Application of the Sea-Level Affecting Marshes Model (SLAMM 6) to Marin Islands NWR

Prepared For: Dr. Brian Czech, Conservation Biologist

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

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

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Introduction

Tidal marshes are among the most susceptible ecosystems to climate change, especially accelerated sea level rise (SLR). The International Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) suggested that global sea level will increase by approximately 30 cm to 100 cm by 2100 (IPCC 2001). Rahmstorf (2007) suggests that this range may be too conservative and that the feasible range by 2100 could be 50 to 140 cm. 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.

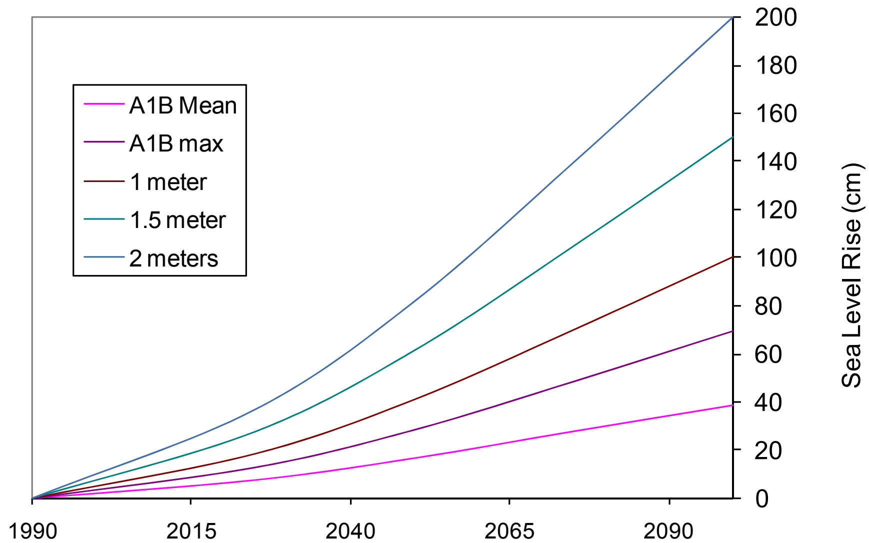
Sea Level Rise Scenarios

SLAMM 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. 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



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 digital elevation map (DEM) used in this model simulation is a combination of IfSAR and USGS NED datasets. The IfSAR, which covers all of the dry land and a portion of the tidal flats, was produced in 2003 for FEMA (Figure 1). The NED was based on 1959 data and has 20-feet contour intervals (Figure 2).

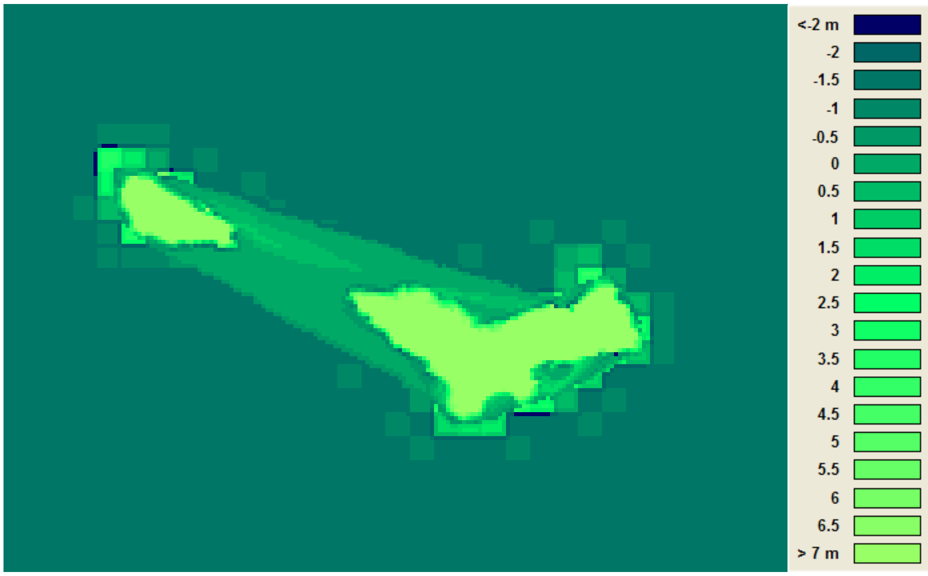


Figure 1: Elevation map of the two Marin Islands produced in SLAMM. Elevations are relative to MTL.

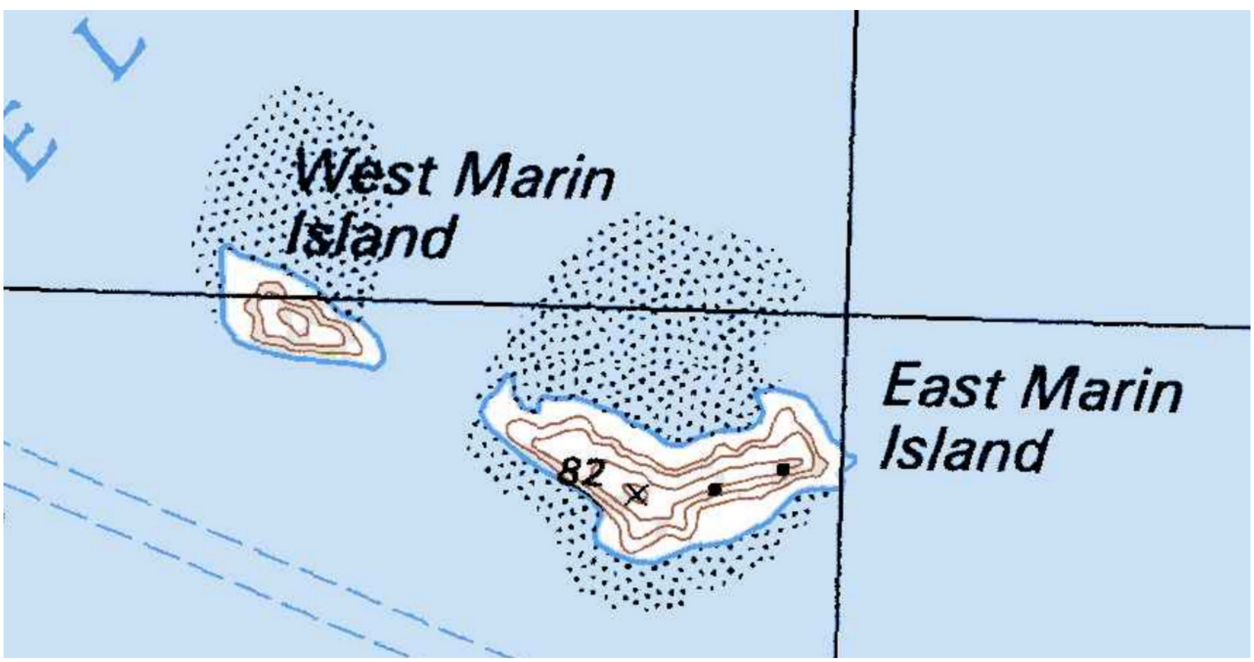


Figure 2: USGS topographical map of Marin Islands NWR.

The wetlands layer for Marin Islands was provided by the San Francisco Estuary Institute and is based on National Wetlands Inventory (NWI) data with a photo date of 1998. Due to the small size of this refuge and the high horizontal resolution of our input data, this refuge was modeled using five-meter cells. The approximately four hundred eighty acre refuge (approved acquisition boundary including water) is composed of the following categories:

Estuarine Open Water	89.8%
Tidal Flat	8.0%
Dry Land	2.2%

The refuge has no impounded zones, according to the National Wetlands Inventory.

The historic trend for sea level rise was estimated 2.01 mm/year using the nearest NOAA gage (9414290, San Francisco, CA). The rate of sea level rise for this refuge is just slightly higher than the global average for the last 100 years (approximately 1.7 mm/year).

Tide range of 1.77 meters was determined using the average of the two nearest NOAA tide gages (9414873, Point San Quentin, San Francisco Bay, CA; 9415009, Point San Pedro, San Francisco Bay, CA) (Figure 3).

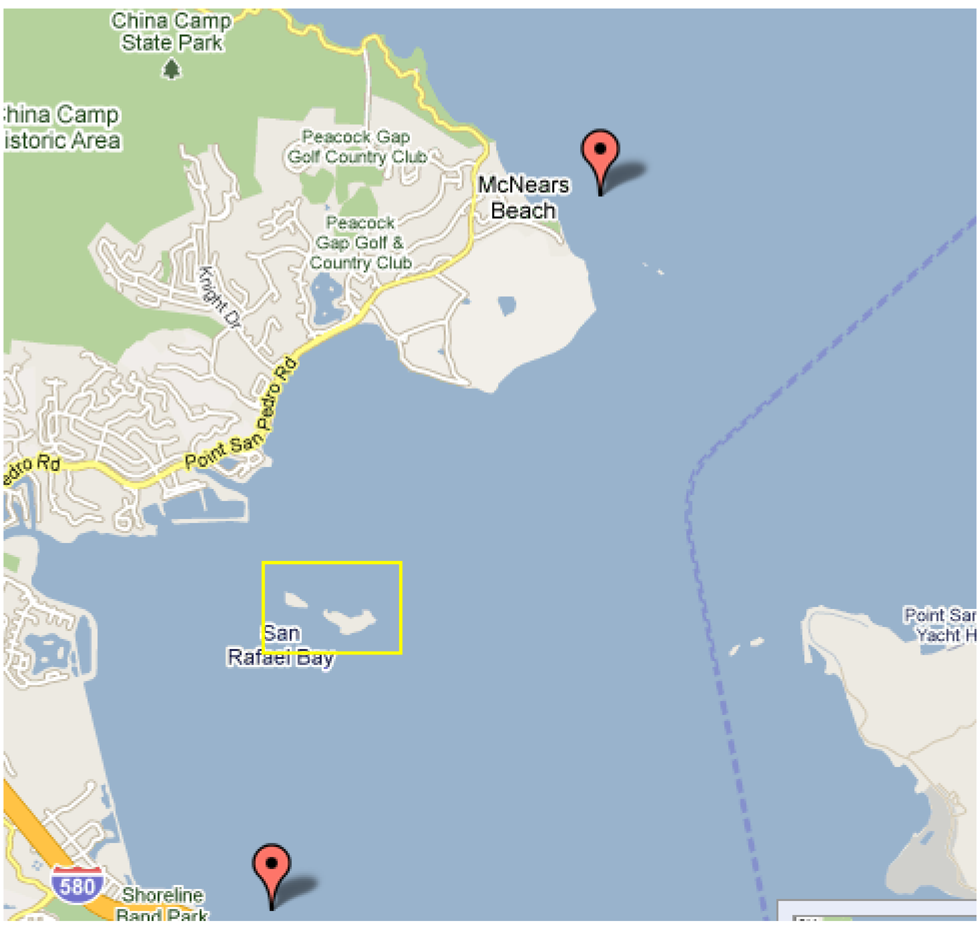


Figure 3: NOAA Gage Relevant to the Study Area.

As this site has no marsh within its boundaries, accretion values were left at zero.

Tidal flat erosion values were estimated based on two studies. One is a San Francisco Bay study that suggests the bay has been mildly depositional from 1983 to 2005 (Jaffe et al., 2006). The other is a study of San Pablo Bay that indicates temporally variable erosion rates based on variable sediment inputs to the bay (Jaffe et al., 1998) with a period ending in 1983 being more subject to erosion. It is unclear whether the Marin Islands will be subject to erosion or deposition during the next century so erosion rates were set to zero and resulting predictions are a function of inundation only.

The MTL to NAVD88 correction was derived using the NOAA VDATUM product. An elevation correction value of 1.0 meters was used for this study area.

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.

SUMMARY OF SLAMM INPUT PARAMETERS FOR MARIN ISLANDS NWR

Parameter	Global	SubSite 1	SubSite 2	SubSite 3
Description	Marin	SubSite 1	SubSite 2	SubSite 3
NWI Photo Date (YYYY)	1998	1998	1998	1998
DEM Date (YYYY)	2003	1959	1959	1959
Direction Offshore [n,s,e,w]	South	North	South	East
Historic Trend (mm/yr)	2.01	2.01	2.01	2.01
MTL-NAVD88 (m)	1	1	1	1
GT Great Diurnal Tide Range (m)	1.77	1.77	1.77	1.77
Salt Elev. (m above MTL)	1.28	1.28	1.28	1.28
Marsh Erosion (horz. m /yr)	0	0	0	0
Swamp Erosion (horz. m /yr)	0	0	0	0
T.Flat Erosion (horz. m /yr)	0	0	0	0
Reg. Flood Marsh Accr (mm/yr)	0	0	0	0
Irreg. Flood Marsh Accr (mm/yr)	0	0	0	0
Tidal Fresh Marsh Accr (mm/yr)	0	0	0	0
Beach Sed. Rate (mm/yr)	0.5	0.5	0.5	0.5
Freq. Overwash (years)	0	0	0	0
Use Elev Pre-processor [True,False]	FALSE	TRUE	TRUE	TRUE

Results

Results from this simulation suggest that refuge tidal flats are vulnerable to the effects of sea level rise. The refuge is predicted to lose nearly one-third of its initial tidal flat in the most conservative scenario. Nearly all tidal flats are predicted lost in scenarios above 1 meter SLR. A few low-elevation pockets of dry land are also predicted to be vulnerable to inundation.

SLR by 2100 (m)	**0.39**	**0.69**	**1**	**1.5**	**2**
Tidal Flat	32%	57%	77%	93%	96%
Undev. Dry Land	12%	14%	16%	17%	18%

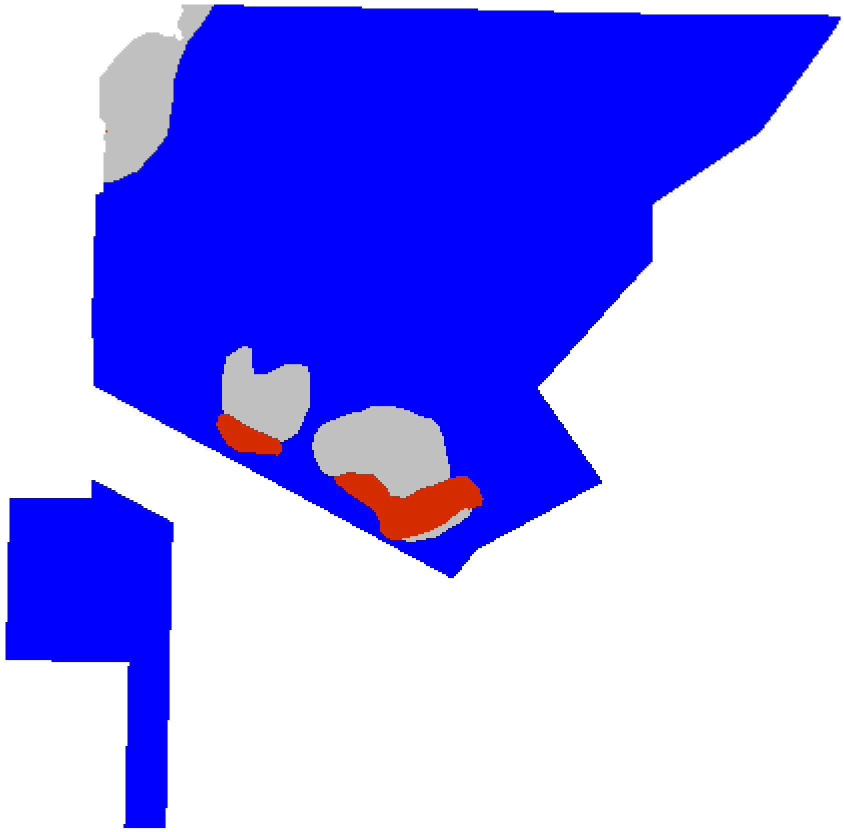
Predicted Loss Rates of Land Categories by 2100 Given Simulated Scenarios of Eustatic Sea Level Rise

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

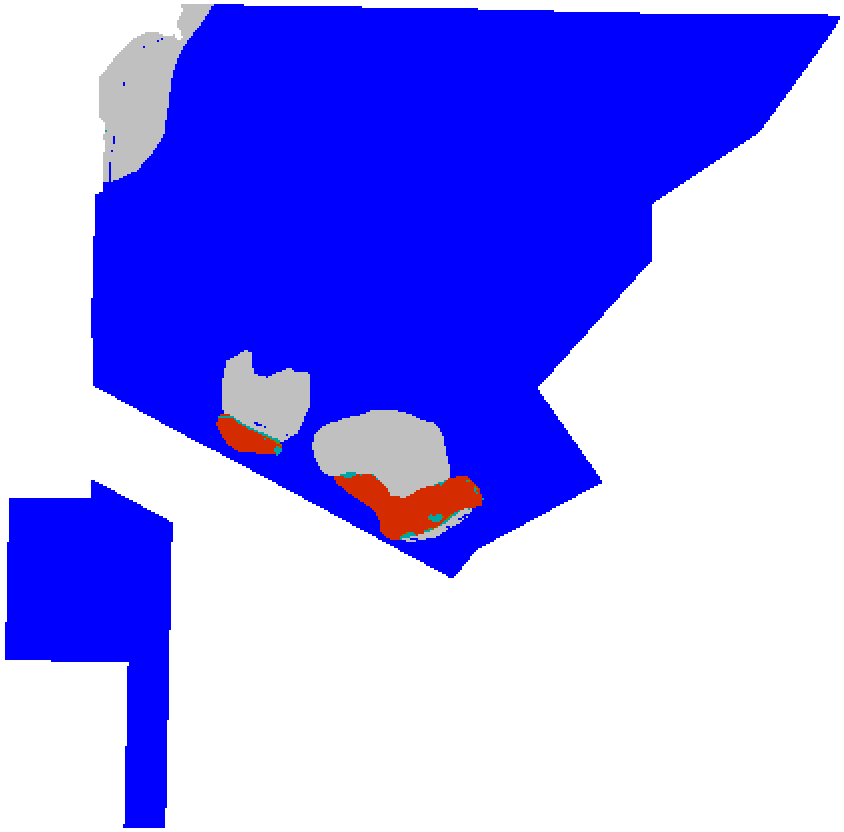
Marin Islands NWR
IPCC Scenario A1B-Mean, 0.39 M SLR Eustatic by 2100

Results in Acres

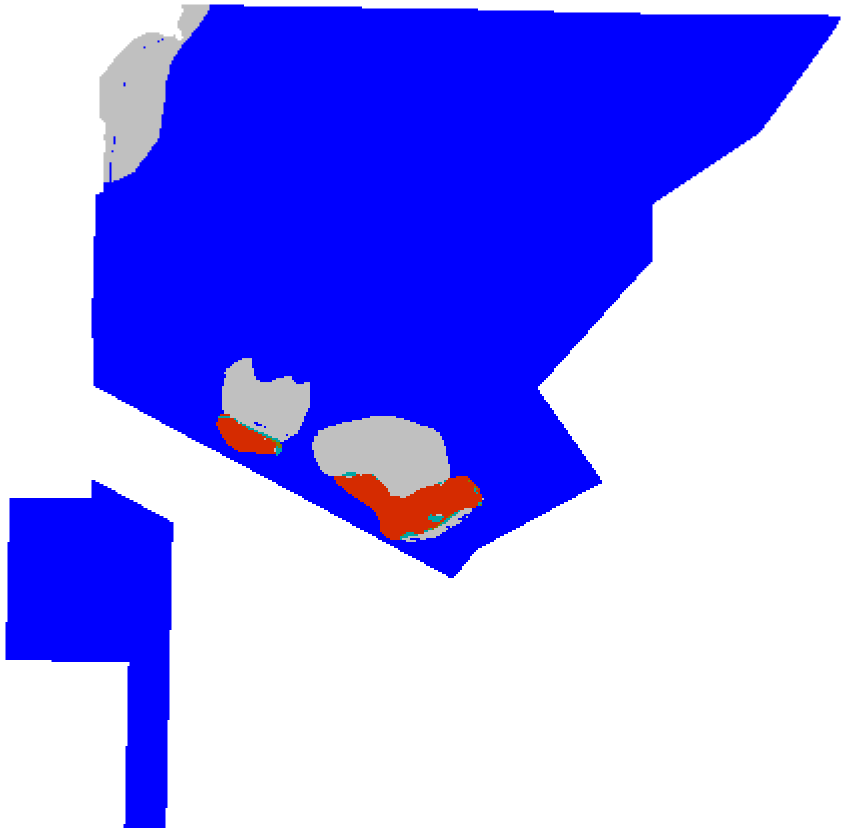
	Initial	2025	2050	2075	2100
Estuarine Open Water	425.0	426.8	429.9	433.7	437.4
Tidal Flat	37.9	36.1	33.2	29.5	25.9
Undev. Dry Land	10.4	9.3	9.2	9.1	9.1
Saltmarsh	0.0	0.8	0.7	0.7	0.7
Trans. Salt Marsh	0.0	0.3	0.2	0.2	0.3
Total (incl. water)	**473.3**	**473.3**	**473.3**	**473.3**	**473.3**



