Application of the Sea-Level Affecting Marshes Model (SLAMM 5.1) to Tijuana Slough 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

October 15, 2009

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

Application of the Sea-Level Affecting Marshes Model (SLAMM 5.1) to Tijuana Slough NWR

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

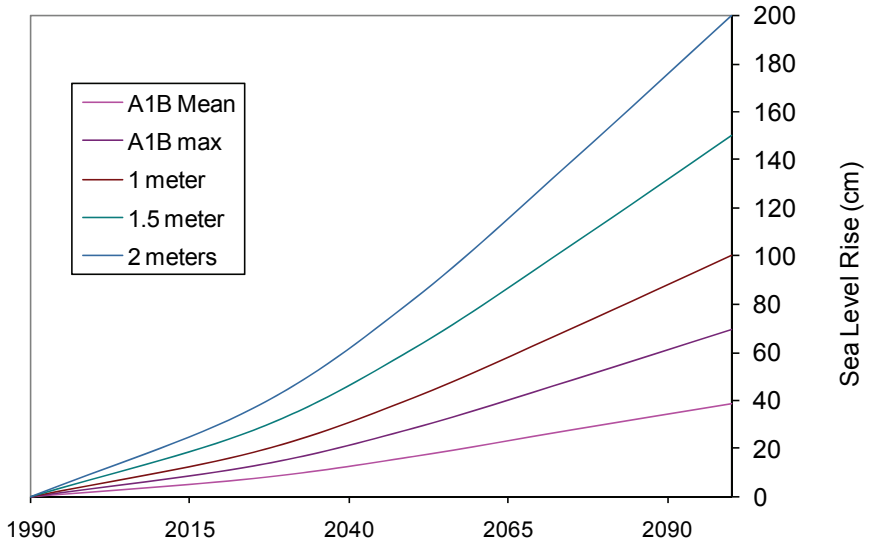
SLAMM 5 was run using scenario A1B from the Special Report on Emissions Scenarios (SRES) – mean and maximum estimates. The A1 scenario assumes that the future world includes very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of 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 Tijuana Slough NWR were based on LiDAR from the 1/9 ARC Second National Elevation Dataset (NED, 2007) and from a NOAA coastal LiDAR survey (2006). Figure 1 illustrates the spatial domain for these two data sets.

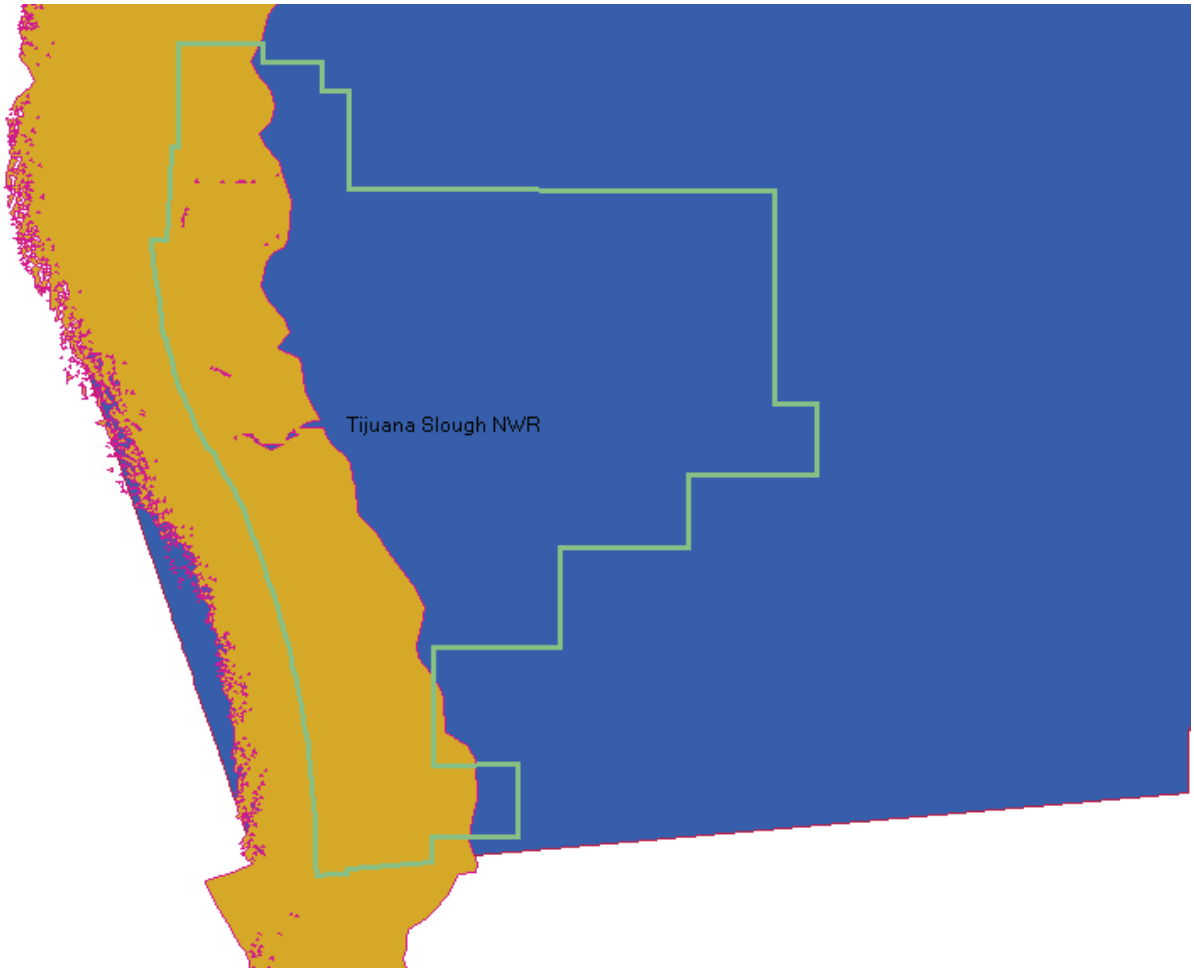


Figure 1: NOAA LiDAR (orange) over NED LiDAR (blue) for SD coast.

The National Wetlands Inventory for Tijuana Slough is based on a photo date of 2002. Converting this NWI survey into 30 meter cells indicates that the approximately two thousand acre refuge (approved acquisition boundary including water) is composed of the categories as shown below:

Developed Dry Land	21.6%
Undeveloped Dry Land	20.7%
Swamp	15.0%
Irreg. Flooded Marsh	13.0%
Reg. Flooded Marsh	12.3%
Estuarine Beach	6.3%
Ocean Beach	3.1%
Estuarine Open Water	2.4%
Tidal Creek	1.7%
Tidal Swamp	1.4%
Inland Fresh Marsh	1.2%

A small swamp region in the south of Tijuana Slough NWR is diked, according to the National Wetlands Inventory (Figure 2.)

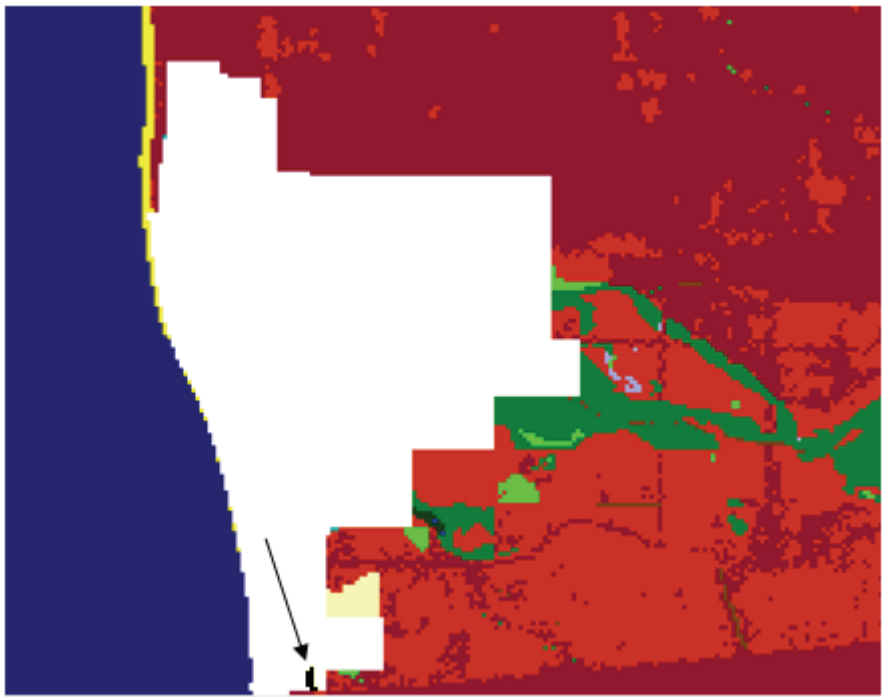


Figure 2: Diked Area (black) within NWR Boundary (white).

The historic trend for sea level rise was estimated at 2 mm/year using the closest coastal tide station (9410230, La Jolla, CA). This measured rate is roughly similar to than the global average for the last 100 years (approximately 1.5-2.0 mm/year) and to the historic eustatic sea level rise assumed within this modeling (1.7 mm/year).

The tidal range for the Tijuana Slough NWR is estimated at 1.63 meters (Figure 3). This value was determined using the nearest NOAA tide gage (9410120, Imperial Beach, Pacific Ocean, CA).

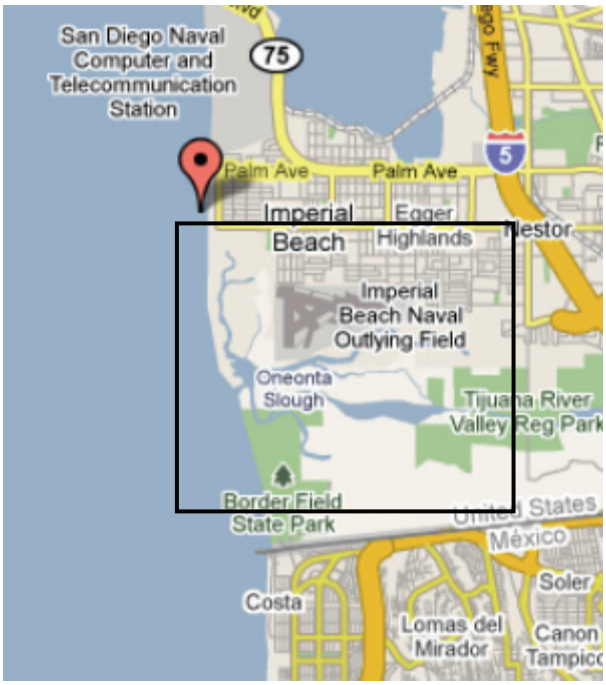


Figure 3: NOAA Gage Relevant to the Study Area (in rectangle).

Accretion rates in salt and irregularly flooded marshes were set to 9.5 mm/year and 5.9 mm/yr in tidal fresh marshes. These rates are based on a studies of accretion rates within Tijuana Slough (Weis et al. 2001, Ward et al. 2003).

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.

Developed vs. undeveloped lands were estimated based on the National Land Cover Database (2001).

