# Application of the Sea-Level Affecting Marshes Model (SLAMM 6) to Kakahai'a NWR

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 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.

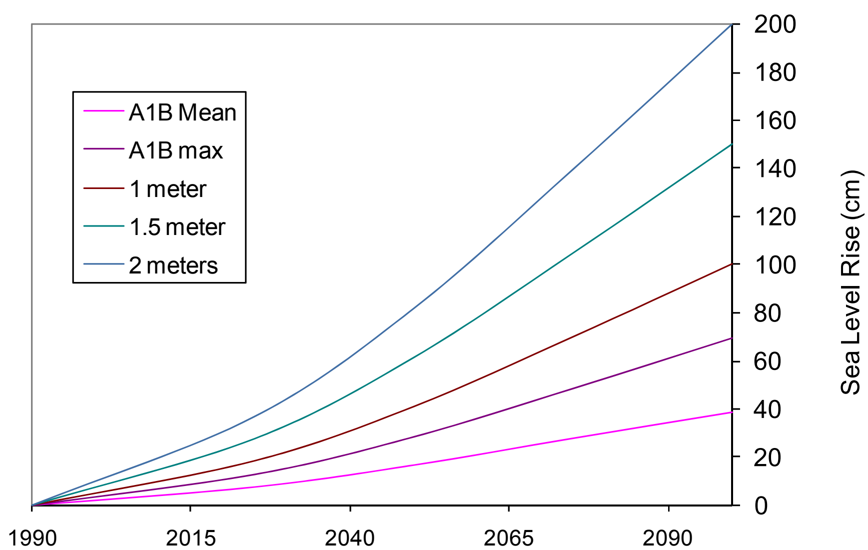
## *Sea Level Rise Scenarios*

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).

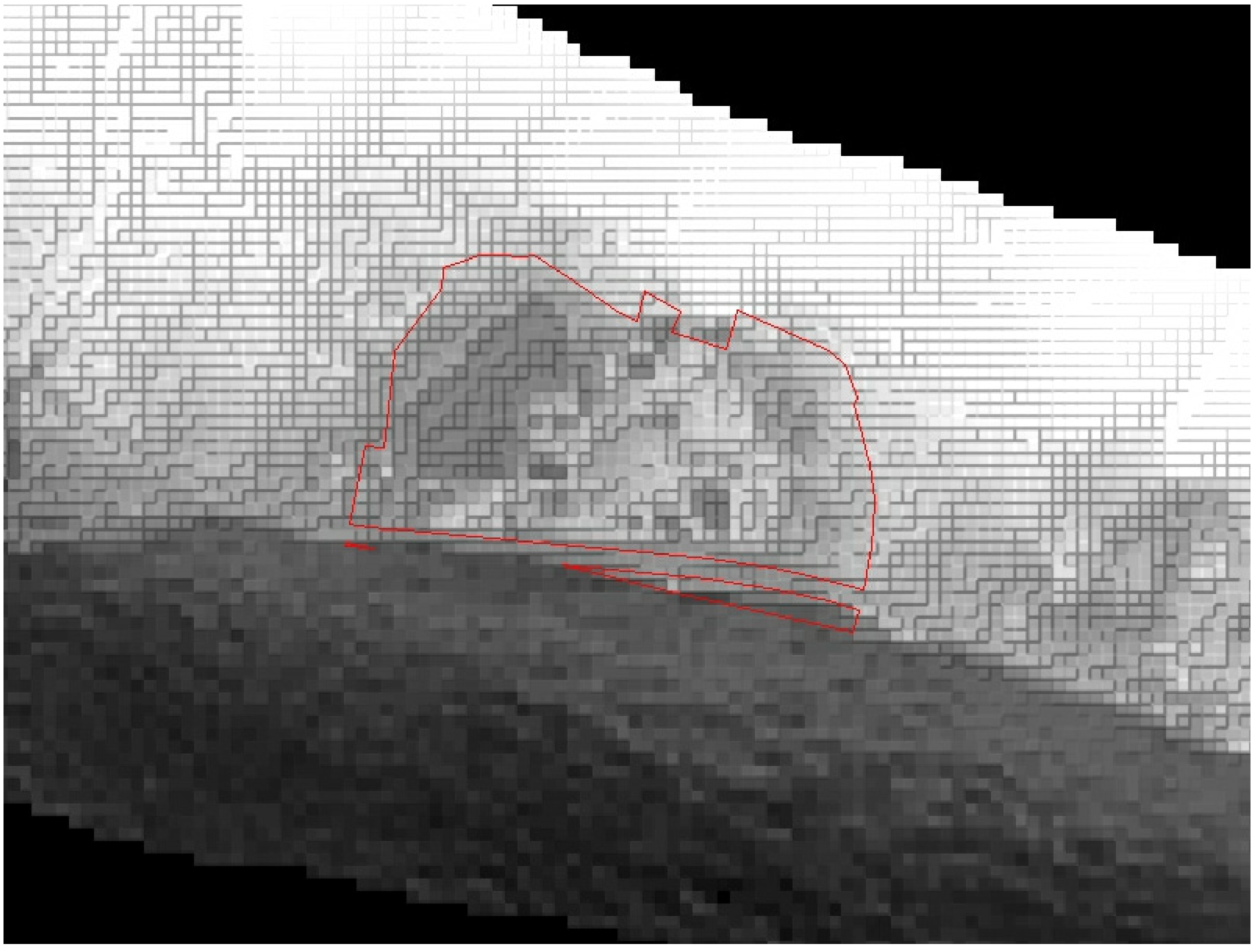


**Figure 1:** DEM source map for Kakahai'a NWR (thin red boundary).

The wetlands layer for the study area was produced by the National Wetlands Inventory and is based on a 1977 photo date. Converting the NWI survey into 15 meter cells indicates that the approximately forty four acre refuge (approved acquisition boundary including water) is primarily composed of the following categories:

| | |
|---|---|
| Undeveloped Dry Land | 38.5% |
| Tidal Fresh Marsh | 31.2% |
| Swamp | 22.7% |
| Inland Fresh Marsh | 4.5% |
| Developed Dry Land | 3.2% |

According to the National Wetland Inventory, Kakahai'a NWR has no impounded regions within the refuge boundary.

