Application of the Sea-Level Affecting Marshes Model (SLAMM 6) to Nisqually 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 m 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).

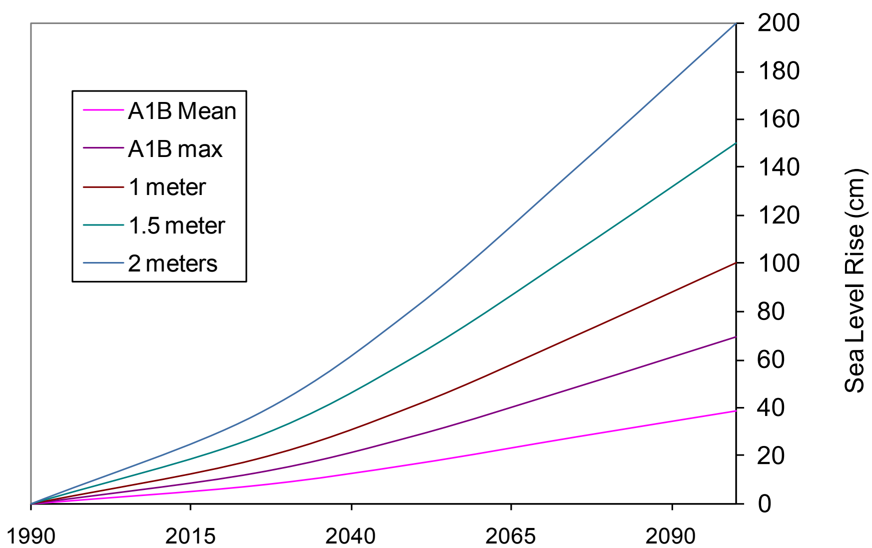


Figure 1. Summary of SLR scenarios utilized

Data Sources and Methods

Elevation Data. The layer used was 2002 bare-earth LiDAR data gathered by the Puget Sound LiDAR Consortium.

Wetland layer. Figure 2 shows the most recent available wetlands layer obtained from a National Wetlands Inventory (NWI), photo dated 1981. Converting the NWI survey into 10 m cells indicated that the approximately 11,500 acre Nisqually NWR (approved acquisition boundary including water) is composed of the following categories:

Land cover type		Area (acres)	Percentage (%)
	Undeveloped Dry Land	5797	50
	Swamp	1390	12
	Inland Fresh Marsh	1308	11
	Estuarine Beach	967	8
	Regularly-flooded Marsh	625	5
	Estuarine Open Water	483	4
	Developed Dry Land	360	3
	Tidal Flat	318	3
	Inland Open Water	107	<1
	Riverine Tidal	48	<1
	Irregularly-flooded Marsh	47	<1
	Tidal Swamp	32	<1
	Inland Shore	3	<1
	Total (incl. water)	**11484**	**100**

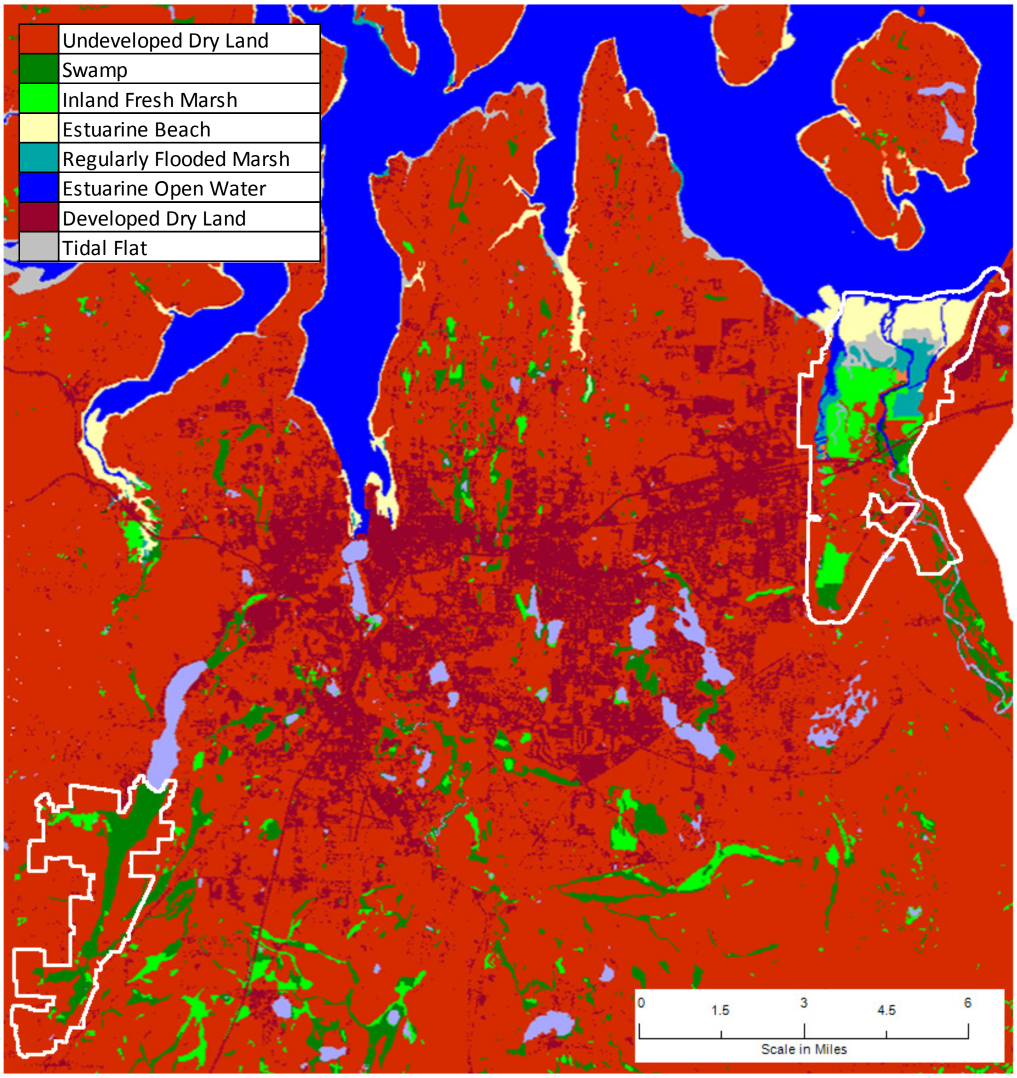


Figure 2. 1981 NWI coverage of the study area. Refuge boundaries are indicated in white

Dikes and Impoundments. Over the past decade, the refuge and its partners, including the Nisqually Tribe and Ducks Unlimited, have restored more than 35 km of the historic tidal slough systems and re-connected historic floodplains to Puget Sound, increasing potential salt marsh habitat in the southern reach of Puget Sound by 50% (source: http://www.nisquallydeltarestoration.org).

The available dike layer was modified to reflect the dike removal and construction that has occurred in the refuge. A map of the current dike system is shown in Figure 3. Because of the changes to the dike configuration, the 1981 wetland layer does not reflect the current land cover of the refuge. Figure 3 also illustrates the conversion of areas that were identified as inland fresh marsh in 1981 to salt marsh made by the SLAMM conceptual model since these areas in the river delta are now subjected to frequent inundation. These areas are initially shown in a brown color as "transitional salt marsh."

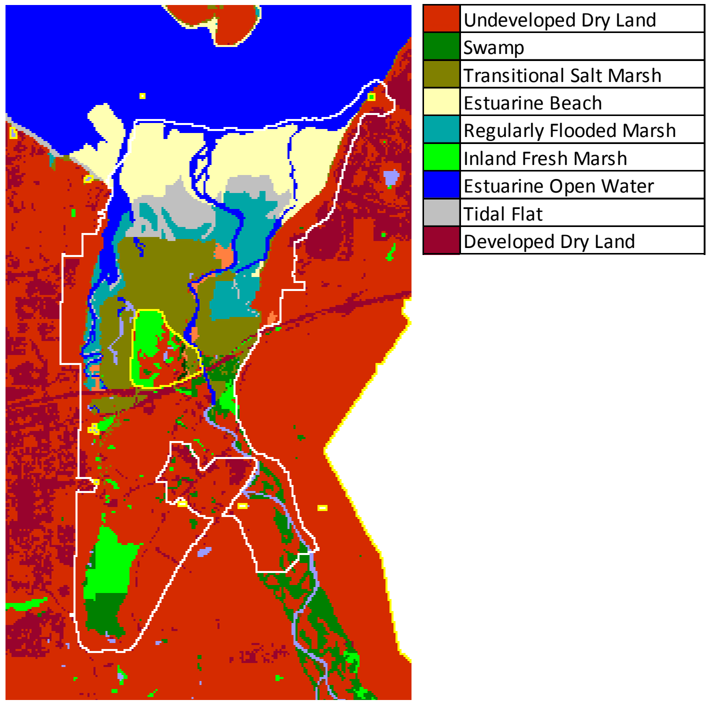


Figure 3. Current diked area shown in yellow, the refuge boundaries at the delta of Nisqually River in white

Model Timesteps. Model forecast data was output for years 2025, 2050, 2075 and 2100 with the initial condition date set to 1981 (the most recent wetland data available). SLAMM uses a built in processor to correct elevations in an attempt to account for any elevation variation due to sea level rise between the wetland photo date and the DEM date.

Historic sea level rise rates. The historic trend for relative sea level rise was estimated at 2.0 mm/yr using the average rate recorded at NOAA gauge station 9447130 in Seattle, WA. The rate of sea level rise for this refuge is slightly higher than the global (eustatic) SLR for the last 100 years (approximately 1.7 mm/year), perhaps suggesting some subsidence in this area.

Tide Ranges. The great diurnal range (GT) measured at the NOAA gauge stations present in the area (shown in Figure 4), is between 4.11 m and 4.41 m. For the simulation the average value of 4.26 m was applied.

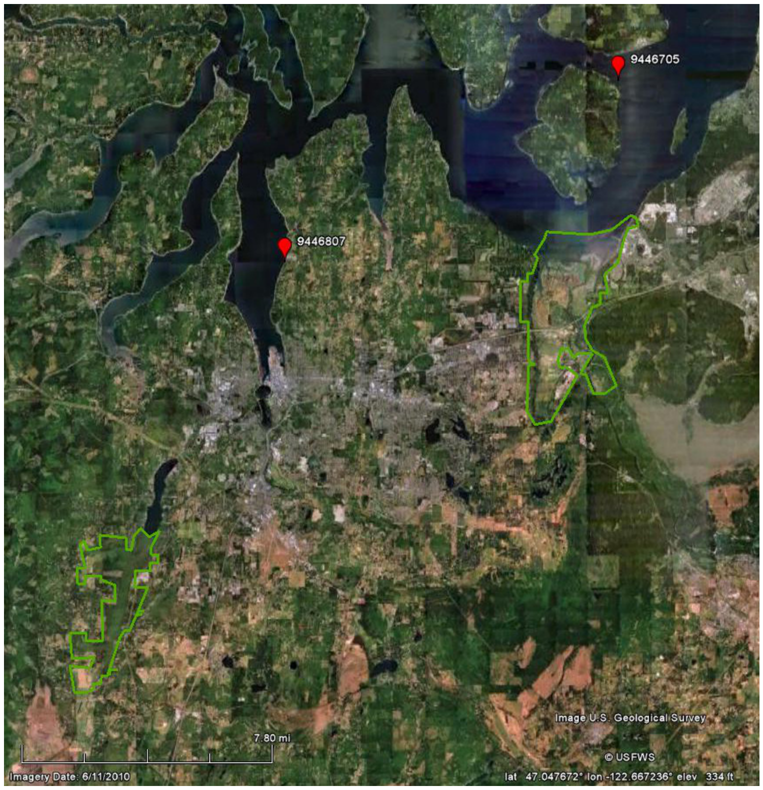


Figure 4. NOAA gauge station locations used for this study. Refuge boundaries in green

Salt elevation. This parameter within SLAMM designates the boundary between wet lands and dry lands or saline wetlands and fresh water wetlands. Based on regional data, for this application, salt elevation was estimated at 1.5 Half Tide Units (HTU), equivalent to 3.2 m above MTL.

Accretion rates. Salt marsh vertical accretion rates were set to 2.8 mm/yr., the average value found in the Nisqually Delta by Thom (1992). Model accretion rates for irregularly-flooded (brackish) marsh were set to SLAMM defaults of 3.75 mm/yr and tidal fresh marsh accretion rates were set to 4 mm/yr. These values fall within the range of Pacific Northwest accretion measurements by Thom (1992) and 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 Tacoma, WA (ID 9446545) Seattle, Puget Sound, WA (ID 9447130) and Bremerton, WA (ID 9445958) are quite similar, (1.31m, 1.32 m, and 1.32 m, respectively). Therefore the average value of 1.32 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 10 m by 10 m cells.

Parameter summary. Tidal data for the upstream portion of McAllister Creek are not available. However, it seems reasonable to assume that south of highway 5, the tide range and salt influence is significantly lower than what is observed further north, in the area of the Nisqually river delta. Elevation data suggest that dry-lands in this region would otherwise be subject to immediate inundation. Therefore, as illustrated in Figure 5, an additional input subsite was defined around the McAllister Creek with reduced tidal ranges. Table 1 summarizes all SLAMM input parameters for the two input subsites. Values for parameters with no specific local information were kept at the model default value.

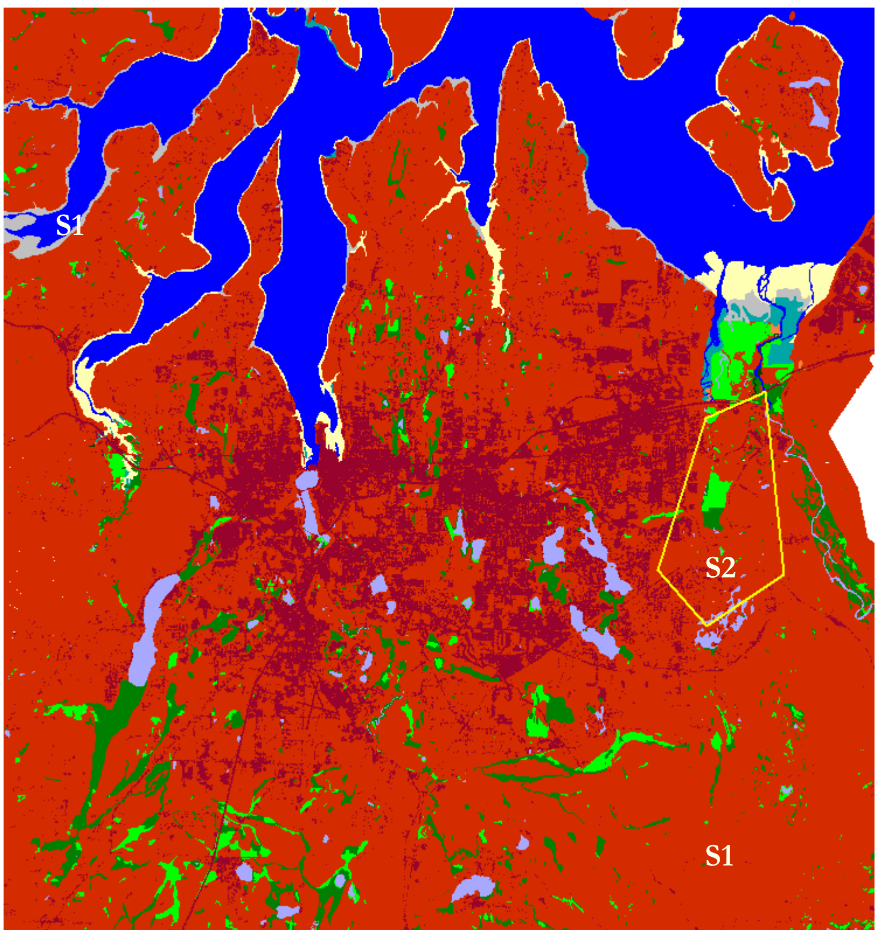


Figure 5. Input subsites for model application

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

Description	Subsite 1	SubSite 2
NWI Photo Date (YYYY)	1981	1981
DEM Date (YYYY)	2002	2002
Direction Offshore [n,s,e,w]	North	North
Historic Trend (mm/yr)	2	2
MTL-NAVD88 (m)	1.32	1.32
GT Great Diurnal Tide Range (m)	4.26	1.6
Salt Elev. (m above MTL)	3.2	1.2
Marsh Erosion (horz. m /yr)	2	2
Swamp Erosion (horz. m /yr)	1	1
Flat Erosion (horz. m /yr)	0.2	0.2
Reg.-Flood Marsh Accr (mm/yr)	2.8	2.8
Irreg.-Flood Marsh Accr (mm/yr)	3.75	3.75
Tidal-Fresh Marsh Accr (mm/yr)	4	4
Inland-Fresh Marsh Accr (mm/yr)	4	4
Mangrove Accr (mm/yr)	7	7
Tidal Swamp Accr (mm/yr)	1.1	1.1
Swamp Accretion (mm/yr)	0.3	0.3
Beach Sed. Rate (mm/yr)	0.5	0.5
Freq. Overwash (years)	0	0
Use Elev Pre-processor [True,False]	FALSE	FALSE

Results

Table 2 presents the land cover by 2100 for the total approved acquisition boundary of Nisqually NWR for each of the five SLR scenarios examined. For this simulation the land-cover losses are calculated in comparison to the 1981 NWI wetland layer. Therefore predicted changes include the result of the combined effects of dike removal and response to SLR. All predicted land-cover losses were observed in the Nisqually river delta section of the refuge. The interior portion of the refuge is predicted to go through no significant change as a function of SLR.

Table 2. Predicted loss rates of land categories by 2100 given simulated scenarios of eustatic SLR at Nisqually 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	5797	5%	6%	6%	9%	12%
Swamp	1390	6%	7%	8%	17%	18%
Inland Fresh Marsh	1308	58%	59%	59%	75%	76%
Estuarine Beach	967	2%	2%	2%	50%	70%
Regularly-flooded Marsh	625	-141%	-148%	-152%	-75%	-69%
Estuarine Open Water	483	-21%	-24%	-25%	-124%	-172%
Developed Dry Land	360	8%	9%	10%	13%	17%
Tidal Flat	318	-13%	-24%	-46%	-246%	-410%
Transitional Salt Marsh([2])	0	-263	-240	-212	-593	-274

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

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

Undeveloped-dry land and swamp are predicted to sustain a similar amount of loss, ranging between 5% and 18% across the SLR scenarios considered. By comparing the initial wetland layer with one adjusted after dike removal, it is possible to estimate that the loss due to dike removal accounts for about 4% of total land cover loss, while the remaining predicted loss is due to sea level rise.

Similarly, of the land cover loss predicted for inland fresh marsh, approximately 60% is due to dike removal while the remaining area covered by this wetland is quite resilient to SLR since it remains protected by dikes. In fact, for SLR scenarios of 1 m by 2100 or less no additional losses are observed, while an additional 16% is lost for the highest SLR scenario considered.

Estuarine beach, which initially accounts for 8% of the refuge area, is not significantly affected by SLR scenarios below equal or below 1 m by 2100. However, for higher SLR scenarios land cover losses range between 50% and 70%.

Regularly-flooded marsh is predicted to significantly increase in acreage as sea level increases, culminating in a 152% gain under the 1 m SLR by 2100 scenario. For higher SLR rates, land cover gains are lower as regularly-flooded marsh itself is predicted to be lost.

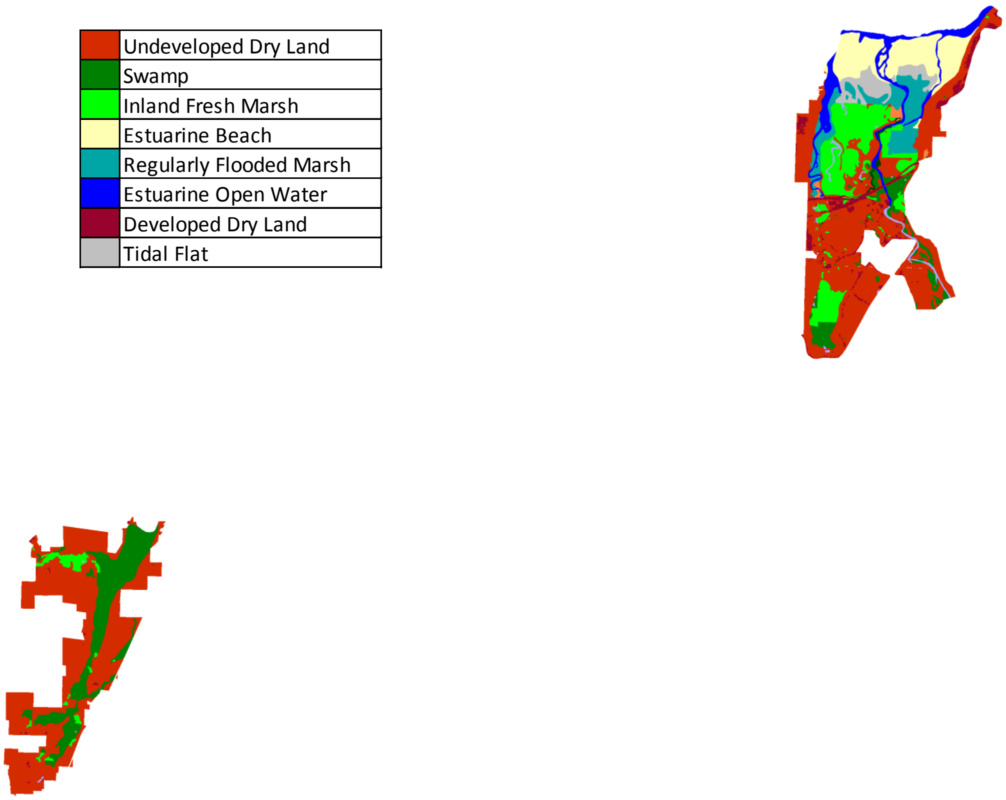
Tidal flat is also predicted to increase in coverage as sea level continues to rise. Tidal flat creation becomes significant under SLR scenarios greater than 1 m by 2100 as a result of regularly-flooded marsh conversion to tidal flat.

Finally, transitional salt marsh is predicted to appear in the refuge as dry lands, swamps, and freshwater wetlands become subject to saline influence. SLAMM predicts that over 1100 acres will initially be covered by this wetland category as a result of dike removal. However, for most SLR scenarios considered, this area is significantly reduced by 2100 as it is predicted to be converted to regularly-flooded marsh and tidal flat.

