Application of the Sea-Level Affecting Marshes Model (SLAMM 6) to Pearl Harbor NWR

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Introduction

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

In an effort to address the potential effects of sea level rise on United States national wildlife refuges, the U. S. Fish and Wildlife Service contracted the application of the SLAMM model for most Region 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 25-year time-step due to storms. Beach migration and transport of sediments are calculated.
- **Saturation:** Coastal swamps and fresh marshes can migrate onto adjacent uplands as a response of the fresh water table to rising sea level close to the coast.

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

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

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

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

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

Sea Level Rise Scenarios

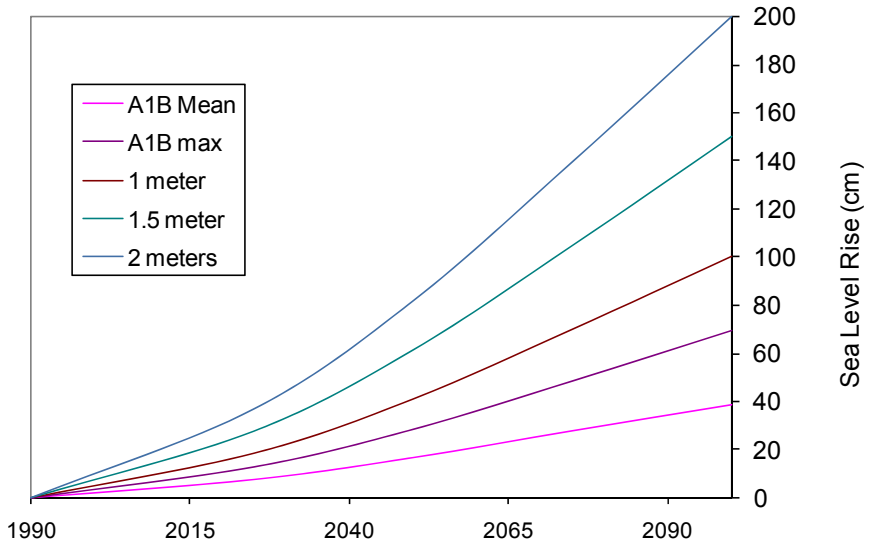
SLAMM 6 was run using scenario A1B from the Special Report on Emissions Scenarios (SRES) – mean and maximum estimates. The A1 scenario assumes that the future world includes very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of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

was run as a part of this project falls near the middle of this estimated range, predicting 0.40 meters of global sea level rise by 2100.

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

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

Figure 1: Summary of SLR Scenarios Utilized



Methods and Data Sources

The digital elevation map used in this simulation was supplied by FEMA (Federal Emergency Management Agency) and is based on high-resolution LiDAR with a 2005 photo date (Figure 1 and Figure 2).

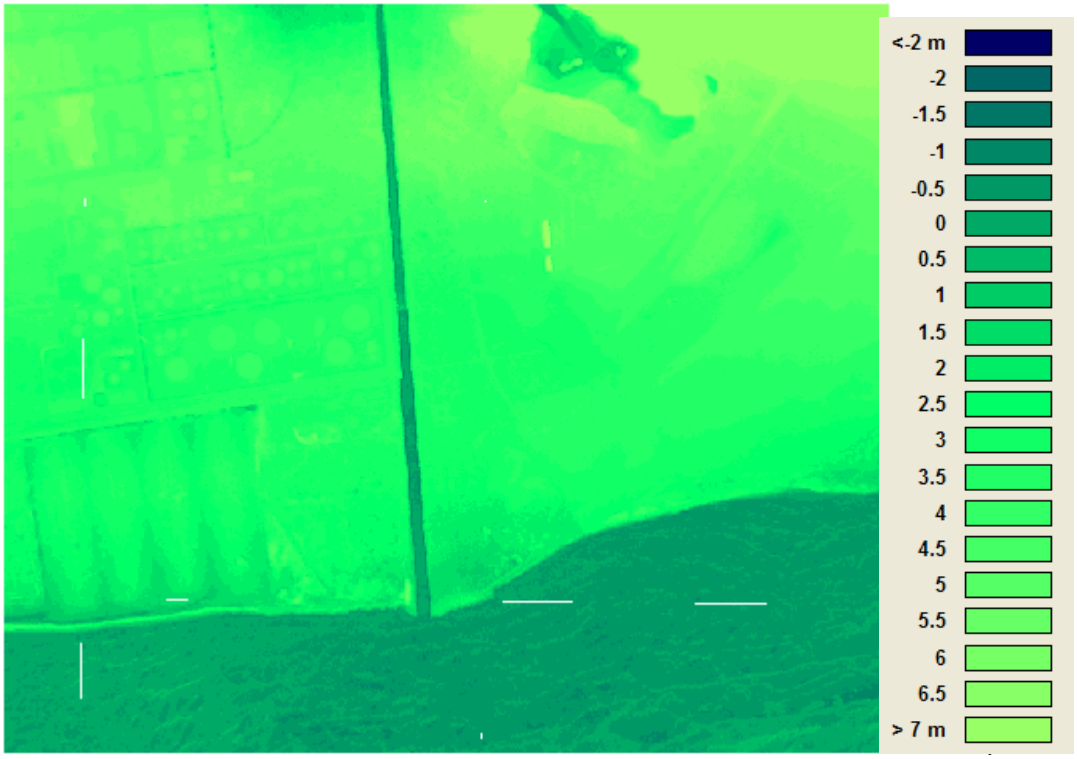


Figure 1: Elevation map of Kalaeloa Unit Relative to MTL as produced by SLAMM.

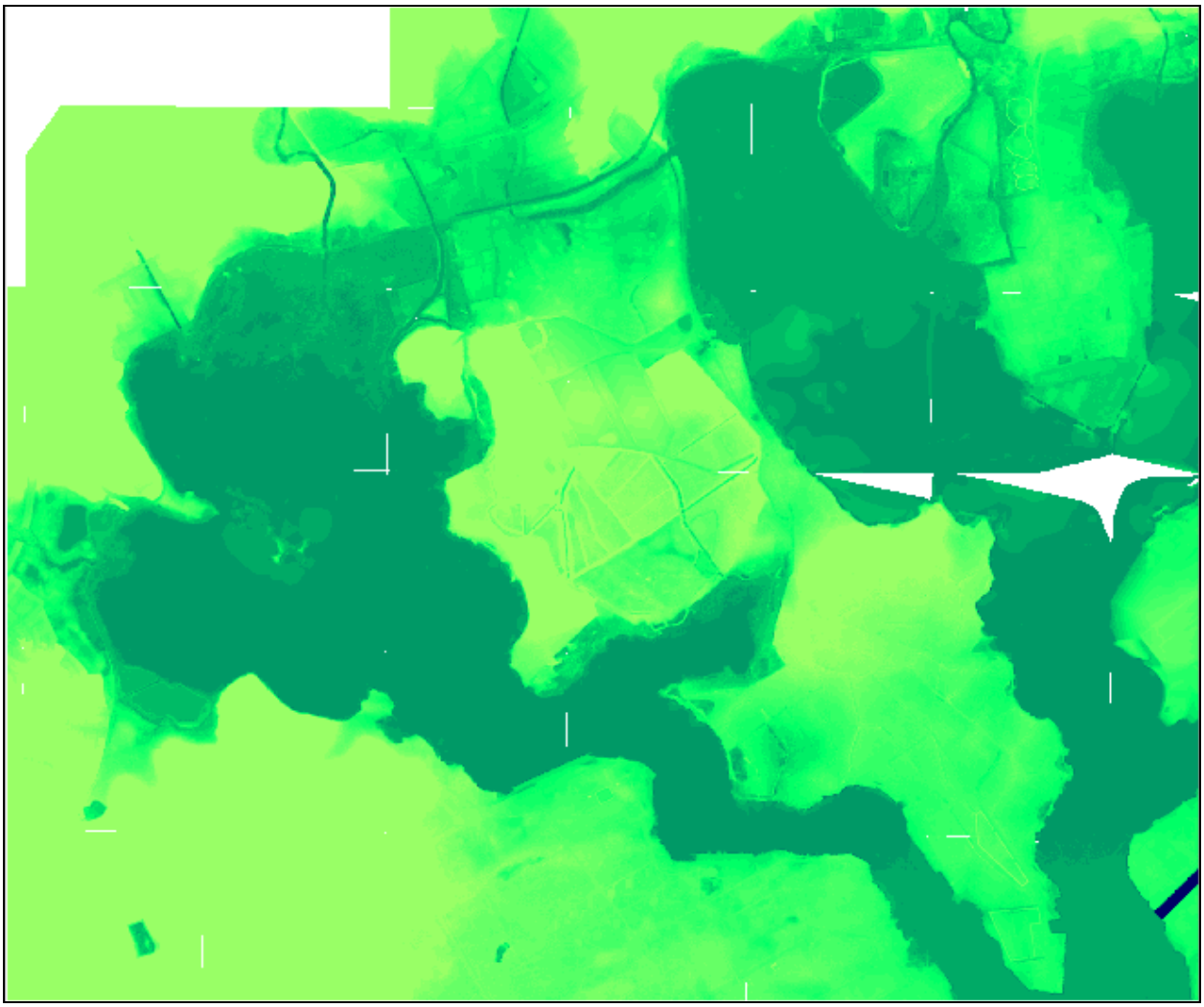


Figure 2: Elevation map of Waiawa and Honouliuli Units as produced by SLAMM. (Lower elevations are darker.)

The wetlands layer for the study area was produced by the National Wetlands Inventory and is based on a 2005 photo date. Converting the NWI survey into 5 meter cells indicates that the approximately one hundred acre refuge (approved acquisition boundary including water) is composed of primarily the following categories:

Undeveloped Dry Land	55.9%
Estuarine Open Water	17.2%
Inland Fresh Marsh	12.3%
Saltmarsh	4.8%
Inland Open Water	4.3%
Mangrove	2.7%
Tidal Flat	2.0%

Pearl Harbor Refuge does not have any impounded areas, according to the National Wetland Inventory.

The historic trend for sea level rise was estimated at 1.5 mm/year using the nearest NOAA gage with SLR data (1612340, Honolulu, HI). This rate is similar to the global average for the last 100 years (approximately 1.7 mm/year).

The tide range was estimated at 0.587 meters (great diurnal range or GT) using the average of the two closest NOAA tide gages (1612404, Ford Island, Ferry Dock, Pearl Harbor, HI; 1612366, Fort Kamehameha, Bishop Point, Pearl Harbor, HI).

Studies of vertical accretion or erosion of marshes within Hawaii were not available. This model application, therefore, utilized default parameter values. This assumption will only have minimal effects on model results, however, as there are few locations with salt marshes identified in the initial land coverage. Those areas are sheltered enough to preclude any SLAMM predictions of erosion, (which are calculated as a function of wave fetch).

No MTL to NAVD correction was required for this simulation because the vertical datum of the elevation data was not NAVD88 but Mean Sea Level. (SLAMM requires that elevation data be expressed in a tidal basis.)

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 5 meter by 5 meter cells. Note that the SLAMM model will also track partial conversion of cells based on elevation and slope.

The biologist for the USFWS Hawaii, Mike Silbernagle, indicated that some changes need to be made to the mangrove coverage in the NWI layer. At the Waiawa Unit, Mr. Silbernagle noted that mangrove had since been removed and is now mud flat. This recommendation was further confirmed with a satellite photo inspection of the unit, and the mangrove was converted to tidal flat following the explanation. At the Honouliuli Unit he noted that mangrove have expanded further into water than depicted in the NWI layer. Satellite imagery appeared to match the simulation NWI layer well, however. Lacking an updated shoreline, this NWI layer was not adjusted.

SUMMARY OF SLAMM INPUT PARAMETERS FOR PEARL HARBOR NWR

Parameter	Global	SubSite 1	SubSite 2	SubSite 3
Description	Pearl Harbor	Honouliuili	Waiawa	Kalaeloa
NWI Photo Date (YYYY)	2005	2005	2005	2005
DEM Date (YYYY)	2005	2005	2005	2005
Direction Offshore [n,s,e,w]	South	North	West	South
Historic Trend (mm/yr)	1.5	1.5	1.5	1.5
MTL-NAVD88 (m)	0	0	0	0
GT Great Diurnal Tide Range (m)	0.587	0.587	0.587	0.587
Salt Elev. (m above MTL)	0.504	0.504	0.504	0.504
Marsh Erosion (horz. m /yr)	1.8	1.8	1.8	1.8
Swamp Erosion (horz. m /yr)	1	1	1	1
T.Flat Erosion (horz. m /yr)	2	2	2	2
Reg. Flood Marsh Accr (mm/yr)	3.9	3.9	3.9	3.9
Irreg. Flood Marsh Accr (mm/yr)	4.7	4.7	4.7	4.7
Tidal Fresh Marsh Accr (mm/yr)	5.9	5.9	5.9	5.9
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	FALSE	FALSE	FALSE

Results

The SLAMM simulation of Pearl Harbor NWR predicts refuge to lose between 8% and 50% of its initial dry land – which comprises roughly more than half of the refuge. Nearly all of the refuge inland fresh marsh is predicted to be lost by the 0.69 meter SLR (sea level rise) scenario. Between 42% and 97% of refuge regularly flooded (salt) marsh is predicted to be lost across all SLR scenarios.

SLR by 2100 (m)	0.39	0.69	1	1.5	2
Undeveloped Dry Land	8%	13%	20%	35%	50%
Inland Fresh Marsh	0%	0%	92%	99%	100%
Saltmarsh	0%	27%	70%	92%	96%
Tidal Flat	7%	-31%	28%	69%	88%

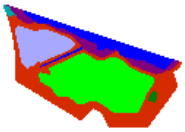
Predicted Loss Rates of Land Categories by 2100 Given Simulated Scenarios of Eustatic Sea Level Rise

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

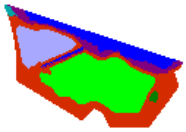
Pearl Harbor Raster
IPCC Scenario A1B-Mean, 0.39 M SLR Eustatic by 2100

Results in Acres

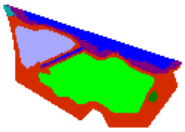
	Initial	2025	2050	2075	2100
Undev. Dry Land	57.2	54.6	54.2	53.4	52.7
Estuarine Open Water	17.6	18.0	18.1	21.1	22.1
Inland Fresh Marsh	12.6	12.6	12.6	12.6	12.6
Saltmarsh	4.9	4.9	4.9	4.9	4.9
Inland Open Water	4.4	4.4	4.4	1.4	0.5
Mangrove	2.7	4.7	5.1	5.9	6.6
Tidal Flat	2.1	2.1	2.1	2.0	1.9
Open Ocean	0.3	0.3	0.3	0.3	0.4
Swamp	0.2	0.2	0.2	0.2	0.2
Rocky Intertidal	0.2	0.2	0.2	0.2	0.2
Trans. Salt Marsh	0.0	0.0	0.0	0.0	0.0
Ocean Beach	0.0	0.2	0.2	0.2	0.1
Total (incl. water)	**102.3**	**102.3**	**102.3**	**102.3**	**102.3**



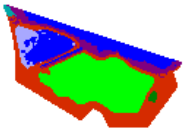
Pearl Harbor NWR, Initial Condition, Honouliuli (left) and Waiawa Units



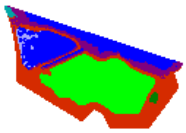
Pearl Harbor NWR, 2025, Scenario A1B Mean, Honouliuli (left) and Waiawa Units



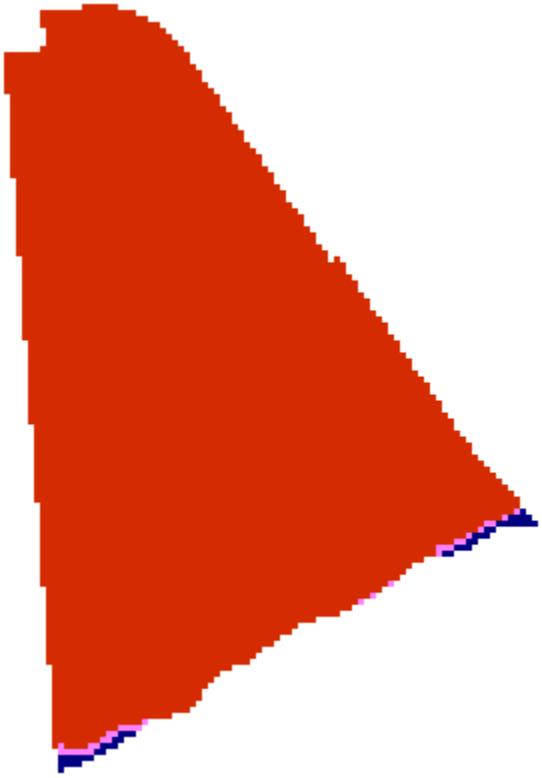
Pearl Harbor NWR, 2050, Scenario A1B Mean, Honouliuli (left) and Waiawa Units



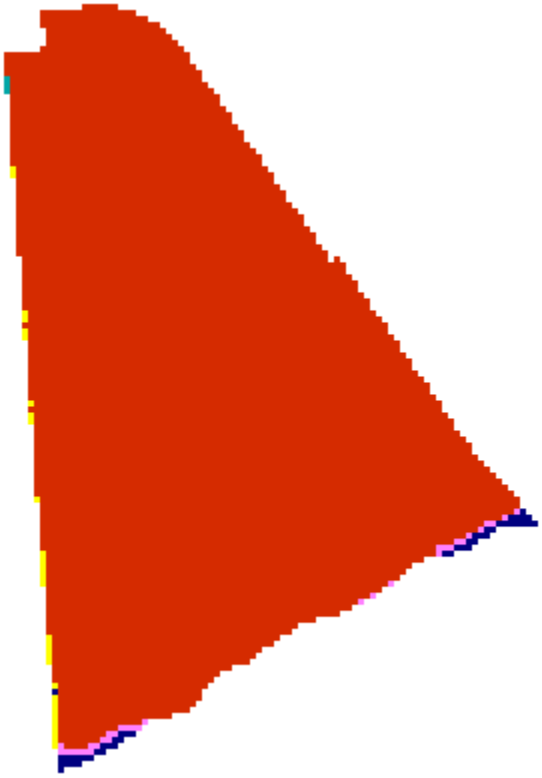
Pearl Harbor NWR, 2075, Scenario A1B Mean, Honouliuli (left) and Waiawa Units



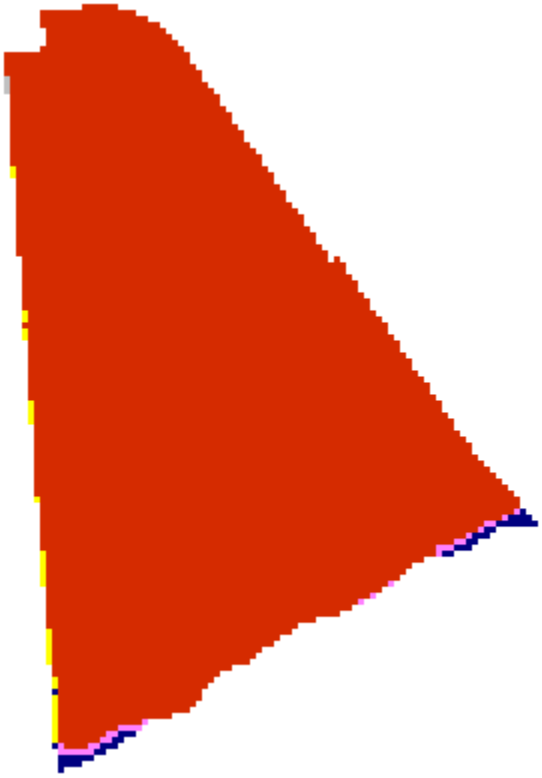
Pearl Harbor NWR, 2100, Scenario A1B Mean, Honouliuli (left) and Waiawa Units



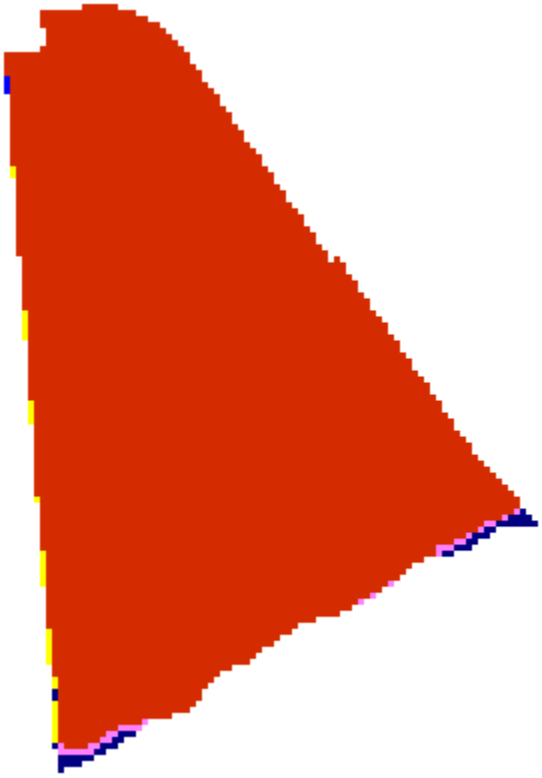
Pearl Harbor NWR, Initial Condition, Kalaeloa Unit



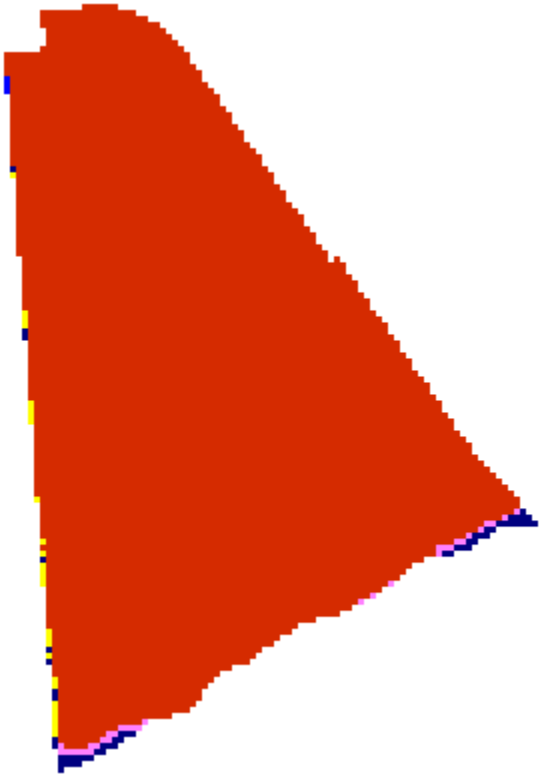
Pearl Harbor NWR, 2025, Scenario A1B Mean, Kalaeloa Unit



Pearl Harbor NWR, 2050, Scenario A1B Mean, Kalaeloa Unit



Pearl Harbor NWR, 2075, Scenario A1B Mean, Kalaeloa Unit

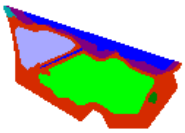


Pearl Harbor NWR, 2100, Scenario A1B Mean, Kalaeloa Unit

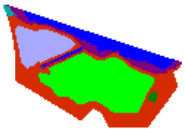
Pearl Harbor Raster
IPCC Scenario A1B-Max, 0.69 M SLR Eustatic by 2100

Results in Acres

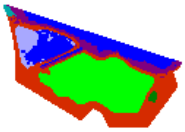
	Initial	2025	2050	2075	2100
Undev. Dry Land	57.2	54.5	53.5	52.1	49.6
Estuarine Open Water	17.6	18.0	20.8	22.5	23.1
Inland Fresh Marsh	12.6	12.6	12.6	12.6	12.6
Saltmarsh	4.9	4.9	4.9	4.5	3.6
Inland Open Water	4.4	4.4	1.7	0.2	0.1
Mangrove	2.7	4.8	5.8	7.2	9.6
Tidal Flat	2.1	2.1	2.1	2.2	2.7
Open Ocean	0.3	0.3	0.3	0.4	0.4
Swamp	0.2	0.2	0.2	0.2	0.2
Rocky Intertidal	0.2	0.2	0.2	0.2	0.2
Trans. Salt Marsh	0.0	0.0	0.0	0.0	0.0
Ocean Beach	0.0	0.2	0.2	0.1	0.1
Total (incl. water)	**102.3**	**102.3**	**102.3**	**102.3**	**102.3**



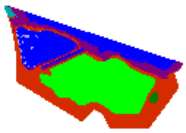
Pearl Harbor NWR, Initial Condition, Honouliuli (left) and Waiawa Units



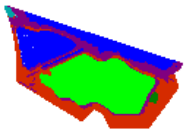
Pearl Harbor NWR, 2025, Scenario A1B Maximum, Honouliuli (left) and Waiawa Units



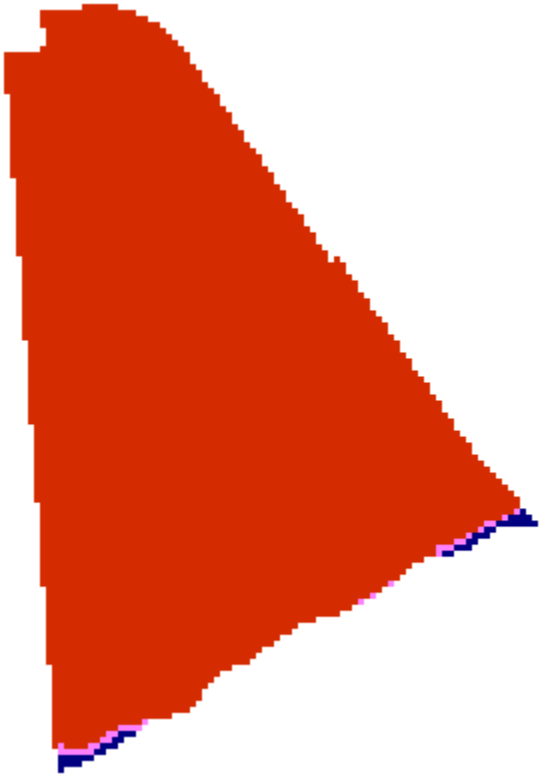
Pearl Harbor NWR, 2050, Scenario A1B Maximum, Honouliuli (left) and Waiawa Units



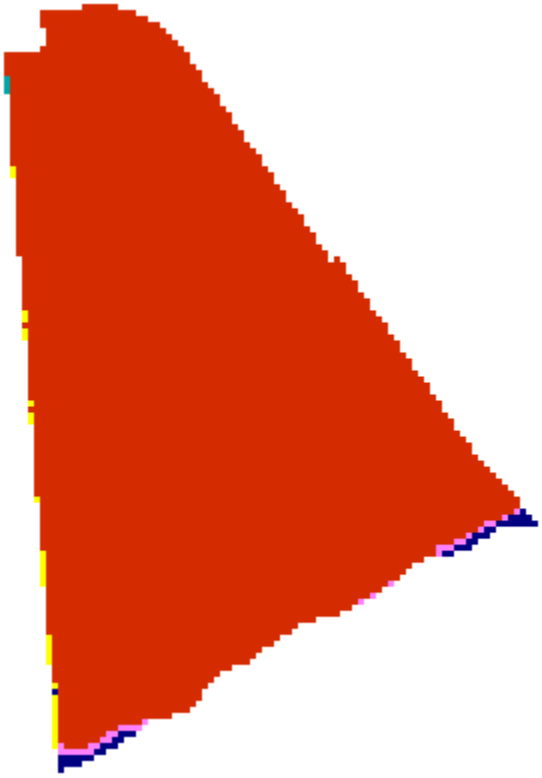
Pearl Harbor NWR, 2075, Scenario A1B Maximum, Honouliuli (left) and Waiawa Units



