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

Prepared For

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

June 21, 2010

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

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


**Introduction** .......... **1**

**Model Summary** .......... **1**

Sea Level Rise Scenarios .......... 1

**Methods and Data Sources** .......... **4**

**Results** .......... **9**

**Discussion** .......... **55**

**References** .......... **57**

**Appendix A: Contextual Results** .......... **60**

# 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.

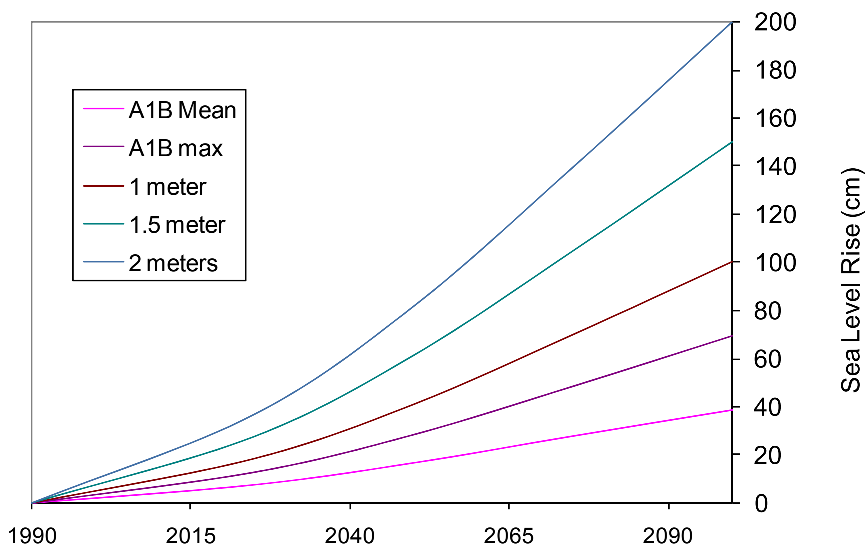
## *Sea Level Rise Scenarios*

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 (DEM) used in this simulation was supplied by USACE (United States Army Corps of Engineers) and is based on high-resolution LiDAR with a 2007 flight date (Figure 2).

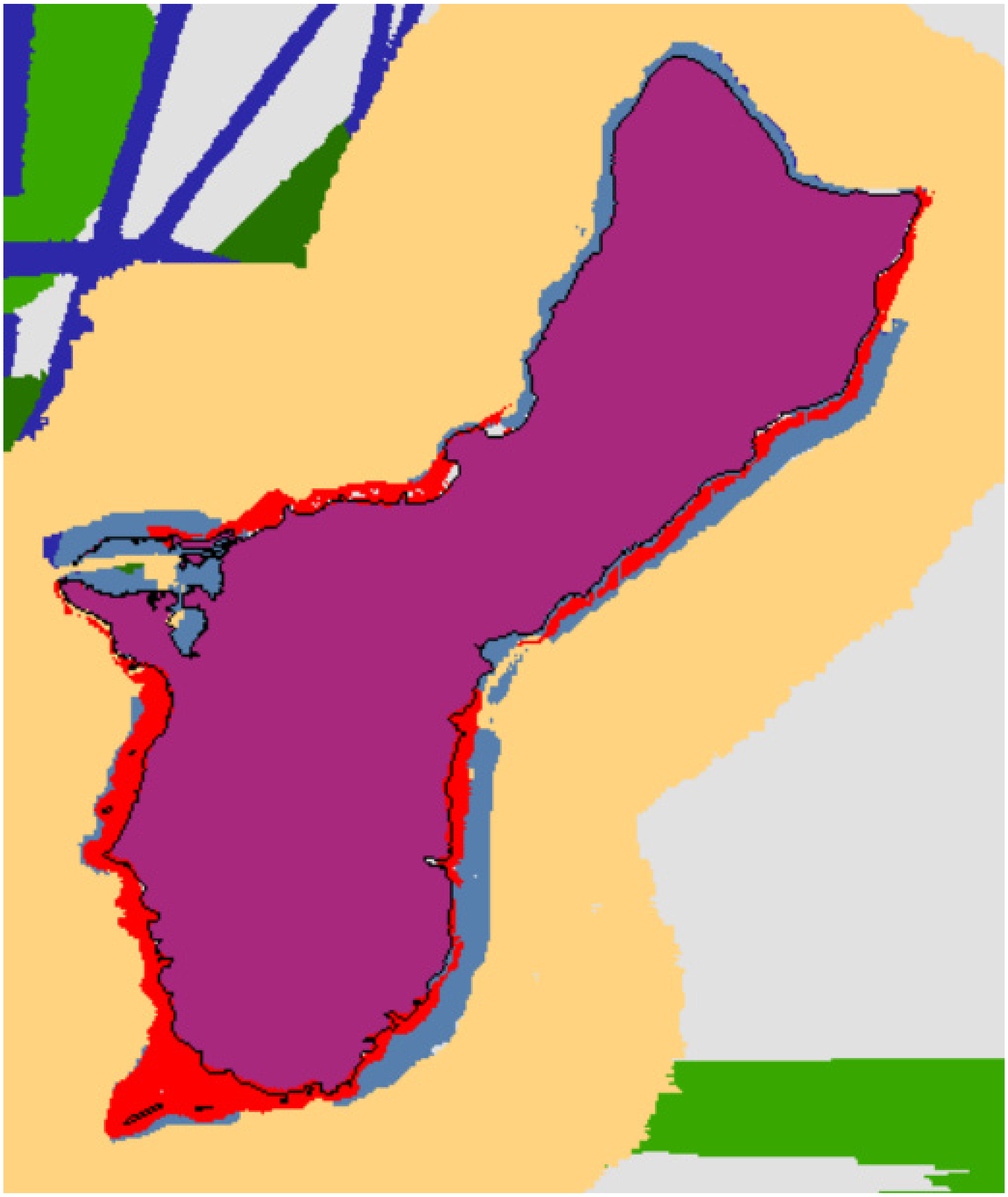


**Figure 1:** DEM sources used for Guam model. Red and purple regions are 2007 USACE LiDAR, bathymetry and topography respectively. Other colors are bathymetry data.

The wetlands layer for the study area was produced by the National Wetlands Inventory and is based on a 1975 photo date. After converting the NWI survey into 30-meter cells, the approximately thirty two thousand eight hundred acre refuge (approved acquisition boundary including water) is composed of the following categories:

| | |
|---|---|
| Undeveloped Dry Land | 85.1% |
| Open Ocean | 10.0% |
| Developed Dry Land | 2.5% |
| Swamp | 1.1% |
| Inland Open Water | 0.6% |
| Inland Fresh Marsh | 0.5% |
| Mangrove | 0.2% |

Guam NWR does have several extremely small and scattered impounded zones within the refuge according to National Wetland Inventory coverage. These areas remain protected within SLAMM simulations.

NOAA estimates the historic trend for sea level rise for Guam at -1.05 mm/year (1630000, Apra Harbor, Guam). This estimated rate of sea level rise for this refuge is considerably lower than the global average for the last 100 years (approximately 1.7 mm/year) suggesting uplift has been occurring at this site. However, these trends are based on the time period from 1948 to 1993 with a much higher trend evident after the earthquake of 1993 (Figure 3).

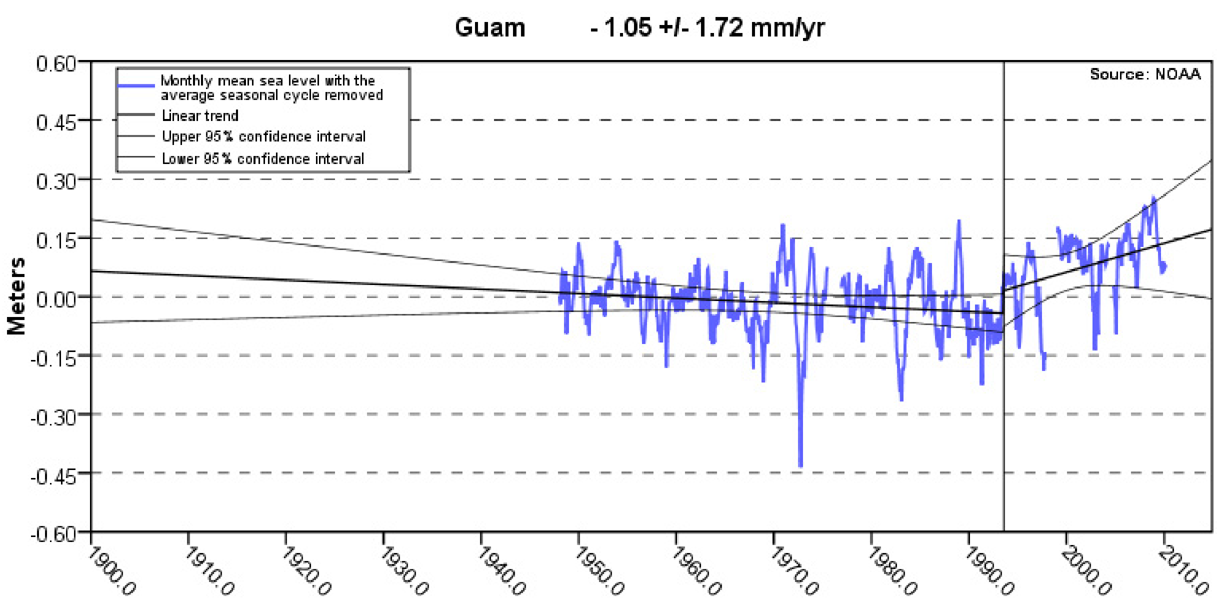



**Figure 2: Long Term SLR trend for Guam, interpreted by NOAA**

Another analysis of this same data set, without a restriction on the time-period, results in a positive trend of 1.34 mm/year (AusAID 2008, Figure 4). This estimate may provide a more measured approach when trying to estimate what will happen in the next 100 years as it incorporates both periods of uplift and subsidence. Church, White, and Hunter (2006) note that for locations within 15 degrees of the equator, such as Guam, the significant interannual variability associated with El Niño southern oscillation events results in large uncertainties in estimates of relative sea-level rise.

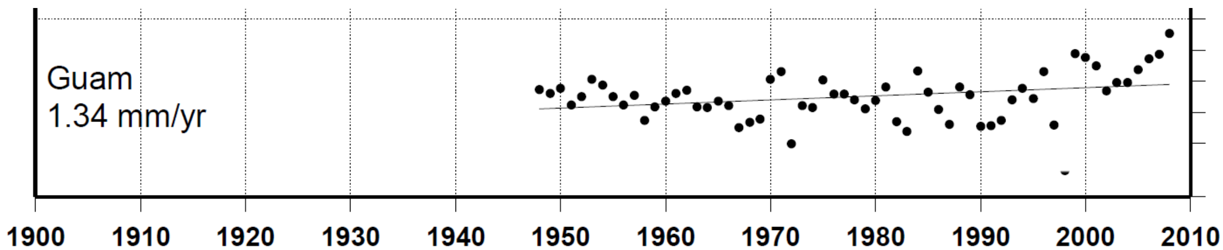



**Figure 3: Long Term SLR trend for Guam, interpreted by AusAID**

Blaz Miklavic, a geological expert regarding vertical land movement in Guam, noted studies of uplift and subsidence on a geological time scales, but not on the smaller time scales more pertinent to SLAMM simulations. Mr. Miklavic did note that it appears that the island may have subsided by about 4.1 cm in the last 50 years. When coupled with global SLR rates of 1.7 mm/year this would result in a historical SLR estimate of 2.5 mm/year. Mr. Miklavic also stated that it would be very difficult to predict the rate of uplift or subsidence that will occur over the next 100 years.

Therefore, the projected rate of island uplift or subsidence will remain a source of model uncertainty for this site. For this project, we used the value of 1.34 mm/year (AusAID 2008). This falls between the NOAA estimate through 1993 of -1.05 mm/year and the higher 2.5 mm/year estimate based on recent subsidence rates. We also ran the model with subsidence rates of -1.05 mm/year and 2.5 mm/year as a bounding analysis. More information about these results may be found in the *Discussion* section below.

The tide range (Great diurnal range or GT) for the eastern shore of the island was estimated at 0.548 using the Pago Bay tide gage (1631428), while the tide range for the western shore was estimated at 0.715 using the Apra Harbor gage (1630000).

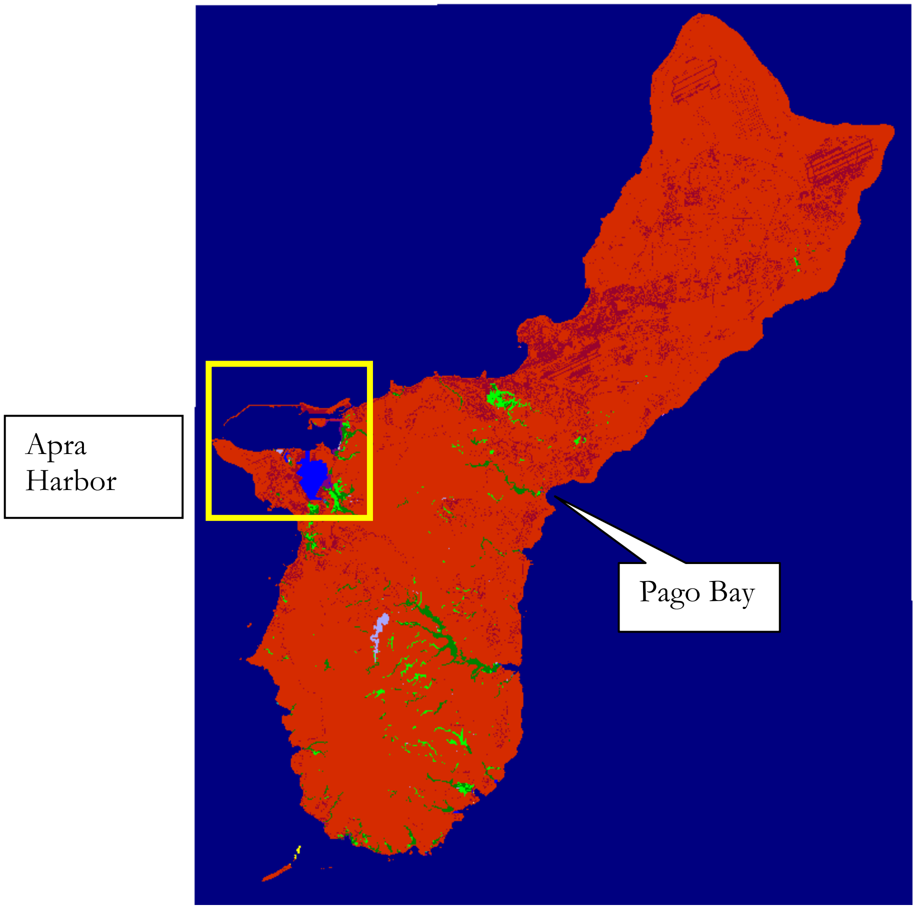



**Figure 4**: General Location of NOAA Gages, Guam.

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. Mangrove accretion rates are set to 7.0 mm/year in the SLAMM model (based on Cahoon et al. 1999) Erosion rates for the marsh-to-water interface were set to 1.8 horizontal meters per year (when adequate wave-setup is present to indicate erosion). Tidal flat erosion rates were set to 2.0 horizontal meters per year.

An elevation correction (MTL - MHHW) of -0.215 meters was used for the west coast and -0.283 for the east. The DEM metadata notes that MHHW was used as the vertical datum for the LiDAR data. The tide gages used to estimate the tide range were therefore used to convert to the model datum of Mean Tide Level (MTL)

Modeled U.S. Fish and Wildlife Service refuge boundaries for Guam 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 30 meter by 30 meter cells. (Note that the SLAMM model will also track partial conversion of cells based on elevation and slope.)

Despite contacting refuge personnel and other scientific experts on the island, we were not able to locate island-specific wetland erosion or accretion data.

## SUMMARY OF SLAMM INPUT PARAMETERS FOR GUAM NWR

| Parameter | | |
|---|---|---|
| Description | West | East |
| NWI Photo Date (YYYY) | 1975 | 1975 |
| DEM Date (YYYY) | 2008 | 2008 |
| Direction Offshore [n,s,e,w] | West | East |
| Historic Trend (mm/yr) | 1.34 | 1.34 |
| MTL-NAVD88 (m) | -0.283 | -0.215 |
| GT Great Diurnal Tide Range (m) | 0.715 | 0.548 |
| Salt Elev. (m above MTL) | 0.51 | 0.39 |
| Marsh Erosion (horz. m /yr) | 1.8 | 1.8 |
| Swamp Erosion (horz. m /yr) | 1 | 1 |
| T.Flat Erosion (horz. m /yr) | 2 | 2 |
| Reg. Flood Marsh Accr (mm/yr) | 3.9 | 3.9 |
| Irreg. Flood Marsh Accr (mm/yr) | 4.7 | 4.7 |
| Tidal Fresh Marsh Accr (mm/yr) | 5.9 | 5.9 |
| Beach Sed. Rate (mm/yr) | 0.5 | 0.5 |
| Freq. Overwash (years) | 15 | 15 |
| Use Elev Pre-processor [True,False] | FALSE | FALSE |

# Results

The SLAMM simulation suggests that the Guam National Wildlife Refuge will be extremely resilient to the effects of sea level rise. Only mangrove, which comprises roughly 0.2% of the entire wetland, is predicted to lose more than 2% in any scenario.

| SLR by 2100 (m) | 0.39 | 0.69 | 1 | 1.5 | 2 |
|---|---|---|---|---|---|
| Undeveloped Dry Land | 0% | 0% | 1% | 1% | 1% |
| Swamp | 0% | 0% | 0% | 0% | 1% |
| Inland Fresh Marsh | 1% | 1% | 1% | 1% | 2% |
| Mangrove | 2% | 2% | 2% | 9% | 21% |

**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:

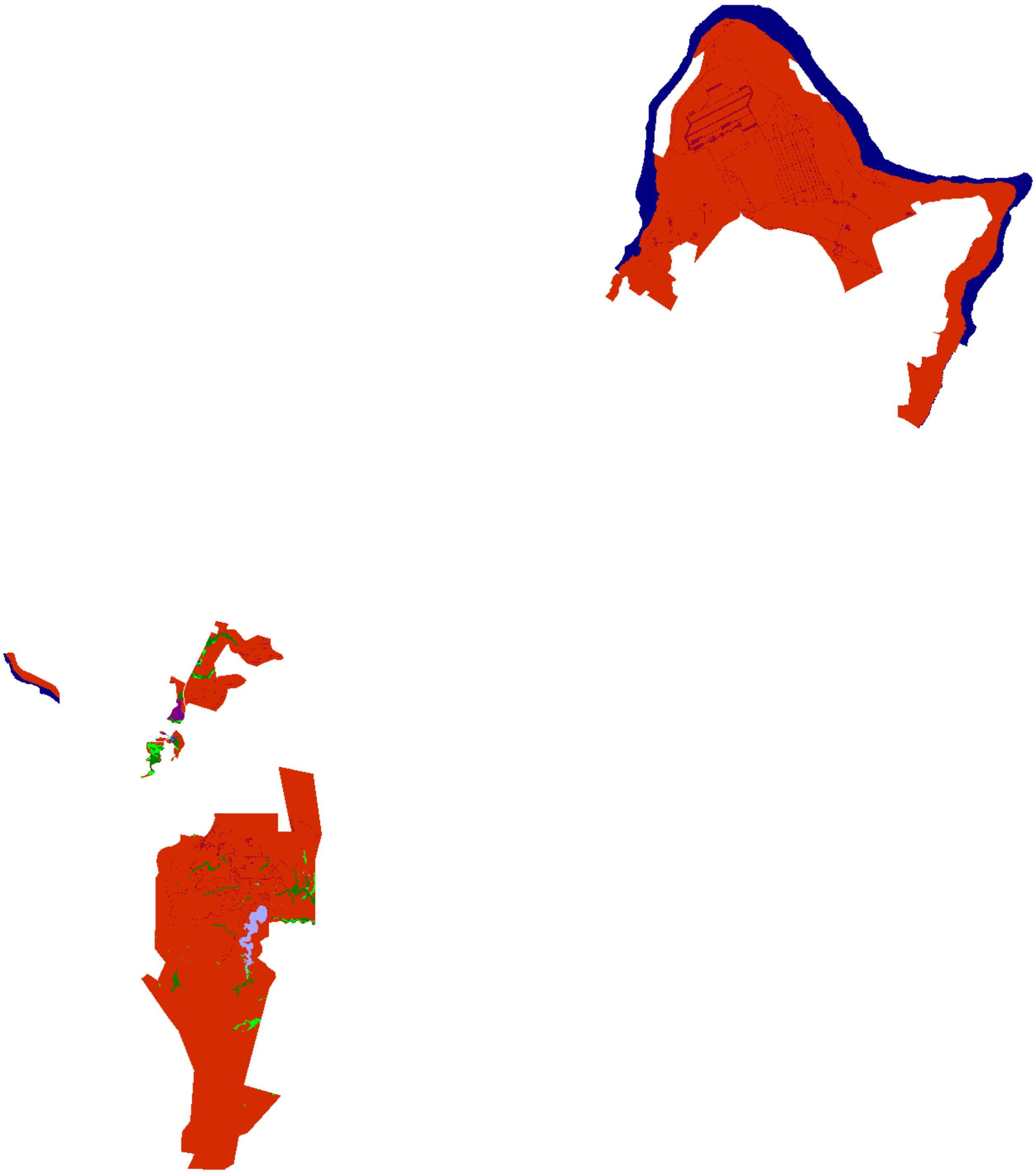
| | |
|---|---|
| Undeveloped Dry Land | |
| Open Ocean | |
| Developed Dry Land | |
| Swamp | |
| Inland Open Water | |
| Inland Fresh Marsh | |
| Mangrove | |
| Regularly Flooded Marsh | |
| Estuarine Open Water | |
| Tidal Flat | |
| Transitional Salt Marsh | |
| Ocean Beach | |

Maps of model results are shown for the NWR boundaries and also for Apra Harbor (Figure 5), where SLR effects are predicted to be somewhat more prominent than most other locations on the island (i.e. some effects are actually visible).

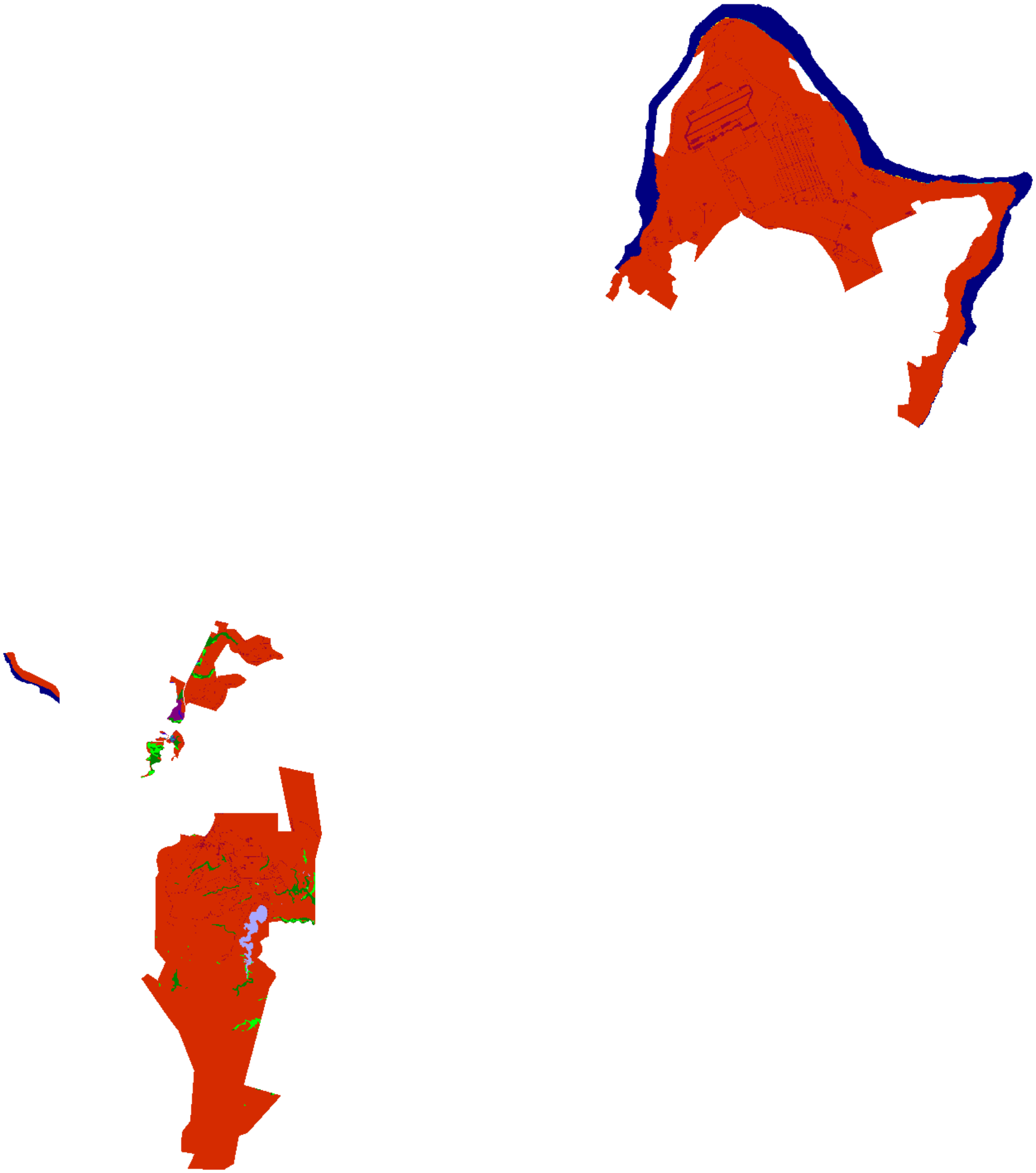
Guam Raster
IPCC Scenario A1B-Mean, 0.39 M SLR Eustatic by 2100

Results in Acres

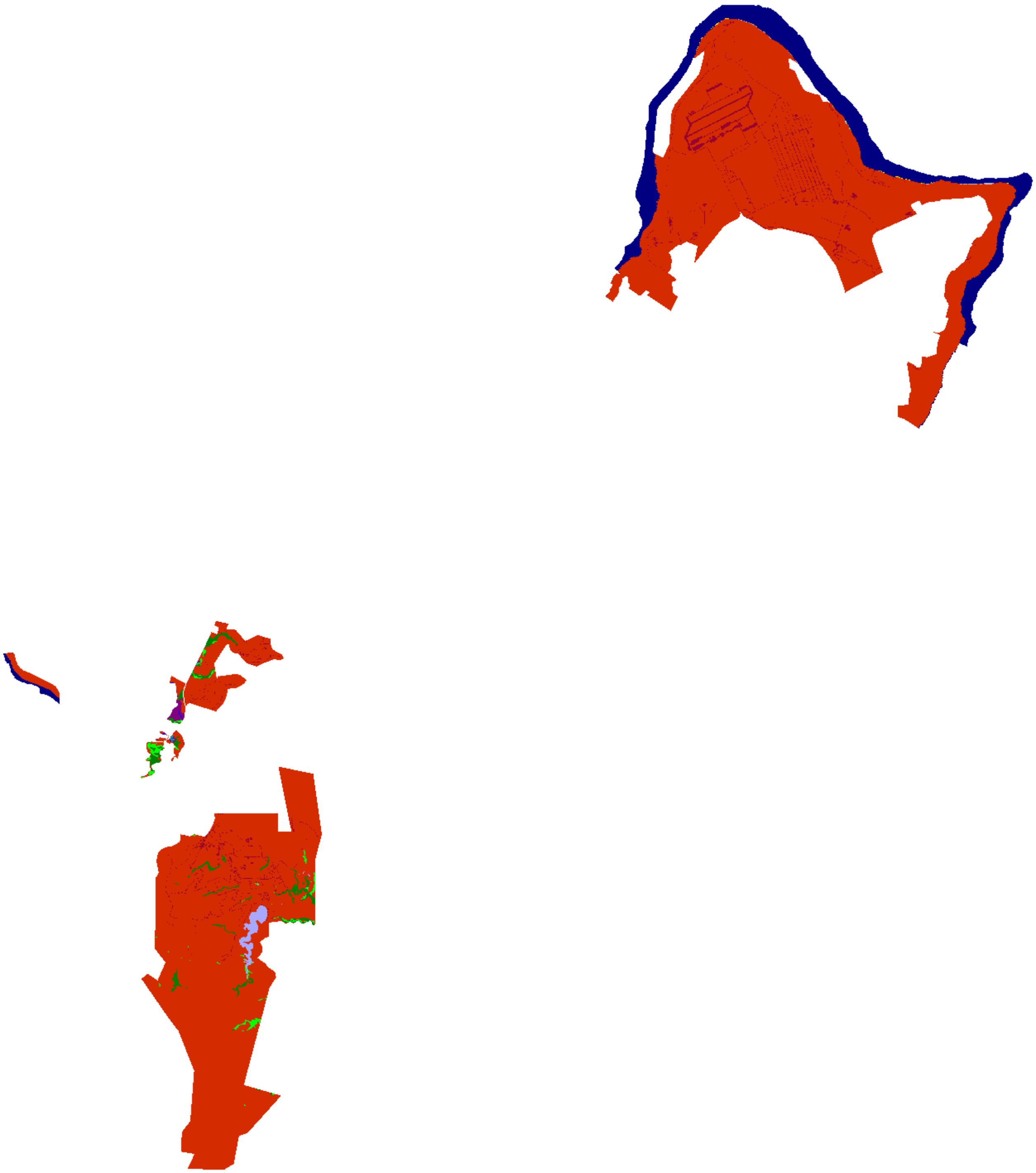
| | Initial | 2025 | 2050 | 2075 | 2100 |
|---|---|---|---|---|---|
| Undeveloped Dry Land | 27888.0 | 27779.4 | 27775.8 | 27771.4 | 27767.1 |
| Open Ocean | 3276.5 | 3338.6 | 3343.5 | 3348.9 | 3353.6 |
| Developed Dry Land | 828.2 | 828.2 | 828.2 | 828.2 | 828.2 |
| Swamp | 345.8 | 345.8 | 345.7 | 345.6 | 345.6 |
| Inland Open Water | 187.3 | 187.3 | 187.3 | 187.3 | 187.3 |
| Inland Fresh Marsh | 162.1 | 161.7 | 161.3 | 161.1 | 161.1 |
| Mangrove | 66.1 | 64.9 | 64.9 | 64.9 | 64.9 |
| Regularly Flooded Marsh | 6.2 | 28.1 | 10.4 | 10.4 | 10.2 |
| Estuarine Open Water | 4.4 | 5.8 | 6.5 | 21.2 | 21.9 |
| Tidal Flat | 0.0 | 0.3 | 18.3 | 5.8 | 5.9 |
| Ocean Beach | 0.0 | 16.5 | 13.6 | 10.6 | 8.2 |
| Trans. Salt Marsh | 0.0 | 8.1 | 9.3 | 9.2 | 10.7 |
| **Total (incl. water)** | **32764.6** | **32764.6** | **32764.6** | **32764.6** | **32764.6** |



