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

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Introduction

Tidal marshes are among the most susceptible ecosystems to climate change, especially accelerated sea level rise (SLR). The International Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) suggested that global sea level will increase by approximately 30 cm to 100 cm by 2100 (IPCC 2001). Rahmstorf (2007) suggests that this range may be too conservative and that the feasible range by 2100 could be 50 to 140 cm. Rising sea levels may result in tidal marsh submergence (Moorhead and Brinson 1995) and habitat migration as salt marshes transgress landward and replace tidal freshwater and brackish marsh (Park et al. 1991).

In an effort to address the potential effects of sea level rise on United States national wildlife refuges, the U. S. Fish and Wildlife Service contracted the application of the SLAMM model for most Region 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 6) that accounts for the dominant processes involved in wetland conversion and shoreline modifications during long-term sea level rise (Park et al. 1989; www.warrenpinnacle.com/prof/SLAMM).

Successive versions of the model have been used to estimate the impacts of sea level rise on the coasts of the U.S. (Titus et al., 1991; Lee, J.K., R.A. Park, and P.W. Mausel. 1992; Park, R.A., J.K. Lee, and D. Canning 1993; Galbraith, H., R. Jones, R.A. Park, J.S. Clough, S. Herrod-Julius, B. Harrington, and G. Page. 2002; National Wildlife Federation et al., 2006; Glick, Clough, et al. 2007; Craft et al., 2009).

Within SLAMM, there are five primary processes that affect wetland fate under different scenarios of sea-level rise:

- **Inundation:** The rise of water levels and the salt boundary are tracked by reducing elevations of each cell as sea levels rise, thus keeping mean tide level (MTL) constant at zero. The effects on each cell are calculated based on the minimum elevation and slope of that cell.
- **Erosion:** Erosion is triggered based on a threshold of maximum fetch and the proximity of the marsh to estuarine water or open ocean. When these conditions are met, horizontal erosion occurs at a rate based on site-specific data.
- **Overwash:** Barrier islands of under 500 meters width are assumed to undergo overwash during each 25-year time-step due to storms. Beach migration and transport of sediments are calculated.
- **Saturation:** Coastal swamps and fresh marshes can migrate onto adjacent uplands as a response of the fresh water table to rising sea level close to the coast.

- **Accretion:** Sea level rise is offset by sedimentation and vertical accretion using average or site-specific values for each wetland category. Accretion rates may be spatially variable within a given model domain or can be specified to respond to feedbacks such as frequency of inundation.

SLAMM Version 6.0 was developed in 2008/2009 and is based on SLAMM 5. SLAMM 6.0 provides backwards compatibility to SLAMM 5, that is, SLAMM 5 results can be replicated in SLAMM 6. However, SLAMM 6 also provides several optional capabilities.

- Accretion Feedback Component: Feedbacks based on wetland elevation, distance to channel, and salinity may be specified. This feedback will be used in USFWS simulations, but only where adequate data exist for parameterization.
- Salinity Model: Multiple time-variable freshwater flows may be specified. Salinity is estimated and mapped at MLLW, MHHW, and MTL. Habitat switching may be specified as a function of salinity. This optional sub-model is not utilized in USFWS simulations.
- Integrated Elevation Analysis: SLAMM will summarize site-specific categorized elevation ranges for wetlands as derived from LiDAR data or other high-resolution data sets. This functionality is used in USFWS simulations to confirm the SLAMM conceptual model at each site.
- Flexible Elevation Ranges for land categories: If site-specific data indicate that wetland elevation ranges are outside of SLAMM defaults, a different range may be specified within the interface. In USFWS simulations, the use of values outside of SLAMM defaults is rarely utilized. If such a change is made, the change and the reason for it are fully documented within the model application reports.
- Many other graphic user interface and memory management improvements are also part of the new version including an updated *Technical Documentation*, and context sensitive help files.

For a thorough accounting of SLAMM model processes and the underlying assumptions and equations, please see the SLAMM 6.0 *Technical Documentation* (Clough, Park, Fuller, 2010). This document is available at http://warrenpinnacle.com/prof/SLAMM

All model results are subject to uncertainty due to limitations in input data, incomplete knowledge about factors that control the behavior of the system being modeled, and simplifications of the system (CREM 2008). Site-specific factors that increase or decrease model uncertainty may be covered in the *Discussion* section of this report.

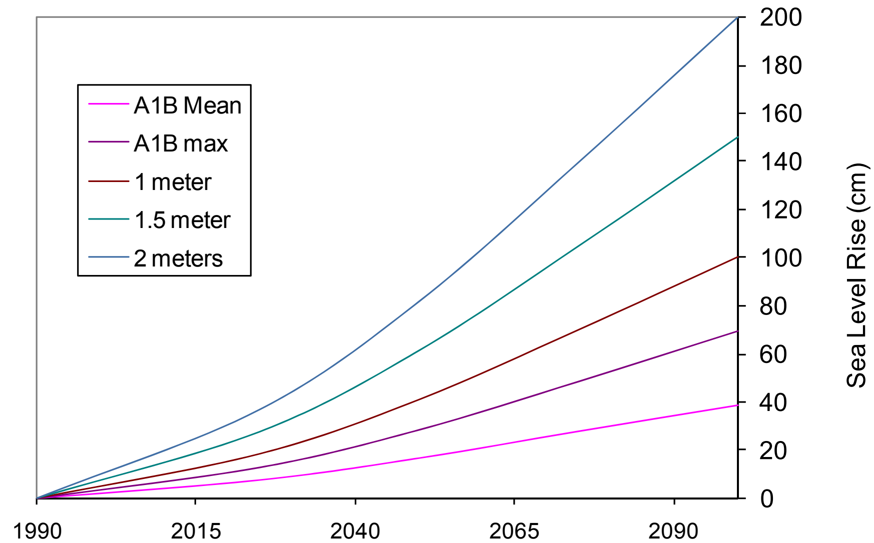
Sea Level Rise Scenarios

SLAMM 6 was run using scenario A1B from the Special Report on Emissions Scenarios (SRES) – mean and maximum estimates. The A1 scenario assumes that the future world includes very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. In particular, the A1B scenario assumes that energy sources will be balanced across all sources. Under the A1B scenario, the IPCC WGI Fourth Assessment Report (IPC, 2007) suggests a likely range of 0.21 to 0.48 meters of sea level rise by 2090-2099 "excluding future rapid dynamical changes in ice flow." The A1B-mean scenario that was run as a part of this project falls near the middle of this estimated range, predicting 0.40 meters of global sea level rise by 2100.

The latest literature (Chen et al., 2006, Monaghan et al., 2006) indicates that the eustatic rise in sea levels is progressing more rapidly than was previously assumed, perhaps due to the dynamic changes in ice flow omitted within the IPCC report's calculations. A recent paper in the journal *Science* (Rahmstorf, 2007) suggests that, taking into account possible model error, a feasible range by 2100 might be 50 to 140 cm. This work was recently updated and the ranges were increased to 75 to 190 cm (Vermeer and Rahmstorf, 2009). Pfeffer et al. (2008) suggests that 2 meters by 2100 is at the upper end of plausible scenarios due to physical limitations on glaciological conditions. A recent US intergovernmental report states "Although no ice-sheet model is currently capable of capturing the glacier speedups in Antarctica or Greenland that have been observed over the last decade, including these processes in models will very likely show that IPCC AR4 projected sea level rises for the end of the 21st century are too low." (US Climate Change Science Program, 2008) A recent paper by Grinsted et. al. (2009) states that "sea level 2090-2099 is projected to be 0.9 to 1.3 m for the A1B scenario, with low probability of the rise being within Intergovernmental Panel on Climate Change (IPCC) confidence limits."

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

Figure 1: Summary of SLR Scenarios Utilized



Methods and Data Sources

The digital elevation map (DEM) used in this model simulation was derived from a combination of sources: 2003 NCALM LiDAR, 2003 USGS/NGA Photogrammetry, 2003 FEMA IfSAR and 50+ year old USGS NED with 20-foot contours and 5-foot supplemental contours (Figure 1). Within the NWR boundaries elevations were provided by LiDAR, ifSAR, and photogrammetry, with some contextual results based on 10 foot contour USGS topographical DEMs.

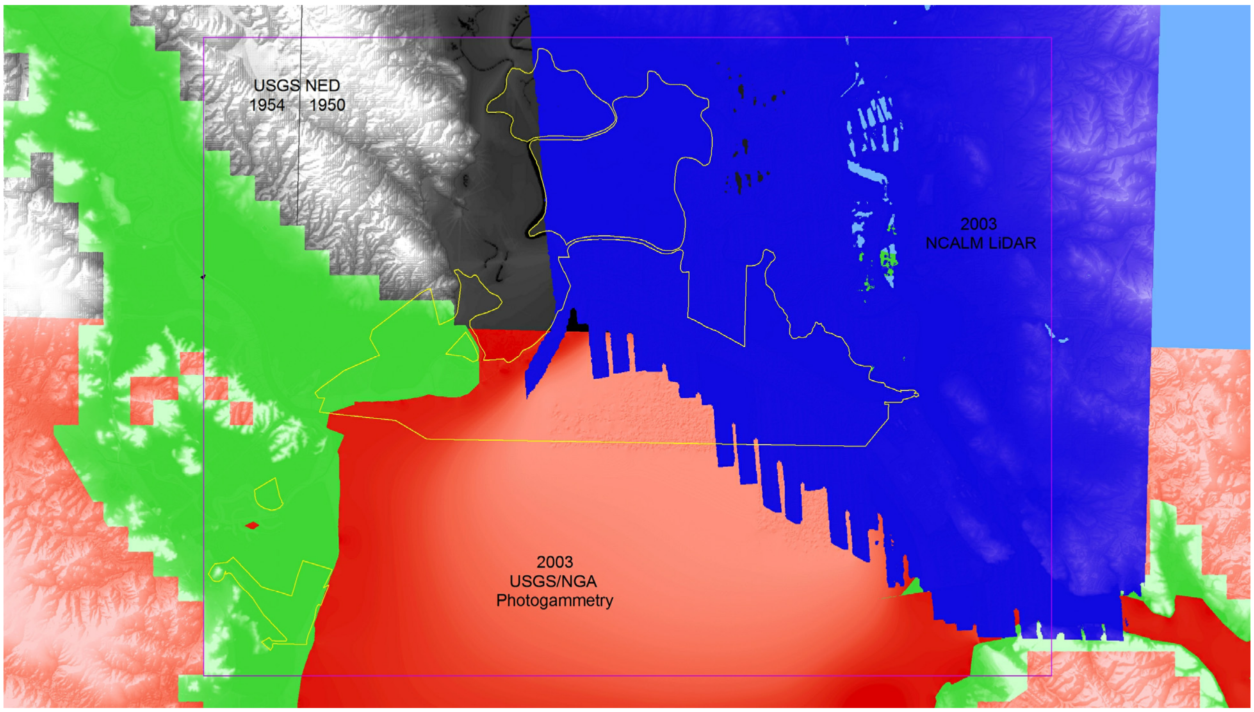


Figure 1: LiDAR coverage map of San Pablo Bay NWR (boundary in yellow). FEMA IfSAR in green.

The wetlands layer for San Pablo Bay was provided by the San Francisco Estuary Institute and is a National Wetlands Inventory coverage (NWI) with a photo date of 1998. Giselle Block, from San Pablo Bay NWR, suggested several changes to the wetland coverage, the largest of which was the replacement of dry land with irregularly flooded marsh ("area 1" in Figure 2). Converting the NWI survey into 30 meter cells indicates that the approximately twenty three thousand five hundred acre refuge (approved acquisition boundary including water) is composed of the following categories:

Dry Land	33.4%
Irregularly Flooded Marsh	25.8%
Estuarine Open Water	21.5%
Tidal Flat	15.9%
Saltmarsh	1.6%
Dev. Dry Land	1.2%

The refuge has numerous impounded zones covering nearly the entire refuge, according to the National Wetlands Inventory (Figure 2).

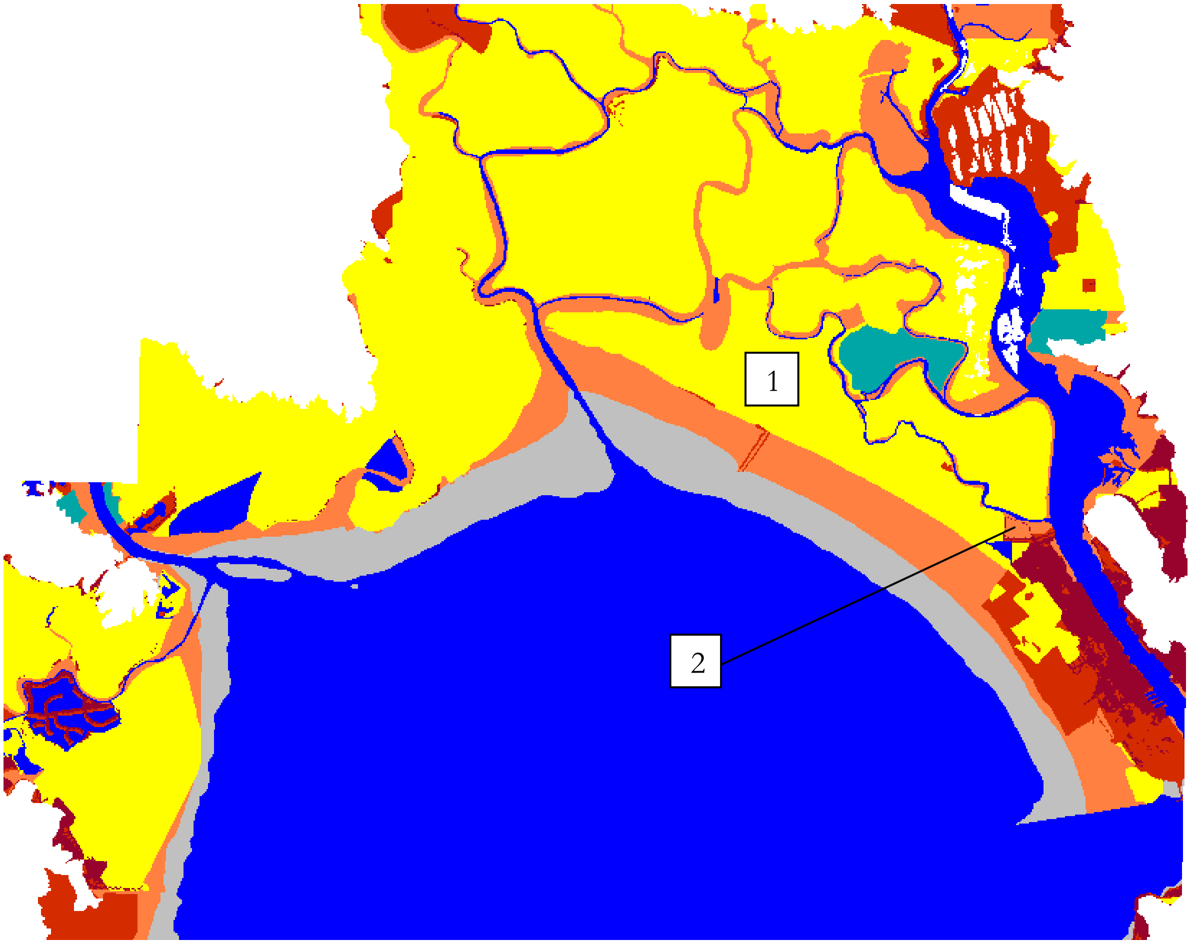


Figure 2: Diked areas in yellow.
(Areas one and two were changed from dry land to irregularly-flooded marsh)

The historic trend for sea level rise was estimated at 2.0 mm/year using the nearest NOAA gage with SLR data (9414523, Redwood City, CA). The historic rate of sea level rise for this refuge is similar to the global average for the last 100 years (approximately 1.7 mm/year).

The site-specific "great diurnal tide range" (GT) was estimated at 1.83 meters using the averages of four nearby NOAA tide gages (9415252, Petaluma River Entrance, CA; 9415218, Mare Island, CA; 9415438, Skaggs Island, Hudeman Slough, CA; 9415415, Edgerley Island, Napa River, CA) (Figure 3).

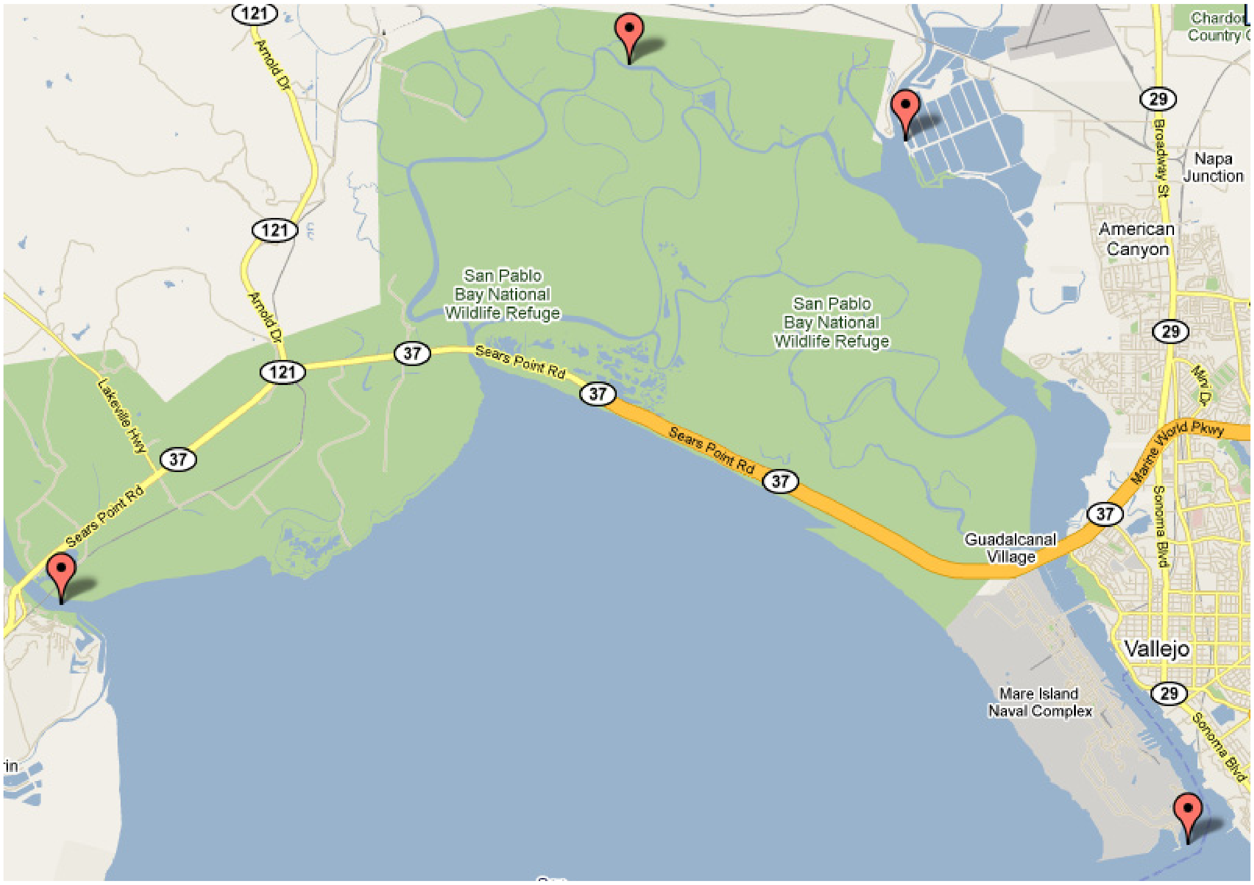


Figure 3: NOAA Gage Relevant to the Study Area.

Irregularly flooded and tidal fresh marsh accretion values for this refuge were determined to be 1.37 mm/year using measured values just northeast of the study site (Culberson, 2004). No local values for regularly-flooded marsh were available, so a low-marsh value of 6.5 mm/year was estimated using a study performed in San Francisco Bay (Patrick, 1990 using the average from Bird Island and Baumberg). SLAMM 6 allows for accretion rates to be subject to feedbacks based on inundation frequency. Insufficient data were available to set up such a relationship for this site. However, having regularly flooded marshes accrete at a rate that is nearly five times the rate of irregularly flooded marshes does incorporate some of this feedback dynamic.

Accretion rates from local, restored areas of the refuge were considered for use as model accretion parameters (USGS, 2004). However, due to dynamic conditions immediately following marsh restoration, the measured accretion values were too high for projection over 100 years (22 to 168 mm/year)

Marsh erosion was assumed to be negligible based on a study of San Pablo Bay that indicates historically variable erosion and deposition rates based on variable sediment inputs to the bay (Jaffe et al., 1998). While the period ending in 1983 was more subject to erosion, only minimal erosion seems to have occurred at refuge marsh-water interfaces (Figure 4). Furthermore, a similar study in San Francisco Bay indicated that the period beyond 1983 was more depositional after an erosional period leading up to 1983 (Jaffe et al., 2006). Given the uncertainty over the erosion or sedimentation regime over the next 100 years, within this analysis marsh losses are estimated based on inundation rather than fixed horizontal rates of erosion.

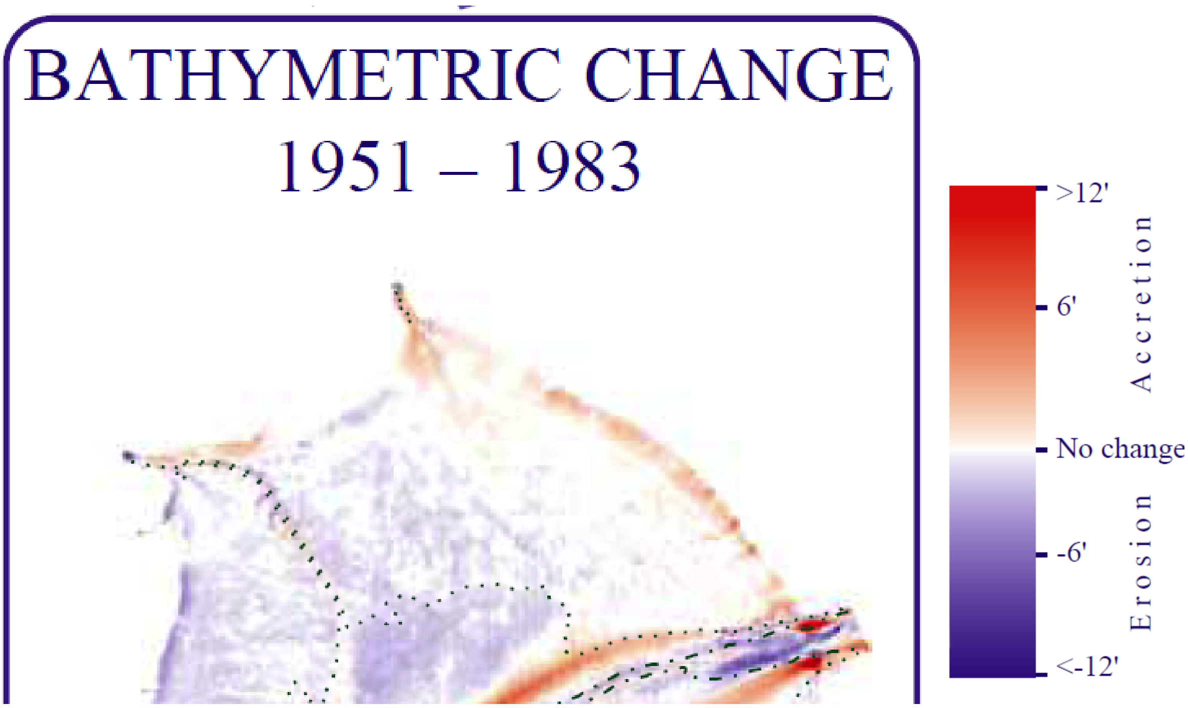


Figure 4: Excerpt from Jaffe, 1998, Showing Minor Erosion at Refuge Boundaries

The MTL to NAVD88 correction was derived using the NOAA VDATUM product. A value of 1.0 meters was used based on the average values from several locations ranging between 0.8 meters and 1.25 meters.