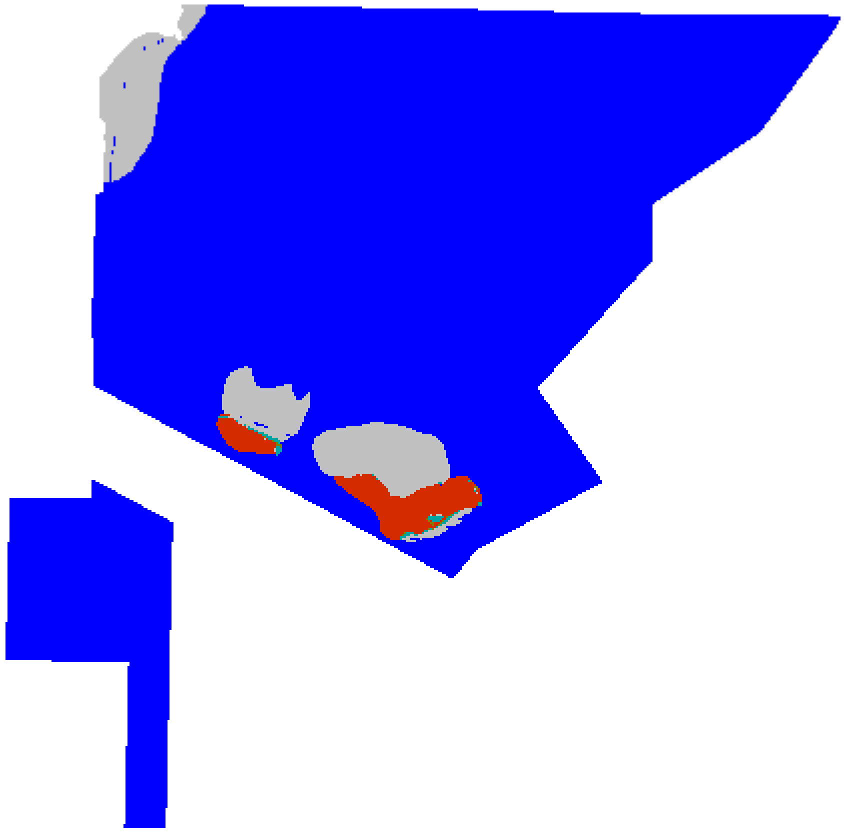
Marin Islands NWR, Initial Condition



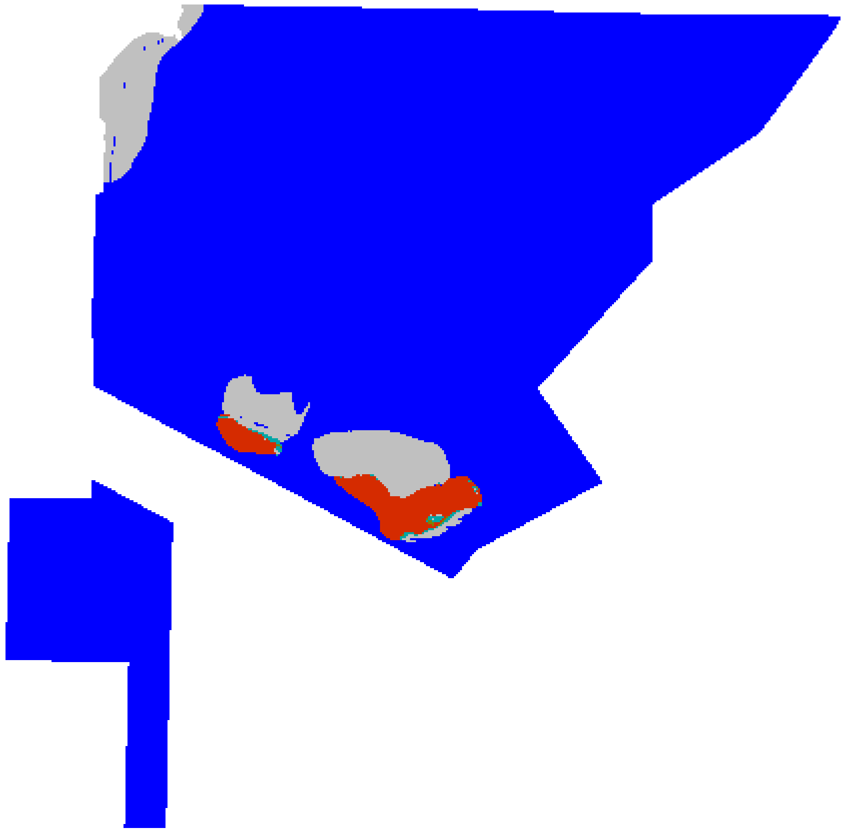
Marin Islands NWR, 2025, Scenario A1B Mean



Marin Islands NWR, 2050, Scenario A1B Mean



Marin Islands NWR, 2075, Scenario A1B Mean

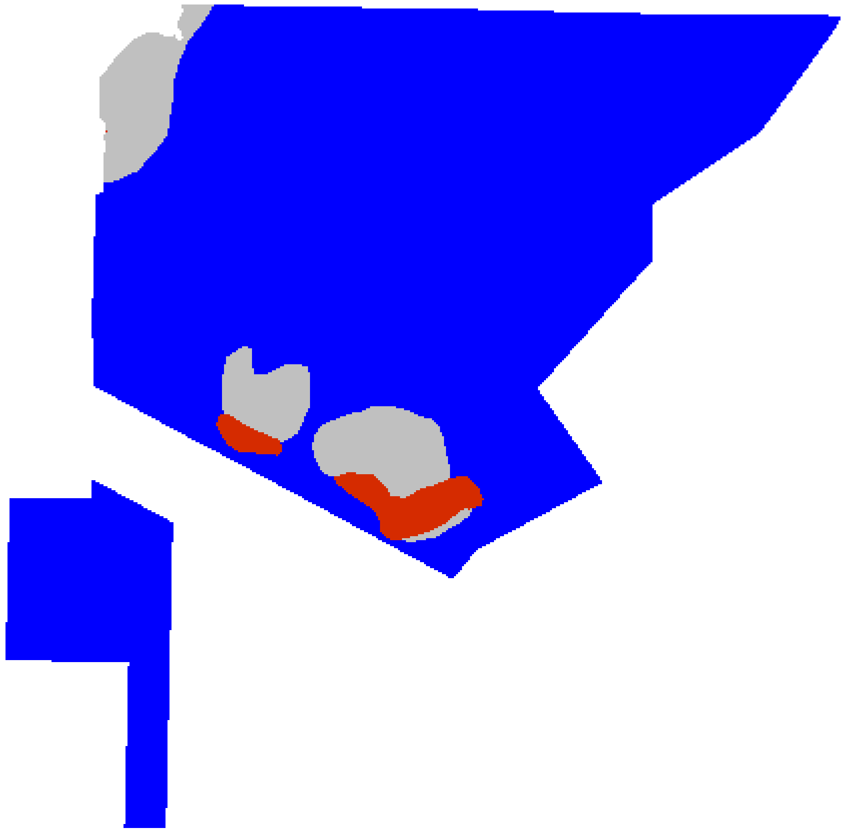


Marin Islands NWR, 2100, Scenario A1B Mean

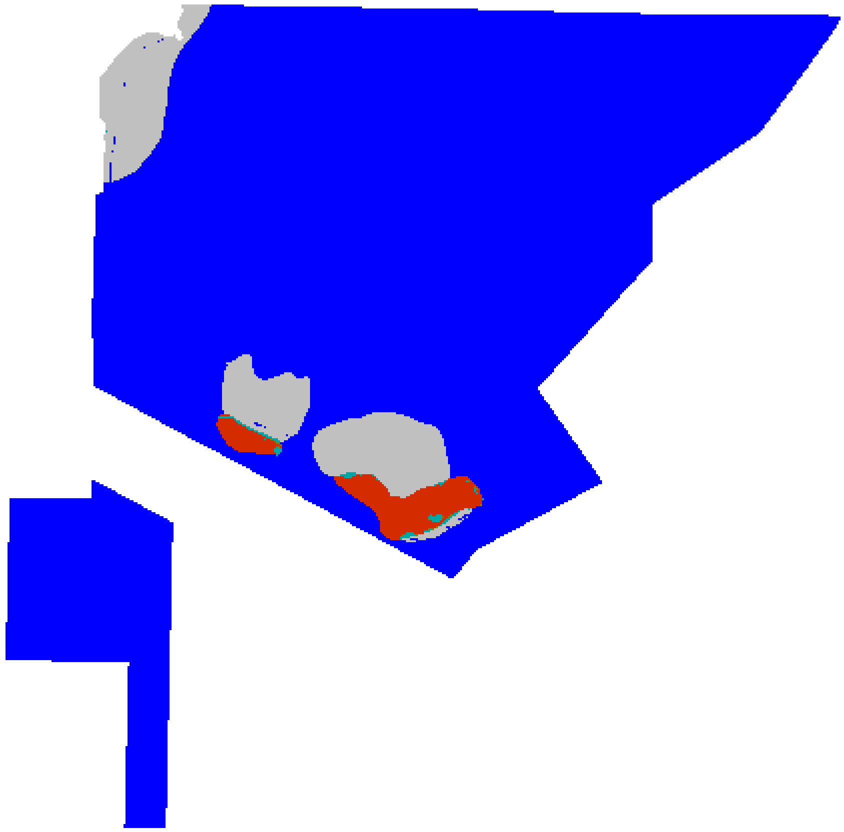
Marin Islands NWR
IPCC Scenario A1B-Max, 0.69 M SLR Eustatic by 2100

Results in Acres

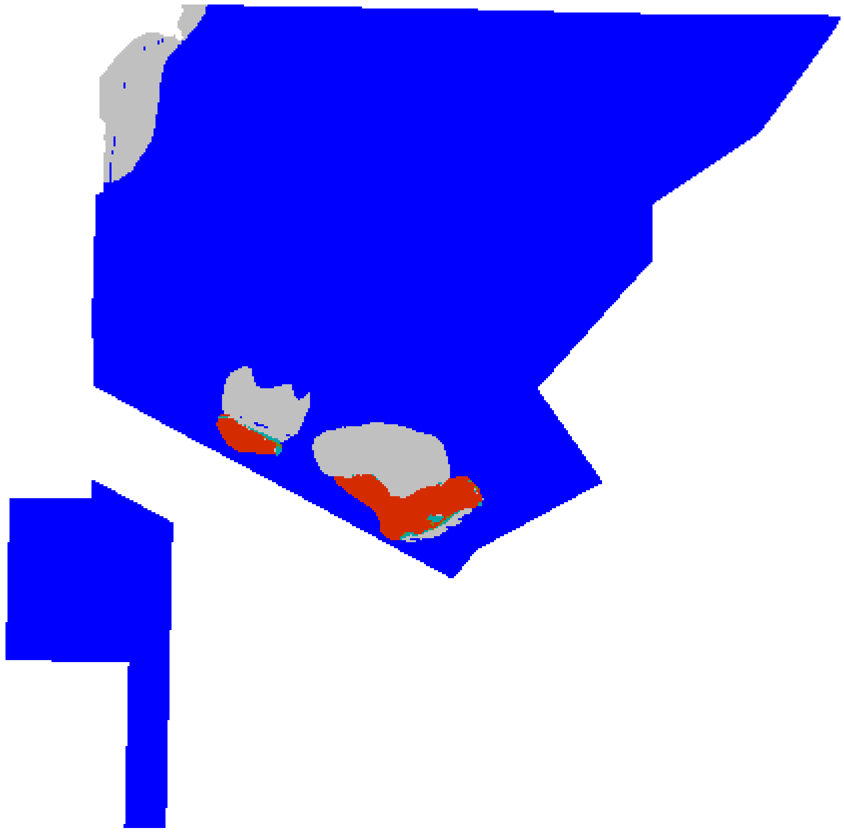
	Initial	2025	2050	2075	2100
Estuarine Open Water	425.0	428.2	433.7	440.6	447.2
Tidal Flat	37.9	34.7	29.5	22.8	16.3
Undev. Dry Land	10.4	9.3	9.1	9.0	8.9
Saltmarsh	0.0	0.8	0.7	0.7	0.6
Trans. Salt Marsh	0.0	0.3	0.2	0.3	0.3
Total (incl. water)	**473.3**	**473.3**	**473.3**	**473.3**	**473.3**



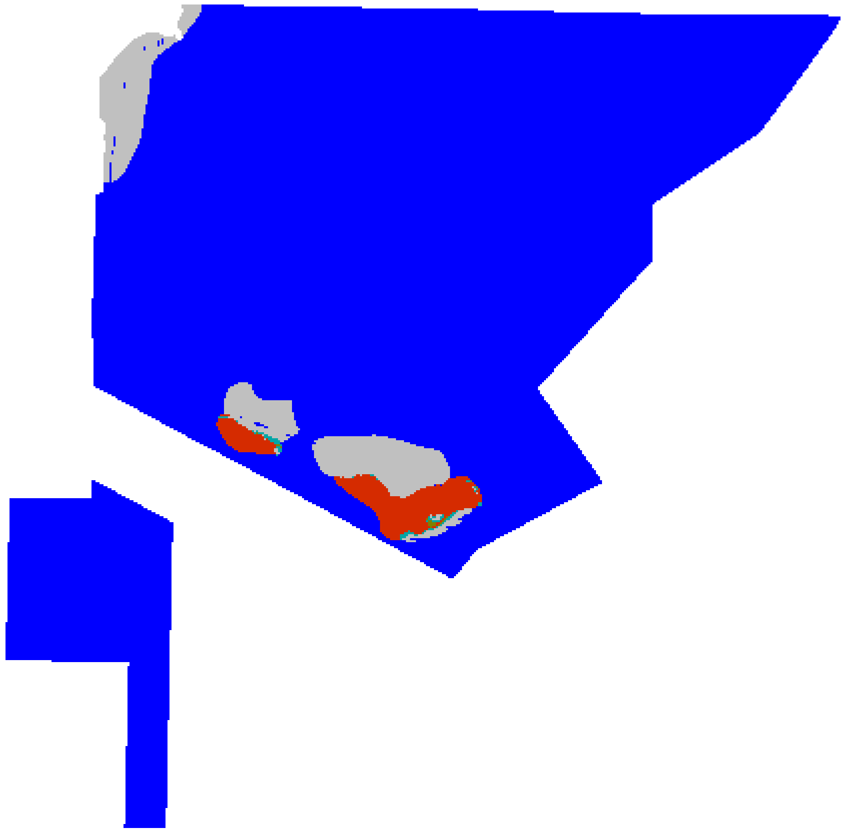
Marin Islands NWR, Initial Condition



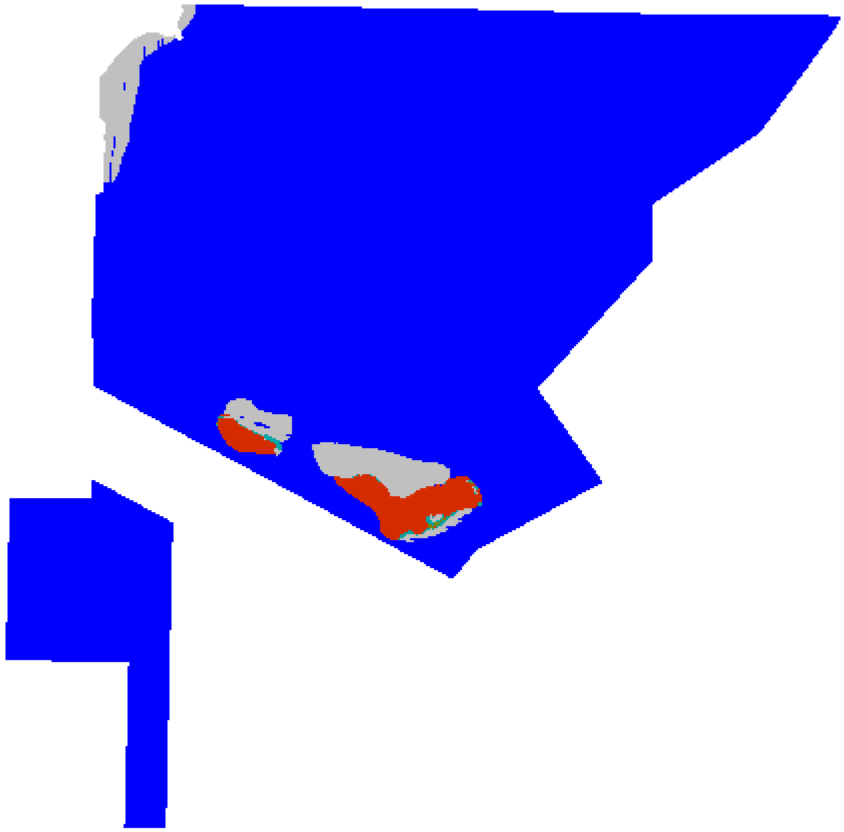
Marin Islands NWR, 2025, Scenario A1B Maximum



Marin Islands NWR, 2050, Scenario A1B Maximum



Marin Islands NWR, 2075, Scenario A1B Maximum

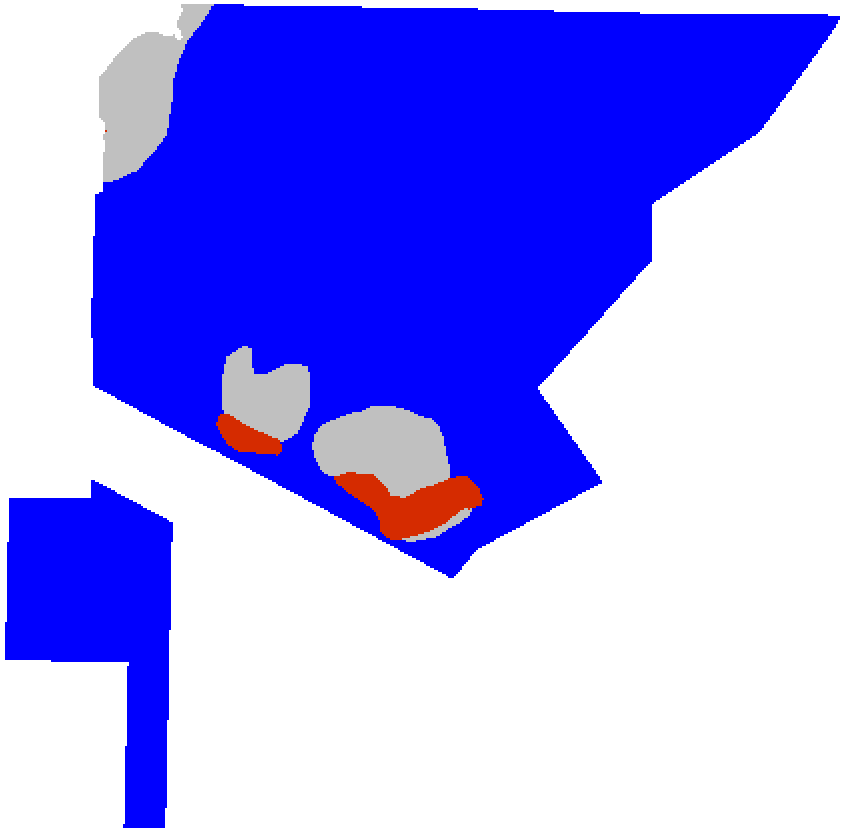


Marin Islands NWR, 2100, Scenario A1B Maximum

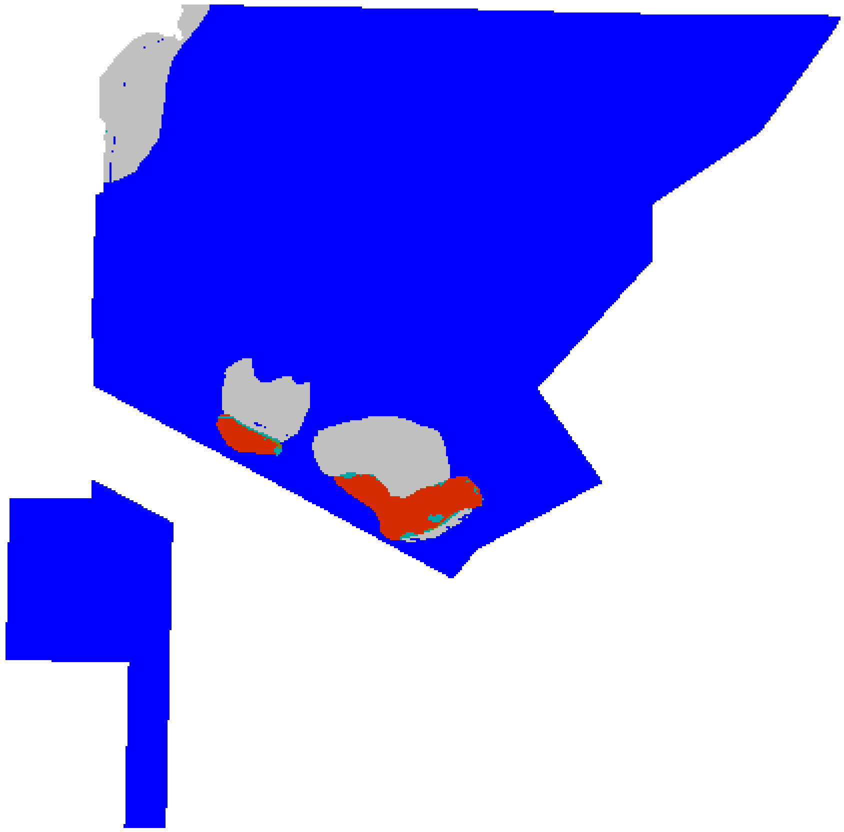
Marin Islands NWR
1 Meter Eustatic SLR by 2100

