Application of the Sea-Level Affecting Marshes Model (SLAMM 5.1) to San Diego Bay NWR

Prepared For: Dr. Brian Czech, Conservation Biologist

U. S. Fish and Wildlife Service
National Wildlife Refuge System
Division of Natural Resources and Conservation Planning
Conservation Biology Program
4401 N. Fairfax Drive - MS 670
Arlington, VA 22203

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Jonathan S. Clough & Evan C. Larson, Warren Pinnacle Consulting, Inc.
PO Box 253, Warren VT, 05674
(802)-496-3476

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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. Pfeffer et al. (2008) suggests that 200 cm by 2100 is at the upper end of plausible scenarios due to physical limitations on glaciological conditions. Rising sea level 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 most Region 8 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 5.0) 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.

SLAMM Version 5.0 is the latest version of the SLAMM Model, developed in 2006/2007 and based on SLAMM 4.0. SLAMM 5.0 provides the following refinements:

- The capability to simulate fixed levels of sea-level rise by 2100 in case IPCC estimates of sea-level rise prove to be too conservative;
- Additional model categories such as "Inland Shore," "Irregularly Flooded (Brackish) Marsh," and "Tidal Swamp."
- *Optional.* In a defined estuary, salt marsh, brackish marsh, and tidal fresh marsh can migrate based on changes in salinity, using a simple though geographically-realistic salt wedge model. This optional model was not used in this model application.

Model results presented in this report were produced using SLAMM version 5.0.1 which was released in early 2008 based on only minor refinements to the original SLAMM 5.0 model. Specifically, the accretion rates for swamps were modified based on additional literature review. For a thorough accounting of SLAMM model processes and the underlying assumptions and equations, please see the SLAMM 5.0.1 technical documentation (Clough and Park, 2008). 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).

Sea Level Rise Scenarios

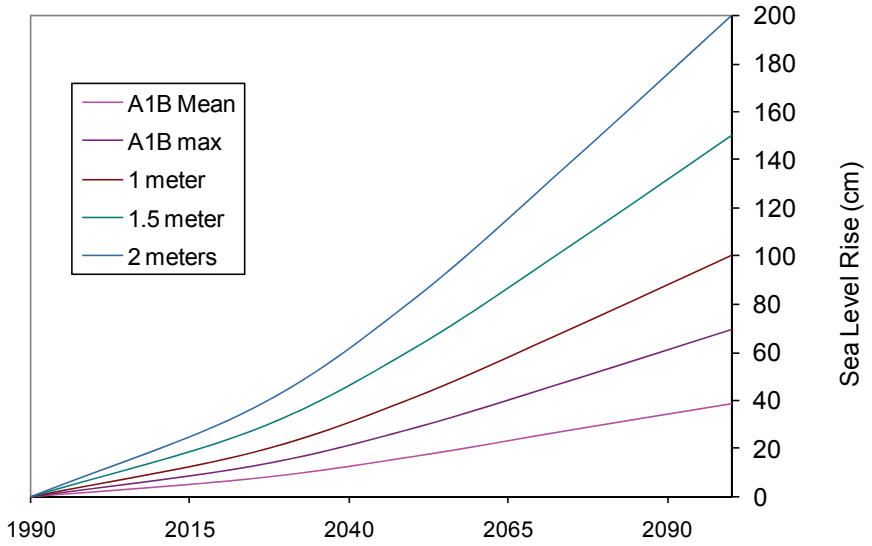
SLAMM 5 was run using scenario A1B from the Special Report on Emissions Scenarios (SRES) – mean and maximum estimates. The A1 scenario assumes that the future world includes very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of 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. 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



Additional information on the development of the SLAMM model is available in the technical documentation, which may be downloaded from the SLAMM website (Clough and Park, 2008).

Methods and Data Sources

The elevation data used for modeling San Diego Bay NWR were based entirely on LIDAR from the 1/9 arc-second National Elevation Dataset. NED metadata indicates that this digital elevation map (DEM) was derived from 2007 flights.

The National Wetlands Inventory for San Diego Bay is based on a photo date of 2002. Developed vs. undeveloped lands were estimated based on the National Land Cover Database (2001). Converting the NWI survey into 30 meter cells indicates that the approximately four thousand two hundred acre refuge (approved acquisition boundary including water) is composed of the categories as shown below:

Estuarine Open Water	44.8%
Tidal Flat	23.2%
Dry Land	11.0%
Estuarine Beach	6.1%
Dev. Dry Land	5.2%
Inland Fresh Marsh	3.4%
Irreg. Flooded Marsh	3.1%
Reg. Flooded Marsh	2.4%

The majority of the tidal flat region in San Diego Bay NWR is diked, according to the National Wetlands Inventory (Figure 1.) SLAMM assumes that diked areas remain protected until local sea level rise exceeds 2 meters relative to land elevations behind the dikes.

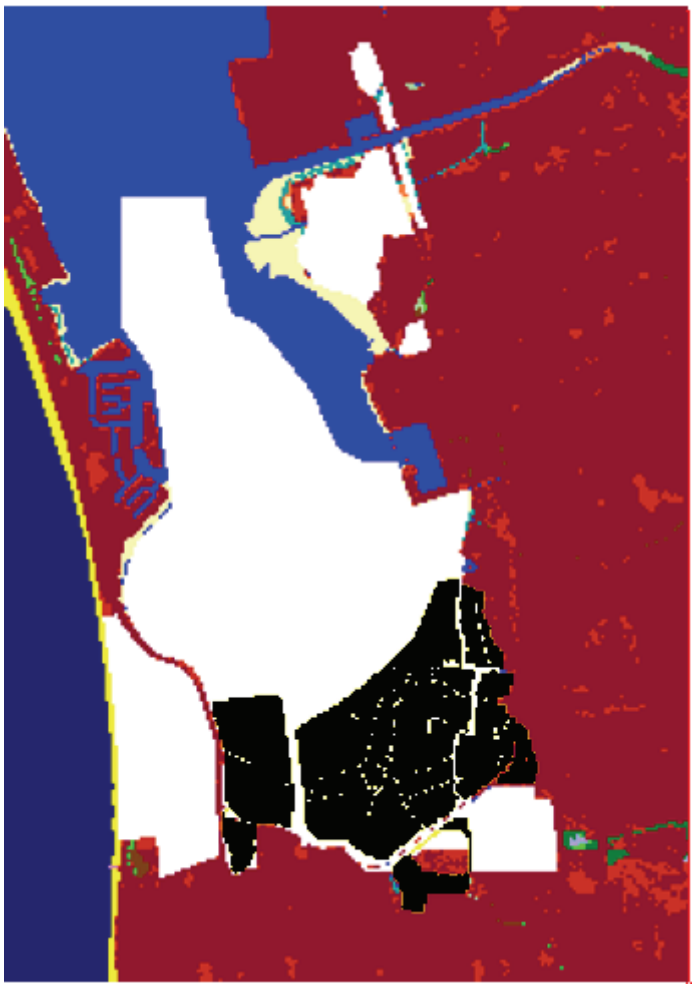


Figure 1: Diked Areas (black) within NWR Boundary (white).

The historic trend for sea level rise was estimated at 2 mm/year using the value from the closest tide

station (9410170, San Diego, CA). For this simulation, the historic eustatic (global average) sea level rise was estimated at 1.7 mm/year.

The tidal range for the San Diego Bay NWR is estimated at 1.745 meters (Figure 2). This value was determined using a NOAA tide gage (9410170, San Diego, CA). The oceanic tidal range was estimated at 1.63 meters, and was estimated from NOAA tide gages outside of San Diego Bay (9410230, La Jolla, CA; 9410396, Oceanside Harbor, CA; 9410120, Imperial Beach, Pacific Ocean, CA).

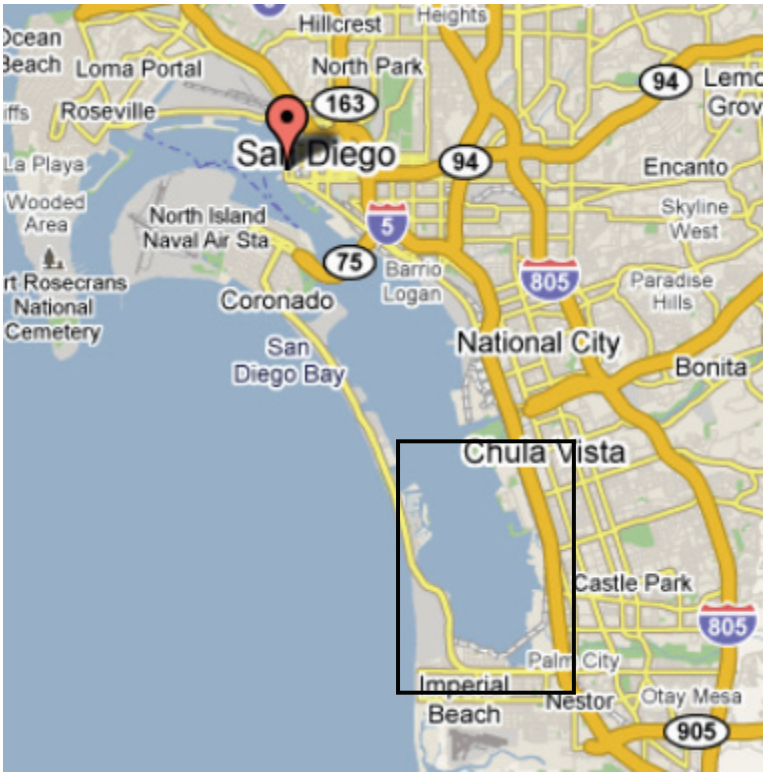


Figure 2: NOAA Gage Relevant to the Study Area (in rectangle).

Accretion rates in salt and irregularly flooded marshes were set to 6.1 mm/year and 5.9 mm/yr in tidal fresh marshes. This rate is based on accretion study results from nearby San Elijo Lagoon (Thum et al. 2000).

The MTL to NAVD correction was derived using the NOAA VDATUM tool. Multiple locations relevant to the study area were processed within VDATUM to derive corrections in the study area. The range of model results was approximately two centimeters (ranging from 0.75 to 0.77 meters). This model application used an average of these values.

Modeled U.S. Fish and Wildlife Service refuge boundaries for California are based on Approved Acquisition Boundaries as published on the FWS National Wildlife Refuge Data and Metadata website. Review of the San Diego Complex Comprehensive Conservation Plan (CCP) confirmed the range of these boundaries.

The cell-size used for this analysis was 30 meter by 30 meter cells. However, the SLAMM model does track partial conversion of cells based on elevation and slope.

SUMMARY OF SLAMM INPUT PARAMETERS FOR SAN DIEGO BAY

Description	,	San Diego Global	San Diego Bay
DEM Source Date (yyyy)	,	2005	2005
NWI_photo_date (yyyy)	,	2002	2002
Direction_OffShore (N|S|E|W)	,	W	W
Historic_trend (mm/yr)	,	2.065	2.065
NAVD88_correction (MTL-NAVD88 in meters)	,	0.76	0.76
Water Depth (m below MLW- N/A)	,	2	2
TideRangeOcean (meters: MHHW-MLLW)	,	1.63	1.745
TideRangeInland (meters)	,	1.63	1.745
Mean High Water Spring (m above MTL)	,	1.22	1.396
MHSW Inland (m above MTL)	,	1.22	1.396
Marsh Erosion (horz meters/year)	,	1.8	1.8
Swamp Erosion (horz meters/year)	,	1	1
TFlat Erosion (horz meters/year) [from 0.5]	,	0.5	0.5
Salt marsh vertical accretion (mm/yr) Final	,	6.1	6.1
Brackish March vert. accretion (mm/yr) Final	,	6.1	6.1
Tidal Fresh vertical accretion (mm/yr) Final	,	5.9	5.9
Beach/T.Flat Sedimentation Rate (mm/yr)	,	1	1
Frequency of Large Storms (yr/washover)	,	0	0
Use Elevation Preprocessor for Wetlands	,	FALSE	FALSE

Results

San Diego Bay NWR is predicted to show some effects from most sea level rise scenarios. Loss of undeveloped dry land – which constitutes roughly one-tenth of this NWR – is predicted to range from 25% to 61% across all scenarios. The majority of irregularly flooded marsh is predicted to be lost in scenarios 1 meter and above, though this category is somewhat resilient under lower scenarios. Loss of inland fresh marsh is less severe, with loss predicted at 10% in the most extreme scenario.