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 similar to the global average for the last 100 years (approximately 1.7 mm/year, IPCC 2007).

The tide range was estimated at 0.46 meters (great diurnal range or GT) using the nearest NOAA tide gage (1613198, Kaunakakai Harbor, HI).

No local marsh accretion or marsh 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, indicated that there is little or no tidal influence within the refuge, as the culvert is typically filled with sand (Figure 3). Flooding occurs during large storms, perhaps once in every four years. Ms. Nakai also indicated that the area of the refuge designated as "tidal fresh marsh" is currently composed primarily of bulrush.


**Figure 2:** Location of culvert filled by sand.

Within this SLAMM application, we utilized a connectivity algorithm to determine when floodwaters are predicted to overtop state highway 450 and result in more frequent flooding and salinity changes within the refuge. Within the refuge there is also a managed impoundment of 5.5 acres to provide shallow-water habitat for wading birds. This impoundment was created in 1983, after the NWI data layer was produced and therefore was not reflected as "impounded" in that dataset. The connectivity algorithm was also used to predict when this diked area will be overtopped by salt water.

According to our elevation dataset while highway 450 blocks salt water access to the refuge, this road is not of particularly high elevation, and ocean water is predicted to overtop the road and the impounded region under various SLR scenarios.

## SUMMARY OF SLAMM INPUT PARAMETERS FOR KAKAHAI'A NWR

| Parameter | Global |
|---|---|
| Description | Kakahai'a |
| NWI Photo Date (YYYY) | 1977 |
| DEM Date (YYYY) | 2007 |
| Direction Offshore [n,s,e,w] | South |
| Historic Trend (mm/yr) | 1.91 |
| "MTL-**MSL"** (m) | -0.007 |
| GT Great Diurnal Tide Range (m) | 0.651 |
| Salt Elev. (m above MTL) | 0.56 |
| 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

Kakahai'a NWR is predicted to show effects from moderate to high estimates of sea level rise, particularly in the categories of swamp and undeveloped dry land. Nearly one quarter of undeveloped dry land is predicted to be lost by 2100 in the 0.69 meter scenario, and 95% of it in the 2-meter scenario. Approximately one half of refuge swamplands are predicted to be subject to saline inundation under the 0.69 meter scenario (by 2100), and essentially all of it subject to conversion in the 2- meter scenario.

| **SLR by 2100 (m)** | **0.39** | **0.69** | **1** | **1.5** | **2** |
|---|---|---|---|---|---|
| Undeveloped Dry Land | 12% | 24% | 44% | 79% | 95% |
| Tidal Fresh Marsh | 1% | 1% | 3% | 13% | 44% |
| Swamp | 0% | 54% | 72% | 95% | 99% |
| Inland Fresh Marsh | 0% | 0% | 43% | 89% | 91% |
| Developed Dry Land | 0% | 10% | 72% | 100% | 100% |

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

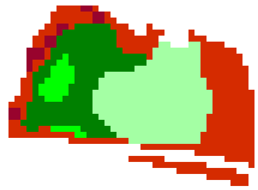
Kakahaia Raster
IPCC Scenario A1B-Mean, 0.39 M SLR Eustatic by 2100

Results in Acres

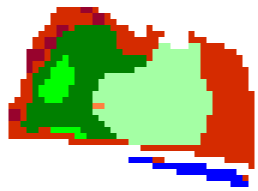
| | Initial | 2025 | 2050 | 2075 | 2100 |
|---|---|---|---|---|---|
| Undeveloped Dry Land | 17.1 | 15.4 | 15.3 | 15.2 | 15.1 |
| Tidal Fresh Marsh | 13.8 | 13.7 | 13.7 | 13.7 | 13.7 |
| Swamp | 10.1 | 10.1 | 10.1 | 10.1 | 10.1 |
| Inland Fresh Marsh | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 |
| Developed Dry Land | 1.4 | 1.4 | 1.4 | 1.4 | 1.4 |
| Trans. Salt Marsh | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Estuarine Open Water | 0.0 | 1.7 | 0.1 | 0.1 | 0.1 |
| Open Ocean | 0.0 | 0.0 | 1.7 | 1.8 | 1.9 |
| Ocean Beach | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Irregularly Flooded Marsh | 0.0 | 0.1 | 0.1 | 0.1 | 0.1 |
| **Total (incl. water)** | **44.4** | **44.4** | **44.4** | **44.4** | **44.4** |

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

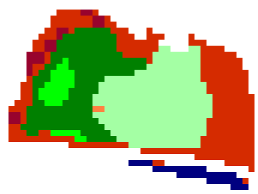
| | |
|---|---|
| Undeveloped Dry Land | |
| Tidal Fresh Marsh | |
| Swamp | |
| Inland Fresh Marsh | |
| Developed Dry Land | |
| Transitional Salt Marsh | |
| Estuarine Open Water | |
| Open Ocean | |
| Ocean Beach | |
| Irregularly Flooded Marsh | |
| Regularly Flooded Marsh | |
| Tidal Flat | |