SUMMARY OF SLAMM INPUT PARAMETERS FOR TIJUANA SLOUGH

Description	,	San Diego Global	Tijuana Slough
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	1.63
TideRangeInland (meters)	,	1.63	1.63
Mean High Water Spring (m above MTL)	,	1.22	1.22
MHSW Inland (m above MTL)	,	1.22	1.22
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	9.5
Brackish March vert. accretion (mm/yr) Final	,	6.1	9.5
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

Portions of Tijuana Slough NWR are predicted to be susceptible to most sea level rise scenarios. Loss of dry land – which constitutes roughly one-fifth of this NWR – is predicted to range from 18% to 73% across all scenarios. Due to relatively high measured accretion rates, irregularly flooded marsh loss (brackish marsh) is predicted only above 1 meter scenarios. Loss of swamp ranges from 6% to 41% across all scenarios.

SLR by 2100 (m)	0.39	0.69	1	1.5	2
Developed Dry Land	5%	8%	11%	17%	25%
Undeveloped Dry Land	18%	32%	45%	63%	73%
Swamp	6%	10%	16%	28%	41%
Irreg. Flooded Marsh	-5%	-6%	-7%	6%	34%
Estuarine Beach	2%	12%	21%	30%	50%
Ocean Beach	60%	46%	30%	69%	79%
Tidal Swamp	43%	59%	69%	82%	90%
Inland Fresh Marsh	13%	14%	20%	27%	39%
Tidal Fresh Marsh	44%	47%	55%	76%	89%

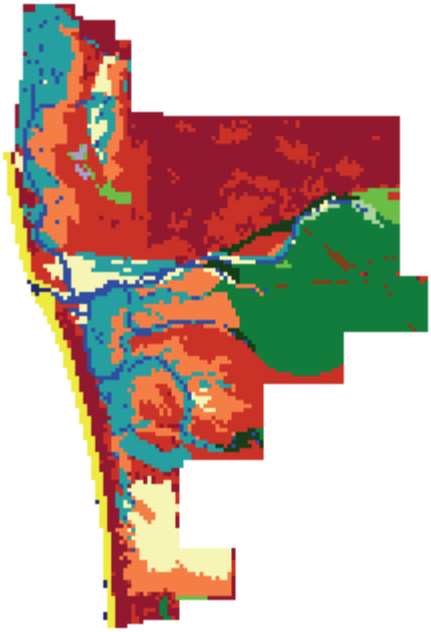
Predicted Loss Rates of Land Categories by 2100 Given Simulated Scenarios of Eustatic Sea Level Rise

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

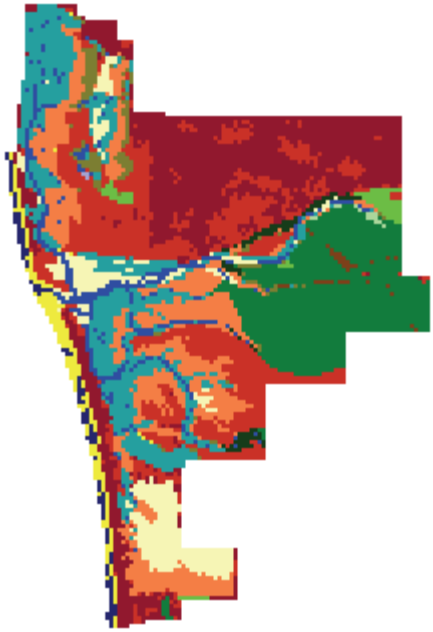
Tijuana Slough NWR
IPCC Scenario A1B-Mean, 0.39 M SLR Eustatic by 2100

Results in Acres

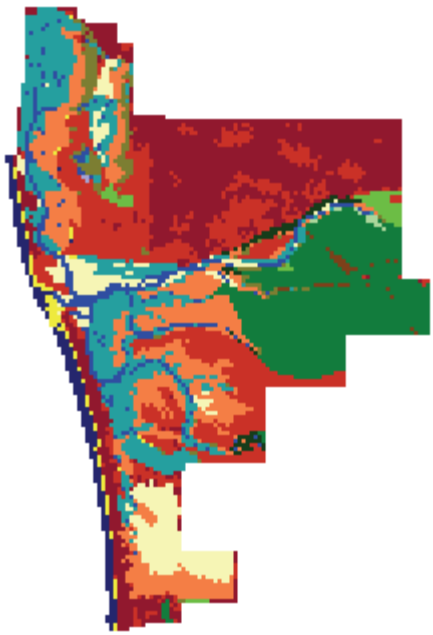
	Initial	2025	2050	2075	2100
Developed Dry Land	418.1	404.7	402.3	399.2	395.7
Undeveloped Dry Land	400.1	365.7	358.3	347.0	329.8
Swamp	290.7	282.9	281.2	277.8	274.1
Brackish Marsh	251.7	260.5	261.9	263.1	263.8
Saltmarsh	238.0	245.5	245.4	243.0	241.5
Estuarine Beach	121.4	123.2	123.1	121.6	119.5
Ocean Beach	60.3	48.3	26.4	22.7	24.1
Estuarine Open Water	46.0	49.1	50.1	52.2	56.2
Tidal Creek	32.5	32.5	32.5	32.5	32.5
Tidal Swamp	27.4	19.8	18.4	16.8	15.5
Inland Fresh Marsh	23.4	20.8	20.5	20.4	20.4
Inland Shore	8.2	8.2	8.2	8.2	8.2
Tidal Fresh Marsh	6.4	3.6	3.6	3.6	3.6
Inland Open Water	3.3	0.7	0.7	0.7	0.4
Open Ocean	3.1	26.7	51.5	61.0	68.1
Riverine Tidal	0.9	0.9	0.7	0.4	0.4
Trans. Salt Marsh	0.0	38.4	46.7	58.0	72.9
Tidal Flat	0.0	0.1	0.1	3.2	4.7
Total (incl. water)	**1931.5**	**1931.5**	**1931.5**	**1931.5**	**1931.5**



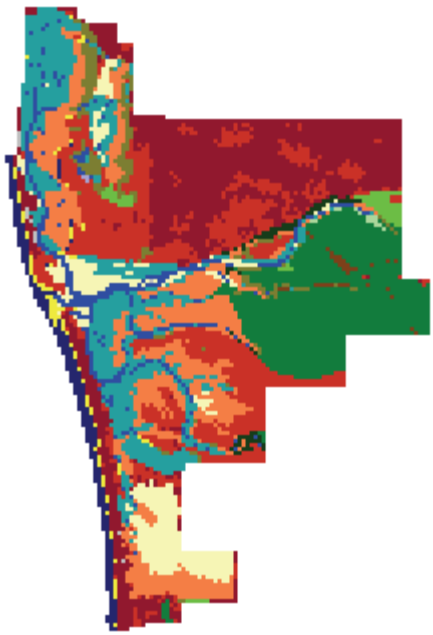
Tijuana Slough NWR, Initial Condition



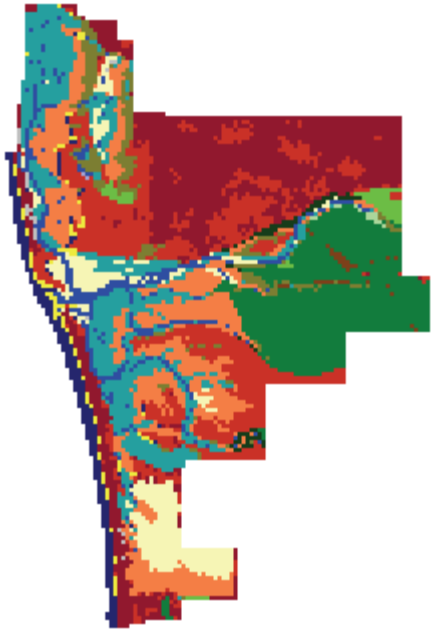
Tijuana Slough NWR, 2025, Scenario A1B Mean



Tijuana Slough NWR, 2050, Scenario A1B Mean



Tijuana Slough NWR, 2075, Scenario A1B Mean

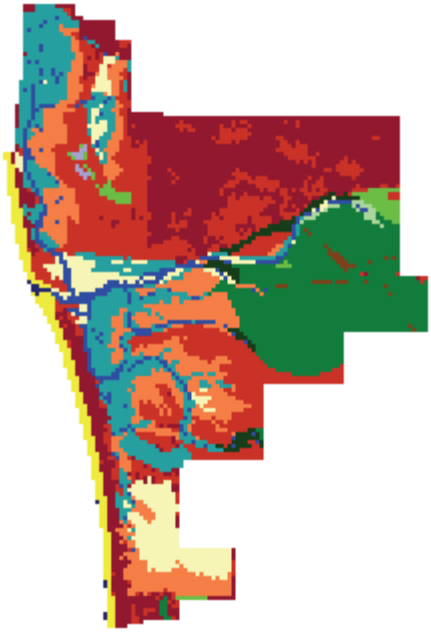


Tijuana Slough NWR, 2100, Scenario A1B Mean

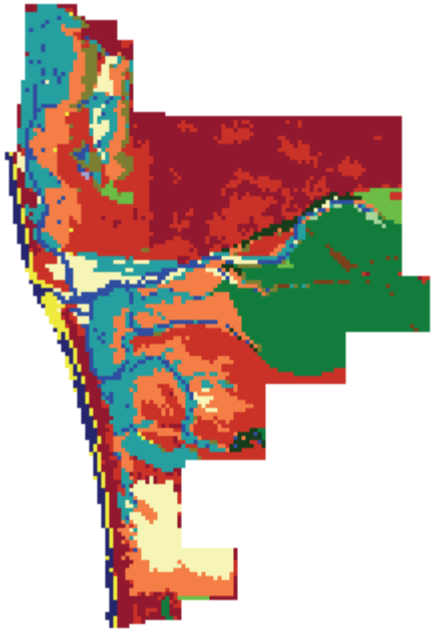
Tijuana Slough NWR
IPCC Scenario A1B-Max, 0.69 M SLR Eustatic by 2100

Results in Acres

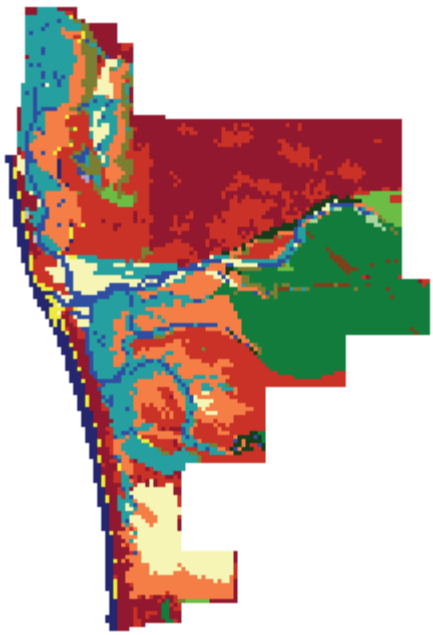
	Initial	2025	2050	2075	2100
Developed Dry Land	418.1	404.1	399.7	393.5	385.6
Undeveloped Dry Land	400.1	363.3	349.3	316.2	270.1
Swamp	290.7	282.3	278.3	271.2	262.4
Brackish Marsh	251.7	261.0	263.5	265.2	268.0
Saltmarsh	238.0	247.0	245.7	242.9	242.1
Estuarine Beach	121.4	123.3	122.1	117.1	107.1
Ocean Beach	60.3	38.3	21.9	22.3	32.8
Estuarine Open Water	46.0	49.3	51.9	56.4	63.5
Tidal Creek	32.5	32.5	32.5	32.5	32.5
Tidal Swamp	27.4	19.2	16.7	14.1	11.2
Inland Fresh Marsh	23.4	20.7	20.5	20.3	20.1
Inland Shore	8.2	8.2	8.2	8.2	8.2
Tidal Fresh Marsh	6.4	3.6	3.6	3.5	3.4
Inland Open Water	3.3	0.7	0.7	0.4	0.2
Open Ocean	3.1	37.3	60.4	75.5	90.9
Riverine Tidal	0.9	0.9	0.4	0.4	0.4
Trans. Salt Marsh	0.0	39.7	54.7	83.8	117.2
Tidal Flat	0.0	0.1	1.4	7.8	15.7
Total (incl. water)	**1931.5**	**1931.5**	**1931.5**	**1931.5**	**1931.5**



