	0.7	0.7
Inland Shore	0.2	0.2	0.2	0.2	0.2
Open Ocean	0.0	1.4	1.6	1.7	2.0
Total (incl. water)	**2002.3**	**2002.3**	**2002.3**	**2002.3**	**2002.3**

Siletz Bay NWR, Initial Condition

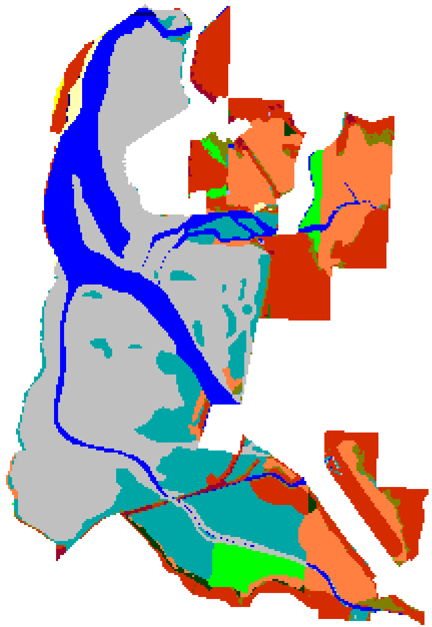
Siletz Bay NWR, 2025, Scenario A1B Mean



Siletz Bay NWR, 2050, Scenario A1B Mean



Siletz Bay NWR, 2075, Scenario A1B Mean



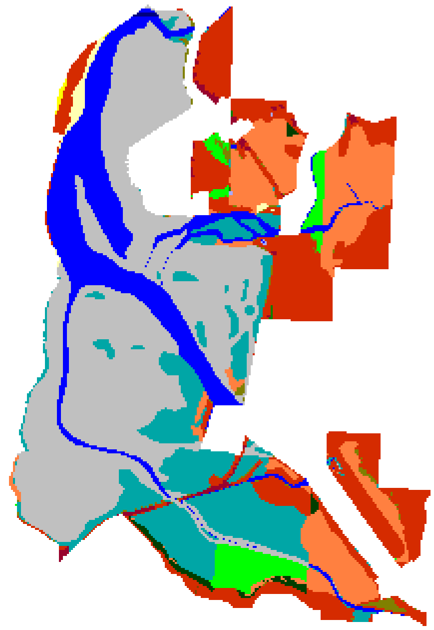
Siletz Bay NWR, 2100, Scenario A1B Mean

Siletz Raster
IPCC Scenario A1B-Max, 0.69 M SLR Eustatic by 2100

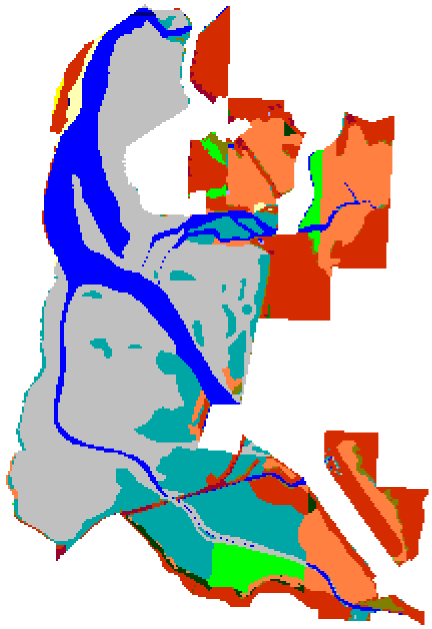
Results in Acres

	Initial	2025	2050	2075	2100
Tidal Flat	715.8	716.2	716.7	717.3	717.9
Undev. Dry Land	395.6	375.3	364.6	341.8	317.5
Saltmarsh	280.6	287.6	291.3	299.1	318.0
Estuarine Open Water	261.3	260.4	260.5	260.6	253.3
Brackish Marsh	234.6	236.1	238.5	239.3	239.9
Inland Fresh Marsh	62.4	60.2	58.7	57.5	56.6
Tidal Swamp	18.1	14.8	11.7	9.5	7.0
Dev. Dry Land	15.3	14.2	14.0	13.7	13.2
Estuarine Beach	9.5	12.1	12.2	12.3	12.4
Trans. Salt Marsh	5.1	20.4	29.1	45.8	53.4
Ocean Beach	1.9	2.0	1.5	0.2	0.0
Inland Open Water	1.1	0.6	0.6	0.5	0.4
Swamp	0.7	0.7	0.7	0.7	0.7
Inland Shore	0.2	0.2	0.2	0.2	0.2
Open Ocean	0.0	1.4	2.1	3.8	11.9
Total (incl. water)	**2002.3**	**2002.3**	**2002.3**	**2002.3**	**2002.3**

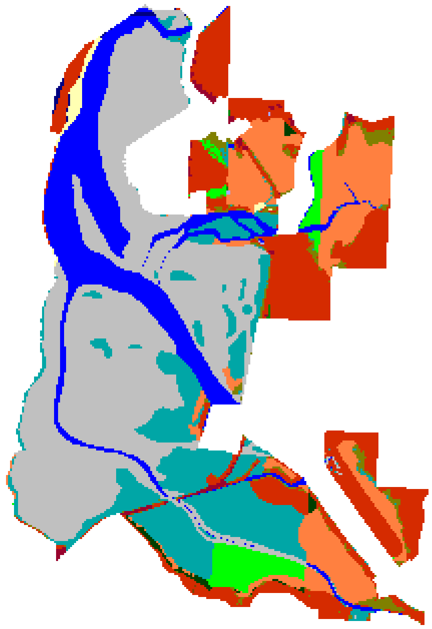
Siletz Bay NWR, Initial Condition



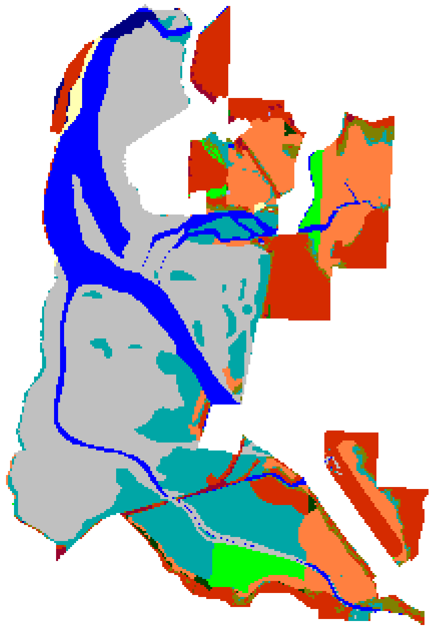
Siletz Bay NWR, 2025, Scenario A1B Maximum



Siletz Bay NWR, 2050, Scenario A1B Maximum



Siletz Bay NWR, 2075, Scenario A1B Maximum



Siletz Bay NWR, 2100, Scenario A1B Maximum

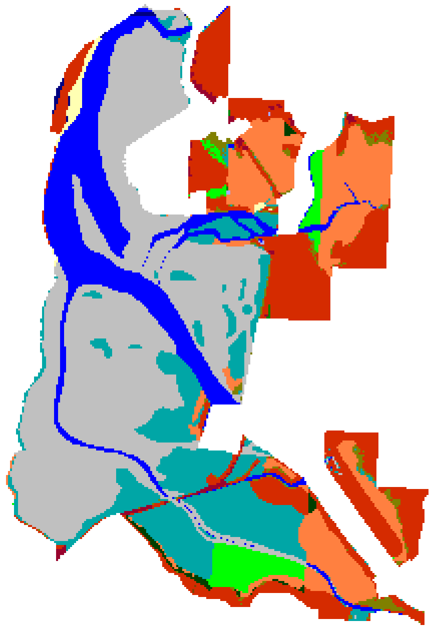
Siletz Raster
1 Meter Eustatic SLR by 2100

Results in Acres

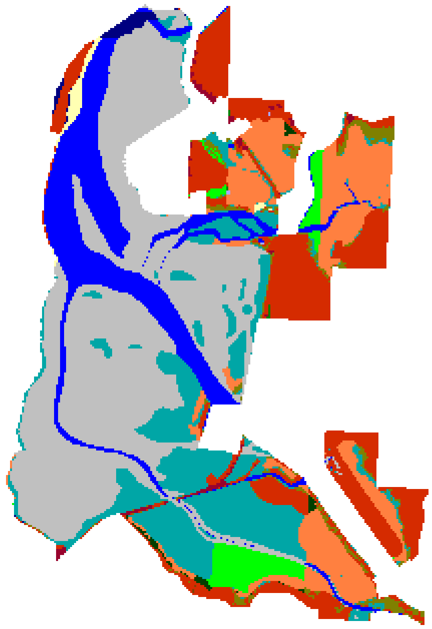
	Initial	2025	2050	2075	2100
Tidal Flat	715.8	716.3	717.2	718.4	727.4
Undev. Dry Land	395.6	372.9	353.6	320.5	291.4
Saltmarsh	280.6	289.1	296.7	319.2	357.1
Estuarine Open Water	261.3	260.5	260.5	253.2	254.0
Brackish Marsh	234.6	237.0	238.8	239.0	229.8
Inland Fresh Marsh	62.4	59.4	57.8	56.3	55.5
Tidal Swamp	18.1	13.6	10.4	7.1	4.3
Dev. Dry Land	15.3	14.2	13.9	13.3	12.2
Estuarine Beach	9.5	12.2	12.3	12.4	12.6
Trans. Salt Marsh	5.1	22.3	36.0	49.7	44.7
Ocean Beach	1.9	2.0	0.7	0.0	0.0
Inland Open Water	1.1	0.6	0.6	0.4	0.3
Swamp	0.7	0.7	0.7	0.7	0.5
Inland Shore	0.2	0.2	0.2	0.2	0.2
Open Ocean	0.0	1.5	3.2	11.8	12.3
Total (incl. water)	**2002.3**	**2002.3**	**2002.3**	**2002.3**	**2002.3**

