Application of the Sea-Level Affecting Marshes Model (SLAMM 5.0) to Salinas River 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. 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 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 4 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 when creating results for Salinas River NWR.

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).

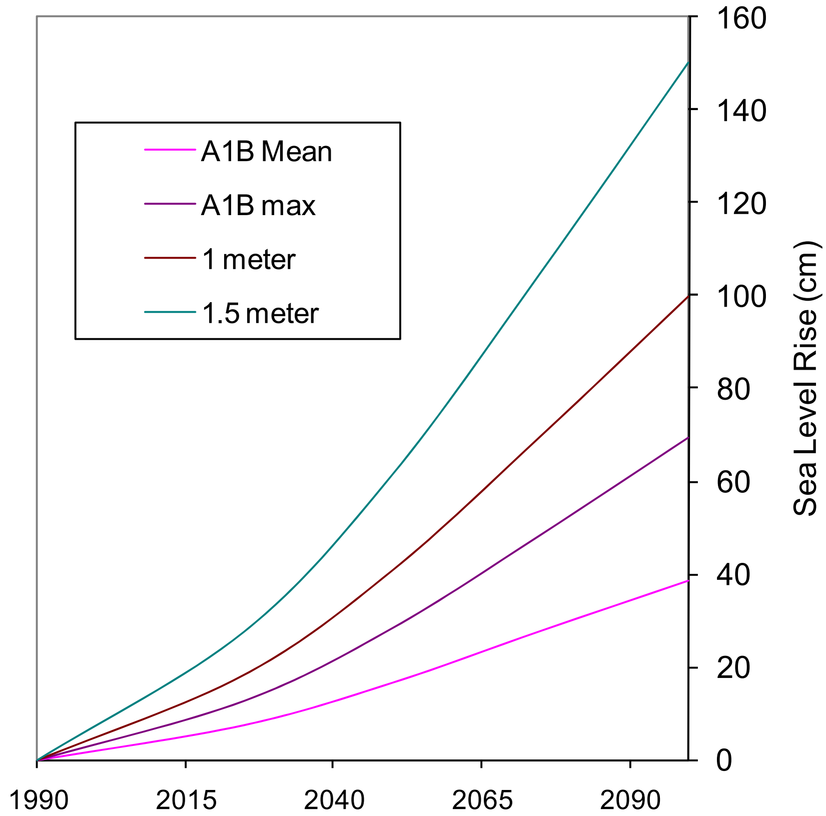
Sea-Level Rise Scenarios

The primary set of eustatic (global) sea level rise scenarios used within SLAMM was derived from the work of the Intergovernmental Panel on Climate Change (IPCC 2001). SLAMM 5 was run using the following IPCC and fixed-rate scenarios:

Scenario	Eustatic SLR by 2025 (cm)	Eustatic SLR by 2050 (cm)	Eustatic SLR by 2075 (cm)	Eustatic SLR by 2100 (cm)
A1B Mean	8	17	28	39
A1B Max	14	30	49	69
1 meter	13	28	48	100
1.5 meter	18	41	70	150

Recent 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 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. To allow for flexibility when interpreting the results, SLAMM was also run assuming 1 meter, 1½ 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

A limited set of LIDAR data was found for Salinas River NWR; LIDAR data were derived from a 1998 flight date (Fig. 2b). Elevation data used are based on a combination of the LIDAR and the National Elevation Dataset (NED).

An examination of the NED metadata indicates that this digital elevation map (DEM) was derived from a 1981 survey as illustrated within USGS topographic map shown below (Fig. 2a). The contour intervals in this map are twenty feet with a ten foot supplemental contour closest to sea-level. The process of creating a digital elevation map from a contour map does attempt to interpolate between contour lines but there is considerable uncertainty in this process. There are few 10 foot contour lines shown within the geographic footprint of this refuge meaning both that elevations are quite low and the elevation data are subject to considerable uncertainty.

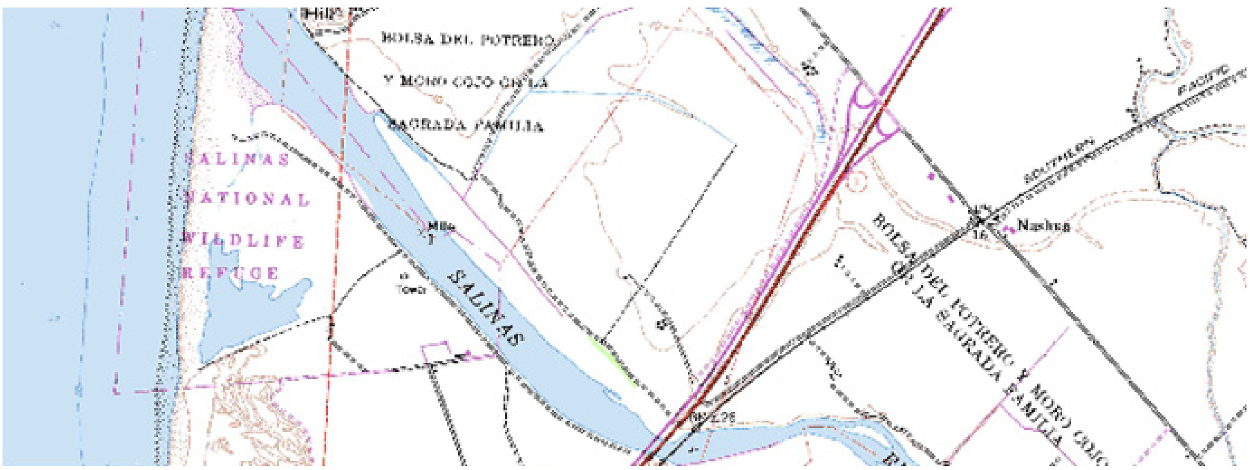


Figure 2a: Salinas River Excerpt from USGS Map.