SLR by 2100 (m)	0.39	0.69	1	1.5	2
Tidal Flat	-3%	-2%	1%	6%	45%
Undeveloped Dry Land	25%	31%	37%	47%	61%
Estuarine Beach	77%	86%	90%	96%	94%
Dev. Dry Land	16%	23%	36%	54%	65%
Inland Fresh Marsh	3%	3%	5%	7%	10%
Irreg. Flooded Marsh	17%	22%	66%	86%	92%

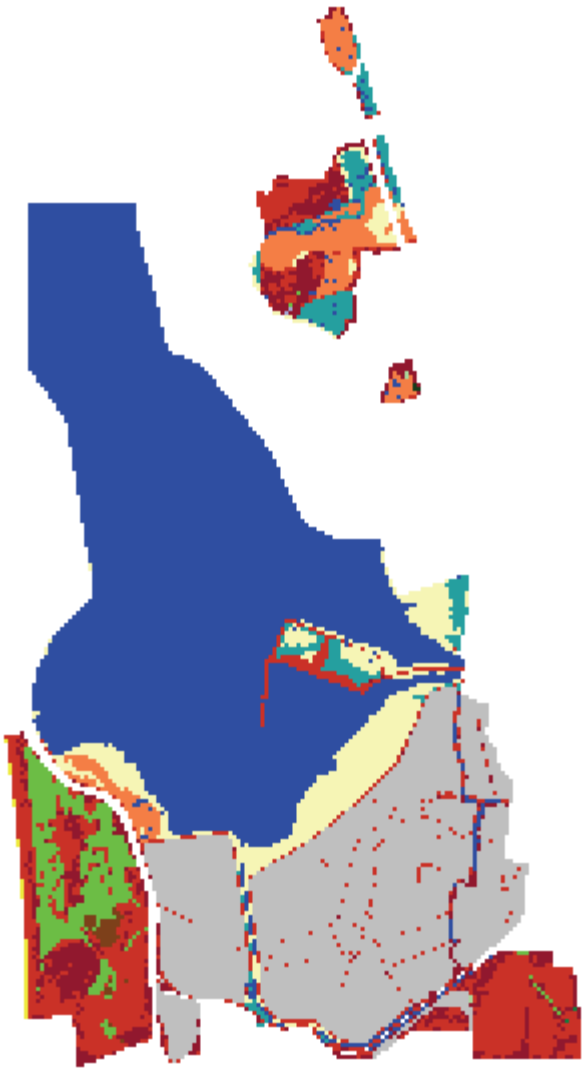
Predicted Loss Rates of Land Categories by 2100 Given Simulated Scenarios of Eustatic Sea Level Rise

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

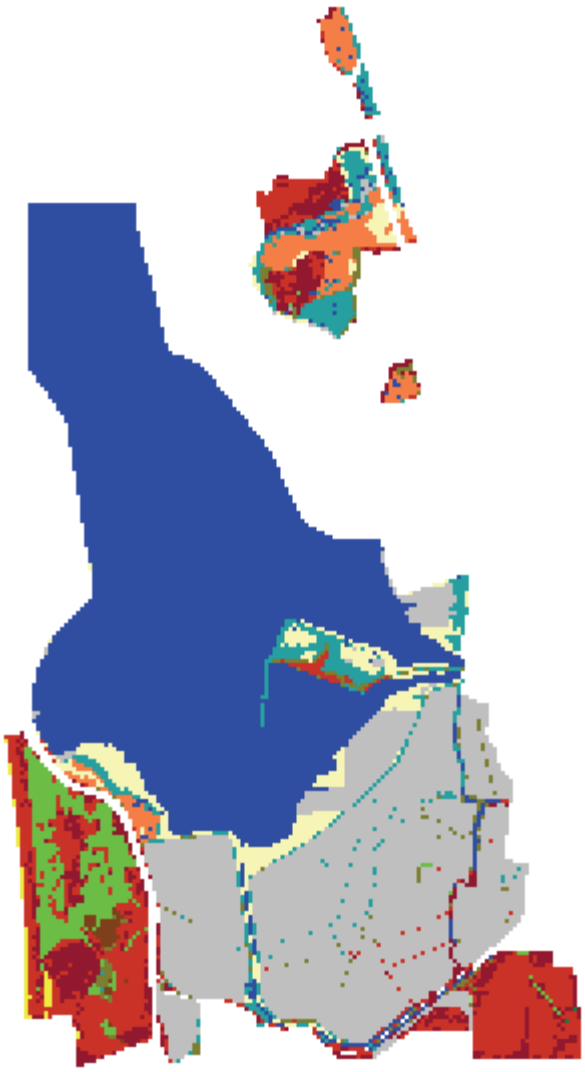
San Diego Bay NWR
IPCC Scenario A1B-Mean, 0.39 M SLR Eustatic by 2100

Results in Acres

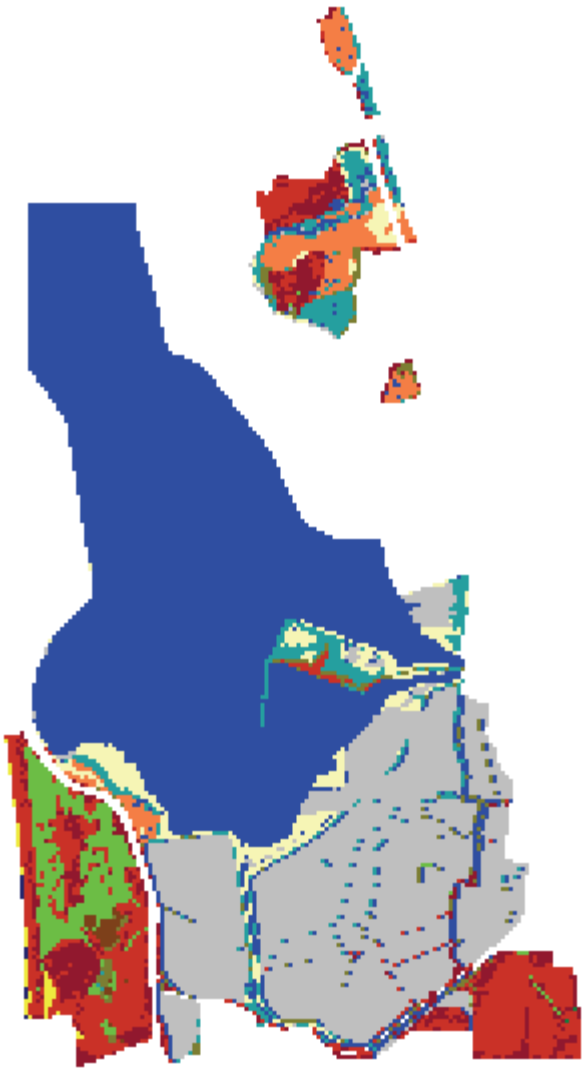
	Initial	2025	2050	2075	2100
Estuarine Open Water	1906.8	1948.1	1991.4	2047.5	2098.1
Tidal Flat	988.8	1064.4	1038.4	1025.2	1013.5
Undev. Dry Land	468.8	377.4	370.3	360.3	350.7
Estuarine Beach	260.2	155.0	141.2	98.4	59.4
Dev. Dry Land	221.7	197.1	194.2	189.7	185.7
Inland Fresh Marsh	144.6	141.0	140.9	140.9	140.9
Brackish Marsh	130.5	107.9	107.9	108.0	108.0
Saltmarsh	101.0	170.6	167.2	167.2	167.2
Inland Shore	12.7	12.7	12.7	12.7	12.7
Tidal Creek	12.0	12.0	12.0	12.0	12.0
Ocean Beach	7.3	14.5	14.5	15.4	16.2
Tidal Fresh Marsh	0.9	0.5	0.5	0.5	0.5
Tidal Swamp	0.7	0.1	0.1	0.0	0.0
Swamp	0.4	0.4	0.4	0.4	0.4
Inland Open Water	0.4	0.2	0.2	0.2	0.2
Trans. Salt Marsh	0.0	54.0	62.2	73.8	84.8
Open Ocean	0.0	0.9	2.6	4.7	6.4
Total (incl. water)	**4256.8**	**4256.8**	**4256.8**	**4256.8**	**4256.8**



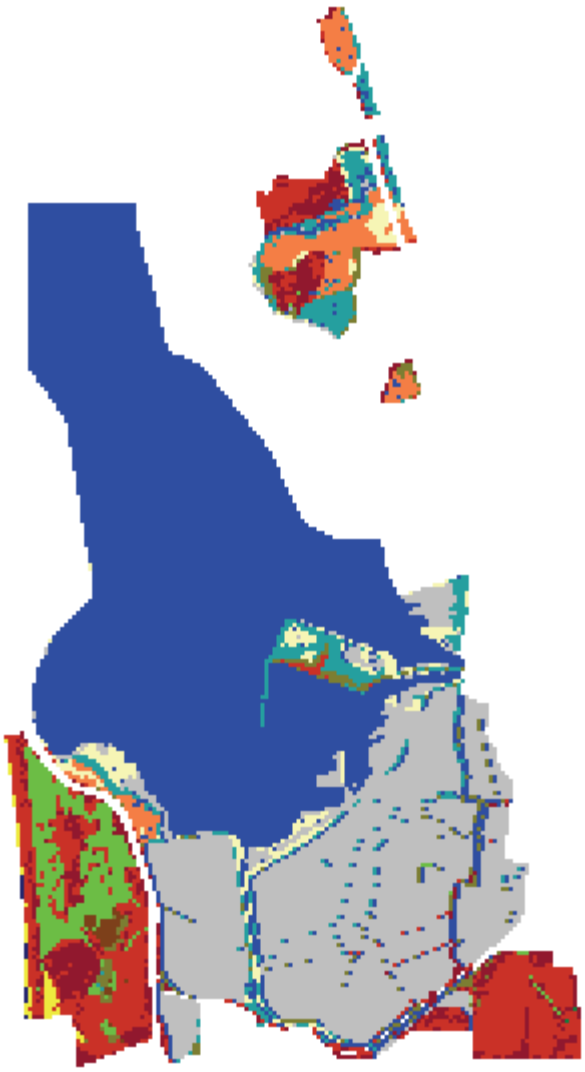
San Diego Bay NWR, Initial Condition



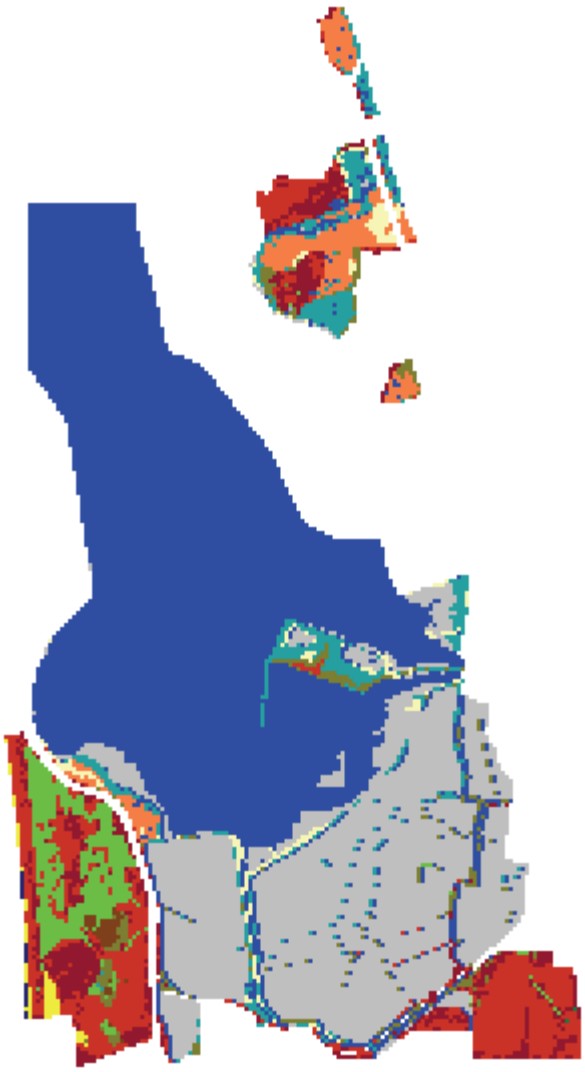
San Diego Bay NWR, 2025, Scenario A1B Mean



San Diego Bay NWR, 2050, Scenario A1B Mean



San Diego Bay NWR, 2075, Scenario A1B Mean

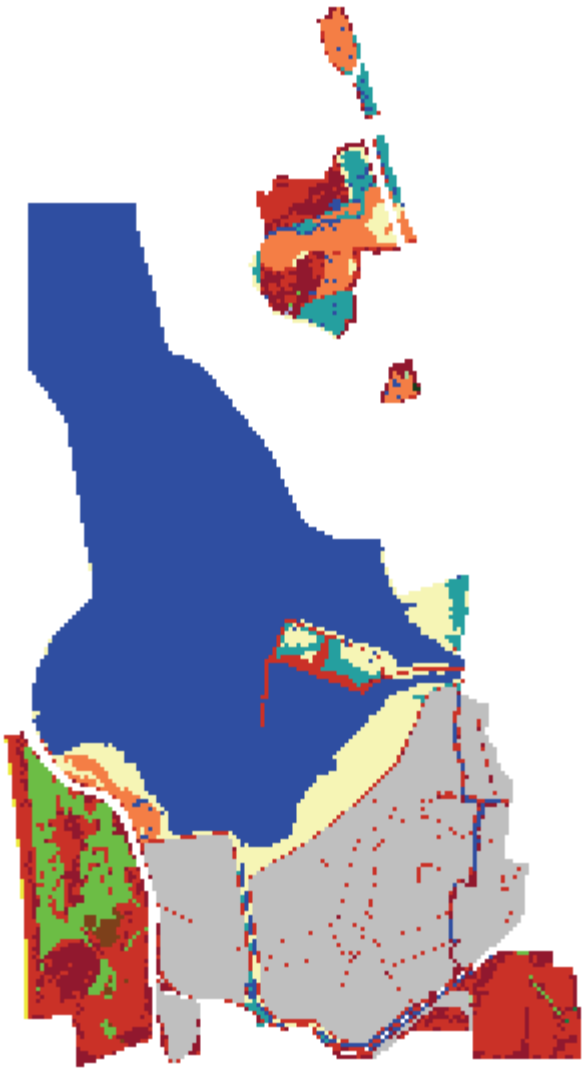


San Diego Bay NWR, 2100, Scenario A1B Mean

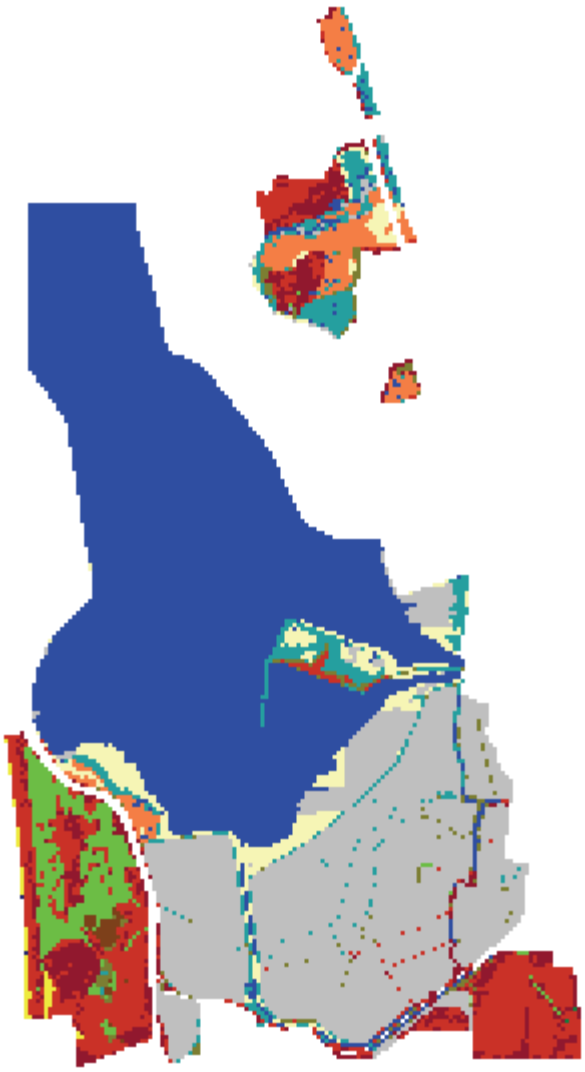
San Diego Bay NWR
IPCC Scenario A1B-Max, 0.69 M SLR Eustatic by 2100

