Application of the Sea-Level Affecting Marshes Model (SLAMM 6) to Crocodile Lake NWR

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Introduction

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

In an effort to address the potential effects of sea level rise on United States national wildlife refuges, the U. S. Fish and Wildlife Service contracted the application of the SLAMM model for most Region 1 refuges. This analysis is designed to assist in the production of comprehensive conservation plans (CCPs) for each refuge along with other long-term management plans.

Model Summary

Changes in tidal marsh area and habitat type in response to sea-level rise were modeled using the Sea Level Affecting Marshes Model (SLAMM 6) that accounts for the dominant processes involved in wetland conversion and shoreline modifications during long-term sea level rise (Park et al. 1989; www.warrenpinnacle.com/prof/SLAMM).

Successive versions of the model have been used to estimate the impacts of sea level rise on the coasts of the U.S. (Titus et al., 1991; Lee, J.K., R.A. Park, and P.W. Mausel. 1992; Park, R.A., J.K. Lee, and D. Canning 1993; Galbraith, H., R. Jones, R.A. Park, J.S. Clough, S. Herrod-Julius, B. Harrington, and G. Page. 2002; National Wildlife Federation et al., 2006; Glick, Clough, et al. 2007; Craft et al., 2009).

Within SLAMM, there are five primary processes that affect wetland fate under different scenarios of sea-level rise:

- **Inundation:** The rise of water levels and the salt boundary are tracked by reducing elevations of each cell as sea levels rise, thus keeping mean tide level (MTL) constant at zero. The effects on each cell are calculated based on the minimum elevation and slope of that cell.
- **Erosion:** Erosion is triggered based on a threshold of maximum fetch and the proximity of the marsh to estuarine water or open ocean. When these conditions are met, horizontal erosion occurs at a rate based on site-specific data.
- **Overwash:** Barrier islands of under 500 meters width are assumed to undergo overwash during each specified interval for large storms. Beach migration and transport of sediments are calculated.
- **Saturation:** Coastal swamps and fresh marshes can migrate onto adjacent uplands as a response of the fresh water table to rising sea level close to the coast.

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

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

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

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

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

Sea Level Rise Scenarios

SLAMM 6 was run using scenario A1B from the Special Report on Emissions Scenarios (SRES) – mean and maximum estimates. The A1 family of scenarios assumes that the future world includes rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. In particular, the A1B scenario assumes that energy sources will be balanced across all sources. Under the A1B scenario, the IPCC WGI Fourth Assessment Report (IPCC, 2007) suggests a likely range of 0.21 to 0.48 meters of sea level rise by 2090-2099 "excluding future rapid dynamical changes in ice flow." The A1B-mean scenario that was run as a part of this project falls near the middle of this estimated range, predicting 0.39 meters of global sea level rise by 2100. A1B-maximum predicts 0.69 meters of global SLR by 2100.

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

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

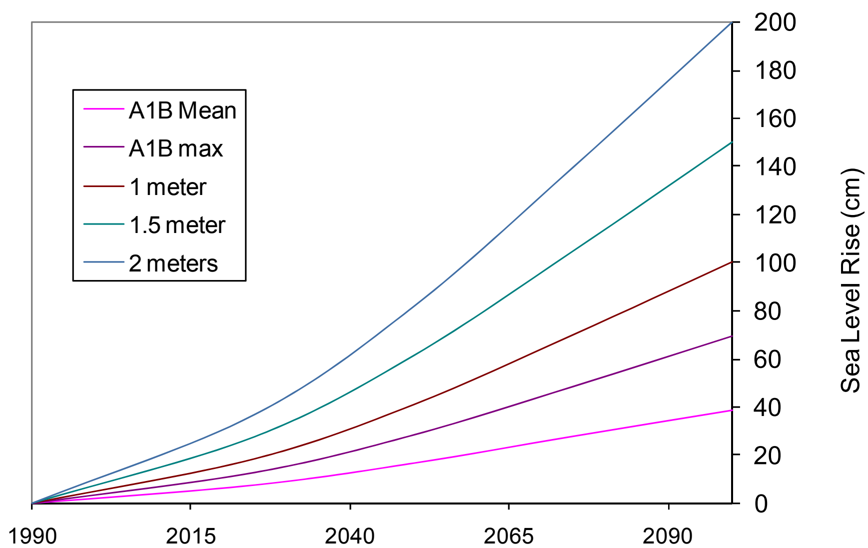


Figure 1: Summary of SLR scenarios utilized

Methods and Data Sources

The digital elevation map used in this simulation was derived from 1/9 arc second LiDAR data covering Miami-Dade county as supplied by USGS with a timestamp of 2008 (Figure 2).

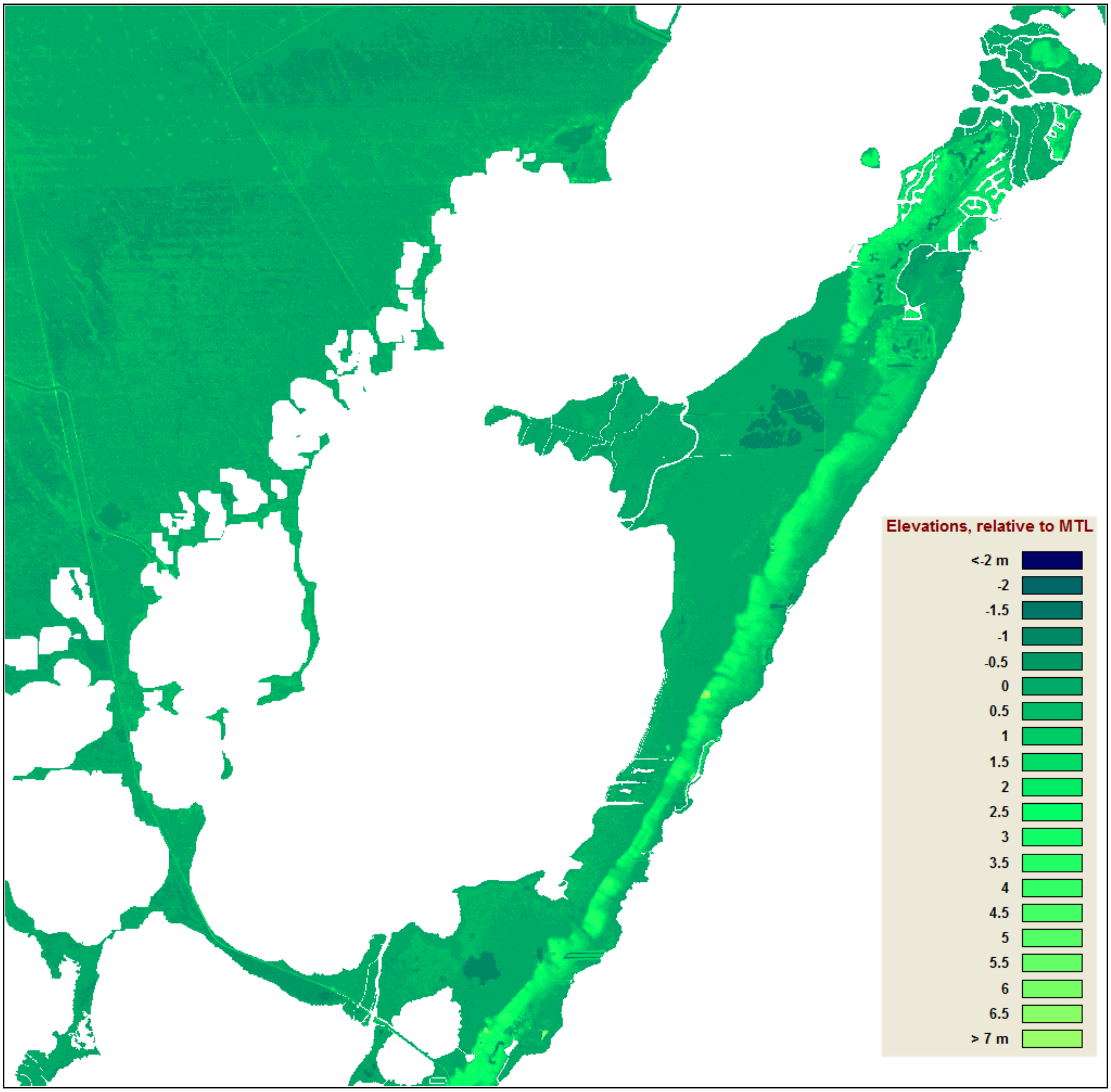


Figure 2: Shade-relief elevation map of refuge. Water cells (white) contain no elevation data.

The wetlands layer for the study area was produced by the National Wetlands Inventory and was based on a 2009 photo date (Figure 3). Converting the NWI survey into 10 meter cells indicated that the approximately 7198 acre refuge (approved acquisition boundary including water) is composed of the following categories (excluding categories below 1%):

	Mangrove	79.7%
	Tidal Swamp	9.8%
	Estuarine Open Water	7.7%
	Undeveloped Dry Land	1.3%
	Tidal Flat	1.1%

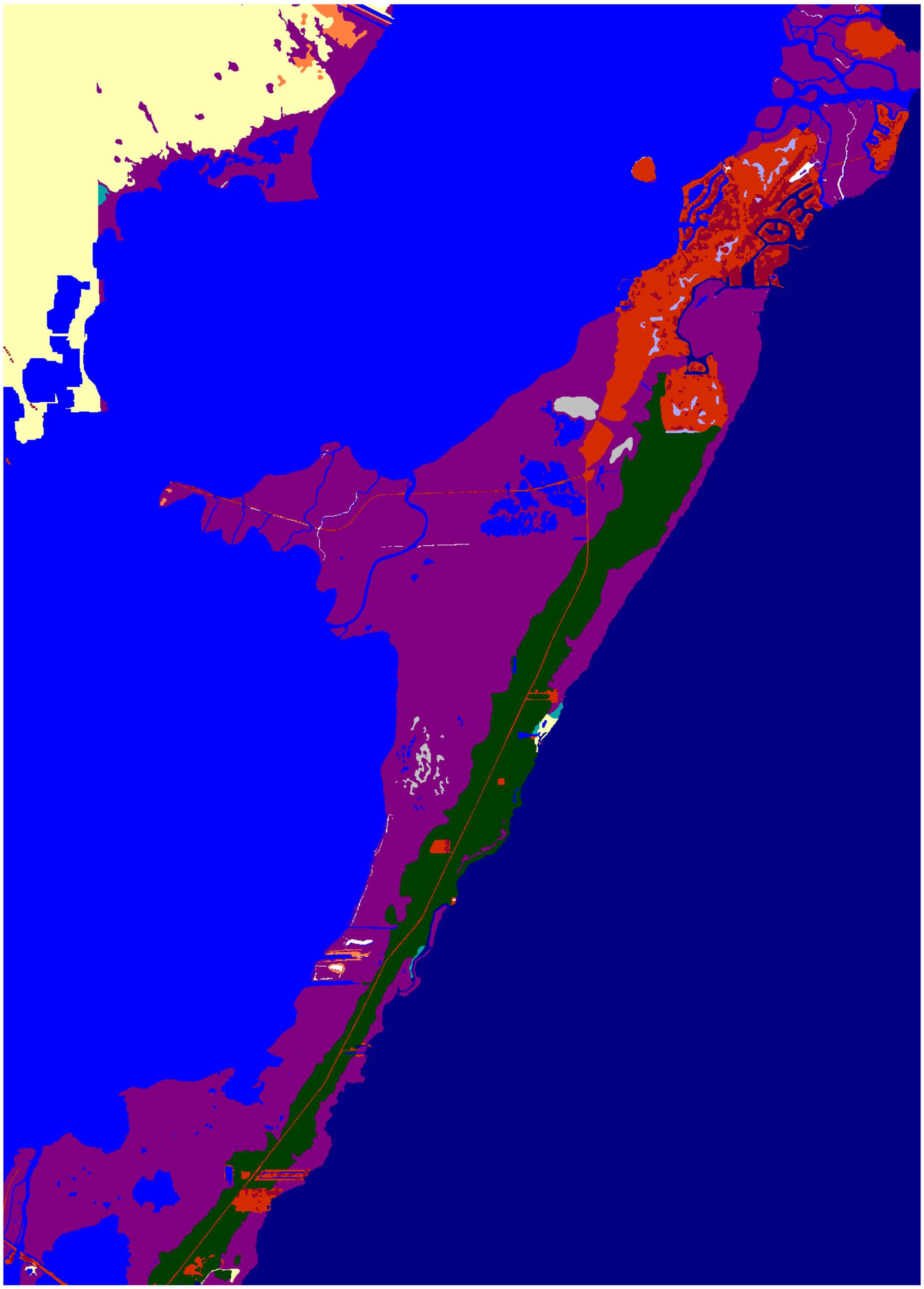


Figure 3: Portion of study area for Crocodile Lake NWR.

According to the National Wetland Inventory, there are no impounded or diked areas within Crocodile Lake NWR.

The historic trend for sea level rise was estimated at 2.39 mm/year using the value of the nearest NOAA gage with SLR data (8723170, Miami Beach, FL). The rate of sea level rise for this refuge has apparently been slightly higher than the global average for the last 100 years (approximately 1.7 mm/year, IPCC 2007a).

Two tide gages were used to estimate the tide ranges for this site (Figure 4). The northern portion of the refuge was estimated to have a great diurnal tide range (GT) of 0.228 meters using the gage at Pumpkin Key, Card Sound, FL (8723506). The southern portion of the refuge was set to 0.193 meters (GT(based on the gage at Card Sound Bridge, FL (8723534). The tide range on the ocean side of the barrier island was set to 0.772 meters using the gage at Ocean Reef Harbor, FL (8723519).

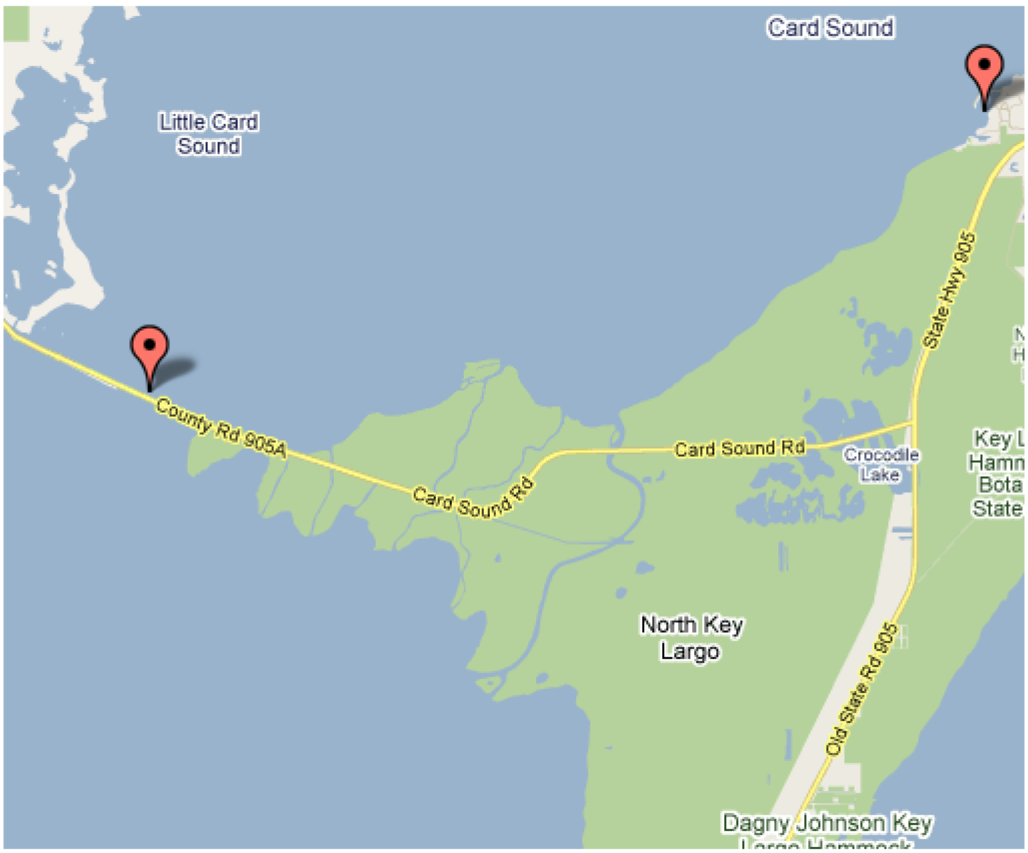


Figure 4: Location of NOAA tides gages used for Crocodile Lake NWR.

The elevation at which estuarine water is predicted to regularly inundate the land (the salt elevation) was estimated based on a frequency of inundation analysis using data from the gage at the Port of West Palm Beach, FL (8722588). This was done to include the effects of wind tides within estimates of land inundation, which were especially important at this site because lunar tides are relatively low in magnitude. The regularly flooded inundation level was assumed to occur where water penetrates at least once every 30 days, or approximately 0.3 meters above mean tide level.

Accretion rates in salt marshes were set to 3.9 mm/year, based on measured rates of accretion in

Georgia Marshes (Craft et. al, 2009). This value is also very close to several studies measuring accretion rates on the Gulf Coast of Florida (St. Marks FL, 4.0 mm/year from Cahoon et. al. 1995, and Hendrickson, J.C. 1997; Ochlockonee River FL, 4.05 mm/year from Hendrickson, J.C. 1997).

The MTL to NAVD88 correction of -0.275 was derived using the NOAA gages.

Modeled U.S. Fish and Wildlife Service refuge boundaries for Florida 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 10 meter by 10 meter cells. Note that the SLAMM model will track partial conversion of cells based on elevation and slope.

SUMMARY OF SLAMM INPUT PARAMETERS FOR CROCODILE LAKE NWR

Parameter	Global	SubSite 1	SubSite 2
Description		SubSite 1	SubSite 2
NWI Photo Date (YYYY)	2009	2009	2009
DEM Date (YYYY)	2008	2008	2008
Direction Offshore [n,s,e,w]	East	West	West
Historic Trend (mm/yr)	2.39	2.39	2.39
MTL-NAVD88 (m)	-0.275	-0.275	-0.275
GT Great Diurnal Tide Range (m)	0.772	0.228	0.193
Salt Elev. (m above MTL)	0.51	0.32	0.3
Marsh Erosion (horz. m /yr)	1.8	1.8	1.8
Swamp Erosion (horz. m /yr)	1	1	1
T.Flat Erosion (horz. m /yr)	0.5	0.5	0.5
Reg. Flood Marsh Accr (mm/yr)	3.9	3.9	3.9
Irreg. Flood Marsh Accr (mm/yr)	4.7	4.7	4.7
Tidal Fresh Marsh Accr (mm/yr)	5.9	5.9	5.9
Beach Sed. Rate (mm/yr)	0.5	0.5	0.5
Freq. Overwash (years)	15	15	15
Use Elev Pre-processor [True,False]	FALSE	FALSE	FALSE

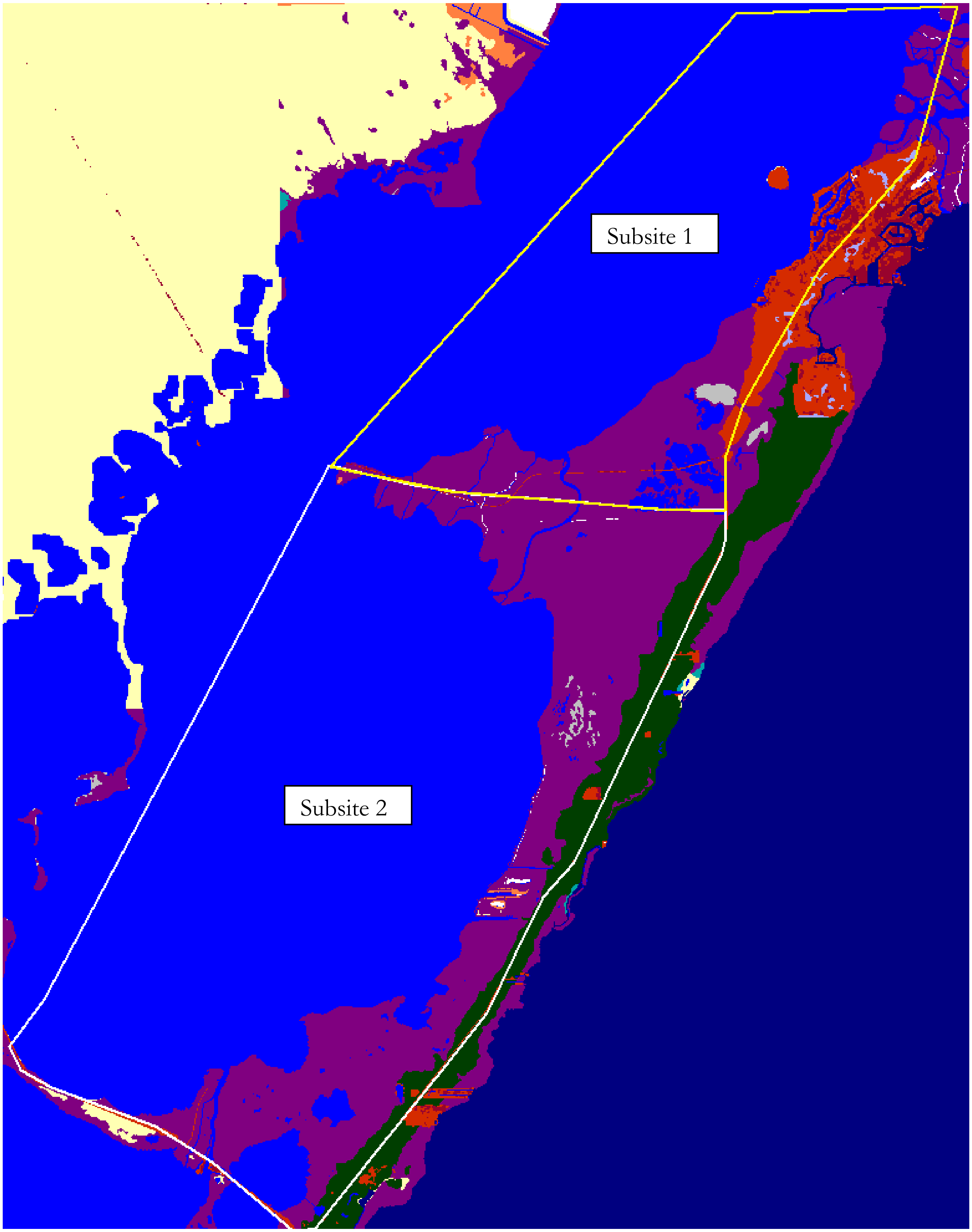


Figure 5: Input subsites for model application.

Results

SLAMM predicts that Crocodile Lake NWR will be moderately impacted depending on the SLR scenario and wetland class. Up to 98% of refuge mangrove, which comprises the vast majority of the refuge, is predicted to be lost in the higher scenarios.

SLR by 2100 (m)	0.39	0.69	1	1.5	2
Mangrove	2%	4%	56%	97%	98%
Tidal Swamp	11%	13%	16%	22%	32%
Undeveloped Dry Land	25%	38%	48%	60%	70%
Tidal Flat	66%	94%	97%	97%	97%

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

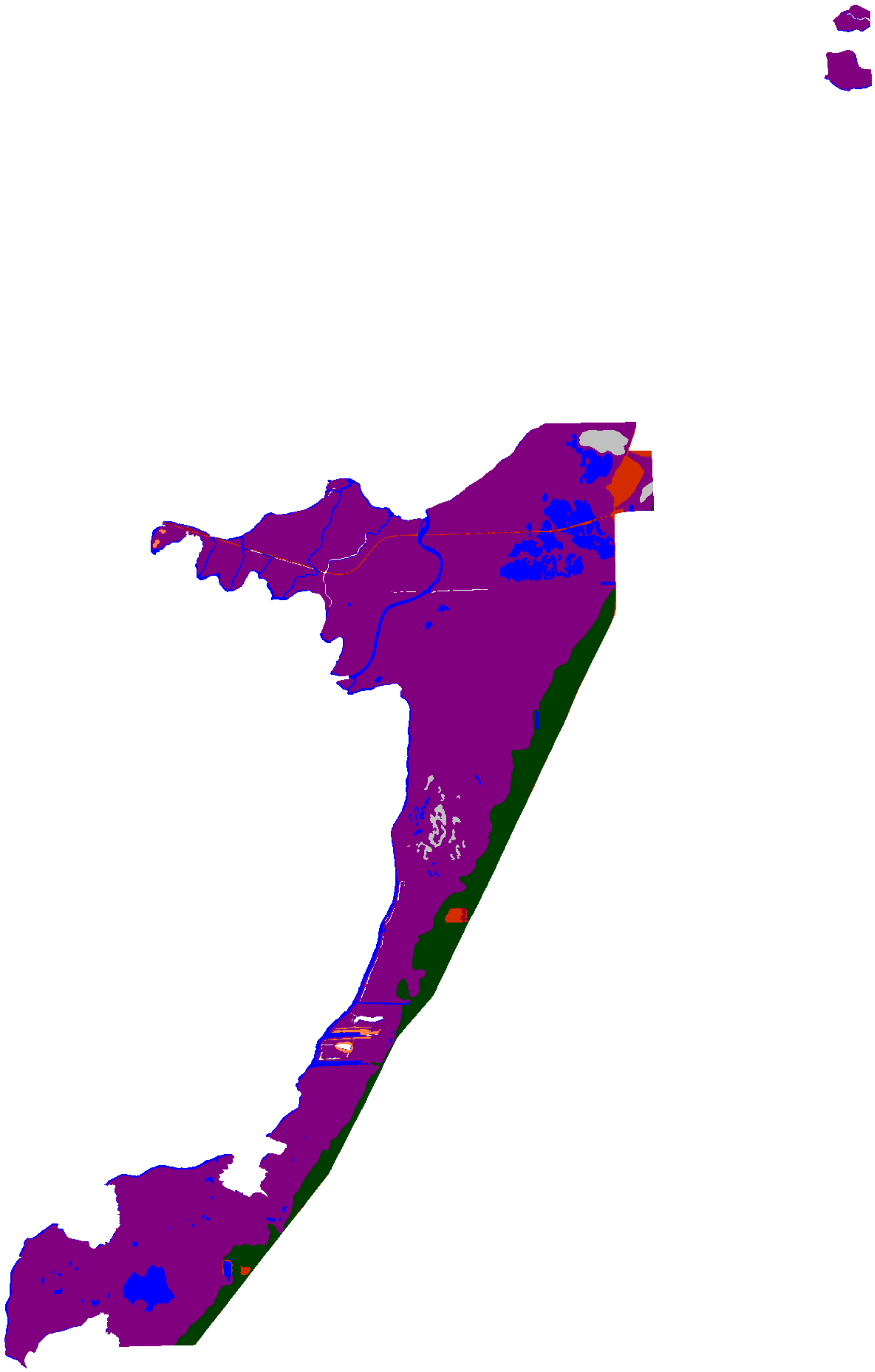
Maps of SLAMM input and output to follow will use the following legend:

Mangrove	
Tidal Swamp	
Estuarine Open Water	
Undeveloped Dry Land	
Tidal Flat	
Irregularly Flooded Marsh	
Developed Dry Land	
Estuarine Beach	