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

SUMMARY OF SLAMM INPUT PARAMETERS FOR SAN PABLO BAY NWR

Parameter	Global	SubSite 1	SubSite 2
Description	San Pablo	PP	SubSite 2
NWI Photo Date (YYYY)	1998	1998	1998
DEM Date (YYYY)	2003	2003	2003
Direction Offshore [n,s,e,w]	South	South	East
Historic Trend (mm/yr)	2	2	2
MTL-NAVD88 (m)	1	1	1
GT Great Diurnal Tide Range (m)	1.83	1.83	1.83
Salt Elev. (m above MTL)	1.22	1.22	1.22
Marsh Erosion (horz. m /yr)	0	0	0
Swamp Erosion (horz. m /yr)	0	0	0
T.Flat Erosion (horz. m /yr)	0	0	0
Reg. Flood Marsh Accr (mm/yr)	6.5	6.5	6.5
Irreg. Flood Marsh Accr (mm/yr)	1.37	1.37	1.37
Tidal Fresh Marsh Accr (mm/yr)	1.37	1.37	1.37
Beach Sed. Rate (mm/yr)	0.5	0.5	0.5
Freq. Overwash (years)	0	0	0
Use Elev Pre-processor [True,False]	FALSE	TRUE	FALSE

Results

The SLAMM simulation of San Pablo Bay NWR indicates significant conversion of irregularly flooded marshes given eustatic SLR scenarios over 0.5 meters by 2100. Overall, between 18% and 86% of irregularly flooded marsh is predicted to be lost across all sea level rise scenarios.

Dry land loss stays low through the 1 meter SLR scenario, above which the refuge is predicted to lose more than 80% of its dry land. This is primarily due to assumed failure of levees when dry land elevations fall more than two meters below mean tide level. Roughly one quarter of developed dry land is predicted to be lost regardless of the simulation utilized.

SLR by 2100 (m)	**0.39**	**0.69**	**1**	**1.5**	**2**
Dry Land	1%	1%	13%	81%	87%
Irregularly Flooded Marsh	18%	49%	64%	84%	86%
Tidal Flat	20%	40%	58%	-3%	33%
Dev. Dry Land	22%	23%	23%	23%	24%

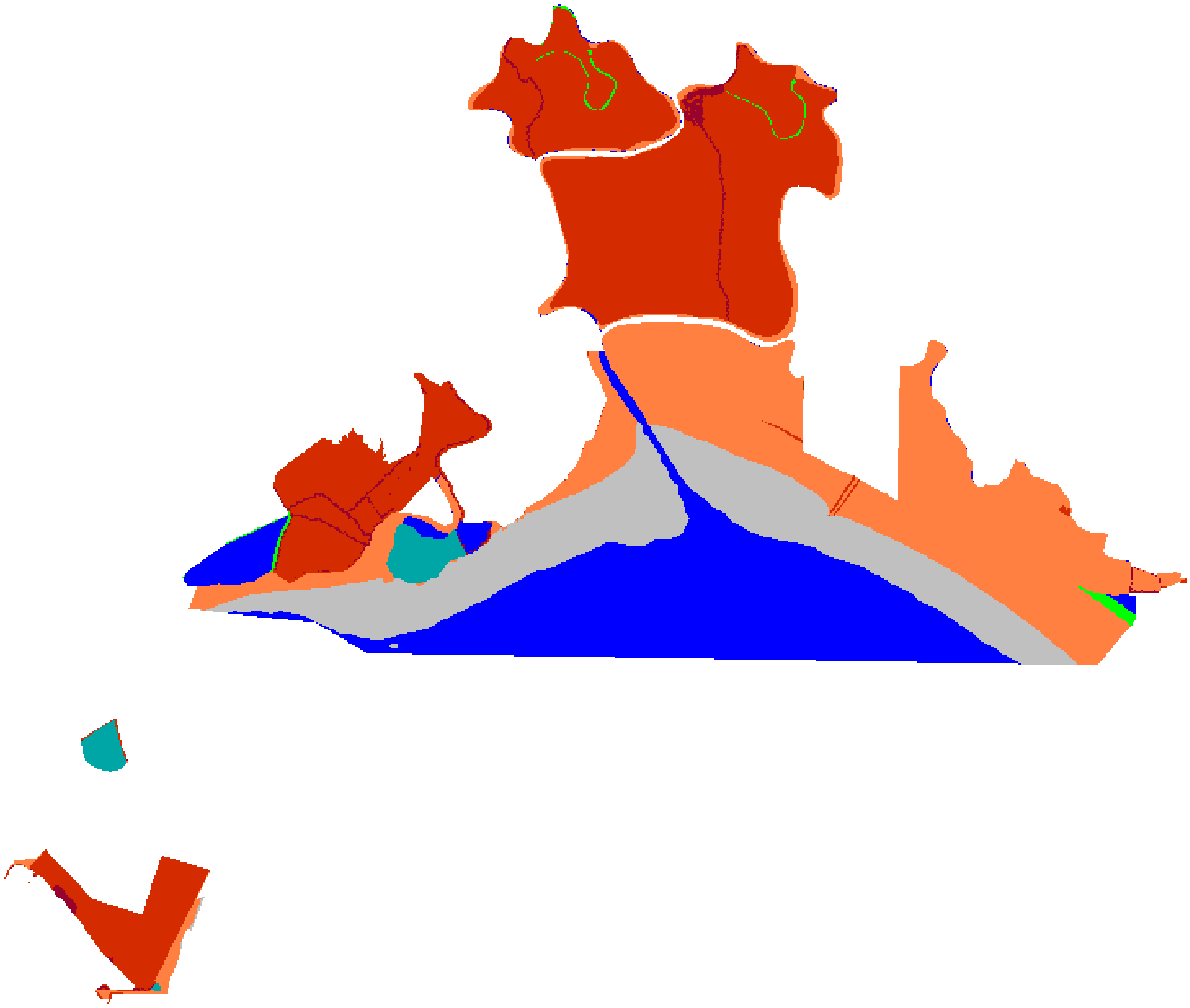
Predicted Loss Rates of Land Categories by 2100 Given Simulated Scenarios of Eustatic Sea Level Rise

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

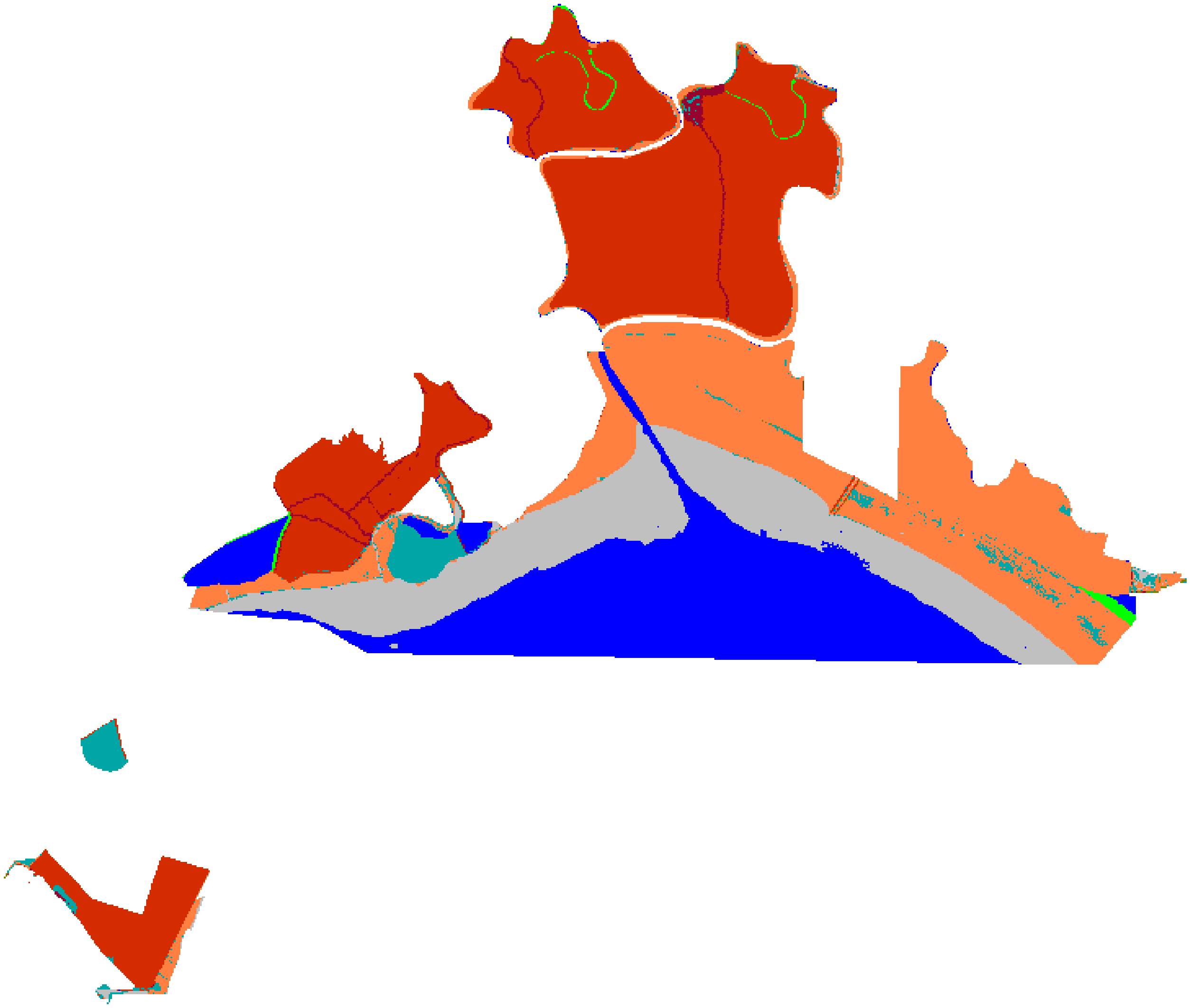
San Pablo Bay NWR
IPCC Scenario A1B-Mean, 0.39 M SLR Eustatic by 2100

Results in Acres

	Initial	2025	2050	2075	2100
Dry Land	7832.5	7790.4	7789.2	7786.9	7780.7
Irregularly Flooded Marsh	6049.1	5703.3	5573.8	5328.2	4956.5
Estuarine Open Water	5042.3	5174.5	5379.4	5660.4	5937.9
Tidal Flat	3739.1	3699.8	3545.0	3266.4	2998.7
Saltmarsh	377.6	712.0	794.6	1043.4	1415.2
Dev. Dry Land	271.8	215.8	214.0	212.7	211.6
Inland Fresh Marsh	116.3	116.3	116.3	115.9	115.0
Tidal Creek	18.5	18.5	18.5	18.5	18.5
Inland Shore	1.3	1.3	1.3	1.3	1.3
Trans. Salt Marsh	0.0	16.7	16.3	14.9	13.2
Total (incl. water)	23448.6	23448.6	23448.6	23448.6	23448.6



San Pablo Bay NWR, Initial Condition



San Pablo Bay NWR, 2025, Scenario A1B Mean

San Pablo Bay NWR, 2050, Scenario A1B Mean

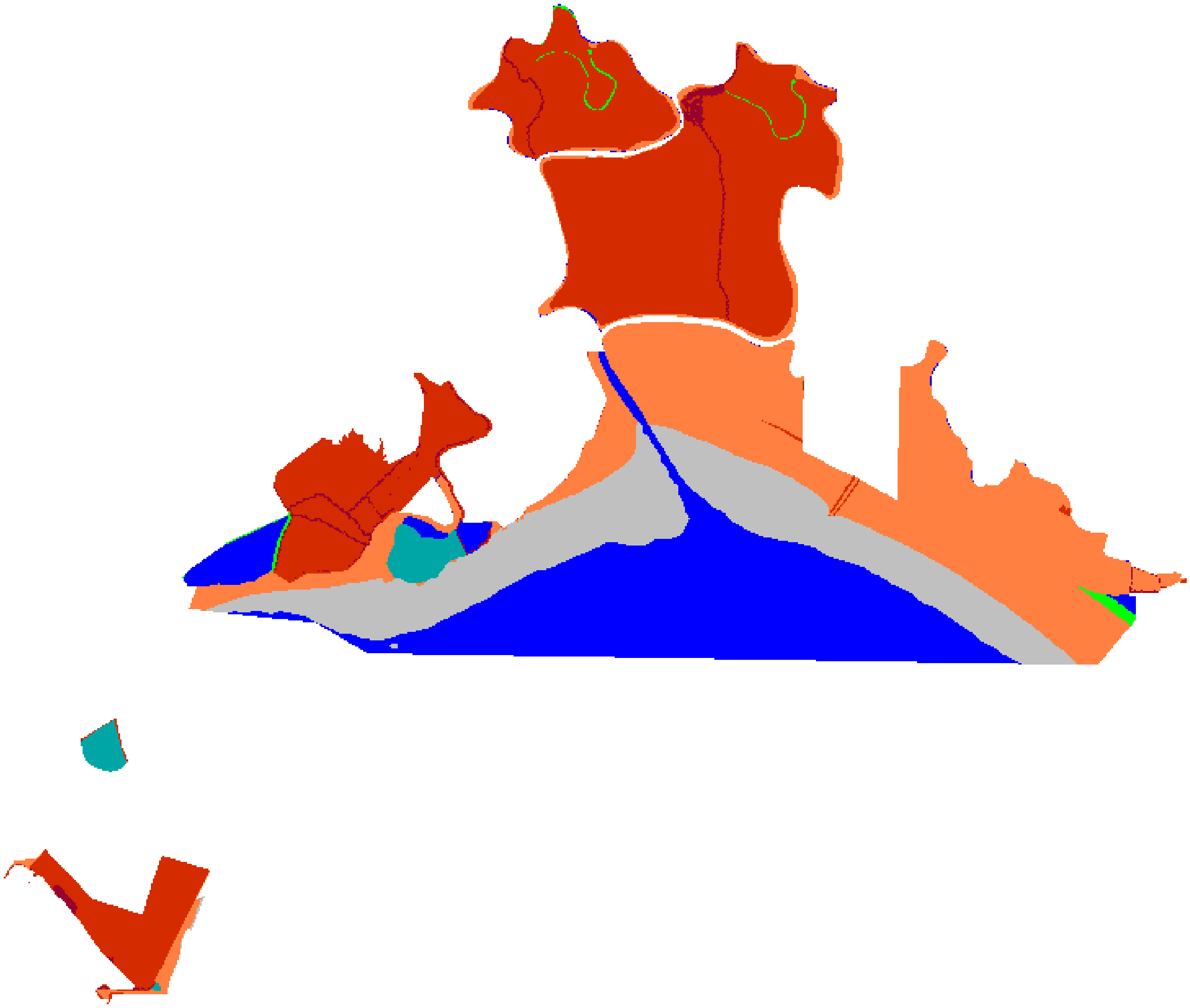
San Pablo Bay NWR, 2075, Scenario A1B Mean

San Pablo Bay NWR, 2100, Scenario A1B Mean

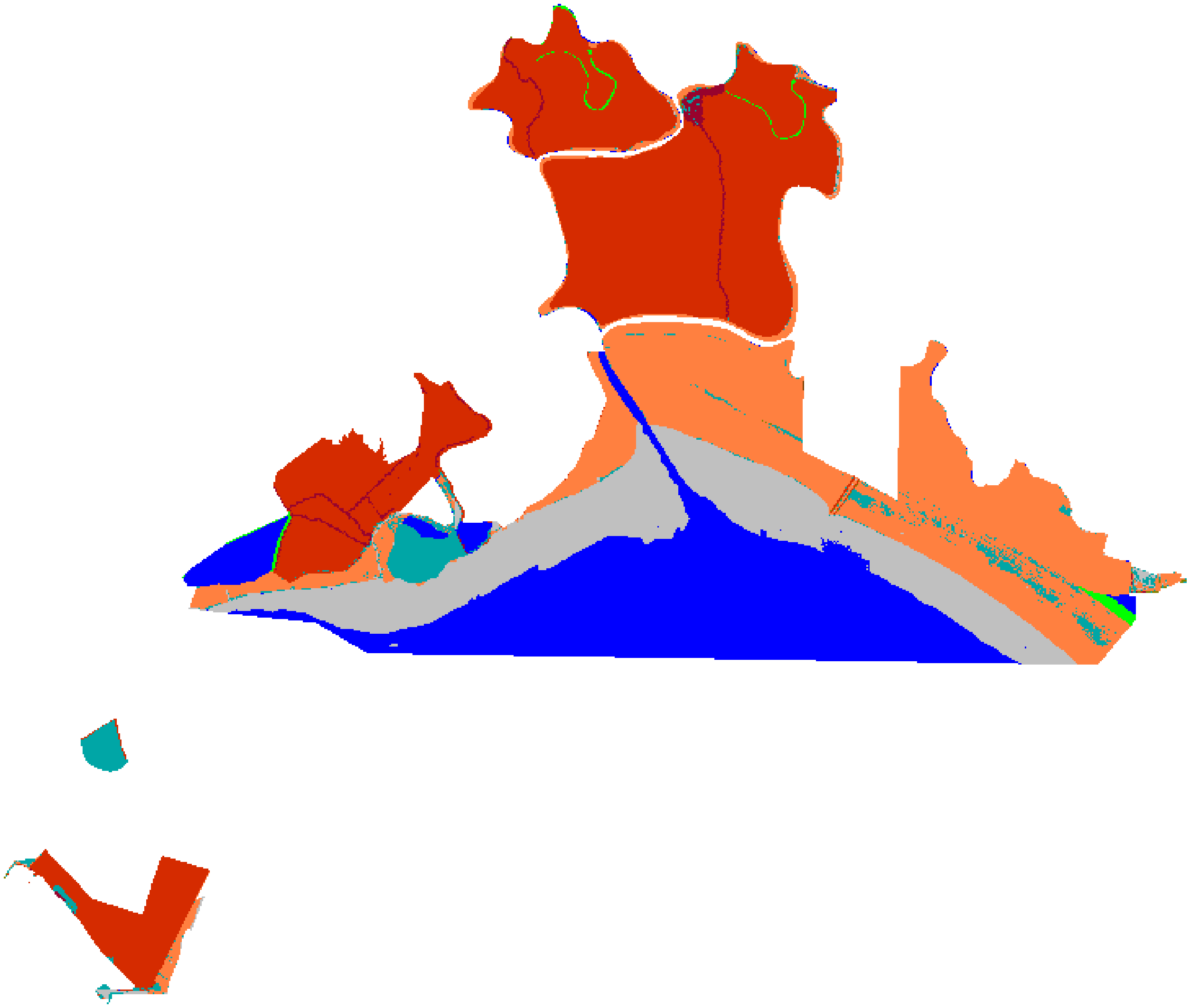
San Pablo Bay NWR
IPCC Scenario A1B-Max, 0.69 M SLR Eustatic by 2100

Results in Acres

	Initial	2025	2050	2075	2100
Dry Land	7832.5	7789.8	7787.2	7771.5	7720.0
Irregularly Flooded Marsh	6049.1	5625.1	5251.7	4339.4	3057.2
Estuarine Open Water	5042.3	5261.1	5629.3	6187.2	6820.9
Tidal Flat	3739.1	3618.9	3304.9	2777.3	2226.9
Saltmarsh	377.6	786.4	1113.7	2017.8	3273.4
Dev. Dry Land	271.8	214.9	212.8	211.0	210.0
Inland Fresh Marsh	116.3	116.3	115.9	114.3	112.1
Tidal Creek	18.5	18.5	18.5	18.5	18.5
Inland Shore	1.3	1.3	1.3	1.3	1.3
Trans. Salt Marsh	0.0	16.3	13.3	10.2	8.2
Total (incl. water)	23448.6	23448.6	23448.6	23448.6	23448.6

