Application of the Sea-Level Affecting Marshes Model (SLAMM 6) to Kealia Pond NWR

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Introduction

Tidal marshes are among the most susceptible ecosystems to climate change, especially accelerated sea level rise (SLR). The Intergovernmental 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 is 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 Irregularly Flooded marsh (Park et al. 1991).

In an effort to address the potential effects of sea level rise on United States national wildlife refuges, the U. S. Fish and Wildlife Service contracted the application of the SLAMM model for most Region 1 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 specified interval for large 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 flooding.

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 test the SLAMM conceptual model at each site. The causes of any discrepancies are then tracked down and reported on within the model application report.
- 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.

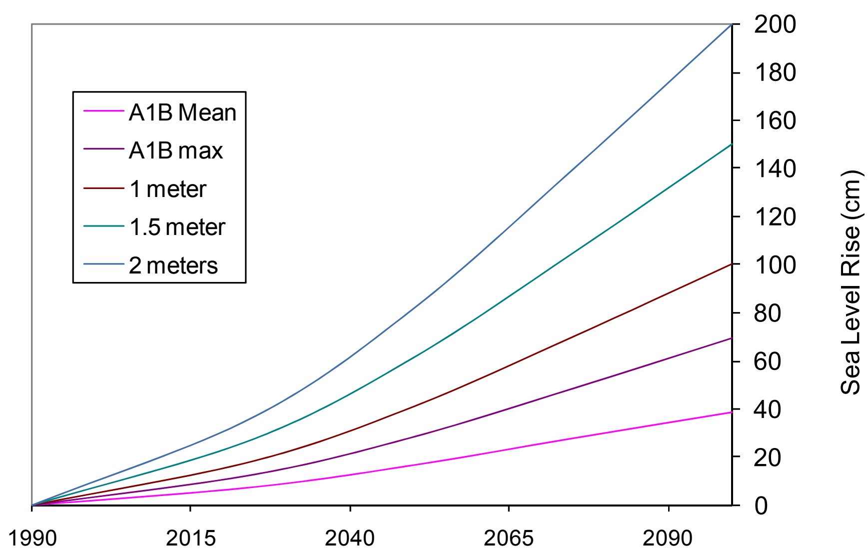
Sea Level Rise Scenarios

SLAMM 6 was run using scenario A1B from the Special Report on Emissions Scenarios (SRES) – mean and maximum estimates. The A1 family of scenarios assumes that the future world includes 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 (IPCC, 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 0.39 meters of global sea level rise by 2100. A1B-maximum predicts 0.69 meters of global SLR 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 of 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…" Grinsted also states that there is a "low probability" that SLR will match the lower IPCC estimates.

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 used in this simulation was supplied by FEMA based on high-resolution LiDAR with a 2007 flight date (Figure 2).

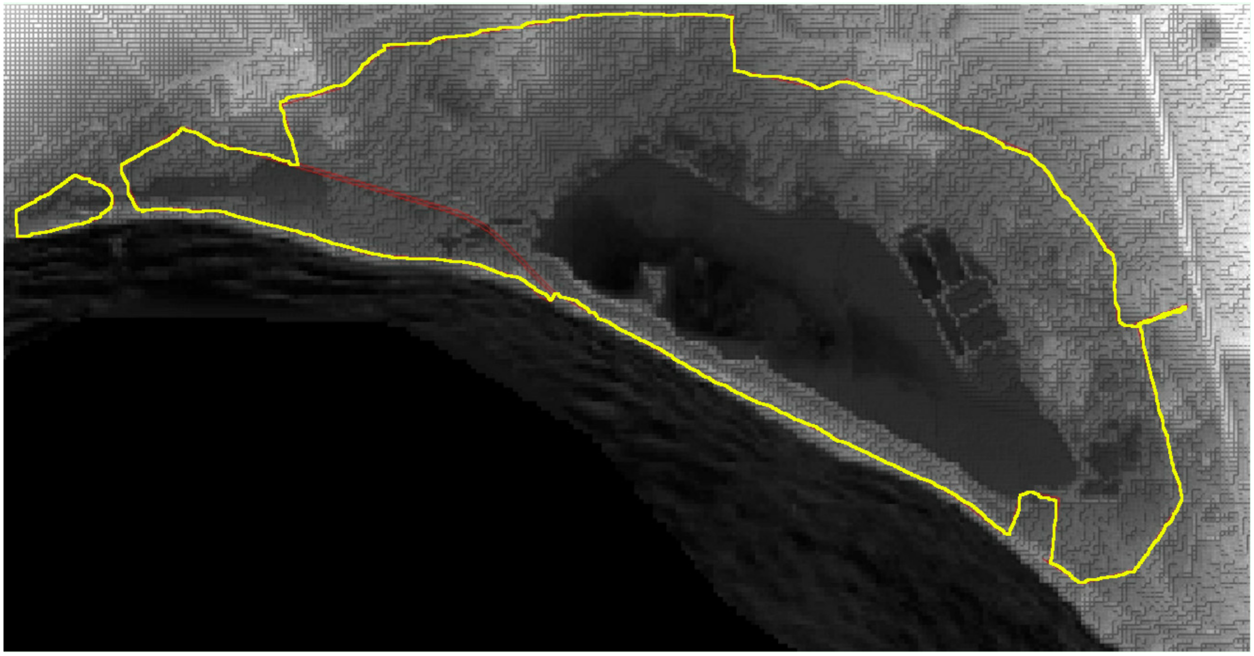


Figure 1: DEM source map for Kealia Pond NWR (yellow boundary).

The wetlands layer for the study area was produced by the National Wetlands Inventory and is based on a 1976 photo date. Converting the NWI survey into 15 meter cells indicates that the approximately seven hundred acre refuge (approved acquisition boundary including water) is composed of the following categories:

Inland Fresh Marsh	41.6%
Inland Open Water	34.2%
Undeveloped Dry Land	21.3%
Swamp	2.1%

According to the National Wetland Inventory, a large fraction of the freshwater in Kealia Pond NWR is impounded.

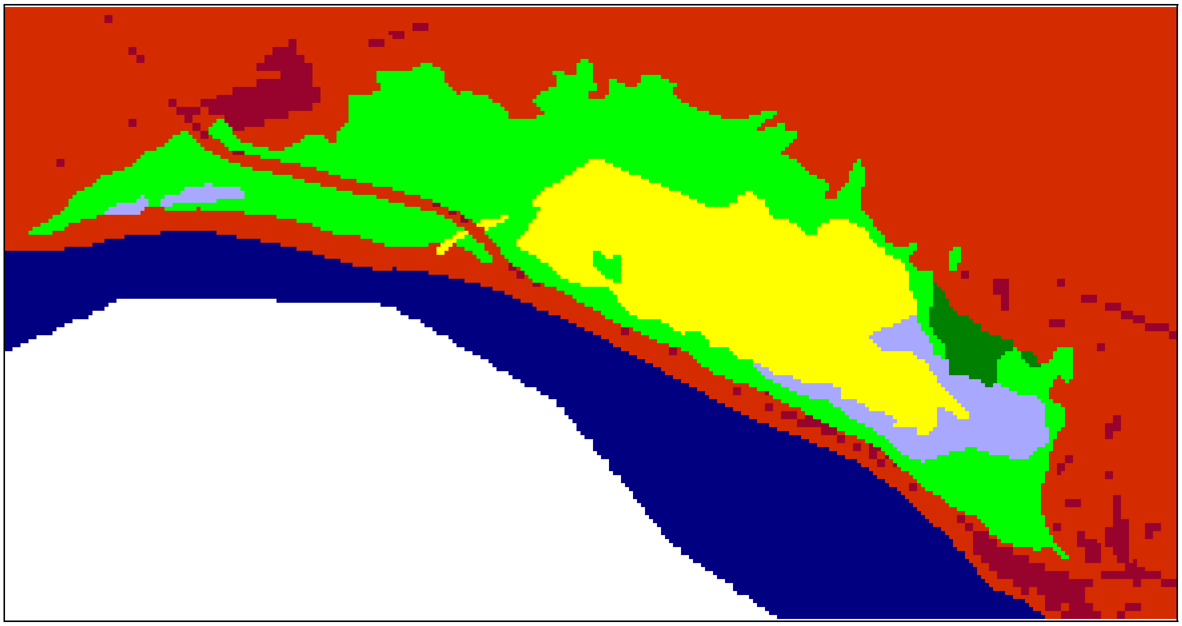


Figure 2: Diked area in yellow.

The historic trend for sea level rise was estimated at 1.53 mm/year using the average of the two nearest NOAA gages with SLR data (1612340, Honolulu, HI; 1615680, Kahului, HI). The rate of sea level rise for this refuge is assumed to be similar to the global average for the last 100 years (approximately 1.7 mm/year, IPCC 2007a).

The tide range was estimated at 0.46 meters (great diurnal range or GT) using the nearest NOAA tide table data (Kihei, Maalaea Bay).

No local accretion or erosion data were available for this study area. Instead, the model used default accretion rates, with fresh marsh accretion values of 5.9 mm/year.

The vertical datum of the elevation data for this region is Mean Sea Level (MSL). Therefore, the model parameterization requires an "MTL – MSL" correction for this simulation. The value of -0.007 was chosen based on the nearest NOAA gage (1613198, Kaunakakai Harbor, HI).

Modeled U.S. Fish and Wildlife Service refuge boundaries for Hawaii 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 15 meter by 15 meter cells. Note that the SLAMM model will track partial conversion of cells based on elevation and slope.

Glynnis Nakai, the refuge manager for this site, mentioned that tidal influence within the refuge is minimal, since the Palalau Outlet is filled with sand most of the year. Ms. Nakai also provided us with the a reference regarding beach erosion rates at the site (Hawaii Office of State Planning, 1991). This document suggests that the beach south of the refuge "Maalea Beach" eroded considerably between 1949 and 1988, ranging from 25 to 55 feet of erosion. In some places trees lining the road there have had roots exposed by wave action. The NWI coverage for this refuge does not include any beach between the land-to-ocean interface, increasing model uncertainty. During some simulations, dry land is predicted to convert to beach on the basis of elevation, however.

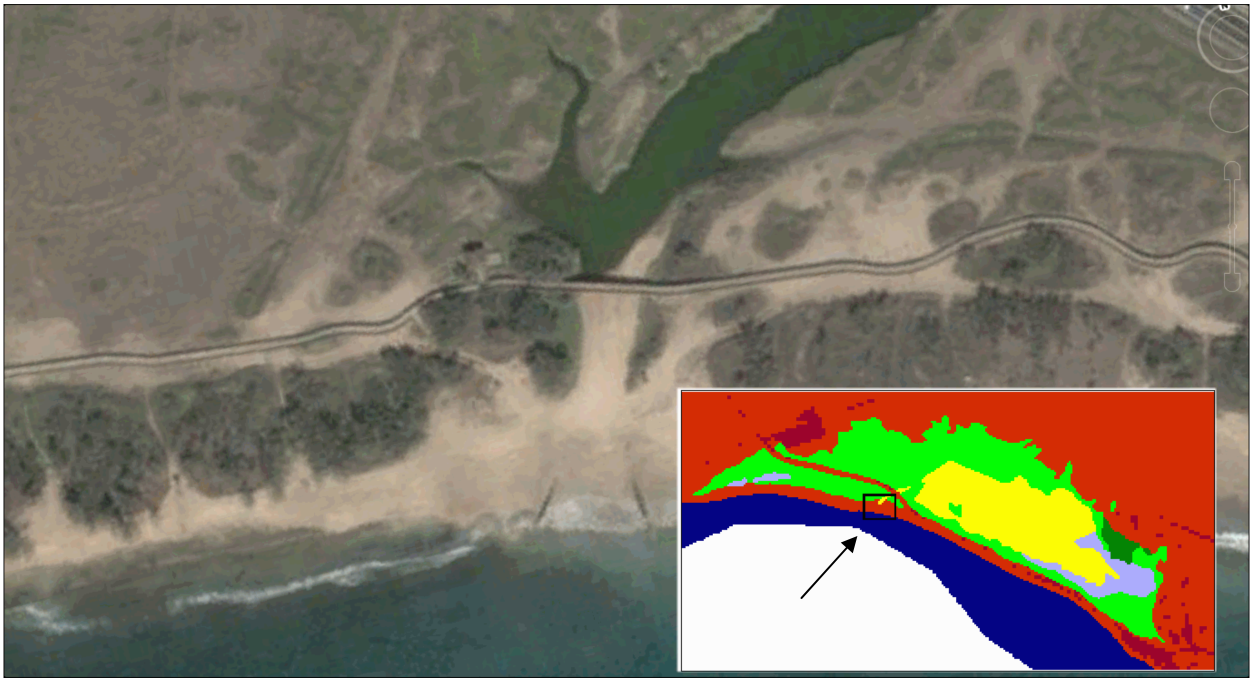


Figure 3: Location of Palalau Outlet mouth within study area and satellite image.