Results in Acres

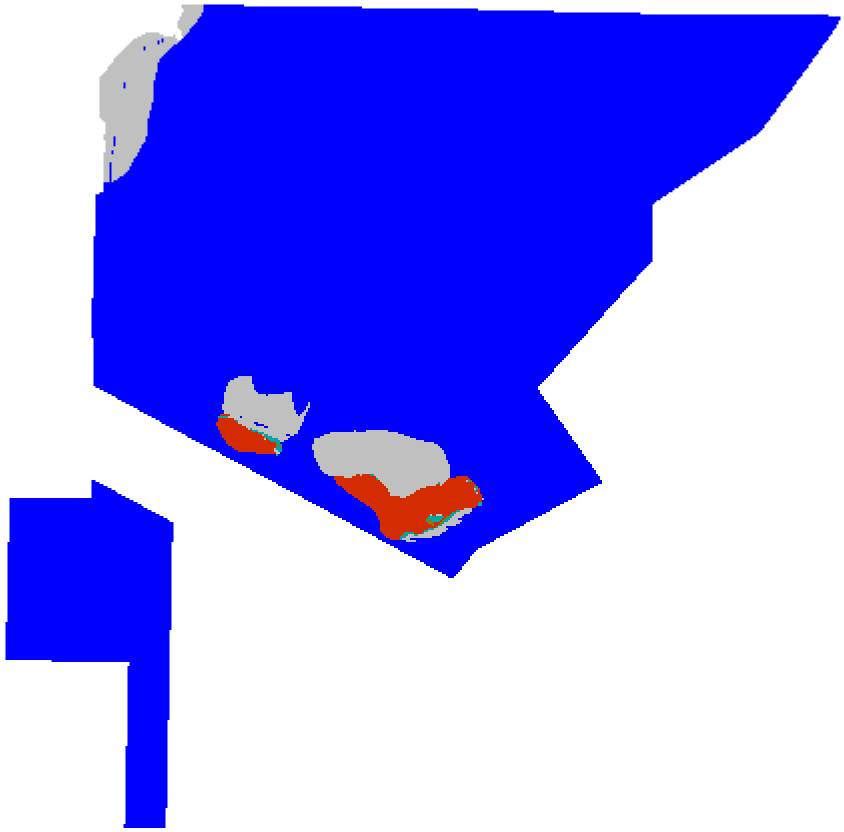
	Initial	2025	2050	2075	2100
Estuarine Open Water	425.0	429.8	437.6	447.1	455.1
Tidal Flat	37.9	33.2	25.7	16.4	8.7
Undev. Dry Land	10.4	9.2	9.1	8.9	8.7
Saltmarsh	0.0	0.9	0.7	0.6	0.6
Trans. Salt Marsh	0.0	0.3	0.2	0.3	0.2
Total (incl. water)	**473.3**	**473.3**	**473.3**	**473.3**	**473.3**



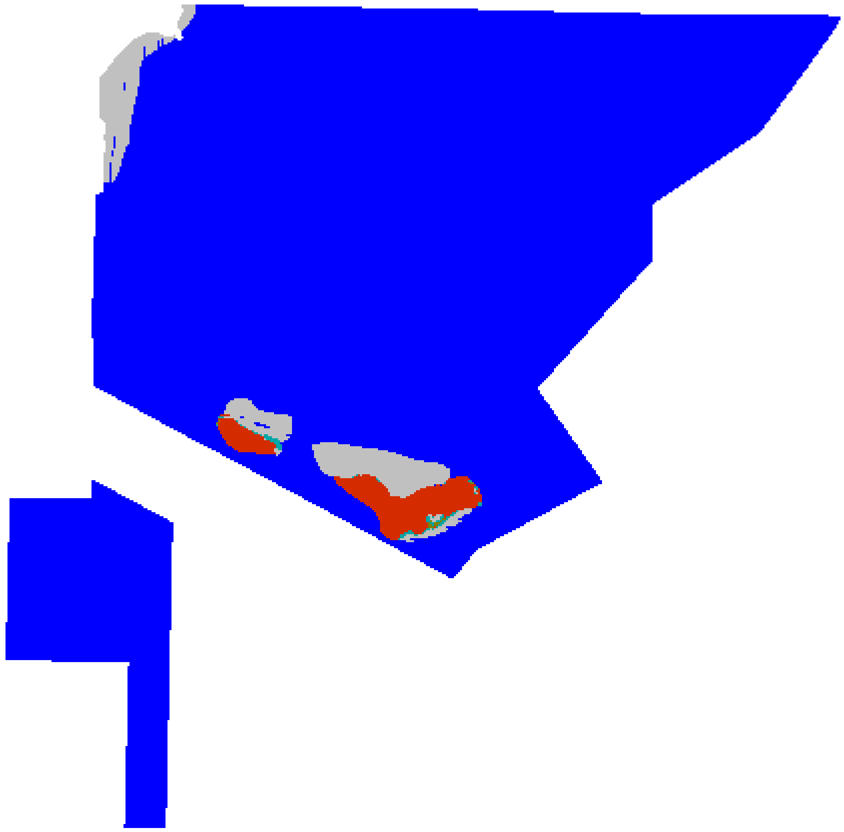
Marin Islands NWR, Initial Condition



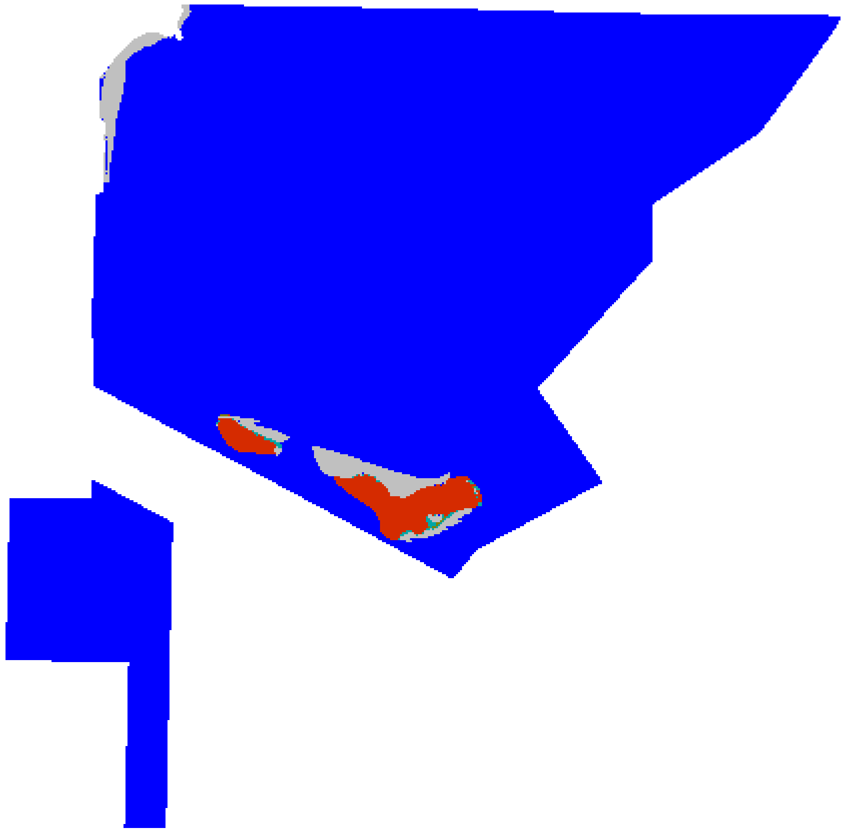
Marin Islands NWR, 2025, 1 meter



Marin Islands NWR, 2050, 1 meter



Marin Islands NWR, 2075, 1 meter

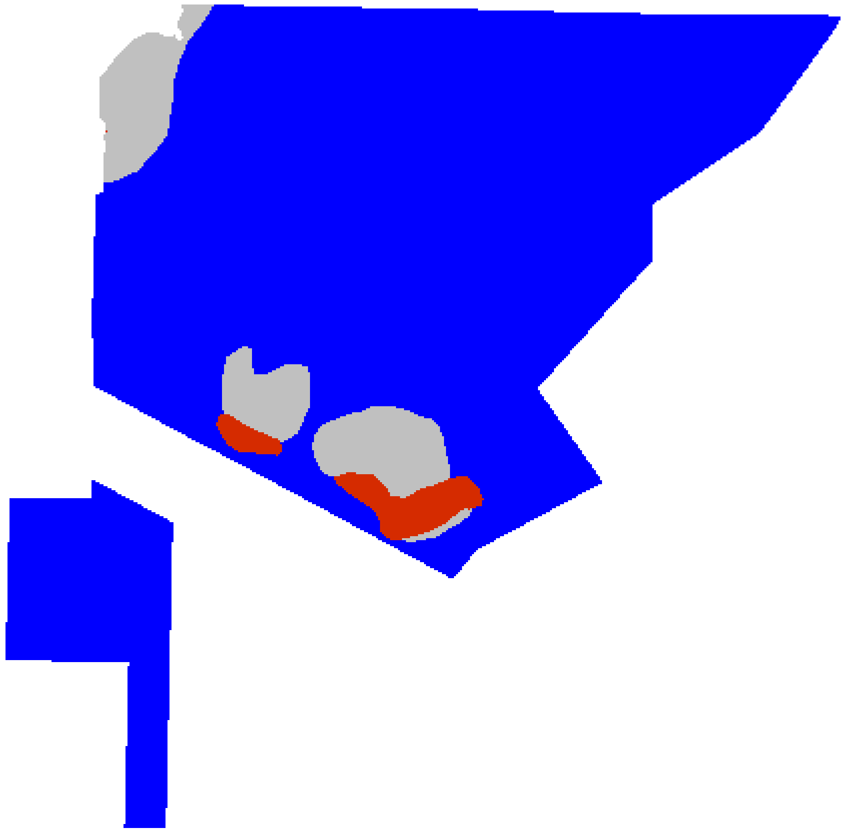


Marin Islands NWR, 2100, 1 meter

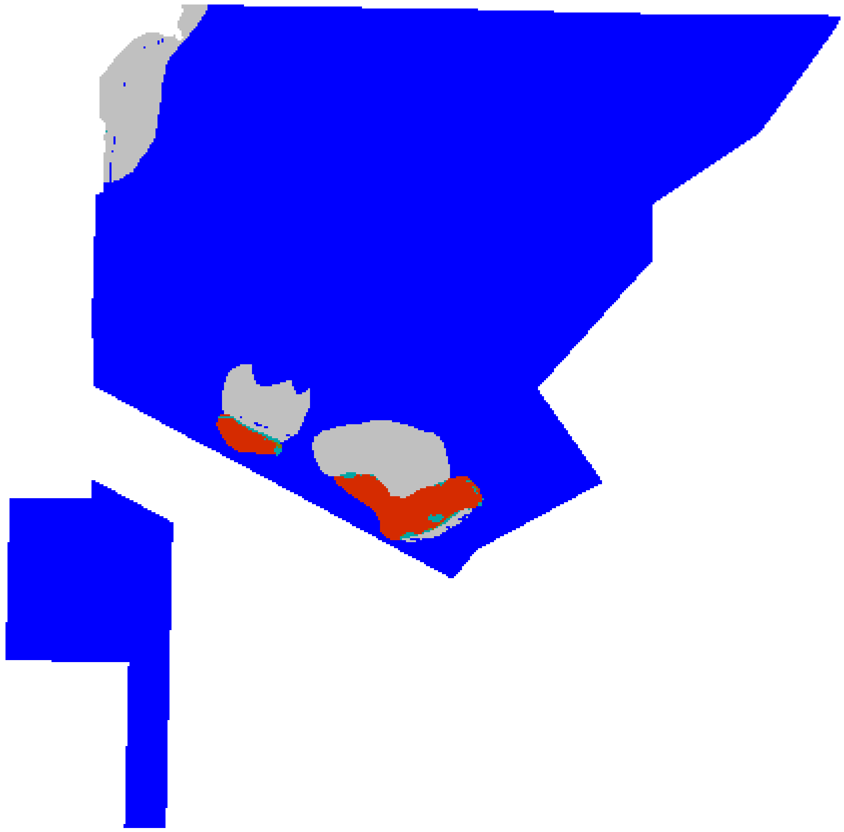
Marin Islands NWR
1.5 Meters Eustatic SLR by 2100

Results in Acres

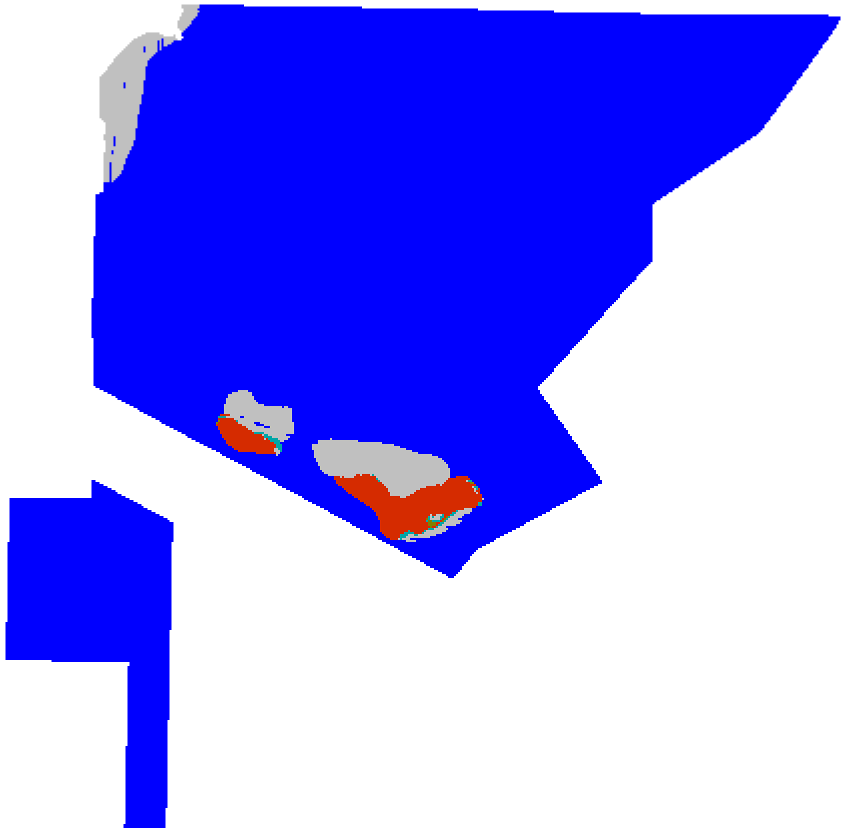
	Initial	2025	2050	2075	2100
Estuarine Open Water	425.0	432.3	443.8	455.5	461.4
Tidal Flat	37.9	30.6	19.6	8.3	2.7
Undev. Dry Land	10.4	9.2	8.9	8.7	8.6
Saltmarsh	0.0	0.9	0.7	0.5	0.5
Trans. Salt Marsh	0.0	0.3	0.2	0.2	0.2
Total (incl. water)	**473.3**	**473.3**	**473.3**	**473.3**	**473.3**