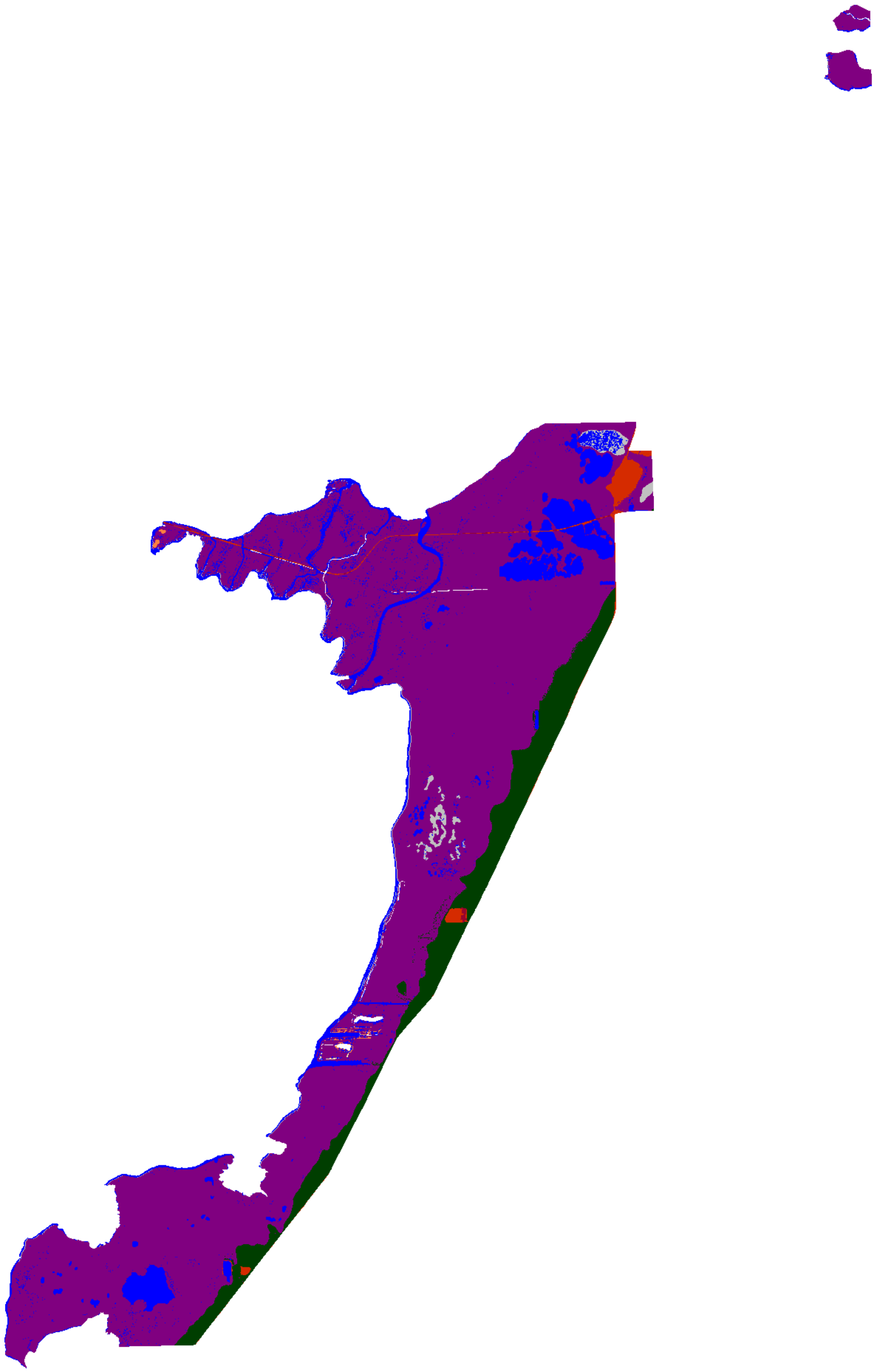
Crocodile Lake NWR
IPCC Scenario A1B-Mean, 0.39 M SLR Eustatic by 2100

Results in Acres

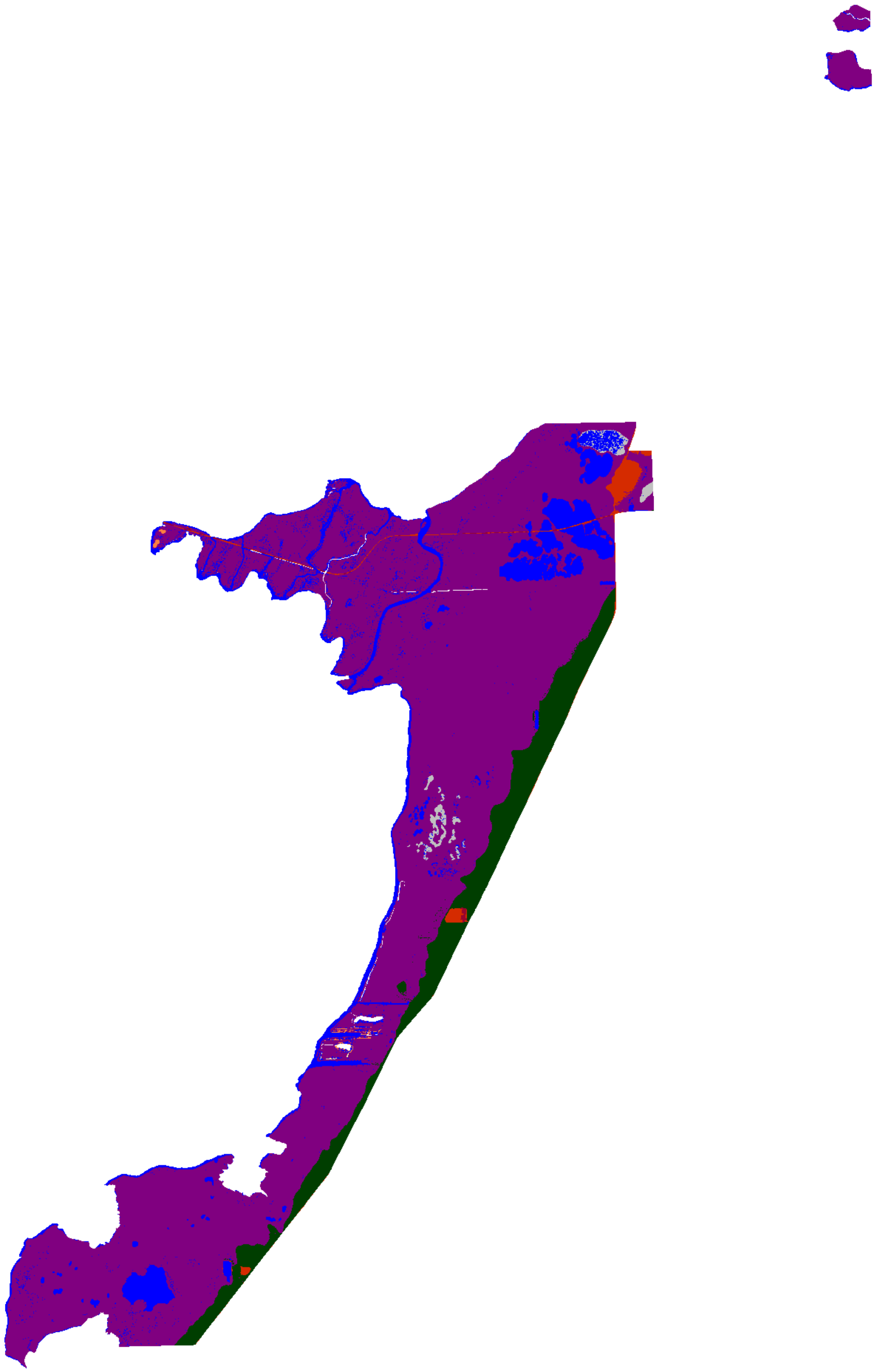
		Initial	2025	2050	2075	2100
	Mangrove	5739.8	5630.9	5643.9	5631.4	5640.3
	Tidal Swamp	702.2	644.2	636.0	629.8	625.1
	Estuarine Open Water	555.8	741.6	771.9	782.9	819.3
	Undeveloped Dry Land	94.1	84.7	80.0	74.6	70.2
	Tidal Flat	78.7	78.9	49.1	62.8	27.1
	Irregularly Flooded Marsh	16.7	8.2	8.2	8.1	8.1
	Developed Dry Land	9.6	8.9	8.7	8.4	8.0
	Estuarine Beach	1.5	1.0	0.8	0.6	0.4
	Total (incl. water)	**7198.4**	**7198.4**	**7198.4**	**7198.4**	**7198.4**



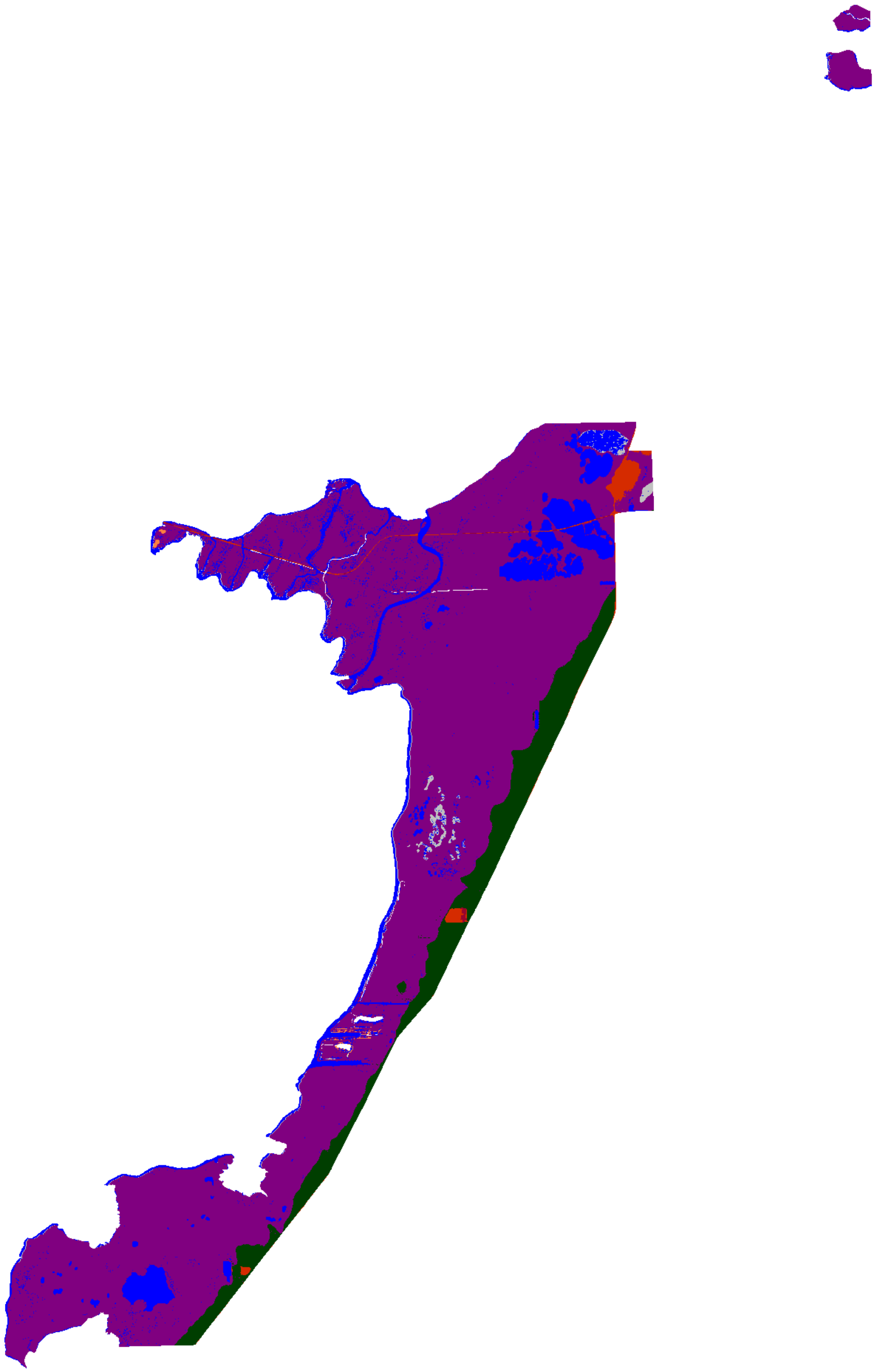
Crocodile Lake NWR, Initial Condition



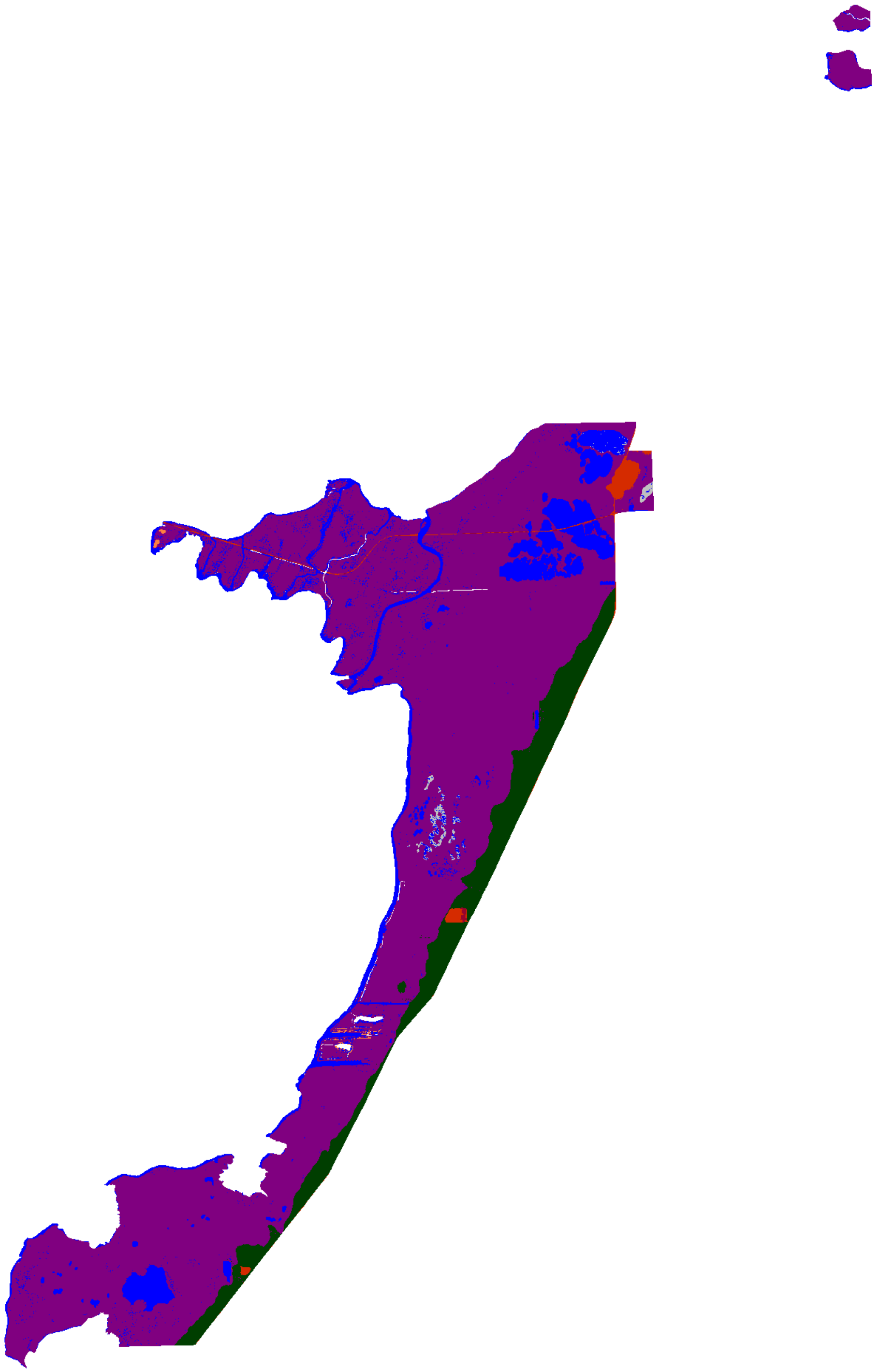
Crocodile Lake NWR, 2025, Scenario A1B Mean



Crocodile Lake NWR, 2050, Scenario A1B Mean



Crocodile Lake NWR, 2075, Scenario A1B Mean

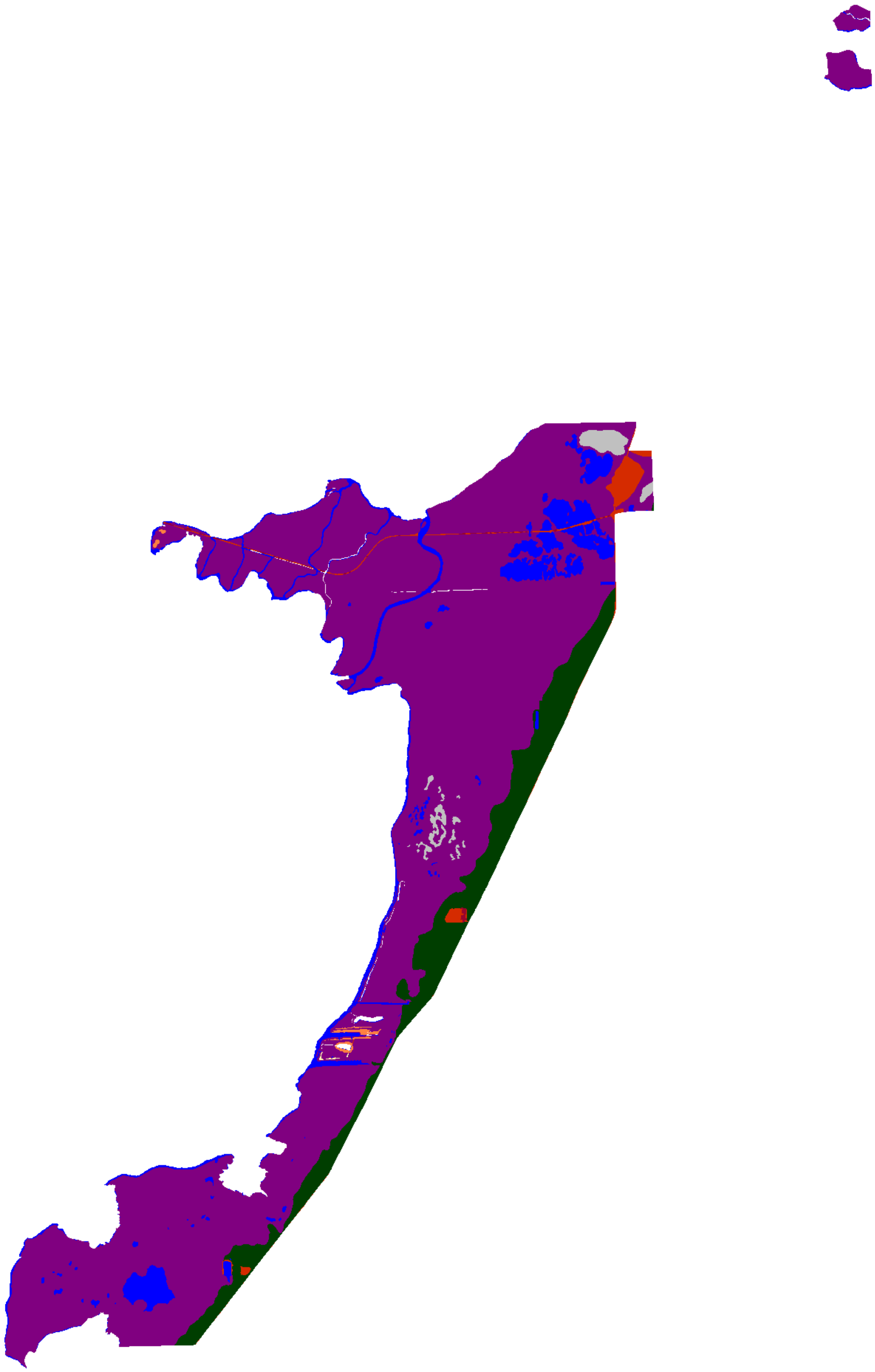


Crocodile Lake NWR, 2100, Scenario A1B Mean

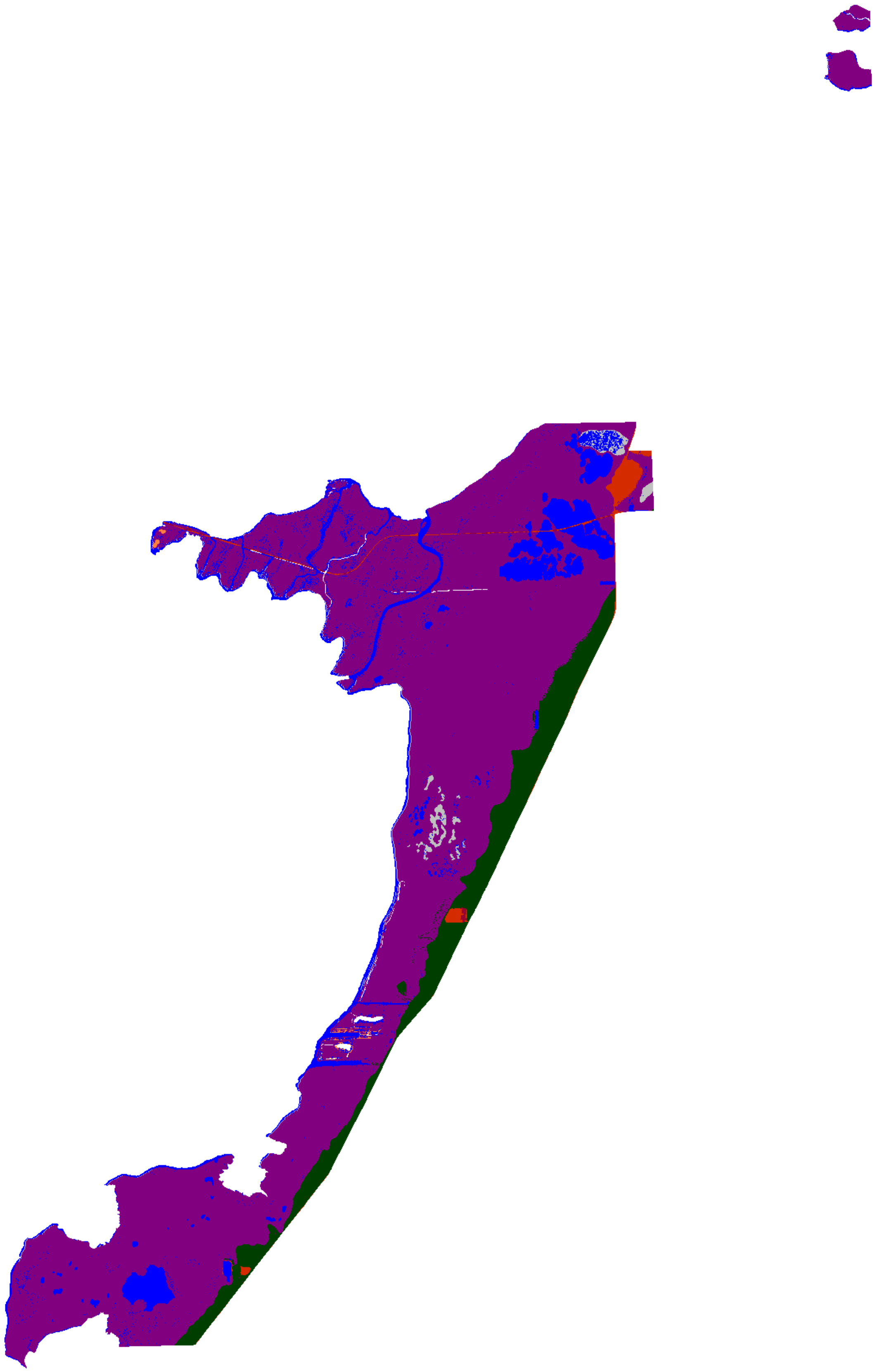
Crocodile Lake NWR
IPCC Scenario A1B-Max, 0.69 M SLR Eustatic by 2100

Results in Acres

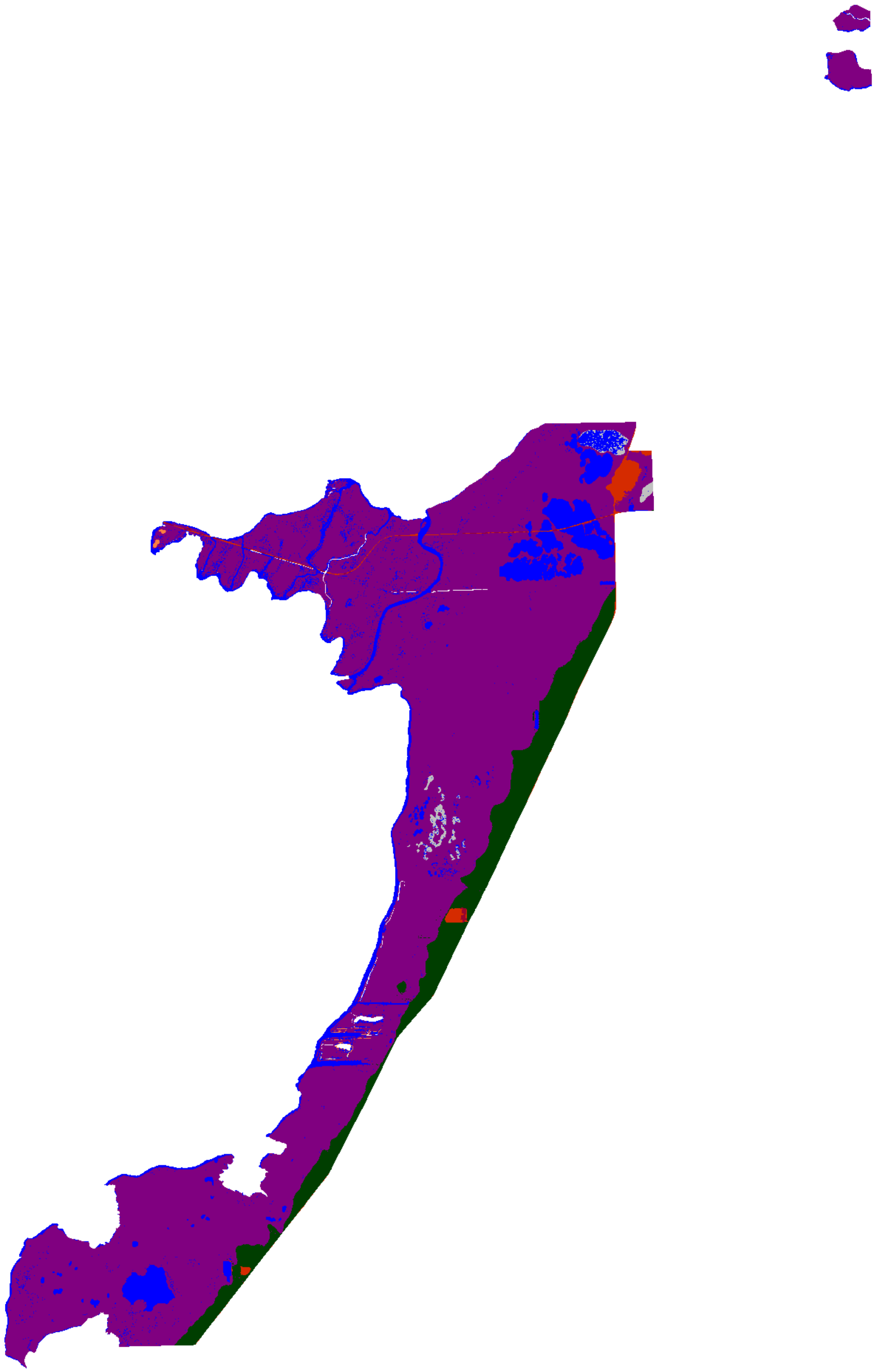
		Initial	2025	2050	2075	2100
	Mangrove	5739.8	5634.0	5654.6	5647.6	5526.4
	Tidal Swamp	702.2	641.4	630.3	620.9	608.8
	Estuarine Open Water	555.8	743.1	778.6	803.9	989.9
	Undeveloped Dry Land	94.1	83.8	76.0	67.0	58.5
	Tidal Flat	78.7	78.2	43.3	46.0	4.4
	Irregularly Flooded Marsh	16.7	8.2	6.6	4.8	3.4
	Developed Dry Land	9.6	8.9	8.5	7.8	6.9
	Estuarine Beach	1.5	0.9	0.6	0.2	0.1
	Total (incl. water)	**7198.4**	**7198.4**	**7198.4**	**7198.4**	**7198.4**