SUMMARY OF SLAMM INPUT PARAMETERS FOR KEALIA POND NWR

Parameter	Global
Description	Kealia Pond
NWI Photo Date (YYYY)	1976
DEM Date (YYYY)	2007
Direction Offshore [n,s,e,w]	South
Historic Trend (mm/yr)	2.32
"MTL-**MSL**" (m)	-0.001
GT Great Diurnal Tide Range (m)	0.61
Salt Elev. (m above MTL)	0.52
Marsh Erosion (horz. m /yr)	1.8
Swamp Erosion (horz. m /yr)	1
T.Flat Erosion (horz. m /yr)	2
Reg. Flood Marsh Accr (mm/yr)	3.9
Irreg. Flood Marsh Accr (mm/yr)	4.7
Tidal Fresh Marsh Accr (mm/yr)	5.9
Beach Sed. Rate (mm/yr)	0.5
Freq. Overwash (years)	15
Use Elev Pre-processor [True,False]	FALSE

Results

SLAMM predicts Kealia Pond NWR to be vulnerable to higher sea level rise (SLR) scenarios. Given one meter of SLR by 2100, over one quarter of inland-fresh marsh is predicted lost along with 16% of dry land. The refuge is predicted to lose nearly all of its inland fresh marsh and swamp by 2100 in the 2-meter scenario.

SLR by 2100 (m)	0.39	0.69	1	1.5	2
Inland Fresh Marsh	0%	3%	27%	70%	91%
Undeveloped Dry Land	1%	6%	16%	61%	83%
Swamp	0%	0%	0%	49%	91%
Developed Dry Land	0%	4%	6%	40%	84%

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

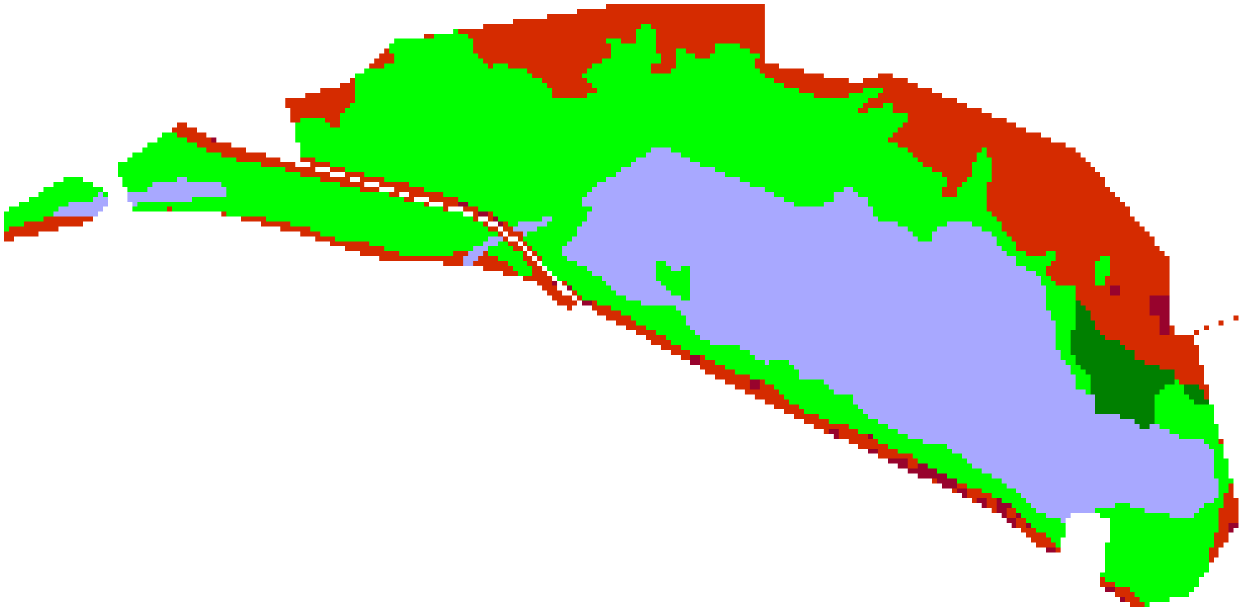
Maps of SLAMM input and output to follow will use the following legend:

Inland Fresh Marsh	
Inland Open Water	
Undeveloped Dry Land	
Swamp	
Developed Dry Land	
Transitional Salt Marsh	
Ocean Beach	
Estuarine Open Water	
Open Ocean	
Estuarine Beach	
Regularly Flooded Marsh	
Tidal Flat	

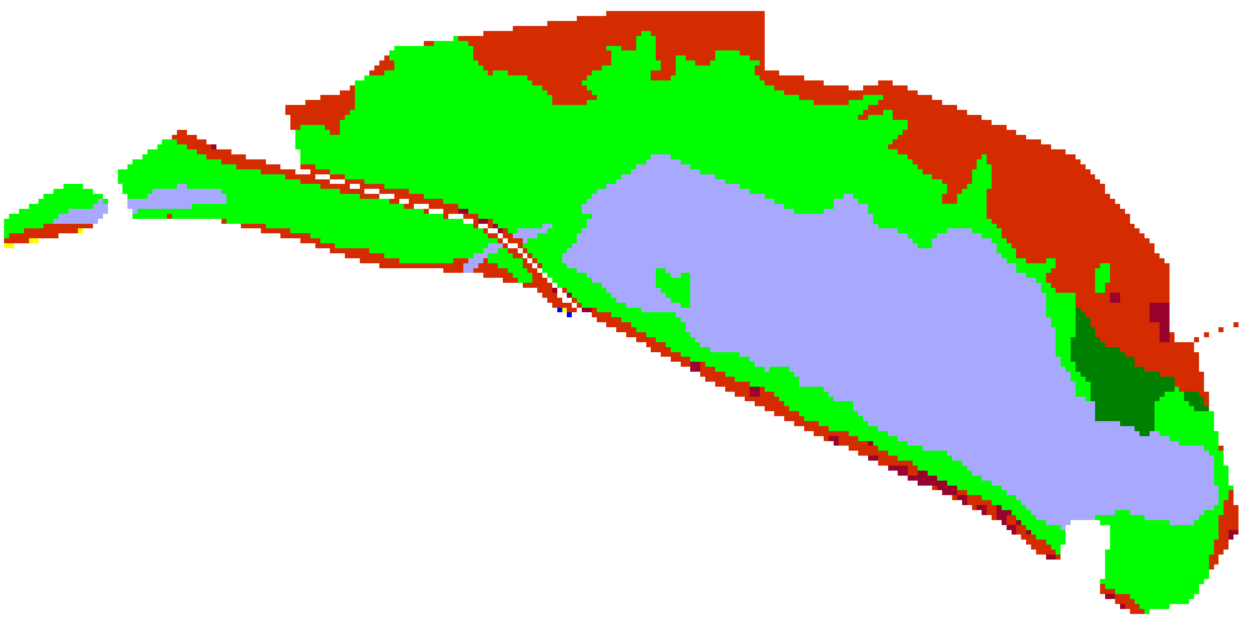
Kealia Raster
IPCC Scenario A1B-Mean, 0.39 M SLR Eustatic by 2100

Results in Acres

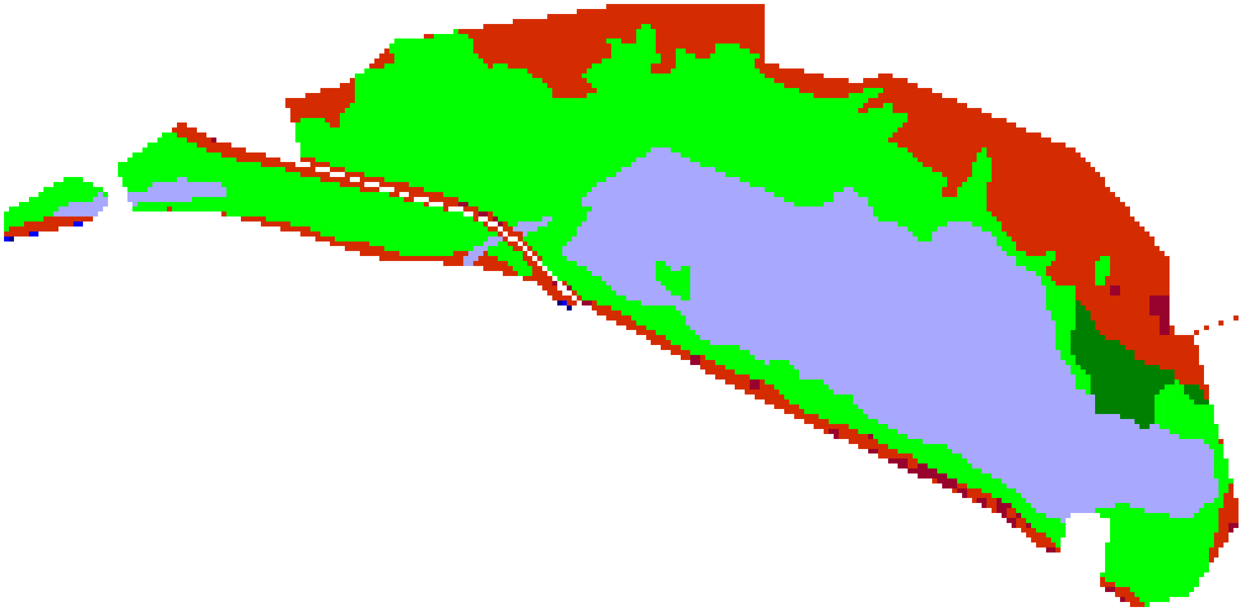
	Initial	2025	2050	2075	2100
Inland Fresh Marsh	292.3	292.3	292.3	292.4	292.5
Inland Open Water	240.1	240.1	240.1	240.1	240.1
Undeveloped Dry Land	149.7	149.1	149.0	148.8	148.6
Swamp	14.5	14.5	14.5	14.5	14.5
Developed Dry Land	5.9	5.9	5.9	5.9	5.9
Estuarine Open Water	0.0	0.1	0.4	0.1	0.1
Open Ocean	0.0	0.1	0.2	0.6	0.7
Ocean Beach	0.0	0.4	0.0	0.0	0.0
Total (incl. water)	**702.5**	**702.5**	**702.5**	**702.5**	**702.5**