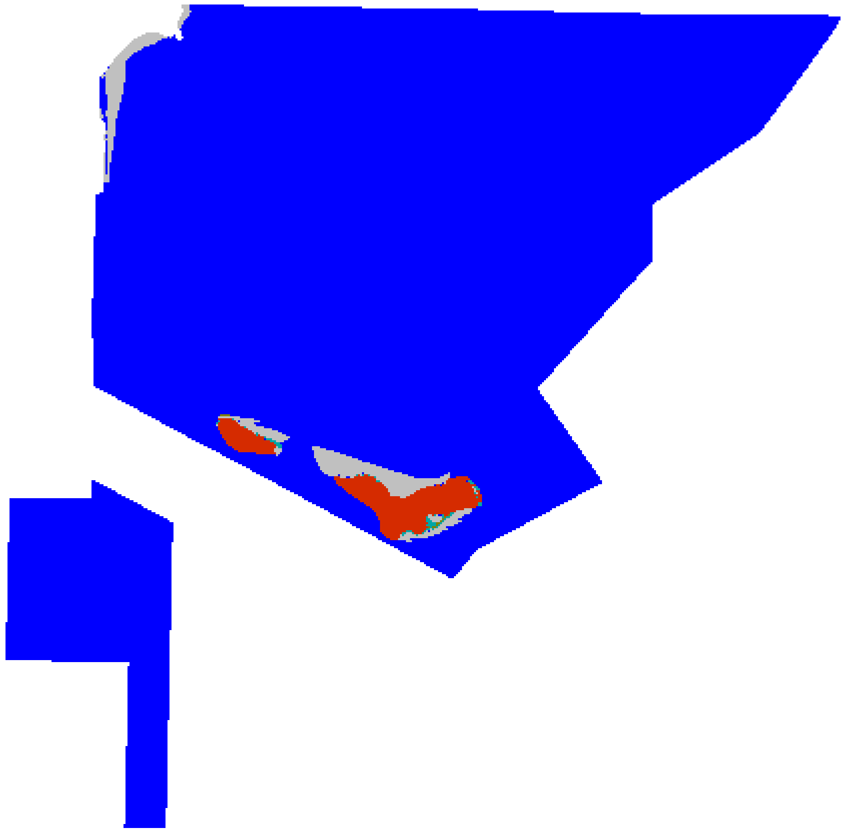
Marin Islands NWR, Initial Condition



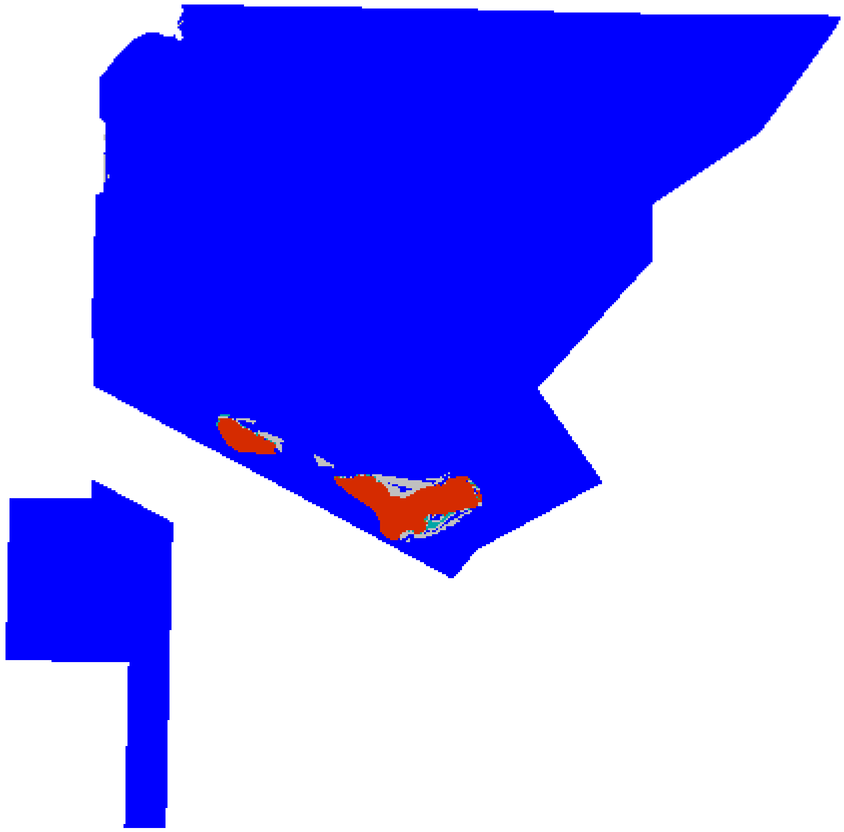
Marin Islands NWR, 2025, 1.5 meter



Marin Islands NWR, 2050, 1.5 meter



Marin Islands NWR, 2075, 1.5 meter

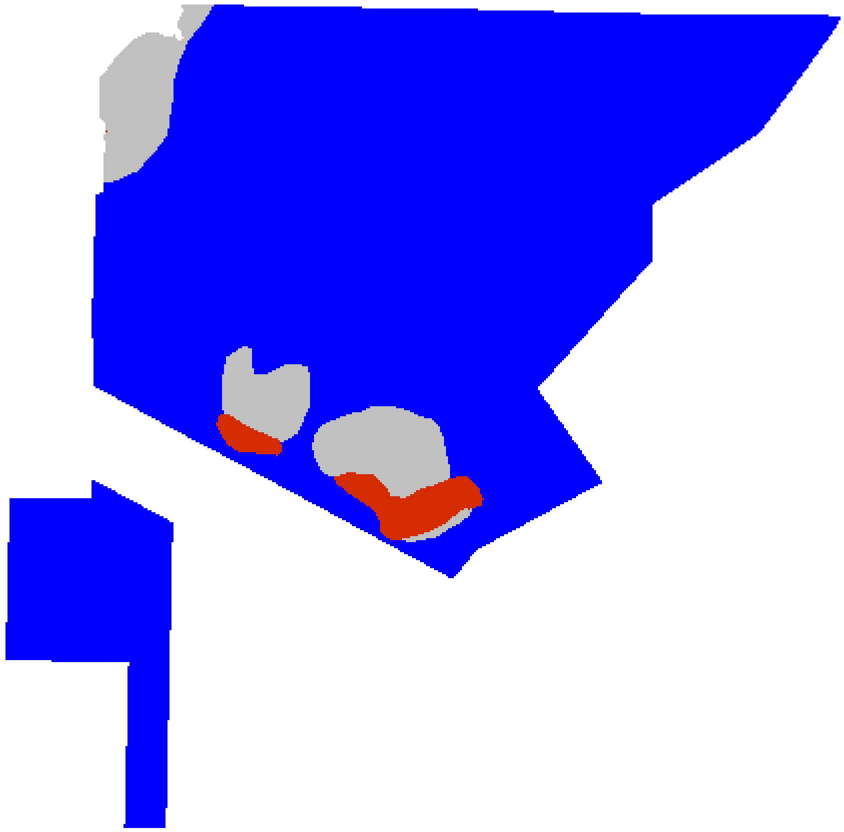


Marin Islands NWR, 2100, 1.5 meter

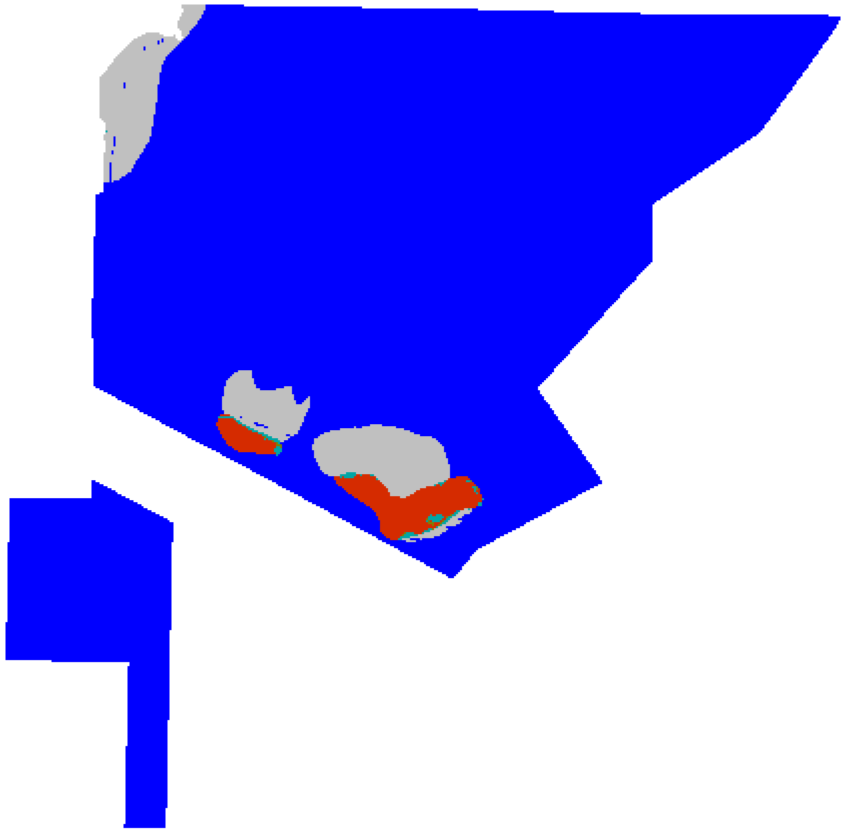
Marin Islands NWR
2 Meters Eustatic SLR by 2100

Results in Acres

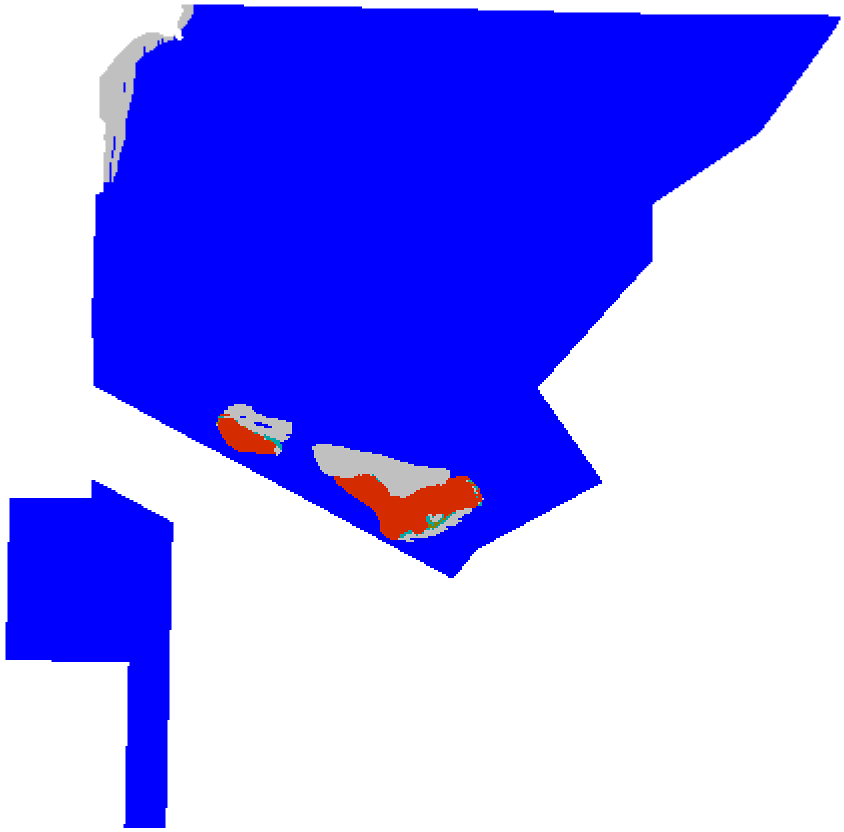
	Initial	2025	2050	2075	2100
Estuarine Open Water	425.0	434.9	449.7	460.2	462.9
Tidal Flat	37.9	28.1	14.0	3.9	1.5
Undev. Dry Land	10.4	9.1	8.8	8.6	8.4
Saltmarsh	0.0	1.0	0.5	0.4	0.3
Trans. Salt Marsh	0.0	0.3	0.3	0.2	0.2
Total (incl. water)	**473.3**	**473.3**	**473.3**	**473.3**	**473.3**



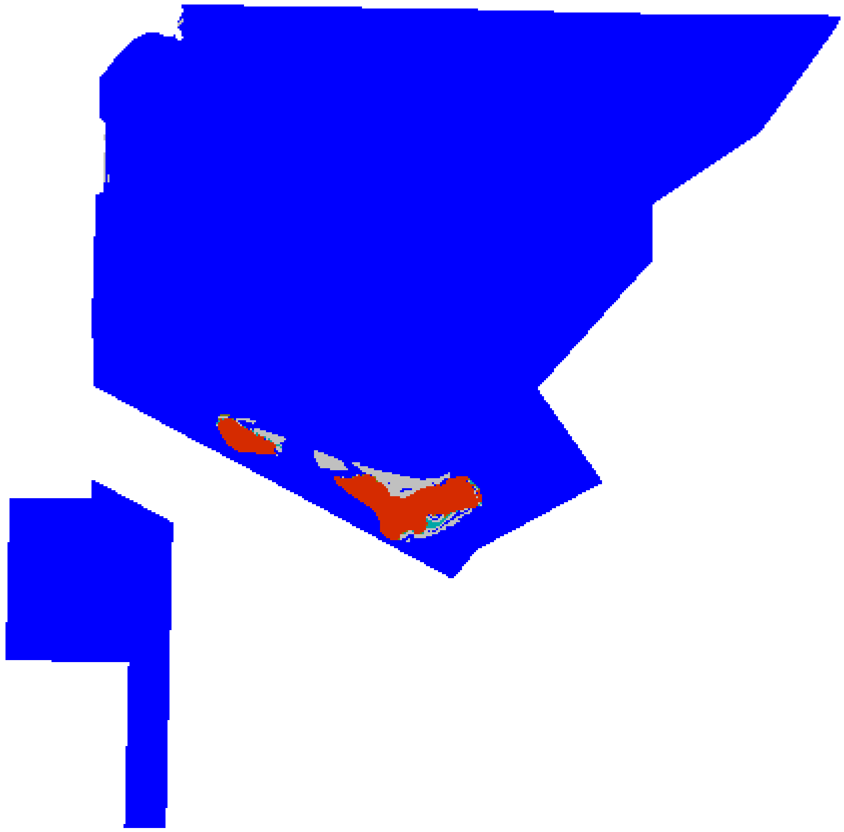
Marin Islands NWR, Initial Condition



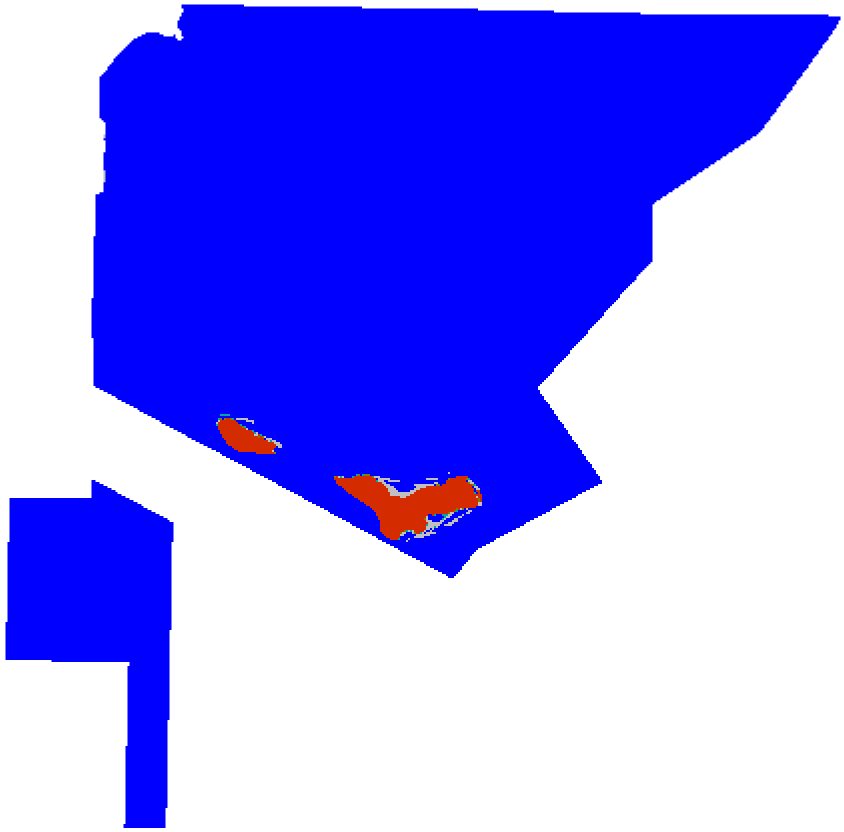
Marin Islands NWR, 2025, 2 meters



Marin Islands NWR, 2050, 2 meters



Marin Islands NWR, 2075, 2 meters



Marin Islands NWR, 2100, 2 meters

Discussion

Based on the land-cover data in this analysis, the Marin Islands NWR is comprised of only two land categories: dry land and tidal flats. The majority of the dry land has elevations considerably above mean tide level, with the exception of an area in the south of East Marin Island.

Elevation data for this site were primarily derived from ifSAR flights. No vertical accuracy information was available from the metadata, but ifSAR tends to have a vertical accuracy that is not as fine as LiDAR data. ifSAR data uses radar rather than lasers and tends to be flown in airplanes of higher heights. This increases model uncertainty relative to LiDAR data, but is definitely preferable to using the USGS-contour-derived elevation maps from the National Elevation Dataset.

In the portion of the map not covered by ifSAR, all tidal flats are located below the first contour (used to derive the National Elevation Dataset). This significantly increases the uncertainty of tidal flat loss predictions due to inundation within those portions of the map (Figure 1).

Another area of uncertainty pertains to erosion and deposition rates projected over the next century. Site-specific data for this location were not available and an analysis of San Pablo Bay to the north suggests that erosion and deposition rates were temporally and spatially variable.

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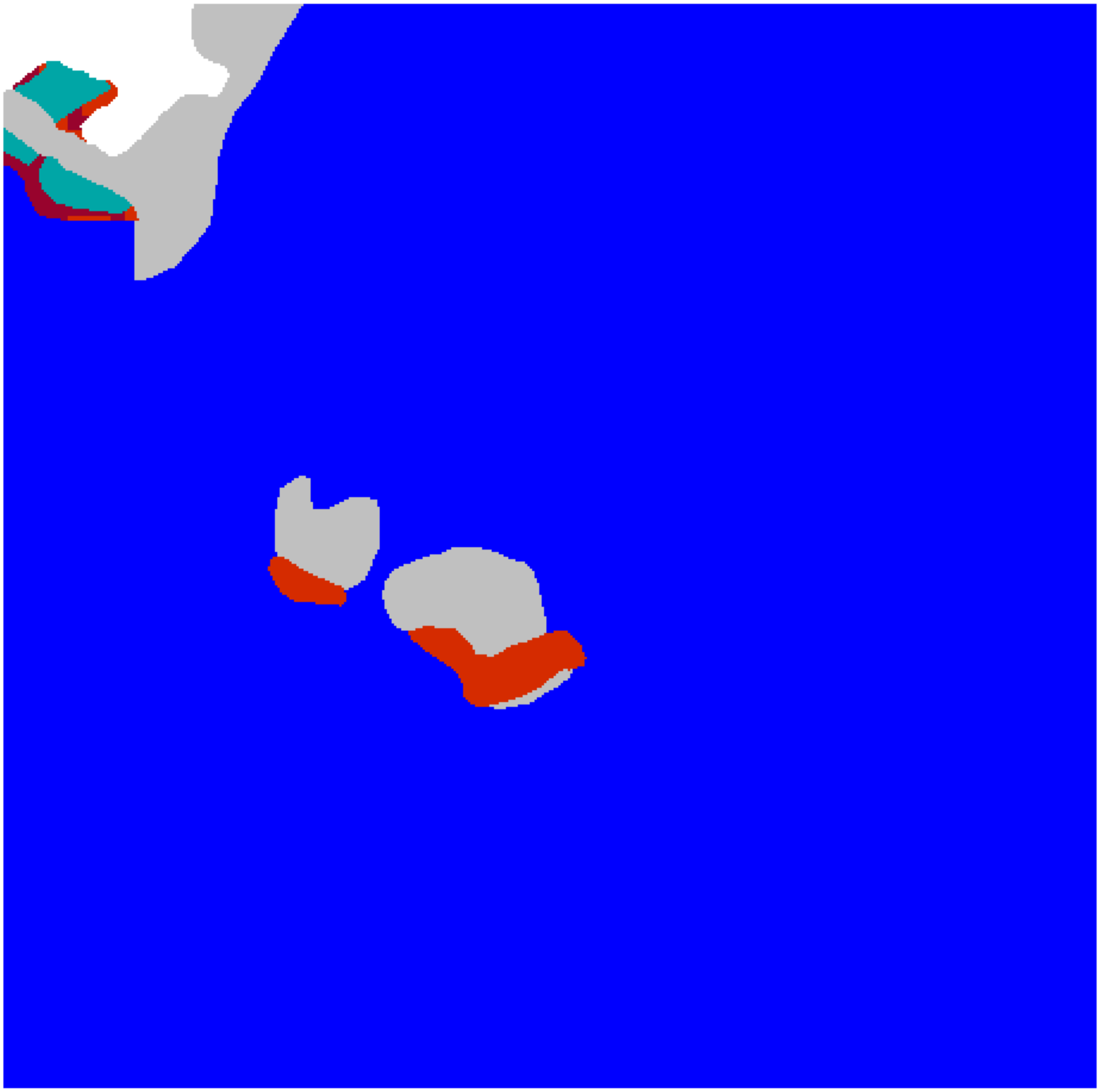
Appendix A: Contextual Results

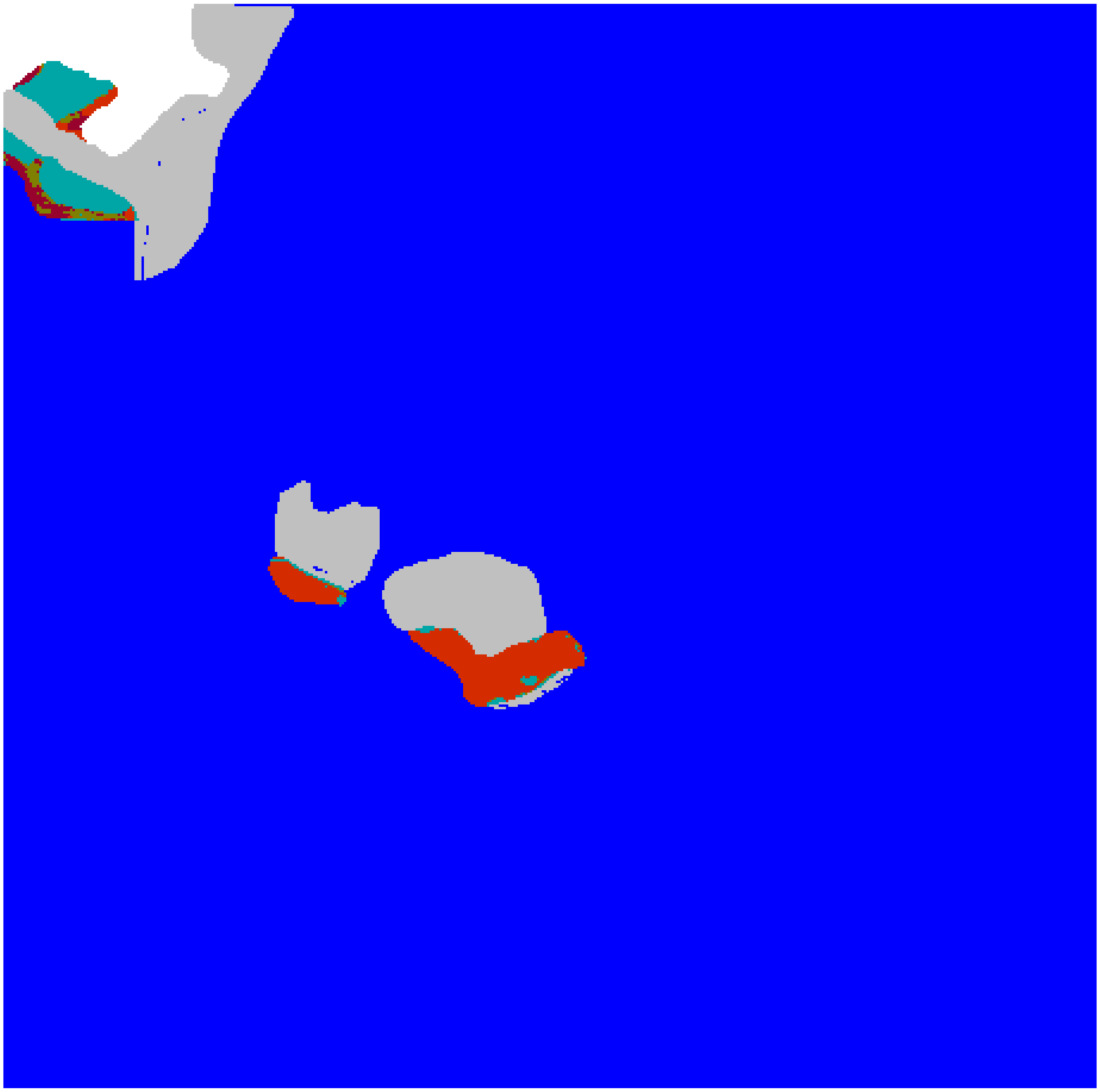
The SLAMM model does take into account the context of the surrounding lands or open water when calculating effects. For example, erosion rates are calculated based on the maximum fetch (wave action) which is estimated by assessing contiguous open water to a given marsh cell. Another example is that inundated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