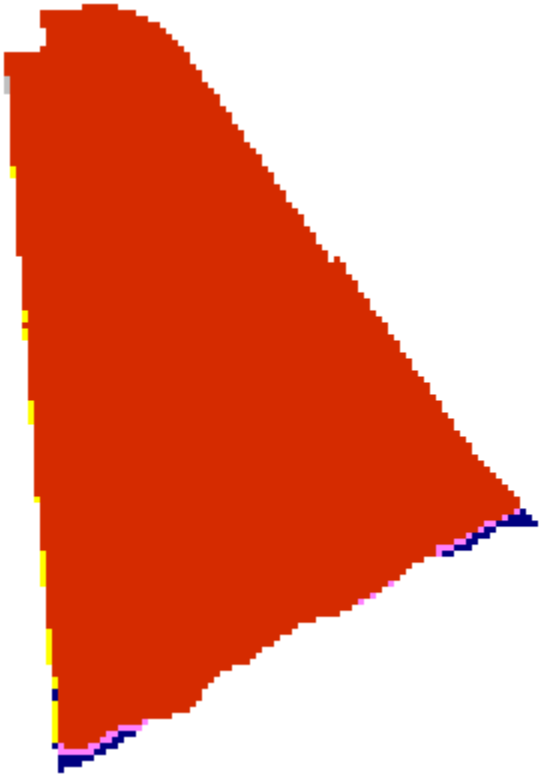
Pearl Harbor NWR, 2100, Scenario A1B Maximum, Honouliuli (left) and Waiawa Units



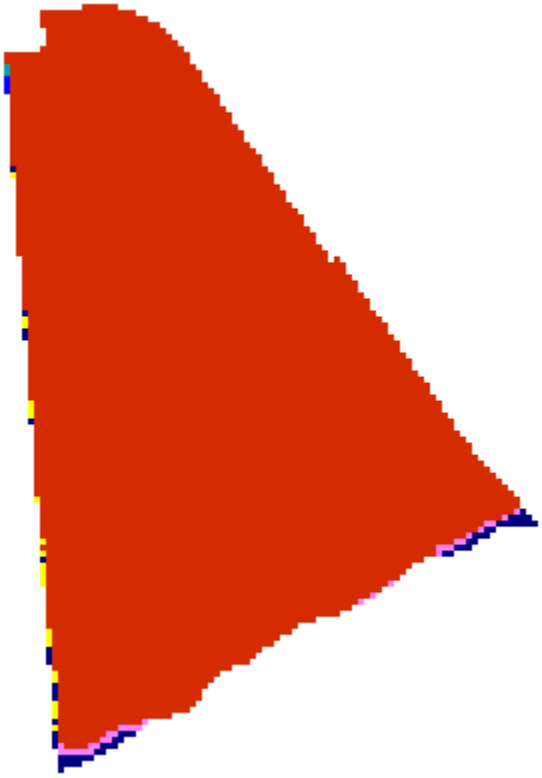
Pearl Harbor NWR, Initial Condition, Kalaeloa Unit



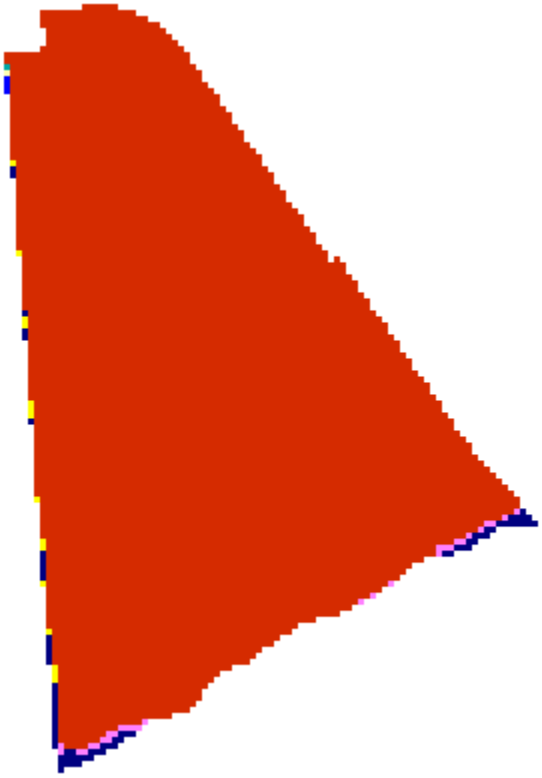
Pearl Harbor NWR, 2025, Scenario A1B Maximum, Kalaeloa Unit



Pearl Harbor NWR, 2050, Scenario A1B Maximum, Kalaeloa Unit



Pearl Harbor NWR, 2075, Scenario A1B Maximum, Kalaeloa Unit

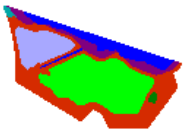


Pearl Harbor NWR, 2100, Scenario A1B Maximum, Kalaeloa Unit

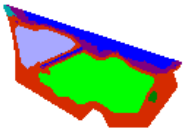
Pearl Harbor Raster
1 Meter Eustatic SLR by 2100

Results in Acres

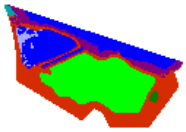
	Initial	2025	2050	2075	2100
Undev. Dry Land	57.2	54.3	52.8	49.9	45.9
Estuarine Open Water	17.6	18.1	22.1	23.7	28.1
Inland Fresh Marsh	12.6	12.6	12.6	12.4	1.0
Saltmarsh	4.9	4.9	4.5	2.9	1.5
Inland Open Water	4.4	4.4	0.6	0.1	0.0
Mangrove	2.7	5.0	6.4	8.9	23.4
Tidal Flat	2.1	2.1	2.3	3.4	1.5
Open Ocean	0.3	0.3	0.4	0.4	0.5
Swamp	0.2	0.2	0.2	0.2	0.1
Rocky Intertidal	0.2	0.2	0.2	0.2	0.2
Trans. Salt Marsh	0.0	0.0	0.0	0.0	0.0
Ocean Beach	0.0	0.2	0.1	0.1	0.1
Total (incl. water)	**102.3**	**102.3**	**102.3**	**102.3**	**102.3**



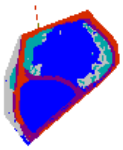
Pearl Harbor NWR, Initial Condition, Honouliuli (left) and Waiawa Units

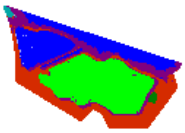


Pearl Harbor NWR, 2025, 1 meter, Honouliuli (left) and Waiawa Units

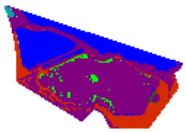


Pearl Harbor NWR, 2050, 1 meter, Honouliuli (left) and Waiawa Units

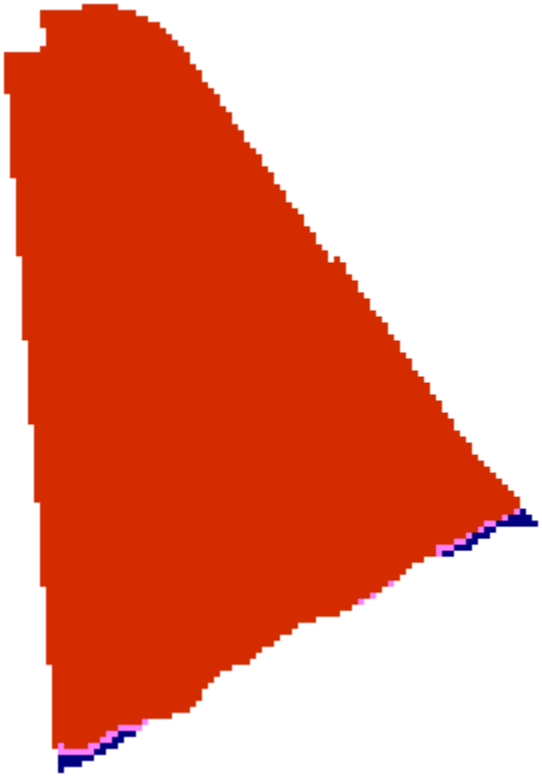




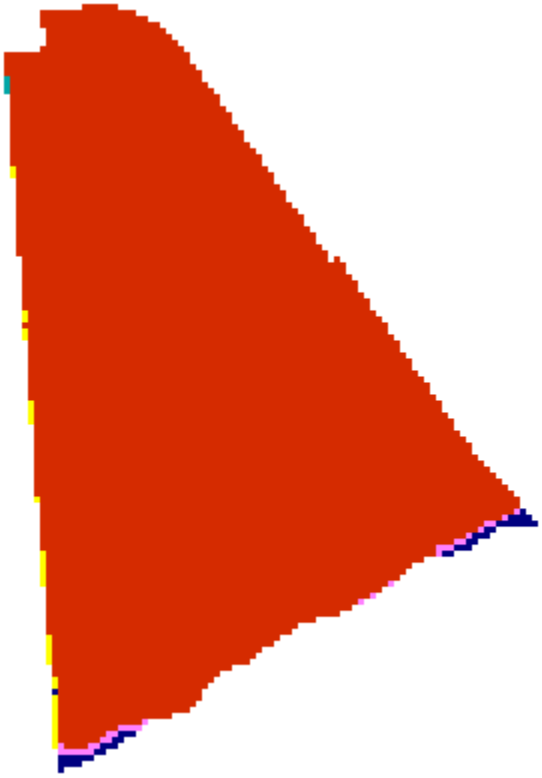
Pearl Harbor NWR, 2075, 1 meter, Honouliuli (left) and Waiawa Units



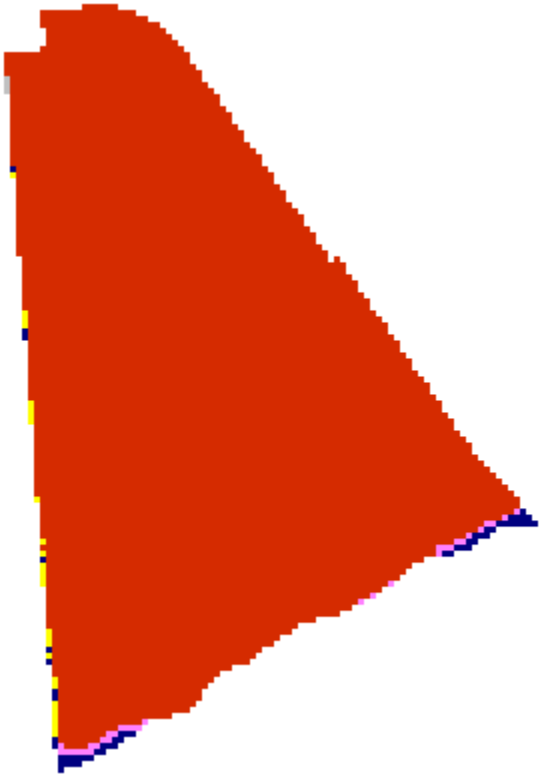
Pearl Harbor NWR, 2100, 1 meter, Honouliuli (left) and Waiawa Units



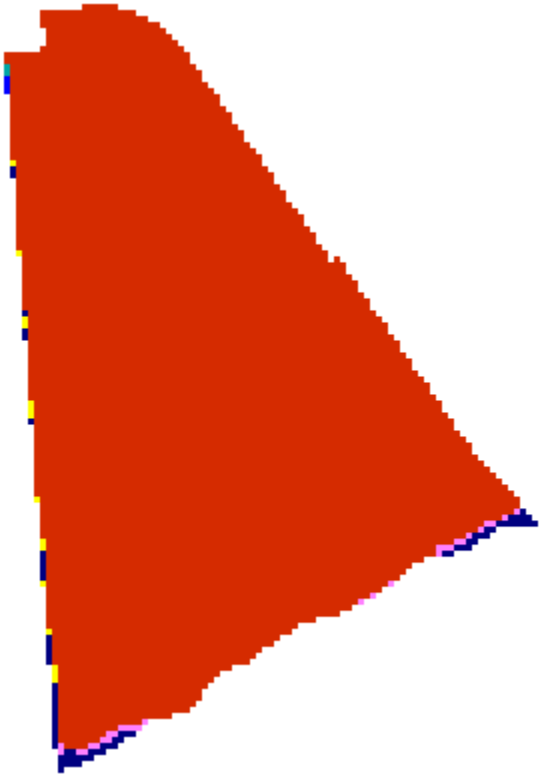
Pearl Harbor NWR, Initial Condition, Kalaeloa Unit



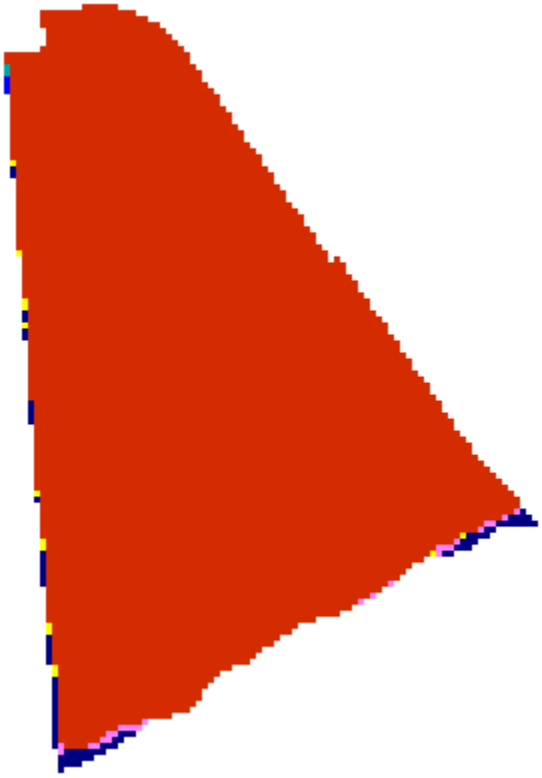
Pearl Harbor NWR, 2025, 1 meter, Kalaeloa Unit



Pearl Harbor NWR, 2050, 1 meter, Kalaeloa Unit



Pearl Harbor NWR, 2075, 1 meter, Kalaeloa Unit

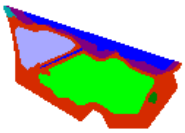


Pearl Harbor NWR, 2100, 1 meter, Kalaeloa Unit

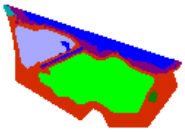
Pearl Harbor Raster
1.5 Meters Eustatic SLR by 2100

Results in Acres

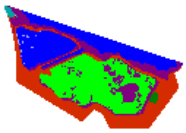
	Initial	2025	2050	2075	2100
Undev. Dry Land	57.2	54.0	50.8	45.7	37.3
Estuarine Open Water	17.6	18.3	23.8	30.2	47.8
Inland Fresh Marsh	12.6	12.6	10.3	0.3	0.1
Saltmarsh	4.9	4.8	3.1	1.0	0.4
Inland Open Water	4.4	4.3	0.1	0.0	0.0
Mangrove	2.7	5.2	9.8	22.1	11.5
Tidal Flat	2.1	2.1	3.5	2.1	0.6
Open Ocean	0.3	0.3	0.4	0.5	0.6
Swamp	0.2	0.2	0.2	0.1	0.0
Rocky Intertidal	0.2	0.2	0.2	0.2	0.1
Trans. Salt Marsh	0.0	0.0	0.0	0.0	0.0
Ocean Beach	0.0	0.2	0.1	0.1	3.8
Total (incl. water)	**102.3**	**102.3**	**102.3**	**102.3**	**102.3**



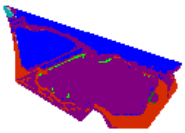
Pearl Harbor NWR, Initial Condition, Honouliuli (left) and Waiawa Units



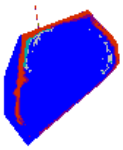
Pearl Harbor NWR, 2025, 1.5 meter, Honouliuli (left) and Waiawa Units

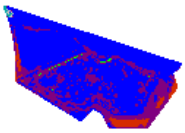


Pearl Harbor NWR, 2050, 1.5 meter, Honouliuli (left) and Waiawa Units

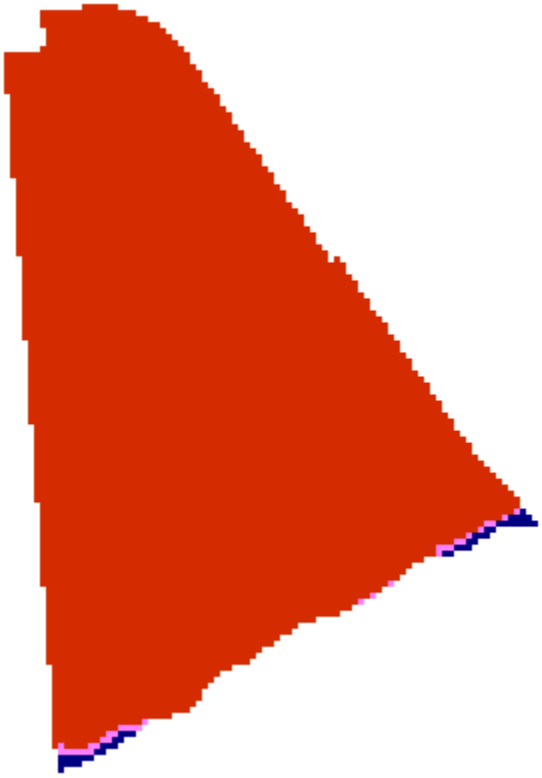


Pearl Harbor NWR, 2075, 1.5 meter, Honouliuli (left) and Waiawa Units

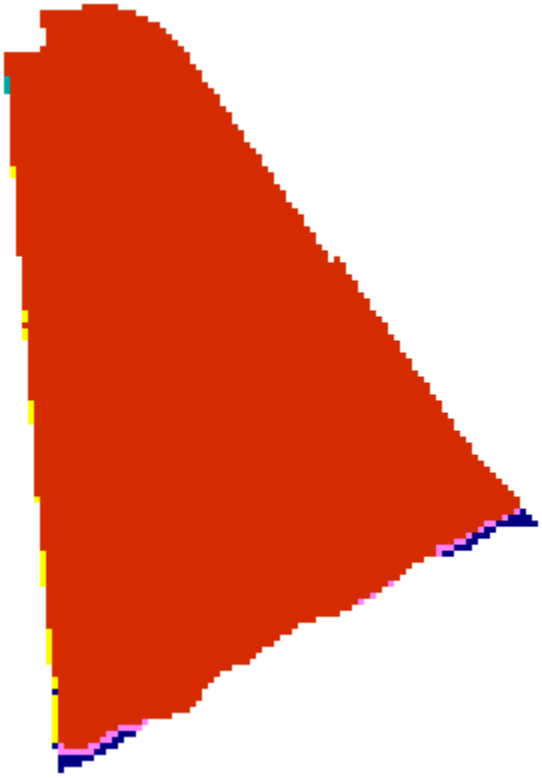




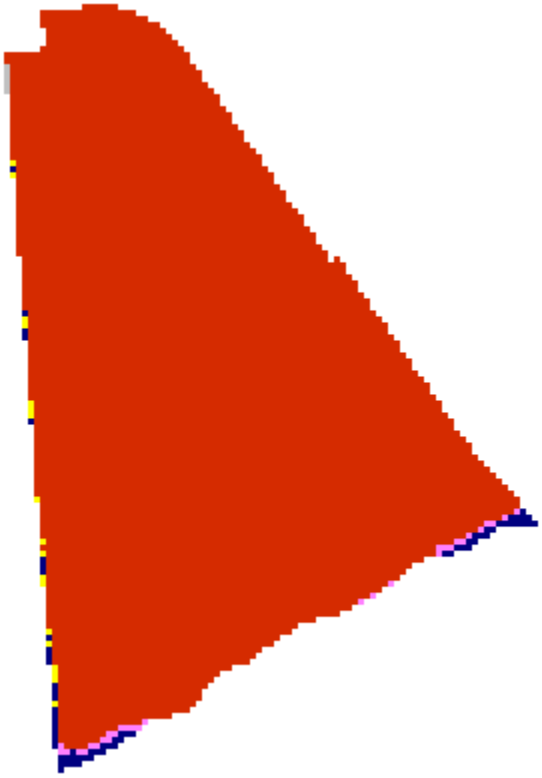
Pearl Harbor NWR, 2100, 1.5 meter, Honouliuli (left) and Waiawa Units



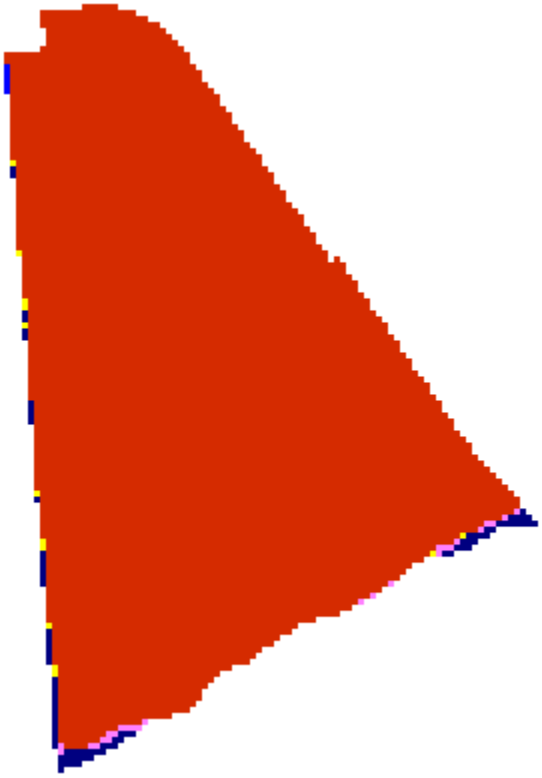
Pearl Harbor NWR, Initial Condition, Kalaeloa Unit



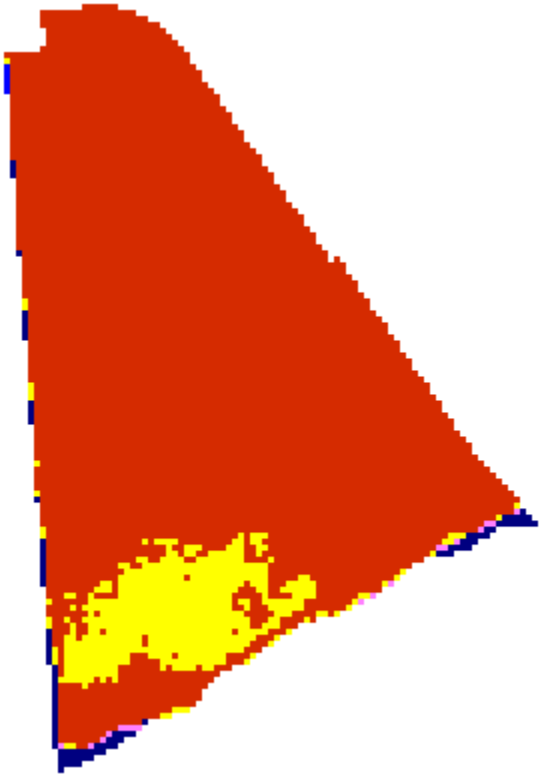
Pearl Harbor NWR, 2025, 1.5 meter, Kalaeloa Unit



Pearl Harbor NWR, 2050, 1.5 meter, Kalaeloa Unit



Pearl Harbor NWR, 2075, 1.5 meter, Kalaeloa Unit

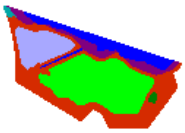


Pearl Harbor NWR, 2100, 1.5 meter, Kalaeloa Unit

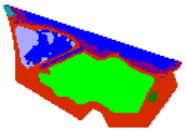
Pearl Harbor Raster
2 Meters Eustatic SLR by 2100

Results in Acres

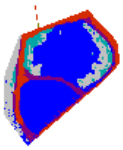
	Initial	2025	2050	2075	2100
Undev. Dry Land	57.2	53.6	48.6	39.5	28.8
Estuarine Open Water	17.6	20.9	25.4	46.6	58.0
Inland Fresh Marsh	12.6	12.6	0.6	0.1	0.0
Saltmarsh	4.9	4.6	1.9	0.4	0.2
Inland Open Water	4.4	2.0	0.1	0.0	0.0
Mangrove	2.7	5.4	20.4	10.9	3.6
Tidal Flat	2.1	2.3	4.3	1.5	0.3
Open Ocean	0.3	0.3	0.5	0.6	1.6
Swamp	0.2	0.2	0.2	0.0	0.0
Rocky Intertidal	0.2	0.2	0.2	0.1	0.1
Trans. Salt Marsh	0.0	0.0	0.0	0.0	0.0
Ocean Beach	0.0	0.2	0.1	2.5	9.9
Total (incl. water)	**102.3**	**102.3**	**102.3**	**102.3**	**102.3**

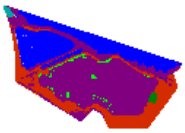


Pearl Harbor NWR, Initial Condition, Honouliuli (left) and Waiawa Units

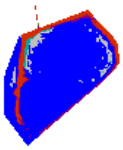


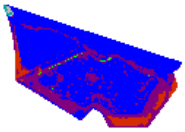
Pearl Harbor NWR, 2025, 2 meters, Honouliuli (left) and Waiawa Units





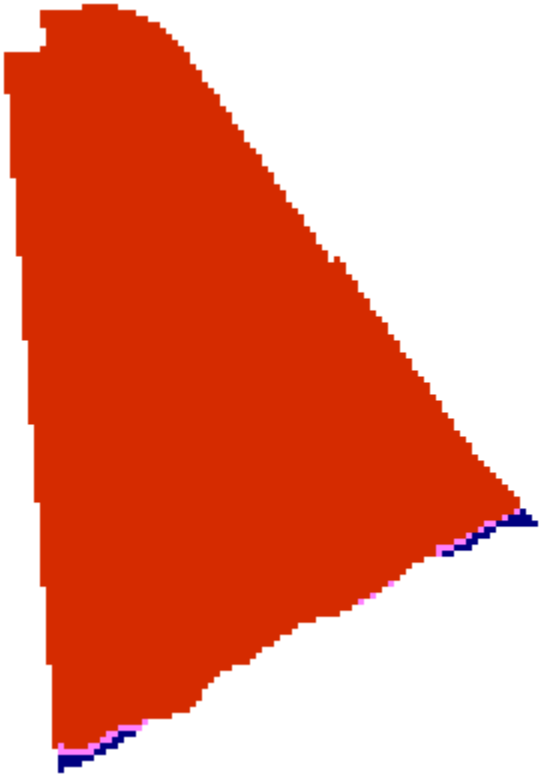
Pearl Harbor NWR, 2050, 2 meters, Honouliuli (left) and Waiawa Units