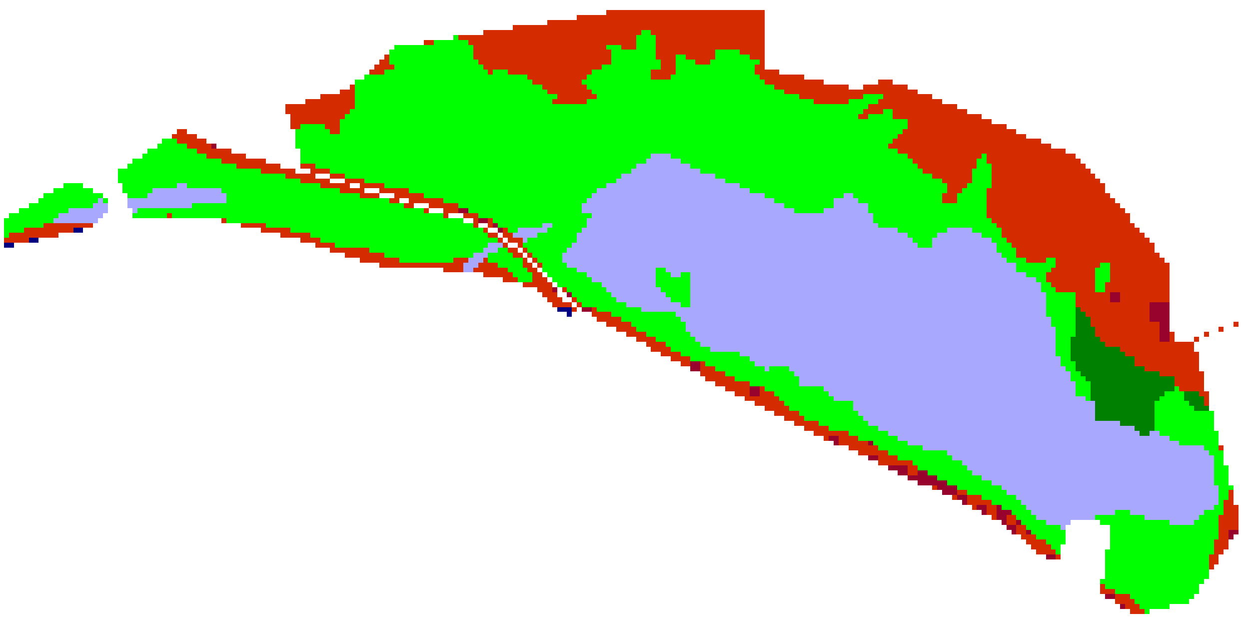
Kealia Pond NWR, Initial Condition



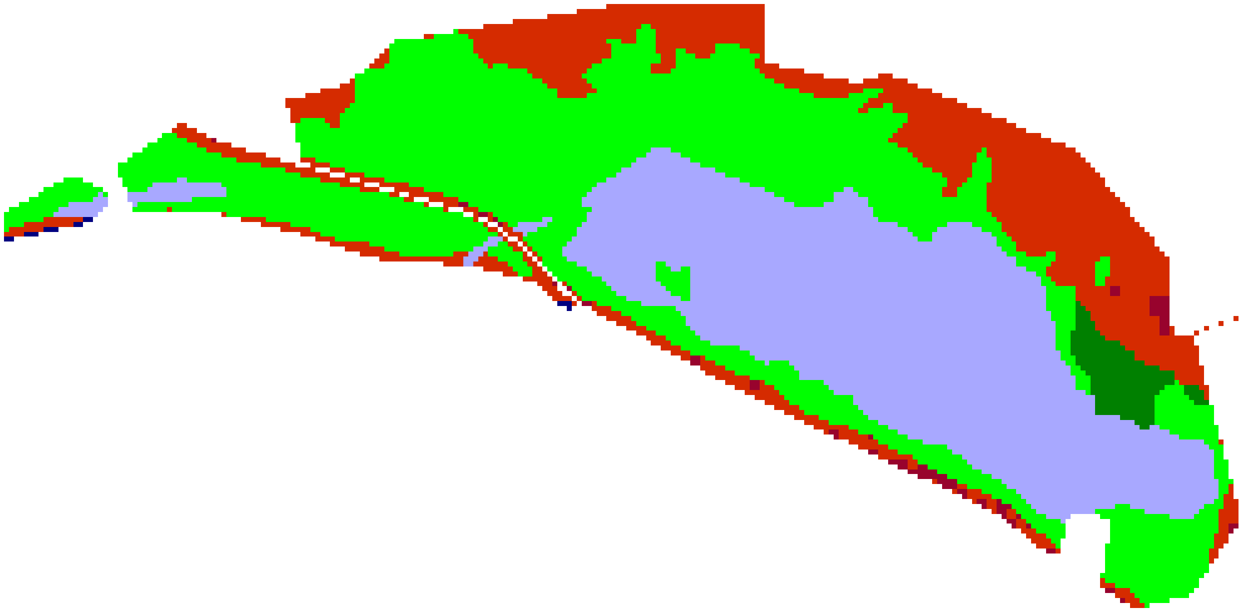
Kealia Pond NWR, 2025, Scenario A1B Mean



Kealia Pond NWR, 2050, Scenario A1B Mean



Kealia Pond NWR, 2075, Scenario A1B Mean



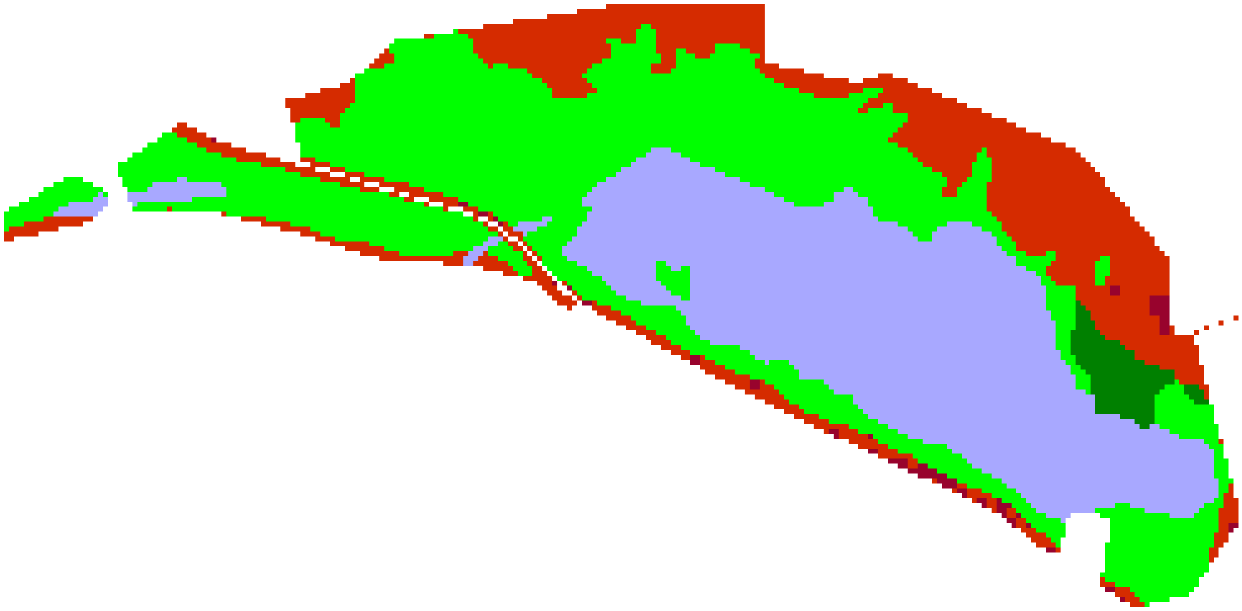
Kealia Pond NWR, 2100, Scenario A1B Mean

Inland Fresh Marsh	
Inland Open Water	
Undeveloped Dry Land	
Swamp	
Developed Dry Land	
Transitional Salt Marsh	
Ocean Beach	
Estuarine Open Water	
Open Ocean	
Estuarine Beach	
Regularly Flooded Marsh	
Tidal Flat	

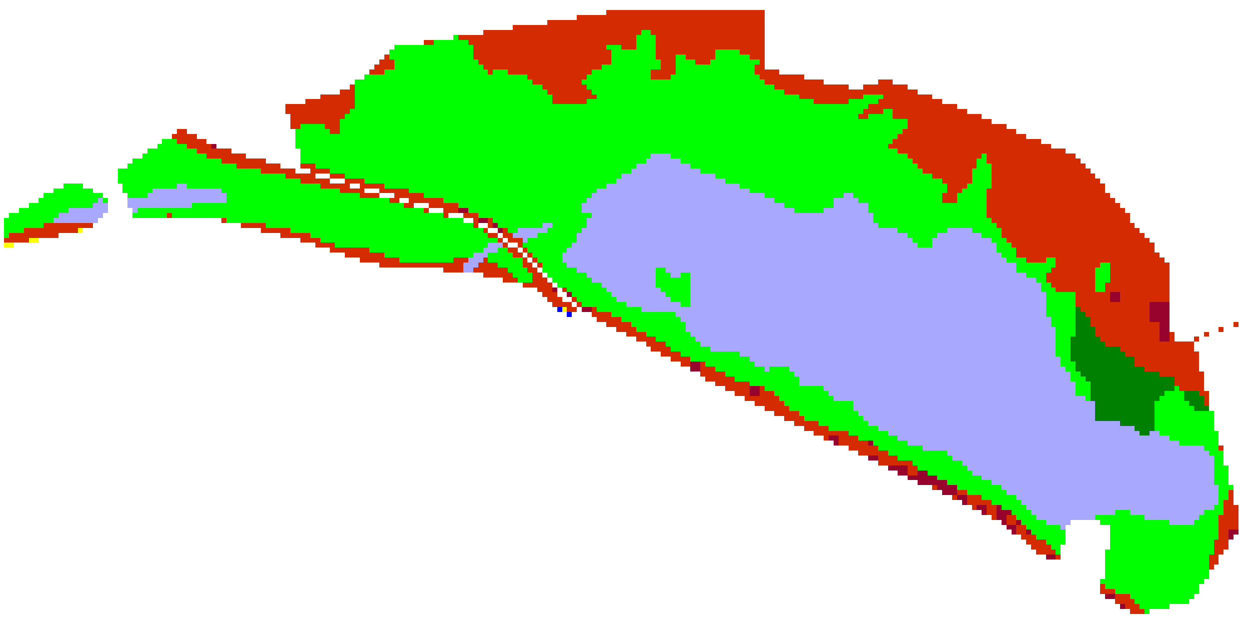
Kealia Raster
IPCC Scenario A1B-Max, 0.69 M SLR Eustatic by 2100

Results in Acres

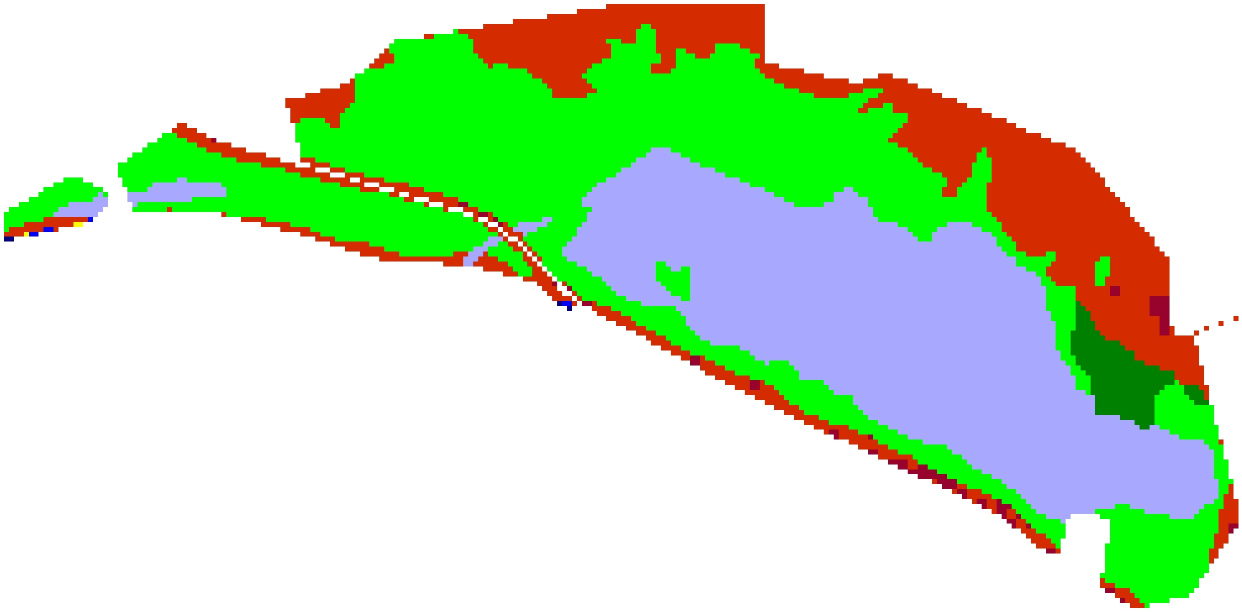
	Initial	2025	2050	2075	2100
Inland Fresh Marsh	292.3	292.3	292.3	292.4	283.8
Inland Open Water	240.1	240.1	240.1	240.1	236.2
Undeveloped Dry Land	149.7	149.1	148.9	148.7	140.4
Swamp	14.5	14.5	14.5	14.5	14.5
Developed Dry Land	5.9	5.9	5.9	5.9	5.7
Estuarine Open Water	0.0	0.1	0.4	0.2	4.4
Open Ocean	0.0	0.1	0.2	0.6	0.8
Ocean Beach	0.0	0.4	0.1	0.1	8.0
Trans. Salt Marsh	0.0	0.0	0.0	0.0	8.8
Total (incl. water)	**702.5**	**702.5**	**702.5**	**702.5**	**702.5**