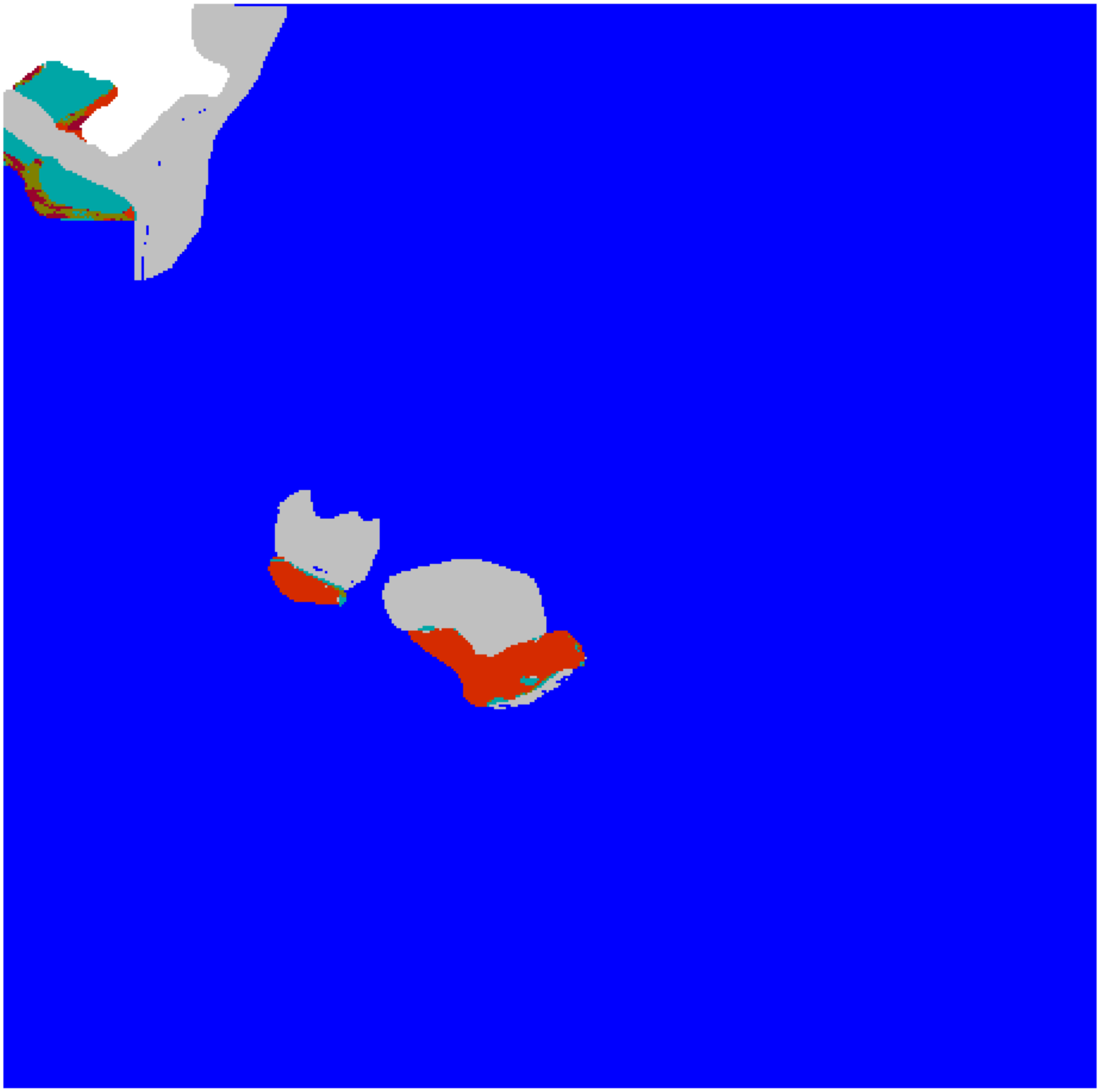
- Results were closely examined (quality assurance) within USFWS refuges but not closely examined for the larger region.
- Site-specific parameters for the model were derived for USFWS refuges whenever possible and may not be regionally applicable.
- Especially in areas where dikes are present, an effort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



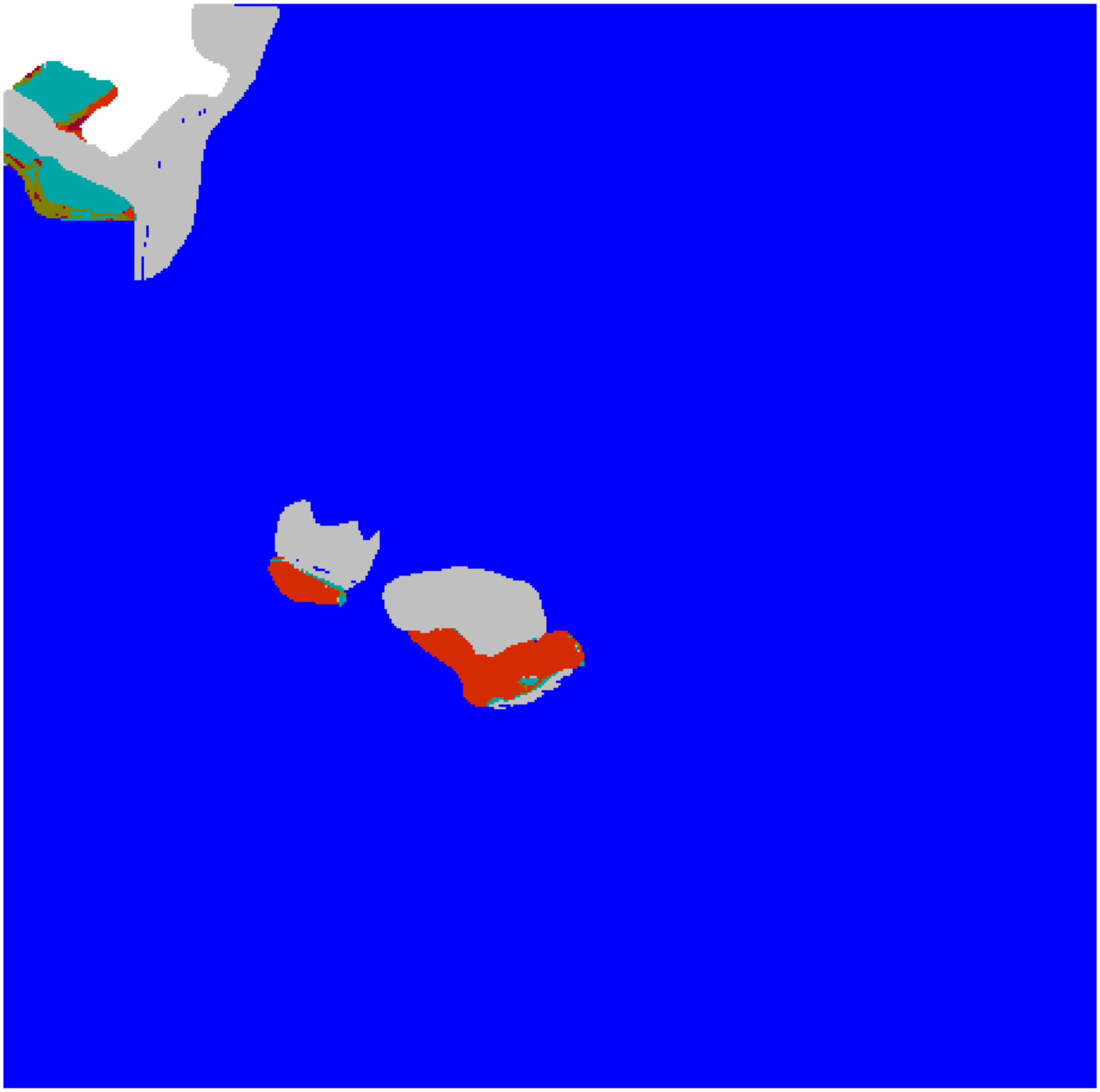
Marin Islands NWR, Initial Condition



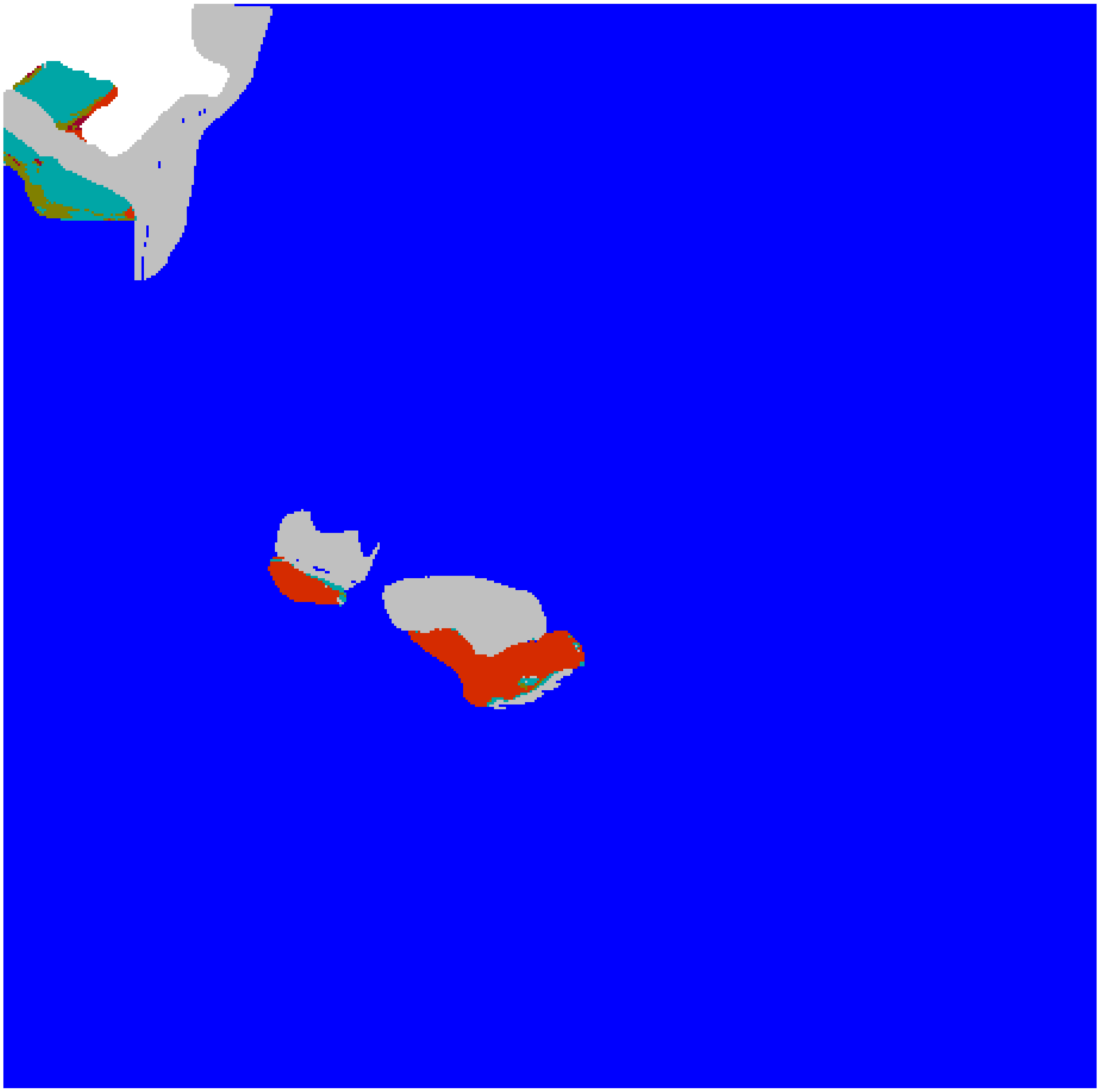
Marin Islands NWR, 2025, Scenario A1B Mean



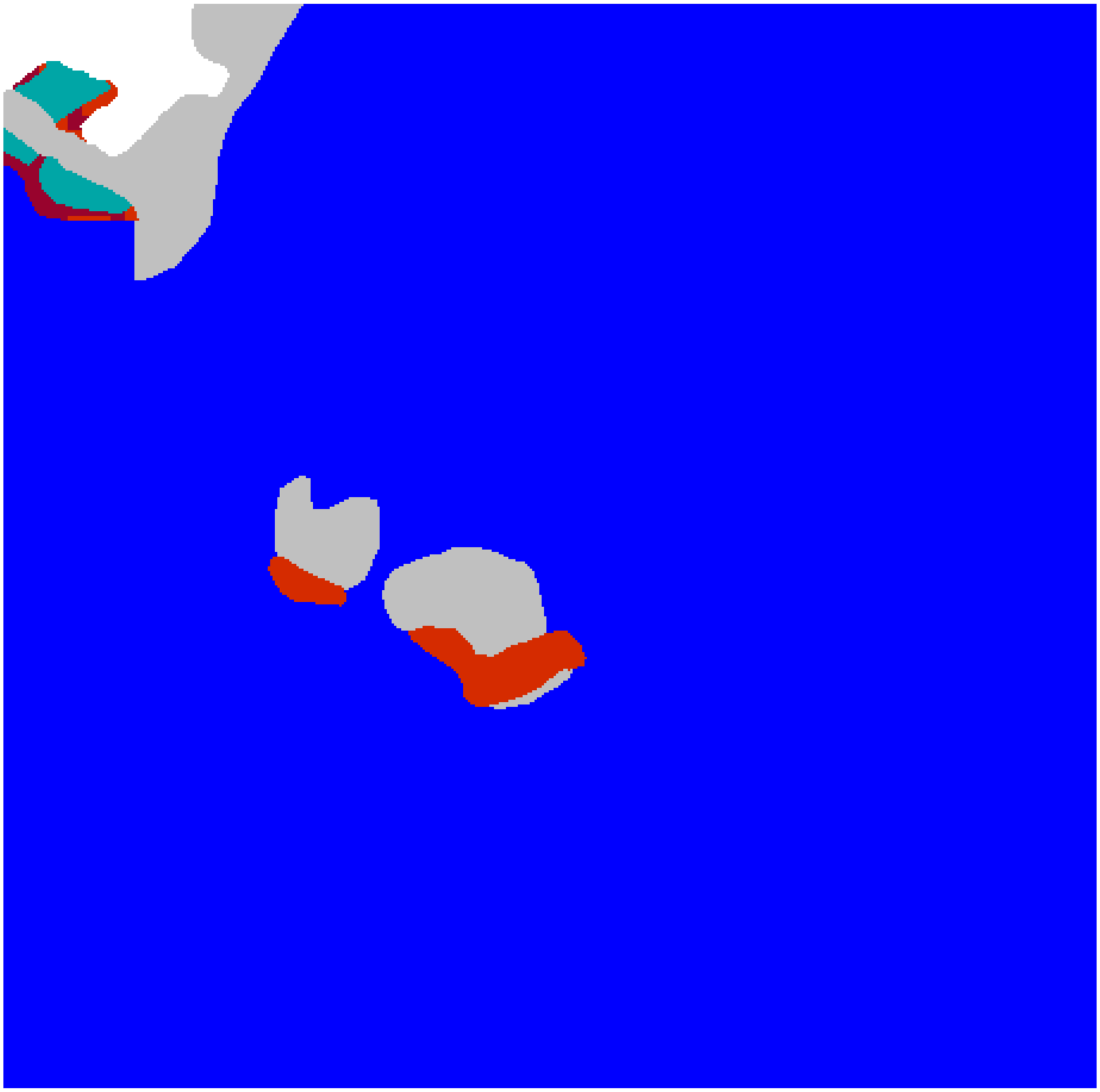
Marin Islands NWR, 2050, Scenario A1B Mean



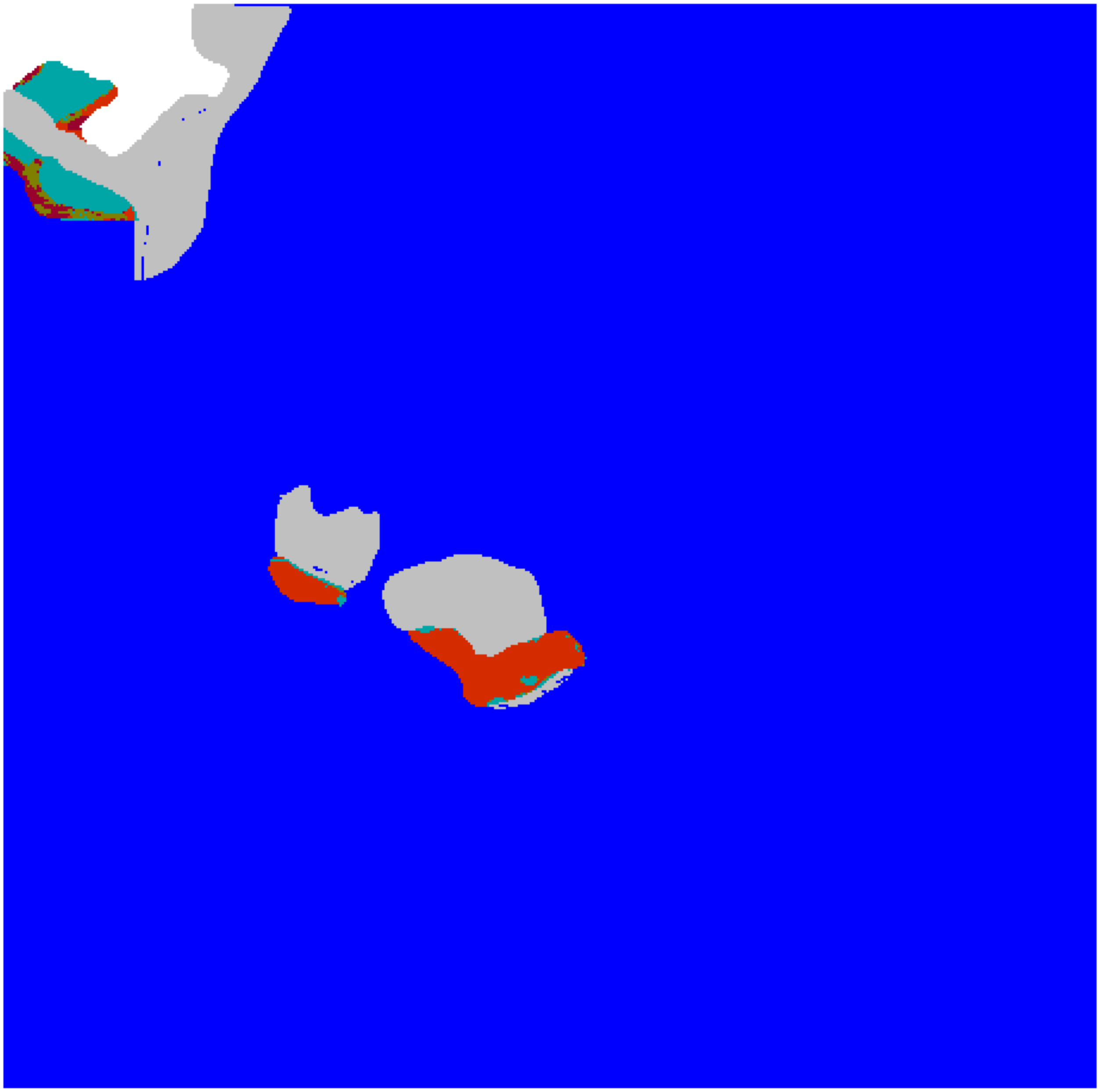
Marin Islands NWR, 2075, Scenario A1B Mean



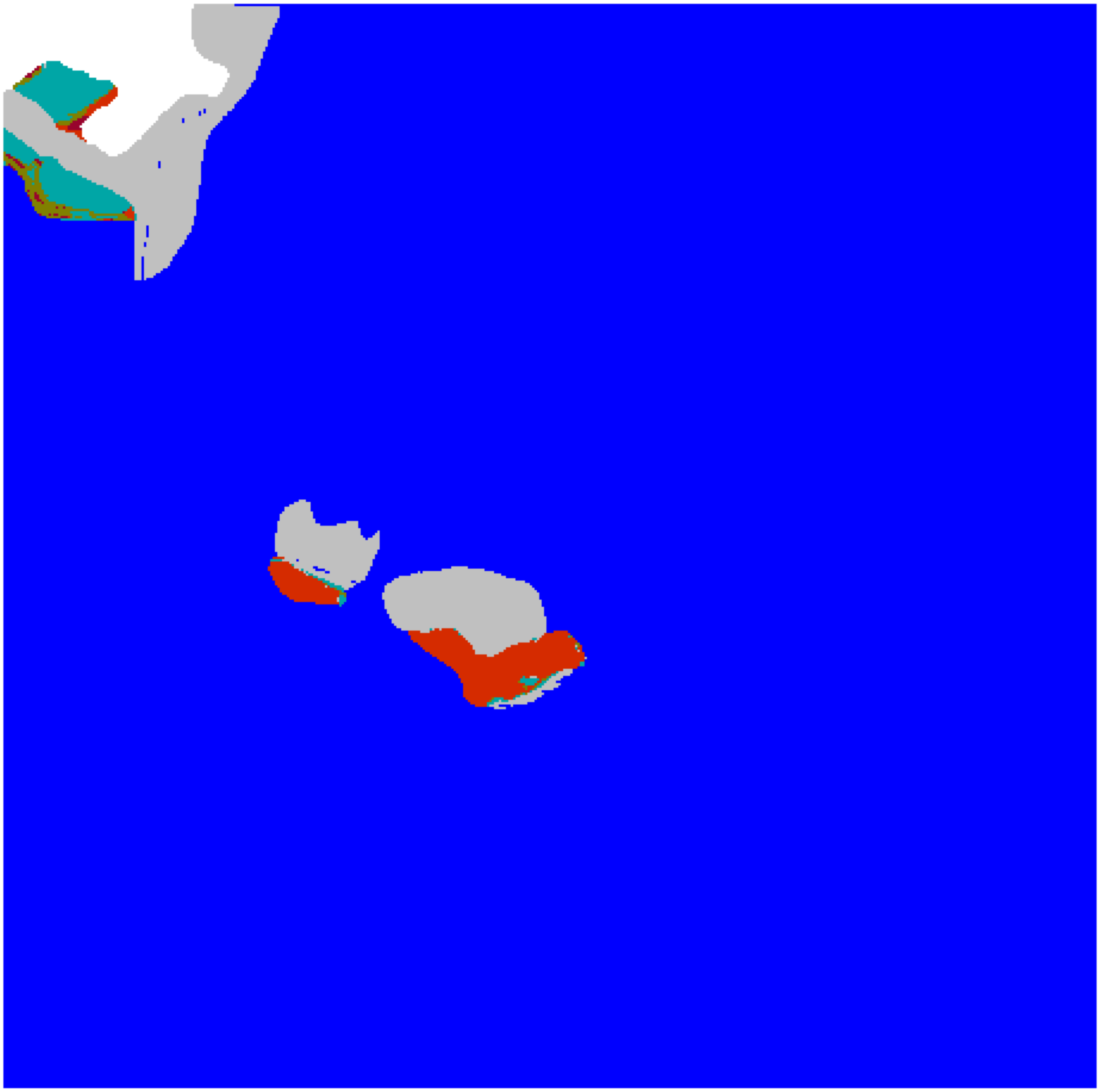
Marin Islands NWR, 2100, Scenario A1B Mean