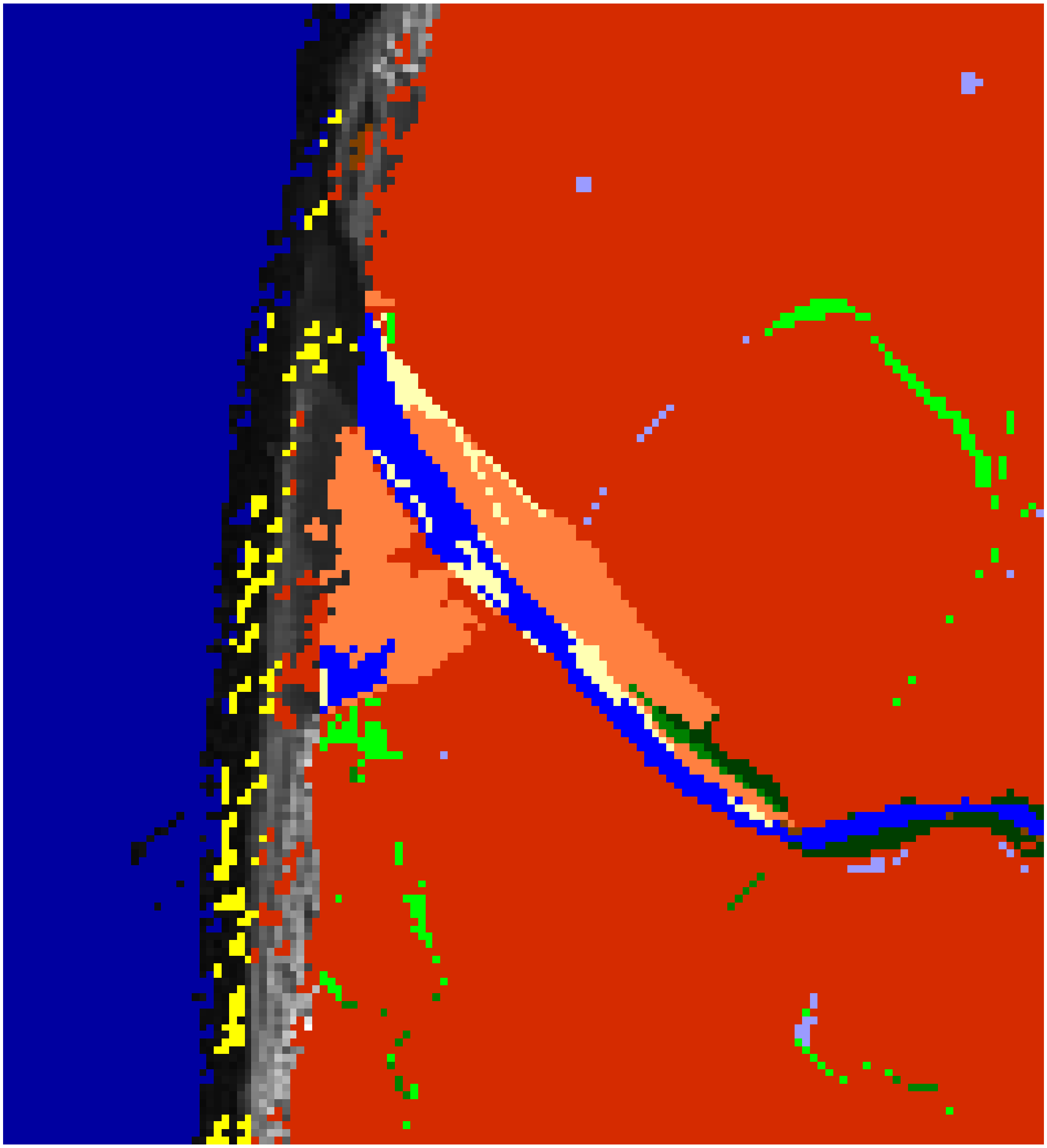


Figure 2b: Salinas River LIDAR coverage (black & white) over NWI map.

The National Wetlands Inventory for Salinas River is based on a photo date of 2005.

Converting the NWI survey into 30 meter cells indicates that the approximately five hundred thirty acre refuge (approved acquisition boundary including water) was composed of the categories as shown below:

Dry Land	28.9%
Brackish Marsh	22.3%
Open Ocean	18.2%
Ocean Beach	14.8%
Estuarine Open Water	10.8%
Estuarine Beach	3.4%
Inland Fresh Marsh	1.6%

There is one diked region in the Salinas River NWR according to the National Wetlands Inventory. SLAMM assumes this area is protected from sea level rise (Fig. 3).

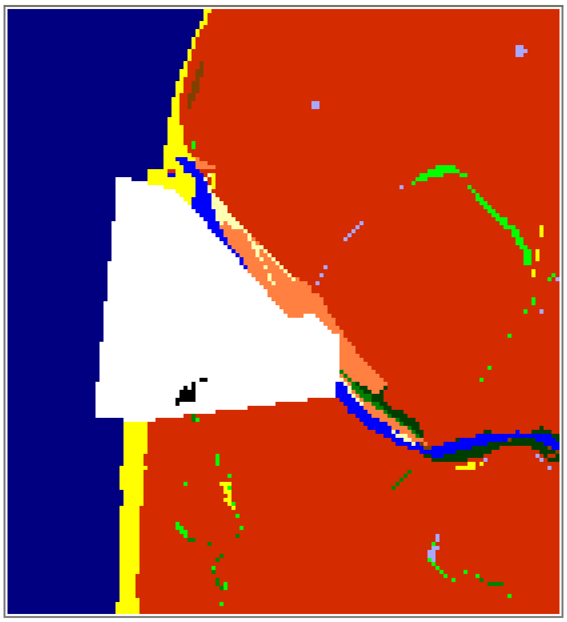


Figure 3: Diked region in black.

The historic trend for sea level rise was estimated at 1.34 mm/year using the value of the closest station (9413450, Monterey California). This measured rate is similar to the global average for the last 100 years (approximately 1.5 mm/year).

The tide range at this site was estimated at 1.63 meters using the average of the five closest NOAA oceanic gages (9413450, Monterey,CA; 9413616, Moss Landing, CA; 9413623, Elkhorn Slough, Entrance Bridge, CA; 9413631, Elkhorn Slough at Elkhorn, CA; 9413663, Elkhorn Slough Railroad Bridge, CA). The USGS topographical map for this region suggests an approximate tidal range of four feet (1.22 meters).