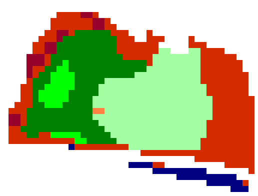
Kakahai'a NWR, Initial Condition



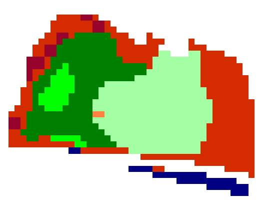
Kakahai'a NWR, 2025, Scenario A1B Mean



Kakahai'a NWR, 2050, Scenario A1B Mean



Kakahai'a NWR, 2075, Scenario A1B Mean



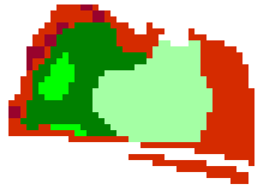
Kakahai'a NWR, 2100, Scenario A1B Mean

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

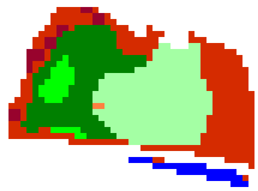
Results in Acres

| | Initial | 2025 | 2050 | 2075 | 2100 |
|---|---|---|---|---|---|
| Undeveloped Dry Land | 17.1 | 15.4 | 15.2 | 14.9 | 13.1 |
| Tidal Fresh Marsh | 13.8 | 13.7 | 13.7 | 13.7 | 13.7 |
| Swamp | 10.1 | 10.1 | 10.1 | 10.1 | 4.6 |
| Inland Fresh Marsh | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 |
| Developed Dry Land | 1.4 | 1.4 | 1.4 | 1.4 | 1.3 |
| Trans. Salt Marsh | 0.0 | 0.0 | 0.0 | 0.0 | 5.4 |
| Estuarine Open Water | 0.0 | 1.8 | 0.1 | 0.4 | 1.0 |
| Open Ocean | 0.0 | 0.0 | 1.8 | 1.9 | 2.2 |
| Ocean Beach | 0.0 | 0.0 | 0.0 | 0.0 | 1.0 |
| Irregularly Flooded Marsh | 0.0 | 0.1 | 0.1 | 0.1 | 0.1 |
| **Total (incl. water)** | **44.4** | **44.4** | **44.4** | **44.4** | **44.4** |

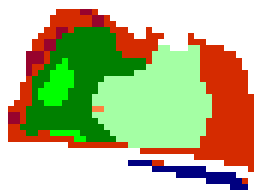
| | |
|---|---|
| Undeveloped Dry Land | |
| Tidal Fresh Marsh | |
| Swamp | |
| Inland Fresh Marsh | |
| Developed Dry Land | |
| Transitional Salt Marsh | |
| Estuarine Open Water | |
| Open Ocean | |
| Ocean Beach | |
| Irregularly Flooded Marsh | |
| Regularly Flooded Marsh | |
| Tidal Flat | |



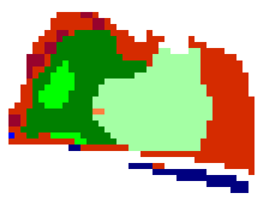
Kakahai'a NWR, Initial Condition



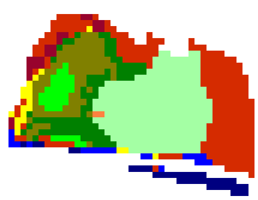
Kakahai'a NWR, 2025, Scenario A1B Maximum



Kakahai'a NWR, 2050, Scenario A1B Maximum



Kakahai'a NWR, 2075, Scenario A1B Maximum



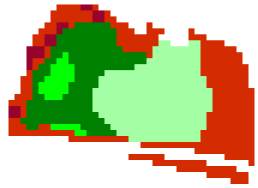
Kakahai'a NWR, 2100, Scenario A1B Maximum

Kakahaia Raster
1 Meter Eustatic SLR by 2100

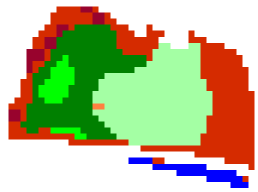
Results in Acres

| | Initial | 2025 | 2050 | 2075 | 2100 |
|---|---|---|---|---|---|
| Undeveloped Dry Land | 17.1 | 15.3 | 15.1 | 13.1 | 9.5 |
| Tidal Fresh Marsh | 13.8 | 13.7 | 13.7 | 13.6 | 13.4 |
| Swamp | 10.1 | 10.1 | 10.1 | 4.6 | 2.8 |
| Inland Fresh Marsh | 2.0 | 2.0 | 2.0 | 2.0 | 1.1 |
| Developed Dry Land | 1.4 | 1.4 | 1.4 | 1.3 | 0.4 |
| Trans. Salt Marsh | 0.0 | 0.0 | 0.0 | 5.5 | 2.9 |
| Estuarine Open Water | 0.0 | 1.8 | 0.2 | 1.1 | 1.7 |
| Open Ocean | 0.0 | 0.0 | 1.8 | 2.0 | 2.6 |
| Ocean Beach | 0.0 | 0.0 | 0.0 | 1.0 | 4.3 |
| Irregularly Flooded Marsh | 0.0 | 0.1 | 0.1 | 0.2 | 0.3 |
| Regularly Flooded Marsh | 0.0 | 0.0 | 0.0 | 0.1 | 5.2 |
| Tidal Flat | 0.0 | 0.0 | 0.0 | 0.0 | 0.2 |
| **Total (incl. water)** | **44.4** | **44.4** | **44.4** | **44.4** | **44.4** |

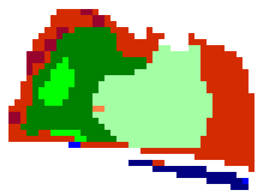
| | |
|---|---|
| Undeveloped Dry Land | |
| Tidal Fresh Marsh | |
| Swamp | |
| Inland Fresh Marsh | |
| Developed Dry Land | |
| Transitional Salt Marsh | |
| Estuarine Open Water | |
| Open Ocean | |
| Ocean Beach | |
| Irregularly Flooded Marsh | |
| Regularly Flooded Marsh | |
| Tidal Flat | |



