Application of the Sea-Level Affecting Marshes Model (SLAMM 6) to San Juan Islands 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).

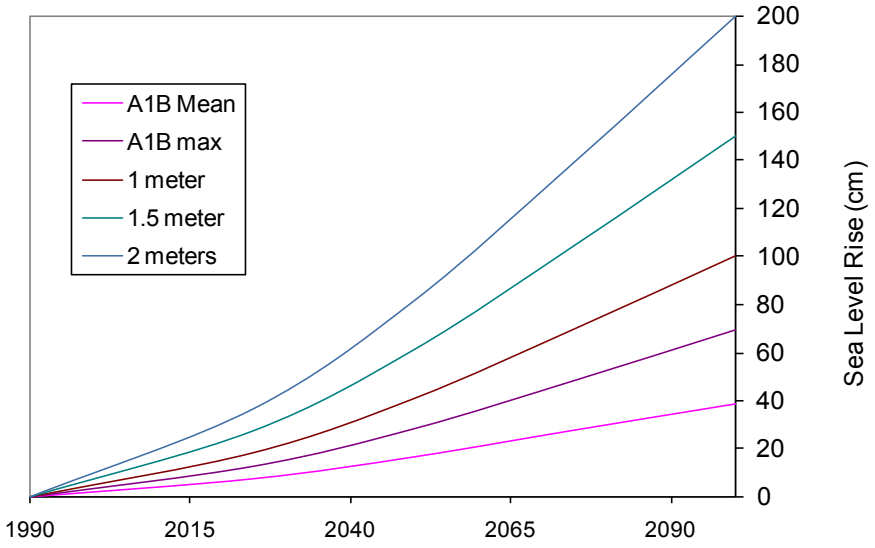


Figure 1. Summary of SLR scenarios utilized

Data Sources and Methods

Wetland layer. Figure 2 shows the most recent available wetlands layer obtained from a National Wetlands Inventory (NWI) photo dated 1980-1981. Converting the NWI survey into 30 m cells indicated that the approximately 460 acre San Juan Islands NWR (approved acquisition boundary including water) is composed of the following categories:

Land cover type		Area (acres)	Percentage (%)
	Undeveloped Dry Land	368	80
	Open Water	50	11
	Rocky Intertidal	23	5
	Ocean Beach	14	3
	Tidal Flat	2.9	<1
	Inland Open Water	0.4	<1
	Total (incl. water)	**459**	**100**

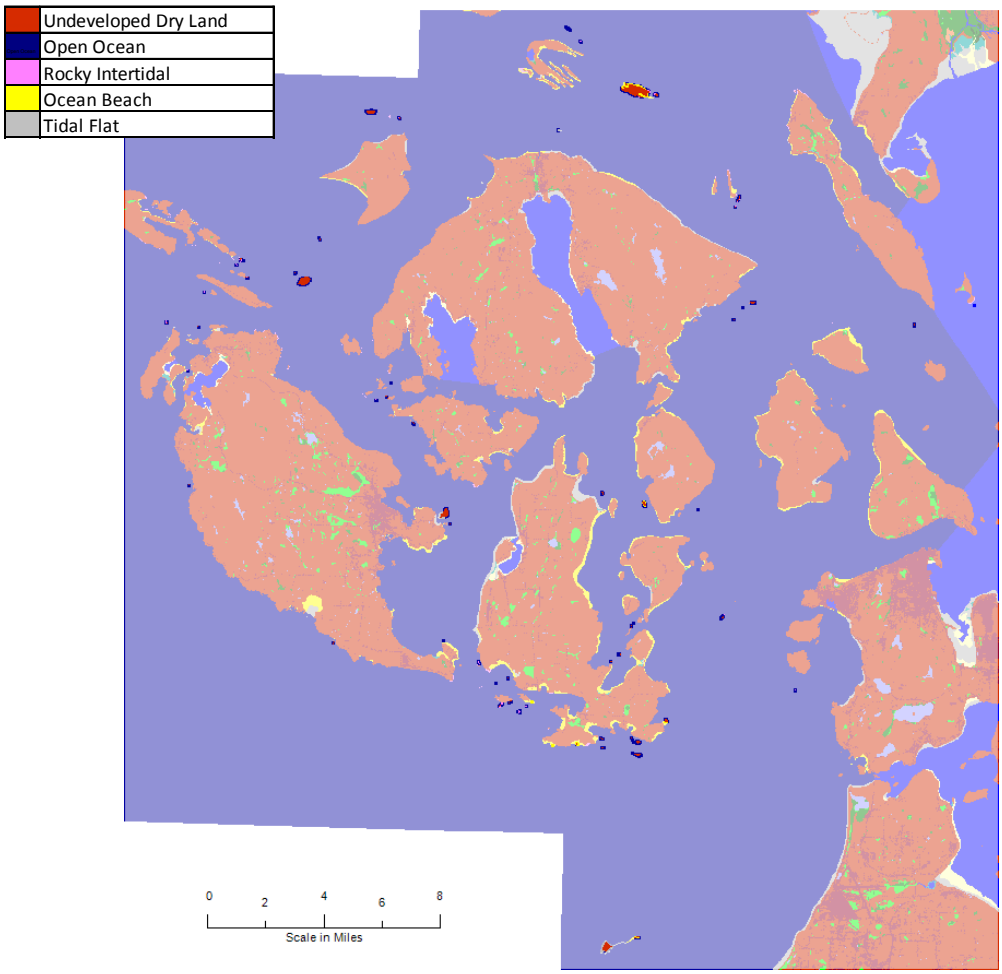


Figure 2. 1980 NWI coverage of the study area
The dozens of islands within the refuge are shown in darker tones.

Elevation Data. The available elevations for the refuge are obtained by combining recent 2006 and 2009 LiDAR data gathered by the Puget Sound LiDAR Consortium and older contour map data from the National Elevation Dataset for the areas not covered by LiDAR (mostly the islands in the north section of the refuge), see Figure 3. Within NED-covered regions, 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.

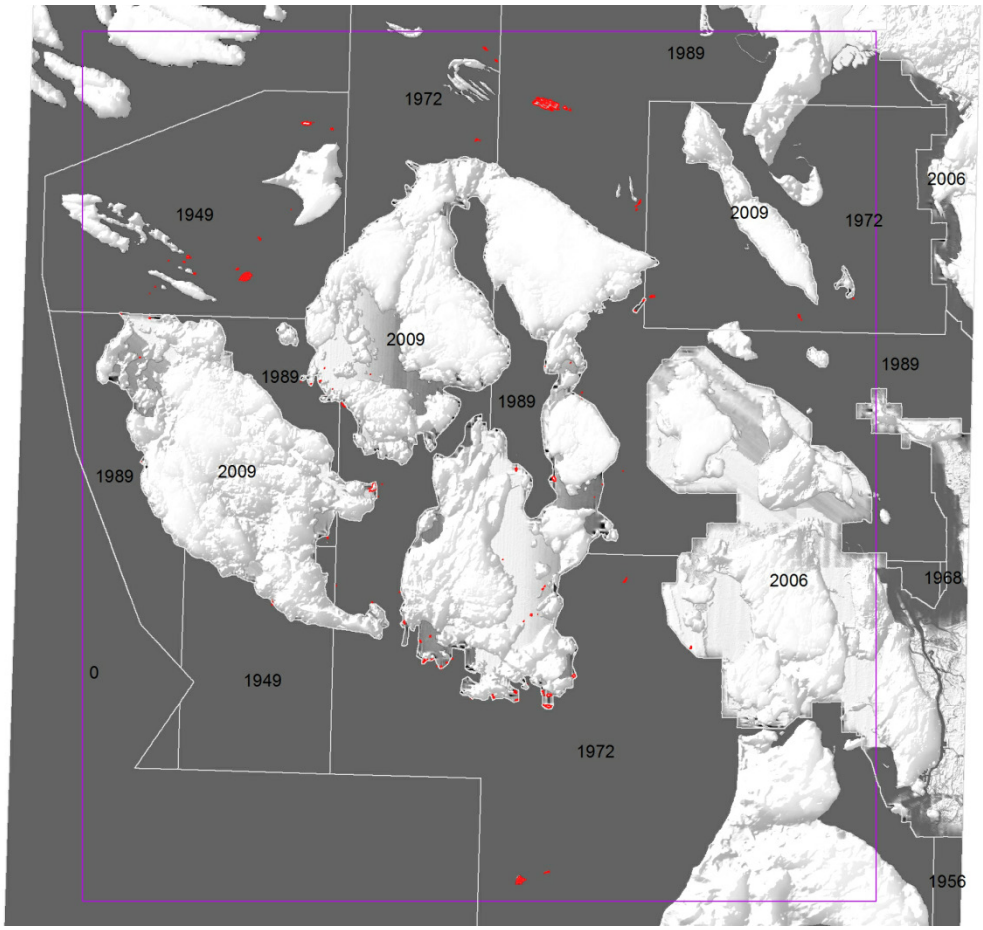


Figure 3. Elevation data photo date. Refuge islands in red.

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 1.0 mm/yr using the average of the two nearest gauge stations with long-term SLR data (NOAA 9444880, Friday Harbor,WA; and Canada 822-101 Victoria). 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 (Mitchell et al. 1994; Verdonck 2006). This mild uplift was assumed to continue to occur through 2100.

Tide Ranges. The great diurnal range or GT measured at the NOAA gauge stations present in the area (shown in Figure 4), is between 2.19 m and 2.64 m without a particular spatial trend. For the simulation the average value of 2.38 m was applied for the entire study area.