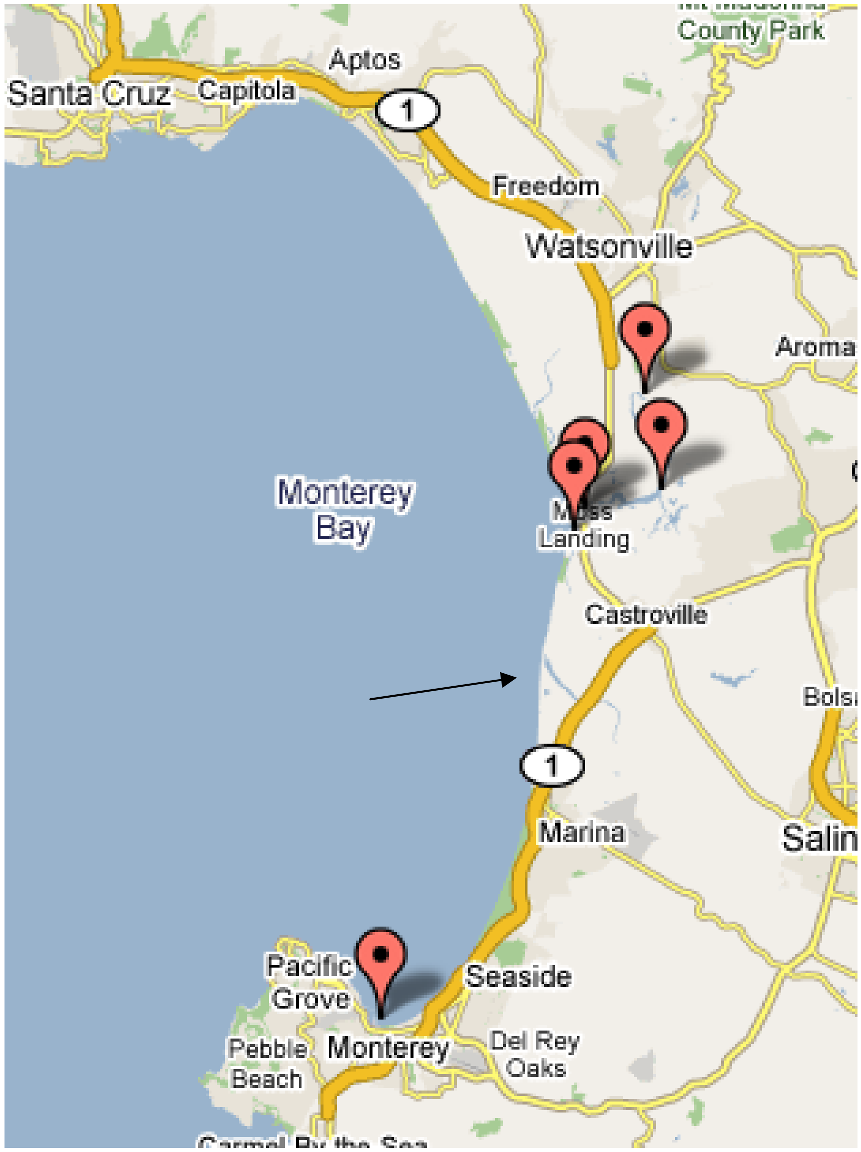


Figure 4: NOAA Gages Relevant to the Study Area.

Accretion rates in salt and brackish marshes were set to 7.0 mm/year, and the rates in tidal fresh marshes to 9.5 mm/year. The values for salt and brackish marshes are from a study measuring accretion rates marshes of San Fransisco Bay, CA and San Pablo Bay, CA (Patrick, W.H. 1990). The tidal fresh marsh value is the mean of a range of accretion values measured in Tijuana Slough, CA (Weis, D.A. et. al. 2001). Our research suggests that accretion rates in California tend to be higher than those measured nationwide (Weis. et. al. 2001; Patrick, 1990; Grismer et al, 2004; Reed, 2002).

Modeled U.S. Fish and Wildlife Service refuge boundaries are based on Approved Acquisition Boundaries as published on the FWS "National Wildlife Refuge Data and Metadata" website, and are current as of October 2008 according to Valerie Howard, Realty Cartographer for Region 8.

Diane Kodama, the Refuge Manager for Salinas River, indicated in a phone call that she was unaware of any local or historical data for accretion or elevation, outside of the data utilized in this report.

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. Note that since the LIDAR data have high accuracy, only the elevations of wetlands classes lying outside of the LIDAR data (i.e. based on NED data) were estimated as a function of the local tidal range using the SLAMM elevation pre-processor.

SUMMARY OF SLAMM INPUT PARAMETERS FOR SALINAS RIVER

Description	Salinas River
DEM Source Date (yyyy)	1981
NWI_photo_date (yyyy)	2005
Direction_OffShore (N|S|E|W)	W
Historic_trend (mm/yr)	1.34
NAVD88_correction (MTL-NAVD88 in meters)	0.901
Water Depth (m below MLW- N/A)	2
TideRangeOcean (meters: MHHW-MLLW)	1.63
TideRangeInland (meters)	1.63
Mean High Water Spring (m above MTL)	1.084
MHSW Inland (m above MTL)	1.084
Marsh Erosion (horz meters/year)	1.8
Swamp Erosion (horz meters/year)	1
TFlat Erosion (horz meters/year) [from 0.5]	0.5
Salt marsh vertical accretion (mm/yr) Final	7
Brackish March vert. accretion (mm/yr) Final	7
Tidal Fresh vertical accretion (mm/yr) Final	9.5
Beach/T.Flat Sedimentation Rate (mm/yr)	0.5
Frequency of Large Storms (yr/washover)	25
Use Elevation Preprocessor for Wetlands	TRUE

Results

Salinas River National Wildlife Refuge is predicted to be vulnerable to sea level rise, especially under more accelerated scenarios. Over two thirds of dry land in the refuge is predicted lost under eustatic sea level rise scenarios exceeding one meter. Brackish marsh – which constitutes roughly one quarter of the refuge – is lost under all scenarios but once SLR exceeds estimated accretion rates, the quantity of loss becomes much greater.

SLR by 2100 (m)	0.39	0.69	1	1.5
Dry Land	6%	10%	70%	76%
Brackish Marsh	27%	27%	36%	97%
Ocean Beach	57%	60%	59%	98%
Estuarine Beach	39%	59%	53%	54%
Inland Open Water	0%	0%	0%	100%

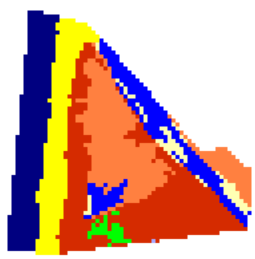
Predicted Loss Rates of Land Categories by 2100 Given Simulated Scenarios of Eustatic Sea Level Rise

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

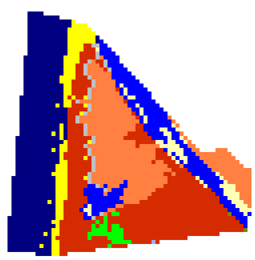
Salinas NWR
IPCC Scenario A1B-Mean, 0.39 M SLR Eustatic by 2100

Results in Acres

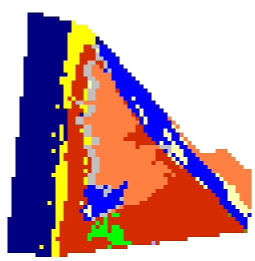
	Initial	2025	2050	2075	2100
Dry Land	152.8	150.5	148.4	146.0	143.7
Brackish Marsh	117.9	108.6	97.3	92.4	85.6
Open Ocean	96.3	135.4	140.9	142.6	143.8
Ocean Beach	78.3	40.3	36.3	34.6	33.7
Estuarine Open Water	57.4	60.0	65.0	71.9	77.3
Estuarine Beach	17.8	15.9	14.6	12.6	10.8
Inland Fresh Marsh	8.2	8.2	8.2	8.2	8.2
Inland Open Water	0.2	0.2	0.2	0.2	0.2
Tidal Flat	0.0	9.4	17.6	19.6	24.7
Trans. Salt Marsh	0.0	0.2	0.4	0.6	0.7
Saltmarsh	0.0	0.0	0.0	0.0	0.0
Total (incl. water)	**528.9**	**528.9**	**528.9**	**528.9**	**528.9**