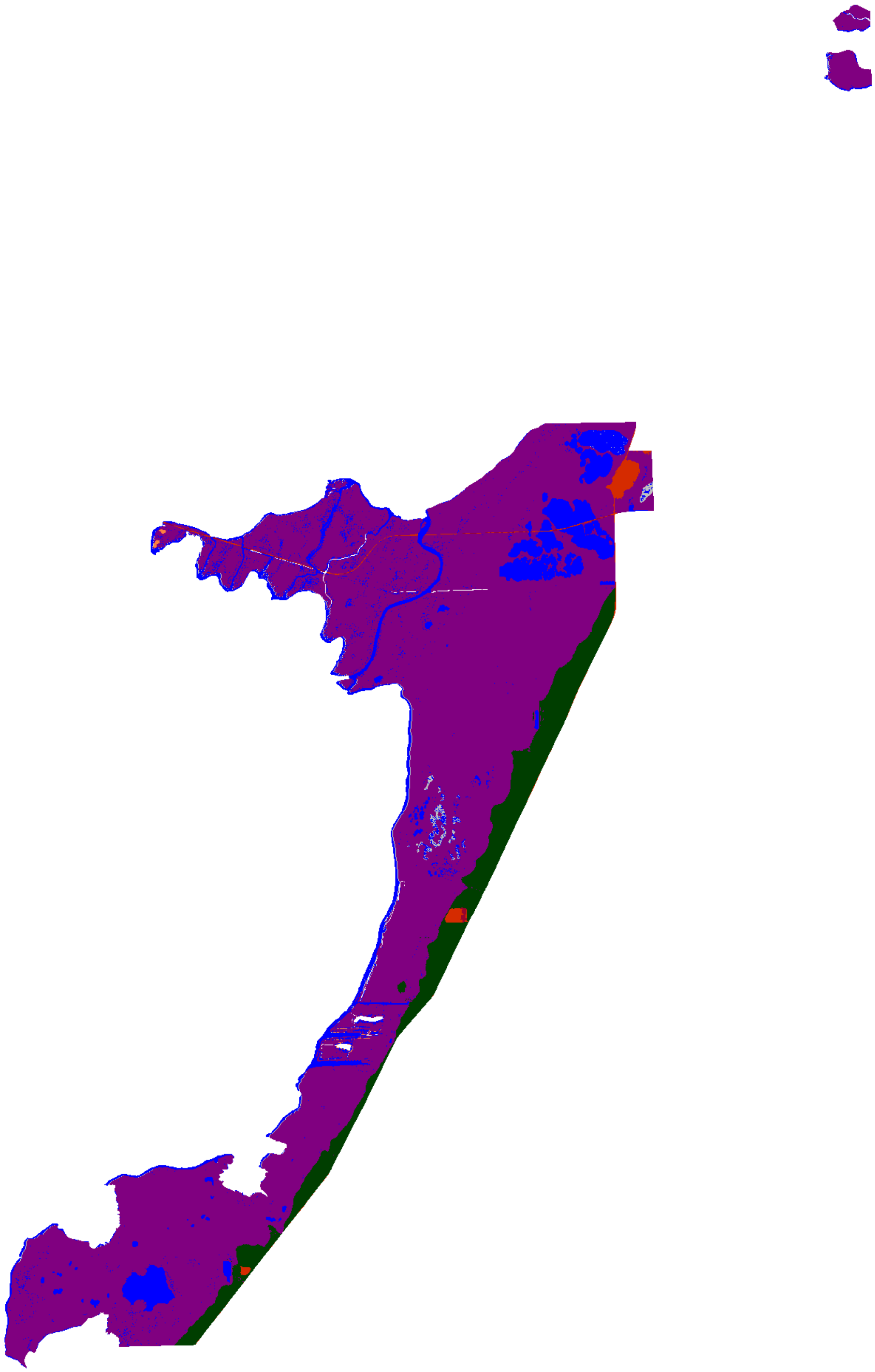
Crocodile Lake NWR, Initial Condition



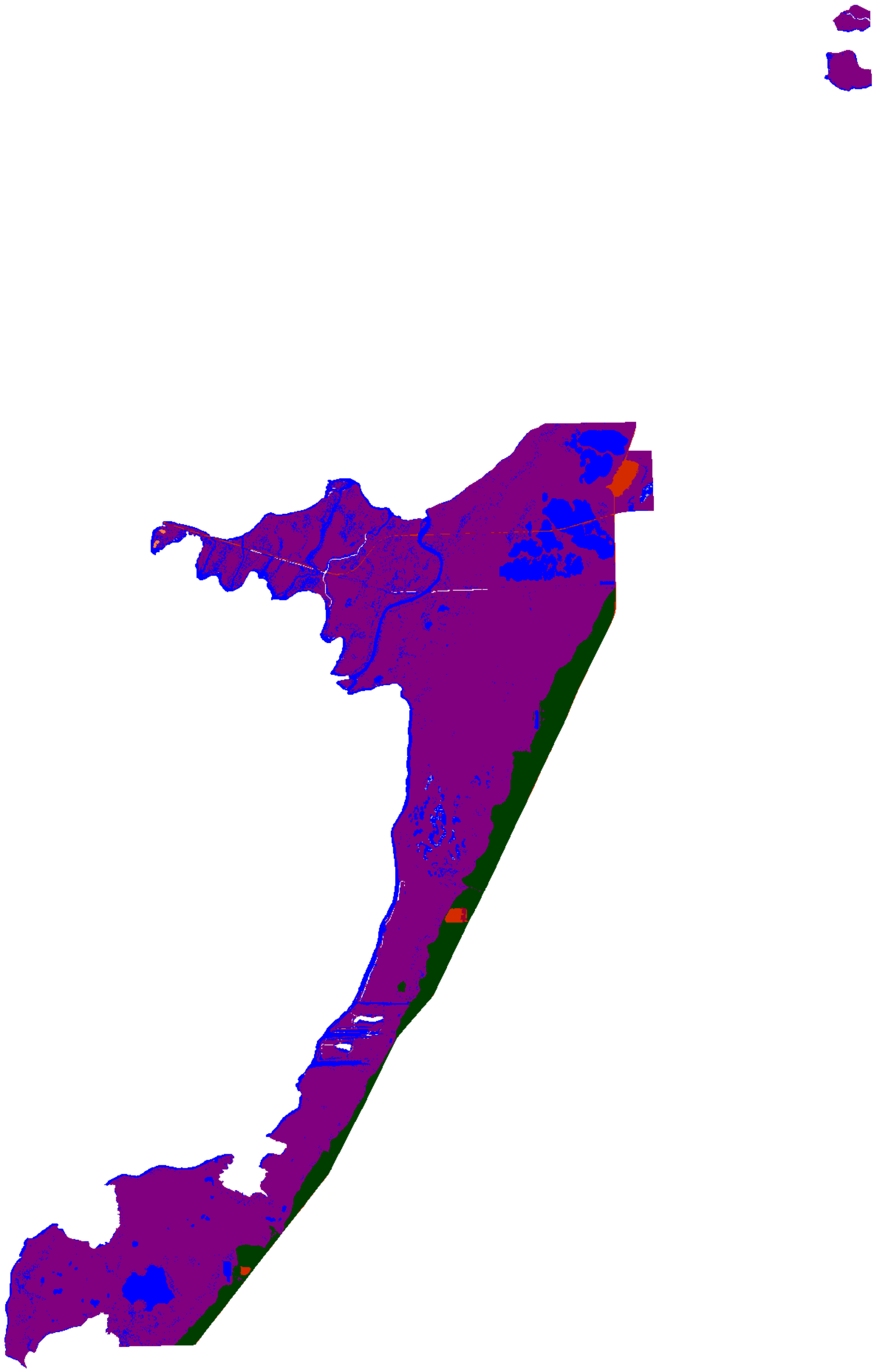
Crocodile Lake NWR, 2025, Scenario A1B Maximum



Crocodile Lake NWR, 2050, Scenario A1B Maximum



Crocodile Lake NWR, 2075, Scenario A1B Maximum

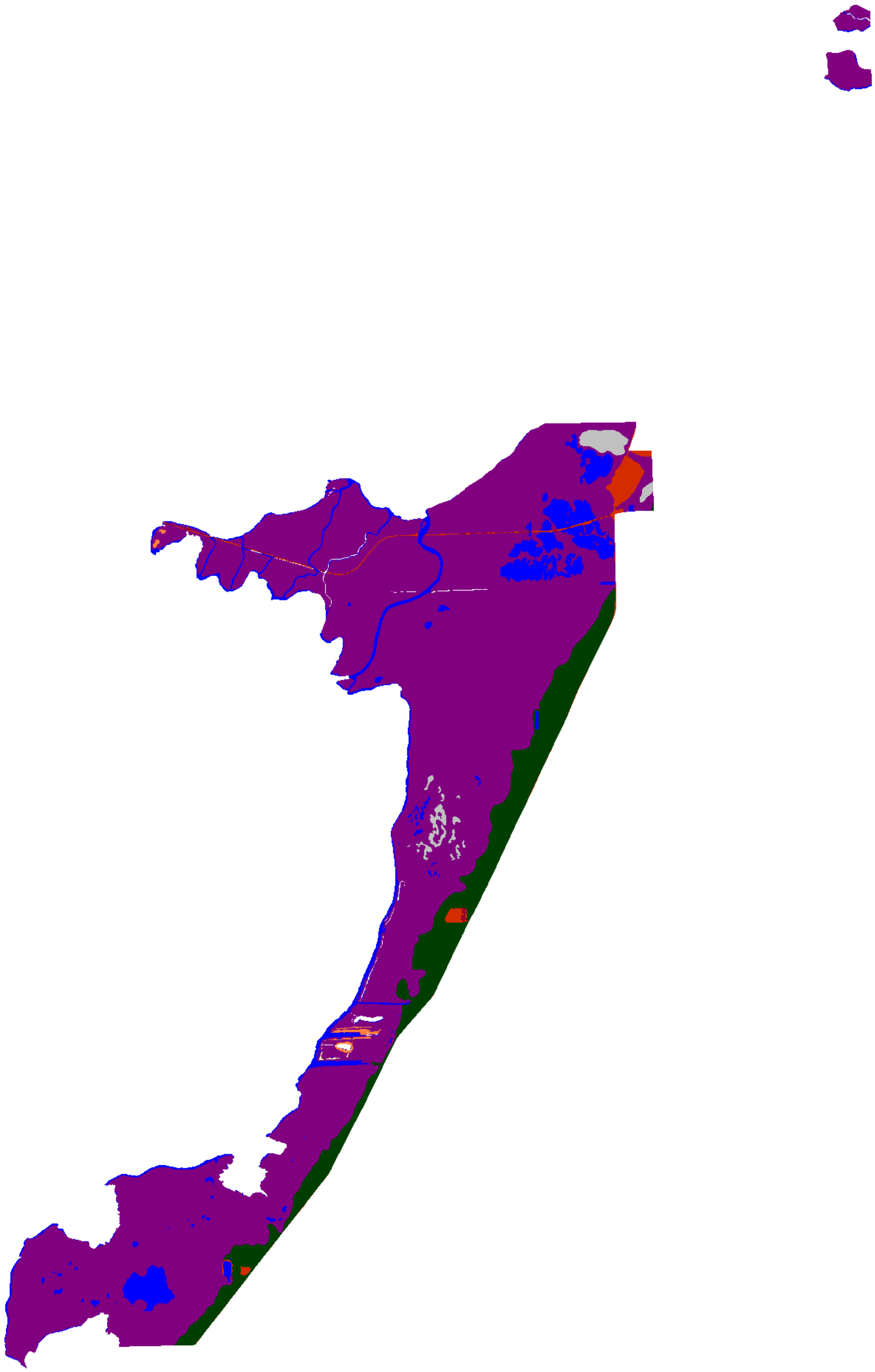


Crocodile Lake NWR, 2100, Scenario A1B Maximum

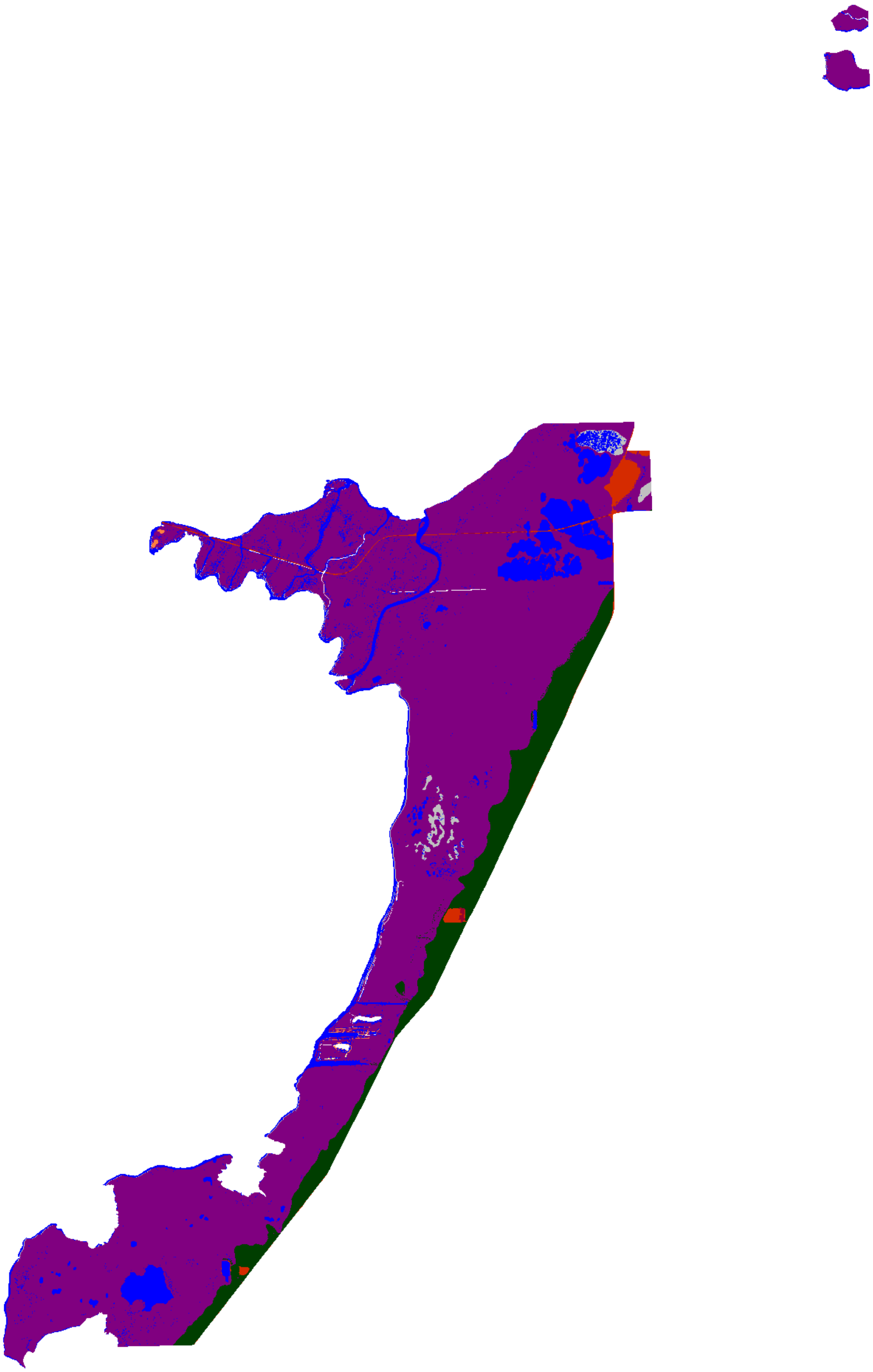
Crocodile Lake NWR
1 Meter Eustatic SLR by 2100

Results in Acres

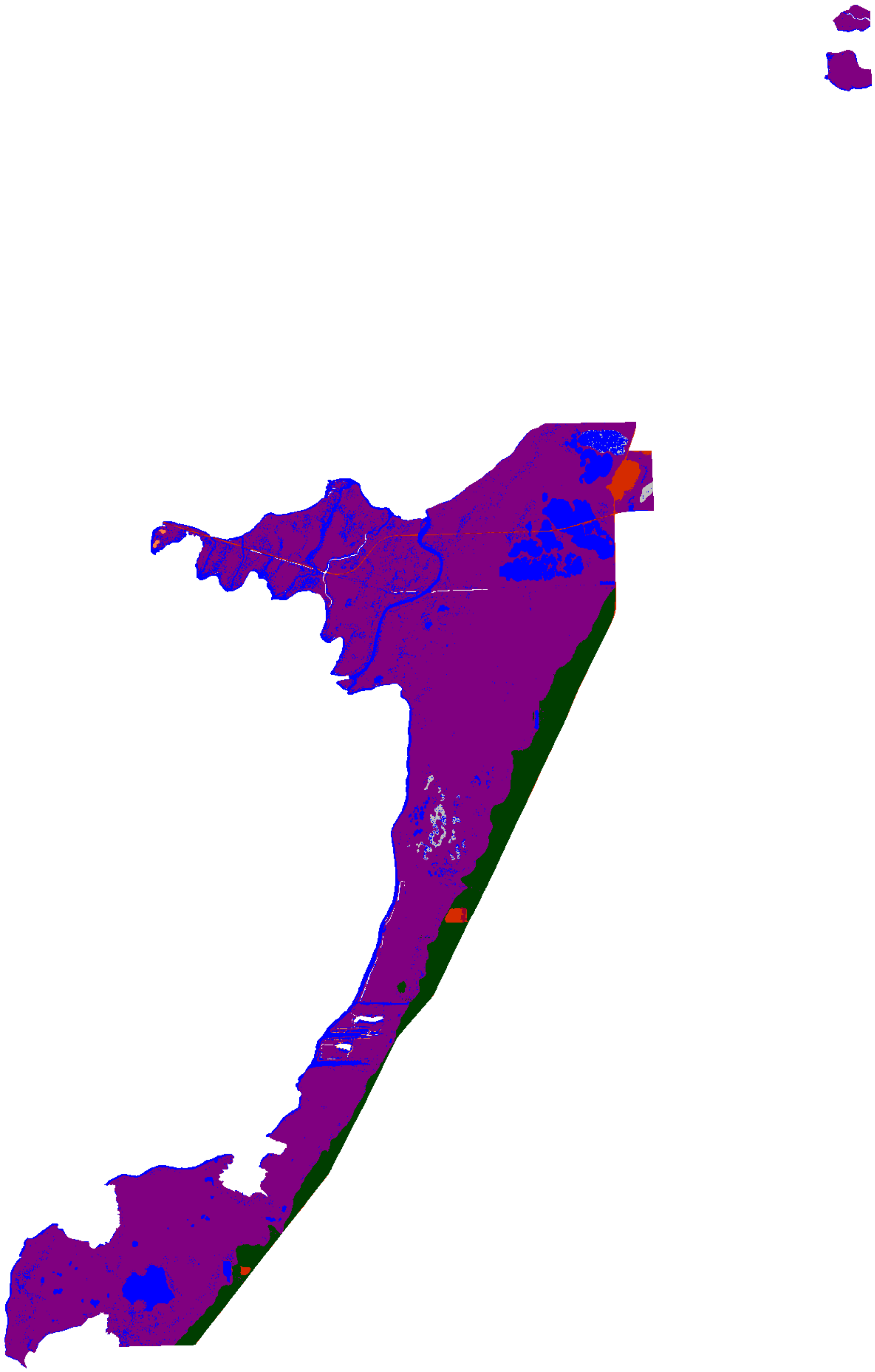
		Initial	2025	2050	2075	2100
	Mangrove	5739.8	5637.3	5518.2	4586.2	2507.7
	Tidal Swamp	702.2	638.8	625.8	609.9	587.8
	Estuarine Open Water	555.8	745.3	934.7	1912.1	4045.4
	Undeveloped Dry Land	94.1	82.7	71.6	60.1	48.8
	Tidal Flat	78.7	77.2	34.5	20.3	2.5
	Irregularly Flooded Marsh	16.7	7.5	5.0	2.6	1.5
	Developed Dry Land	9.6	8.8	8.2	7.1	4.7
	Estuarine Beach	1.5	0.9	0.5	0.1	0.0
	Total (incl. water)	**7198.4**	**7198.4**	**7198.4**	**7198.4**	**7198.4**