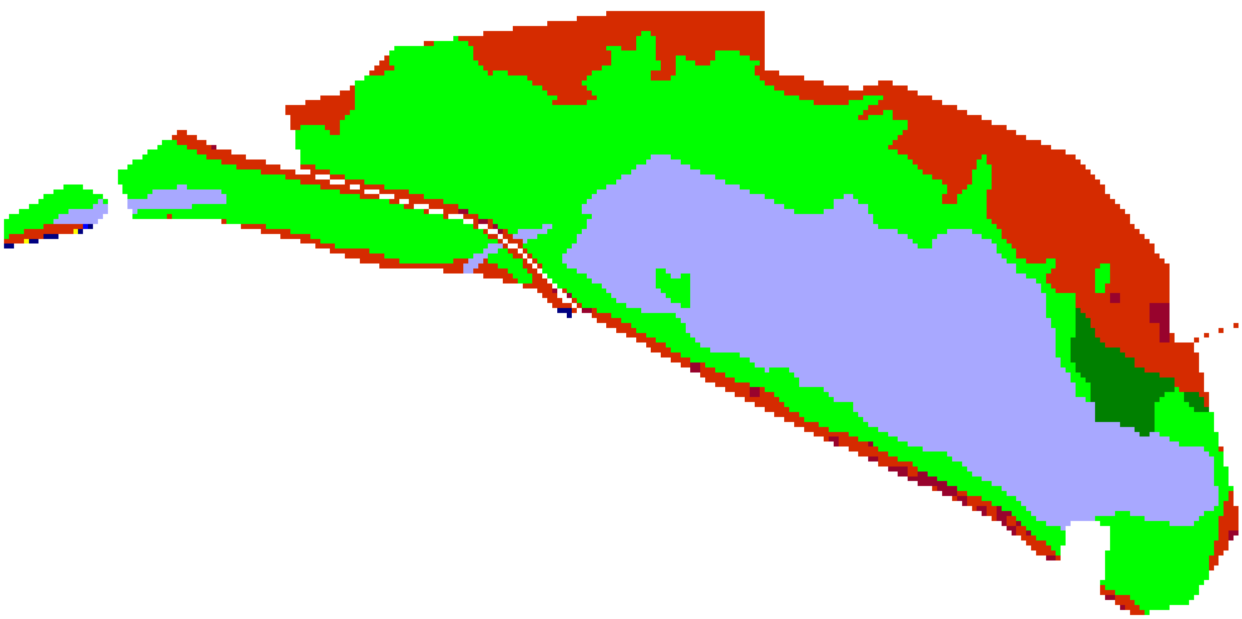
Kealia Pond NWR, Initial Condition



Kealia Pond NWR, 2025, Scenario A1B Maximum



Kealia Pond NWR, 2050, Scenario A1B Maximum



Kealia Pond NWR, 2075, Scenario A1B Maximum

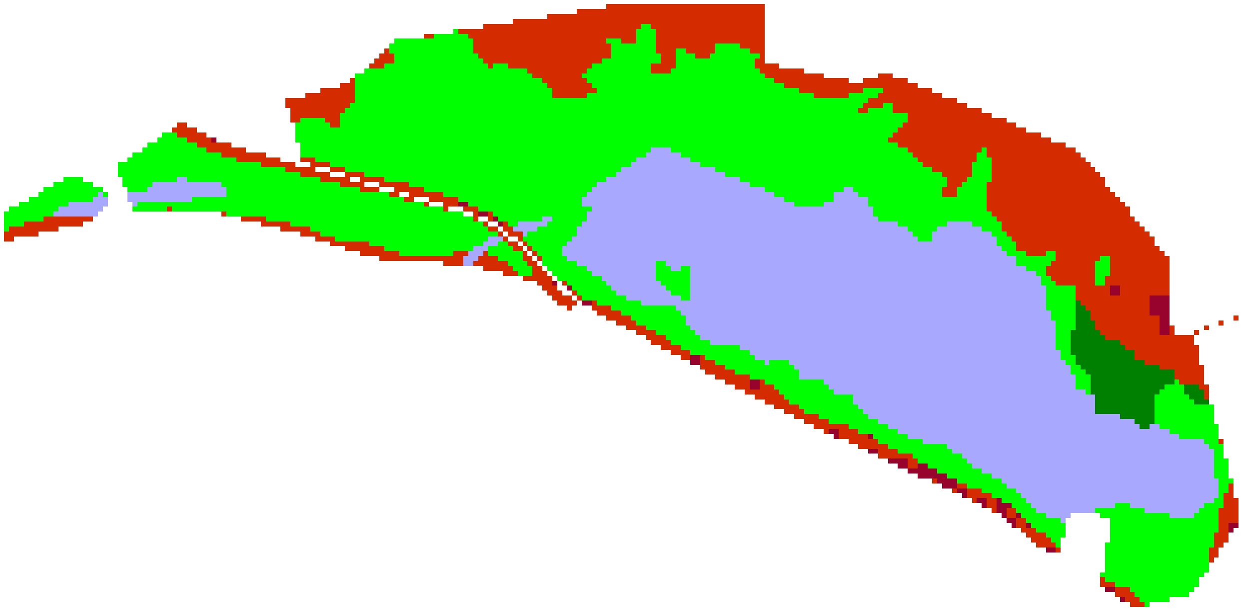
Kealia Pond NWR, 2100, Scenario A1B Maximum

Inland Fresh Marsh	
Inland Open Water	
Undeveloped Dry Land	
Swamp	
Developed Dry Land	
Transitional Salt Marsh	
Ocean Beach	
Estuarine Open Water	
Open Ocean	
Estuarine Beach	
Regularly Flooded Marsh	
Tidal Flat	

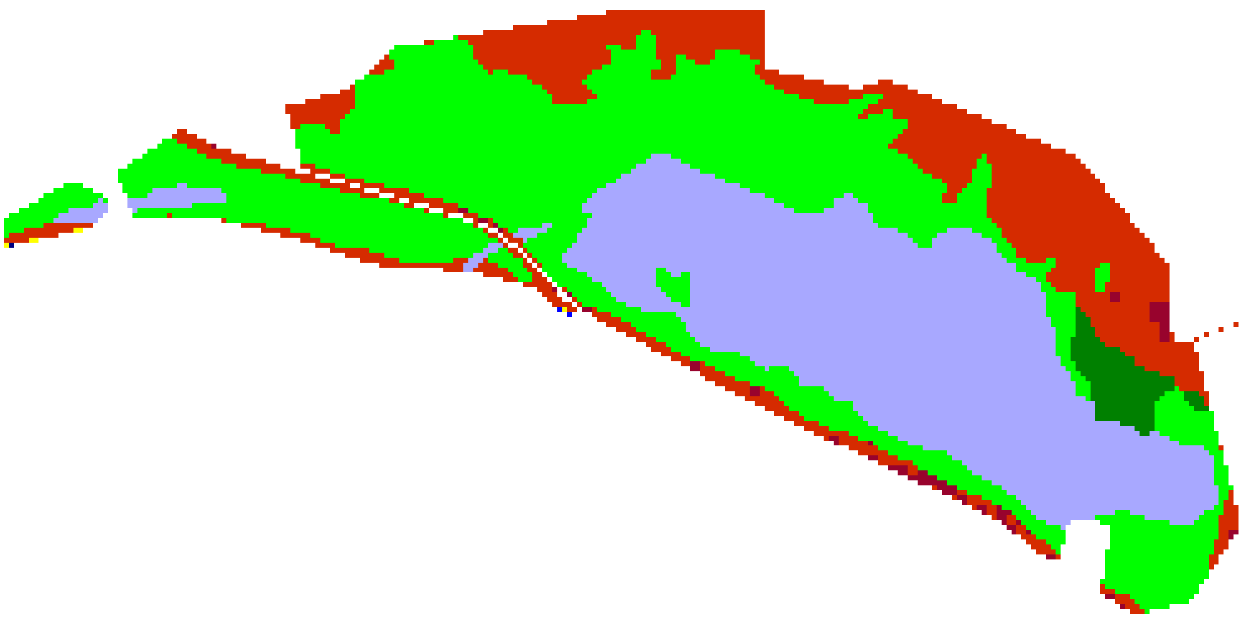
Kealia Raster
1 Meter Eustatic SLR by 2100

Results in Acres

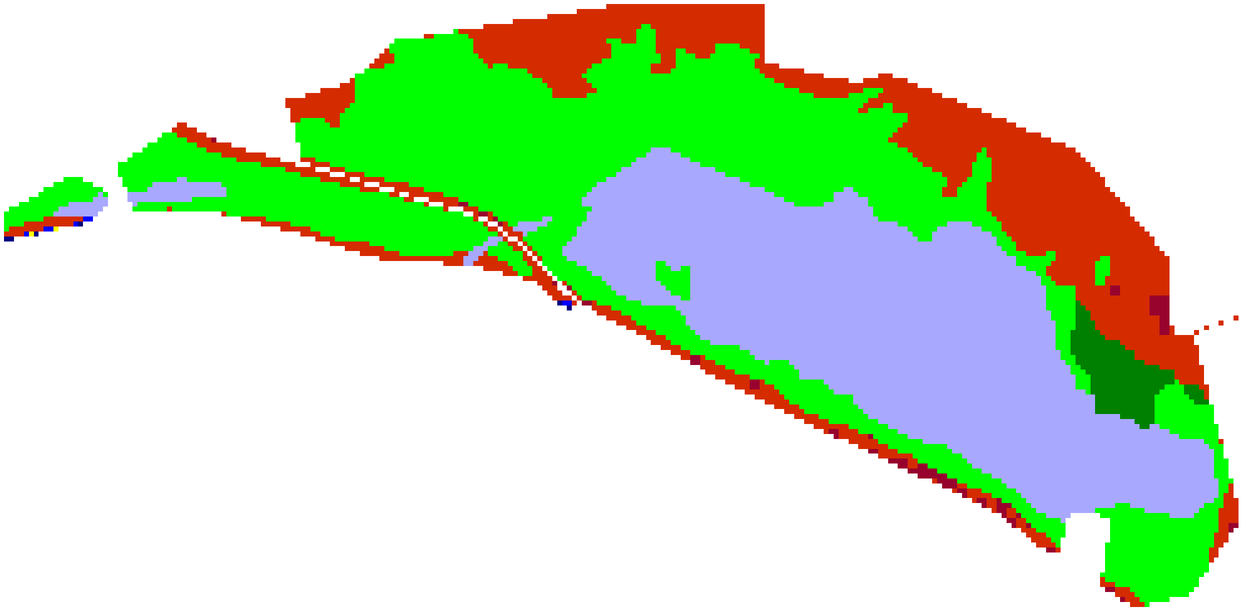
	Initial	2025	2050	2075	2100
Inland Fresh Marsh	292.3	292.3	292.3	256.2	214.5
Inland Open Water	240.1	240.1	240.1	235.5	235.1
Undeveloped Dry Land	149.7	149.0	148.8	140.5	125.9
Swamp	14.5	14.5	14.5	14.5	14.5
Developed Dry Land	5.9	5.9	5.9	5.7	5.5
Estuarine Open Water	0.0	0.1	0.4	5.1	6.3
Open Ocean	0.0	0.1	0.3	0.8	4.4
Ocean Beach	0.0	0.4	0.1	8.1	7.3
Trans. Salt Marsh	0.0	0.0	0.0	36.3	54.3
Regularly Flooded Marsh	0.0	0.0	0.0	0.0	34.7
Total (incl. water)	**702.5**	**702.5**	**702.5**	**702.5**	**702.5**