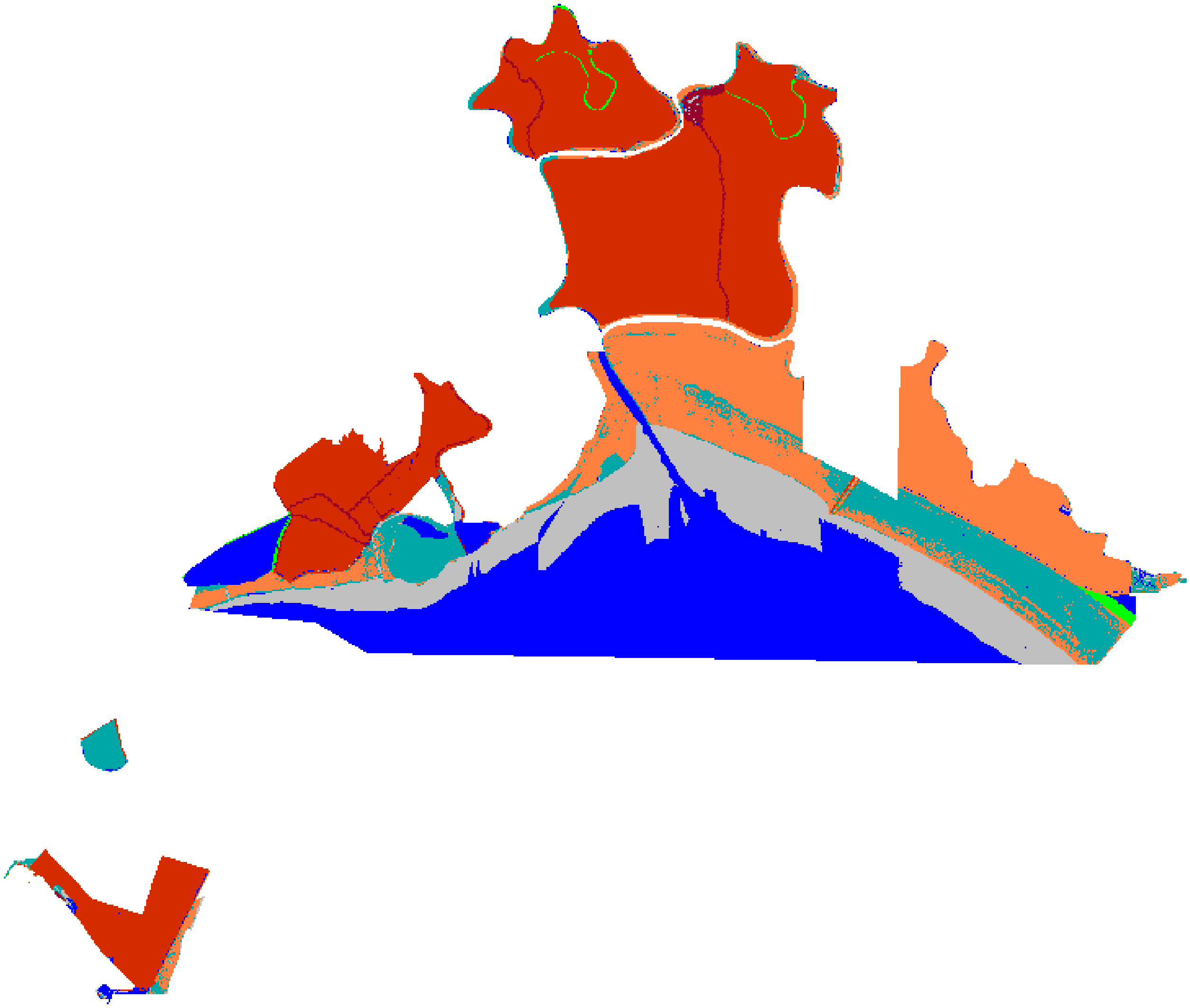


San Pablo Bay NWR, Initial Condition

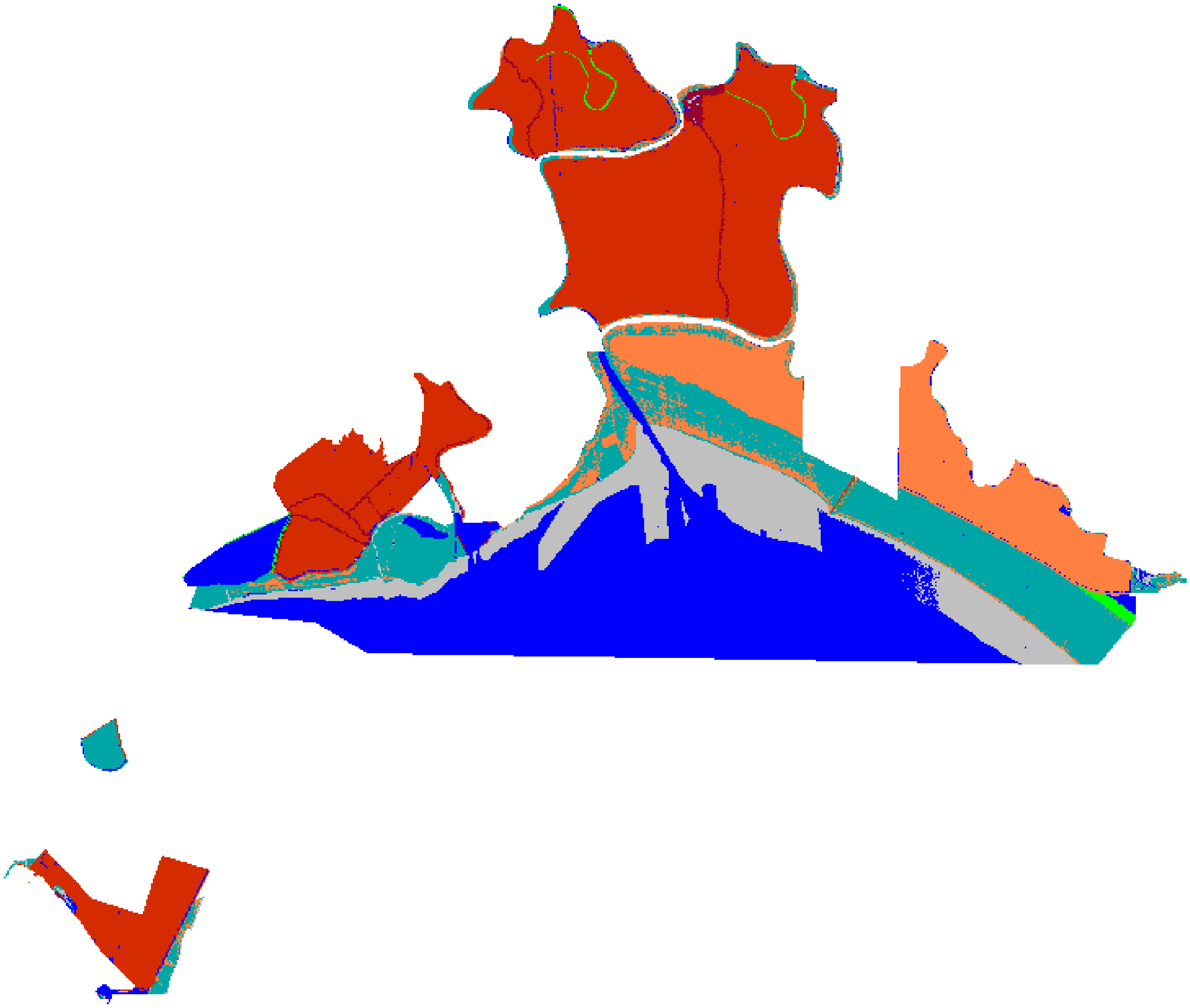


San Pablo Bay NWR, 2025, Scenario A1B Maximum

San Pablo Bay NWR, 2050, Scenario A1B Maximum



San Pablo Bay NWR, 2075, Scenario A1B Maximum

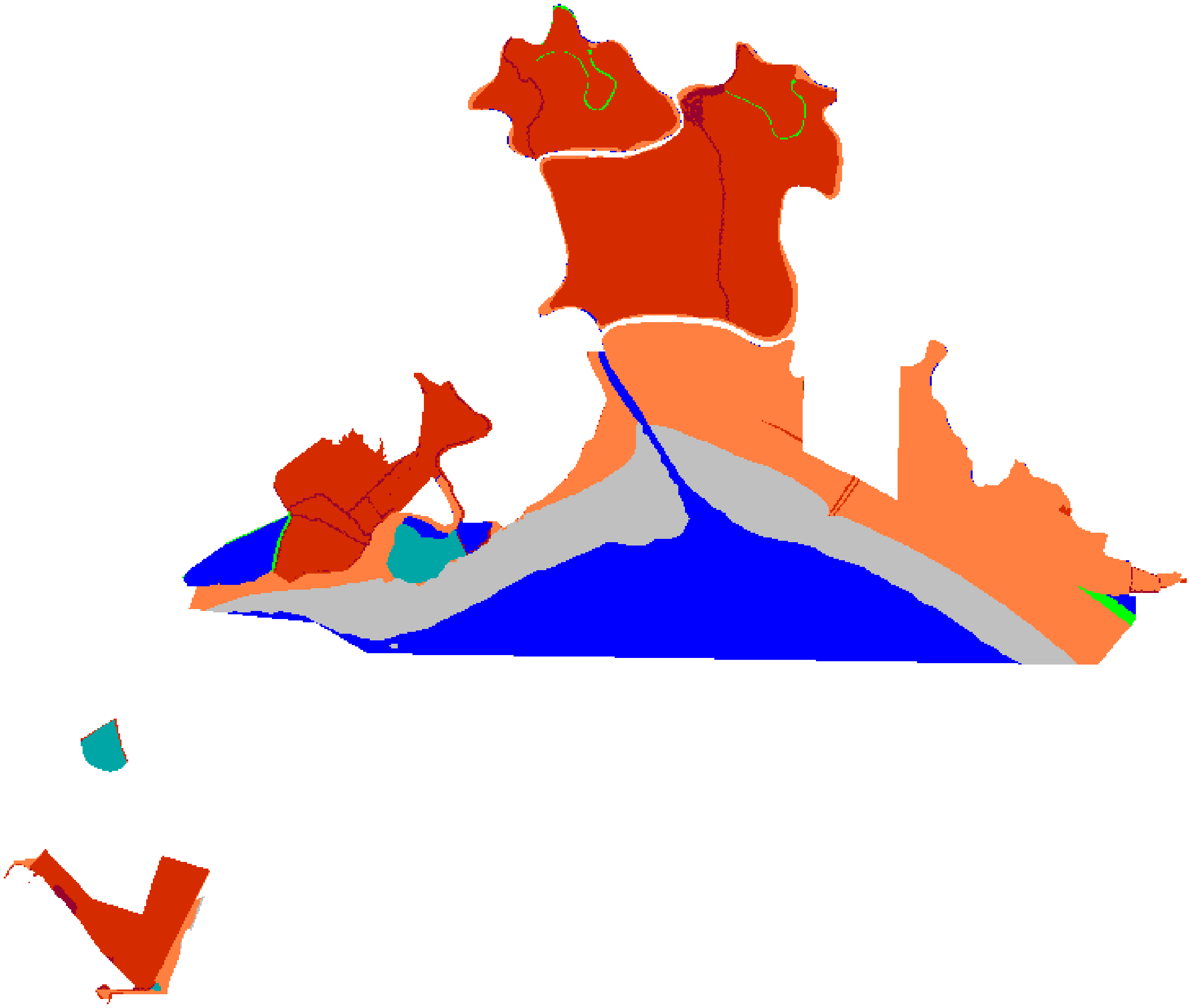


San Pablo Bay NWR, 2100, Scenario A1B Maximum

San Pablo Bay NWR
1 Meter Eustatic SLR by 2100

Results in Acres

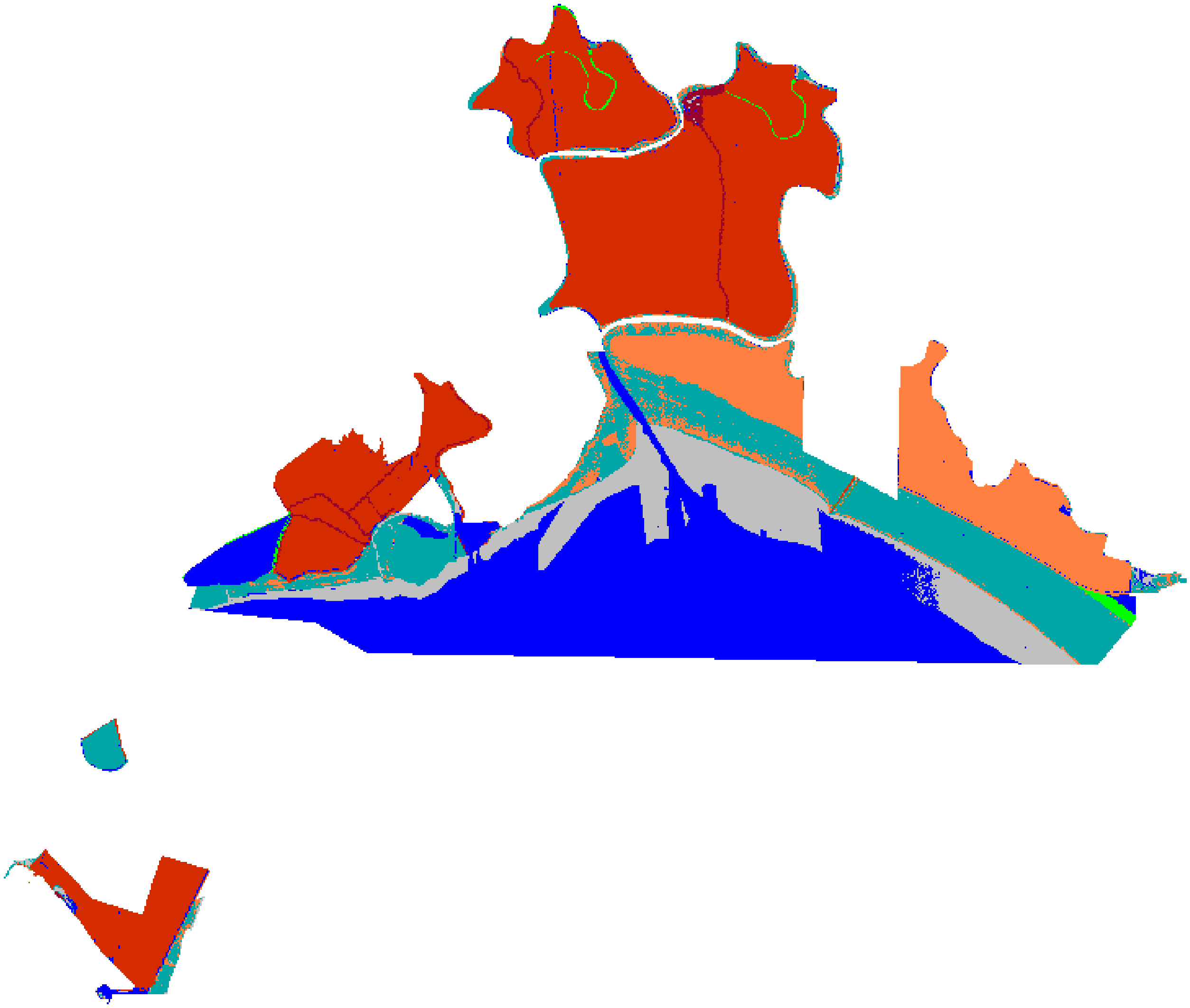
	Initial	2025	2050	2075	2100
Dry Land	7832.5	7789.3	7782.1	7725.8	6823.4
Irregularly Flooded Marsh	6049.1	5527.7	4702.6	2950.3	2203.7
Estuarine Open Water	5042.3	5354.3	5926.2	6802.0	8723.5
Tidal Flat	3739.1	3532.6	3037.3	2267.8	1586.3
Saltmarsh	377.6	879.1	1643.5	3353.0	3777.1
Dev. Dry Land	271.8	214.2	211.8	210.1	209.2
Inland Fresh Marsh	116.3	116.3	115.0	112.3	100.7
Tidal Creek	18.5	18.5	18.5	18.5	18.5
Inland Shore	1.3	1.3	1.3	1.3	0.9
Trans. Salt Marsh	0.0	15.1	10.3	7.5	5.1
Total (incl. water)	23448.6	23448.6	23448.6	23448.6	23448.6



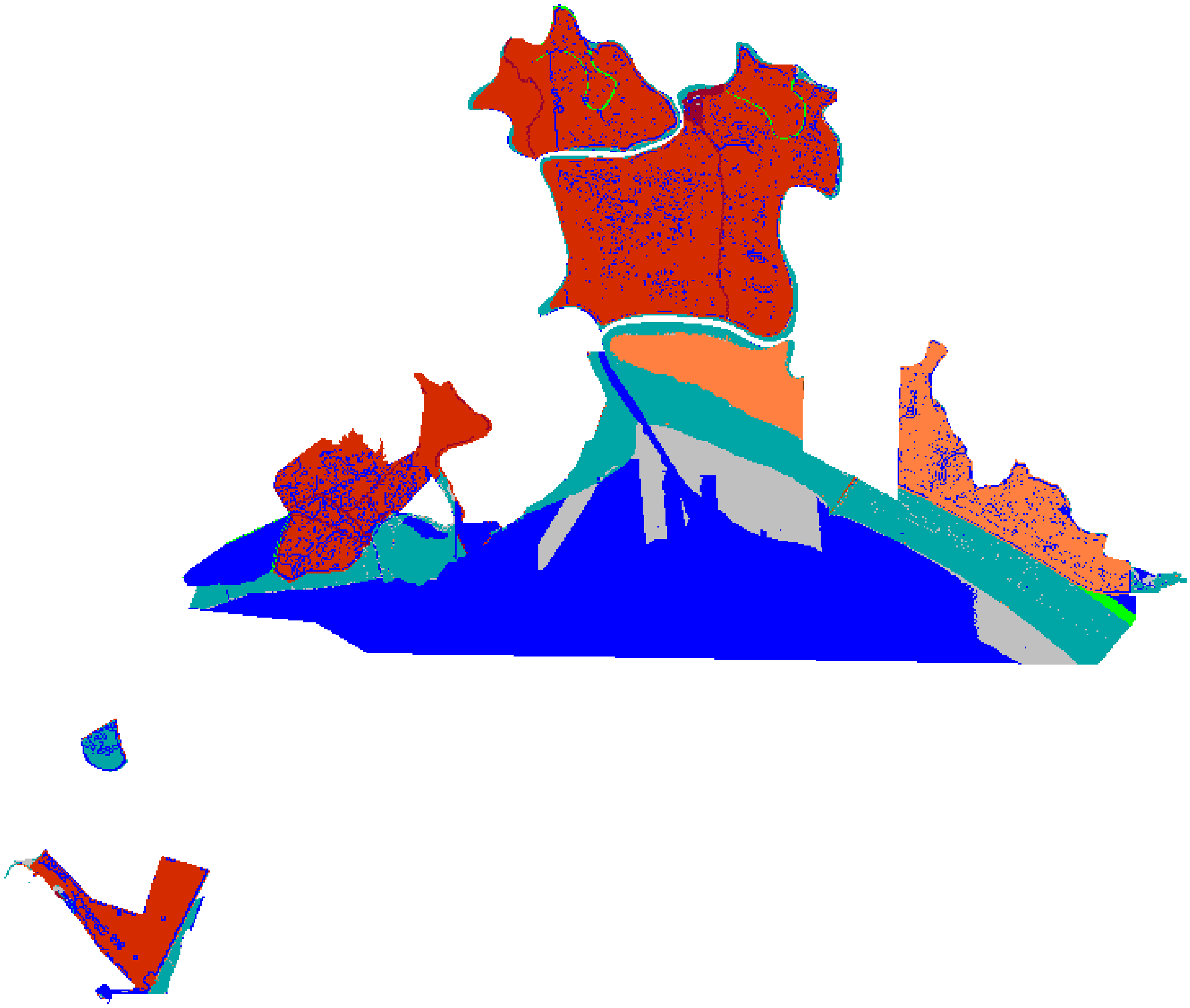
San Pablo Bay NWR, Initial Condition

San Pablo Bay NWR, 2025, 1 meter

San Pablo Bay NWR, 2050, 1 meter



San Pablo Bay NWR, 2075, 1 meter

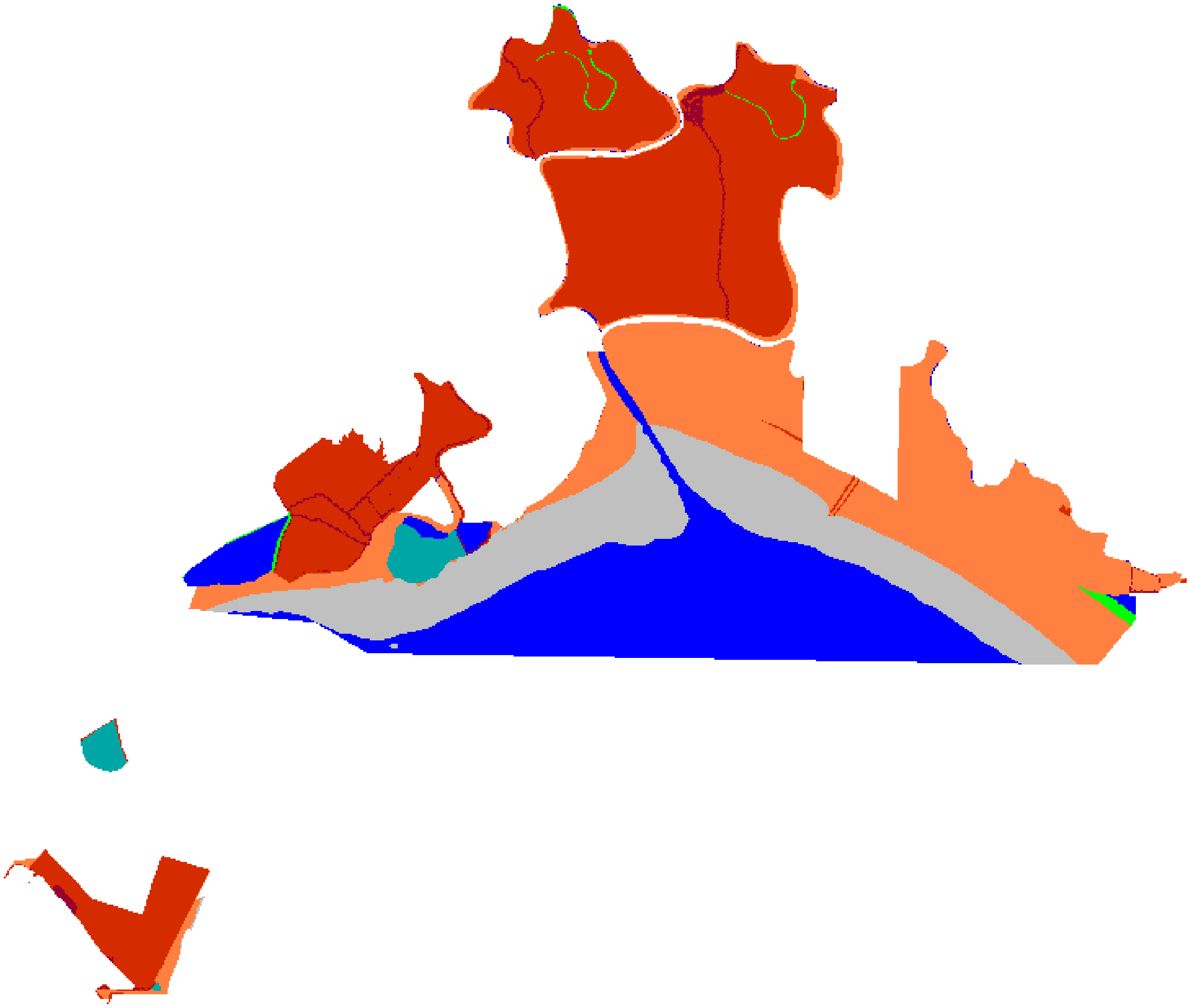


San Pablo Bay NWR, 2100, 1 meter

San Pablo Bay NWR
1.5 Meters Eustatic SLR by 2100

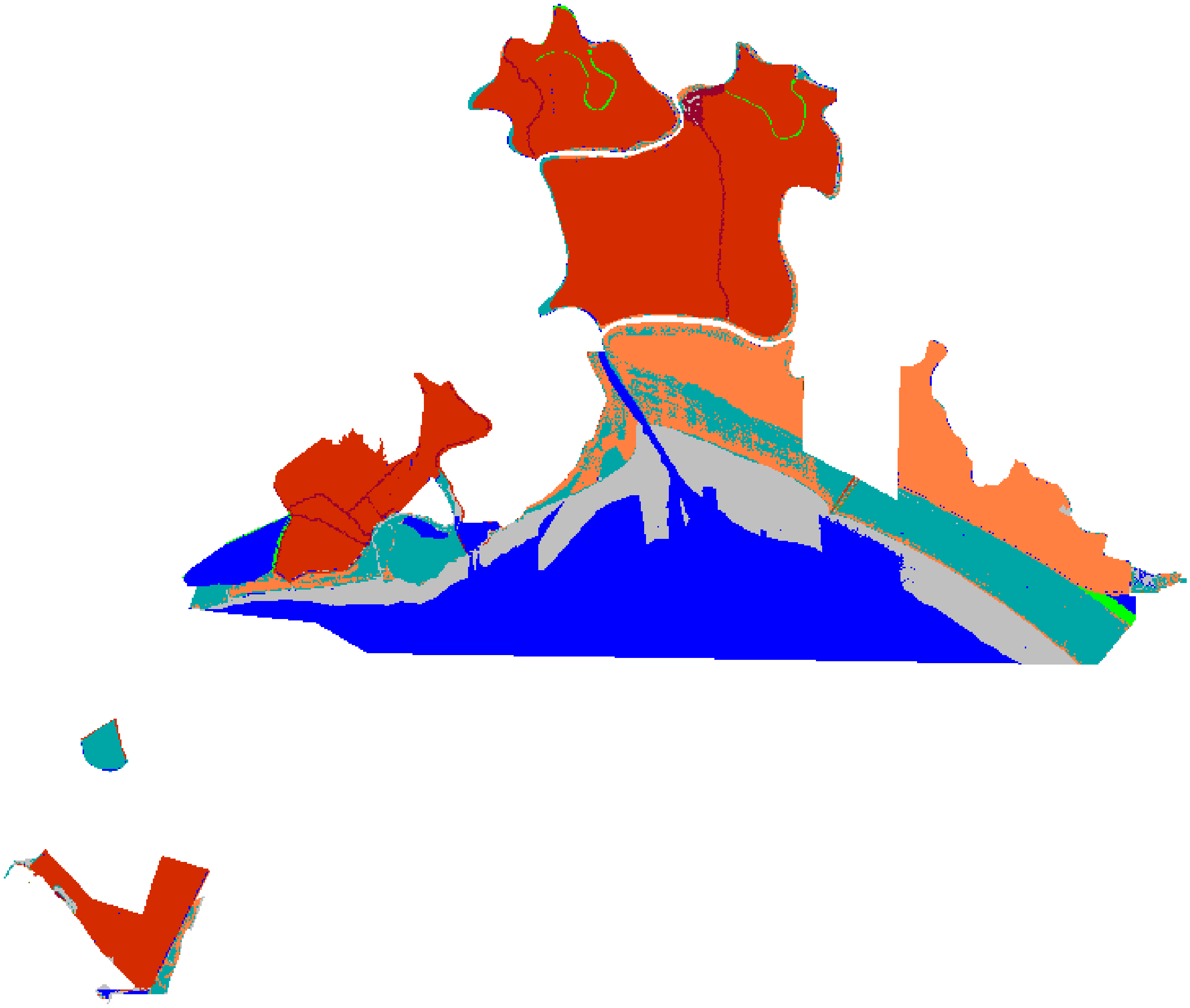
Results in Acres

	Initial	2025	2050	2075	2100
Dry Land	7832.5	7788.3	7758.4	5644.2	1498.8
Irregularly Flooded Marsh	6049.1	5308.7	3473.1	2054.6	962.7
Estuarine Open Water	5042.3	5513.0	6405.1	10138.3	16406.5
Tidal Flat	3739.1	3386.0	2628.3	2627.5	3860.6
Saltmarsh	377.6	1090.1	2831.4	2654.7	426.4
Dev. Dry Land	271.8	213.3	210.5	209.2	208.2
Inland Fresh Marsh	116.3	116.3	113.4	94.7	62.7
Tidal Creek	18.5	18.5	18.5	18.5	18.5
Inland Shore	1.3	1.3	1.3	0.9	0.0
Trans. Salt Marsh	0.0	13.1	8.4	6.0	4.1
Total (incl. water)	23448.6	23448.6	23448.6	23448.6	23448.6