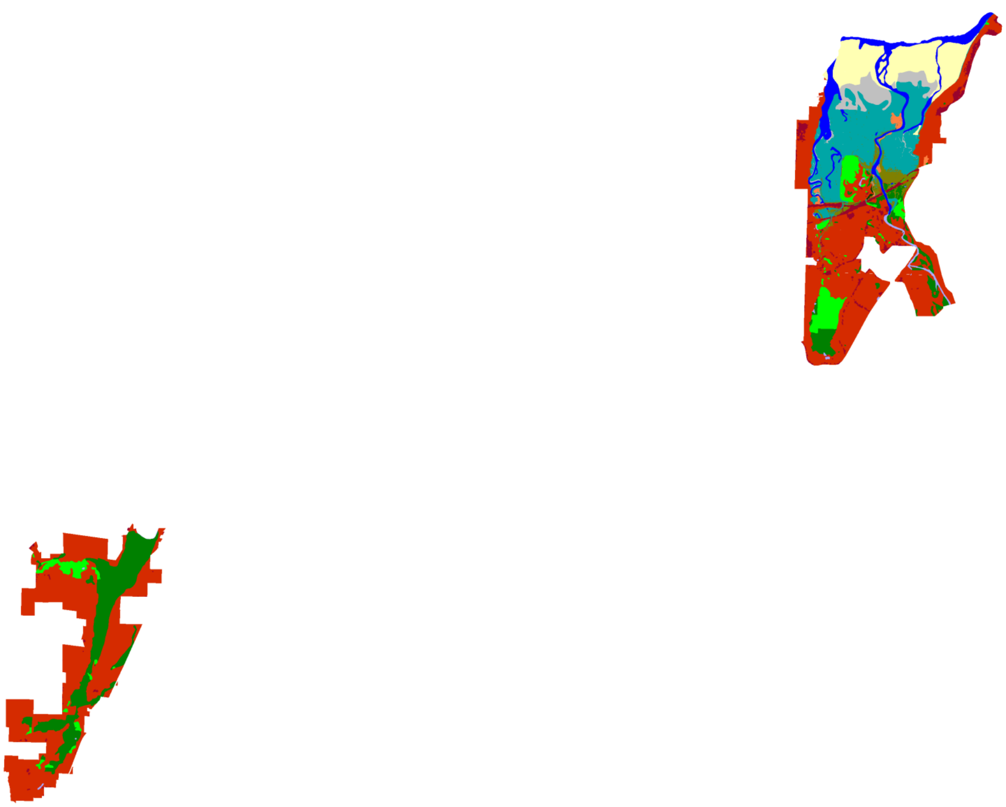
Nisqually NWR
IPCC Scenario A1B-Mean, 0.39 m SLR eustatic by 2100

Results in Acres

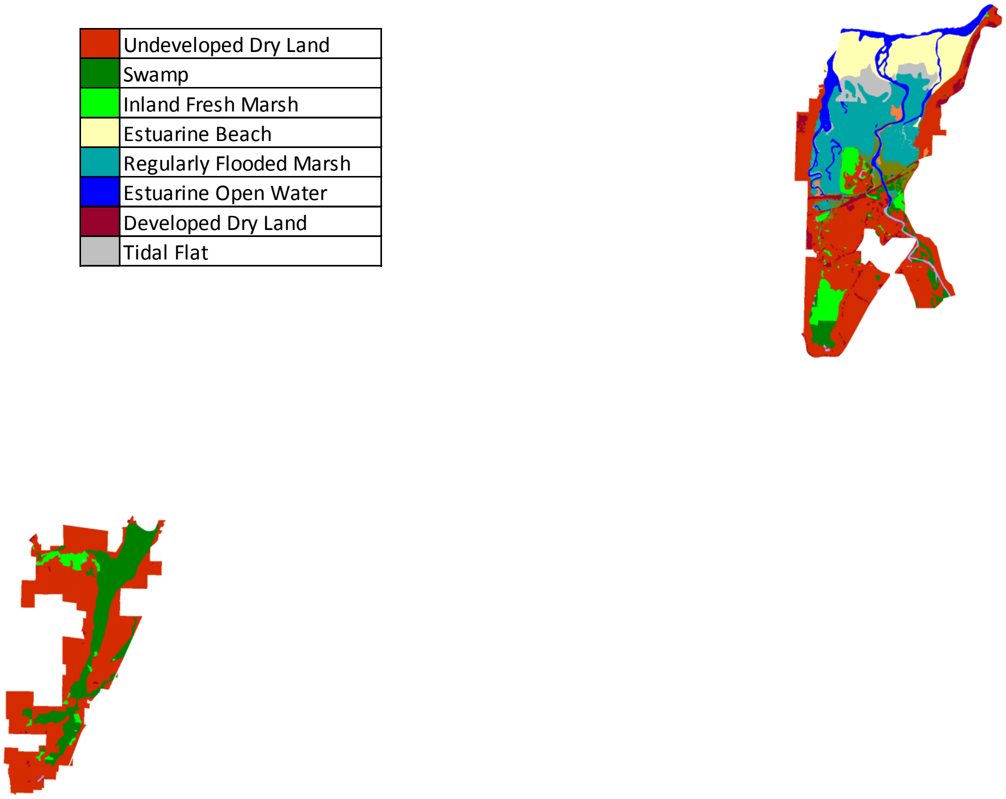
		Initial	2025	2050	2075	2100
	Undeveloped Dry Land	5797	5520	5512	5505	5497
	Swamp	1390	1326	1319	1312	1305
	Inland Fresh Marsh	1308	546	546	546	546
	Estuarine Beach	967	961	960	956	952
	Regularly-flooded Marsh	625	1511	1503	1504	1505
	Estuarine Open Water	483	573	575	580	586
	Developed Dry Land	360	334	333	332	331
	Tidal Flat	318	342	351	355	358
	Inland Open Water	107	72	72	72	72
	Riverine Tidal	48	1	1	0	0
	Irregularly-flooded Marsh	47	60	60	60	60
	Tidal Swamp	32	7	7	7	7
	Inland Shore	3	3	3	3	3
	Transitional Salt Marsh	0	229	243	253	263
	Total (incl. water)	**11484**	**11484**	**11484**	**11484**	**11484**



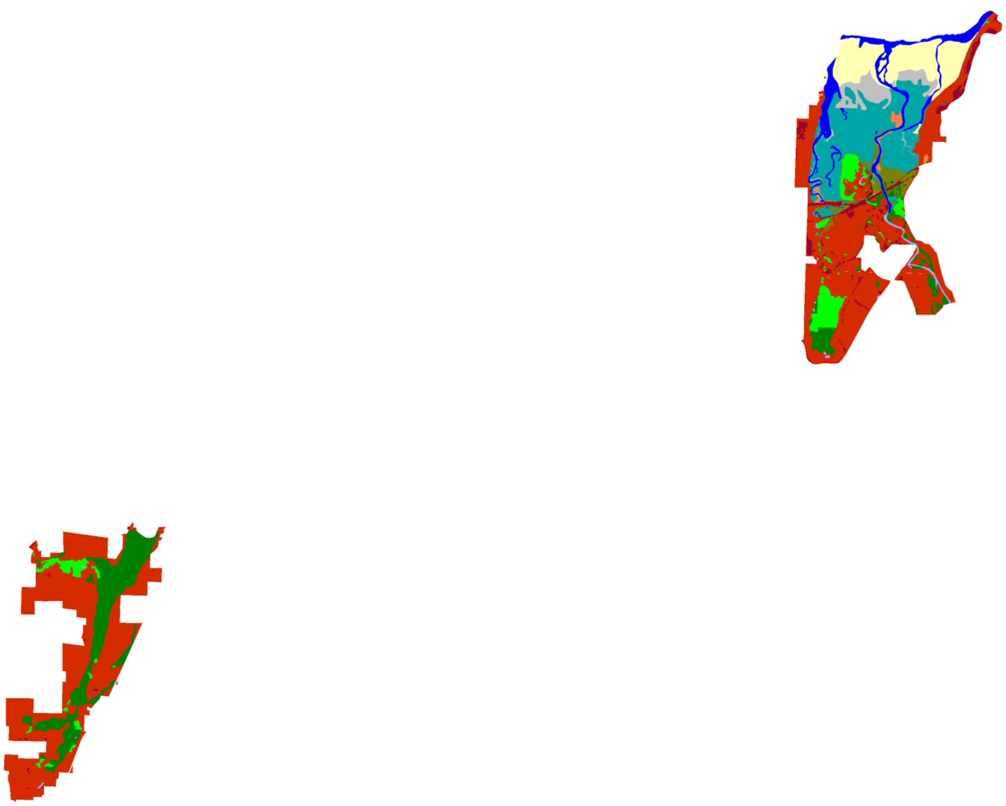
Nisqually NWR, Initial Condition



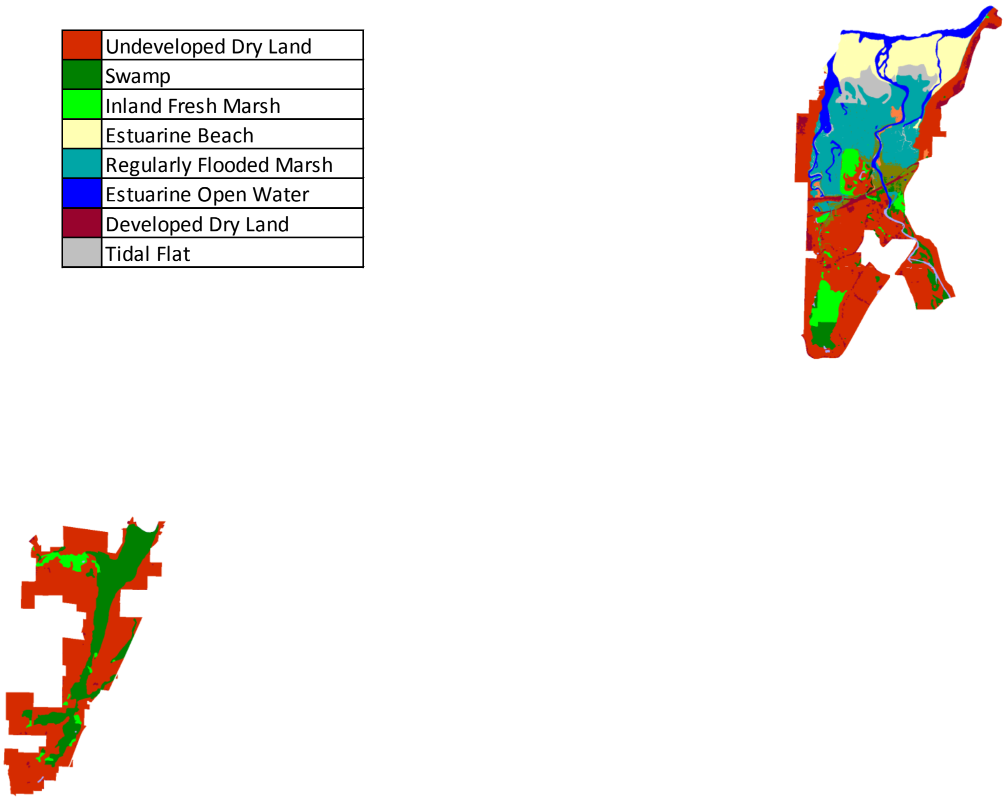
Nisqually NWR, 2025, Scenario A1B Mean, 0.39 m SLR



Nisqually NWR, 2050, Scenario A1B Mean, 0.39 m SLR



Nisqually NWR, 2075, Scenario A1B Mean, 0.39 m SLR

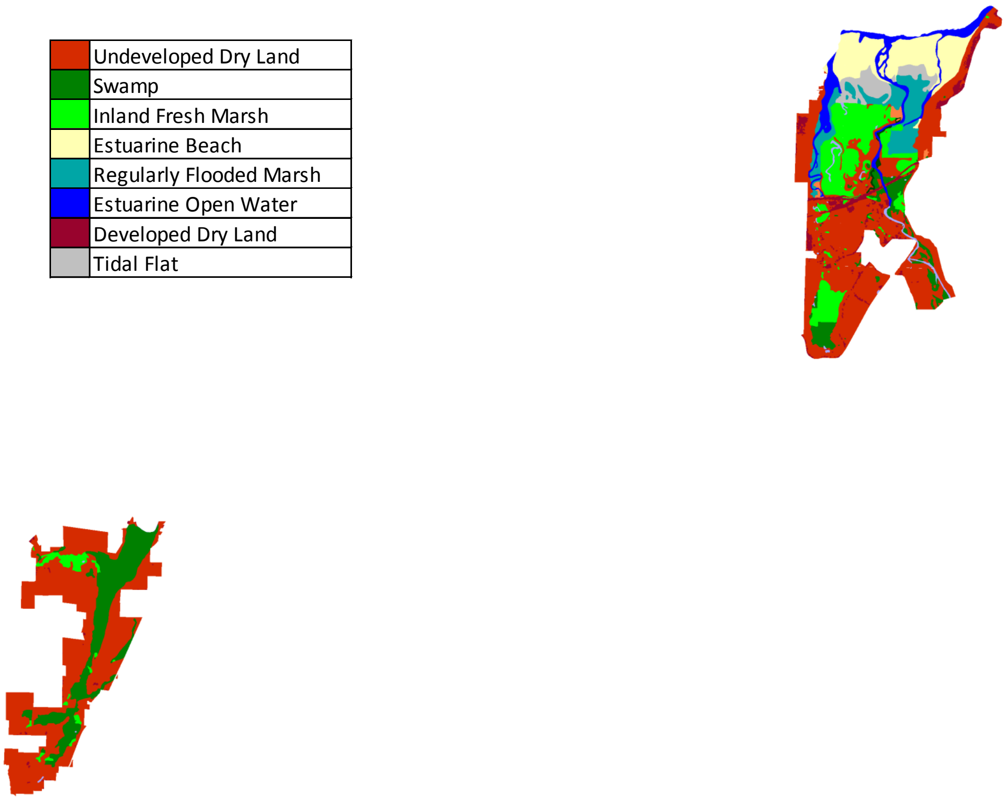


Nisqually NWR, 2100, Scenario A1B Mean, 0.39 m SLR

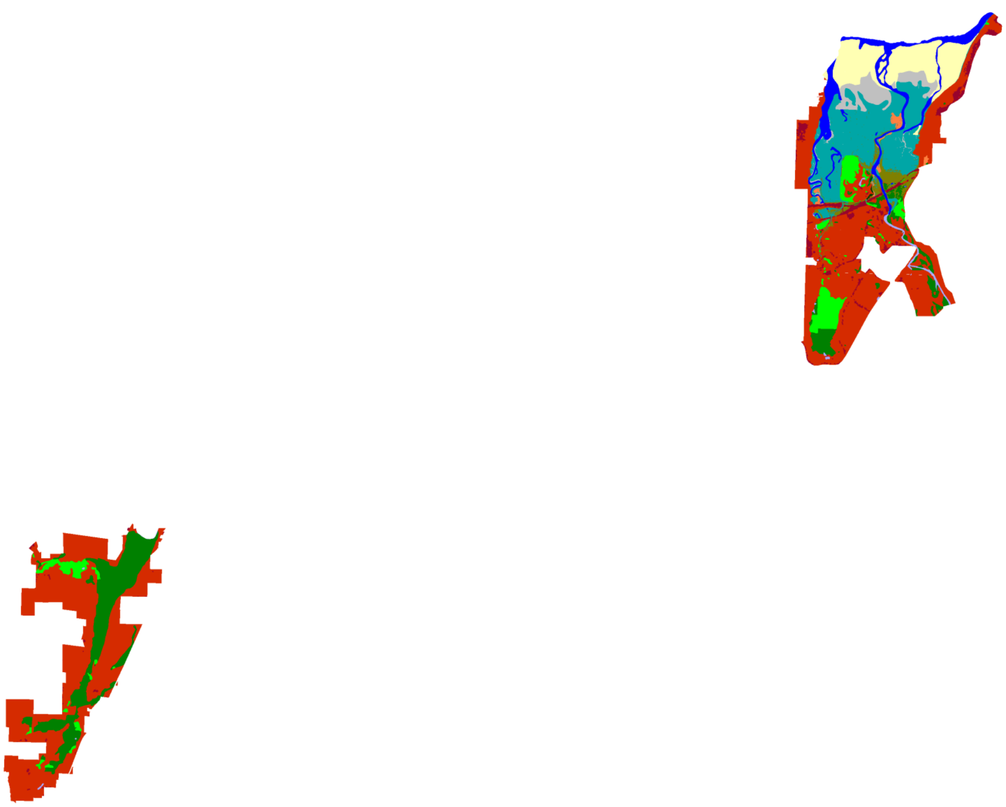
Nisqually NWR
IPCC Scenario A1B-Max, 0.69 m SLR eustatic by 2100

Results in Acres

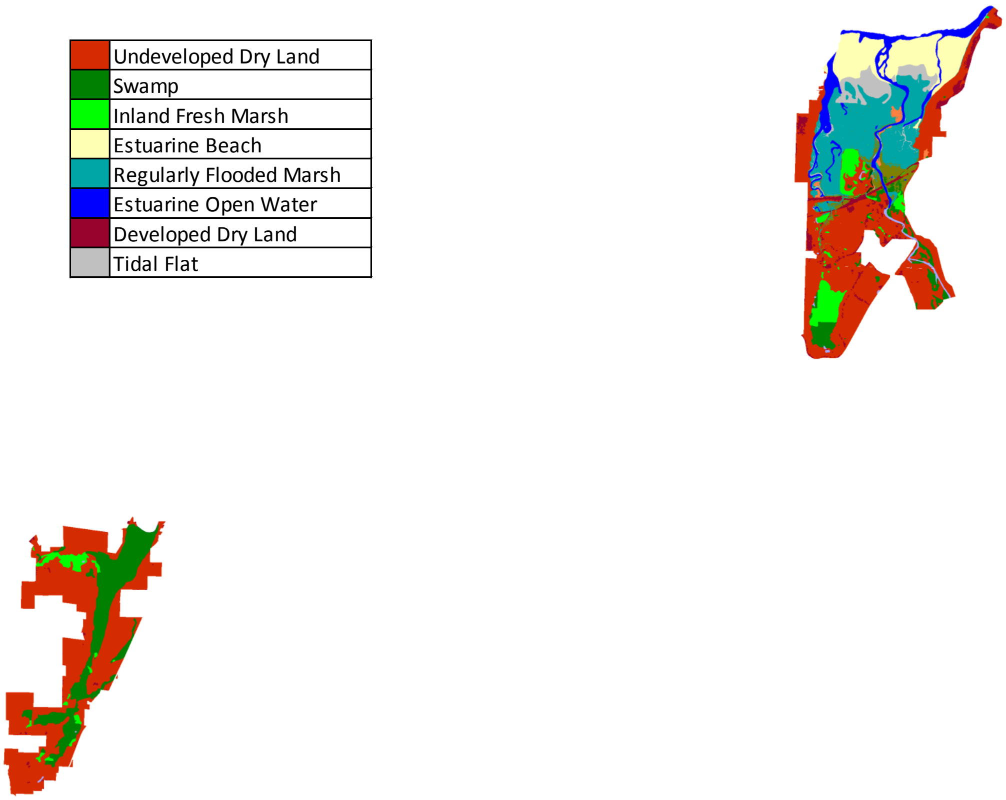
		Initial	2025	2050	2075	2100
	Undeveloped Dry Land	5797	5515	5504	5486	5469
	Swamp	1390	1322	1311	1298	1288
	Inland Fresh Marsh	1308	546	545	544	542
	Estuarine Beach	967	961	960	956	952
	Regularly-flooded Marsh	625	1522	1522	1538	1551
	Estuarine Open Water	483	573	576	584	600
	Developed Dry Land	360	333	332	329	327
	Tidal Flat	318	345	362	375	394
	Inland Open Water	107	72	72	69	59
	Riverine Tidal	48	1	0	0	0
	Irregularly-flooded Marsh	47	60	59	56	53
	Tidal Swamp	32	7	7	7	6
	Inland Shore	3	3	3	3	3
	Transitional Salt Marsh	0	225	231	239	240
	Total (incl. water)	**11484**	**11484**	**11484**	**11484**	**11484**



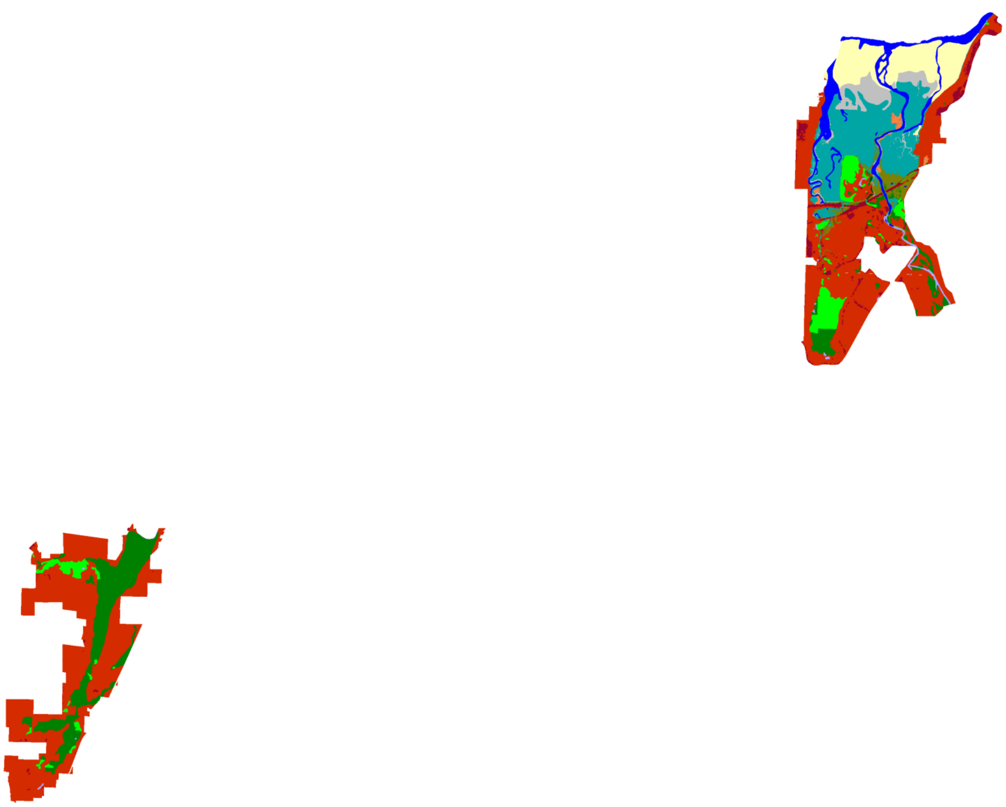
Nisqually NWR, Initial Condition



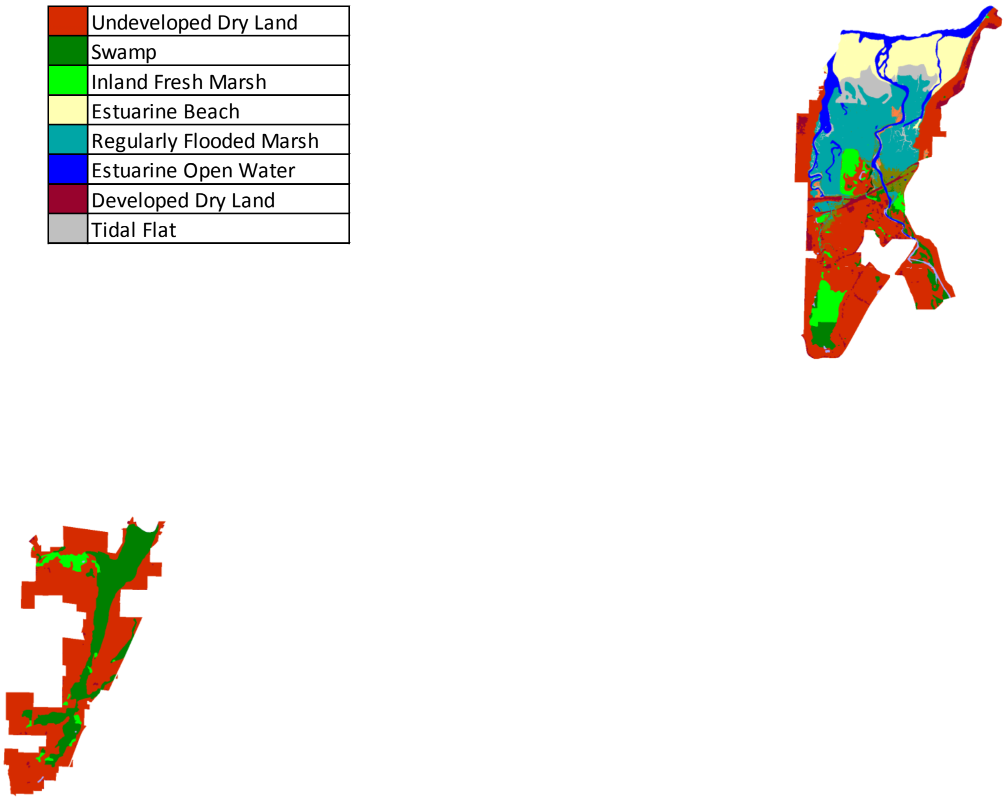
Nisqually NWR, 2025, Scenario A1B Maximum, 0.69 m SLR