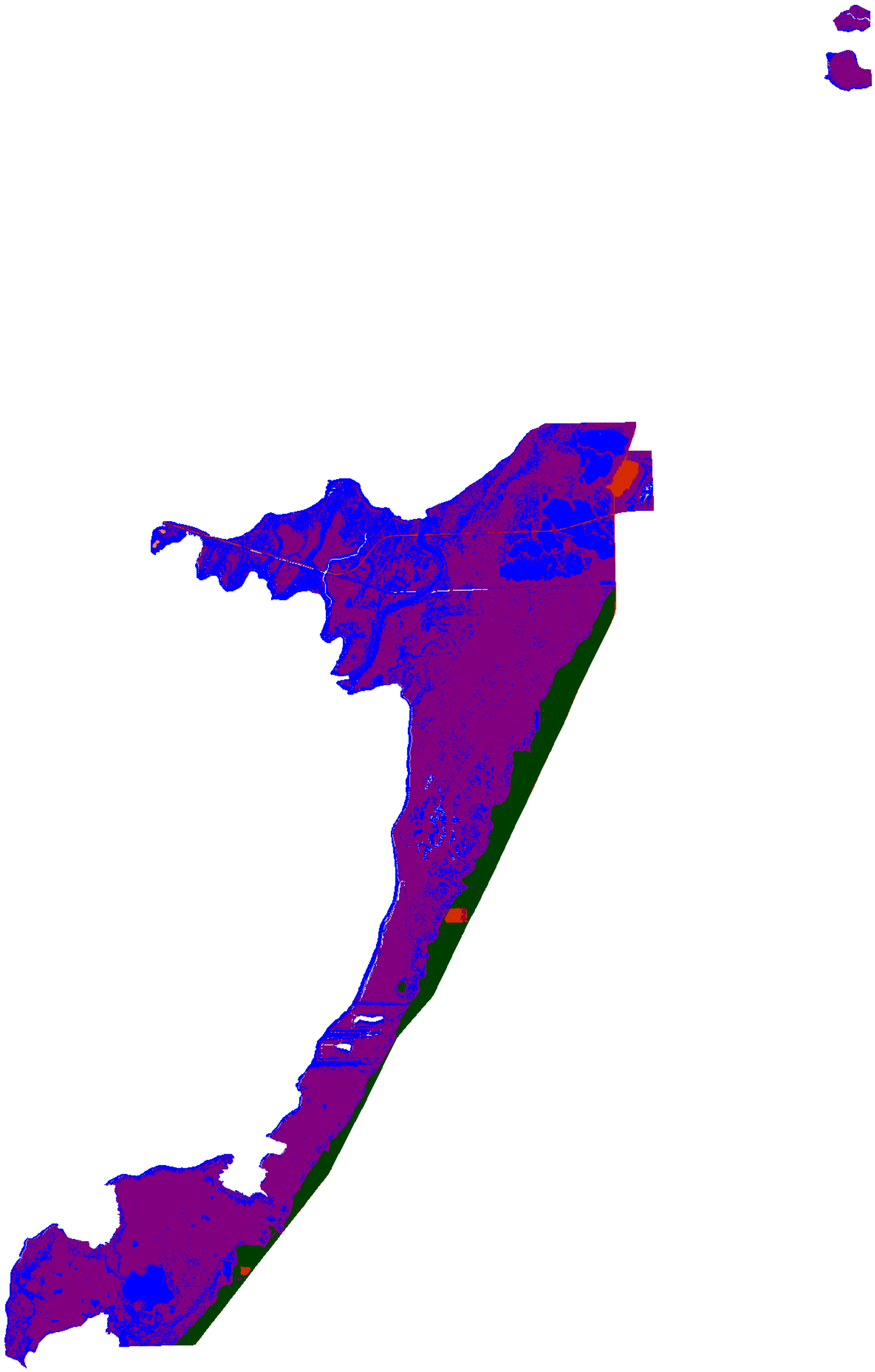
Crocodile Lake NWR, Initial Condition



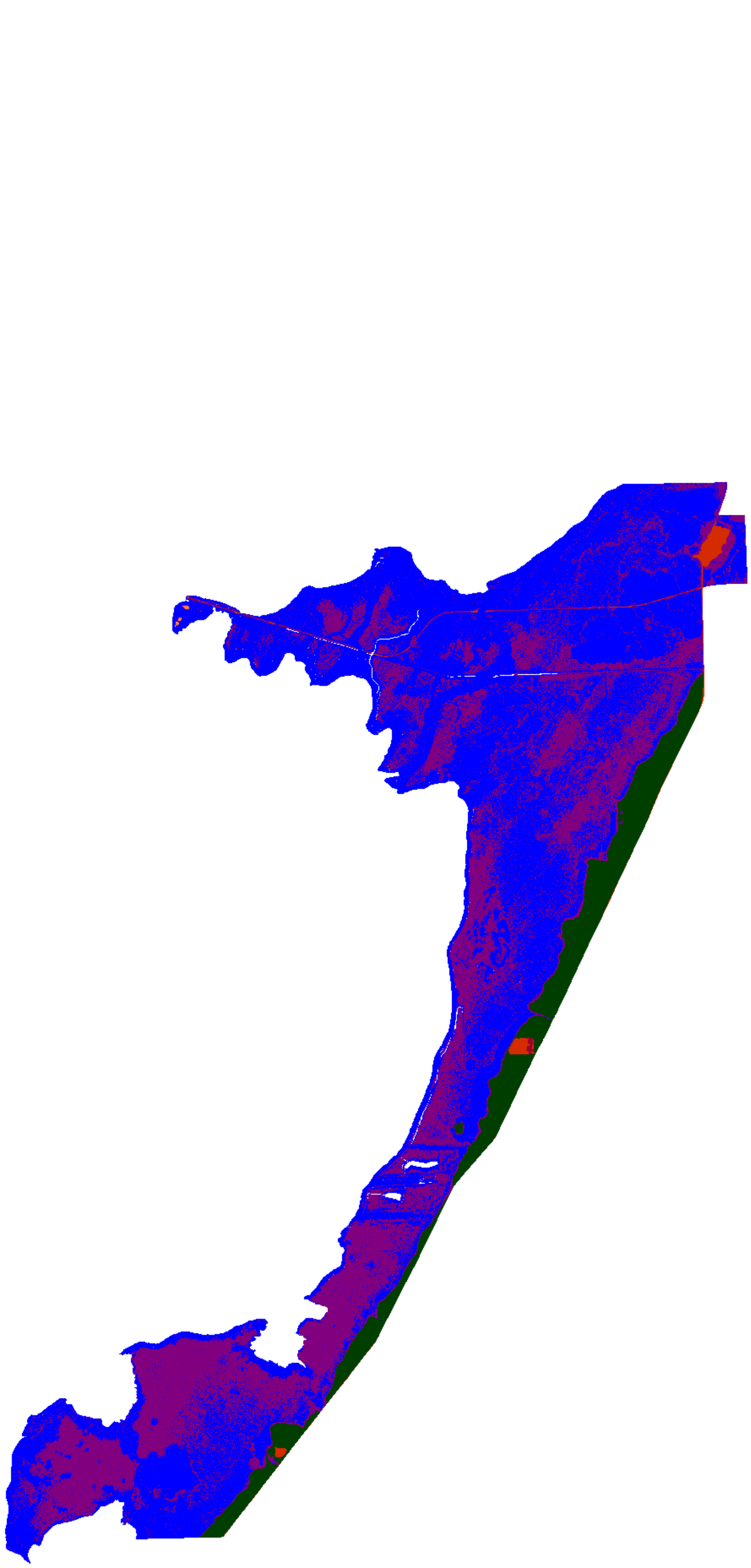
Crocodile Lake NWR, 2025, 1 Meter



Crocodile Lake NWR, 2050, 1 Meter



Crocodile Lake NWR, 2075, 1 Meter

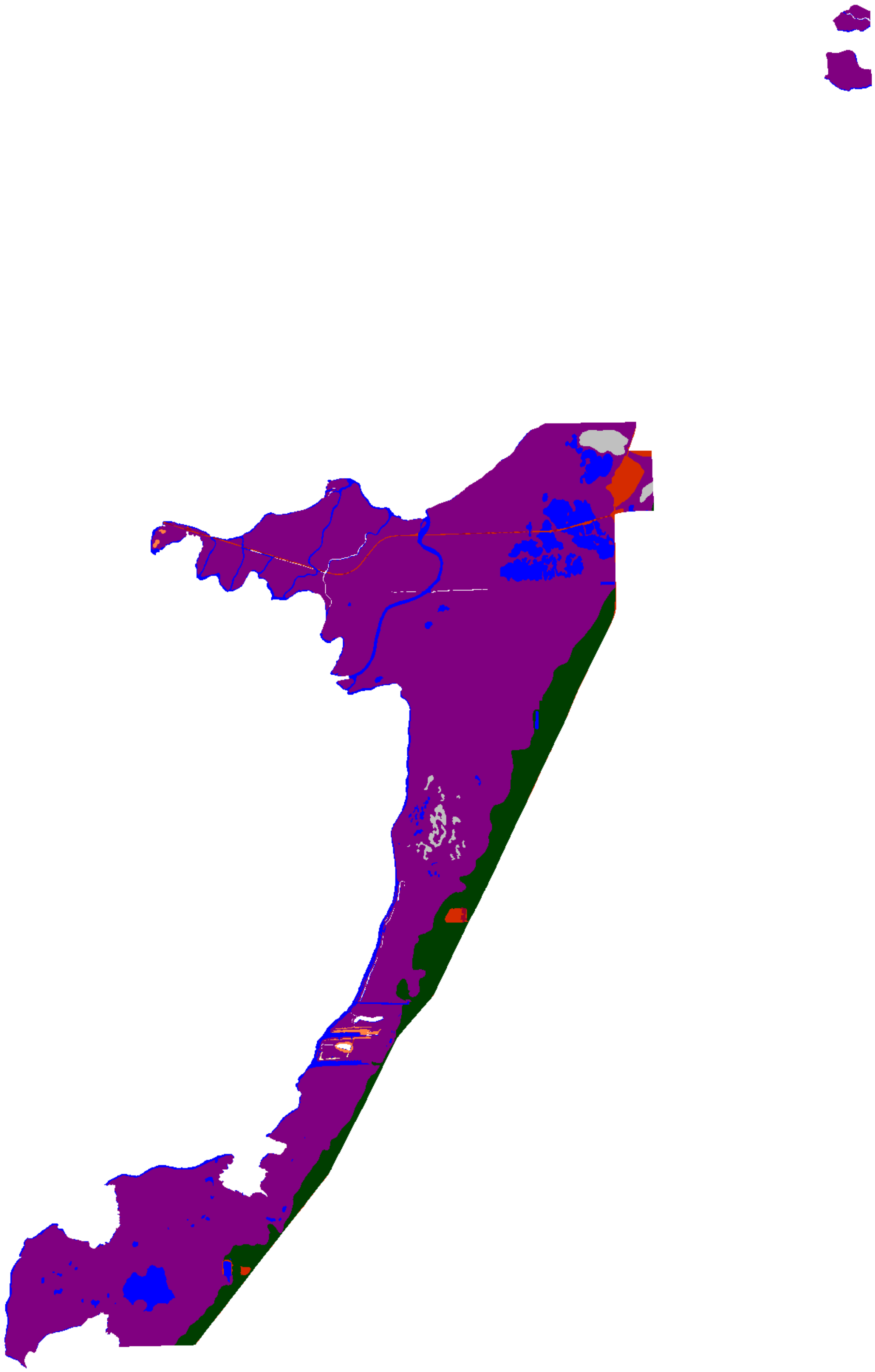


Crocodile Lake NWR, 2100, 1 Meter

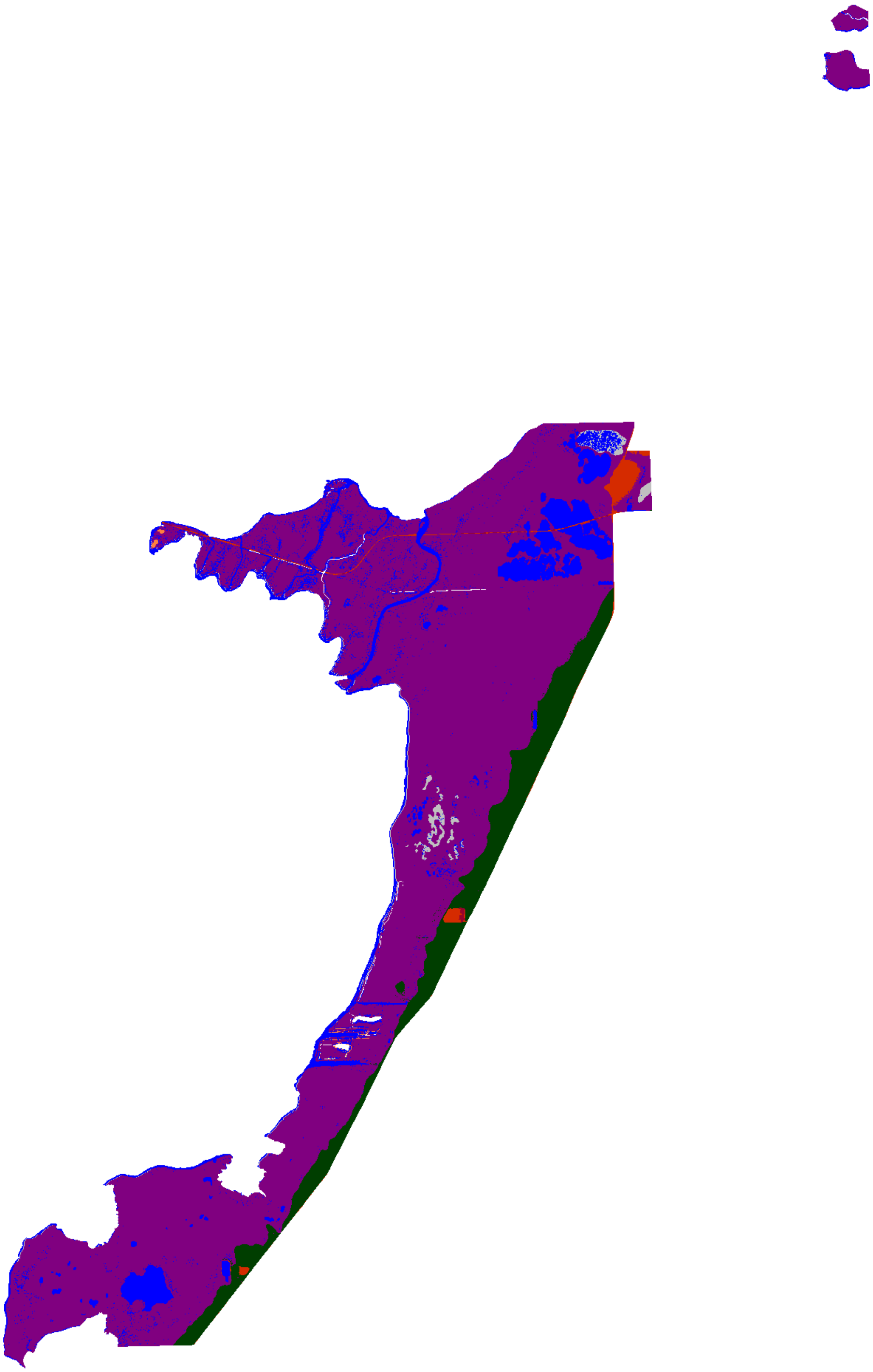
Crocodile Lake NWR
1.5 Meters Eustatic SLR by 2100

Results in Acres

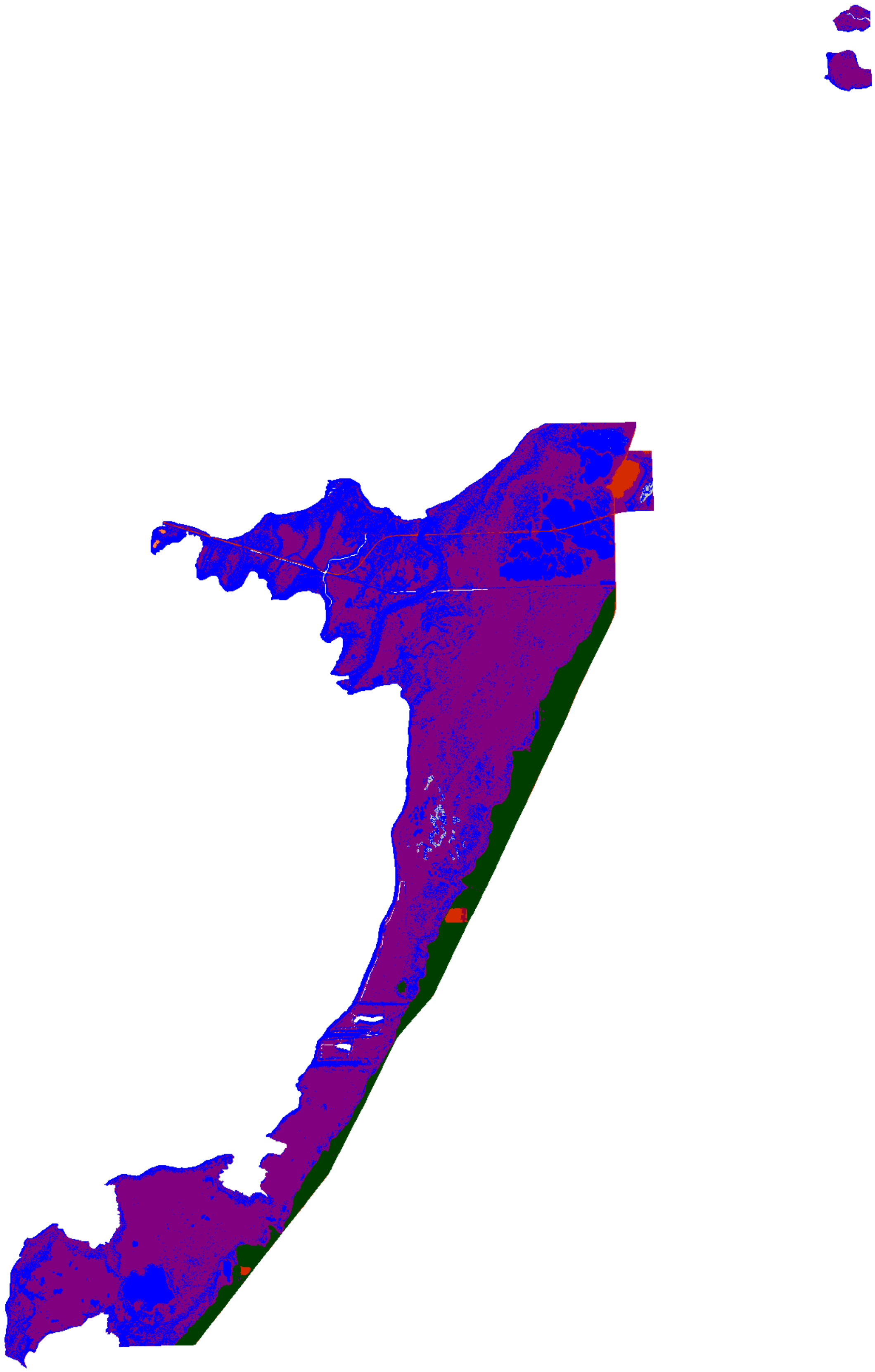
		Initial	2025	2050	2075	2100
	Mangrove	5739.8	5580.8	4306.5	1077.6	174.1
	Tidal Swamp	702.2	635.0	617.6	587.2	545.2
	Estuarine Open Water	555.8	812.2	2179.8	5474.9	6435.2
	Undeveloped Dry Land	94.1	80.6	65.9	49.5	37.9
	Tidal Flat	78.7	74.0	17.7	3.3	2.4
	Irregularly Flooded Marsh	16.7	6.3	3.0	1.2	0.6
	Developed Dry Land	9.6	8.7	7.7	4.9	3.1
	Estuarine Beach	1.5	0.8	0.2	0.0	0.0
	Total (incl. water)	**7198.4**	**7198.4**	**7198.4**	**7198.4**	**7198.4**



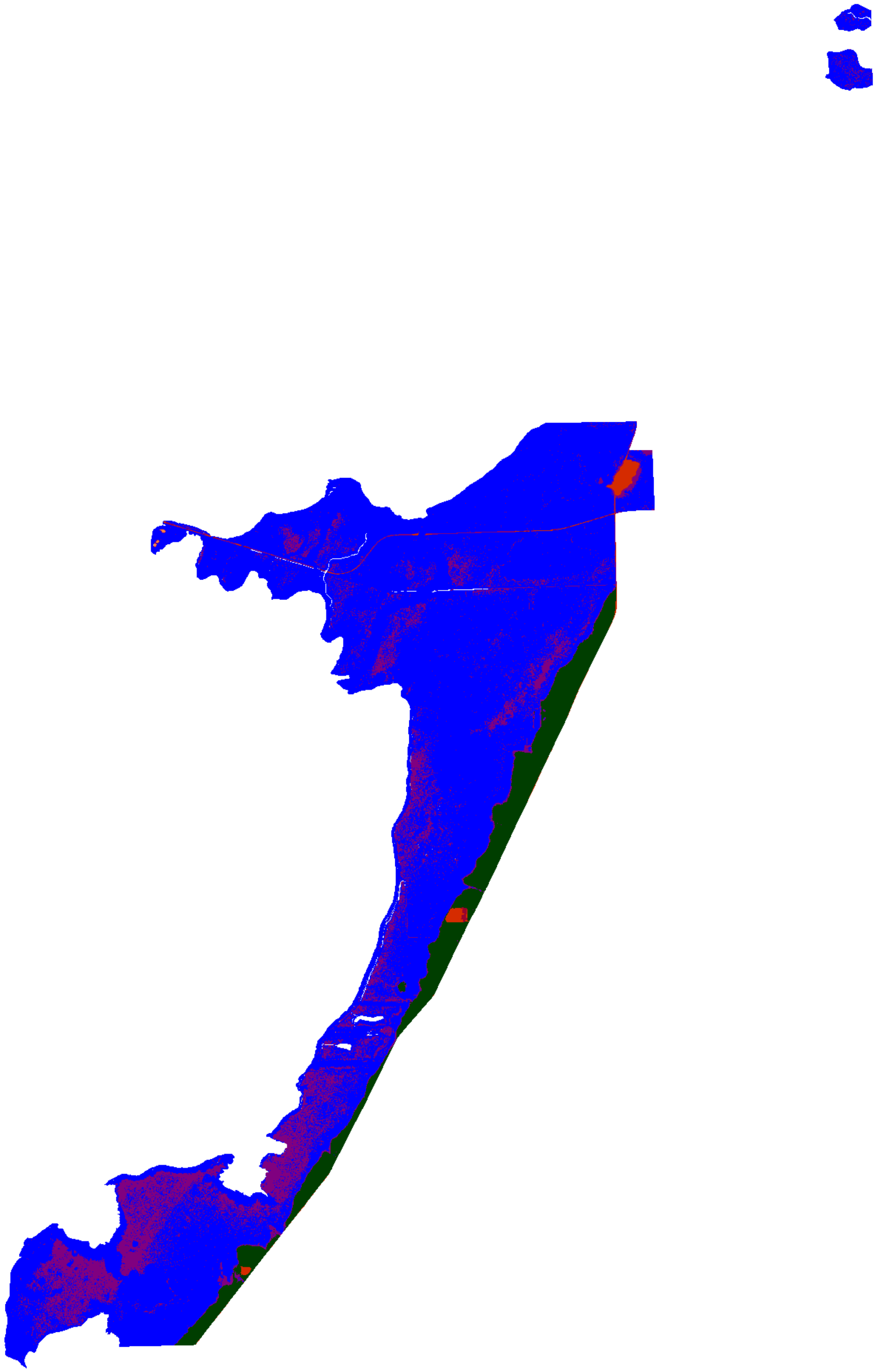
Crocodile Lake NWR, Initial Condition



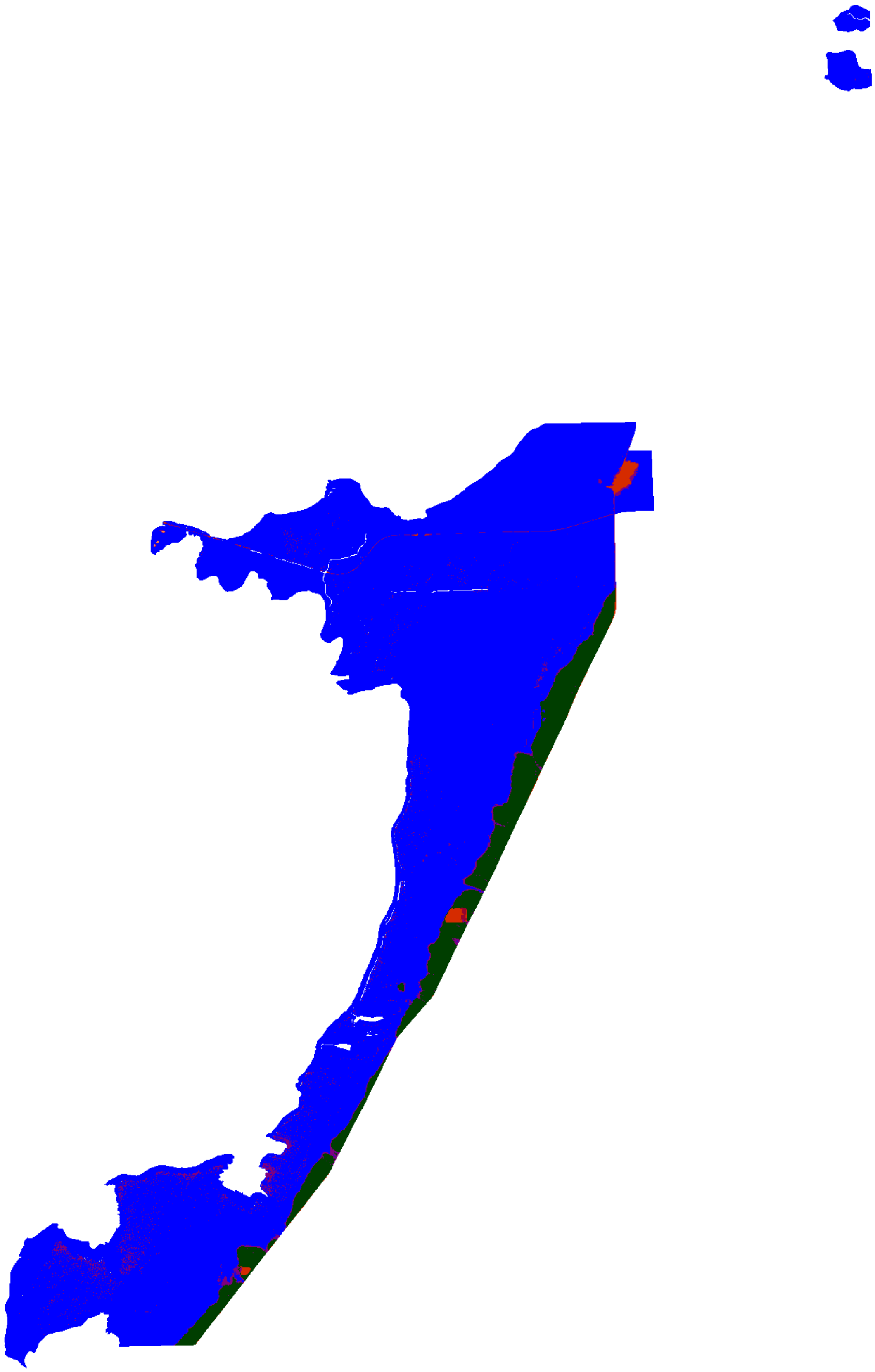
Crocodile Lake NWR, 2025, 1.5 Meters



Crocodile Lake NWR, 2050, 1.5 Meters



Crocodile Lake NWR, 2075, 1.5 Meters

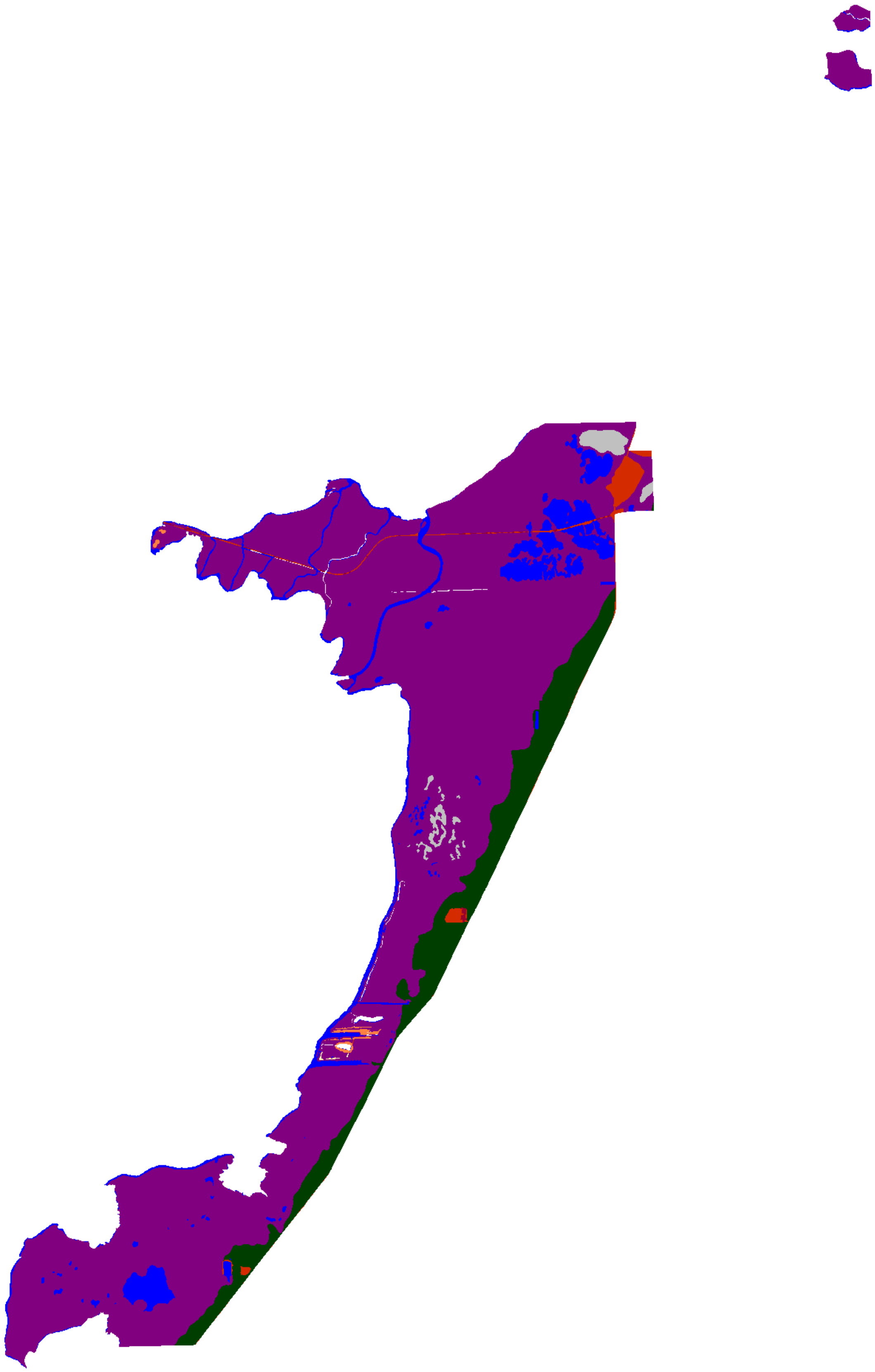


Crocodile Lake NWR, 2100, 1.5 Meters

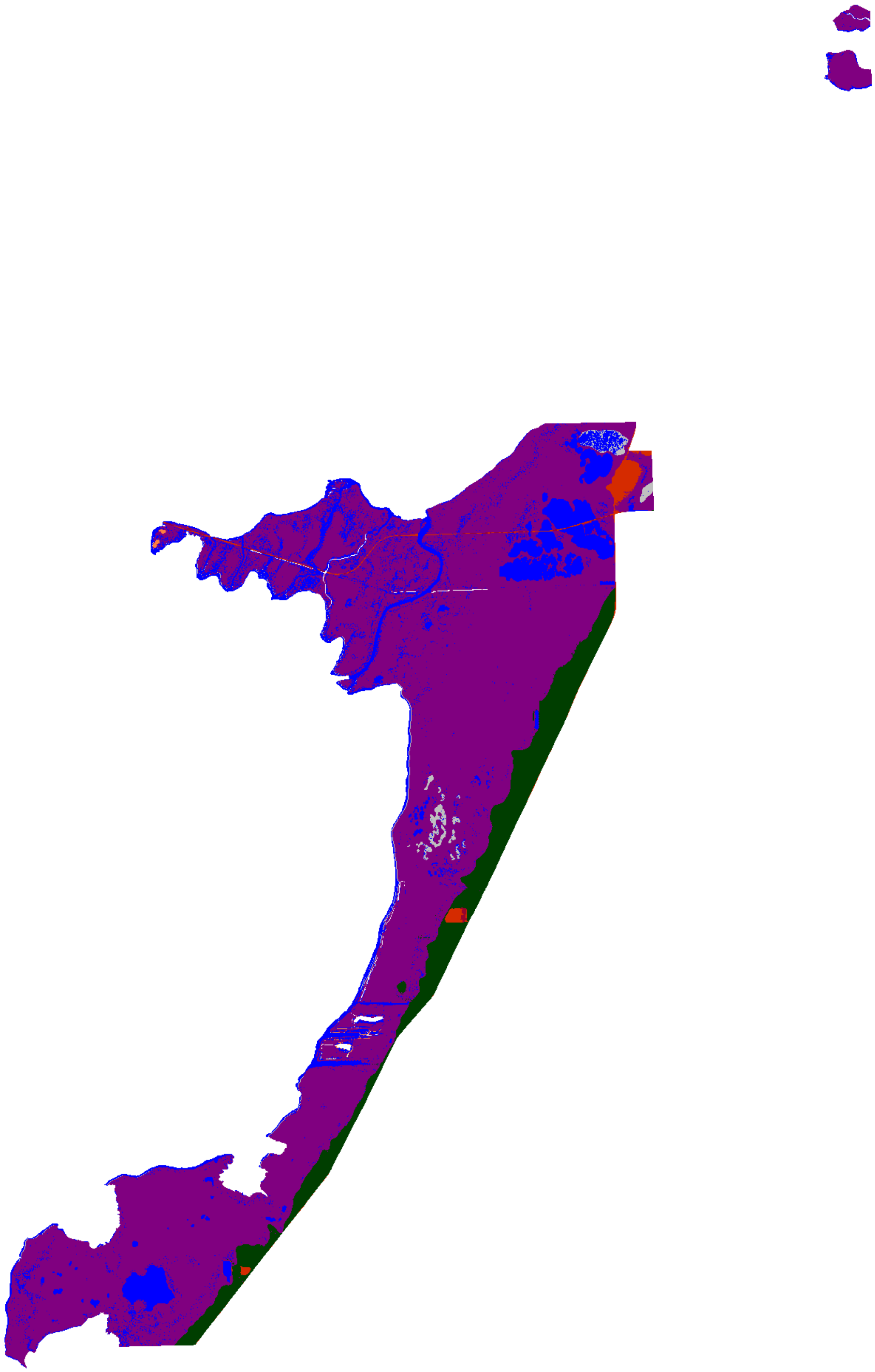
Crocodile Lake NWR
2 Meters Eustatic SLR by 2100