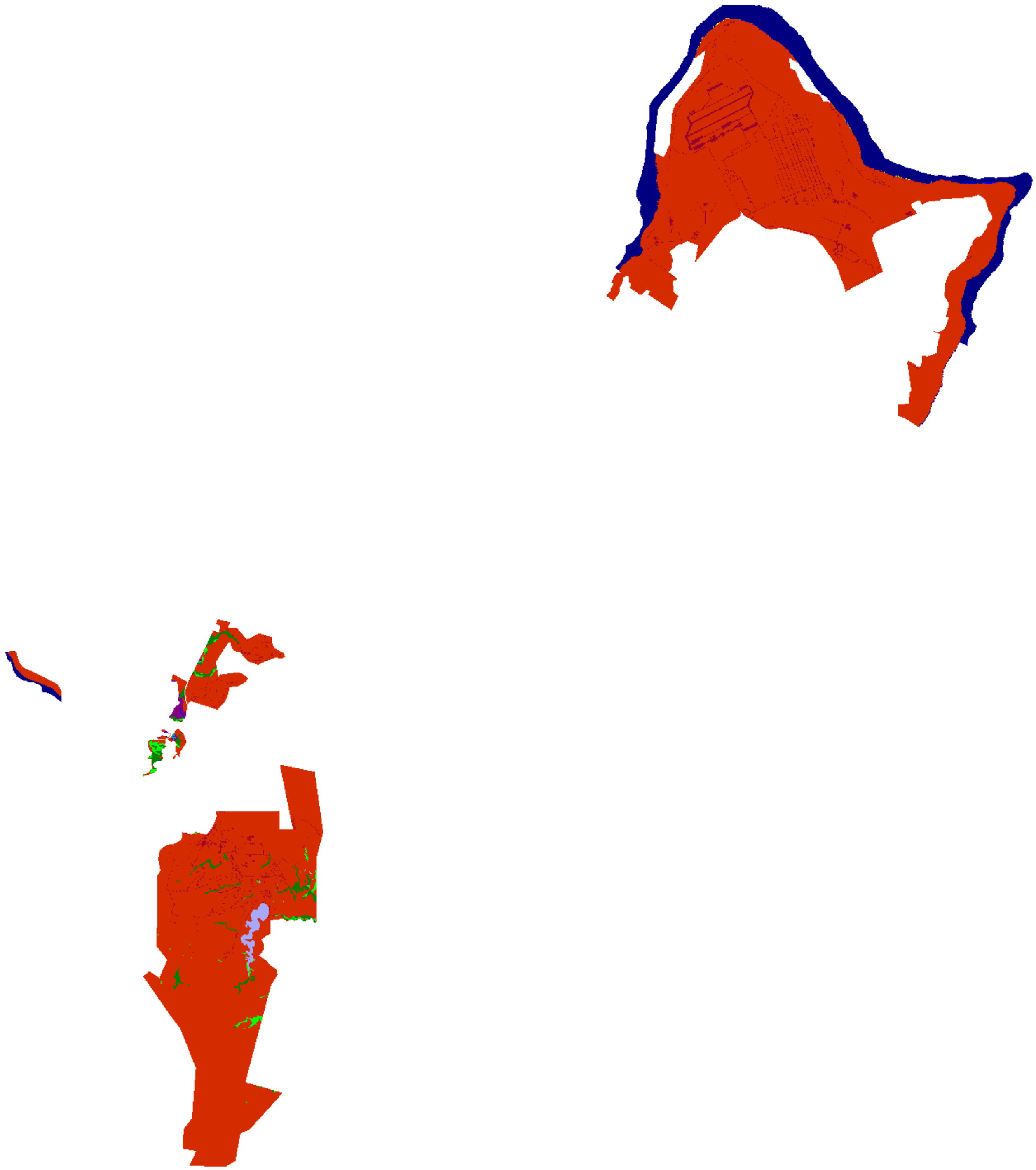
Guam NWR, Initial Condition



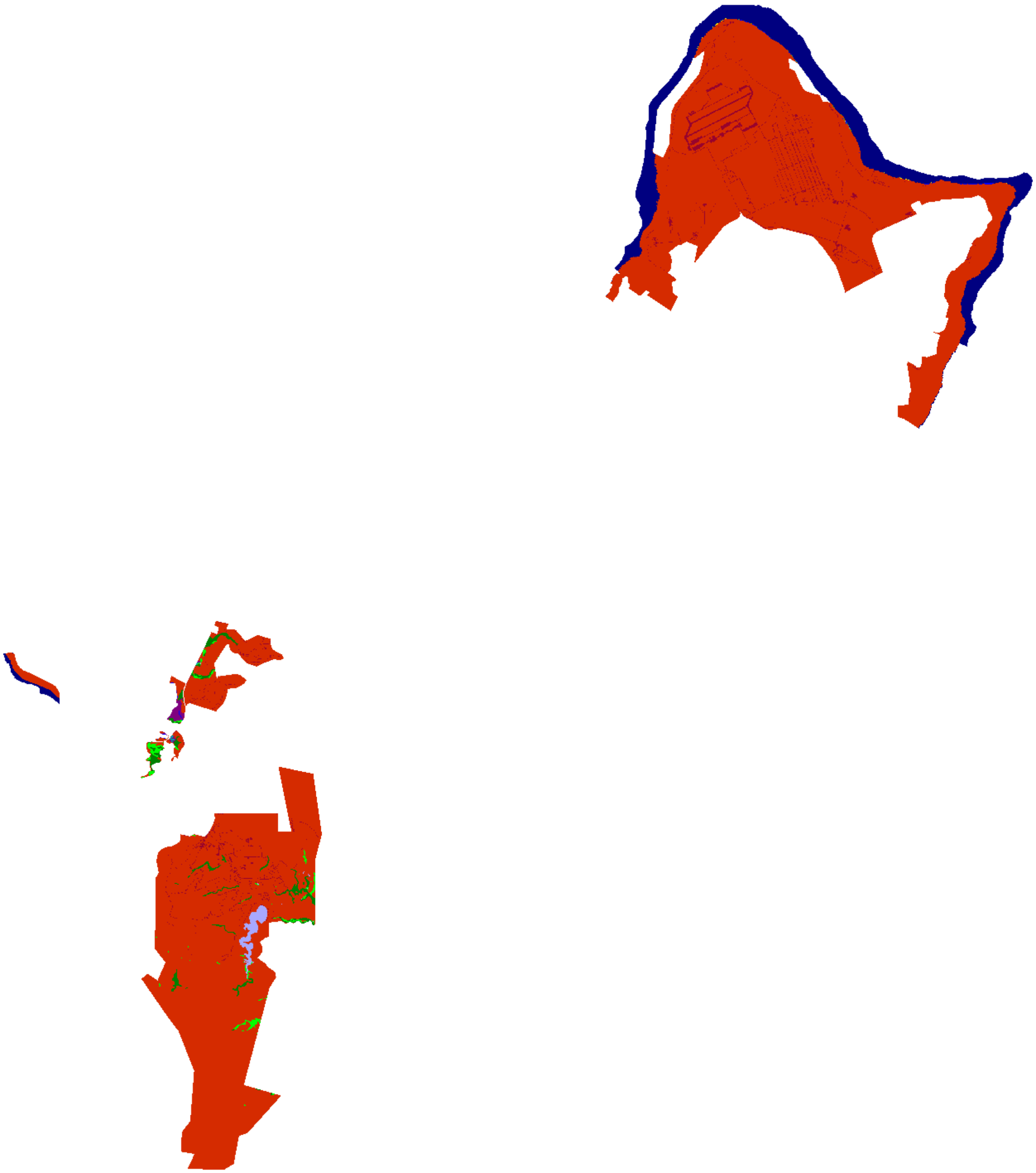
Guam NWR, 2025, Scenario A1B Mean



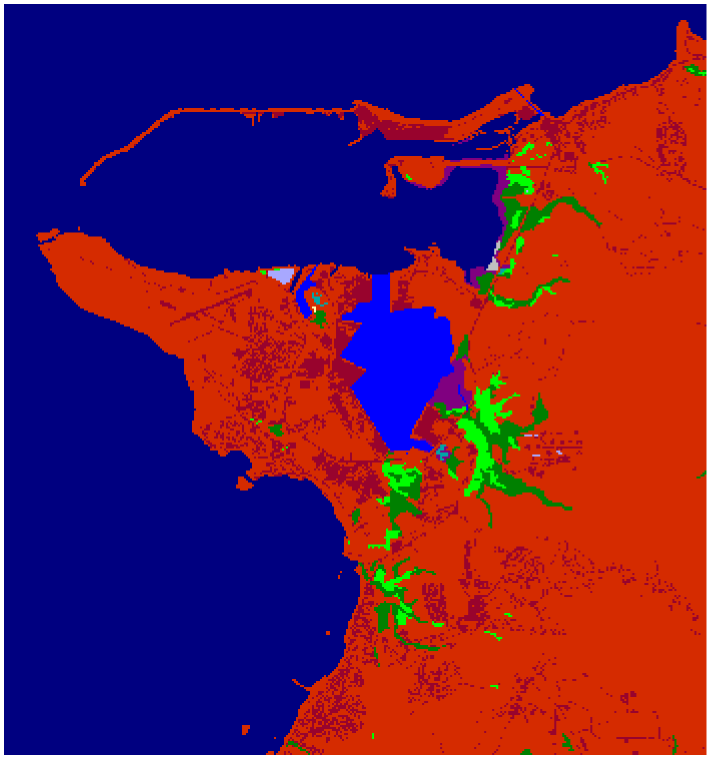
Guam NWR, 2050, Scenario A1B Mean



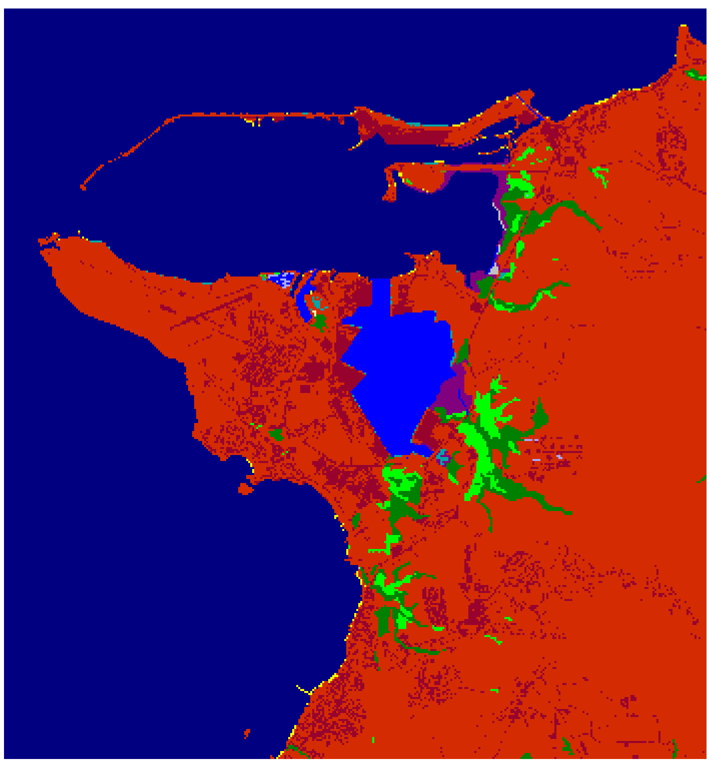
Guam NWR, 2075, Scenario A1B Mean



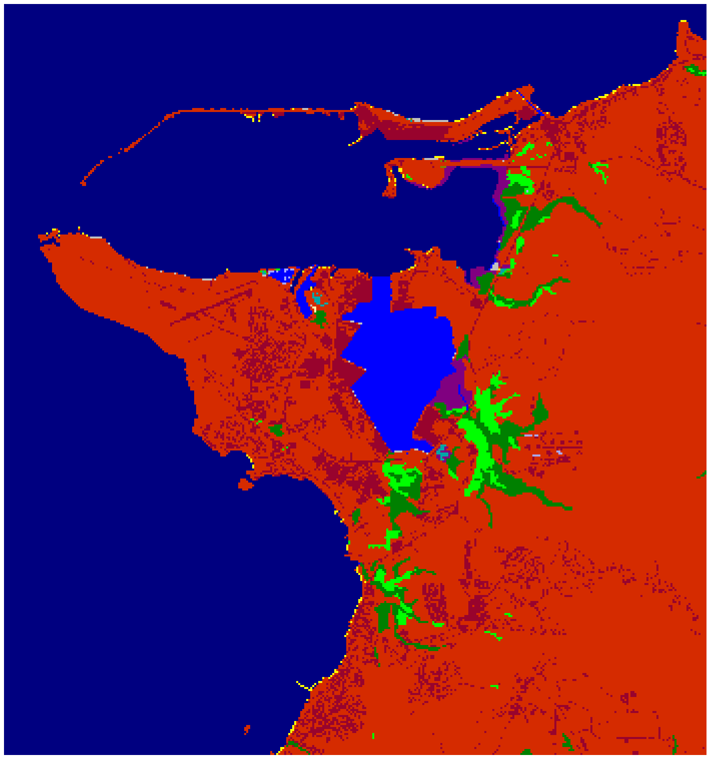
Guam NWR, 2100, Scenario A1B Mean



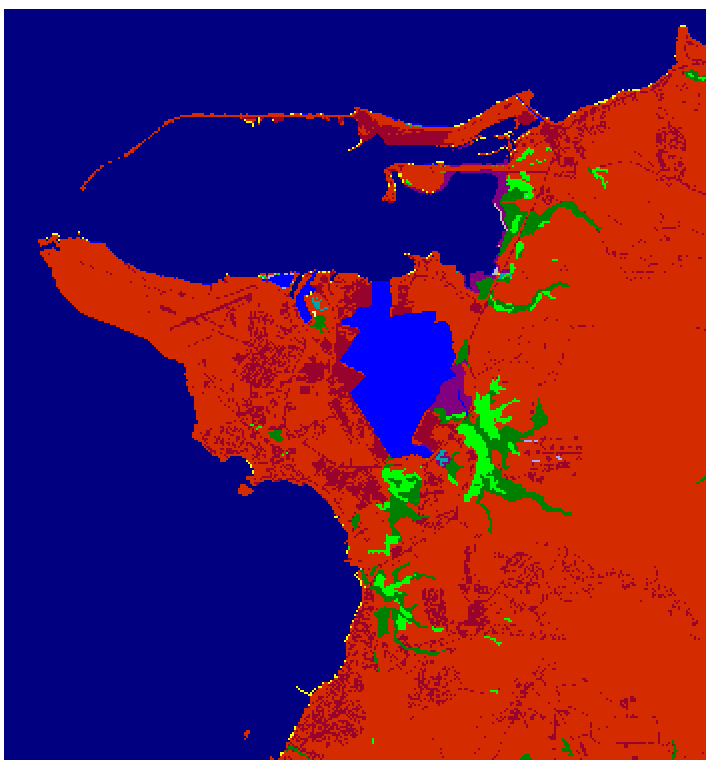
Guam NWR, Initial Condition, Apra Harbor



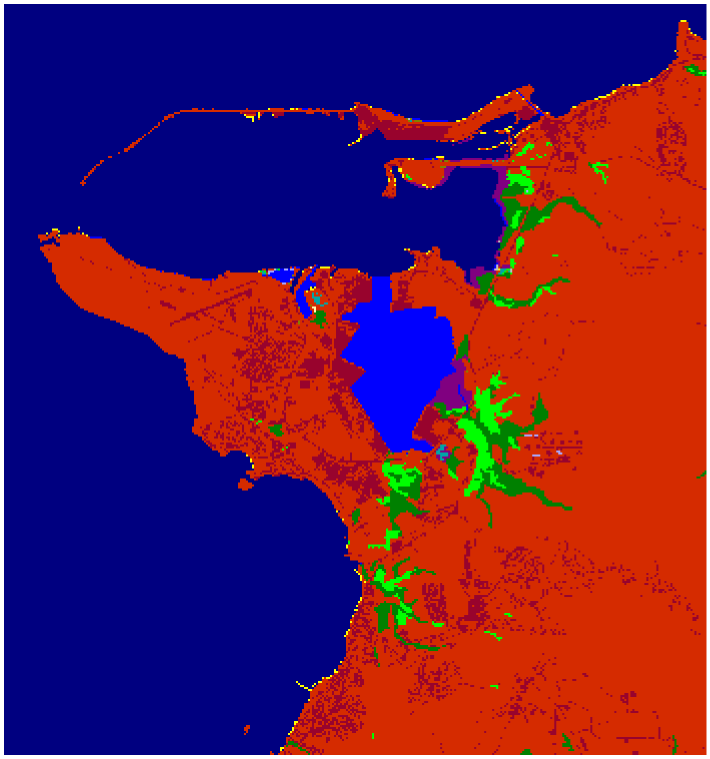
Guam NWR, 2025, Scenario A1B Mean, Apra Harbor



Guam NWR, 2050, Scenario A1B Mean, Apra Harbor



Guam NWR, 2075, Scenario A1B Mean, Apra Harbor



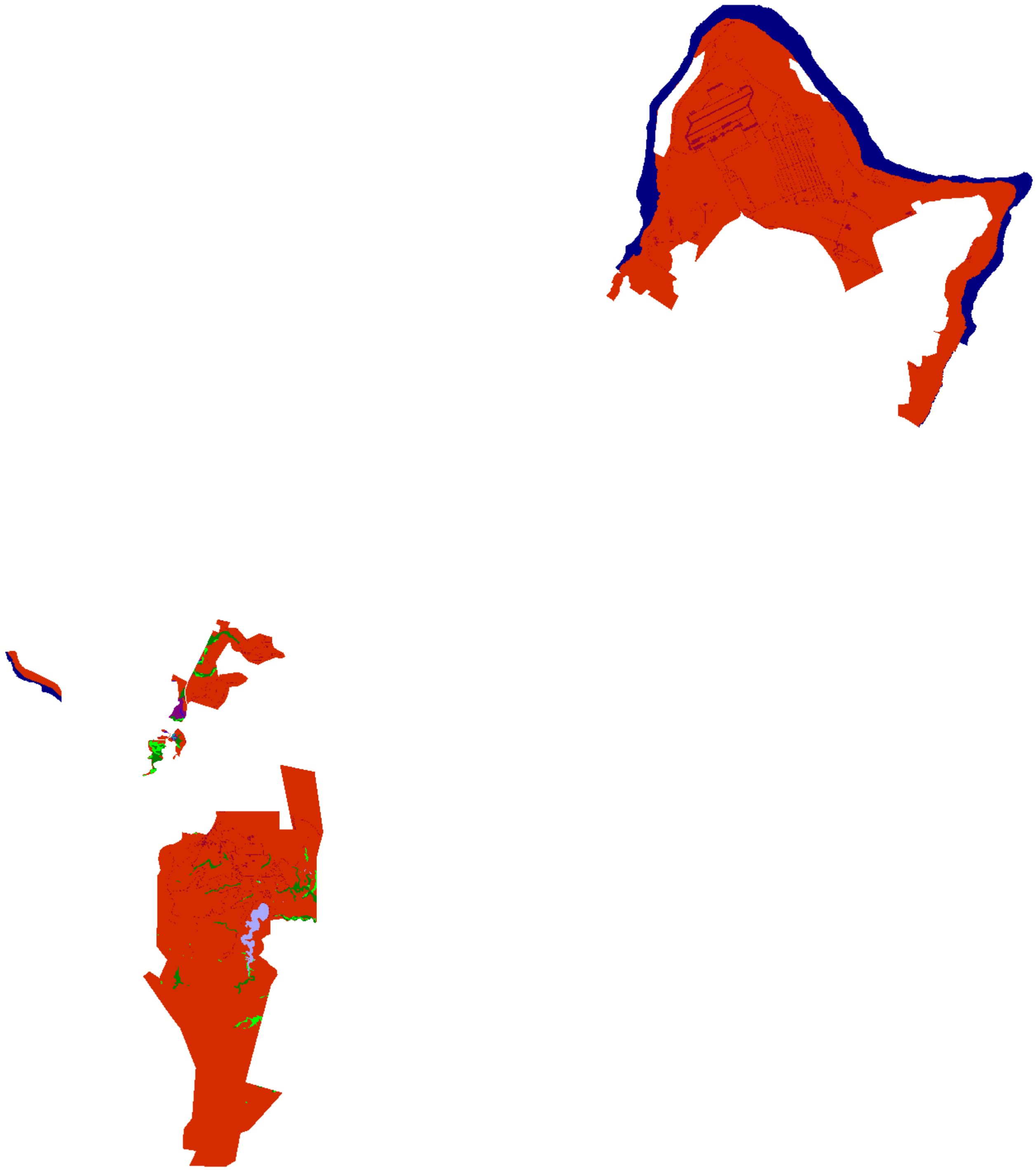
Guam NWR, 2100, Scenario A1B Mean, Apra Harbor

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

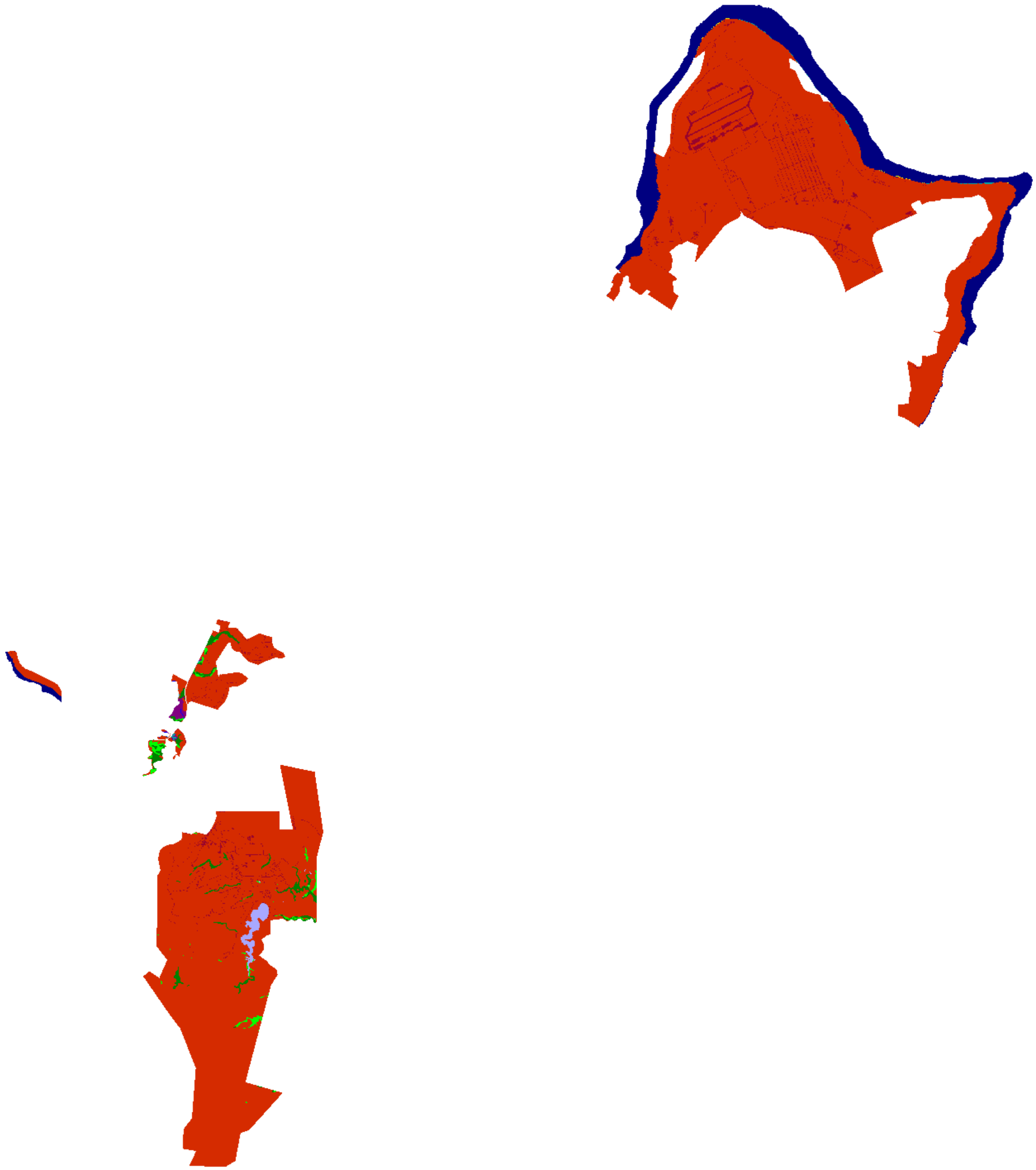
Guam Raster
IPCC Scenario A1B-Max, 0.69 M SLR Eustatic by 2100

Results in Acres

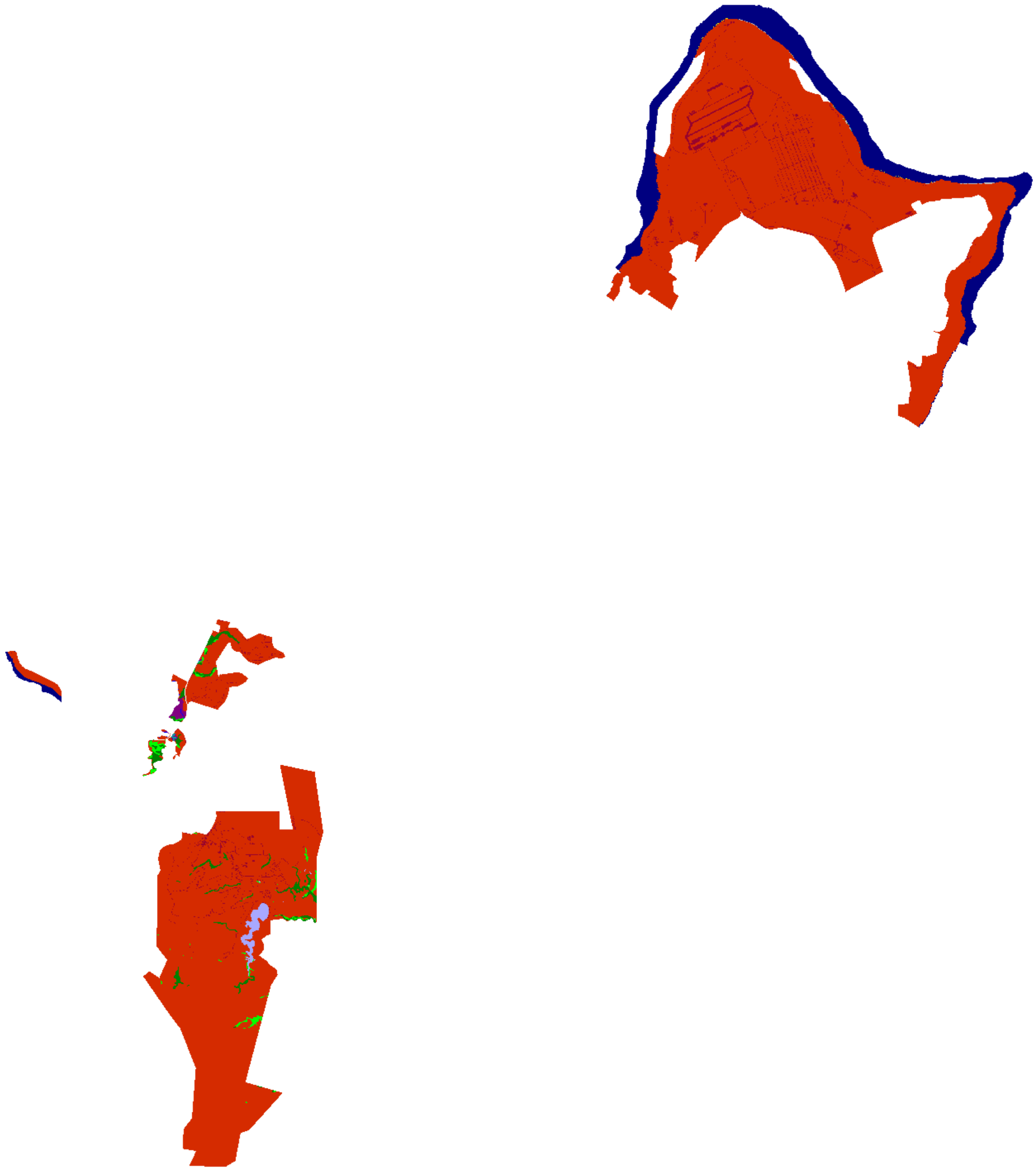
| | Initial | 2025 | 2050 | 2075 | 2100 |
|---|---|---|---|---|---|
| Undeveloped Dry Land | 27888.0 | 27777.1 | 27770.8 | 27762.9 | 27755.1 |
| Open Ocean | 3276.5 | 3345.5 | 3353.3 | 3361.9 | 3368.0 |
| Developed Dry Land | 828.2 | 828.2 | 828.2 | 828.2 | 828.2 |
| Swamp | 345.8 | 345.7 | 345.6 | 345.6 | 345.6 |
| Inland Open Water | 187.3 | 187.3 | 187.3 | 187.3 | 187.3 |
| Inland Fresh Marsh | 162.1 | 161.5 | 161.0 | 160.8 | 160.7 |
| Mangrove | 66.1 | 64.9 | 64.9 | 64.9 | 64.9 |
| Regularly Flooded Marsh | 6.2 | 29.0 | 10.4 | 10.5 | 11.5 |
| Estuarine Open Water | 4.4 | 5.9 | 6.6 | 24.1 | 25.0 |
| Tidal Flat | 0.0 | 0.3 | 19.8 | 3.8 | 3.7 |
| Ocean Beach | 0.0 | 10.9 | 6.5 | 2.2 | 0.6 |
| Trans. Salt Marsh | 0.0 | 8.4 | 10.1 | 12.5 | 14.0 |
| **Total (incl. water)** | **32764.6** | **32764.6** | **32764.6** | **32764.6** | **32764.6** |