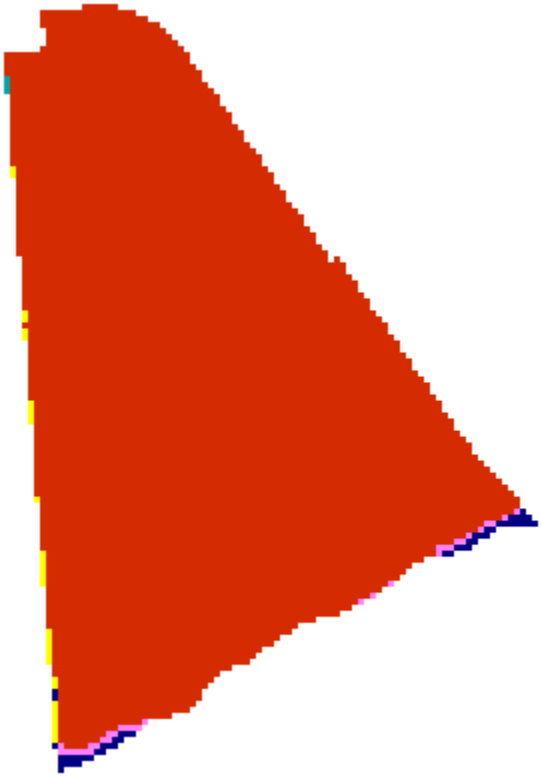


Pearl Harbor NWR, 2075, 2 meters, Honouliuli (left) and Waiawa Units

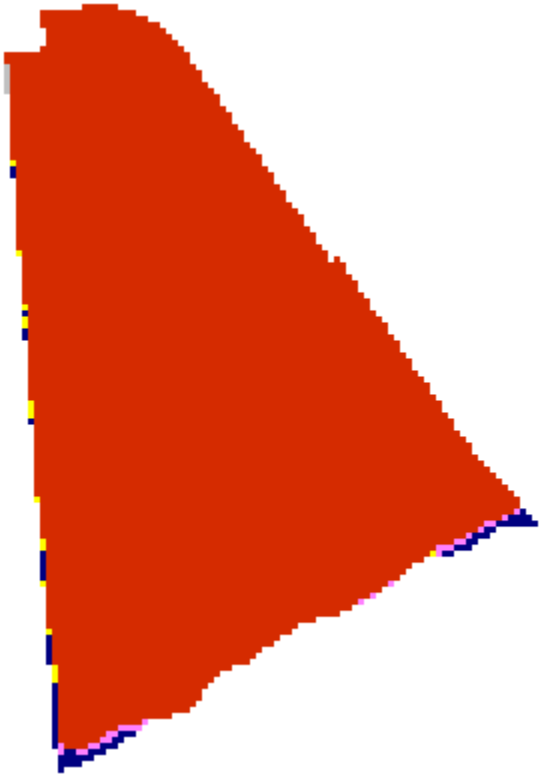
Pearl Harbor NWR, 2100, 2 meters, Honouliuli (left) and Waiawa Units



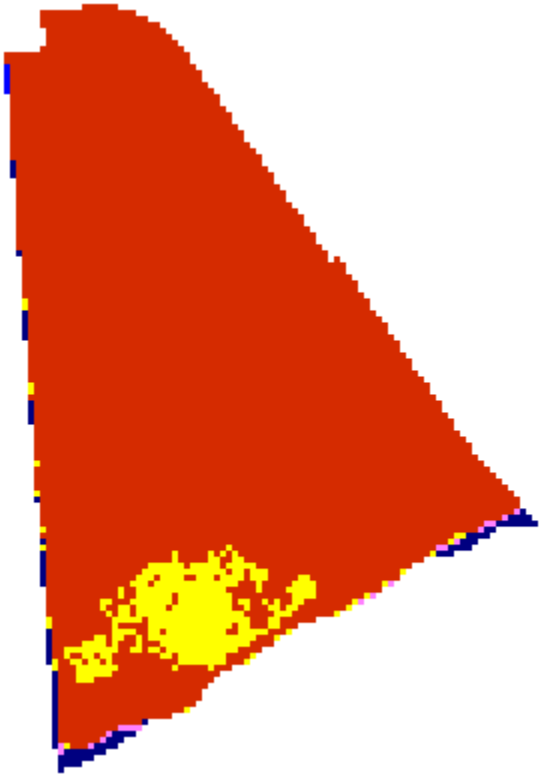
Pearl Harbor NWR, Initial Condition, Kalaeloa Unit



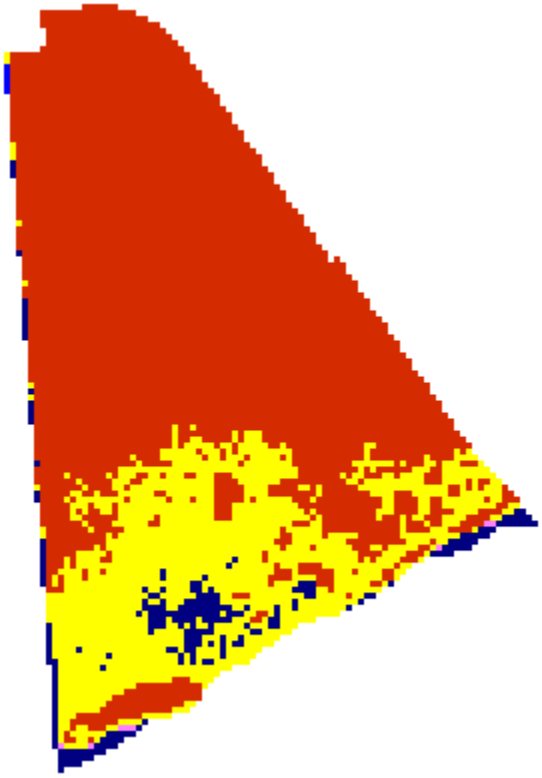
Pearl Harbor NWR, 2025, 2 meters, Kalaeloa Unit



Pearl Harbor NWR, 2050, 2 meters, Kalaeloa Unit



Pearl Harbor NWR, 2075, 2 meters, Kalaeloa Unit



Pearl Harbor NWR, 2100, 2 meters, Kalaeloa Unit

Discussion

Model predictions suggest that irregularly flooded marshes in the Waiawa unit will start to degrade in scenarios of over 0.69 meters eustatic SLR and be nearly completely eliminated in scenarios of over 1 meter of eustatic SLR.

Predictions for the Honouliuli unit suggest that inland fresh marsh will be subject to saline inundation and conversion to mangrove swamp under SLR scenarios of 1 meter eustatic SLR or greater.

Although the Kalaeloa Unit is more resilient to SLR effects than the rest of the refuge complex, in scenarios exceeding 1.5 meters of eustatic SLR, considerable low-lying coastal areas are predicted to convert to beach.

Due to high-vertical-resolution LiDAR coverage for this entire site, uncertainty about land elevations is considerably reduced. This, along with the five-meter cell resolution, assists in refining inundation predictions.

Saltmarsh accretion rates in the Waiwa unit are highly uncertain. No studies of wetland accretion in Hawaii were found within the scientific literature. Furthermore, there is always uncertainty about how regularly-flooded marsh will respond to the signal of increased sea level rise. For this reason, the exact timing and extent of saltmarsh loss in this unit is subject to additional uncertainty.

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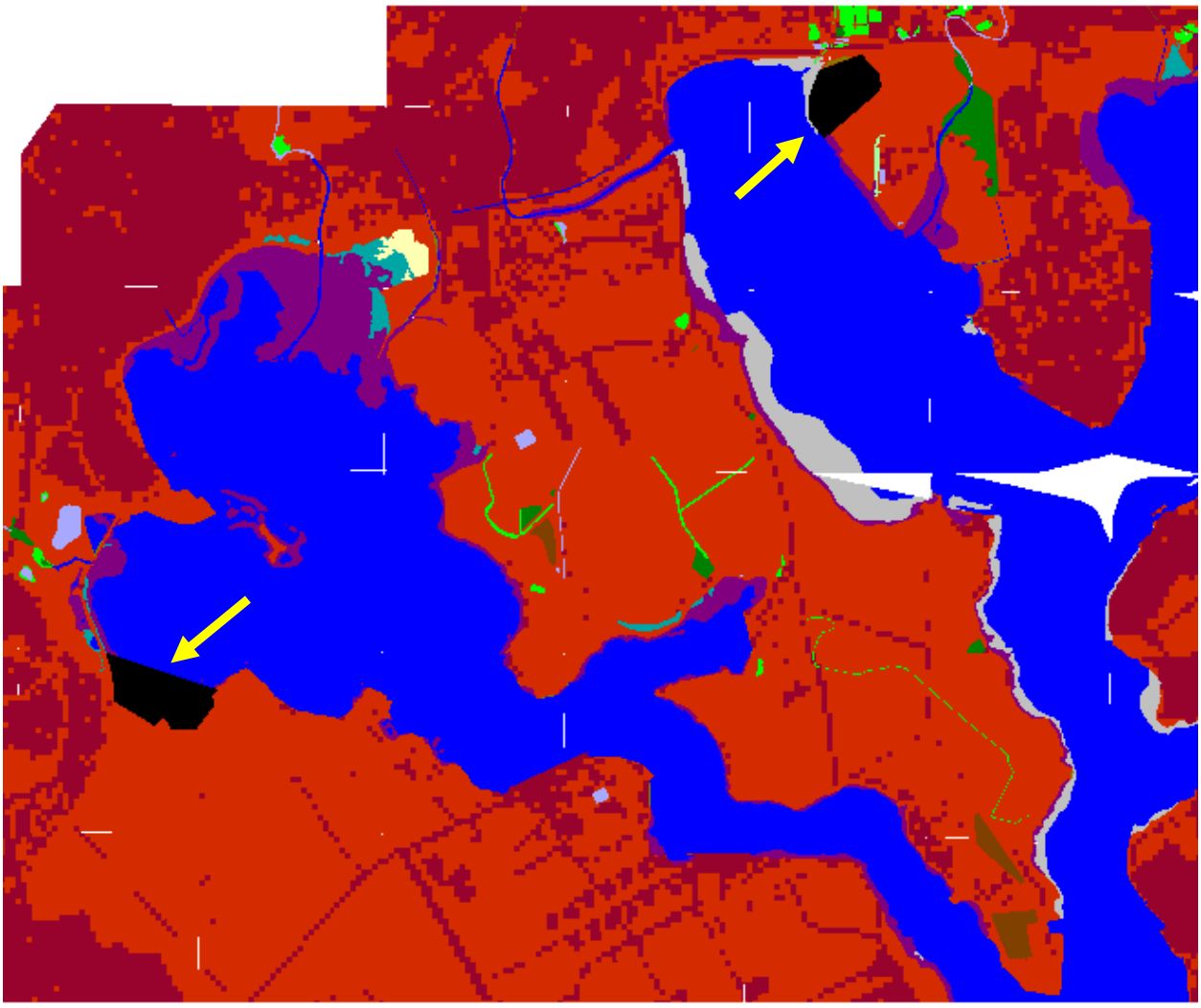
Appendix A: Contextual Results

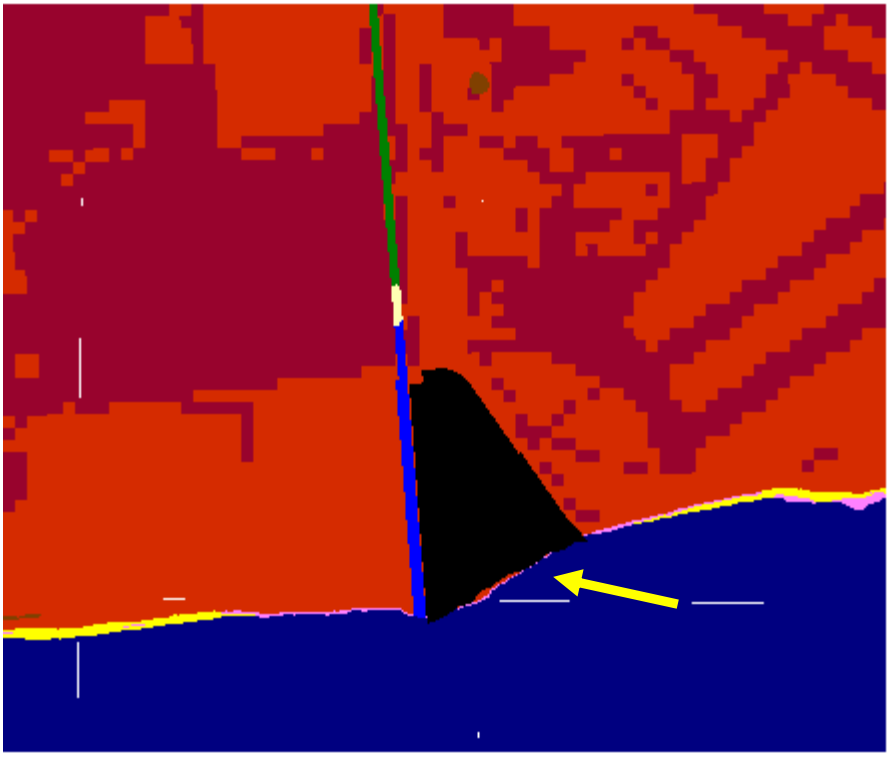
The SLAMM model does take into account the context of the surrounding lands or open water when calculating effects. For example, erosion rates are calculated based on the maximum fetch (wave action) which is estimated by assessing contiguous open water to a given marsh cell. Another example is that inundated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

For this reason, an area larger than the boundaries of the USFWS refuge was modeled. These results maps are presented here with the following caveats:

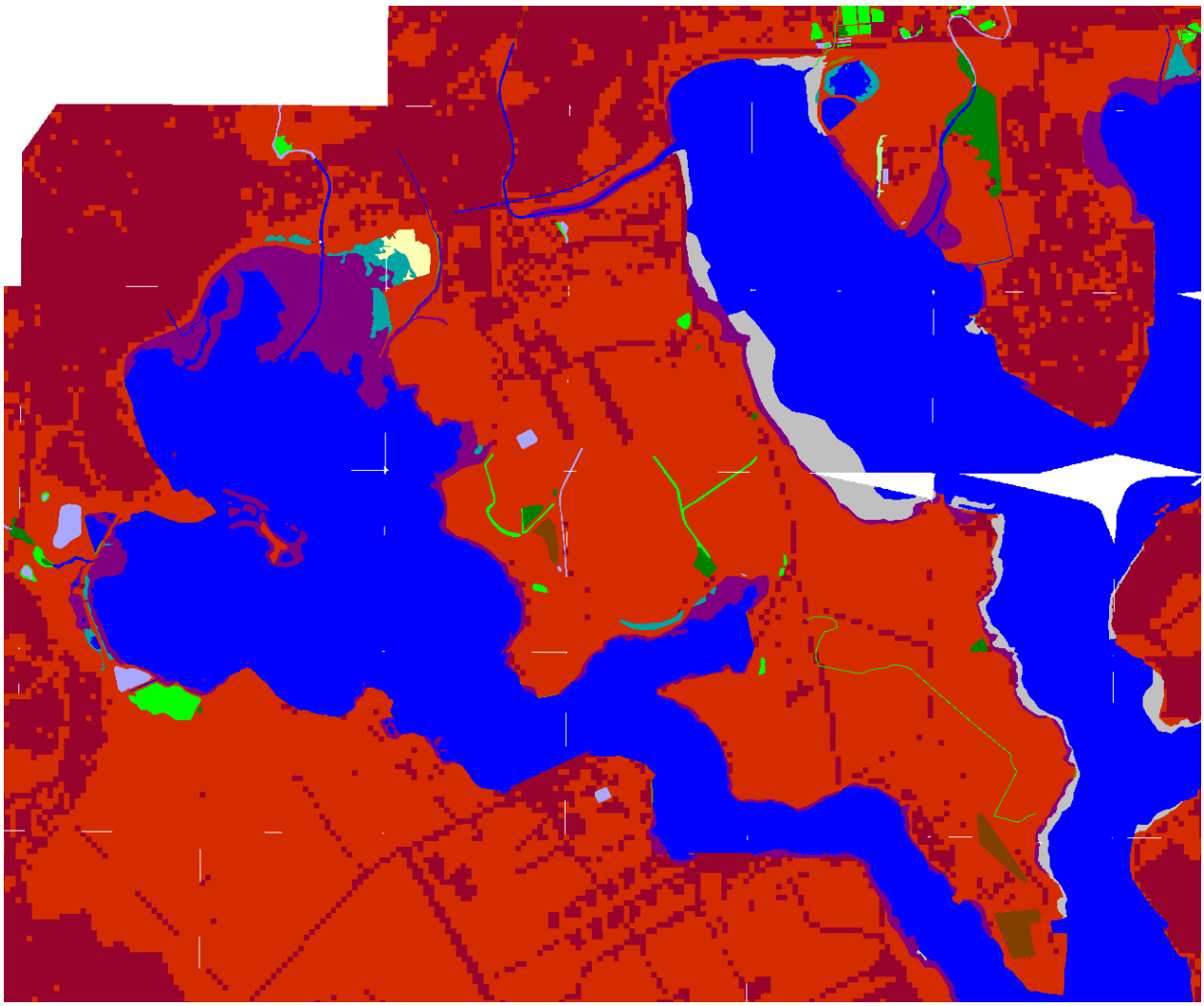
- Results were closely examined (quality assurance) within USFWS refuges but not closely examined for the larger region.
- Site-specific parameters for the model were derived for USFWS refuges whenever possible and may not be regionally applicable.
- Especially in areas where dikes are present, an effort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



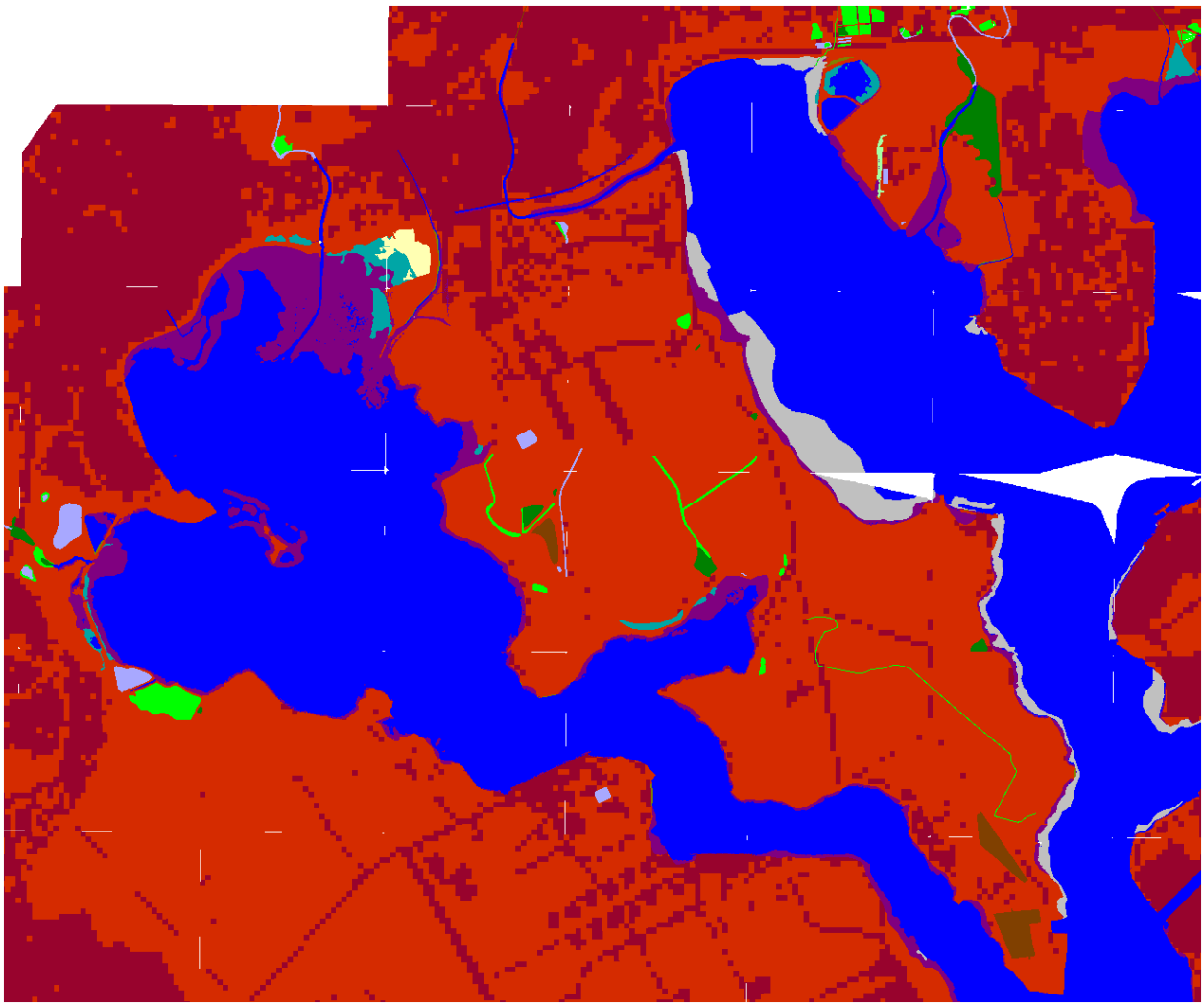
Location of Honouliuli and Waiawa Units of Pearl Harbor National Wildlife Refuge within simulation context (black).



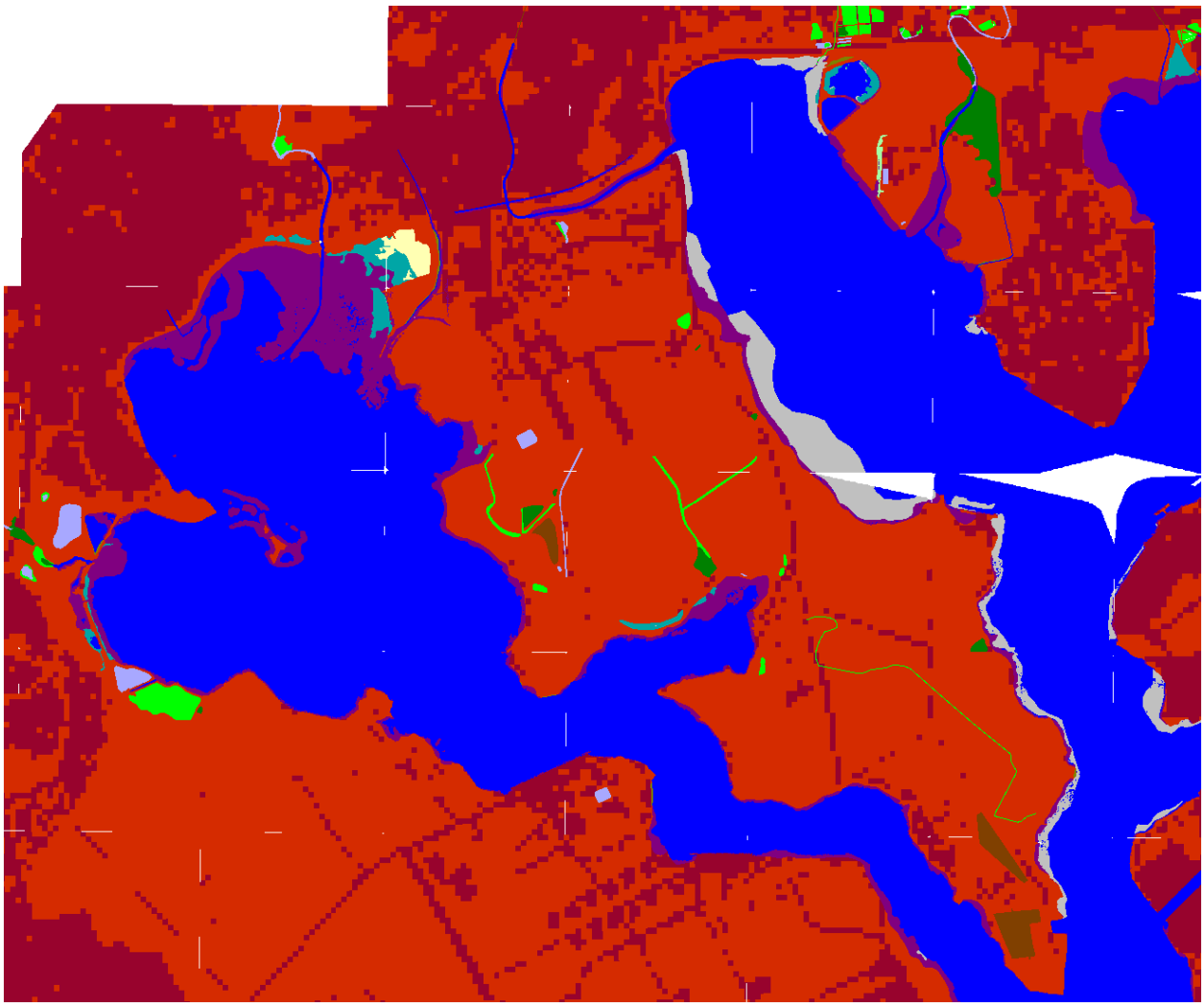
Location of Kalaeloa Unit of Pearl Harbor National Wildlife Refuge within simulation context (black).