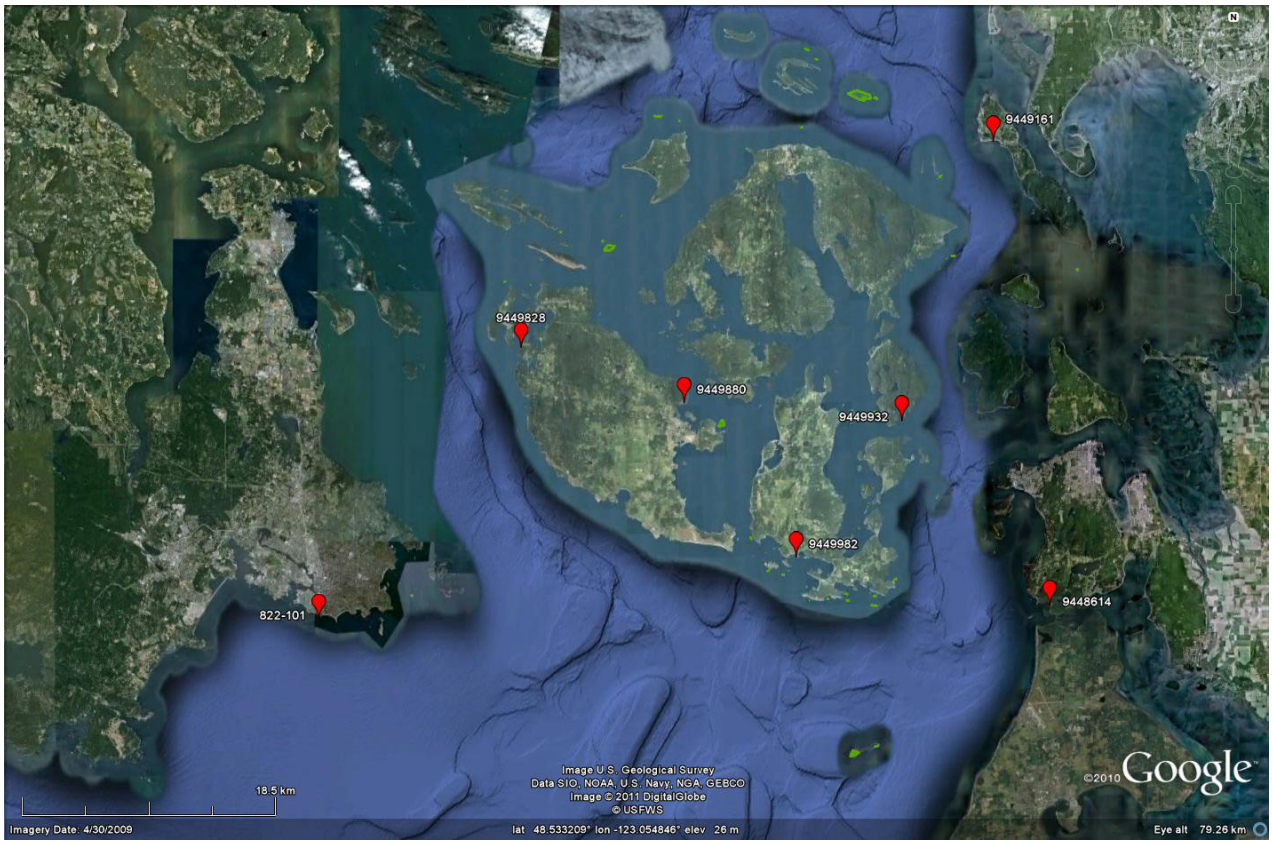


Figure 4. NOAA gauge station locations used for this study. Refuge boundaries in green

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 derived 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 corrections at gauge stations Blaine, Drayton Harbor, WA (ID 9449679); Turner Bay, WA (ID 9448657) and Sneeoosh Point, WA (ID 9448576) are quite similar, 1.42-1.36-1.33 m respectively. Therefore the average value of 1.37 m was applied as elevation correction for the entire study area.

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 30 m by 30 m cells.

Parameter summary. Table 1 summarizes all SLAMM input parameters for the study area.

Table 1. Summary of SLAMM input parameters for San Juan Islands NWR. The study area was divided in different model subsites depending on the DEM source and dates.

Description	San Juan Islands
NWI Photo Date (YYYY)	1981
DEM Date (YYYY)	2009
Direction Offshore [n,s,e,w]	South
Historic Trend (mm/yr)	0.97
MTL-NAVD88 (m)	1.37
GT Great Diurnal Tide Range (m)	2.38
Salt Elev. (m above MTL)	1.79
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
Use Elev Pre-processor [True,False]	†

† TRUE for NED covered areas, FALSE otherwise.

Results

This simulation of the San Juan Islands NWR predicts that moderate dry-land loss will occur within refuge lands, ranging from 8% to 17%. Table 2 presents the land cover by 2100 of the total refuge area for each of the five SLR scenarios examined.

Table 2. Predicted wetland coverage loss by 2100 given simulated scenarios of eustatic SLR at San Juan Islands 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
Undeveloped Dry Land	367.6	8%	11%	13%	16%	17%
Rocky Intertidal	23.4	37%	32%	45%	64%	75%
Ocean Beach	14.5	-47% (1)	-143%	-173%	-197%	-272%
Tidal Flat	2.9	100%	66%	72%	97%	97%
Regularly Flooded Marsh(2)	0.0	0.0	0.1	0.1	0.4	0.6

(1) A negative number indicates a land cover gain

(2) As this category was not initially present, the acreage coverage is reported

Rocky intertidal acreage is predicted to be slowly inundated as sea level continues to rise, with losses of 37% to 75% predicted. Beaches, which cover 14.5 acres of the refuge today, are predicted to increase up to 54 acres (272% gain) under the scenario of 2 m of SLR by 2100 due to the conversion of dry lands at the site. The model also predicts a minor formation of regularly flooded marsh as dry land lost. These results may be affected by the uncertainty of the elevation data that in many areas is not LiDAR and therefore subjected to the elevation pre-processor module of SLAMM.

Due to the dispersed nature of the refuge, it is not possible to show changes for all the islands on one map while also portraying them in sufficient detail (refuge islands show up as tiny, nearly imperceptible dots on the page). Therefore this section includes maps showing the changes predicted by SLAMM for three of the biggest islands in the refuge (shown in Figure 5), while the summary table presents numerical metrics for the entire refuge area.

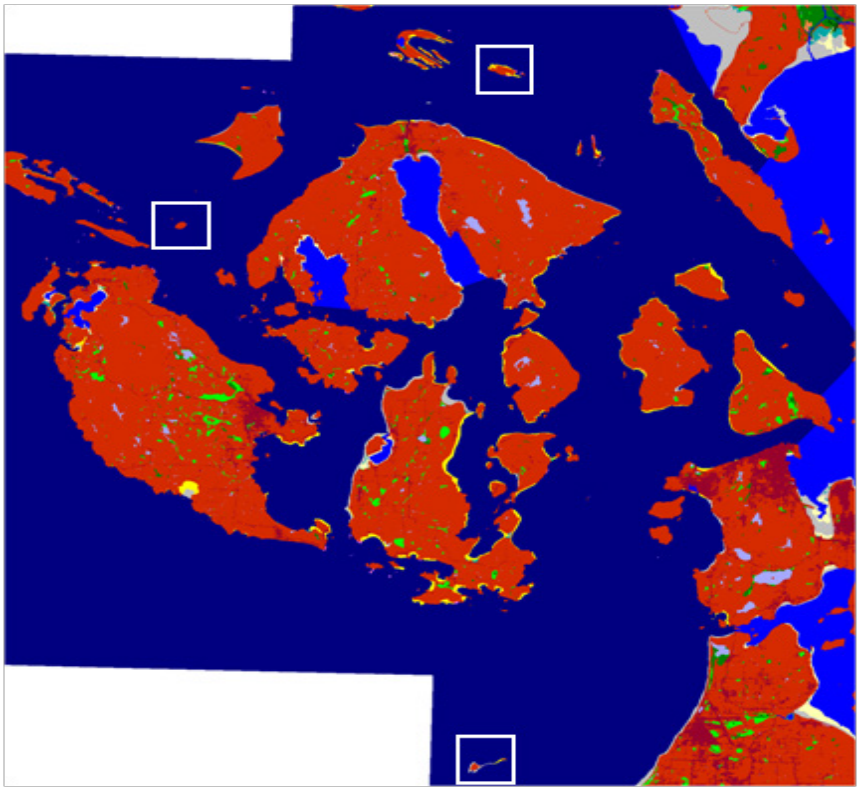


Figure 5. Islands chosen for map results

San Juan Islands NWR
IPCC Scenario A1B-Mean, 0.39 m SLR eustatic by 2100

Results in Acres

		Initial	2025	2050	2075	2100
	Undeveloped Dry Land	368	348	346	343	340
	Open Ocean	50	70	74	78	83
	Rocky Intertidal	23	19	18	16	15
	Ocean Beach	14	21	21	21	21
	Tidal Flat	3	0	0	0	0
	Total	**459**	**459**	**459**	**459**	**459**

San Juan Islands NWR, Initial Condition

San Juan Islands NWR, 2025, Scenario A1B Mean, 0.39 m SLR

San Juan Islands NWR, 2050, Scenario A1B Mean, 0.39 m SLR

San Juan Islands NWR, 2075, Scenario A1B Mean, 0.39 m SLR

San Juan Islands NWR, 2100, Scenario A1B Mean, 0.39 m SLR

San Juan Islands NWR
IPCC Scenario A1B-Max, 0.69 m SLR eustatic by 2100

Results in Acres

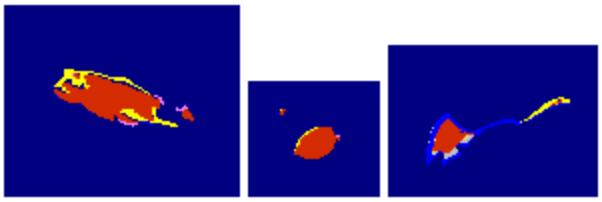
		Initial	2025	2050	2075	2100
	Undeveloped Dry Land	368	347	342	335	328
	Open Ocean	50	61	65	72	78
	Rocky Intertidal	23	21	20	18	16
	Ocean Beach	14	27	29	32	35
	Tidal Flat	3	3	2	2	1
	Total	**458**	**459**	**459**	**458**	**458**