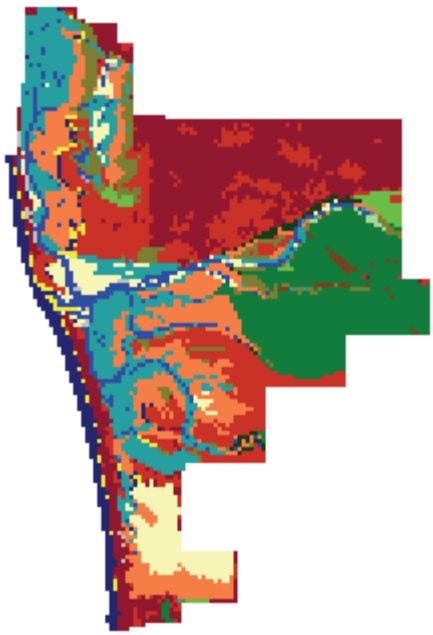
Tijuana Slough NWR, Initial Condition



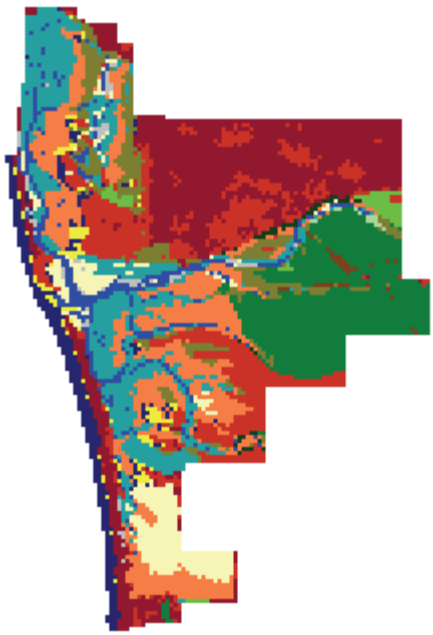
Tijuana Slough NWR, 2025, Scenario A1B Maximum



Tijuana Slough NWR, 2050, Scenario A1B Maximum



Tijuana Slough NWR, 2075, Scenario A1B Maximum

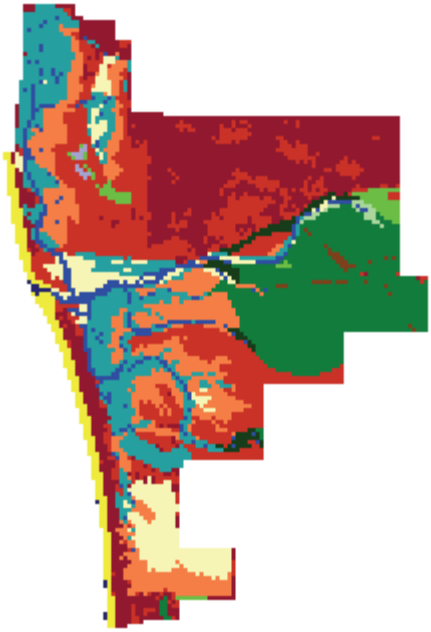


Tijuana Slough NWR, 2100, Scenario A1B Maximum

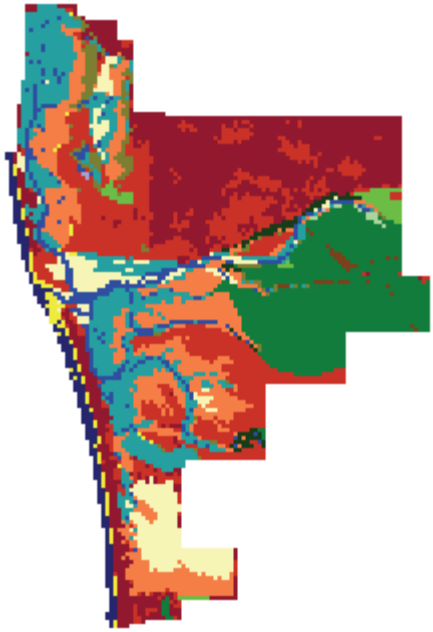
Tijuana Slough NWR
1 Meter Eustatic SLR by 2100

Results in Acres

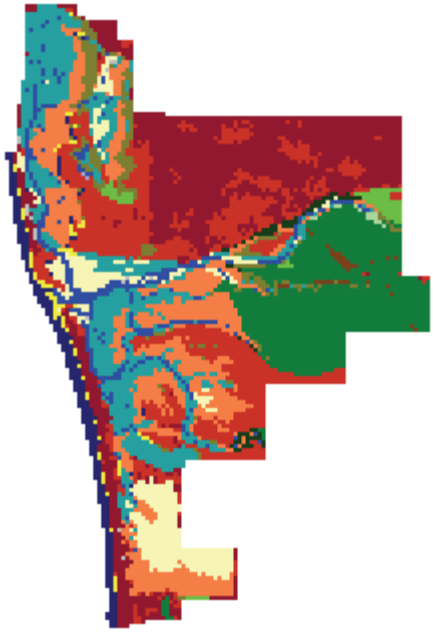
	Initial	2025	2050	2075	2100
Developed Dry Land	418.1	403.3	396.8	386.6	372.3
Undeveloped Dry Land	400.1	360.6	335.7	274.7	219.3
Swamp	290.7	281.6	274.7	263.1	244.9
Brackish Marsh	251.7	261.7	264.5	268.3	270.4
Saltmarsh	238.0	248.7	246.0	246.8	248.9
Estuarine Beach	121.4	123.2	119.8	106.8	95.9
Ocean Beach	60.3	29.0	20.2	27.8	42.4
Estuarine Open Water	46.0	49.7	54.0	62.0	73.7
Tidal Creek	32.5	32.5	32.5	32.5	32.5
Tidal Swamp	27.4	18.4	15.3	11.2	8.4
Inland Fresh Marsh	23.4	20.7	20.4	19.7	18.7
Inland Shore	8.2	8.2	8.2	8.2	8.2
Tidal Fresh Marsh	6.4	3.6	3.4	3.2	2.9
Inland Open Water	3.3	0.7	0.4	0.2	0.0
Open Ocean	3.1	47.5	68.6	91.0	114.2
Riverine Tidal	0.9	0.7	0.4	0.4	0.2
Trans. Salt Marsh	0.0	41.3	65.8	112.1	154.6
Tidal Flat	0.0	0.2	4.7	16.9	24.0
Total (incl. water)	**1931.5**	**1931.5**	**1931.5**	**1931.5**	**1931.5**



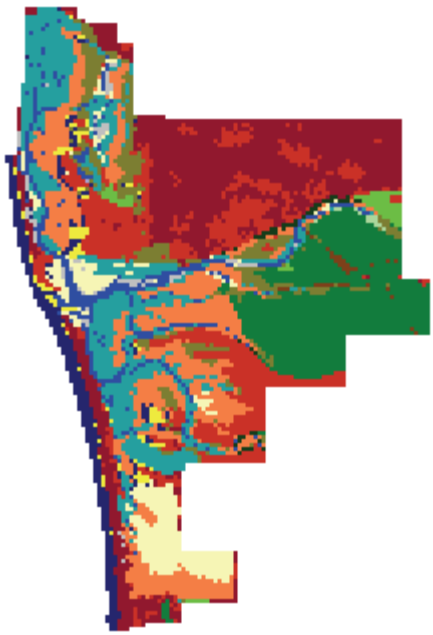
Tijuana Slough NWR, Initial Condition



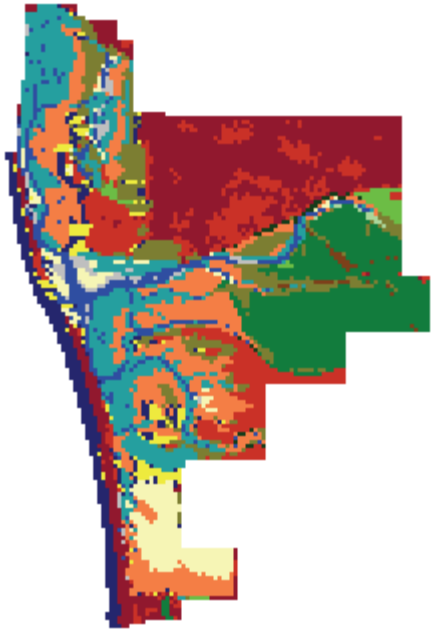
Tijuana Slough NWR, 2025, 1 meter



Tijuana Slough NWR, 2050, 1 meter



Tijuana Slough NWR, 2075, 1 meter

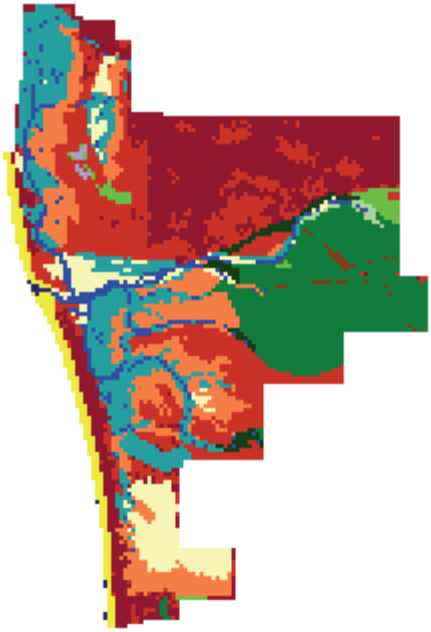


Tijuana Slough NWR, 2100, 1 meter

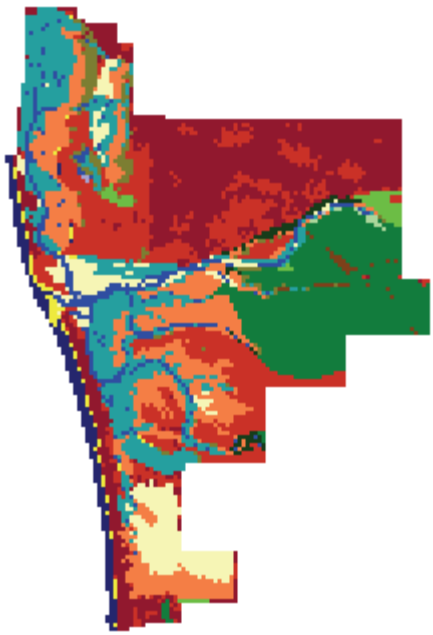
Tijuana Slough NWR
1.5 Meters Eustatic SLR by 2100