Results in Acres

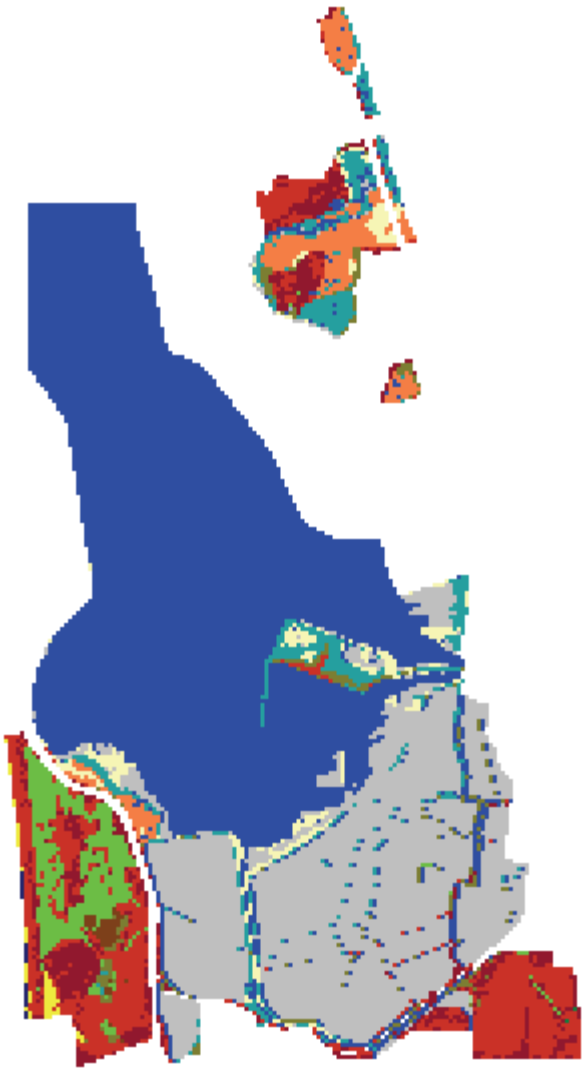
	Initial	2025	2050	2075	2100
Estuarine Open Water	1906.8	1950.4	2028.3	2080.2	2135.3
Tidal Flat	988.8	1067.8	1050.1	1047.0	1008.2
Undev. Dry Land	468.8	375.0	362.1	344.8	325.0
Estuarine Beach	260.2	149.7	94.2	48.1	37.1
Dev. Dry Land	221.7	196.3	190.5	183.0	170.8
Inland Fresh Marsh	144.6	140.9	140.7	140.5	139.9
Brackish Marsh	130.5	107.9	108.0	106.7	101.4
Saltmarsh	101.0	173.3	169.7	172.9	179.1
Inland Shore	12.7	12.7	12.7	12.7	12.7
Tidal Creek	12.0	12.0	12.0	12.0	12.0
Ocean Beach	7.3	14.4	14.4	15.4	18.9
Tidal Fresh Marsh	0.9	0.5	0.5	0.5	0.4
Tidal Swamp	0.7	0.1	0.0	0.0	0.0
Swamp	0.4	0.4	0.4	0.4	0.4
Inland Open Water	0.4	0.2	0.2	0.0	0.0
Trans. Salt Marsh	0.0	53.7	67.7	83.8	103.0
Open Ocean	0.0	1.6	5.1	8.8	12.6
Total (incl. water)	**4256.8**	**4256.8**	**4256.8**	**4256.8**	**4256.8**



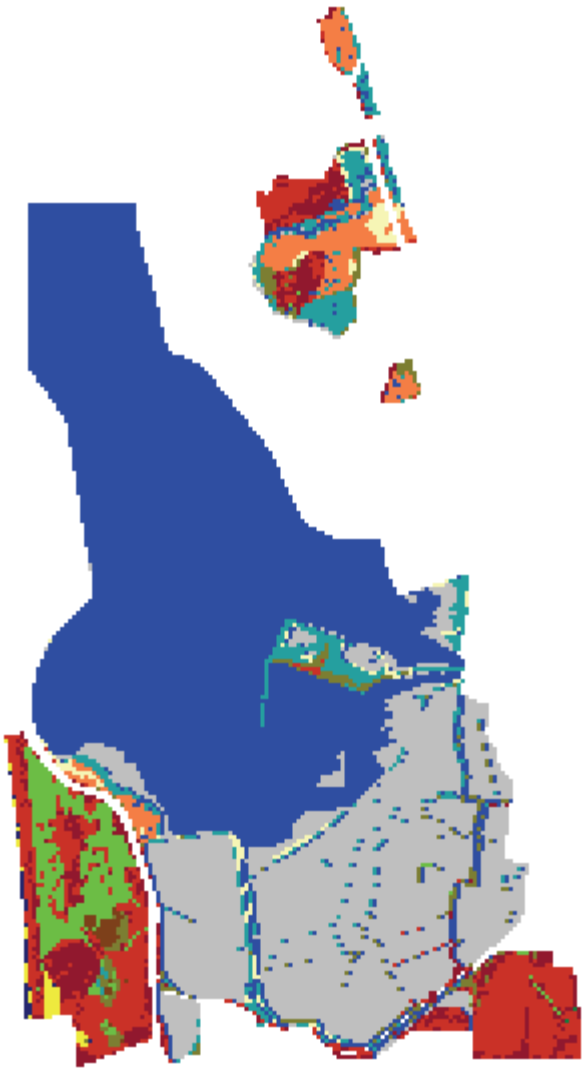
San Diego Bay NWR, Initial Condition



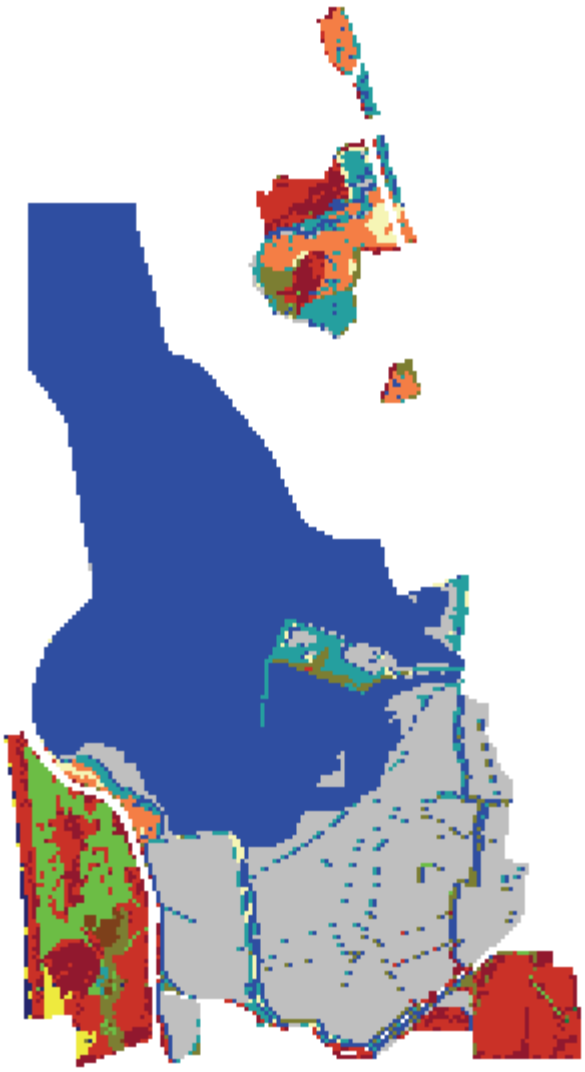
San Diego Bay NWR, 2025, Scenario A1B Maximum



San Diego Bay NWR, 2050, Scenario A1B Maximum



San Diego Bay NWR, 2075, Scenario A1B Maximum

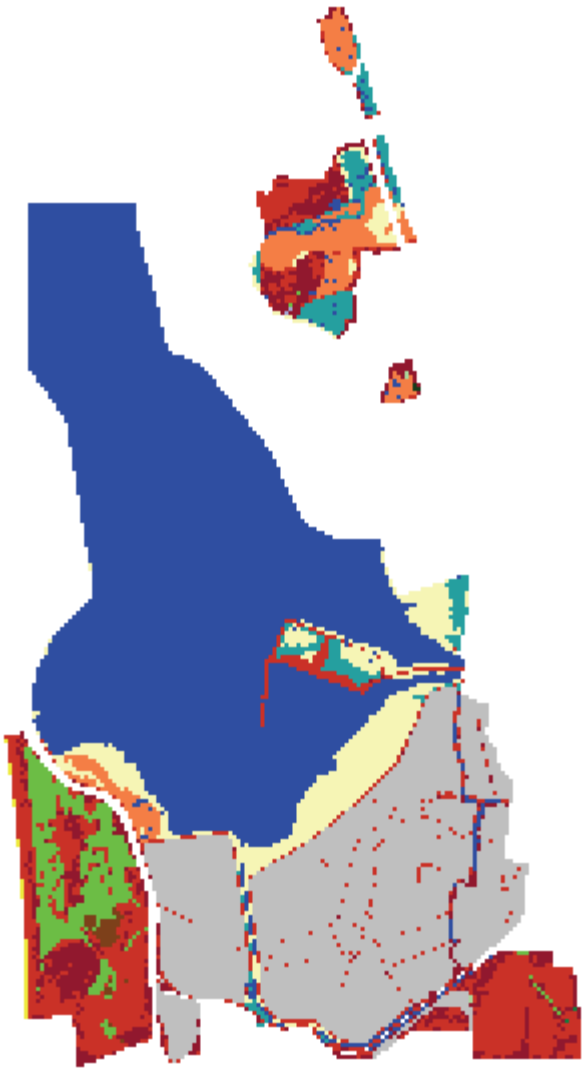


San Diego Bay NWR, 2100, Scenario A1B Maximum

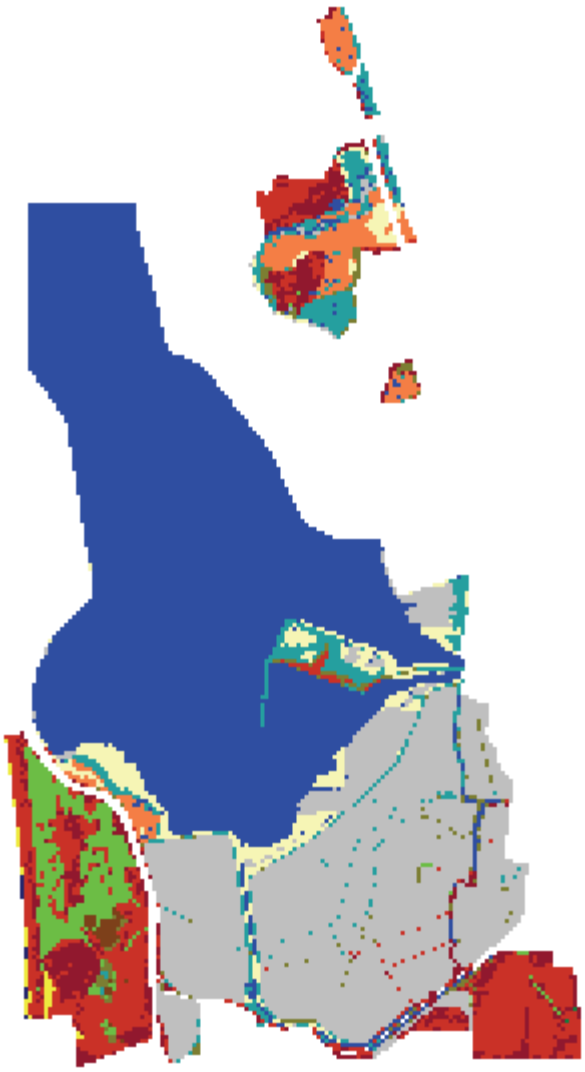
San Diego Bay NWR
1 Meter Eustatic SLR by 2100