Siletz Bay NWR, Initial Condition

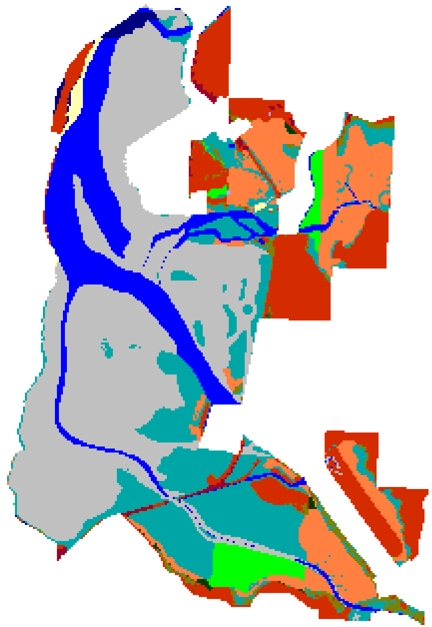
Siletz Bay NWR, 2025, 1 meter



Siletz Bay NWR, 2050, 1 meter



Siletz Bay NWR, 2075, 1 meter



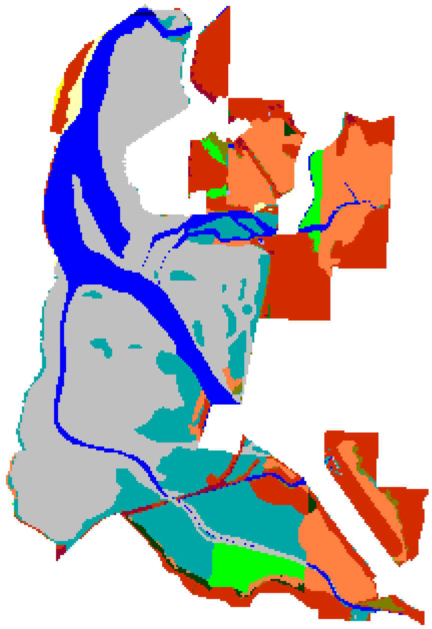
Siletz Bay NWR, 2100, 1 meter

Siletz Raster
1.5 Meters Eustatic SLR by 2100

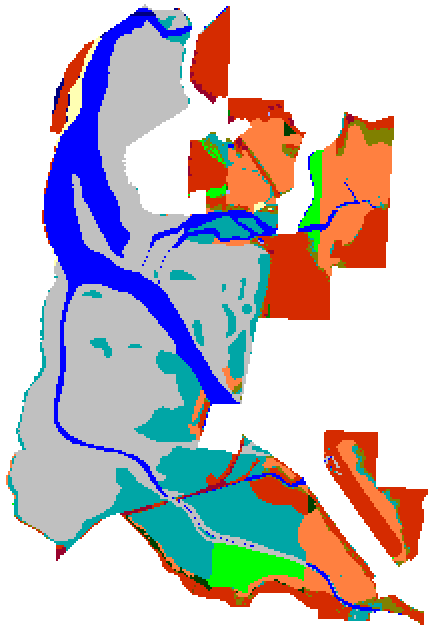
Results in Acres

	Initial	2025	2050	2075	2100
Tidal Flat	715.8	716.5	718.1	733.5	811.7
Undev. Dry Land	395.6	368.2	333.6	290.8	261.8
Saltmarsh	280.6	292.5	311.4	361.5	458.7
Estuarine Open Water	261.3	260.5	260.6	254.1	263.8
Brackish Marsh	234.6	237.9	238.7	216.9	81.9
Inland Fresh Marsh	62.4	58.5	56.6	55.3	54.4
Tidal Swamp	18.1	12.1	8.2	4.0	1.6
Dev. Dry Land	15.3	14.1	13.6	12.2	10.4
Estuarine Beach	9.5	12.2	12.4	12.6	12.2
Trans. Salt Marsh	5.1	24.8	43.6	48.3	32.2
Ocean Beach	1.9	1.3	0.0	0.1	0.1
Inland Open Water	1.1	0.6	0.5	0.3	0.2
Swamp	0.7	0.7	0.7	0.4	0.1
Inland Shore	0.2	0.2	0.2	0.2	0.2
Open Ocean	0.0	2.3	4.0	12.2	13.0
Total (incl. water)	**2002.3**	**2002.3**	**2002.3**	**2002.3**	**2002.3**