Nisqually NWR, 2050, Scenario A1B Maximum, 0.69 m SLR



Nisqually NWR, 2075, Scenario A1B Maximum, 0.69 m SLR

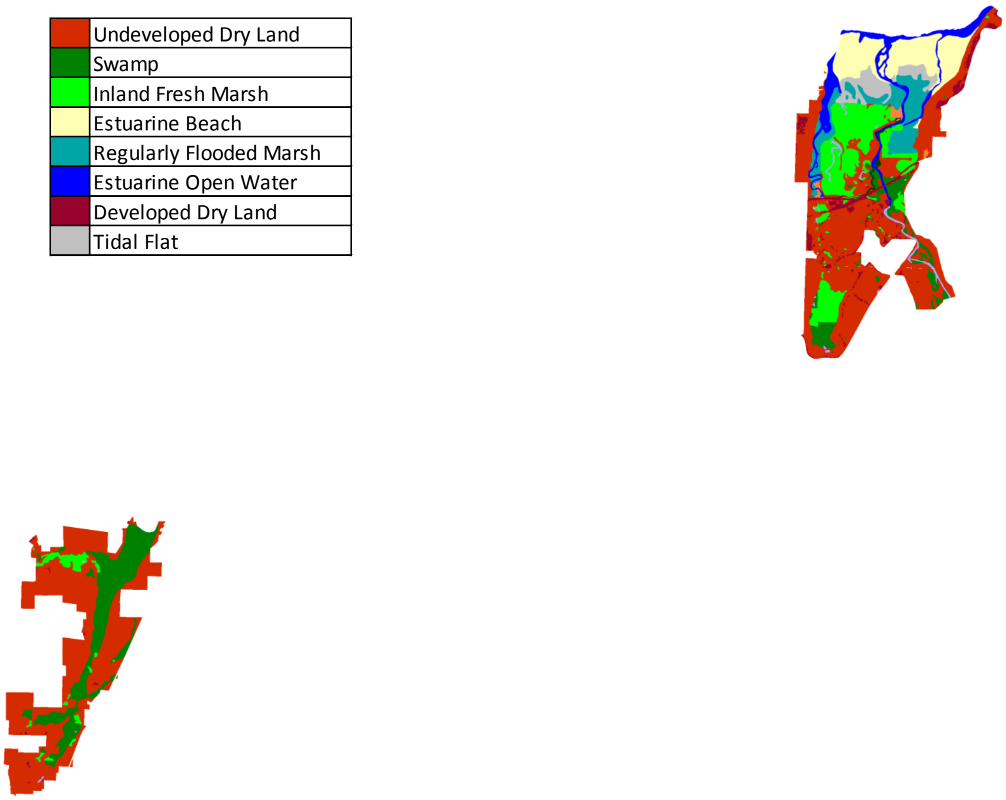


Nisqually NWR, 2100, Scenario A1B Maximum, 0.69 m SLR

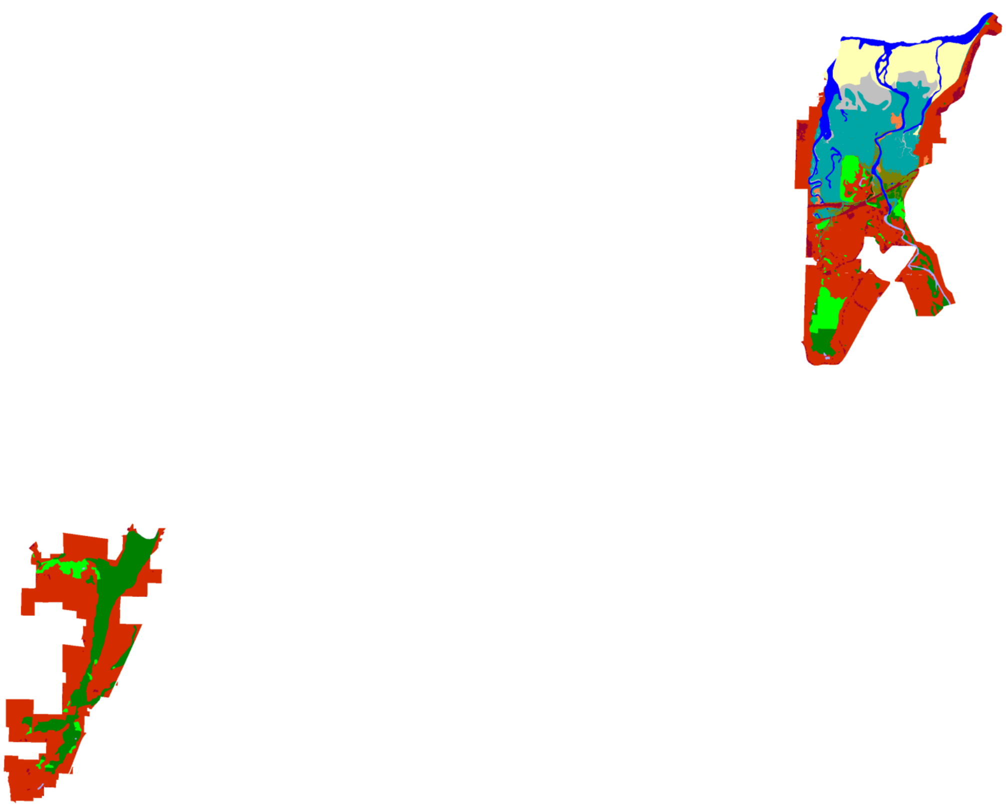
Nisqually NWR
1 m eustatic SLR by 2100

Results in Acres

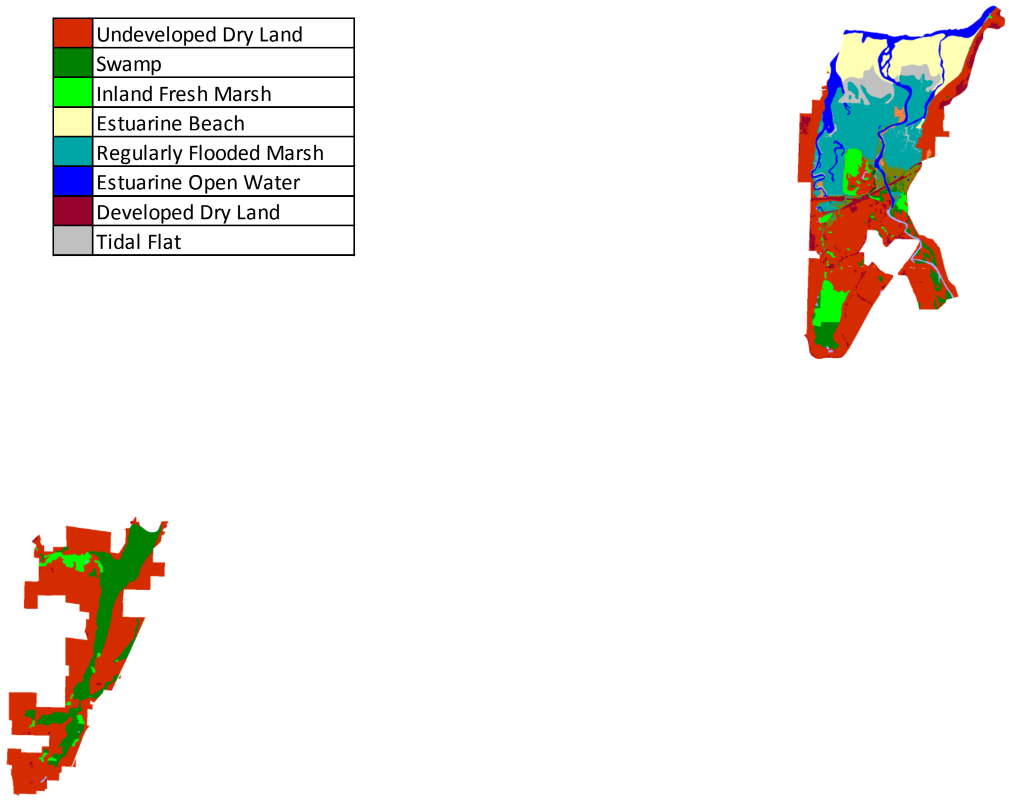
		Initial	2025	2050	2075	2100
	Undeveloped Dry Land	5797	5512	5496	5468	5436
	Swamp	1390	1318	1304	1288	1280
	Inland Fresh Marsh	1308	546	544	541	536
	Estuarine Beach	967	961	960	956	952
	Regularly-flooded Marsh	625	1532	1543	1563	1572
	Estuarine Open Water	483	574	576	586	604
	Developed Dry Land	360	333	330	327	323
	Tidal Flat	318	349	375	405	463
	Inland Open Water	107	72	72	68	56
	Riverine Tidal	48	1	0	0	0
	Irregularly-flooded Marsh	47	59	56	50	40
	Tidal Swamp	32	7	7	6	6
	Inland Shore	3	3	3	3	3
	Transitional Salt Marsh	0	219	218	223	212
	Total (incl. water)	**11484**	**11484**	**11484**	**11484**	**11484**



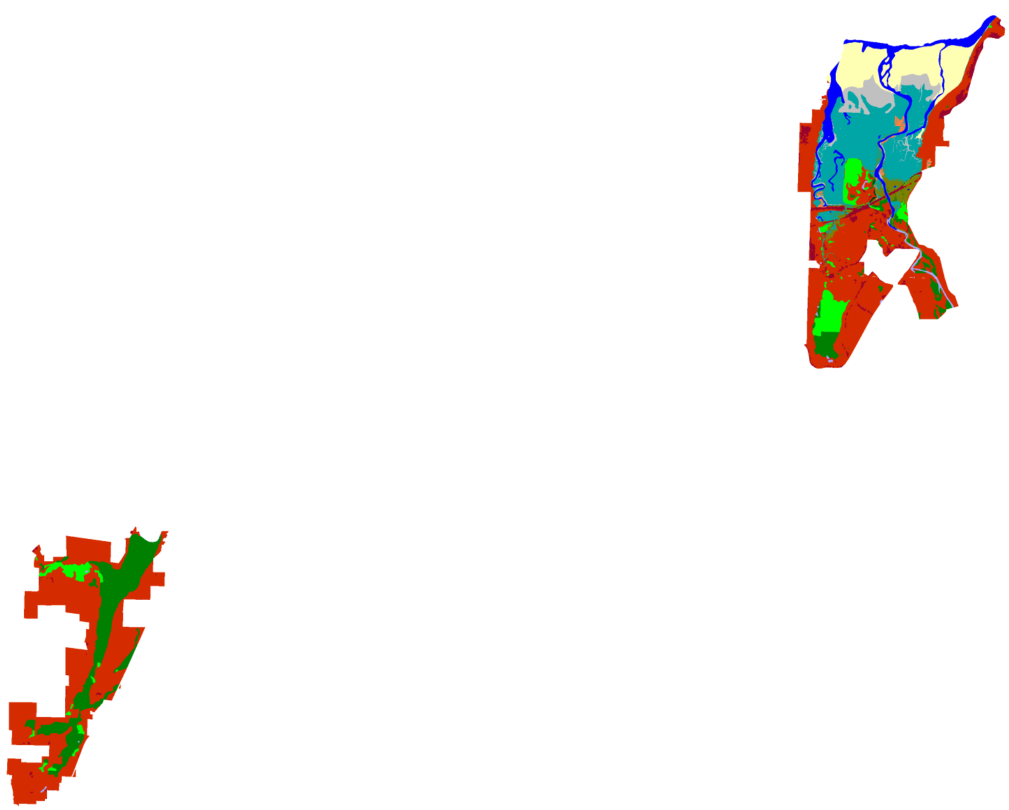
Nisqually NWR, Initial Condition



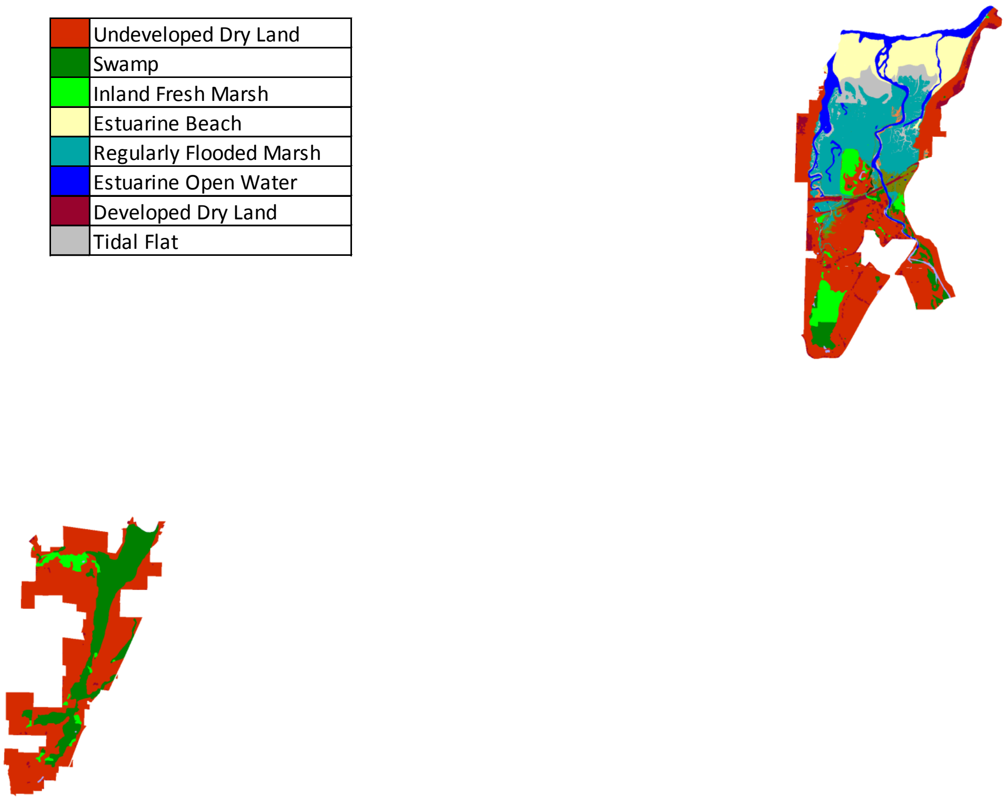
Nisqually NWR, 2025, 1 m SLR



Nisqually NWR, 2050, 1 m SLR



Nisqually NWR, 2075, 1 m SLR

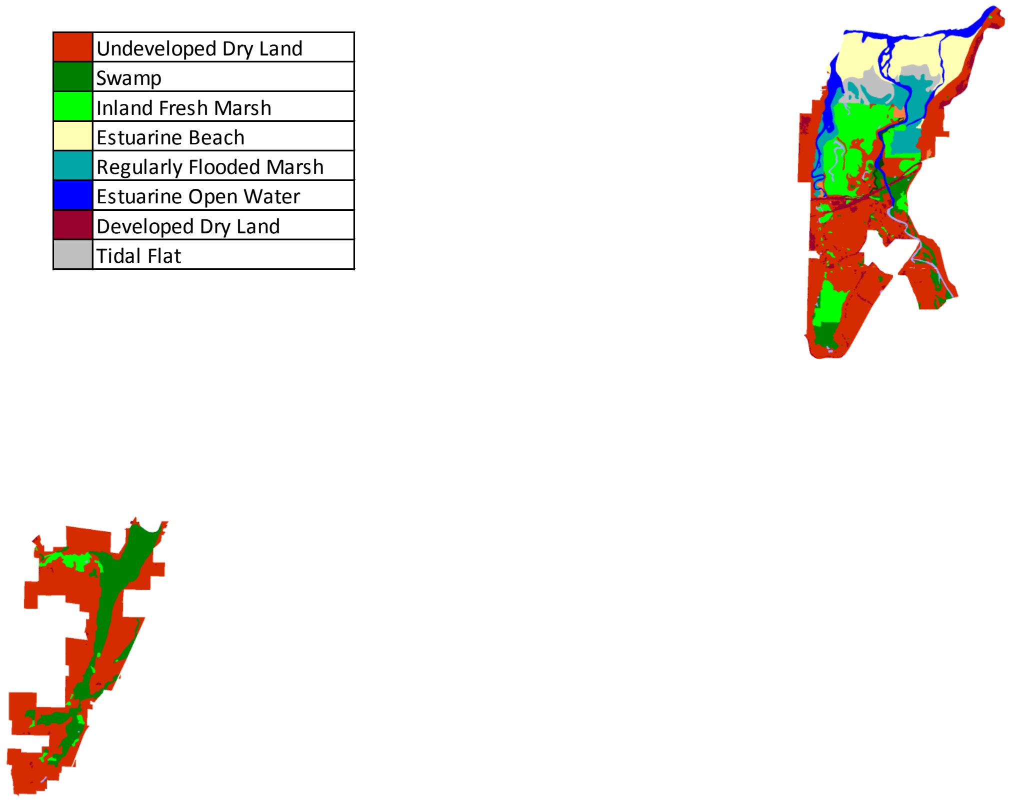


Nisqually NWR, 2100, 1 m SLR

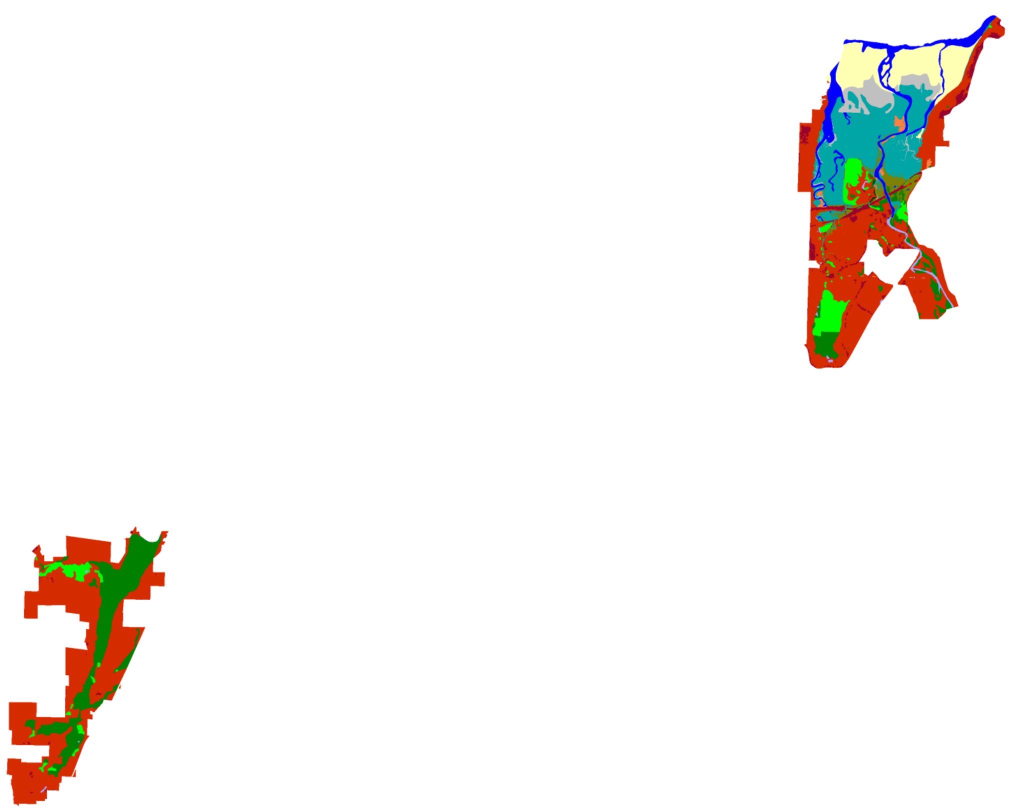
Nisqually NWR
1.5 m eustatic SLR by
2100

Results in Acres

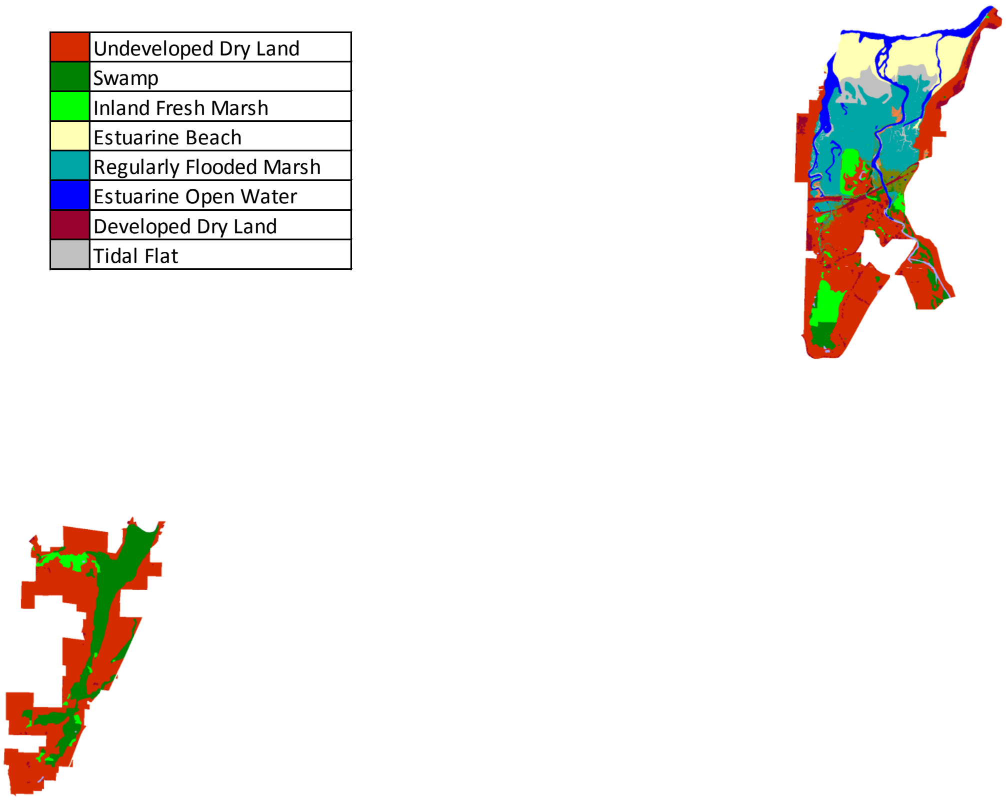
		Initial	2025	2050	2075	2100
	Undeveloped Dry Land	5797	5505	5477	5431	5256
	Swamp	1390	1312	1291	1280	1156
	Inland Fresh Marsh	1308	545	541	530	326
	Estuarine Beach	967	961	960	956	481
	Regularly-flooded Marsh	625	1551	1566	1538	1091
	Estuarine Open Water	483	574	580	599	1083
	Developed Dry Land	360	332	328	323	314
	Tidal Flat	318	356	404	539	1103
	Inland Open Water	107	72	68	56	52
	Riverine Tidal	48	0	0	0	0
	Irregularly-flooded Marsh	47	57	50	31	18
	Tidal Swamp	32	7	6	6	6
	Inland Shore	3	3	3	3	3
	Transitional Salt Marsh	0	210	209	192	593
	Total (incl. water)	**11484**	**11484**	**11484**	**11484**	**11484**