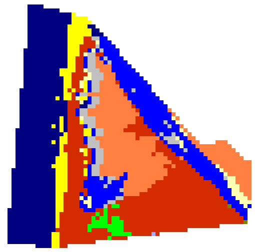
Salinas River NWR, Initial Condition

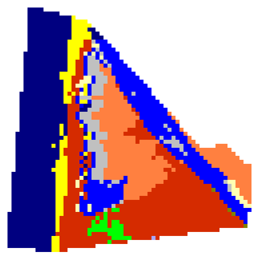


Salinas River NWR, 2025, Scenario A1B Maximum



Salinas River NWR, 2050, Scenario A1B Maximum

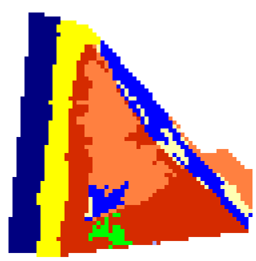

Salinas River NWR, 2075, Scenario A1B Maximum


Salinas River NWR, 2100, Scenario A1B Maximum

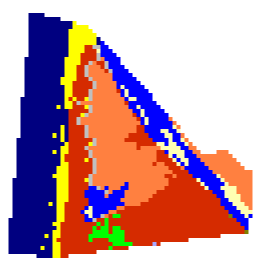
Salinas NWR
IPCC Scenario A1B-Max, 0.69 M SLR Eustatic by 2100

Results in Acres

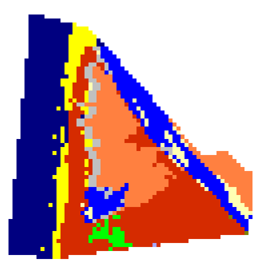
	Initial	2025	2050	2075	2100
Dry Land	152.8	149.4	145.9	141.7	137.6
Brackish Marsh	117.9	108.6	97.4	92.4	85.6
Open Ocean	96.3	139.6	142.5	145.5	147.9
Ocean Beach	78.3	36.8	36.3	33.3	31.3
Estuarine Open Water	57.4	60.7	67.1	75.5	82.5
Estuarine Beach	17.8	15.5	12.3	9.5	7.2
Inland Fresh Marsh	8.2	8.2	8.2	8.2	8.2
Inland Open Water	0.2	0.2	0.2	0.2	0.2
Tidal Flat	0.0	9.4	18.4	21.6	26.9
Trans. Salt Marsh	0.0	0.3	0.6	0.9	1.3



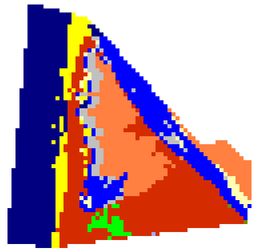
Salinas River NWR, Initial Condition



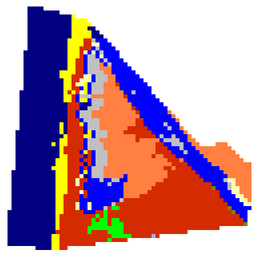
Salinas River NWR, 2025, Scenario A1B Maximum



Salinas River NWR, 2050, Scenario A1B Maximum



Salinas River NWR, 2075, Scenario A1B Maximum

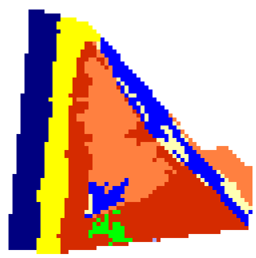


Salinas River NWR, 2100, Scenario A1B Maximum

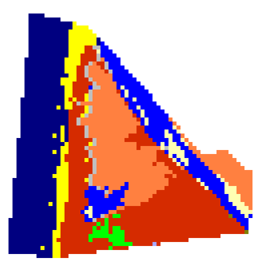
Salinas NWR
1 Meter Eustatic SLR by 2100

Results in Acres

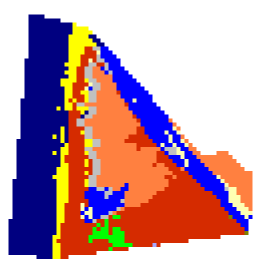
	Initial	2025	2050	2075	2100
Dry Land	152.8	148.2	143.2	137.5	45.2
Brackish Marsh	117.9	108.5	97.3	92.4	75.2
Open Ocean	96.3	141.6	144.3	147.8	151.9
Ocean Beach	78.3	35.6	36.0	32.9	32.1
Estuarine Open Water	57.4	61.9	69.3	78.3	87.4
Estuarine Beach	17.8	14.3	10.0	7.5	8.3
Inland Fresh Marsh	8.2	8.2	8.2	8.2	8.2
Inland Open Water	0.2	0.2	0.2	0.2	0.2
Tidal Flat	0.0	10.0	19.6	22.6	28.5
Trans. Salt Marsh	0.0	0.4	0.7	1.2	82.8
Saltmarsh	0.0	0.0	0.0	0.2	9.1
Total (incl. water)	**528.9**	**528.9**	**528.9**	**528.9**	**528.9**



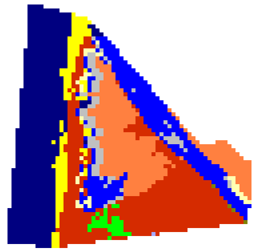
Salinas River NWR, Initial Condition



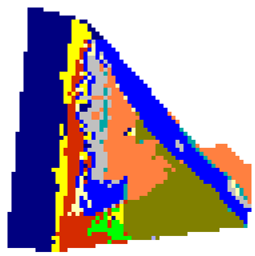
Salinas River NWR, 2025, 1 meter



Salinas River NWR, 2050, 1 meter



Salinas River NWR, 2075, 1 meter

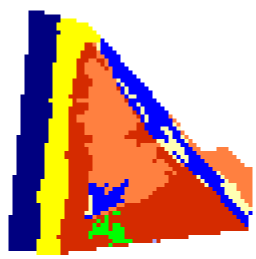


Salinas River NWR, 2100, 1 meter

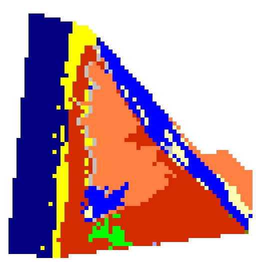
Salinas NWR
1.5 Meters Eustatic SLR by 2100

Results in Acres

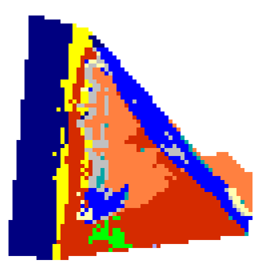
	Initial	2025	2050	2075	2100
Dry Land	152.8	145.9	138.9	43.8	36.7
Brackish Marsh	117.9	108.5	86.4	41.7	3.8
Open Ocean	96.3	142.3	150.1	182.0	188.2
Ocean Beach	78.3	36.4	32.2	3.6	1.2
Estuarine Open Water	57.4	63.7	71.8	86.5	96.8
Estuarine Beach	17.8	12.4	7.5	9.0	8.2
Inland Fresh Marsh	8.2	8.2	8.2	8.2	8.2
Inland Open Water	0.2	0.2	0.2	0.2	0.0
Tidal Flat	0.0	10.6	27.4	29.6	54.0
Saltmarsh	0.0	0.0	5.4	41.6	131.2
Trans. Salt Marsh	0.0	0.6	0.7	82.7	0.4
Total (incl. water)	**528.9**	**528.9**	**528.9**	**528.9**	**528.9**