San Juan Islands NWR, Initial Condition

San Juan Islands NWR, 2025, Scenario A1B Maximum, 0.69 m SLR

San Juan Islands NWR, 2050, Scenario A1B Maximum, 0.69 m SLR

San Juan Islands NWR, 2075, Scenario A1B Maximum, 0.69 m SLR



San Juan Islands NWR, 2100, Scenario A1B Maximum, 0.69 m SLR

San Juan Islands NWR
1 m eustatic SLR by 2100

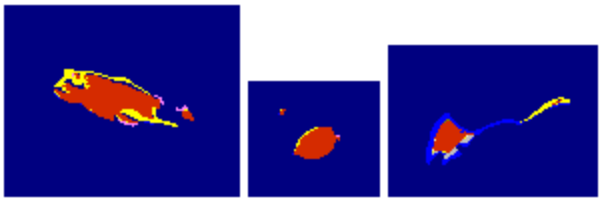
Results in Acres

		Initial	2025	2050	2075	2100
	Undeveloped Dry Land	368	345	337	327	320
	Open Ocean	50	62	69	78	86
	Rocky Intertidal	23	21	19	16	13
	Ocean Beach	14	28	31	37	40
	Tidal Flat	3	2	2	1	1
	Total	**458**	**459**	**458**	**458**	**458**

San Juan Islands NWR, Initial Condition

San Juan Islands NWR, 2025, 1 m SLR

San Juan Islands NWR, 2050, 1 m SLR



San Juan Islands NWR, 2075, 1 m SLR

San Juan Islands NWR, 2100, 1 m SLR

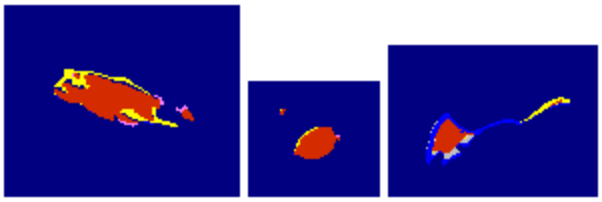
San Juan Islands NWR
1.5 m eustatic SLR by 2100

Results in Acres

		Initial	2025	2050	2075	2100
	Undeveloped Dry Land	368	342	329	318	310
	Open Ocean	50	65	75	86	96
	Rocky Intertidal	23	20	16	12	9
	Ocean Beach	14	30	36	42	43
	Tidal Flat	3	2	1	1	0
	Total	**458**	**458**	**458**	**458**	**458**

San Juan Islands NWR, Initial Condition

San Juan Islands NWR, 2025, 1.5 m SLR



San Juan Islands NWR, 2050, 1.5 m SLR

San Juan Islands NWR, 2075, 1.5 m SLR

San Juan Islands NWR, 2100, 1.5 m SLR

San Juan Islands NWR
2 m eustatic SLR by 2100

Results in Acres

		Initial	2025	2050	2075	2100
	Undeveloped Dry Land	368	338	323	311	305
	Open Ocean	50	68	80	93	103
	Rocky Intertidal	23	19	14	9	6
	Ocean Beach	14	32	40	44	44
	Tidal Flat	3	2	1	0	0
	Total	**458**	**458**	**458**	**458**	**458**

San Juan Islands NWR, Initial Condition

San Juan Islands NWR, 2025, 2 m SLR

San Juan Islands NWR, 2050, 2 m SLR

San Juan Islands NWR, 2075, 2 m SLR

San Juan Islands NWR, 2100, 2 m SLR

Discussion

Much of the refuge land within San Juan Islands is at high enough elevation to be resilient to the possible effects of SLR by 2100. However, up to 17% of dry land is predicted to be converted to ocean beach and open water as sea levels rise up to two meters.

It is important to note that not all elevation data used in this analysis are derived from LiDAR data (Figure 3). In non-LiDAR areas elevations were derived from NED, based on 1949-1979 data with contour intervals of 20 feet. Thus, considerable additional uncertainty in land elevations in these locations is certainly present.

Ocean beaches and tidal flats are predicted to persist and even increase in some cases, due to the conversion of dry lands. It is also possible that some of this land will become rocky-intertidal, depending on the substrate of the dry land being inundated.

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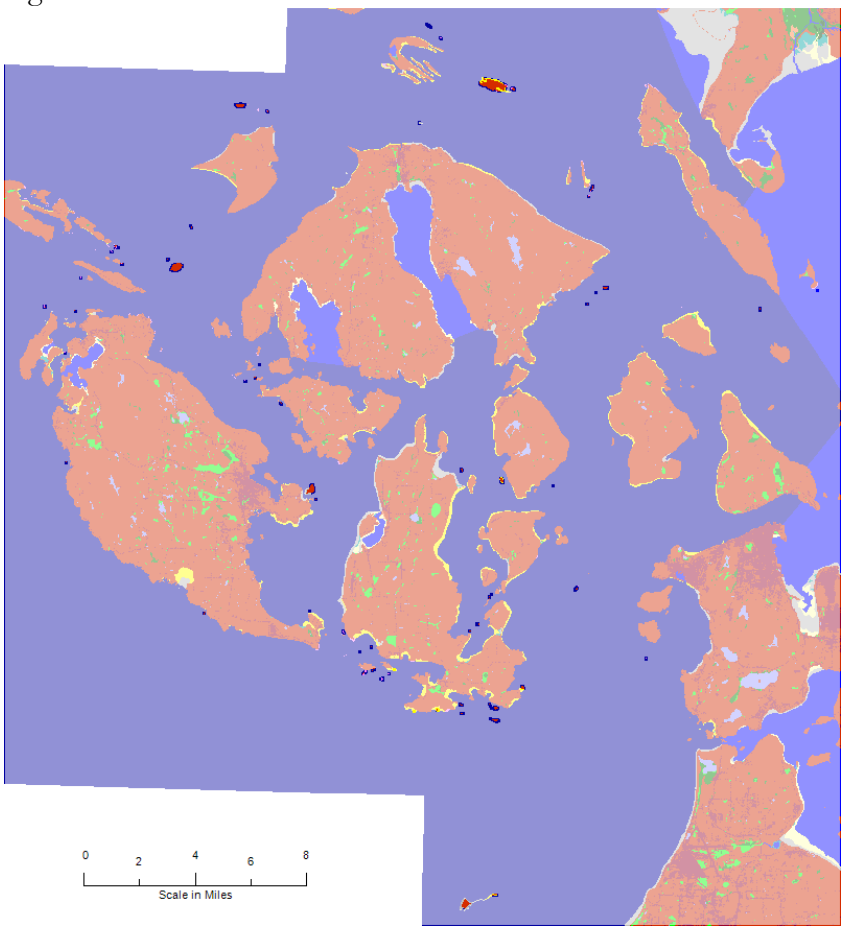
Appendix A: Contextual Results

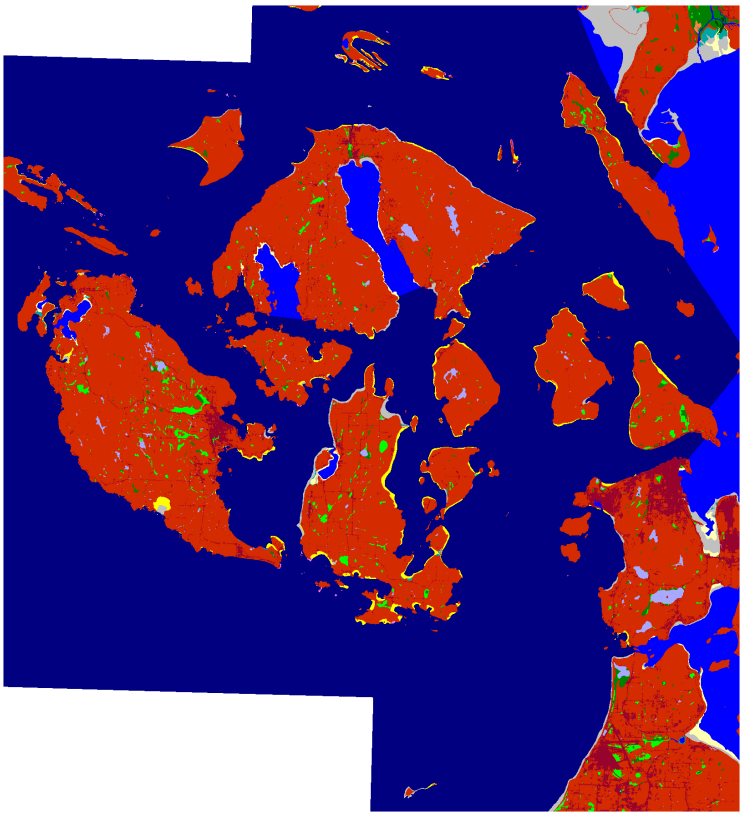
The SLAMM model does take into account the context of the surrounding lands or open water when calculating effects. For example, erosion rates are calculated based on the maximum fetch (wave action) which is estimated by assessing contiguous open water to a given marsh cell. Another example is that inundated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