Nisqually NWR, Initial Condition



Nisqually NWR, 2025, 1.5 m SLR



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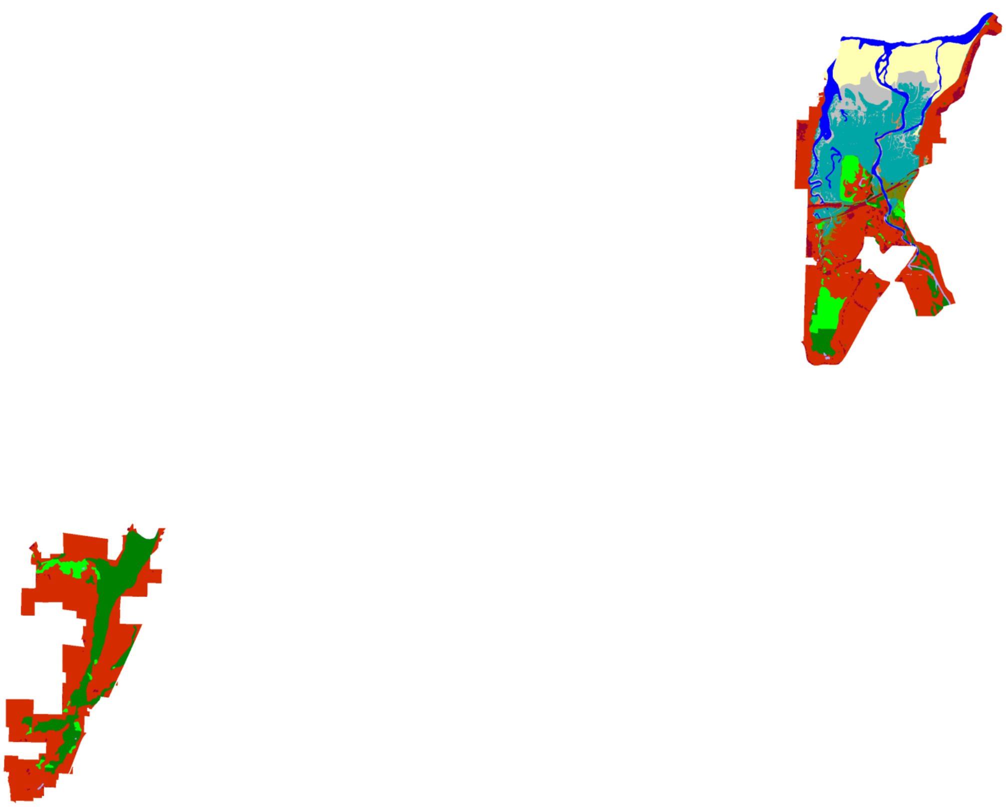

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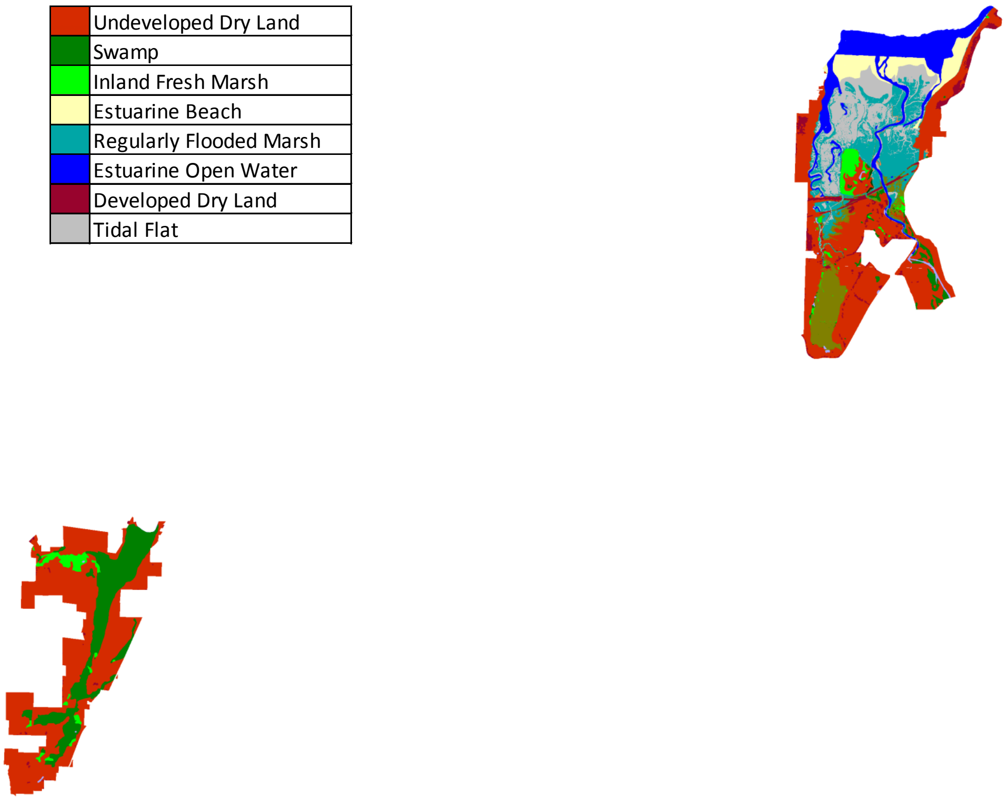
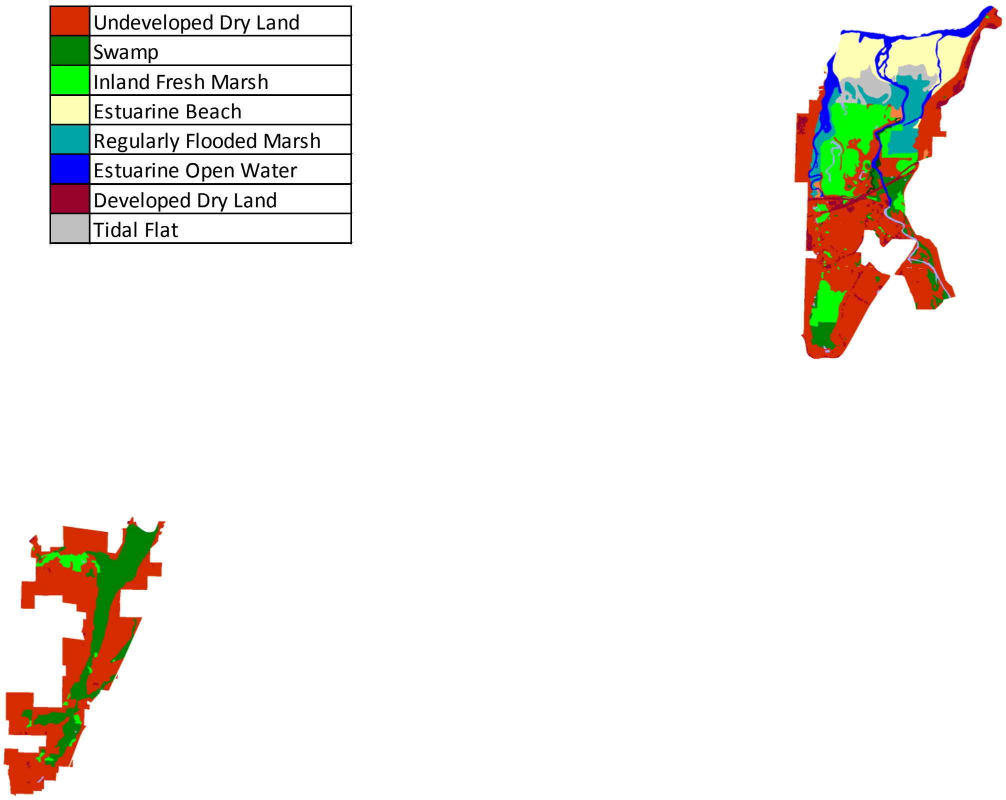


Nisqually NWR, 2100, 1.5 m SLR

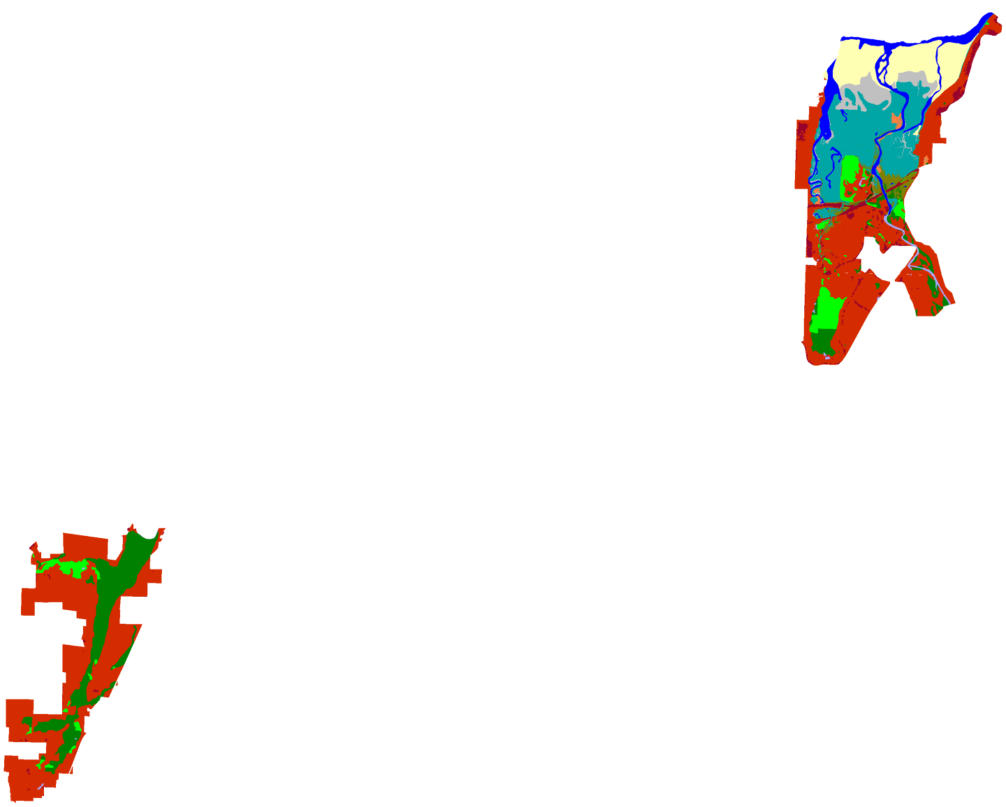
Nisqually NWR
2 m eustatic SLR by 2100

Results in Acres

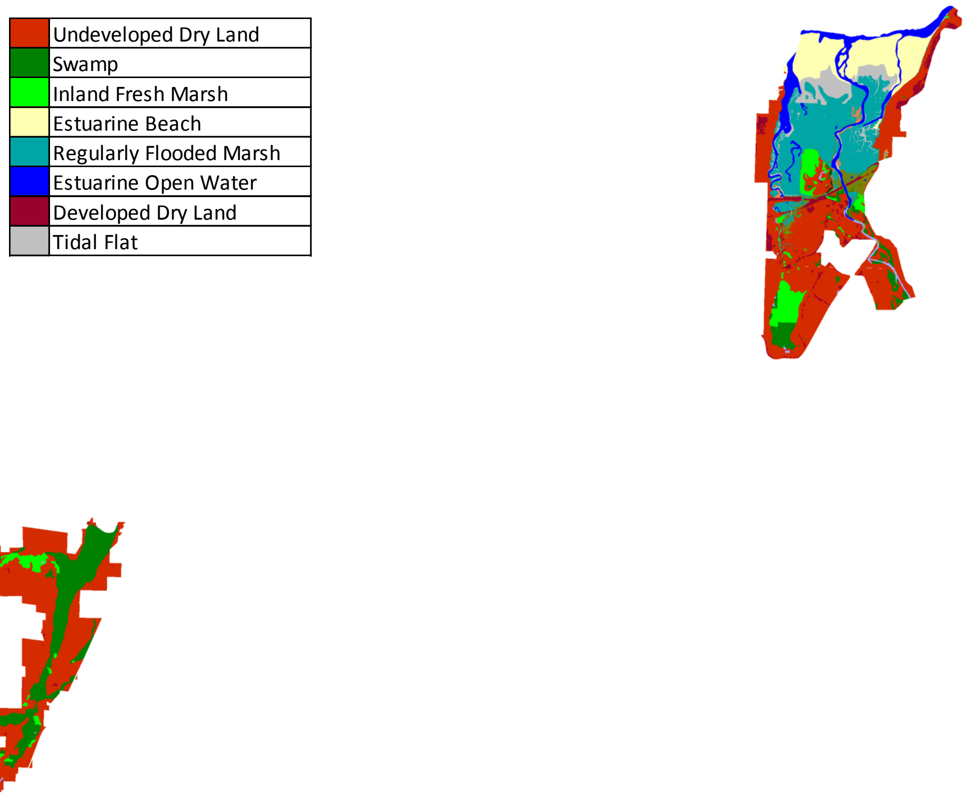
		Initial	2025	2050	2075	2100
	Undeveloped Dry Land	5797	5499	5456	5288	5115
	Swamp	1390	1306	1284	1159	1146
	Inland Fresh Marsh	1308	544	536	327	308
	Estuarine Beach	967	961	960	486	287
	Regularly-flooded Marsh	625	1568	1577	1115	1053
	Estuarine Open Water	483	574	581	1075	1314
	Developed Dry Land	360	331	325	317	299
	Tidal Flat	318	363	447	1059	1624
	Inland Open Water	107	72	67	53	46
	Riverine Tidal	48	0	0	0	0
	Irregularly-flooded Marsh	47	55	40	18	10
	Tidal Swamp	32	7	6	6	6
	Inland Shore	3	3	3	3	3
	Transitional Salt Marsh	0	203	199	577	274
	Total (incl. water)	**11484**	**11484**	**11484**	**11484**	**11484**



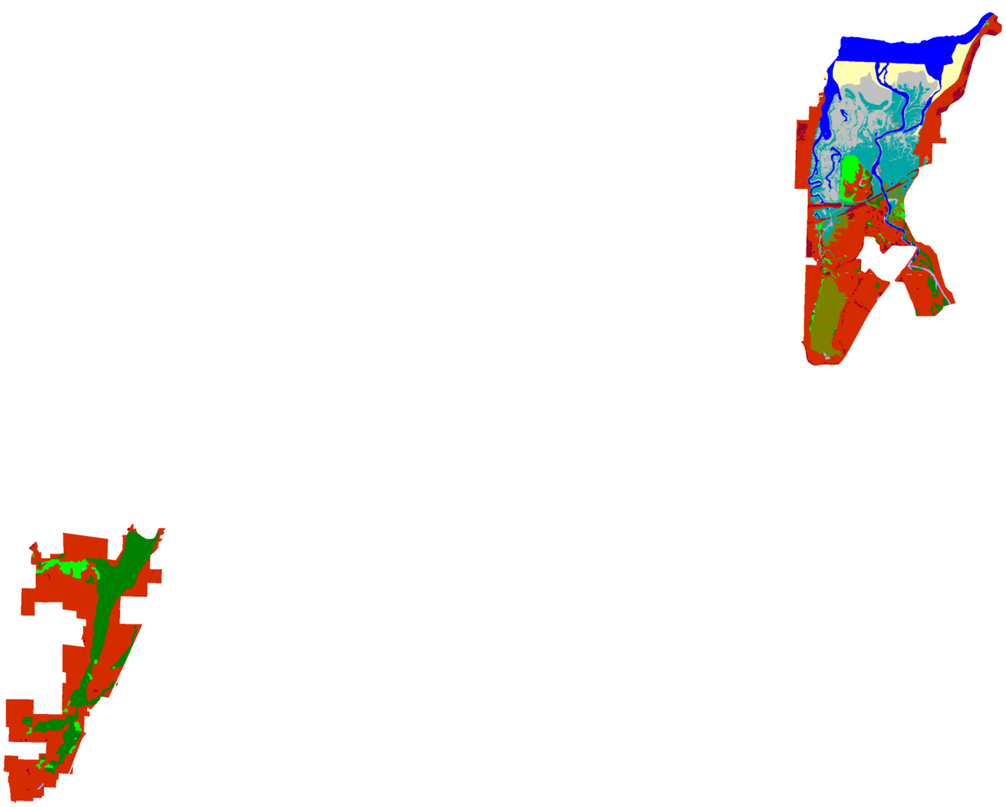
Nisqually NWR, Initial Condition



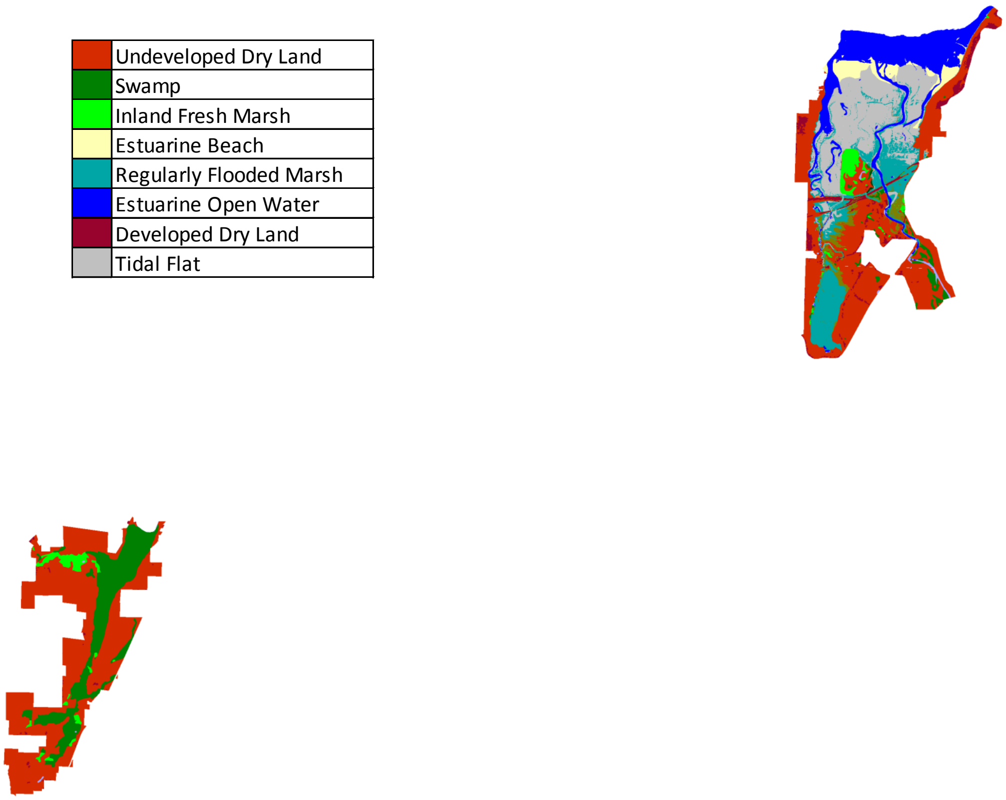
Nisqually NWR, 2025, 2 m SLR



Nisqually NWR, 2050, 2 m SLR



Nisqually NWR, 2075, 2 m SLR



Nisqually NWR, 2100, 2 m SLR

Discussion

Model results for Nisqually NWR indicate that wetlands in the Nisqually River delta will be affected by the SLR scenarios examined. However, these results also reflect the restoration efforts that have taken place in the past decade. As anticipated by project planners, SLAMM suggests dike removal results in the conversion of fresh marshes to salt marshes. Below 1 m of SLR by 2100, the majority of changes to the refuge appear to be due to the removal of the dike system in the Nisqually river delta unit of the refuge. This result suggests that, if the effect of dike removal is not considered, refuge wetlands appear resilient to SLR up to 1 m by 2100. At SLR scenarios greater than 1 m by 2100, SLAMM predicts refuge wetlands to sustain considerable losses.

SLAMM predicts increases in sea level to cause wetlands in the Nisqually River delta unit of the refuge to convert to open water or tidal flat in scenarios of over 1 m by 2100. However, even for the highest SLR scenarios examined, salt-marsh coverage remains widespread, comprising over 10% of the total refuge area. Some inland-fresh marsh is predicted to be resilient to SLR up to 2 m by 2100 because it is protected by the remaining dike system.

Because of the elevation distribution and accretion rates applied, the 1 m SLR scenario seems a break point for several wetland categories. Under lower SLR rates, losses are limited and mostly lead to an increase of regularly and irregularly-flooded marshes. At higher SLR rates, complete inundation and tidal flat formation are predicted to prevail. However, it is important to note that the result for the southern portion of the Nisqually River delta unit are subject to some uncertainty. Dry lands and fresh water marshes in this portion of the refuge are predicted to be resilient up to 1.5 meters of SLR; however, these results are uncertain due to a lack of tide data for this region.

For salt marsh, site-specific accretion data were taken from the available literature and applied to the entire study area. However, additional measurements of accretion for other wetland types could provide better predictions of marsh losses in the future. In addition, when dikes are removed accretion tends to become extremely dynamic due to the reintroduction of sediment to low-elevation wetlands. Such dynamic changes in accretion are not accounted for in this model.

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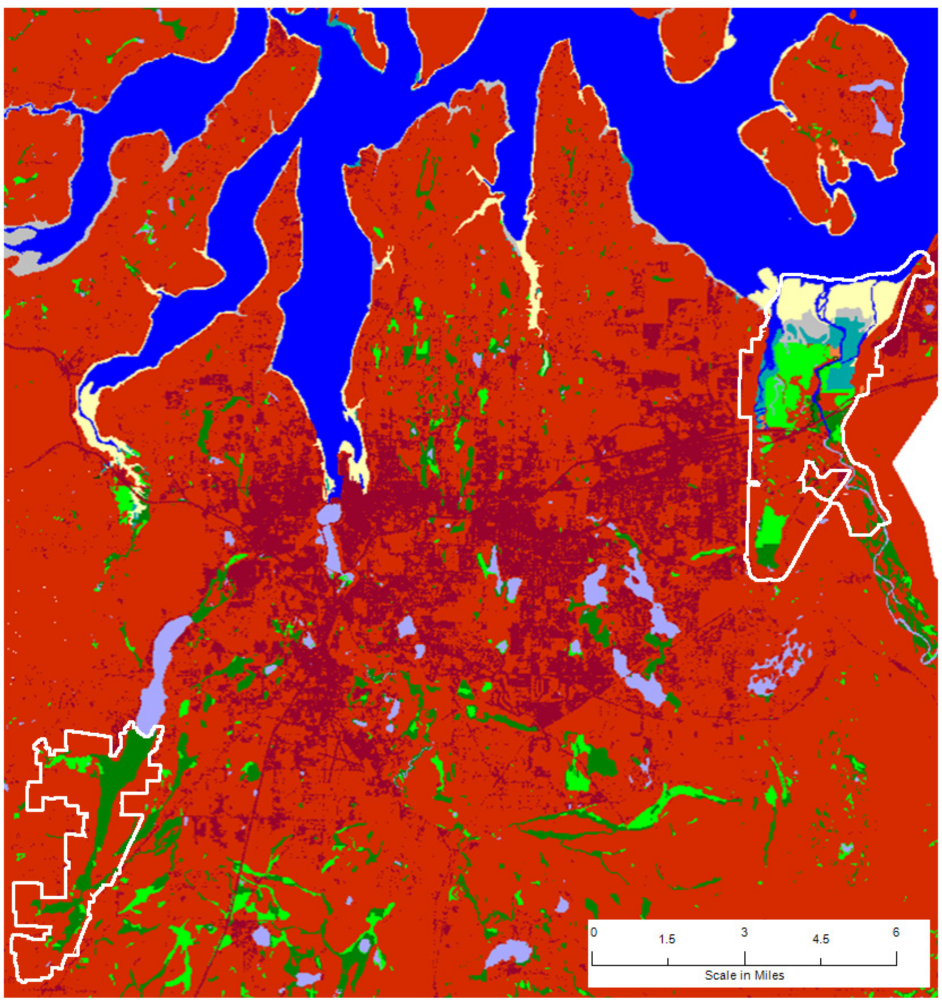
Appendix A: Contextual Results