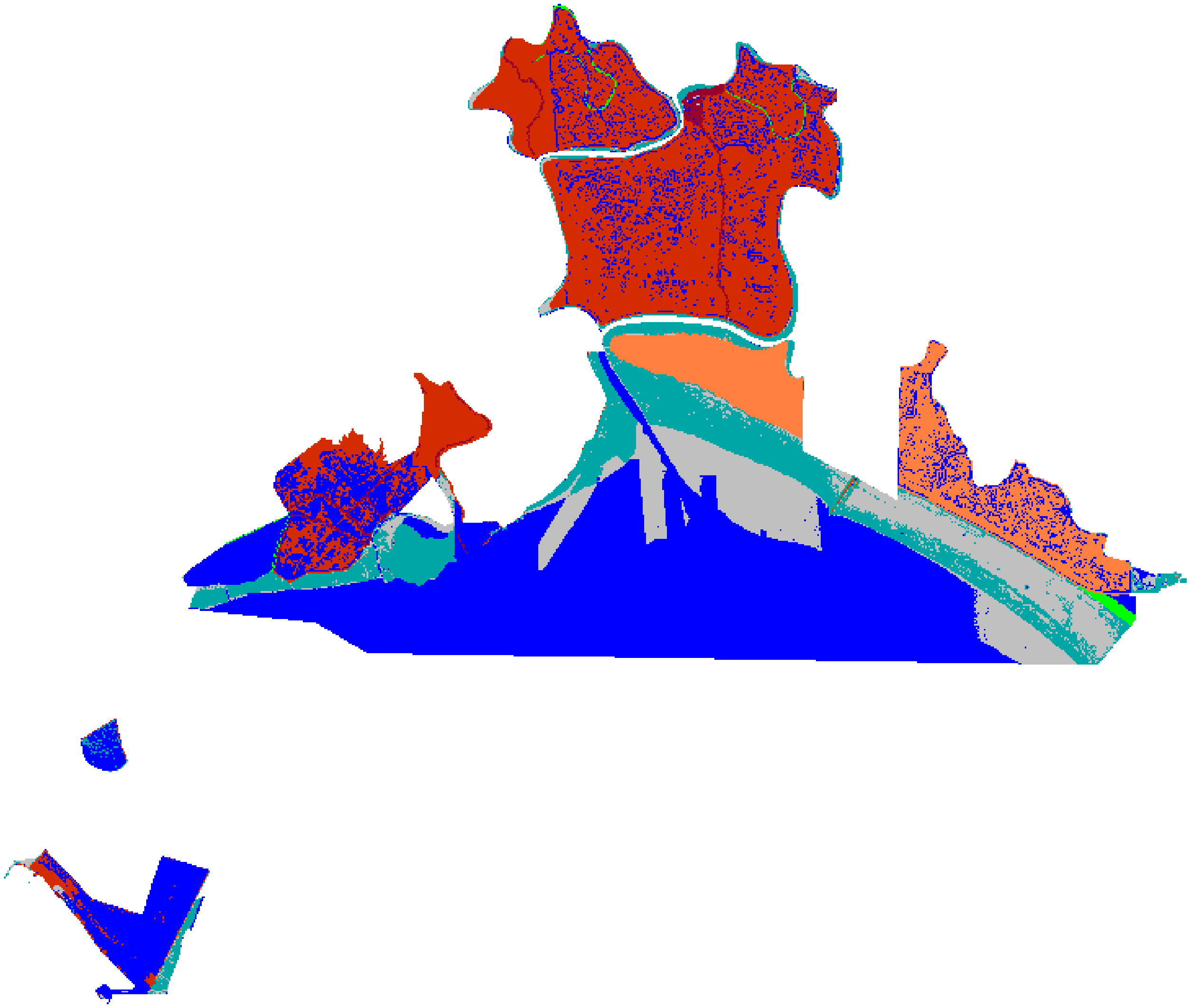


San Pablo Bay NWR, Initial Condition

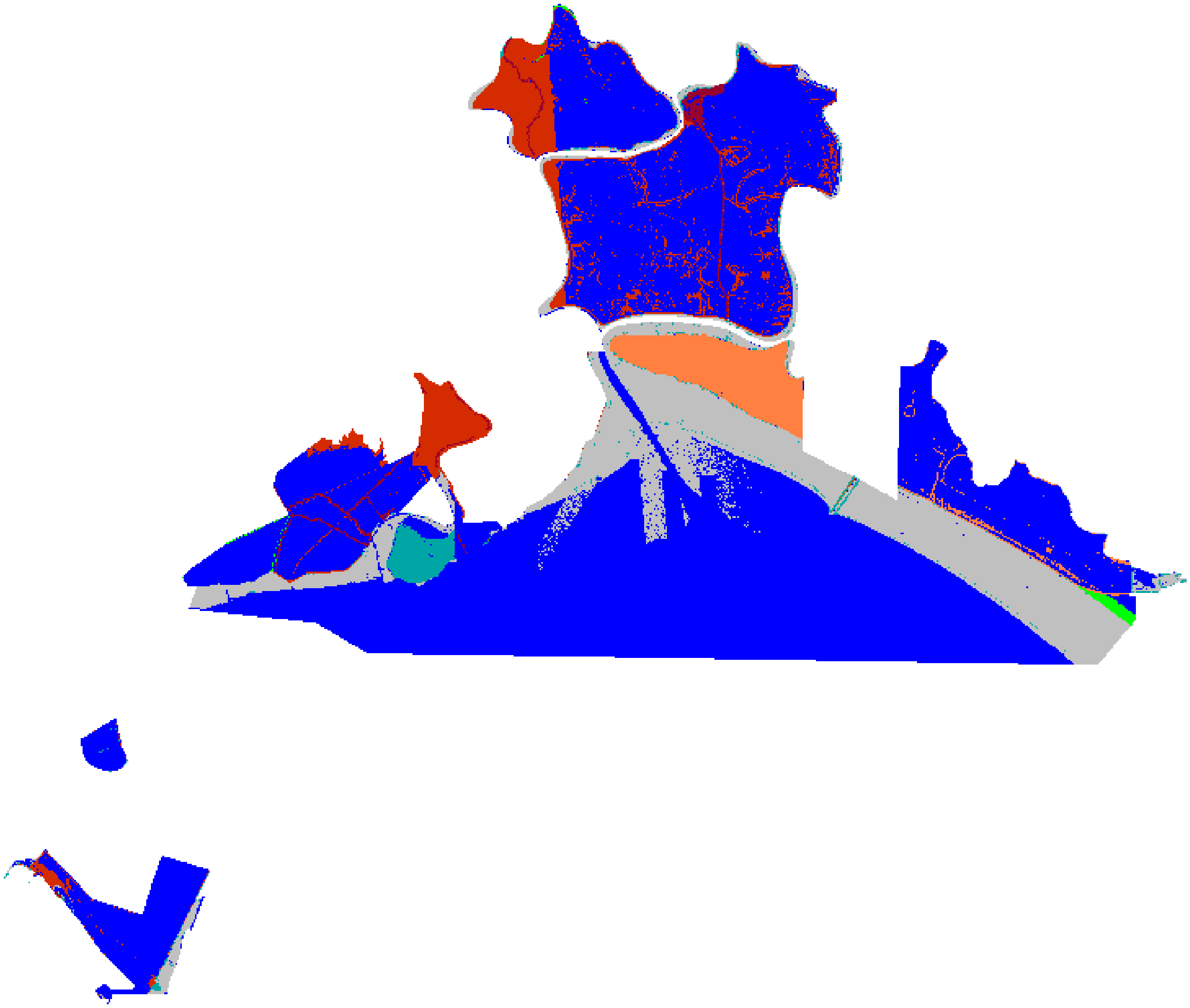
San Pablo Bay NWR, 2025, 1.5 meter



San Pablo Bay NWR, 2050, 1.5 meter



San Pablo Bay NWR, 2075, 1.5 meter

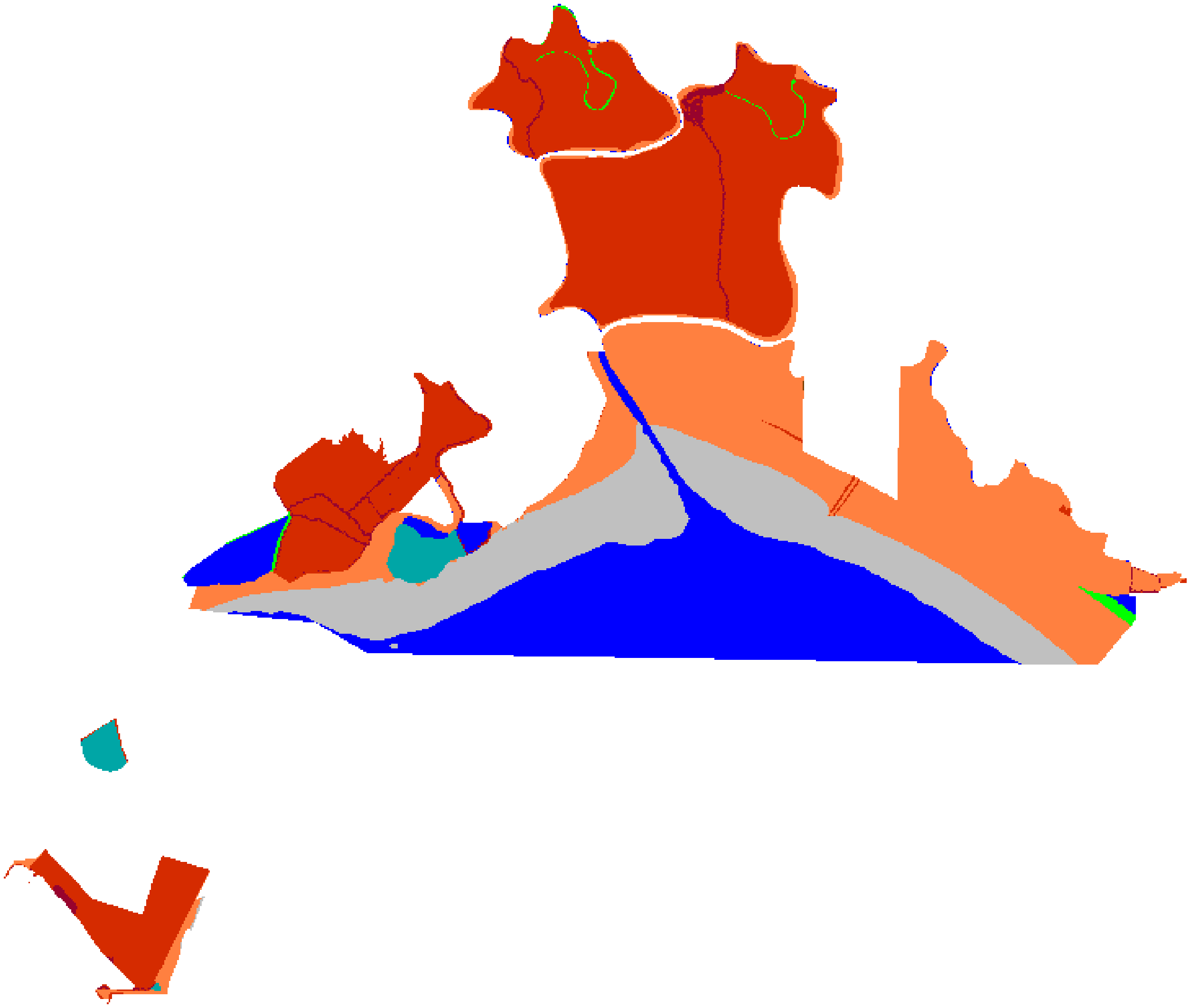


San Pablo Bay NWR, 2100, 1.5 meter

San Pablo Bay NWR
2 Meters Eustatic SLR by 2100

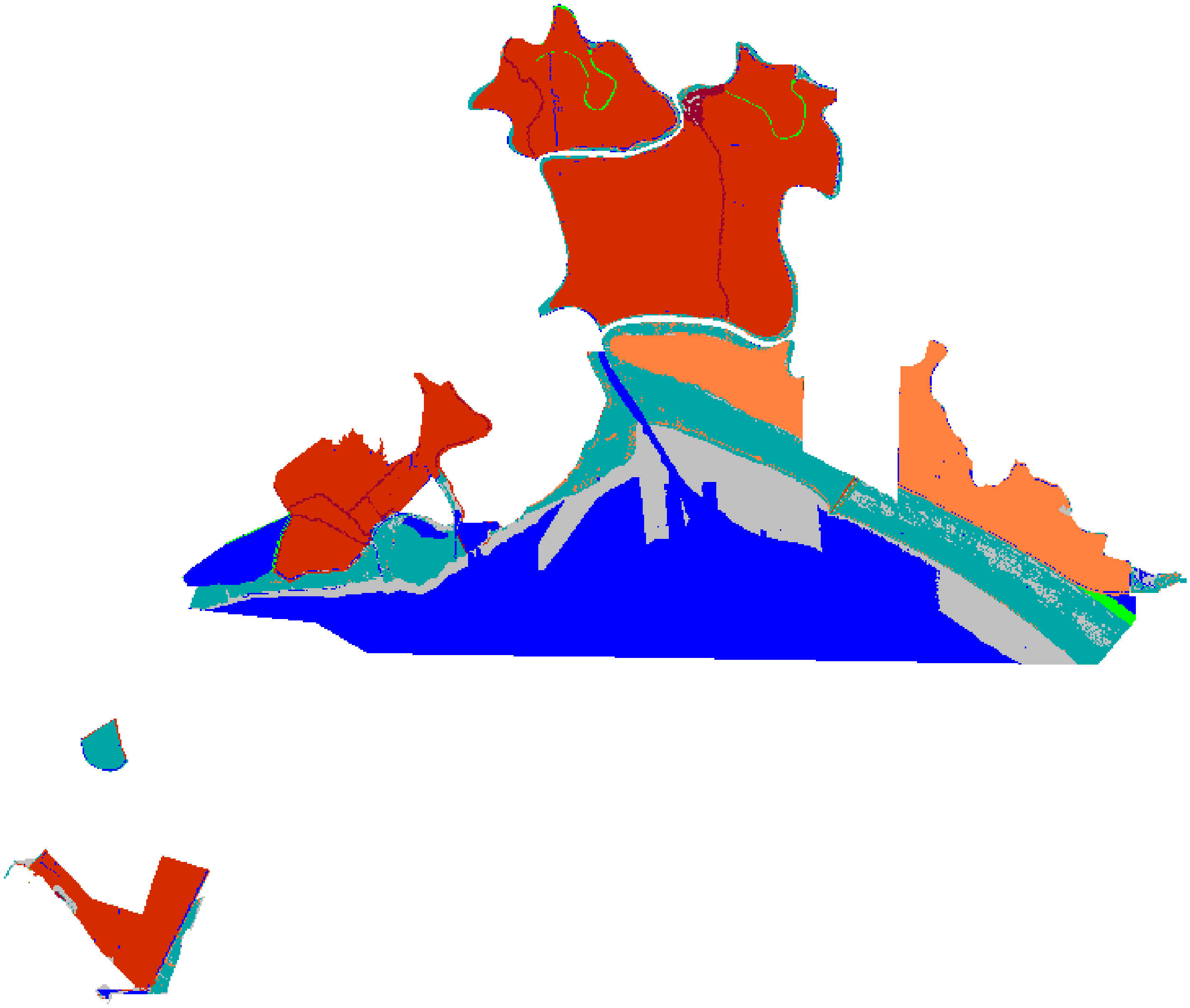
Results in Acres

	Initial	2025	2050	2075	2100
Dry Land	7832.5	7786.7	7696.7	2104.5	1047.8
Irregularly Flooded Marsh	6049.1	4982.2	2538.4	1052.3	858.1
Estuarine Open Water	5042.3	5691.4	7023.7	15343.1	18529.9
Tidal Flat	3739.1	3222.5	2364.6	4057.6	2489.5
Saltmarsh	377.6	1406.7	3475.8	594.5	234.3
Dev. Dry Land	271.8	212.6	209.8	208.6	207.3
Inland Fresh Marsh	116.3	115.6	110.5	63.4	60.0
Tidal Creek	18.5	18.5	18.5	18.5	18.5
Inland Shore	1.3	1.3	1.3	0.0	0.0
Trans. Salt Marsh	0.0	11.0	9.2	6.1	3.1
Total (incl. water)	23448.6	23448.6	23448.6	23448.6	23448.6



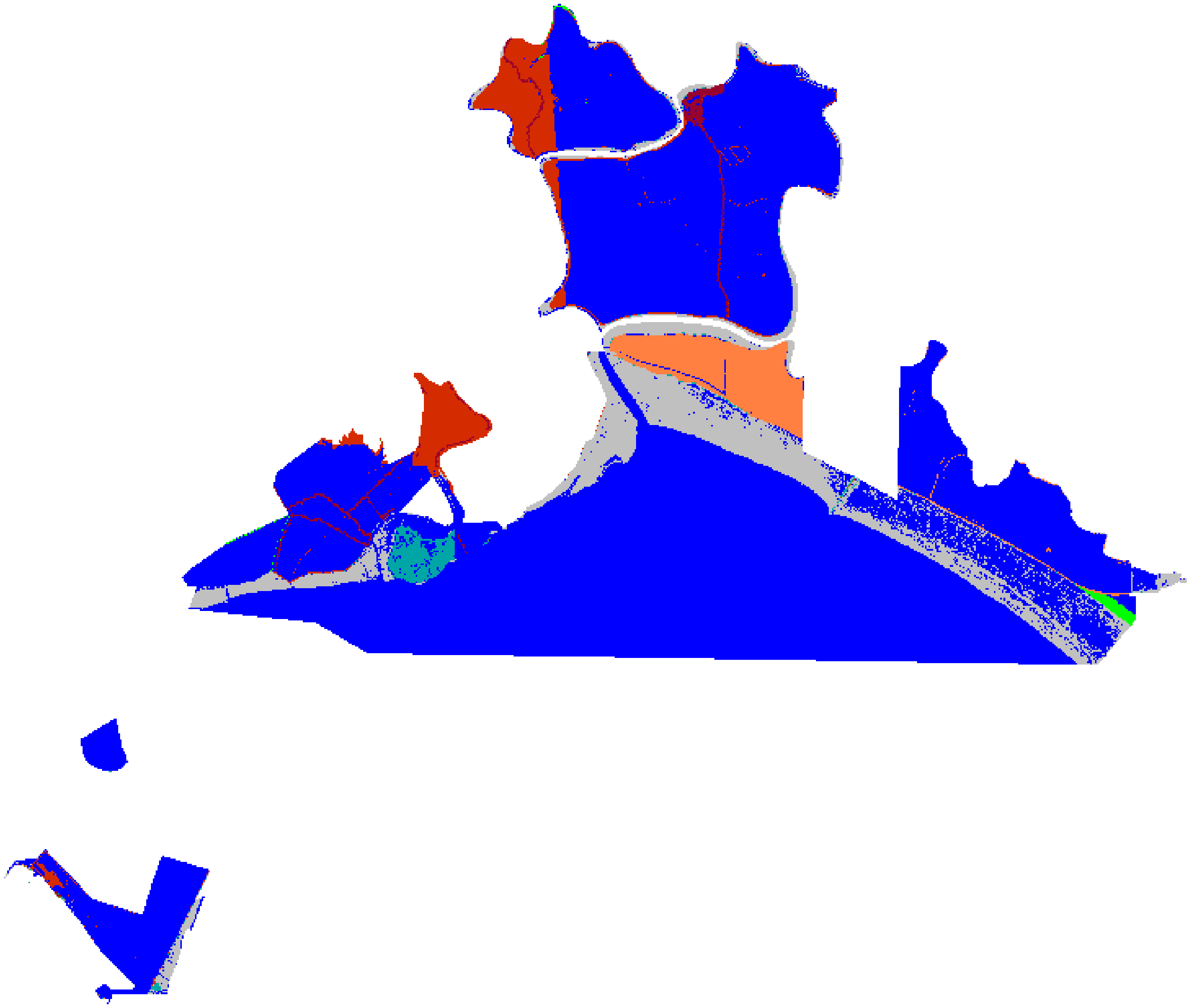
San Pablo Bay NWR, Initial Condition

San Pablo Bay NWR, 2025, 2 meters



San Pablo Bay NWR, 2050, 2 meters

San Pablo Bay NWR, 2075, 2 meters



San Pablo Bay NWR, 2100, 2 meters

Discussion

Probably the most significant model prediction for this site is the conversion of irregularly flooded (high) marshes into regularly flooded salt marshes (and even tidal flats) under higher rates of sea level rise. Accretion rates are predicted to jump by a factor of five when high marshes become regularly inundated due to relatively high suspended sediment at this site. Further feedbacks to accretion rates (for example, when regularly flooded marshes fall further in elevation and become inundated more frequently) are not included in this model simulation.

Another notable model prediction is the conversion of dry lands to open water. There is an admittedly somewhat arbitrary model assumption that diked lands that fall two meters below mean tide level are subject to conversion to open water. Model results based on this assumption – like the flooding of diked dry lands in the higher SLR scenarios – are therefore subject to uncertainty. However, according to Giselle Block, a wildlife biologist at San Pablo NWR, many of the dikes in this region are poorly maintained and are already breached by large storm events.

Some land-cover data received did not initially match up with SLAMM elevation expectations. Based on these concerns, we also communicated with Giselle Block regarding the accuracy of the land-cover data. After examining our NWI layer, Block provided us with feedback concerning wetland types she felt were mischaracterized. As noted in Figure 2, areas one and two were changed from dry land to irregularly-flooded (high) marsh in response to this communication. The areas protected by dikes were also refined at this time. These changes brought the site more into alignment with the SLAMM conceptual model.

The mosaic nature of the elevation data covering this site (Figure 1) can increase model uncertainty. Some elevation data sets did not seamlessly link vertically with others. This resulted in interesting shapes in model results (especially for tidal flats) that are likely artifacts of stitching together multiple elevation data sets.

San Pablo Bay NWR has been heavily modified over the past century for the purpose of grazing, water diversions, and salt production. The addition of manmade channels and culverts makes the area more hydrodynamically complex. SLAMM is not a hydrodynamic model, which can also increase model uncertainty in such a heavily modified area.

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.

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

Clark, J. S. and W. A. Patterson III. 1984. Pollen, Pb-210 and sedimentation in the intertidal environment. Journal of Sedimentary Petrology 54(4):1249-1263.

Clough, J.S. Park, R.A. and R. Fuller, 2010, *SLAMM Technical Documentation, Release 6.0 beta, Draft,* January 2010, 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

Culberson, S.D., Foin, T.C.et Collins, J.N., 2004.The role of sedimentation in estuarine marsh development within the San Francisco estuary, California, USA.Journal of Coastal Research, 20:970-979.

Erwin, RM, GM Sanders, DJ Prosser, and DR Cahoon. 2006. High tides and rising seas: potential effects on estuarine waterbirds. Pages 214-228 in: Terrestrial Vertebrates of Tidal Marshes: Evolution, Ecology, and Conservation (R. Greenberg, J. Maldonado, S. Droege, and M.V. McDonald, eds.). Studies in Avian Biology No. 32, Cooper Ornithological Society.

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

Hardaway, C.S. and G.L. Anderson, 1980. *Shoreline Erosion in Virginia.* Sea Grant Program, Marine Advisory Service, Virginia Institute of Marine Science, Gloucester Point, VA, 25 p.

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.