Results in Acres

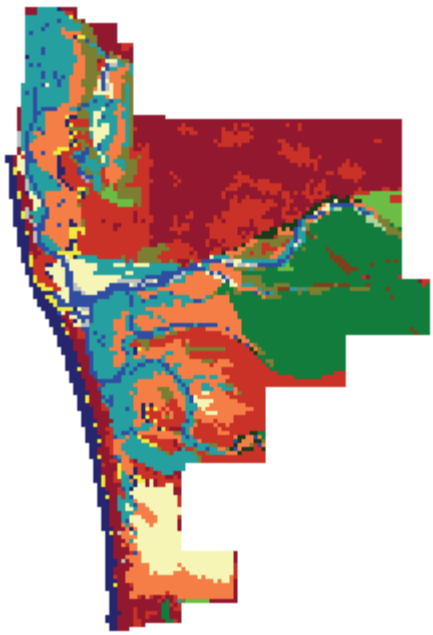
	Initial	2025	2050	2075	2100
Developed Dry Land	418.1	401.6	391.2	372.1	346.5
Undeveloped Dry Land	400.1	355.7	302.1	218.3	148.6
Swamp	290.7	280.3	267.7	244.0	209.2
Brackish Marsh	251.7	262.7	266.6	263.3	236.4
Saltmarsh	238.0	251.7	253.6	290.2	394.2
Estuarine Beach	121.4	122.9	113.2	95.7	85.0
Ocean Beach	60.3	21.8	18.9	18.1	18.8
Estuarine Open Water	46.0	50.1	57.1	76.3	107.3
Tidal Creek	32.5	32.5	32.5	32.5	32.5
Tidal Swamp	27.4	17.3	12.5	8.1	4.9
Inland Fresh Marsh	23.4	20.6	19.6	18.2	17.0
Inland Shore	8.2	8.2	8.2	8.2	8.0
Tidal Fresh Marsh	6.4	3.5	3.1	2.4	1.5
Inland Open Water	3.3	0.7	0.4	0.0	0.0
Open Ocean	3.1	56.2	83.4	132.7	183.4
Riverine Tidal	0.9	0.7	0.4	0.2	0.0
Trans. Salt Marsh	0.0	44.3	88.3	127.1	122.5
Tidal Flat	0.0	0.6	12.7	24.2	15.8
Total (incl. water)	**1931.5**	**1931.5**	**1931.5**	**1931.5**	**1931.5**



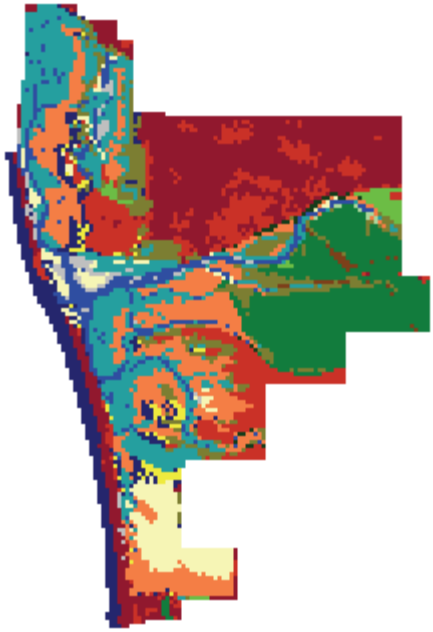
Tijuana Slough NWR, Initial Condition



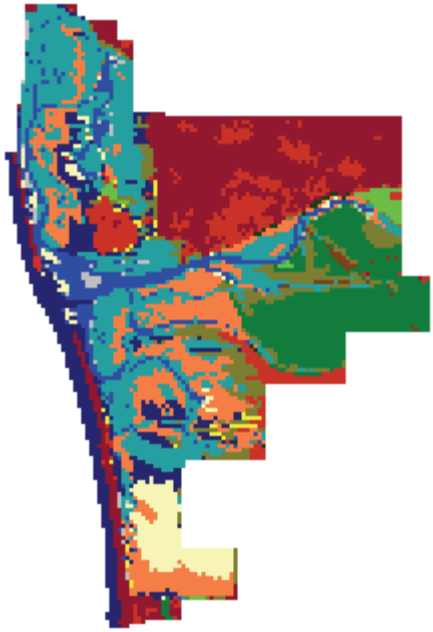
Tijuana Slough NWR, 2025, 1.5 meter



Tijuana Slough NWR, 2050, 1.5 meter



Tijuana Slough NWR, 2075, 1.5 meter

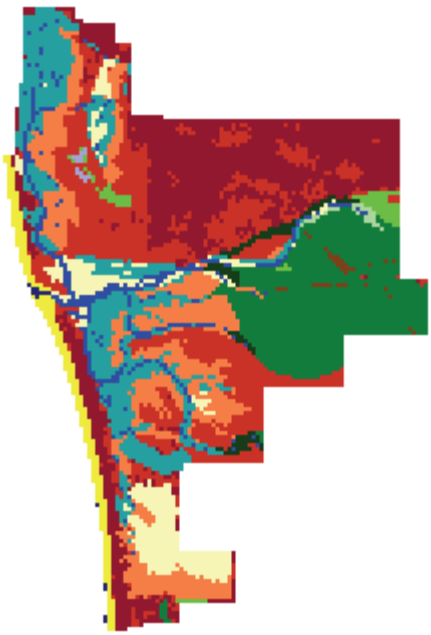


Tijuana Slough NWR, 2100, 1.5 meter

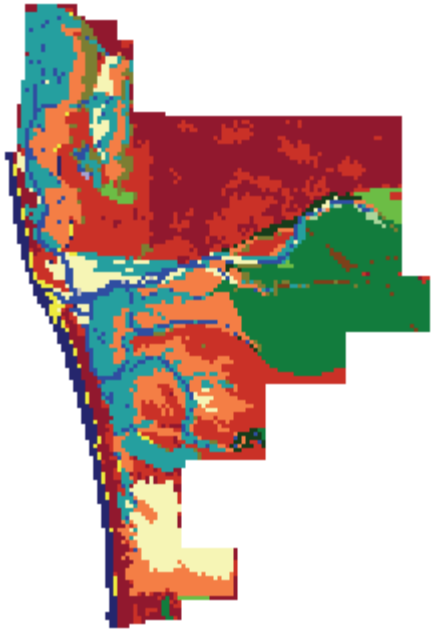
Tijuana Slough NWR
2 Meters Eustatic SLR by 2100

Results in Acres

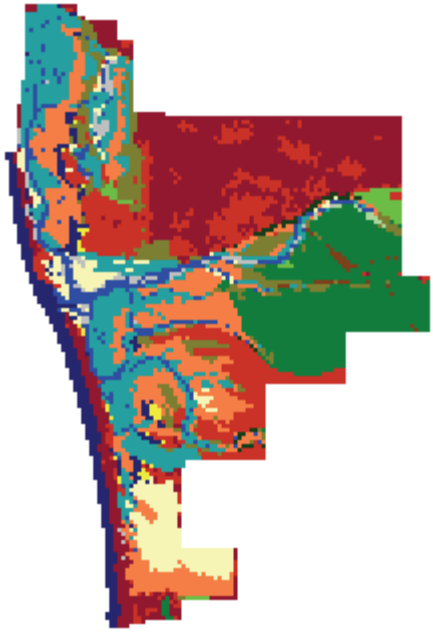
	Initial	2025	2050	2075	2100
Developed Dry Land	418.1	399.9	384.7	356.3	313.8
Undeveloped Dry Land	400.1	350.0	265.5	166.8	109.6
Swamp	290.7	278.2	260.5	219.7	170.8
Brackish Marsh	251.7	263.4	263.0	209.8	166.2
Saltmarsh	238.0	255.0	271.6	403.9	398.4
Estuarine Beach	121.4	122.4	104.8	87.9	60.2
Ocean Beach	60.3	18.5	16.3	18.9	12.4
Estuarine Open Water	46.0	50.9	61.7	107.0	158.8
Tidal Creek	32.5	32.5	32.5	32.5	32.5
Tidal Swamp	27.4	16.4	10.4	5.7	2.6
Inland Fresh Marsh	23.4	20.5	18.8	17.2	14.1
Inland Shore	8.2	8.2	8.2	8.2	7.5
Tidal Fresh Marsh	6.4	3.4	2.8	1.5	0.7
Inland Open Water	3.3	0.7	0.2	0.0	0.0
Open Ocean	3.1	61.4	98.3	162.4	228.8
Riverine Tidal	0.9	0.4	0.2	0.0	0.0
Trans. Salt Marsh	0.0	48.6	109.0	113.9	98.1
Tidal Flat	0.0	1.1	22.8	19.9	157.1
Total (incl. water)	**1931.5**	**1931.5**	**1931.5**	**1931.5**	**1931.5**



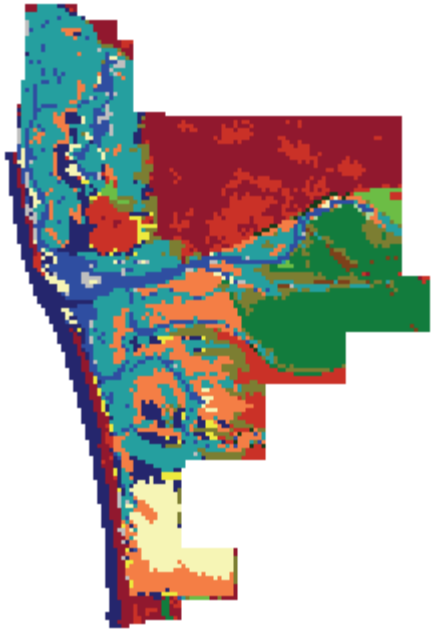
Tijuana Slough NWR, Initial Condition



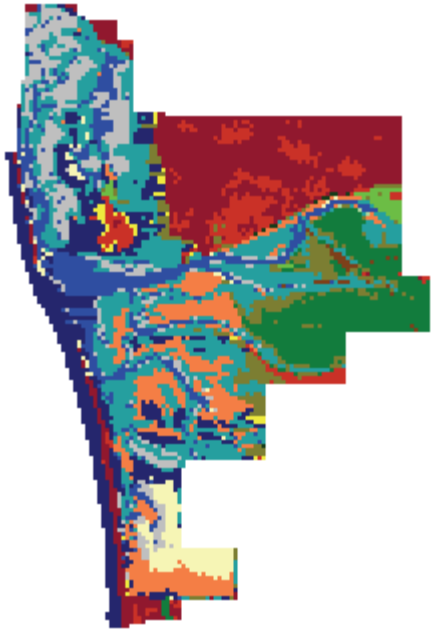
Tijuana Slough NWR, 2025, 2 meter



Tijuana Slough NWR, 2050, 2 meter



Tijuana Slough NWR, 2075, 2 meter



Tijuana Slough NWR, 2100, 2 meter

Discussion

Tijuana Slough model results are somewhat less uncertain than some other sites modeled due to full LiDAR coverage and NWR-specific accretion data. Relatively high measurements for marsh accretion rates help to explain the wetland resiliency seen in all scenarios but the most extreme.

When inundated, dry land converts first to transitional marsh and later to regularly flooded marsh. Initial loss of dry land occurs when the dry land cell falls below the "salt boundary," which is defined in this modeling as the elevation at which flooding is predicted to occur at least one time per month.