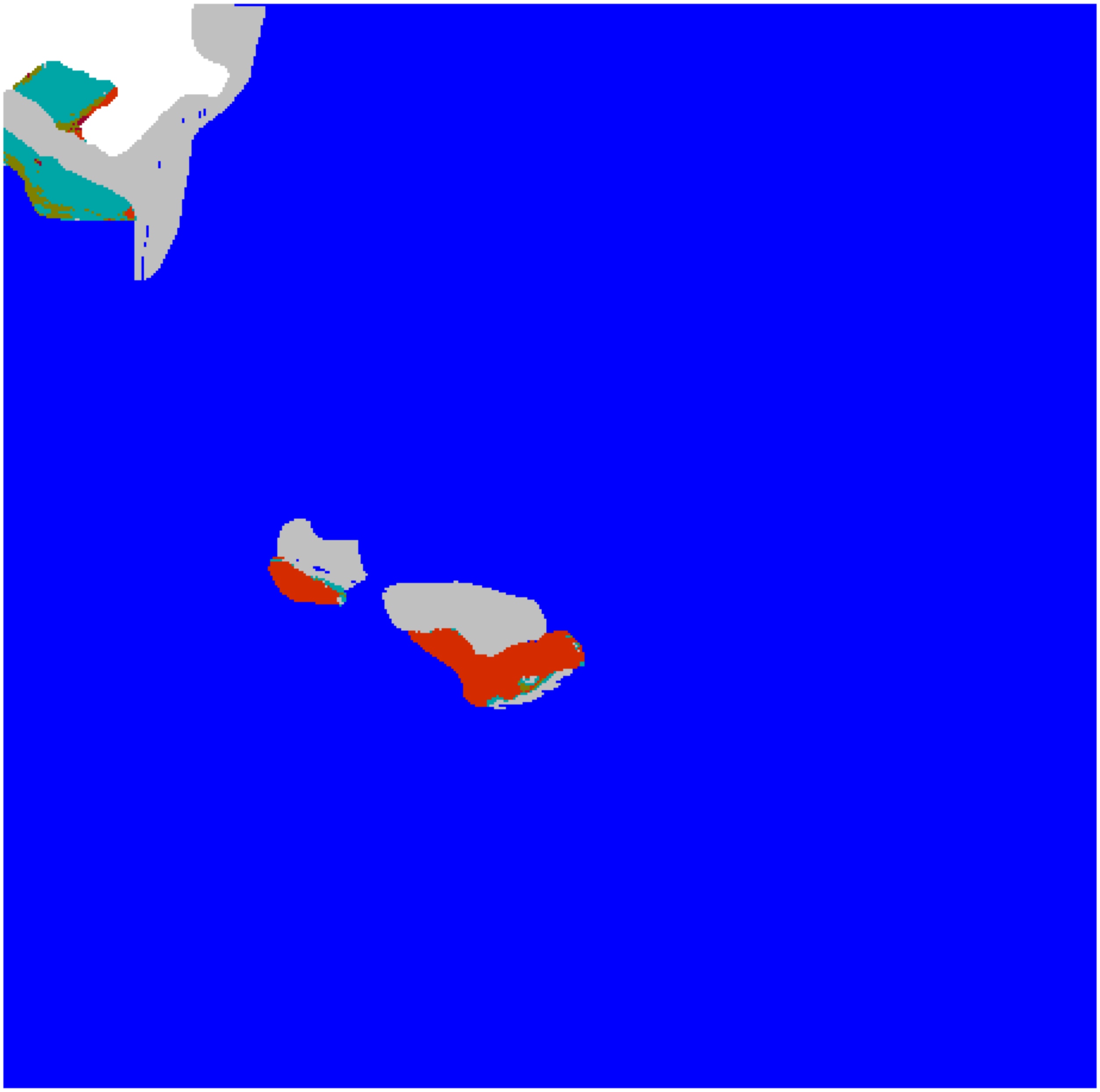
Marin Islands NWR, Initial Condition



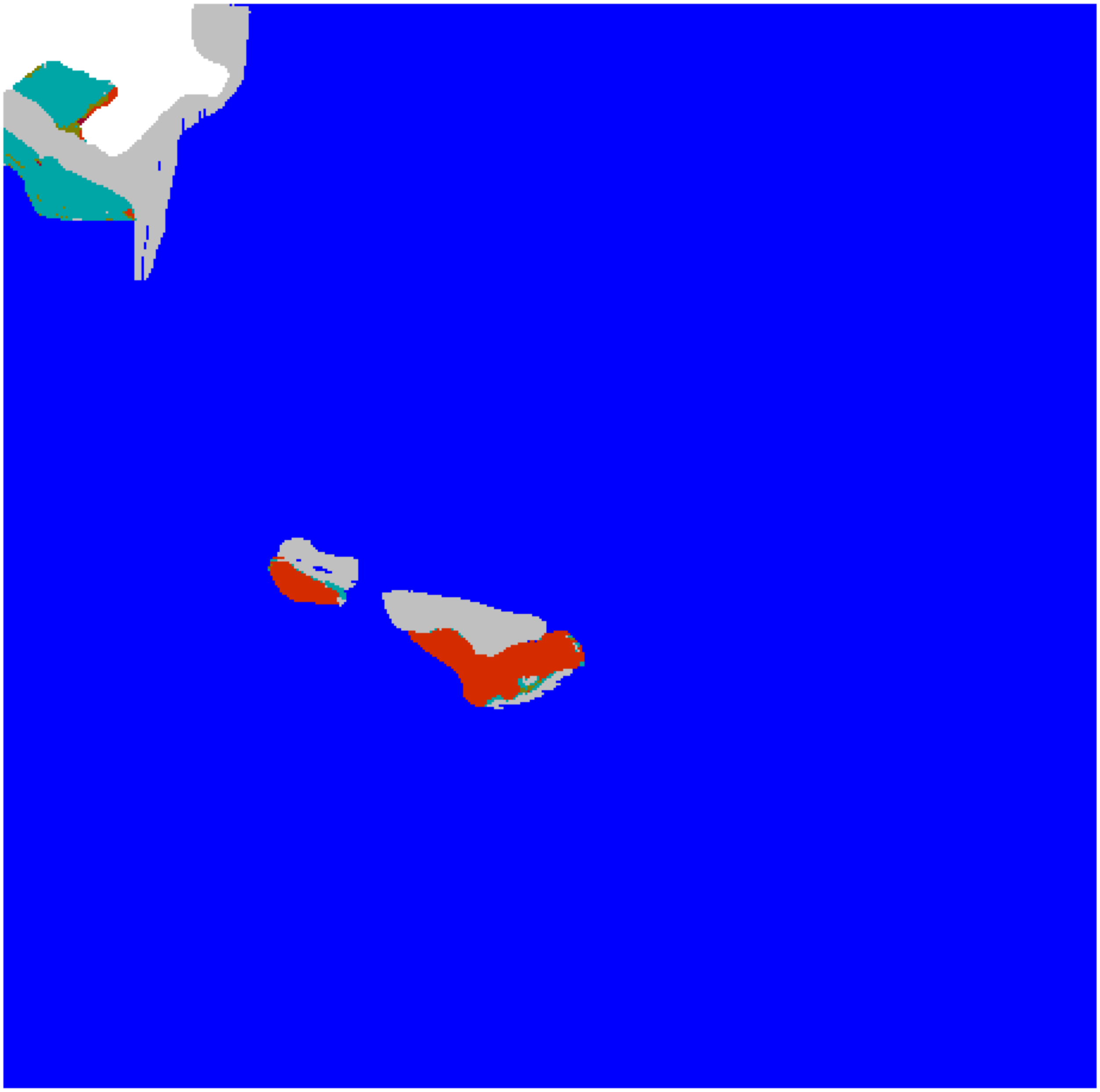
Marin Islands NWR, 2025, Scenario A1B Maximum



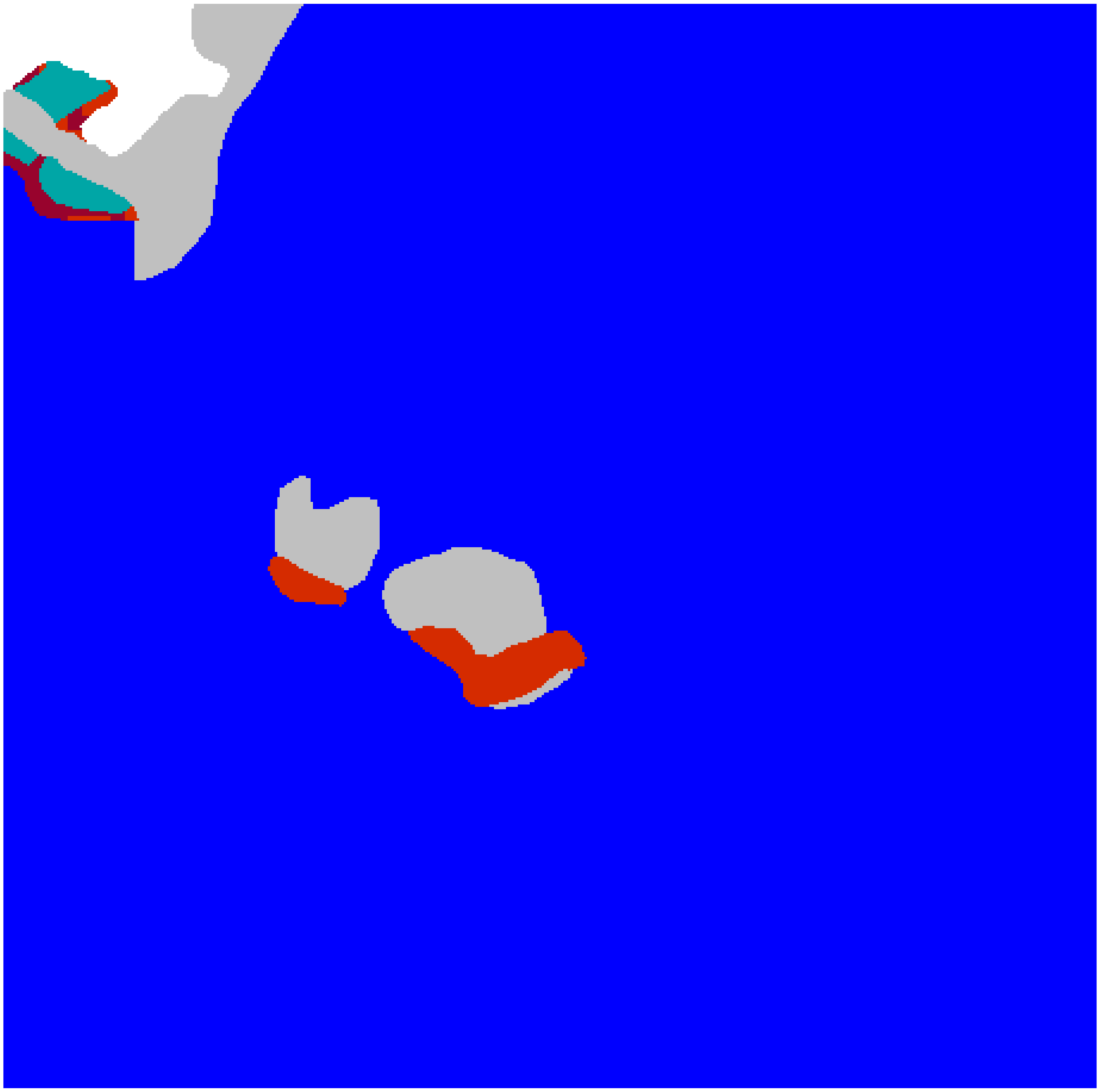
Marin Islands NWR, 2050, Scenario A1B Maximum



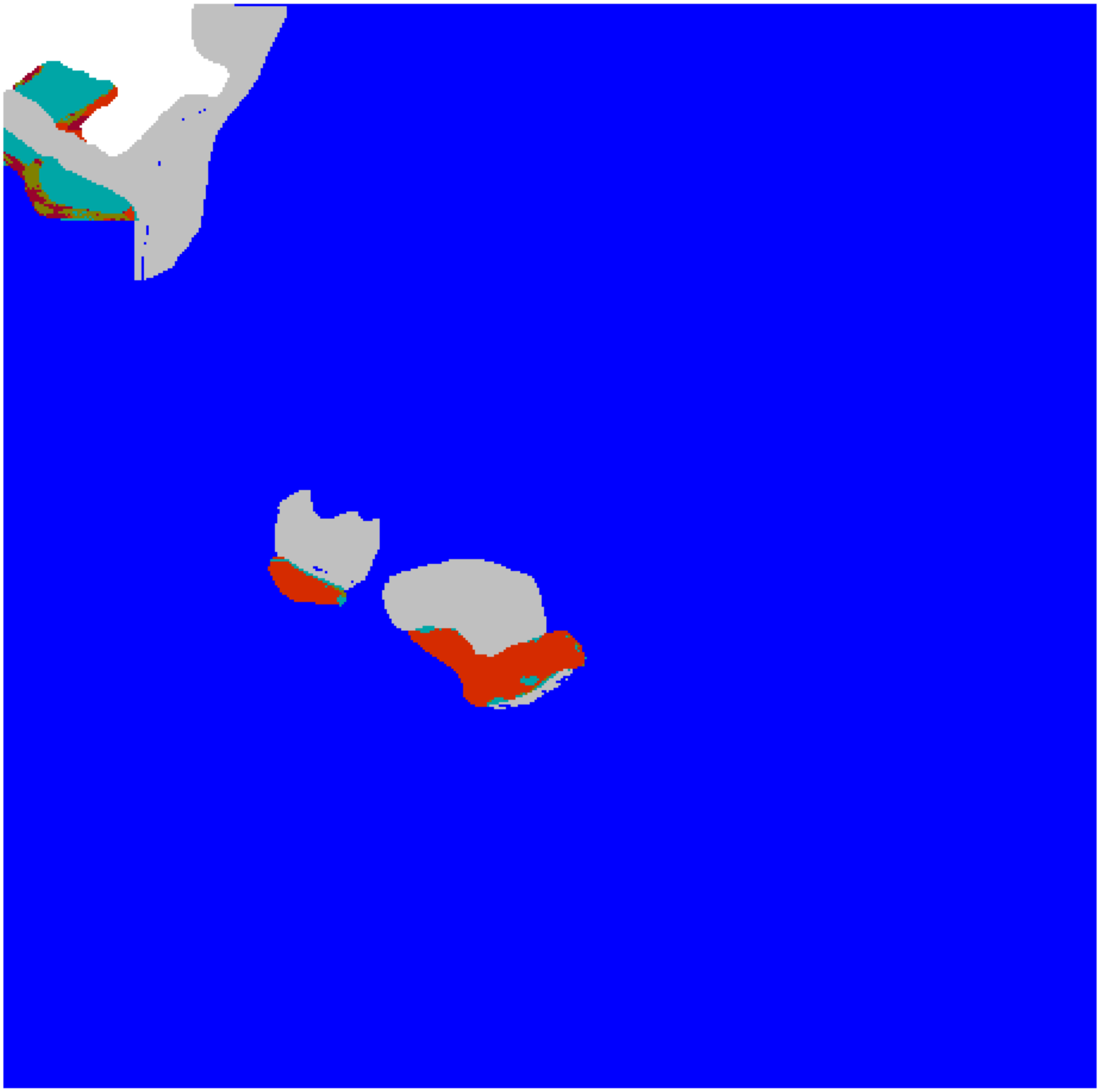
Marin Islands NWR, 2075, Scenario A1B Maximum



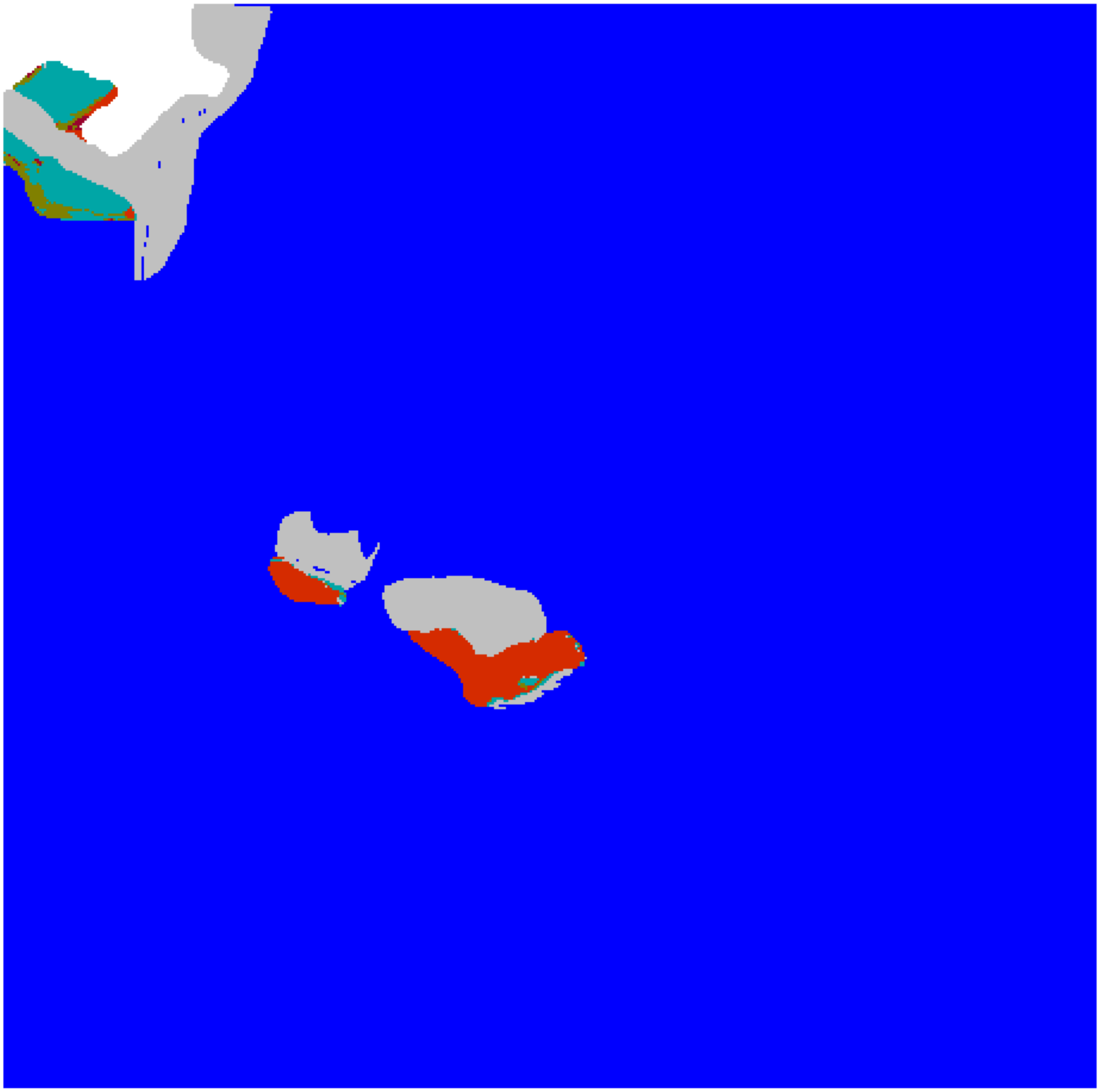
Marin Islands NWR, 2100, Scenario A1B Maximum