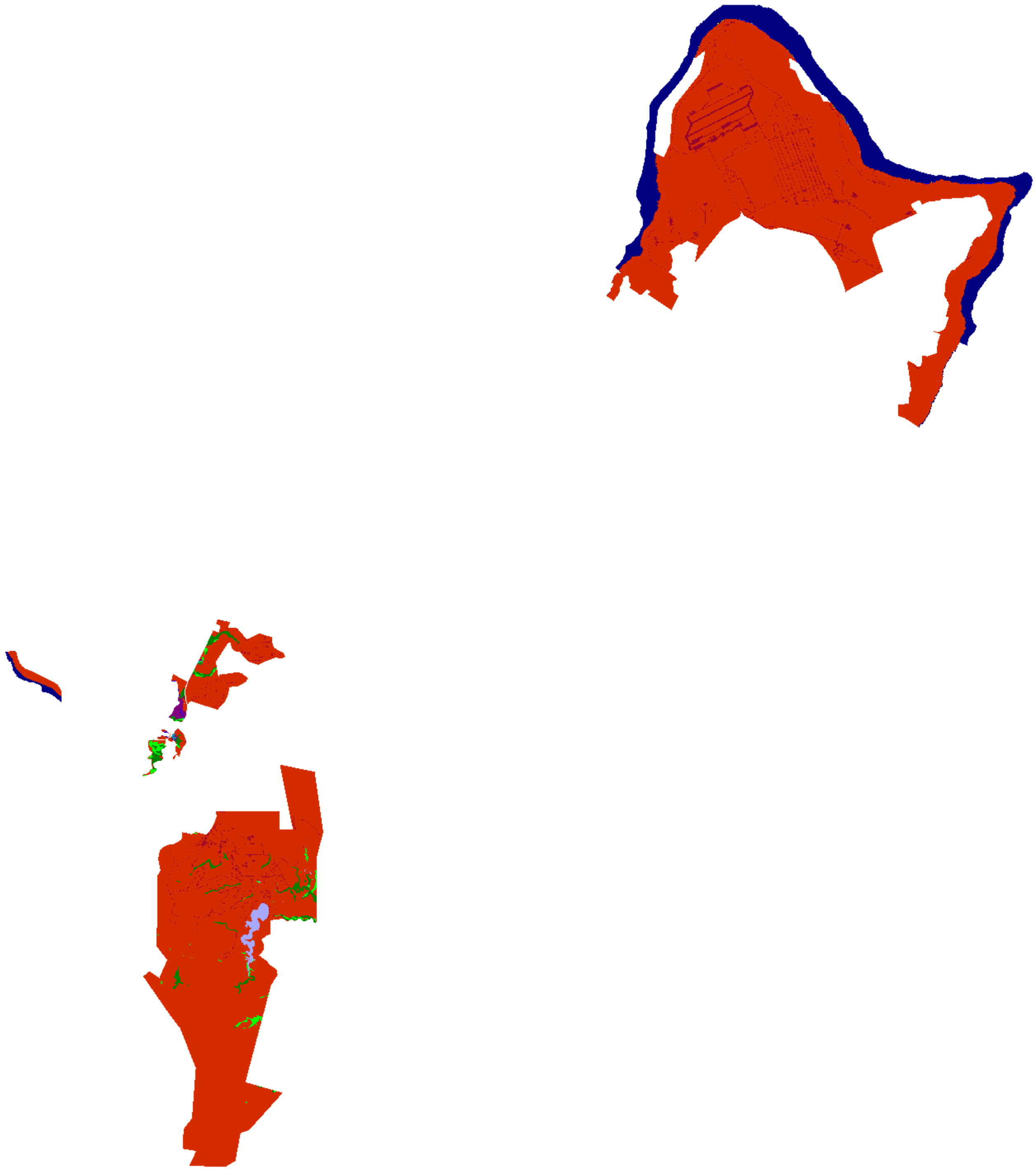
Guam NWR, Initial Condition



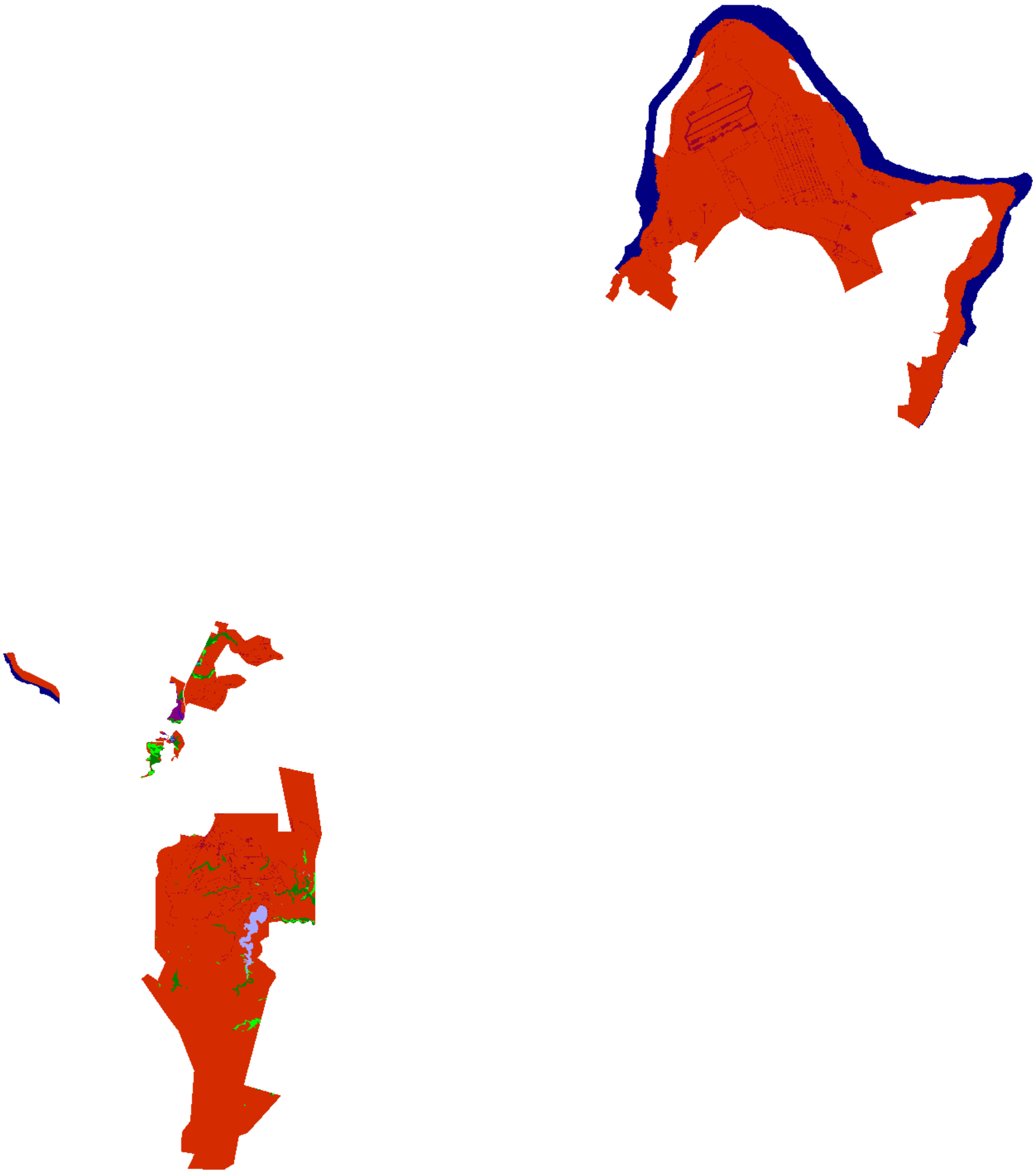
Guam NWR, 2025, Scenario A1B Maximum



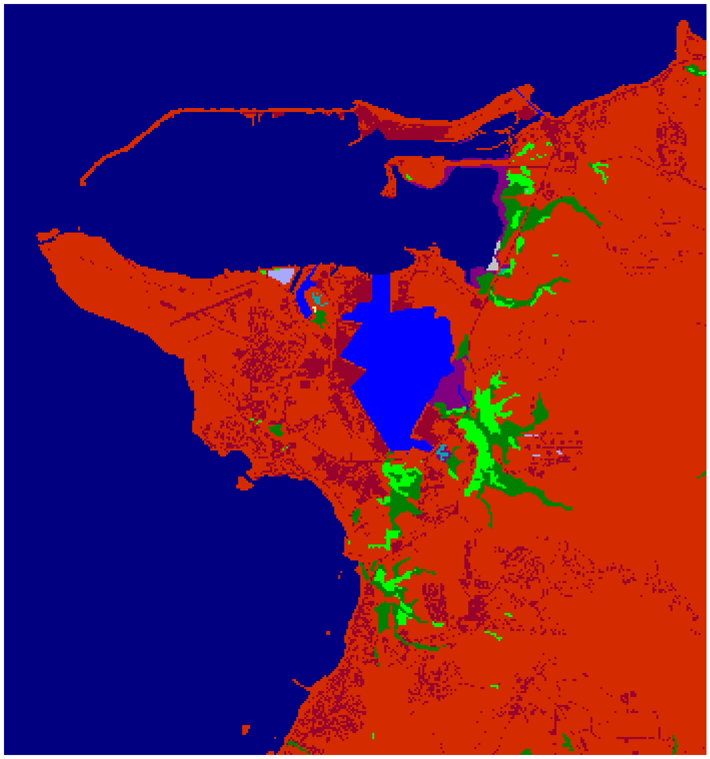
Guam NWR, 2050, Scenario A1B Maximum



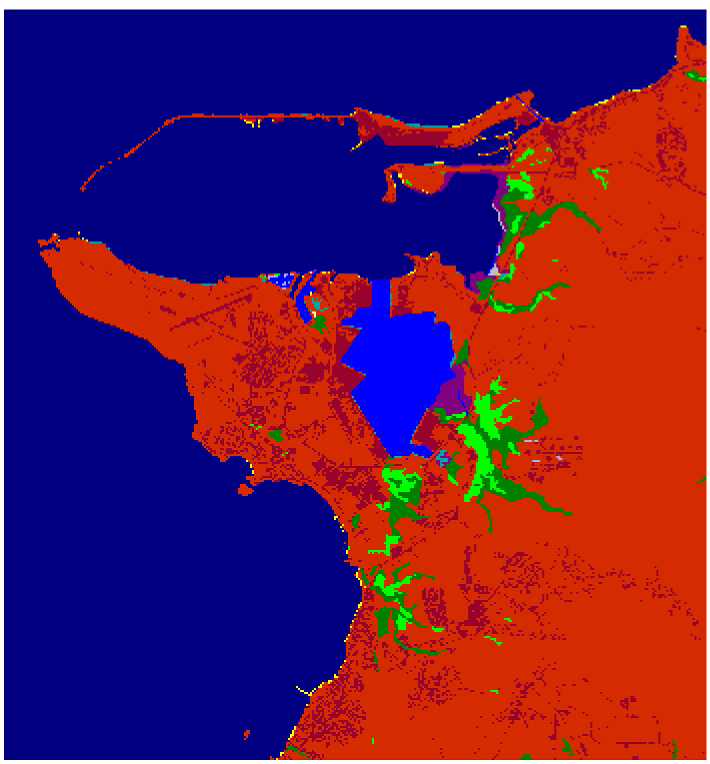
Guam NWR, 2075, Scenario A1B Maximum



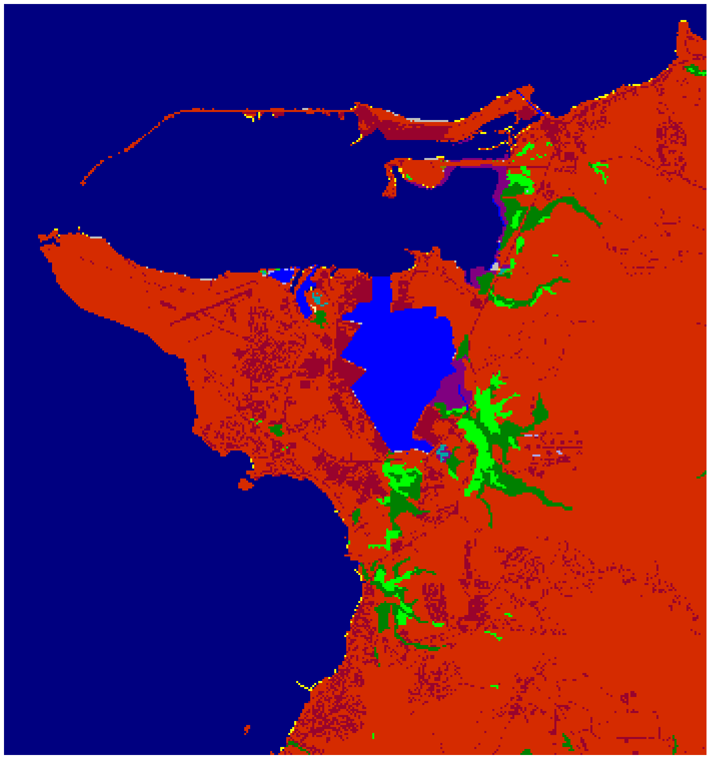
Guam NWR, 2100, Scenario A1B Maximum



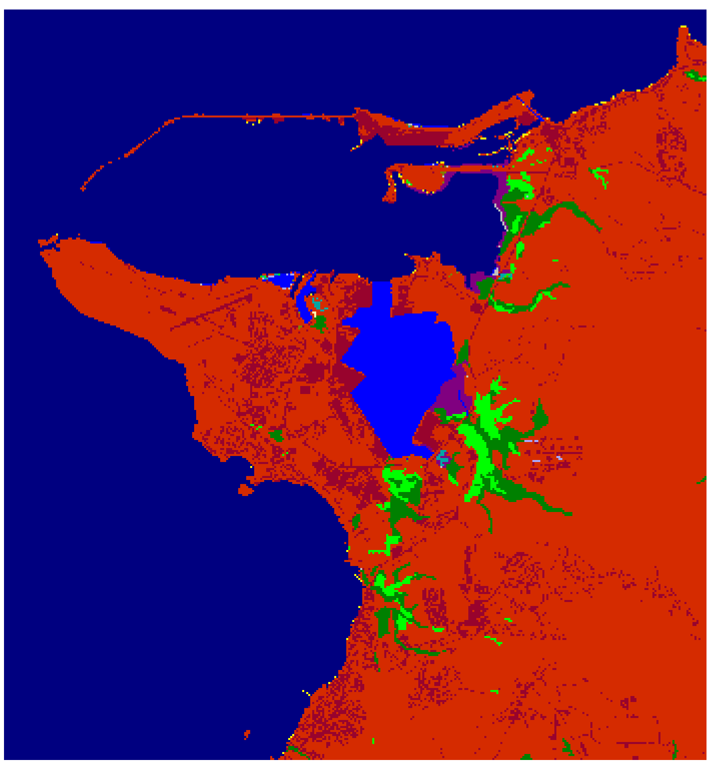
Guam NWR, Initial Condition, Apra Harbor



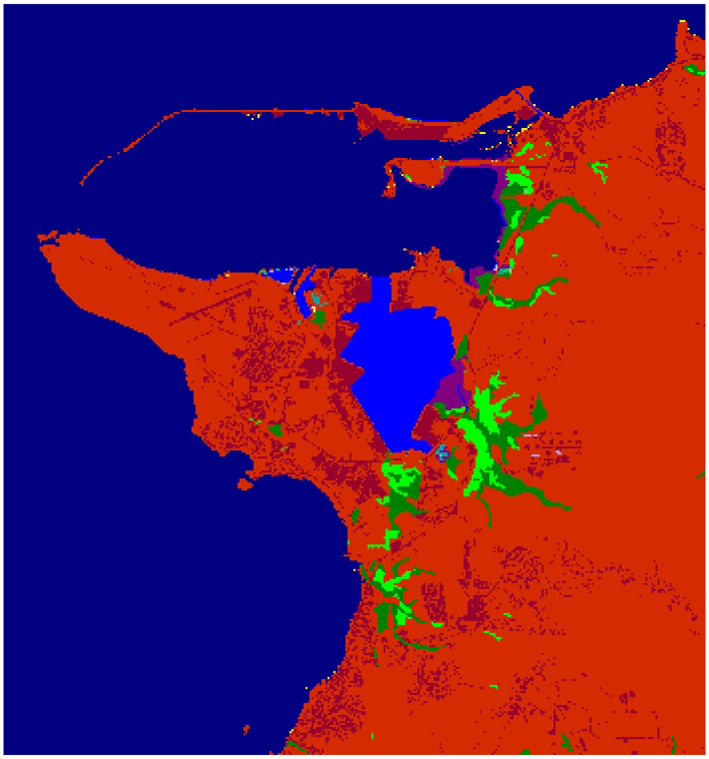
Guam NWR, 2025, Scenario A1B Maximum, Apra Harbor



Guam NWR, 2050, Scenario A1B Maximum, Apra Harbor



Guam NWR, 2075, Scenario A1B Maximum, Apra Harbor



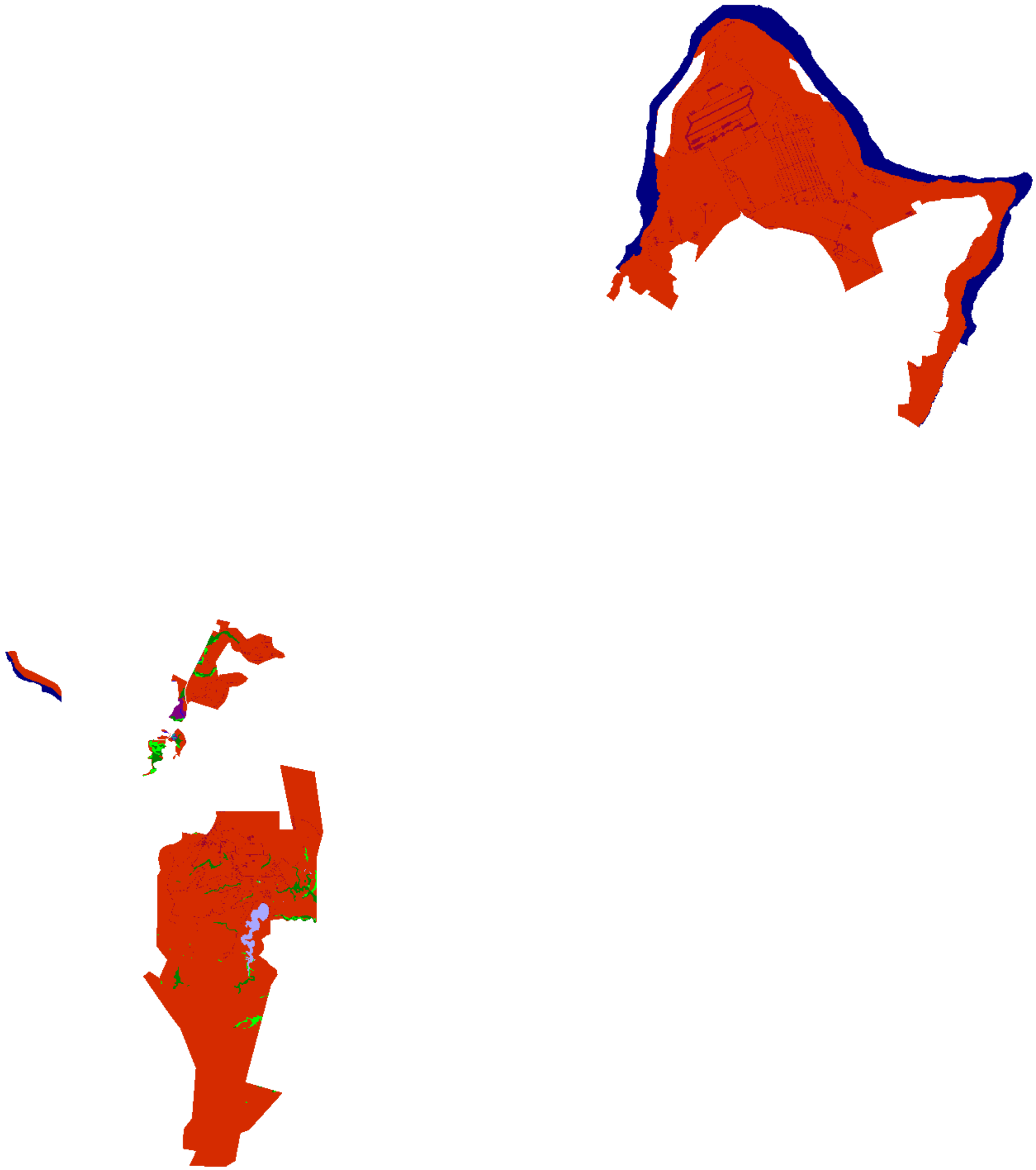
Guam NWR, 2100, Scenario A1B Maximum, Apra Harbor

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

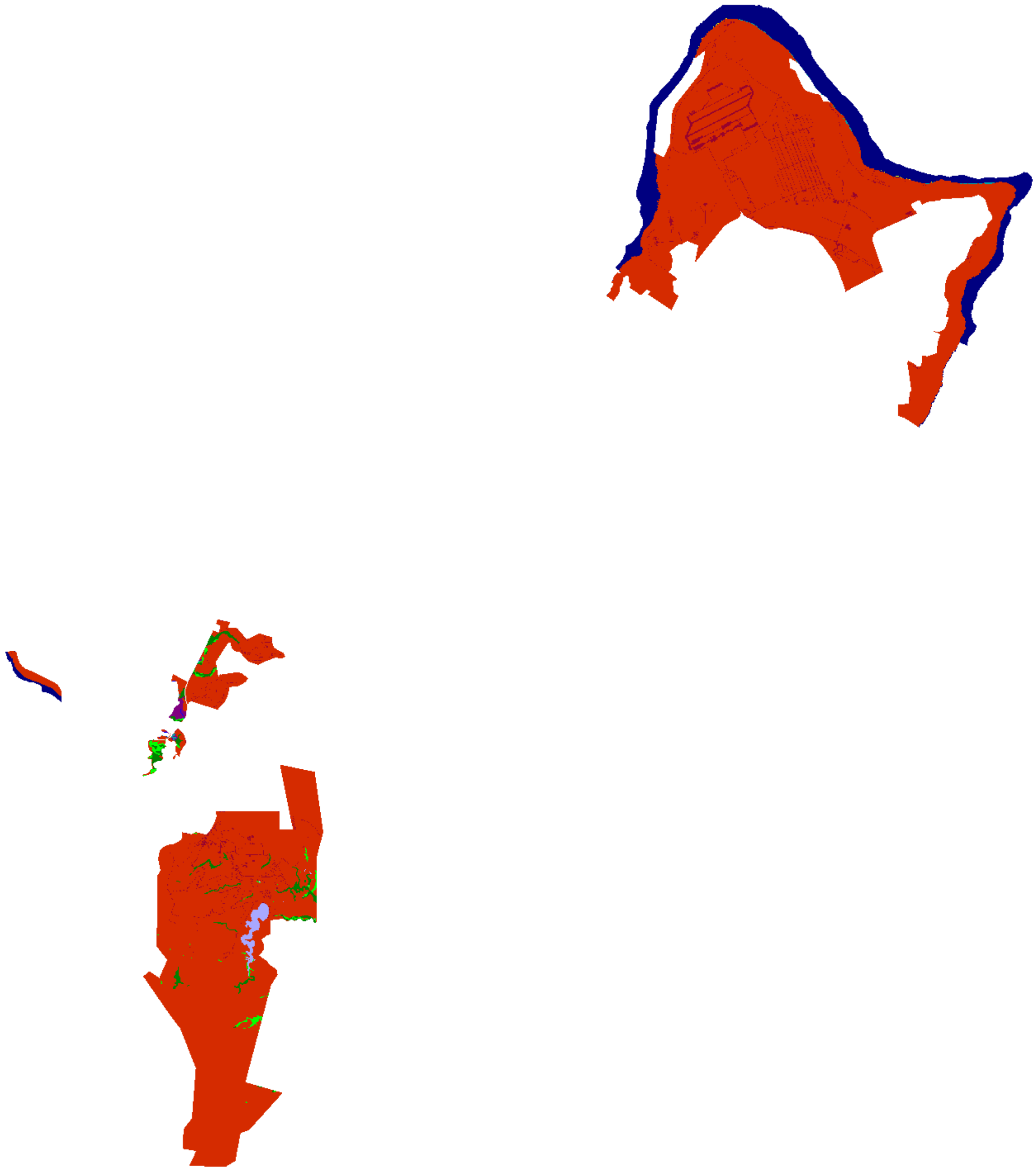
Guam Raster
1 Meter Eustatic SLR by 2100

Results in Acres

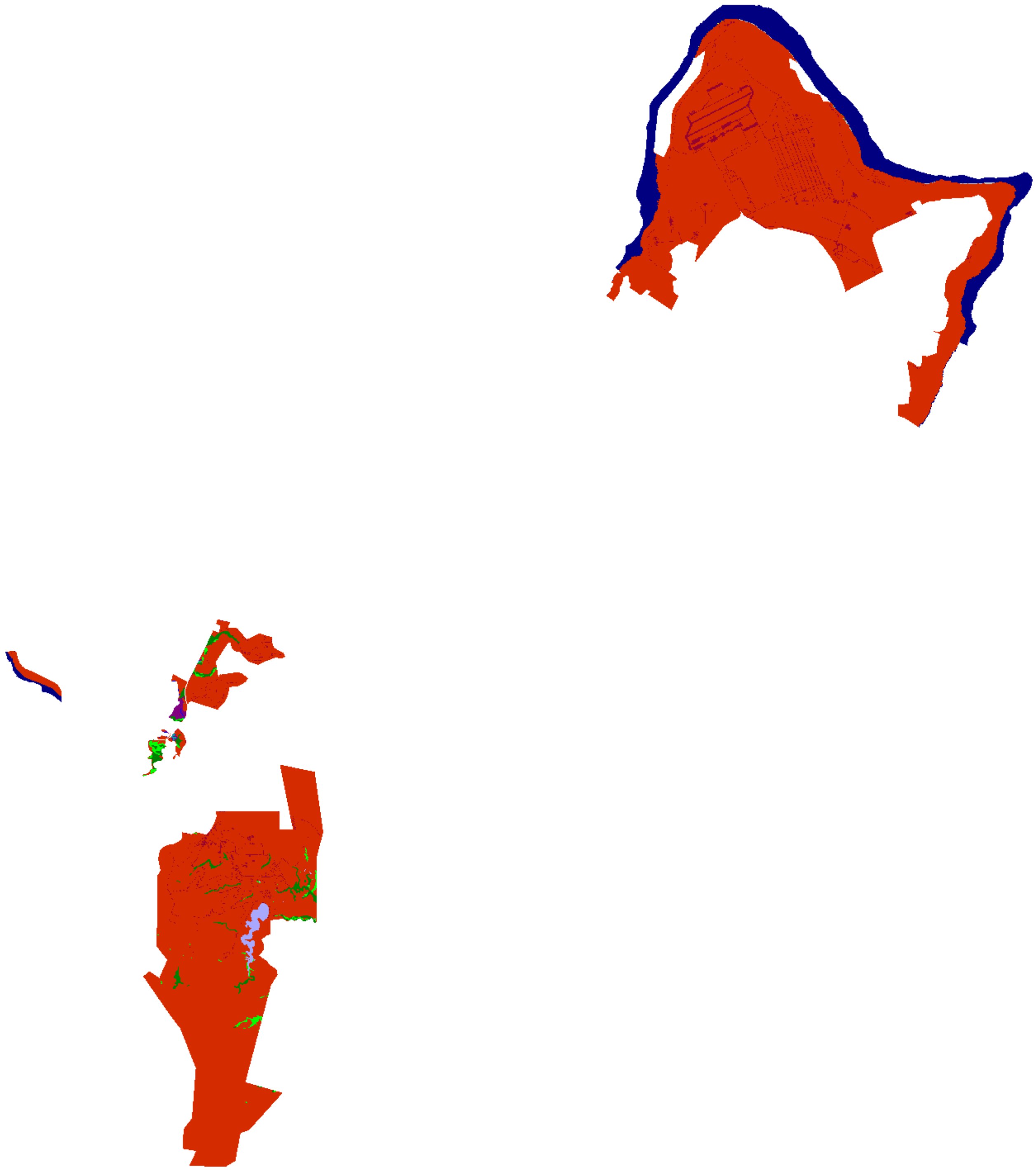
| | Initial | 2025 | 2050 | 2075 | 2100 |
|---|---|---|---|---|---|
| Undeveloped Dry Land | 27888.0 | 27774.8 | 27765.6 | 27754.2 | 27742.4 |
| Open Ocean | 3276.5 | 3351.1 | 3361.0 | 3368.5 | 3375.0 |
| Developed Dry Land | 828.2 | 828.2 | 828.2 | 828.2 | 828.2 |
| Swamp | 345.8 | 345.7 | 345.6 | 345.6 | 345.4 |
| Inland Open Water | 187.3 | 187.3 | 187.3 | 187.3 | 187.3 |
| Inland Fresh Marsh | 162.1 | 161.4 | 160.8 | 160.6 | 160.4 |
| Mangrove | 66.1 | 64.9 | 64.9 | 64.9 | 64.5 |
| Regularly Flooded Marsh | 6.2 | 30.0 | 10.5 | 10.8 | 12.8 |
| Estuarine Open Water | 4.4 | 5.9 | 6.8 | 27.5 | 30.8 |
| Tidal Flat | 0.0 | 0.3 | 21.8 | 4.5 | 4.3 |
| Ocean Beach | 0.0 | 6.7 | 1.6 | 0.2 | 0.2 |
| Trans. Salt Marsh | 0.0 | 8.5 | 10.4 | 12.4 | 13.1 |
| Estuarine Beach | 0.0 | 0.0 | 0.0 | 0.1 | 0.3 |
| **Total (incl. water)** | **32764.6** | **32764.6** | **32764.6** | **32764.6** | **32764.6** |



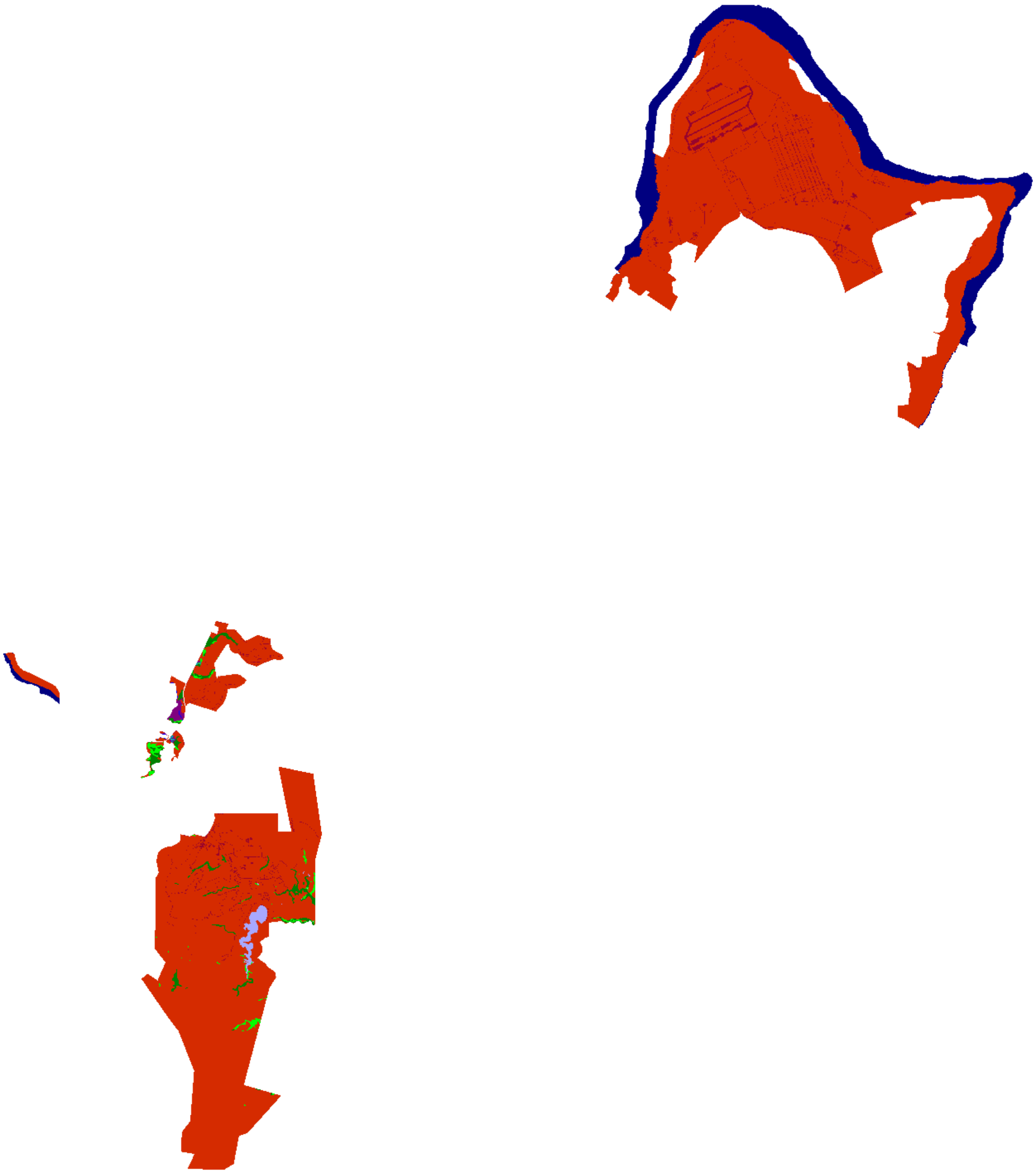
Guam NWR, Initial Condition



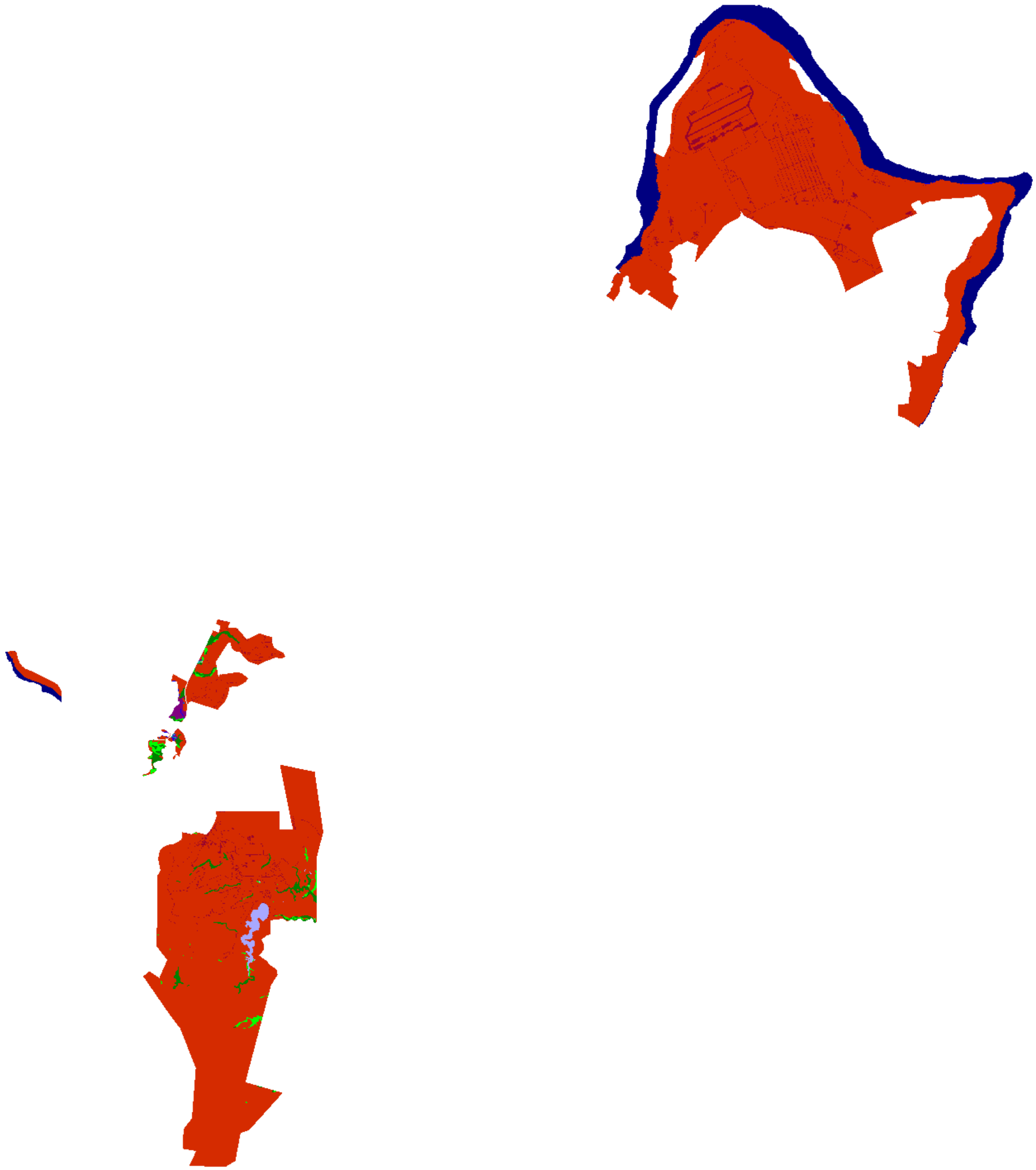
Guam NWR, 2025, 1 meter



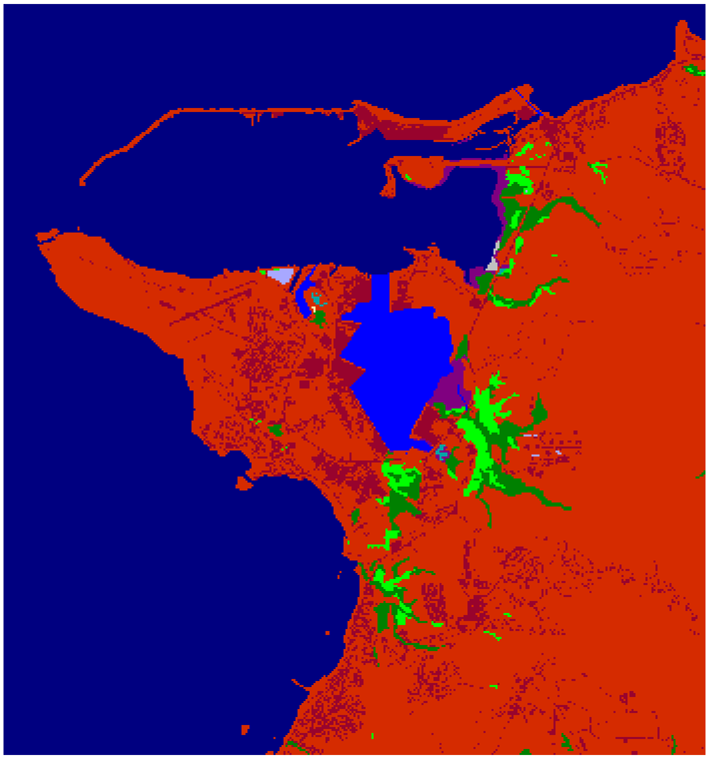
Guam NWR, 2050, 1 meter



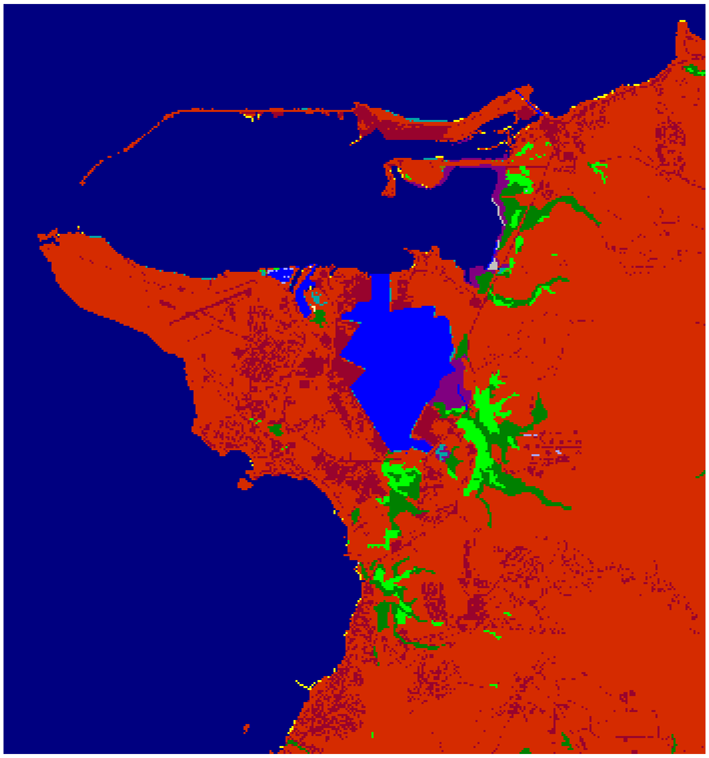
Guam NWR, 2075, 1 meter



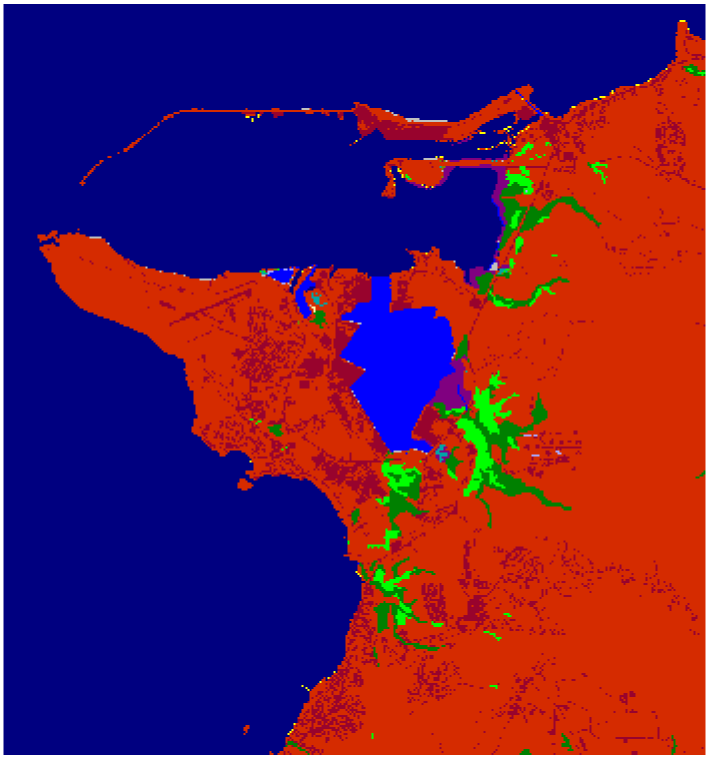
Guam NWR, 2100, 1 meter



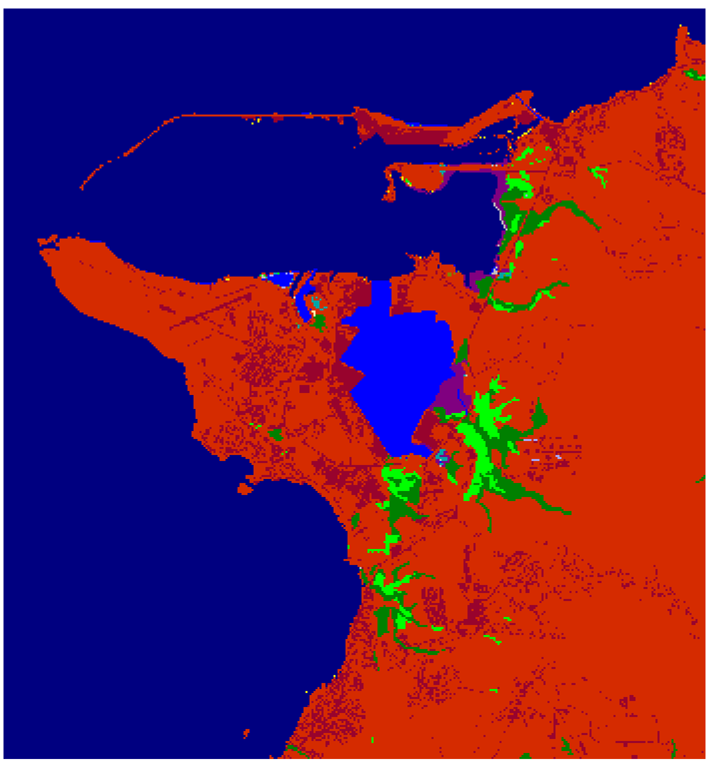
Guam NWR, Initial Condition, Apra Harbor