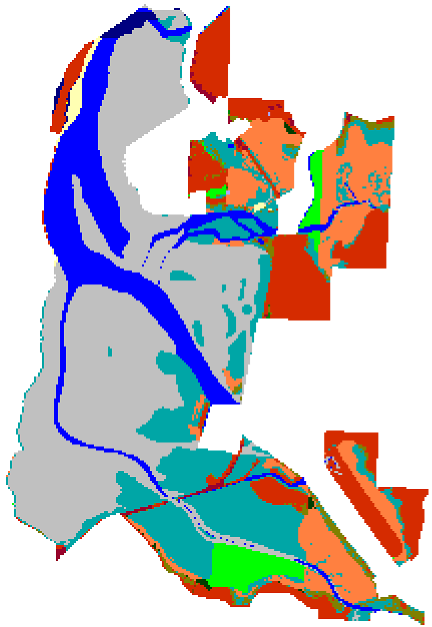
Siletz Bay NWR, Initial Condition



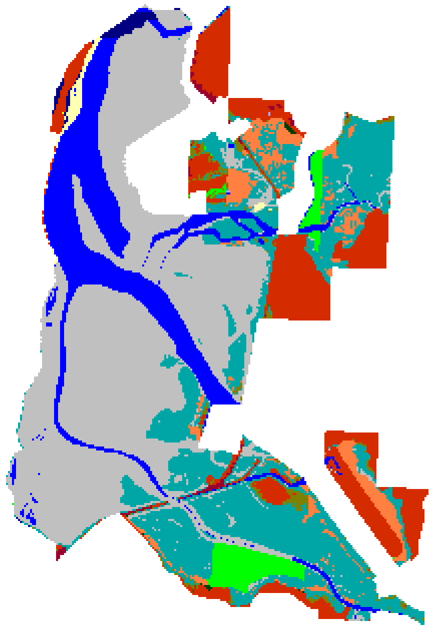
Siletz Bay NWR, 2025, 1.5 meter



Siletz Bay NWR, 2050, 1.5 meter



Siletz Bay NWR, 2075, 1.5 meter



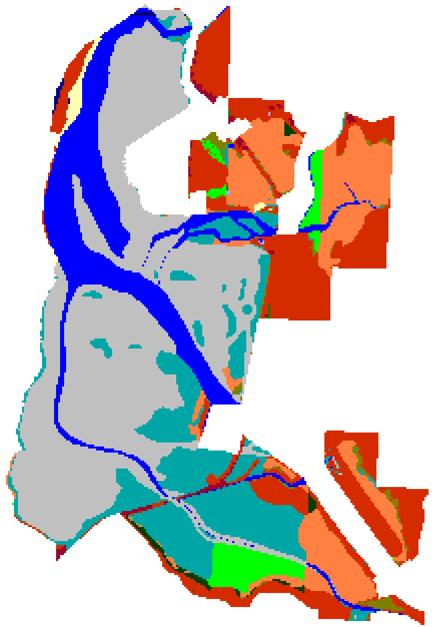
Siletz Bay NWR, 2100, 1.5 meter

Siletz Raster
2 Meters Eustatic SLR by 2100

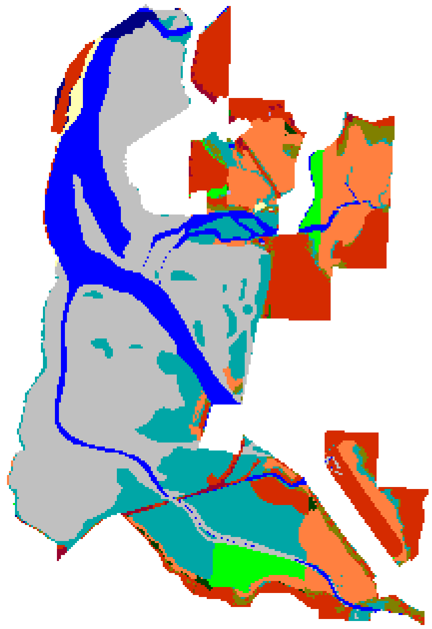
Results in Acres

	Initial	2025	2050	2075	2100
Tidal Flat	715.8	716.8	721.1	793.4	511.3
Undev. Dry Land	395.6	362.5	313.7	268.9	236.0
Saltmarsh	280.6	296.2	323.6	436.3	169.4
Estuarine Open Water	261.3	260.5	253.3	256.4	938.0
Brackish Marsh	234.6	238.2	235.4	105.2	32.3
Inland Fresh Marsh	62.4	58.0	55.7	54.6	53.1
Tidal Swamp	18.1	11.1	6.0	1.9	1.0
Dev. Dry Land	15.3	14.0	13.1	10.9	8.9
Estuarine Beach	9.5	12.3	12.5	12.8	4.9
Trans. Salt Marsh	5.1	27.8	54.8	48.5	33.5
Ocean Beach	1.9	0.5	0.1	0.1	0.0
Inland Open Water	1.1	0.6	0.4	0.3	0.1
Swamp	0.7	0.7	0.7	0.1	0.0
Inland Shore	0.2	0.2	0.2	0.2	0.2
Open Ocean	0.0	3.1	11.8	12.7	13.7
Total (incl. water)	**2002.3**	**2002.3**	**2002.3**	**2002.3**	**2002.3**

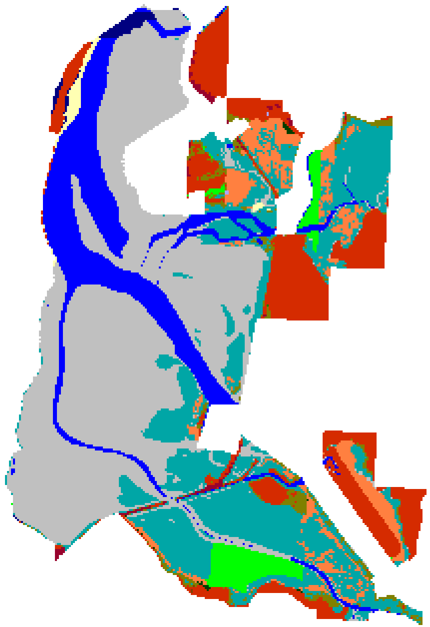
Siletz Bay NWR, Initial Condition



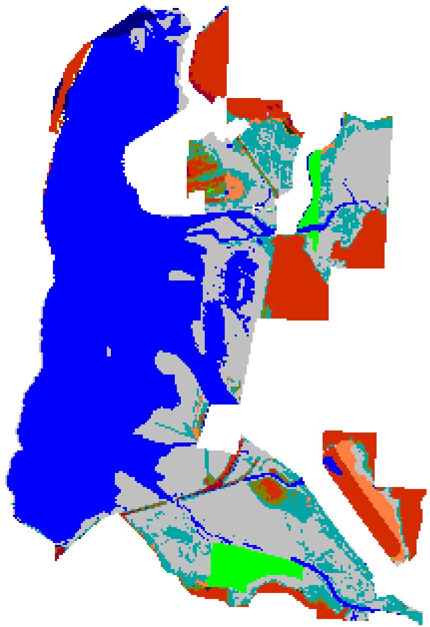
Siletz Bay NWR, 2025, 2 meters



Siletz Bay NWR, 2050, 2 meters



Siletz Bay NWR, 2075, 2 meters



Siletz Bay NWR, 2100, 2 meters

Discussion

Relative to many other refuges, Siletz NWR is predicted to be fairly resilient to sea level rise. The best available elevation data suggest that wetlands within this refuge exist at relatively high elevations. This means little wetland change is predicted in scenarios below 1.5 meters of eustatic SLR by 2100. Dry land is predicted to be more vulnerable with 12% to 40% lost over the full range of SLR scenarios explored.

Siletz Bay NWR is covered with high-vertical-resolution LiDAR elevation data which reduces model uncertainty and refines model predictions to some extent. For example the information that tidal flats exist at high elevations within the tidal frame is critical to predicting their relative resilience to SLR.

A study from Oregon State University indicates that the sedimentation rates for the Siletz River Estuary have been especially high due to logging activities in the nearby watersheds (Pakenham, 2009). This helps to explain higher wetland elevations at this site. However, this SLAMM simulation did not assume higher than regional accretion rates both due to a lack of specific local accretion data and also uncertainty about the extent of future sedimentation caused by logging activities.

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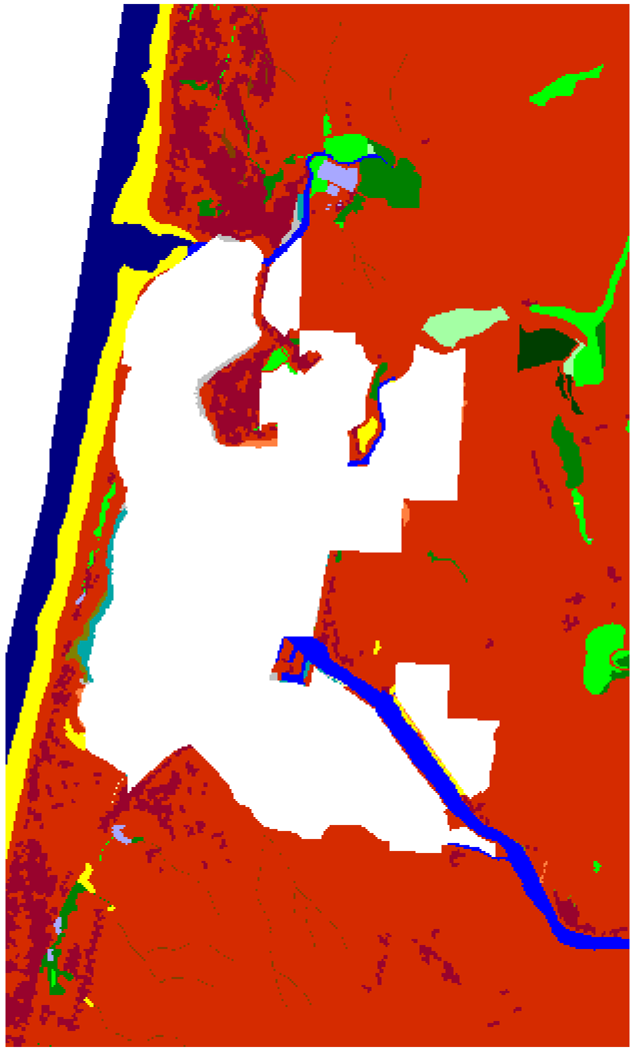
Appendix A: Contextual Results

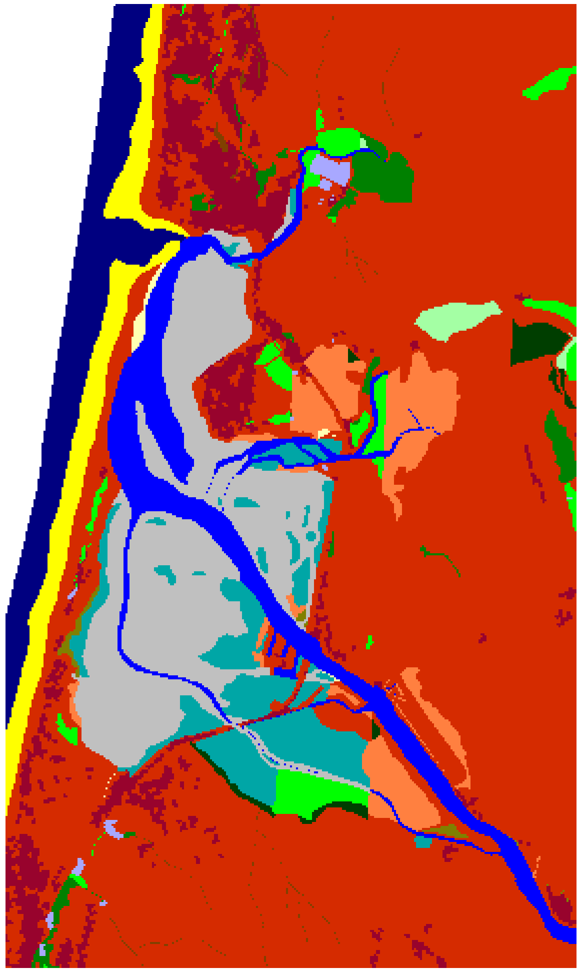
The SLAMM model does take into account the context of the surrounding lands or open water when calculating effects. For example, erosion rates are calculated based on the maximum fetch (wave action) which is estimated by assessing contiguous open water to a given marsh cell. Another example is that inundated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

For this reason, an area larger than the boundaries of the USFWS refuge was modeled. These results maps are presented here with the following caveats:

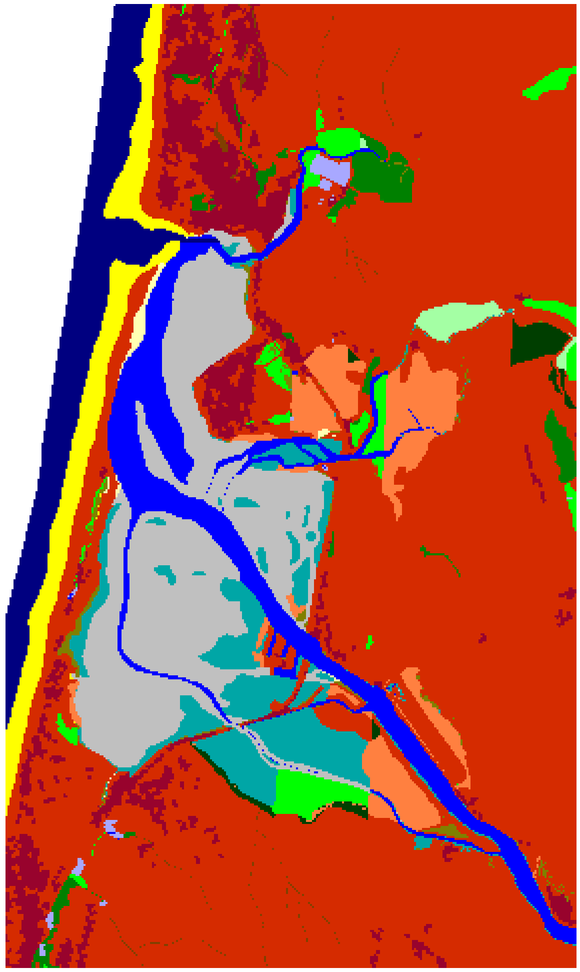
- Results were closely examined (quality assurance) within USFWS refuges but not closely examined for the larger region.
- Site-specific parameters for the model were derived for USFWS refuges whenever possible and may not be regionally applicable.
- Especially in areas where dikes are present, an effort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



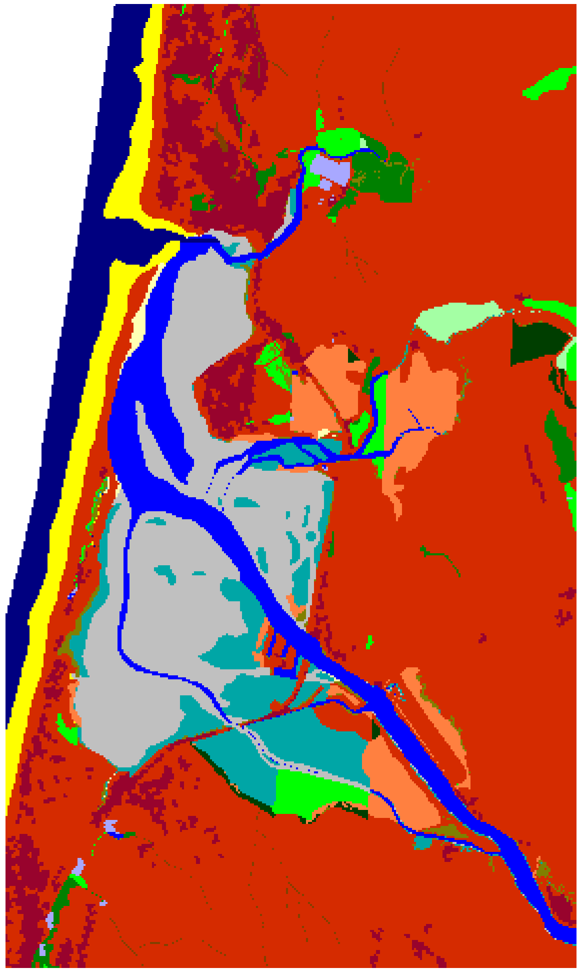
Location of Siletz Bay National Wildlife Refuge within simulation context (white).



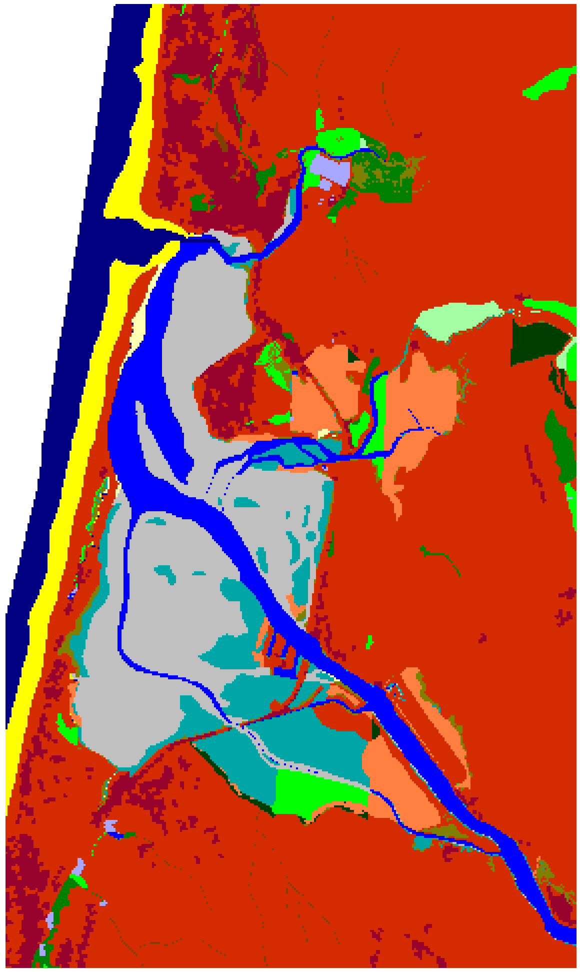
Siletz Bay Context, Initial Condition

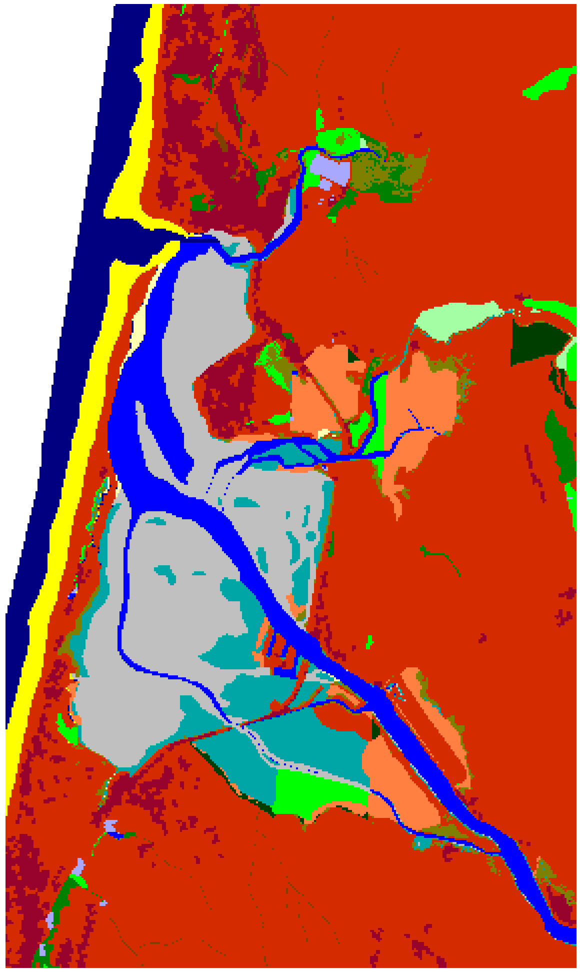


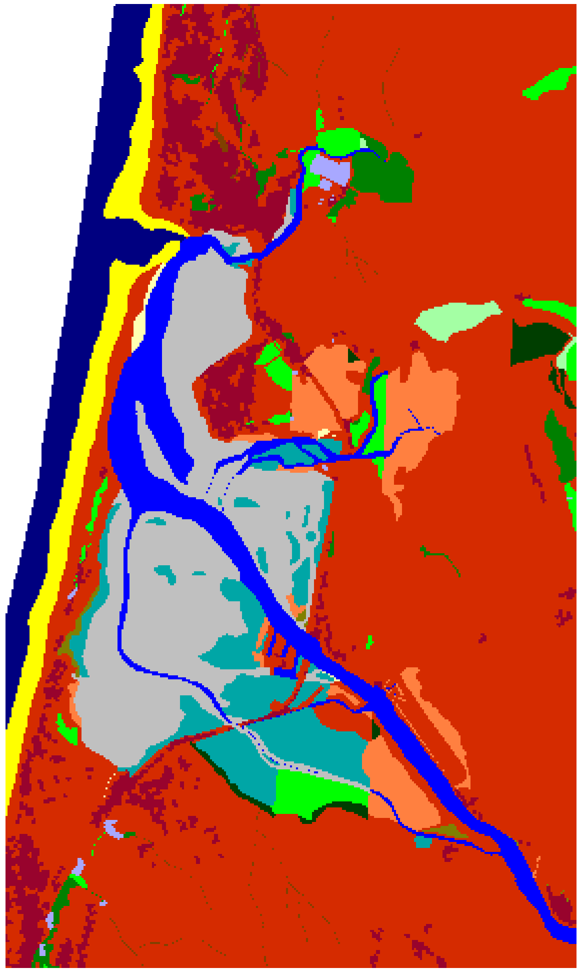
Siletz Bay Context, 2025, Scenario A1B Mean