Swamps and tidal swamps, most of which are further inland, experience conversion to transitional marsh and brackish marsh, respectively. Swamp loss rates are approximately linear in their relationship to modeled SLR scenarios, with a steady rise from 6% to 41%. Lack of accurate tidal data for this inland area makes these results somewhat uncertain however.

This report displays results with the "protect developed" flag 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 it means that tables of results may overestimate the resilience of wetlands.

References

Cahoon, D.R., J. W. Day, Jr., and D. J. Reed, 1999. "The influence of surface and shallow subsurface soil processes on wetland elevation: A synthesis." *Current Topics in Wetland Biogeochemistry*, 3, 72-88.

Cashin Associates. 2006b. *Spotted Turtles: Use of Mosquito-control Ditches*. Suffolk County Vector Control and Wetlands Management Long-Term Plan and Environmental Impact.

Chen, J. L., Wilson, C. R., Tapley, B. D., 2006 "Satellite Gravity Measurements Confirm Accelerated Melting of Greenland Ice Sheet" *Science* 2006 0: 1129007

Clough, J.S. and R.A. Park, 2007, *Technical Documentation for SLAMM 5.0.1* February 2008, Jonathan S. Clough, Warren Pinnacle Consulting, Inc, Richard A. Park, Eco Modeling. http://warrenpinnacle.com/prof/SLAMM

Craft C, Clough J, Ehman J, Guo H, Joye S, Machmuller M, Park R, and Pennings S. Effects of Accelerated Sea Level Rise on Delivery of Ecosystem Services Provided by Tidal Marshes: A Simulation of the Georgia (USA) Coast. *Frontiers in Ecology and the Environment*. 2009; 7, doi:10.1890/070219

Council for Regulatory Environmental Modeling, (CREM) 2008. *Draft guidance on the development, evaluation, and application of regulatory environmental* models P Pascual, N Stiber, E Sunderland - Washington DC: Draft, August 2008

Glick, Clough, et al. *Sea-level Rise and Coastal Habitats in the Pacific Northwest An Analysis for Puget Sound, Southwestern Washington, and Northwestern Oregon* July 2007 http://www.nwf.org/sealevelrise/pdfs/PacificNWSeaLevelRise.pdf

IPCC, 2001: *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change* [Houghton, J.T.,Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K.Maskell, and C.A. Johnson (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 881pp.

Lee, J.K., R.A. Park, and P.W. Mausel. 1992. Application of Geoprocessing and Simulation Modeling to Estimate Impacts of Sea Level Rise on the Northeast Coast of Florida. *Photogrammetric Engineering and Remote Sensing* 58:11:1579-1586.

McLetchie, K.M. 2006. A Retrospective Study of Salt Marsh Response to Historical Anthropogenic Modifications at Seatuck and Tijuana Slough National Wildlife Refuges. Marine Sciences Research Center, Stony Brook.

Meehl GA, Stocker TF, Collins WD, Friedlingstein P, Gaye AT, Gregory JM, Kitoh A, Knutti R, Murphy JM, Noda A, Raper SCB, Watterson IG, Weaver AJ and Zhao ZC. 2007. Global climate projections. Pp. 747-845. In: Solomon S, Qin, D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor, M and Miller HL, (eds.) *Climate change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK: Cambridge University Press.

Monaghan, A. J. *et al,* 2006 "Insignificant Change in Antarctic Snowfall Since the International Geophysical Year" *Science* 2006 313: 827-831.

Moorhead, KK and Brinson MM. 1995. Response of wetlands to rising sea level in the lower coastal plain of North Carolina. *Ecological Applications* 5: 261-271.

National Wildlife Fed 'n et al., *An Unfavorable Tide: Global Warming, Coastal Habitats and Sportfishing in Florida* 4, 6 (2006). http://www.targetglobalwarming.org/files/AnUnfavorableTideReport.pdf

Orson, R.A., R.S. Warren, and W.A. Neiring, 1998: Interpreting sea level rise and rates of vertical marsh accretion in a southern New England tidal salt marsh. *Estuarine, Coastal and Shelf Science*, 47, 419-429.

Park, R.A., J.K. Lee, and D. Canning. 1993. Potential Effects of Sea Level Rise on Puget Sound Wetlands. *Geocarto International* 8(4):99-110.

Park, R.A., M.S. Trehan, P.W. Mausel, and R.C. Howe. 1989a. The Effects of Sea Level Rise on U.S. Coastal Wetlands. In *The Potential Effects of Global Climate Change on the United States: Appendix B - Sea Level Rise,* edited by J.B. Smith and D.A. Tirpak, 1-1 to 1-55. EPA-230-05-89-052. Washington, D.C.: U.S. Environmental Protection Agency.

Park, RA, JK Lee, PW Mausel and RC Howe. 1991. Using remote sensing for modeling the impacts of sea level rise. *World Resources Review* 3:184-220.

Patrick, W. H., Jr., And R. D. Delaune. 1990. Subsidence, accretion and sea level rise in south San Francisco Bay marshes. *Limnol. Oceanogr.* 35: 1389-l 395.

Pfeffer, Harper, O'Neel, 2008. Kinematic Constraints on Glacier Contributions to 21st-Century Sea-Level Rise. *Science*, Vol. 321, No. 5894. (5 September 2008), pp. 1340-134

Rahmstorf, Stefan 2007, "A Semi-Empirical Approach to Projecting Future Sea-Level Rise," *Science* 2007 315: 368-370.

Reed, D.J., D.A. Bishara, D.R. Cahoon, J. Donnelly, M. Kearney, A.S. Kolker, L.L. Leonard, R.A. Orson, and J.C. Stevenson, 2008: "Site-Specific Scenarios for Wetlands Accretion in the Mid-Atlantic Region. Section 2.1" in *Background Documents Supporting Climate Change Science Program Synthesis and Assessment Product 4.1: Coastal Elevations and Sensitivity to Sea Level Rise*, J.G. Titus and E.M. Strange (eds.), EPA430R07004, Washington, DC: U.S. EPA. http://www.epa.gov/climatechange/effects/downloads/section2_1.pdf

Stevenson and Kearney, 2008, "Impacts of Global Climate Change and Sea-Level Rise on Tidal Wetlands" Pending chapter of manuscript by University of California Press.

Thum, Alan, PhD, Gibson, Doug, Laton, Richard, and Foster, John. Sediment Quality And Depositional Environment Of San Elijo Lagoon, Technical Report Prepared for: Coastal Conservancy and U.S. Fish & Wildlife Service.

Titus, J.G., R.A. Park, S.P. Leatherman, J.R. Weggel, M.S. Greene, P.W. Mausel, M.S. Trehan, S. Brown, C. Grant, and G.W. Yohe. 1991. Greenhouse Effect and Sea Level Rise: Loss of Land and the Cost of Holding Back the Sea. *Coastal Management* 19:2:171-204.

Ward, K.M., Callaway, J.C. and Zedler, J.B. 2003. Episodic colonization of an intertidal mudflat by native cordgrass (Spartina foliosa) at Tijuana Estuary. Estuaries 26, 116–130.

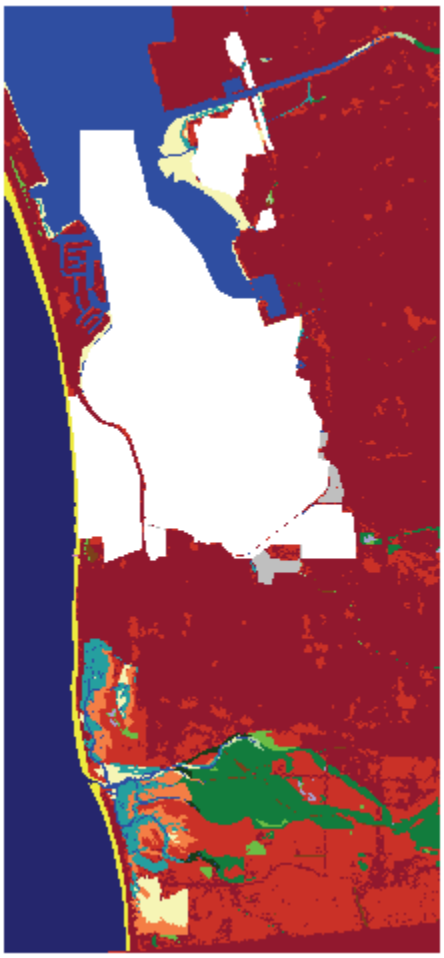
Weis, D. A., Callaway, A. B. and Gersberg, R. M., 2001.Vertical accretion rates and heavy metal chronologies in wetland sediments of the Tijuana Estuary. *Estuaries*, 24(6A), 840-850.

Appendix A: Contextual Results

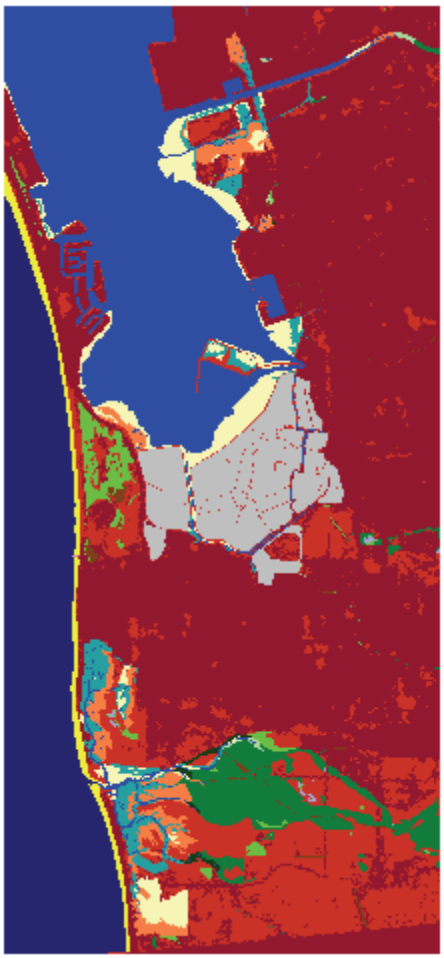
The SLAMM model does take into account the context of the surrounding lands or open water when calculating effects. For example, erosion rates are calculated based on the maximum fetch (wave action) which is estimated by assessing contiguous open water to a given marsh cell. Another example is that inundated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

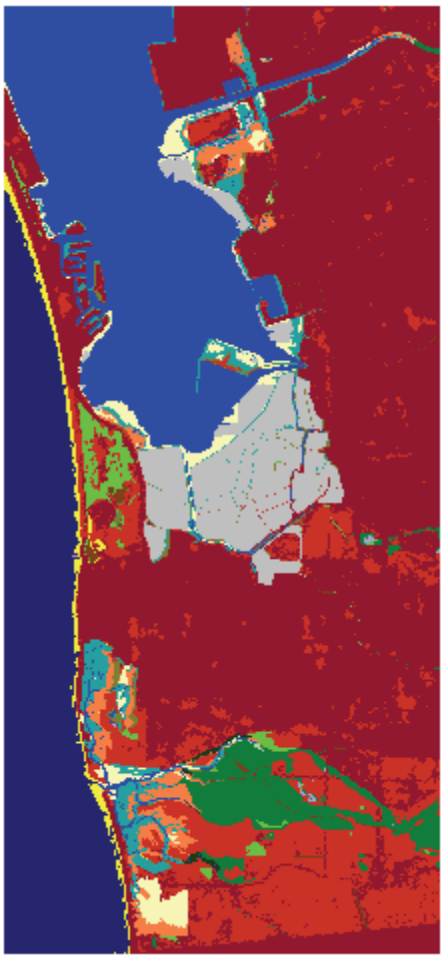
- Results were closely examined (quality assurance) within USFWS refuges but not closely examined for the larger region.
- Site-specific parameters for the model were derived for USFWS refuges whenever possible and may not be regionally applicable.
- Especially in areas where dikes are present, an effort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