Results in Acres

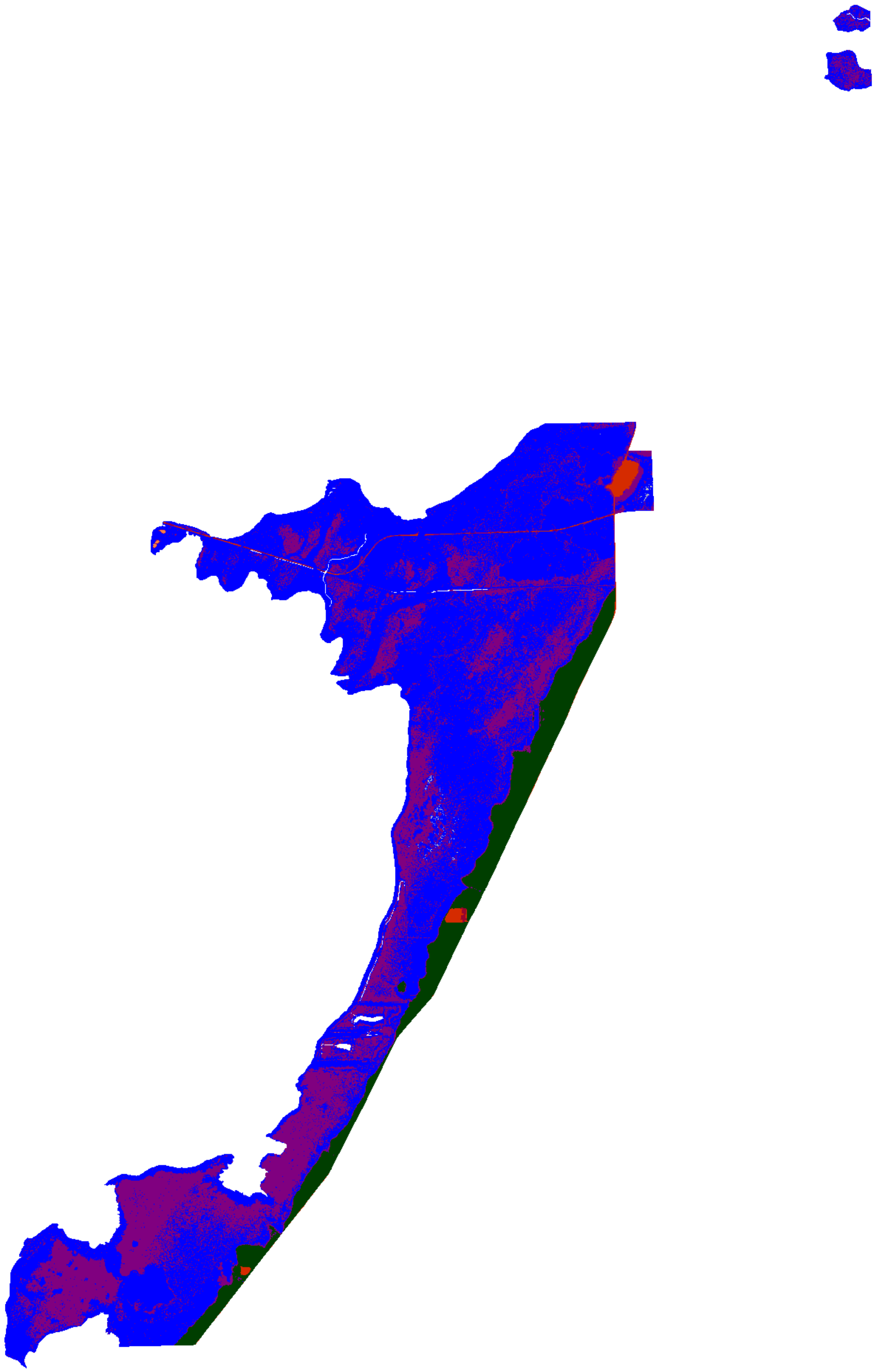
		Initial	2025	2050	2075	2100
	Mangrove	5739.8	5433.2	2087.3	186.1	109.5
	Tidal Swamp	702.2	632.2	607.8	560.9	475.5
	Estuarine Open Water	555.8	970.8	4428.8	6405.6	6580.7
	Undeveloped Dry Land	94.1	78.5	60.0	40.8	28.2
	Tidal Flat	78.7	69.0	5.4	0.9	2.1
	Irregularly Flooded Marsh	16.7	5.6	1.9	0.7	0.1
	Developed Dry Land	9.6	8.6	7.1	3.5	2.3
	Estuarine Beach	1.5	0.7	0.1	0.0	0.0
	Total (incl. water)	**7198.4**	**7198.4**	**7198.4**	**7198.4**	**7198.4**



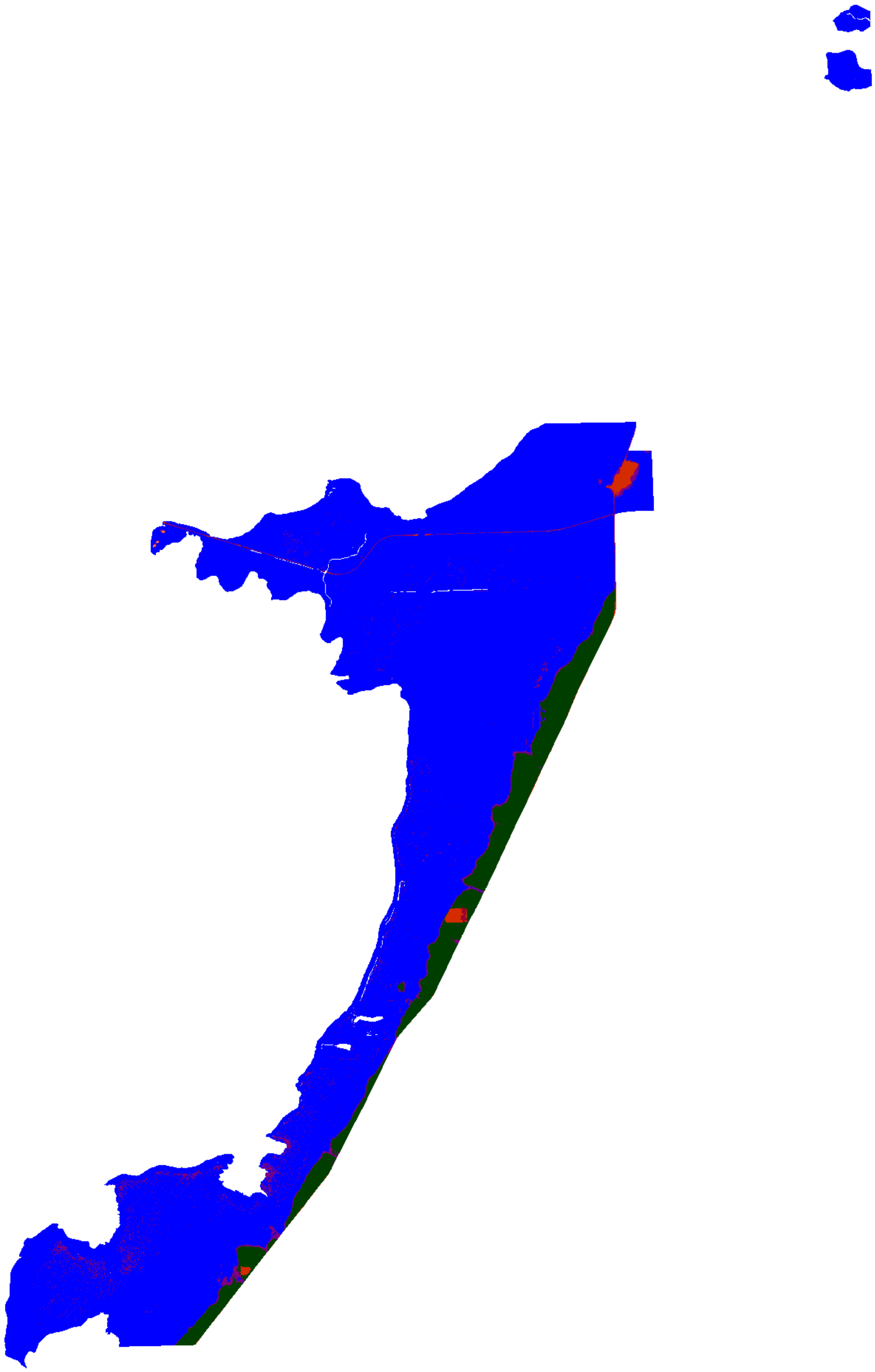
Crocodile Lake NWR, Initial Condition



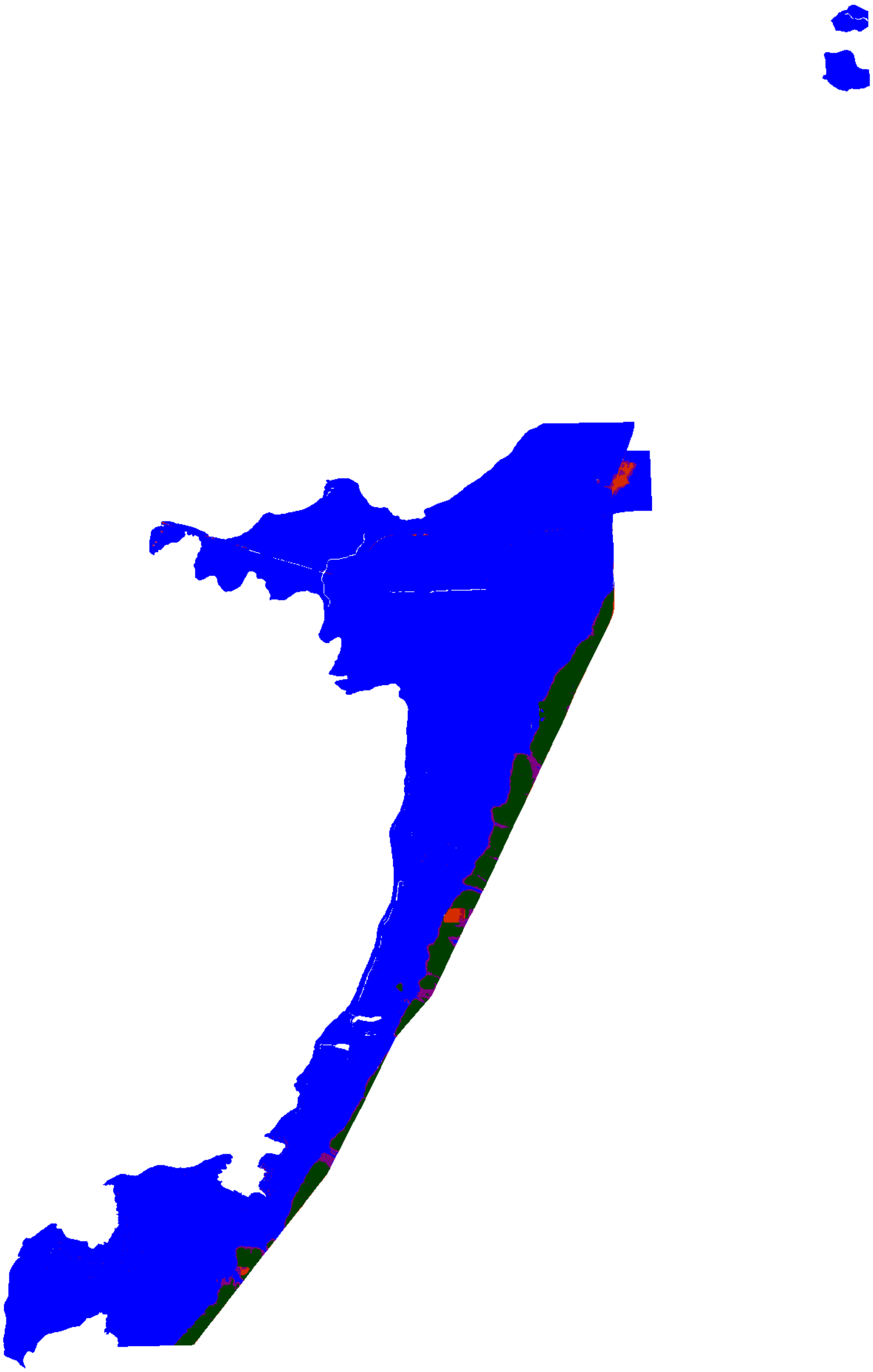
Crocodile Lake NWR, 2025, 2 Meters



Crocodile Lake NWR, 2050, 2 Meters



Crocodile Lake NWR, 2075, 2 Meters



Crocodile Lake NWR, 2100, 2 Meters

Discussion

The majority of Crocodile Lake National Wildlife Refuge is composed of mangrove habitat. In sea level rise scenarios of 1 meter and above (by 2100), the majority of refuge mangrove is predicted to be submerged. Most of the refuge's tidal swamp is situated in comparatively high elevations, making it more resilient.

Mangroves have been shown to have a relatively high vertical accretion rate (Cahoon et al. 1999) and also can thrive over a relatively wide elevation range. Model uncertainty for this application is increased, however by the reliance on off-site mangrove accretion data. Additionally, SLAMM does not account for potential killing frosts which can have a significant effect on mangrove biomass.

Elevation data at this site were derived from 2008 LiDAR flights and wetland maps are also up-to-date. The quality of the input data is high and model uncertainty on this basis is significantly reduced.

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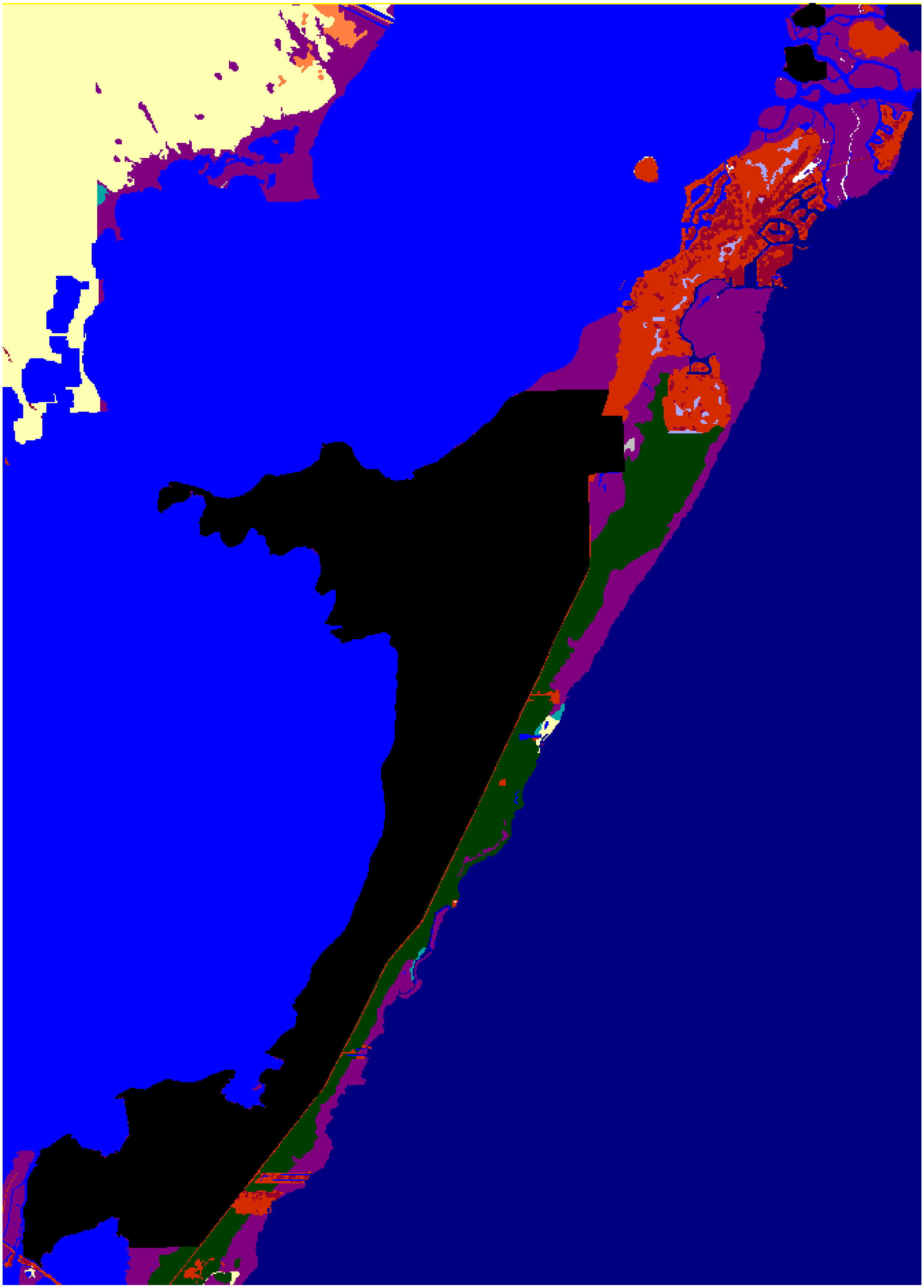
Appendix A: Contextual Results

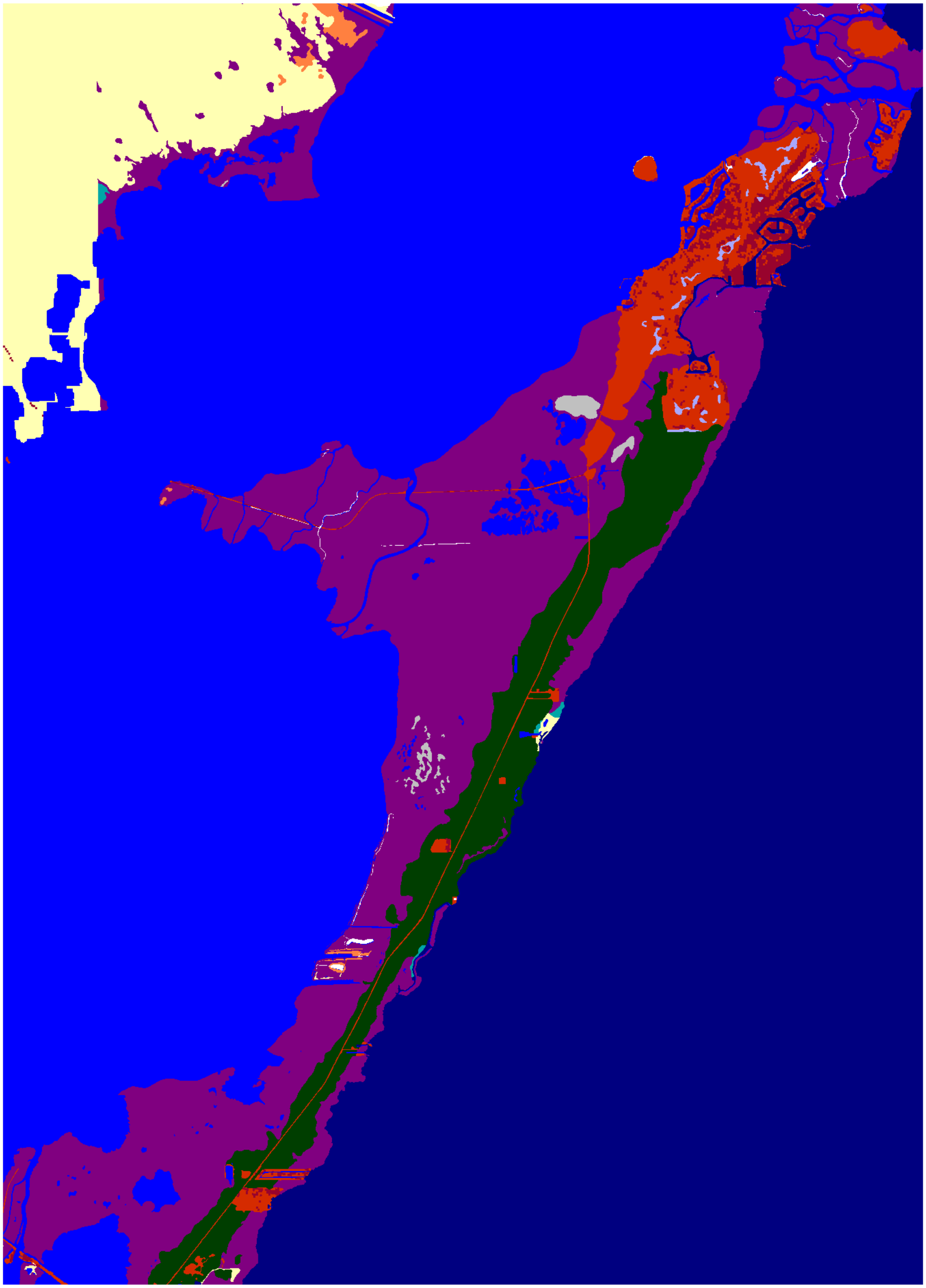
The SLAMM model does take into account the context of the surrounding lands or open water when calculating effects. For example, erosion rates are calculated based on the maximum fetch (wave action) which is estimated by assessing contiguous open water to a given marsh cell. Another example is that inundated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

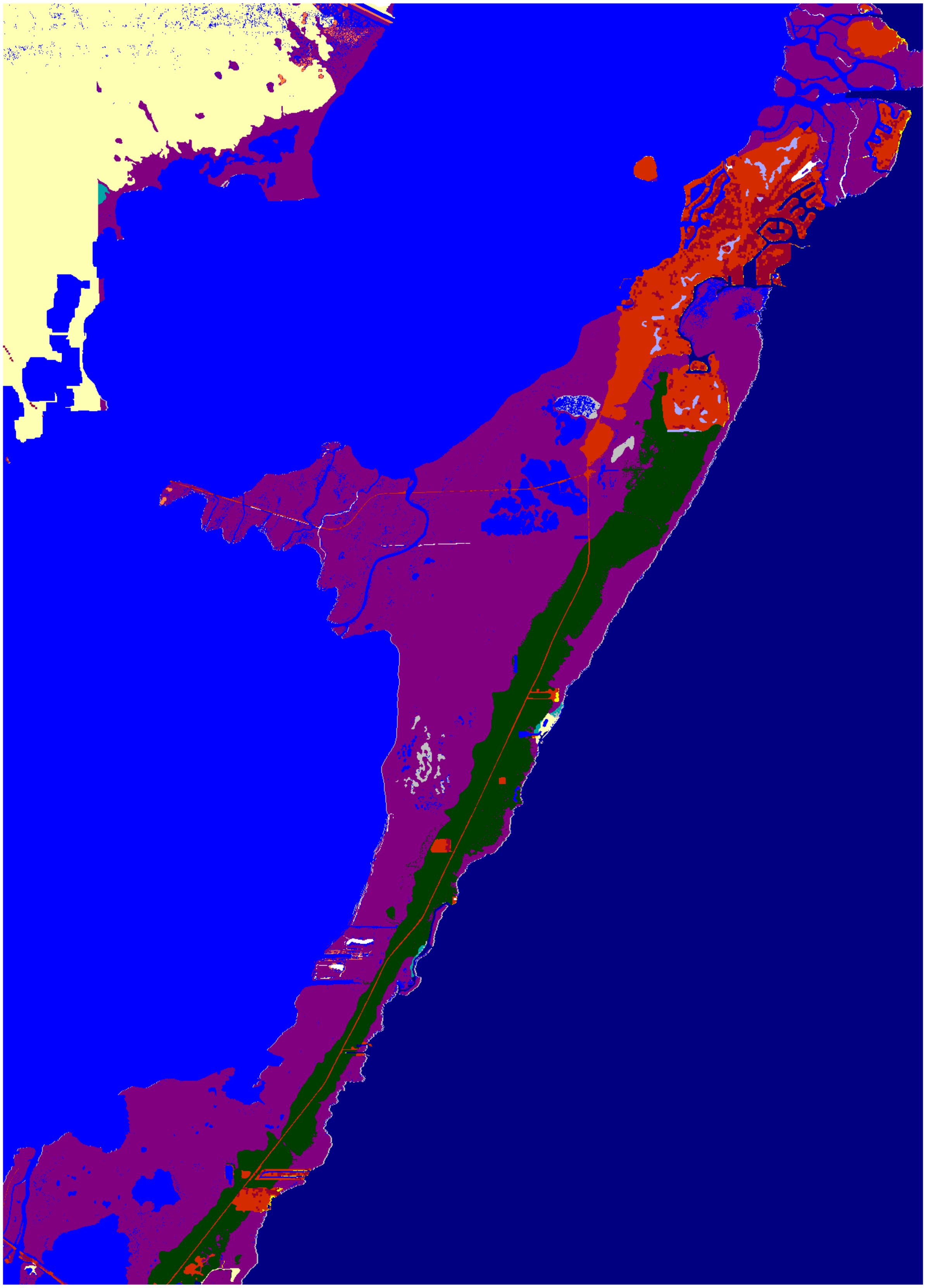
- Results were closely examined (quality assurance) within USFWS refuges but not closely examined for the larger region.
- Site-specific parameters for the model were derived for USFWS refuges whenever possible and may not be regionally applicable.
- Especially in areas where dikes are present, an effort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