Jaffe, Smith, and Torresan, 1998. Sedimentation and Bathymetric Change in San Pablo Bay: 1856–1983, USGS Open-File Report 98-759.

Jaffe, B. E., and A. C. Foxgrover. 2006. Sediment Deposition and Erosion in South San Francisco Bay, California from 1956 to 2005. U.S. Geological Survey Open-File Report 2006–1262, 24 pp. http://pubs.usgs.gov/of/2006/1287.

Kraft, J.C., Yi, H., Khalequzzaman, M., 1992. Geologic and human factors in the decline of the salt marsh lithosome: the Delaware Estuary and Atlantic Coastal zone. *Sedimentary Geology* 80, 233-246.

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.

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.

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

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, Subsidence, accretion, and sea level rise in south San Francisco Bay marshes, Limnol.Oceanogr., 35, 1389–1395, 1990.

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.

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.

United States Fish and Wildlife Service. 2009. Bombay Hook National Wildlife Refuge: Draft Comprehensive Conservation Plan and Environmental Assessment.

USGS, 2004, Restoration Research and Monitoring in Bayland Wetlands of San Francisco Bay: The Tolay Creek Restoration Project 2004 Progress Report (USGS unpublished)

Vermeer, M., and Rahmstorf, S. (2009) Global sea level linked to global temperature. *Proceedings of the National Academy of Sciences,* 106:21527–21532.

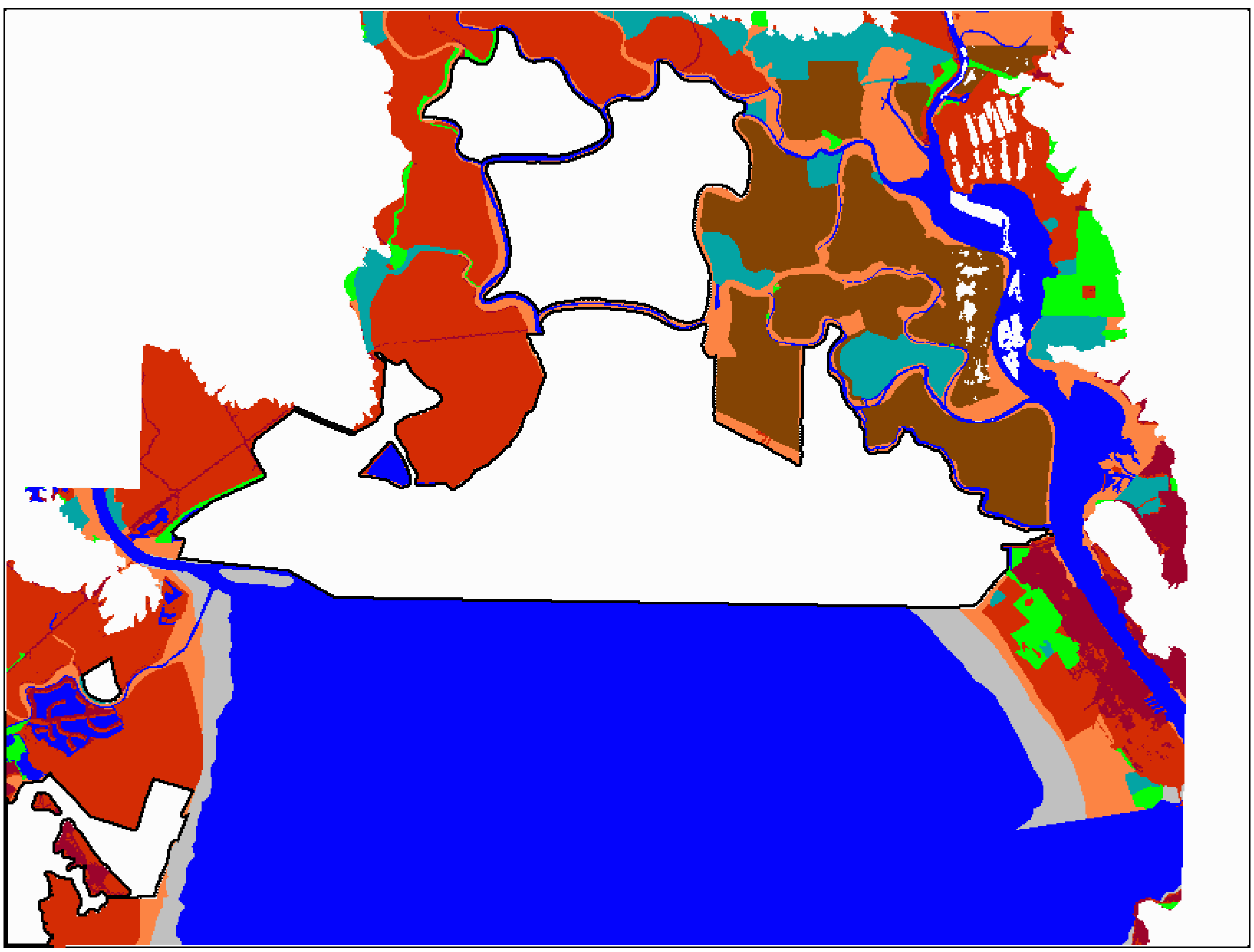
Watson, E. B. 2004. "Changing elevation, accretion, and tidal marsh plant assemblages in South San Francisco Bay tidal marsh." Estuaries 27(4):684–698.

Appendix A: Contextual Results

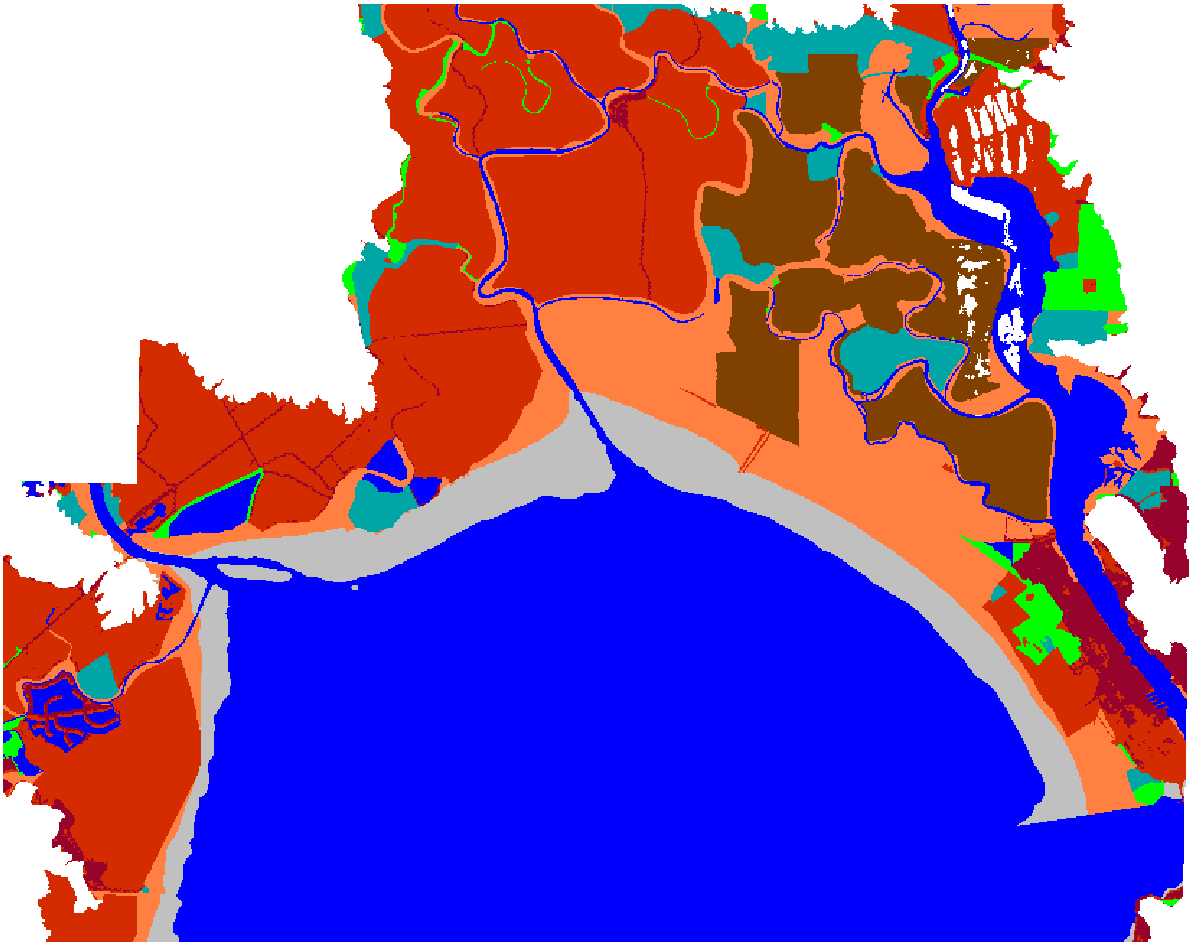
The SLAMM model does take into account the context of the surrounding lands or open water when calculating effects. For example, erosion rates are calculated based on the maximum fetch (wave action) which is estimated by assessing contiguous open water to a given marsh cell. Another example is that inundated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

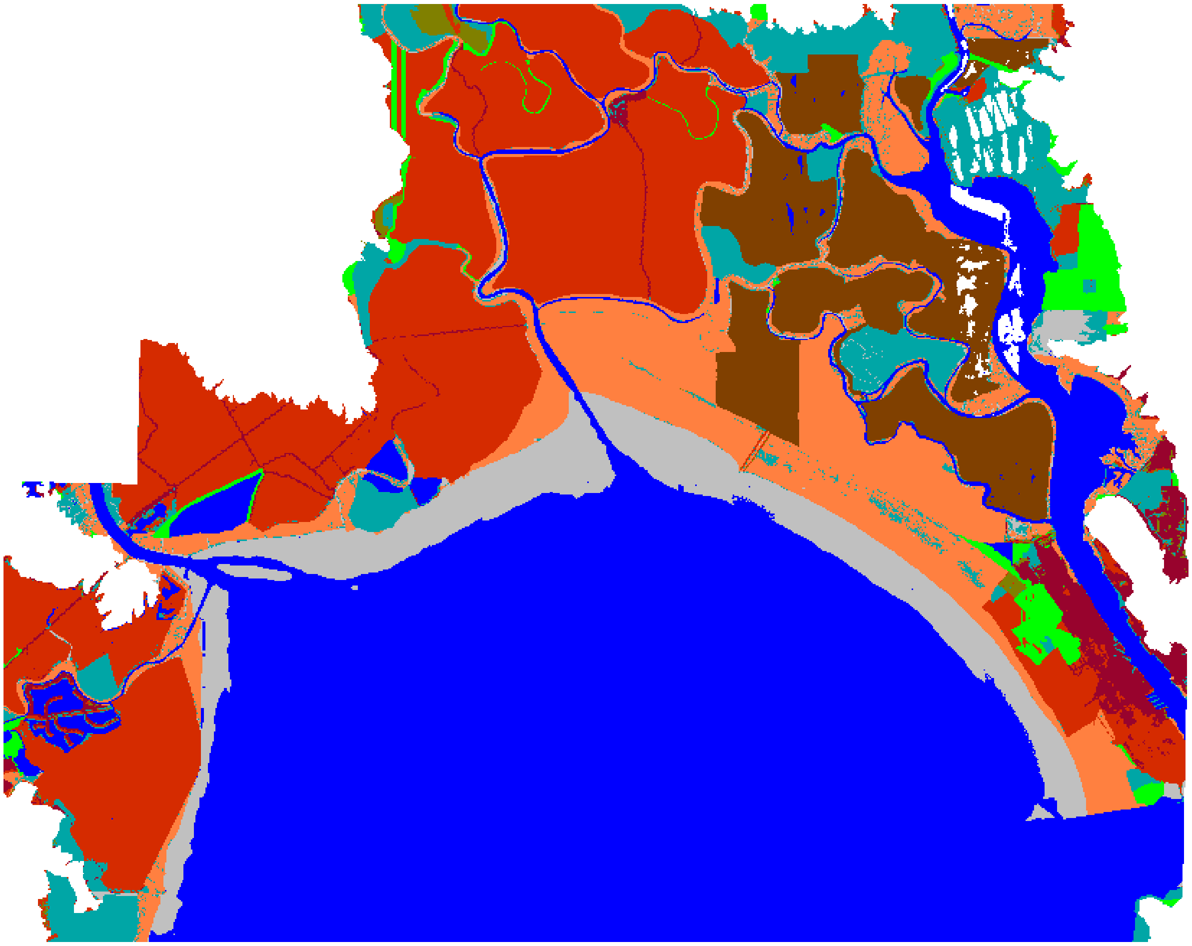
- Results were closely examined (quality assurance) within USFWS refuges but not closely examined for the larger region.
- Site-specific parameters for the model were derived for USFWS refuges whenever possible and may not be regionally applicable.
- Especially in areas where dikes are present, an effort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



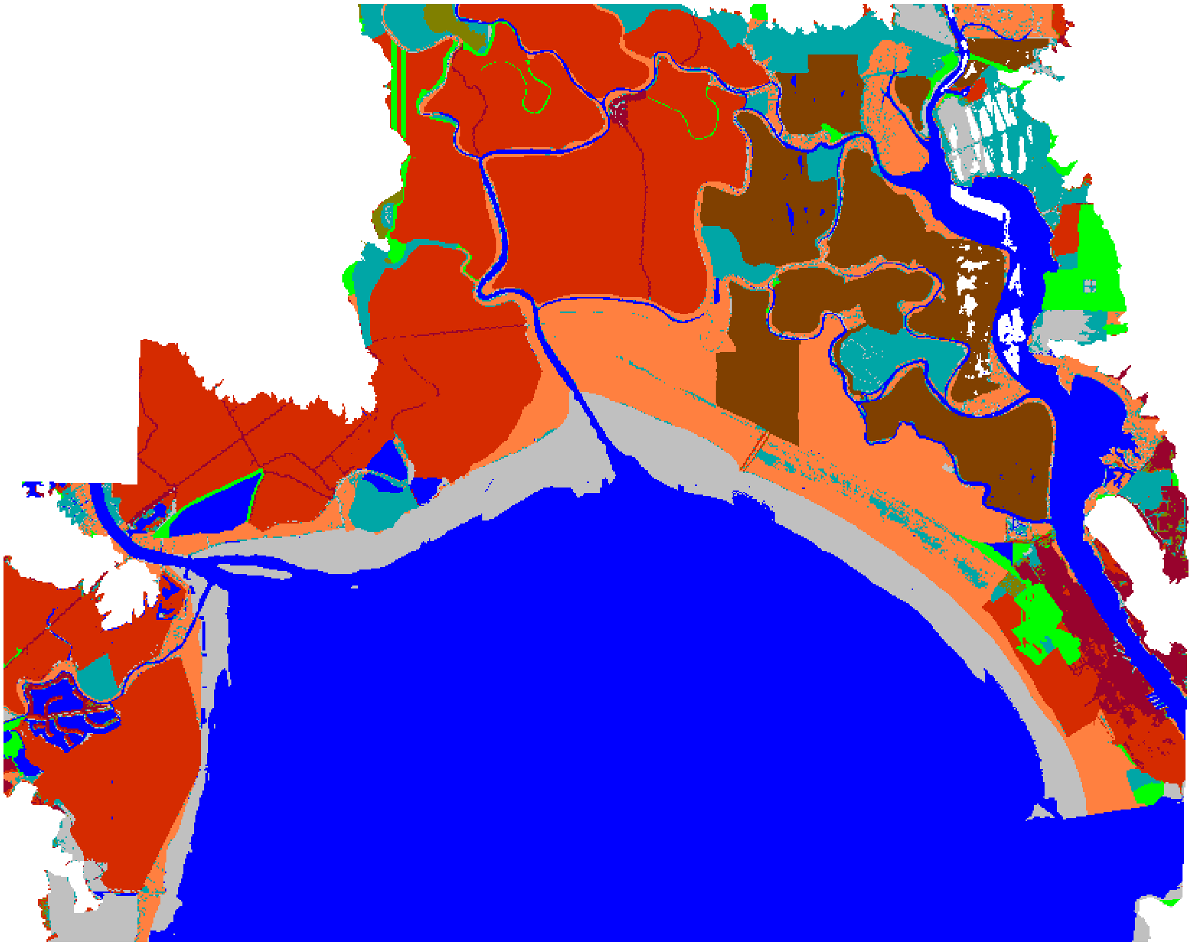
Location of San Pablo Bay National Wildlife Refuge within simulation context



San Pablo Bay NWR, Initial Condition



San Pablo Bay NWR, 2025, Scenario A1B Mean



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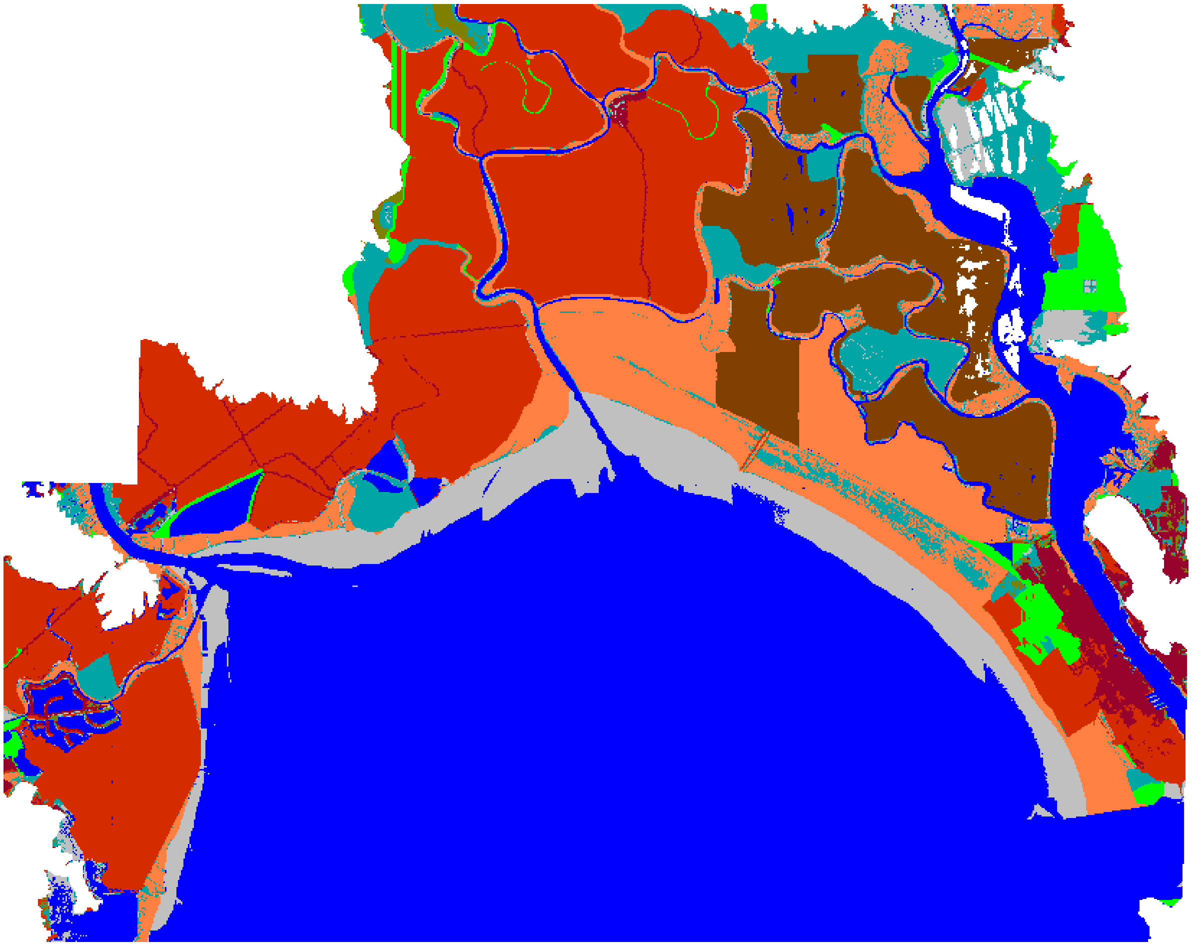
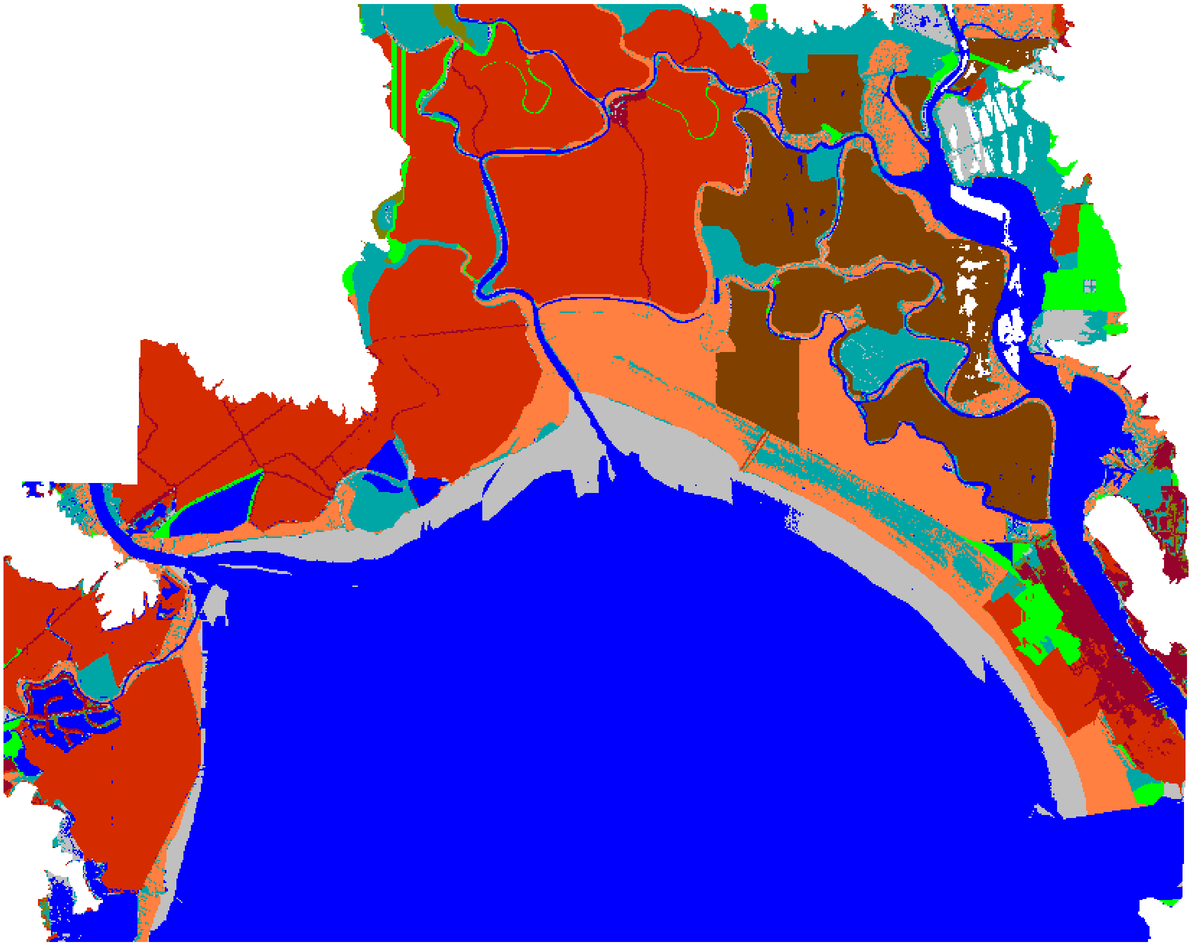
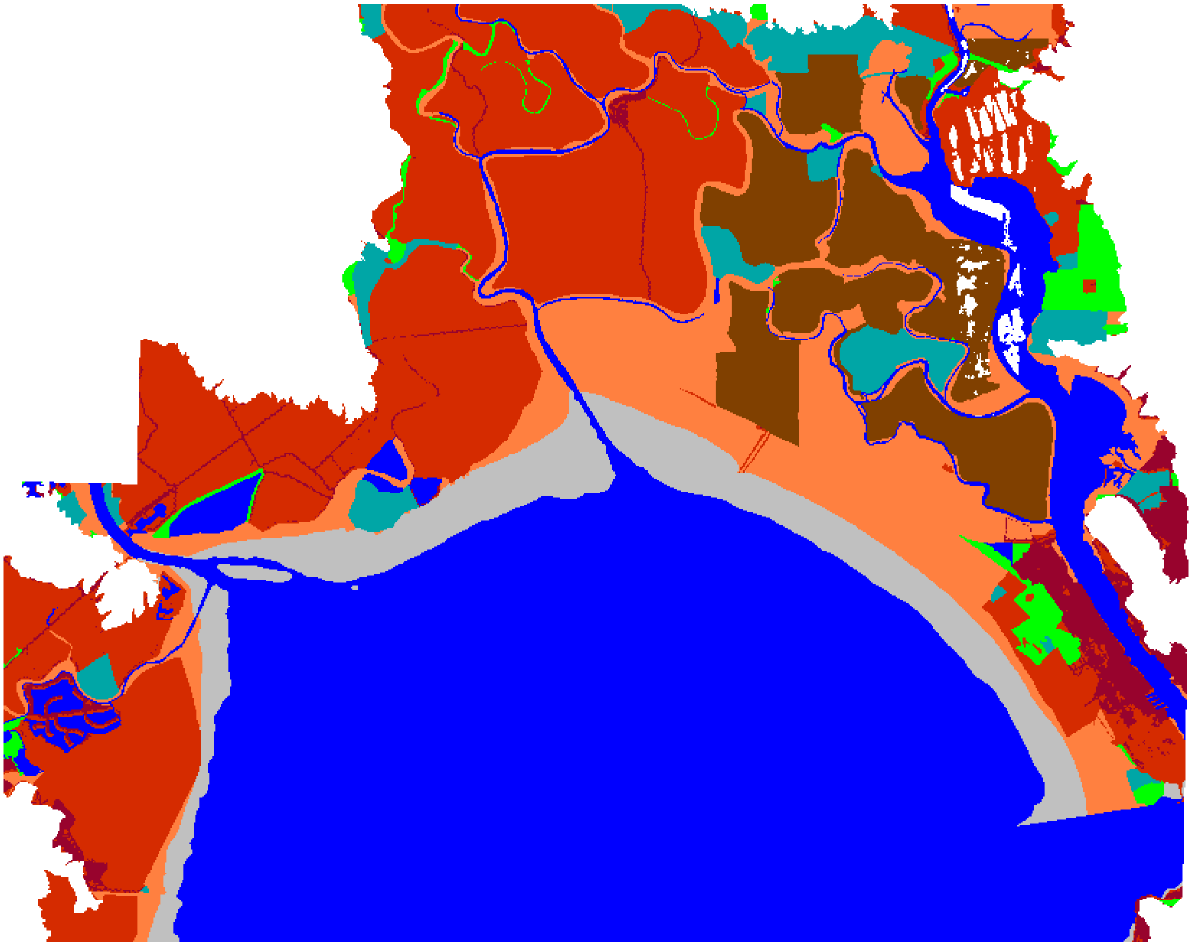