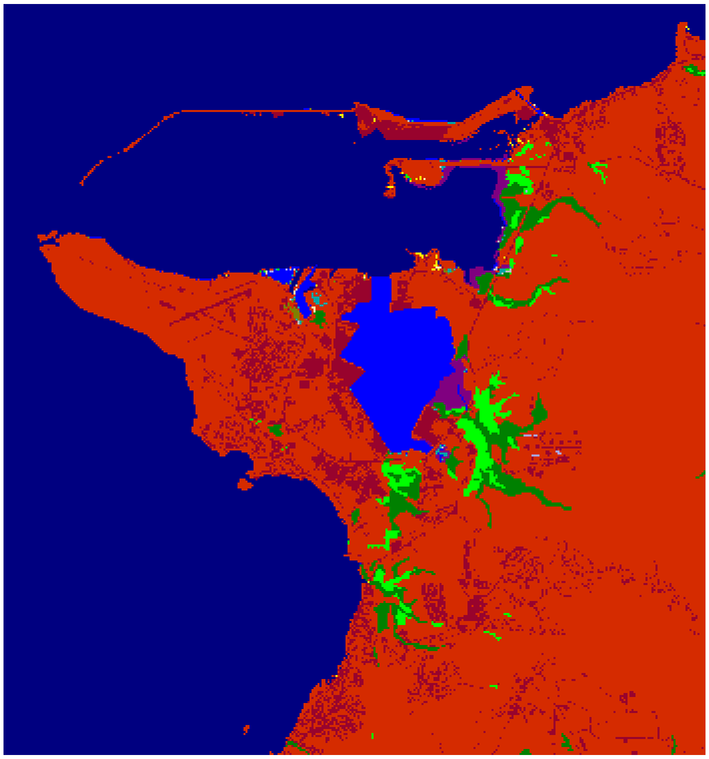
Guam NWR, 2025, 1 meter, Apra Harbor



Guam NWR, 2050, 1 meter, Apra Harbor



Guam NWR, 2075, 1 meter, Apra Harbor



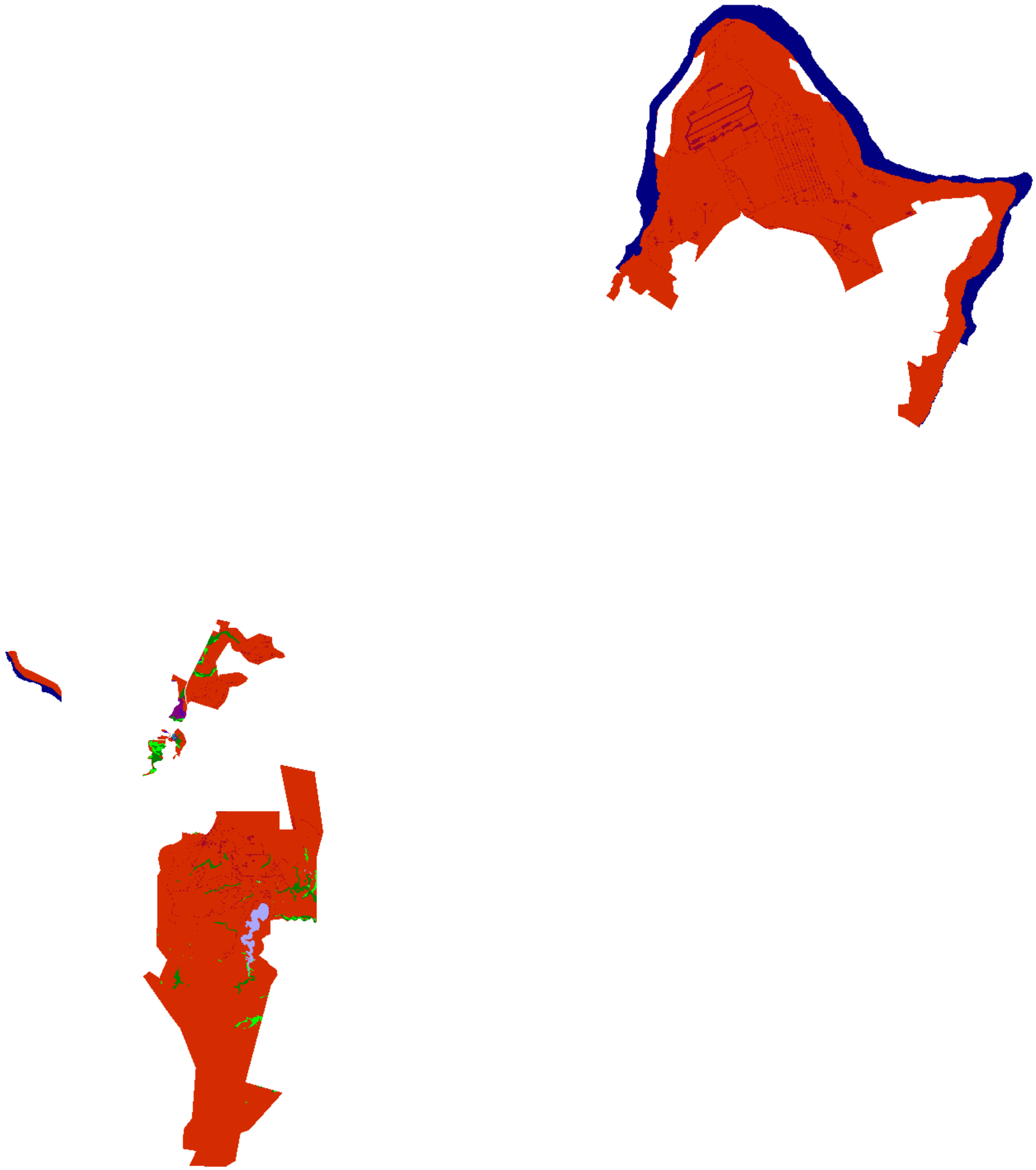
Guam NWR, 2100, 1 meter, Apra Harbor

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

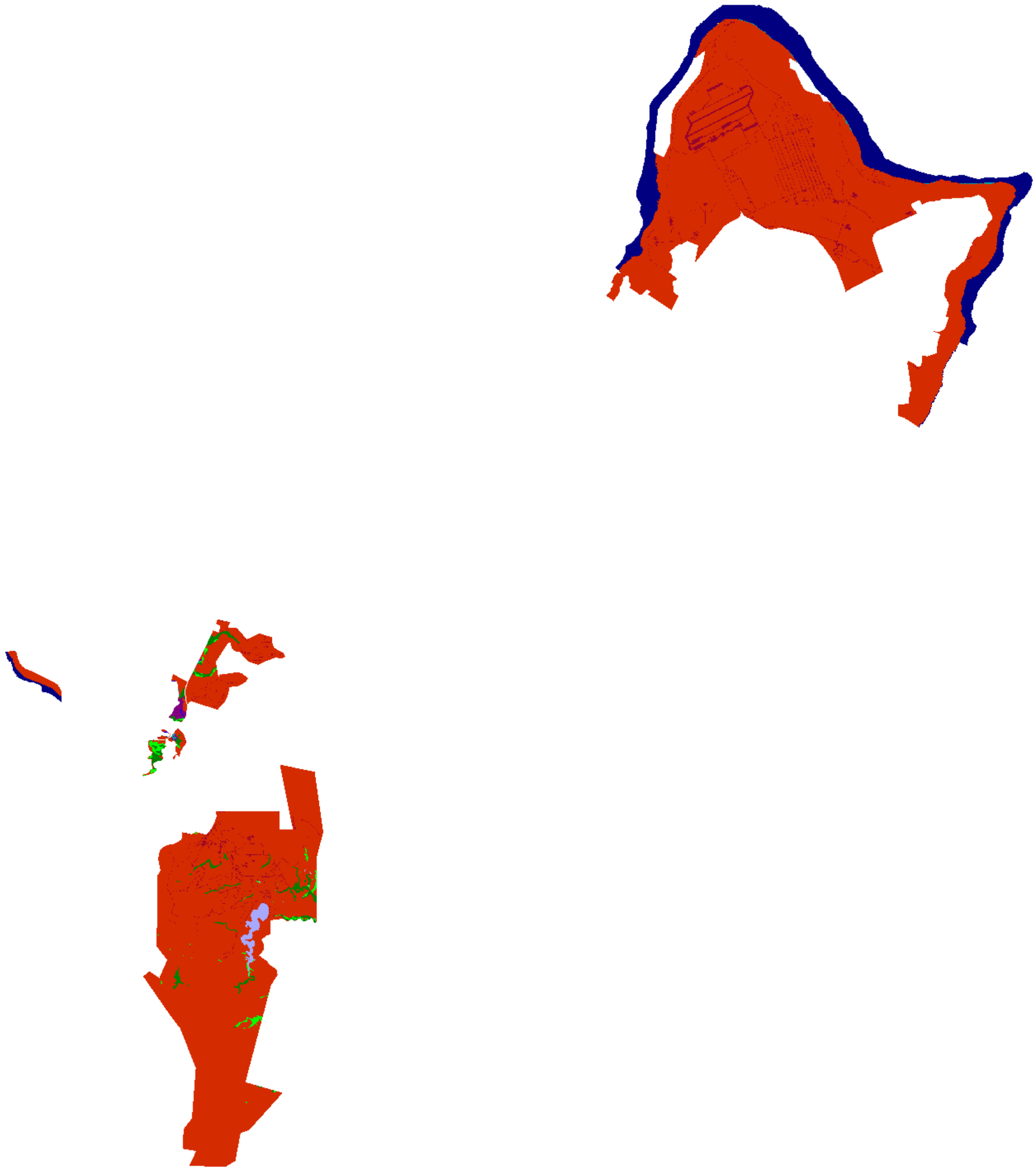
Guam Raster
1.5 Meters Eustatic SLR by 2100

Results in Acres

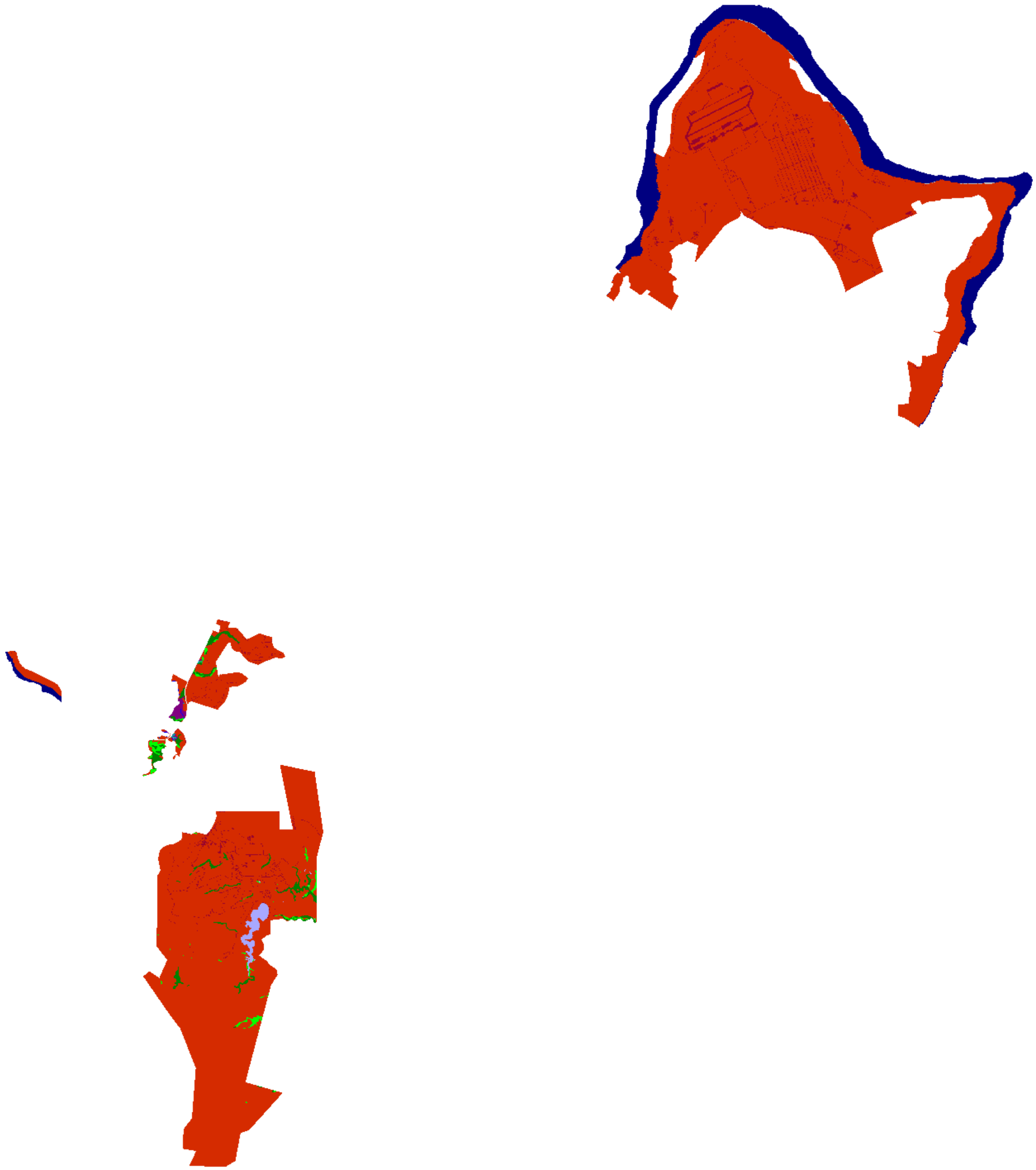
| | Initial | 2025 | 2050 | 2075 | 2100 |
|---|---|---|---|---|---|
| Undeveloped Dry Land | 27888.0 | 27770.8 | 27757.0 | 27736.3 | 27720.4 |
| Open Ocean | 3276.5 | 3358.1 | 3367.0 | 3376.1 | 3386.2 |
| Developed Dry Land | 828.2 | 828.2 | 828.2 | 828.2 | 828.2 |
| Swamp | 345.8 | 345.6 | 345.6 | 345.2 | 344.8 |
| Inland Open Water | 187.3 | 187.3 | 187.3 | 187.3 | 187.3 |
| Inland Fresh Marsh | 162.1 | 161.3 | 160.6 | 160.4 | 160.3 |
| Mangrove | 66.1 | 64.9 | 64.6 | 63.0 | 60.0 |
| Regularly Flooded Marsh | 6.2 | 31.6 | 17.0 | 11.6 | 21.1 |
| Estuarine Open Water | 4.4 | 6.0 | 7.3 | 33.7 | 43.8 |
| Tidal Flat | 0.0 | 0.3 | 25.3 | 7.1 | 4.7 |
| Ocean Beach | 0.0 | 1.8 | 0.1 | 0.2 | 0.0 |
| Trans. Salt Marsh | 0.0 | 8.7 | 4.8 | 15.4 | 7.3 |
| Estuarine Beach | 0.0 | 0.0 | 0.0 | 0.3 | 0.5 |
| **Total (incl. water)** | **32764.6** | **32764.6** | **32764.6** | **32764.6** | **32764.6** |



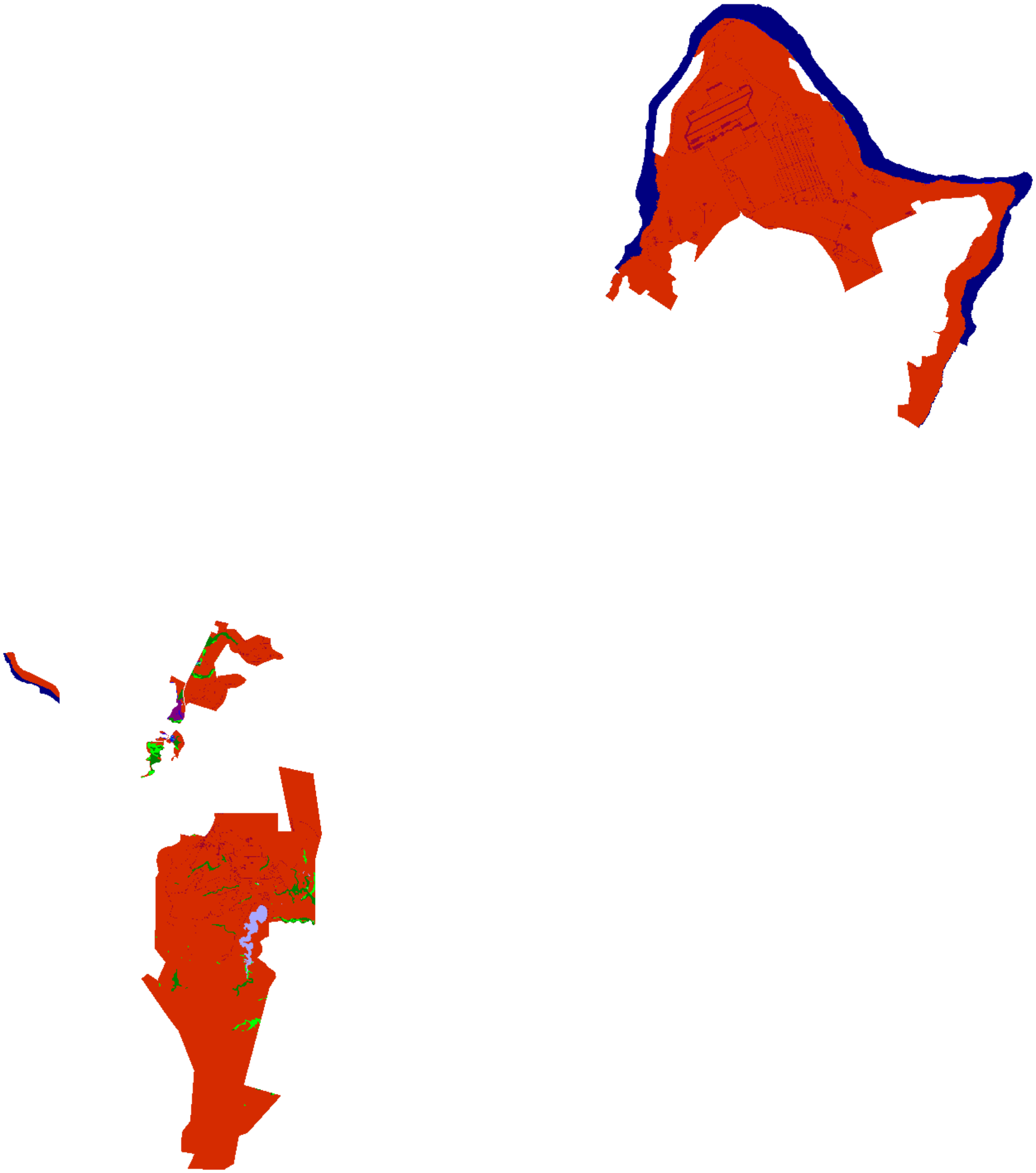
Guam NWR, Initial Condition



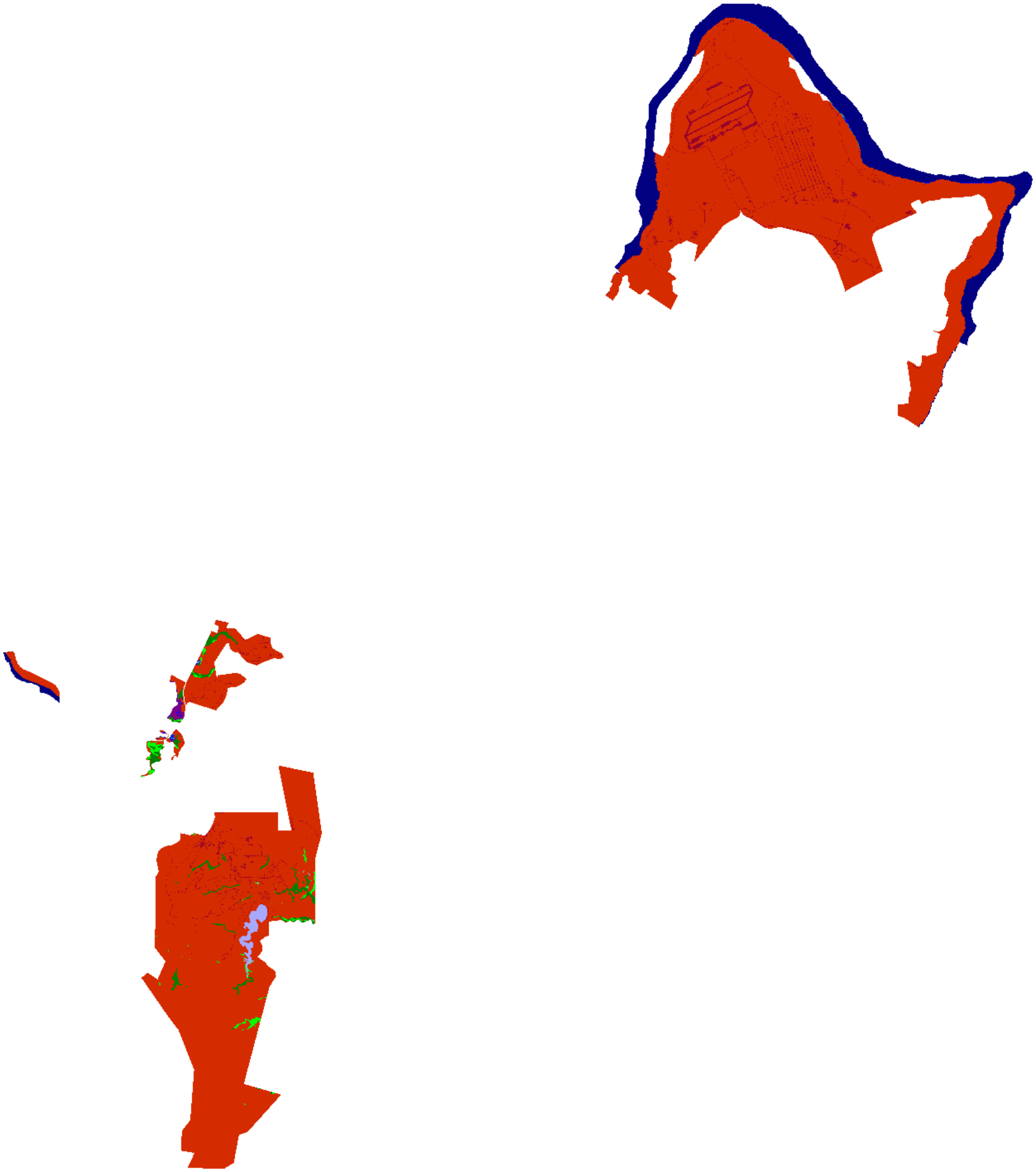
Guam NWR, 2025, 1.5 meter



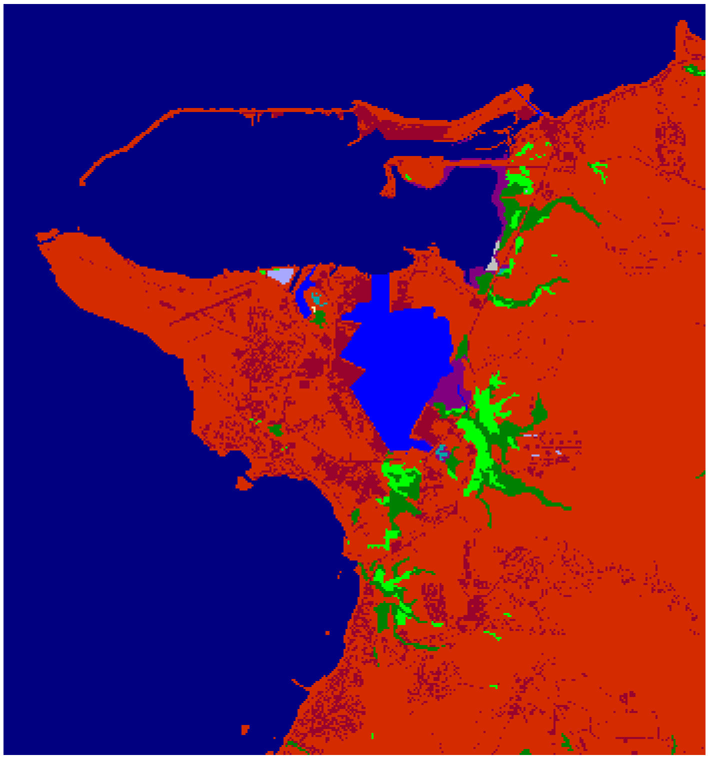
Guam NWR, 2050, 1.5 meter



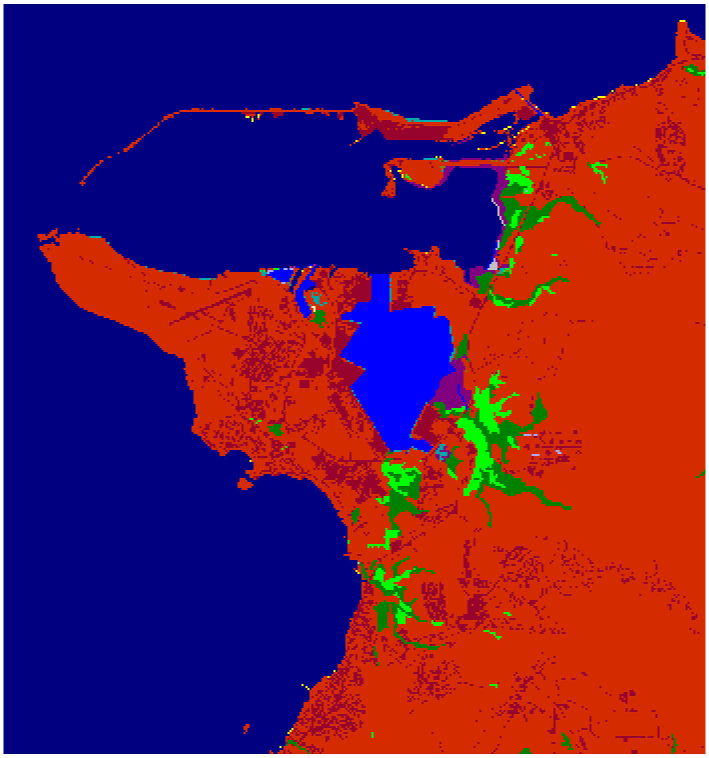
Guam NWR, 2075, 1.5 meter



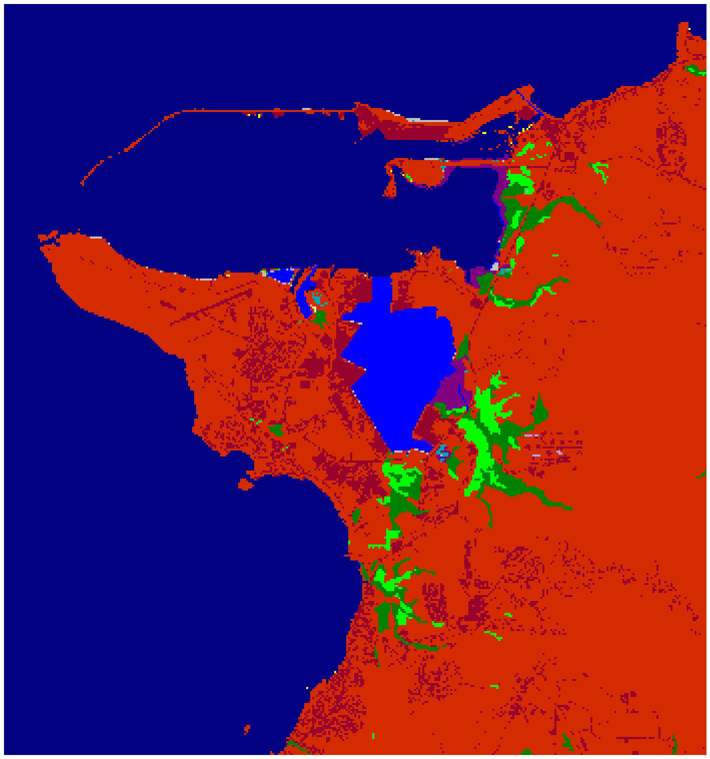
Guam NWR, 2100, 1.5 meter



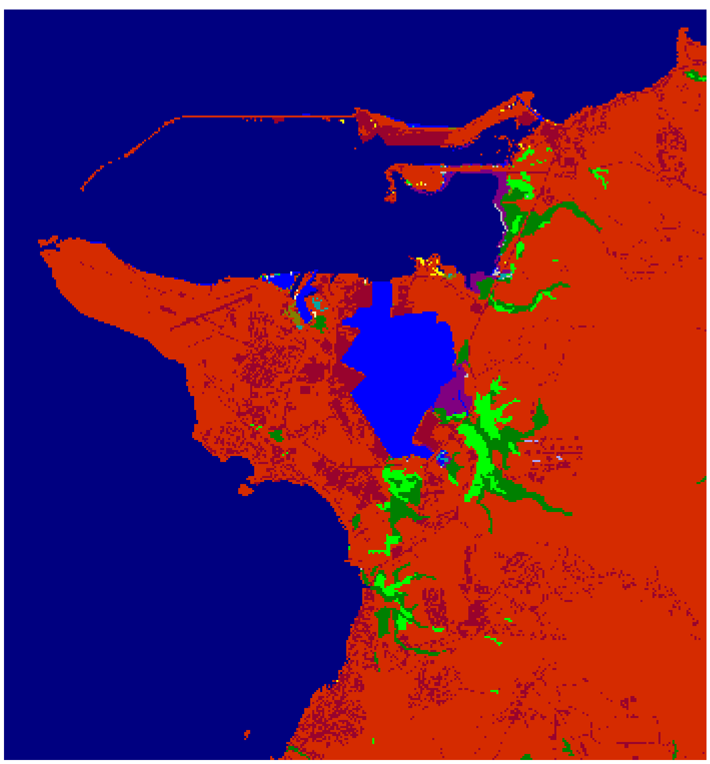
Guam NWR, Initial Condition, Apra Harbor