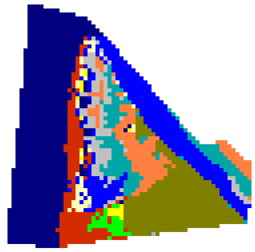
Salinas River NWR, Initial Condition



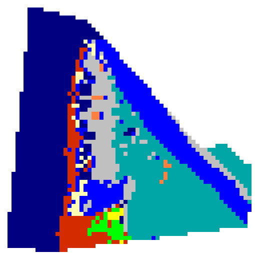
Salinas River NWR, 2025, 1.5 meter



Salinas River NWR, 2050, 1.5 meter



Salinas River NWR, 2075, 1.5 meter



Salinas River NWR, 2100, 1.5 meter

Discussion:

The SLAMM model results predict that Salinas River NWR will be affected by sea level rise. Even in the most conservative 0.39 scenario, the refuge is predicted to lose roughly one quarter of its brackish (irregularly flooded) marsh by 2100. In the most extreme 1.5 meter scenario the refuge is predicted to lose nearly all of its brackish marsh to salt marsh. Dry land is predicted to remain relatively unchanged below the 1 meter scenario, at which point roughly three-quarters is lost.

As noted above, the elevation data for this site use both LIDAR and NED data. The LIDAR covers only about 300 meters in from the ocean, and therefore only the western-most fraction of the NWR is based on LIDAR flights. This analysis should be revisited if higher quality elevation data become available for the entire spatial domain of the refuge.

Another area of model uncertainty is accretion rates. There were no measured accretion rates for this refuge meaning that regional averages needed to be utilized in this modeling. Refuge accretion rates are likely to be spatially variable and potentially temporally variable as well. More precise information about the rate of accretion within this refuge would further reduce uncertainty in model results.

In regions of NED data, wetlands elevations were estimated as a function of tidal range. This procedure, while based on known physical relationships, is also subject to uncertainty.

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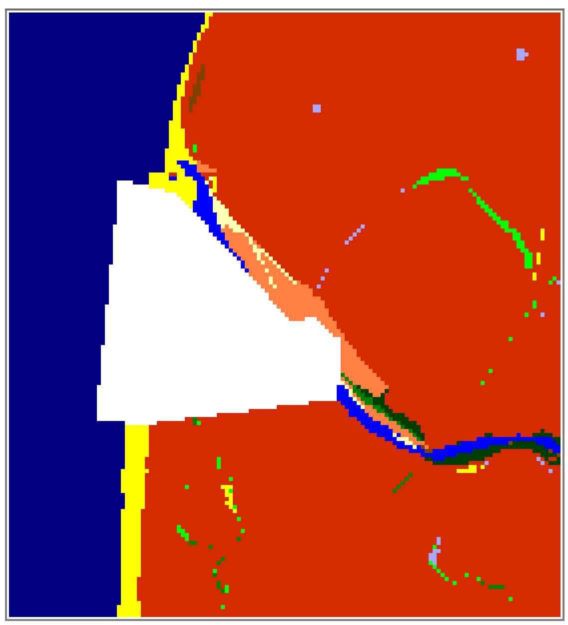
Appendix A: Contextual Results

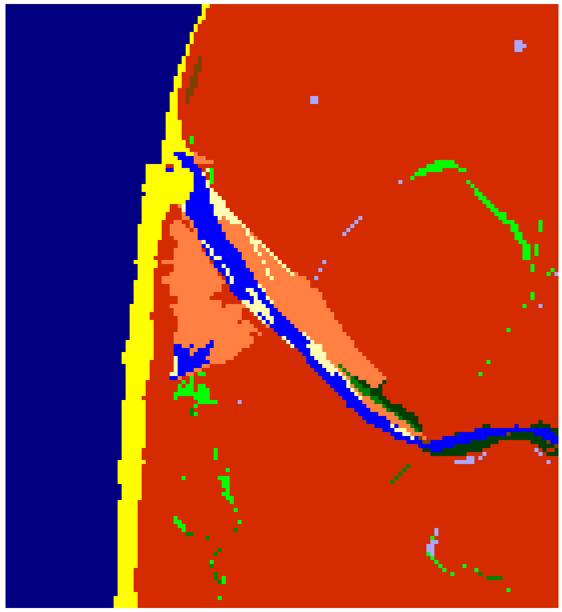
The SLAMM model does take into account the context of the surrounding lands or open water when calculating effects. For example, erosion rates are calculated based on the maximum fetch (wave action) which is estimated by assessing contiguous open water to a given marsh cell. Another example is that inundated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

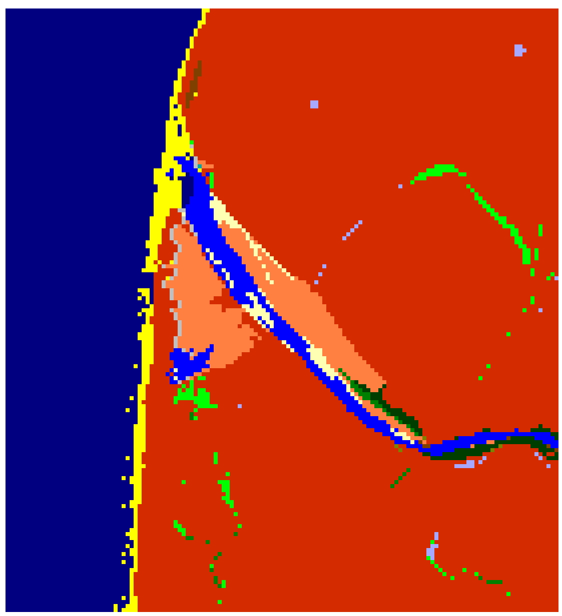
- Results were closely examined (quality assurance) within USFWS refuges but not closely examined for the larger region.
- Site-specific parameters for the model were derived for USFWS refuges whenever possible and may not be regionally applicable.
- Especially in areas where dikes are present, an effort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



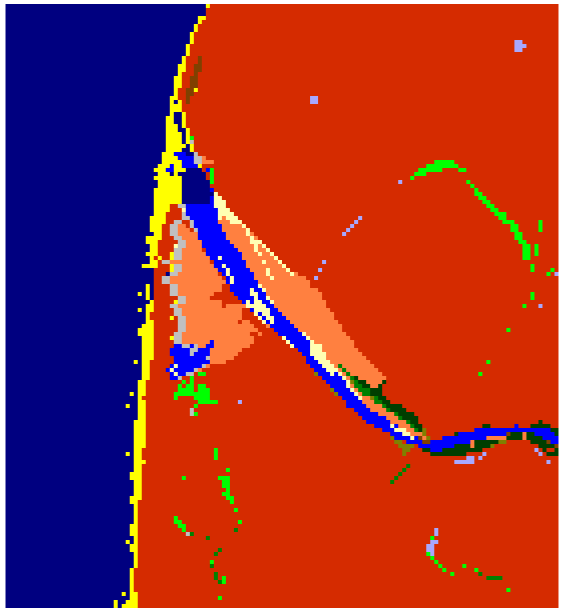
Location of Salinas River National Wildlife Refuge (white areas) within simulation context