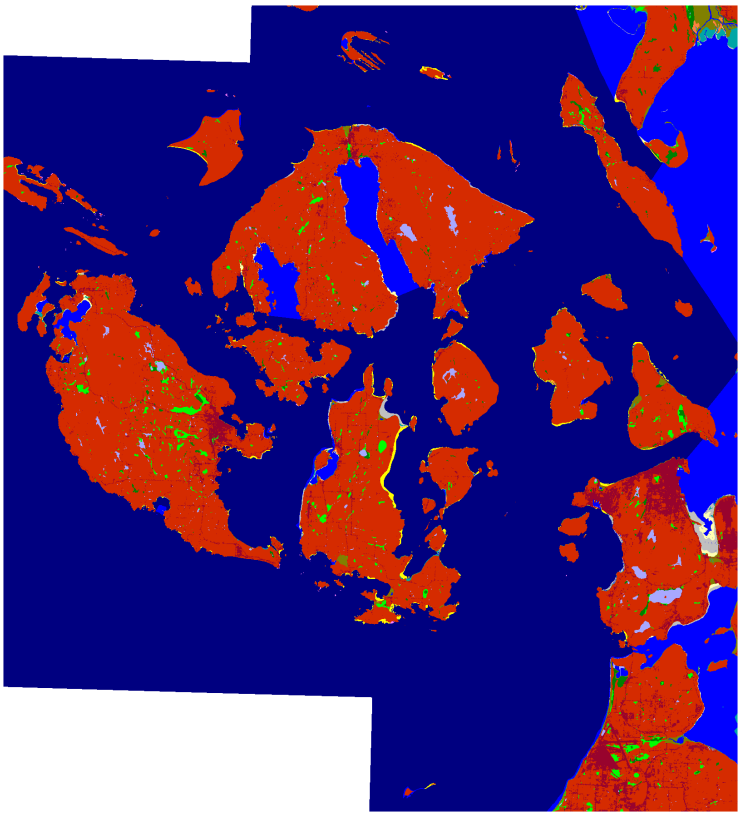
- Results were closely examined (quality assurance) within USFWS refuges but not closely examined for the larger region.
- Site-specific parameters for the model were derived for USFWS refuges whenever possible and may not be regionally applicable.
- Especially in areas where dikes are present, an effort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



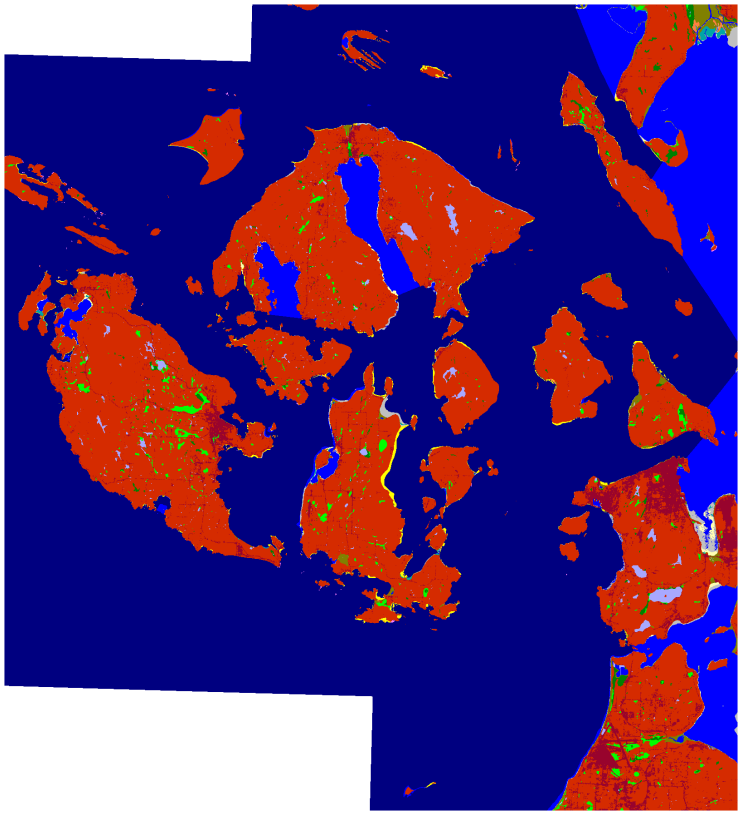
San Juan Islands National Wildlife Refuges within simulation context (yellow).



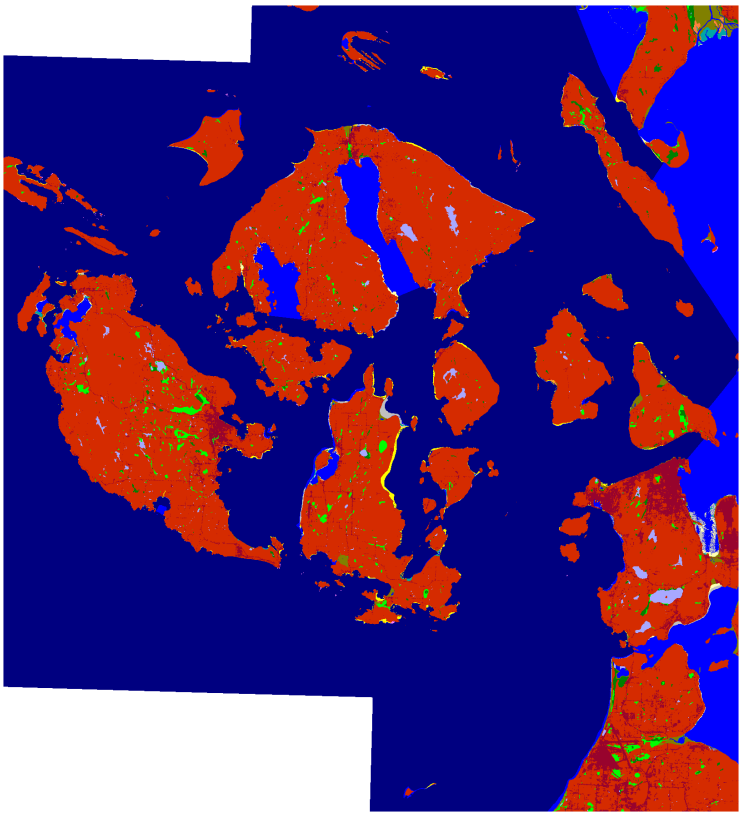
San Juan Islands NWR, Initial Condition



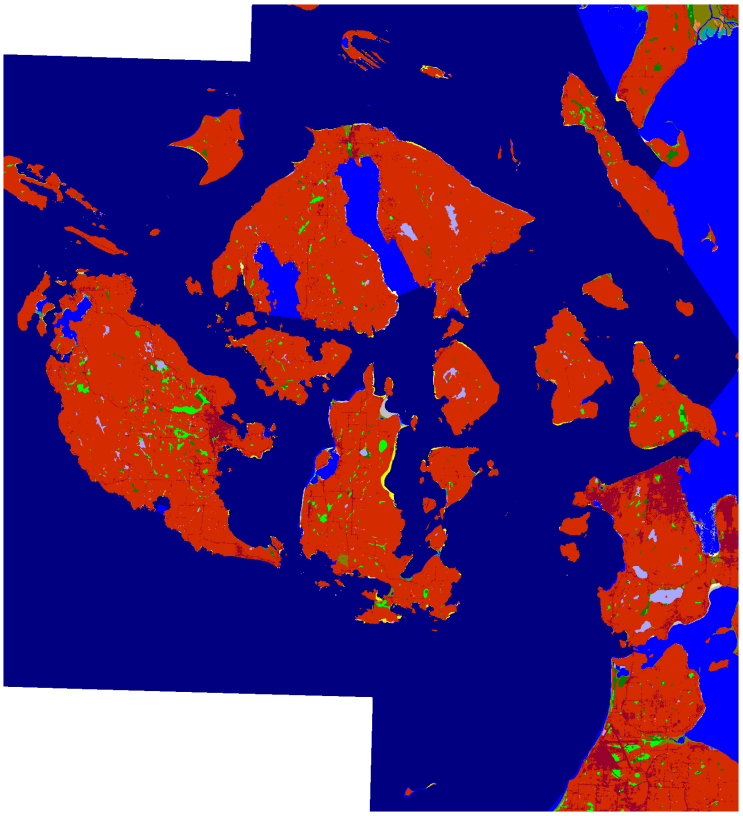
San Juan Islands NWR, 2025, Scenario A1B Mean, 0.39 m SLR



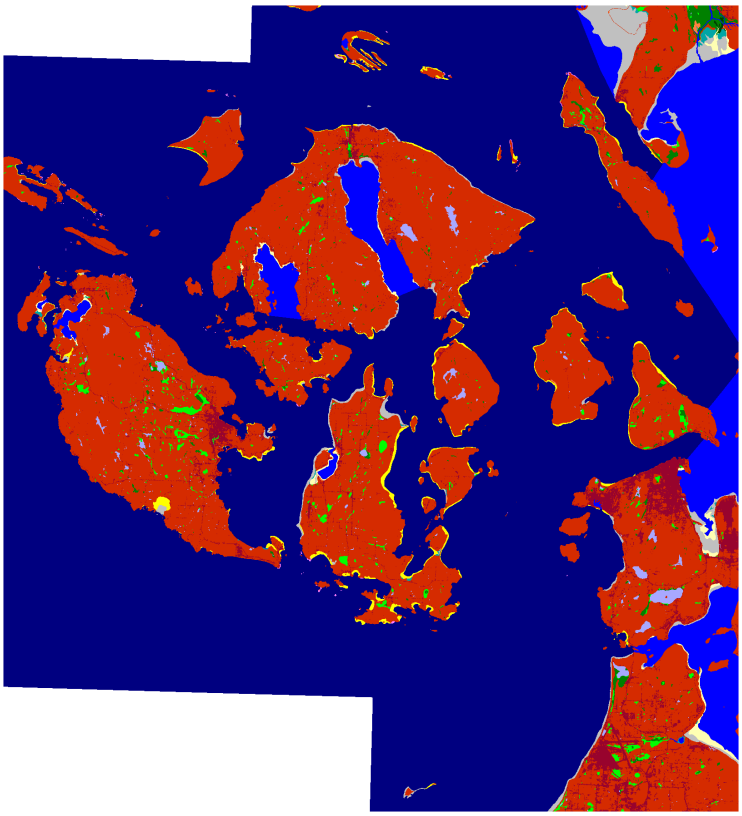
San Juan Islands NWR, 2050, Scenario A1B Mean, 0.39 m SLR