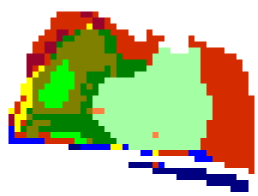
Kakahai'a NWR, Initial Condition



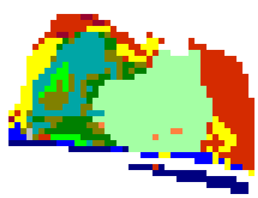
Kakahai'a NWR, 2025, 1 meter



Kakahai'a NWR, 2050, 1 meter



Kakahai'a NWR, 2075, 1 meter



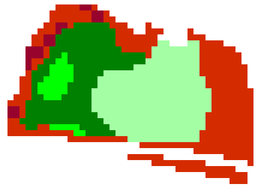
Kakahai'a NWR, 2100, 1 meter

Kakahaia Raster
1.5 Meters Eustatic SLR by 2100

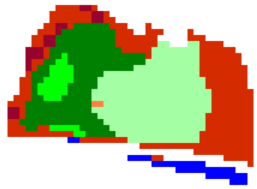
Results in Acres

| | Initial | 2025 | 2050 | 2075 | 2100 |
|---|---|---|---|---|---|
| Undeveloped Dry Land | 17.1 | 15.2 | 13.9 | 9.1 | 3.6 |
| Tidal Fresh Marsh | 13.8 | 13.7 | 13.5 | 13.1 | 12.1 |
| Swamp | 10.1 | 10.1 | 5.0 | 2.4 | 0.5 |
| Inland Fresh Marsh | 2.0 | 2.0 | 1.8 | 0.3 | 0.2 |
| Developed Dry Land | 1.4 | 1.4 | 1.3 | 0.3 | 0.0 |
| Trans. Salt Marsh | 0.0 | 0.0 | 5.2 | 4.1 | 1.7 |
| Estuarine Open Water | 0.0 | 1.9 | 0.9 | 2.0 | 1.9 |
| Open Ocean | 0.0 | 0.0 | 1.9 | 2.4 | 5.0 |
| Ocean Beach | 0.0 | 0.0 | 0.6 | 4.6 | 8.3 |
| Irregularly Flooded Marsh | 0.0 | 0.1 | 0.3 | 0.4 | 0.7 |
| Regularly Flooded Marsh | 0.0 | 0.0 | 0.1 | 5.4 | 4.0 |
| Tidal Flat | 0.0 | 0.0 | 0.0 | 0.1 | 6.4 |
| **Total (incl. water)** | **44.4** | **44.4** | **44.4** | **44.4** | **44.4** |

| | |
|---|---|
| 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 | |



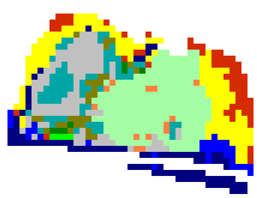
Kakahai'a NWR, Initial Condition



Kakahai'a NWR, 2025, 1.5 meter

Kakahai'a NWR, 2050, 1.5 meter

Kakahai'a NWR, 2075, 1.5 meter



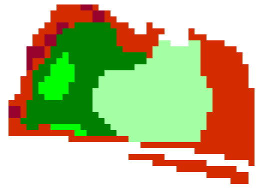
Kakahai'a NWR, 2100, 1.5 meter

Kakahaia Raster
2 Meters Eustatic SLR by 2100

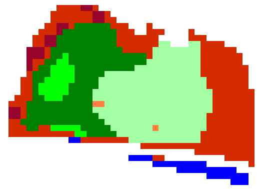
Results in Acres

| | Initial | 2025 | 2050 | 2075 | 2100 |
|---|---|---|---|---|---|
| Undeveloped Dry Land | 17.1 | 15.2 | 11.7 | 4.6 | 0.9 |
| Tidal Fresh Marsh | 13.8 | 13.6 | 13.3 | 11.9 | 7.8 |
| Swamp | 10.1 | 10.1 | 3.9 | 0.7 | 0.1 |
| Inland Fresh Marsh | 2.0 | 2.0 | 0.5 | 0.2 | 0.2 |
| Developed Dry Land | 1.4 | 1.4 | 1.0 | 0.0 | 0.0 |
| Trans. Salt Marsh | 0.0 | 0.0 | 7.7 | 3.0 | 0.5 |
| Estuarine Open Water | 0.0 | 2.0 | 2.0 | 2.0 | 2.2 |
| Open Ocean | 0.0 | 0.0 | 2.0 | 3.7 | 10.9 |
| Ocean Beach | 0.0 | 0.0 | 1.9 | 8.2 | 6.0 |
| Irregularly Flooded Marsh | 0.0 | 0.2 | 0.4 | 1.1 | 3.9 |
| Regularly Flooded Marsh | 0.0 | 0.0 | 0.2 | 7.6 | 3.5 |
| Tidal Flat | 0.0 | 0.0 | 0.0 | 1.4 | 8.5 |
| **Total (incl. water)** | **44.4** | **44.4** | **44.4** | **44.4** | **44.4** |

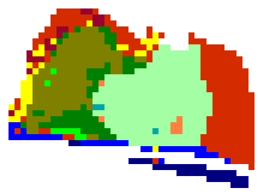
| | |
|---|---|
| Undeveloped Dry Land | |
| Tidal Fresh Marsh | |
| Swamp | |
| Inland Fresh Marsh | |
| Developed Dry Land | |
| Transitional Salt Marsh | |
| Estuarine Open Water | |
| Open Ocean | |
| Ocean Beach | |
| Irregularly Flooded Marsh | |
| Regularly Flooded Marsh | |
| Tidal Flat | |



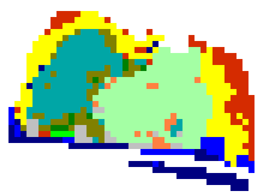
Kakahai'a NWR, Initial Condition



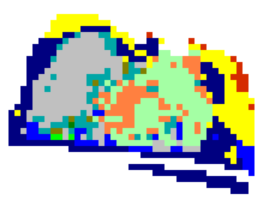
Kakahai'a NWR, 2025, 2 meters



Kakahai'a NWR, 2050, 2 meters



Kakahai'a NWR, 2075, 2 meters



Kakahai'a NWR, 2100, 2 meters

# Discussion

There is currently little or no tidal influence within Kakahai'a NWR due to a levee-like highway between the refuge and the ocean. While there is a culvert under this road, it is generally blocked by sand and sediment. This geography provides some protection against saline flooding, but such protection is predicted to be inadequate under moderate-to-high SLR scenarios.

This model simulation utilized a "connectivity algorithm" to determine when dry land and existing levees will be overtopped. There is some uncertainty in this result as the existing culvert will likely allow for saline inundation prior to overtopping of other dry lands. However, even if the culvert remains clogged, or is outfitted with a tidal gate, saline inundation is predicted when sea level rises by 0.69 meters, a degree of sea level rise that some scientists believe is likely by 2100 (see the section on *Sea Level Rise Scenarios* above). Any vertical-error in the existing LiDAR dataset would also increase uncertainty in these particular model results.