Results in Acres

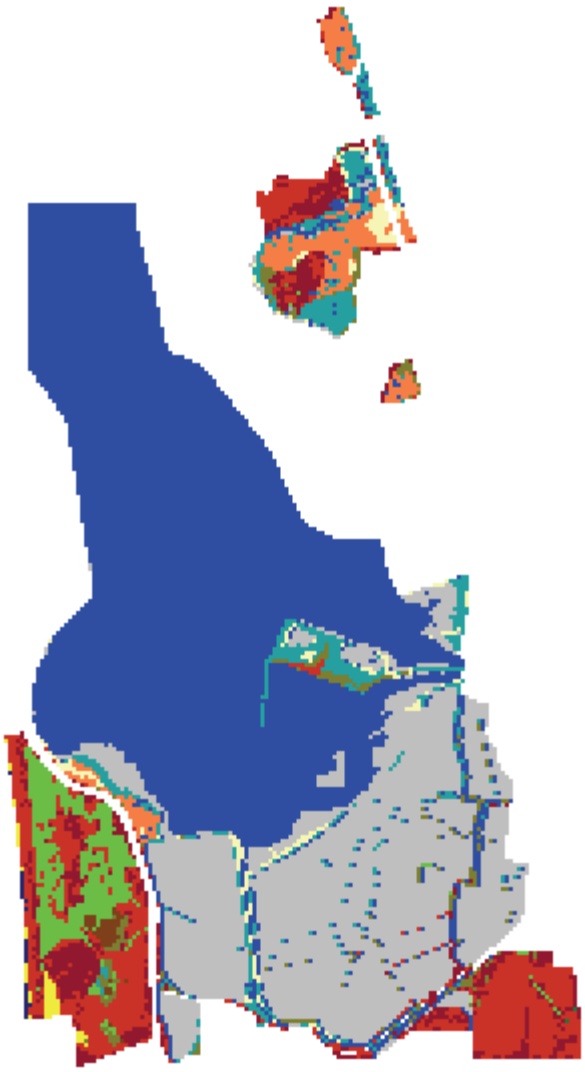
	Initial	2025	2050	2075	2100
Estuarine Open Water	1906.8	1954.3	2045.1	2105.4	2226.8
Tidal Flat	988.8	1072.1	1077.2	1059.9	982.3
Undev. Dry Land	468.8	372.4	353.3	327.2	296.9
Estuarine Beach	260.2	142.0	56.5	37.1	26.3
Dev. Dry Land	221.7	195.2	186.9	172.5	141.2
Inland Fresh Marsh	144.6	140.8	140.1	138.6	137.5
Brackish Marsh	130.5	107.9	103.1	73.9	44.6
Saltmarsh	101.0	175.7	177.2	198.3	214.9
Inland Shore	12.7	12.7	12.7	12.7	12.7
Tidal Creek	12.0	12.0	12.0	12.0	12.0
Ocean Beach	7.3	14.2	14.7	16.6	29.6
Tidal Fresh Marsh	0.9	0.5	0.4	0.4	0.4
Tidal Swamp	0.7	0.1	0.0	0.0	0.0
Swamp	0.4	0.4	0.4	0.4	0.4
Inland Open Water	0.4	0.2	0.2	0.0	0.0
Trans. Salt Marsh	0.0	53.9	69.7	88.5	109.7
Open Ocean	0.0	2.4	7.2	13.4	21.5
Total (incl. water)	**4256.8**	**4256.8**	**4256.8**	**4256.8**	**4256.8**



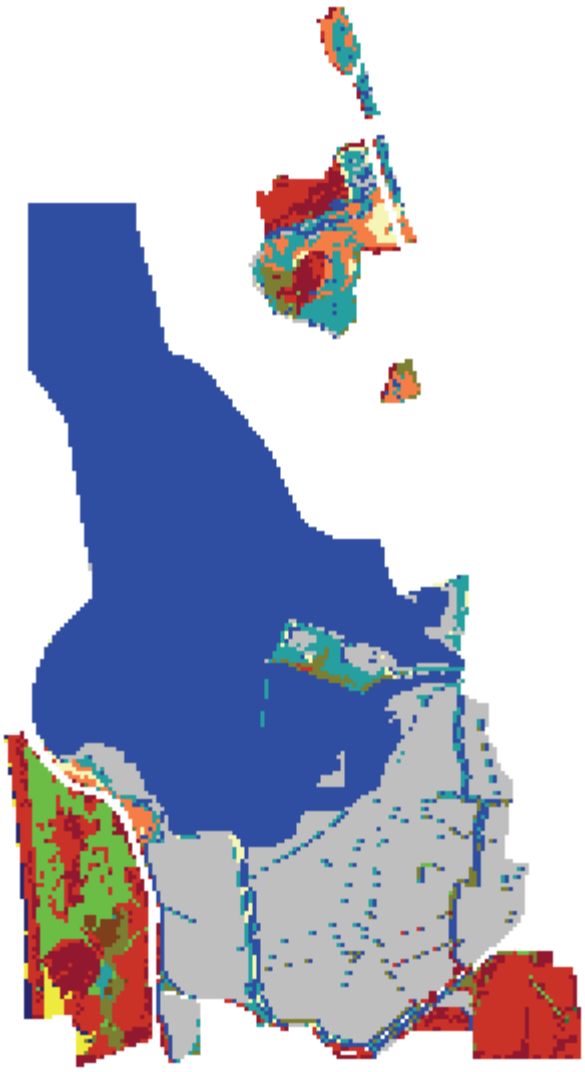
San Diego Bay NWR, Initial Condition



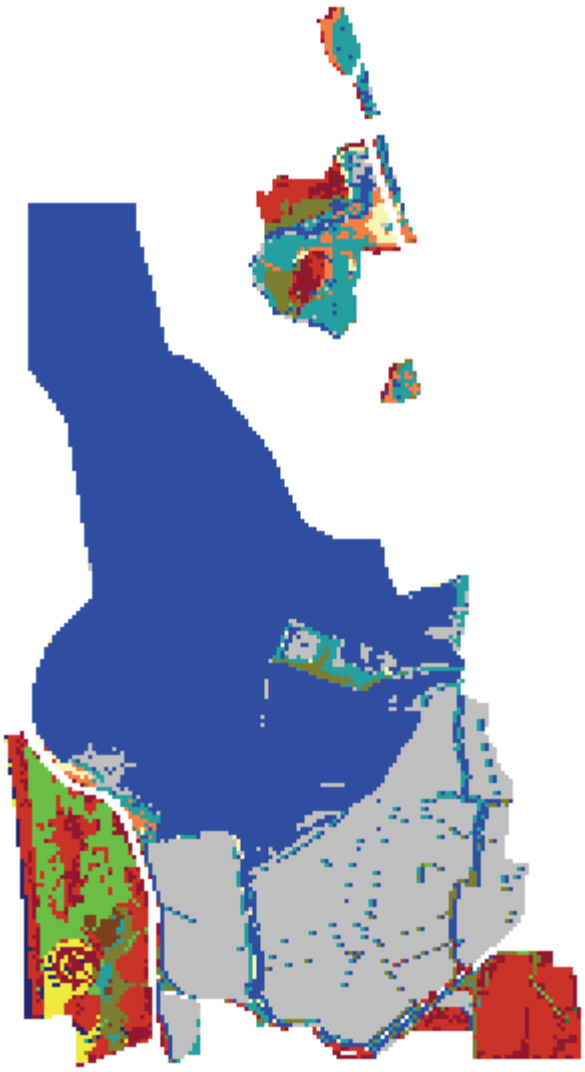
San Diego Bay NWR, 2025, 1 meter



San Diego Bay NWR, 2050, 1 meter



San Diego Bay NWR, 2075, 1 meter

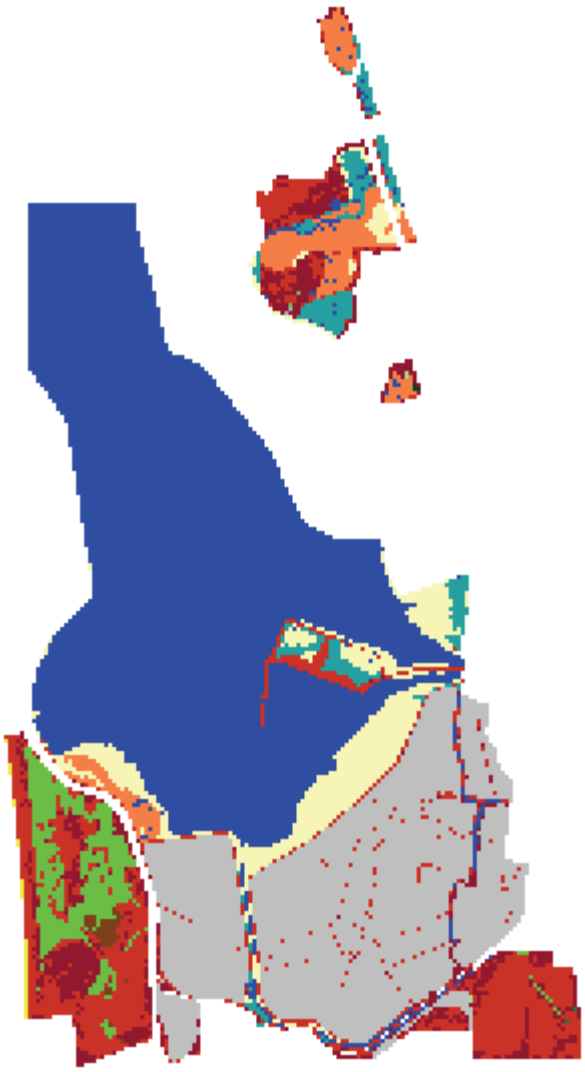


San Diego Bay NWR, 2100, 1 meter

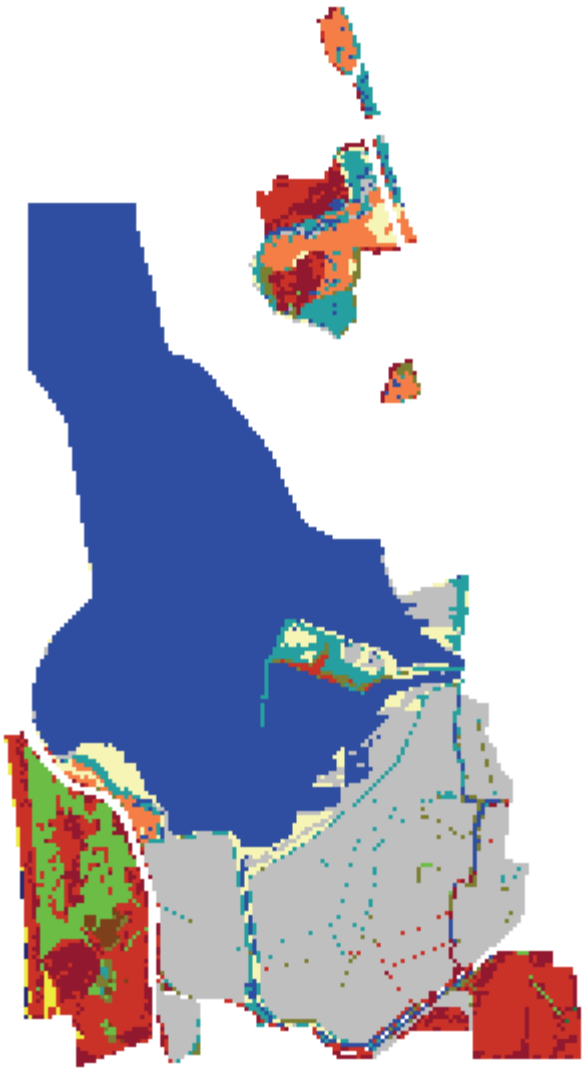
San Diego Bay NWR
1.5 Meters Eustatic SLR by 2100

Results in Acres

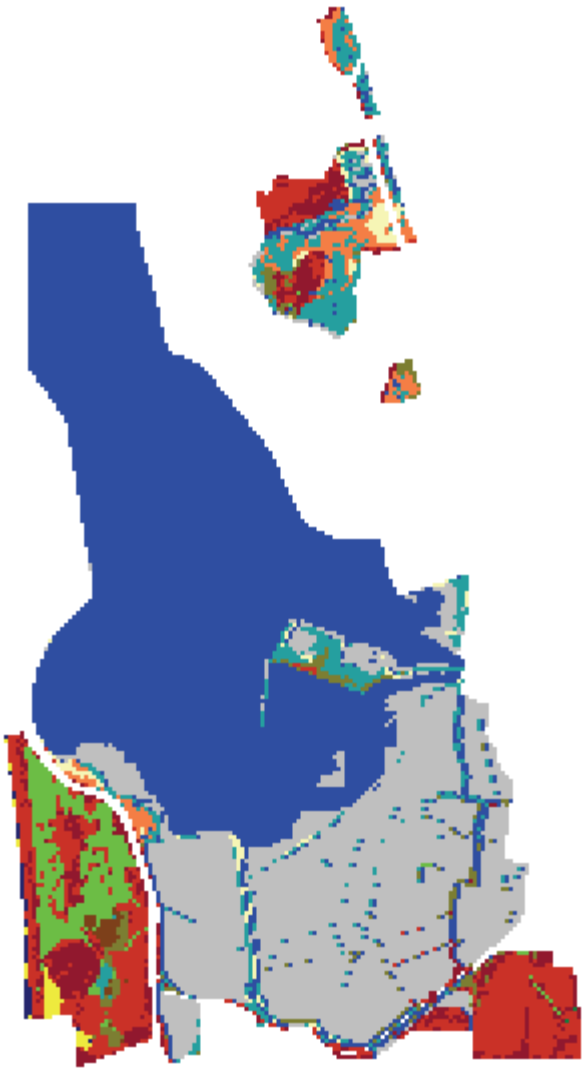
	Initial	2025	2050	2075	2100
Estuarine Open Water	1906.8	1981.5	2071.1	2235.0	2448.8
Tidal Flat	988.8	1067.8	1096.8	1011.2	932.8
Undev. Dry Land	468.8	367.8	338.4	296.1	249.7
Estuarine Beach	260.2	121.4	41.7	25.0	10.7
Dev. Dry Land	221.7	192.9	179.8	140.3	101.2
Inland Fresh Marsh	144.6	140.4	138.4	136.9	135.1
Brackish Marsh	130.5	104.7	66.9	30.0	17.7
Saltmarsh	101.0	181.5	200.8	217.5	172.7
Inland Shore	12.7	12.7	12.7	12.7	12.0
Tidal Creek	12.0	12.0	12.0	12.0	12.0
Ocean Beach	7.3	13.5	12.9	16.0	14.3
Tidal Fresh Marsh	0.9	0.5	0.4	0.3	0.2
Tidal Swamp	0.7	0.0	0.0	0.0	0.0
Swamp	0.4	0.4	0.4	0.4	0.4
Inland Open Water	0.4	0.2	0.0	0.0	0.0
Trans. Salt Marsh	0.0	55.0	71.3	87.3	80.3
Open Ocean	0.0	4.3	13.4	36.2	68.9
Total (incl. water)	**4256.8**	**4256.8**	**4256.8**	**4256.8**	**4256.8**