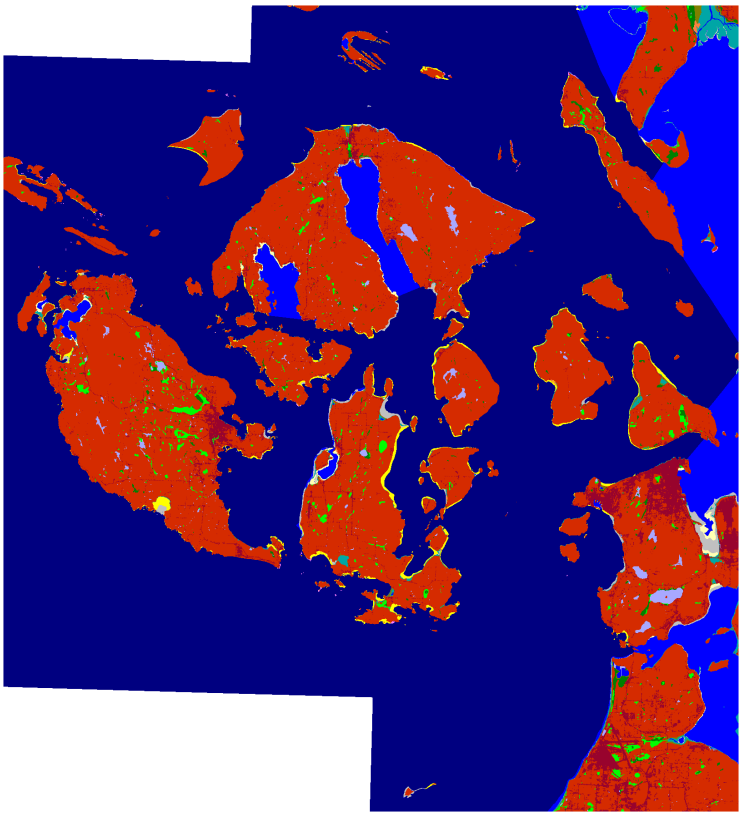
San Juan Islands NWR, 2075, Scenario A1B Mean, 0.39 m SLR



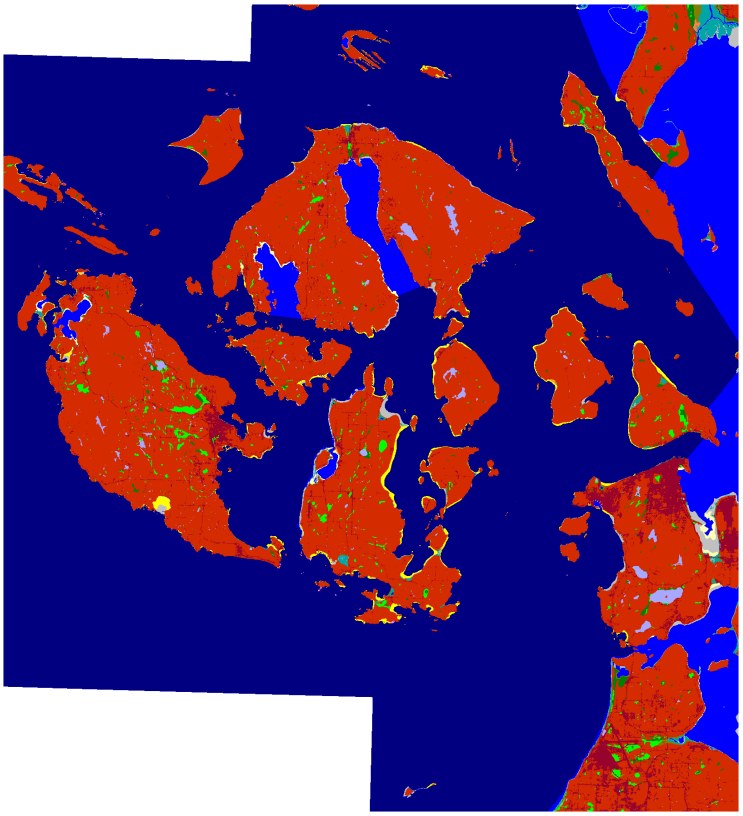
San Juan Islands NWR, 2100, Scenario A1B Mean, 0.39 m SLR



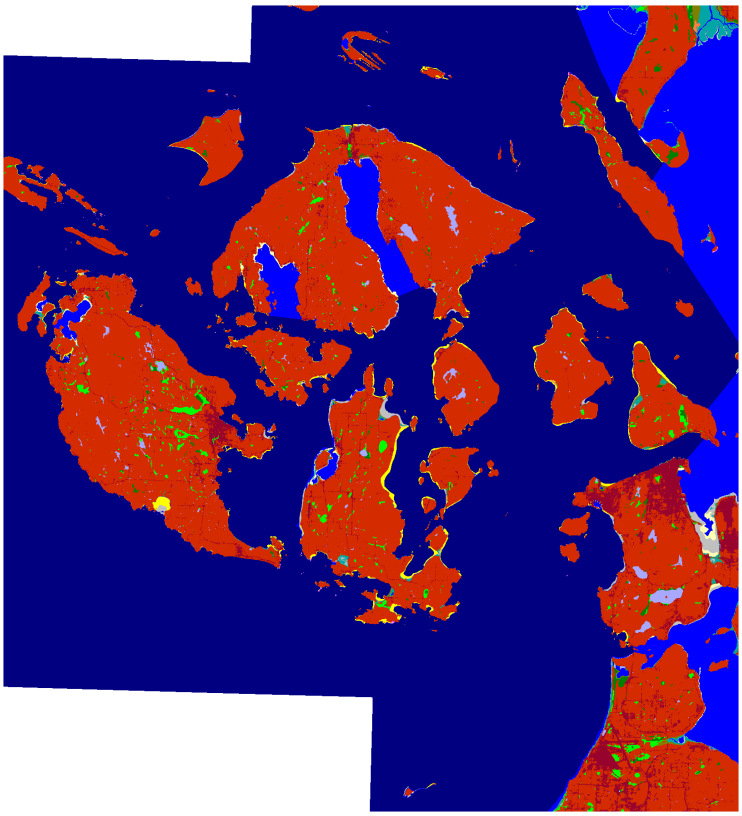
San Juan Islands NWR, Initial Condition



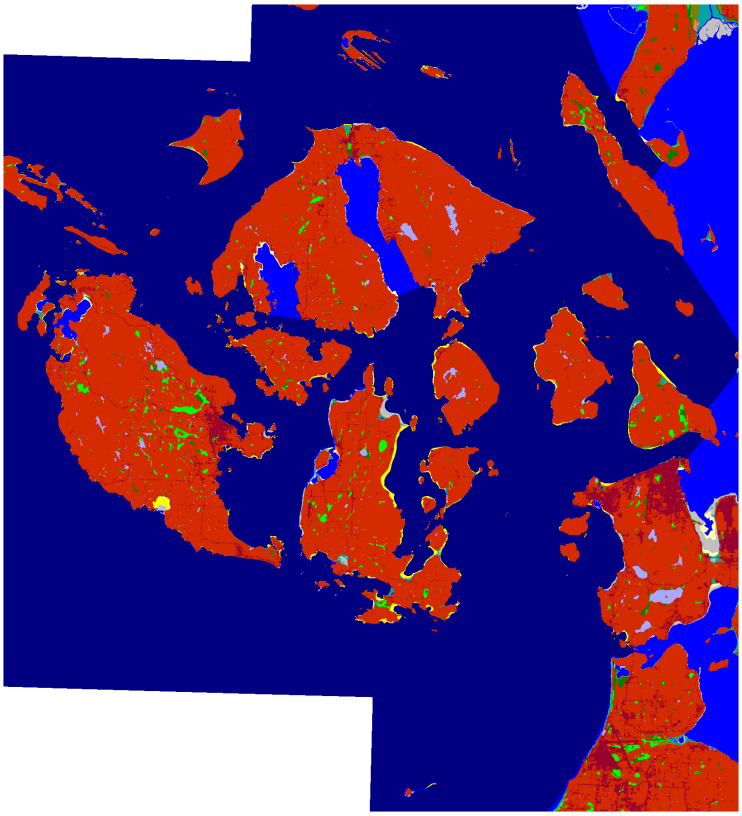
San Juan Islands NWR, 2025, Scenario A1B Maximum, 0.69 m SLR



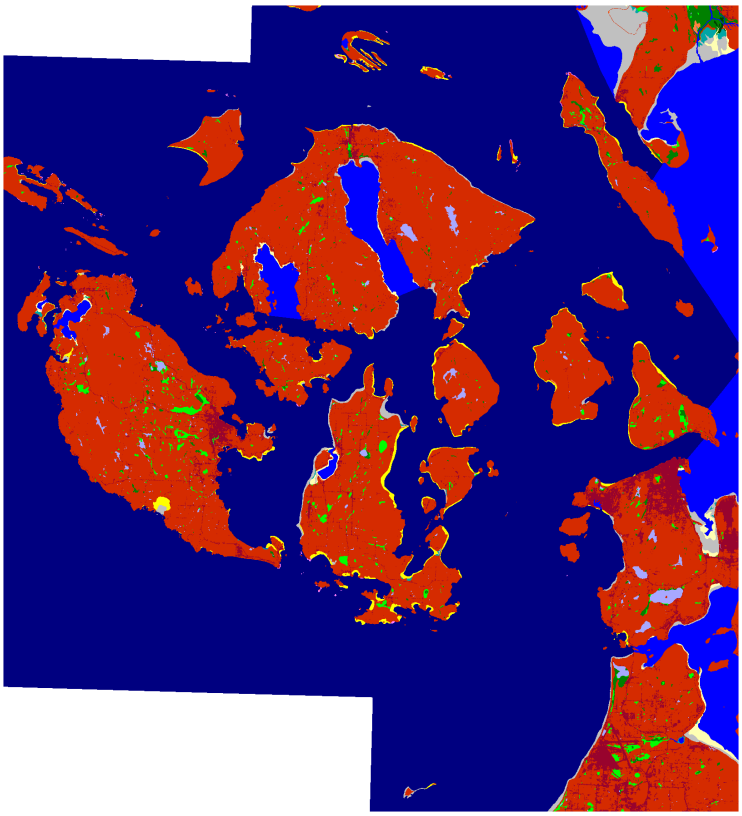
San Juan Islands NWR, 2050, Scenario A1B Maximum, 0.69 m SLR