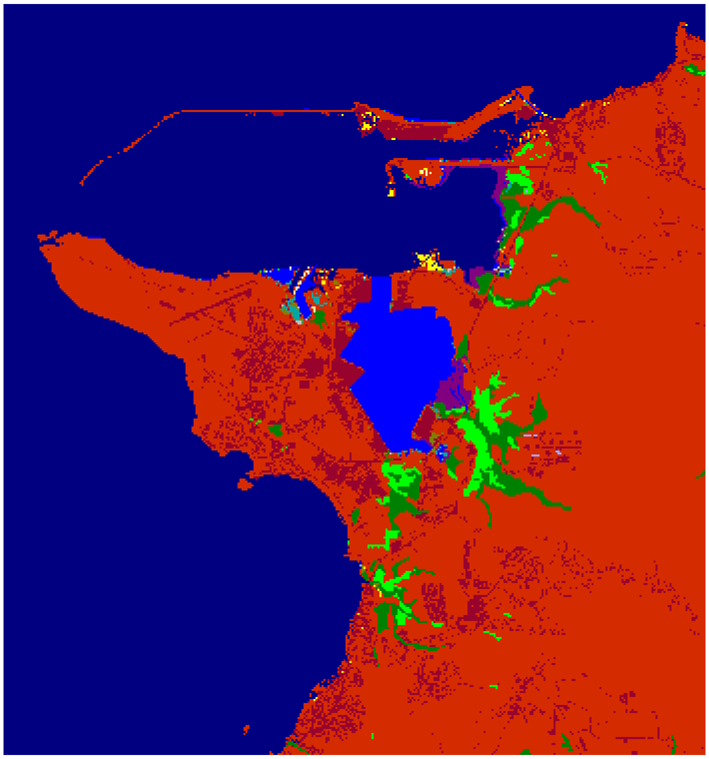
Guam NWR, 2025, 1.5 meter, Apra Harbor



Guam NWR, 2050, 1.5 meter, Apra Harbor



Guam NWR, 2075, 1.5 meter, Apra Harbor



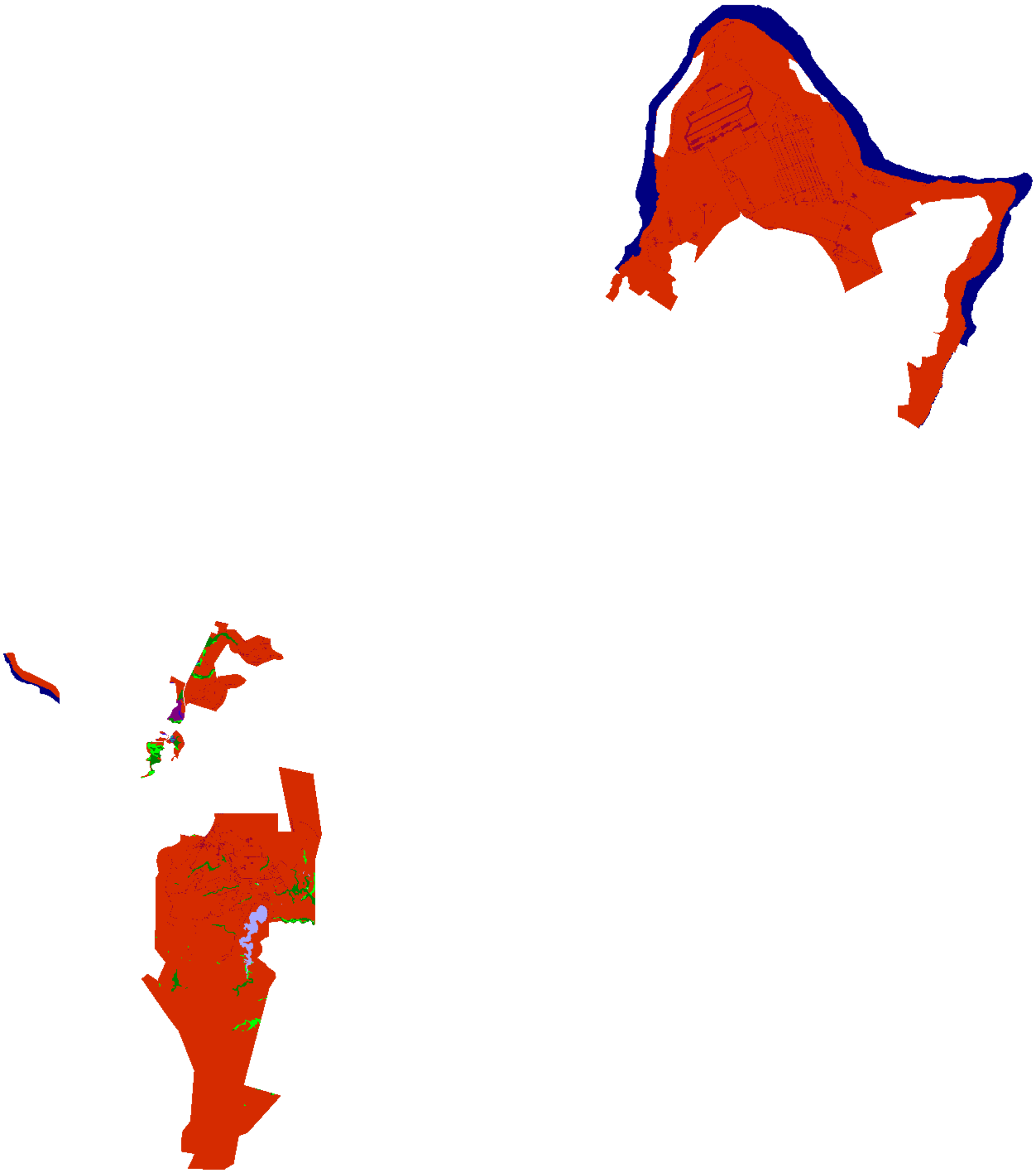
Guam NWR, 2100, 1.5 meter, Apra Harbor

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

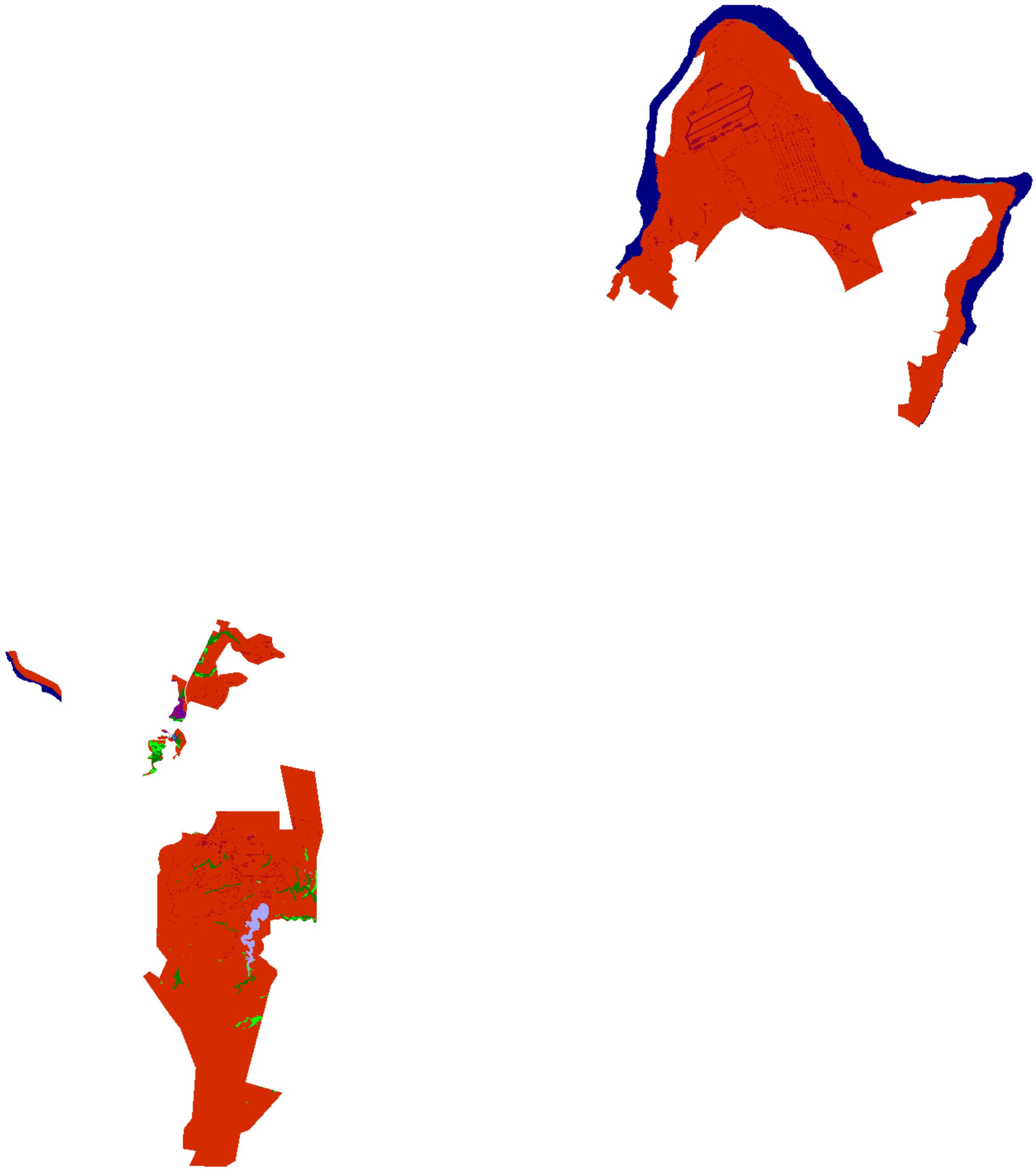
Guam Raster
2 Meters Eustatic SLR by 2100

Results in Acres

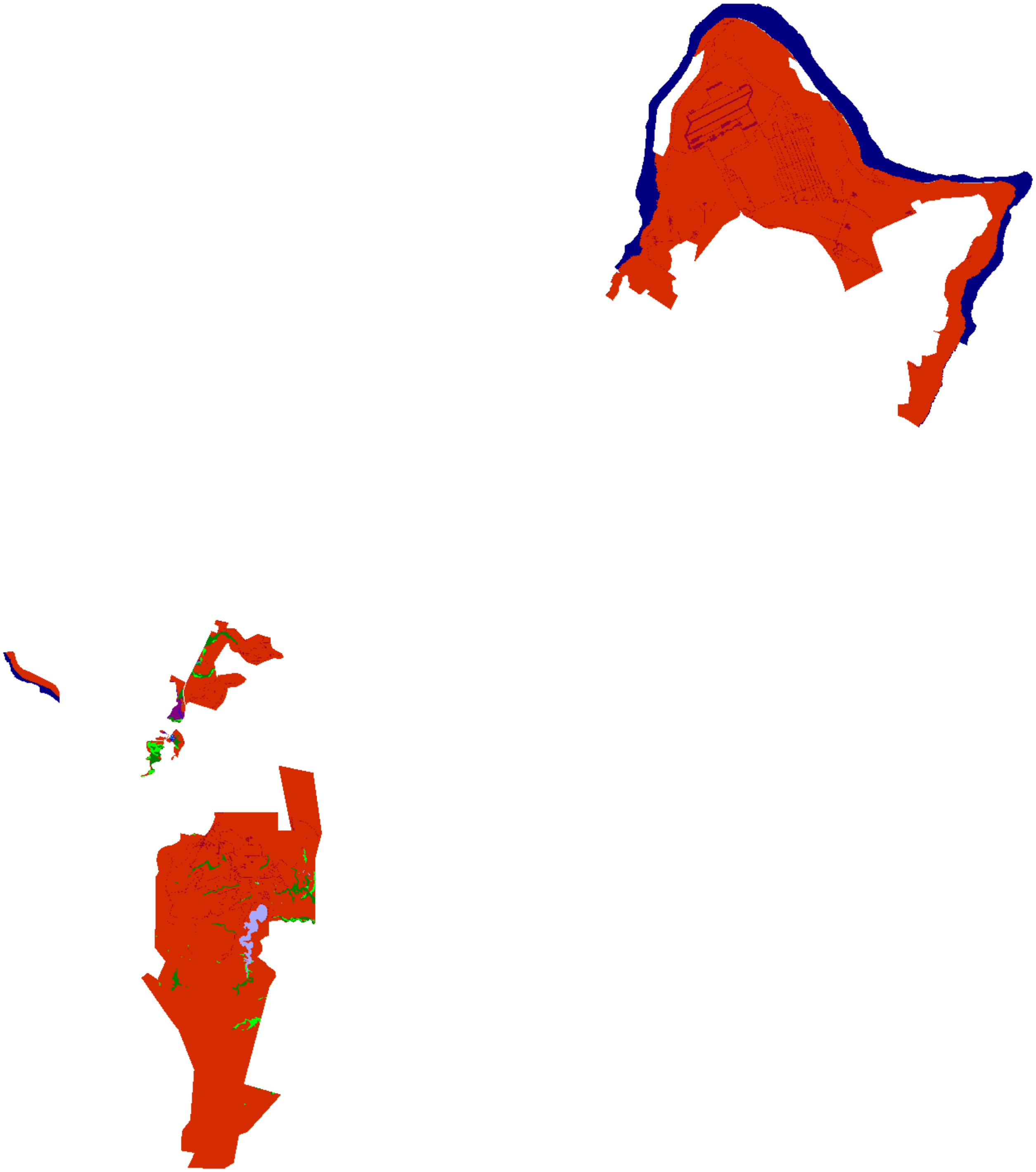
| | Initial | 2025 | 2050 | 2075 | 2100 |
|---|---|---|---|---|---|
| Undeveloped Dry Land | 27888.0 | 27766.9 | 27748.2 | 27725.8 | 27701.3 |
| Open Ocean | 3276.5 | 3361.6 | 3371.5 | 3383.7 | 3396.7 |
| Developed Dry Land | 828.2 | 828.2 | 828.2 | 828.2 | 828.1 |
| Swamp | 345.8 | 345.6 | 345.5 | 344.9 | 343.1 |
| Inland Open Water | 187.3 | 187.3 | 187.3 | 187.3 | 187.3 |
| Inland Fresh Marsh | 162.1 | 161.1 | 160.5 | 160.3 | 158.8 |
| Mangrove | 66.1 | 64.8 | 63.4 | 59.3 | 52.2 |
| Regularly Flooded Marsh | 6.2 | 33.0 | 10.5 | 17.0 | 12.9 |
| Estuarine Open Water | 4.4 | 6.2 | 8.9 | 40.8 | 54.9 |
| Tidal Flat | 0.0 | 0.4 | 27.6 | 6.5 | 13.2 |
| Ocean Beach | 0.0 | 0.3 | 0.1 | 0.2 | 0.2 |
| Trans. Salt Marsh | 0.0 | 9.1 | 13.0 | 10.6 | 15.0 |
| Estuarine Beach | 0.0 | 0.0 | 0.0 | 0.1 | 1.1 |
| **Total (incl. water)** | **32764.6** | **32764.6** | **32764.6** | **32764.6** | **32764.6** |



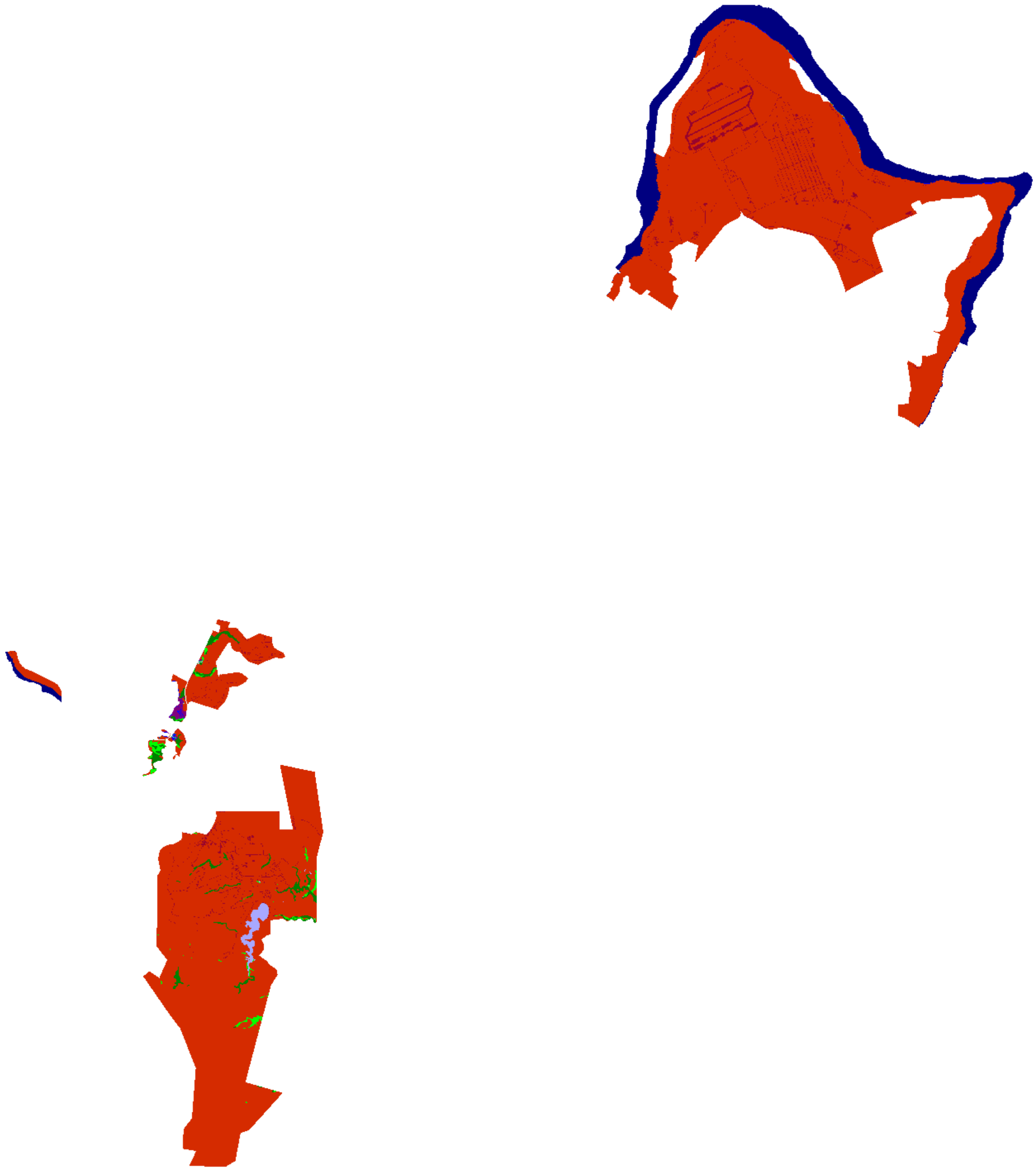
Guam NWR, Initial Condition



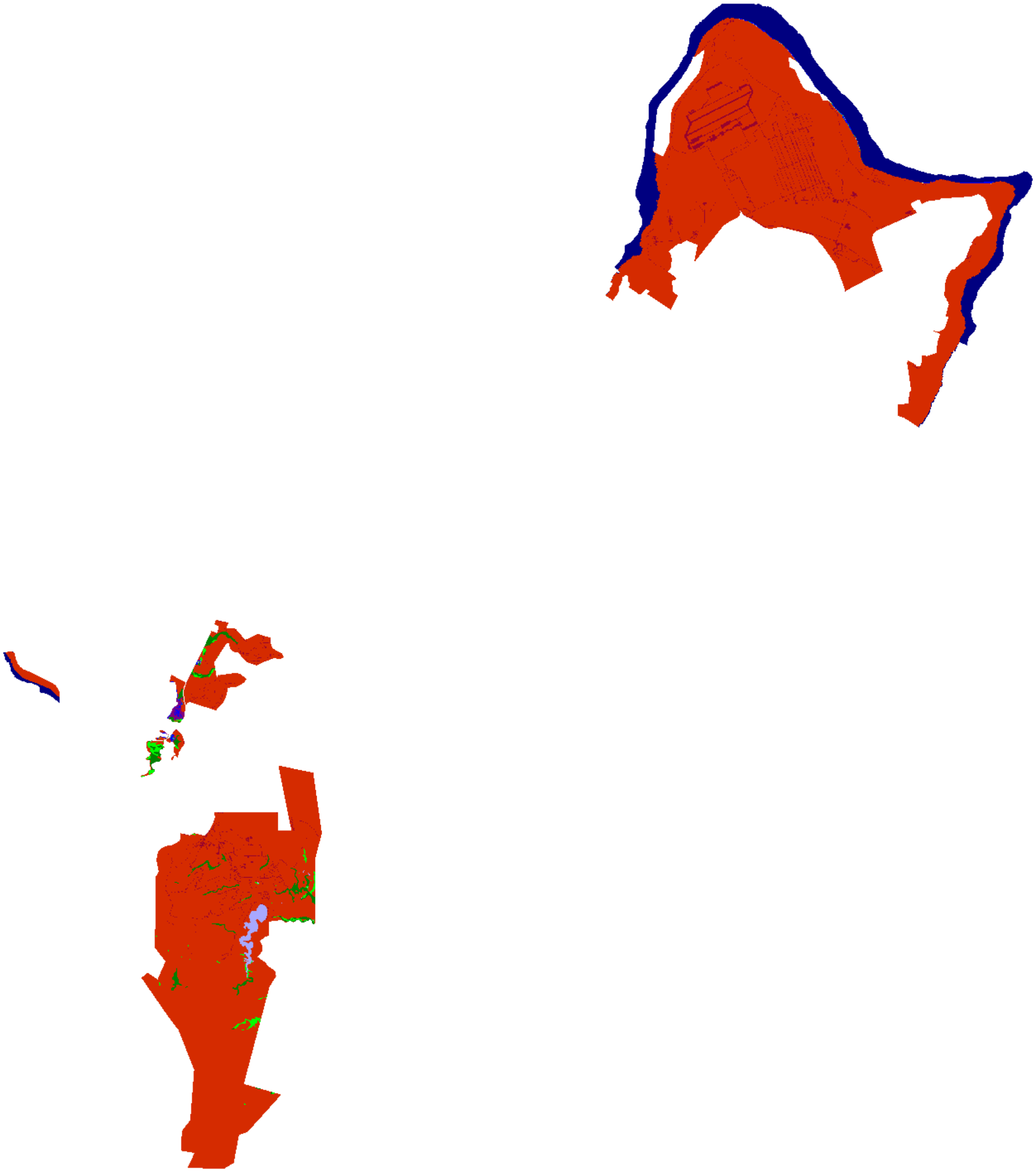
Guam NWR, 2025, 2 meters



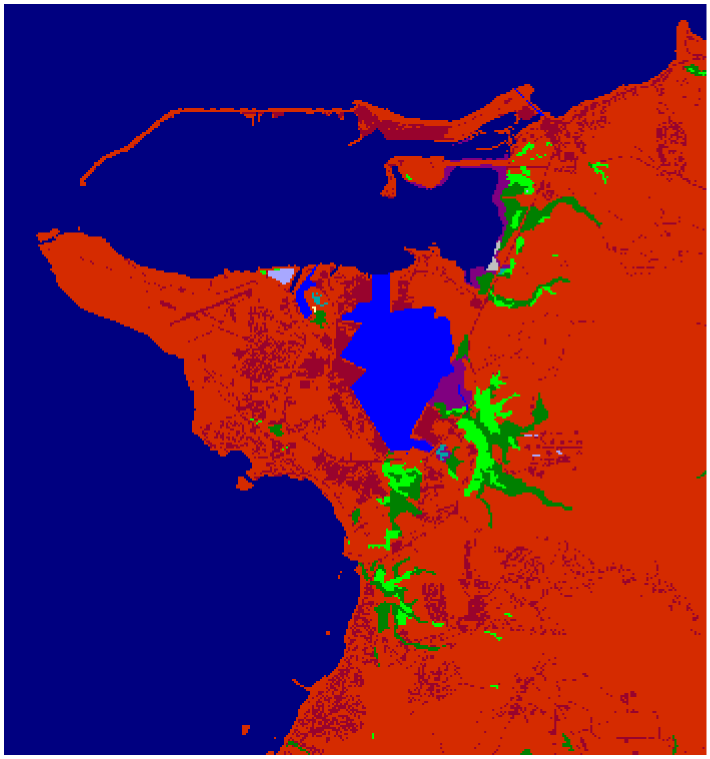
Guam NWR, 2050, 2 meters



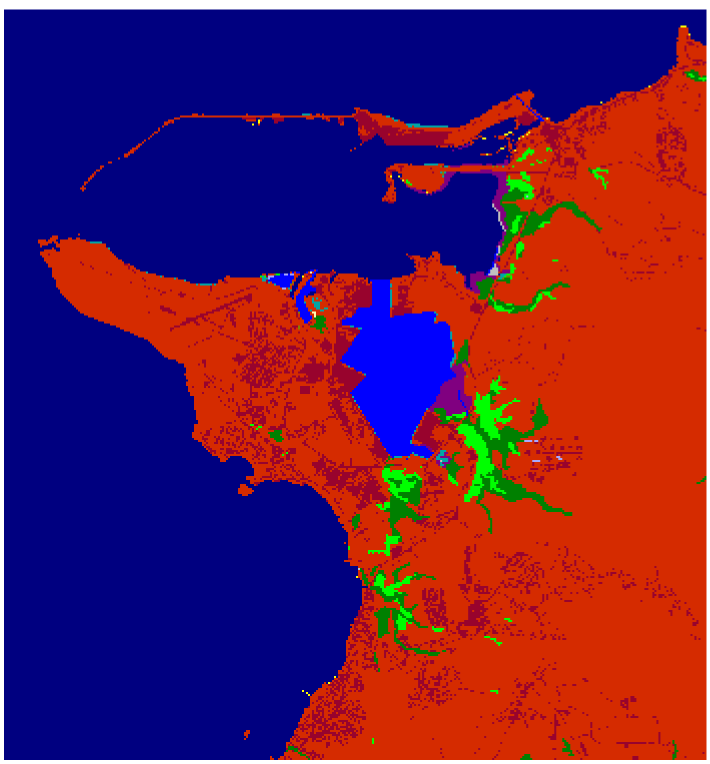
Guam NWR, 2075, 2 meters



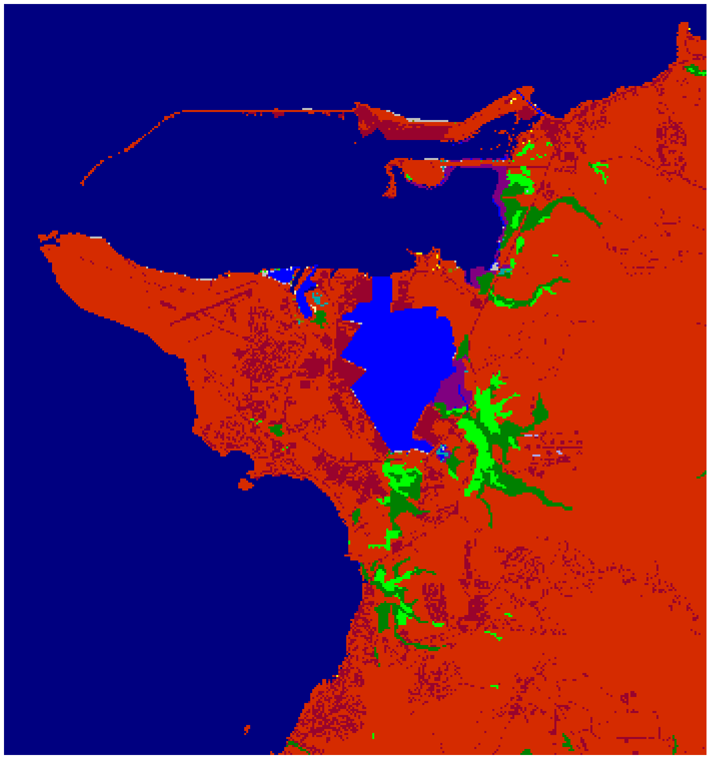
Guam NWR, 2100, 2 meters



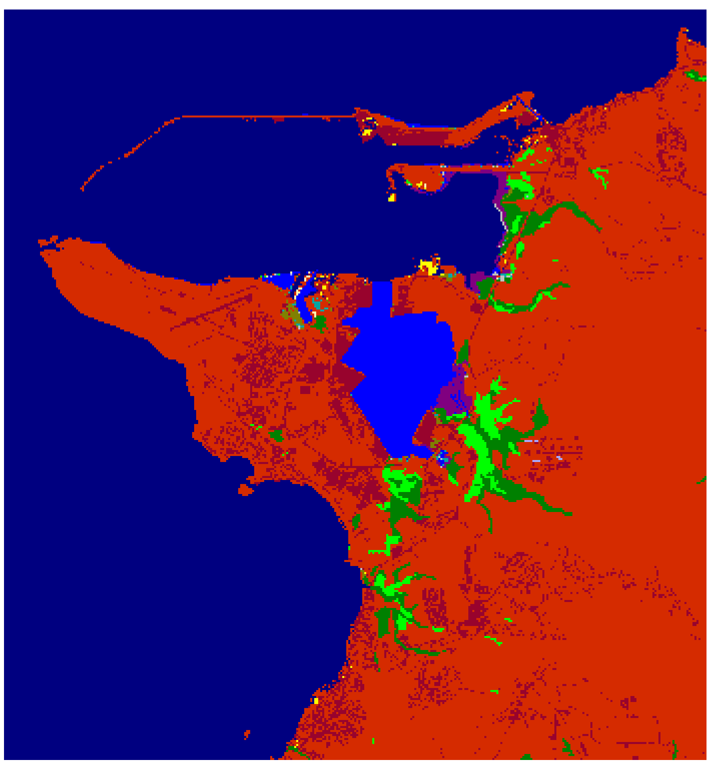
Guam NWR, Initial Condition, Apra Harbor



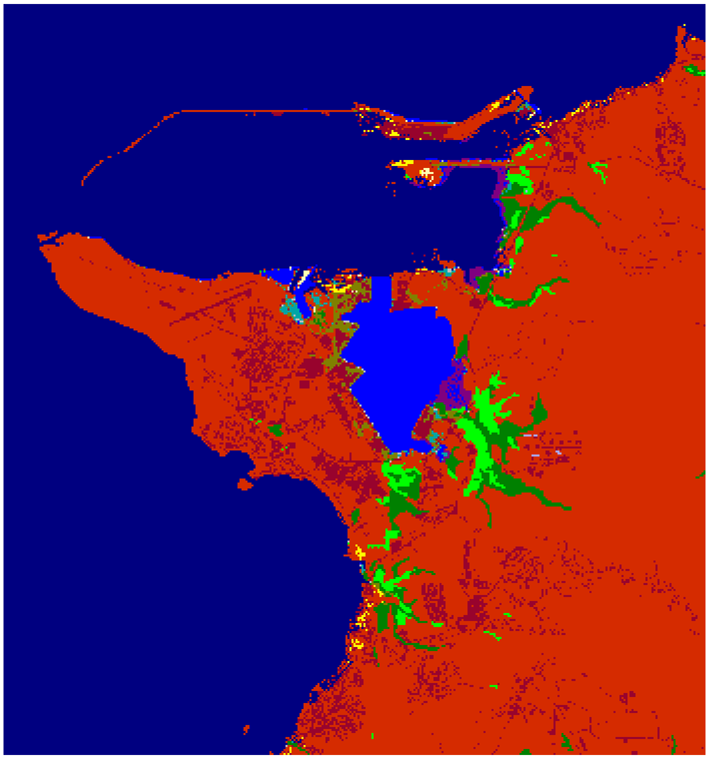
Guam NWR, 2025, 2 meters, Apra Harbor



Guam NWR, 2050, 2 meters, Apra Harbor



Guam NWR, 2075, 2 meters, Apra Harbor



Guam NWR, 2100, 2 meters, Apra Harbor

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

# Discussion

Based on these model results, refuge locations in this island are predicted to be quite resilient to SLR. The majority of the refuge consists of non-coastal, high-elevation dry land. The only vulnerable refuge land is located in the Apra Harbor region.

Model results are uncertain, though, due to difficulties in projecting future rates of subsidence or uplift. As discussed above, there is considerable uncertainty even about what has been happening in the past with regards to these factors, along with significant spatial variability. Estimates of historical SLR at the site ranged from -1.05 to 2.4 mm/year. For this reason, the model was also run with historic SLR parameters of both -1.05 and 2.4 mm/year as a bounding analysis to determine the effects of this parameter. (Within SLAMM, historic SLR trends are then projected through the year 2100 while adding various scenarios of eustatic SLR.)

When the model was run with uplift resulting in historical SLR of -1.05 mm/year, the results changed only slightly with slightly less dry land subject to inundation under the one-meter scenario and mangroves subject to slightly less loss as well.

| SLR by 2100 (m) | 0.39 | 0.69 | 1 | 1.5 | 2 |
|---|---|---|---|---|---|
| Undeveloped Dry Land | 0% | 0% | 1% | 1% | 1% |
| Swamp | 0% | 0% | 0% | 0% | 1% |
| Inland Fresh Marsh | 1% | 1% | 1% | 1% | 2% |
| Mangrove | 2% | 2% | 2% | 9% | 21% |

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

| SLR by 2100 (m) | 0.39 | 0.69 | 1 | 1.5 | 2 |
|---|---|---|---|---|---|
| Undeveloped Dry Land | 0% | 0% | 0% | 1% | 1% |
| Swamp | 0% | 0% | 0% | 0% | 1% |
| Inland Fresh Marsh | 1% | 1% | 1% | 1% | 2% |
| Mangrove | 3% | 3% | 3% | 6% | 17% |

Predicted Loss Rates of Land Categories by 2100 Given Simulated Scenarios of Eustatic Sea Level Rise .
**Bounding Simulation with Historical SLR set to -1.05 mm/year.**

When the model was run with subsidence resulting in historical SLR of 2.5 mm/year, the results also changed only slightly with more mangrove loss predicted in scenarios of and exceeding 1.5 meters of eustatic SLR by 2100.

| SLR by 2100 (m) | 0.39 | 0.69 | 1 | 1.5 | 2 |
|---|---|---|---|---|---|
| Undeveloped Dry Land | 0% | 0% | 1% | 1% | 1% |
| Swamp | 0% | 0% | 0% | 0% | 1% |
| Inland Fresh Marsh | 1% | 1% | 1% | 1% | 2% |
| Mangrove | 2% | 2% | 3% | 11% | 24% |

Predicted Loss Rates of Land Categories by 2100 Given Simulated Scenarios of Eustatic Sea Level Rise .
**Bounding Simulation with Historical SLR set to 2.5 mm/year.**

Therefore, based on this analysis, although there is uncertainty as to the rate of subsidence and uplift at this island, the elevations of land within the National Wildlife Refuge protects it from the effects of SLR under most scenarios (so long as future uplift or subsidence rates remain within the range tested).

The refuge at Apra Harbor consists of swamp, mangrove and inland fresh marsh. Except for the mangrove, essentially none of the wetland types modeled are lost in any scenario.

# References

AusAid 2008: Pacific Country Report on Sea Level & Climate: Their Present State, Niue. December 2008. Australian Agency for International Development (AusAid).

Cahoon, D.R., J. W. Day, Jr., and D. J. Reed, 1999. "The influence of surface and shallow subsurface soil processes on wetland elevation: A synthesis." *Current Topics in Wetland Biogeochemistry*, 3, 72-88.

Chen, J. L., Wilson, C. R., Tapley, B. D., 2006 "Satellite Gravity Measurements Confirm Accelerated Melting of Greenland Ice Sheet" *Science* 2006 0: 1129007

Church, J.A., White, N.J. and Hunter, J.R.2006. "Sea-level rise at tropical Pacific and Indian Ocean" *Global and Planetary Change,* Volume 53, Issue 3, September 2006, Pages 155-168

Clark, J. S. and W. A. Patterson III. 1984. Pollen, Pb-210 and sedimentation in the intertidal environment. Journal of Sedimentary Petrology 54(4):1249-1263.

Clough, J.S. Park, R.A. and R. Fuller, 2010, *SLAMM Technical Documentation, Release 6.0 beta, Draft,* January 2010, http://warrenpinnacle.com/prof/SLAMM

Craft C, Clough J, Ehman J, Guo H, Joye S, Machmuller M, Park R, and Pennings S. Effects of Accelerated Sea Level Rise on Delivery of Ecosystem Services Provided by Tidal Marshes: A Simulation of the Georgia (USA) Coast. *Frontiers in Ecology and the Environment.* 2009; 7, doi:10.1890/070219

Council for Regulatory Environmental Modeling, (CREM) 2008. *Draft guidance on the development, evaluation, and application of regulatory environmental* models P Pascual, N Stiber, E Sunderland - Washington DC: Draft, August 2008

Erwin, RM, GM Sanders, DJ Prosser, and DR Cahoon. 2006. High tides and rising seas: potential effects on estuarine waterbirds. Pages 214-228 in: Terrestrial Vertebrates of Tidal Marshes: Evolution, Ecology, and Conservation (R. Greenberg, J. Maldonado, S. Droege, and M.V. McDonald, eds.). Studies in Avian Biology No. 32, Cooper Ornithological Society.