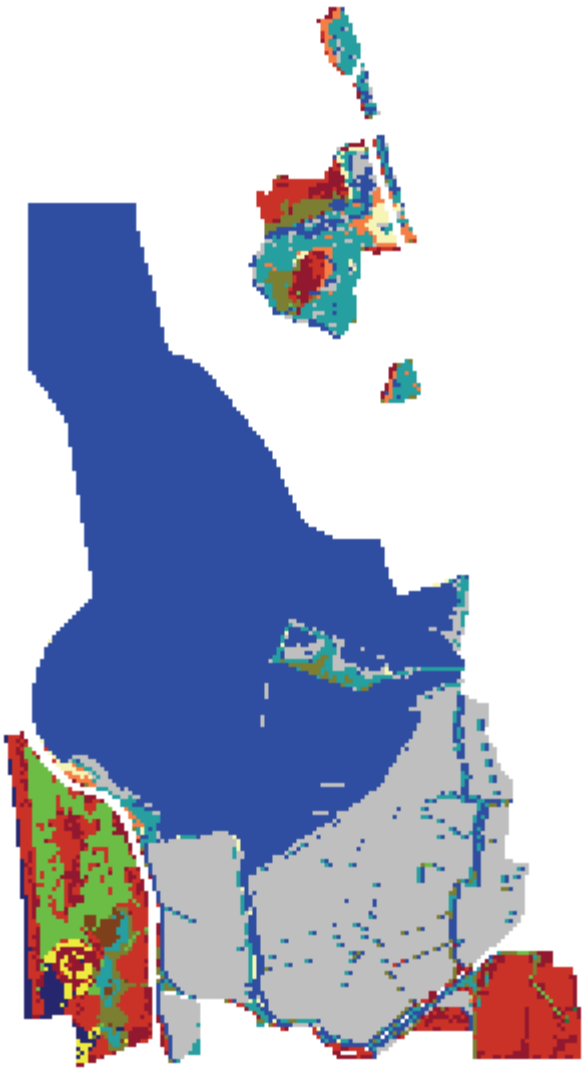
San Diego Bay NWR, Initial Condition



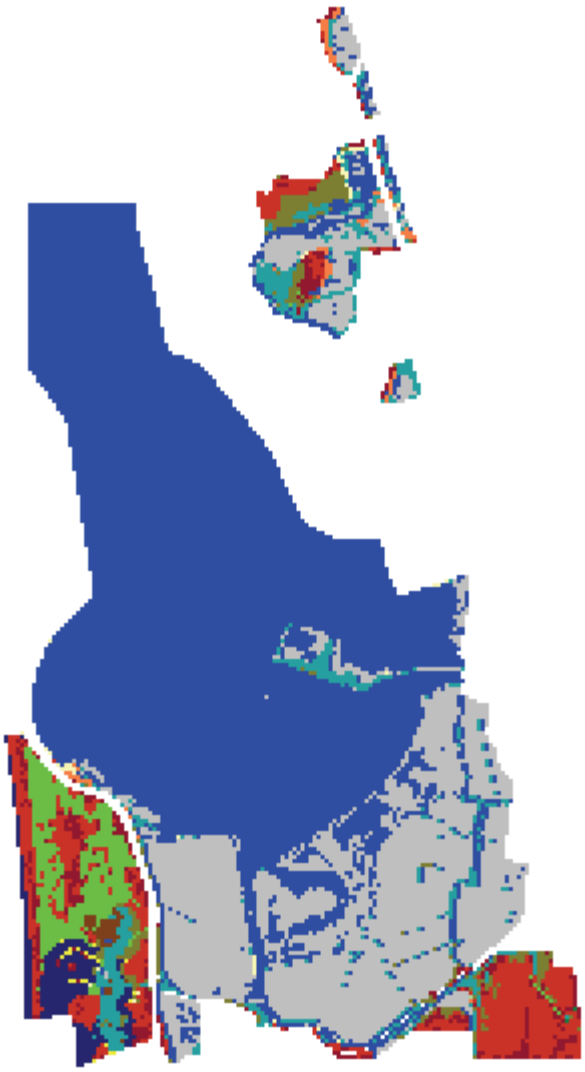
San Diego Bay NWR, 2025, 1.5 meter



San Diego Bay NWR, 2050, 1.5 meter



San Diego Bay NWR, 2075, 1.5 meter

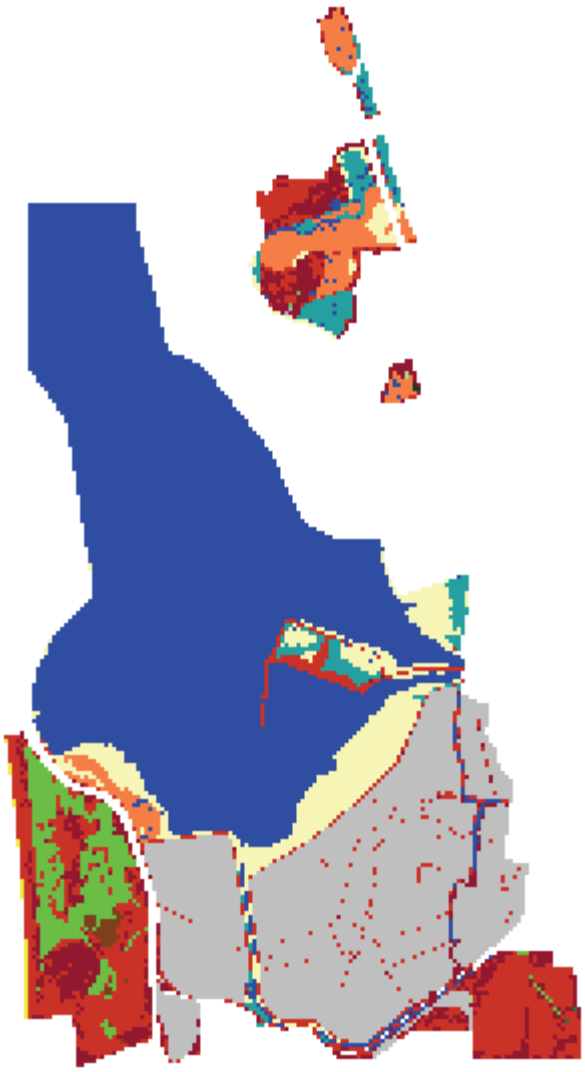


San Diego Bay NWR, 2100, 1.5 meter

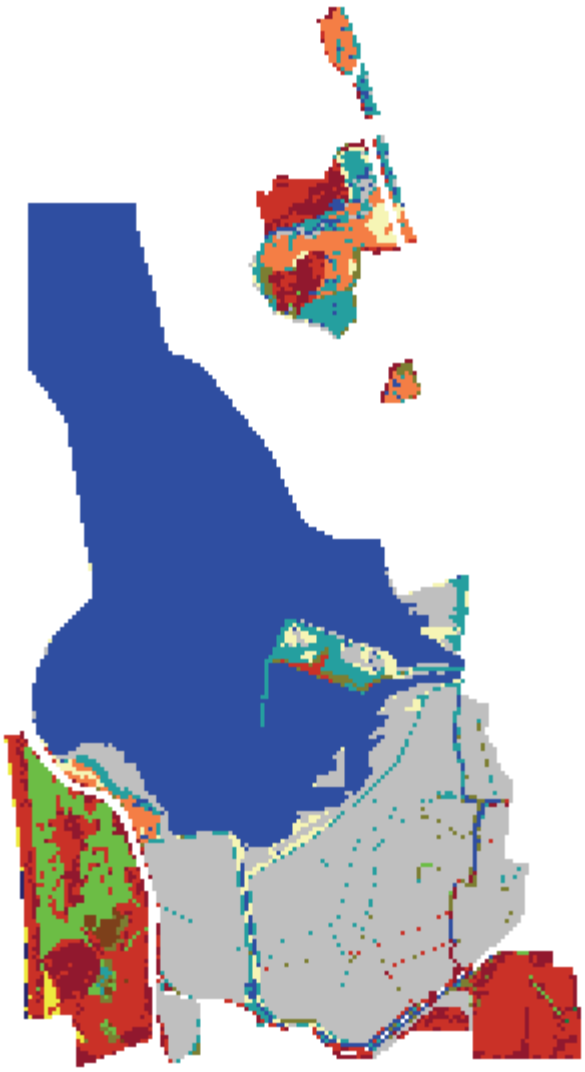
San Diego Bay NWR
2 Meters Eustatic SLR by 2100

Results in Acres

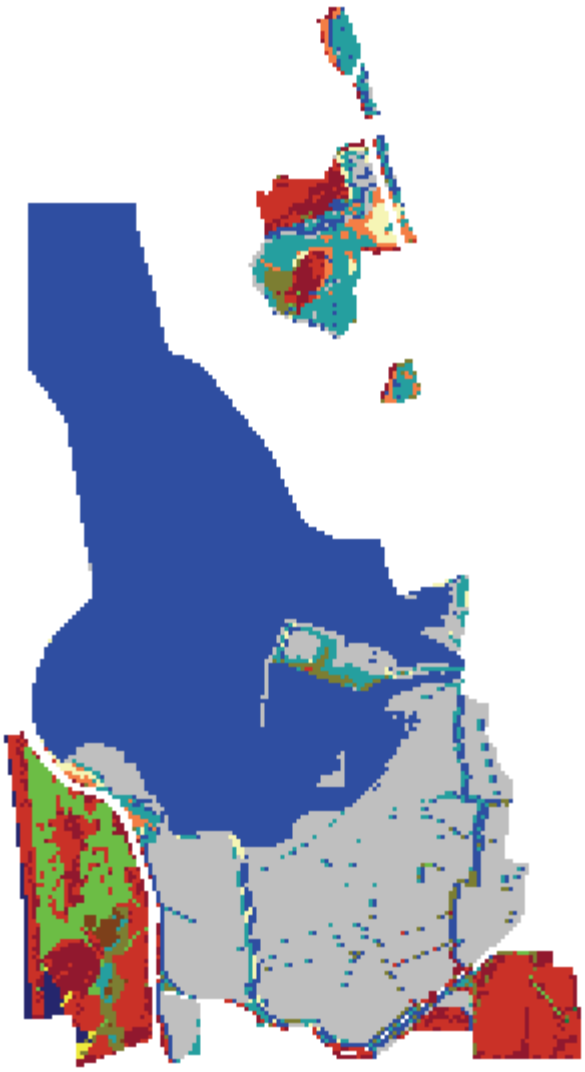
	Initial	2025	2050	2075	2100
Estuarine Open Water	1906.8	1995.3	2095.2	2339.9	2924.9
Tidal Flat	988.8	1101.9	1113.8	1038.9	547.8
Undev. Dry Land	468.8	362.7	323.0	263.8	180.7
Estuarine Beach	260.2	77.1	34.5	15.8	14.5
Dev. Dry Land	221.7	190.7	168.8	110.7	77.8
Inland Fresh Marsh	144.6	139.9	137.6	135.1	130.3
Brackish Marsh	130.5	98.4	39.2	17.4	10.9
Saltmarsh	101.0	190.1	212.0	155.4	154.1
Inland Shore	12.7	12.7	12.7	12.5	8.1
Tidal Creek	12.0	12.0	12.0	12.0	12.0
Ocean Beach	7.3	13.1	9.9	17.5	7.3
Tidal Fresh Marsh	0.9	0.4	0.4	0.2	0.2
Tidal Swamp	0.7	0.0	0.0	0.0	0.0
Swamp	0.4	0.4	0.4	0.4	0.4
Inland Open Water	0.4	0.2	0.0	0.0	0.0
Trans. Salt Marsh	0.0	55.5	76.1	79.9	89.2
Open Ocean	0.0	6.3	21.4	57.1	98.5
Total (incl. water)	**4256.8**	**4256.8**	**4256.8**	**4256.8**	**4256.8**