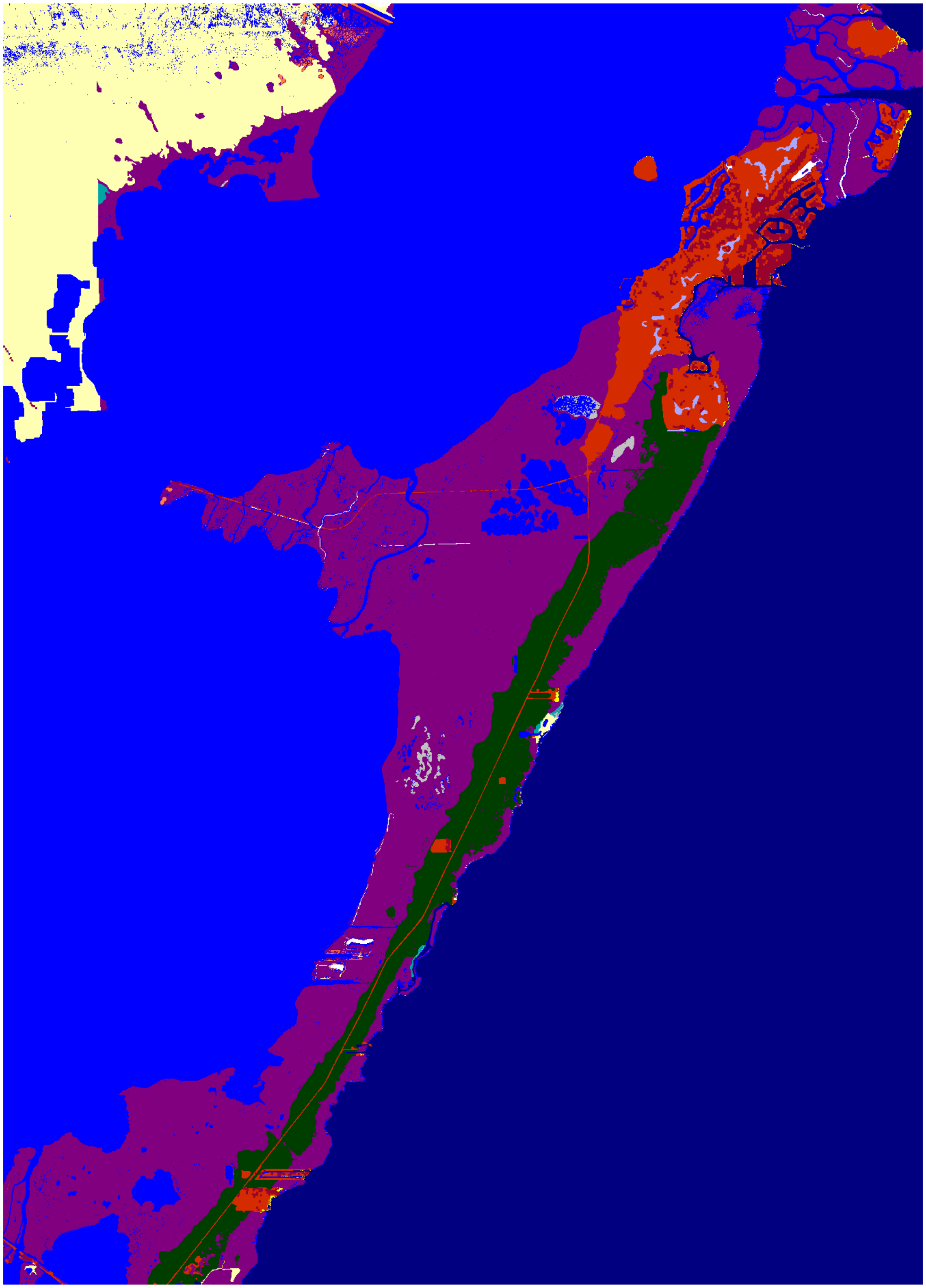
Crocodile Lake National Wildlife Refuge within simulation context (black).



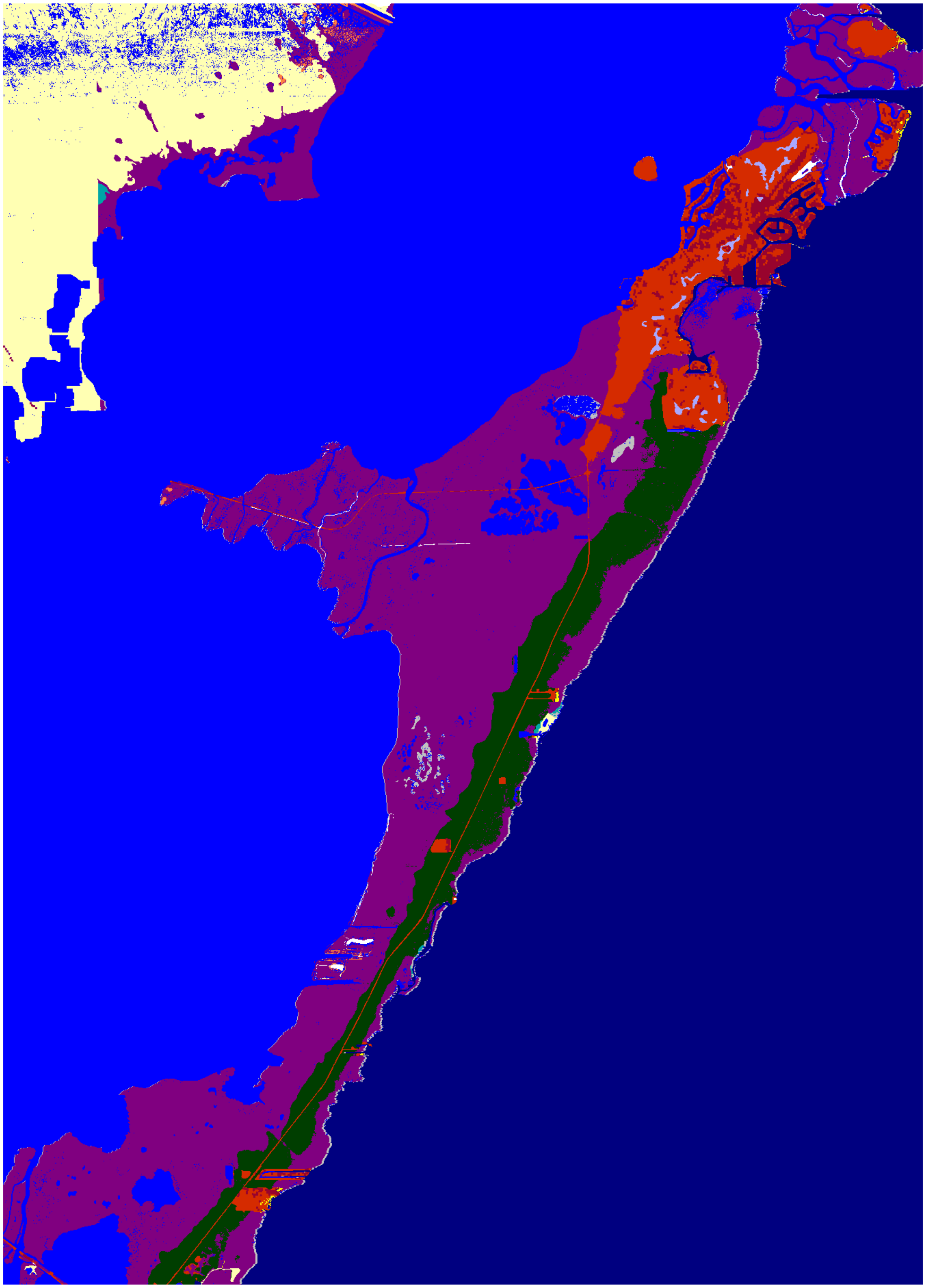
Crocodile Lake Context, Initial Condition



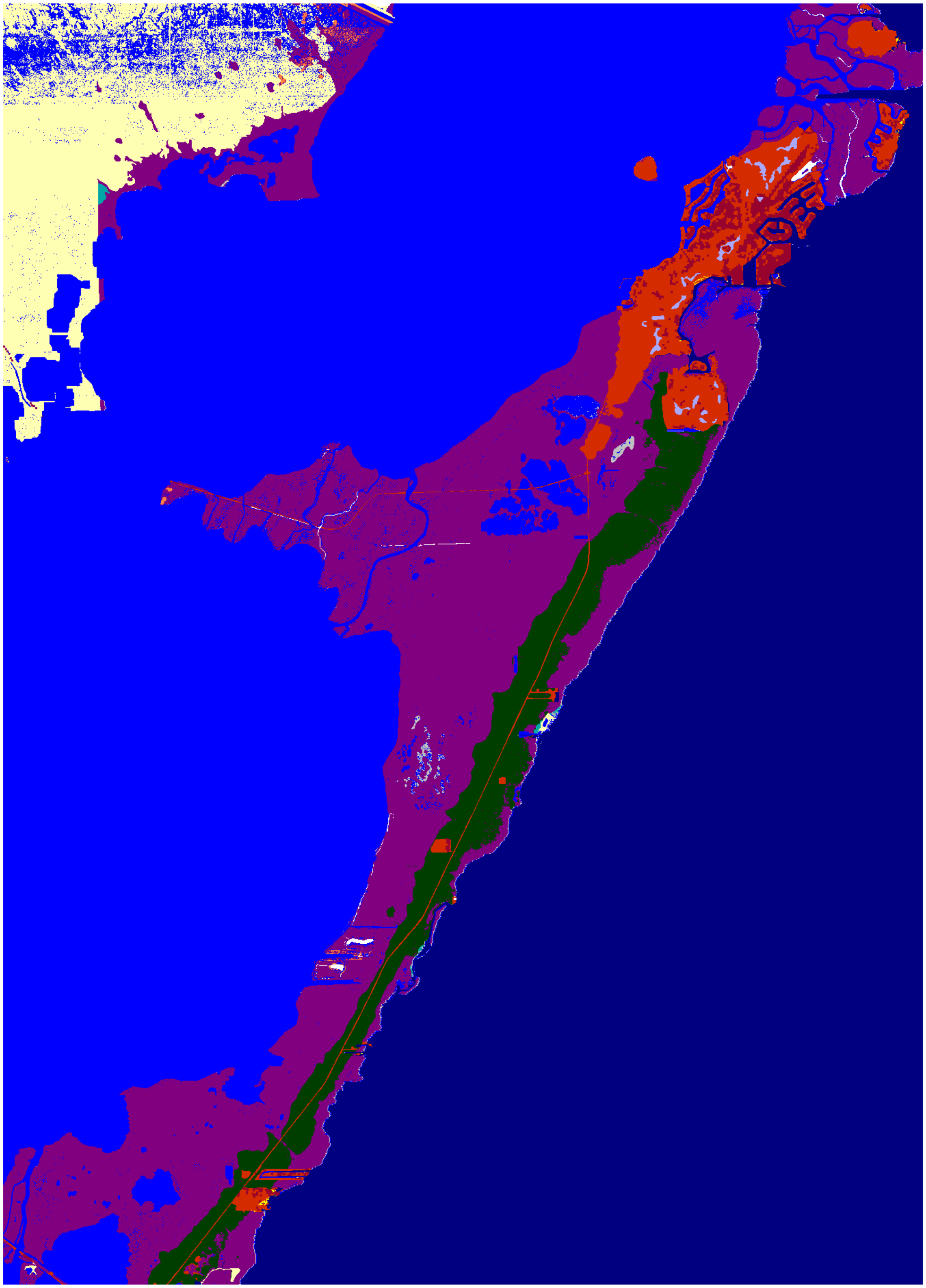
Crocodile Lake Context, 2025, Scenario A1B Mean



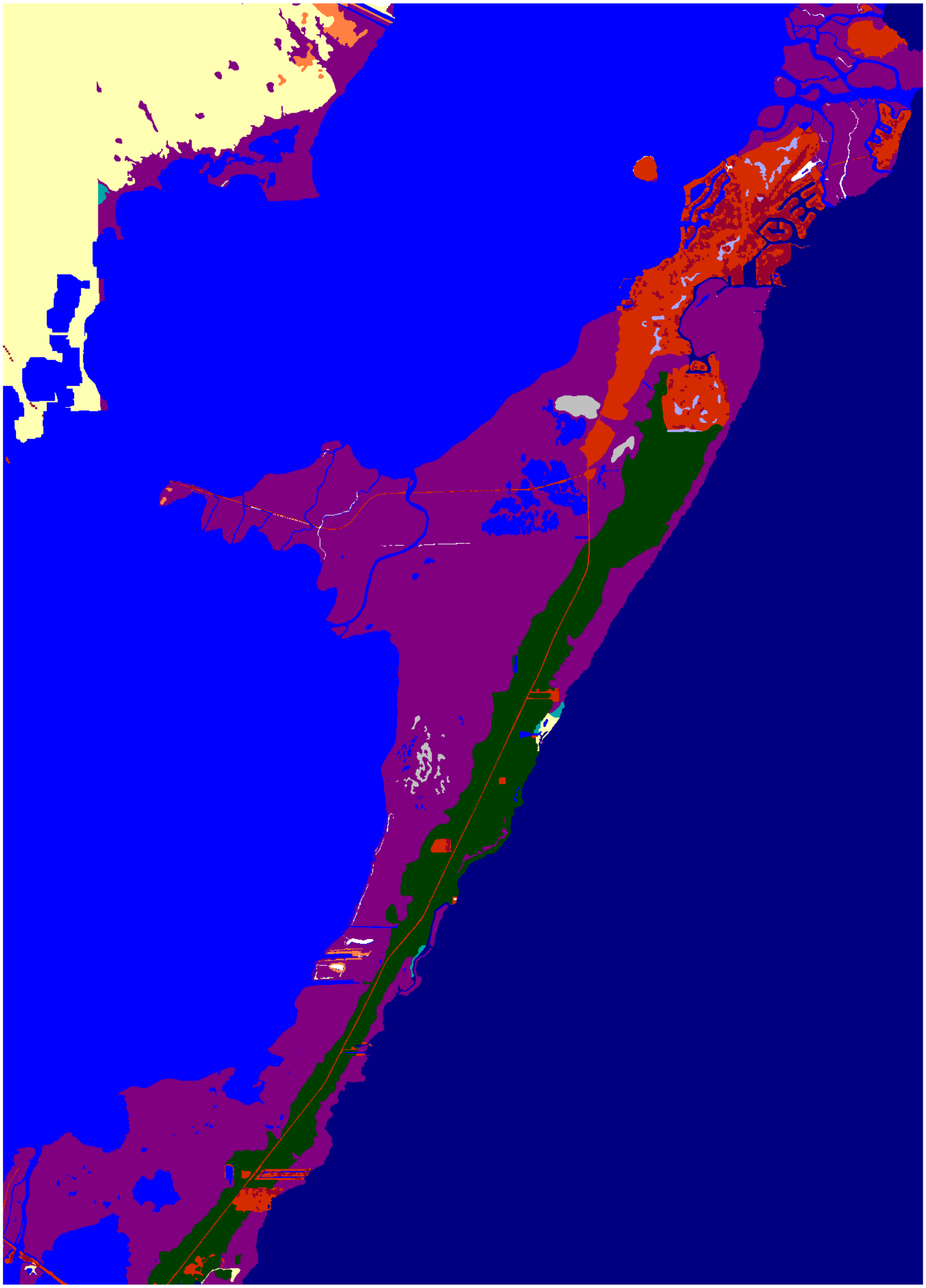
Crocodile Lake Context, 2050, Scenario A1B Mean



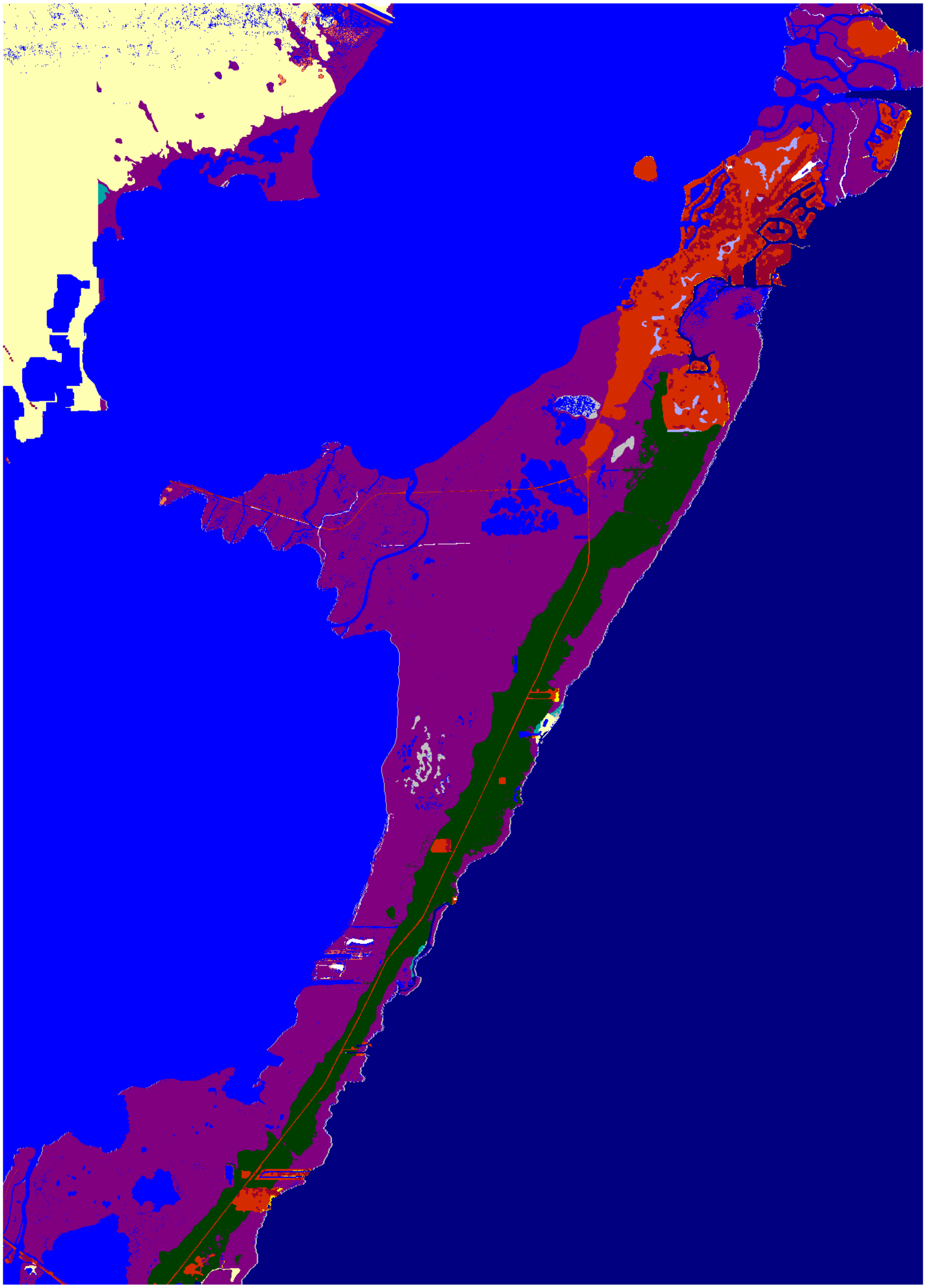
Crocodile Lake Context, 2075, Scenario A1B Mean



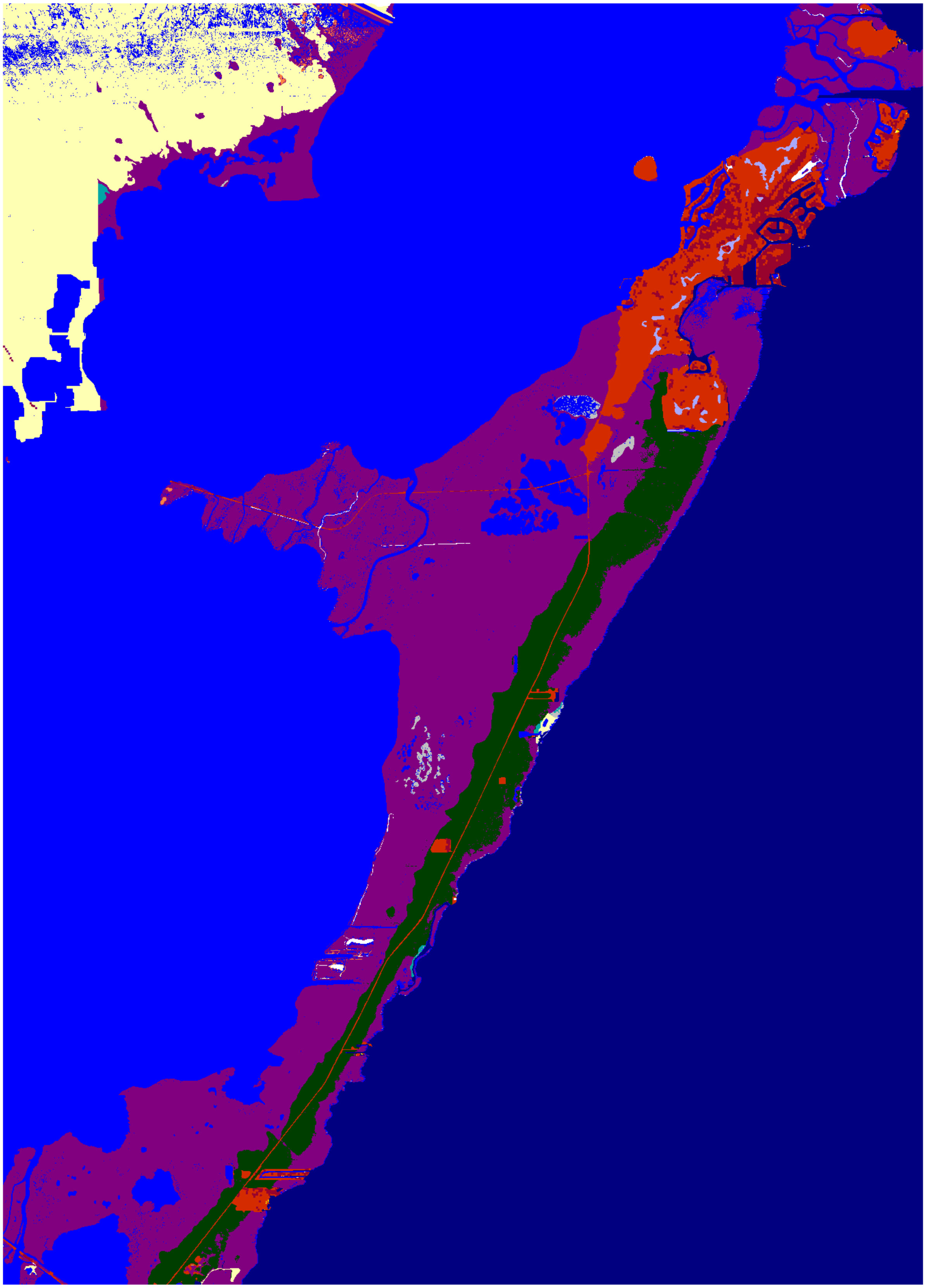
Crocodile Lake Context, 2100, Scenario A1B Mean



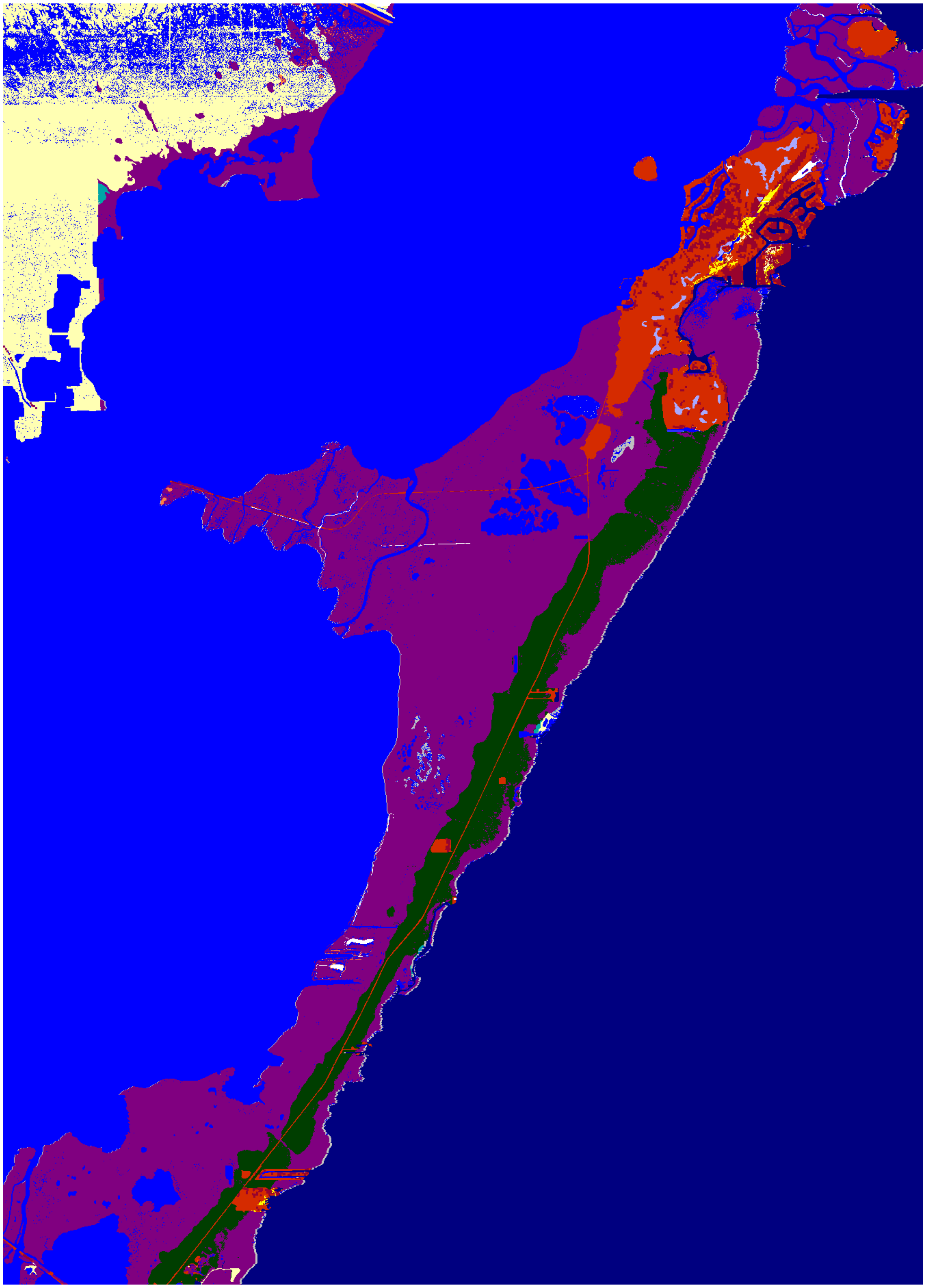
Crocodile Lake Context, Initial Condition