Glick, Clough, et al. *Sea-level Rise and Coastal Habitats in the Pacific Northwest An Analysis for Puget Sound, Southwestern Washington, and Northwestern Oregon* July 2007 http://www.nwf.org/sealevelrise/pdfs/PacificNWSeaLevelRise.pdf

IPCC, 2001: *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change* [Houghton, J.T.,Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K.Maskell, and C.A. Johnson (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 881pp.

Lee, J.K., R.A. Park, and P.W. Mausel. 1992. Application of Geoprocessing and Simulation Modeling to Estimate Impacts of Sea Level Rise on the Northeast Coast of Florida. *Photogrammetric Engineering and Remote Sensing* 58:11:1579-1586.

Meehl GA, Stocker TF, Collins WD, Friedlingstein P, Gaye AT, Gregory JM, Kitoh A, Knutti R, Murphy JM, Noda A, Raper SCB, Watterson IG, Weaver AJ and Zhao ZC. 2007. Global climate projections. Pp. 747-845. In: Solomon S, Qin, D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor, M and Miller HL, (eds.) *Climate change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK: Cambridge University Press.

Monaghan, A. J. *et al,* 2006 "Insignificant Change in Antarctic Snowfall Since the International Geophysical Year" *Science* 2006 313: 827-831.

National Wildlife Fed 'n et al., *An Unfavorable Tide: Global Warming, Coastal Habitats and Sportfishing in Florida* 4, 6 (2006). http://www.targetglobalwarming.org/files/AnUnfavorableTideReport.pdf

Pakenham, Anna. (2009). Patterns of Sediment Accumulation in the Siletz River Estuary, Oregon (Dissertation). Oregon State University.

Park, R.A., J.K. Lee, and D. Canning. 1993. Potential Effects of Sea Level Rise on Puget Sound Wetlands. *Geocarto International* 8(4):99-110.

Park, R.A., M.S. Trehan, P.W. Mausel, and R.C. Howe. 1989a. The Effects of Sea Level Rise on U.S. Coastal Wetlands. In *The Potential Effects of Global Climate Change on the United States: Appendix B - Sea Level Rise,* edited by J.B. Smith and D.A. Tirpak, 1-1 to 1-55. EPA-230-05-89-052. Washington, D.C.: U.S. Environmental Protection Agency.

Park, RA, JK Lee, PW Mausel and RC Howe. 1991. Using remote sensing for modeling the impacts of sea level rise. *World Resources Review* 3:184-220.

Pfeffer, Harper, O'Neel, 2008. Kinematic Constraints on Glacier Contributions to 21st-Century Sea-Level Rise. *Science*, Vol. 321, No. 5894. (5 September 2008), pp. 1340-134

Rahmstorf, Stefan 2007, "A Semi-Empirical Approach to Projecting Future Sea-Level Rise," *Science* 2007 315: 368-370.

Reed, D.J., D.A. Bishara, D.R. Cahoon, J. Donnelly, M. Kearney, A.S. Kolker, L.L. Leonard, R.A. Orson, and J.C. Stevenson, 2008: "Site-Specific Scenarios for Wetlands Accretion in the Mid-Atlantic Region. Section 2.1" in *Background Documents Supporting Climate Change Science Program Synthesis and Assessment Product 4.1: Coastal Elevations and Sensitivity to Sea Level Rise*, J.G. Titus and E.M. Strange (eds.), EPA430R07004, Washington, DC: U.S. EPA. http://www.epa.gov/climatechange/effects/downloads/section2_1.pdf

Stevenson and Kearney, 2008, "Impacts of Global Climate Change and Sea-Level Rise on Tidal Wetlands" Pending chapter of manuscript by University of California Press.

Titus, J.G., R.A. Park, S.P. Leatherman, J.R. Weggel, M.S. Greene, P.W. Mausel, M.S. Trehan, S. Brown, C. Grant, and G.W. Yohe. 1991. Greenhouse Effect and Sea Level Rise: Loss of Land and the Cost of Holding Back the Sea. *Coastal Management* 19:2:171-204.

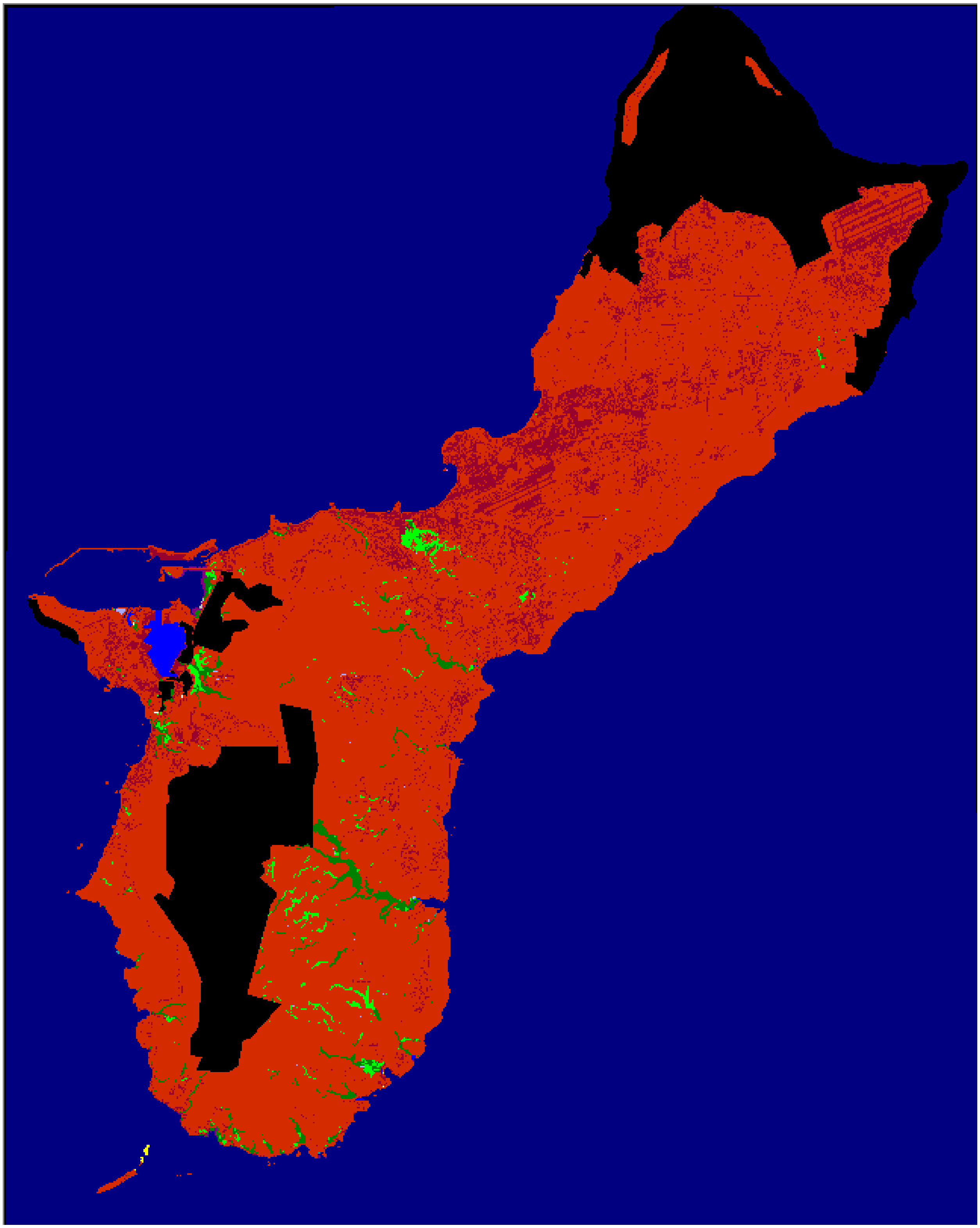
United States Fish and Wildlife Service, Federal Highway Administration Western Federal Lands Highway Division. 2009. Environmental Assessment for the Ni-les'tun Unit of the Guam National Wildlife Refuge Restoration and North Bank Land Improvement Project

# Appendix A: Contextual Results

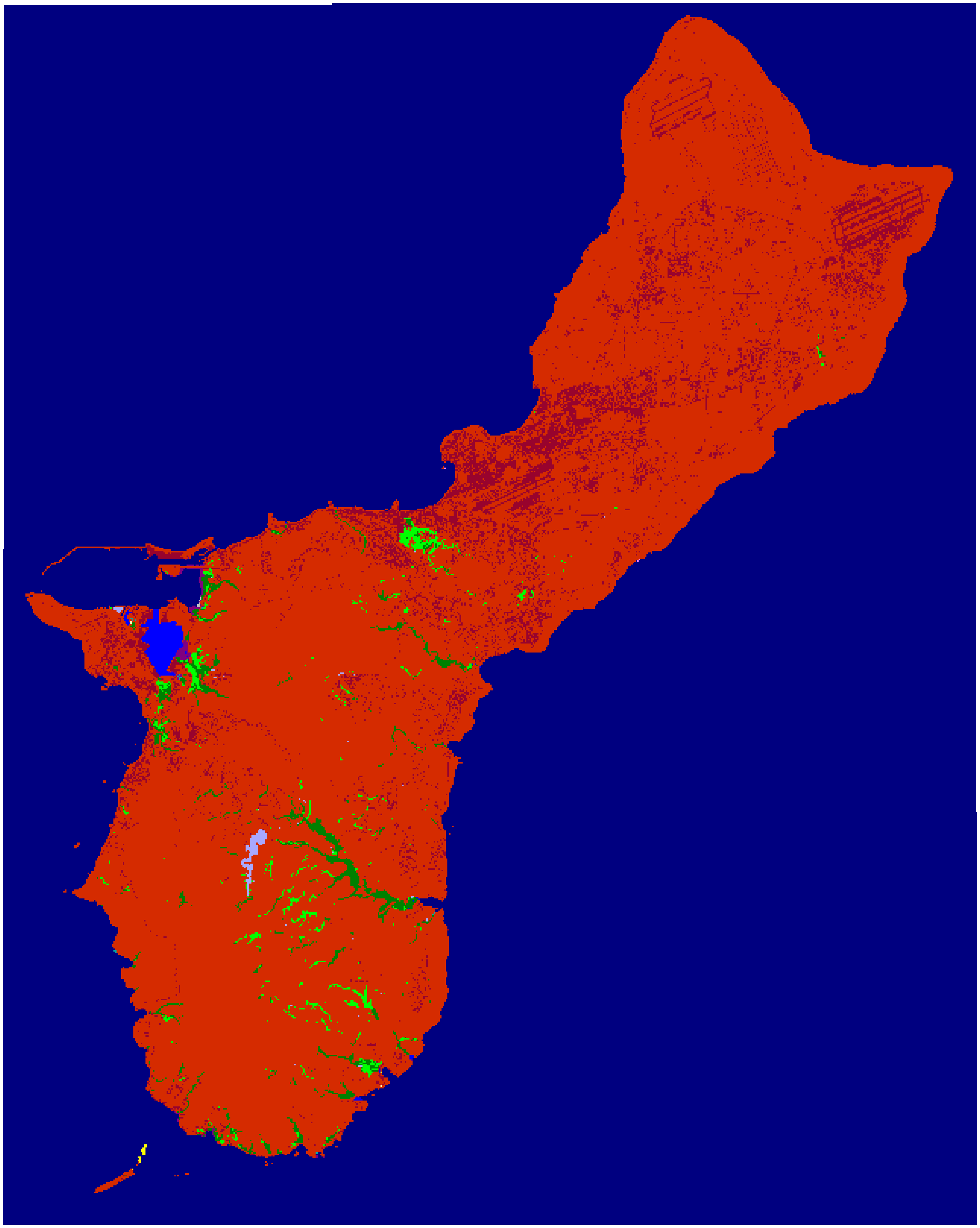
The SLAMM model does take into account the context of the surrounding lands or open water when calculating effects. For example, erosion rates are calculated based on the maximum fetch (wave action) which is estimated by assessing contiguous open water to a given marsh cell. Another example is that inundated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

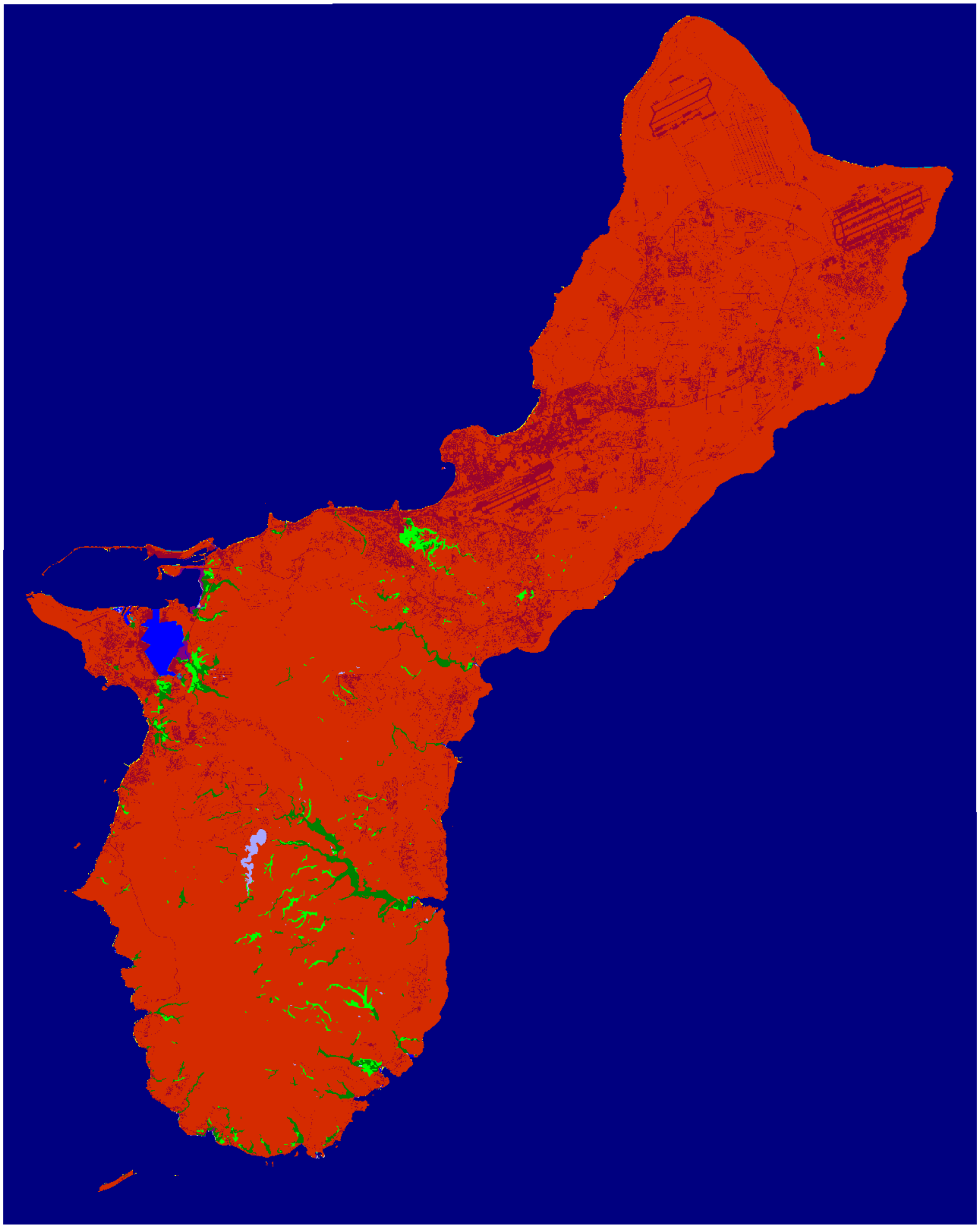
- Results were closely examined (quality assurance) within USFWS refuges but not closely examined for the larger region.
- Site-specific parameters for the model were derived for USFWS refuges whenever possible and may not be regionally applicable.
- Especially in areas where dikes are present, an effort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



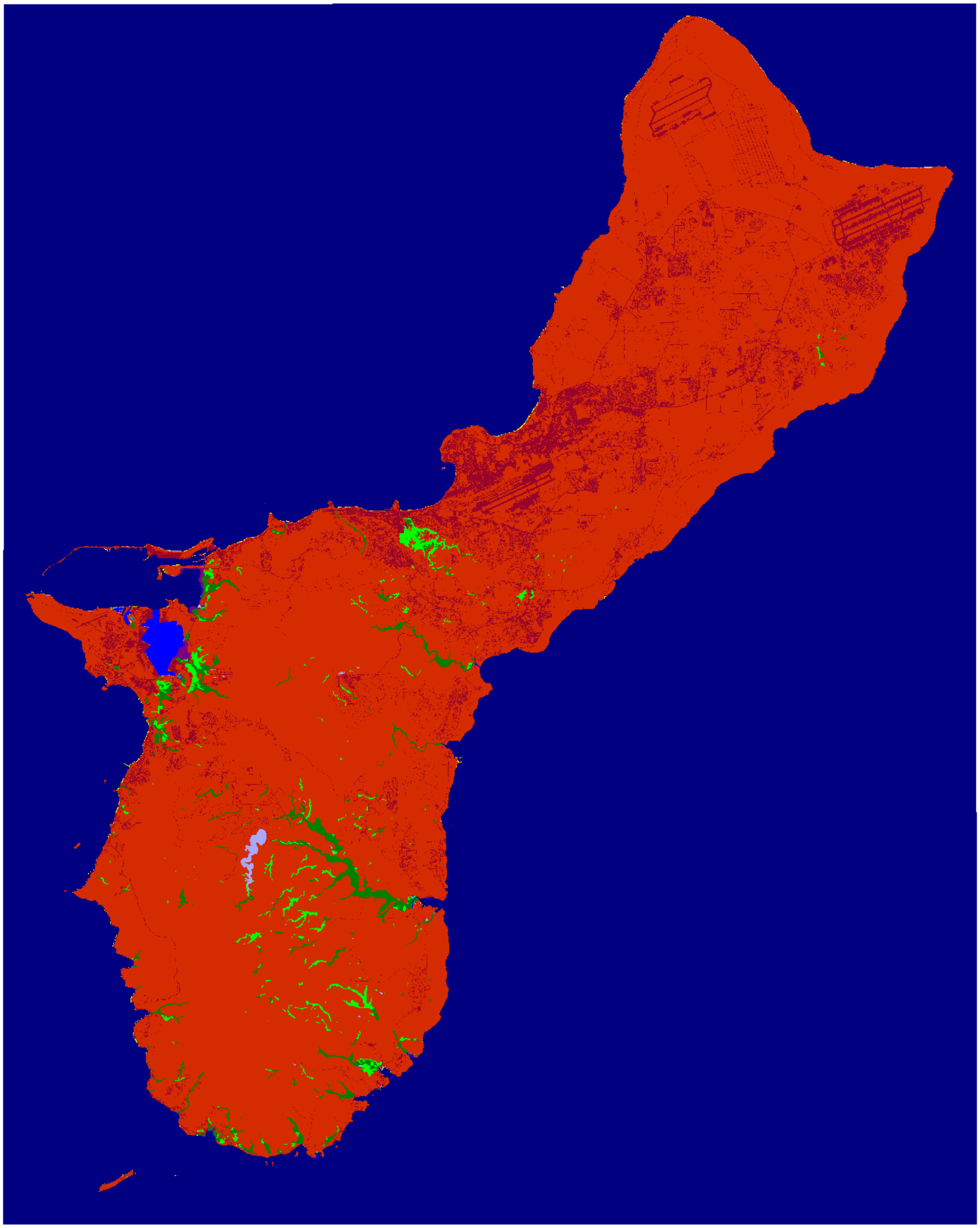
Guam National Wildlife Refuge within simulation context (black).