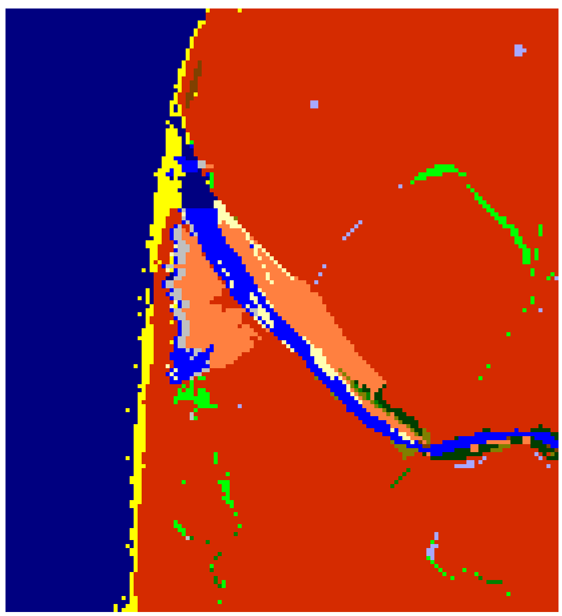
Salinas River NWR, Initial Condition



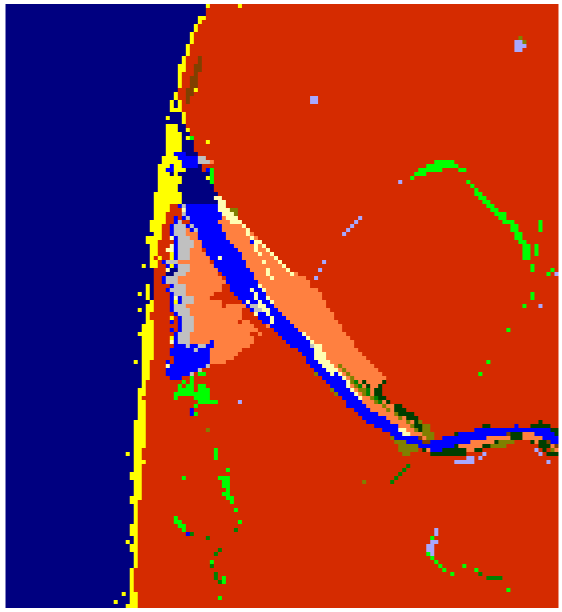
Salinas River NWR, 2025, Scenario A1B Mean



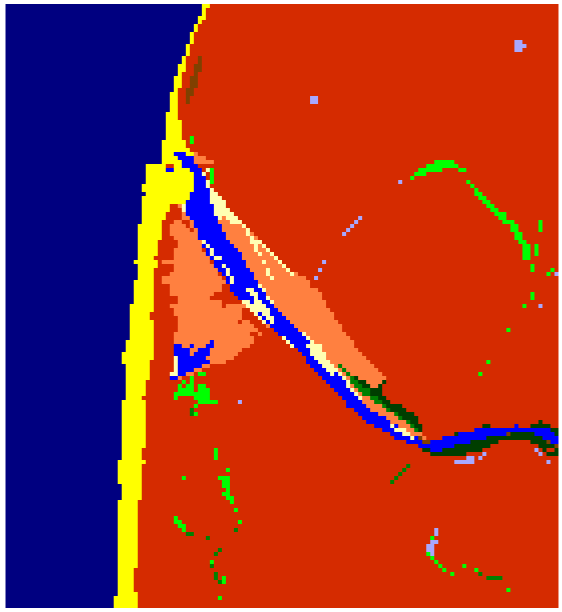
Salinas River NWR, 2050, Scenario A1B Mean



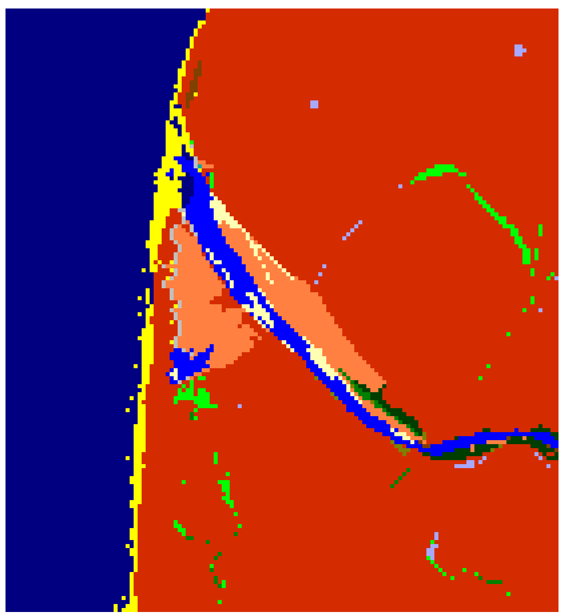
Salinas River NWR, 2075, Scenario A1B Mean



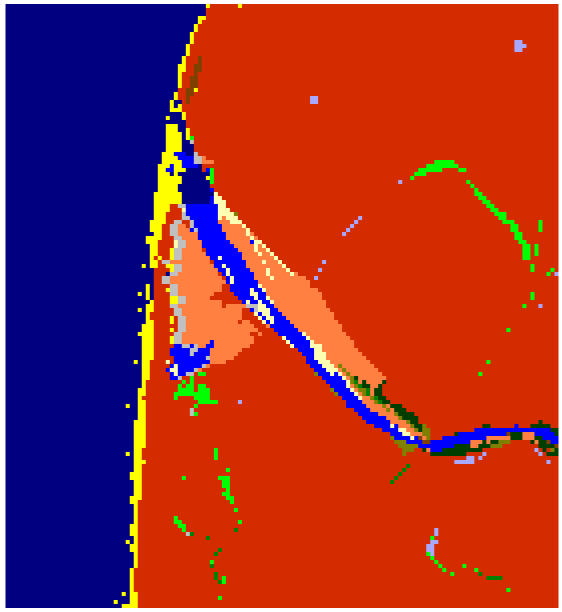
Salinas River NWR, 2100, Scenario A1B Mean