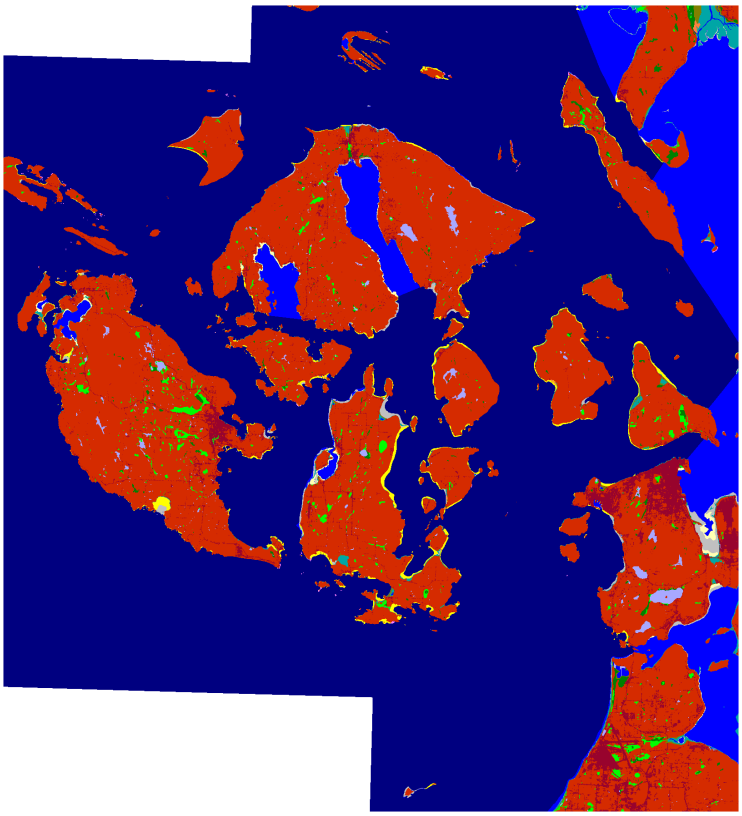
San Juan Islands NWR, 2075, Scenario A1B Maximum, 0.69 m SLR



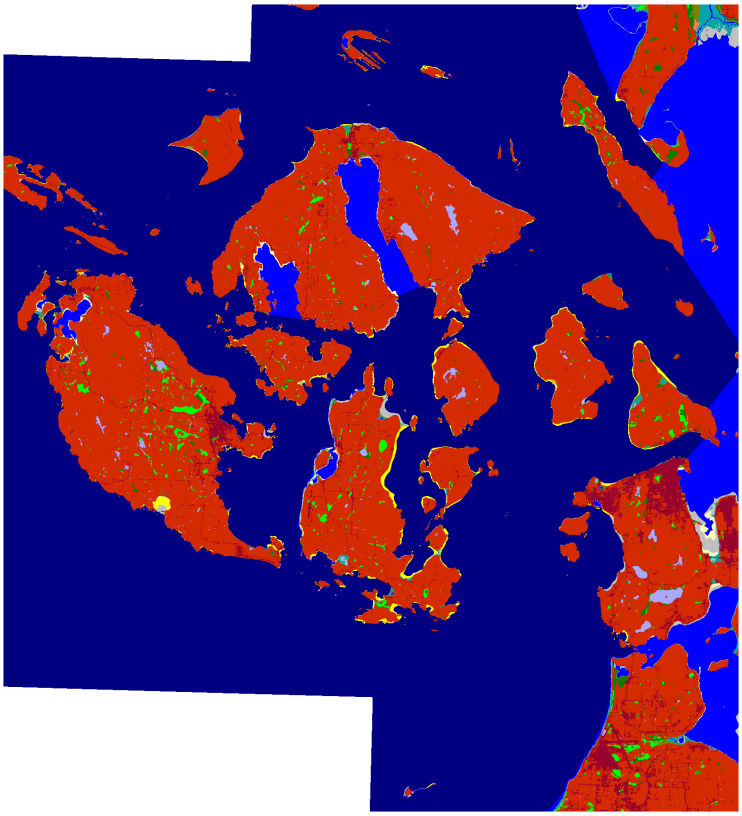
San Juan Islands NWR, 2100, Scenario A1B Maximum, 0.69 m SLR