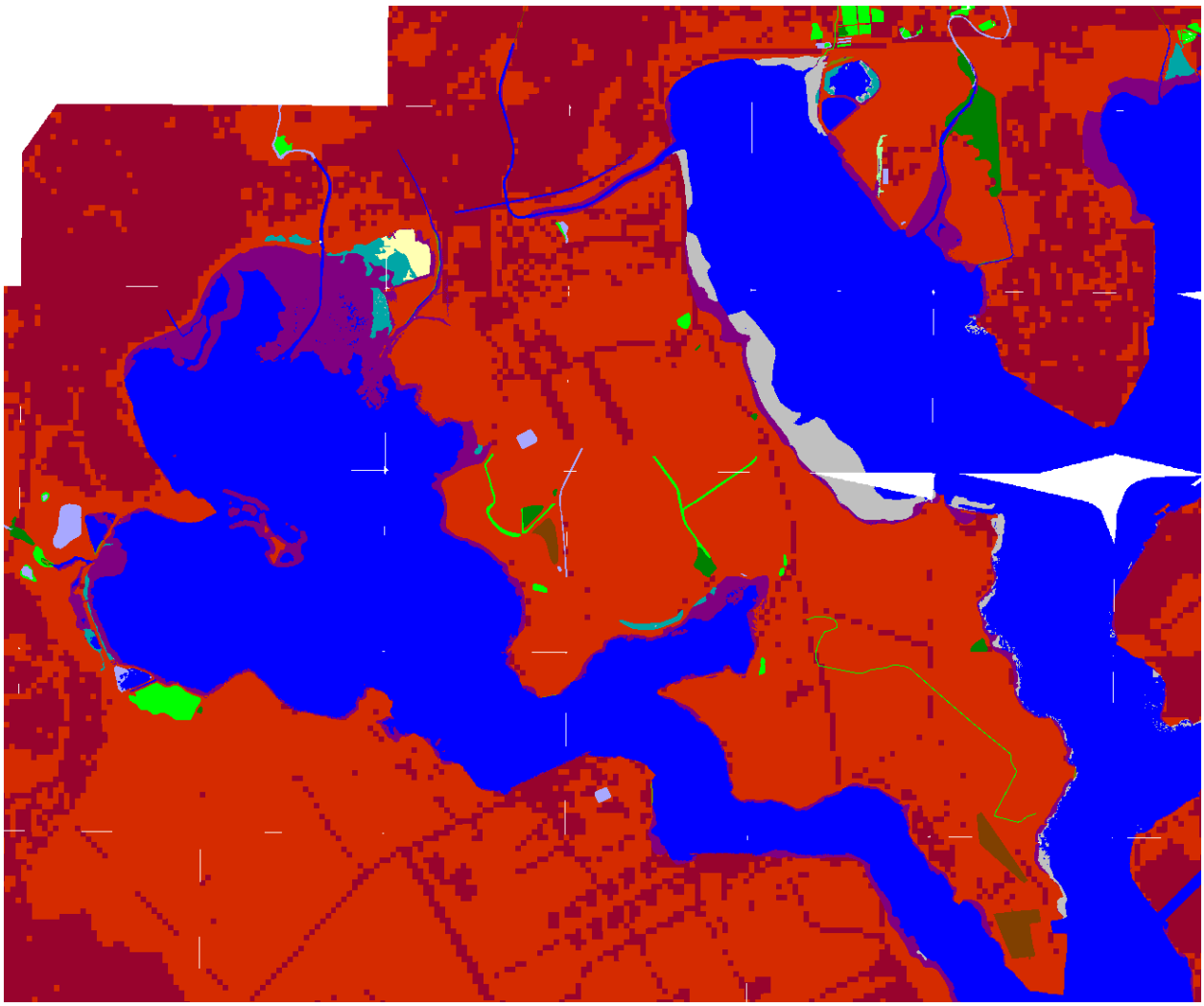
Pearl Harbor Context, Initial Condition



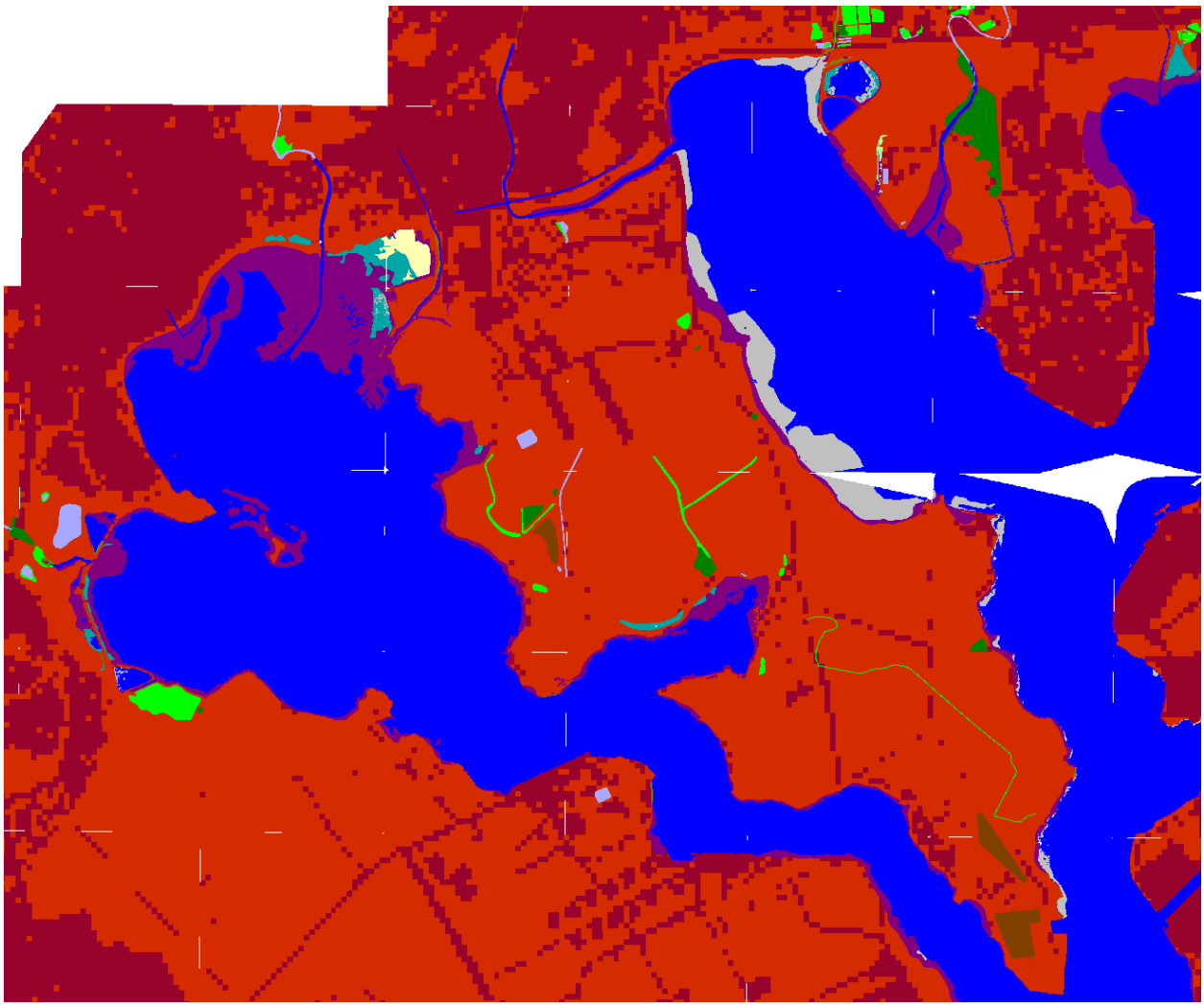
Pearl Harbor Context, 2025, Scenario A1B Mean



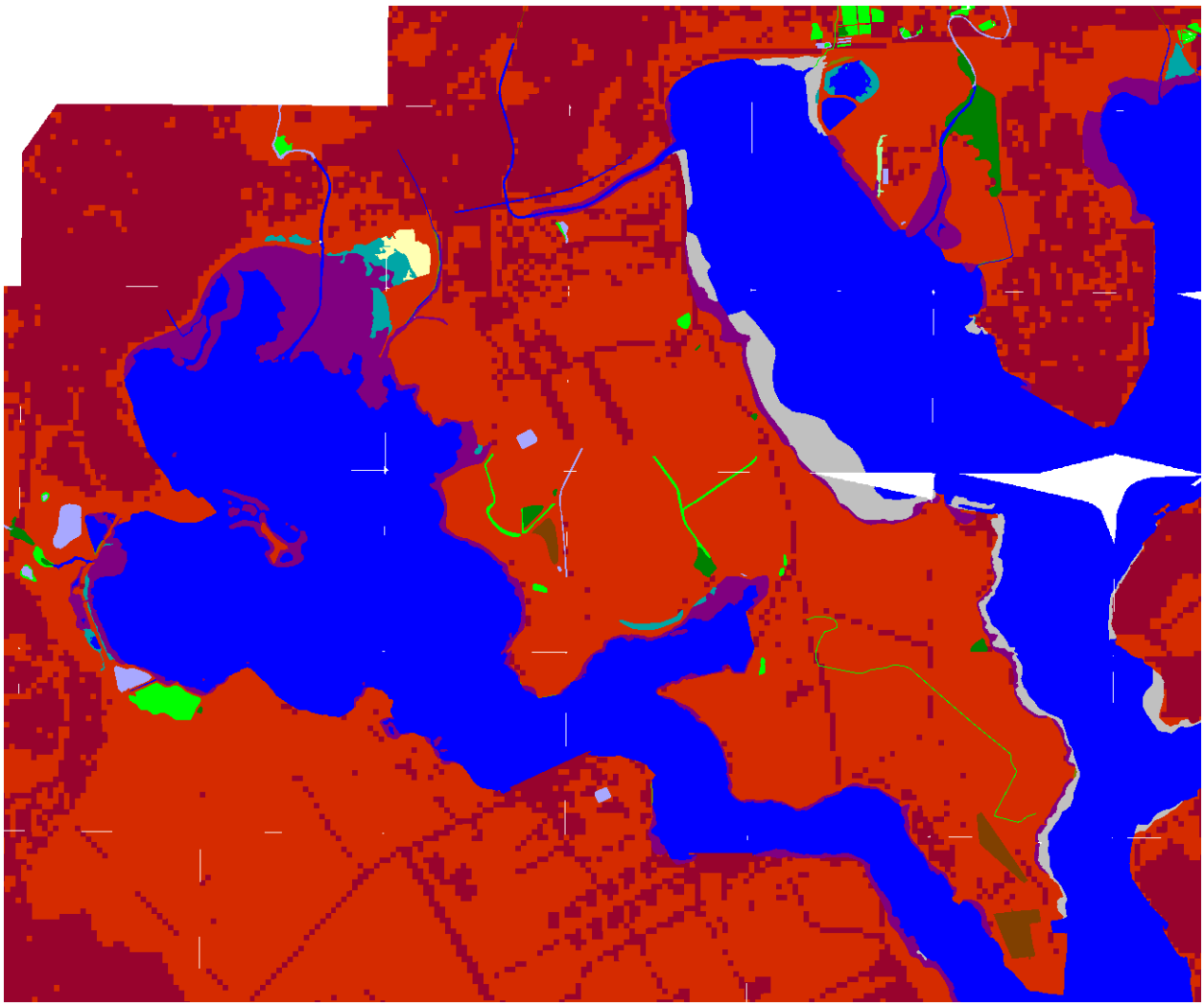
Pearl Harbor Context, 2050, Scenario A1B Mean



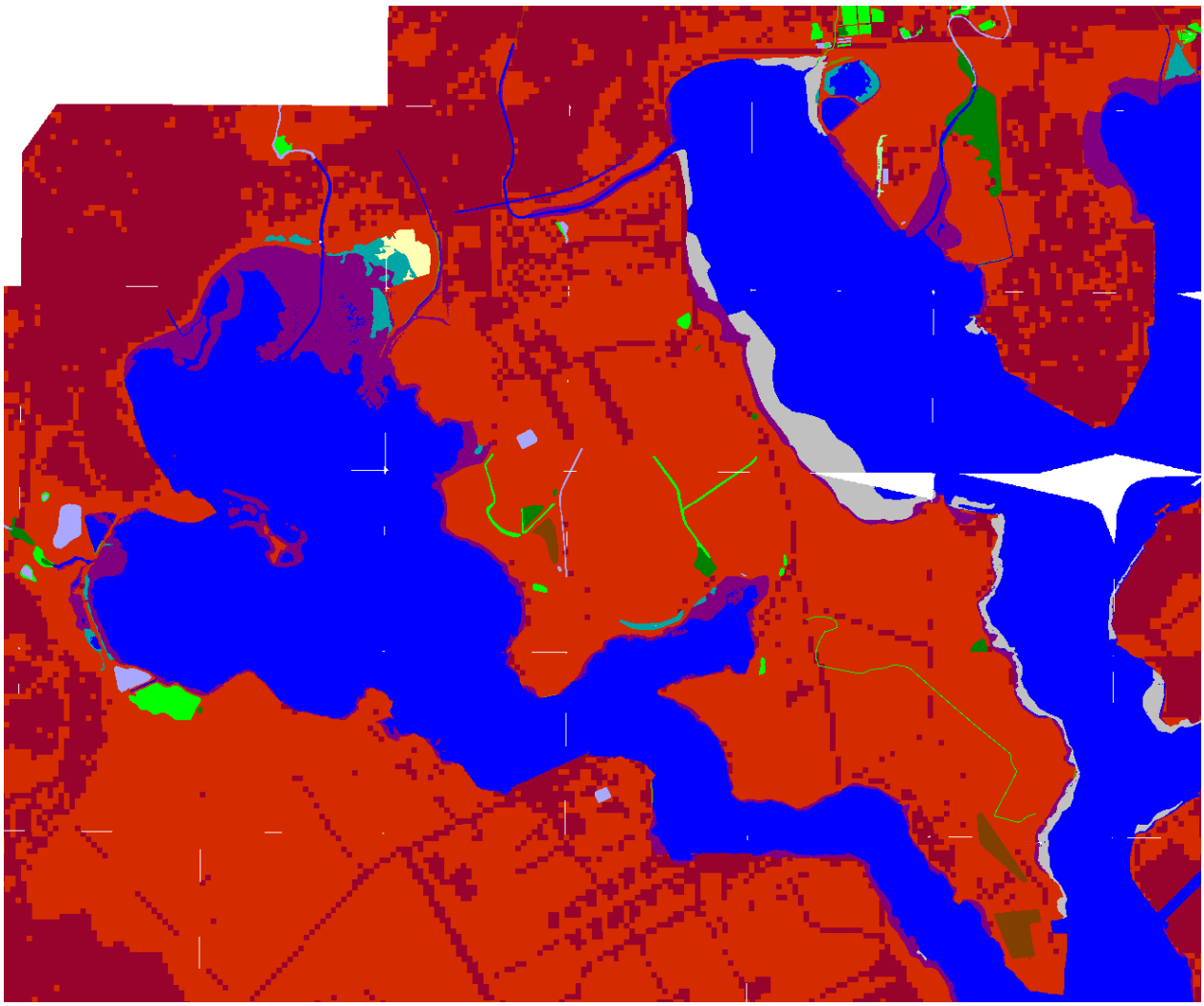
Pearl Harbor Context, 2075, Scenario A1B Mean



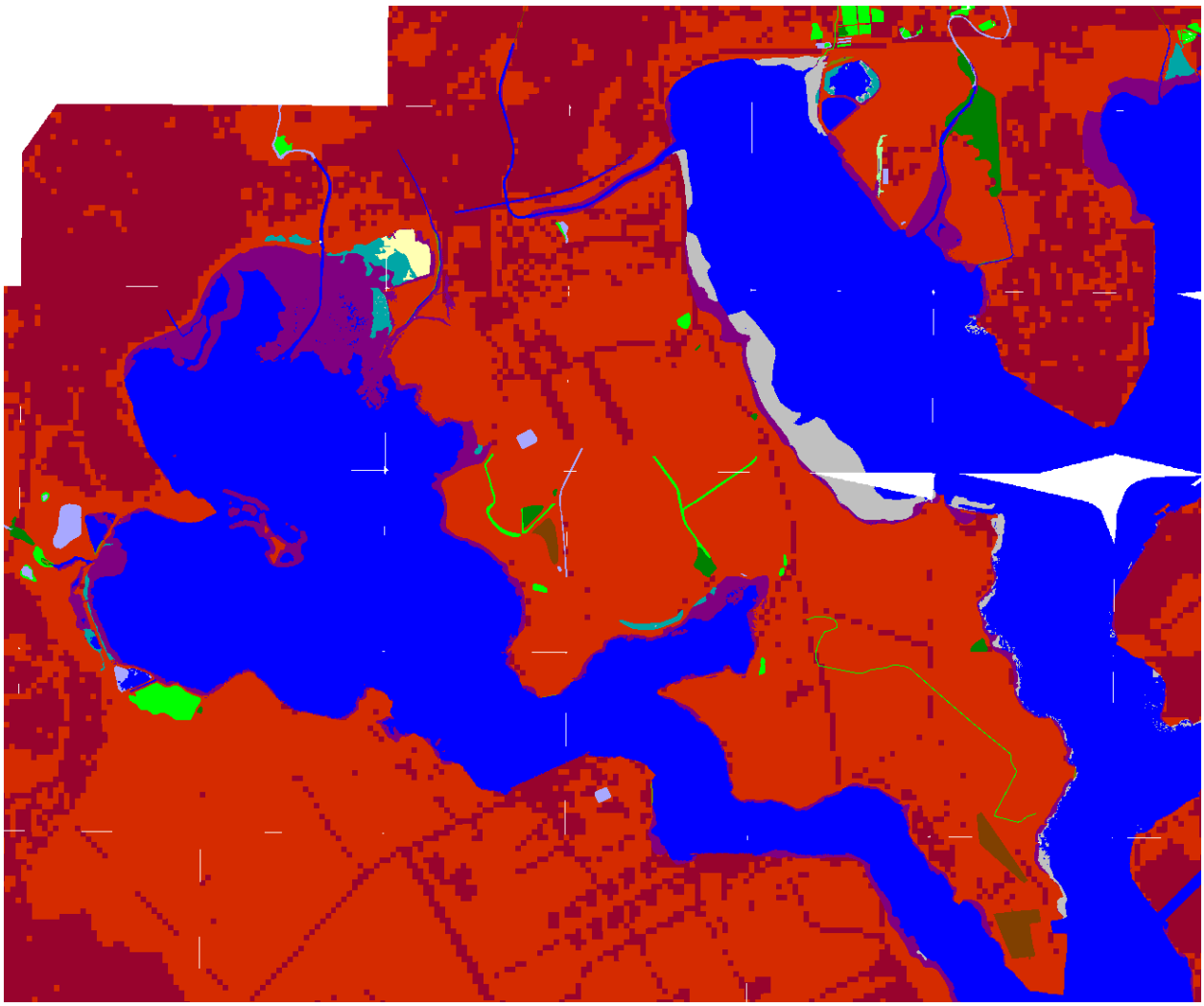
Pearl Harbor Context, 2100, Scenario A1B Mean



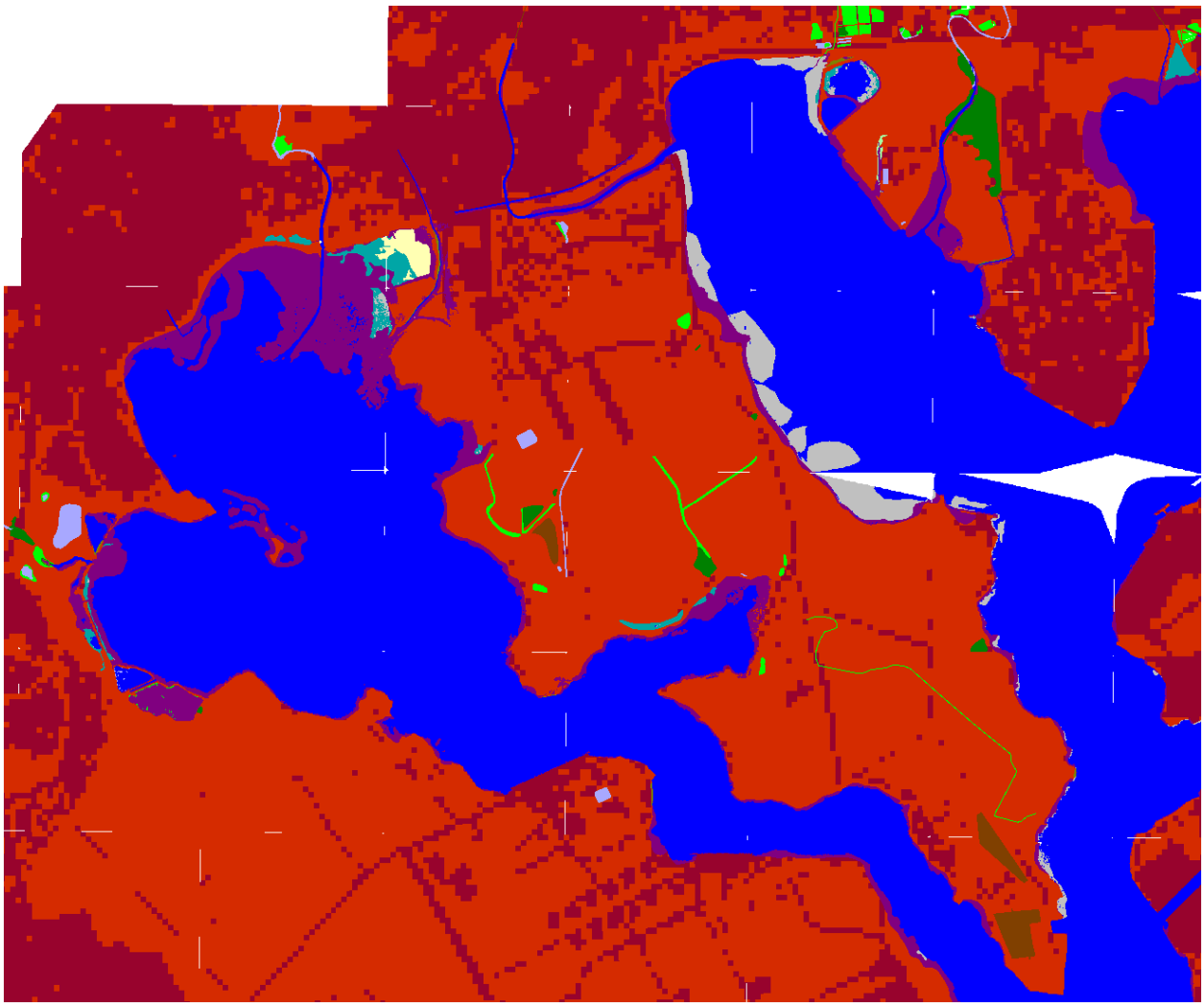
Pearl Harbor Context, Initial Condition



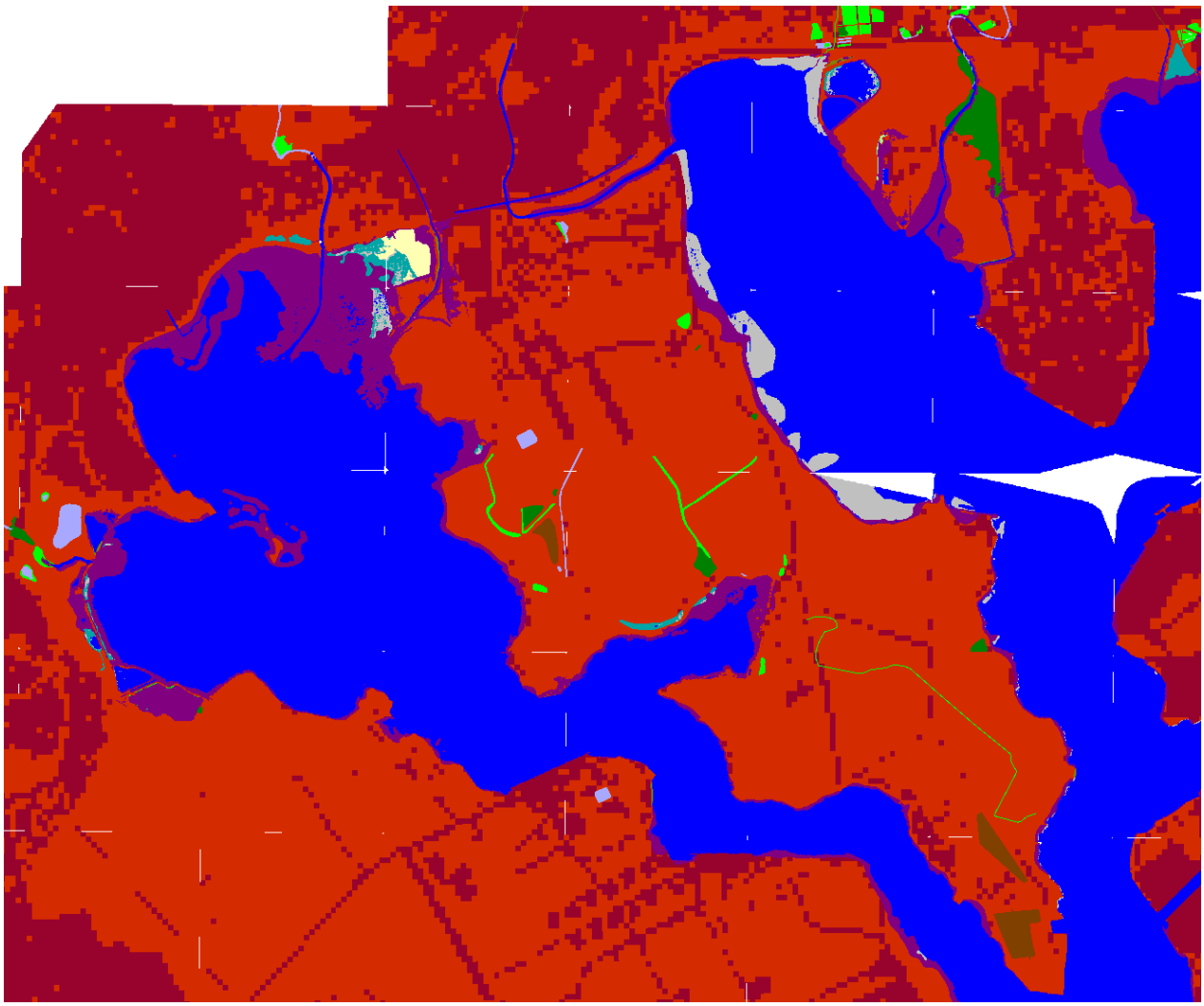
Pearl Harbor Context, 2025, Scenario A1B Maximum



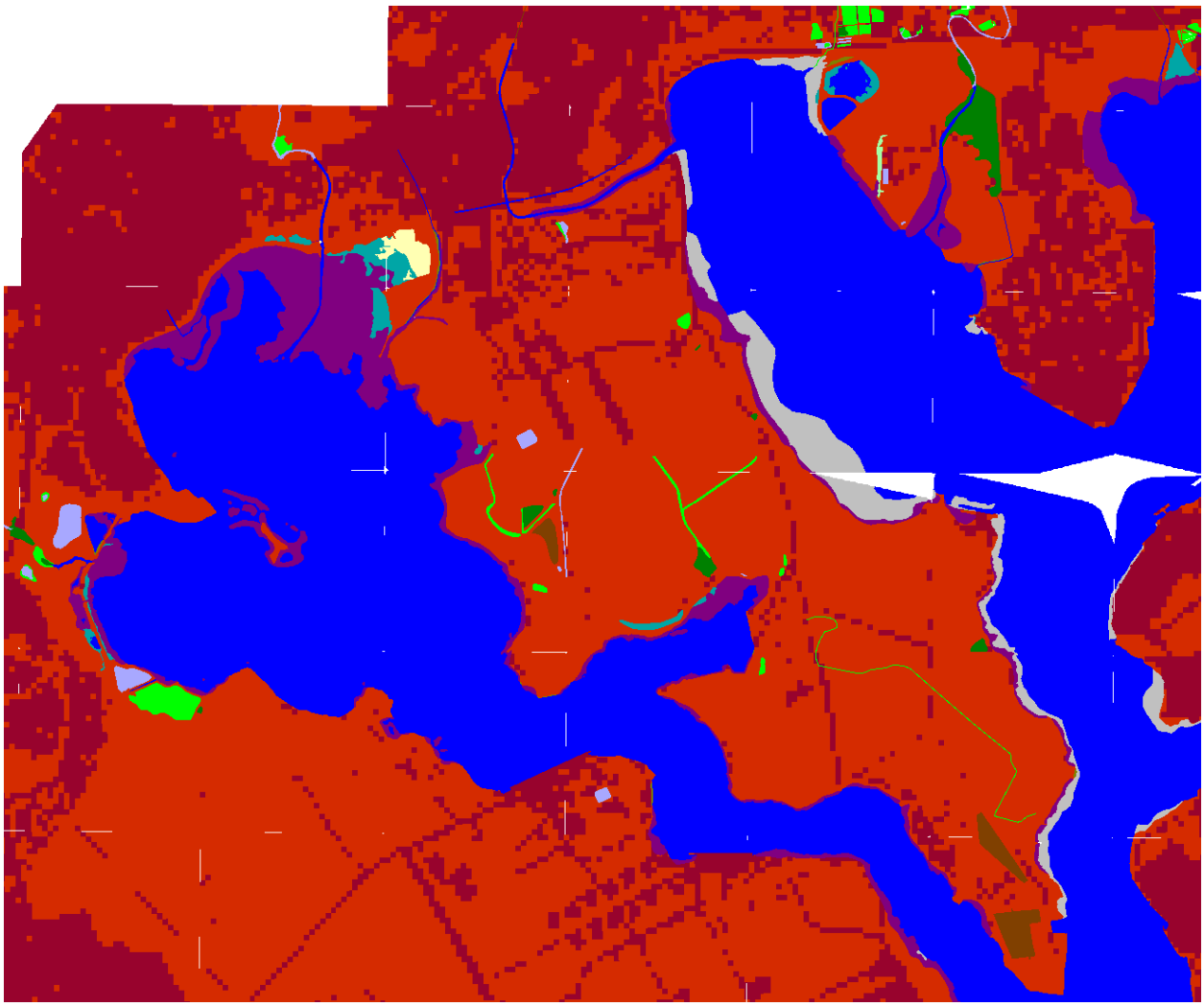
Pearl Harbor Context, 2050, Scenario A1B Maximum