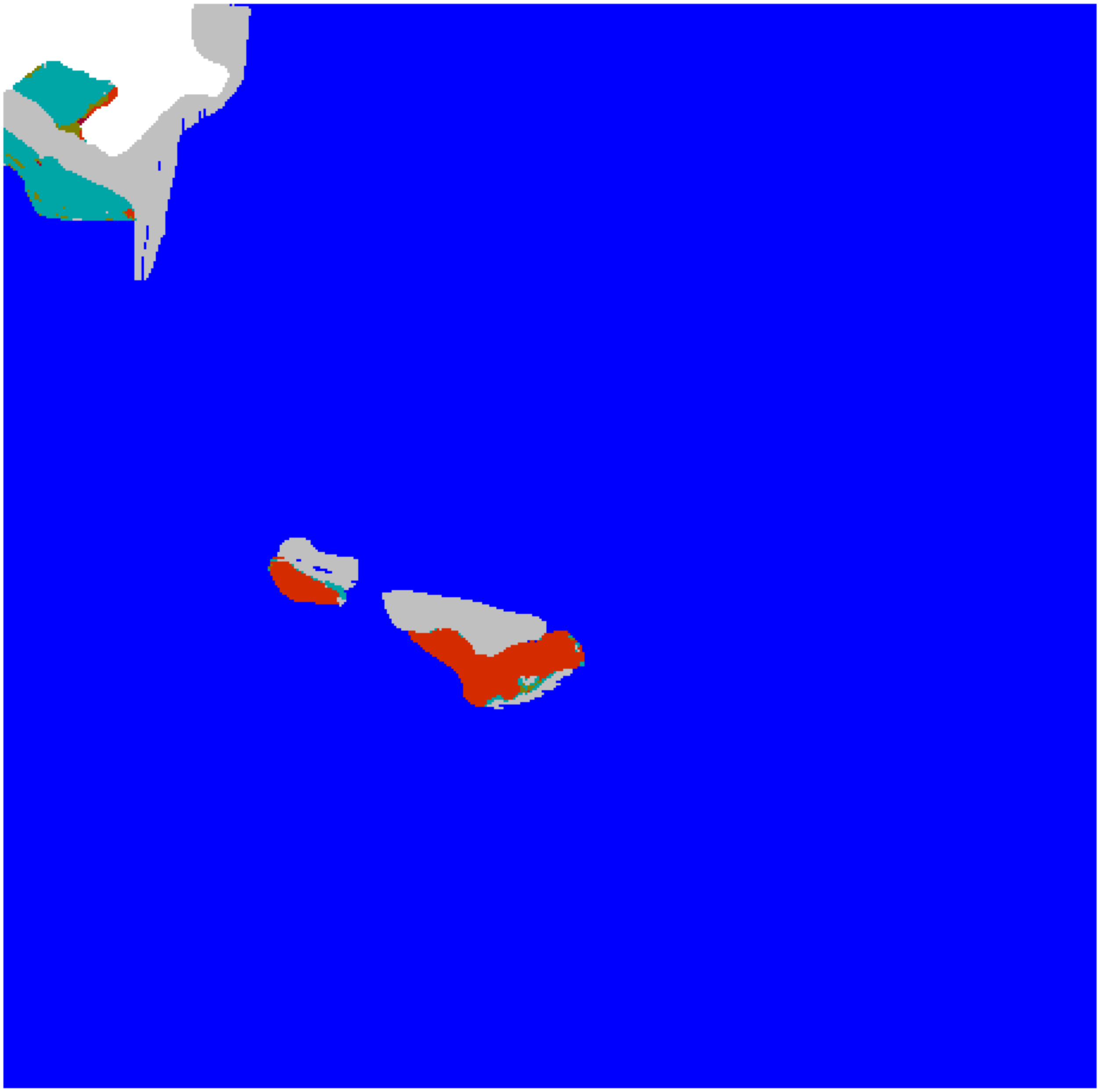
Marin Islands NWR, Initial Condition



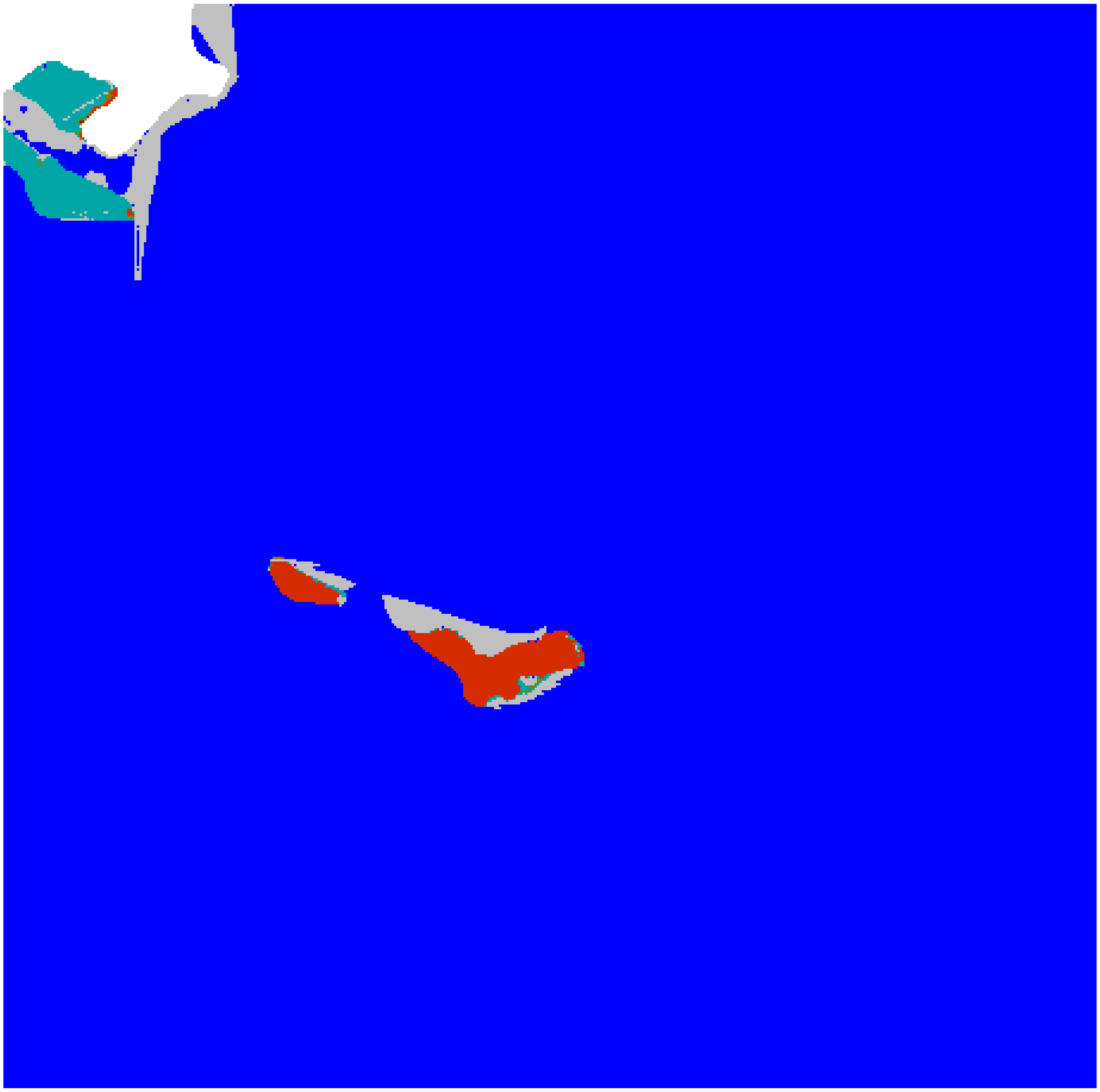
Marin Islands NWR, 2025, 1 meter



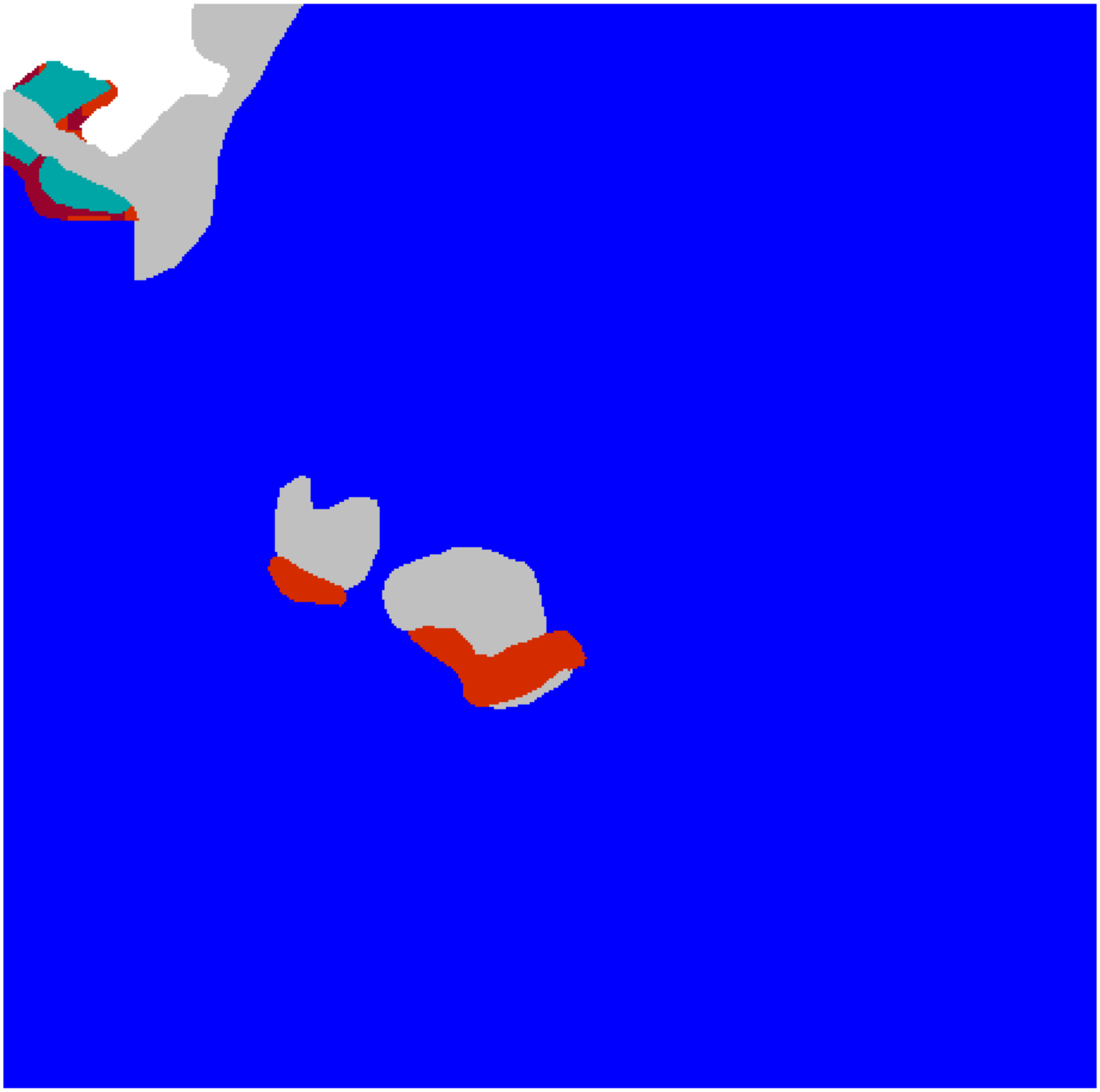
Marin Islands NWR, 2050, 1 meter



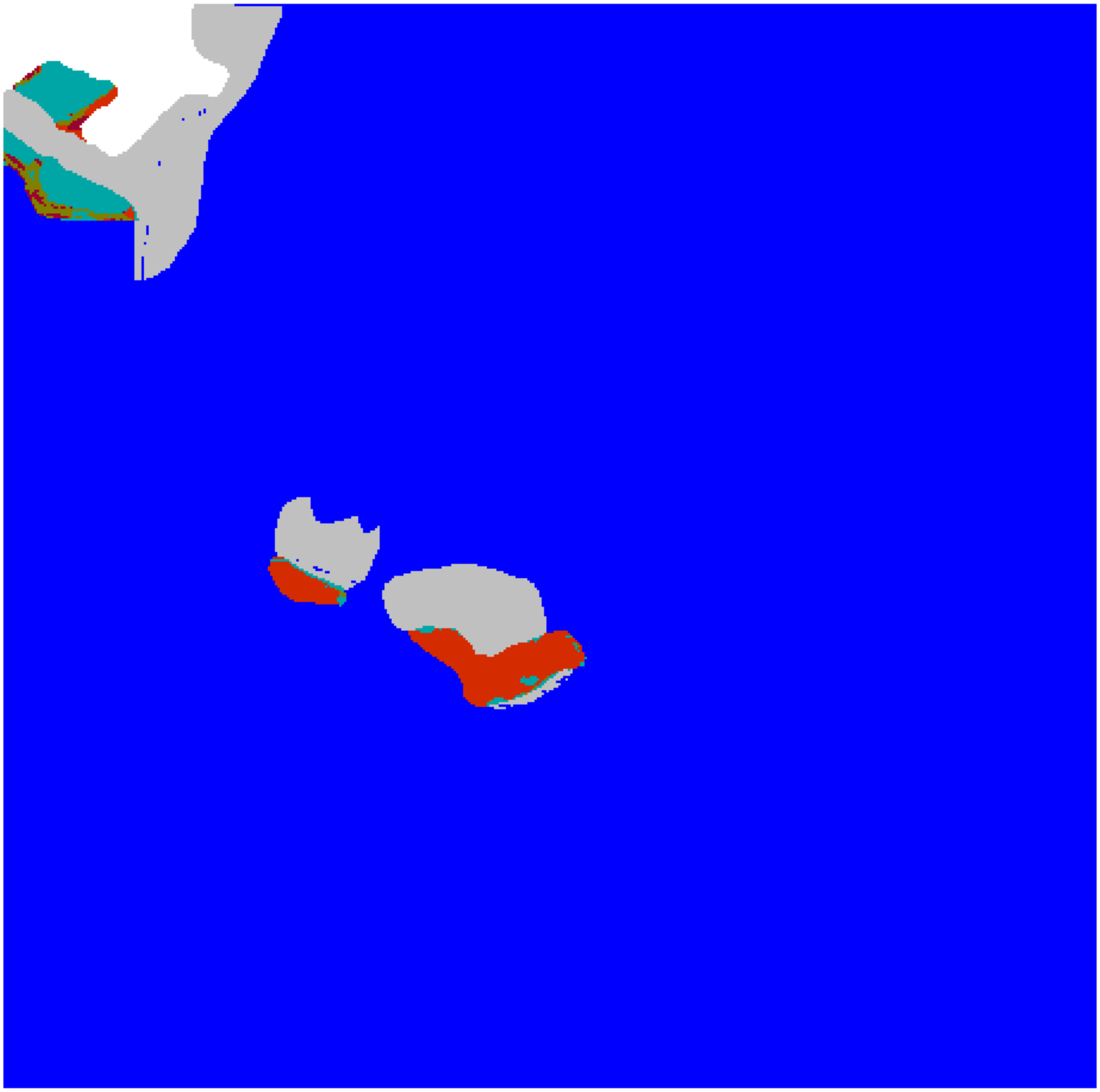
Marin Islands NWR, 2075, 1 meter



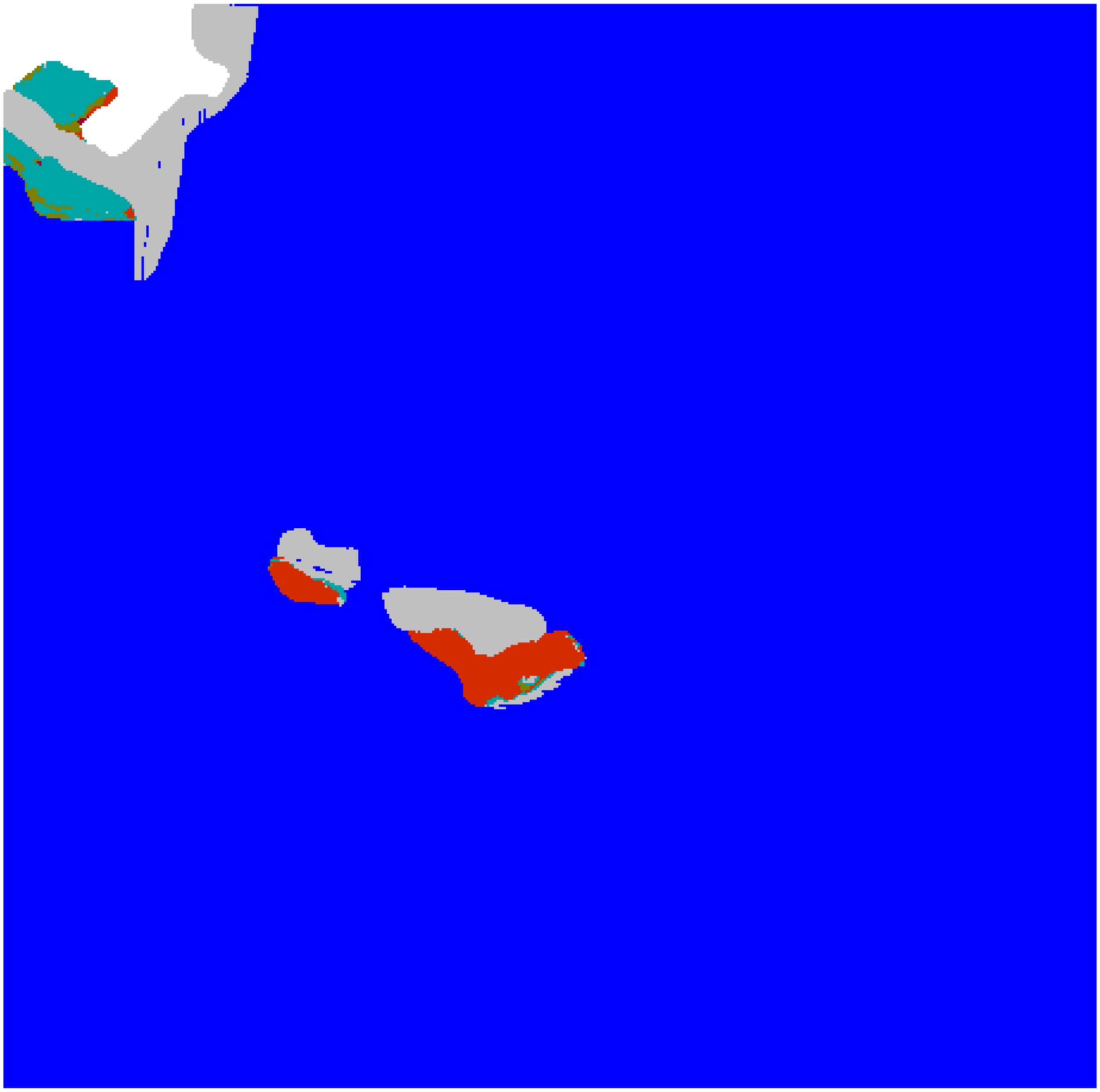
Marin Islands NWR, 2100, 1 meter



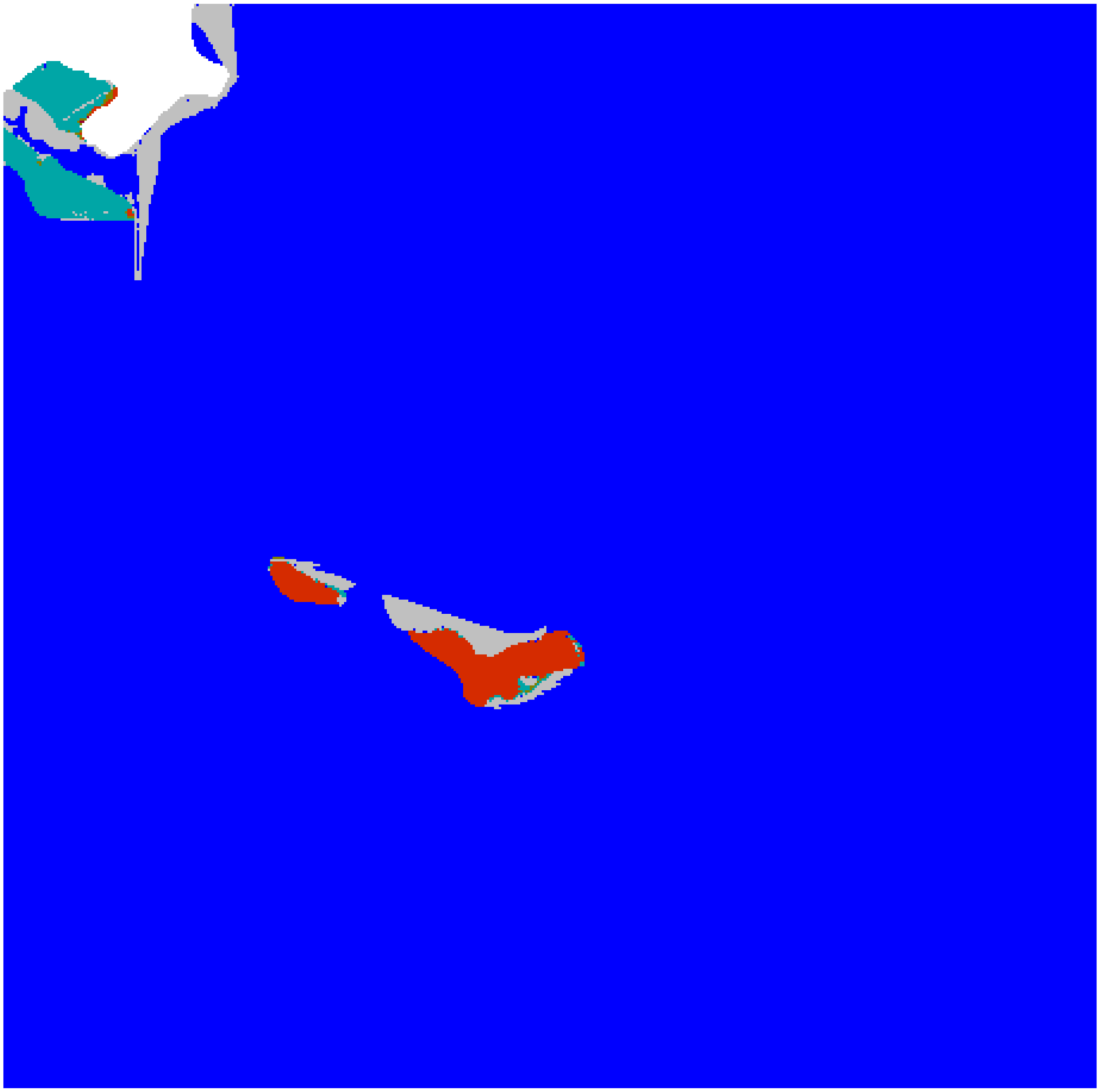
Marin Islands NWR, Initial Condition



Marin Islands NWR, 2025, 1.5 meter