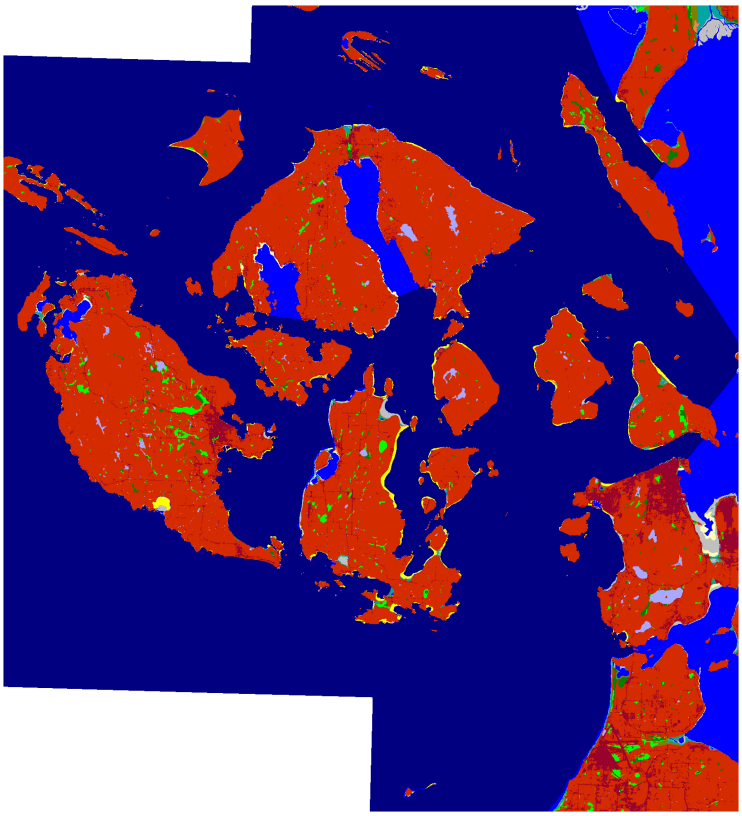
San Juan Islands NWR, Initial Condition



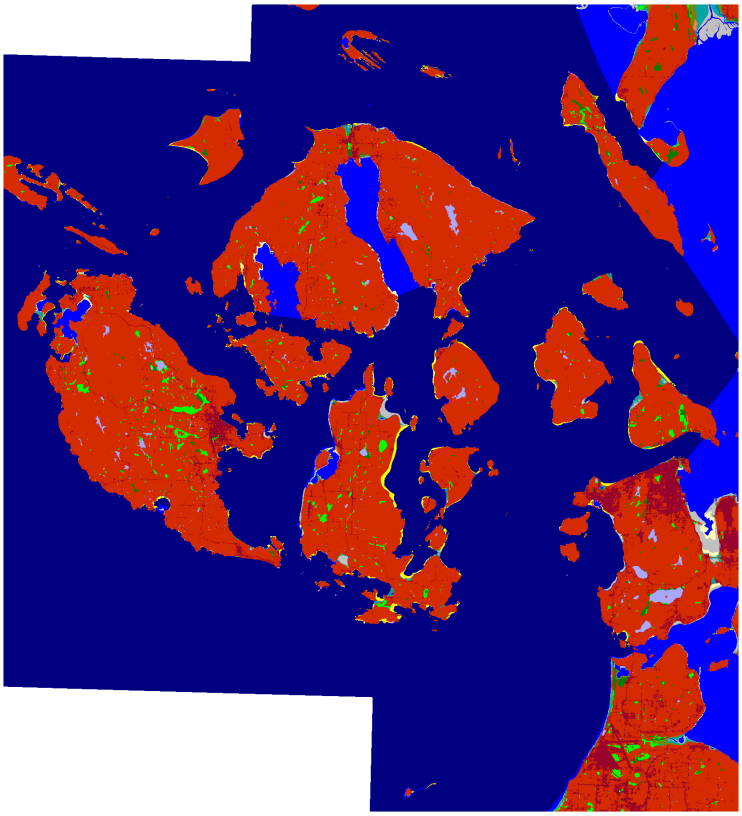
San Juan Islands NWR, 2025, 1 m SLR



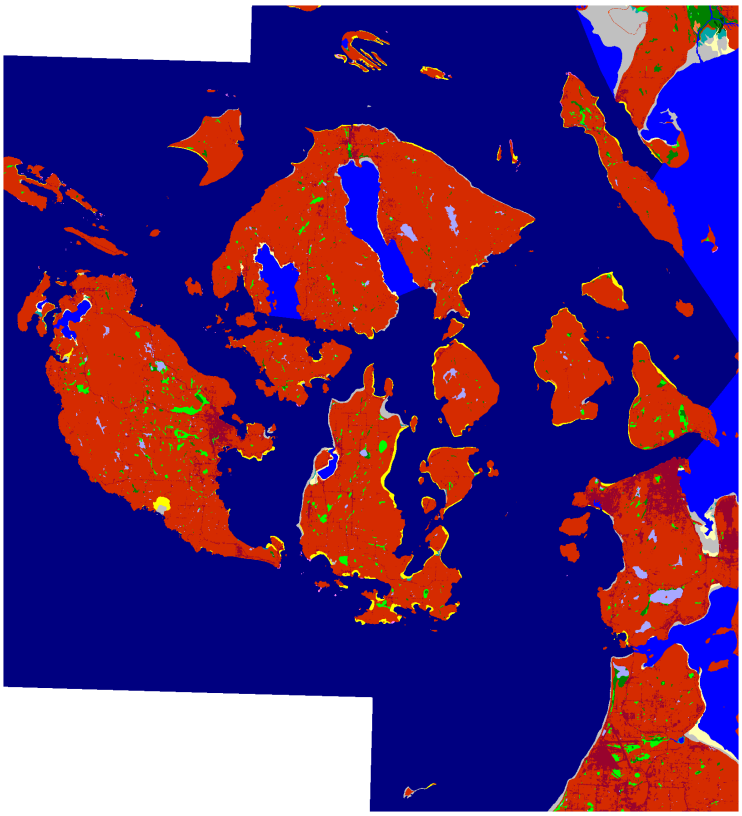
San Juan Islands NWR, 2050, 1 m SLR



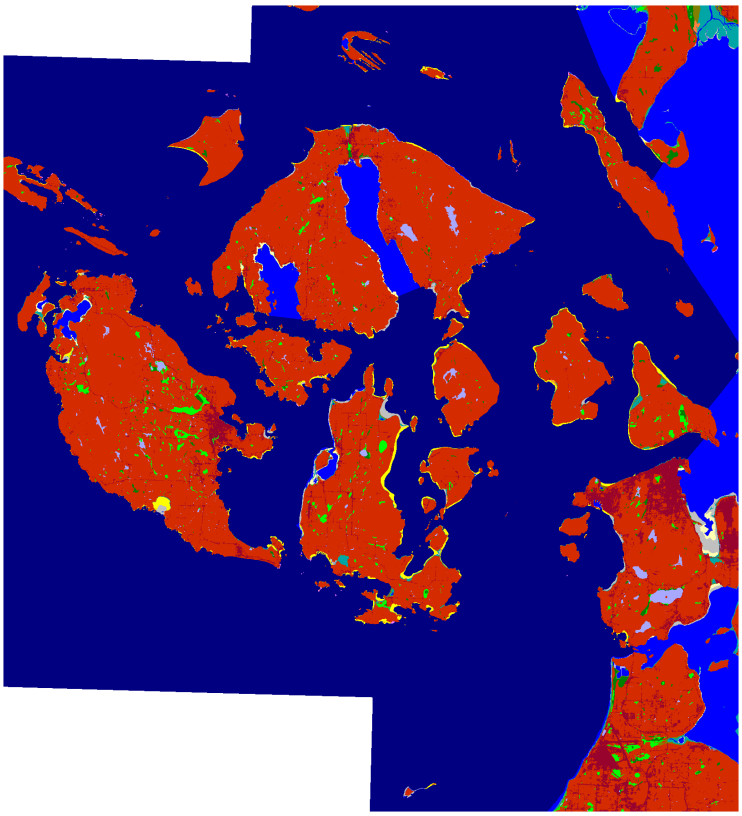
San Juan Islands NWR, 2075, 1 meter



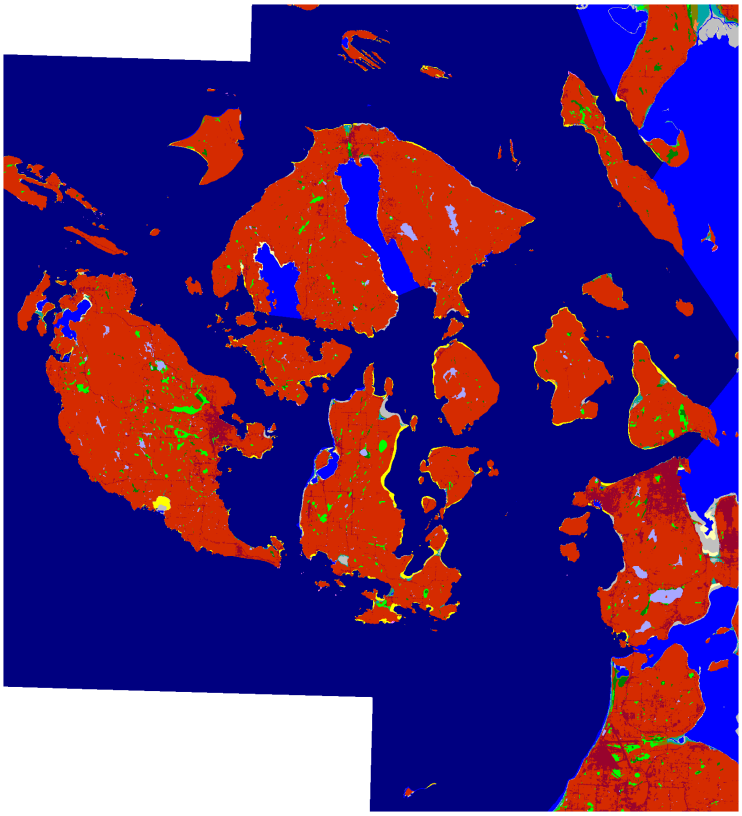
San Juan Islands NWR, 2100, 1 m SLR



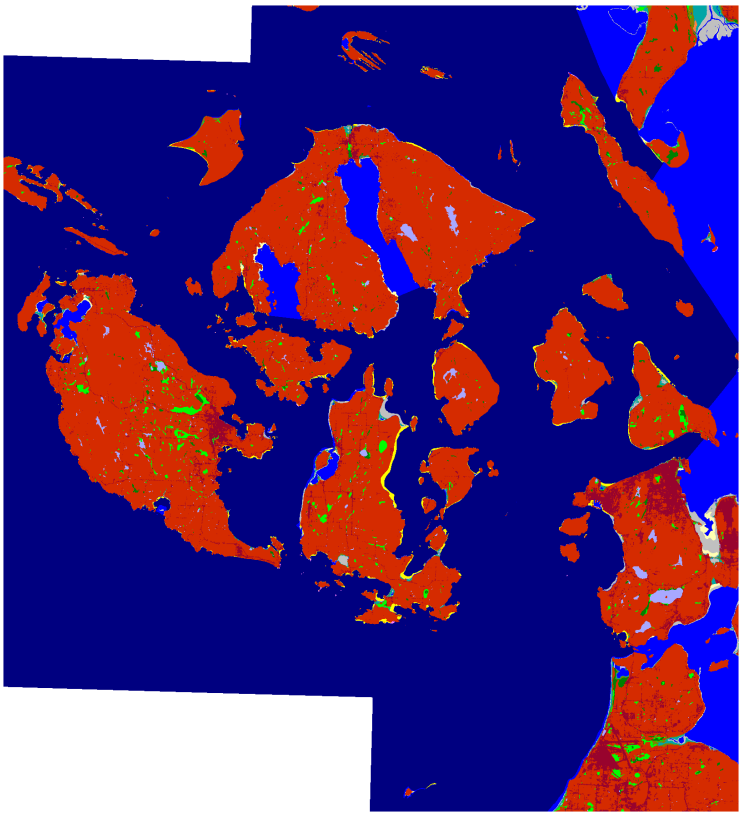
San Juan Islands NWR, Initial Condition



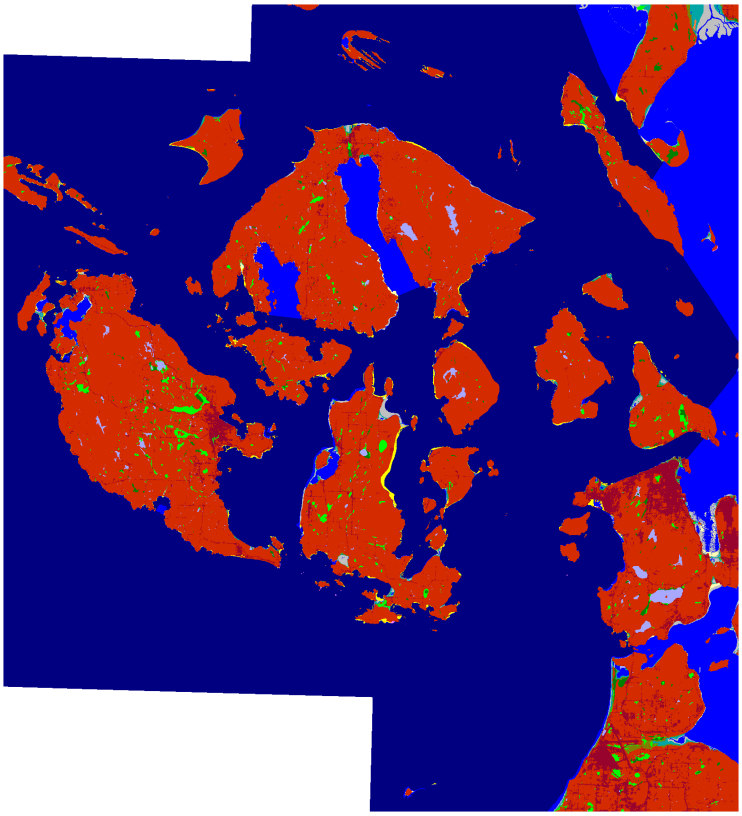