Kealia Pond NWR, Initial Condition

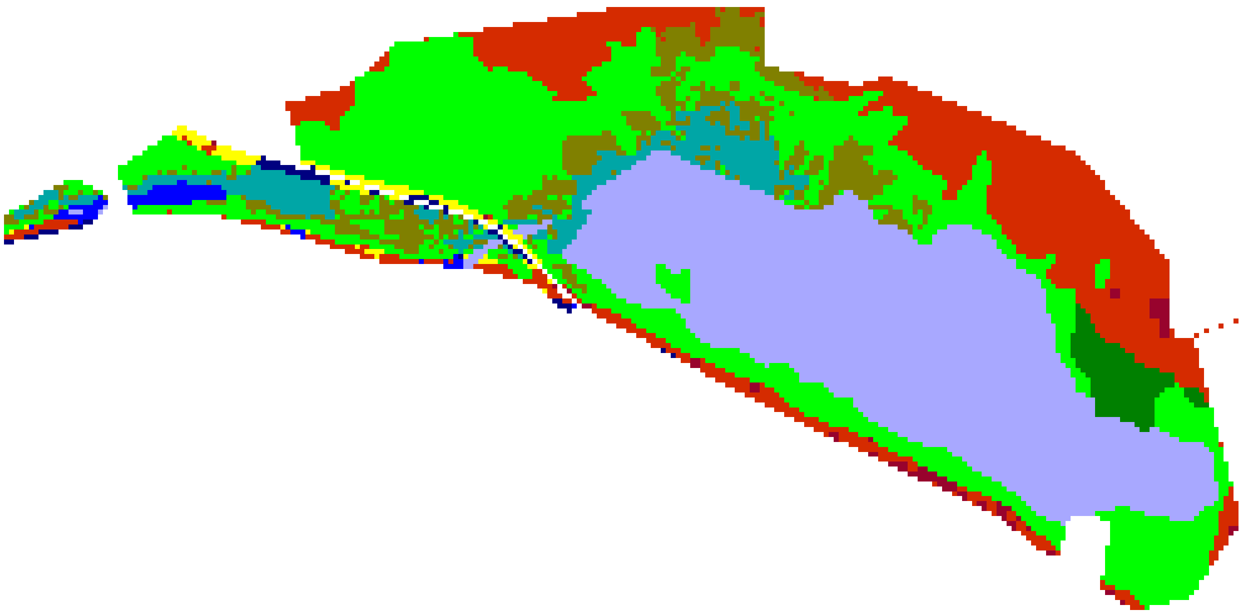


Kealia Pond NWR, 2025, 1 meter



Kealia Pond NWR, 2050, 1 meter

Kealia Pond NWR, 2075, 1 meter



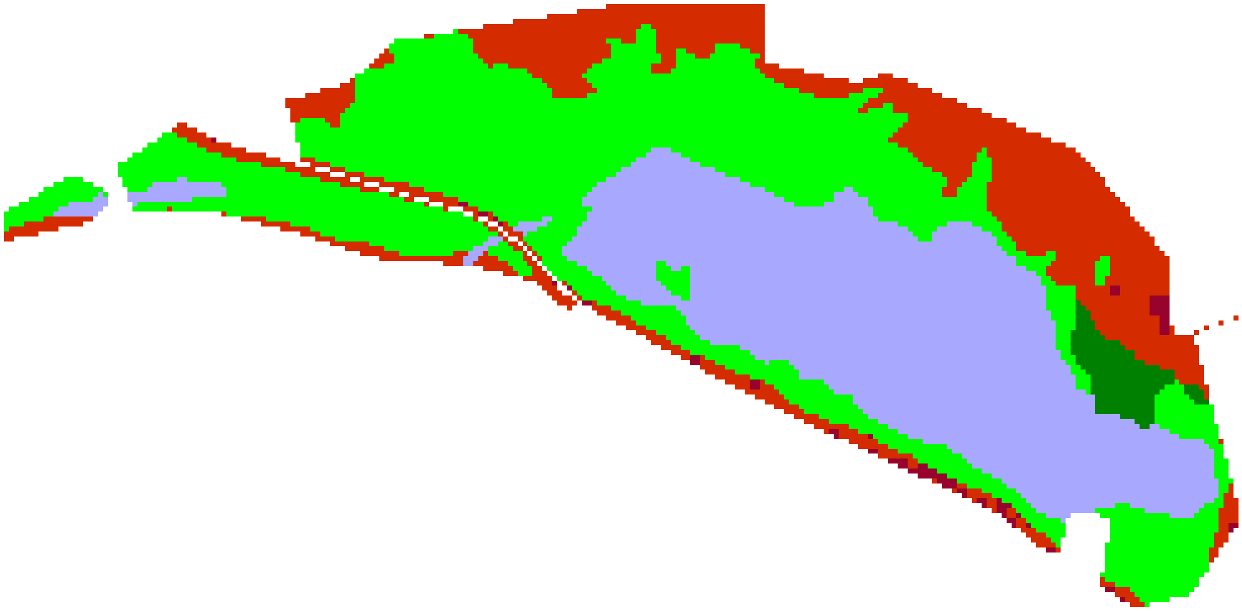
Kealia Pond NWR, 2100, 1 meter

Inland Fresh Marsh	
Inland Open Water	
Undeveloped Dry Land	
Swamp	
Developed Dry Land	
Transitional Salt Marsh	
Ocean Beach	
Estuarine Open Water	
Open Ocean	
Estuarine Beach	
Regularly Flooded Marsh	
Tidal Flat	

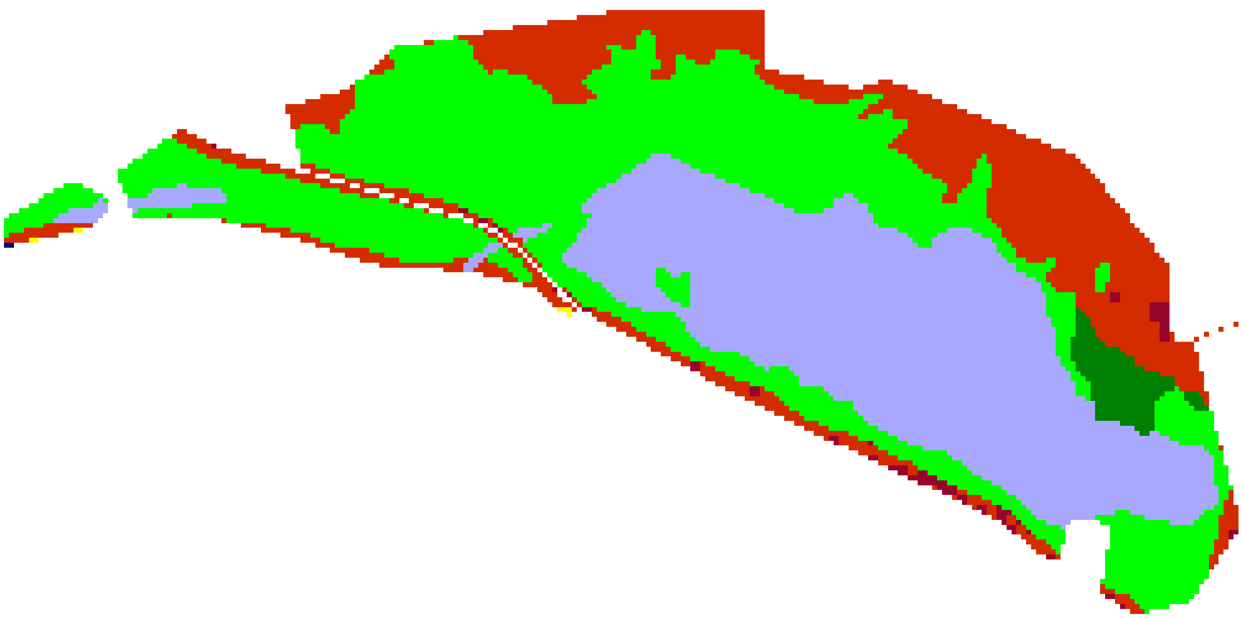
Kealia Raster
1.5 Meters Eustatic SLR by 2100

Results in Acres

	Initial	2025	2050	2075	2100
Inland Fresh Marsh	292.3	292.3	249.9	170.9	88.6
Inland Open Water	240.1	240.1	235.6	235.1	215.3
Undeveloped Dry Land	149.7	149.0	141.3	124.6	58.9
Swamp	14.5	14.5	14.5	14.5	7.4
Developed Dry Land	5.9	5.9	5.7	5.5	3.5
Trans. Salt Marsh	0.0	0.0	42.5	91.0	151.3
Ocean Beach	0.0	0.6	8.0	8.2	3.3
Estuarine Open Water	0.0	0.0	4.6	6.2	32.7
Open Ocean	0.0	0.2	0.4	4.2	11.0
Estuarine Beach	0.0	0.0	0.1	0.0	0.4
Regularly Flooded Marsh	0.0	0.0	0.0	42.5	90.9
Tidal Flat	0.0	0.0	0.0	0.0	39.4
Total (incl. water)	**702.5**	**702.5**	**702.5**	**702.5**	**702.5**