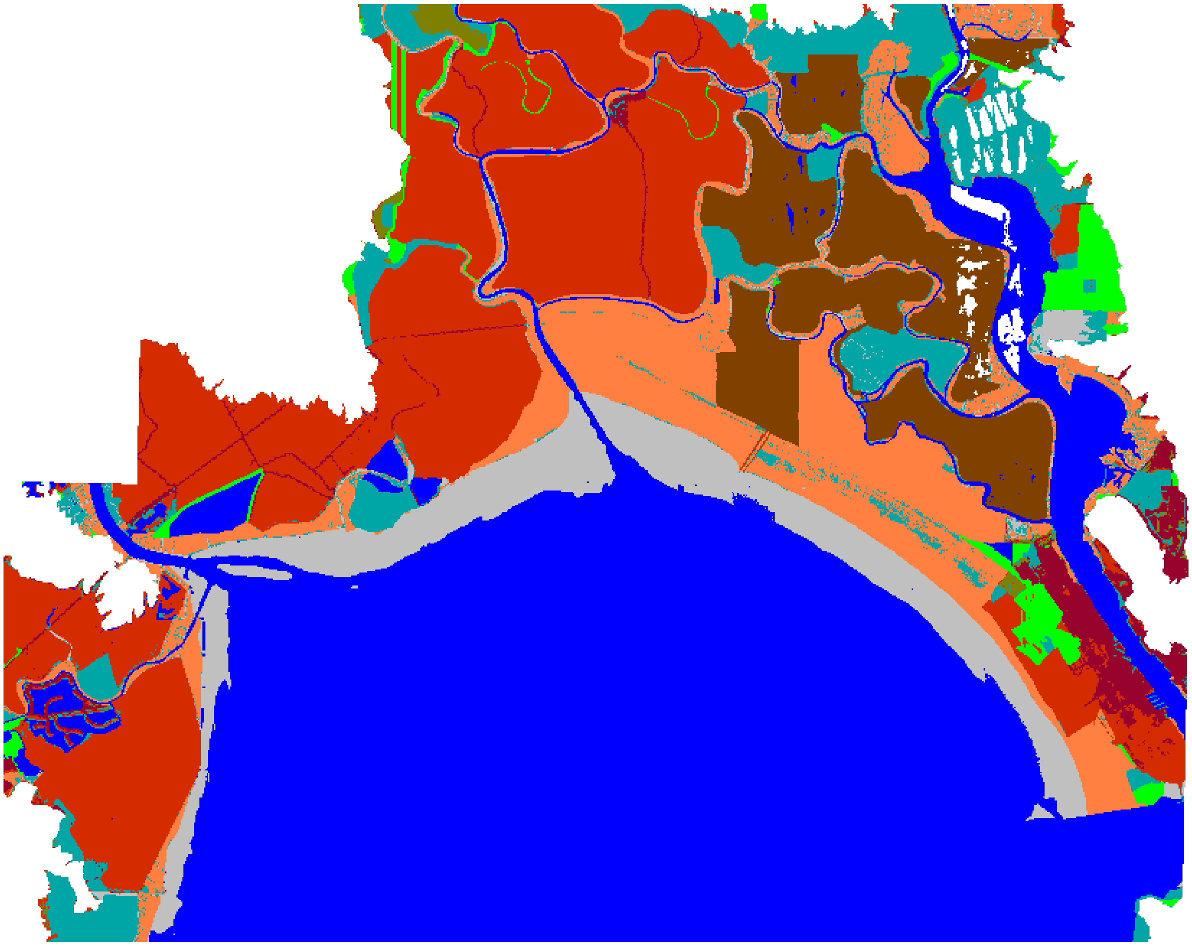
San Pablo Bay NWR, 2075, Scenario A1B Mean

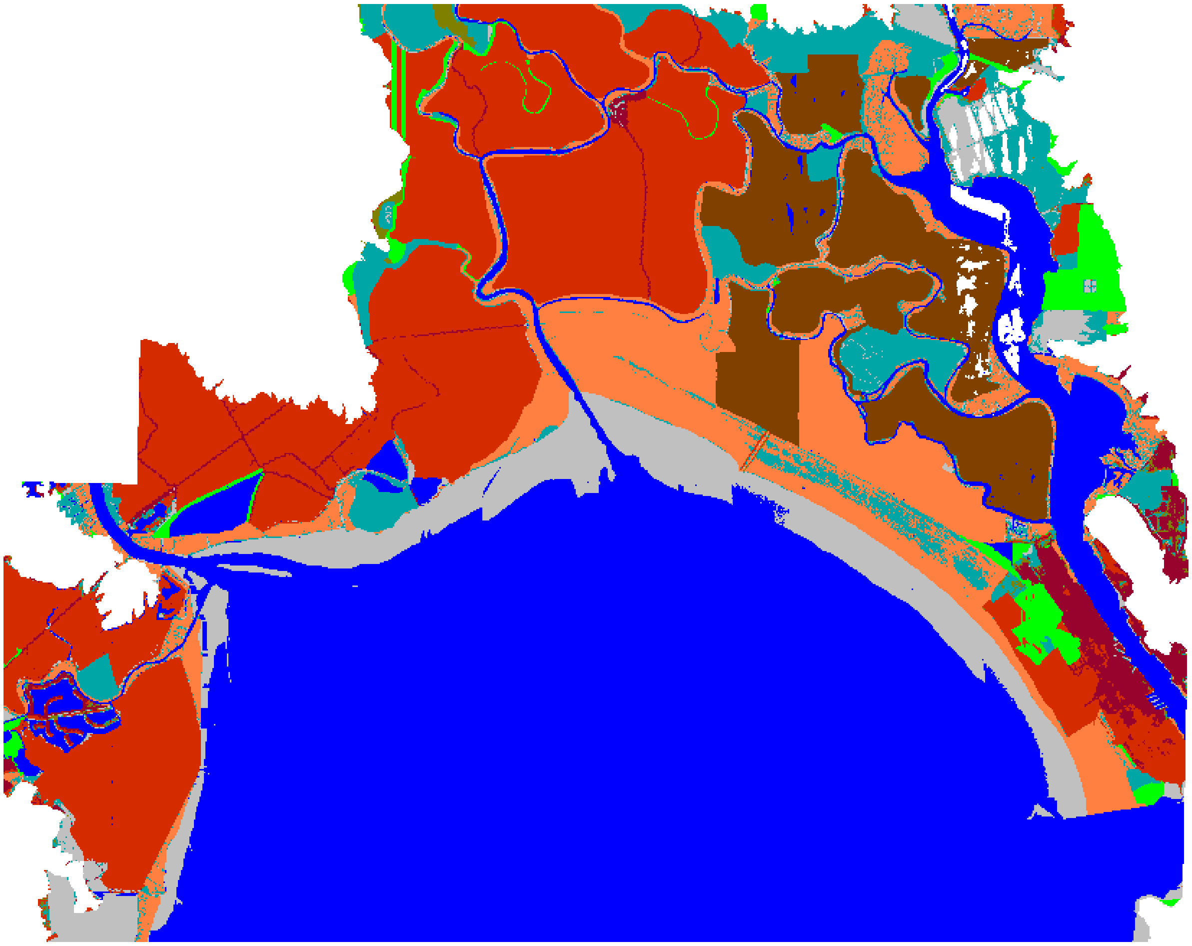


San Pablo Bay NWR, 2100, Scenario A1B Mean

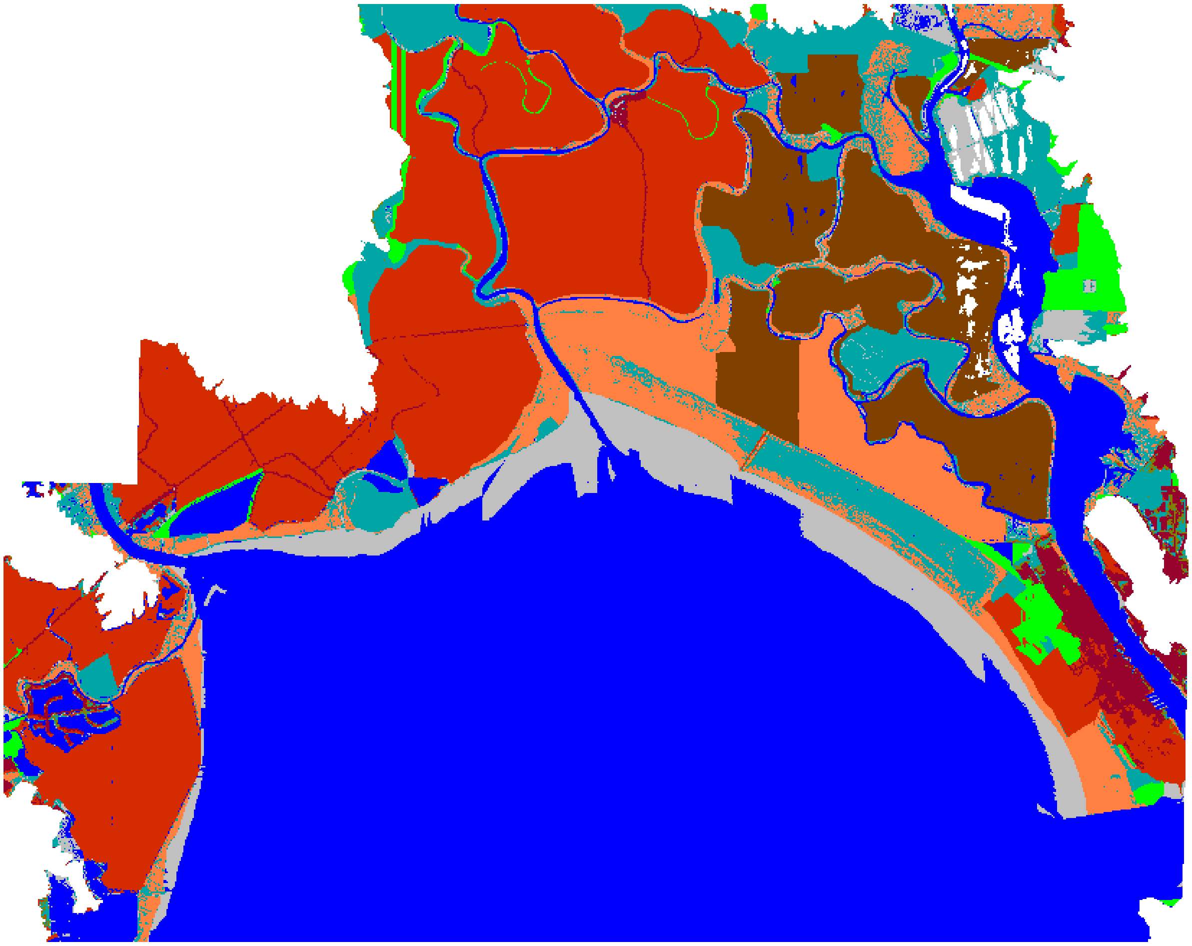


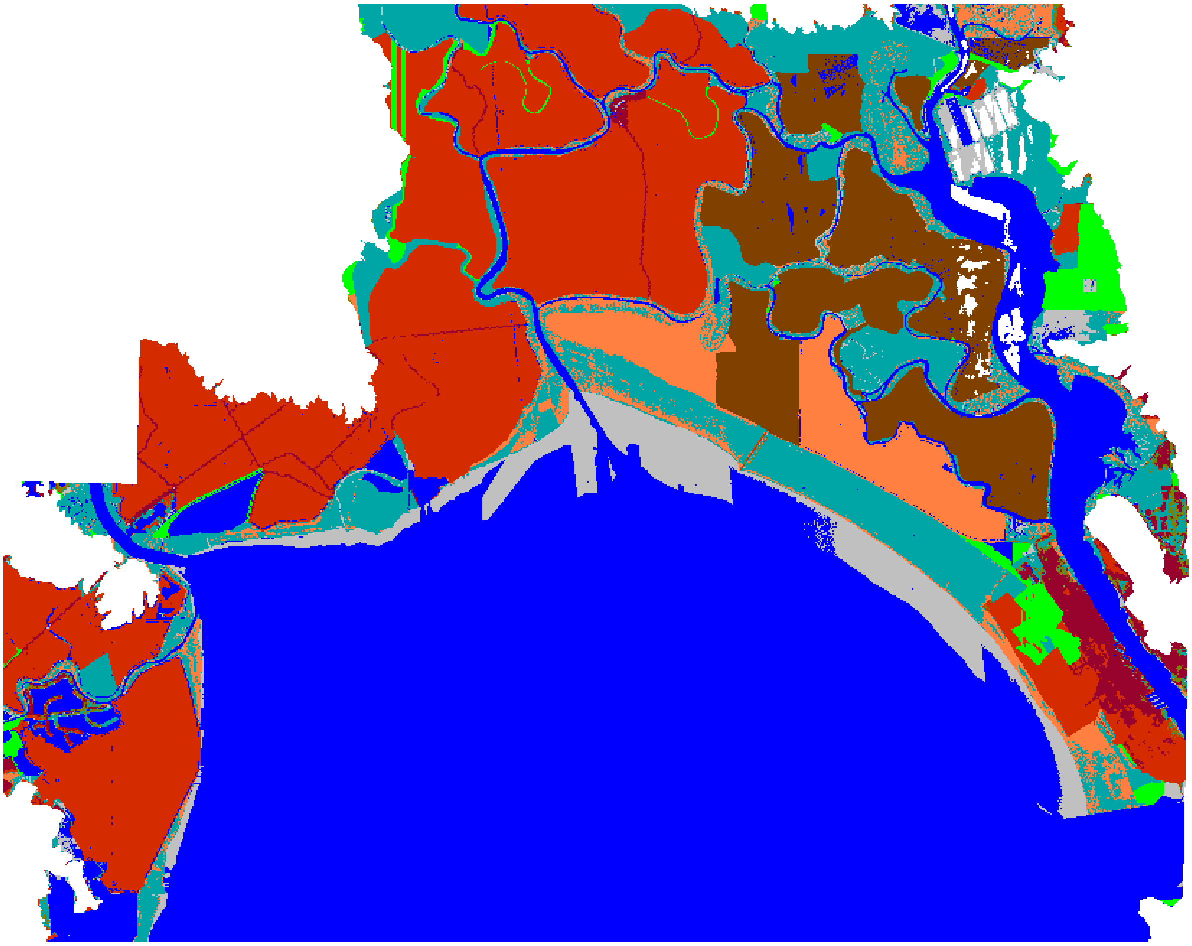
San Pablo Bay NWR, Initial Condition

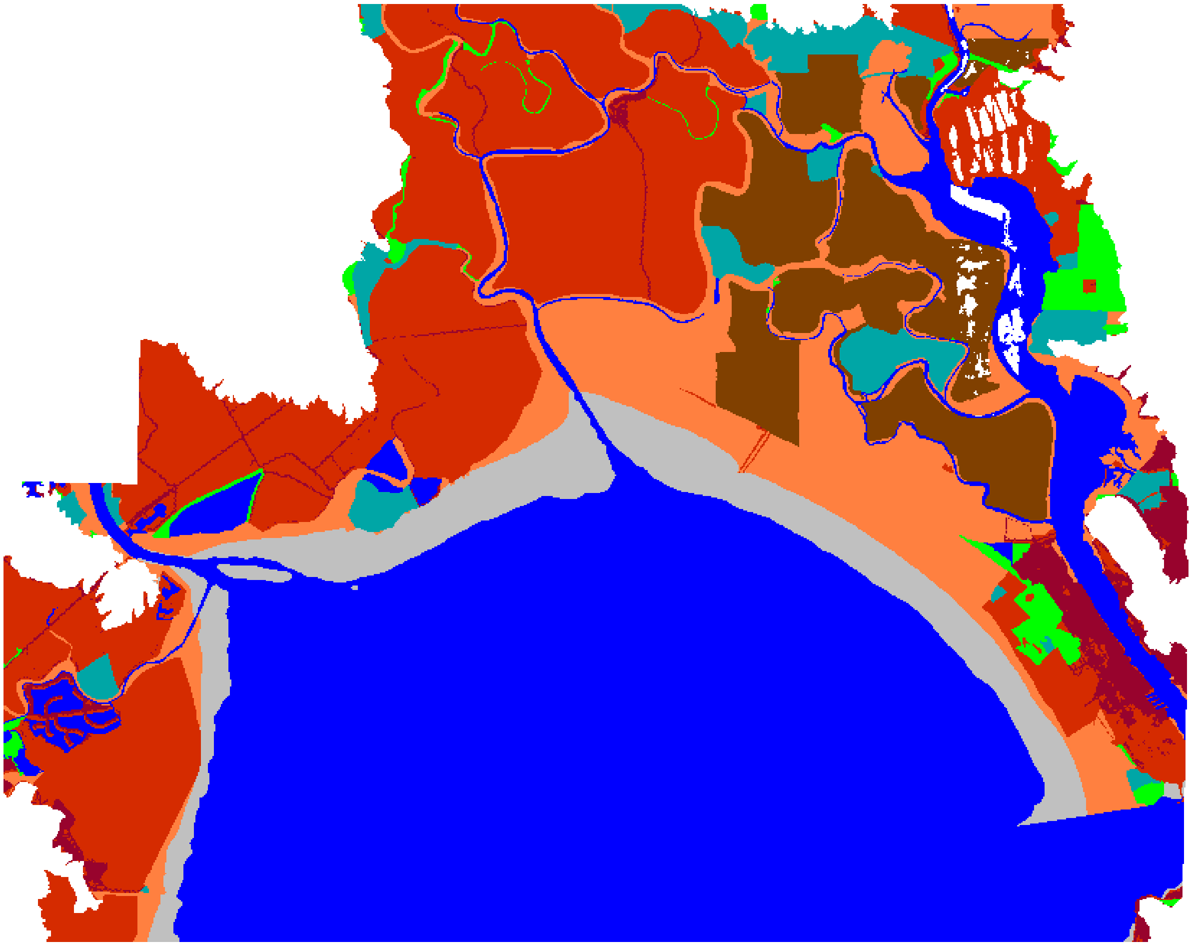

San Pablo Bay NWR, 2025, Scenario A1B Maximum



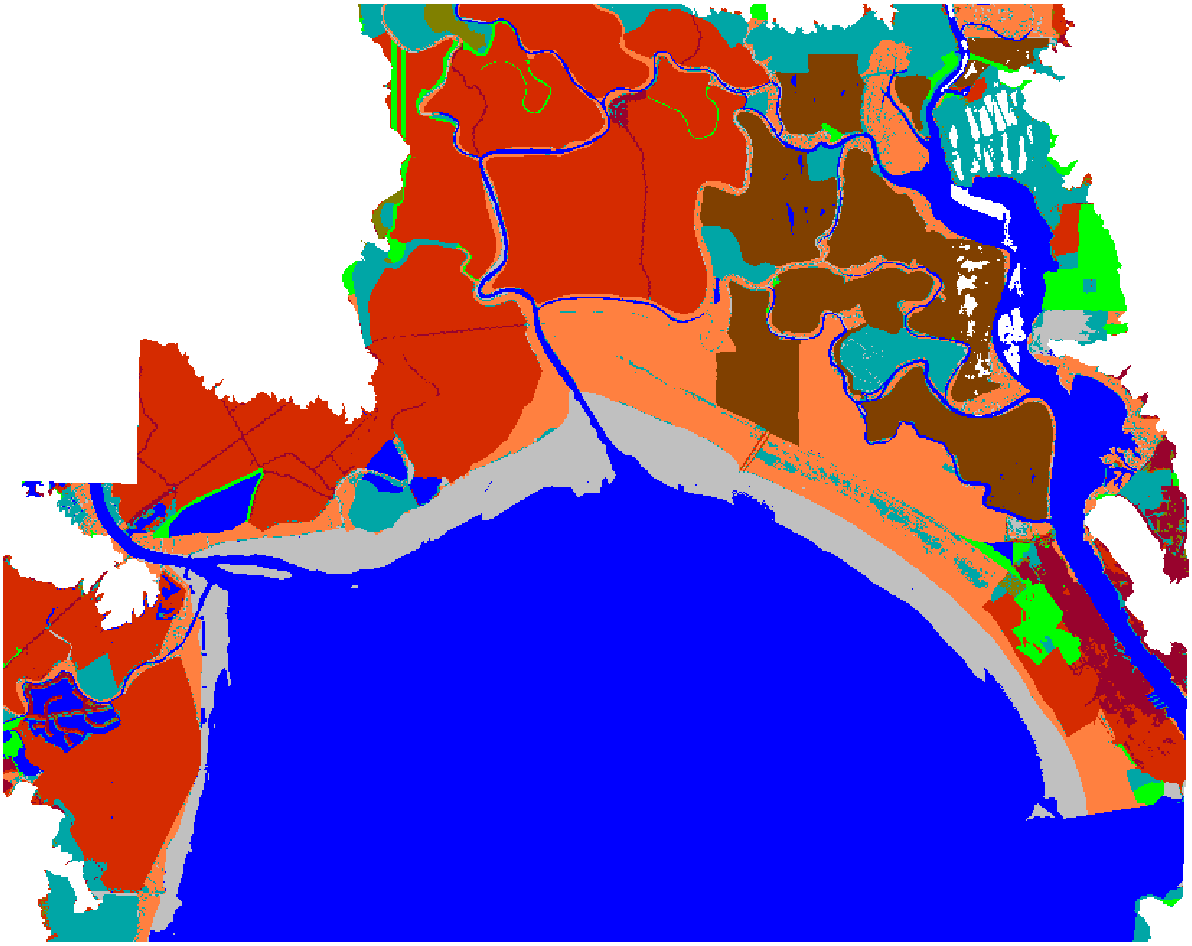
San Pablo Bay NWR, 2050, Scenario A1B Maximum