San Juan Islands NWR, 2025, 1.5 m SLR



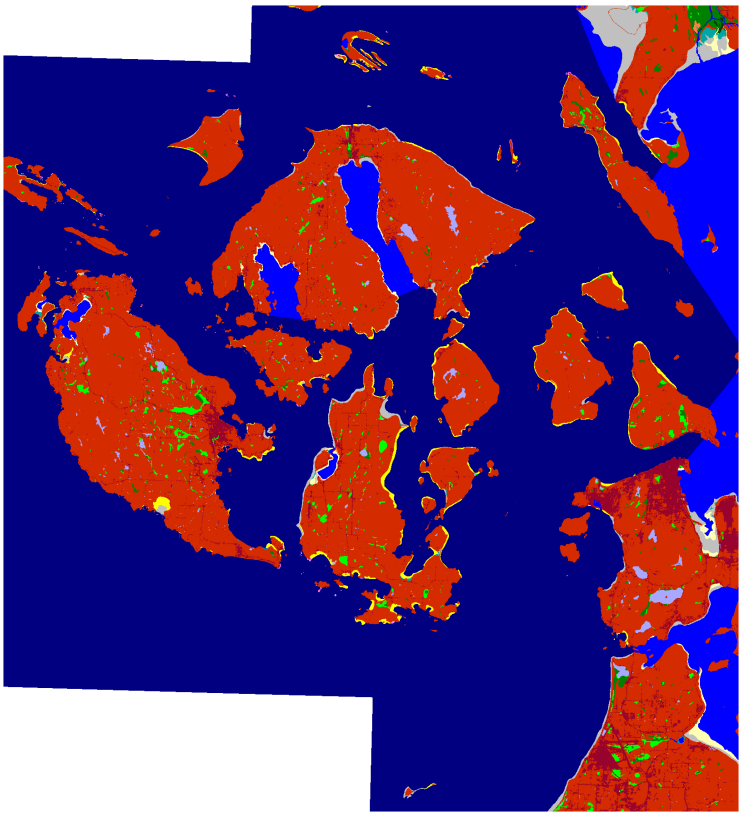
San Juan Islands NWR, 2050, 1.5 m SLR



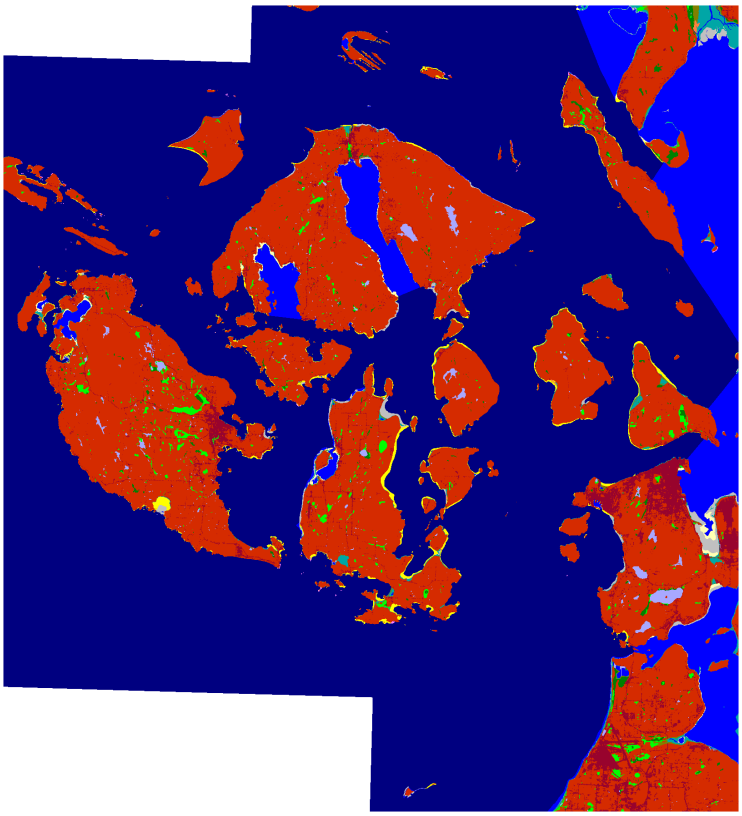
San Juan Islands NWR, 2075, 1.5 m SLR



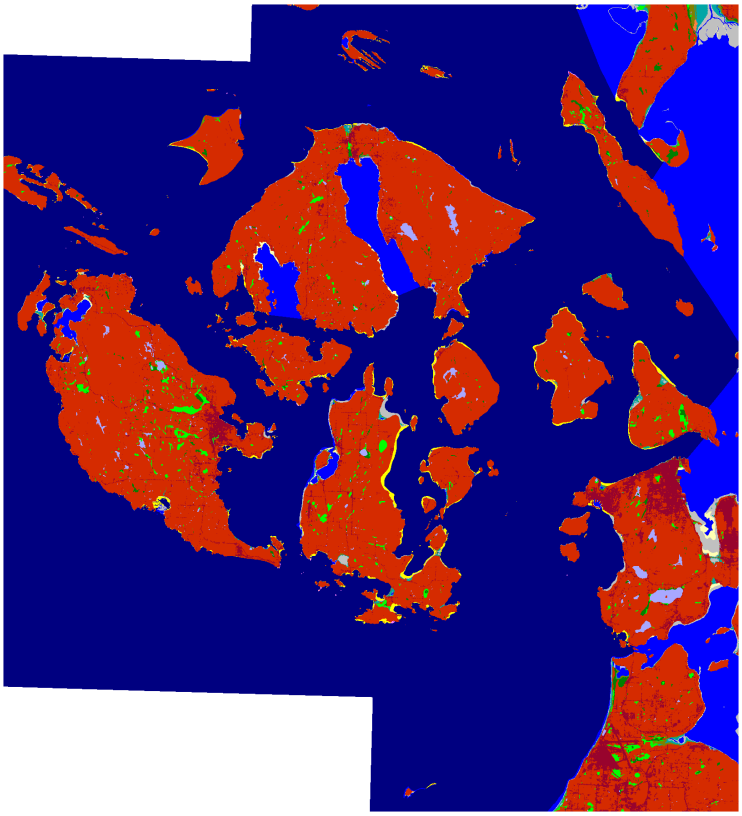
San Juan Islands NWR, 2100, 1.5 m SLR



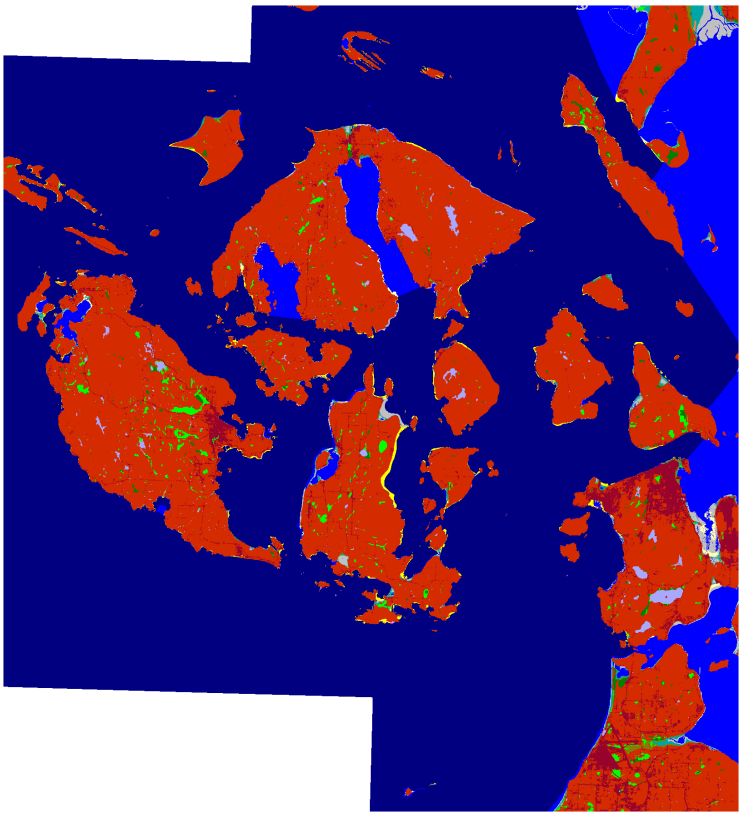
San Juan Islands NWR, Initial Condition



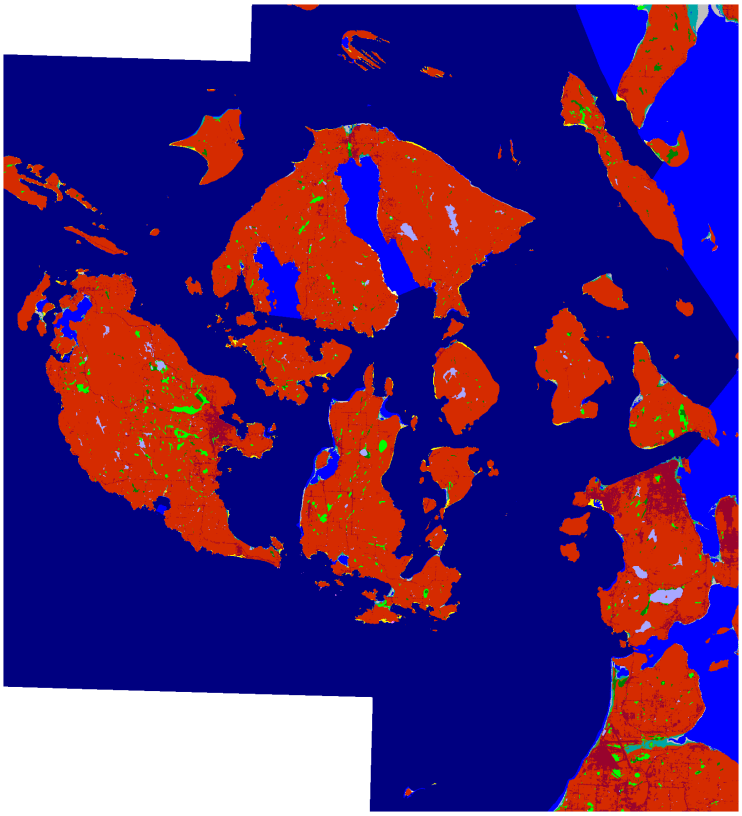
San Juan Islands NWR, 2025, 2 m SLR



San Juan Islands NWR, 2050, 2 m SLR



San Juan Islands NWR, 2075, 2 m SLR



San Juan Islands NWR, 2100, 2 m SLR