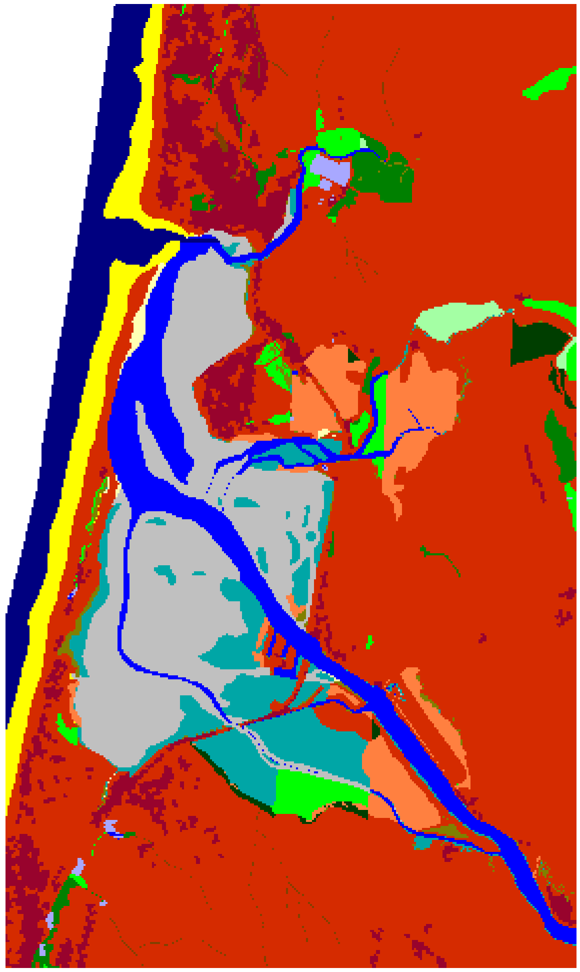


Siletz Bay Context, 2050, Scenario A1B Mean

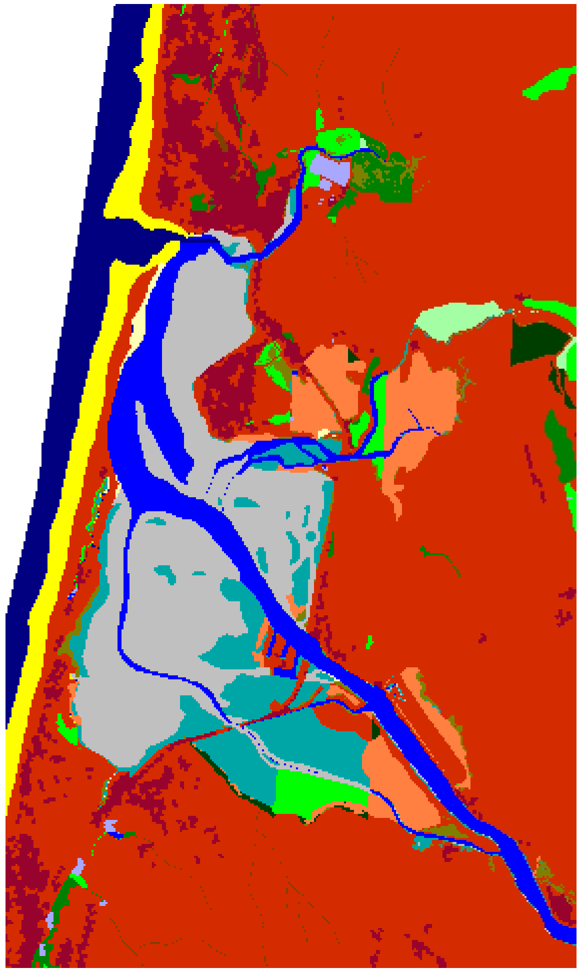

Siletz Bay Context, 2075, Scenario A1B Mean


Siletz Bay Context, 2100, Scenario A1B Mean

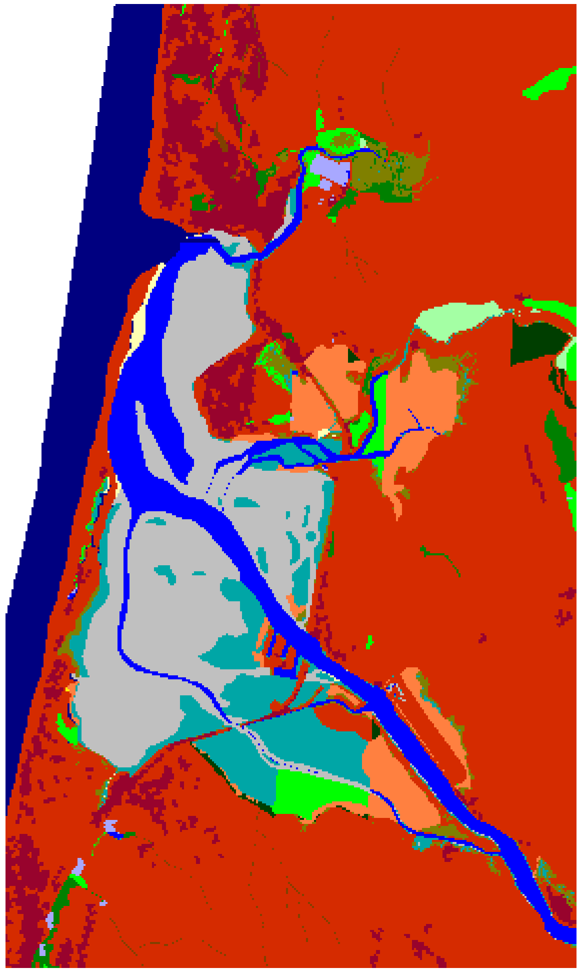

Siletz Bay Context, Initial Condition



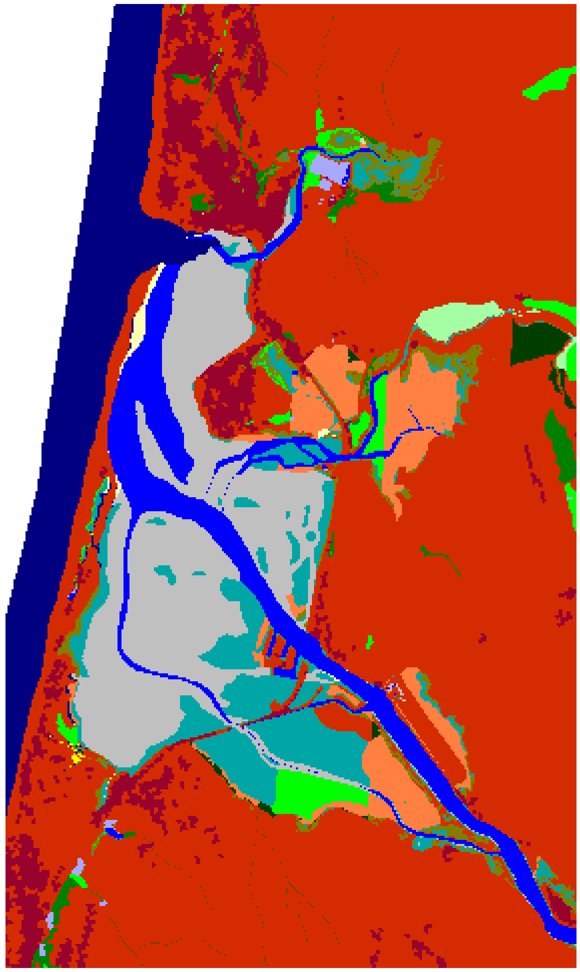
Siletz Bay Context, 2025, Scenario A1B Maximum



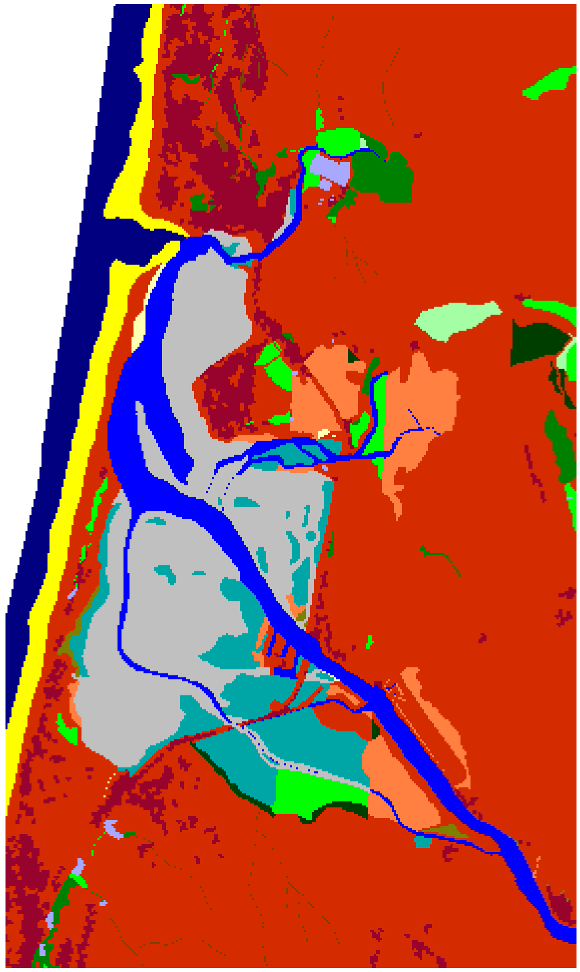
Siletz Bay Context, 2050, Scenario A1B Maximum