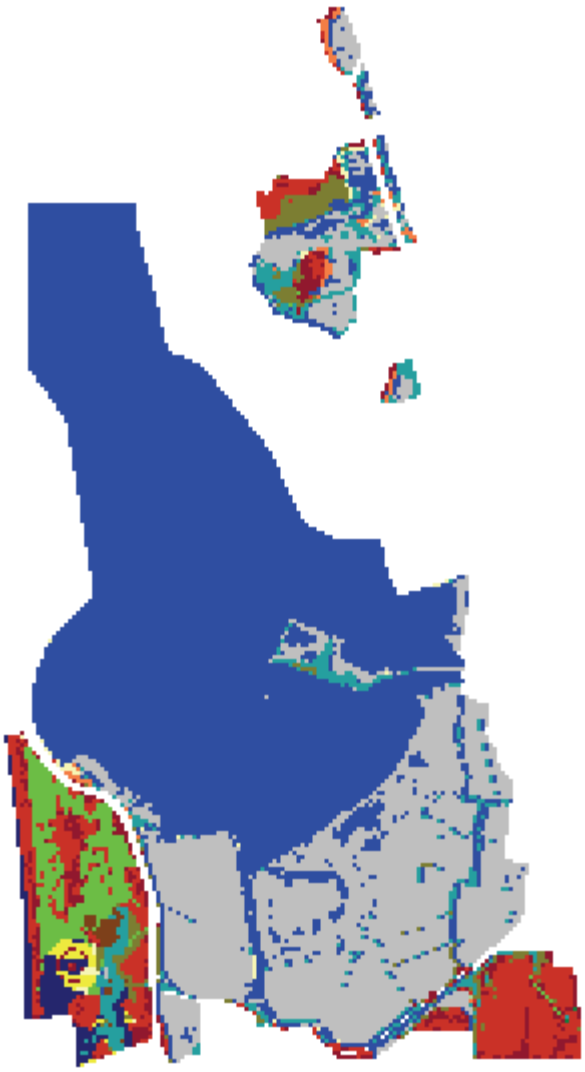
San Diego Bay NWR, Initial Condition



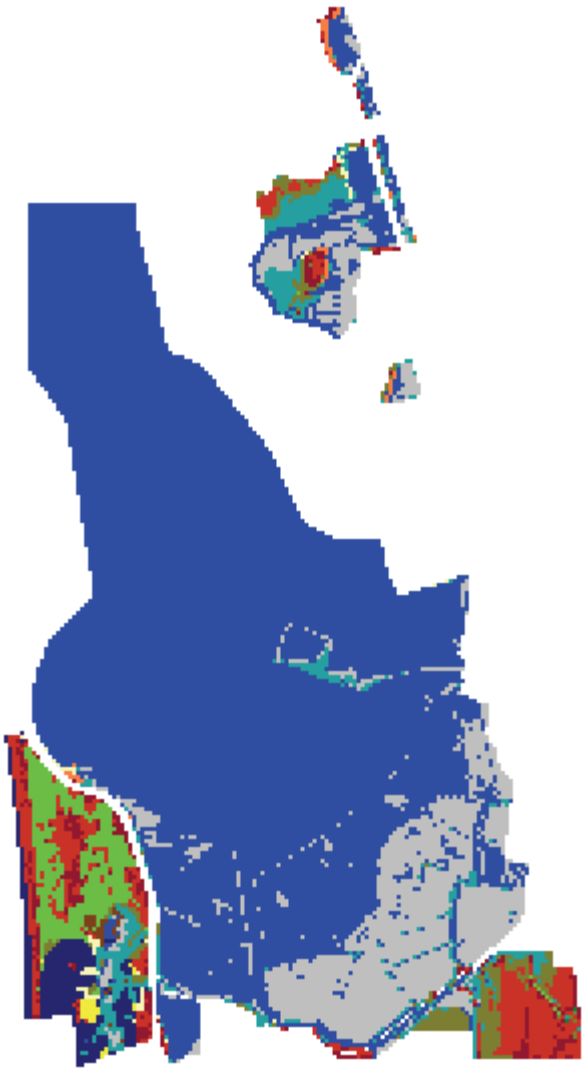
San Diego Bay NWR, 2025, 2 meter



San Diego Bay NWR, 2050, 2 meter



San Diego Bay NWR, 2075, 2 meter



San Diego Bay NWR, 2100, 2 meter

Discussion

Model results suggest that San Diego Bay NWR will have a variable response to sea level rise, depending on the extent of the rise by 2100. Irregularly flooded marshes are predicted to partially convert to regularly flooded (salt marshes) under most scenarios. However, the conversion largely proceeds to tidal flats and open water by 2100, under a scenario of 1.5 meters of eustatic SLR by 2100 or worse. Loss of inland fresh marsh remains relatively low (10% in the worst-case scenario) because the majority of this marsh lies well above the salt boundary in the southwest portion of the refuge.

High quality LiDAR data were available for the entire site, reducing model uncertainty. However, marsh accretion rates are a source of model uncertainty as there were no directly measured accretion rates within the NWR; accretion rates were based on measurements from San Elijo Lagoon.

This report displays results with "protect developed" turned off. In other words, wetlands were allowed to expand over developed lands. This allows maps to indicate which developed lands are predicted to be subject to inundation but means that tables of results may slightly overestimate the resilience of wetlands.

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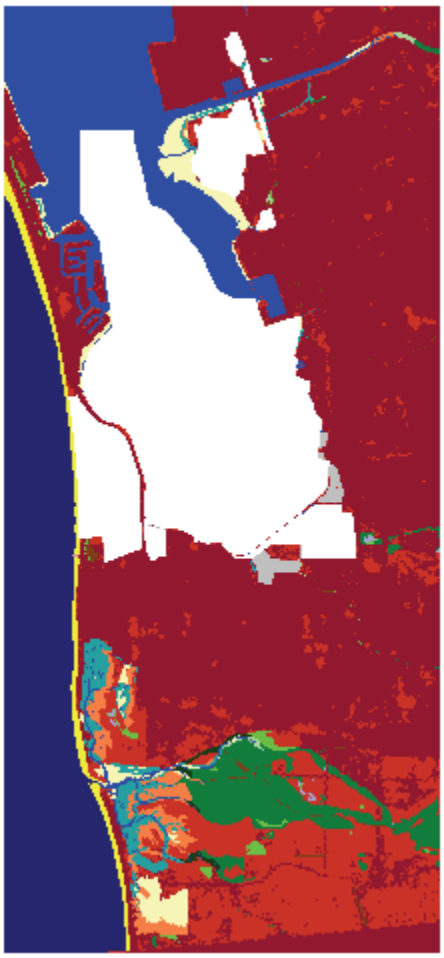
Appendix A: Contextual Results

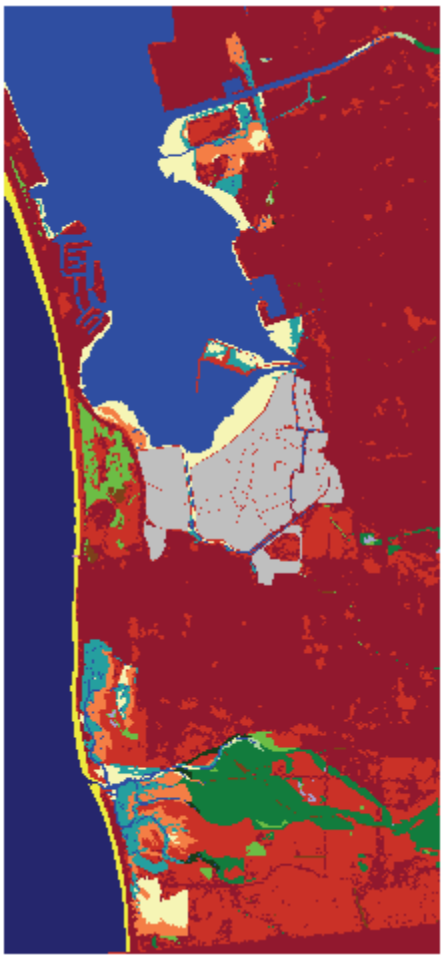
The SLAMM model does take into account the context of the surrounding lands or open water when calculating effects. For example, erosion rates are calculated based on the maximum fetch (wave action) which is estimated by assessing contiguous open water to a given marsh cell. Another example is that inundated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

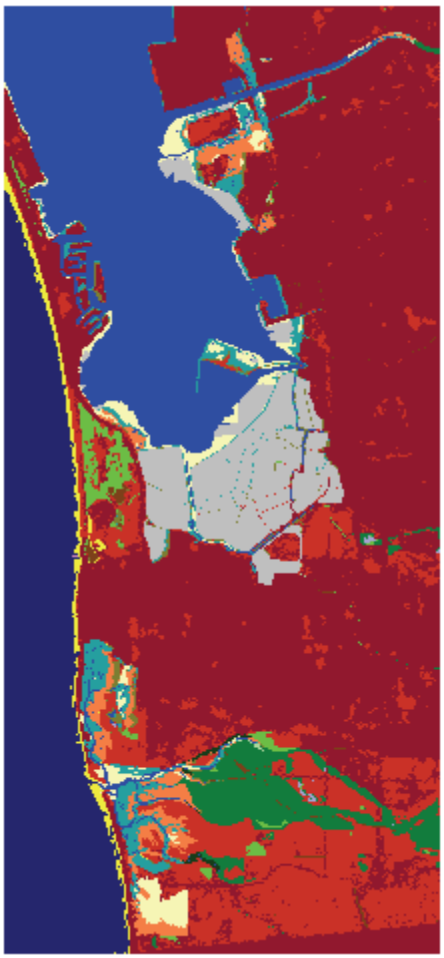
- Results were closely examined (quality assurance) within USFWS refuges but not closely examined for the larger region.
- Site-specific parameters for the model were derived for USFWS refuges whenever possible and may not be regionally applicable.
- Especially in areas where dikes are present, an effort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



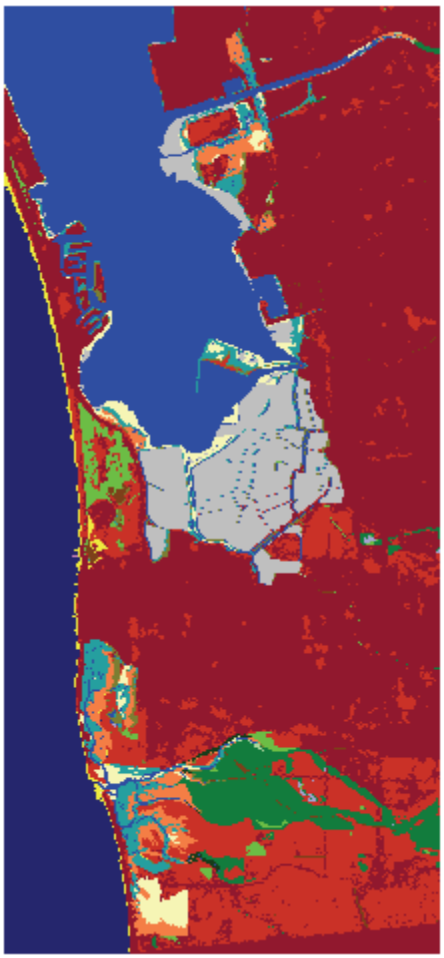
Location of San Diego Bay National Wildlife Refuge (white area in rectangle) within simulation context



San Diego Bay NWR, Initial Condition



San Diego Bay NWR, 2025, Scenario A1B Mean



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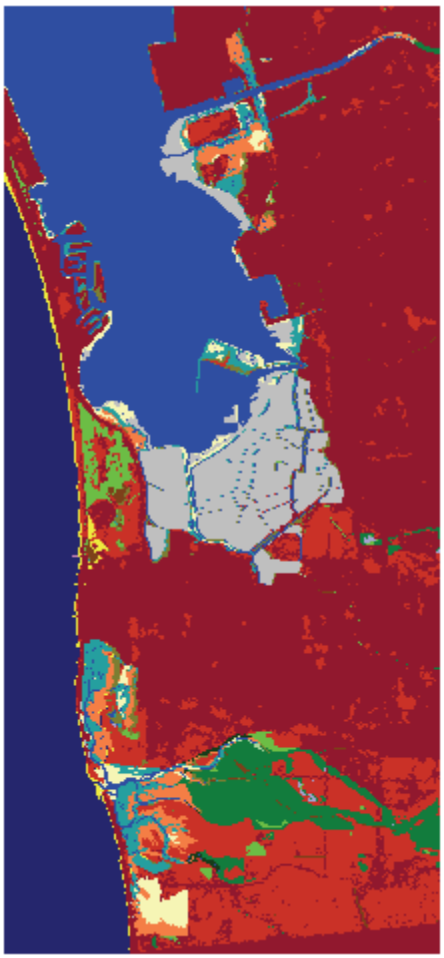
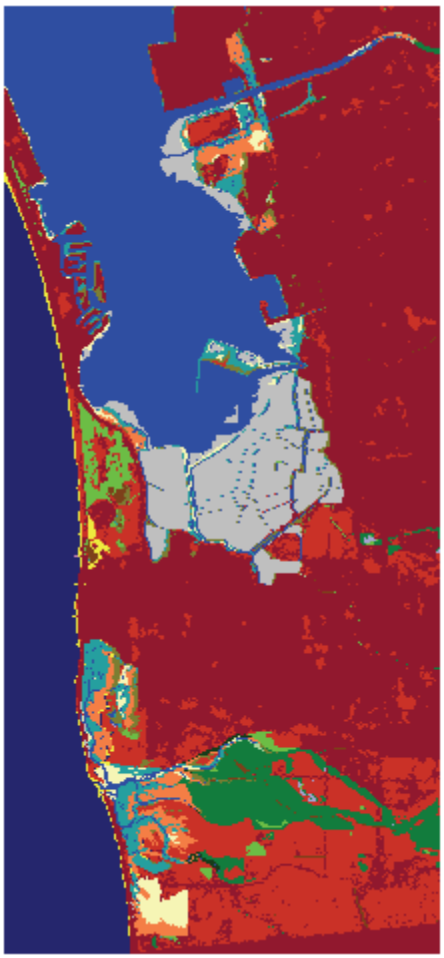
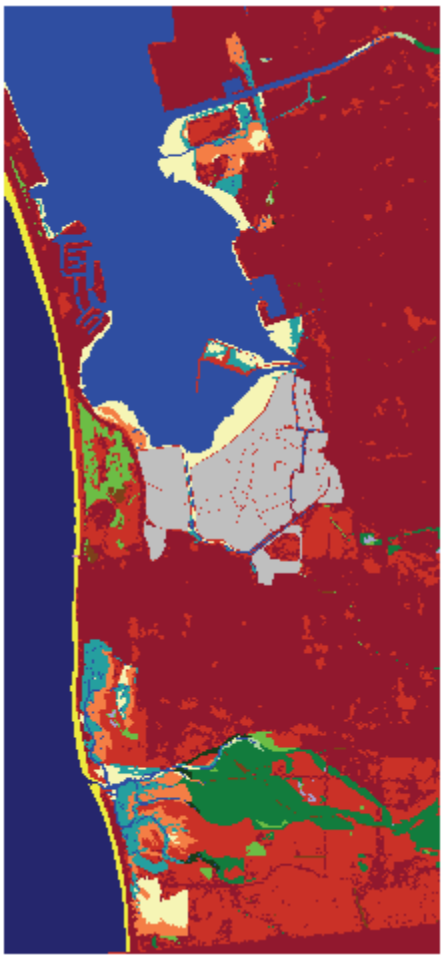