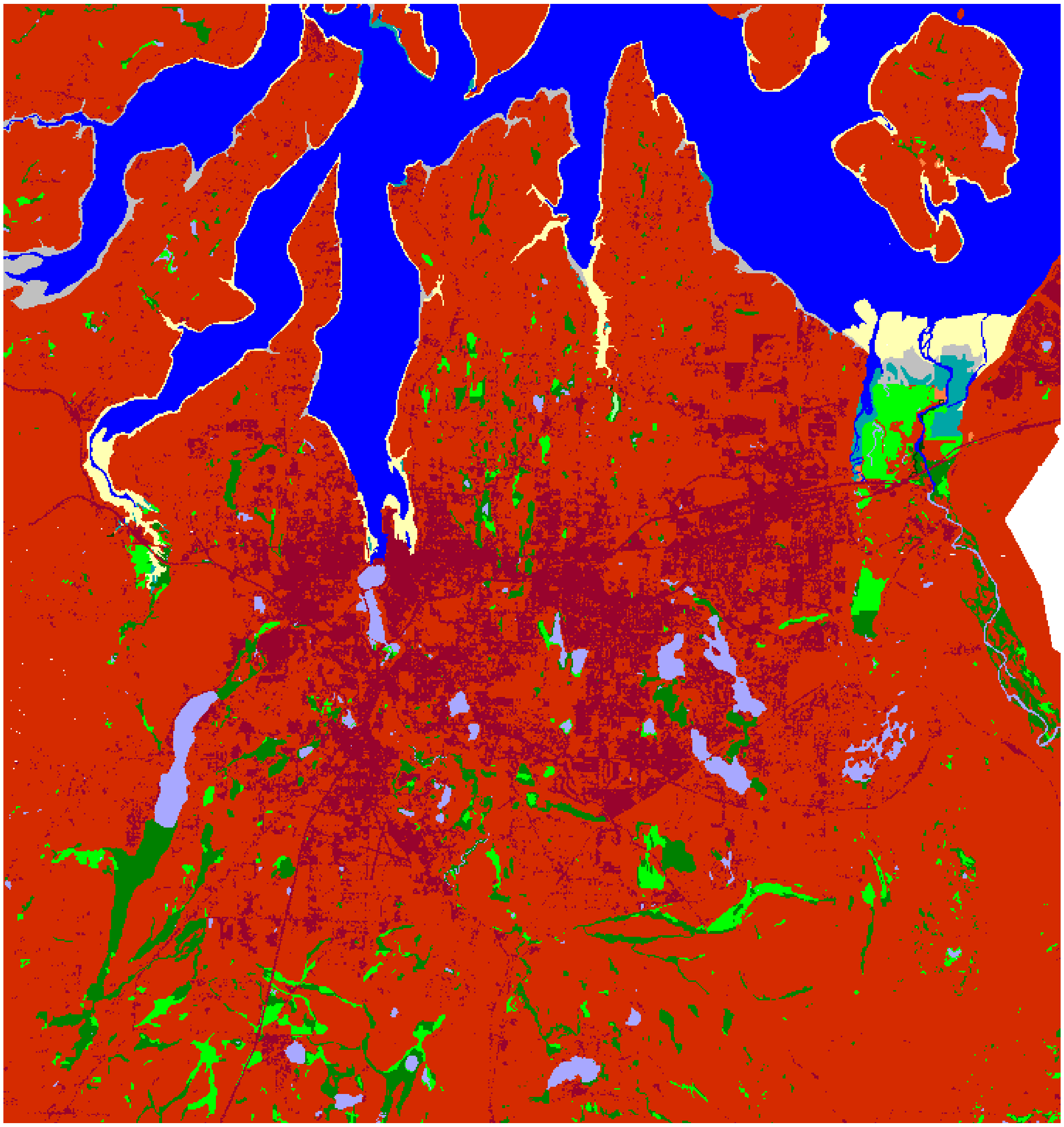
The SLAMM model does take into account the context of the surrounding lands or open water when calculating effects. For example, erosion rates are calculated based on the maximum fetch (wave action) which is estimated by assessing contiguous open water to a given marsh cell. Another example is that inundated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

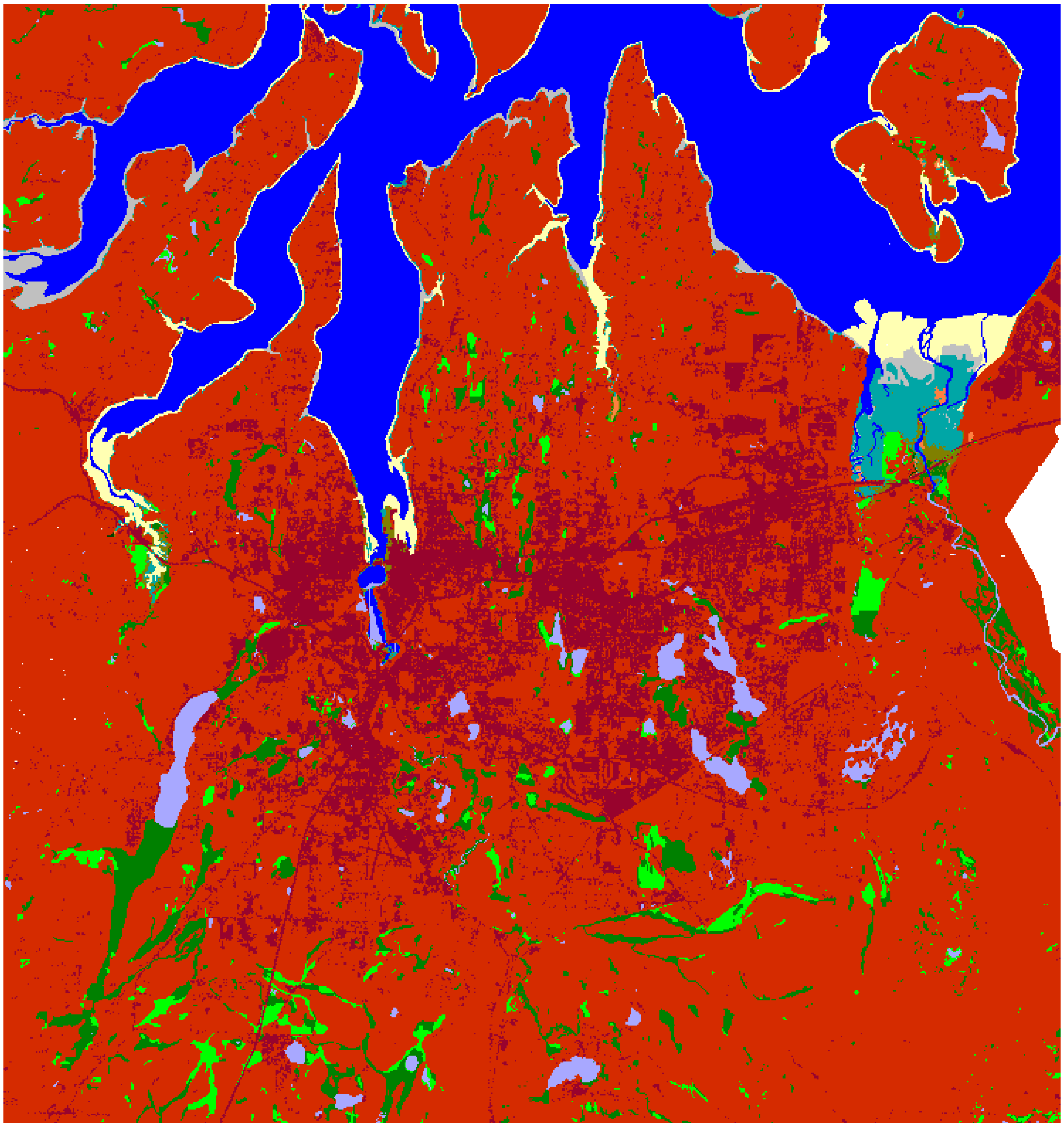
- Results were closely examined (quality assurance) within USFWS refuges but not closely examined for the larger region.
- Site-specific parameters for the model were derived for USFWS refuges whenever possible and may not be regionally applicable.
- Especially in areas where dikes are present, an effort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



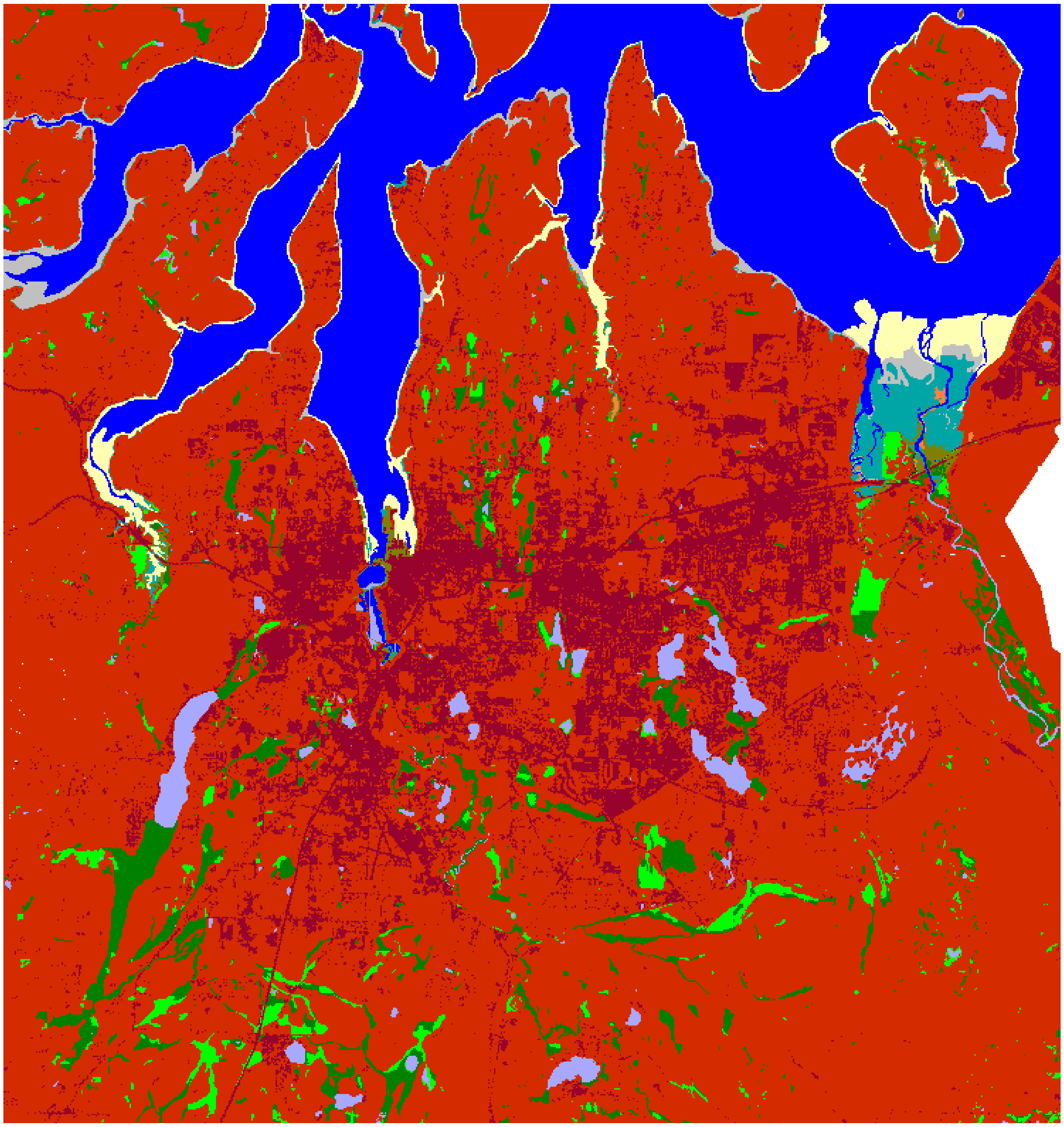
Nisqually National Wildlife Refuge within simulation context (white).



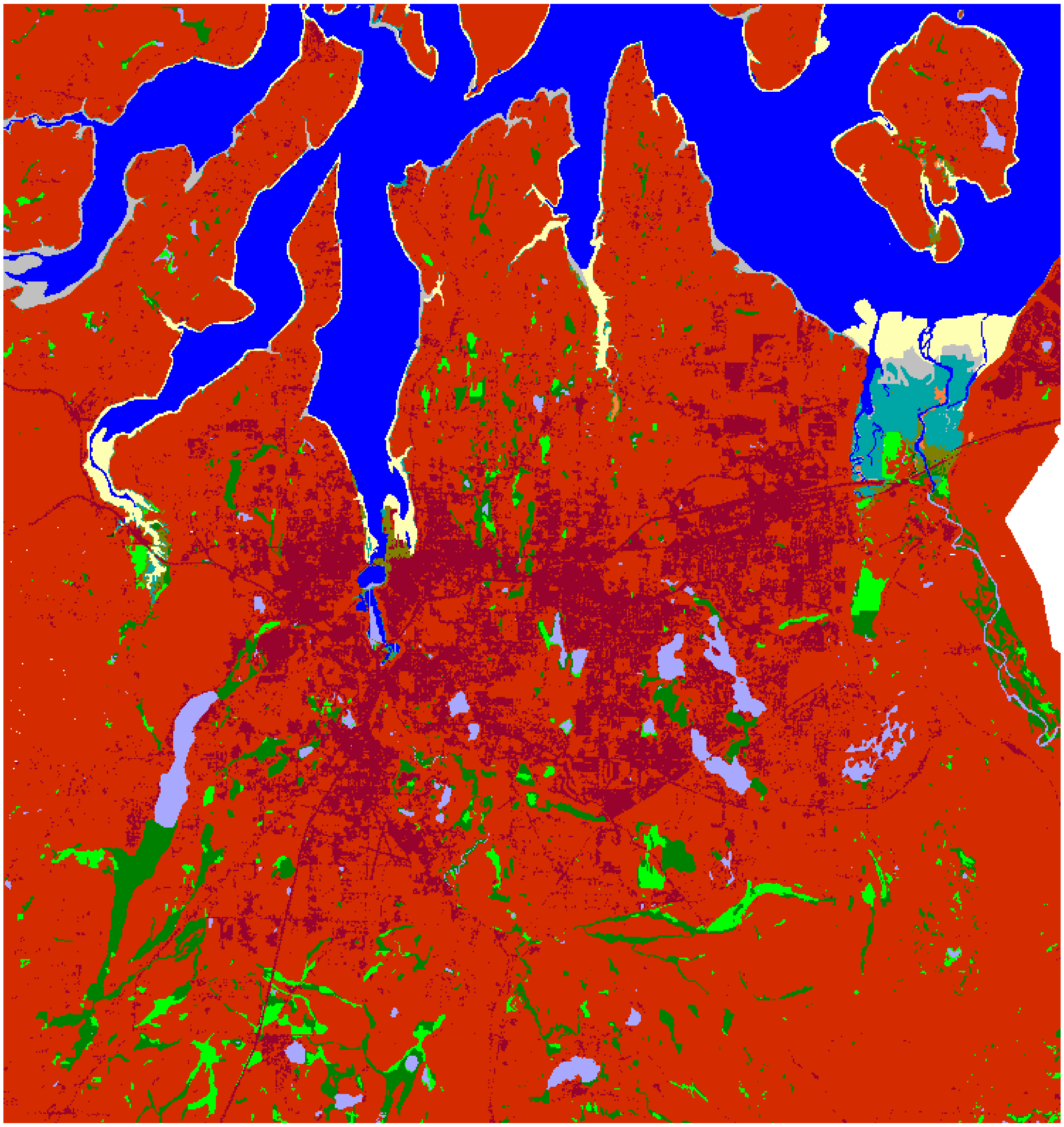
Nisqually NWR, Initial Condition



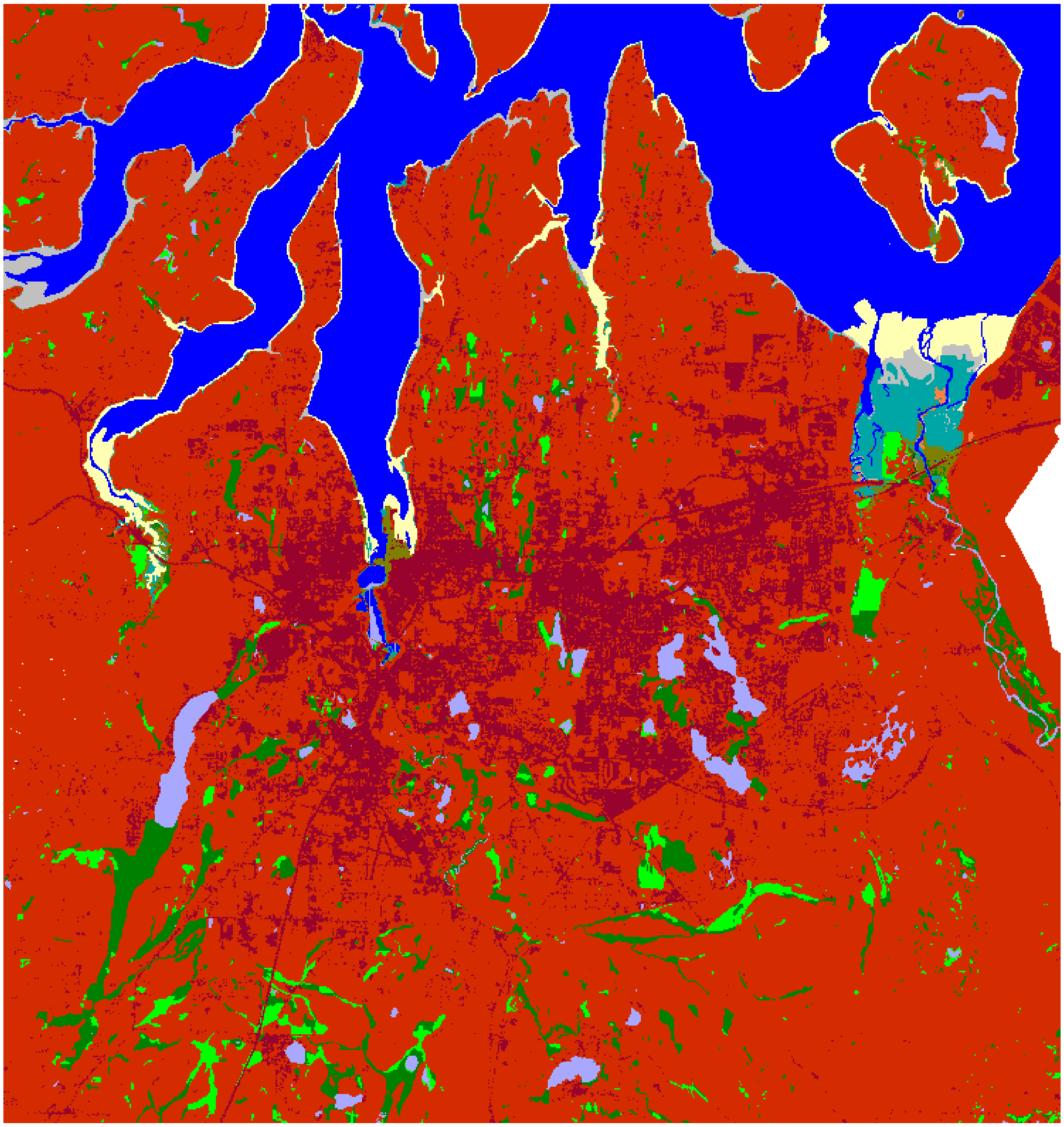
Nisqually NWR, 2025, Scenario A1B Mean, 0.39 m SLR



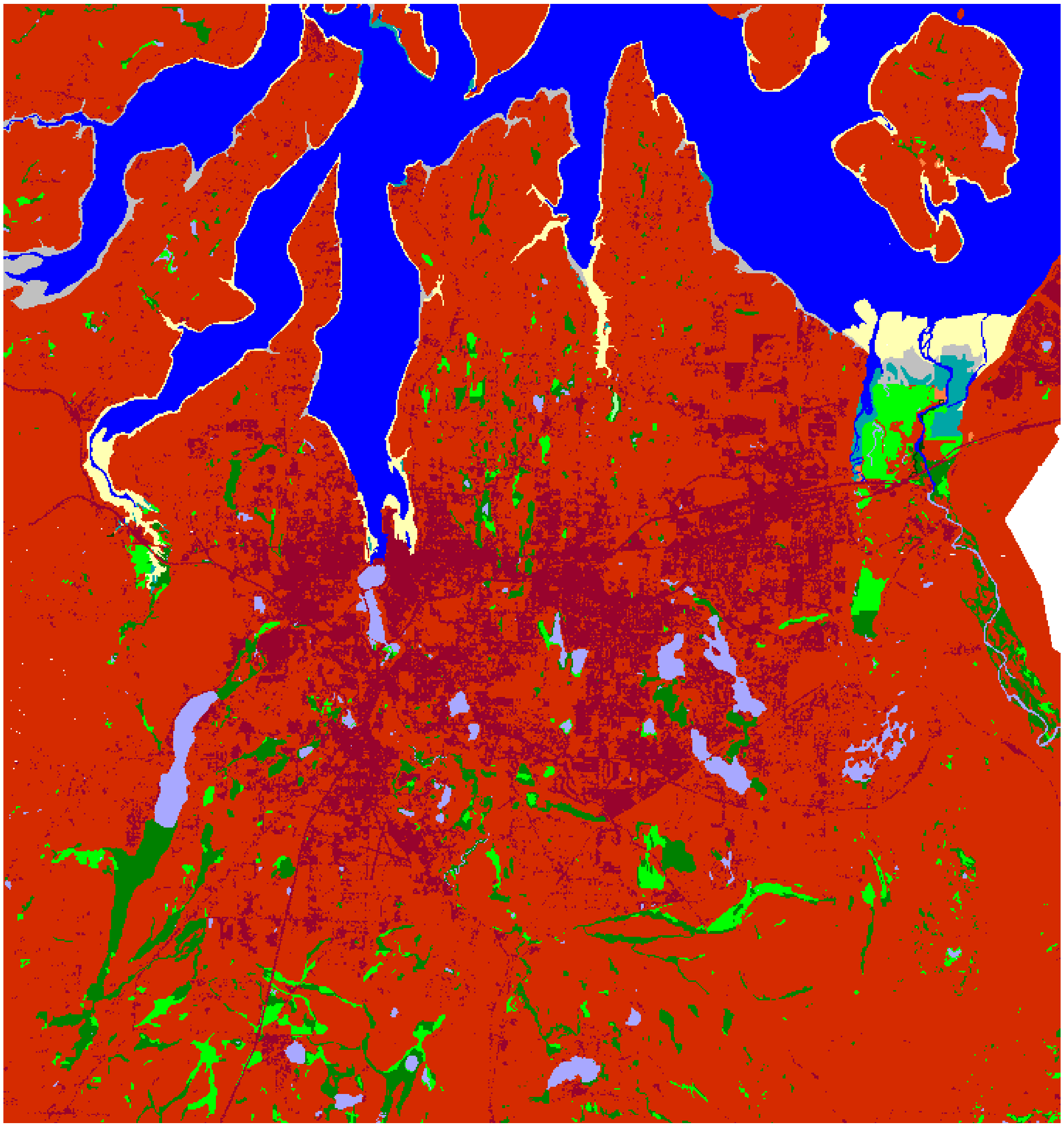
Nisqually NWR, 2050, Scenario A1B Mean, 0.39 m SLR