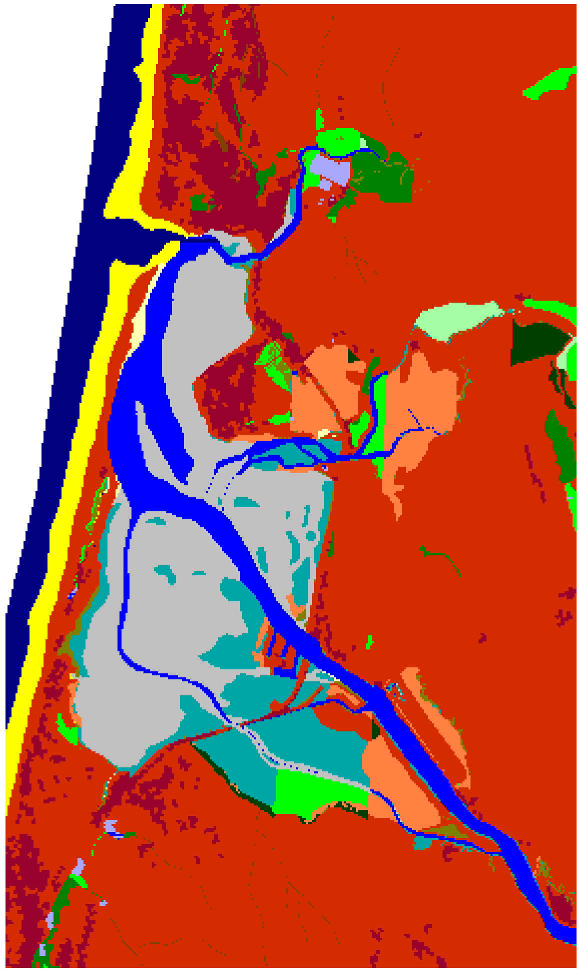
Siletz Bay Context, 2075, Scenario A1B Maximum



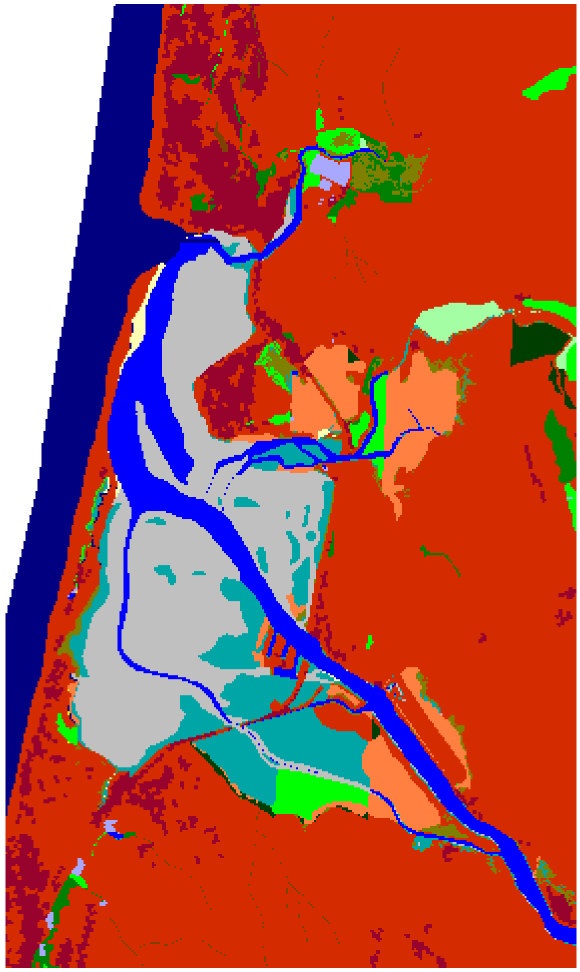
Siletz Bay Context, 2100, Scenario A1B Maximum