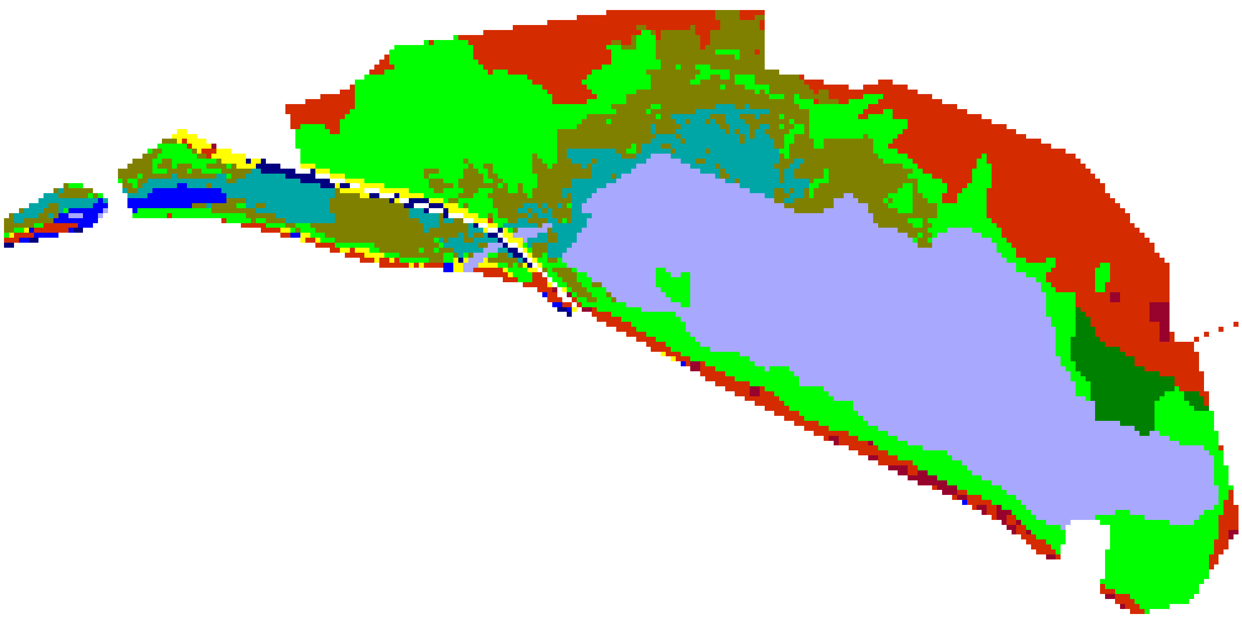


Kealia Pond NWR, Initial Condition

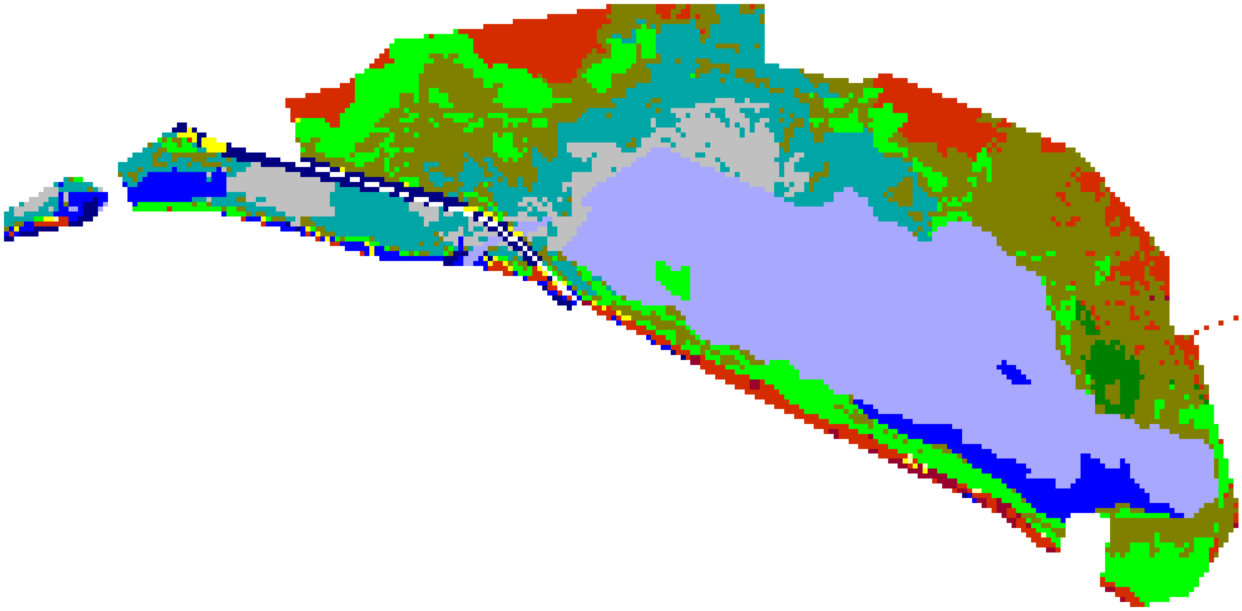


Kealia Pond NWR, 2025, 1.5 meter

Kealia Pond NWR, 2050, 1.5 meter



Kealia Pond NWR, 2075, 1.5 meter



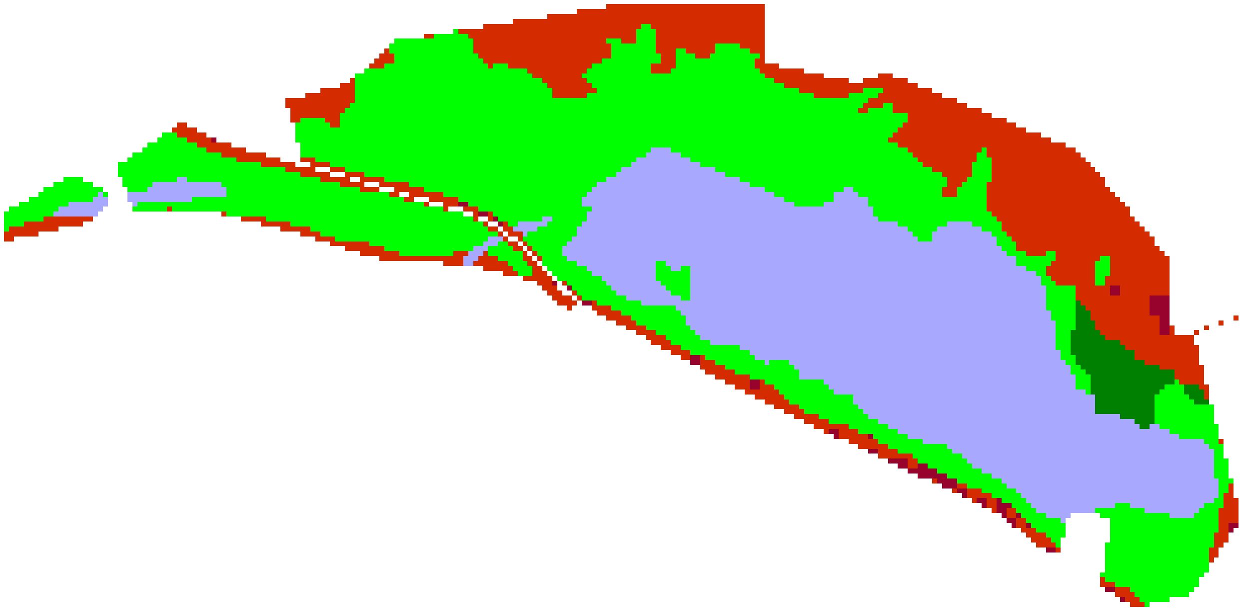
Kealia Pond NWR, 2100, 1.5 meter

Inland Fresh Marsh	
Inland Open Water	
Undeveloped Dry Land	
Swamp	
Developed Dry Land	
Transitional Salt Marsh	
Ocean Beach	
Estuarine Open Water	
Open Ocean	
Estuarine Beach	
Regularly Flooded Marsh	
Tidal Flat	

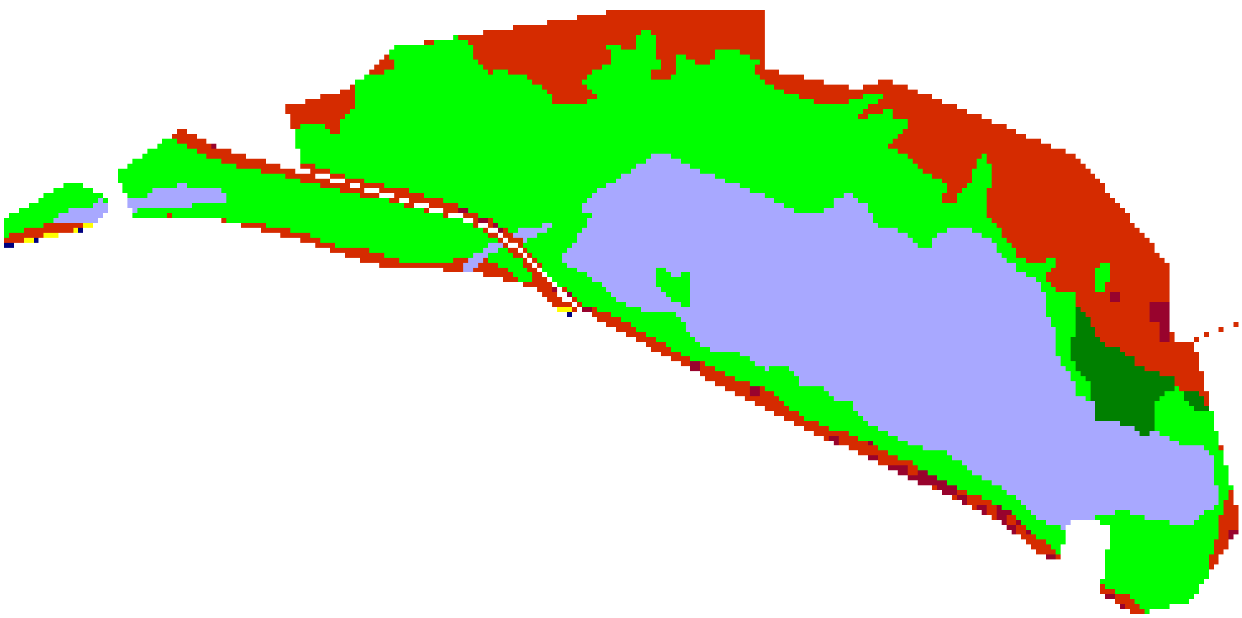
Kealia Raster
2 Meters Eustatic SLR by 2100

Results in Acres

	Initial	2025	2050	2075	2100
Inland Fresh Marsh	292.3	292.3	192.3	82.9	24.9
Inland Open Water	240.1	240.1	235.3	215.5	193.0
Undeveloped Dry Land	149.7	148.9	131.6	68.5	24.8
Swamp	14.5	14.5	14.5	8.7	1.2
Developed Dry Land	5.9	5.9	5.6	3.8	0.9
Trans. Salt Marsh	0.0	0.0	107.4	173.4	95.4
Ocean Beach	0.0	0.6	10.1	5.2	7.4
Estuarine Open Water	0.0	0.0	5.0	28.3	62.6
Open Ocean	0.0	0.2	0.5	8.5	15.7
Estuarine Beach	0.0	0.0	0.1	0.2	1.7
Regularly Flooded Marsh	0.0	0.0	0.0	107.4	172.2
Tidal Flat	0.0	0.0	0.0	0.0	102.6
Total (incl. water)	**702.5**	**702.5**	**702.5**	**702.5**	**702.5**