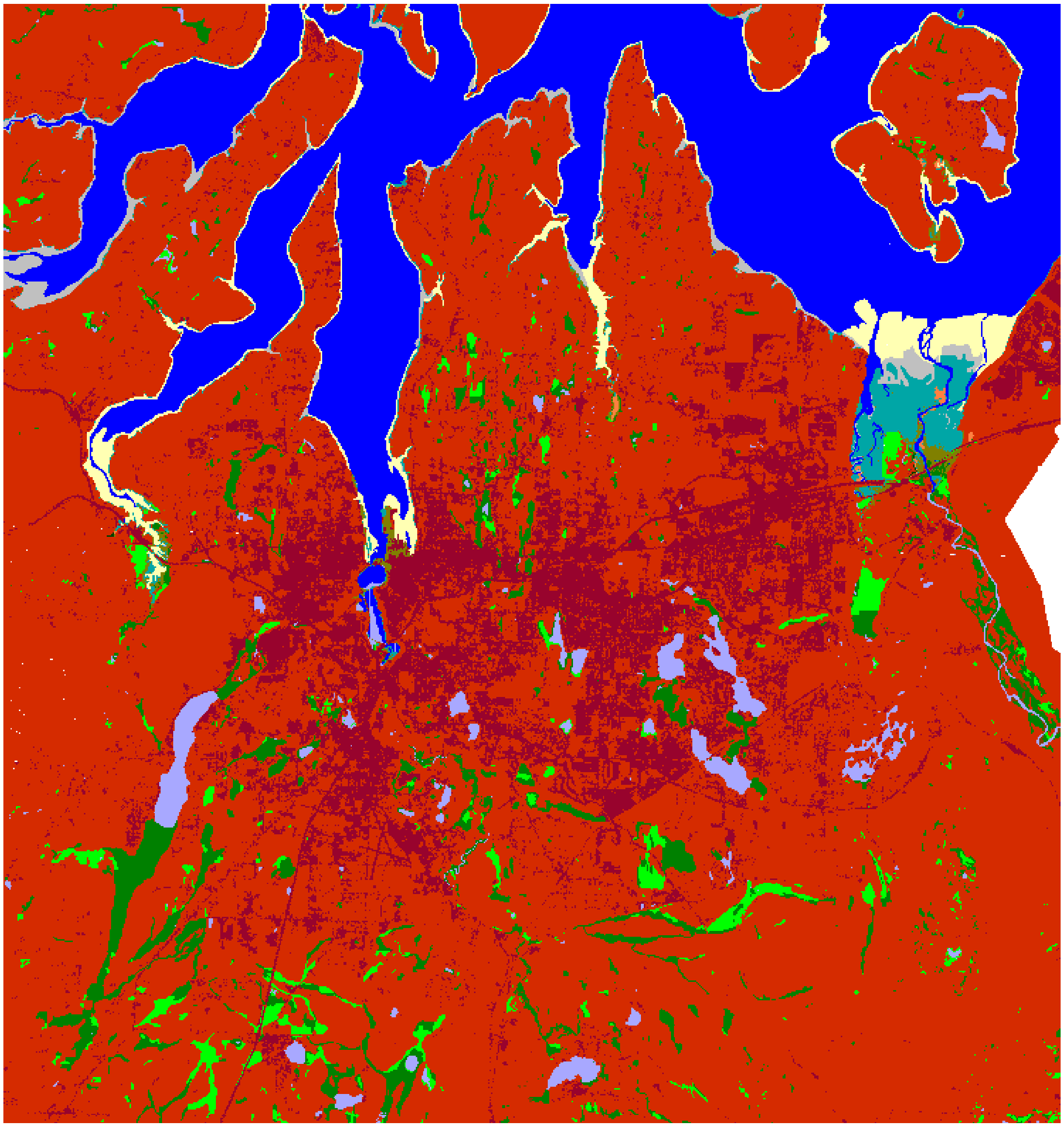
Nisqually NWR, 2075, Scenario A1B Mean, 0.39 m SLR



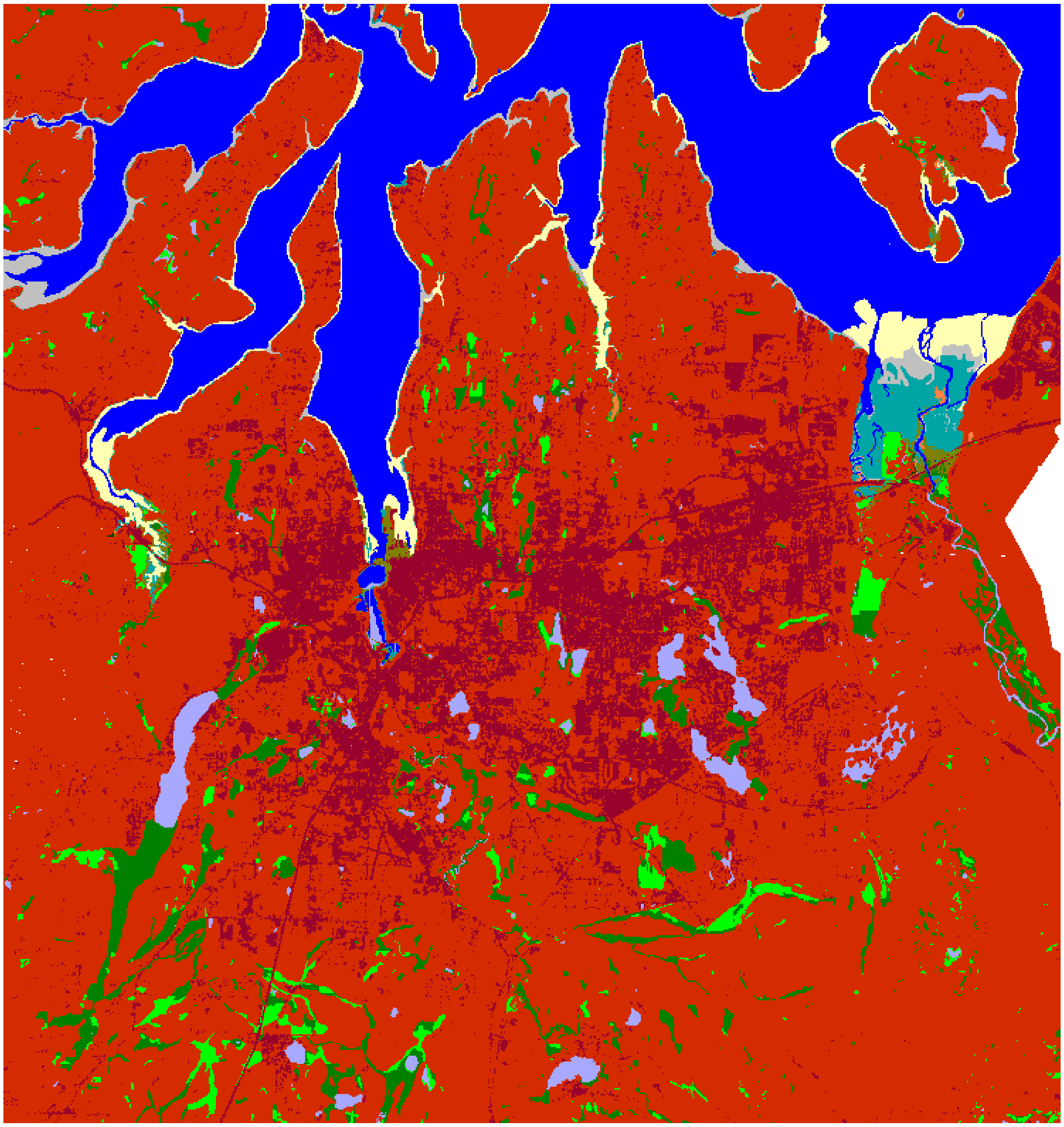
Nisqually NWR, 2100, Scenario A1B Mean, 0.39 m SLR



Nisqually NWR, Initial Condition



Nisqually NWR, 2025, Scenario A1B Maximum, 0.69 m SLR



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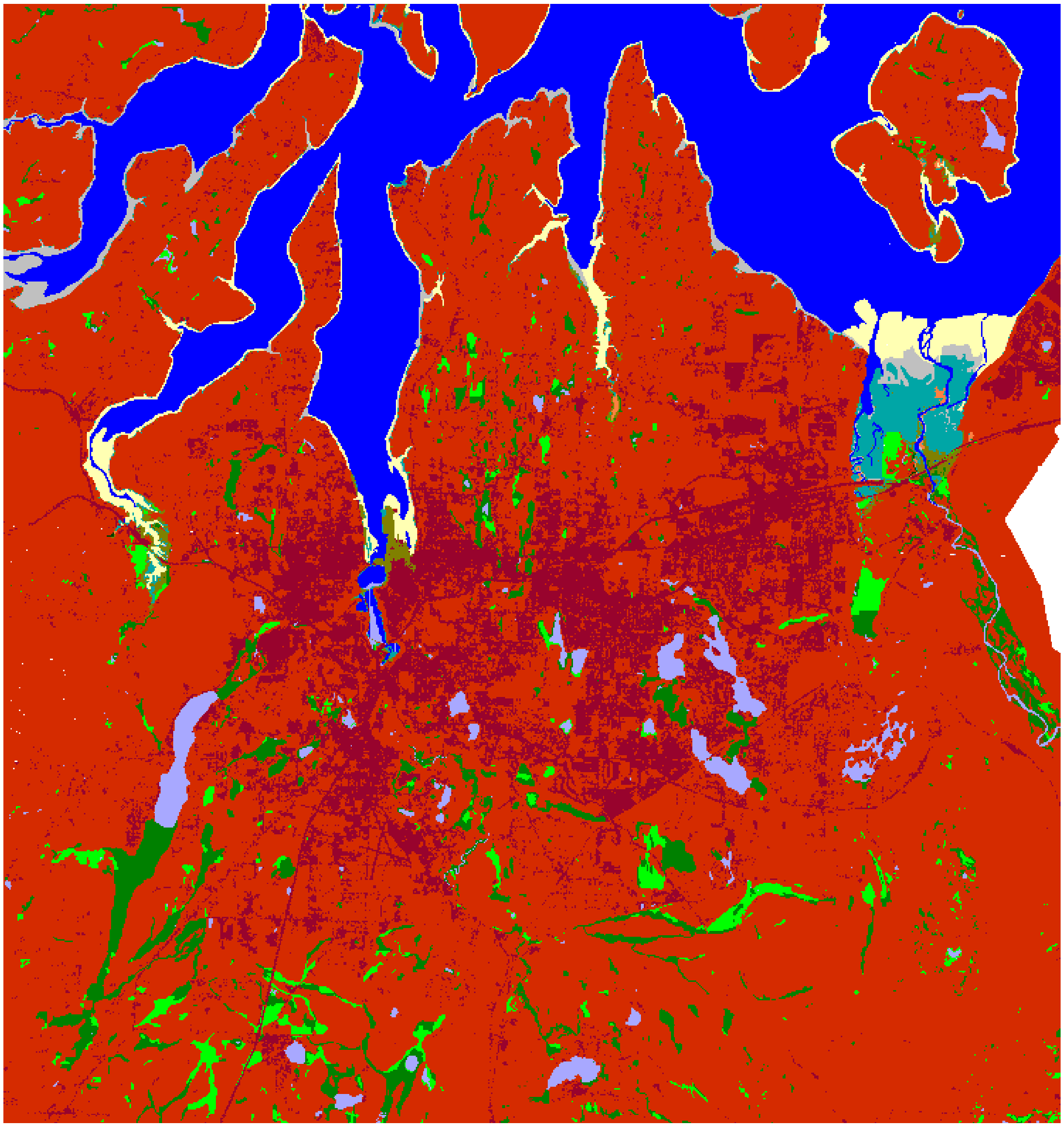

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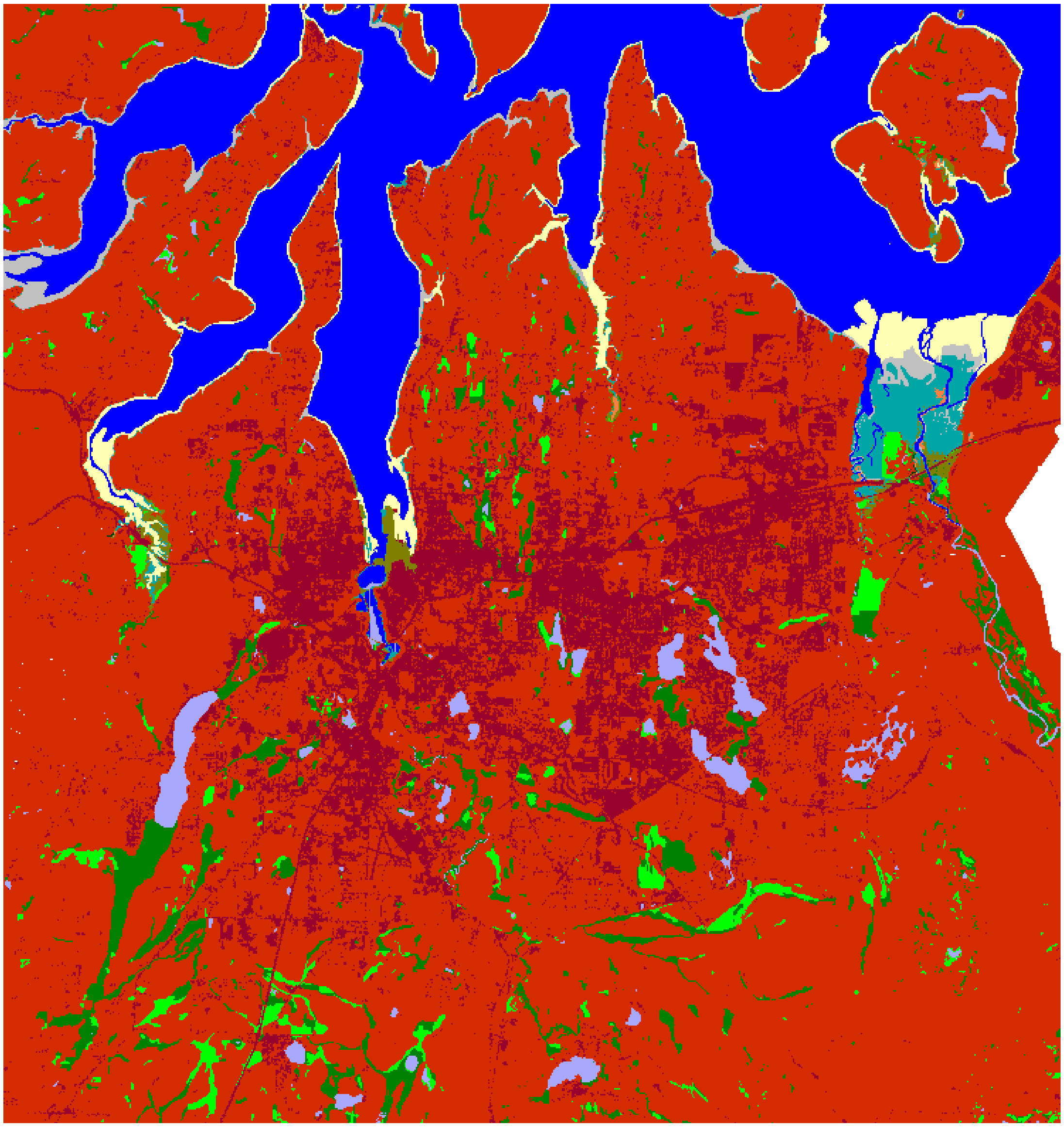

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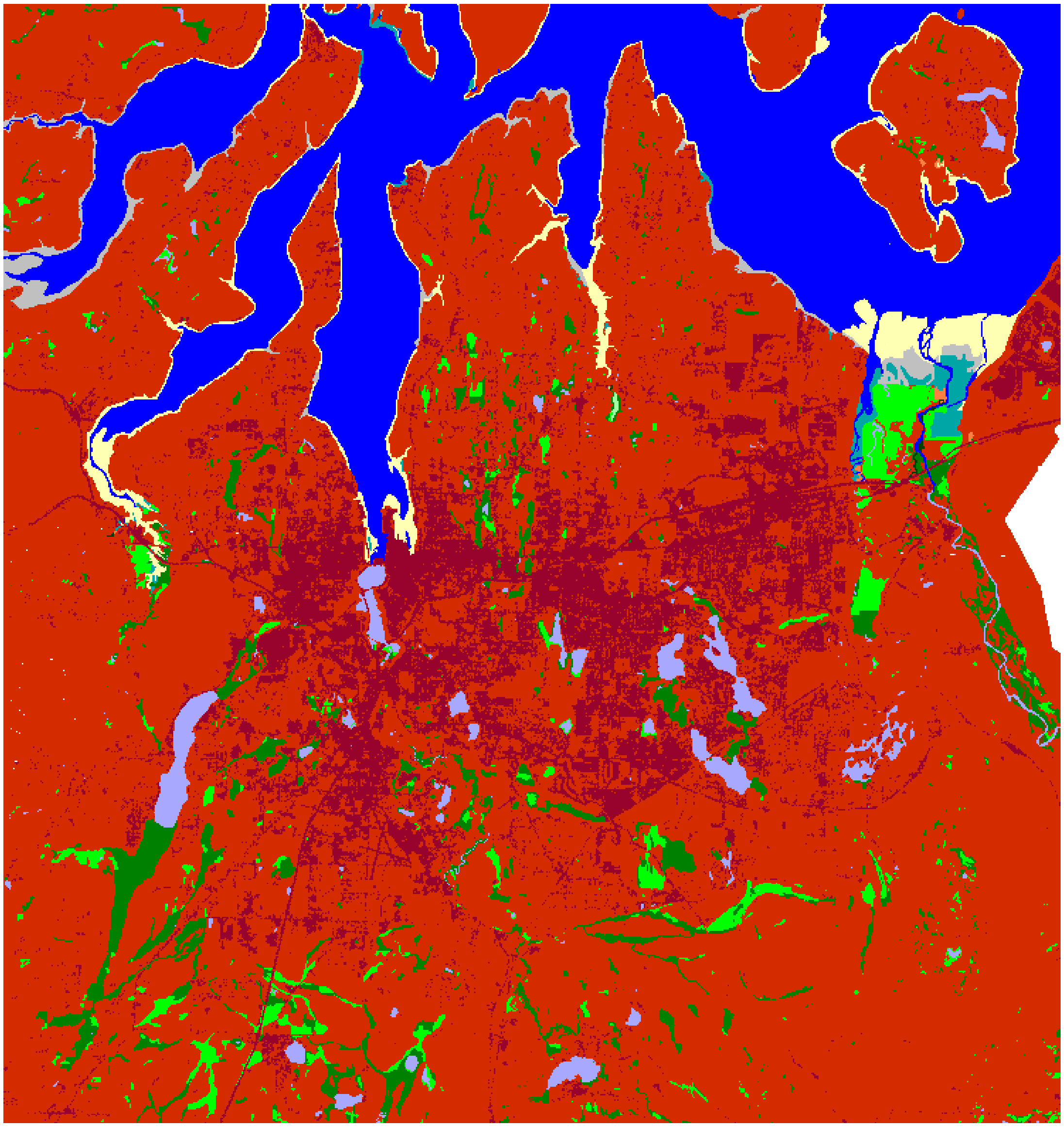

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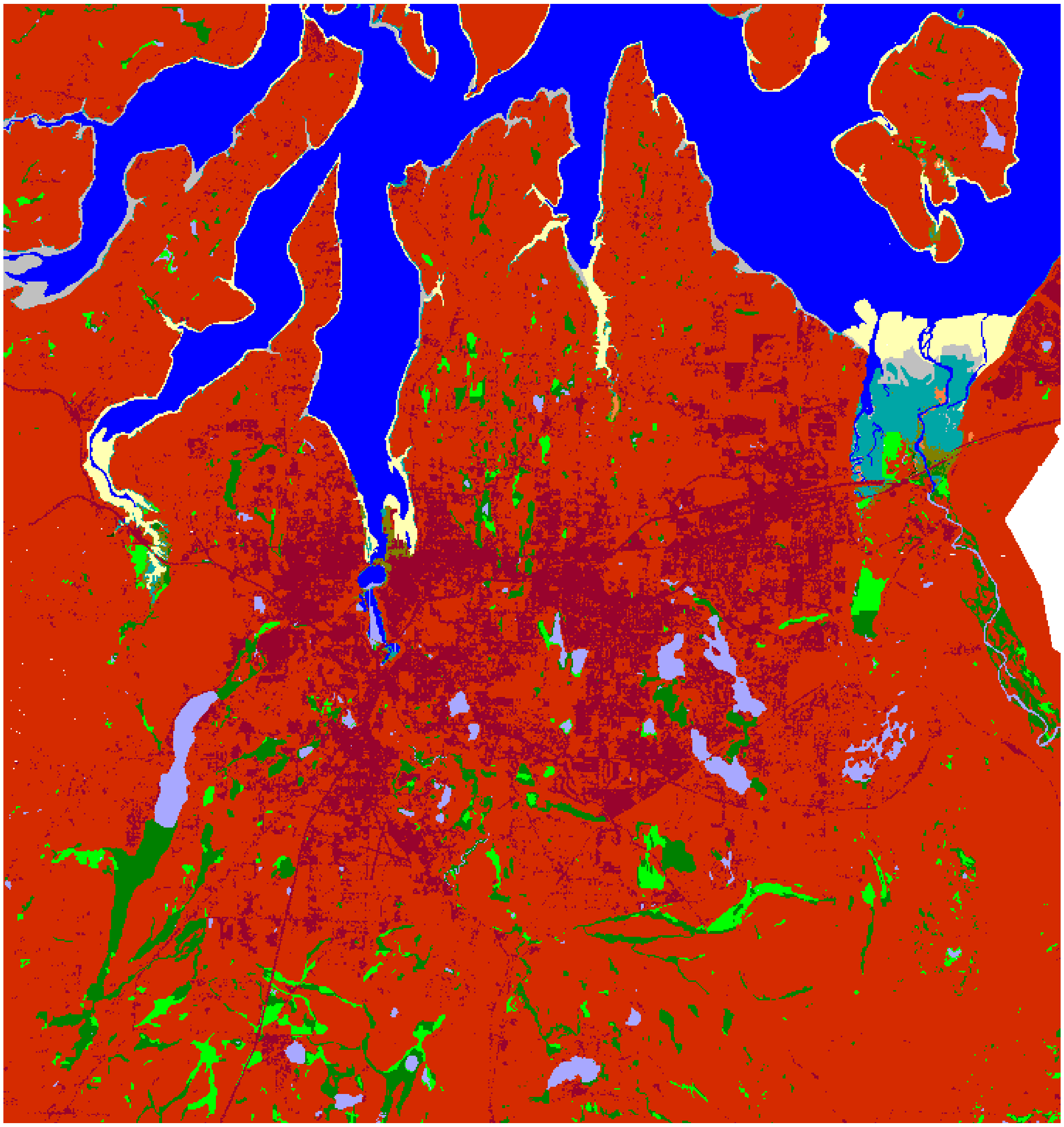
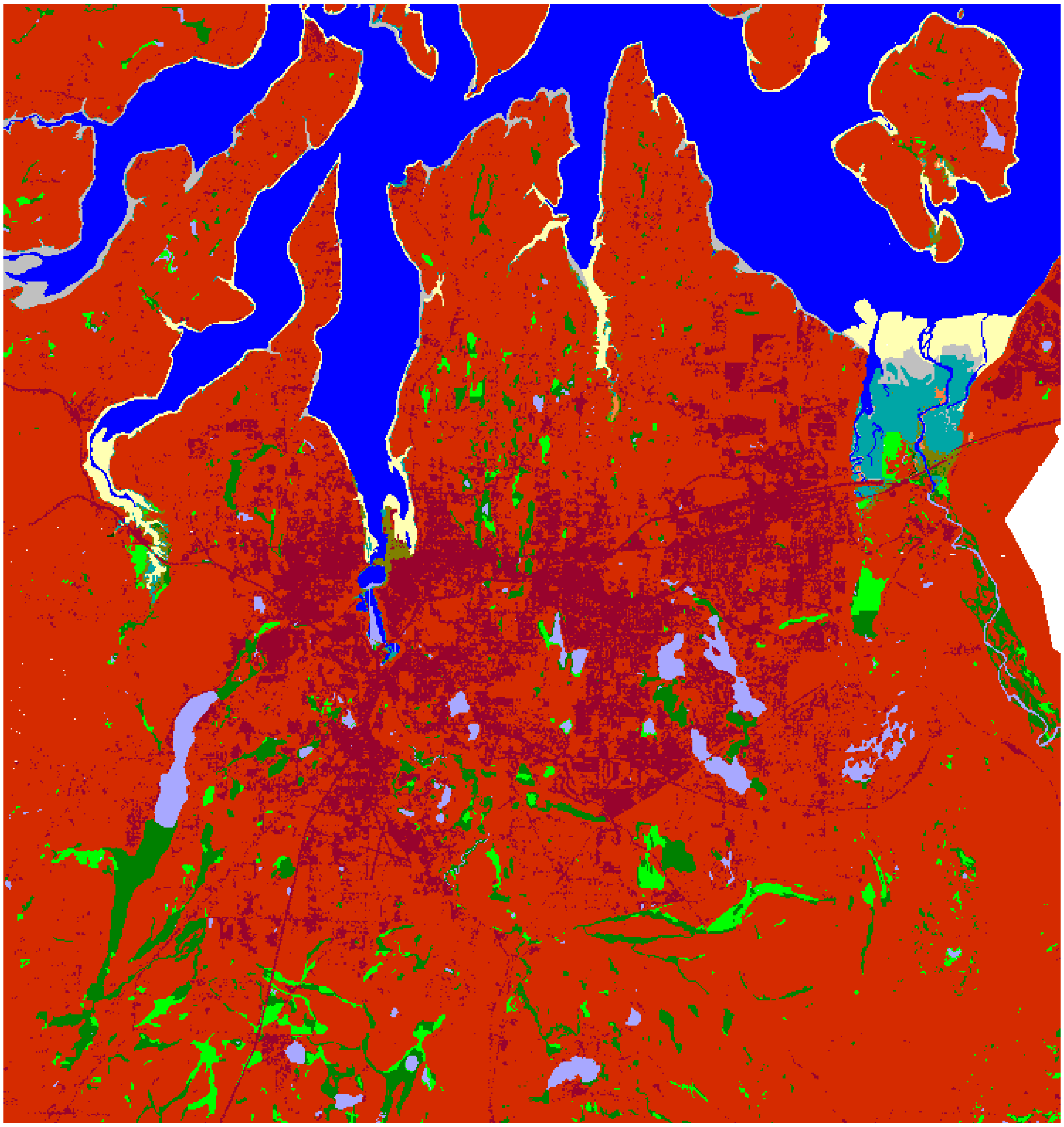