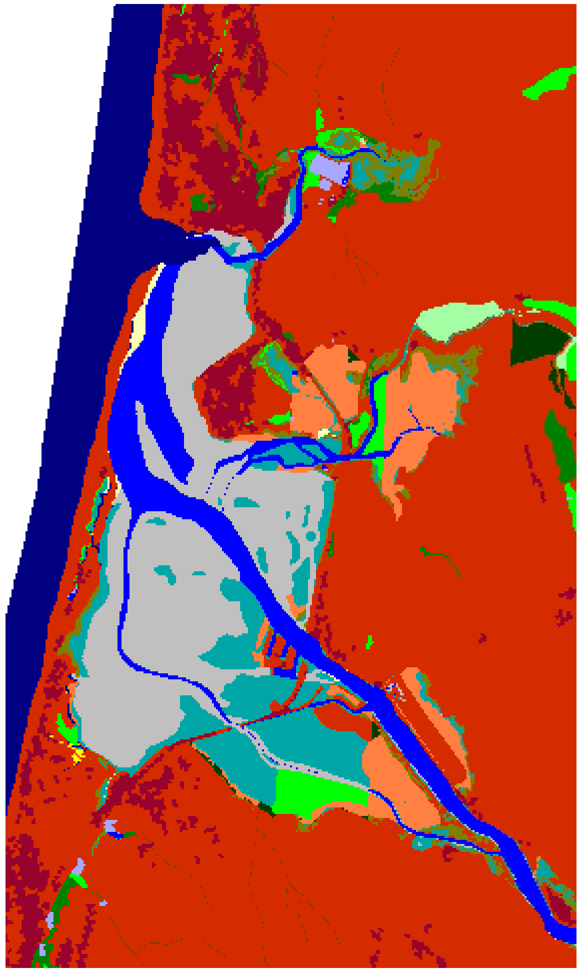
Siletz Bay Context, Initial Condition



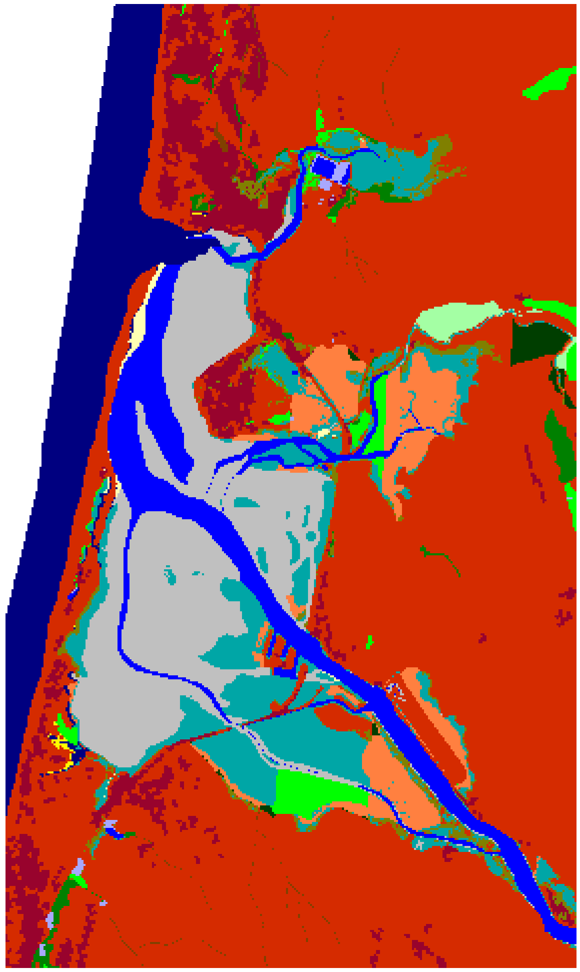
Siletz Bay Context, 2025, 1 meter



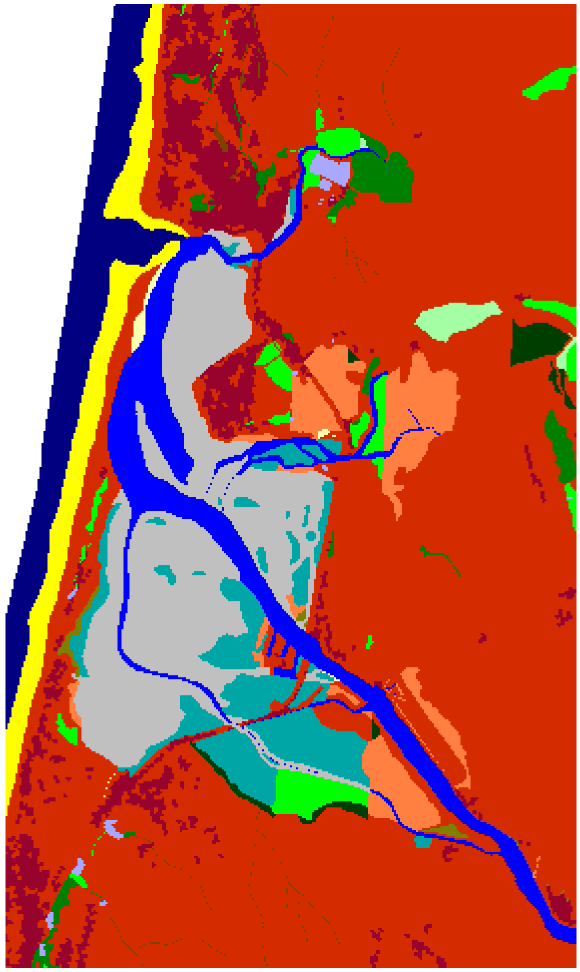
Siletz Bay Context, 2050, 1 meter

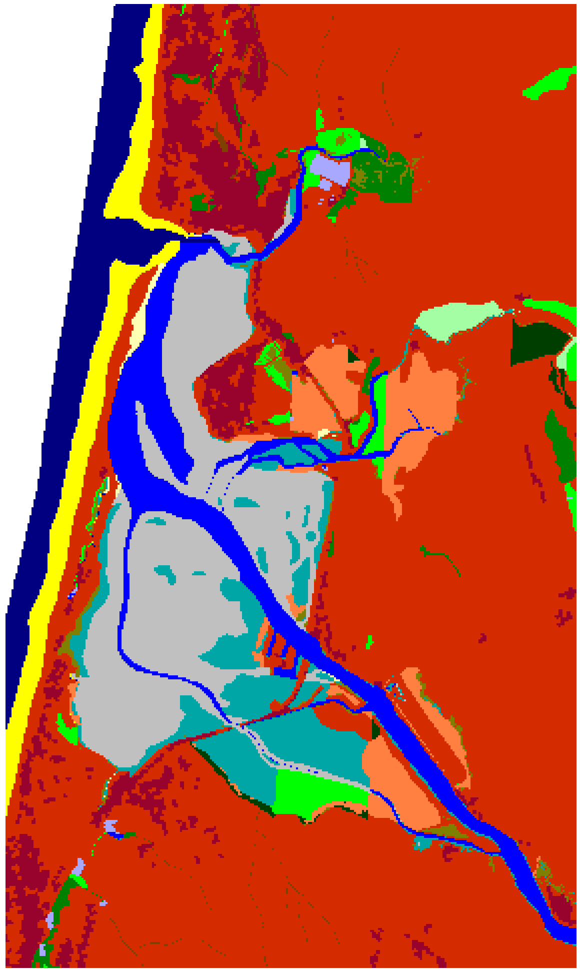


Siletz Bay Context, 2075, 1 meter

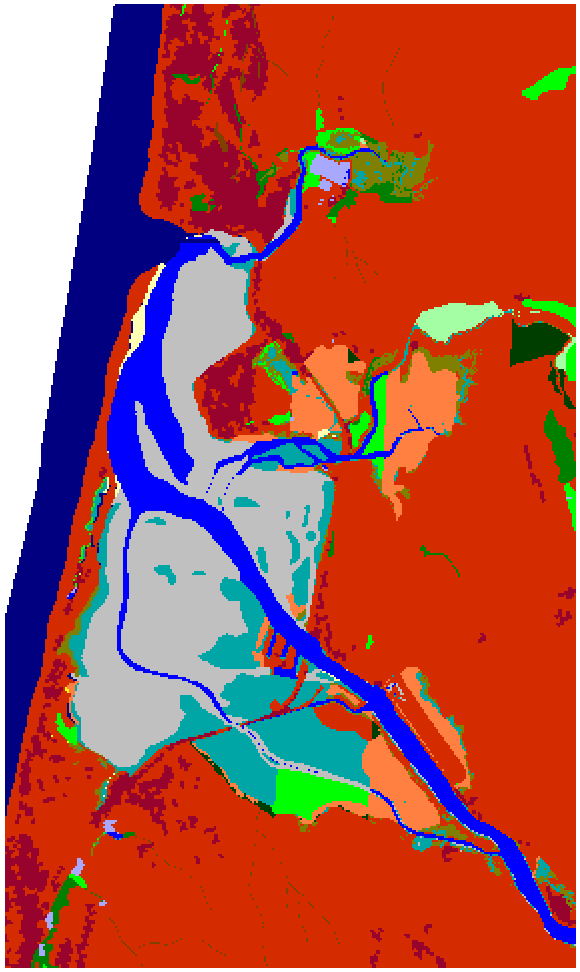


Siletz Bay Context, 2100, 1 meter

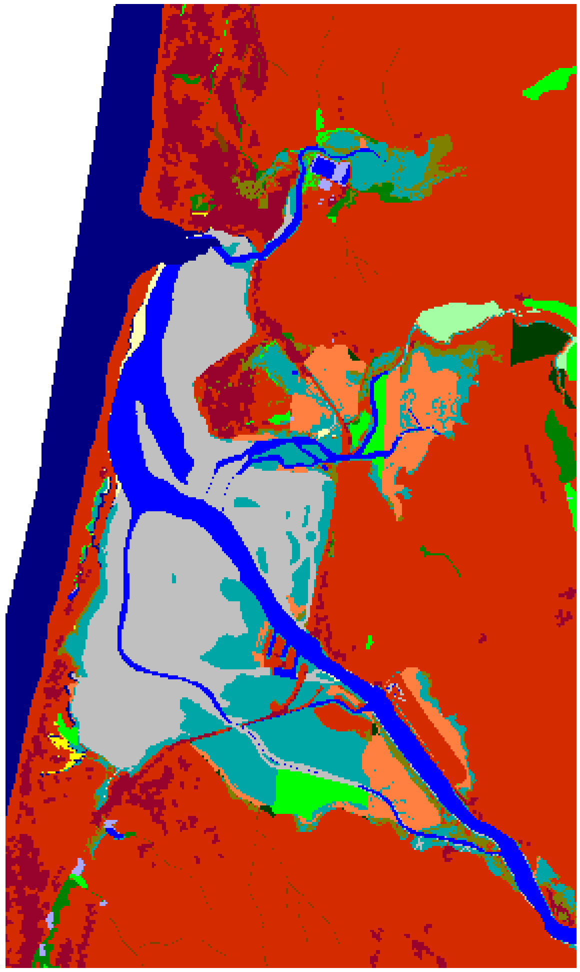

Siletz Bay Context, Initial Condition



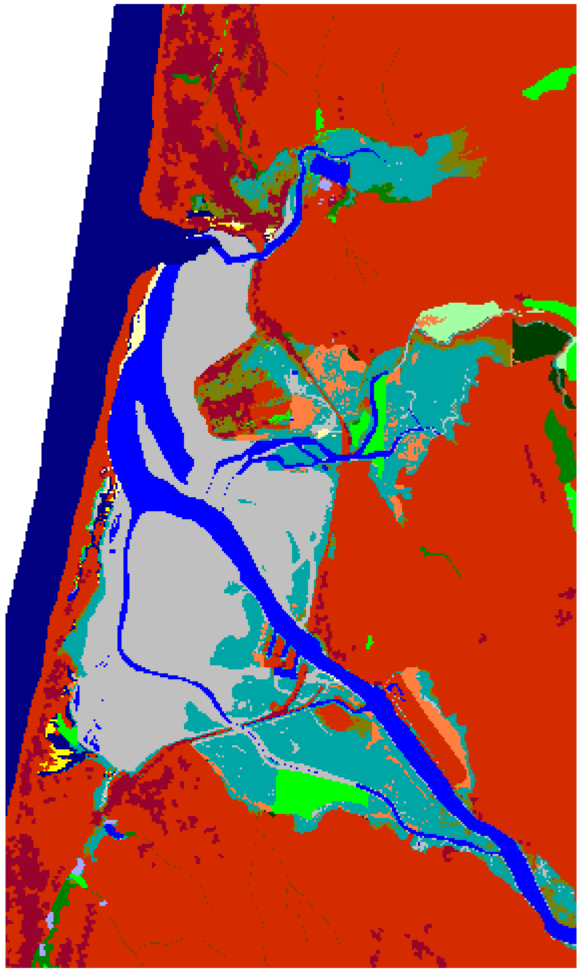