San Pablo Bay NWR, 2075, Scenario A1B Maximum

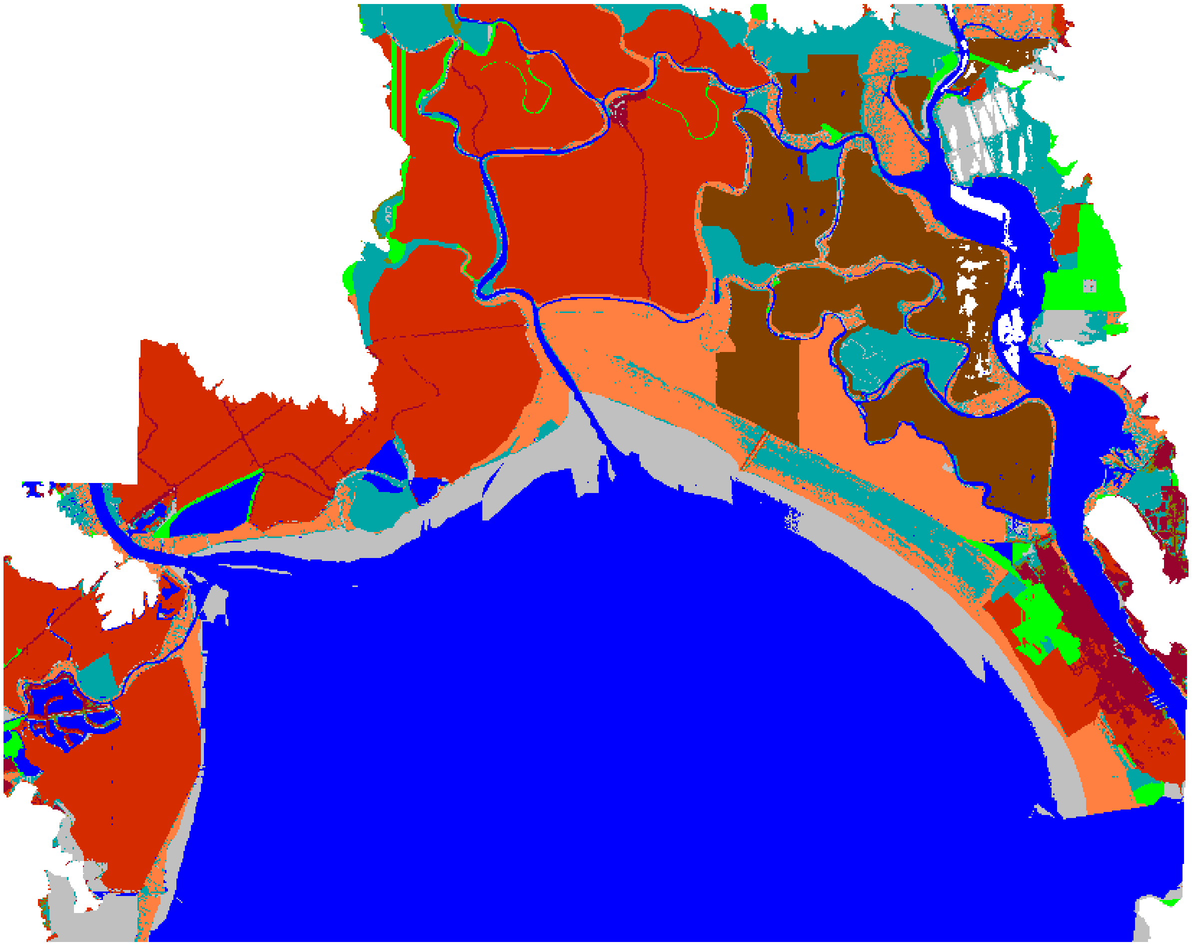

San Pablo Bay NWR, 2100, Scenario A1B Maximum



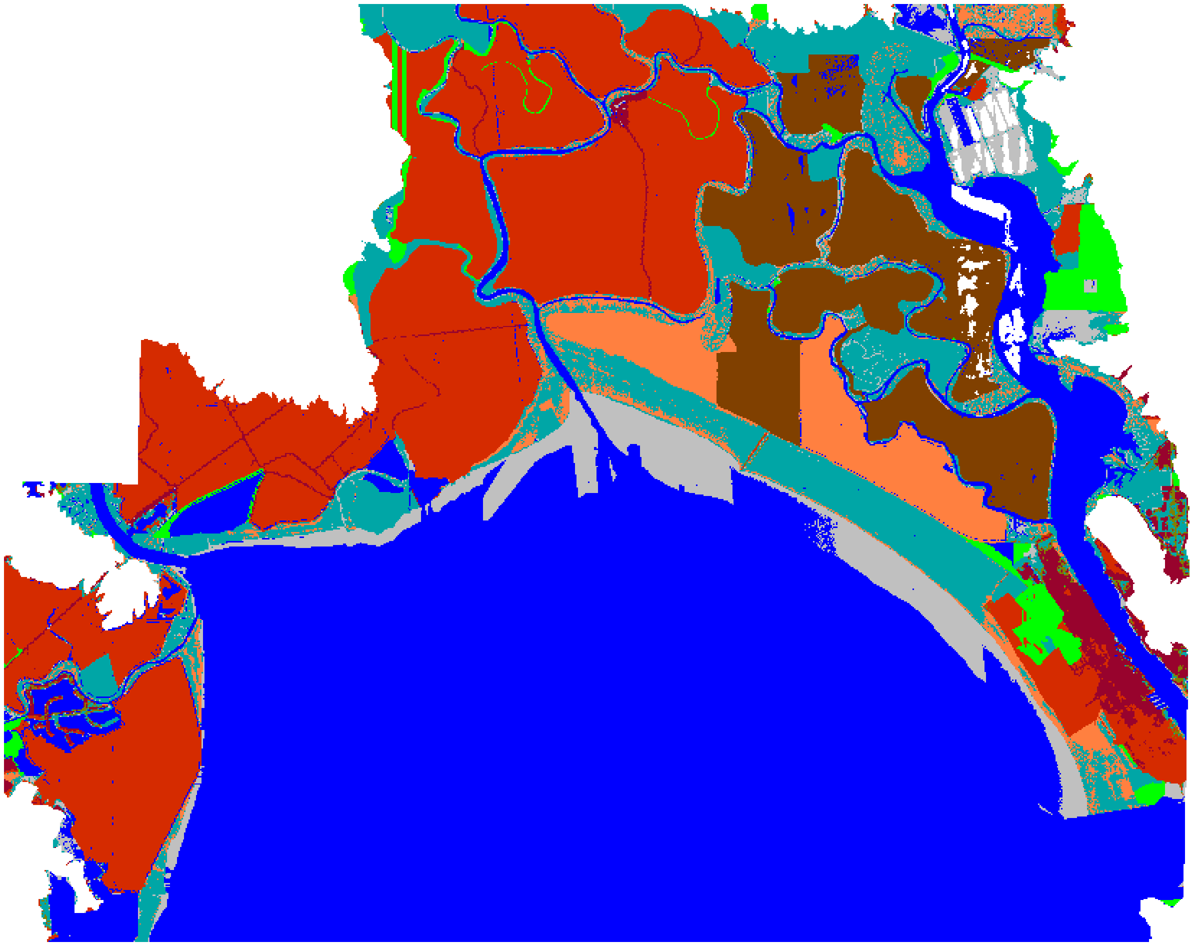
San Pablo Bay NWR, Initial Condition



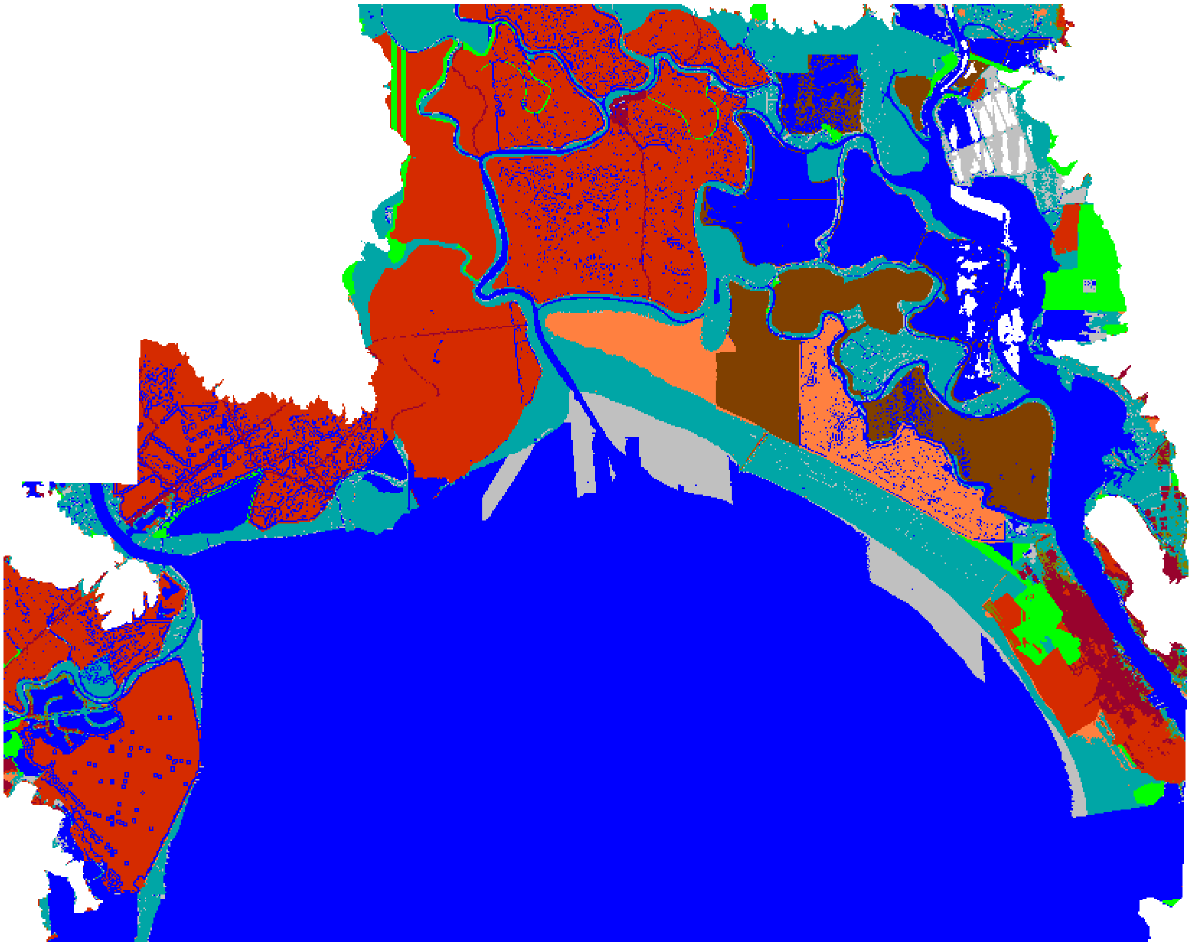
San Pablo Bay NWR, 2025, 1 meter



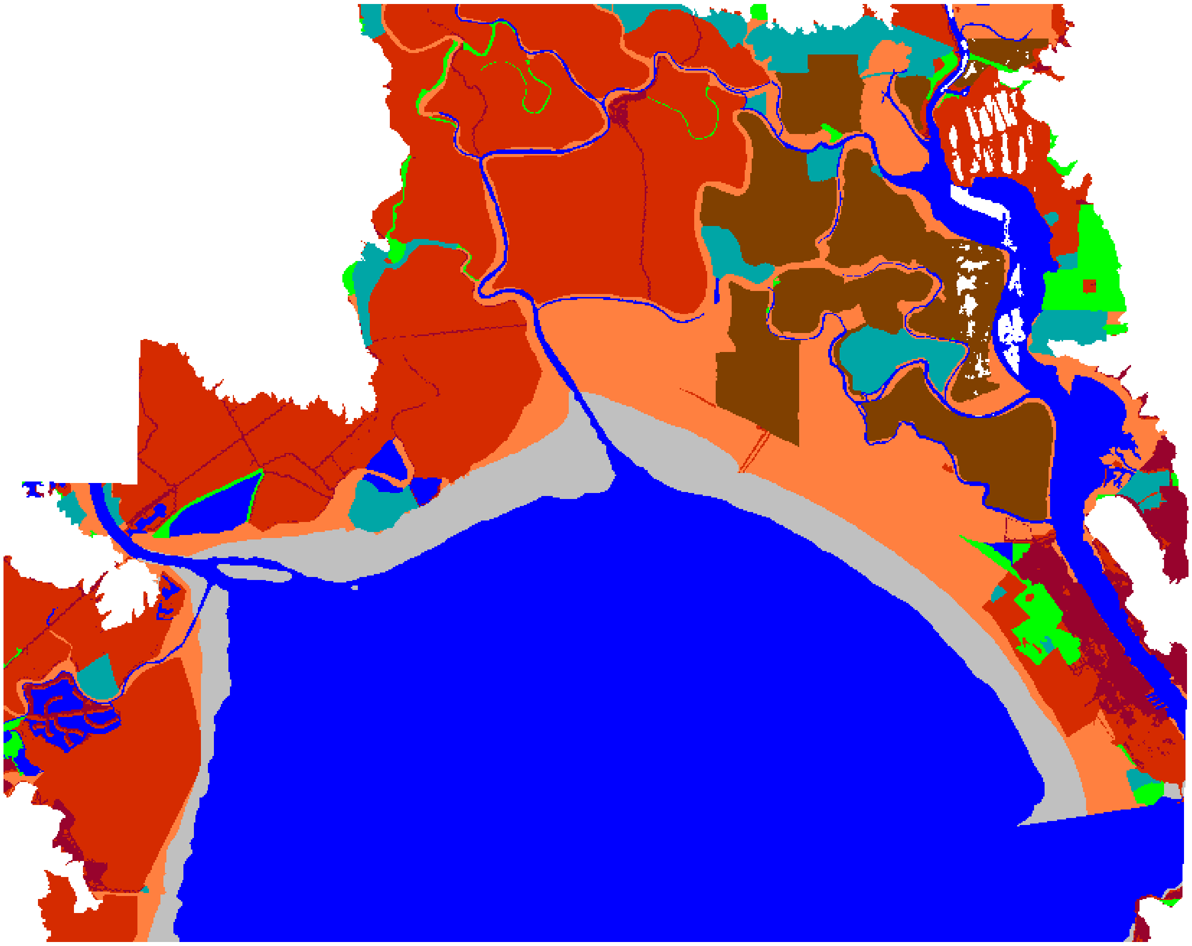
San Pablo Bay NWR, 2050, 1 meter



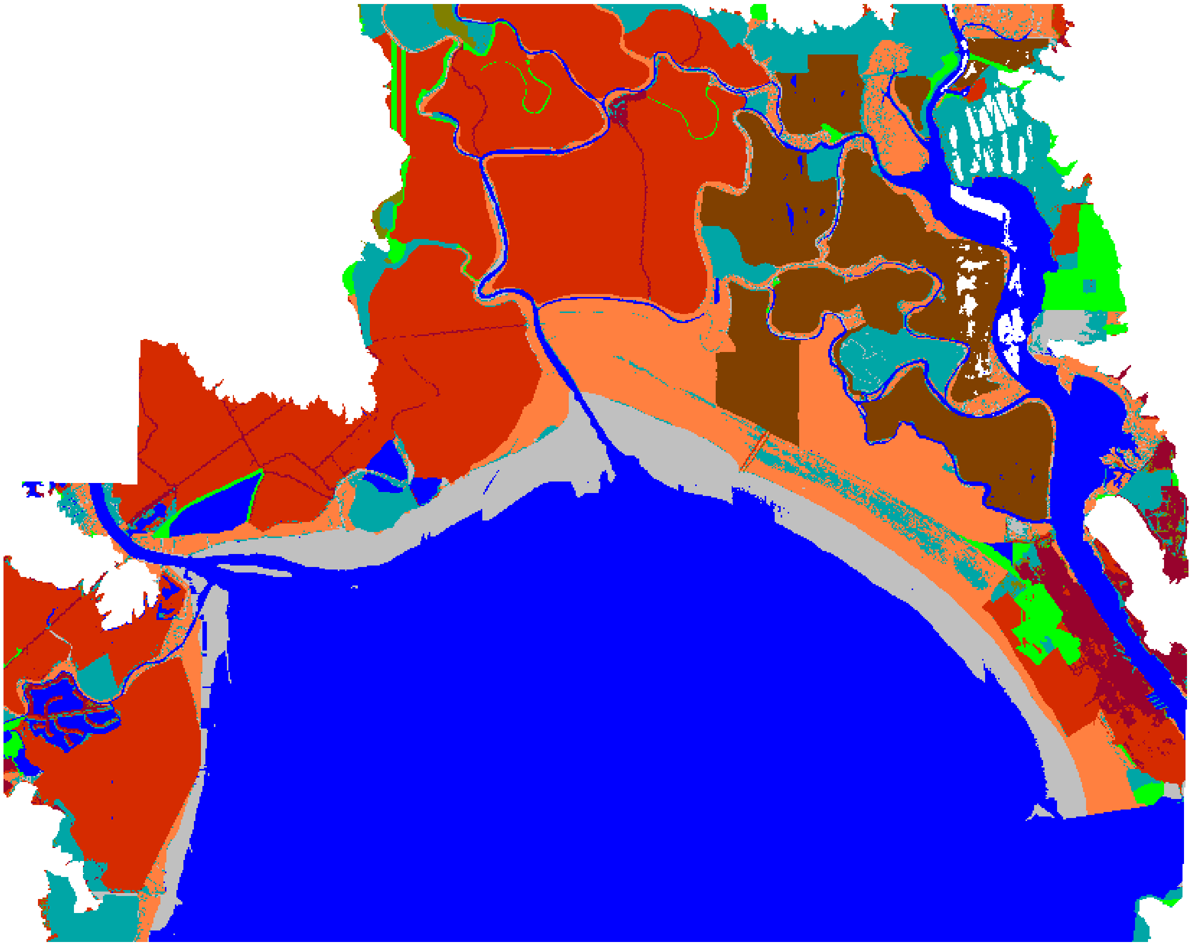
San Pablo Bay NWR, 2075, 1 meter



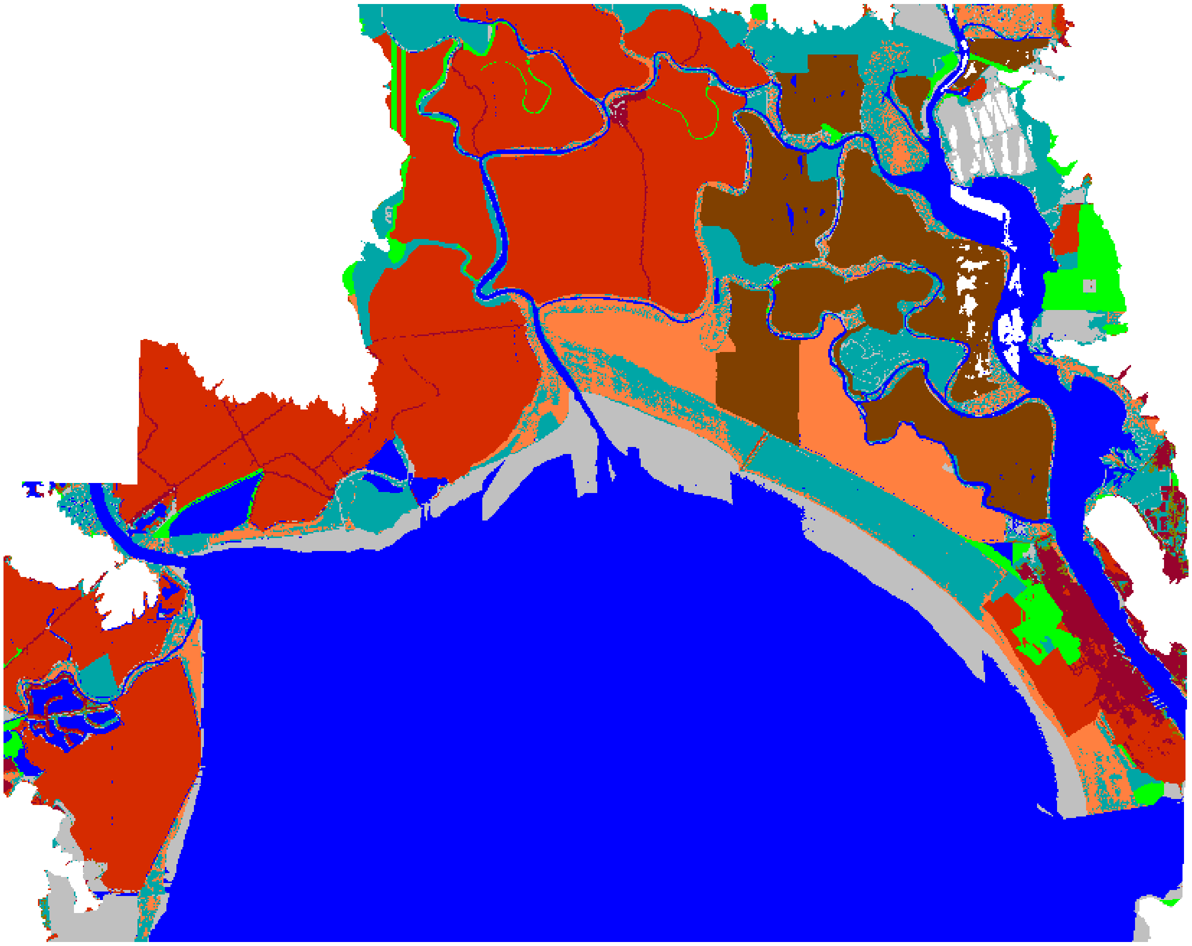
San Pablo Bay NWR, 2100, 1 meter



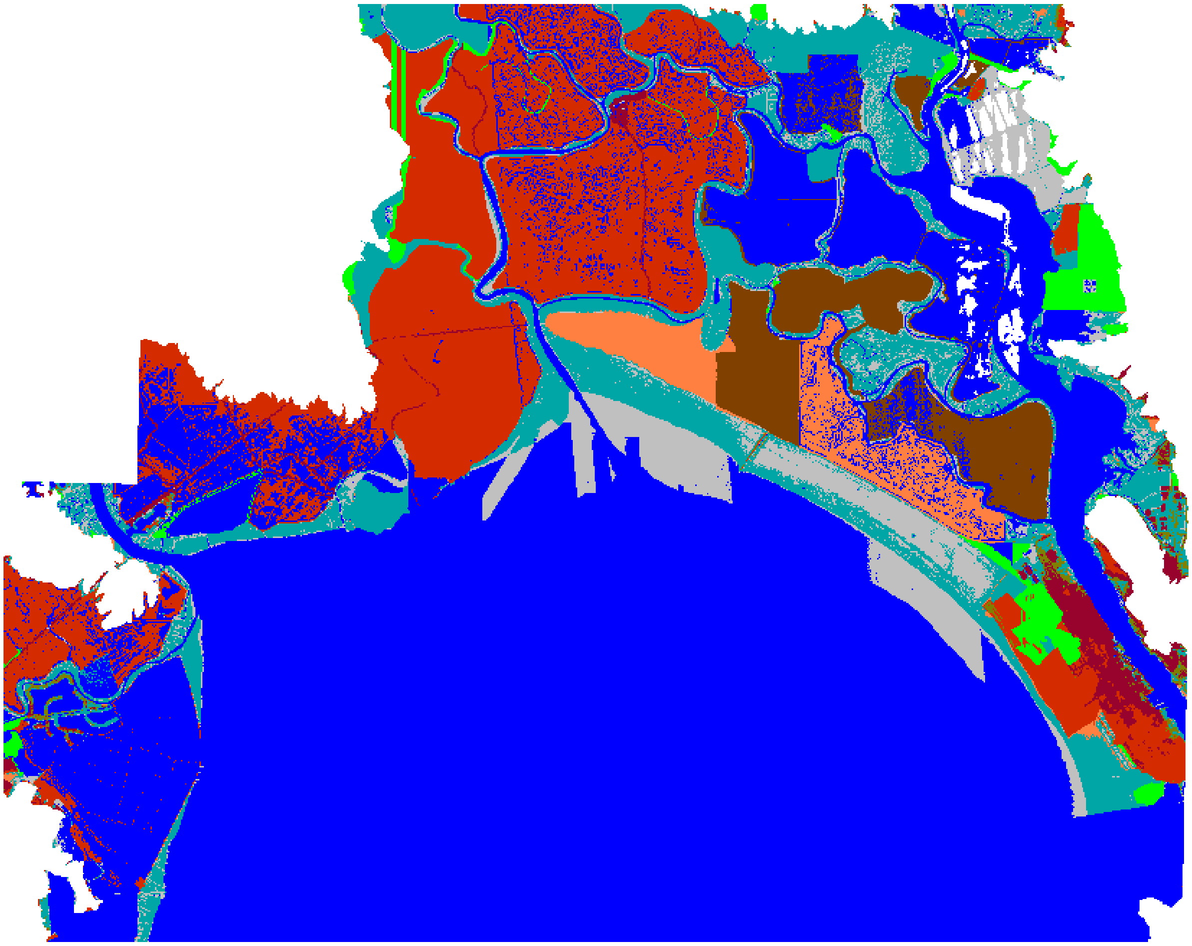
San Pablo Bay NWR, Initial Condition