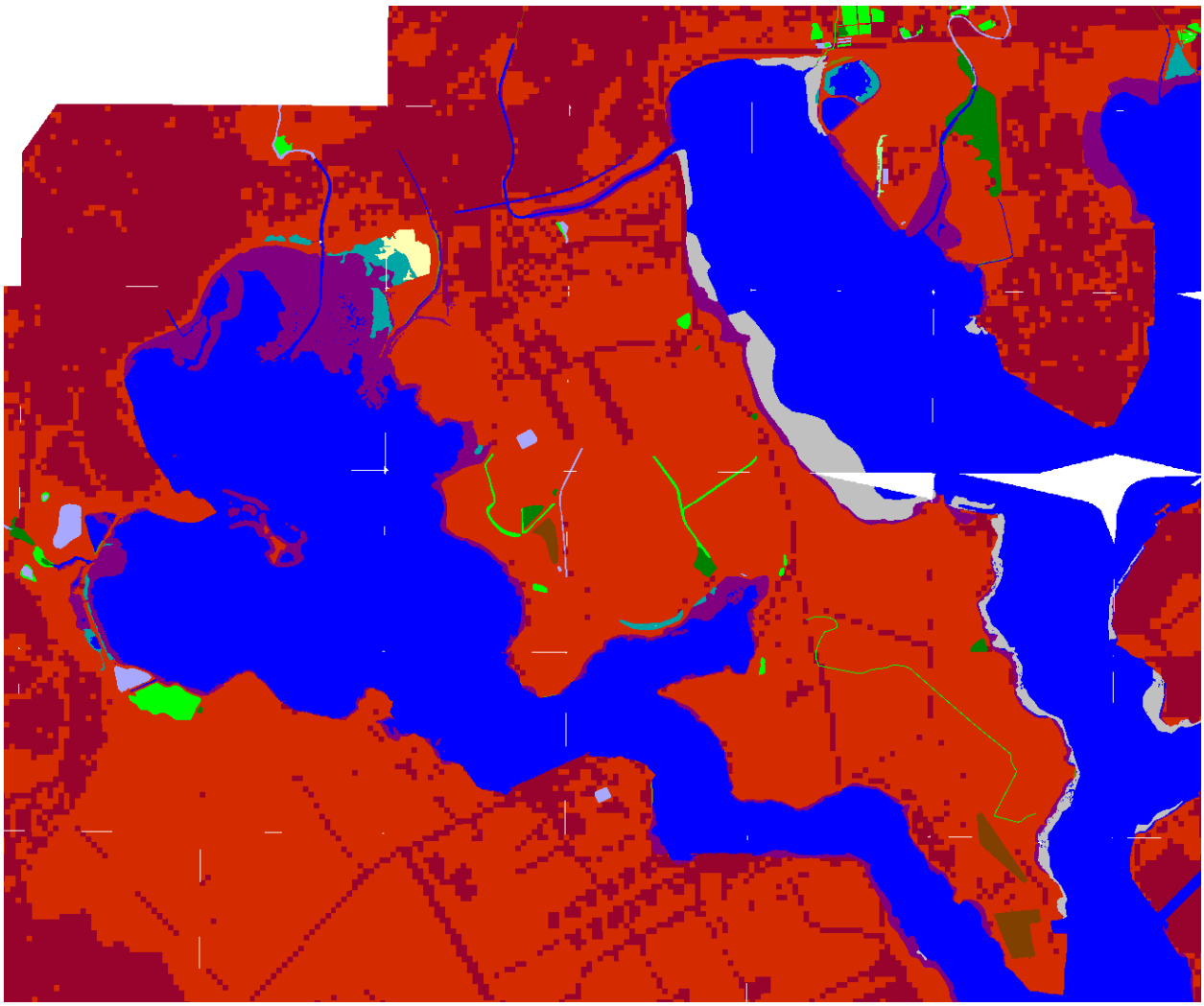
Pearl Harbor Context, 2075, Scenario A1B Maximum



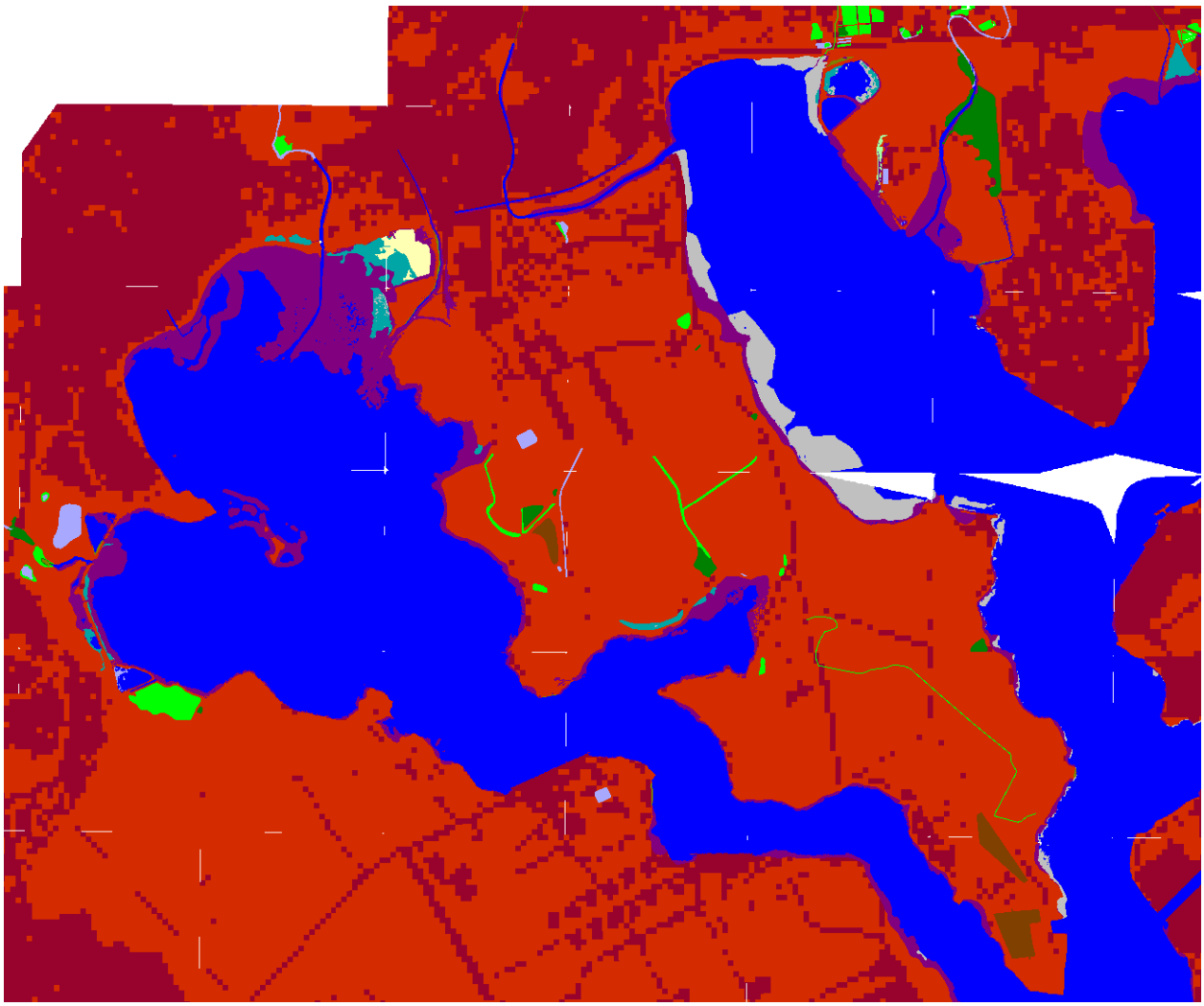
Pearl Harbor Context, 2100, Scenario A1B Maximum