Siletz Bay Context, 2025, 1.5 meter



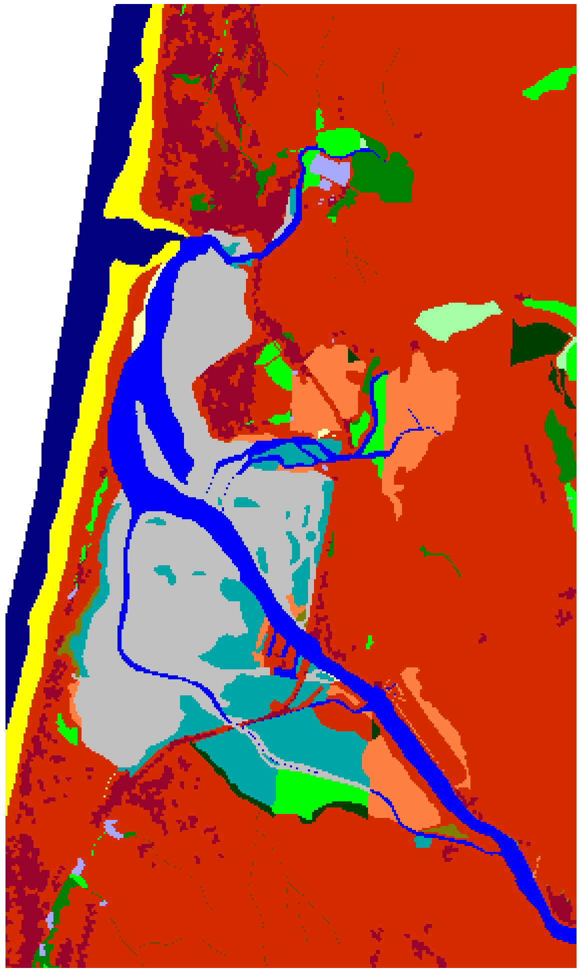
Siletz Bay Context, 2050, 1.5 meter



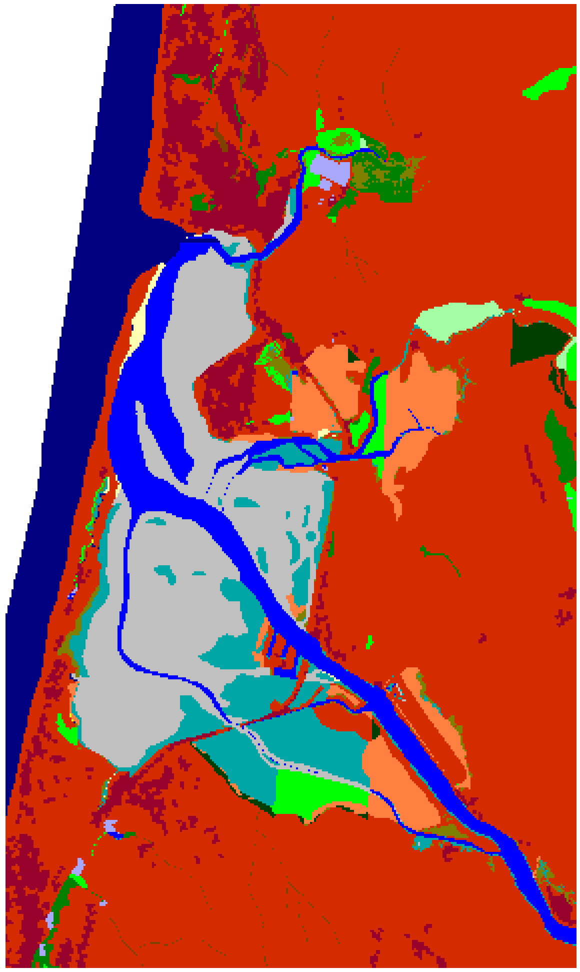
Siletz Bay Context, 2075, 1.5 meter



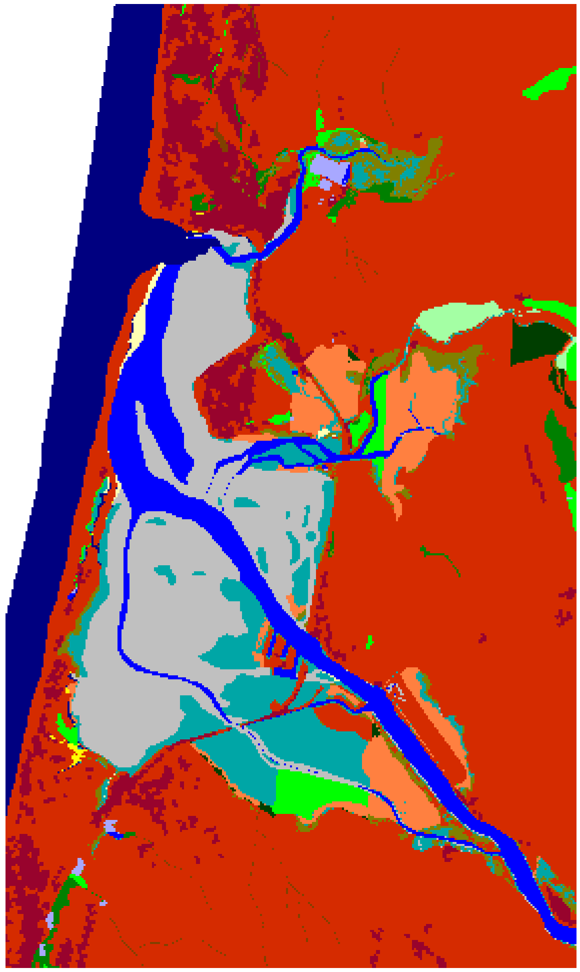
Siletz Bay Context, 2100, 1.5 meter



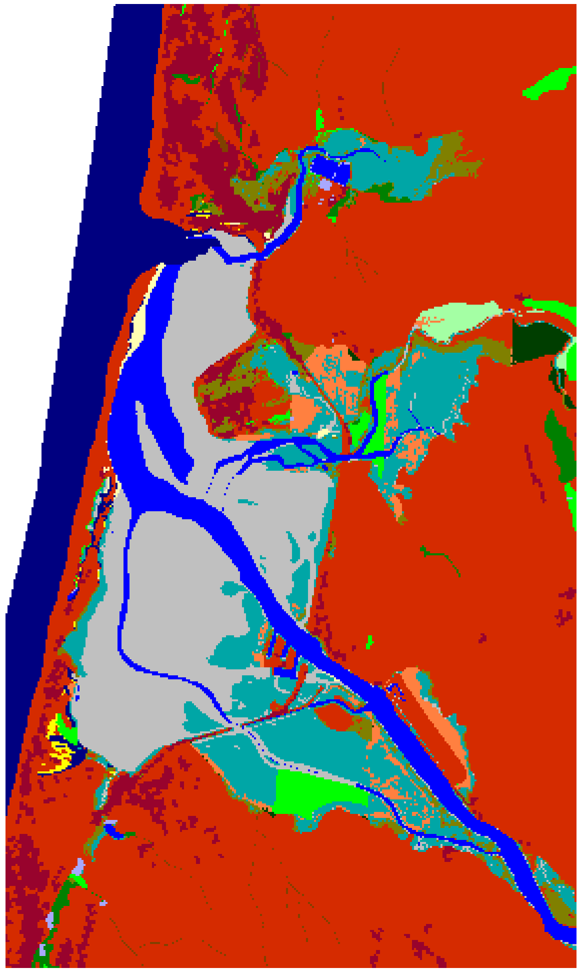
Siletz Bay Context, Initial Condition



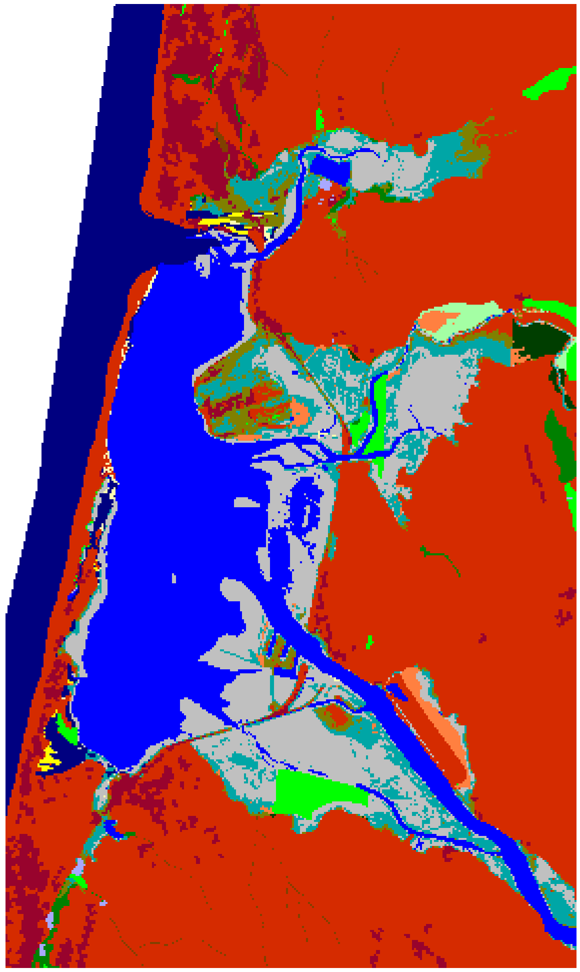
Siletz Bay Context, 2025, 2 meter



Siletz Bay Context, 2050, 2 meter



Siletz Bay Context, 2075, 2 meter



Siletz Bay Context, 2100, 2 meter