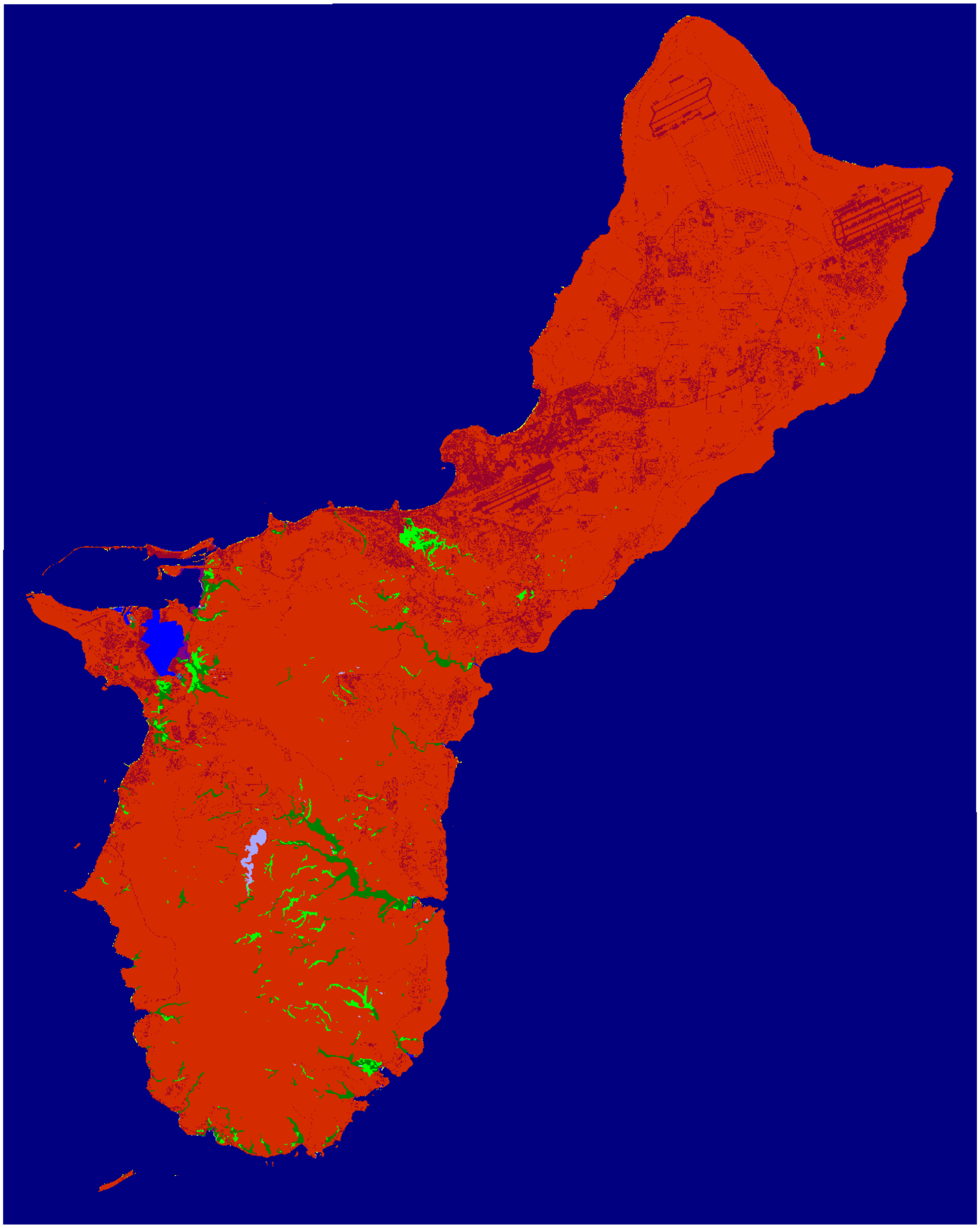
Guam Context, Initial Condition



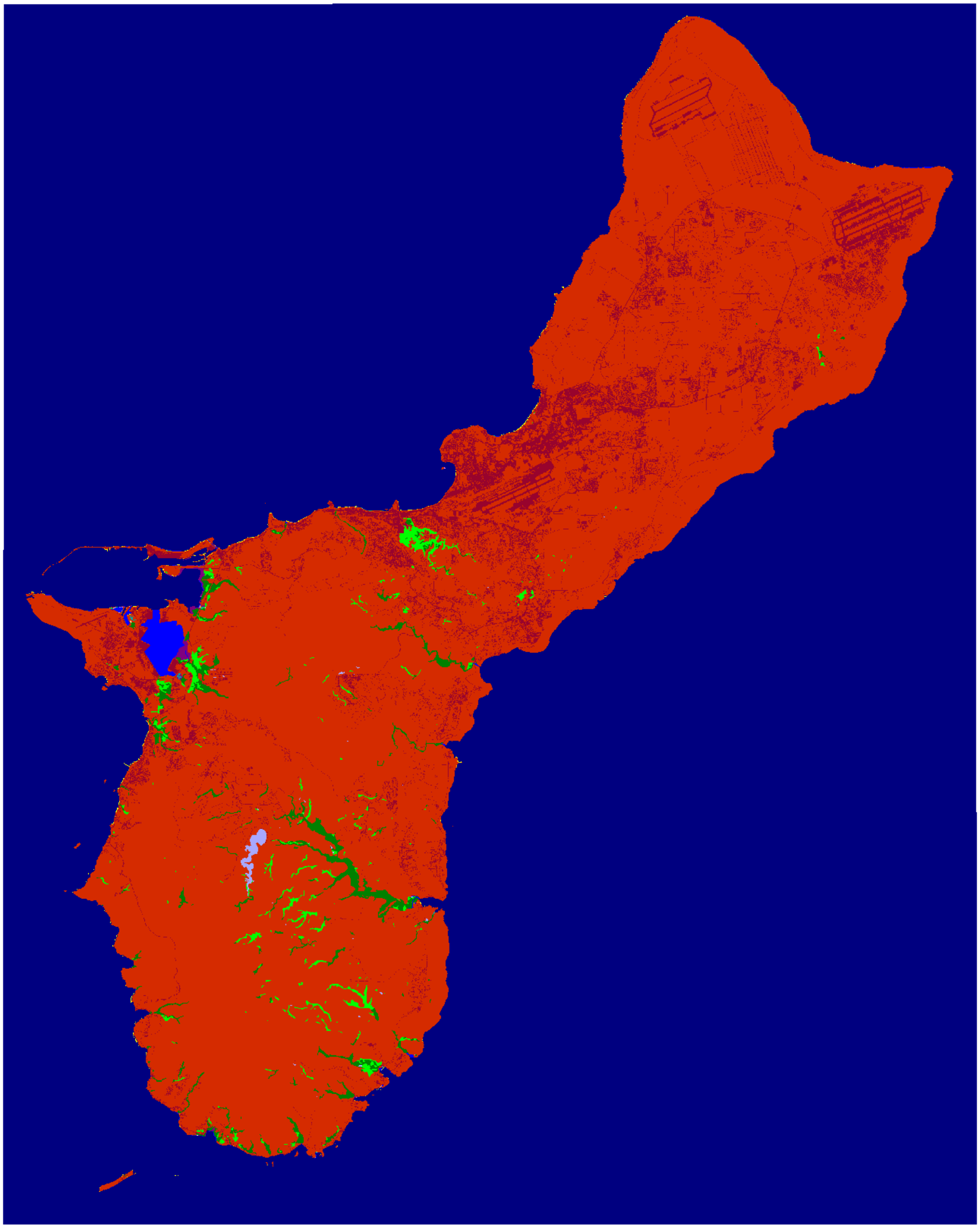
Guam Context, 2025, Scenario A1B Mean



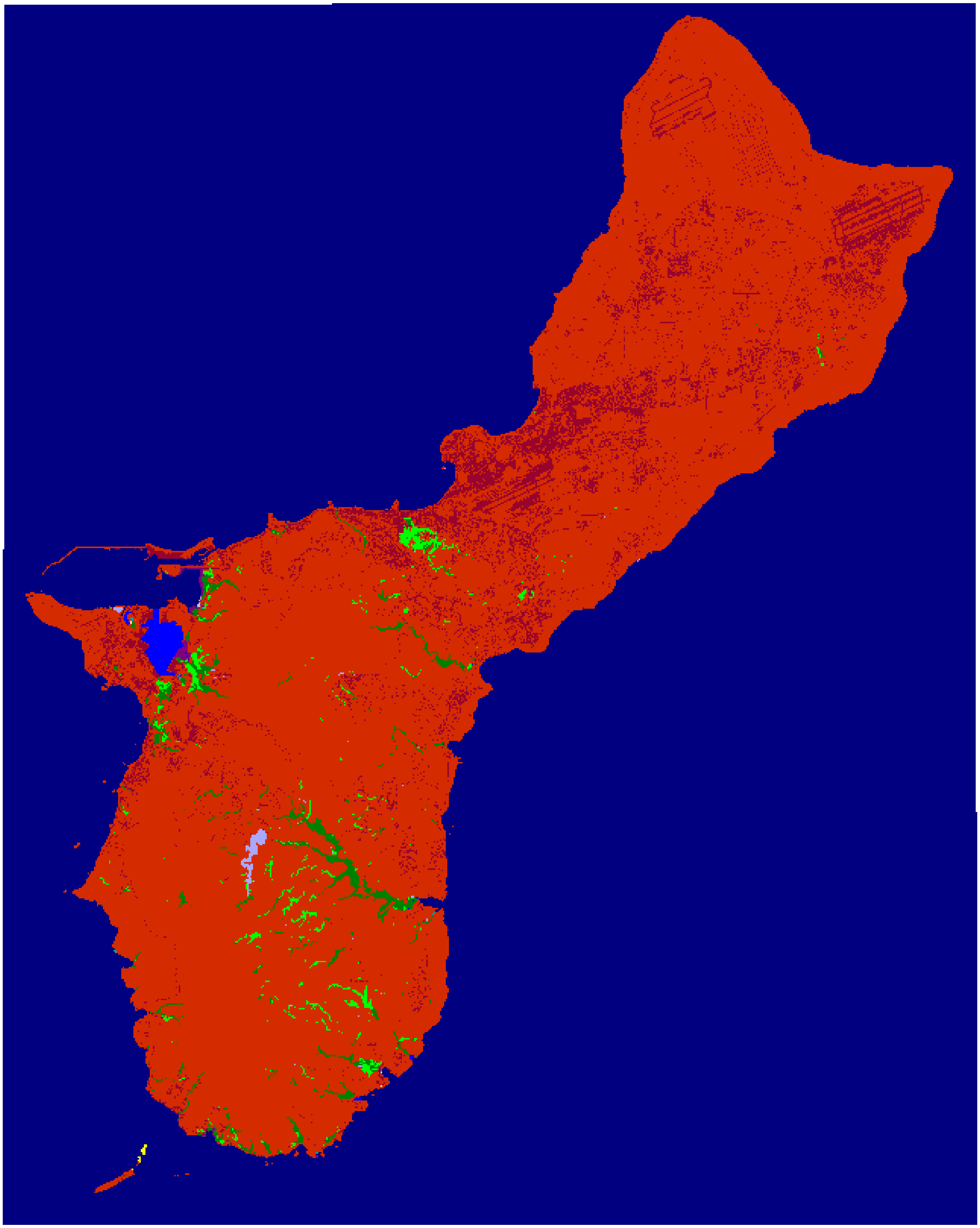
Guam Context, 2050, Scenario A1B Mean



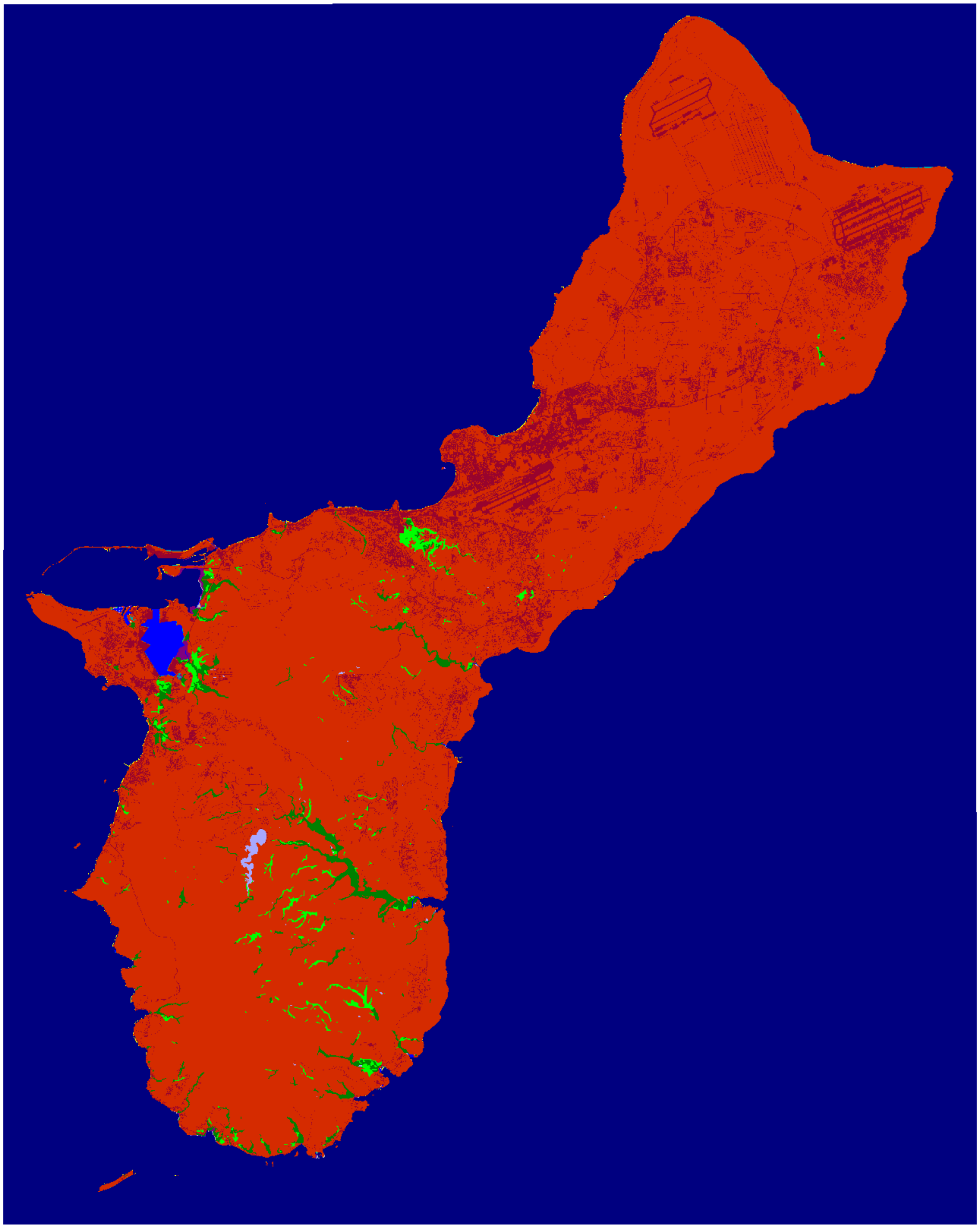
Guam Context, 2075, Scenario A1B Mean



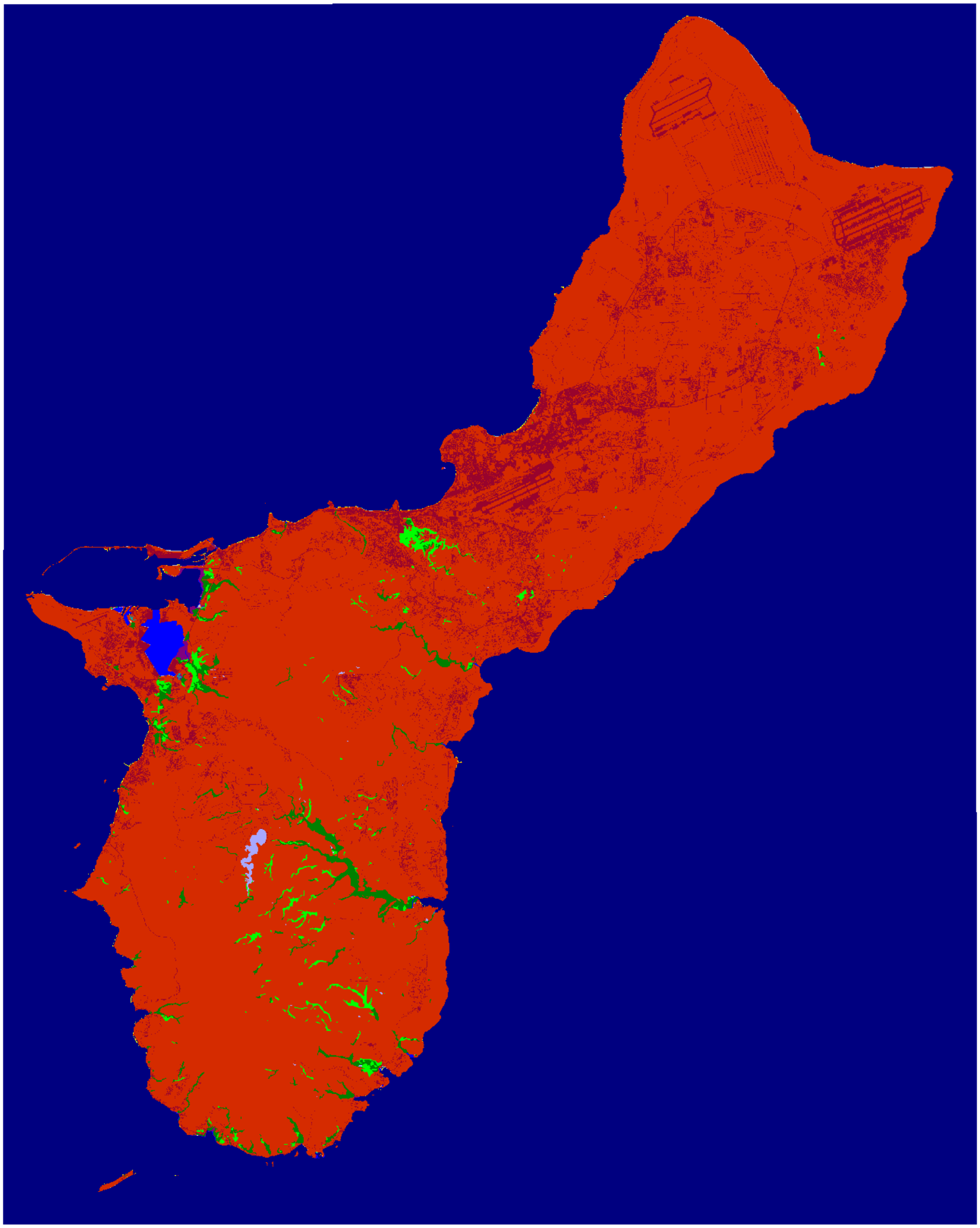
Guam Context, 2100, Scenario A1B Mean



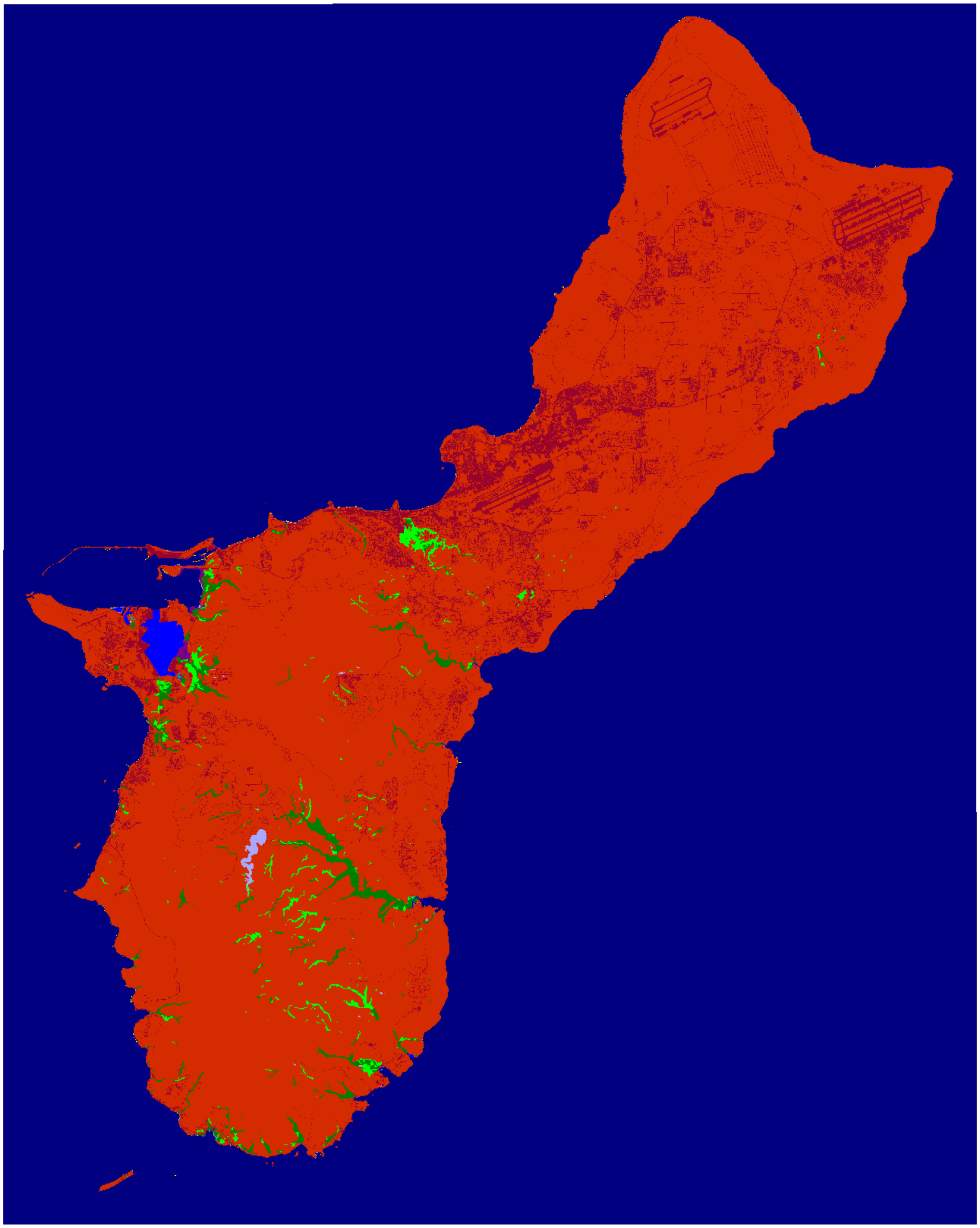
Guam Context, Initial Condition



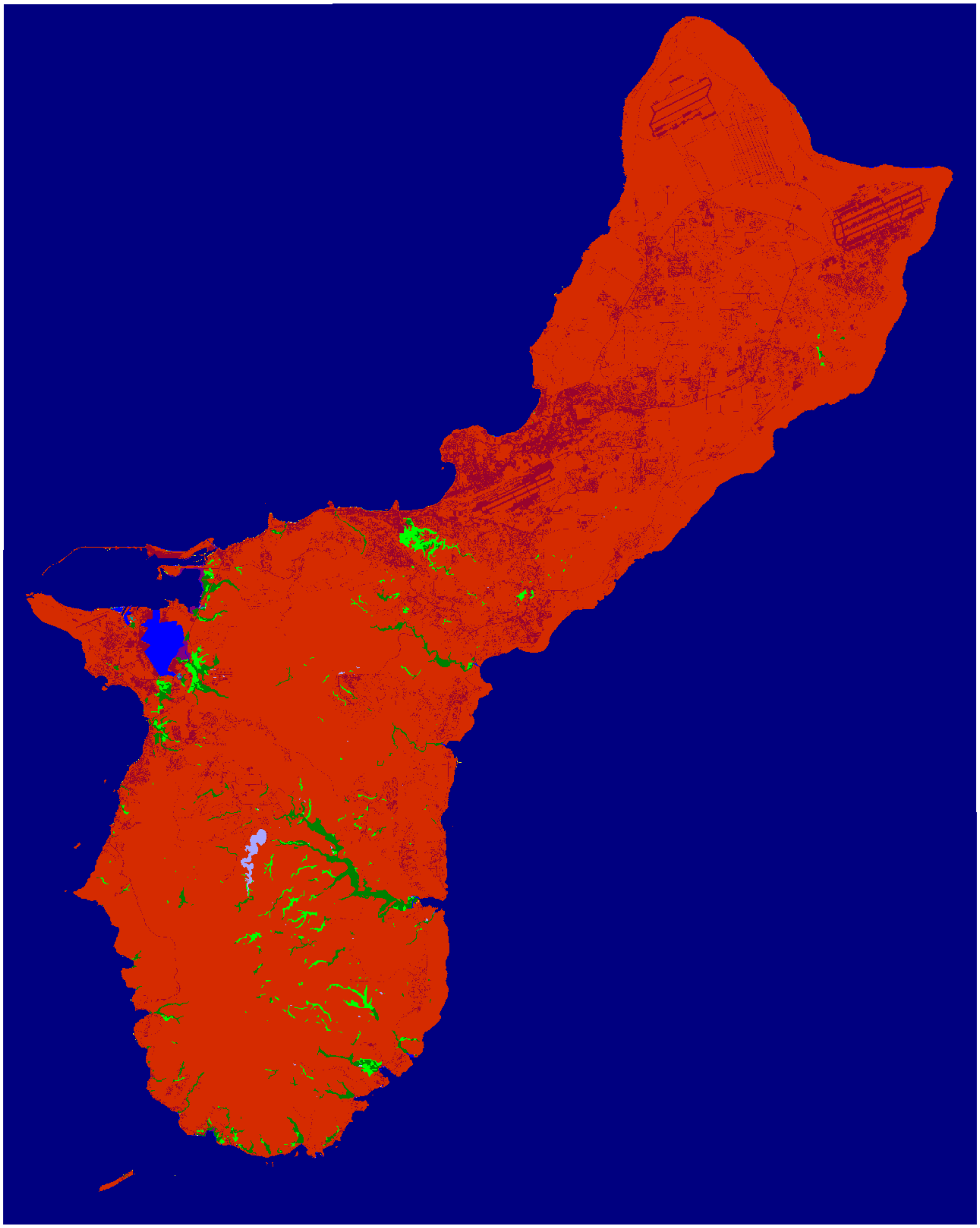
Guam Context, 2025, Scenario A1B Maximum



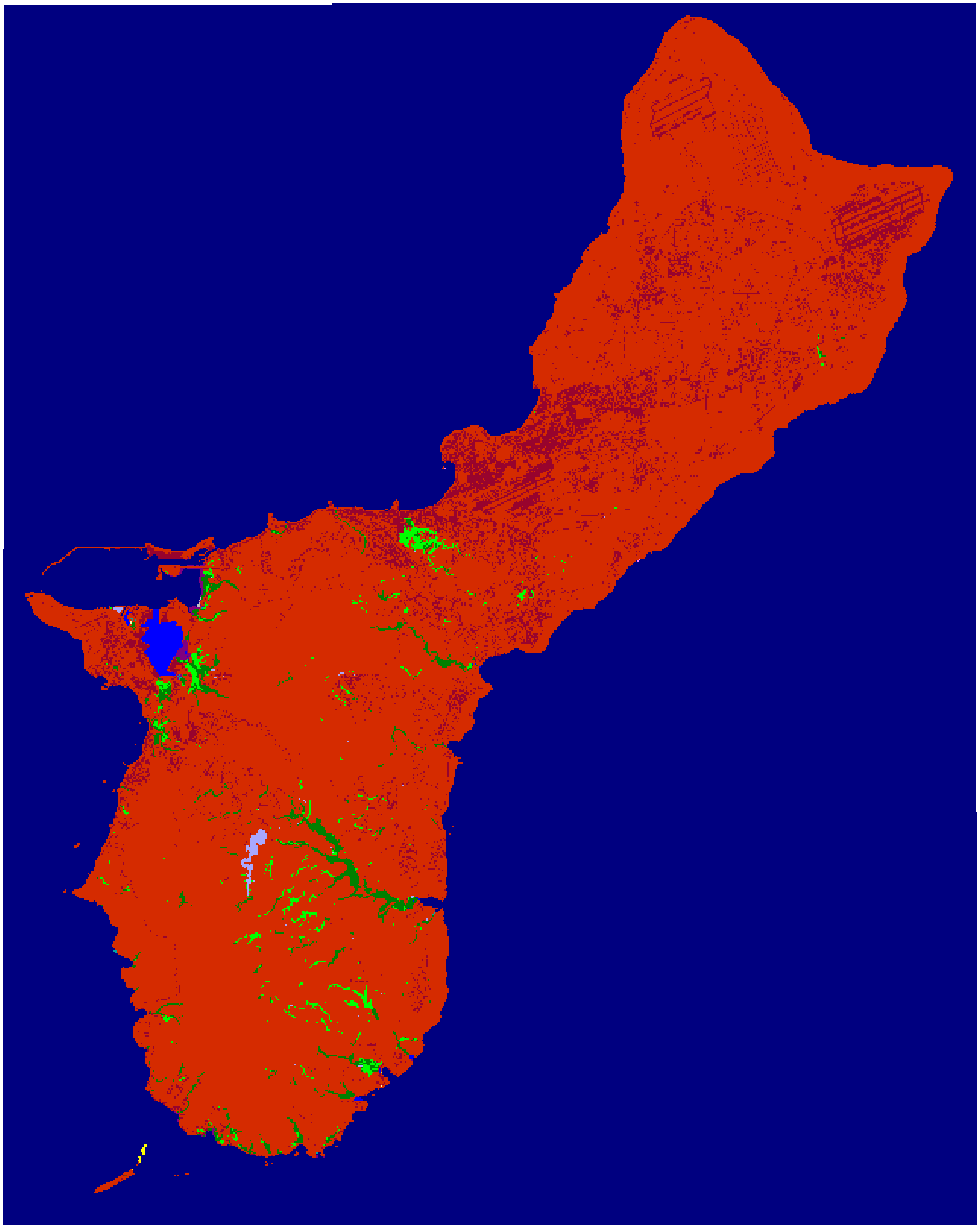
Guam Context, 2050, Scenario A1B Maximum



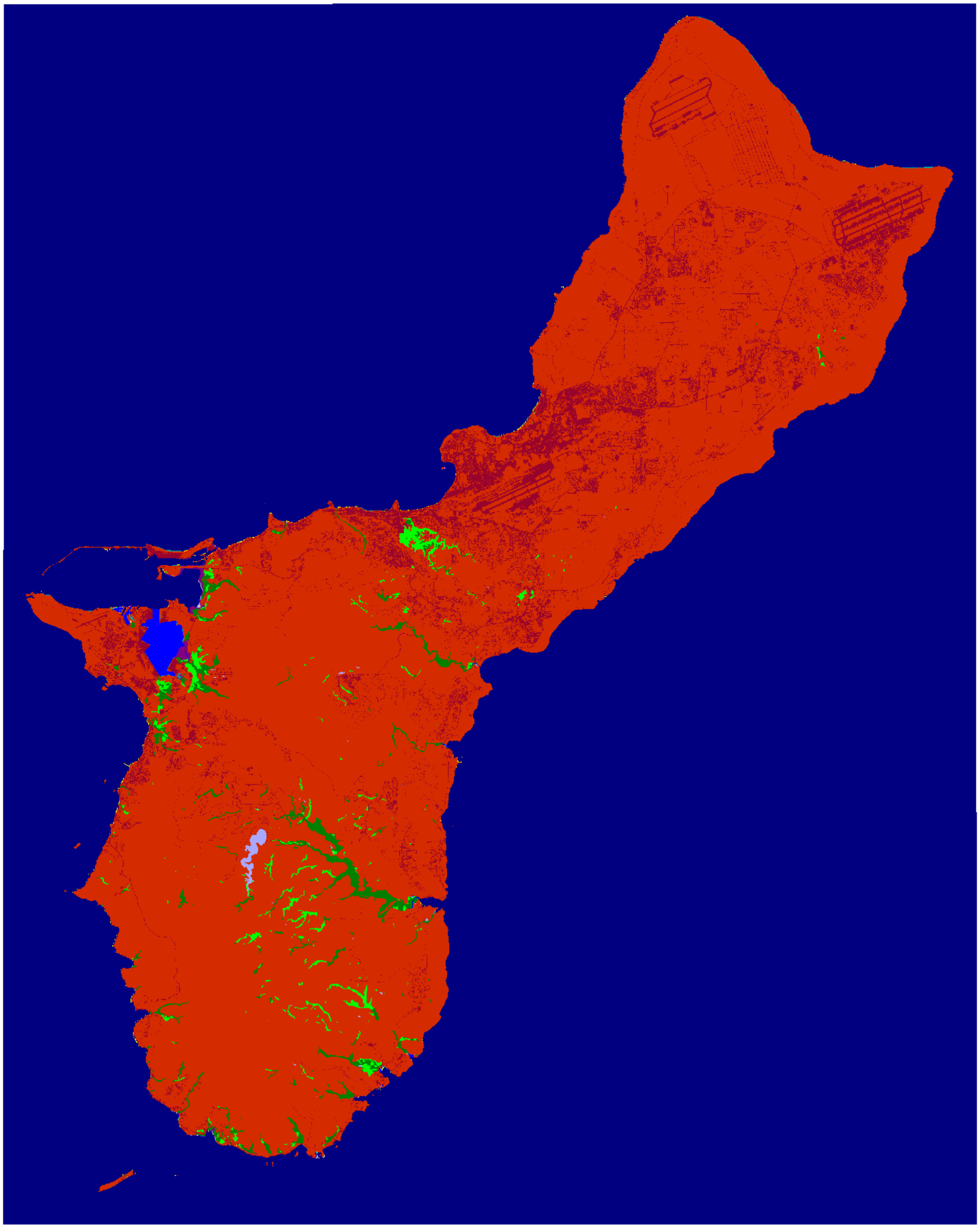
Guam Context, 2075, Scenario A1B Maximum



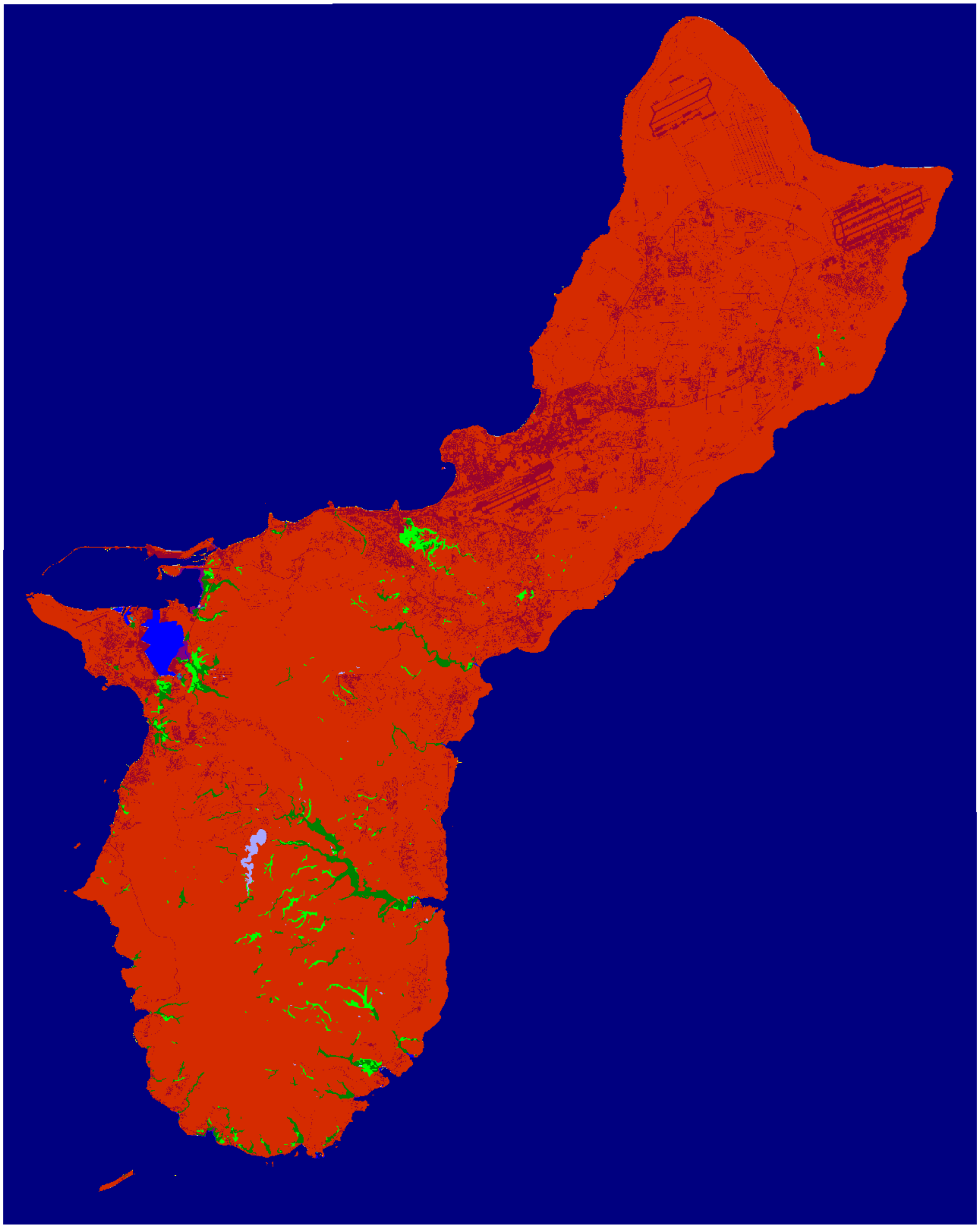
Guam Context, 2100, Scenario A1B Maximum