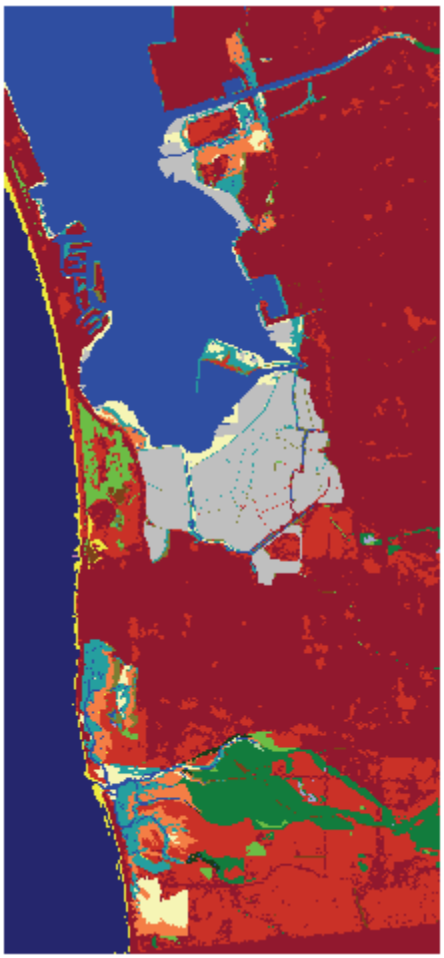
San Diego Bay NWR, 2075, Scenario A1B Mean



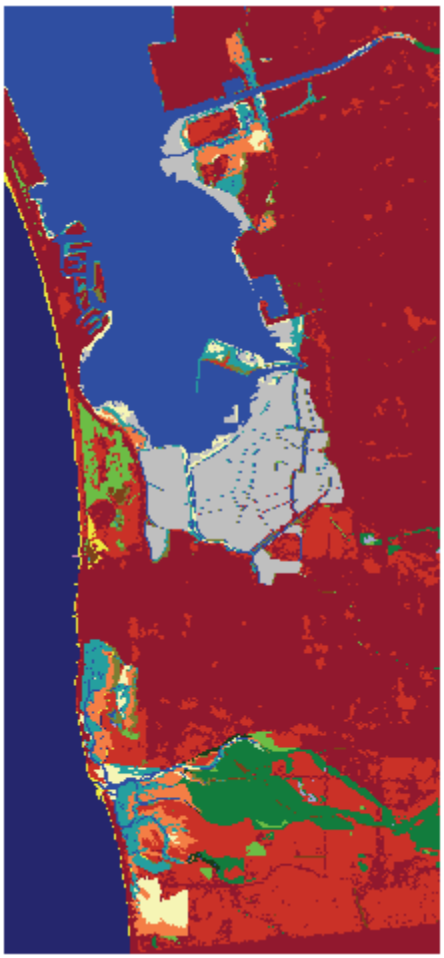
San Diego Bay NWR, 2100, Scenario A1B Mean



San Diego Bay NWR, Initial Condition



San Diego Bay NWR, 2025, Scenario A1B Maximum



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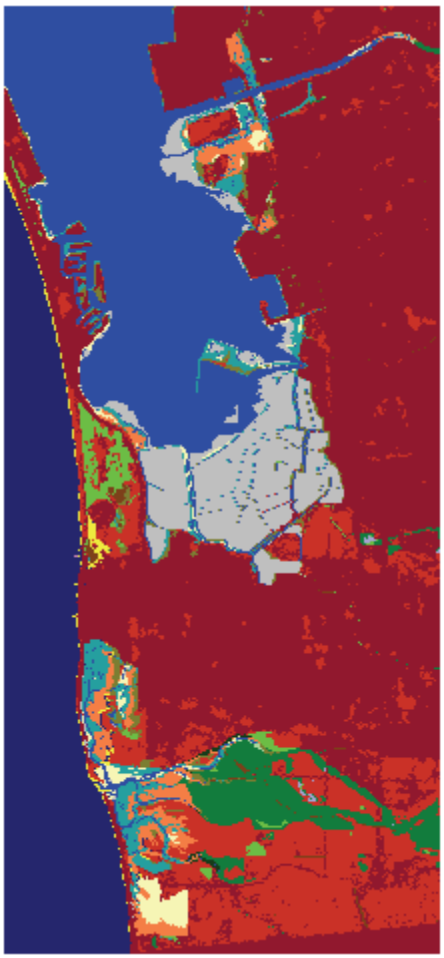
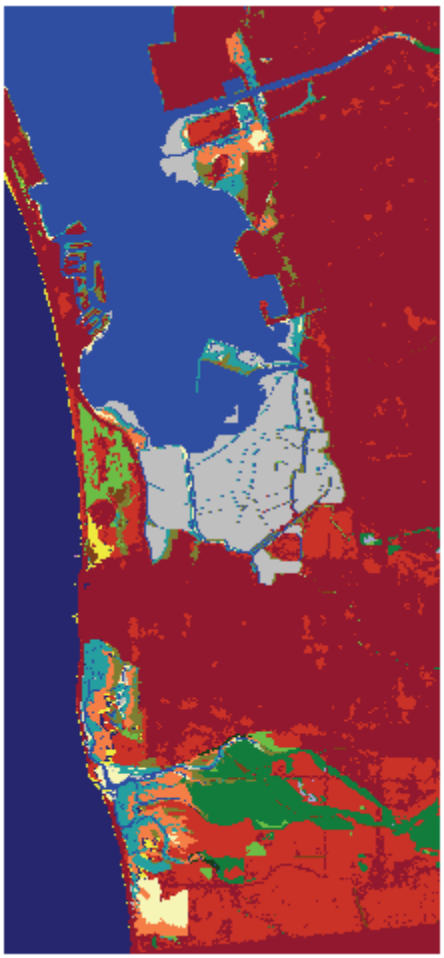
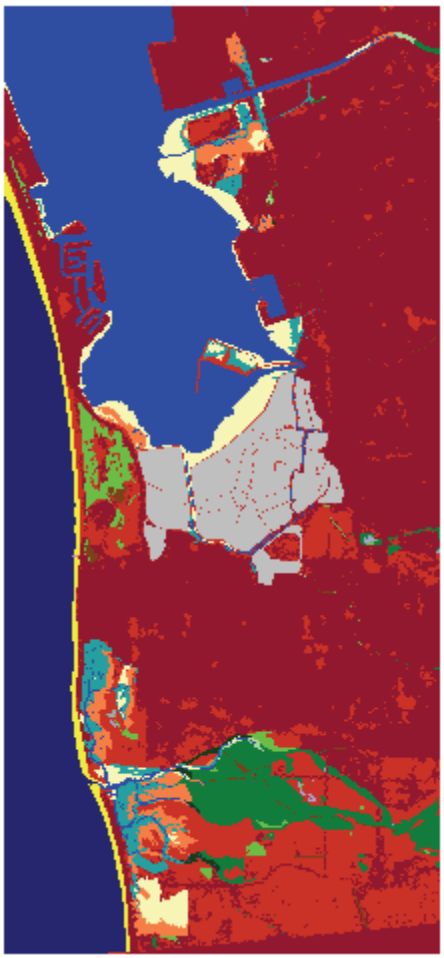


San Diego Bay NWR, 2075, Scenario A1B Maximum



San Diego Bay NWR, 2100, Scenario A1B Maximum



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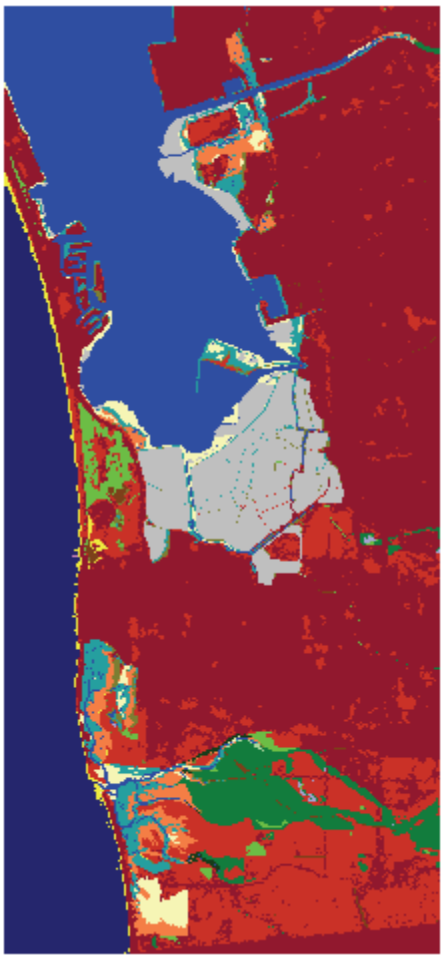
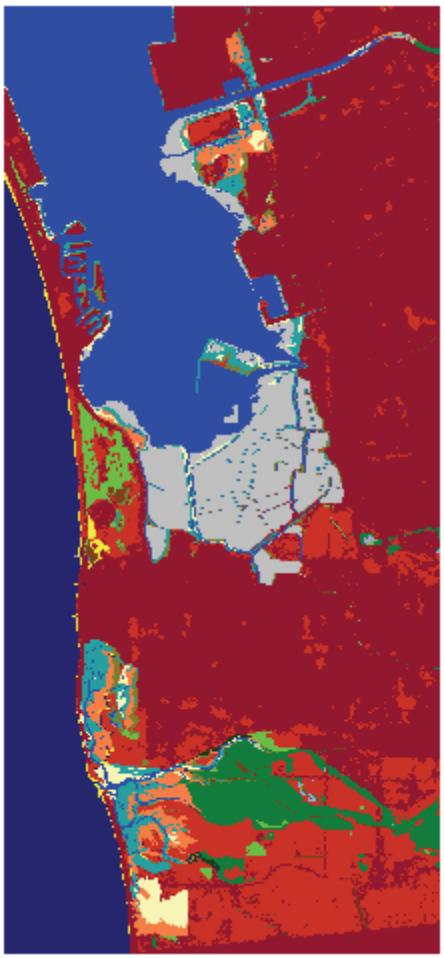


San Diego Bay NWR, 2025, 1 meter



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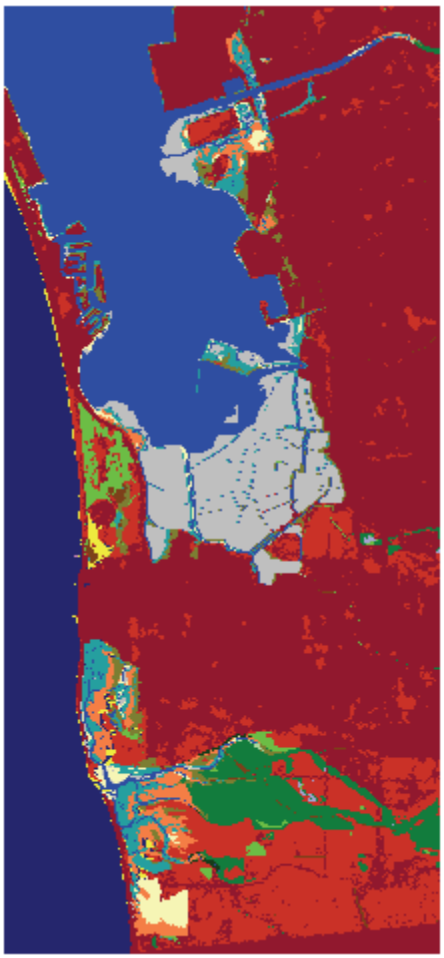
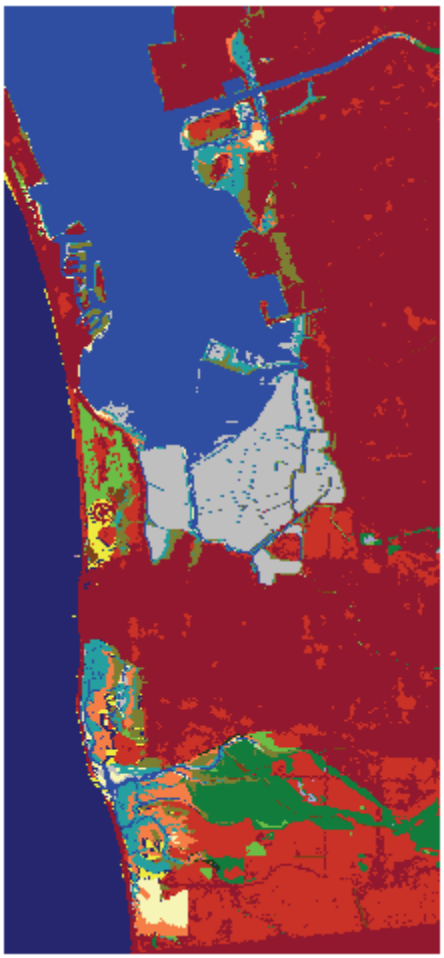
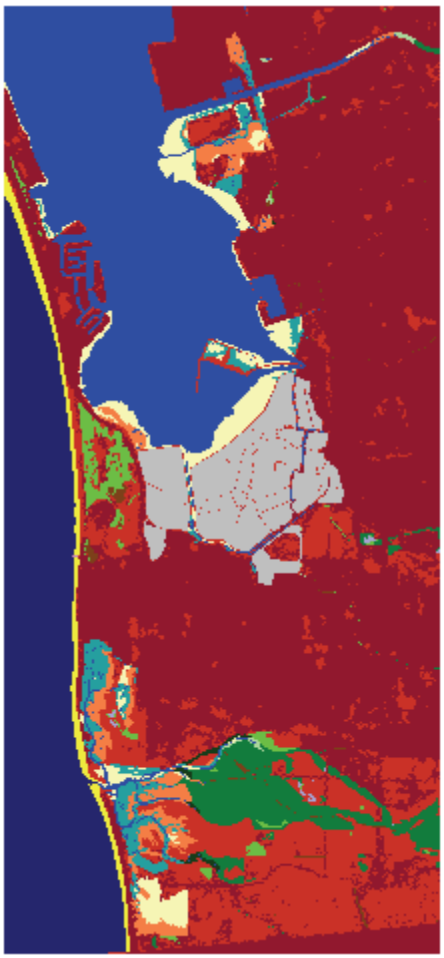