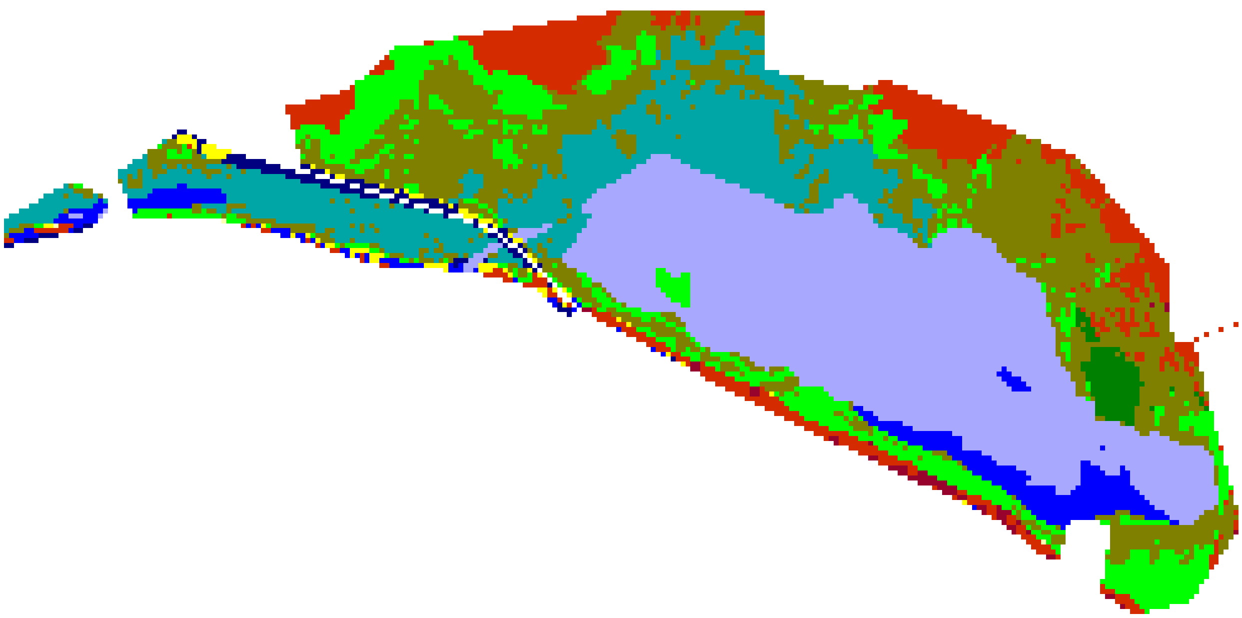


Kealia Pond NWR, Initial Condition

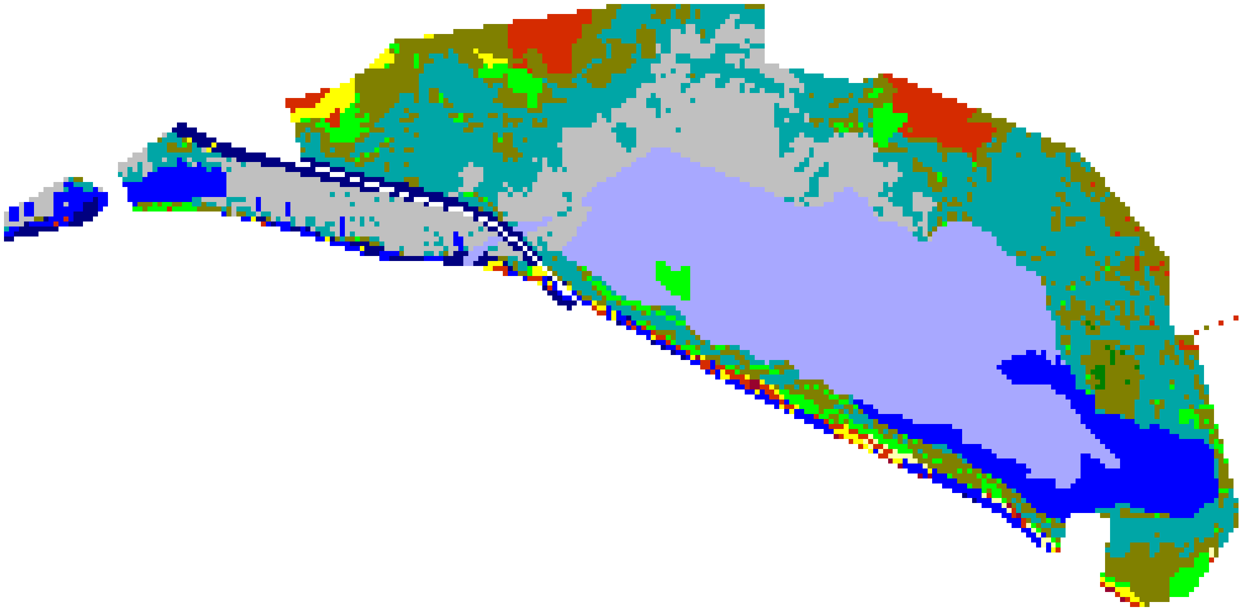


Kealia Pond NWR, 2025, 2 meters

Kealia Pond NWR, 2050, 2 meters



Kealia Pond NWR, 2075, 2 meters



Kealia Pond NWR, 2100, 2 meters

Undeveloped Dry Land	
Tidal Fresh Marsh	
Swamp	
Inland Fresh Marsh	
Developed Dry Land	
Transitional Salt Marsh	
Estuarine Open Water	
Open Ocean	
Ocean Beach	
Irregularly Flooded Marsh	
Regularly Flooded Marsh	
Tidal Flat	

Discussion

Kealia Pond NWR manages to remain relatively unaffected by inundation effects through the 0.69 meter scenario. It is in the 1-meter scenario that rising waters begin to have an impact on the main part of the refuge. The dry land (and beaches) between the refuge and the ocean, which acts as a natural impoundment against inundation, becomes heavily eroded in higher scenarios.

There is little or no tidal influence within the refuge, according to Glynnis Nakai. After one meter of SLR, however, salt water is predicted to move beyond the road barrier. Within this SLAMM application, we utilized a connectivity algorithm to determine when floodwaters are predicted to penetrate beyond the road resulting in more frequent flooding and salinity changes within the refuge. Under the highest SLR scenarios, highway 310 is predicted to be regularly flooded and convert to ocean beach or open water.

As the NWI dataset is roughly 30 years old, there is a considerable amount of uncertainty regarding current wetland type and location. On the other hand, high vertical-resolution LiDAR data allows for more precise estimation of water flows and frequency of wetland inundation.

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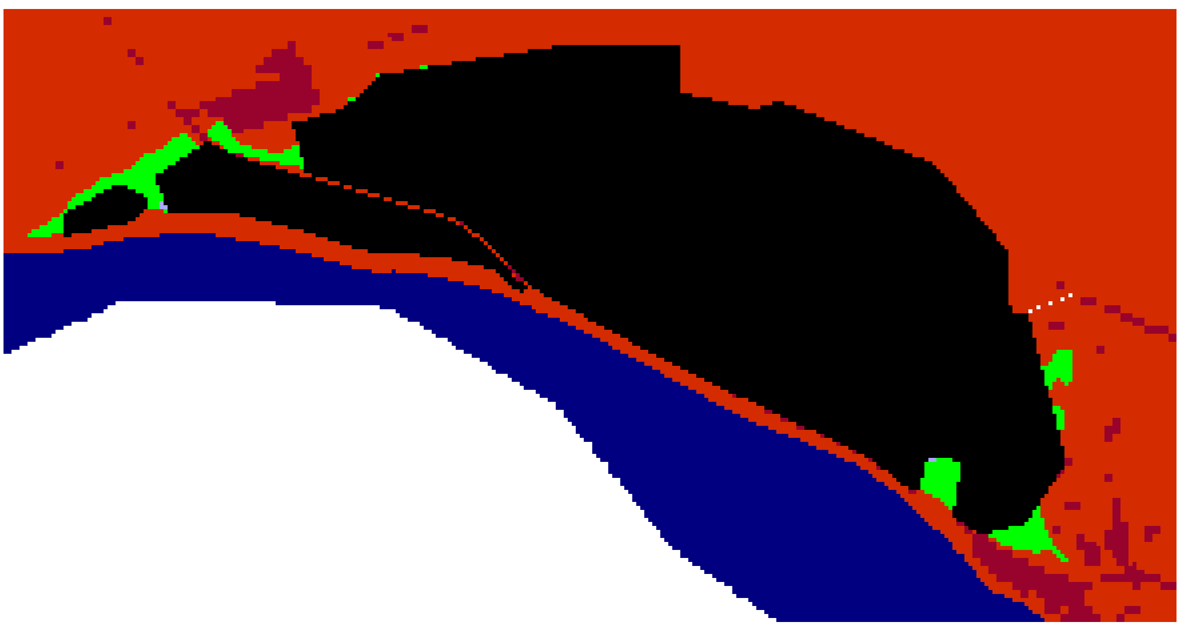
Appendix A: Contextual Results

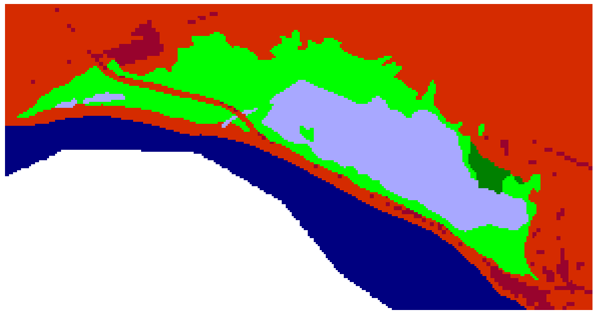
The SLAMM model does take into account the context of the surrounding lands or open water when calculating effects. For example, erosion rates are calculated based on the maximum fetch (wave action) which is estimated by assessing contiguous open water to a given marsh cell. Another example is that inundated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

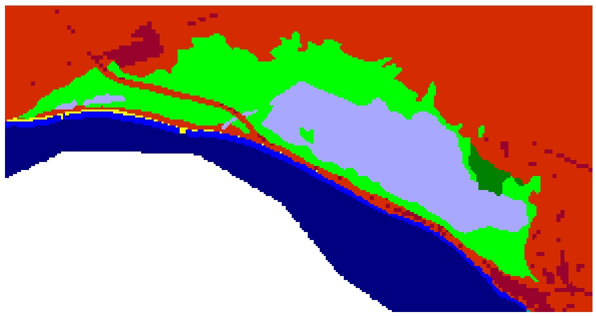
- Results were closely examined (quality assurance) within USFWS refuges but not closely examined for the larger region.
- Site-specific parameters for the model were derived for USFWS refuges whenever possible and may not be regionally applicable.
- Especially in areas where dikes are present, an effort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



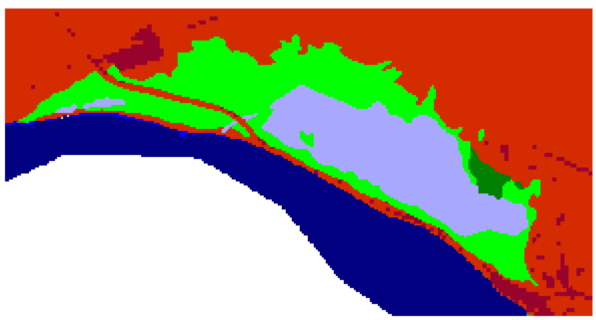
Kealia Pond National Wildlife Refuge within simulation context (black).



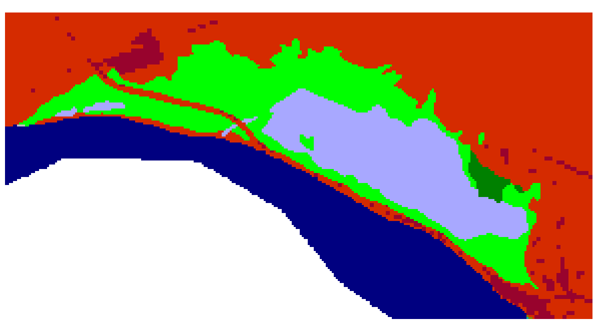
Kealia Pond Context, Initial Condition



Kealia Pond Context, 2025, Scenario A1B Mean

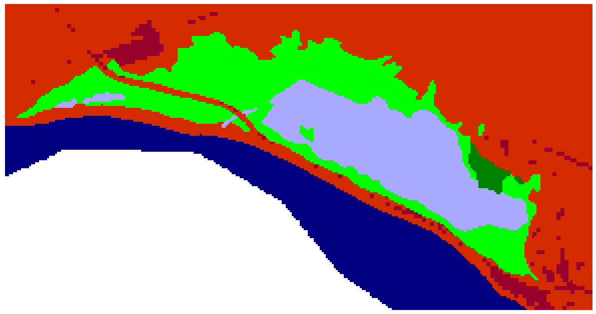


Kealia Pond Context, 2050, Scenario A1B Mean

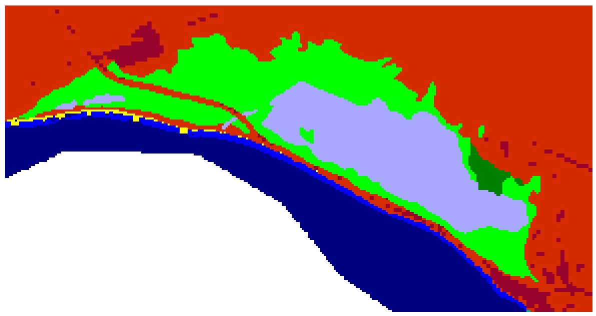


Kealia Pond Context, 2075, Scenario A1B Mean

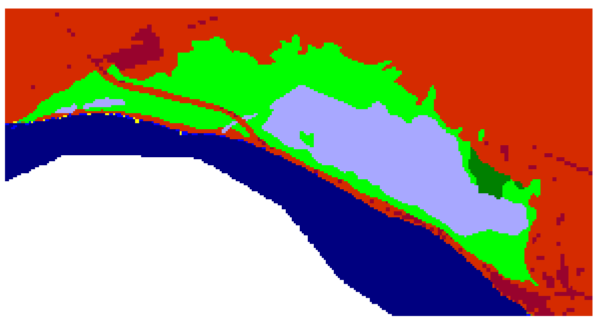
Kealia Pond Context, 2100, Scenario A1B Mean