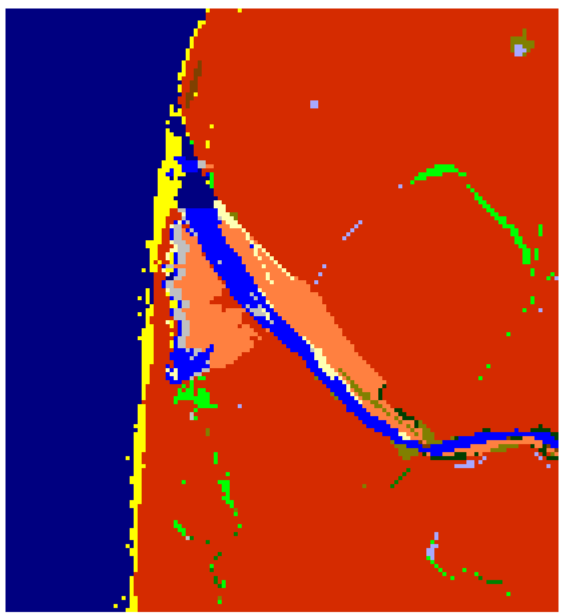
Salinas River NWR, Initial Condition



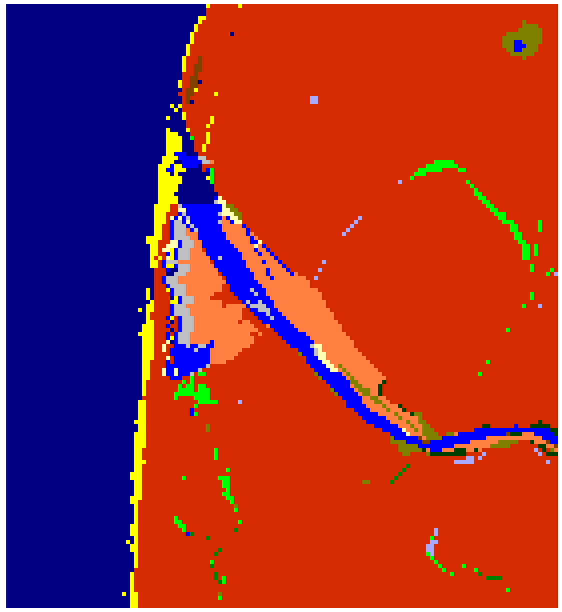
Salinas River NWR, 2025, Scenario A1B Maximum



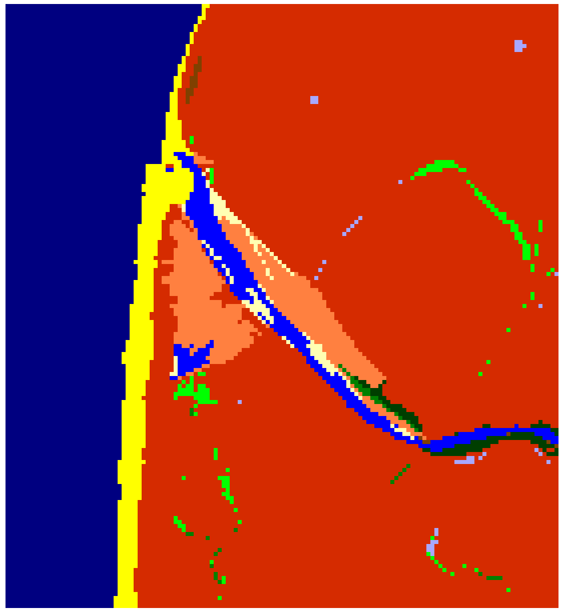
Salinas River NWR, 2050, Scenario A1B Maximum



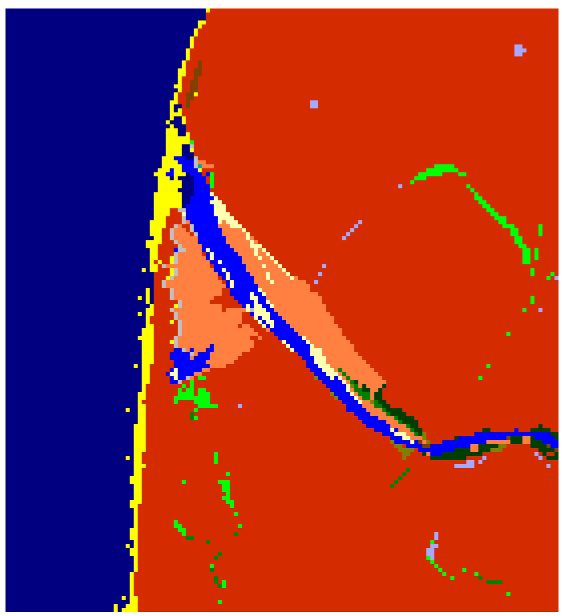
Salinas River NWR, 2075, Scenario A1B Maximum



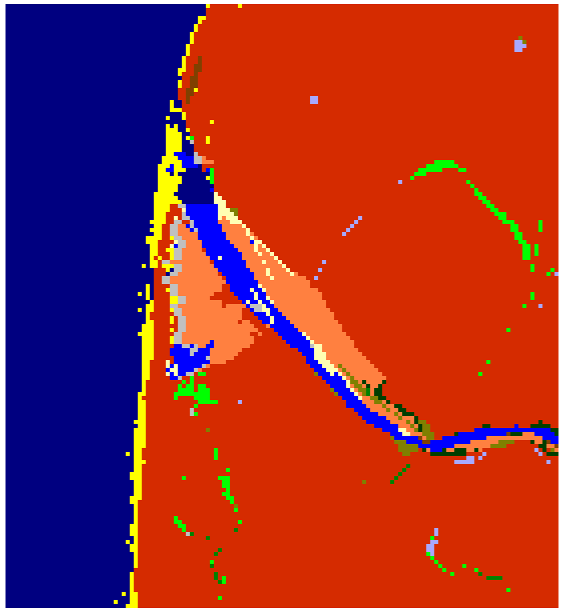
Salinas River NWR, 2100, Scenario A1B Maximum