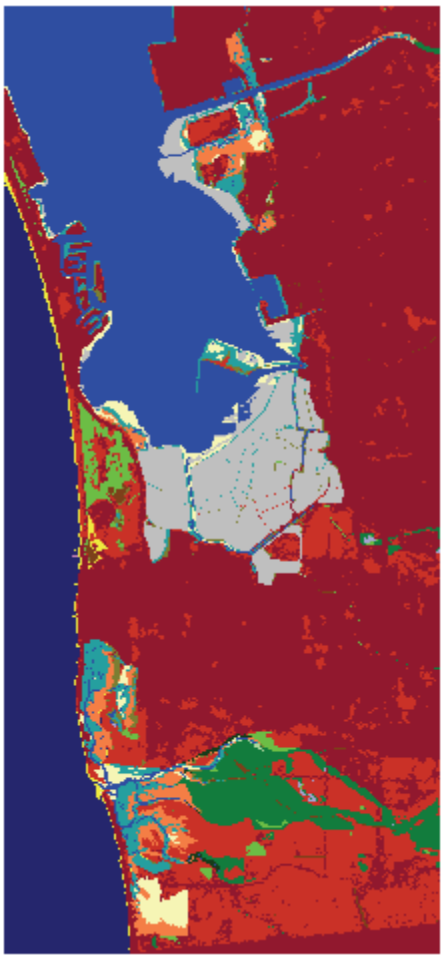
San Diego Bay NWR, 2075, 1 meter



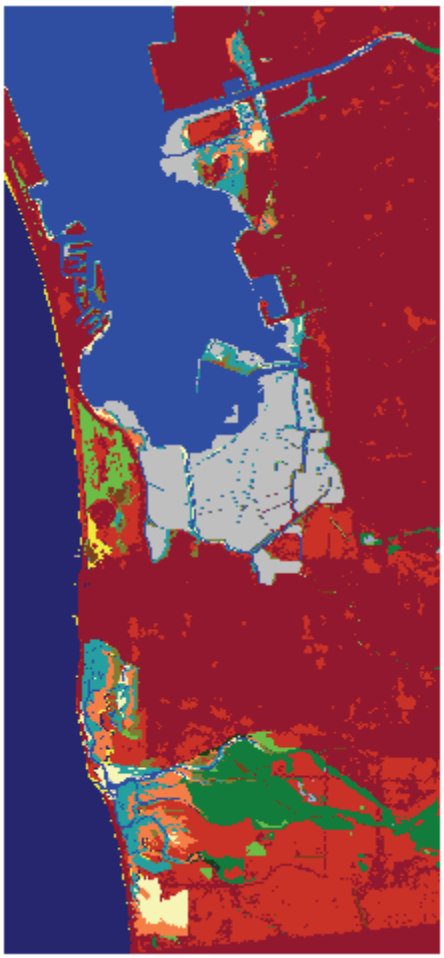
San Diego Bay NWR, 2100, 1 meter



San Diego Bay NWR, Initial Condition



San Diego Bay NWR, 2025, 1.5 meter



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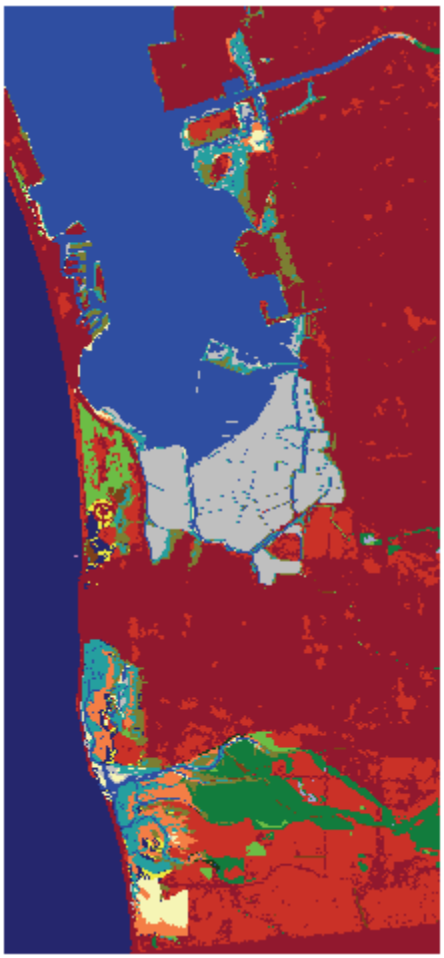
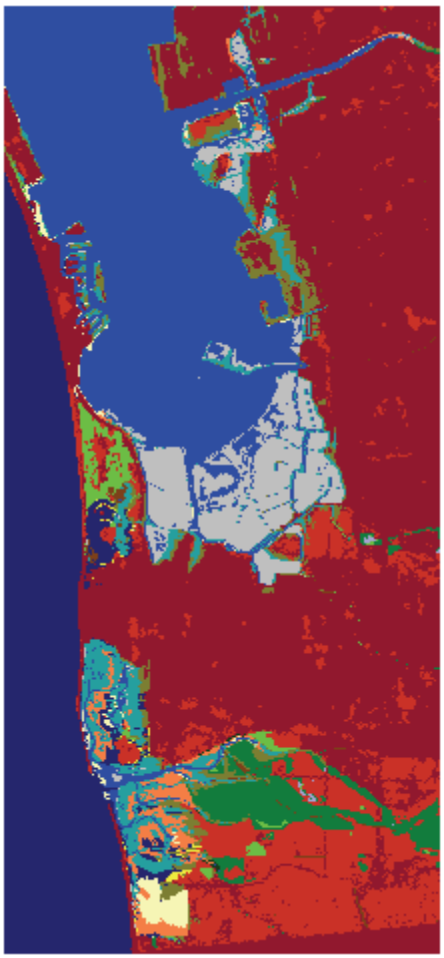
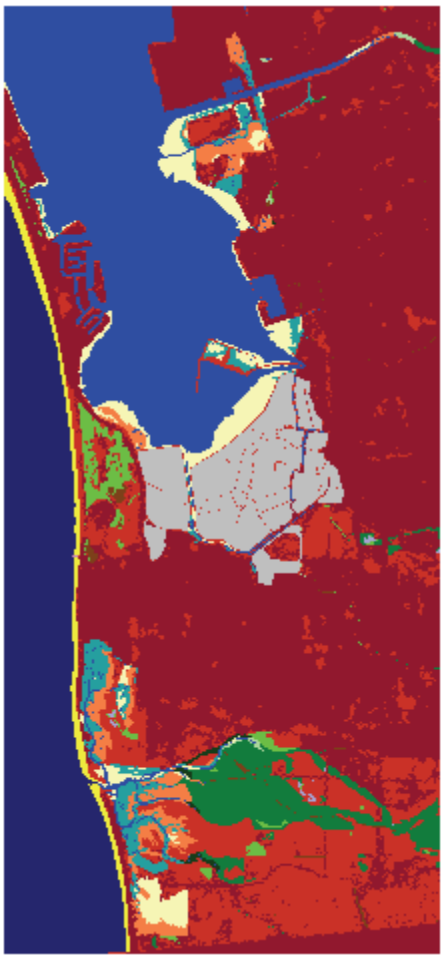


San Diego Bay NWR, 2075, 1.5 meter



San Diego Bay NWR, 2100, 1.5 meter



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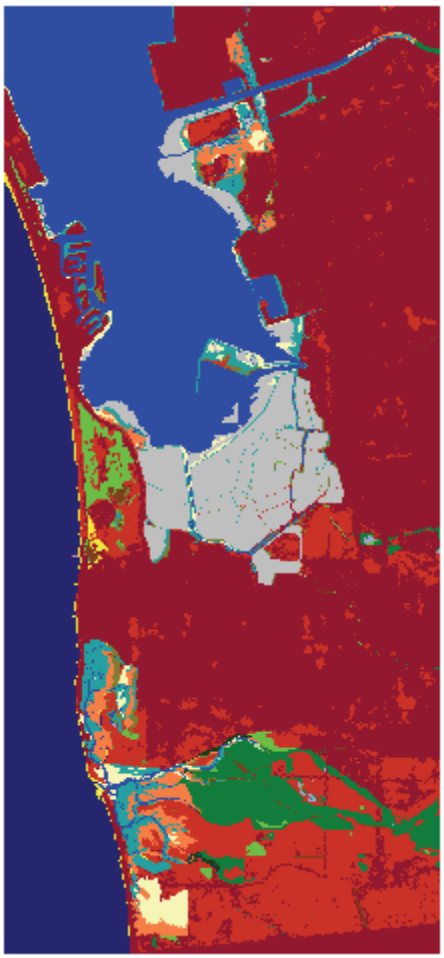
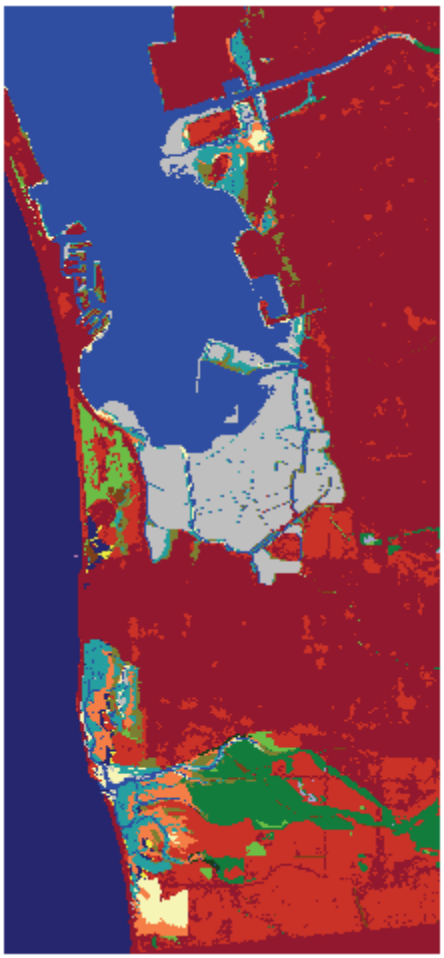


San Diego Bay NWR, 2025, 2 meter



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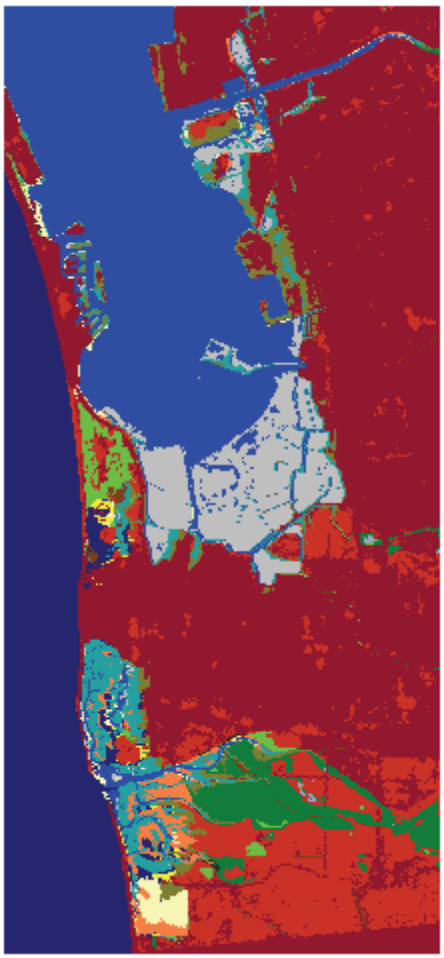

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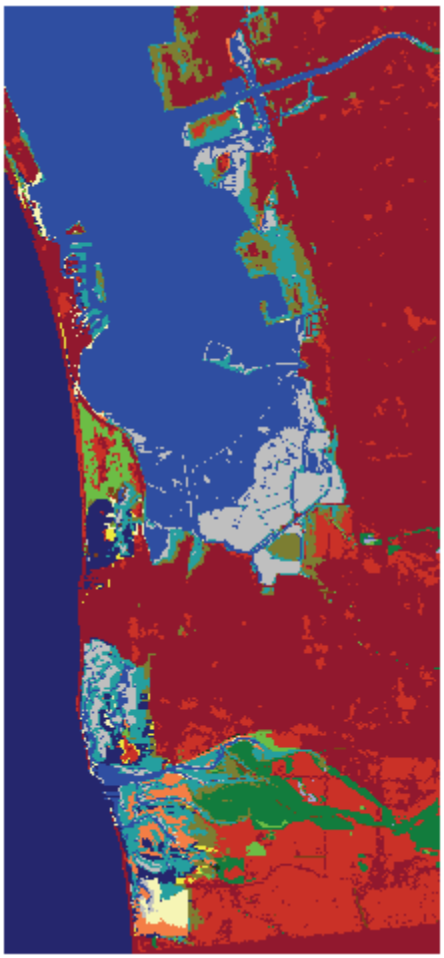

San Diego Bay NWR, 2100, 2 meter