The creation date of the NWI layer for this refuge is 1977, just one year after refuge establishment. The age of the NWI dataset introduces some uncertainty into the simulation results, particularly with regards to current wetland type. For example, viewed from satellite, the western area designated as swamp appears more like dry land at the time of the satellite photo (Figure 3).

There is also uncertainty as to future management plans for the refuge, further enhancement of impounded areas to maintain and enhance shallow-water habitat for example.


**Figure 3**: Satellite image of the refuge.

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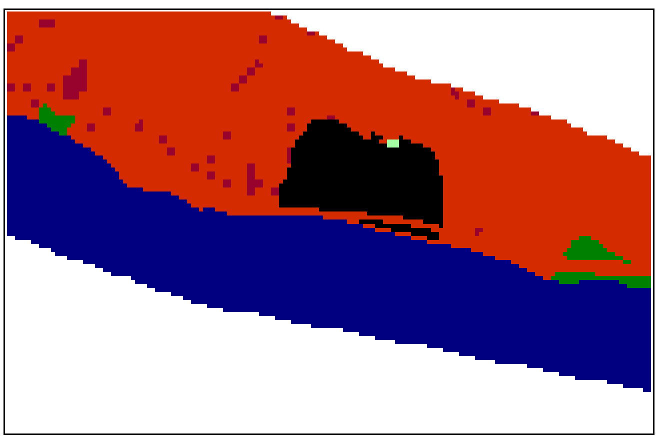
# Appendix A: Contextual Results

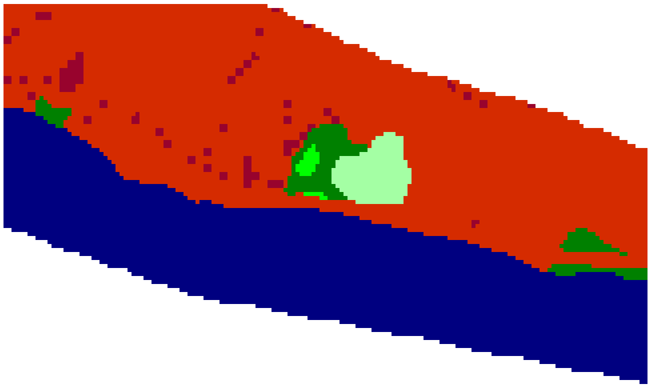
The SLAMM model does take into account the context of the surrounding lands or open water when calculating effects. For example, erosion rates are calculated based on the maximum fetch (wave action) which is estimated by assessing contiguous open water to a given marsh cell. Another example is that inundated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

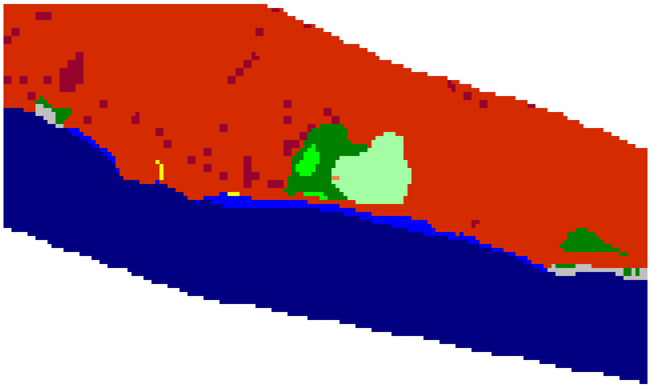
- Results were closely examined (quality assurance) within USFWS refuges but not closely examined for the larger region.
- Site-specific parameters for the model were derived for USFWS refuges whenever possible and may not be regionally applicable.
- Especially in areas where dikes are present, an effort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



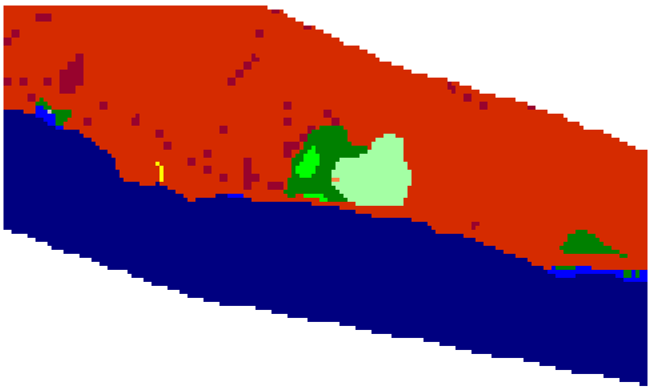
Kakahai'a National Wildlife Refuge within simulation context (black).



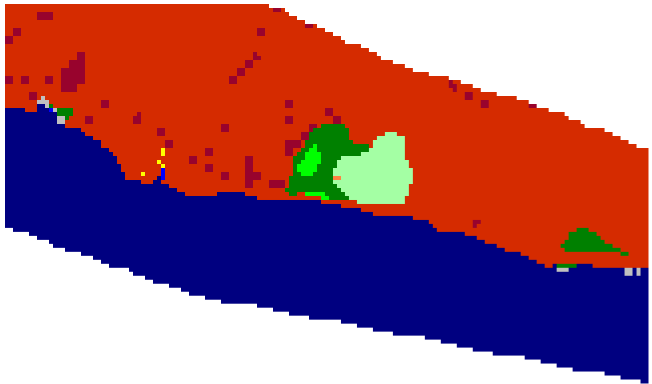
Kakahai'a Context, Initial Condition



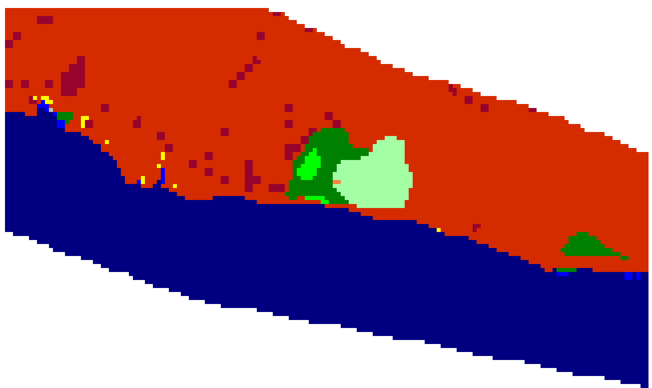
Kakahai'a Context, 2025, Scenario A1B Mean