Kealia Pond Context, Initial Condition



Kealia Pond Context, 2025, Scenario A1B Maximum



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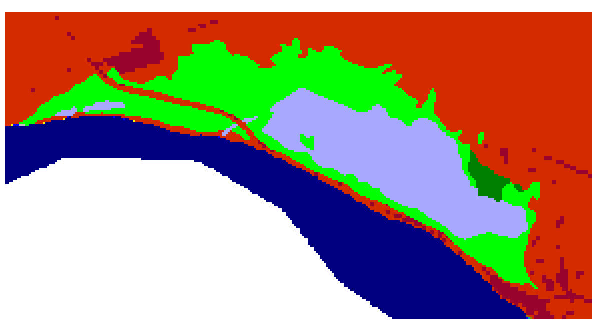
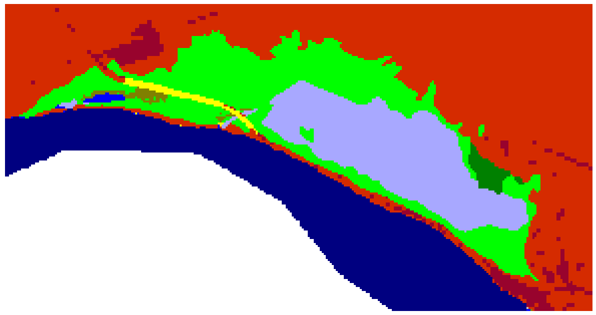
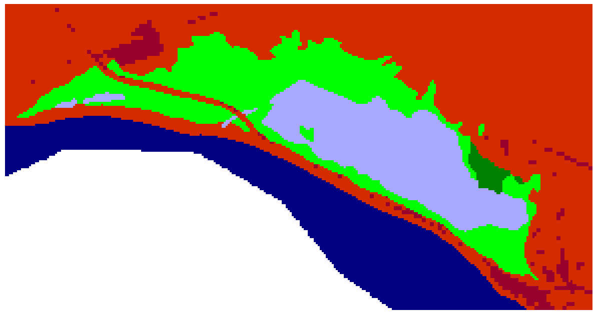


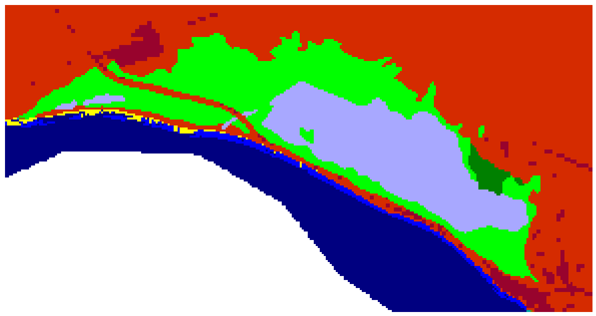
Kealia Pond Context, 2075, Scenario A1B Maximum



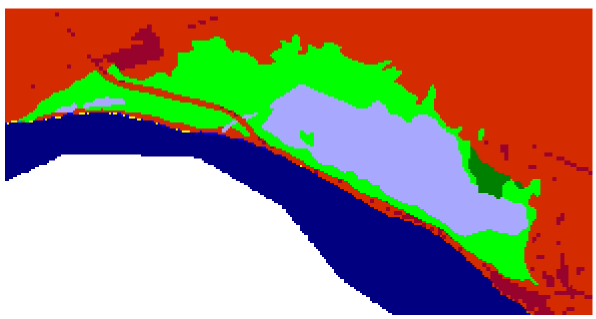
Kealia Pond Context, 2100, Scenario A1B Maximum



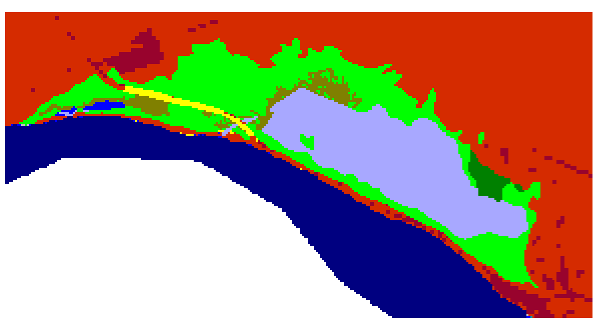
Kealia Pond Context, Initial Condition



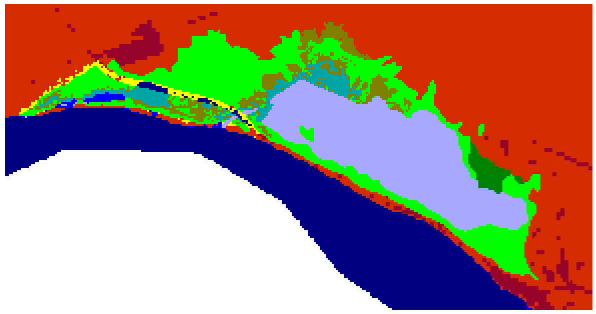
Kealia Pond Context, 2025, 1 meter



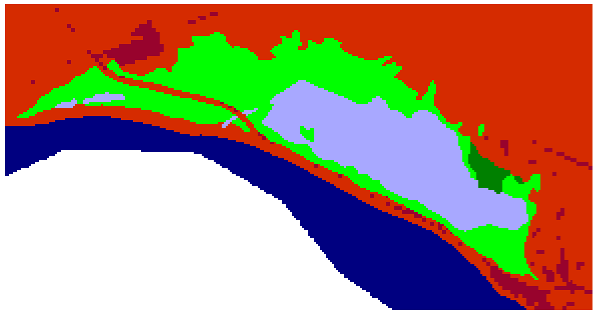
Kealia Pond Context, 2050, 1 meter



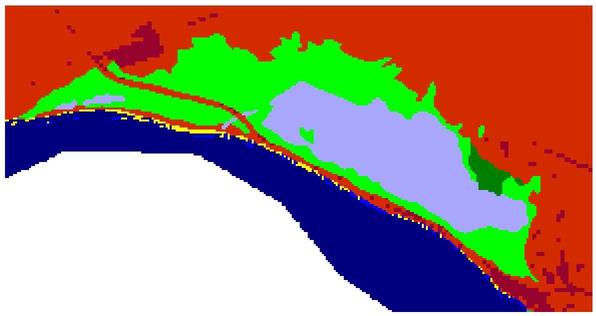
Kealia Pond Context, 2075, 1 meter



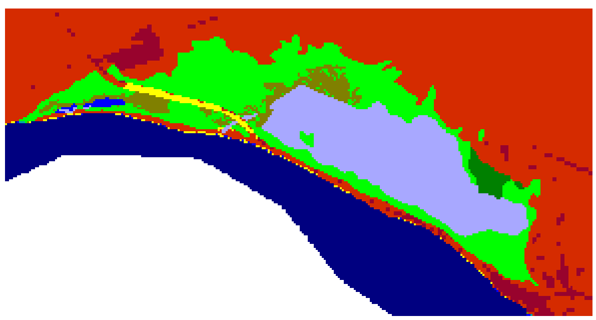
Kealia Pond Context, 2100, 1 meter



Kealia Pond Context, Initial Condition



Kealia Pond Context, 2025, 1.5 meter



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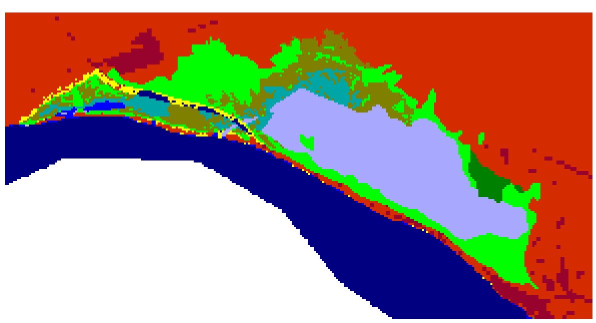
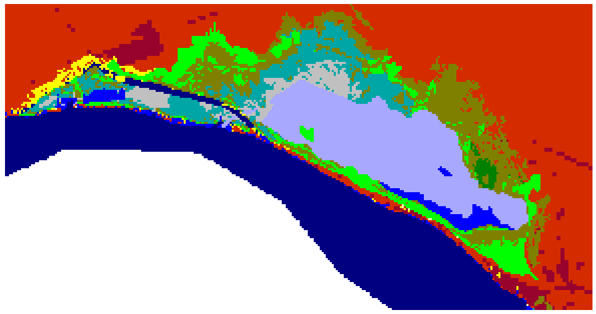
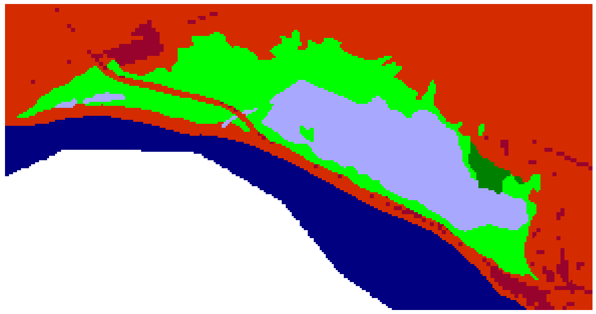
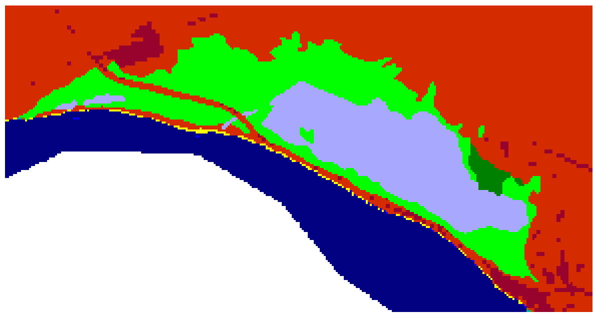


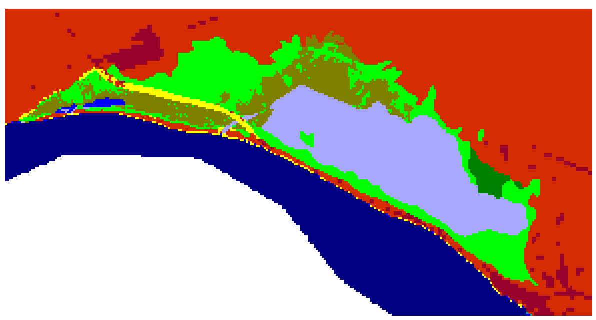
Kealia Pond Context, 2075, 1.5 meter

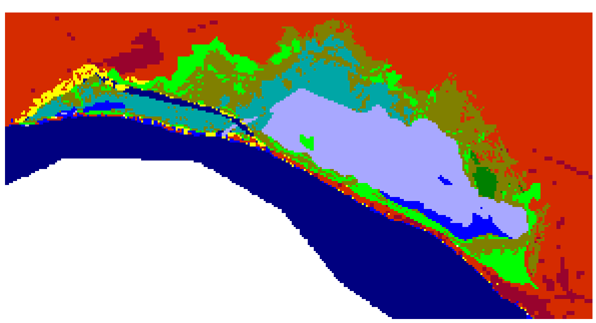


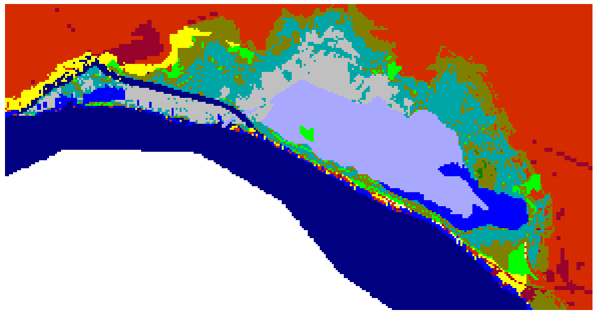
Kealia Pond Context, 2100, 1.5 meter


Kealia Pond Context, Initial Condition


Kealia Pond Context, 2025, 2 meter


Kealia Pond Context, 2050, 2 meter


Kealia Pond Context, 2075, 2 meter


Kealia Pond Context, 2100, 2 meter