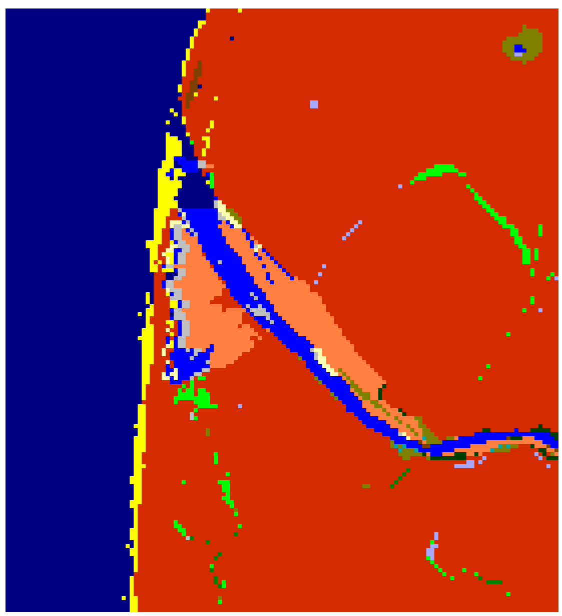
Salinas River NWR, Initial Condition



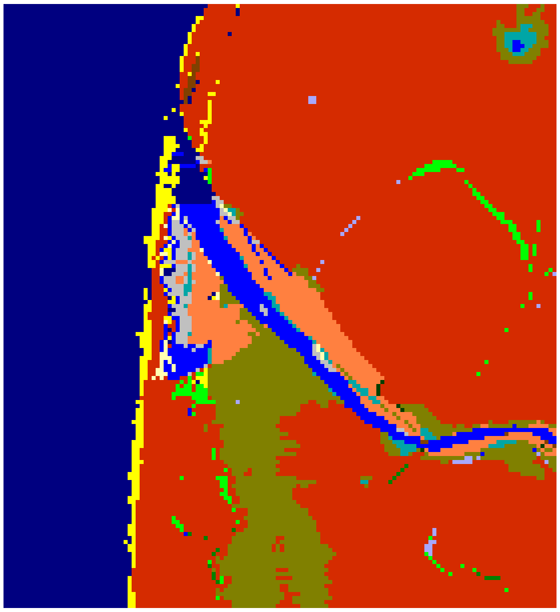
Salinas River NWR, 2025, 1 meter



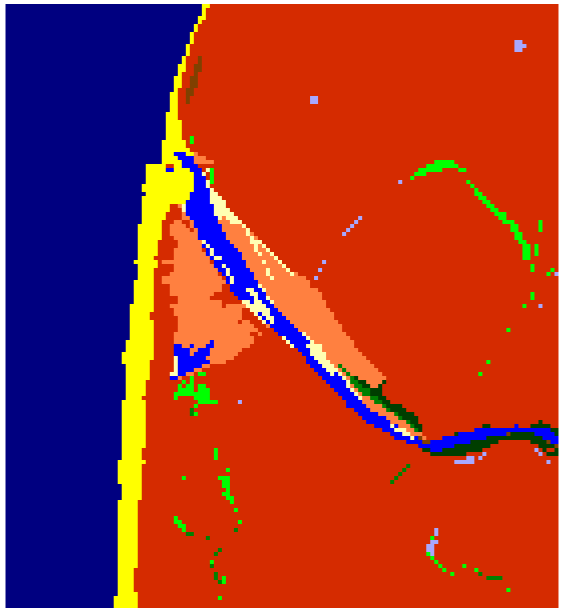
Salinas River NWR, 2050, 1 meter



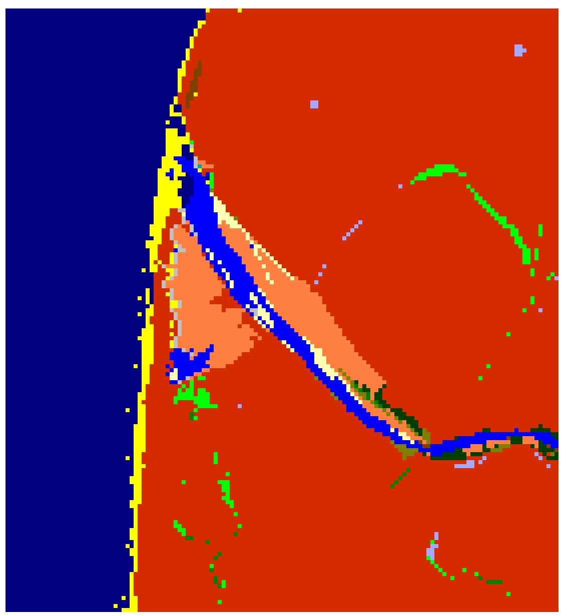
Salinas River NWR, 2075, 1 meter



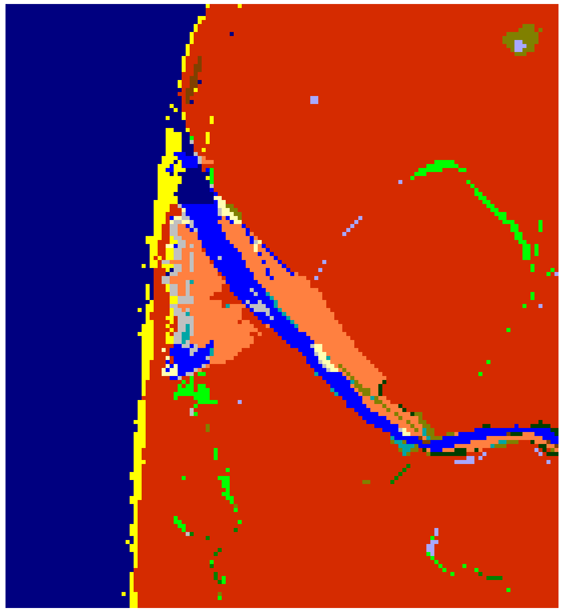
Salinas River NWR, 2100, 1 meter



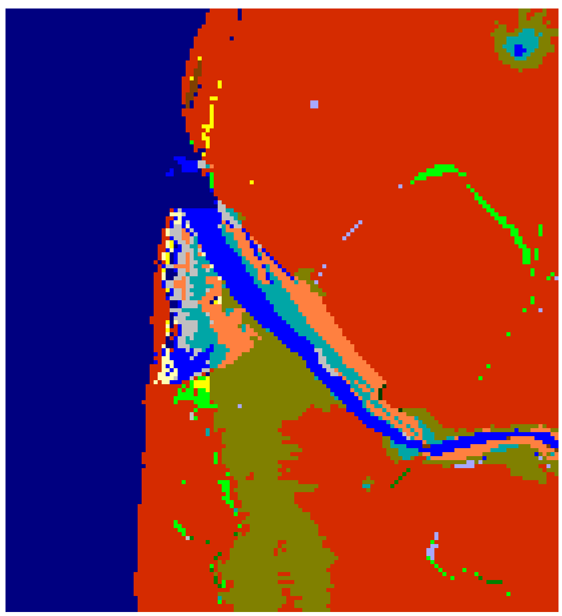
Salinas River NWR, Initial Condition



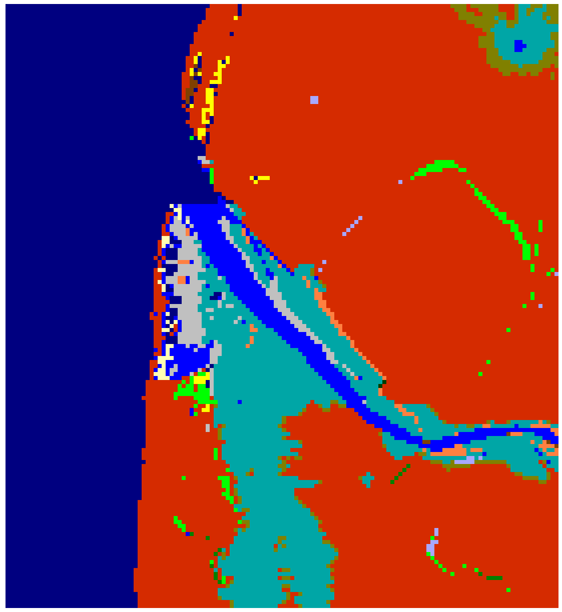
Salinas River NWR, 2025, 1.5 meter



Salinas River NWR, 2050, 1.5 meter



Salinas River NWR, 2075, 1.5 meter



Salinas River NWR, 2100, 1.5 meter