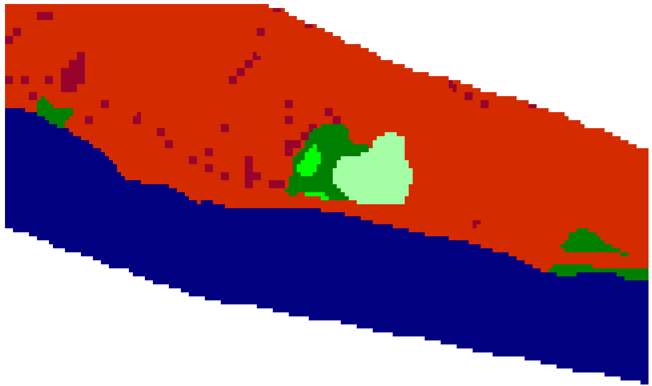
Kakahai'a Context, 2050, Scenario A1B Mean



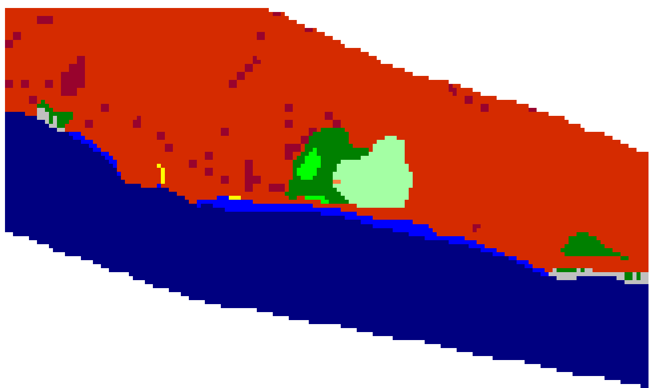
Kakahai'a Context, 2075, Scenario A1B Mean



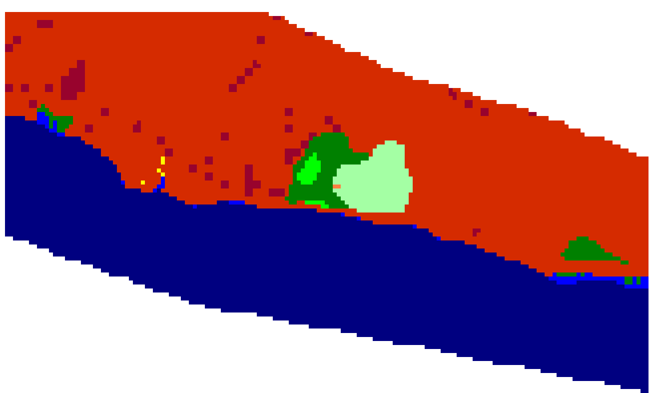
Kakahai'a Context, 2100, Scenario A1B Mean



Kakahai'a Context, Initial Condition



Kakahai'a Context, 2025, Scenario A1B Maximum



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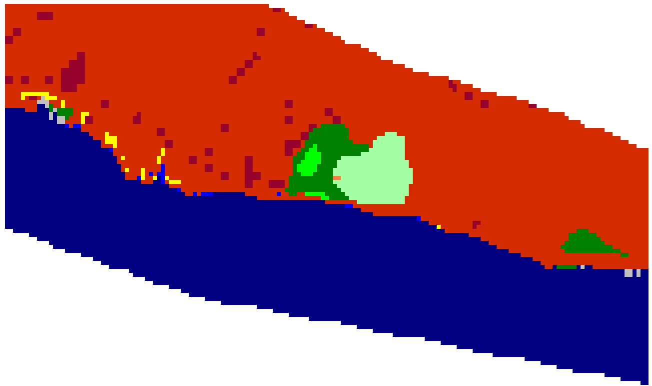

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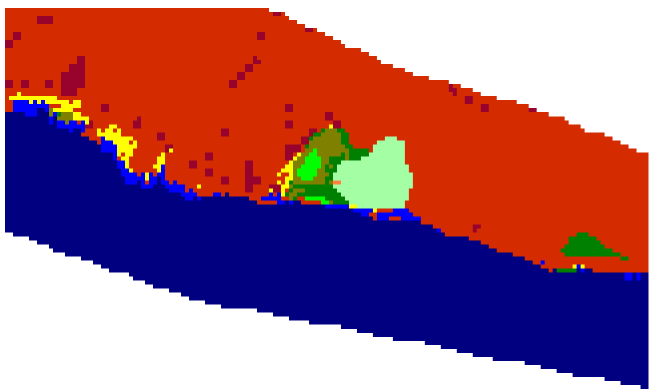
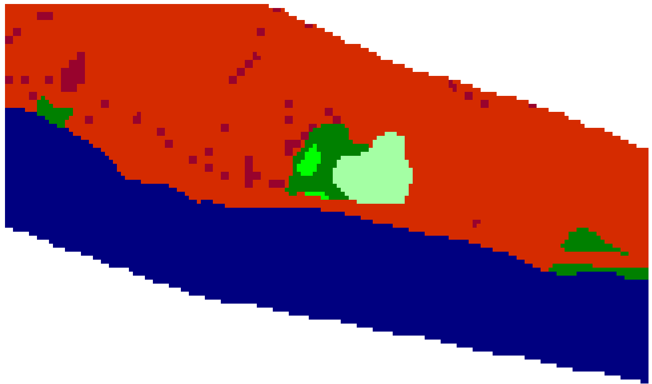
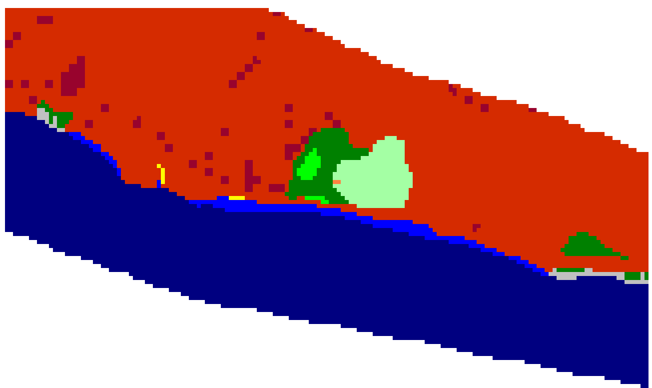