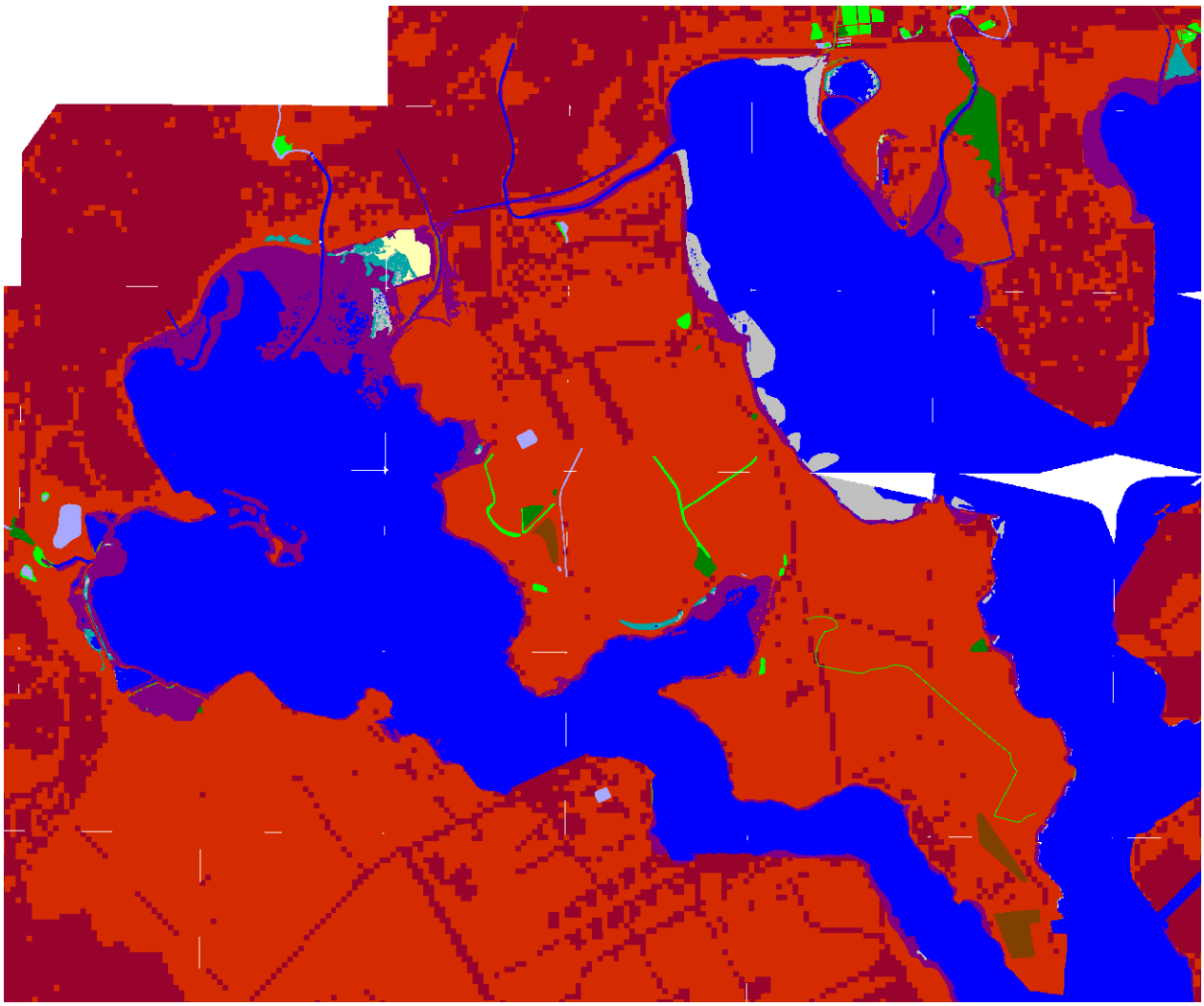
Pearl Harbor Context, Initial Condition



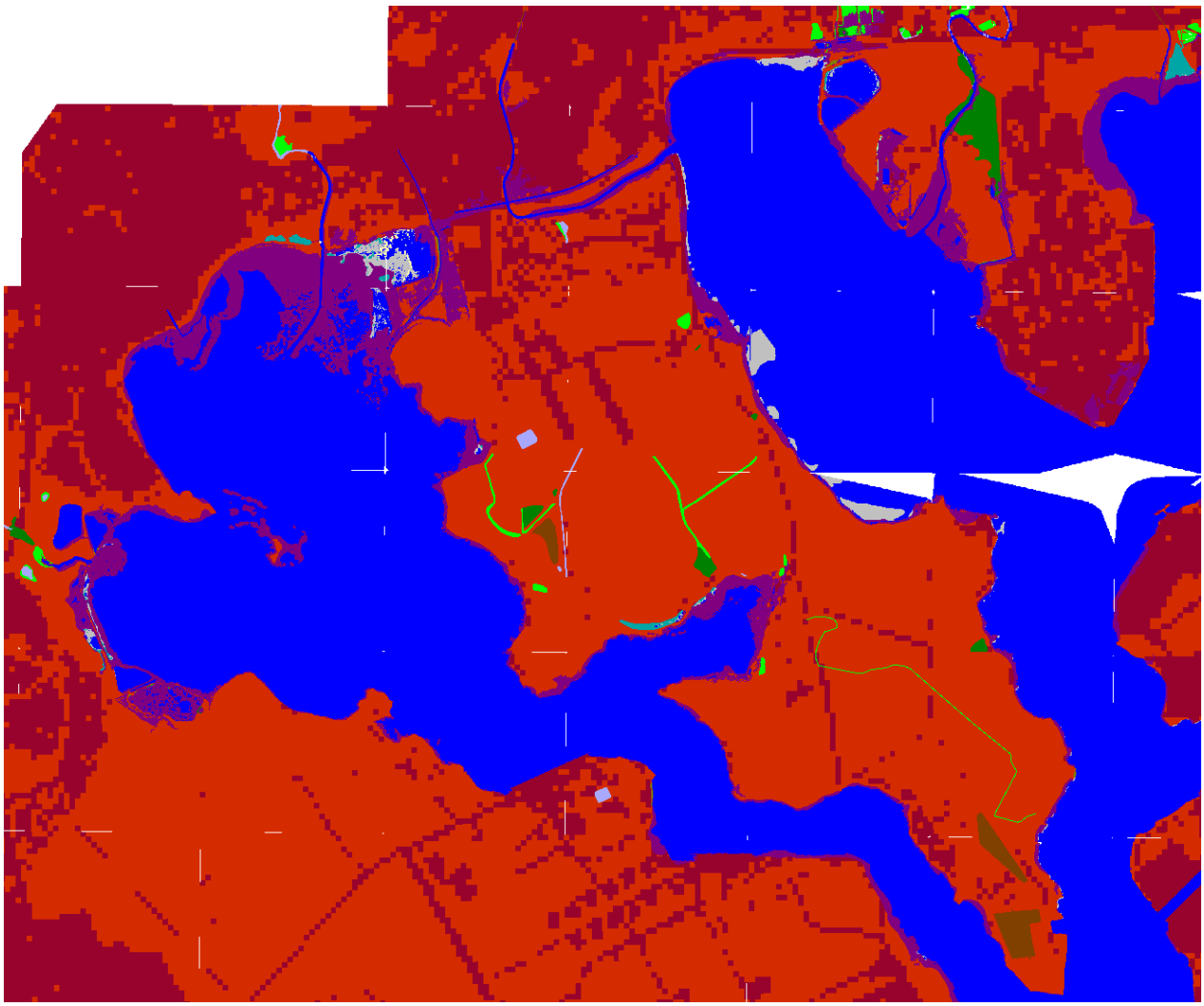
Pearl Harbor Context, 2025, 1 meter



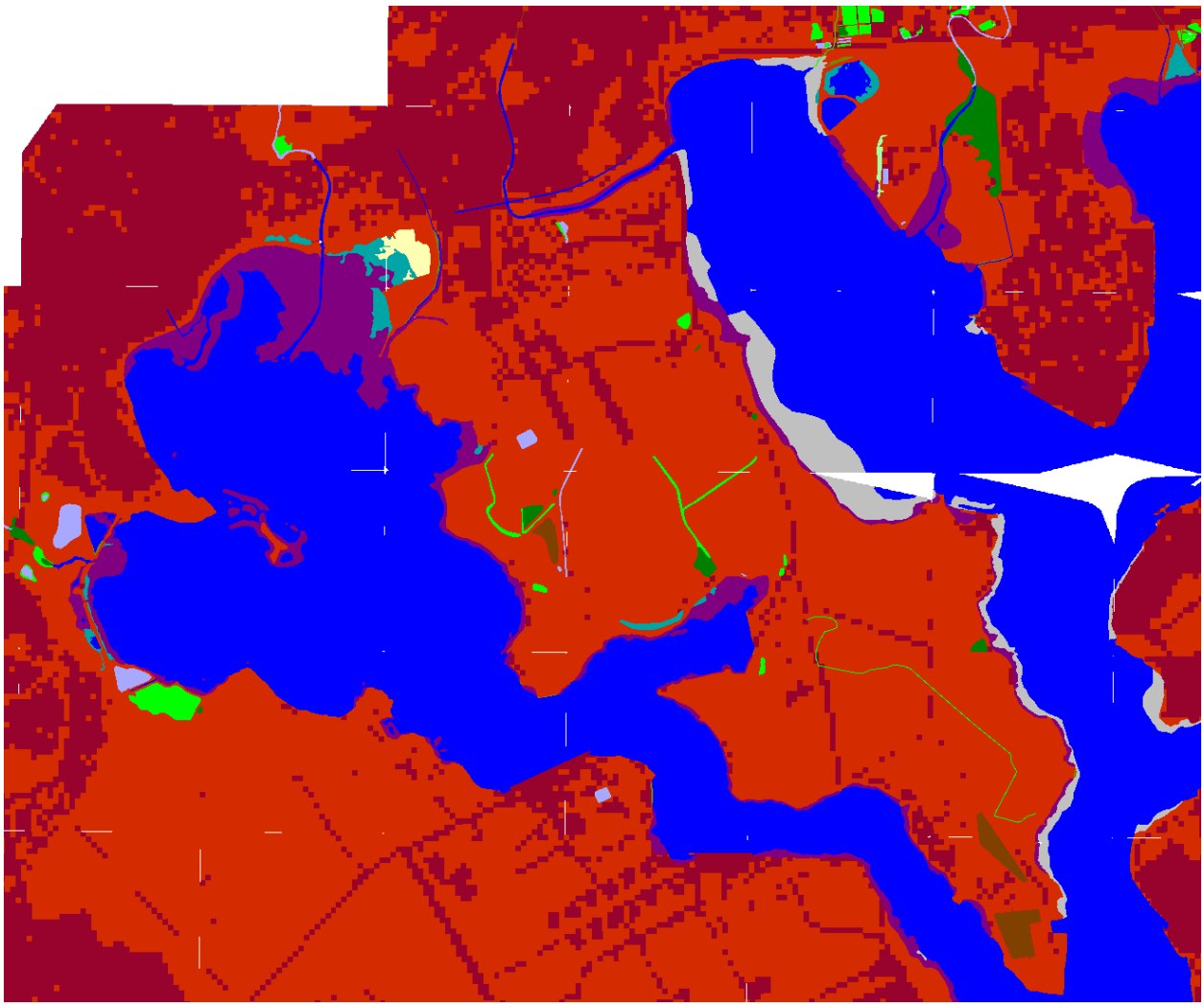
Pearl Harbor Context, 2050, 1 meter



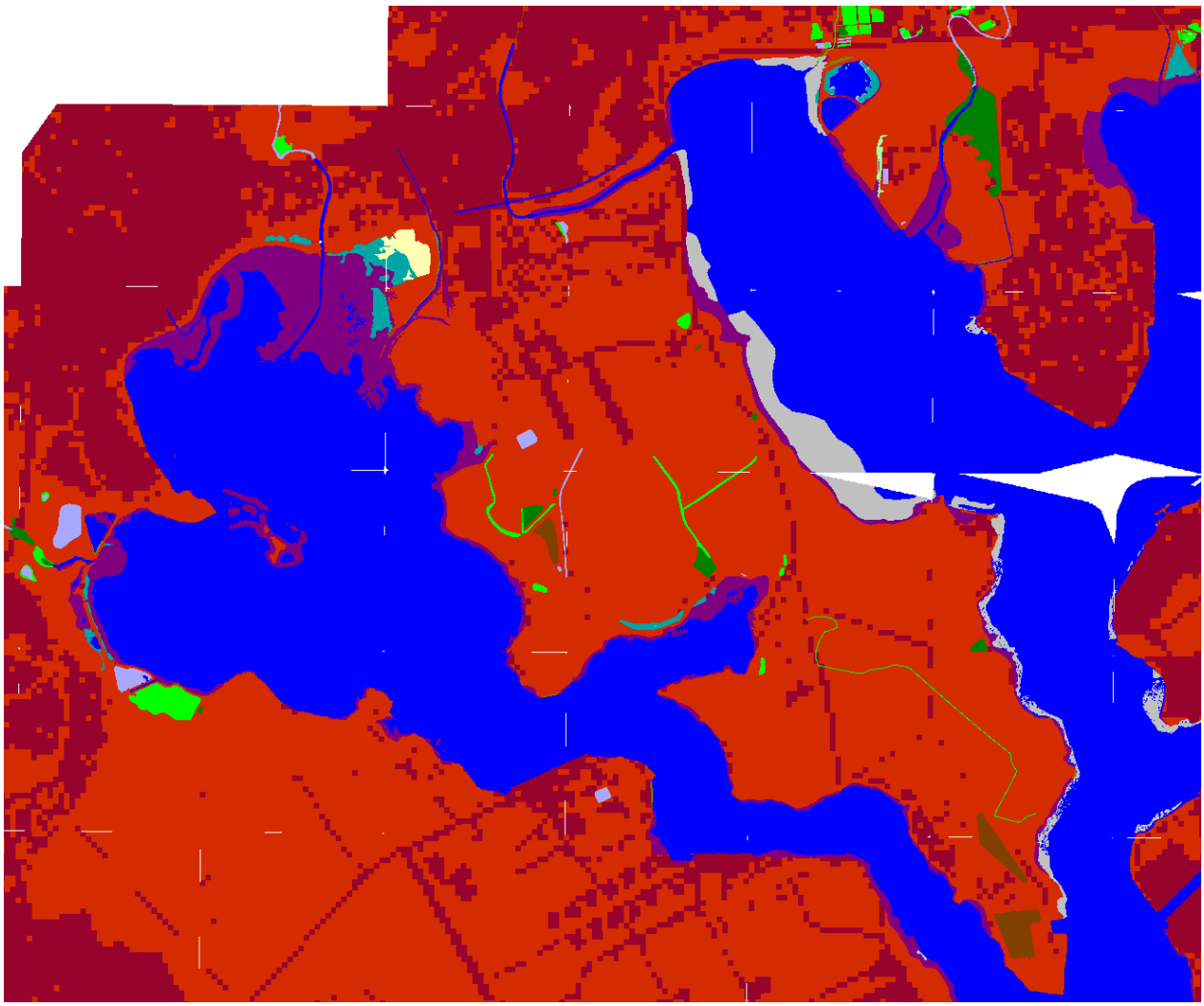
Pearl Harbor Context, 2075, 1 meter



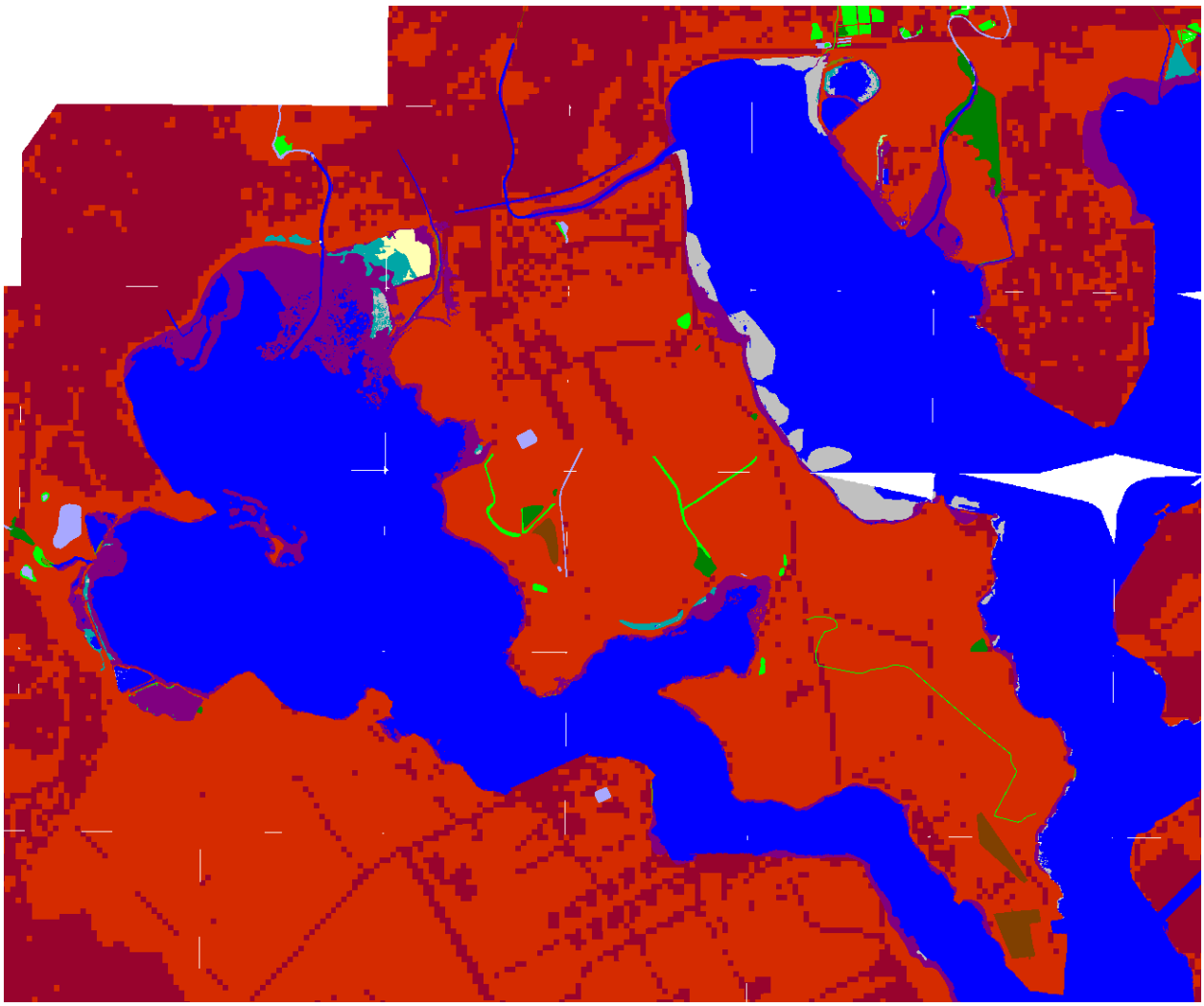
Pearl Harbor Context, 2100, 1 meter



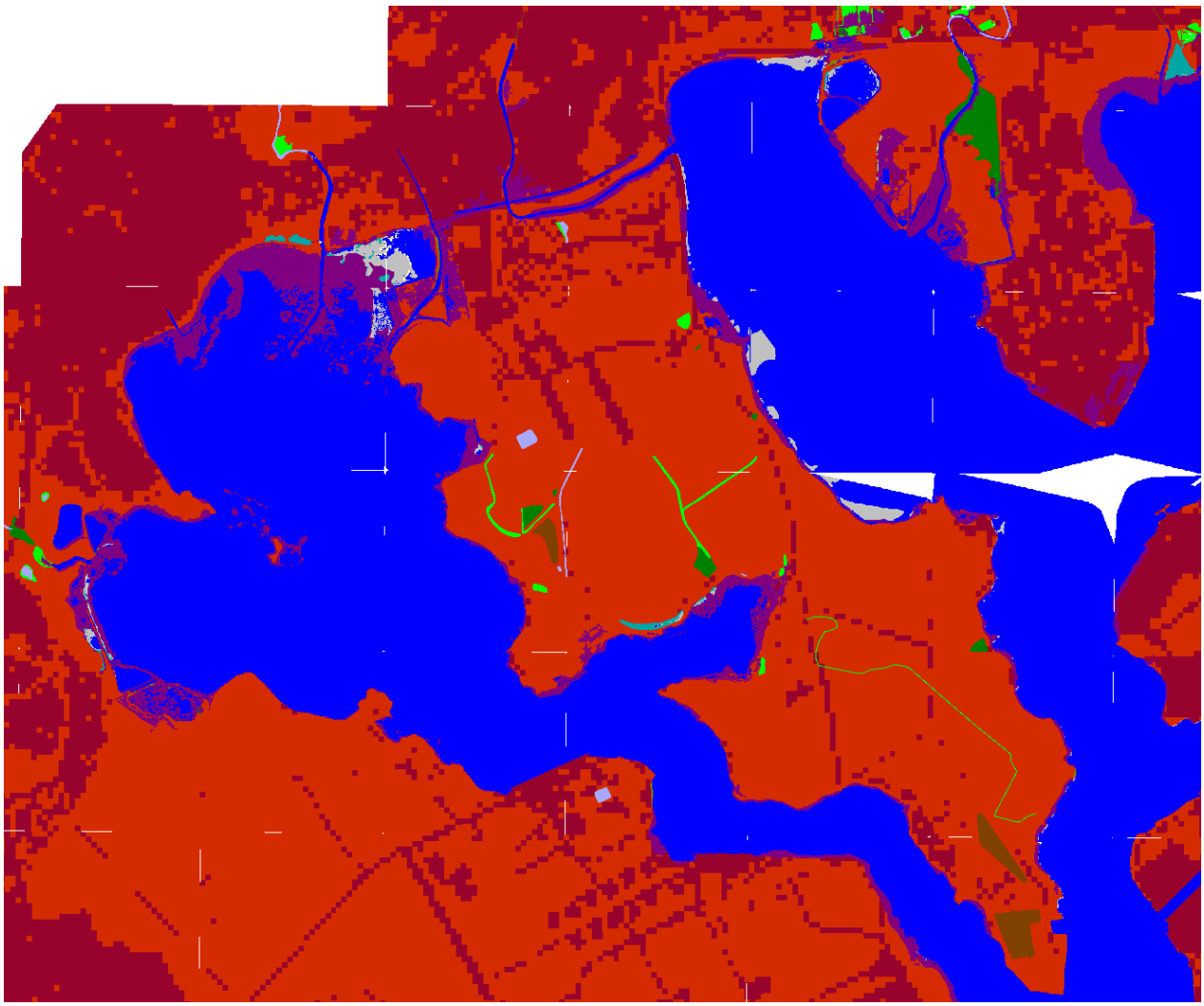
Pearl Harbor Context, Initial Condition



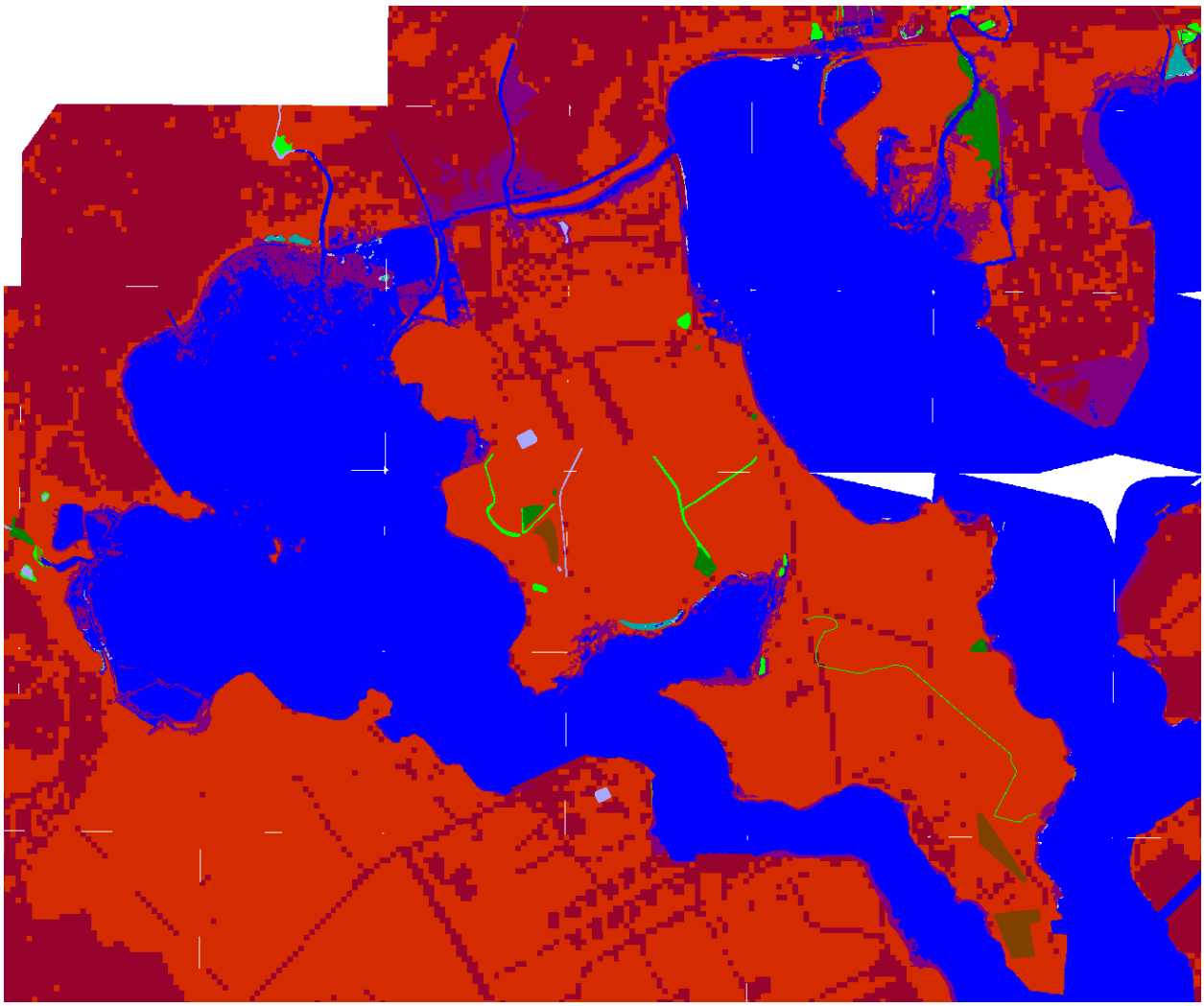
Pearl Harbor Context, 2025, 1.5 meter



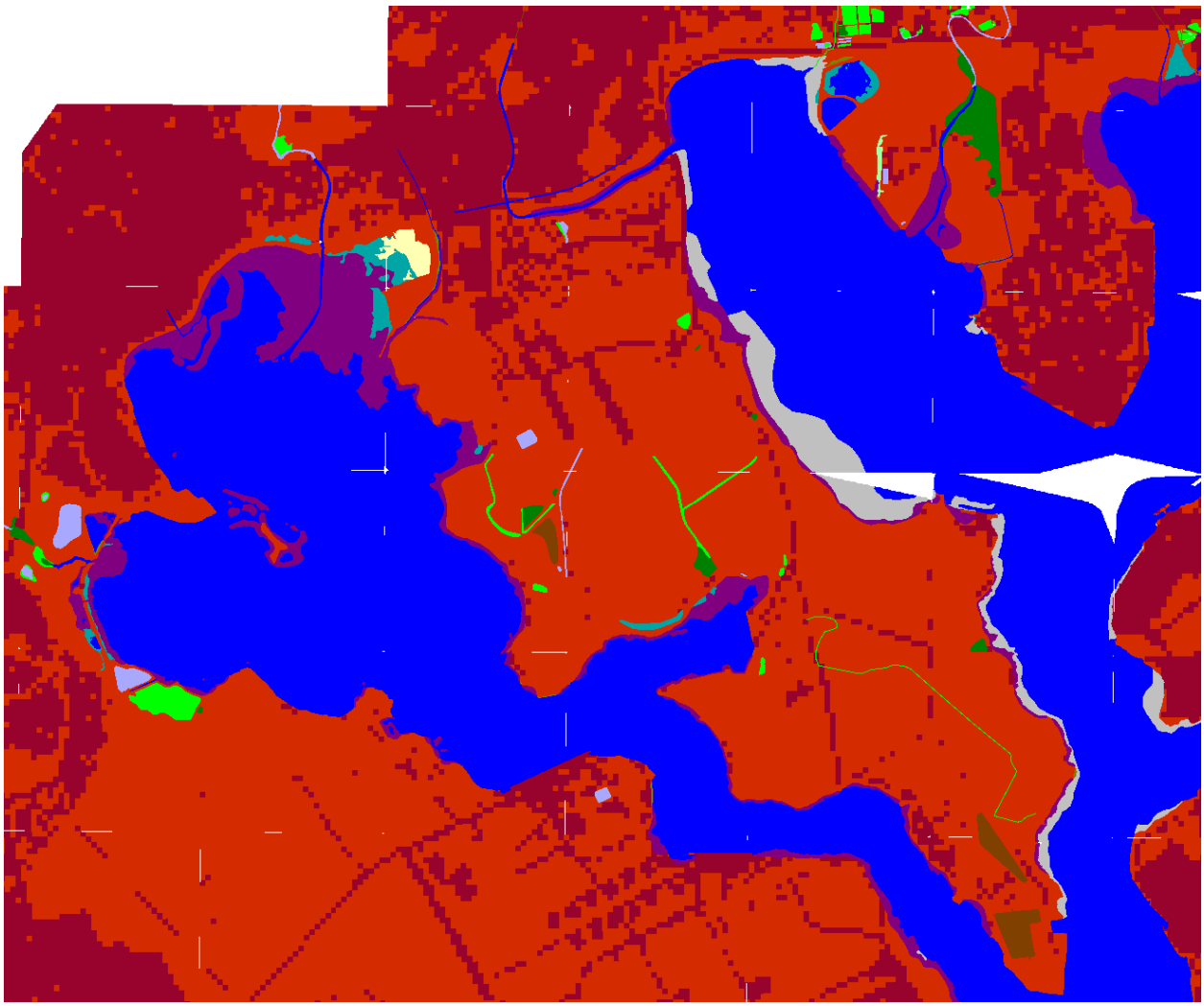
Pearl Harbor Context, 2050, 1.5 meter



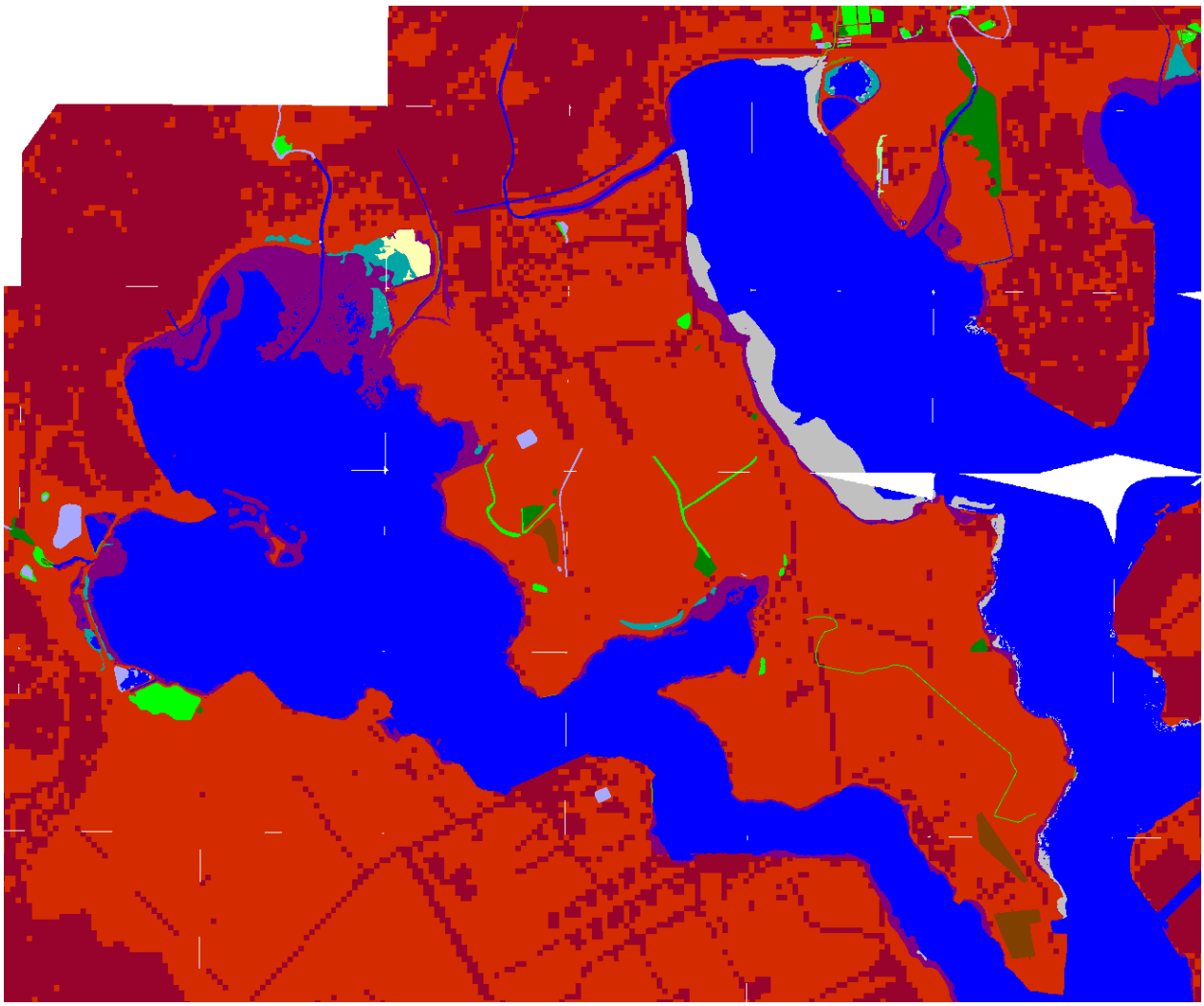
Pearl Harbor Context, 2075, 1.5 meter



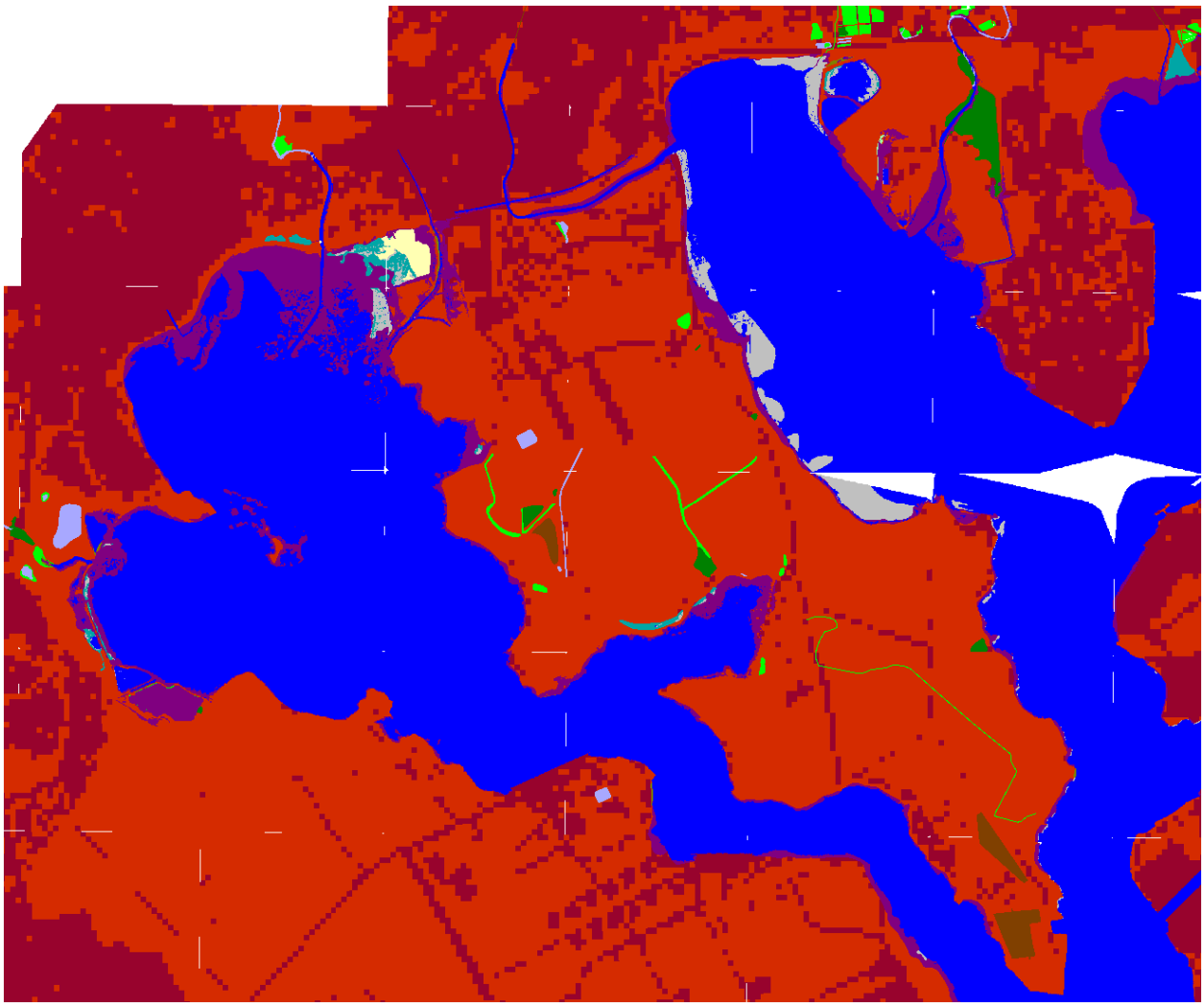
Pearl Harbor Context, 2100, 1.5 meter



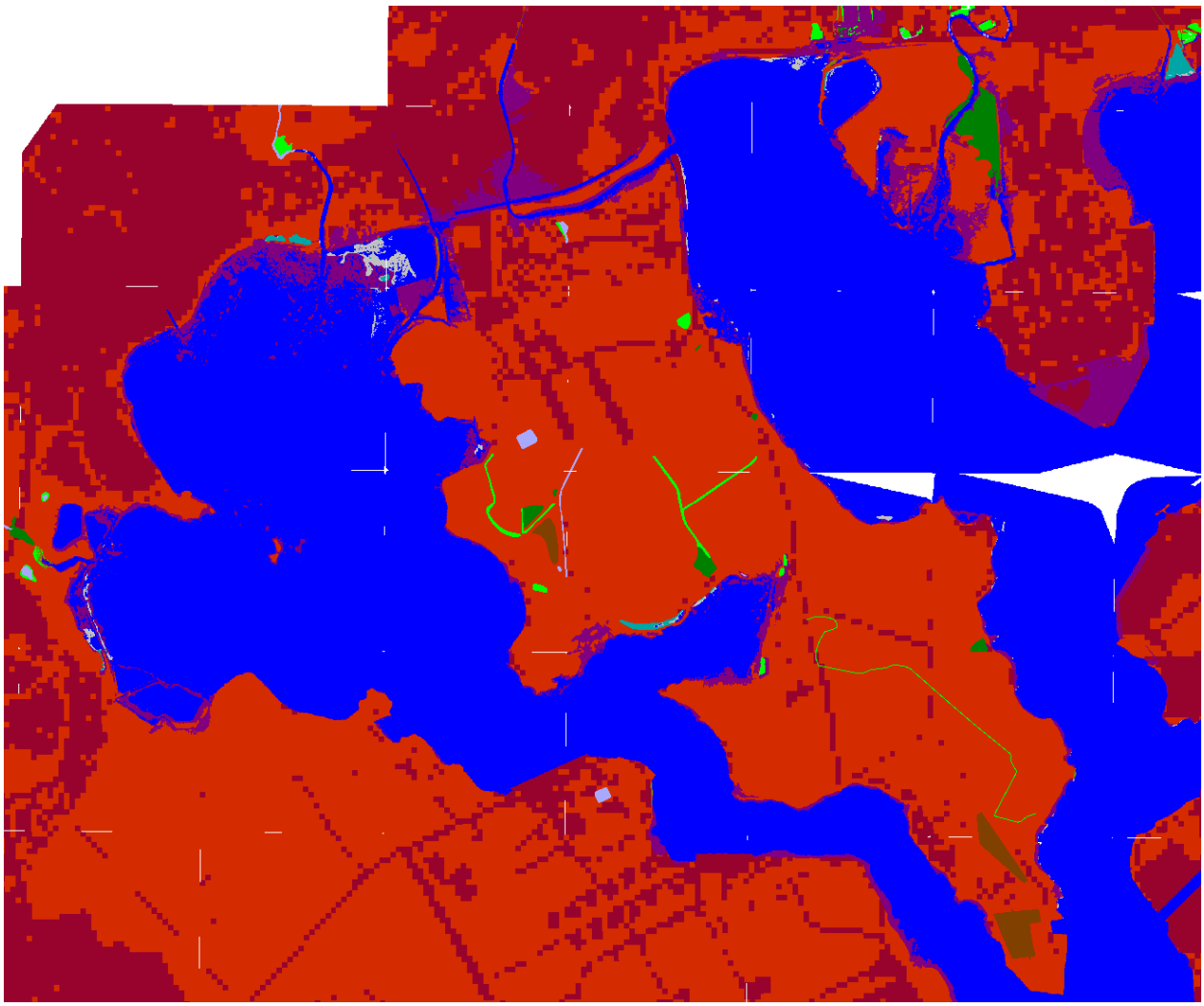
Pearl Harbor Context, Initial Condition



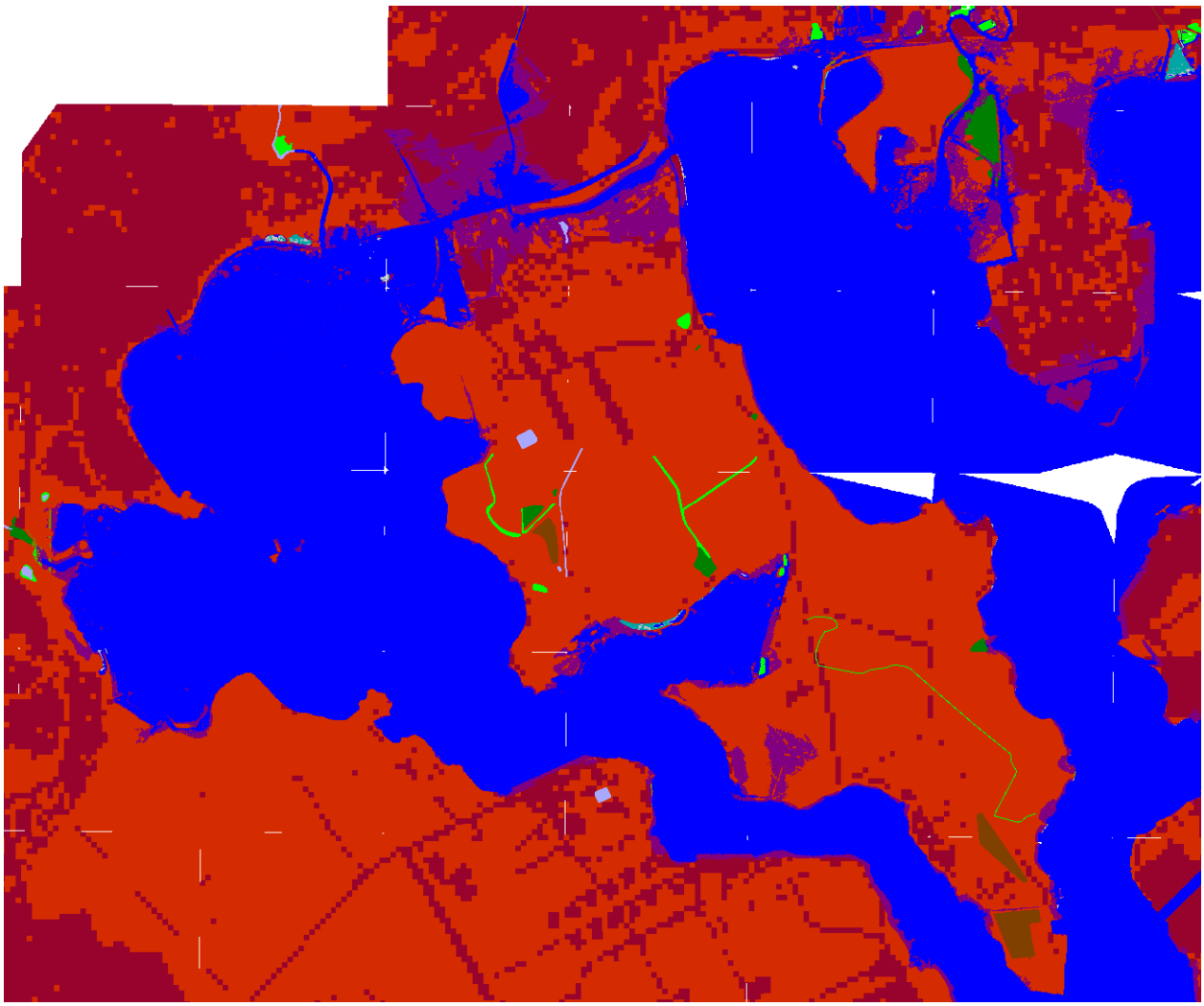
Pearl Harbor Context, 2025, 2 meter



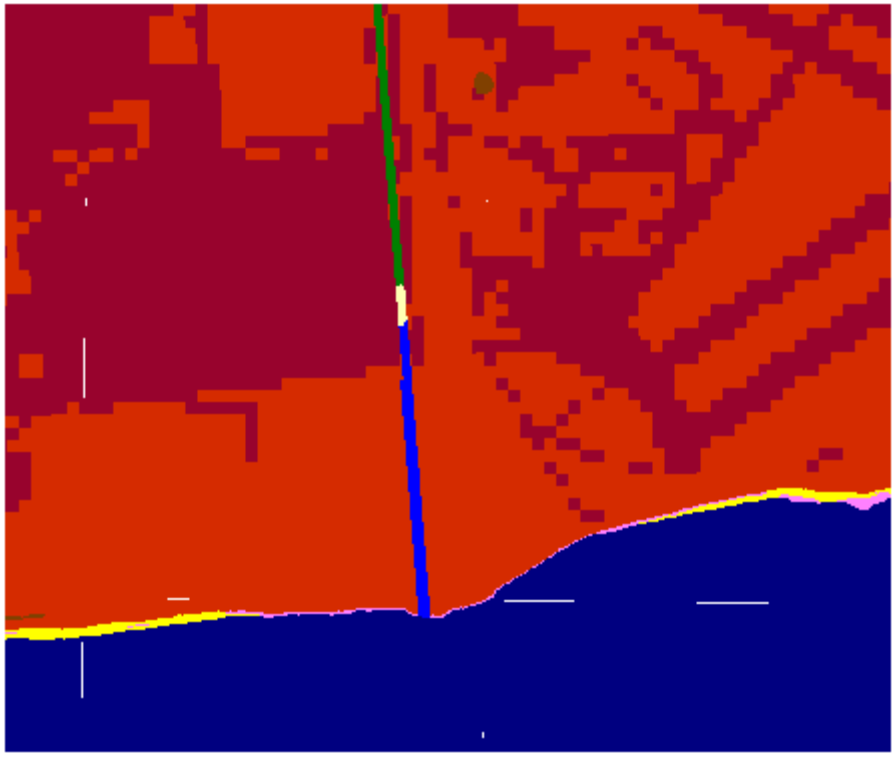
Pearl Harbor Context, 2050, 2 meter