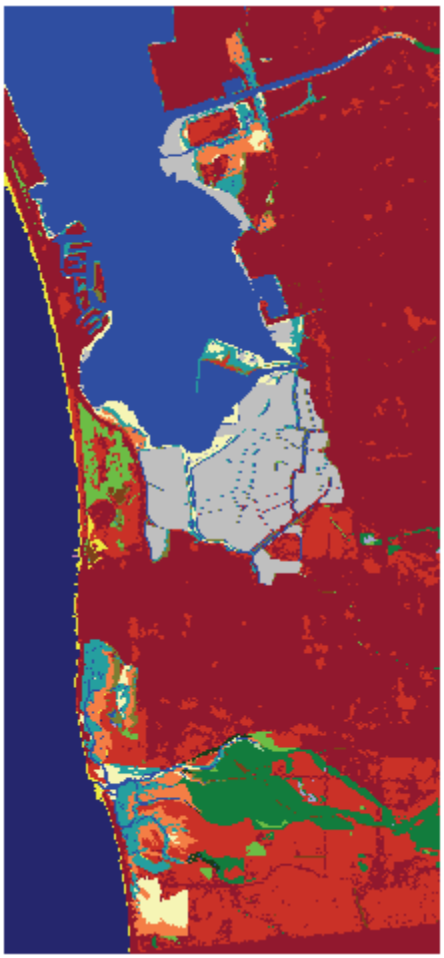
Location of Tijuana Slough National Wildlife Refuge (white area in rectangle) within simulation context



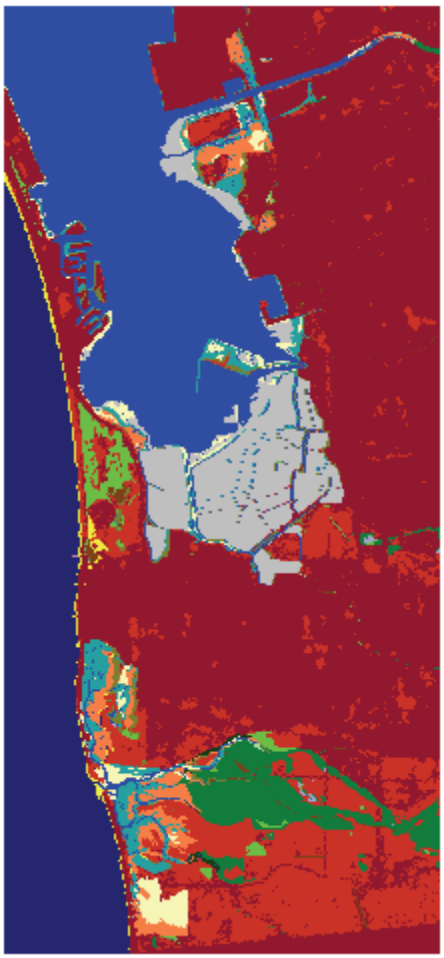
Tijuana Slough NWR, Initial Condition



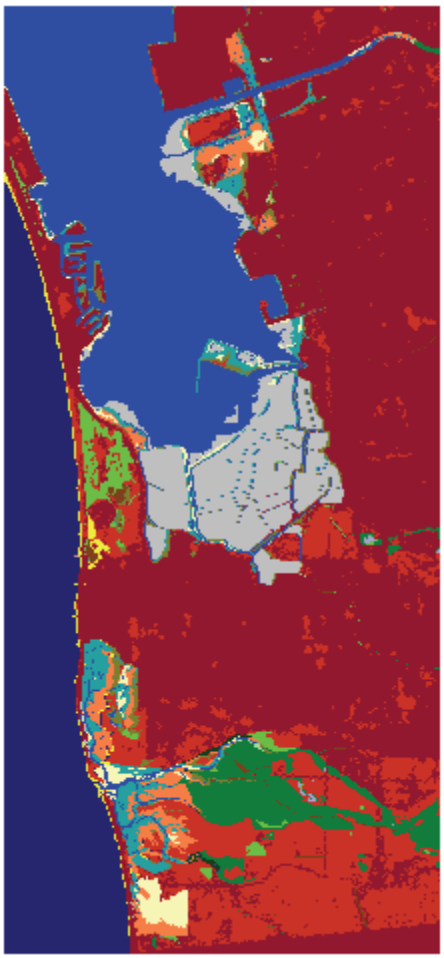
Tijuana Slough NWR, 2025, Scenario A1B Mean



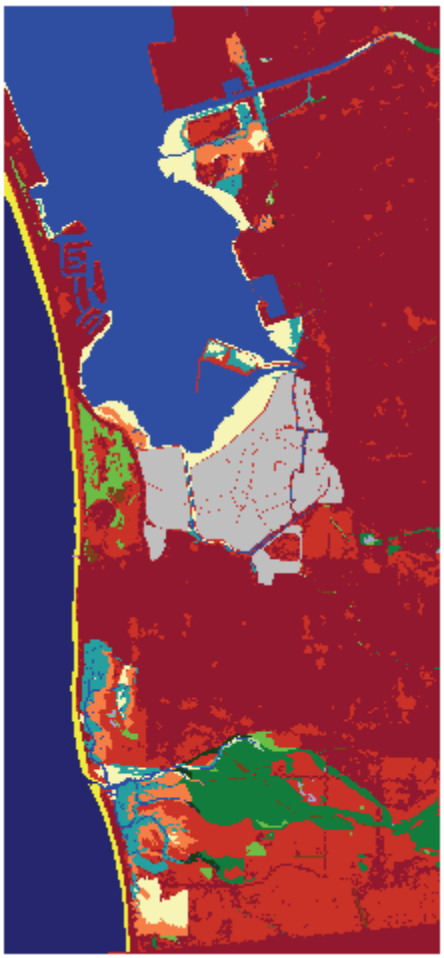
Tijuana Slough NWR, 2050, Scenario A1B Mean



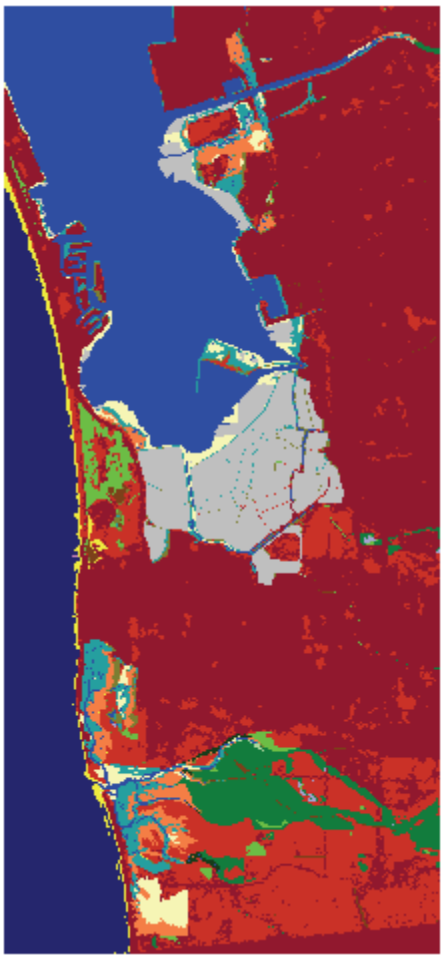
Tijuana Slough NWR, 2075, Scenario A1B Mean



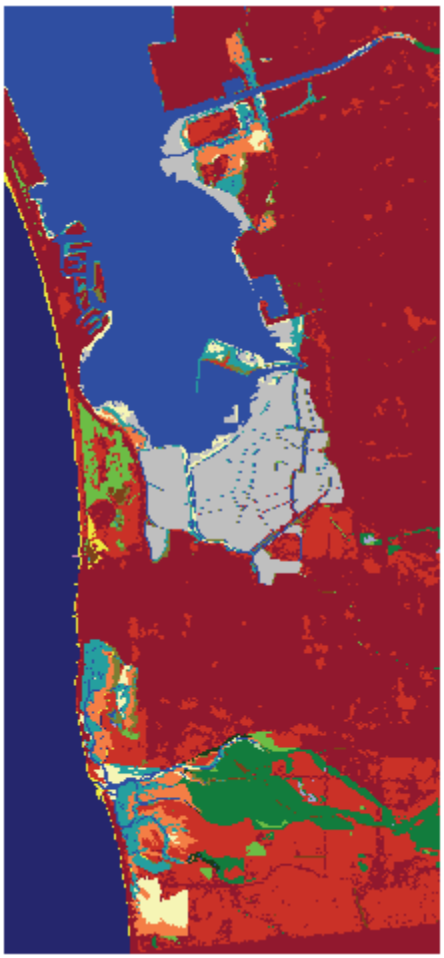
Tijuana Slough NWR, 2100, Scenario A1B Mean



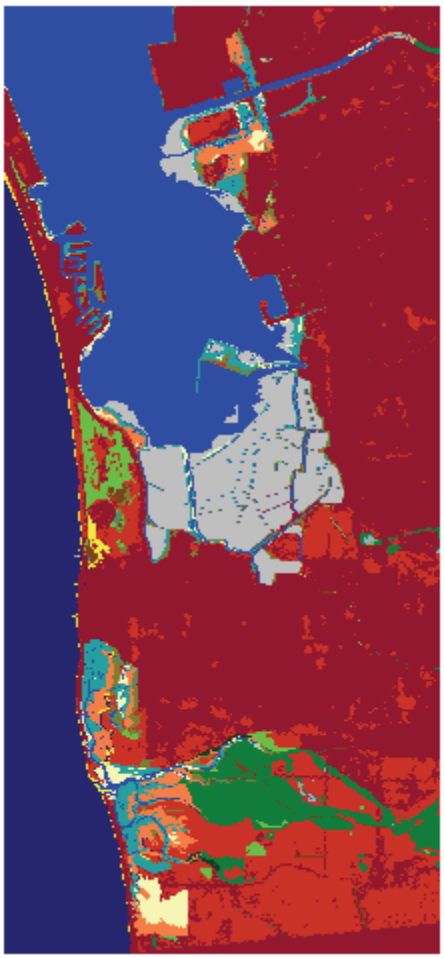
Tijuana Slough NWR, Initial Condition



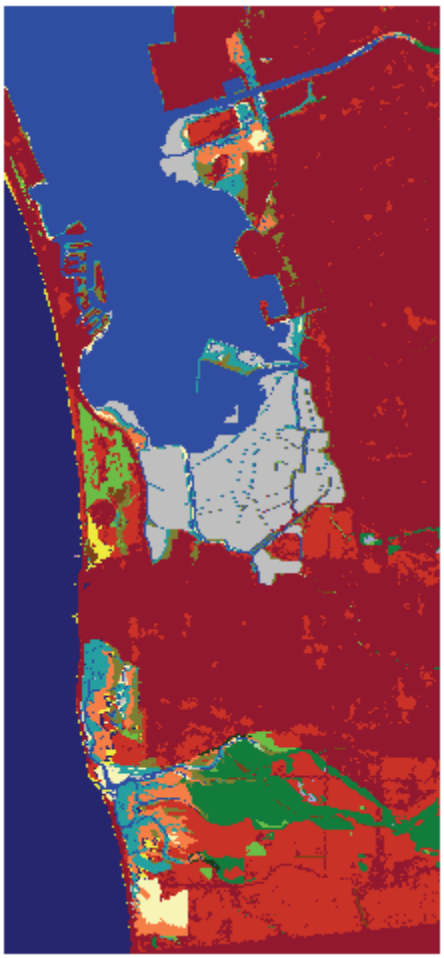
Tijuana Slough NWR, 2025, Scenario A1B Maximum