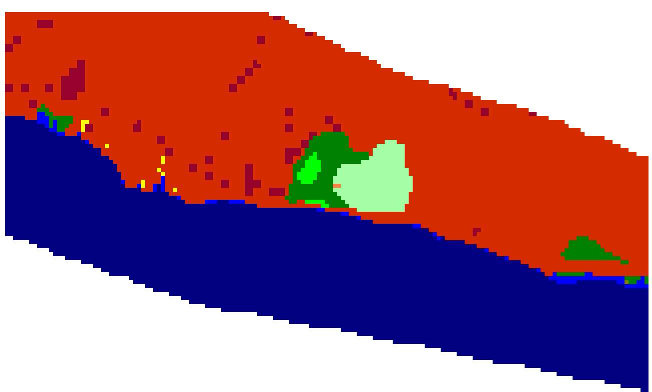
Kakahai'a Context, 2100, Scenario A1B Maximum



Kakahai'a Context, Initial Condition



Kakahai'a Context, 2025, 1 meter



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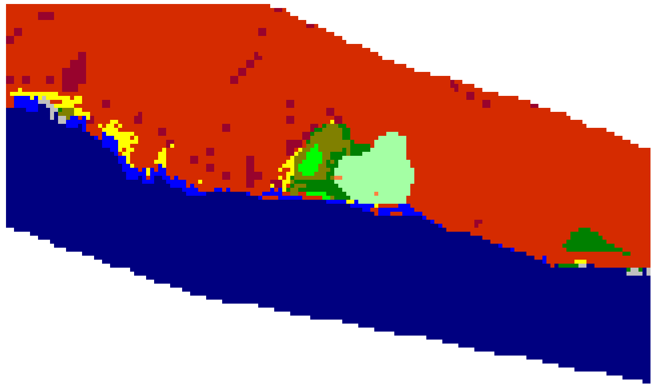

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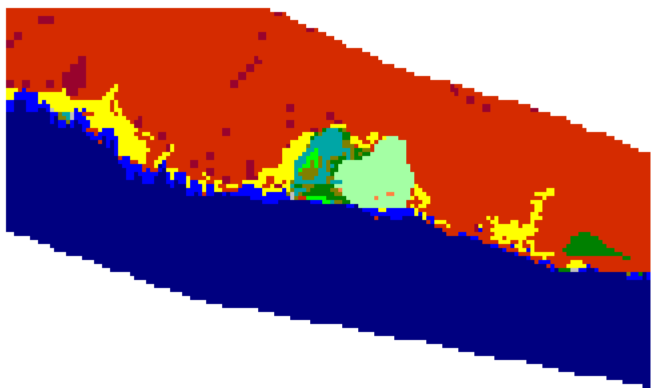

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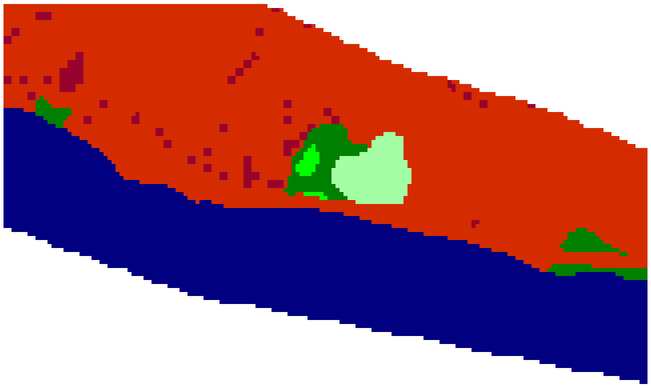
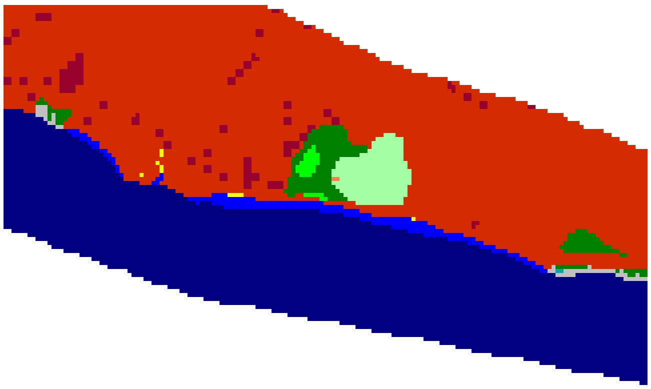
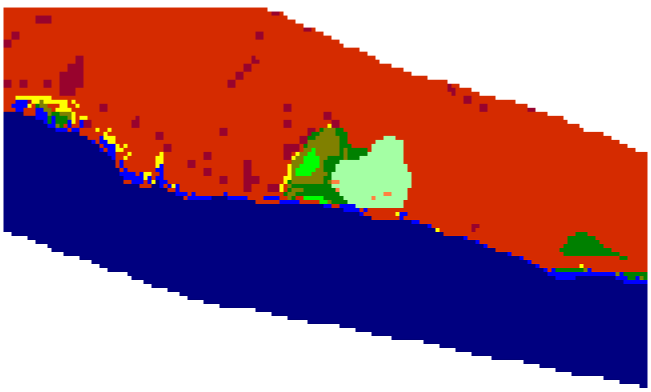