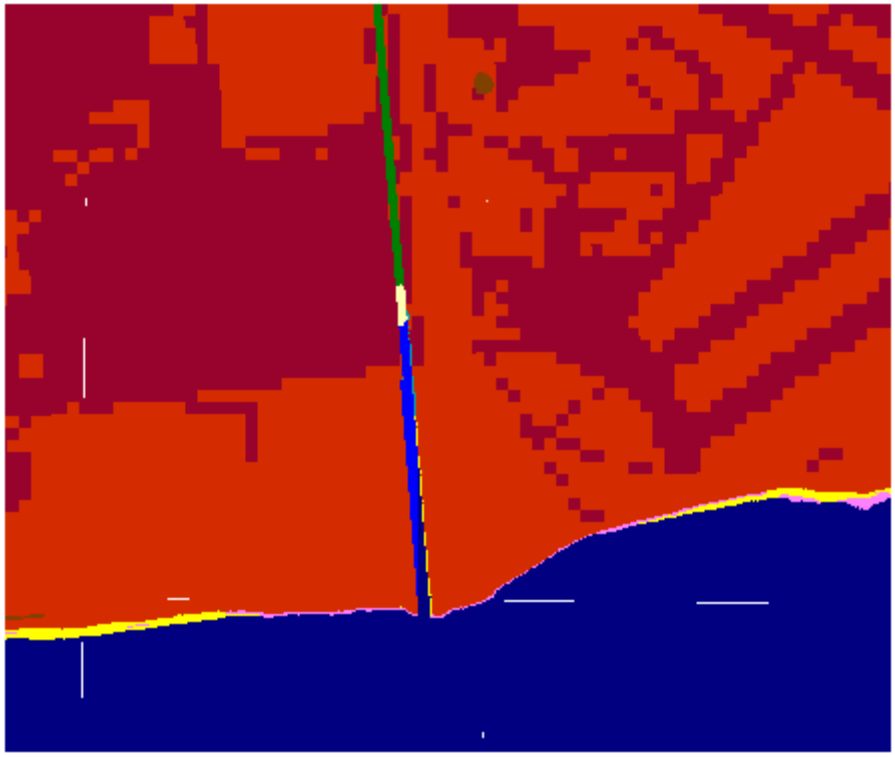
Pearl Harbor Context, 2075, 2 meter



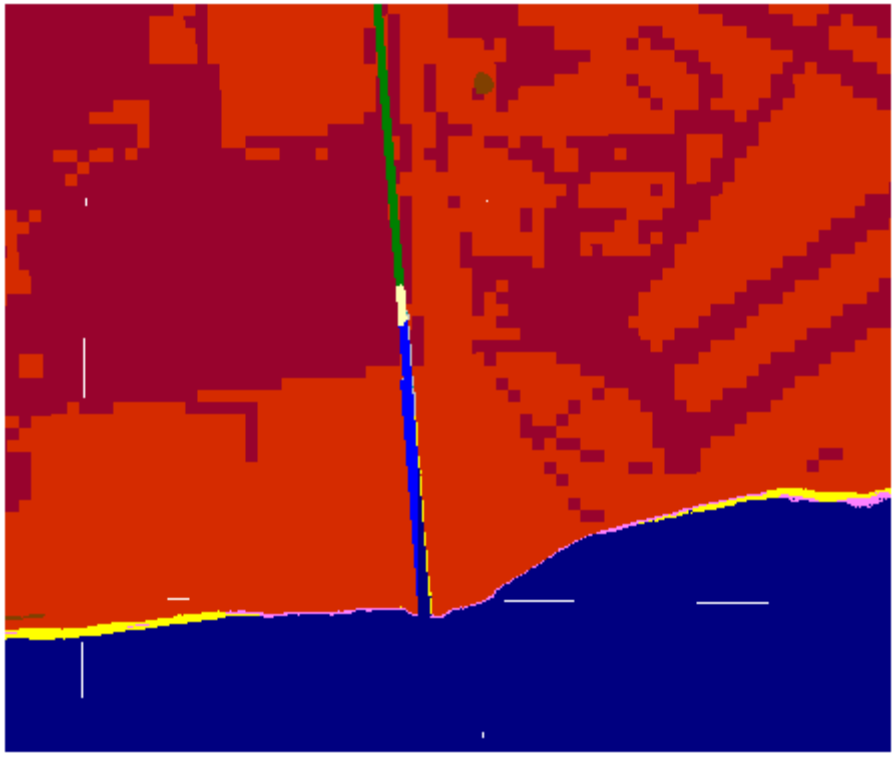
Pearl Harbor Context, 2100, 2 meter



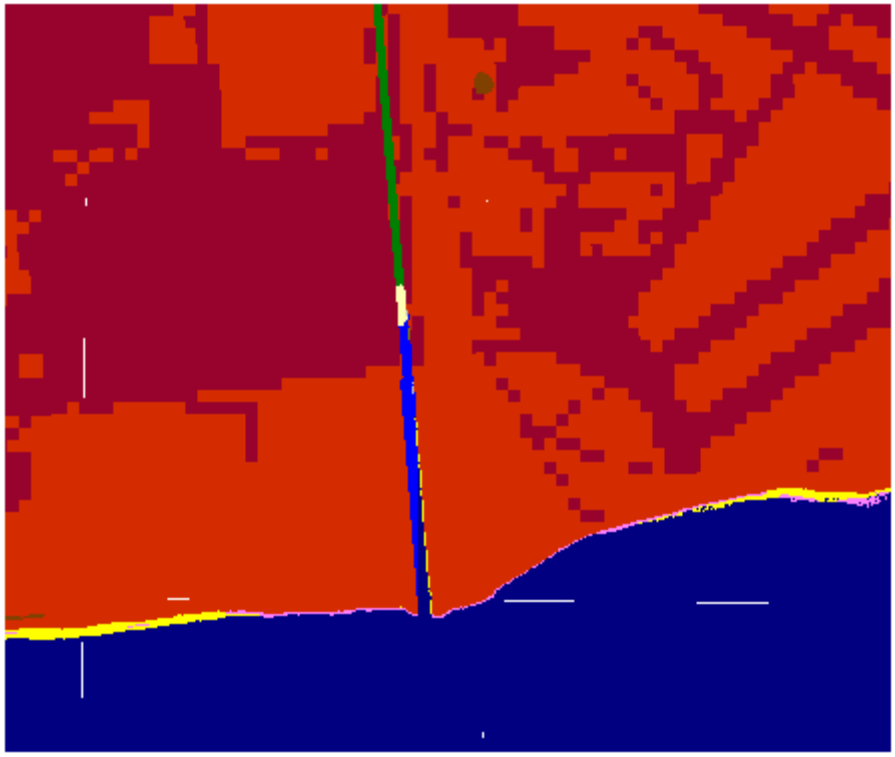
Pearl Harbor Context, Initial Condition



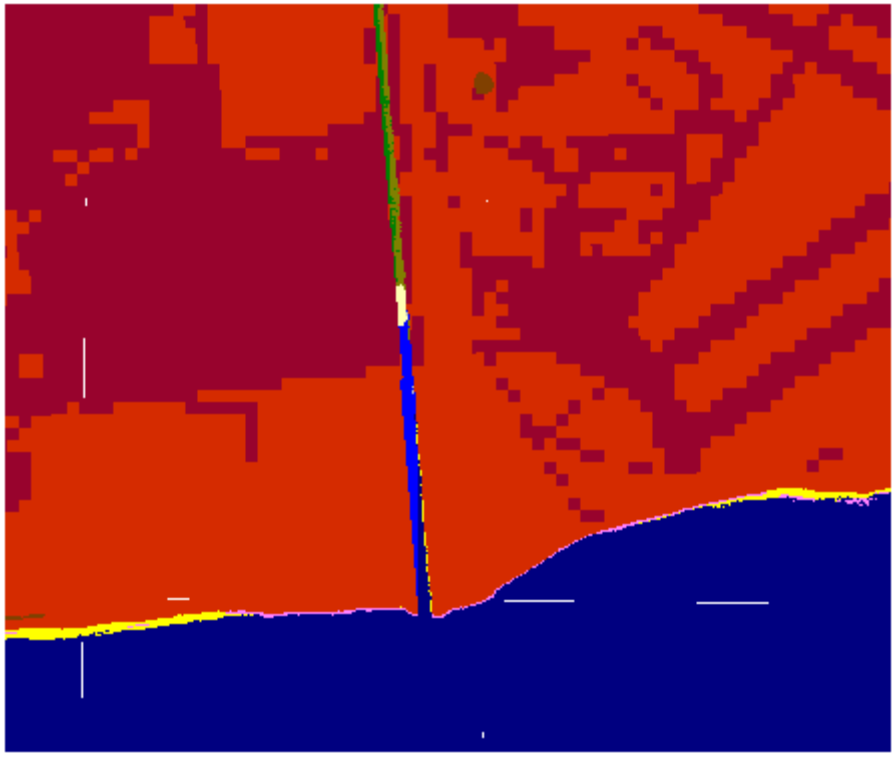
Pearl Harbor Context, 2025, Scenario A1B Mean



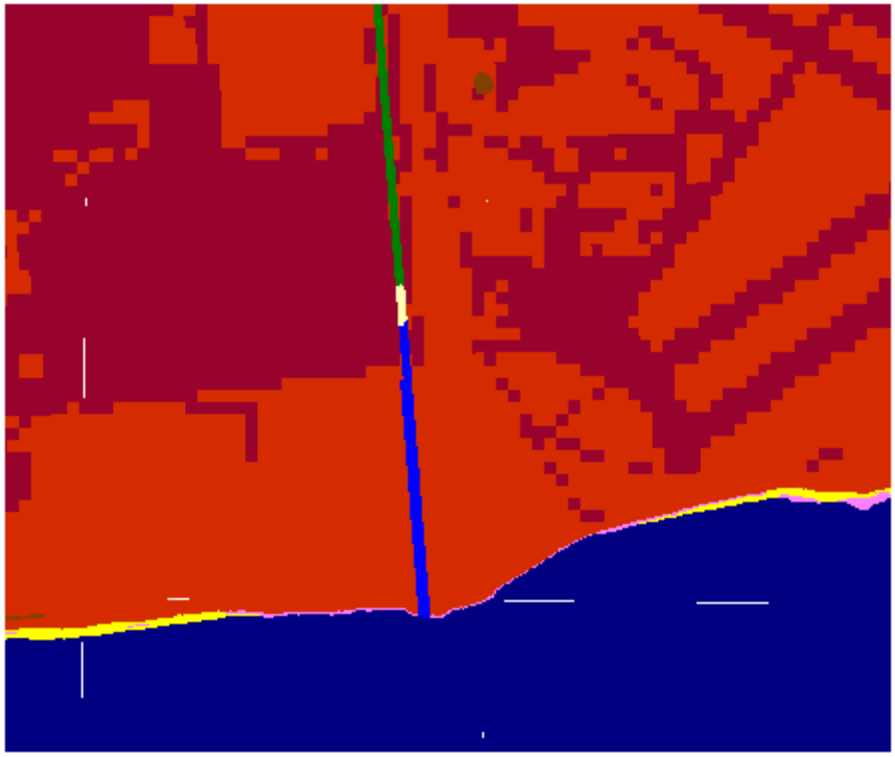
Pearl Harbor Context, 2050, Scenario A1B Mean



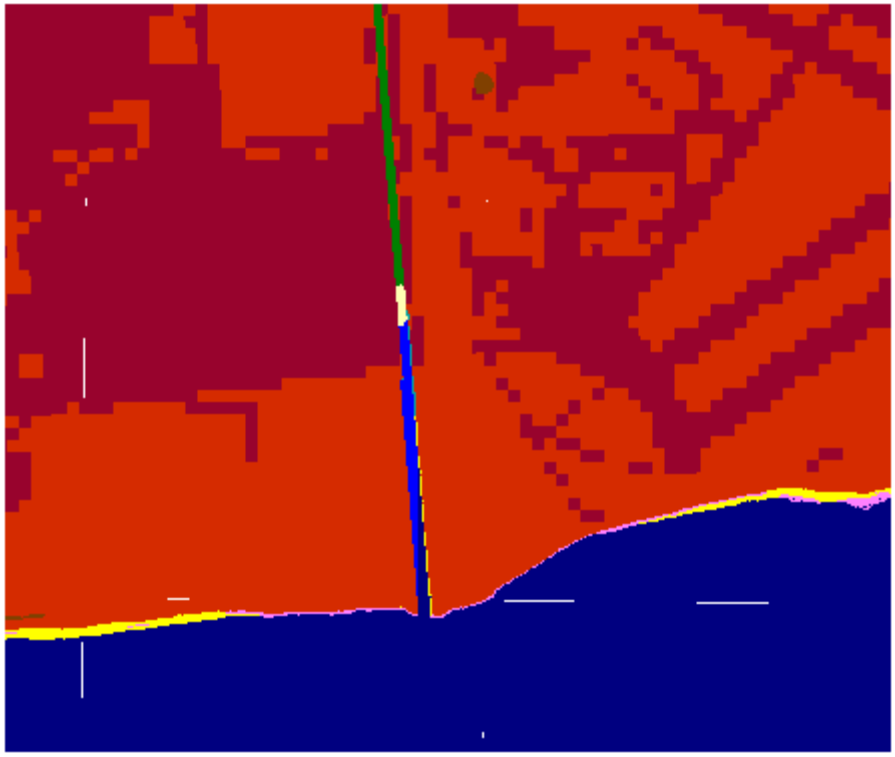
Pearl Harbor Context, 2075, Scenario A1B Mean



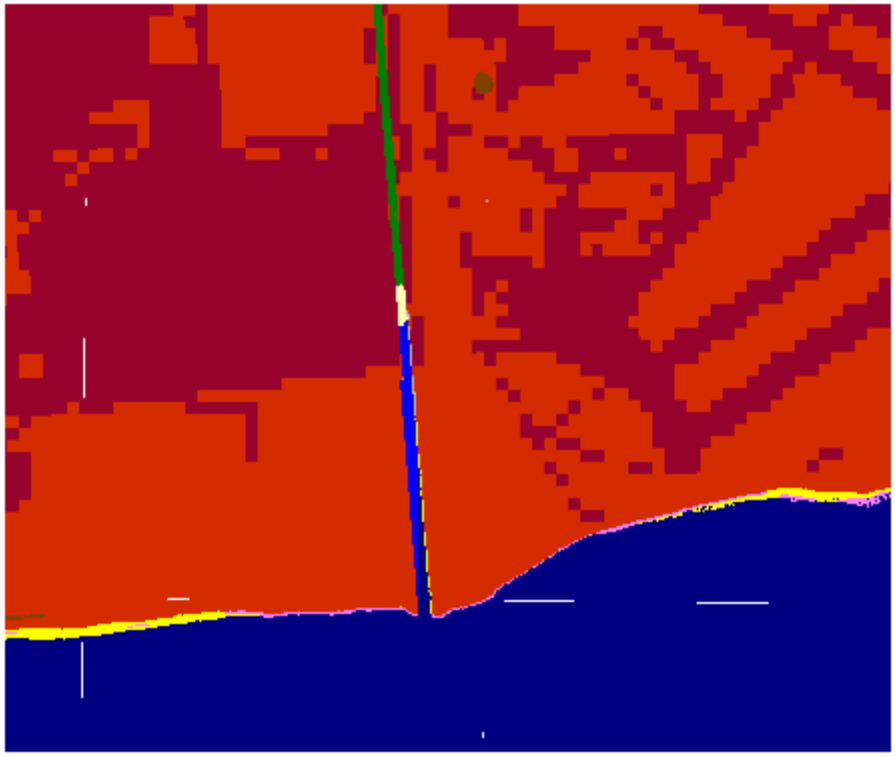
Pearl Harbor Context, 2100, Scenario A1B Mean



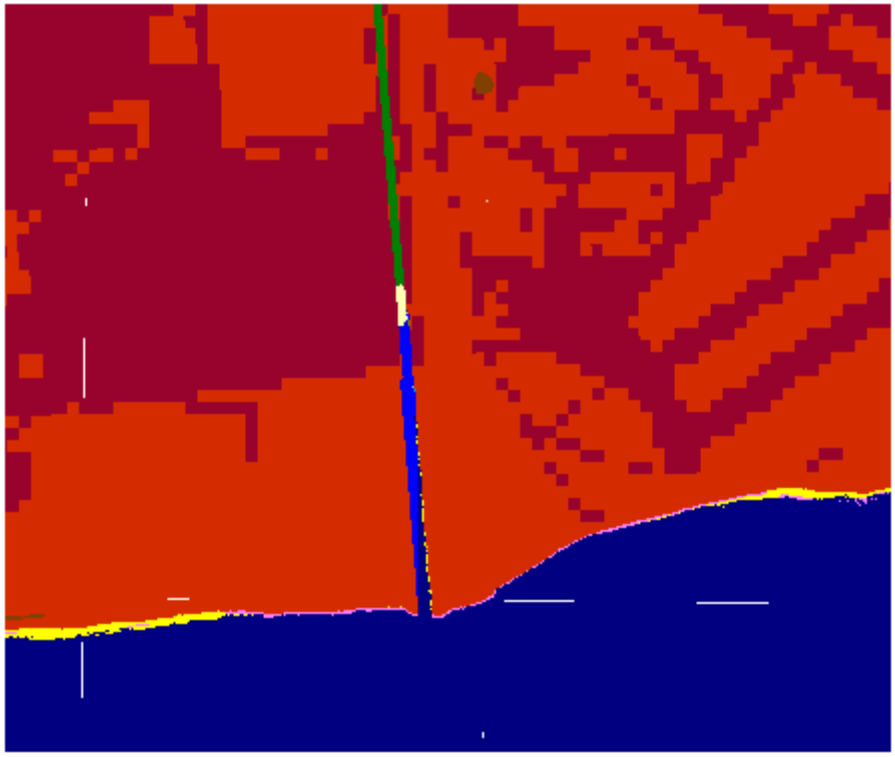
Pearl Harbor Context, Initial Condition



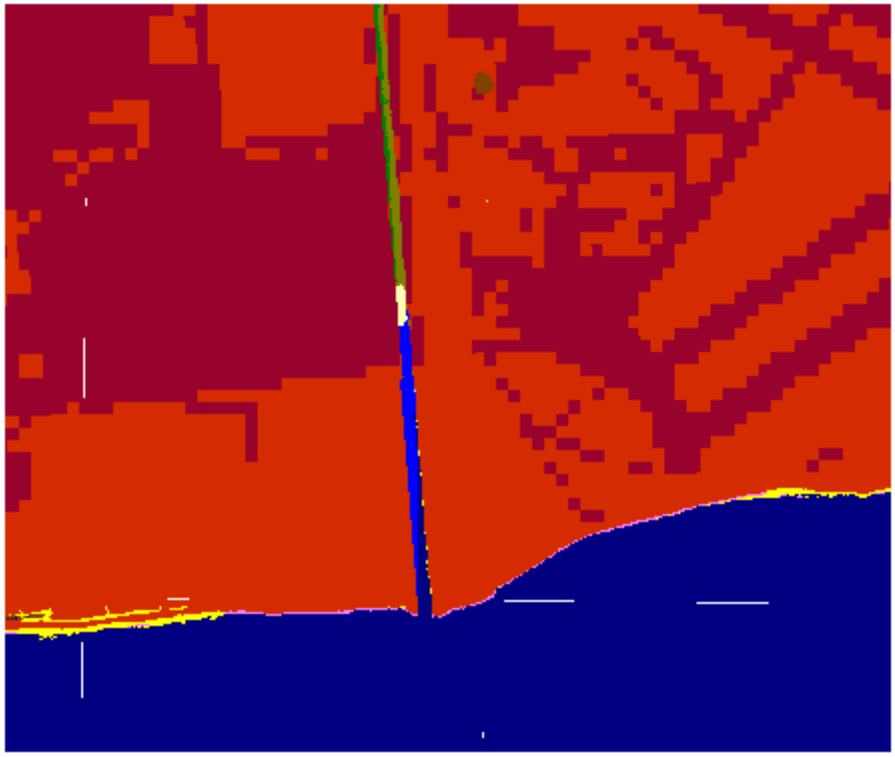
Pearl Harbor Context, 2025, Scenario A1B Maximum



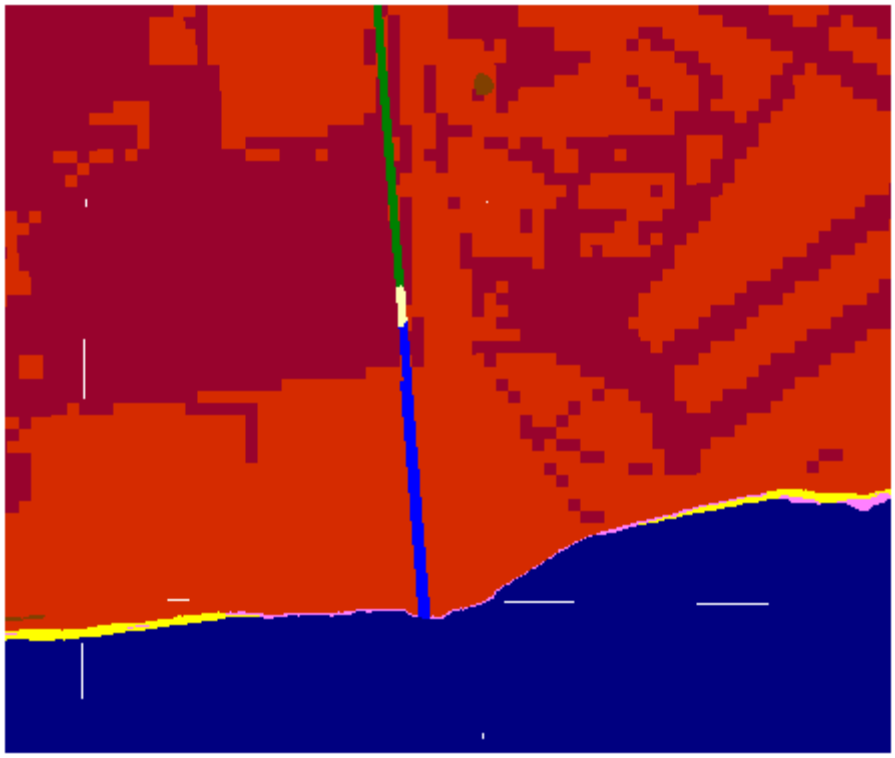
Pearl Harbor Context, 2050, Scenario A1B Maximum



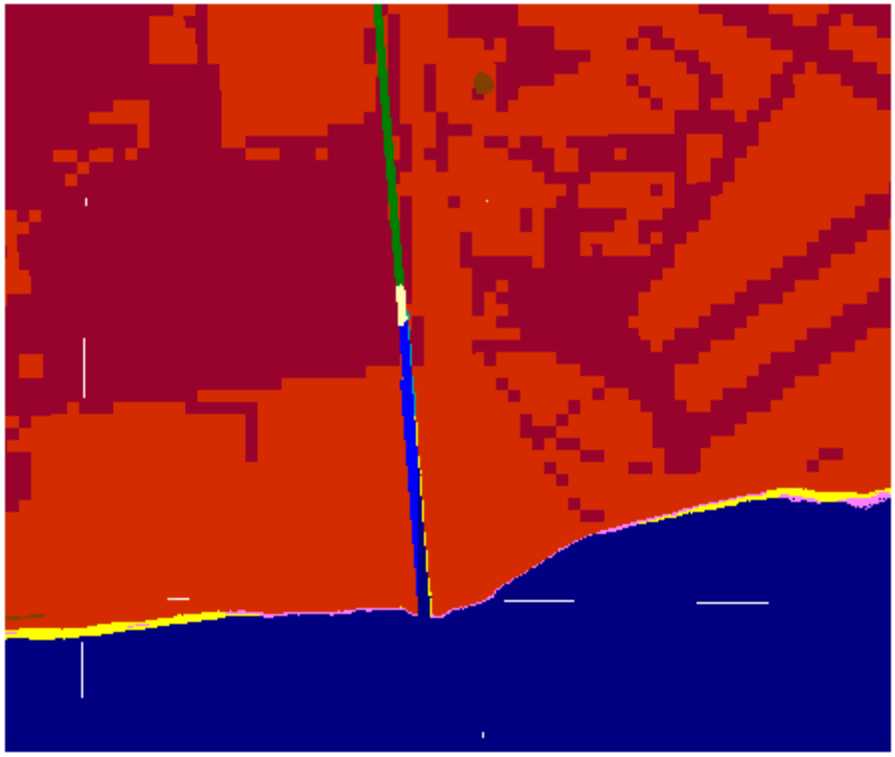
Pearl Harbor Context, 2075, Scenario A1B Maximum



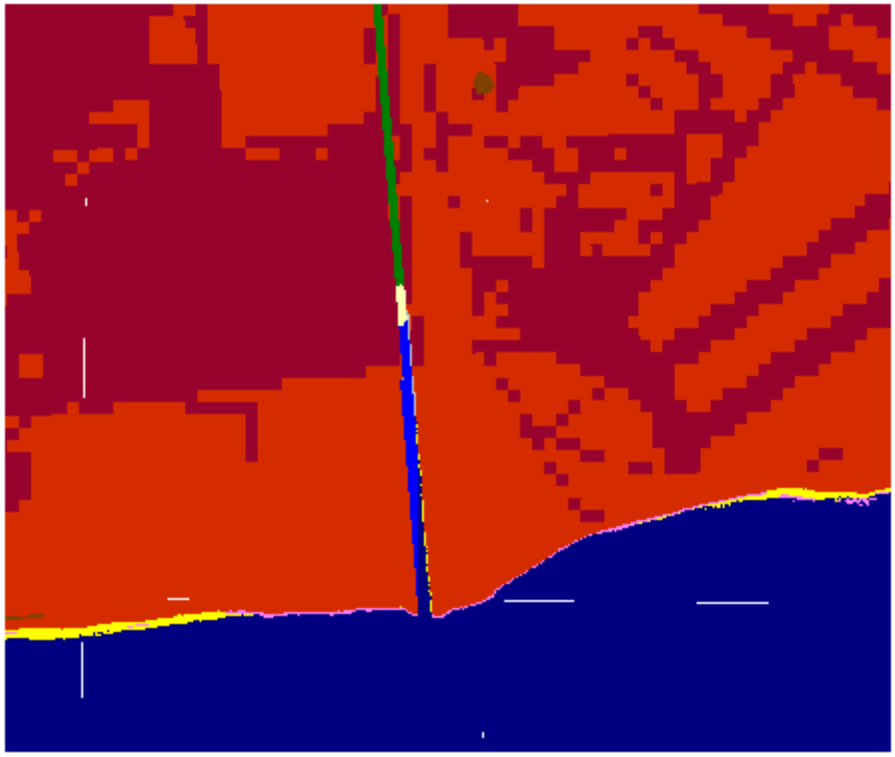
Pearl Harbor Context, 2100, Scenario A1B Maximum