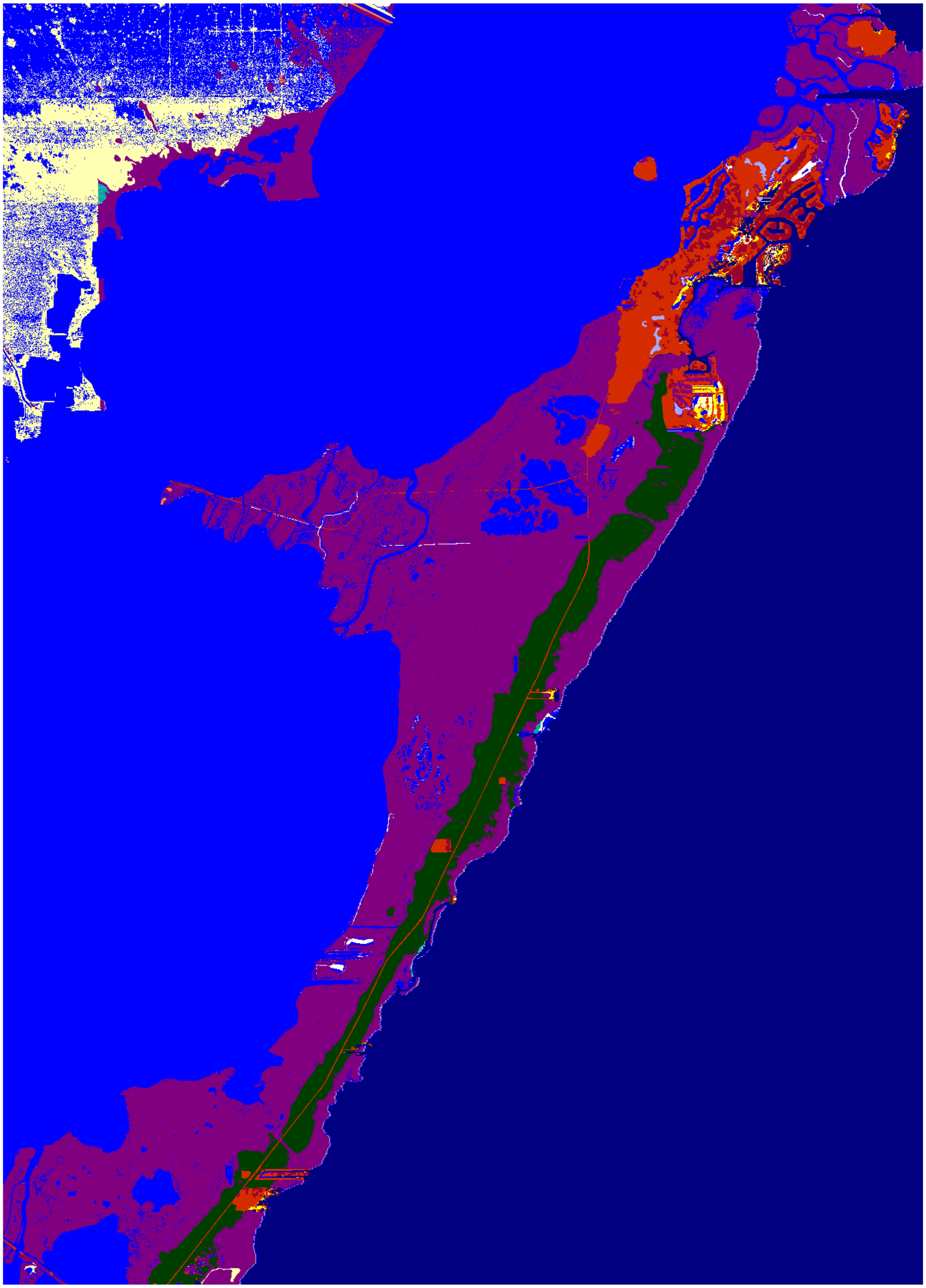
Crocodile Lake Context, 2025, Scenario A1B Maximum



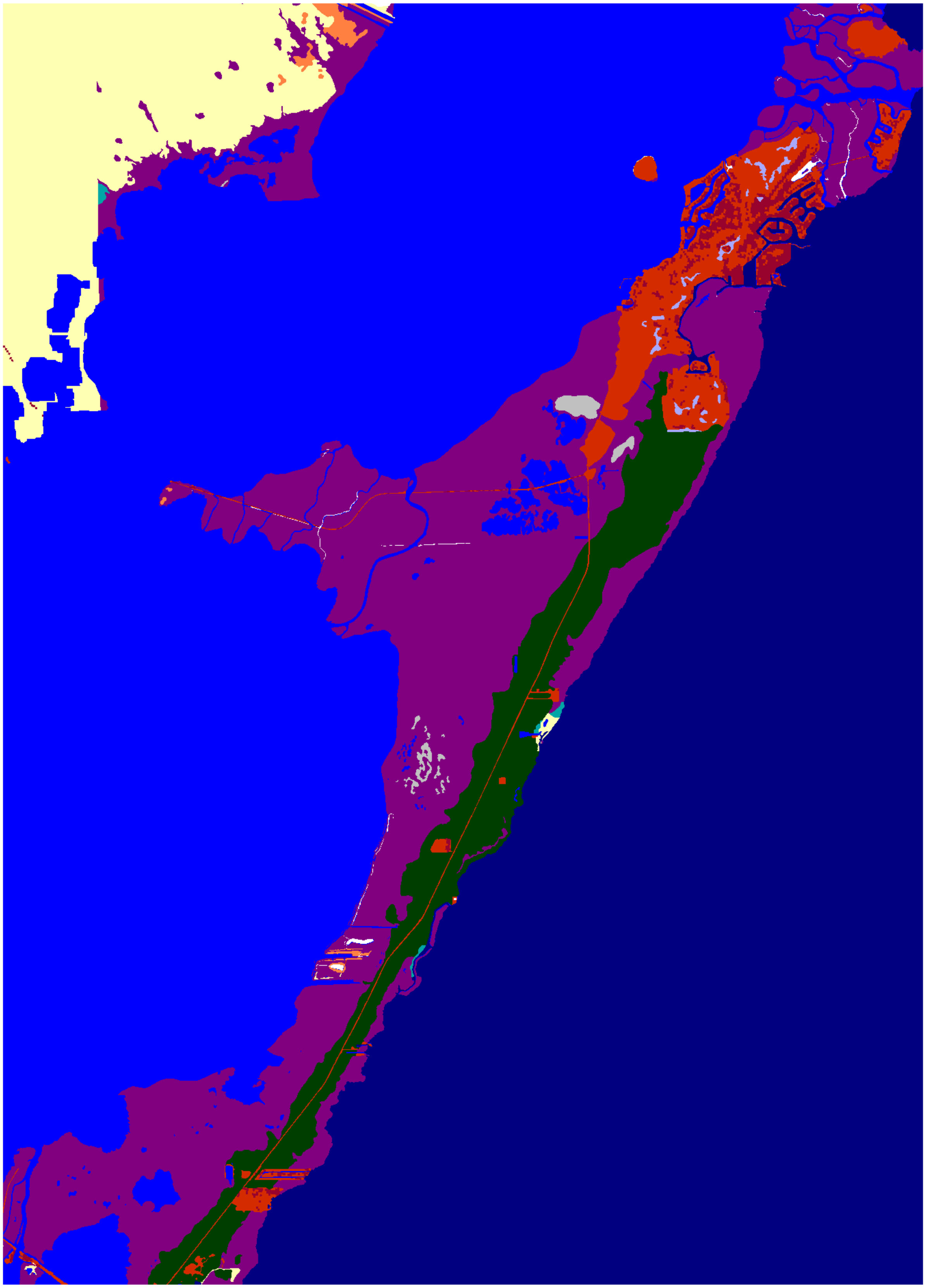
Crocodile Lake Context, 2050, Scenario A1B Maximum



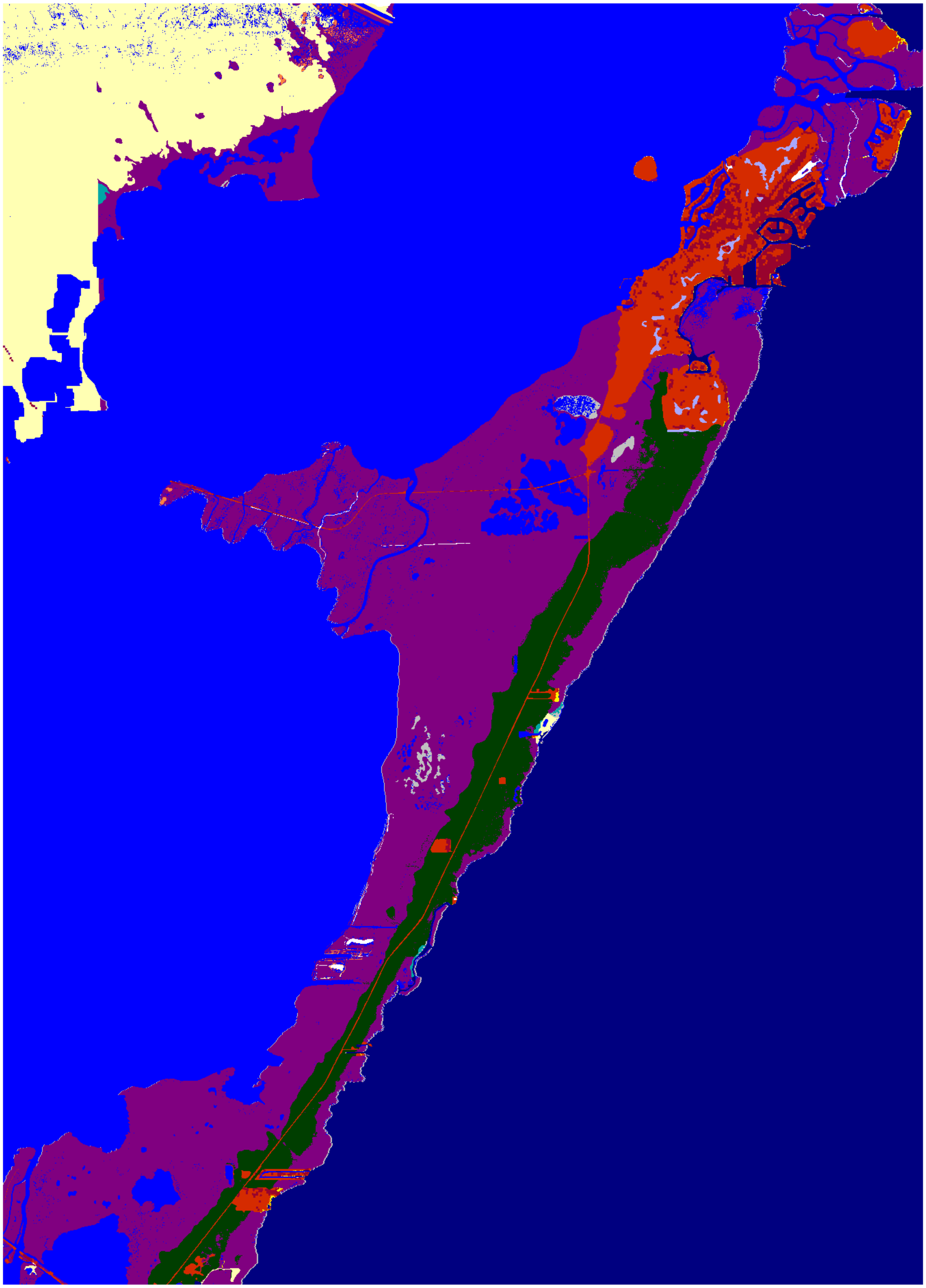
Crocodile Lake Context, 2075, Scenario A1B Maximum



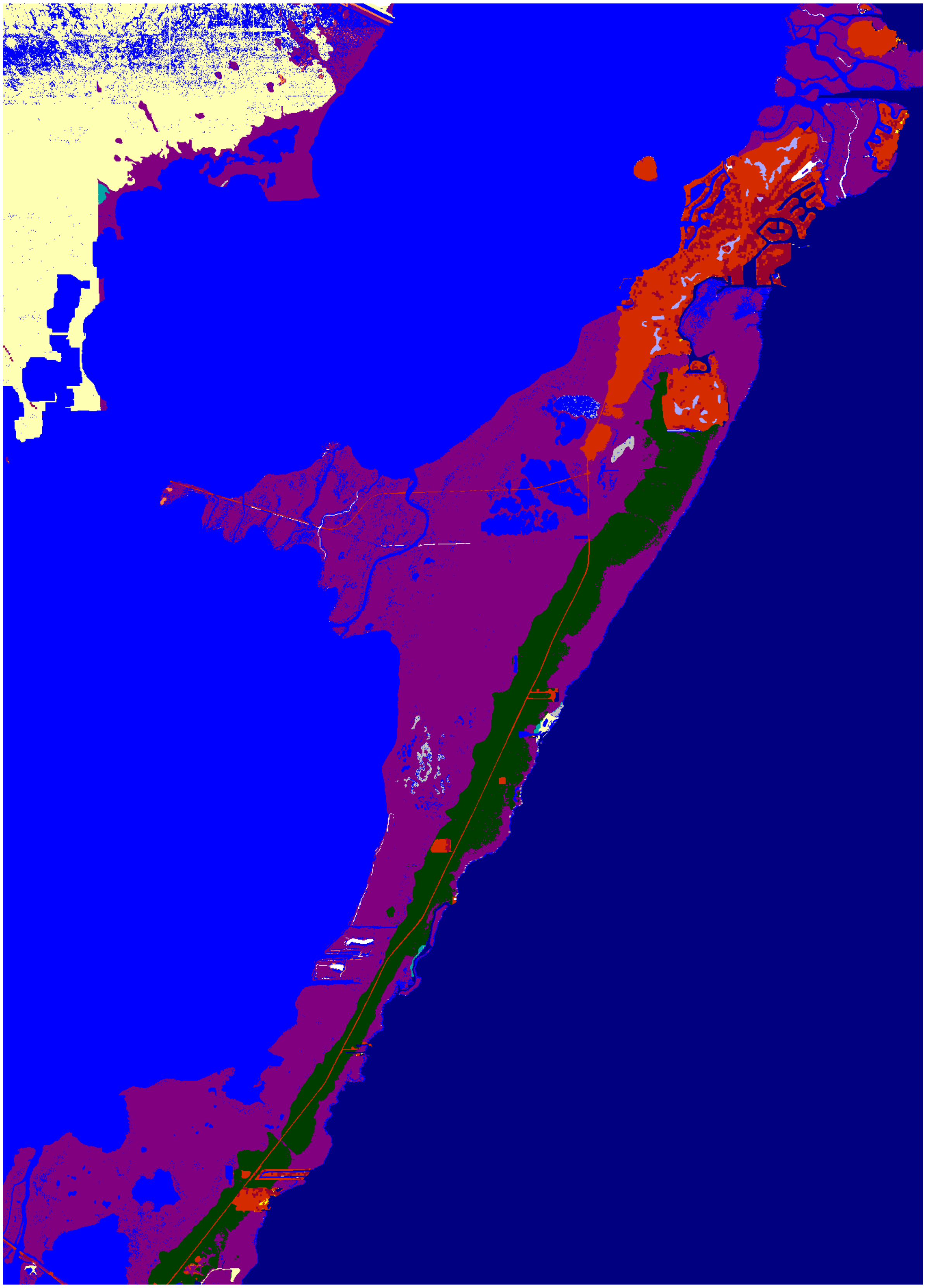
Crocodile Lake Context, 2100, Scenario A1B Maximum



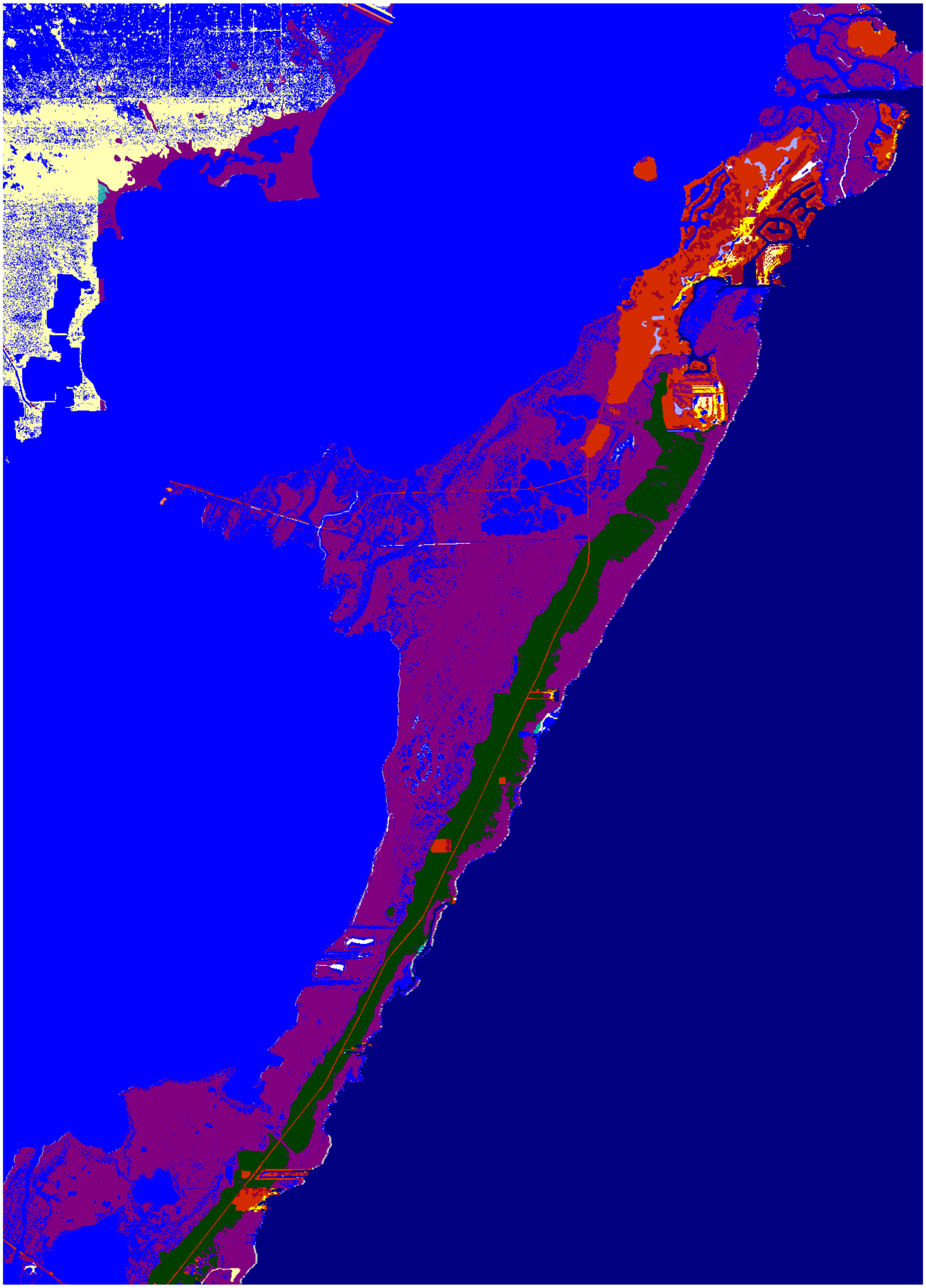
Crocodile Lake Context, Initial Condition