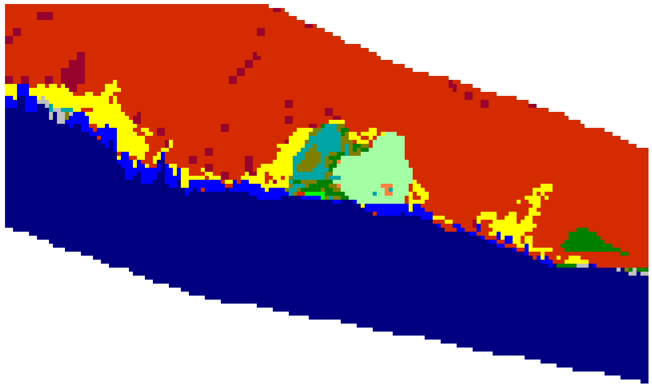
Kakahai’a Context, Initial Condition



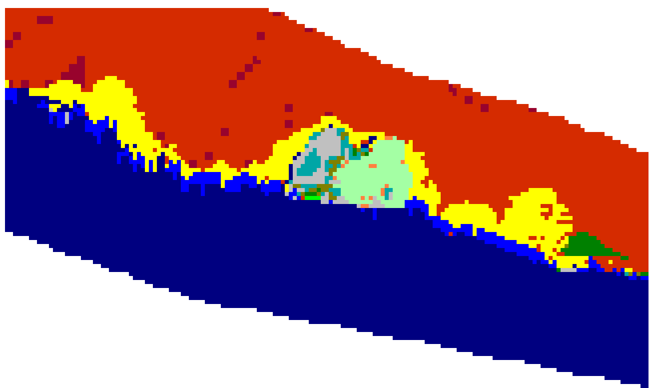
Kakahai’a Context, 2025, 1.5 meter



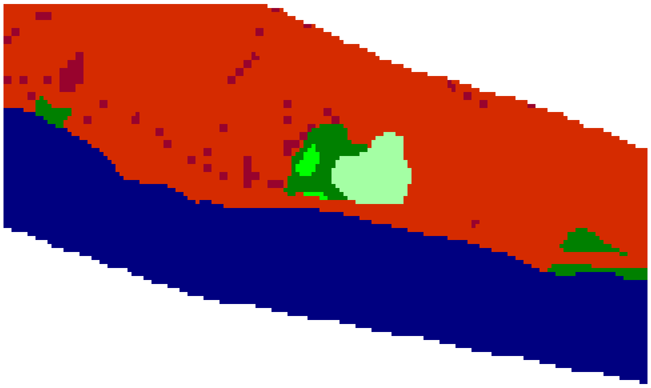
Kakahai’a Context, 2050, 1.5 meter



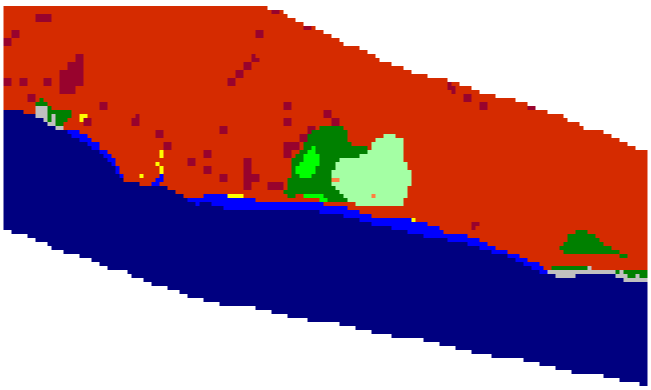
Kakahai'a Context, 2075, 1.5 meter



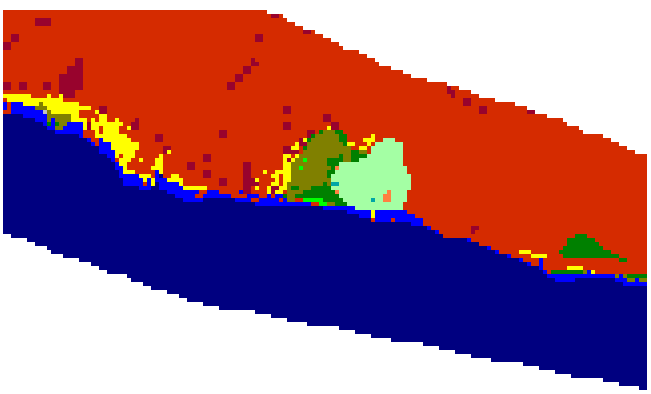
Kakahai'a Context, 2100, 1.5 meter



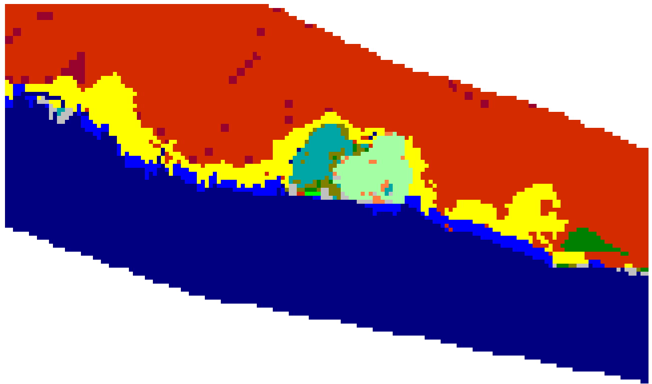
Kakahai'a Context, Initial Condition



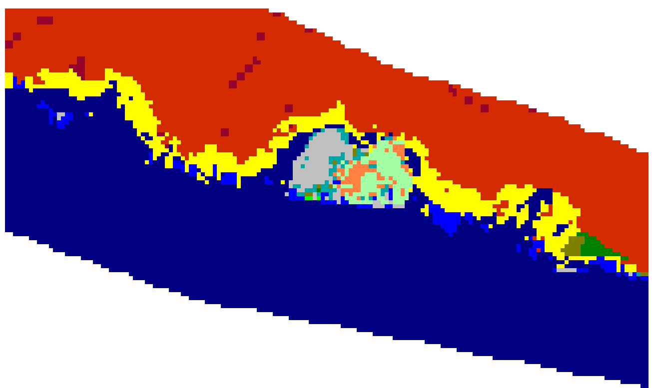
Kakahai'a Context, 2025, 2 meter



Kakahai'a Context, 2050, 2 meter



Kakahai'a Context, 2075, 2 meter



Kakahai'a Context, 2100, 2 meter