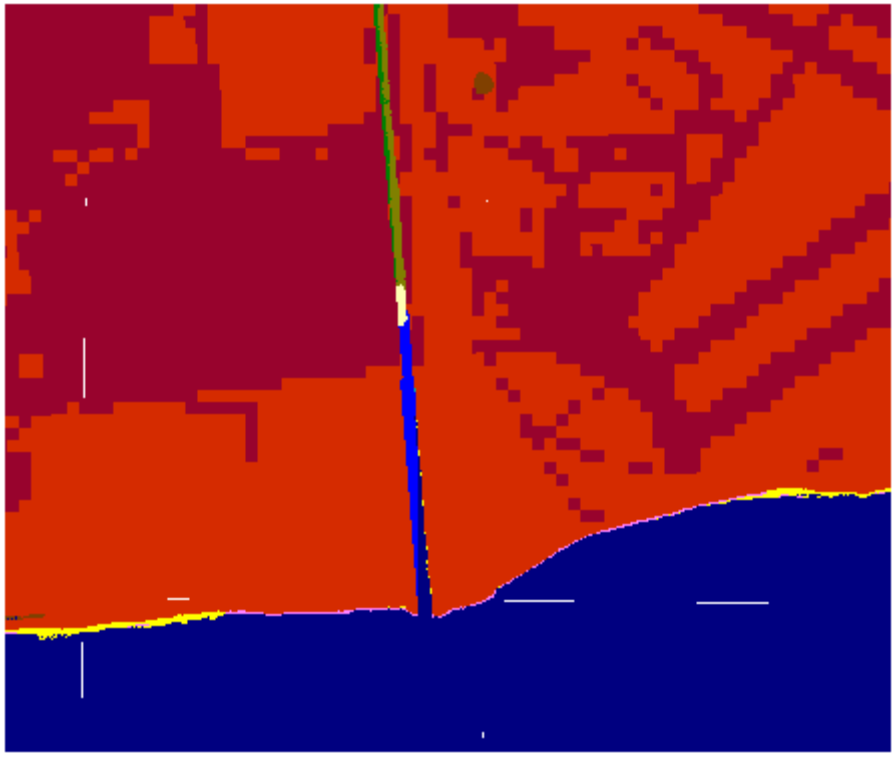
Pearl Harbor Context, Initial Condition



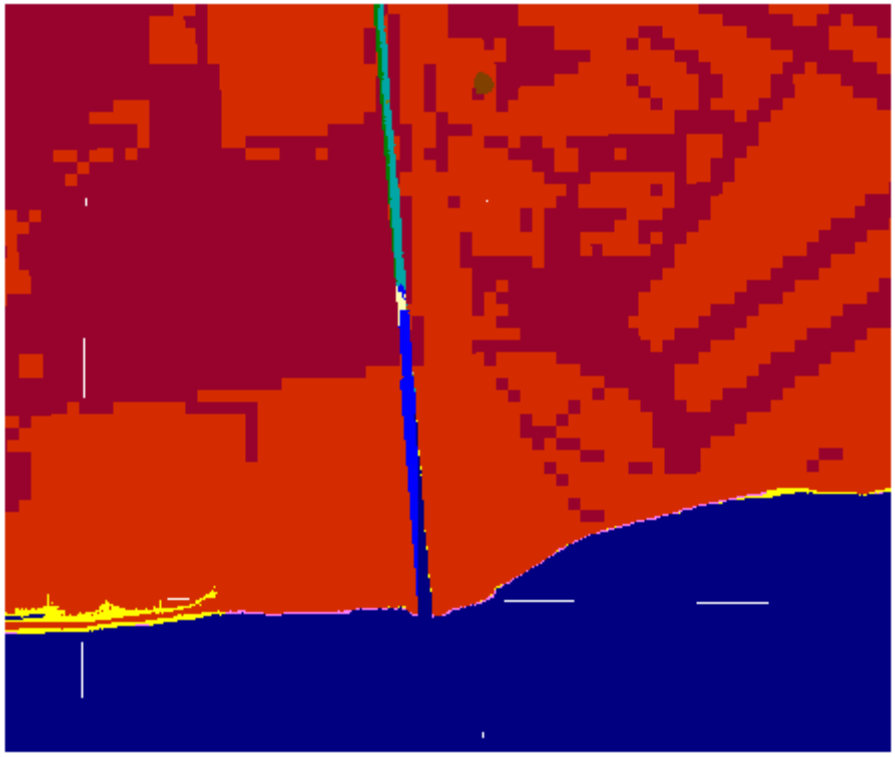
Pearl Harbor Context, 2025, 1 meter



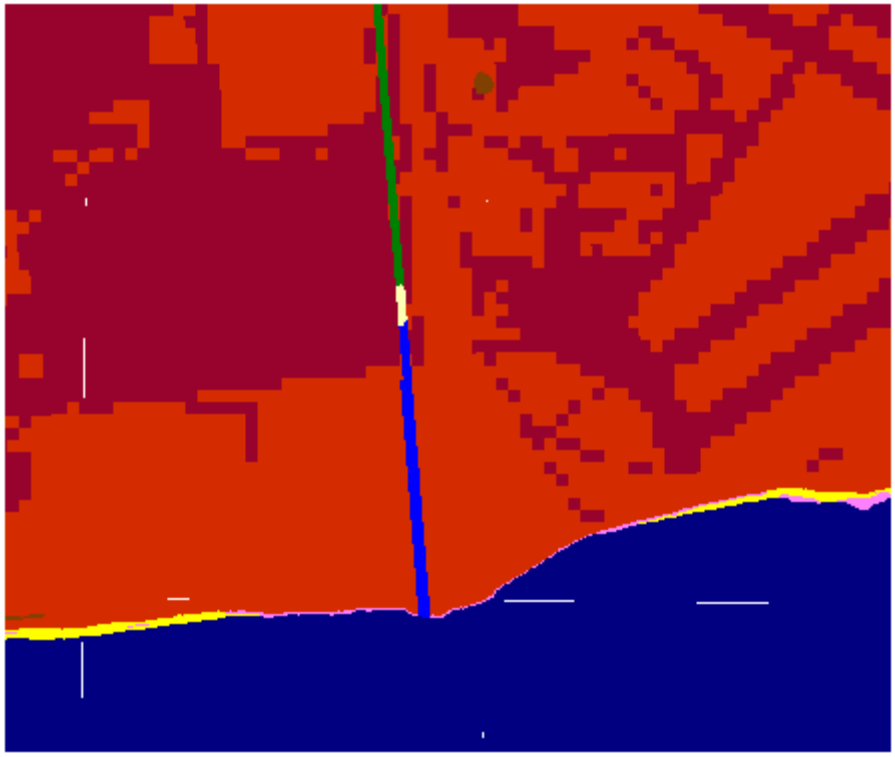
Pearl Harbor Context, 2050, 1 meter



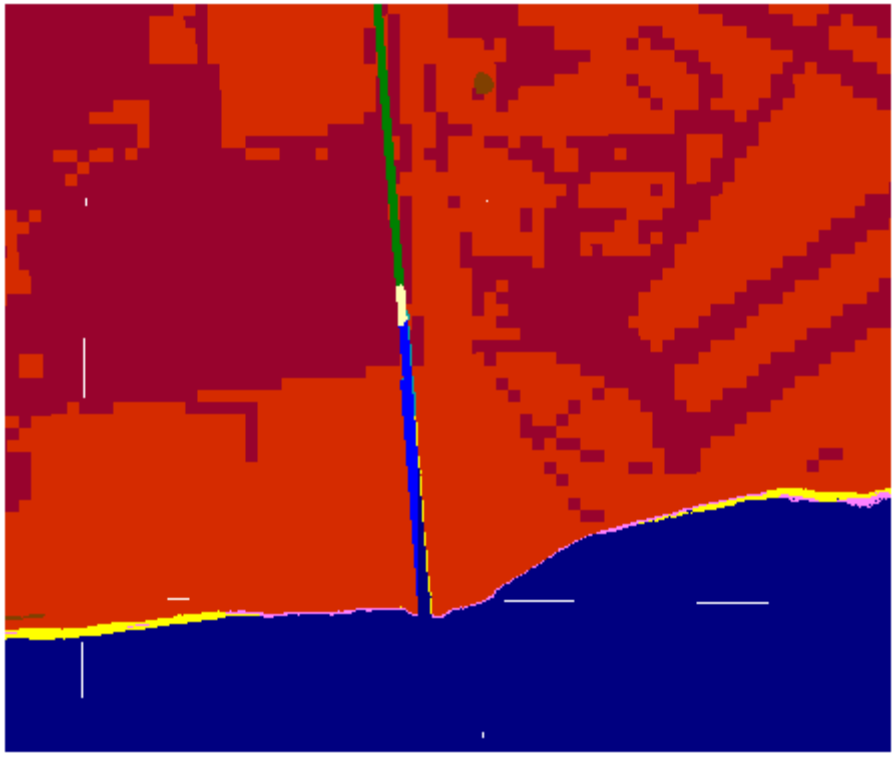
Pearl Harbor Context, 2075, 1 meter



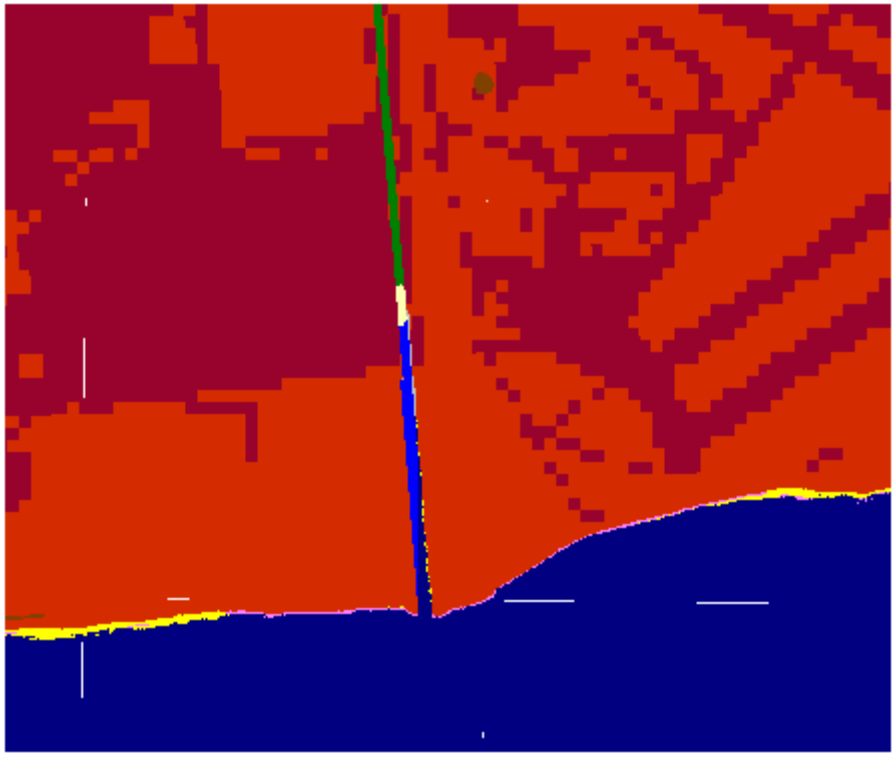
Pearl Harbor Context, 2100, 1 meter



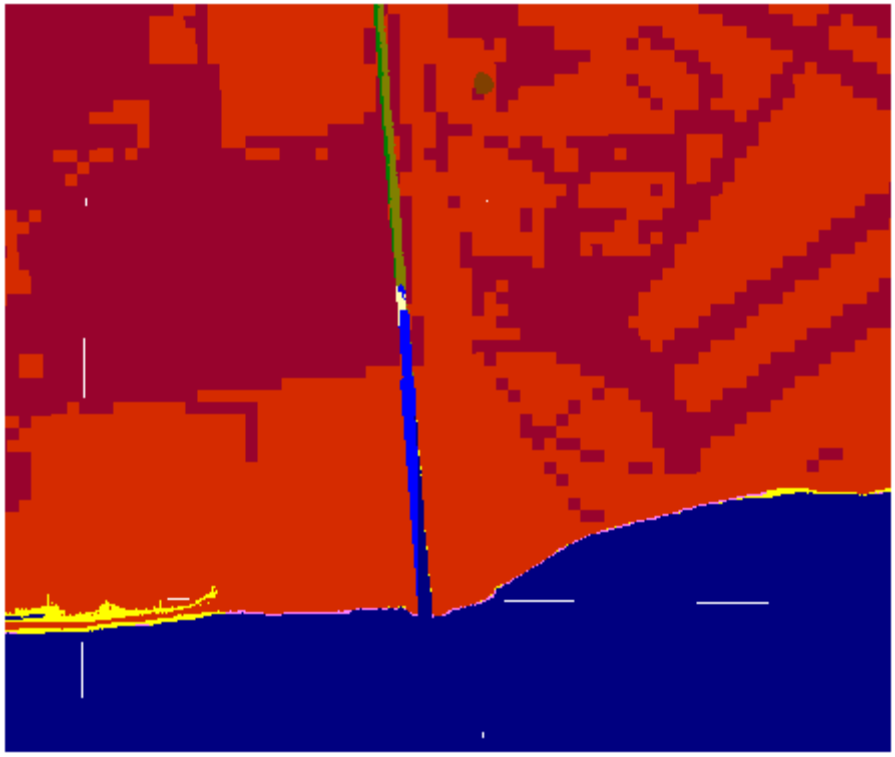
Pearl Harbor Context, Initial Condition



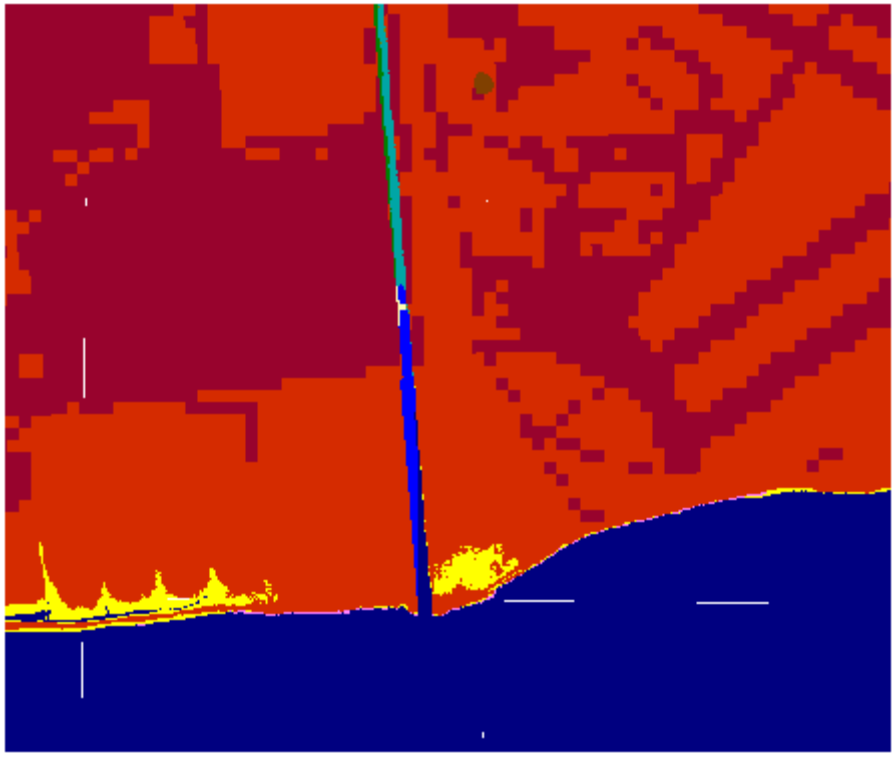
Pearl Harbor Context, 2025, 1.5 meter



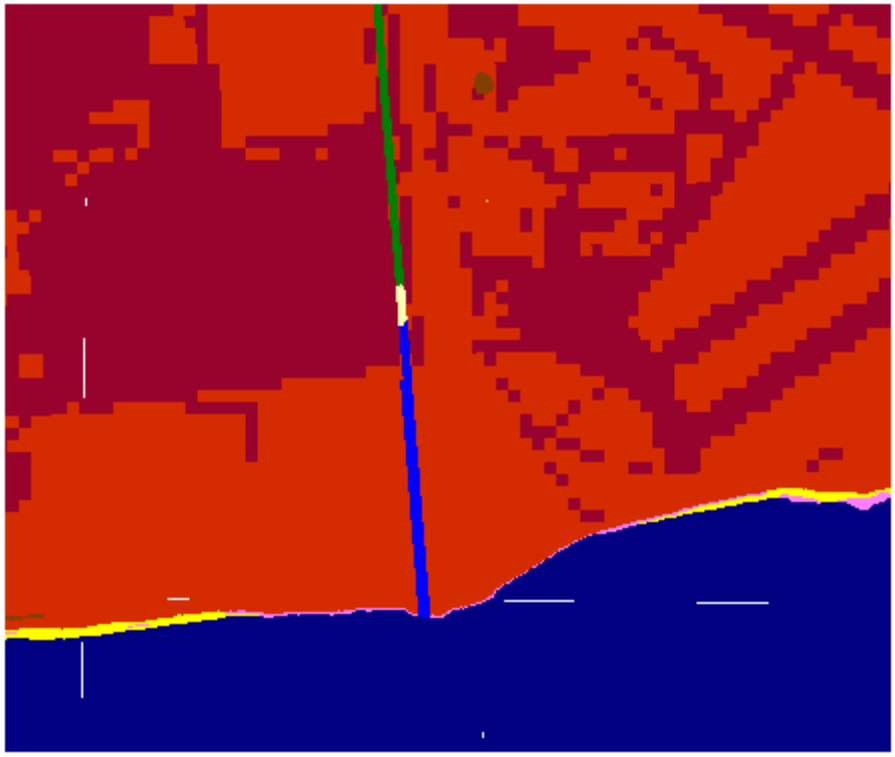
Pearl Harbor Context, 2050, 1.5 meter



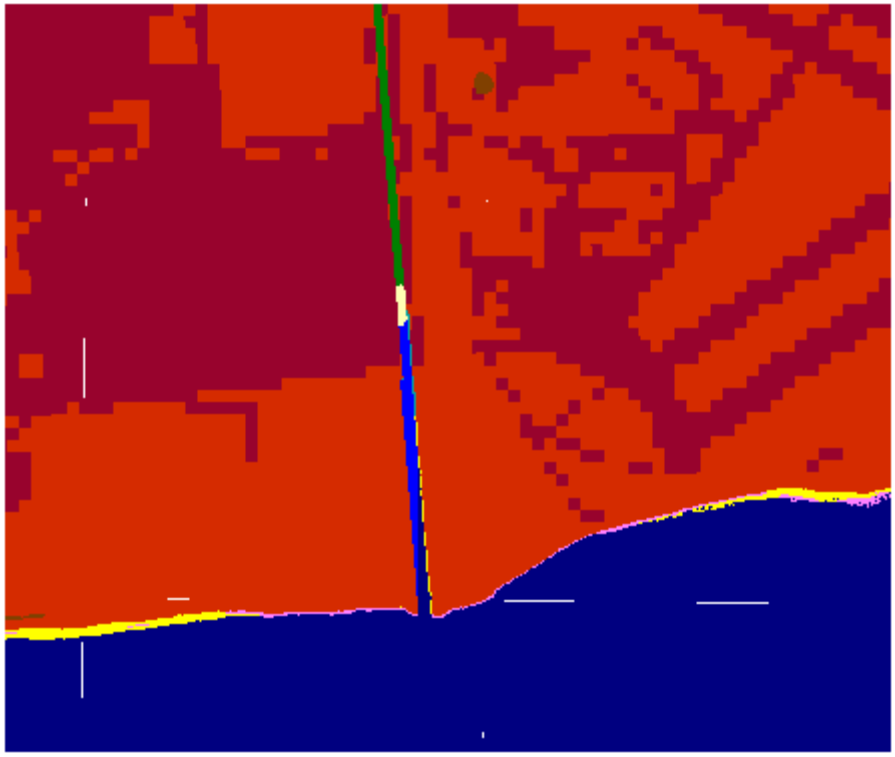
Pearl Harbor Context, 2075, 1.5 meter



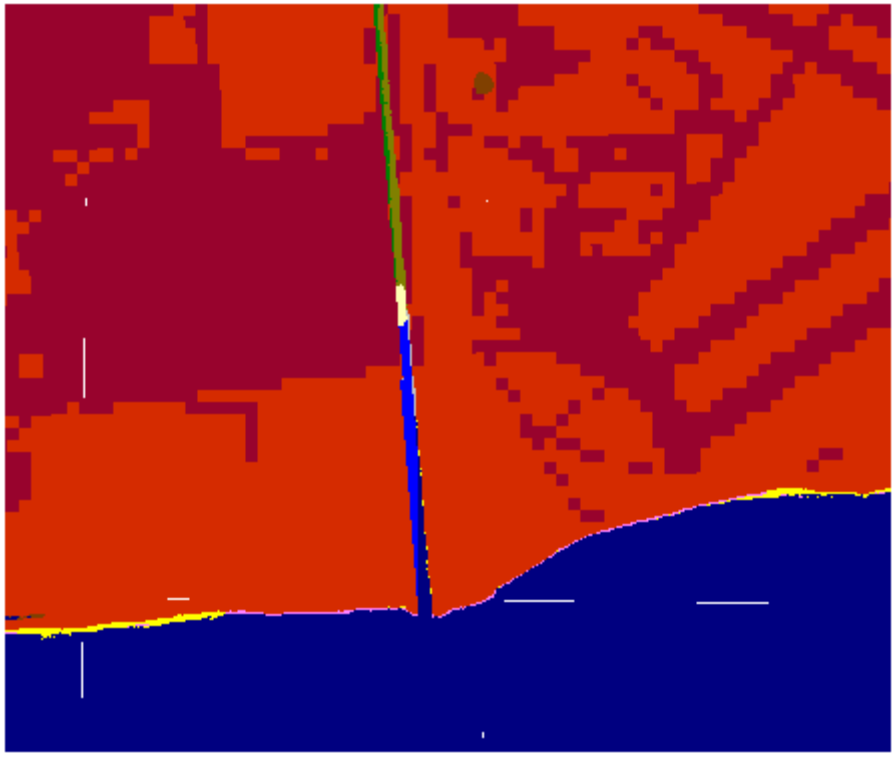
Pearl Harbor Context, 2100, 1.5 meter



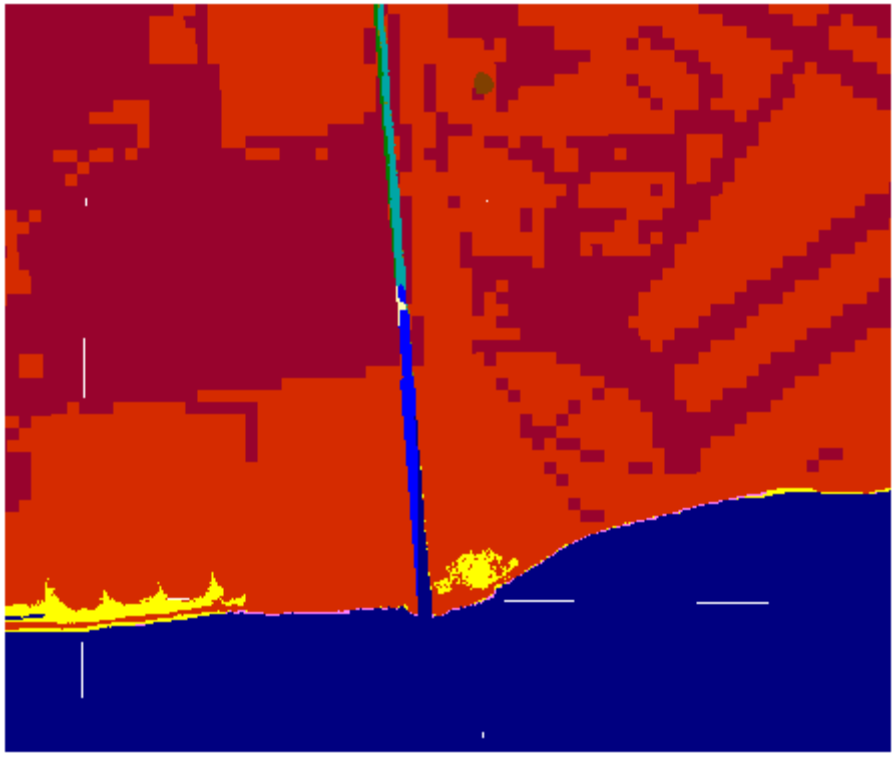
Pearl Harbor Context, Initial Condition



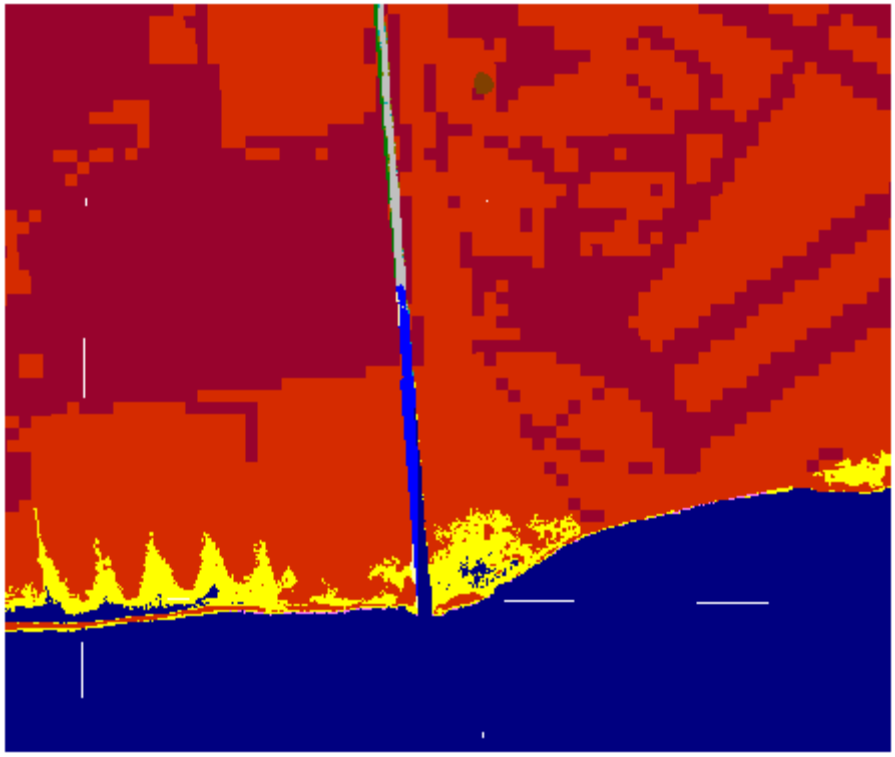
Pearl Harbor Context, 2025, 2 meter



Pearl Harbor Context, 2050, 2 meter



Pearl Harbor Context, 2075, 2 meter



Pearl Harbor Context, 2100, 2 meter