Nisqually NWR, 2025, 1 m SLR



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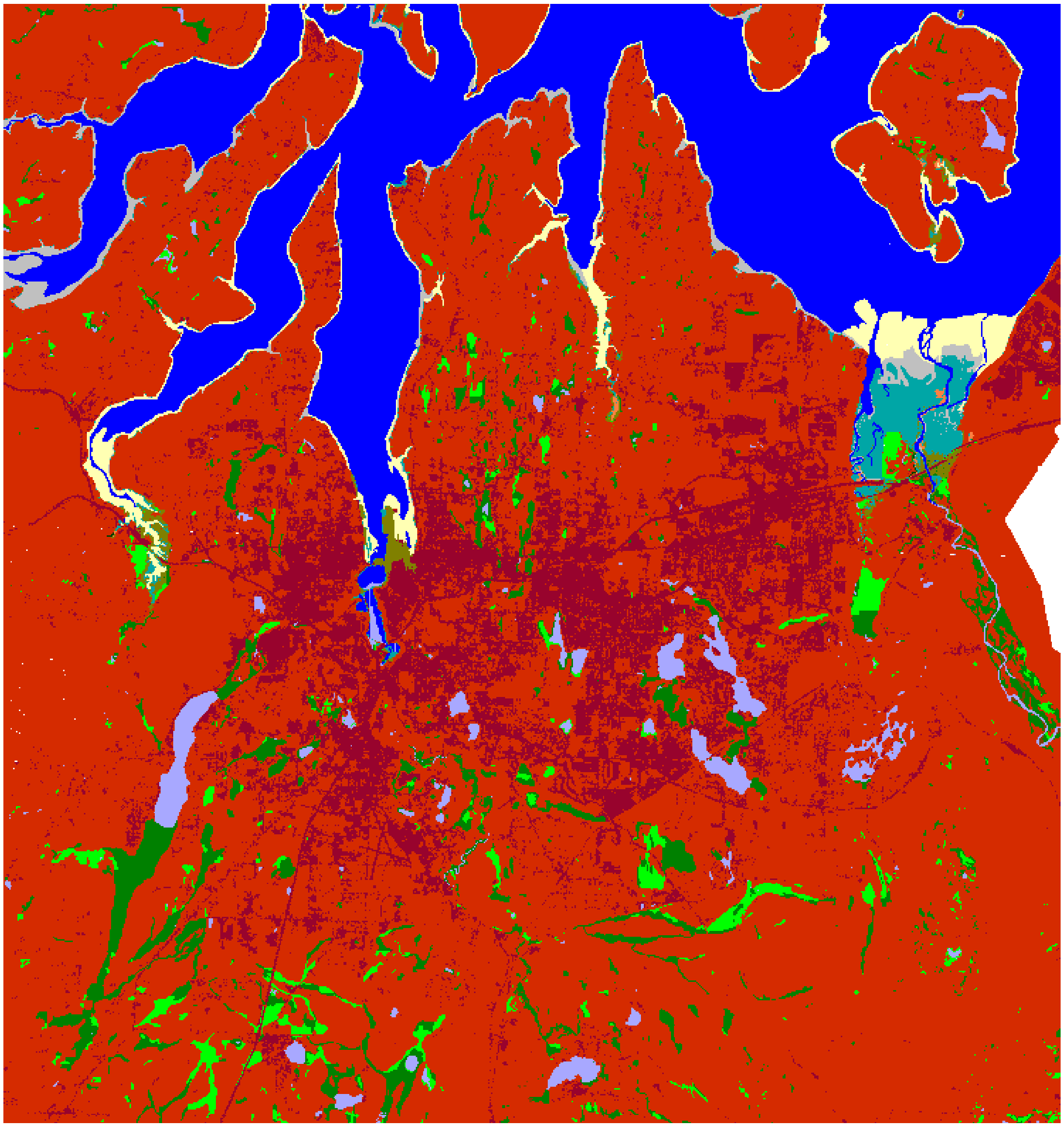

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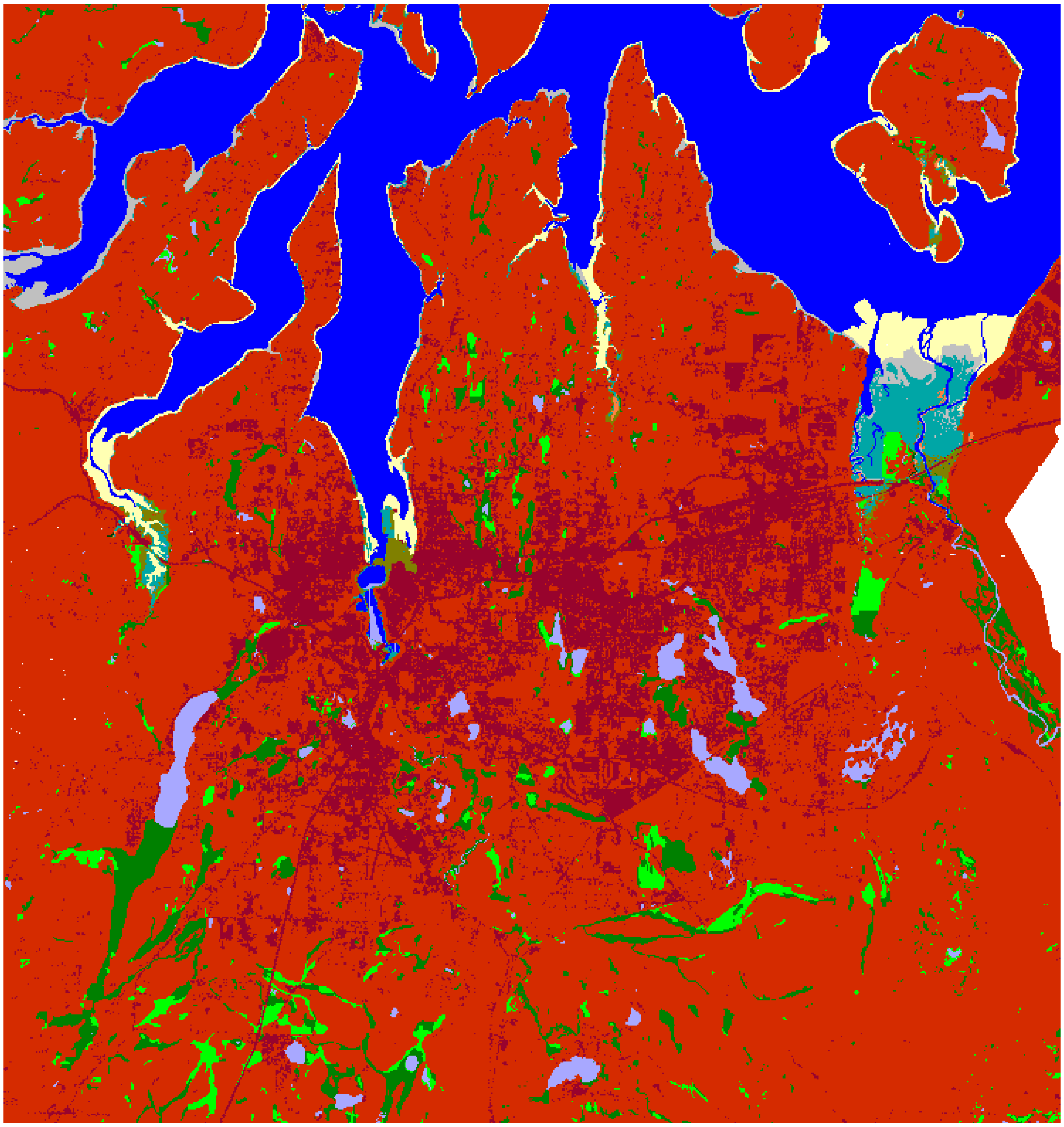

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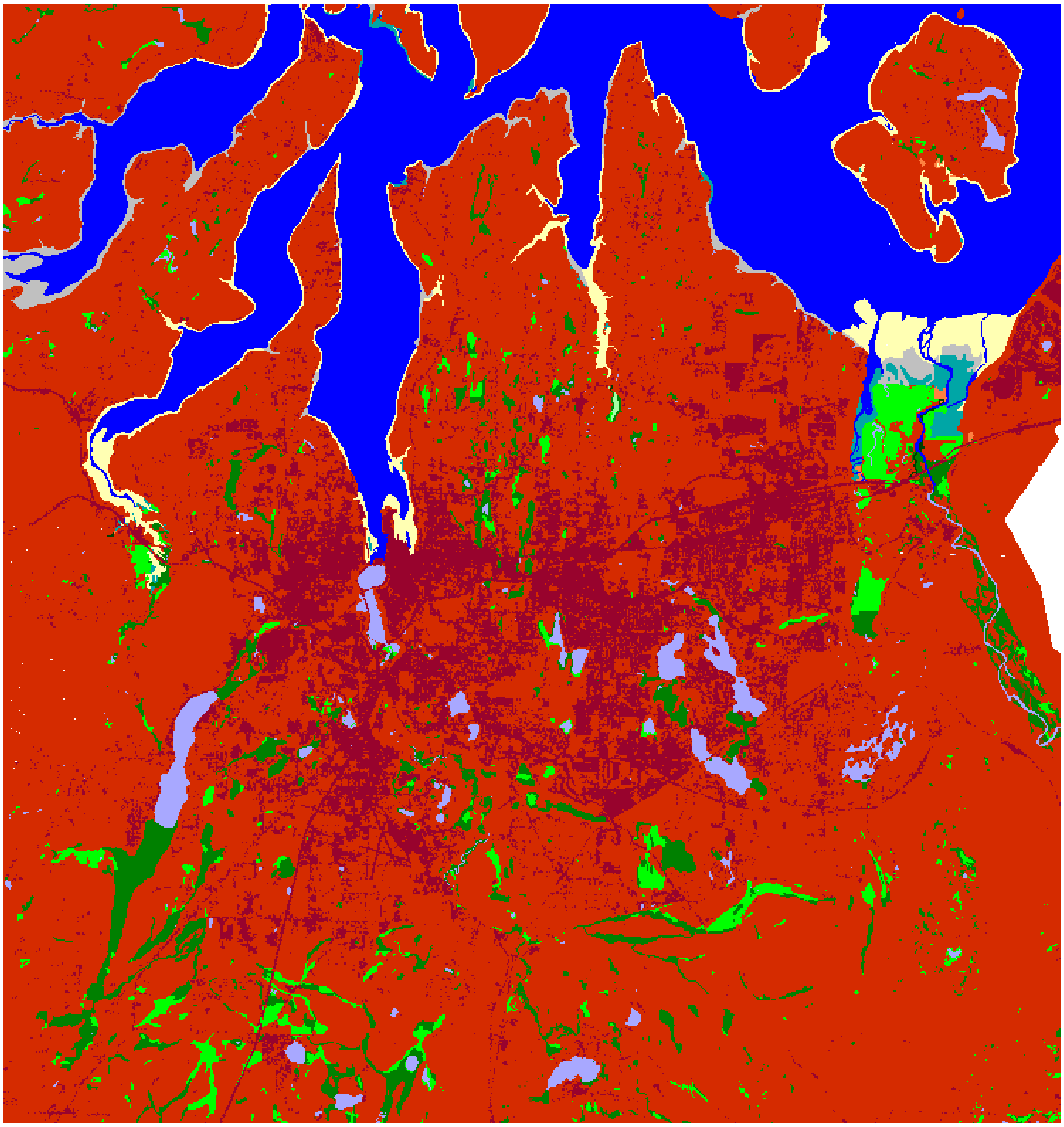

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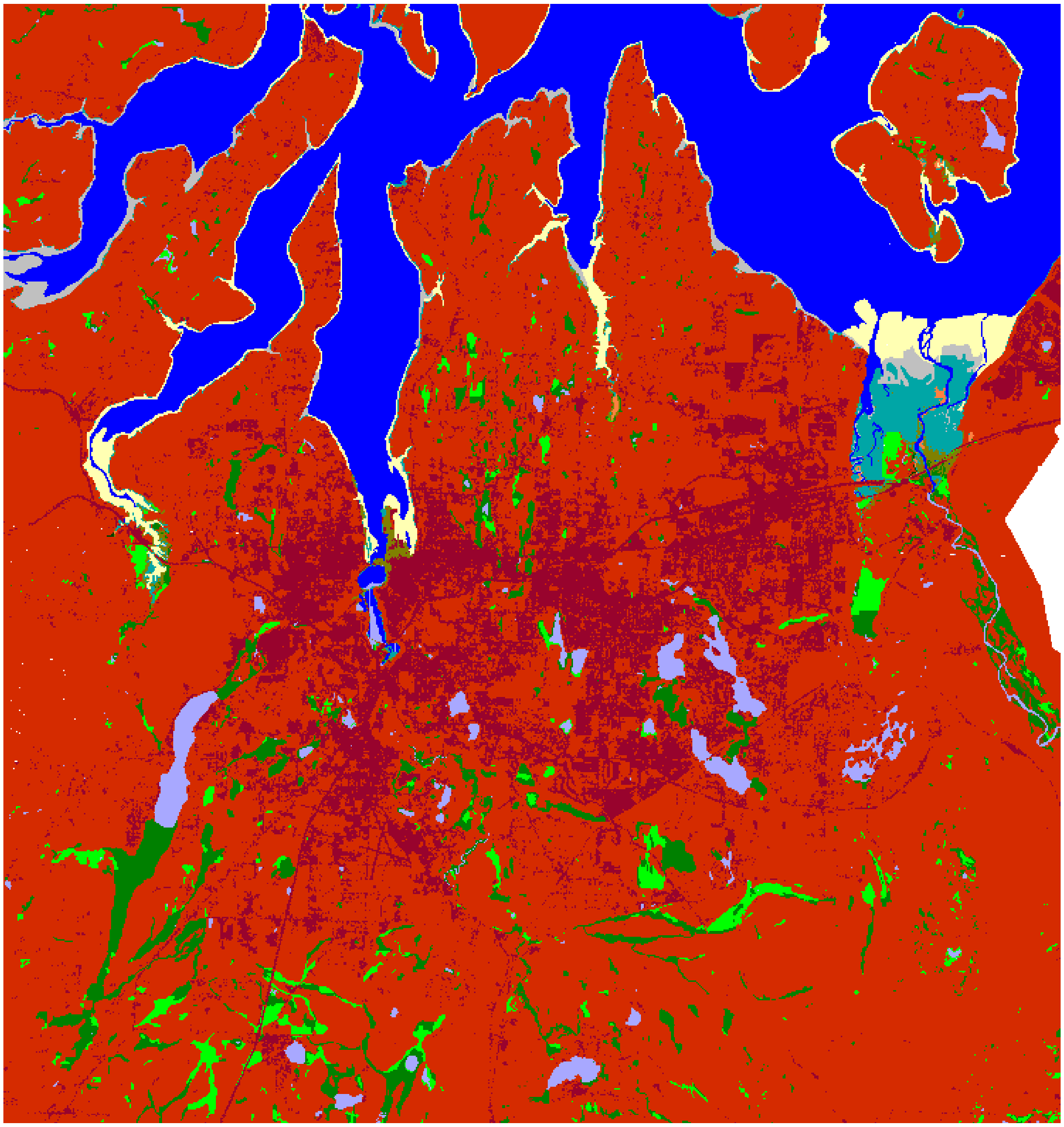

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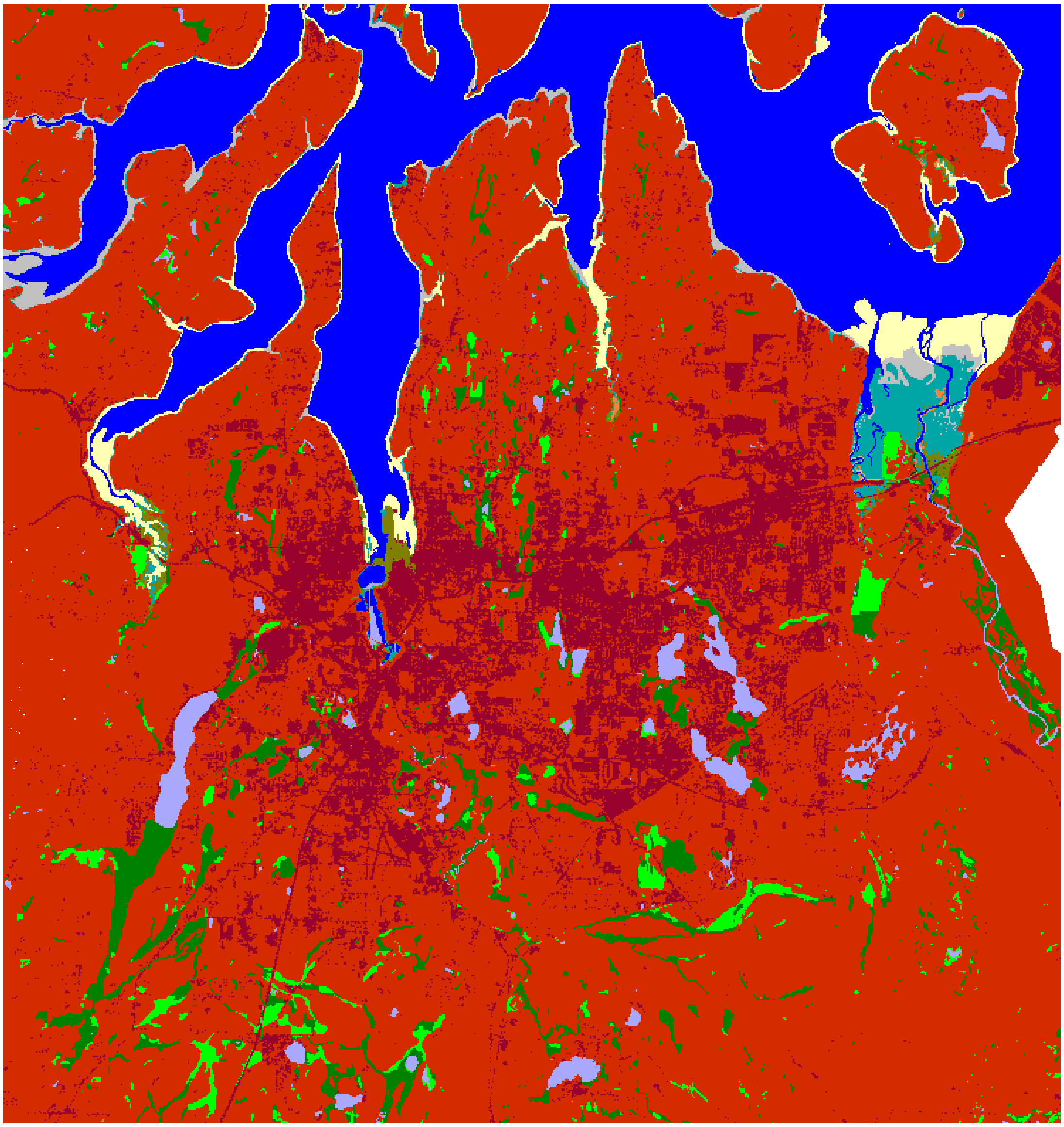

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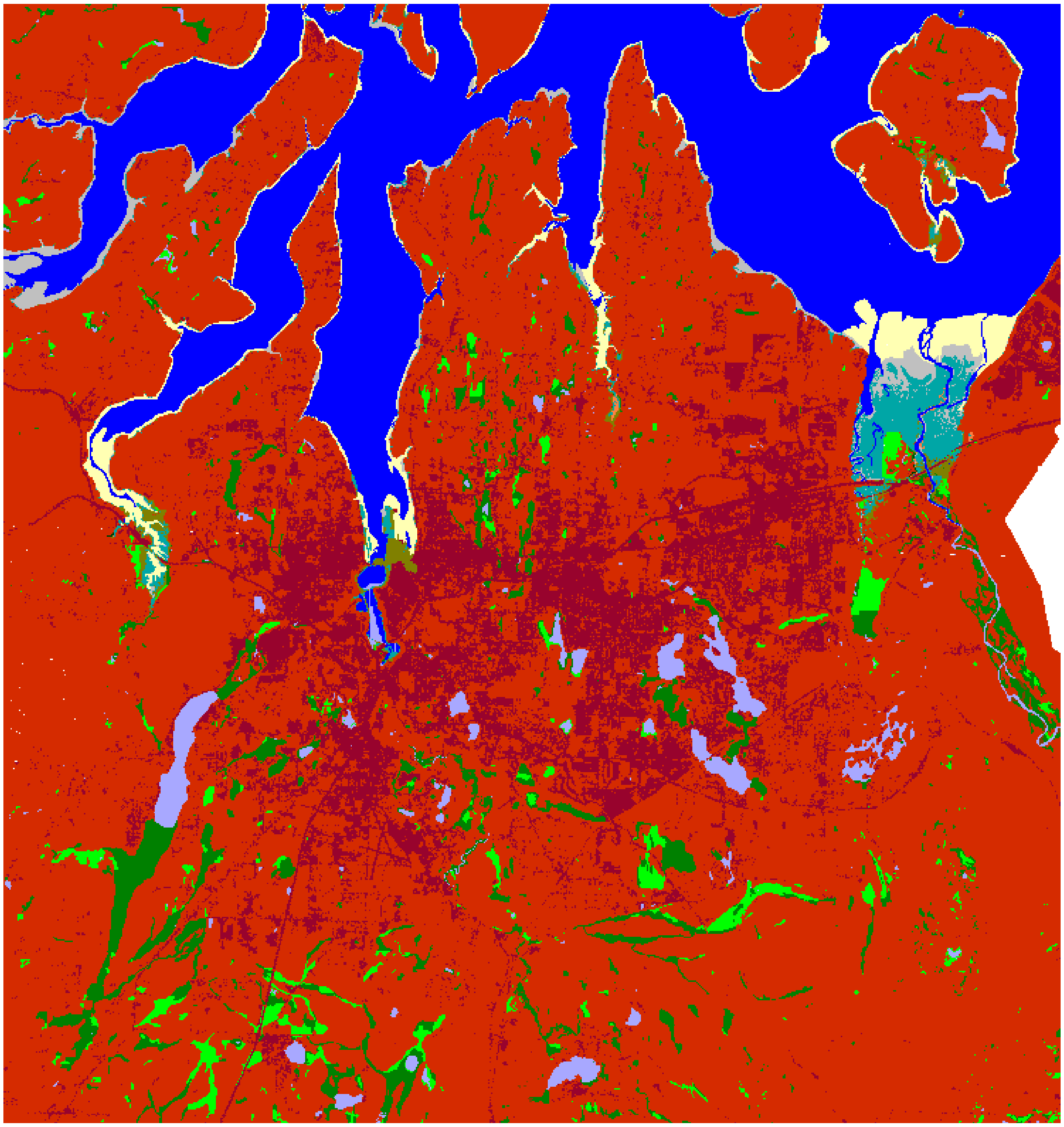