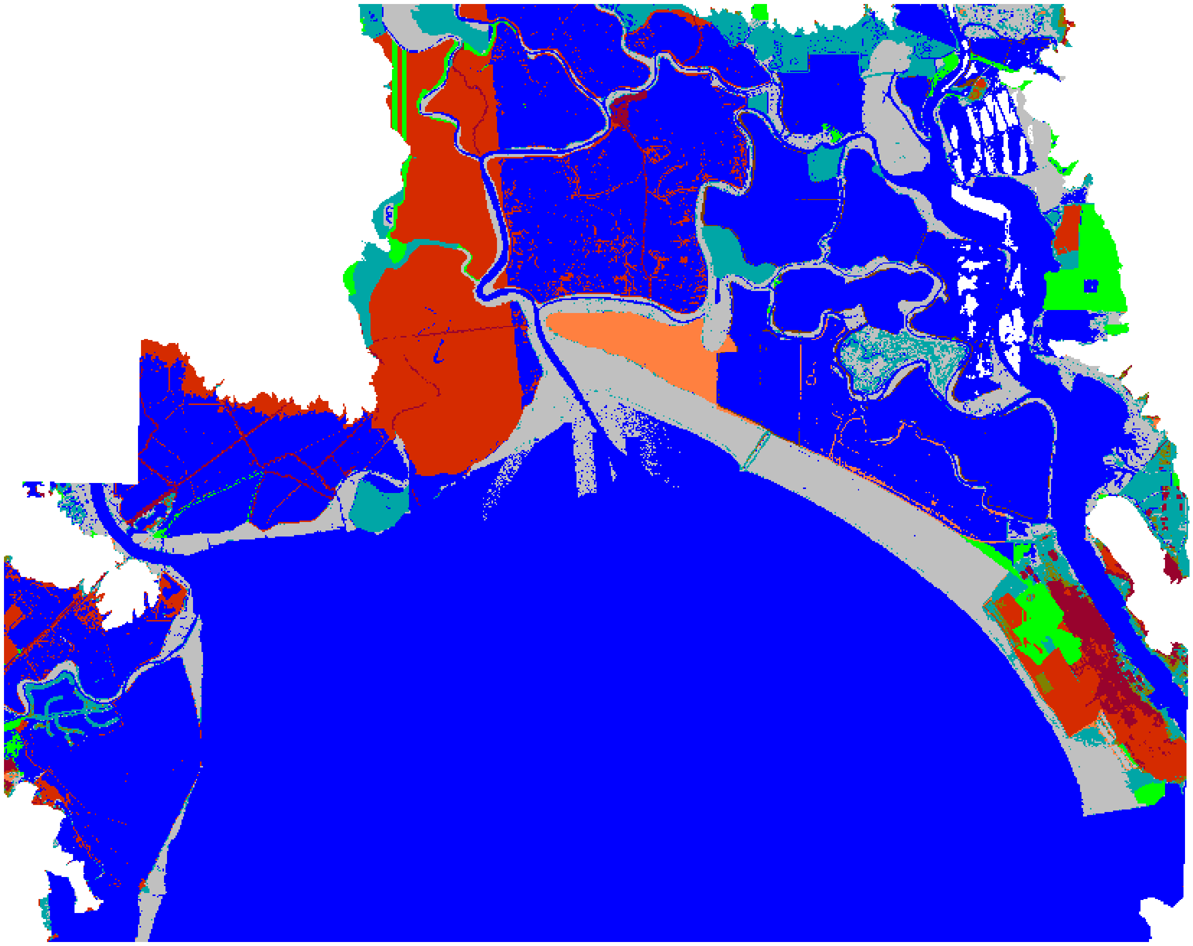
San Pablo Bay NWR, 2025, 1.5 meter



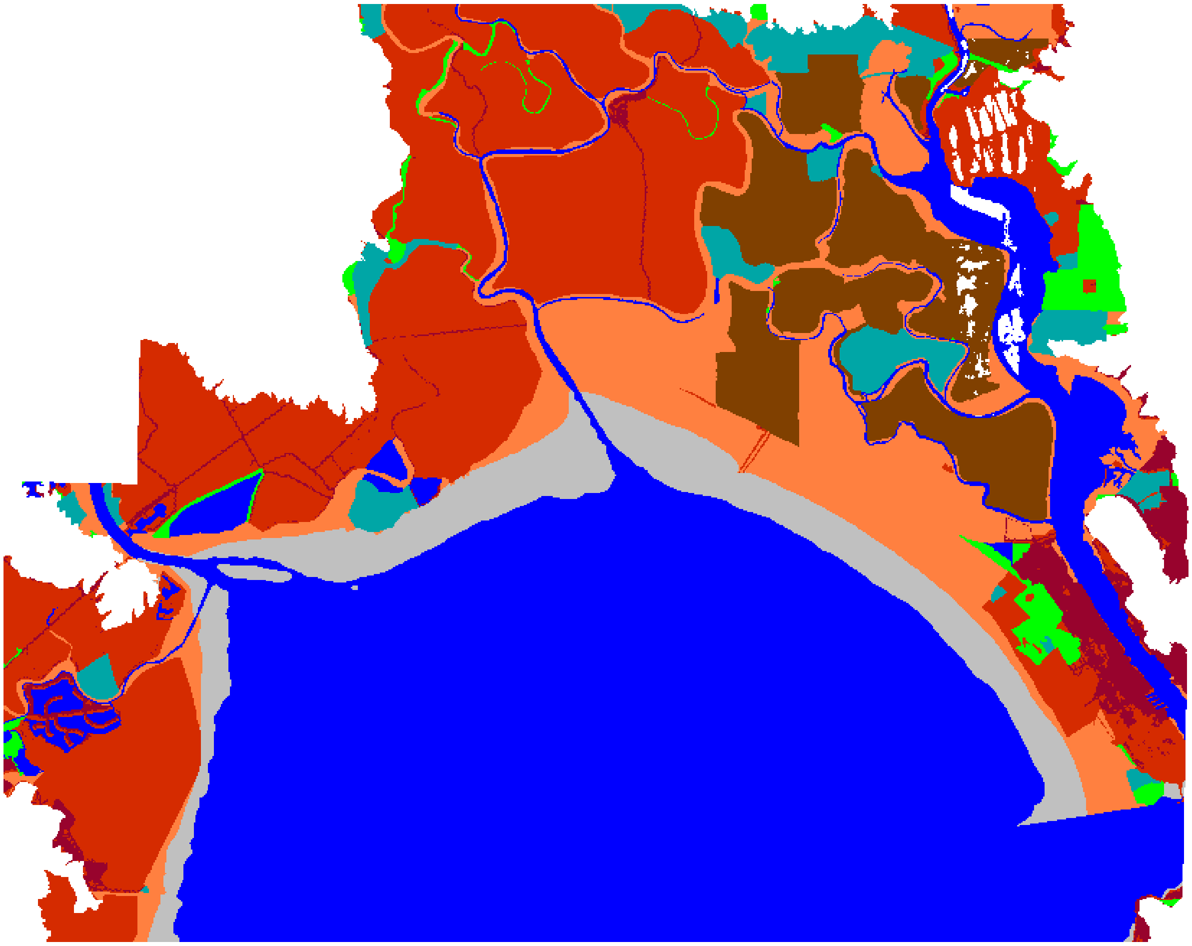
San Pablo Bay NWR, 2050, 1.5 meter



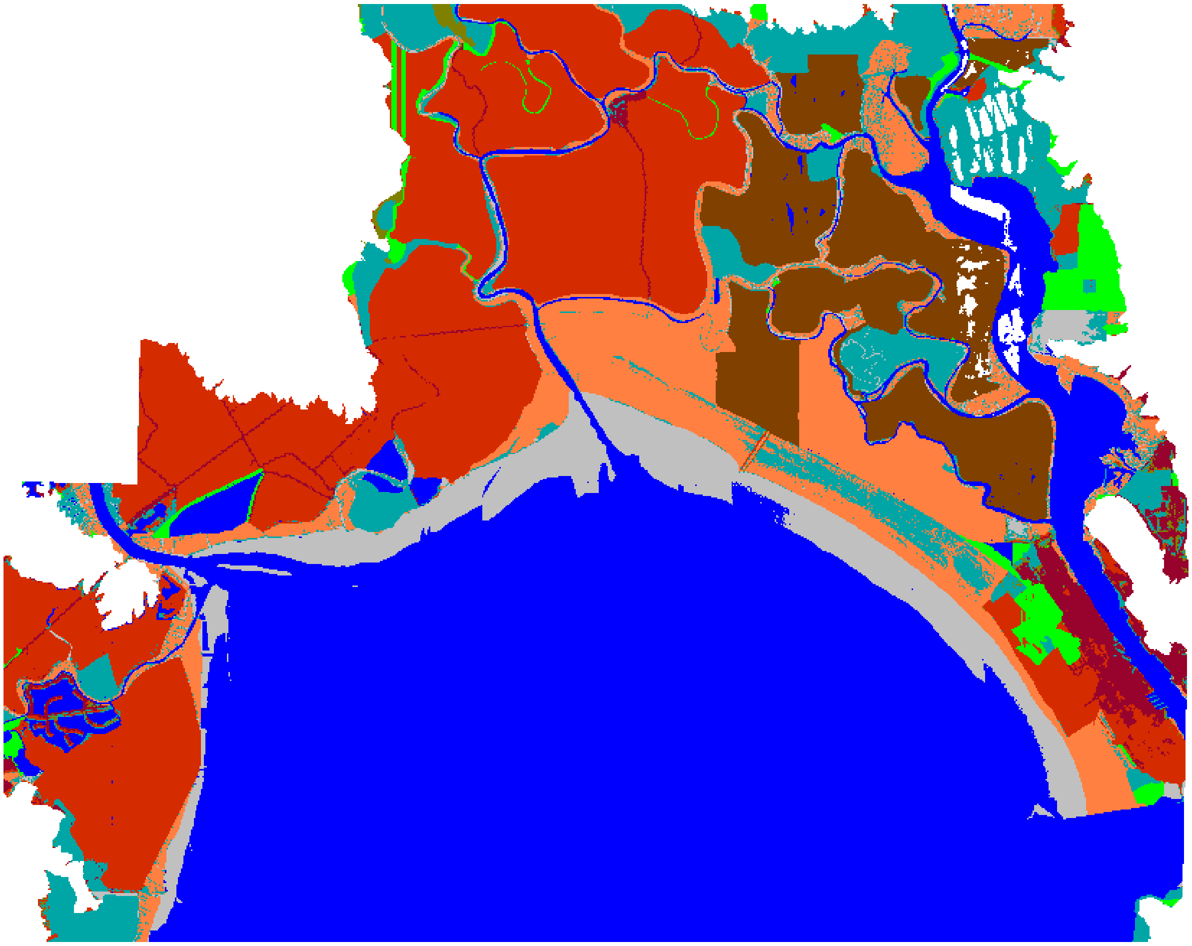
San Pablo Bay NWR, 2075, 1.5 meter

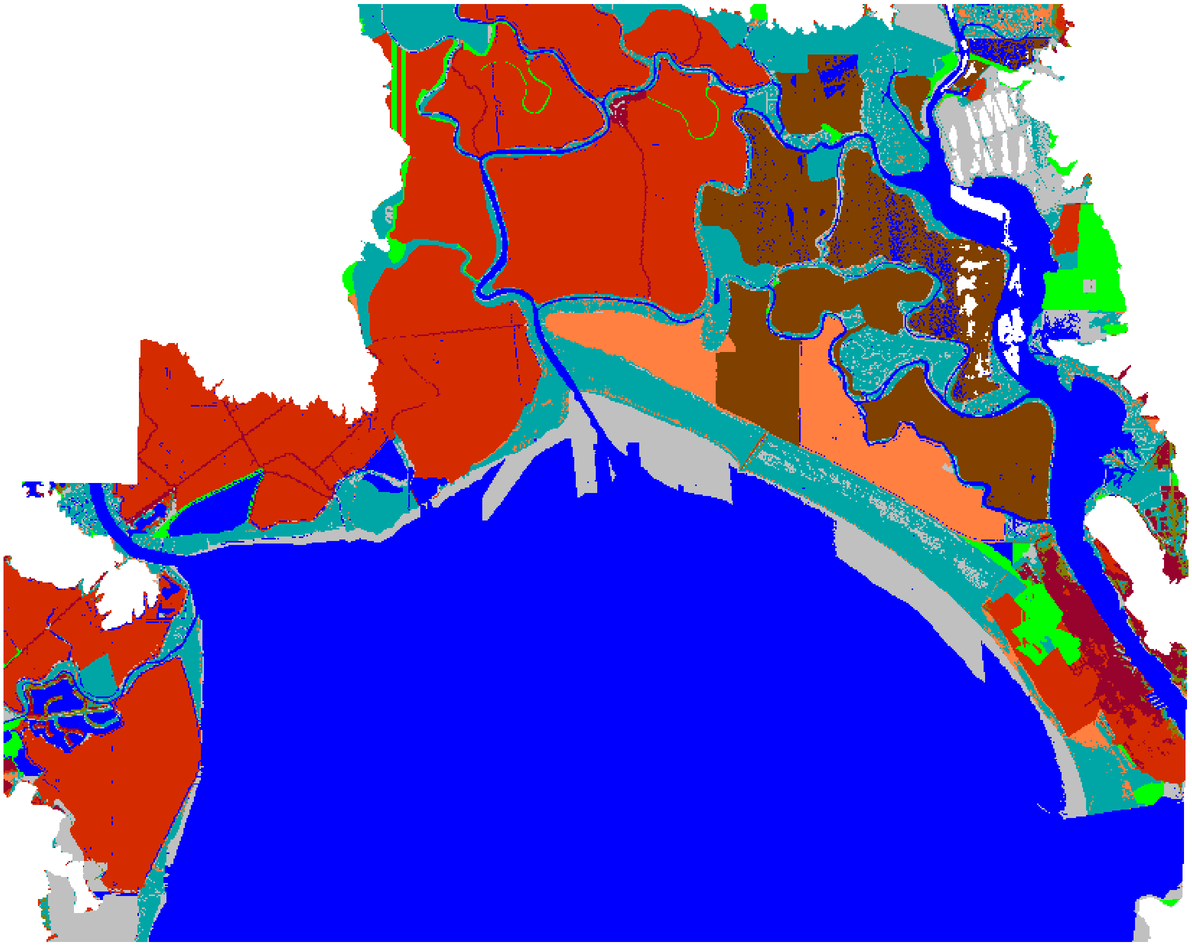


San Pablo Bay NWR, 2100, 1.5 meter

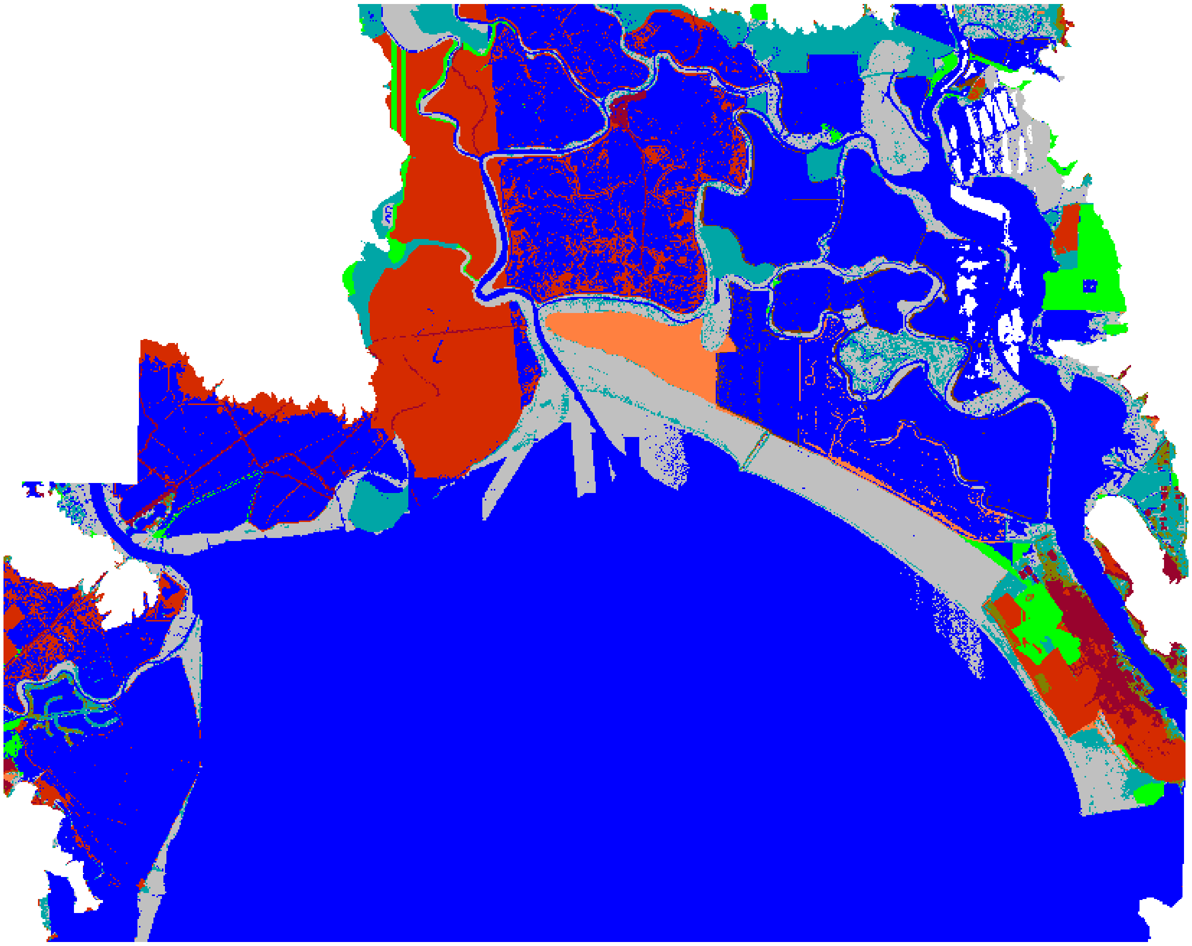


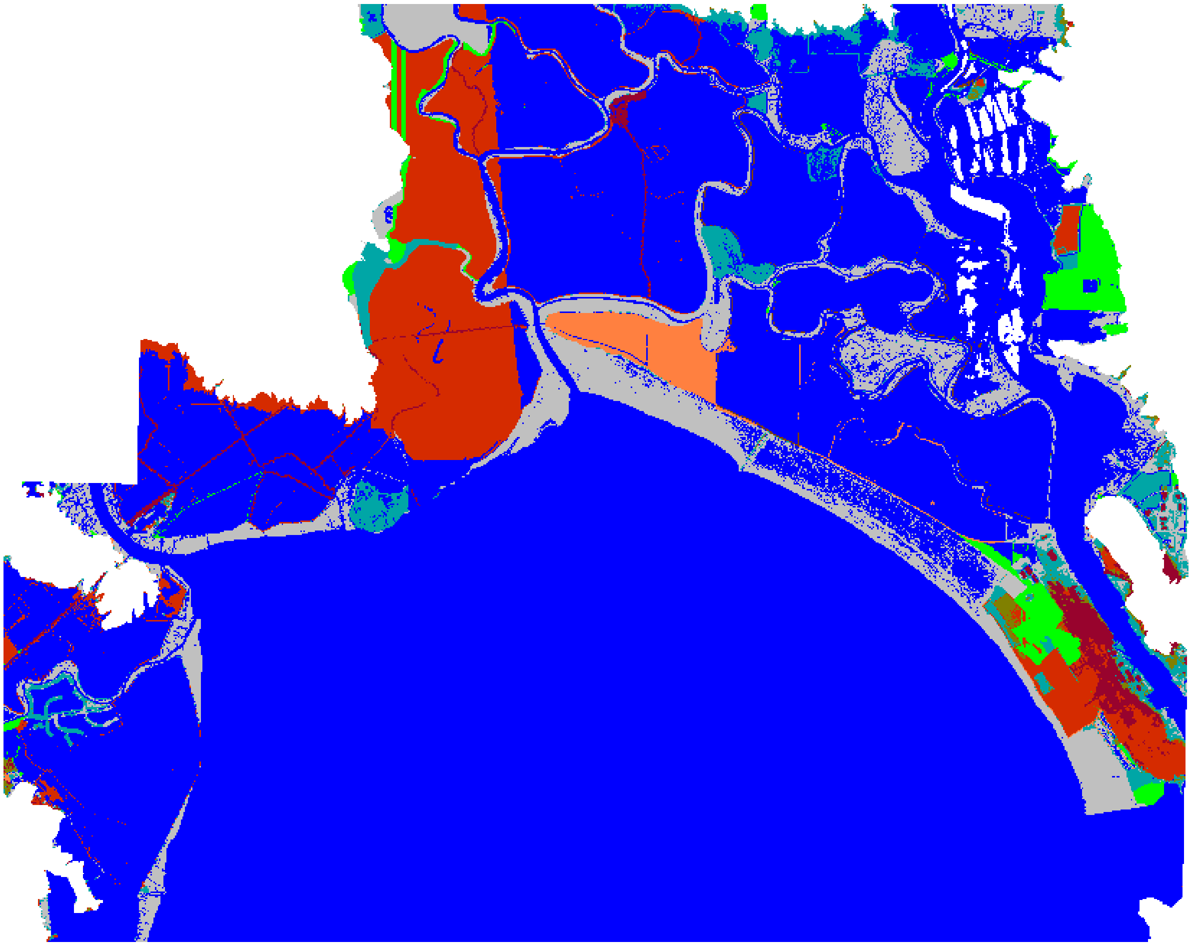
San Pablo Bay NWR, Initial Condition


San Pablo Bay NWR, 2025, 2 meter



San Pablo Bay NWR, 2050, 2 meter


San Pablo Bay NWR, 2075, 2 meter



San Pablo Bay NWR, 2100, 2 meter