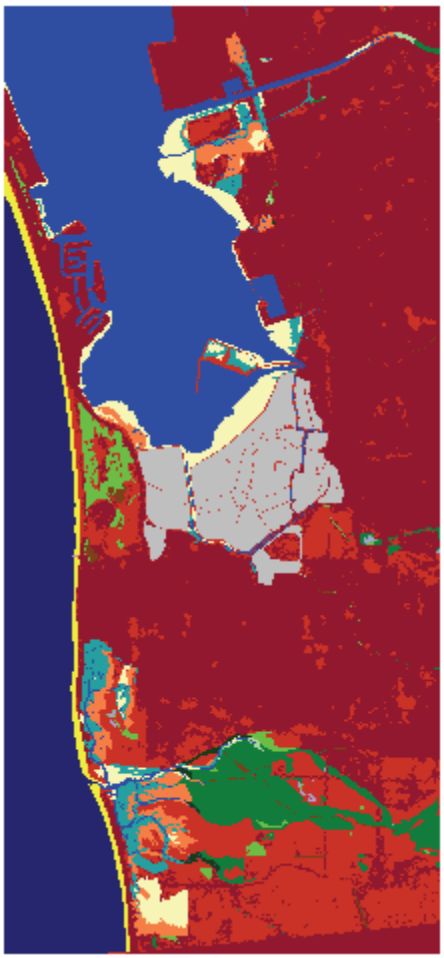
Tijuana Slough NWR, 2050, Scenario A1B Maximum



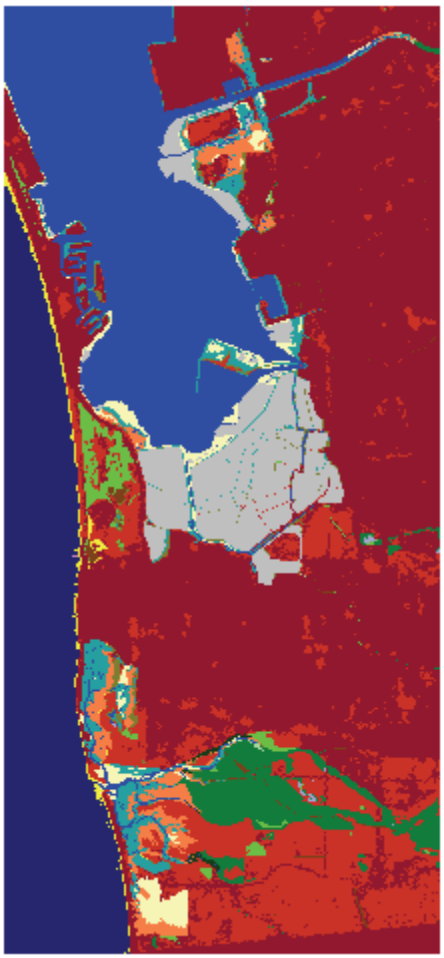
Tijuana Slough NWR, 2075, Scenario A1B Maximum



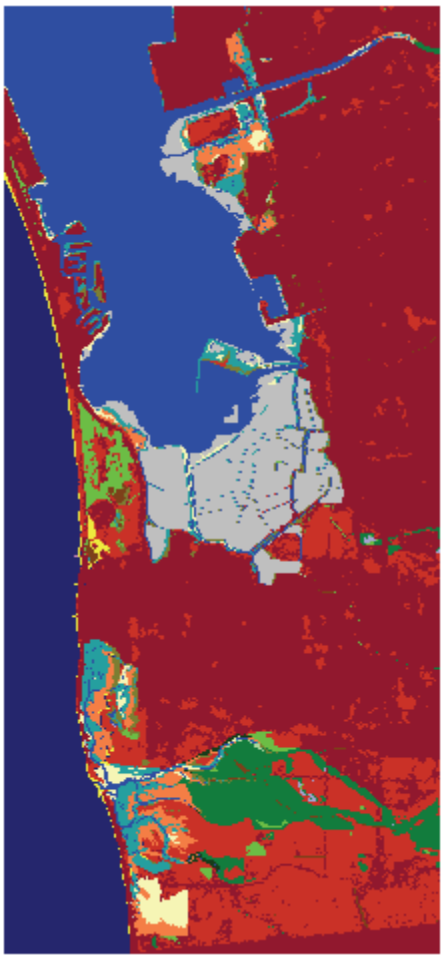
Tijuana Slough NWR, 2100, Scenario A1B Maximum