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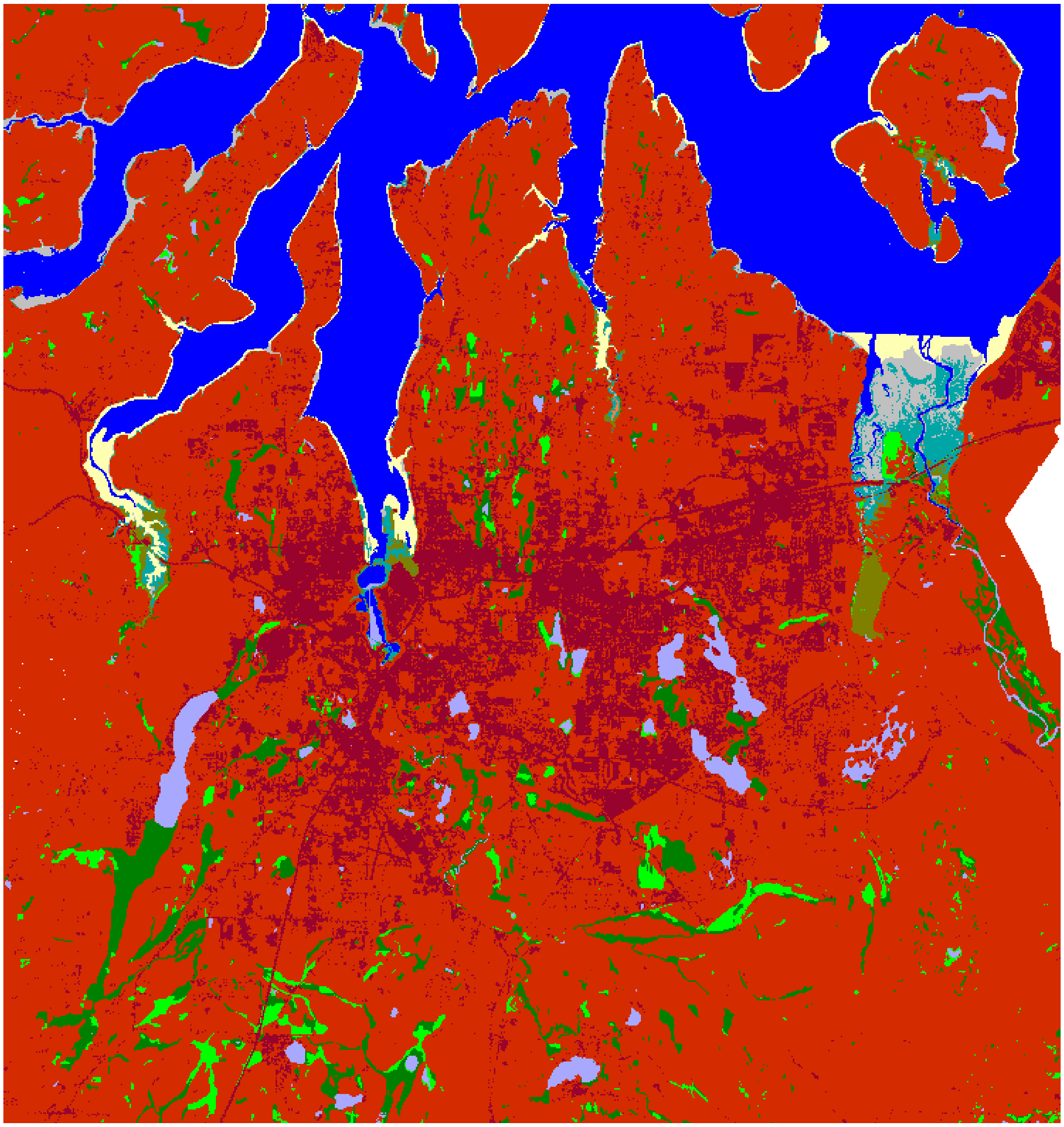

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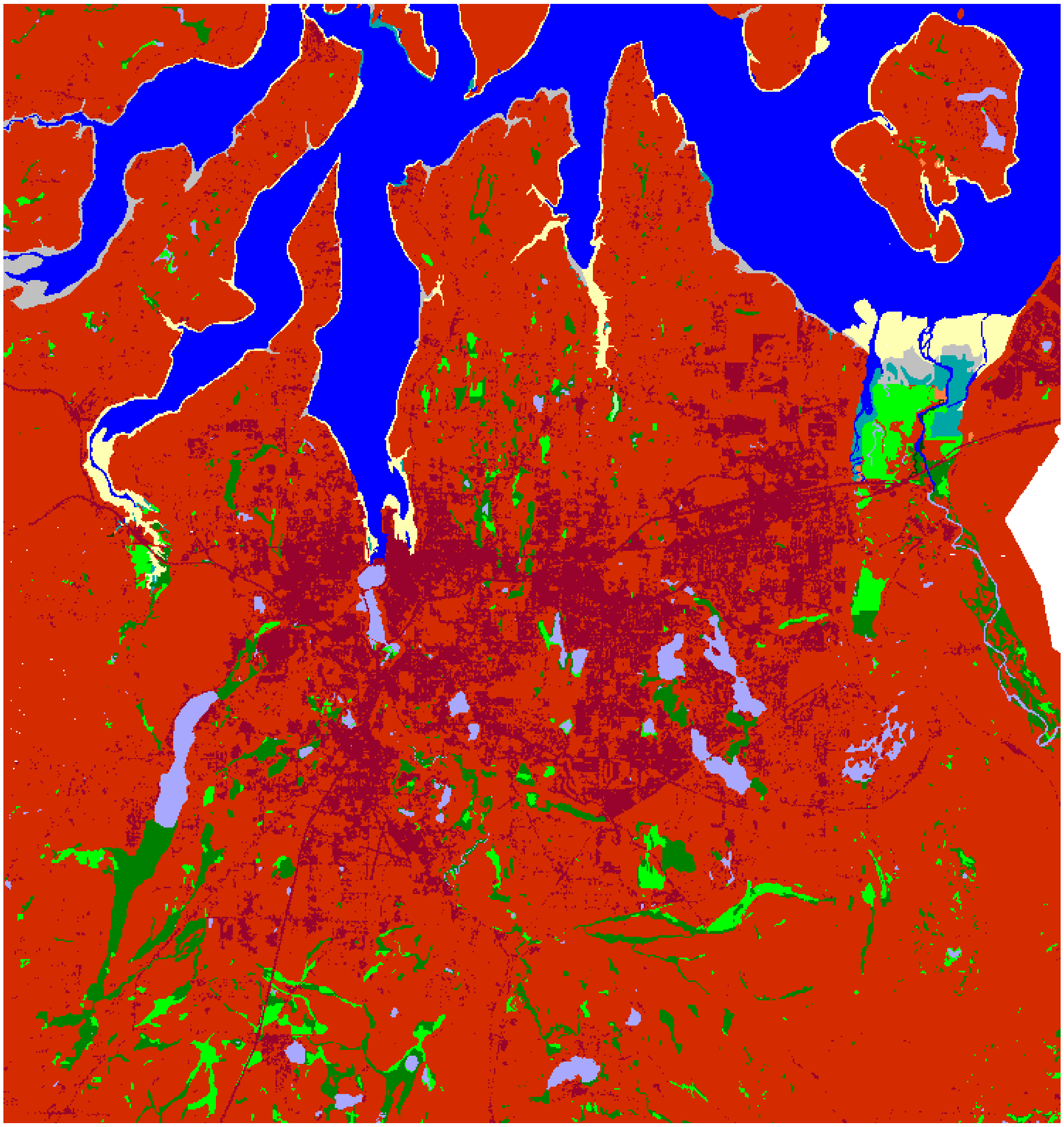

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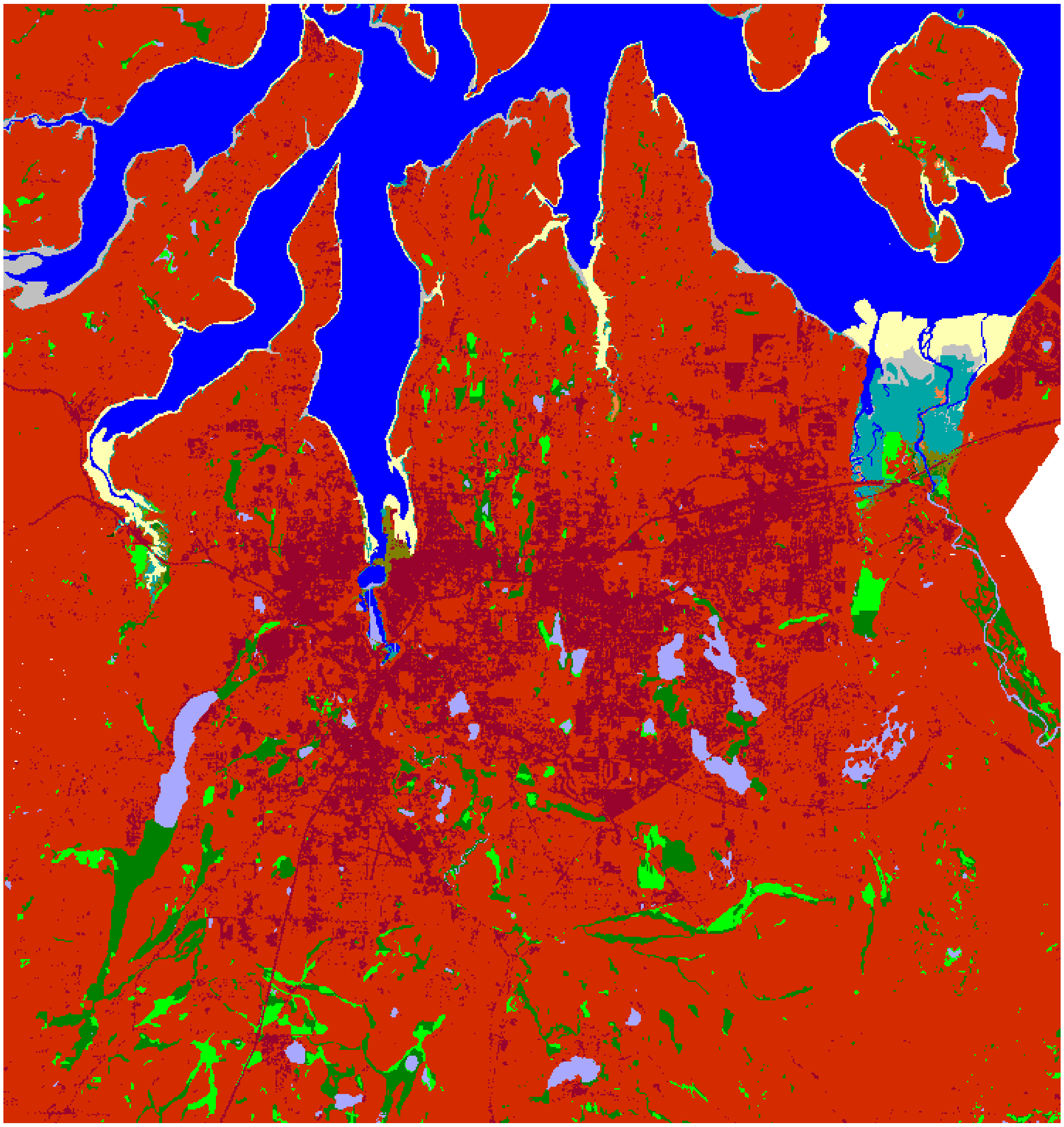
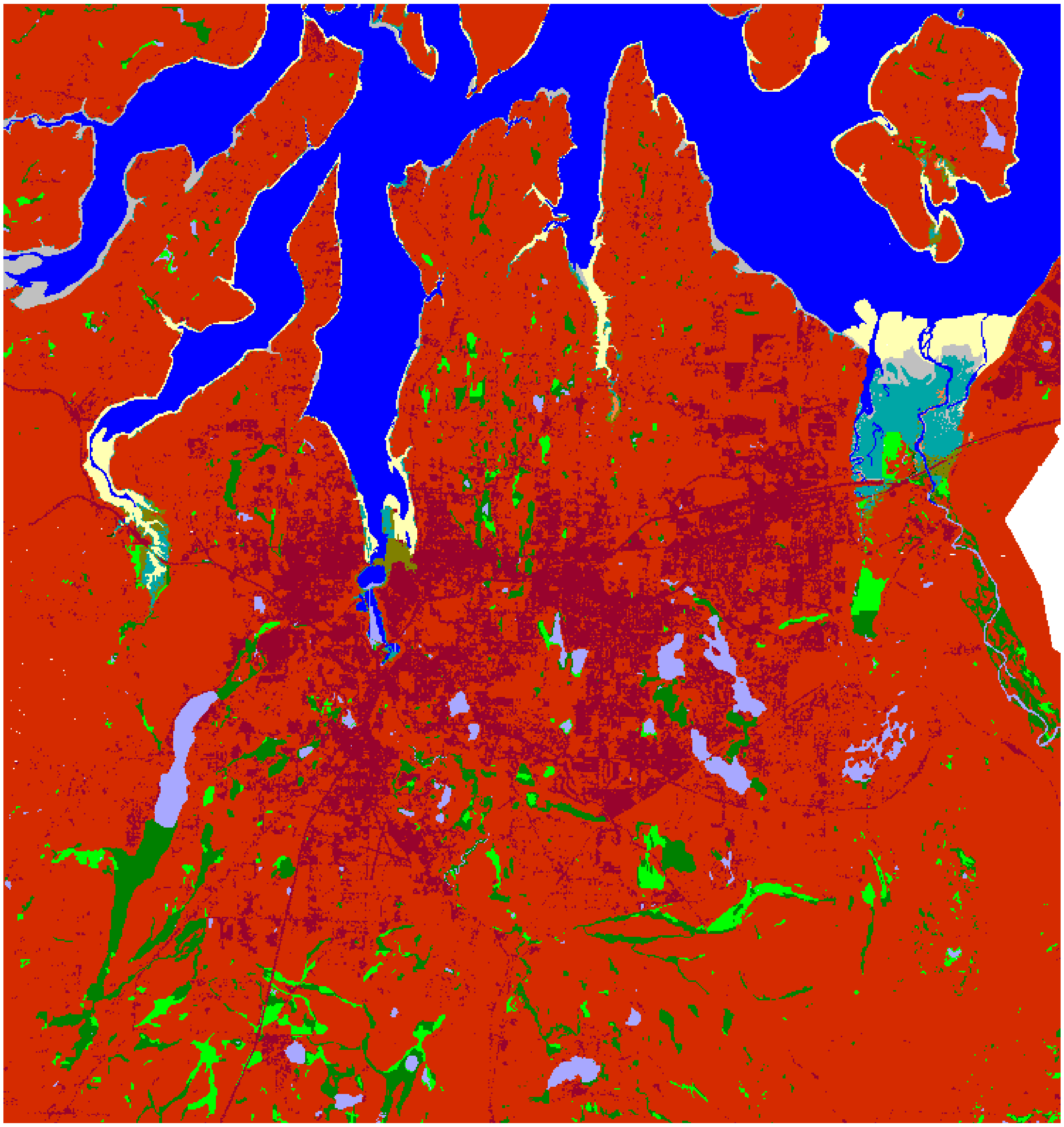


Nisqually NWR, 2025, 2 m SLR



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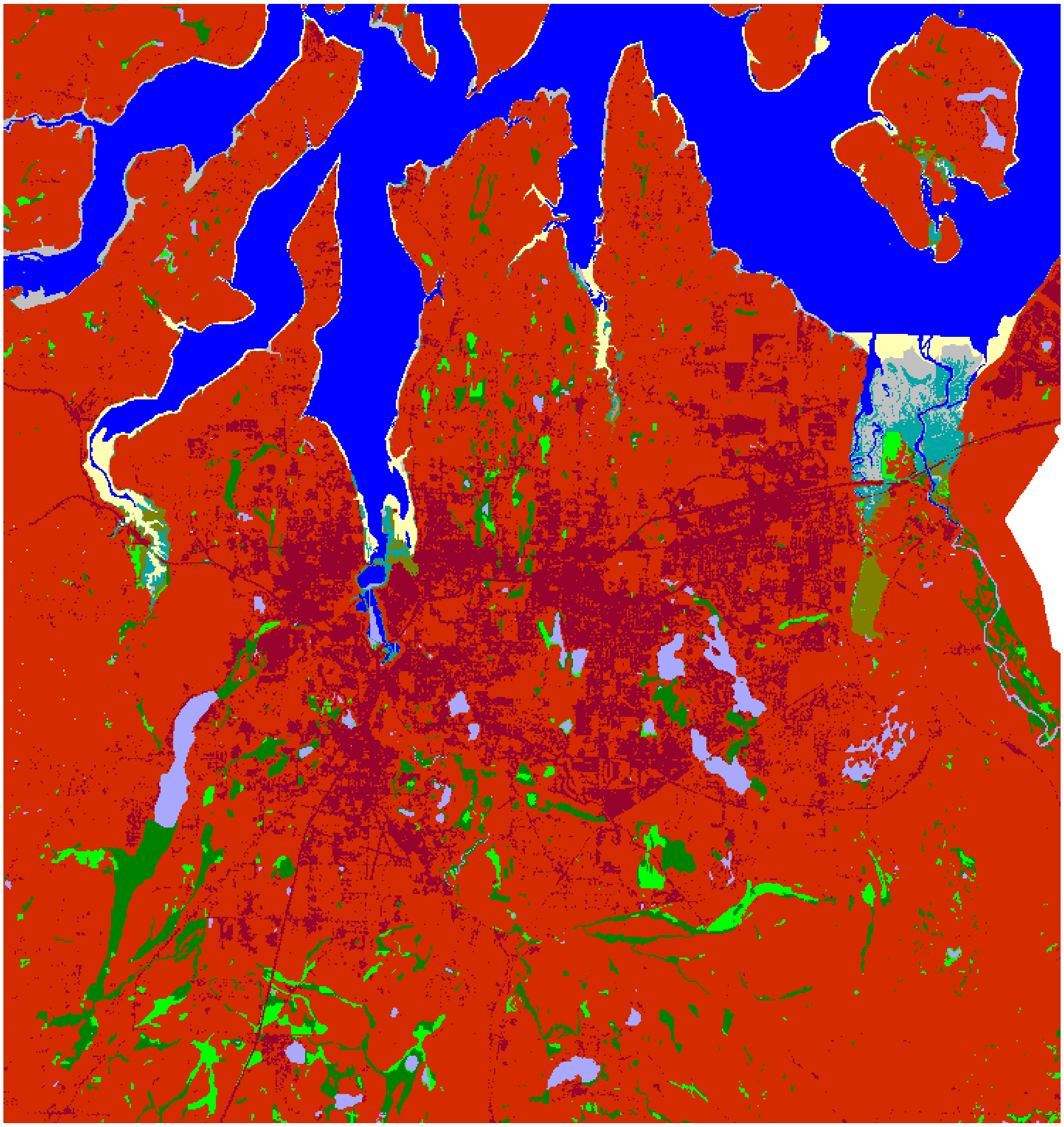
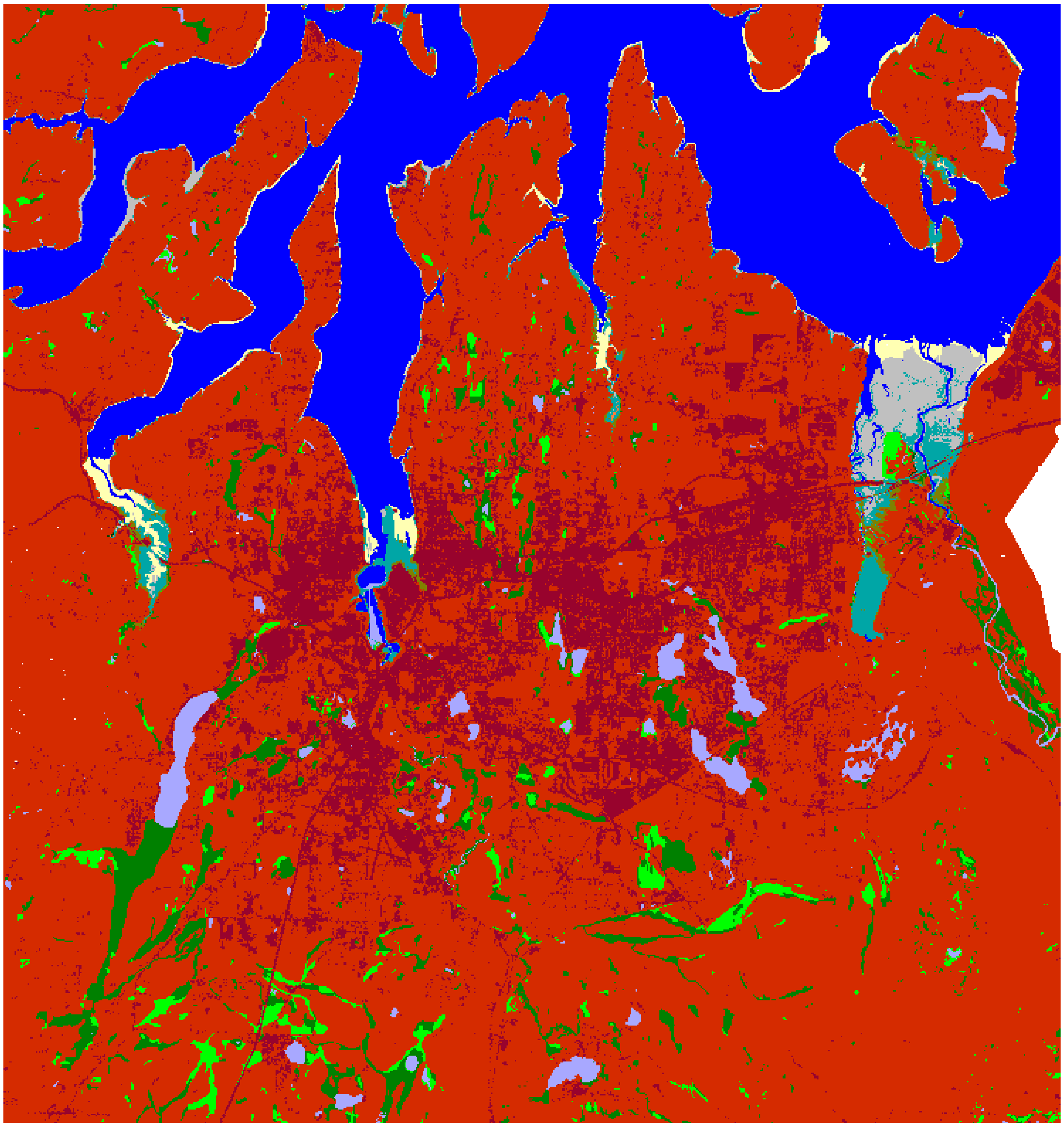


Nisqually NWR, 2075, 2 m SLR



Nisqually NWR, 2100, 2 m SLR