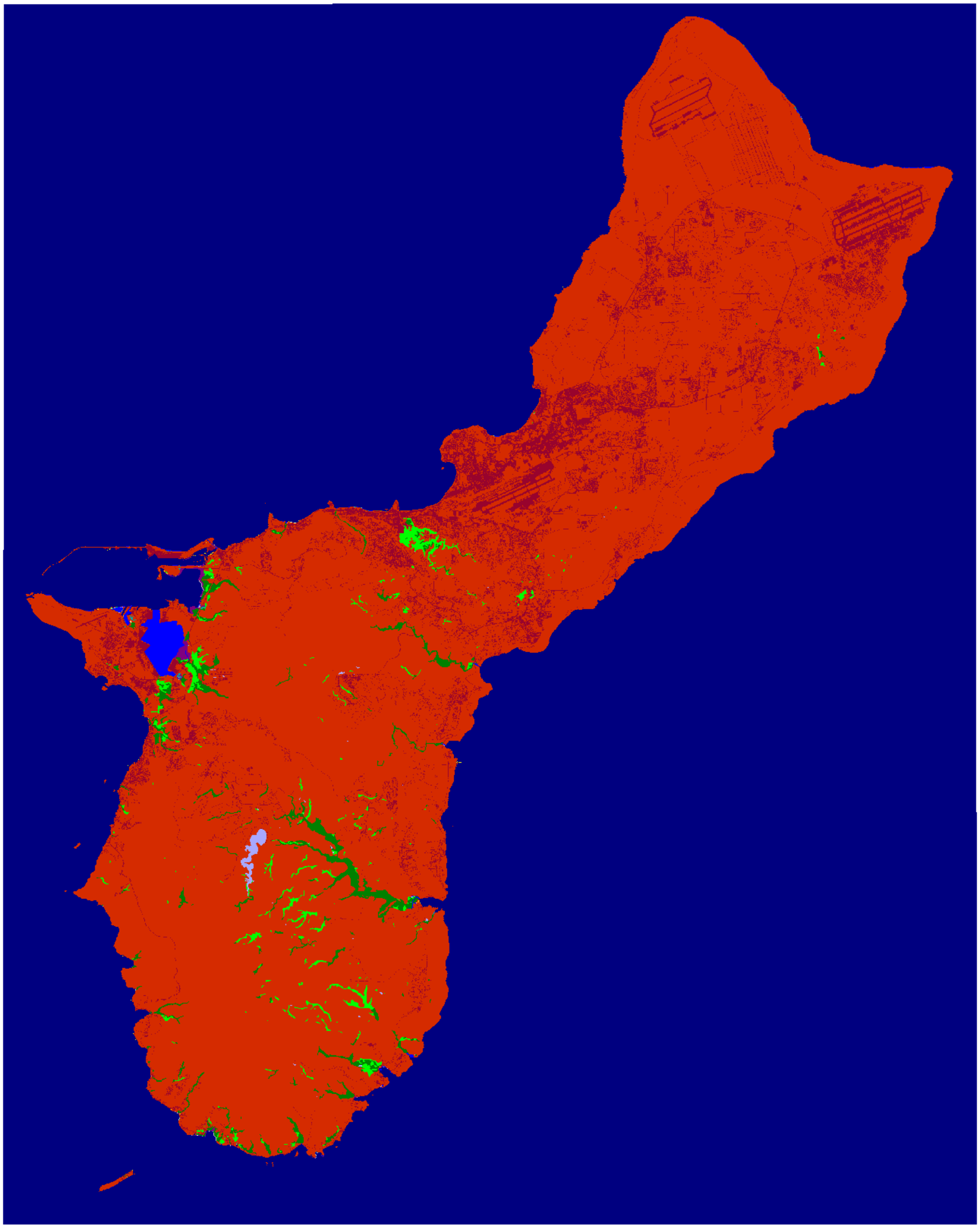
Guam Context, Initial Condition



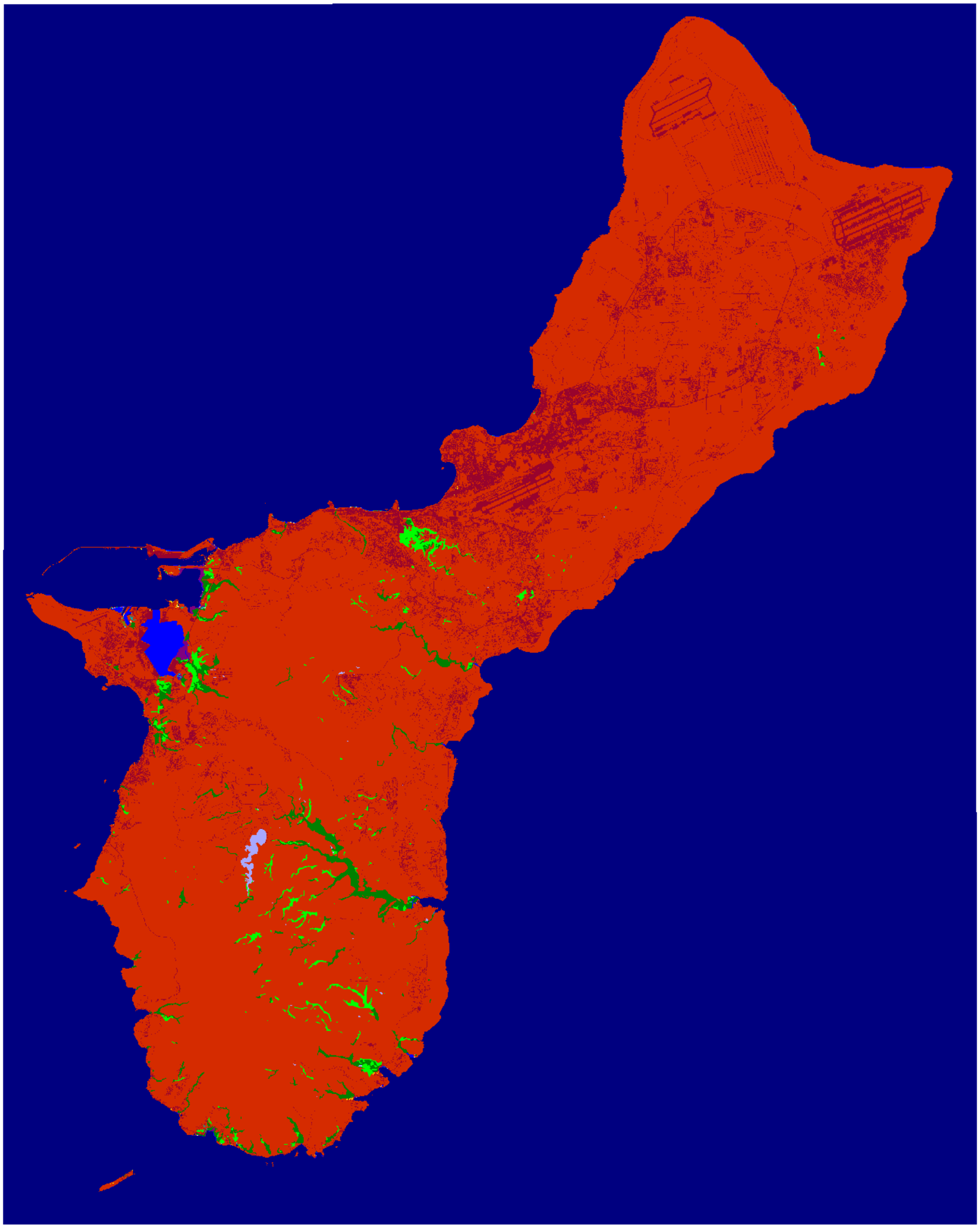
Guam Context, 2025, 1 meter



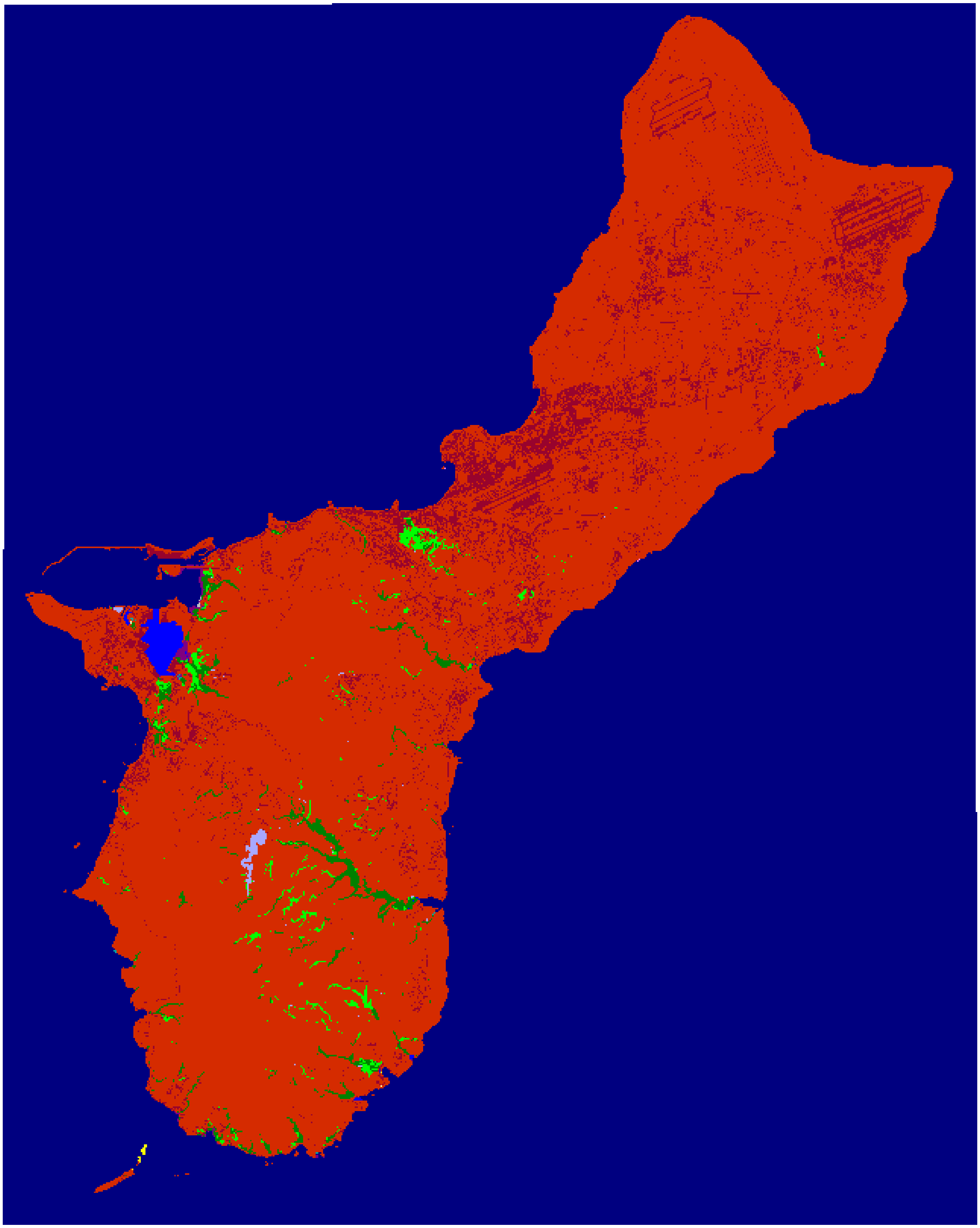
Guam Context, 2050, 1 meter



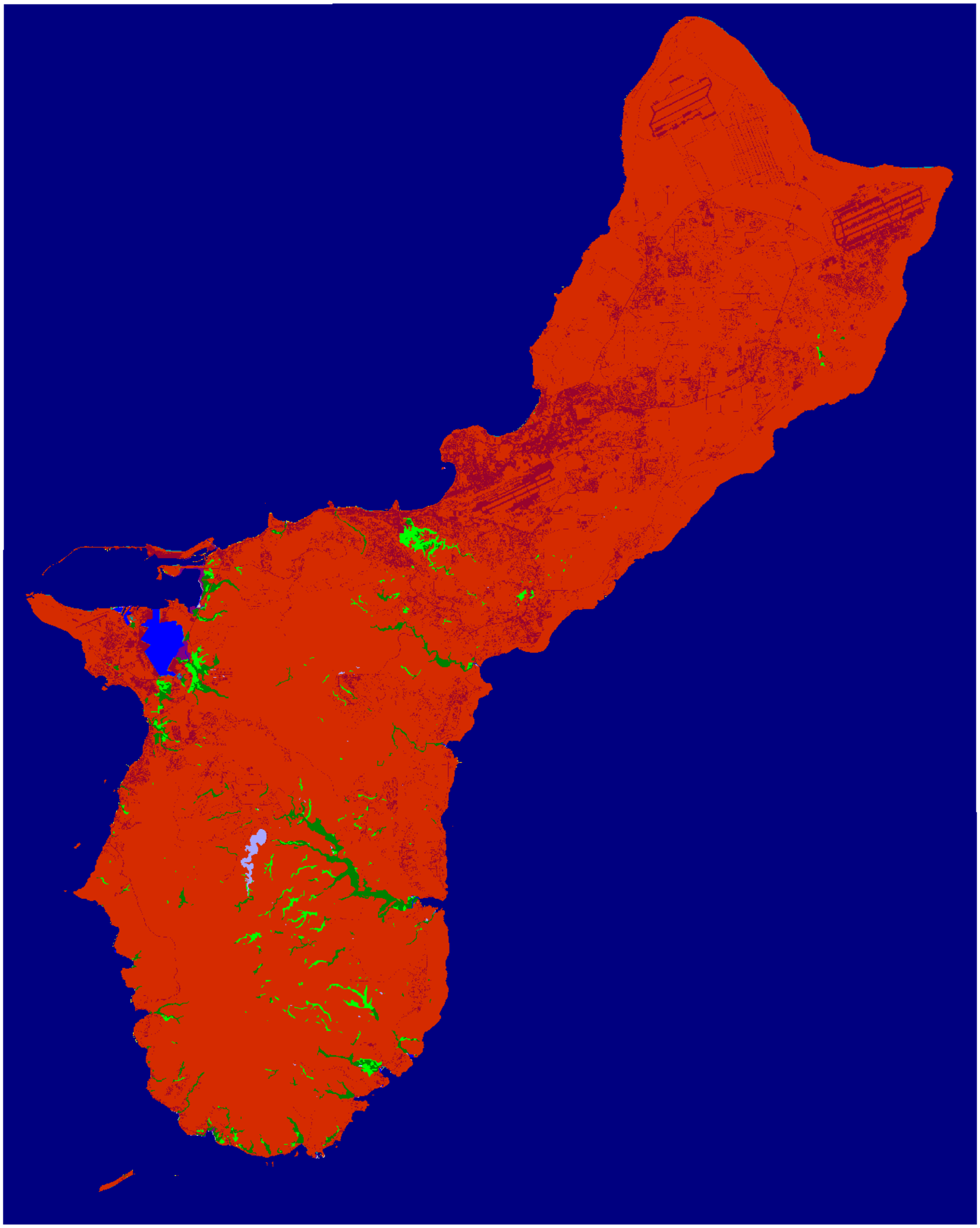
Guam Context, 2075, 1 meter



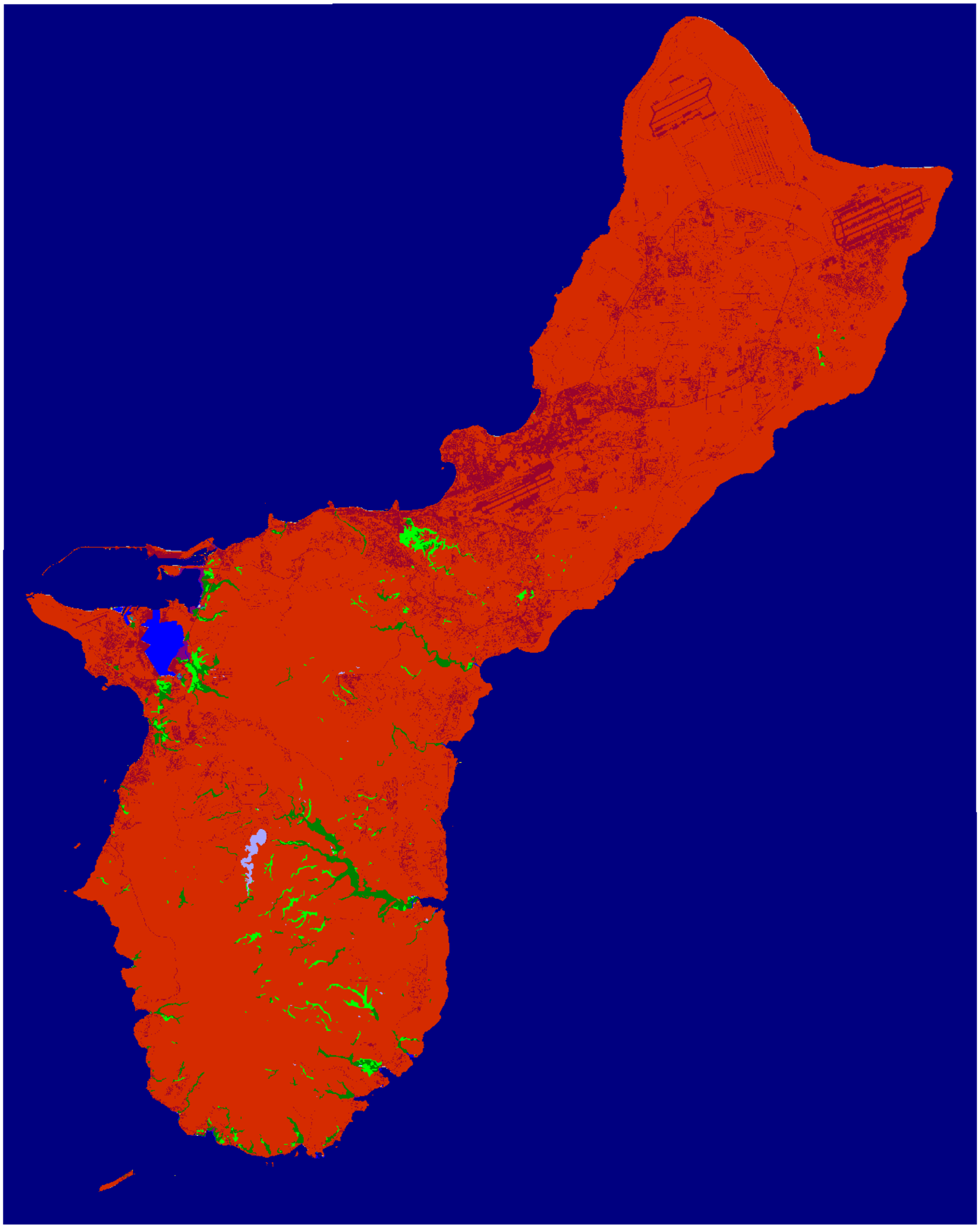
Guam Context, 2100, 1 meter



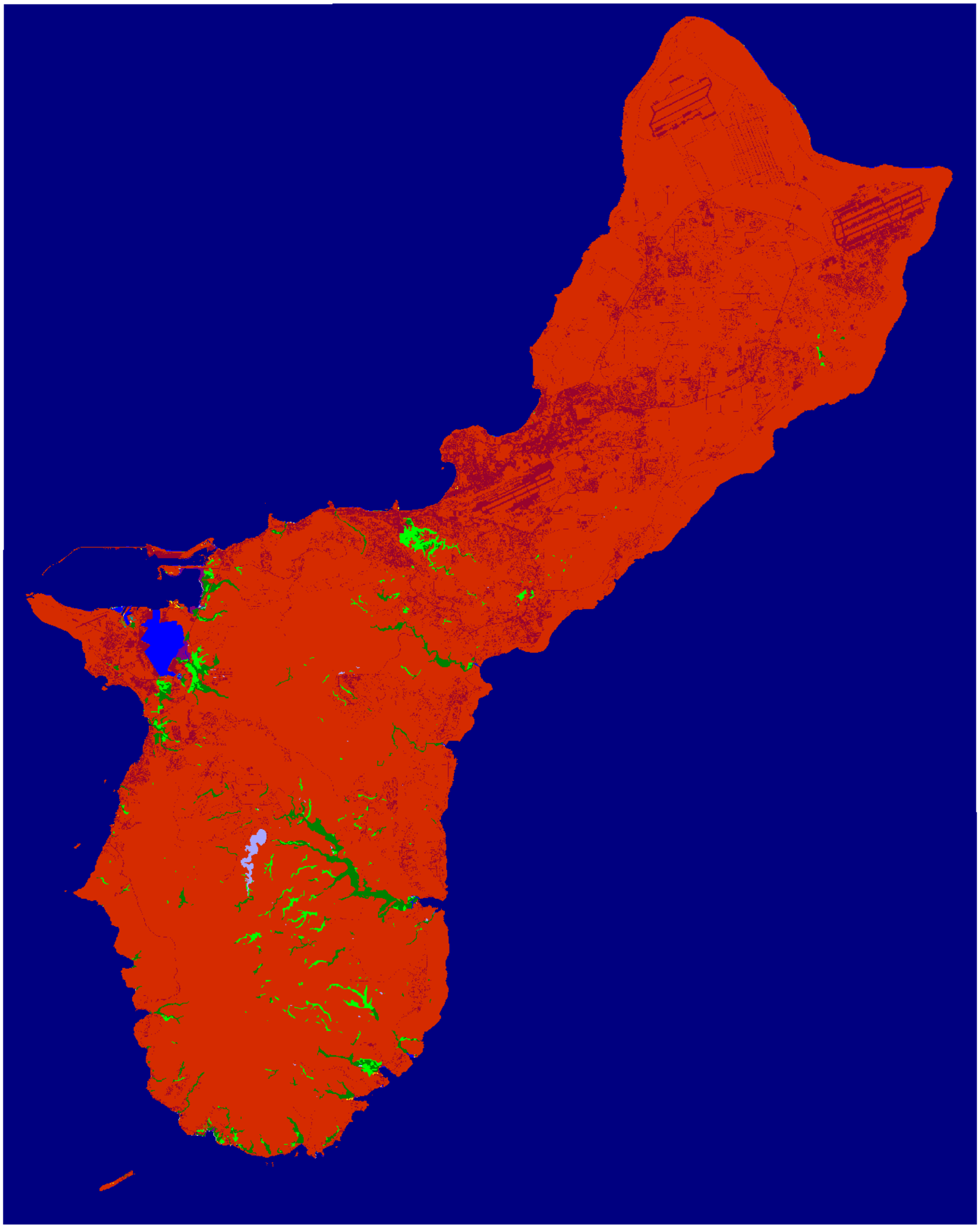
Guam Context, Initial Condition



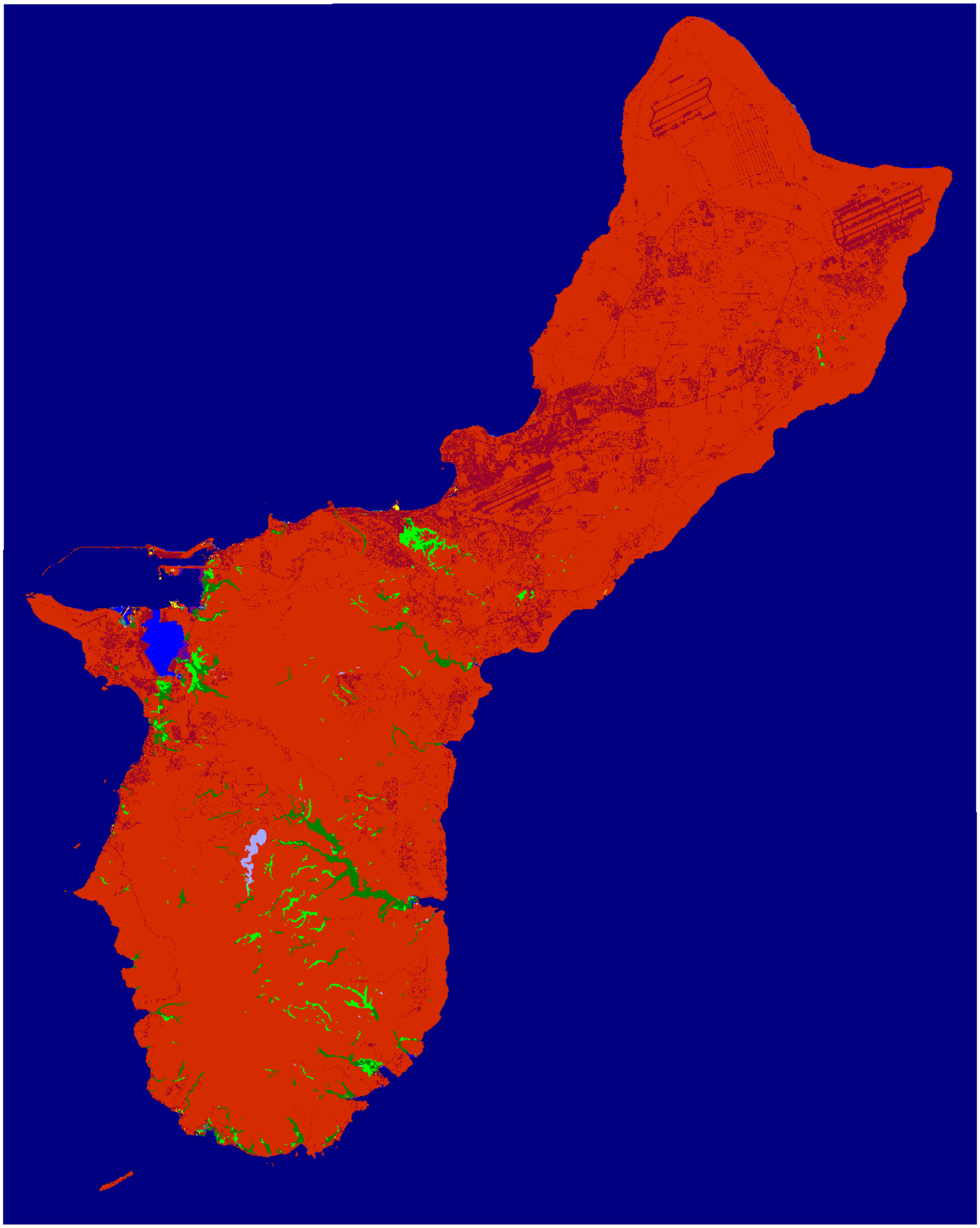
Guam Context, 2025, 1.5 meter



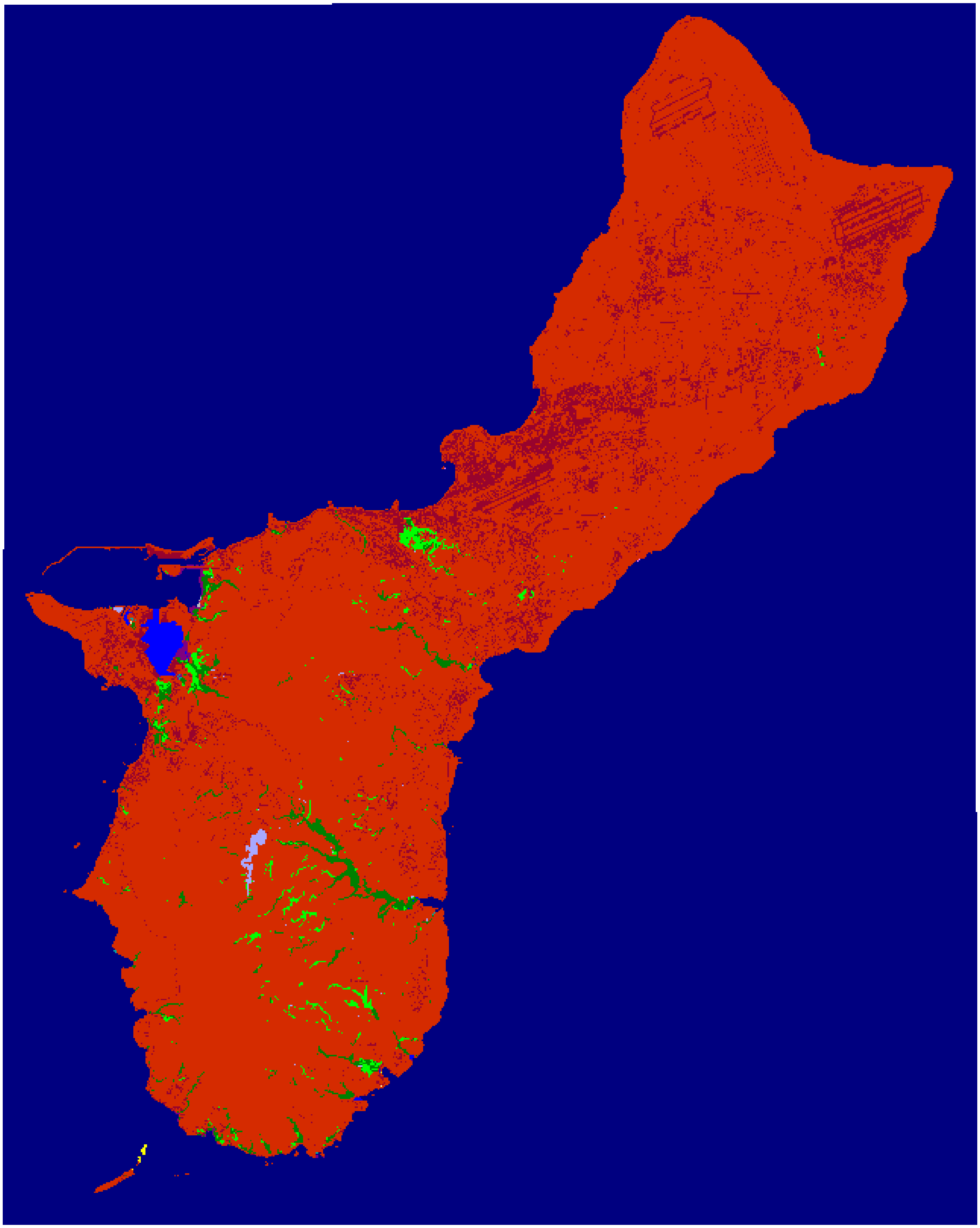
Guam Context, 2050, 1.5 meter



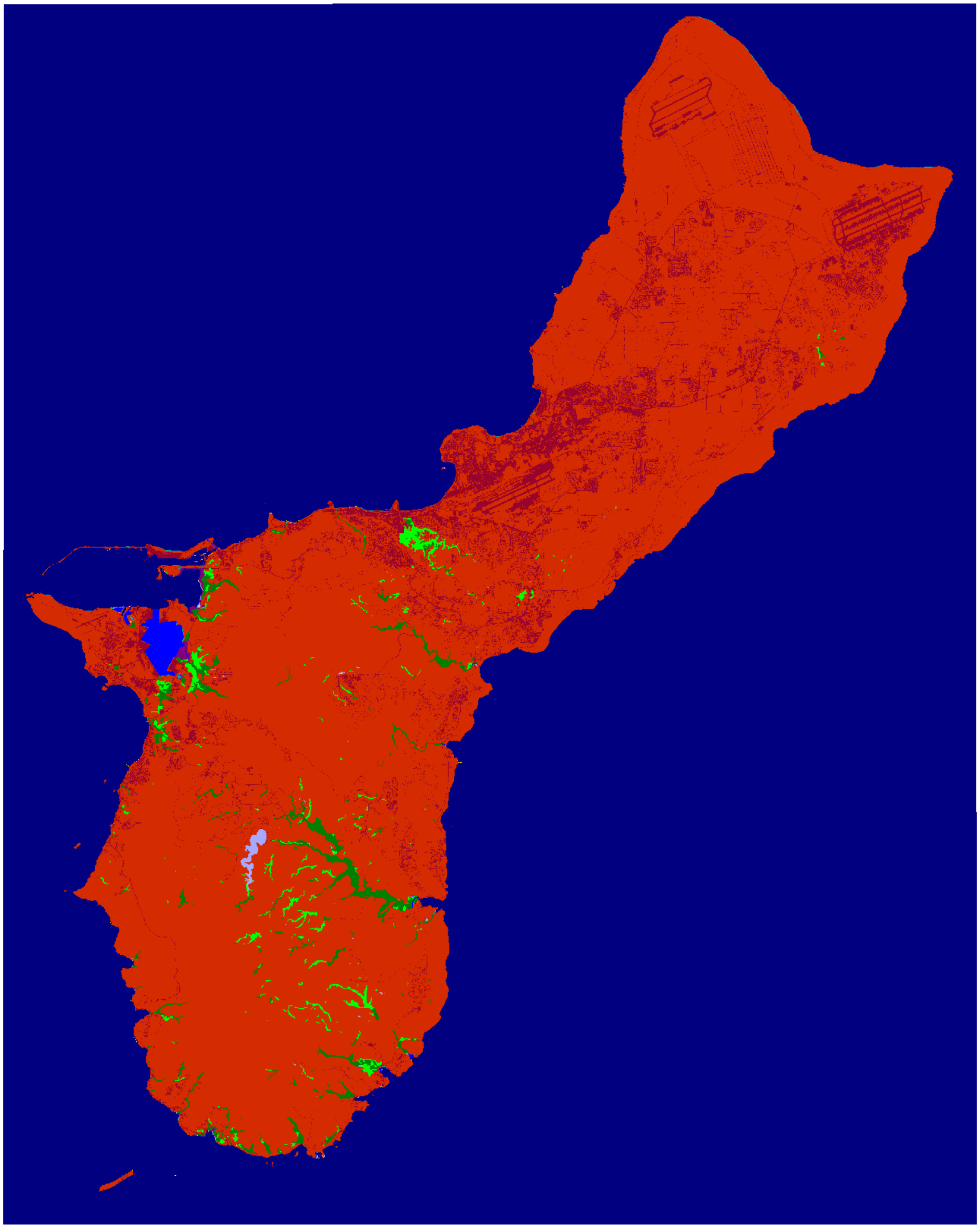
Guam Context, 2075, 1.5 meter



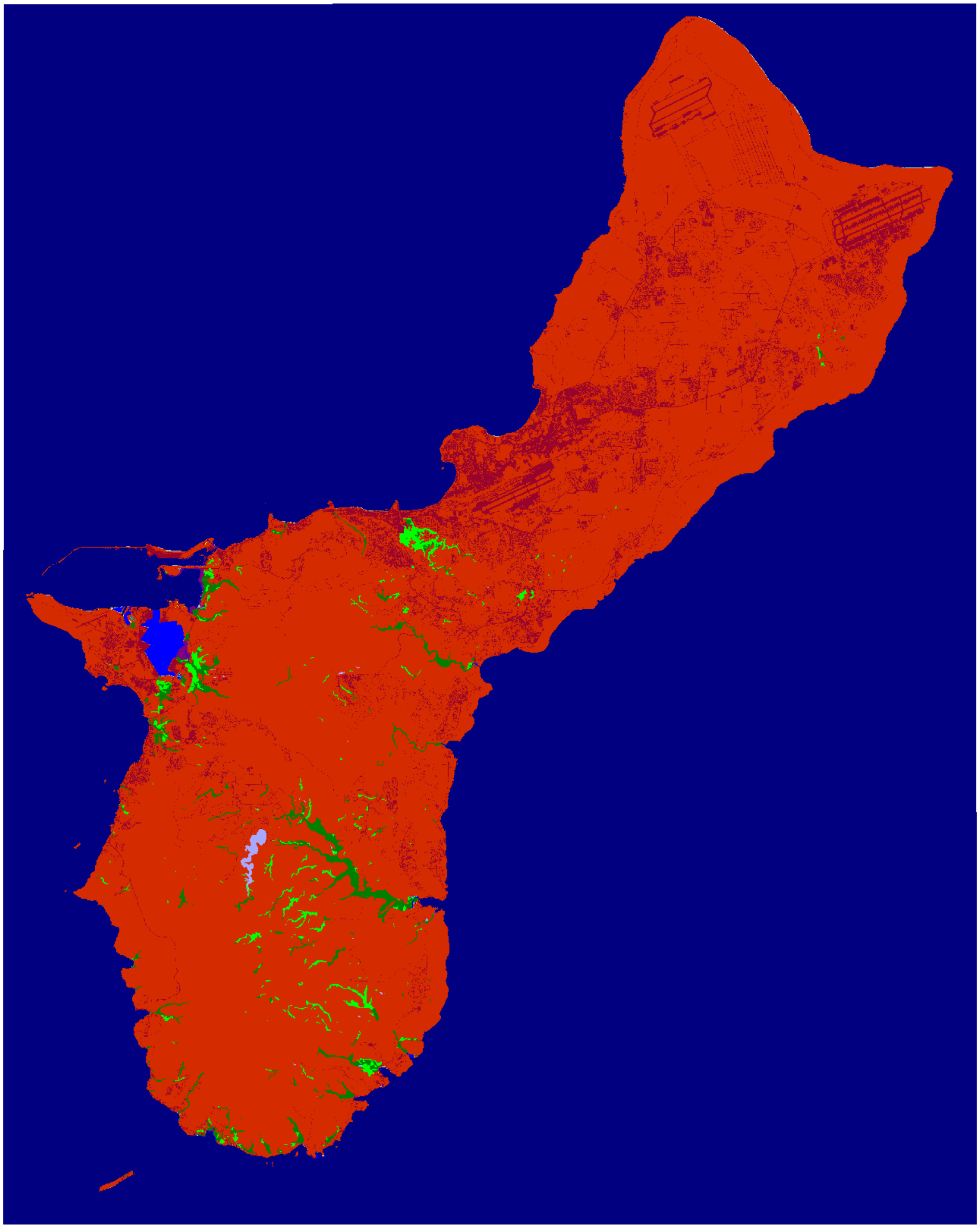
Guam Context, 2100, 1.5 meter



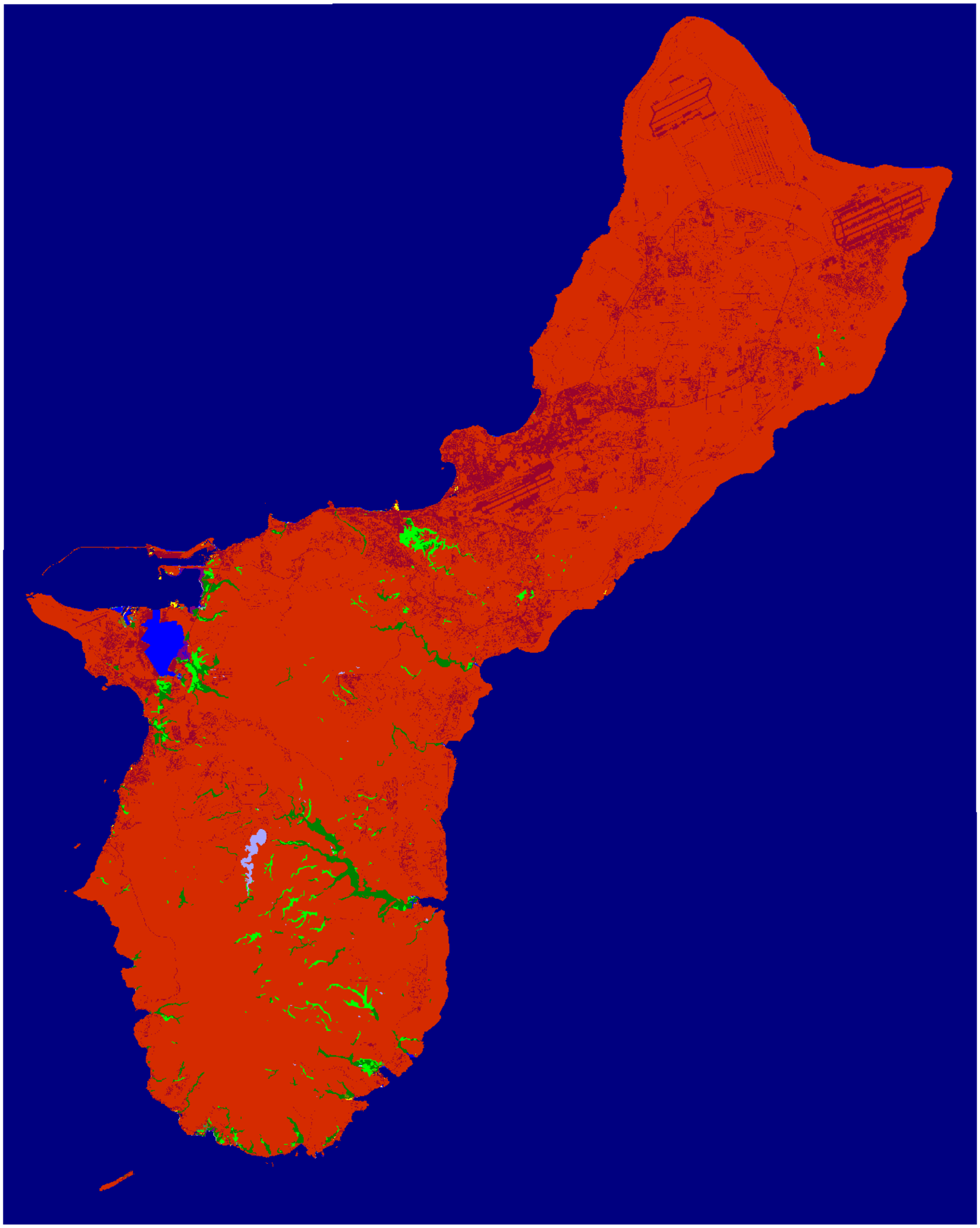
Guam Context, Initial Condition



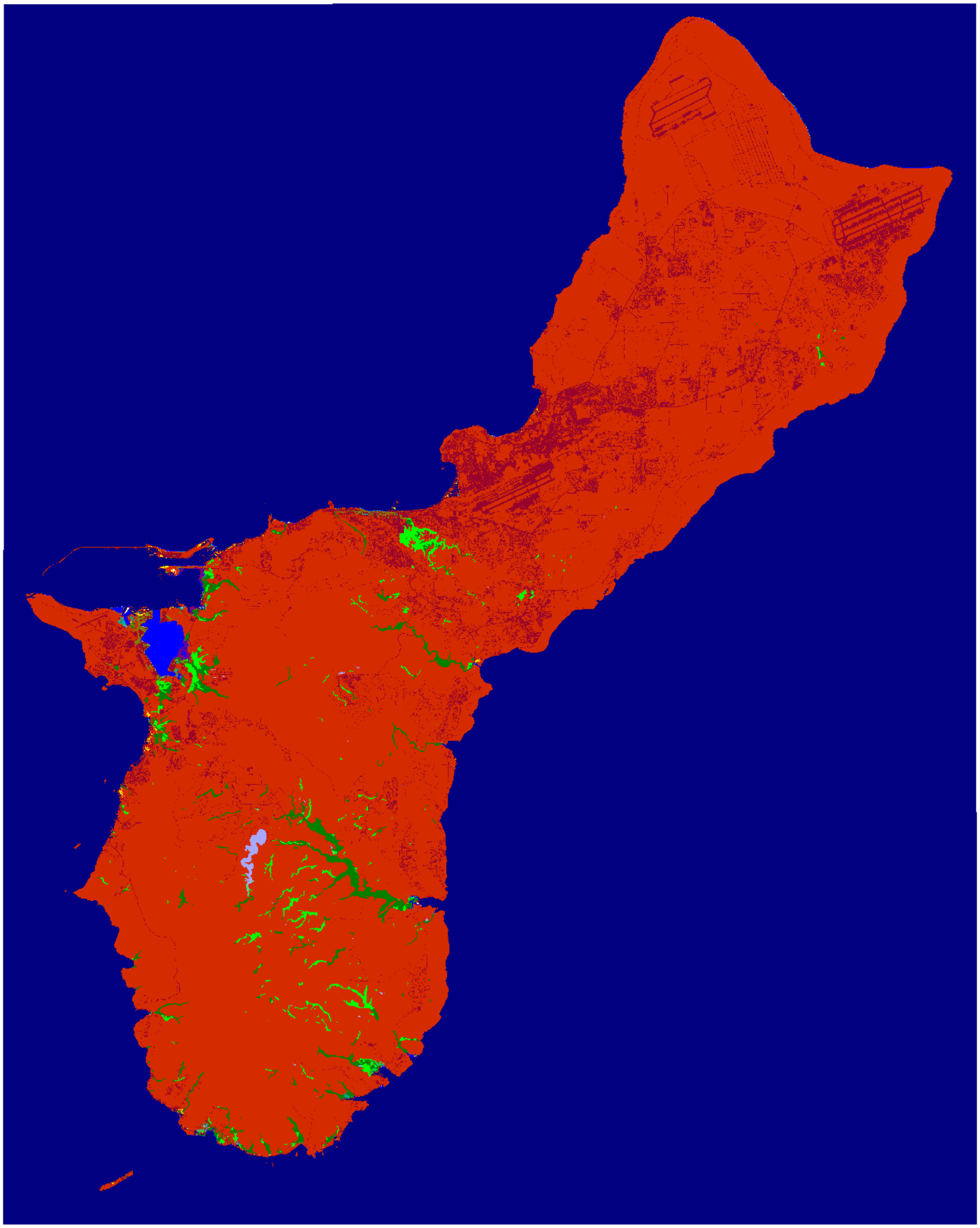
Guam Context, 2025, 2 meter



Guam Context, 2050, 2 meter



Guam Context, 2075, 2 meter



Guam Context, 2100, 2 meter