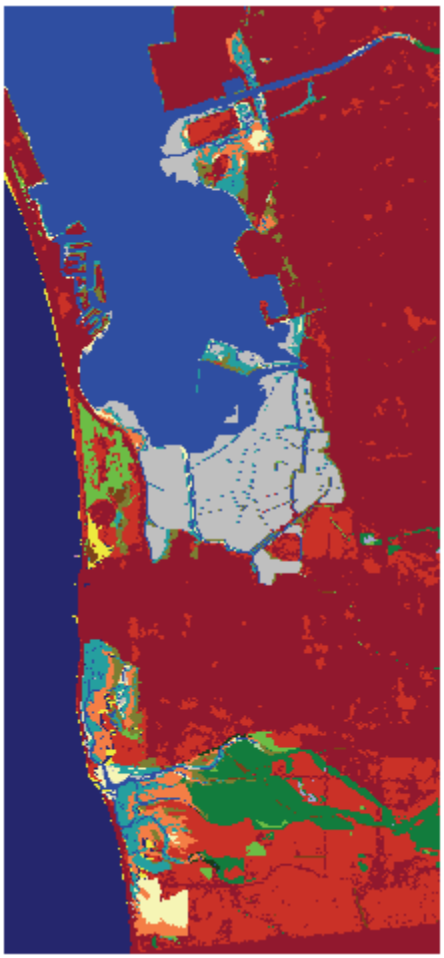
Tijuana Slough NWR, Initial Condition



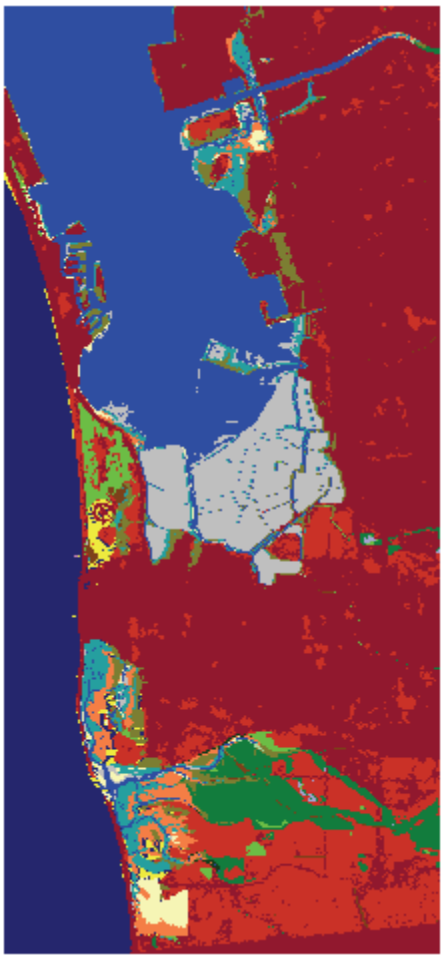
Tijuana Slough NWR, 2025, 1 meter



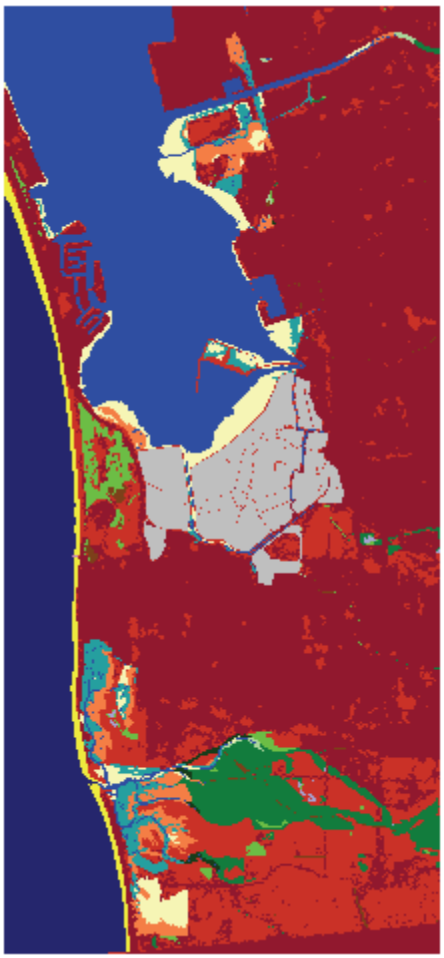
Tijuana Slough NWR, 2050, 1 meter



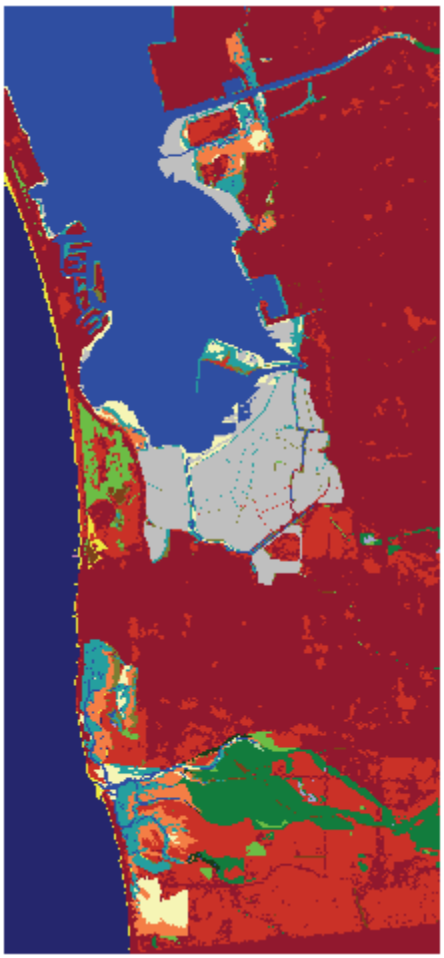
Tijuana Slough NWR, 2075, 1 meter



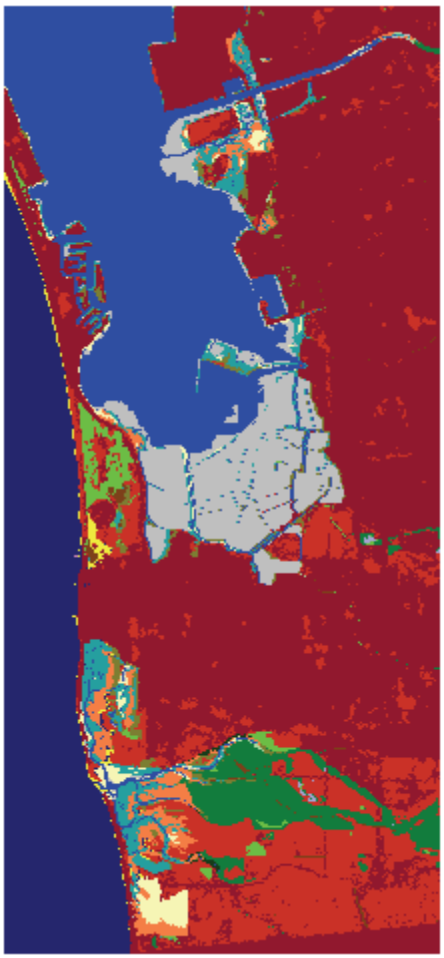
Tijuana Slough NWR, 2100, 1 meter



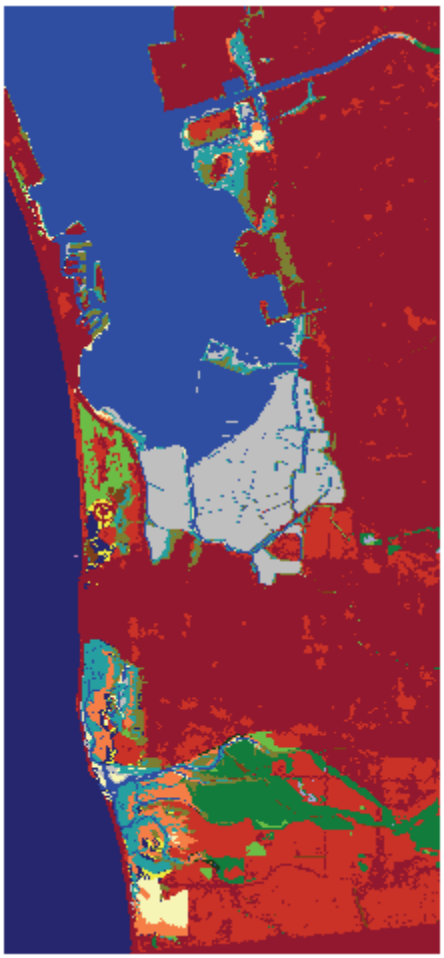
Tijuana Slough NWR, Initial Condition



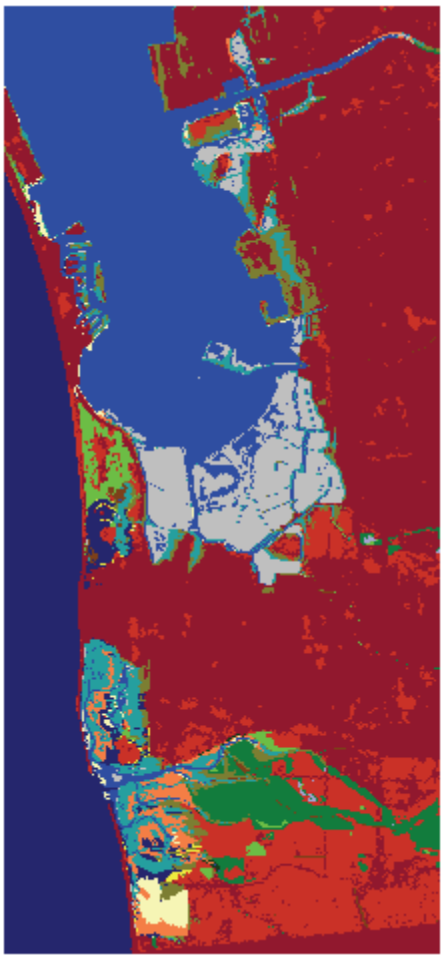
Tijuana Slough NWR, 2025, 1.5 meter



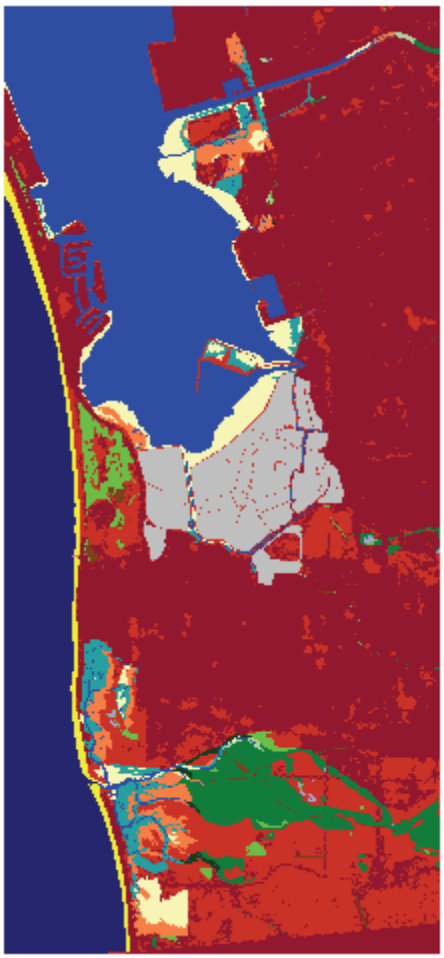
Tijuana Slough NWR, 2050, 1.5 meter



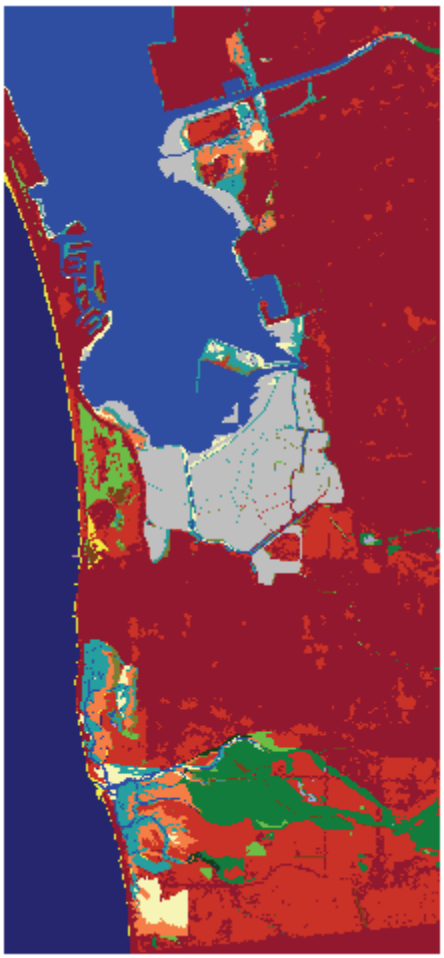
Tijuana Slough NWR, 2075, 1.5 meter



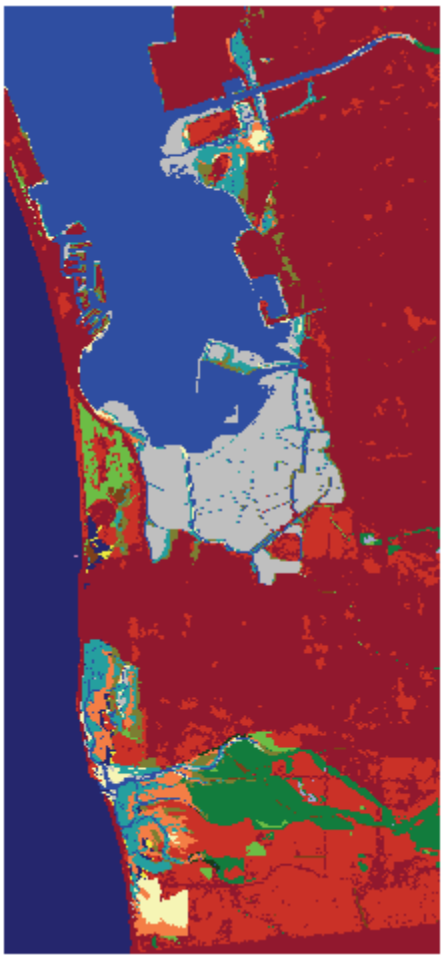
Tijuana Slough NWR, 2100, 1.5 meter



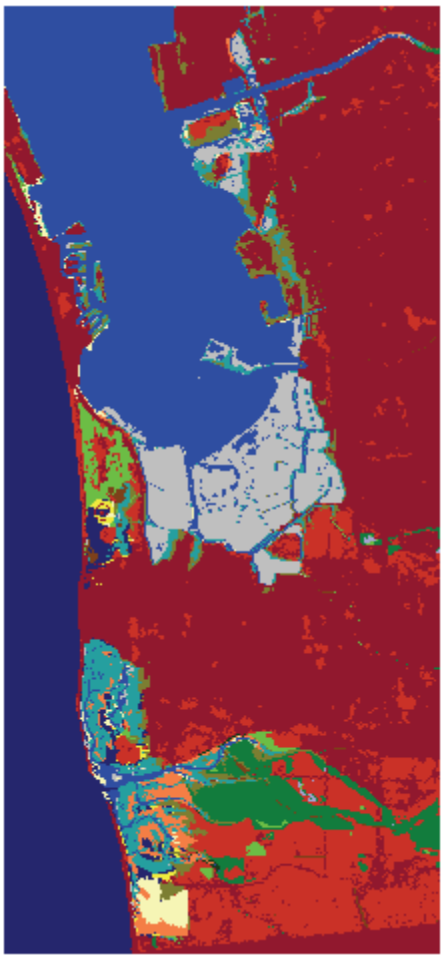
Tijuana Slough NWR, Initial Condition



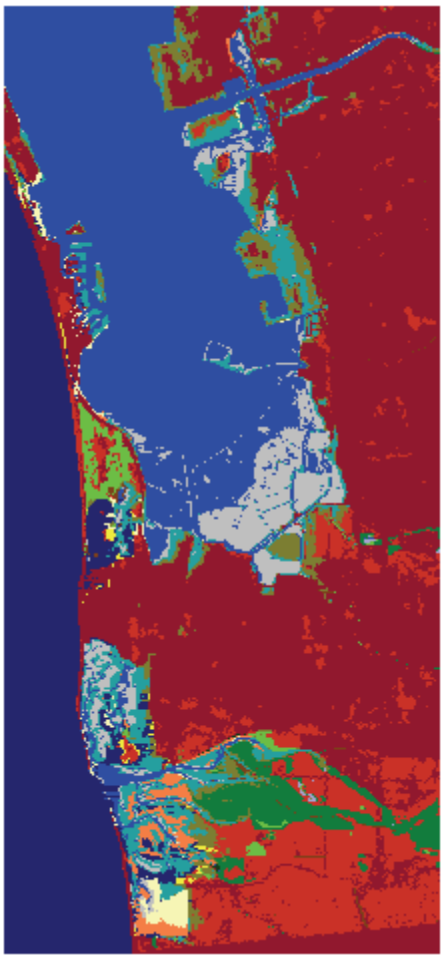
Tijuana Slough NWR, 2025, 2 meter



Tijuana Slough NWR, 2050, 2 meter



Tijuana Slough NWR, 2075, 2 meter



Tijuana Slough NWR, 2100, 2 meter