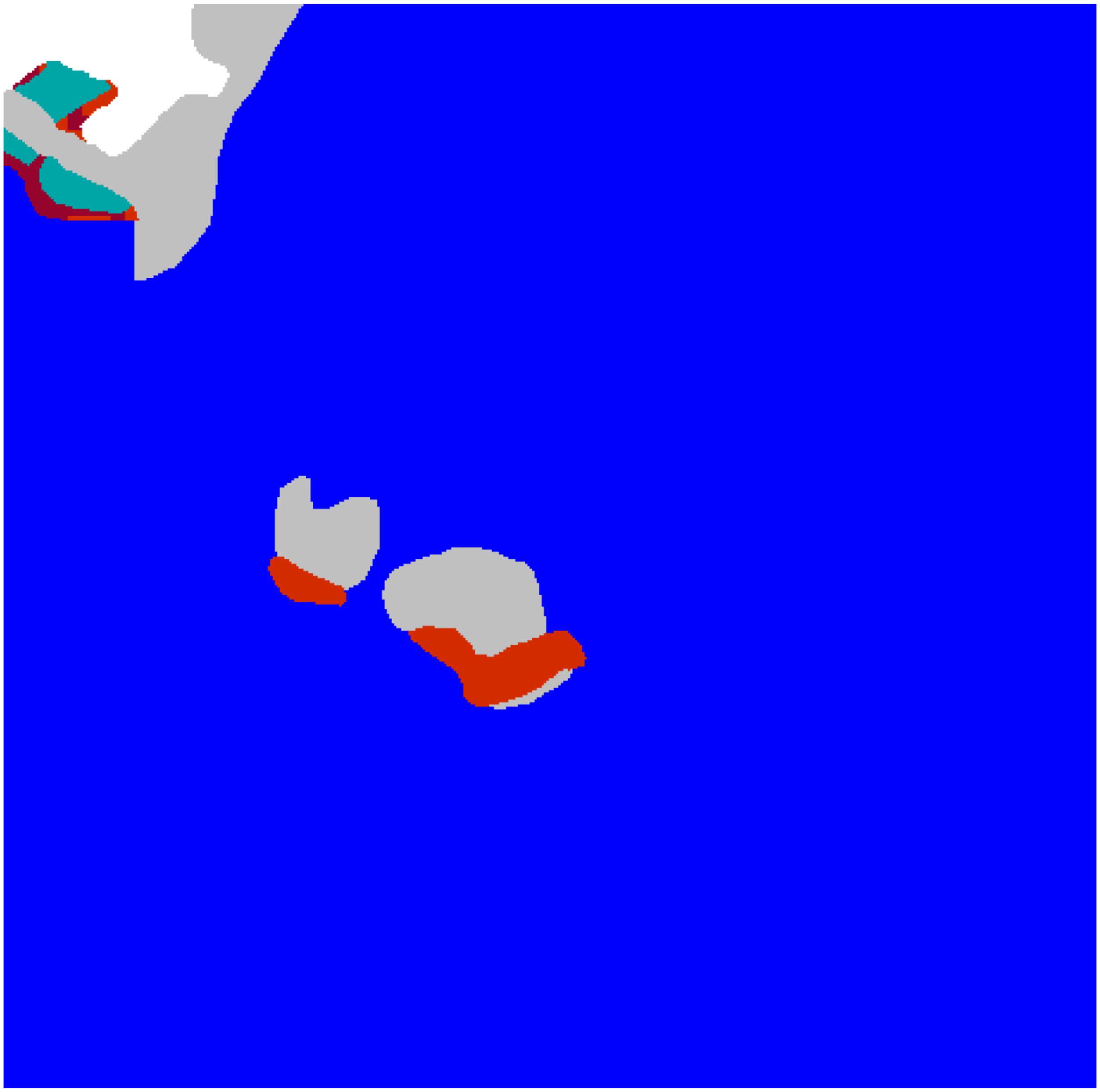


Marin Islands NWR, 2050, 1.5 meter

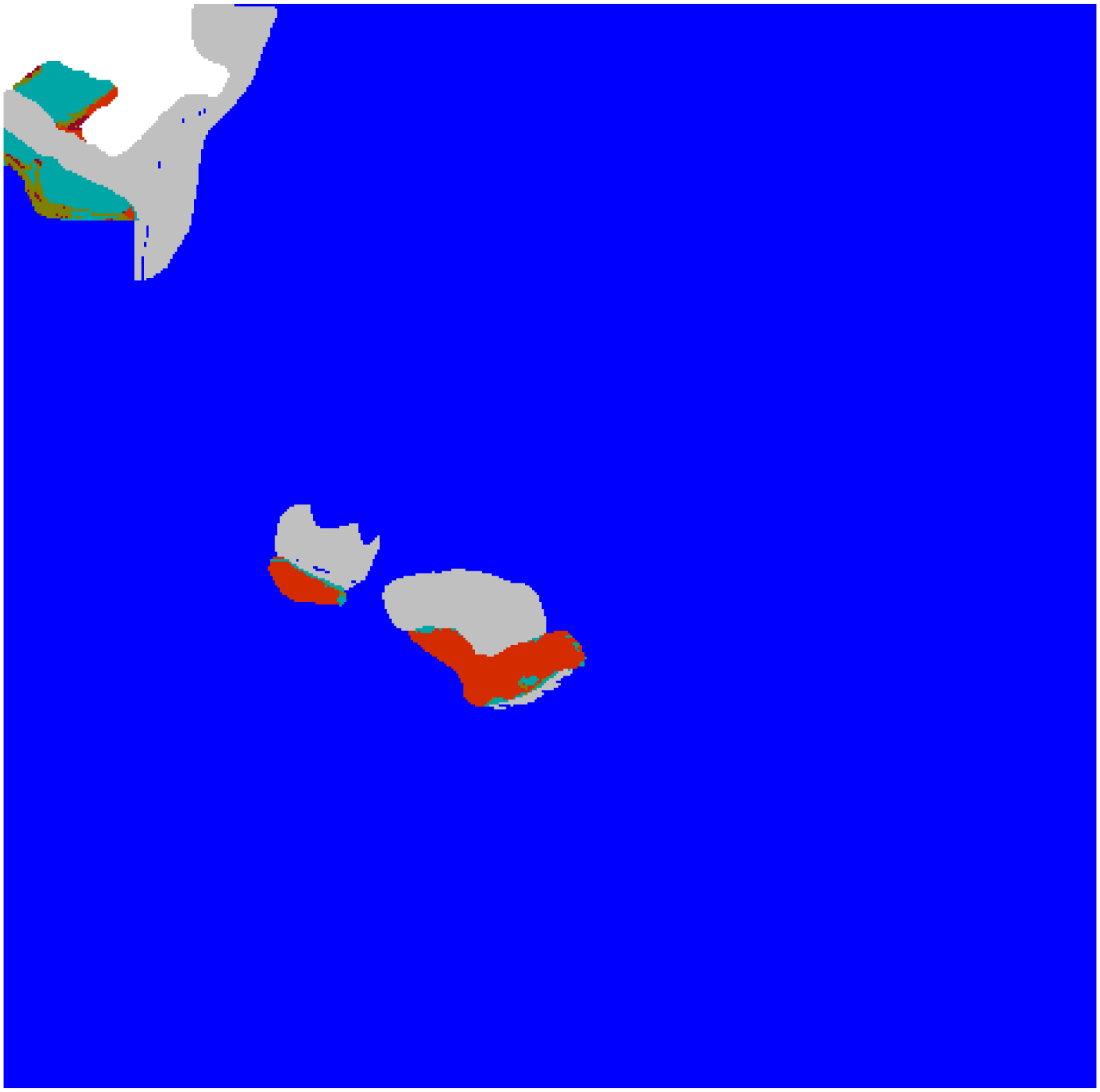


Marin Islands NWR, 2075, 1.5 meter

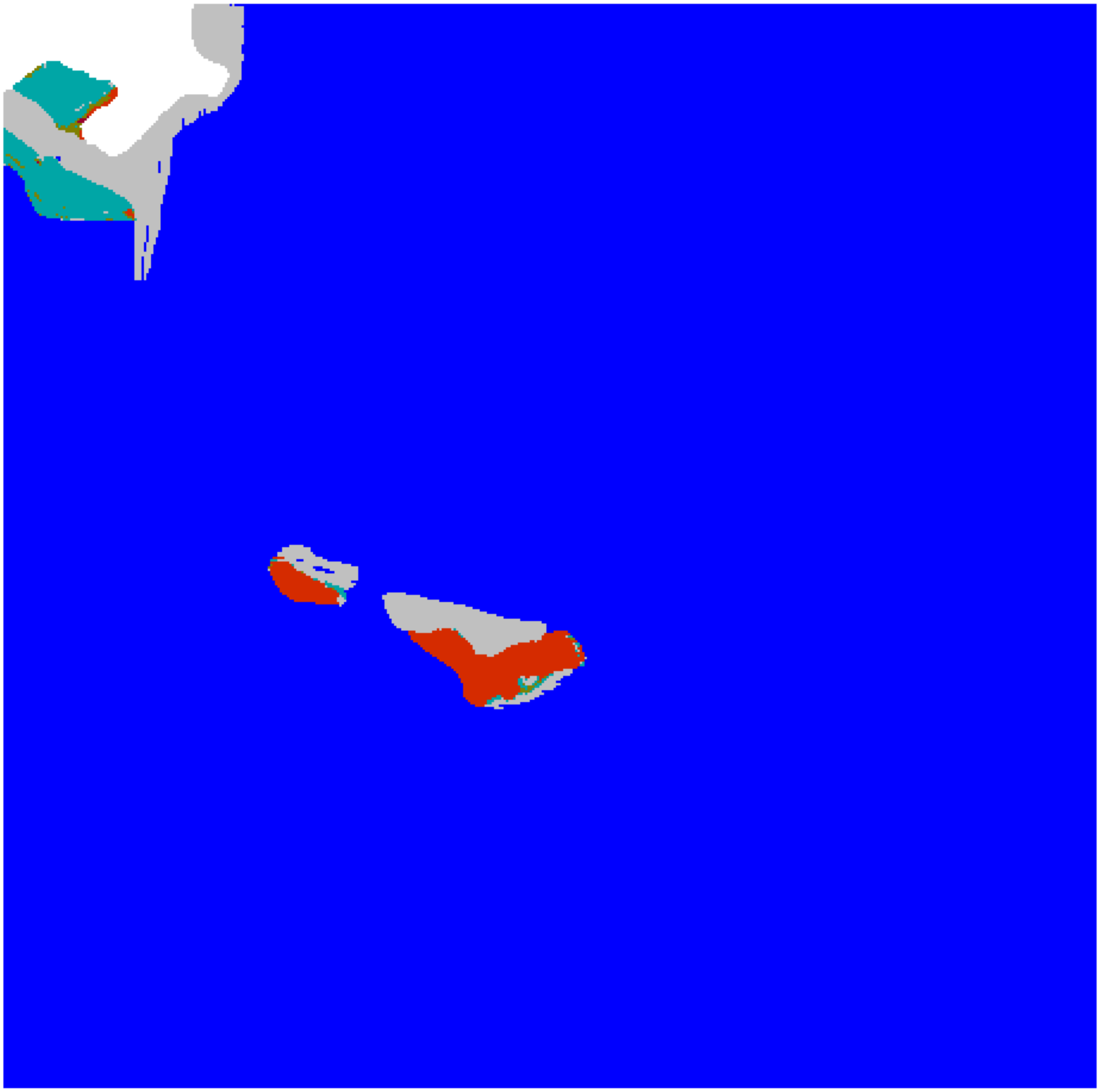
Marin Islands NWR, 2100, 1.5 meter



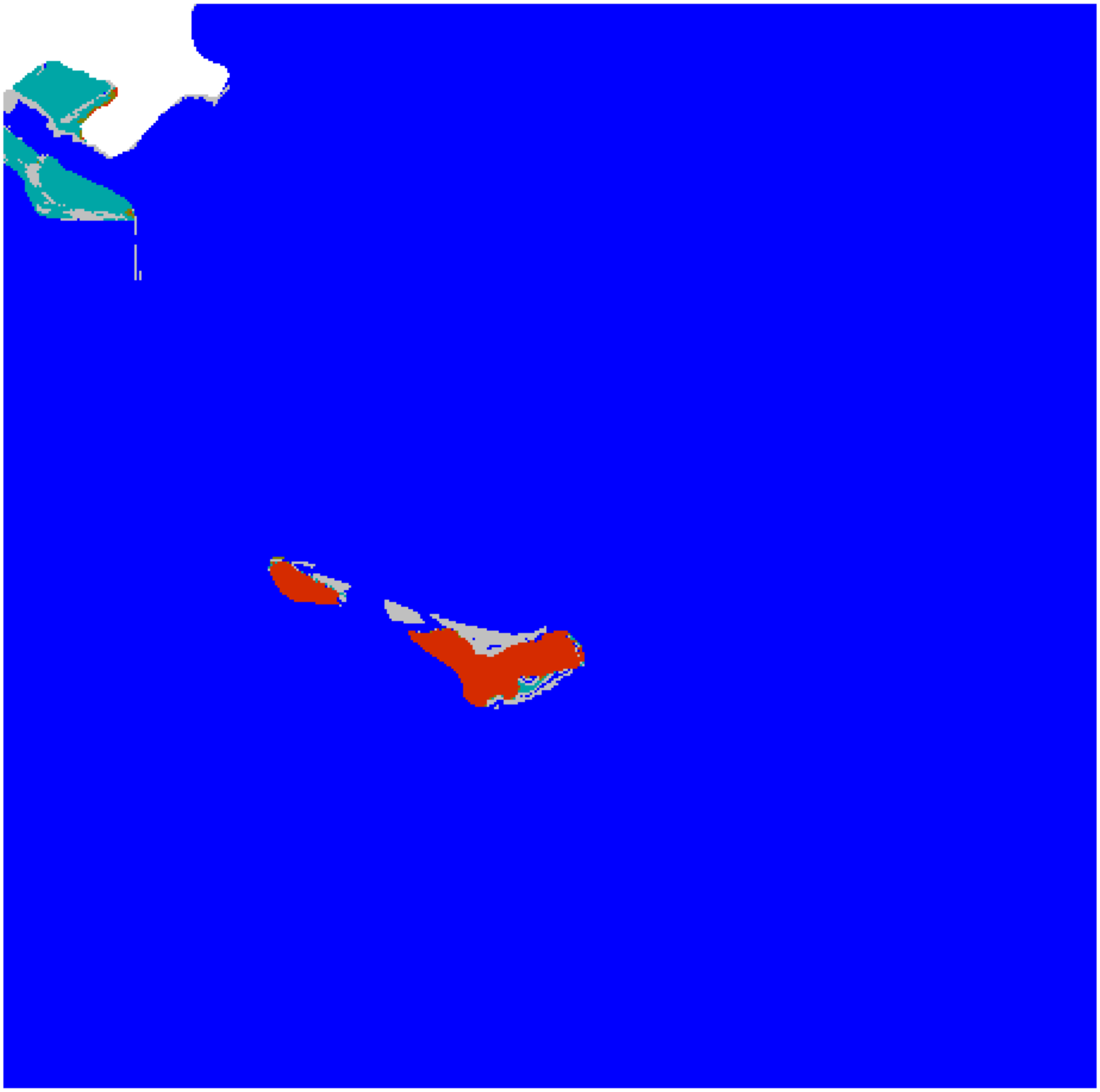
Marin Islands NWR, Initial Condition



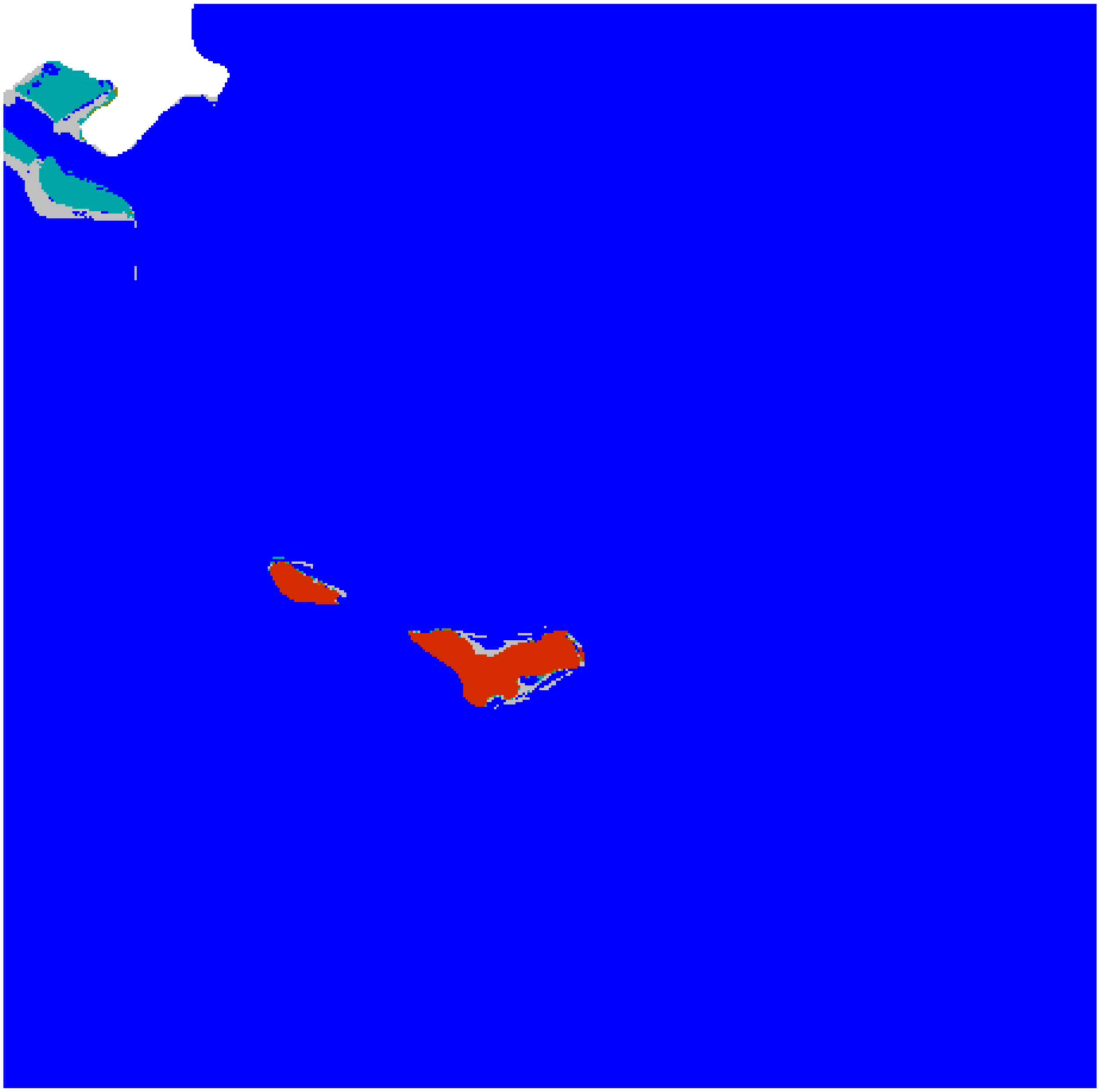
Marin Islands NWR, 2025, 2 meter



Marin Islands NWR, 2050, 2 meter



Marin Islands NWR, 2075, 2 meter



Marin Islands NWR, 2100, 2 meter