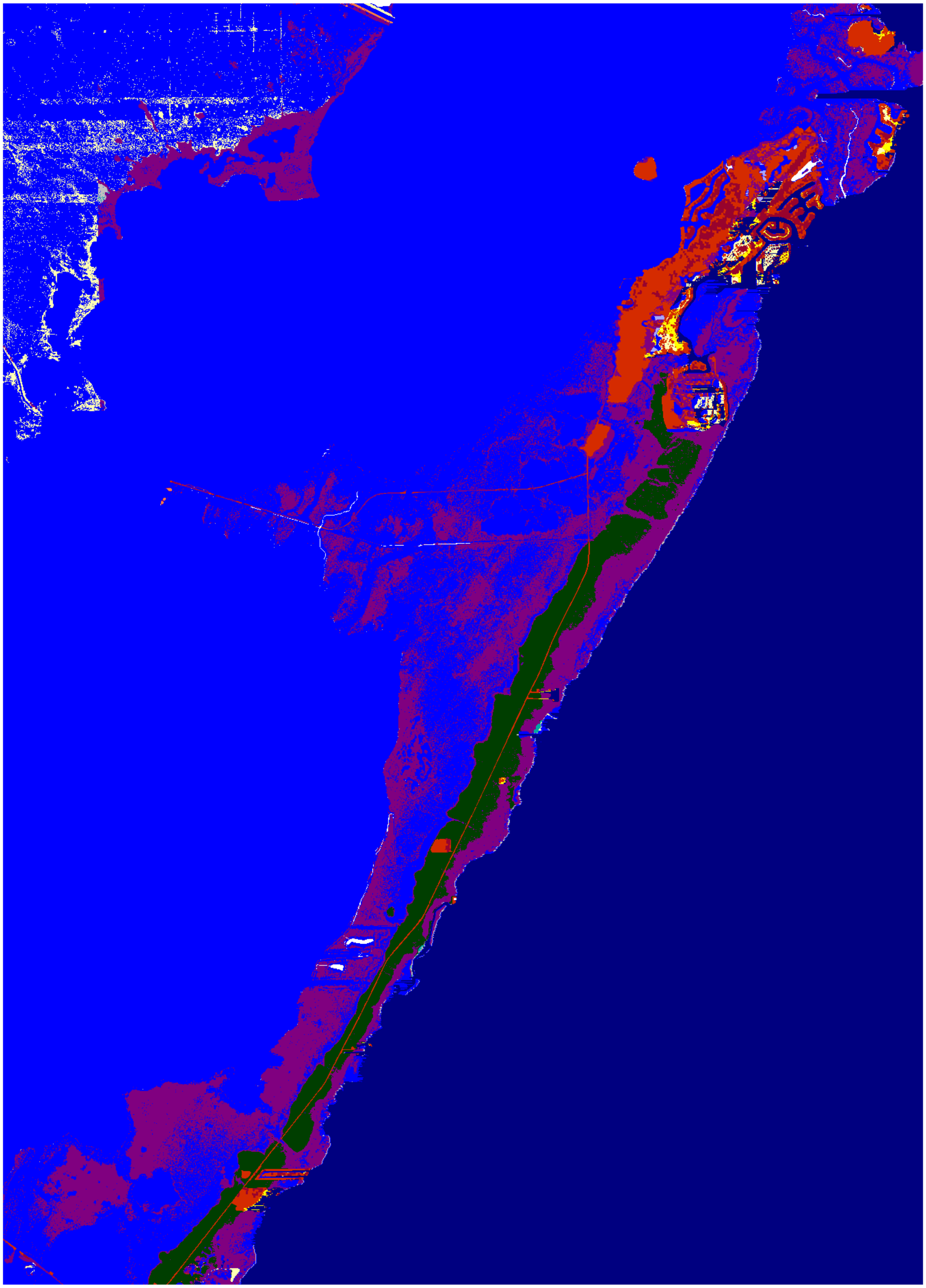
Crocodile Lake Context, 2025, 1 meter



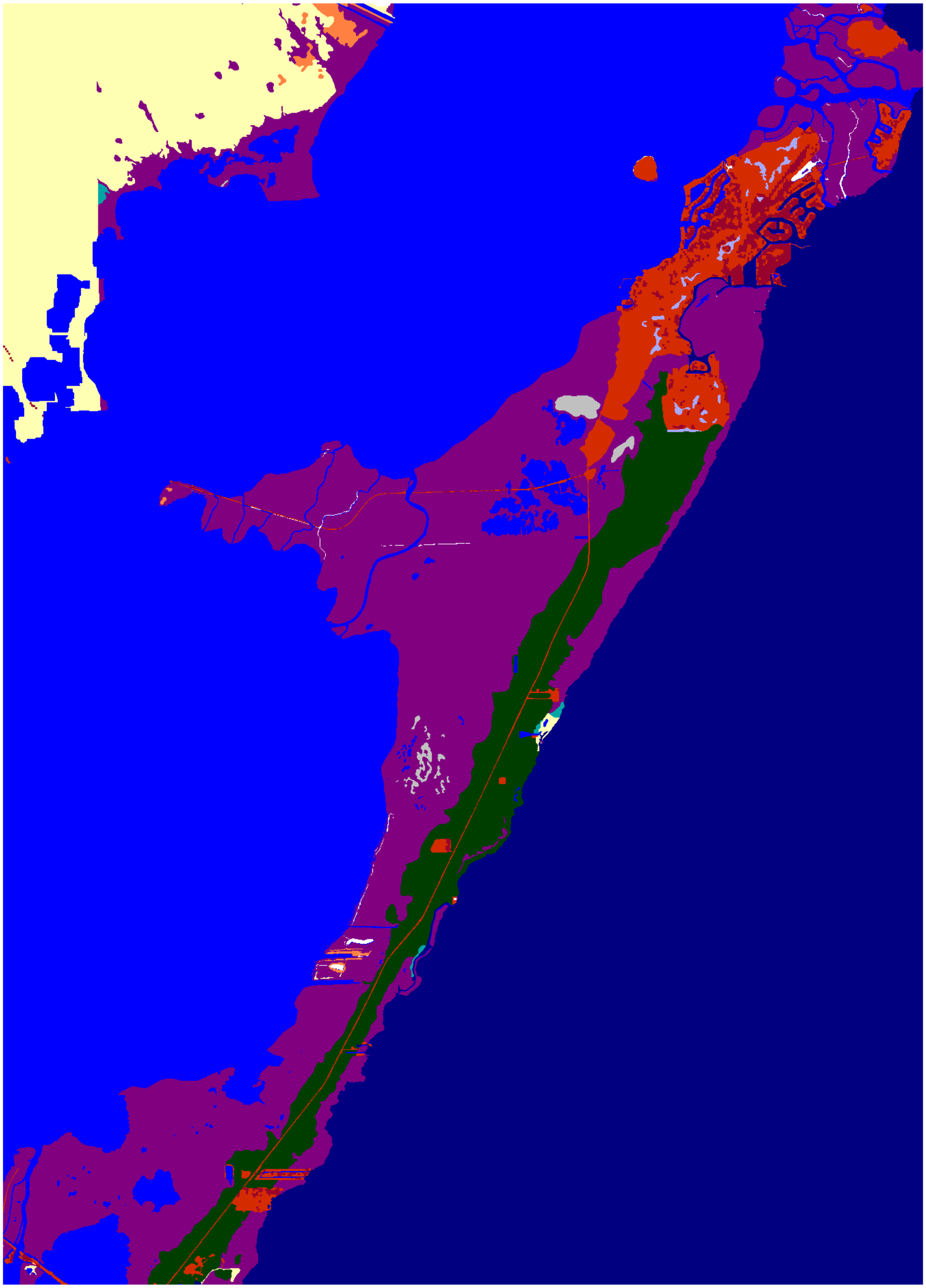
Crocodile Lake Context, 2050, 1 meter



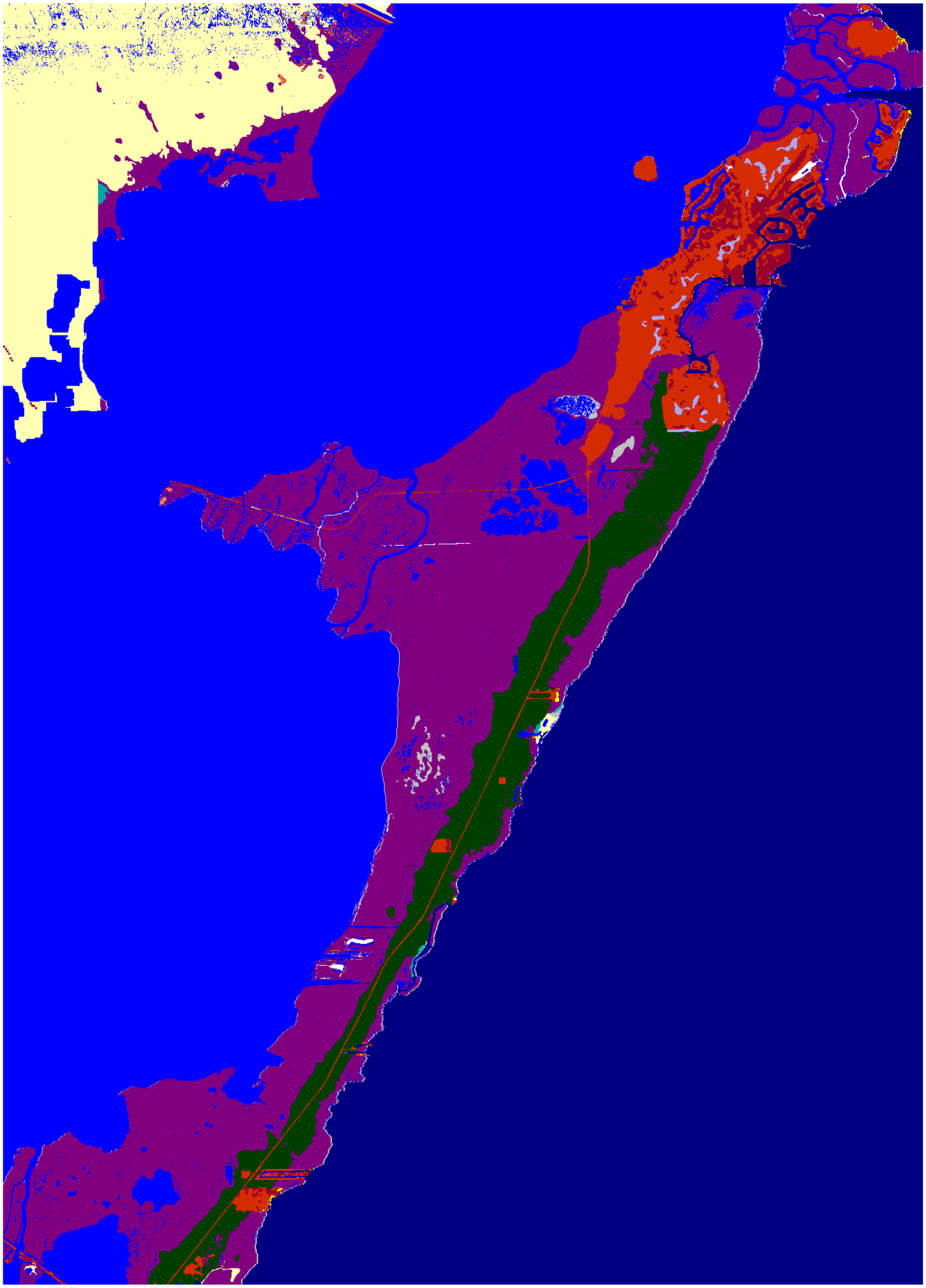
Crocodile Lake Context, 2075, 1 meter



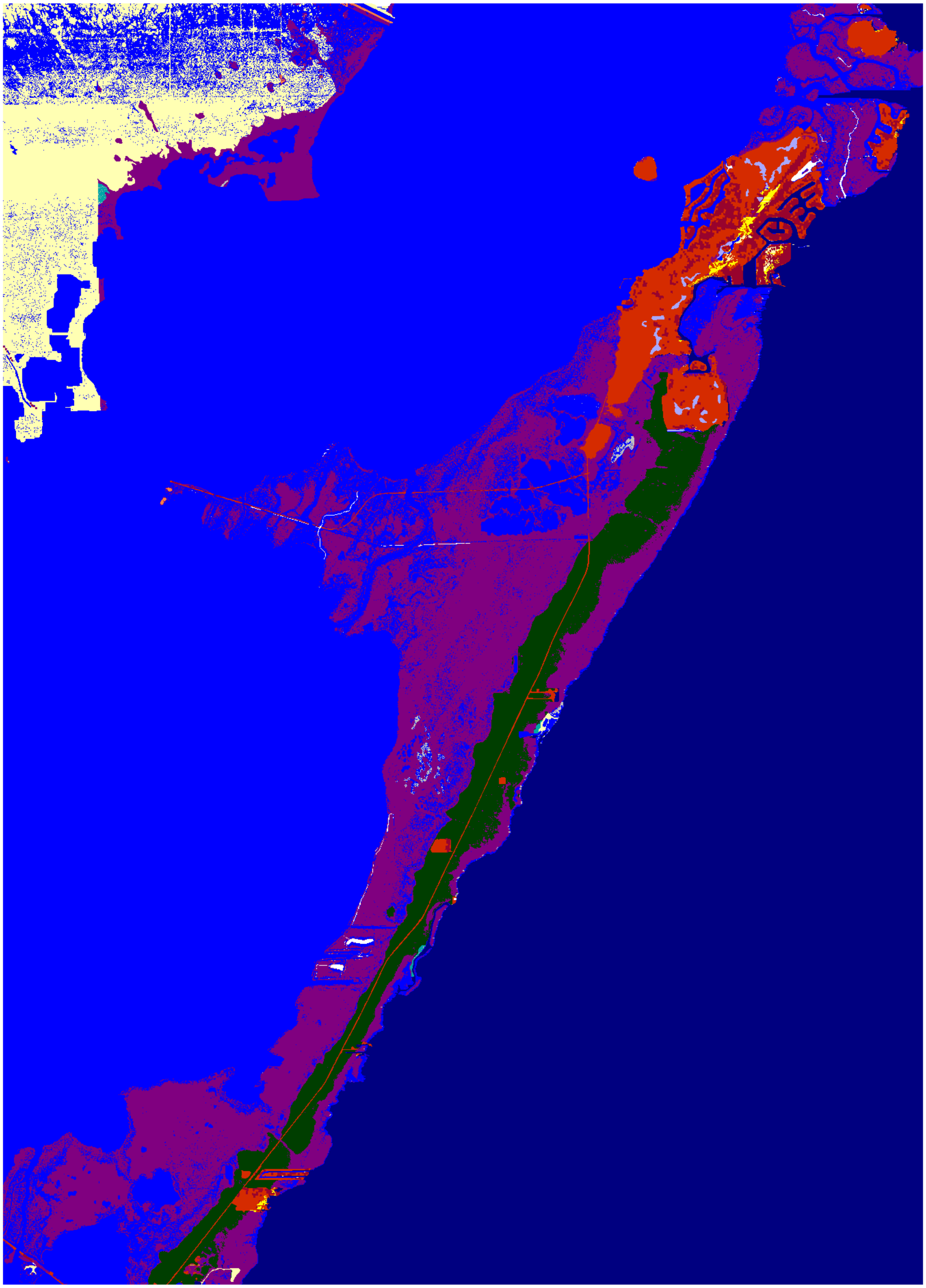
Crocodile Lake Context, 2100, 1 meter



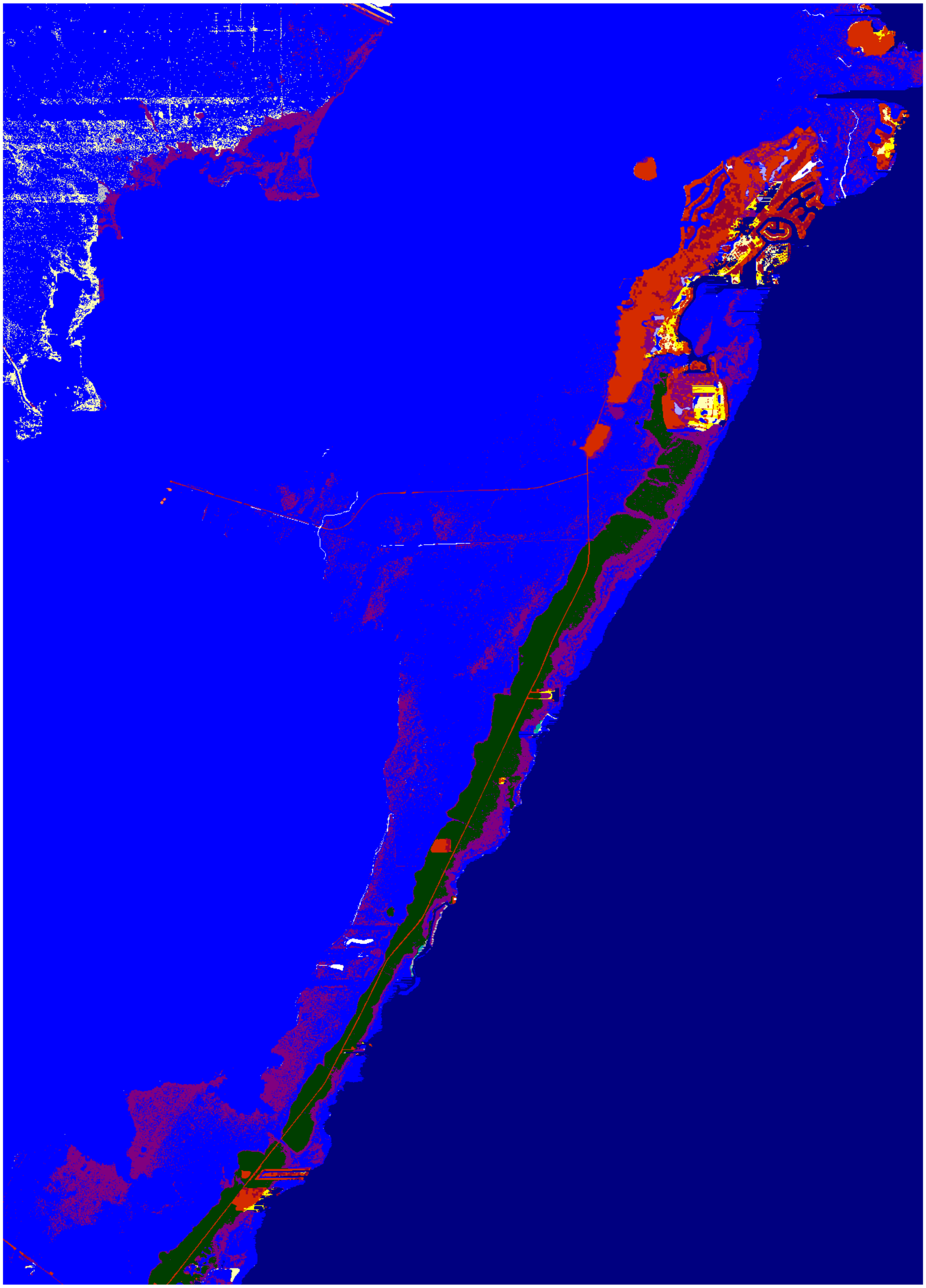
Crocodile Lake Context, Initial Condition



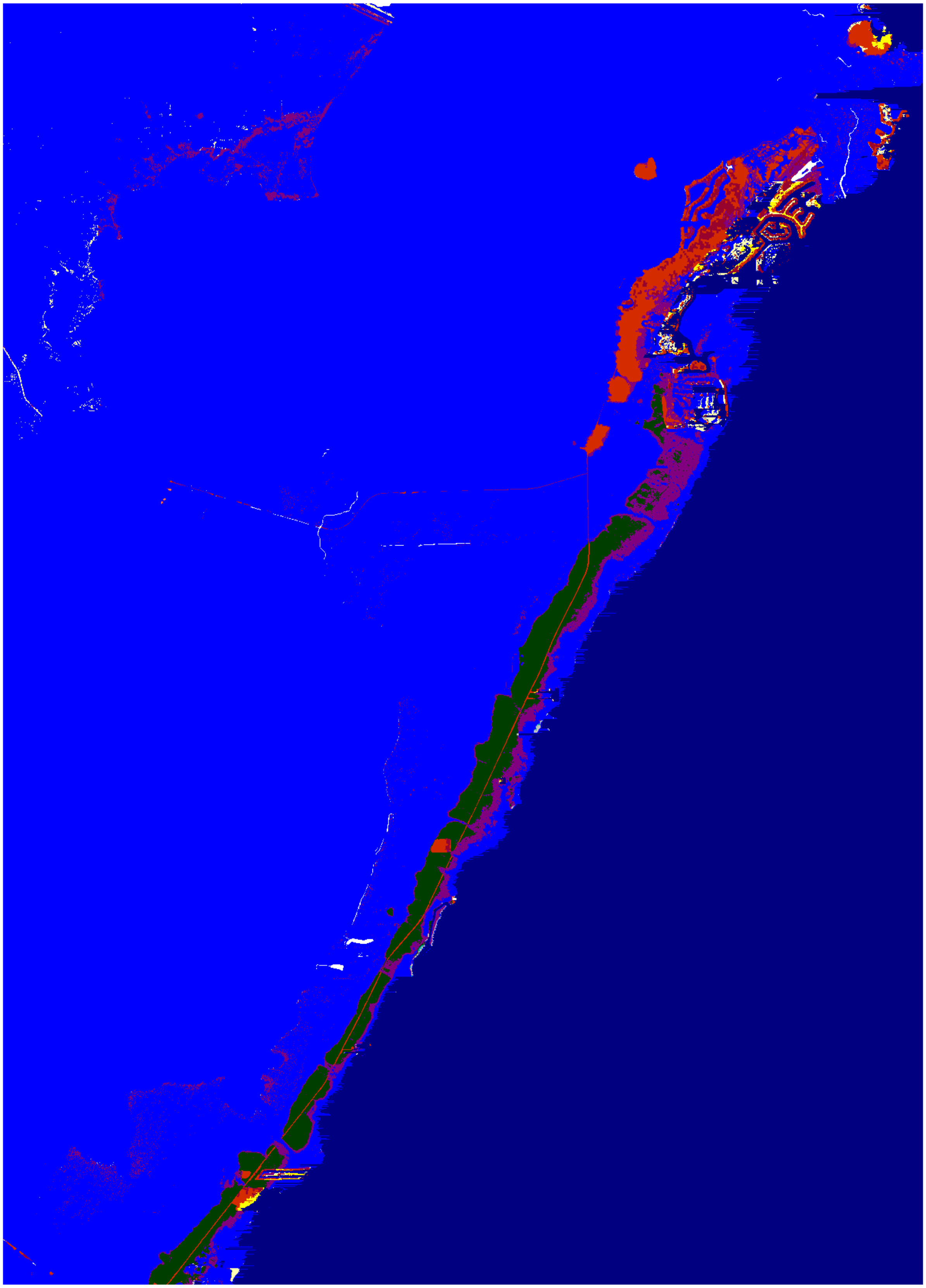
Crocodile Lake Context, 2025, 1.5 meter



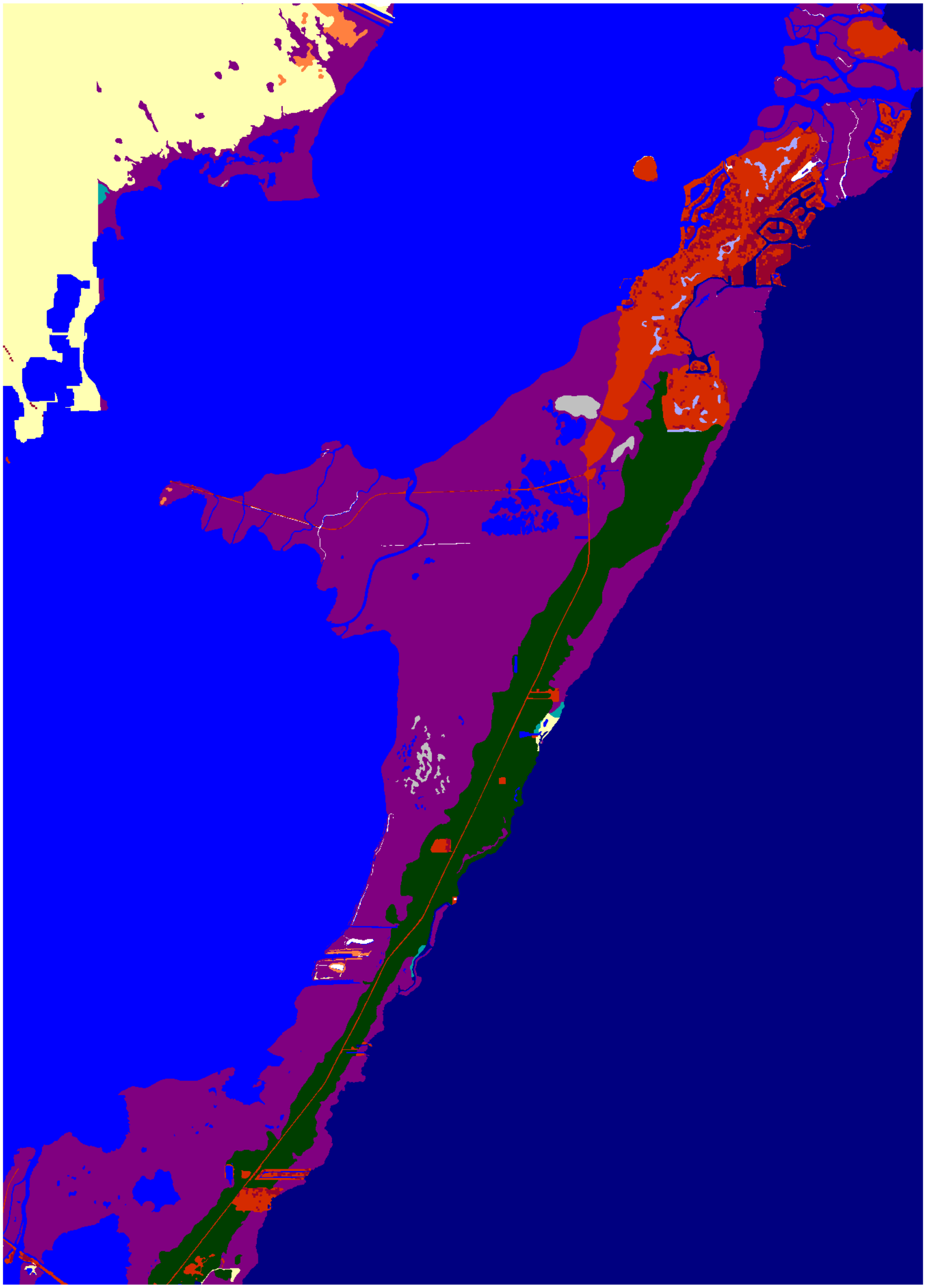
Crocodile Lake Context, 2050, 1.5 meter



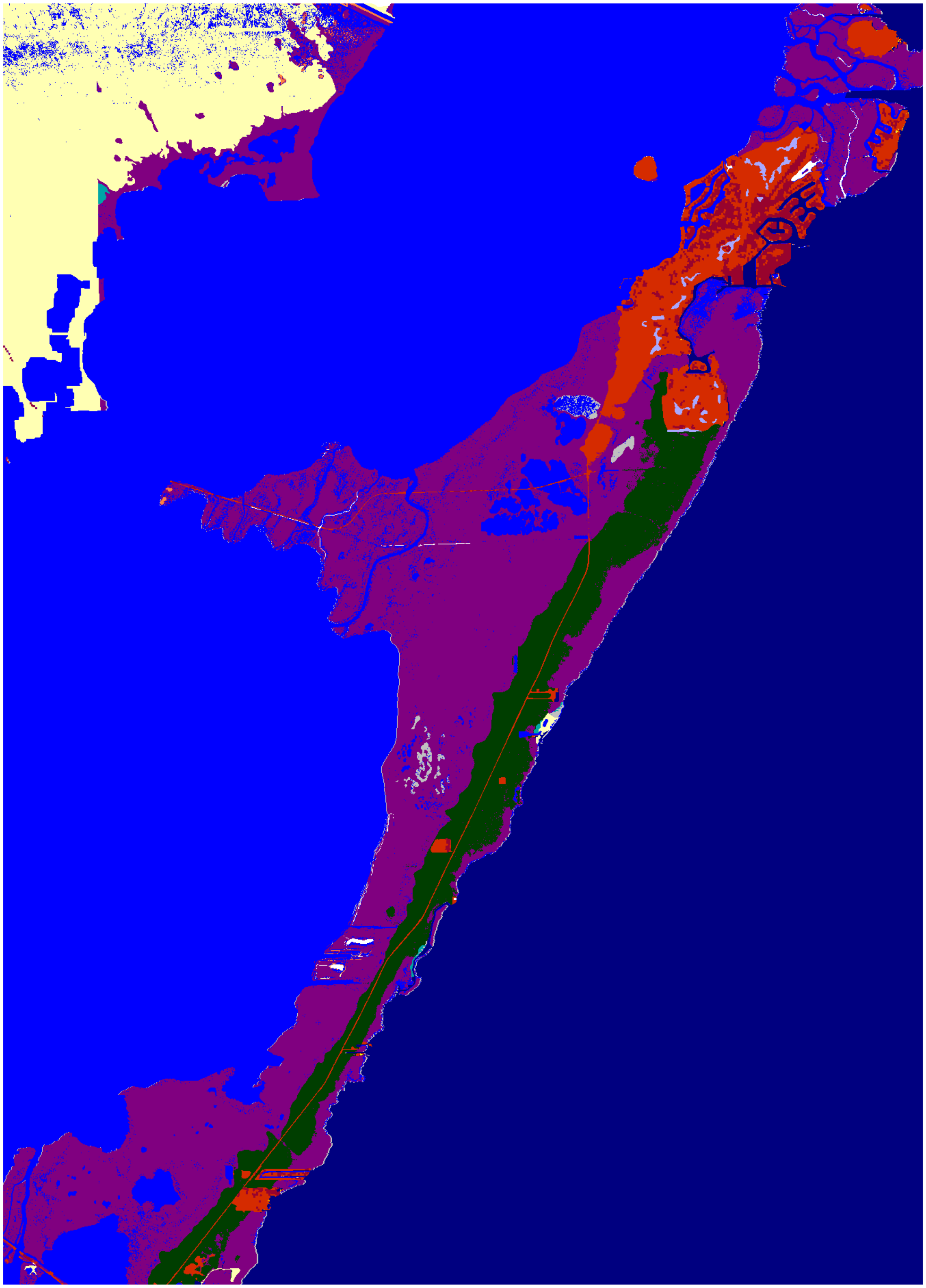
Crocodile Lake Context, 2075, 1.5 meter



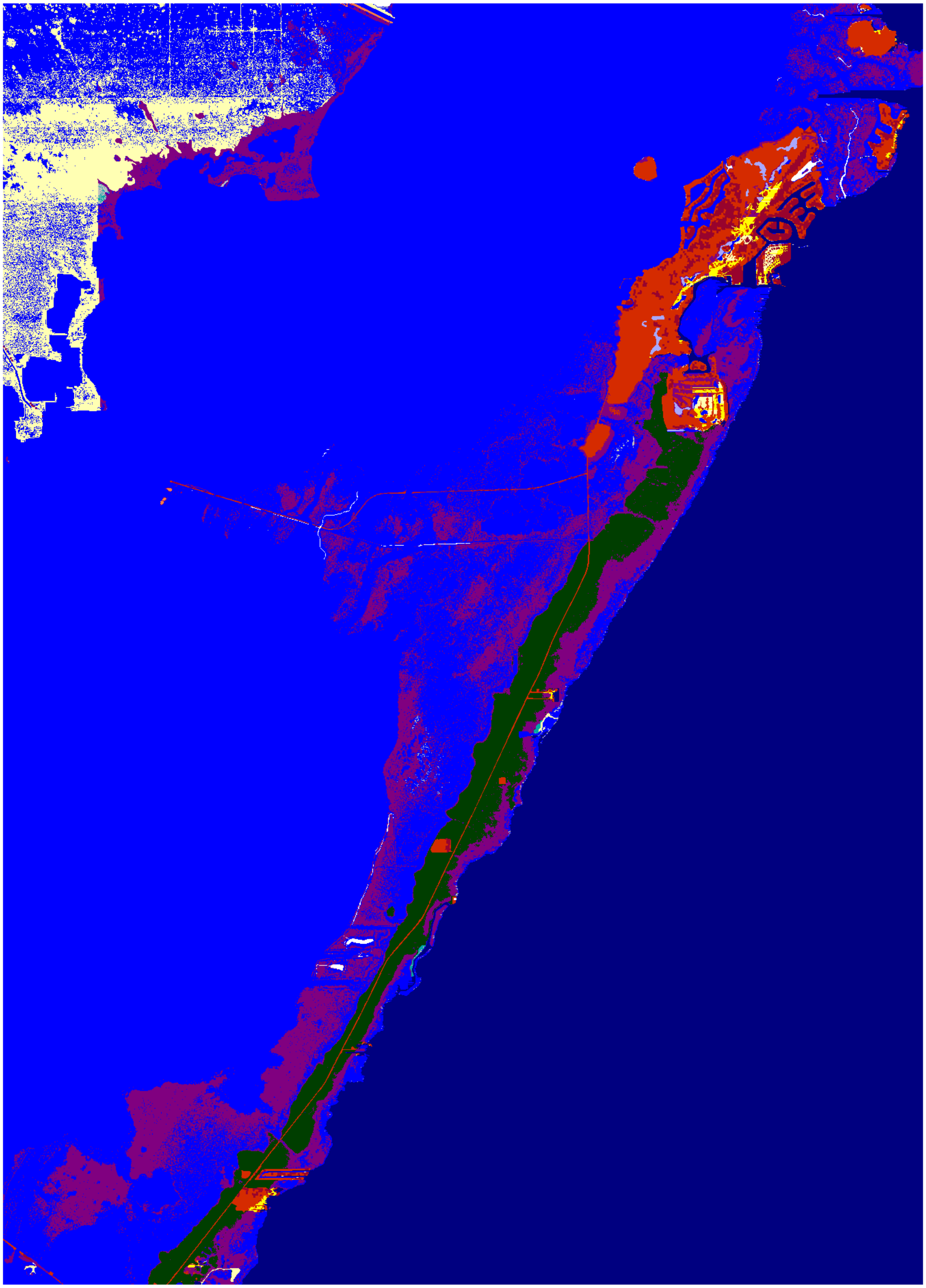
Crocodile Lake Context, 2100, 1.5 meter



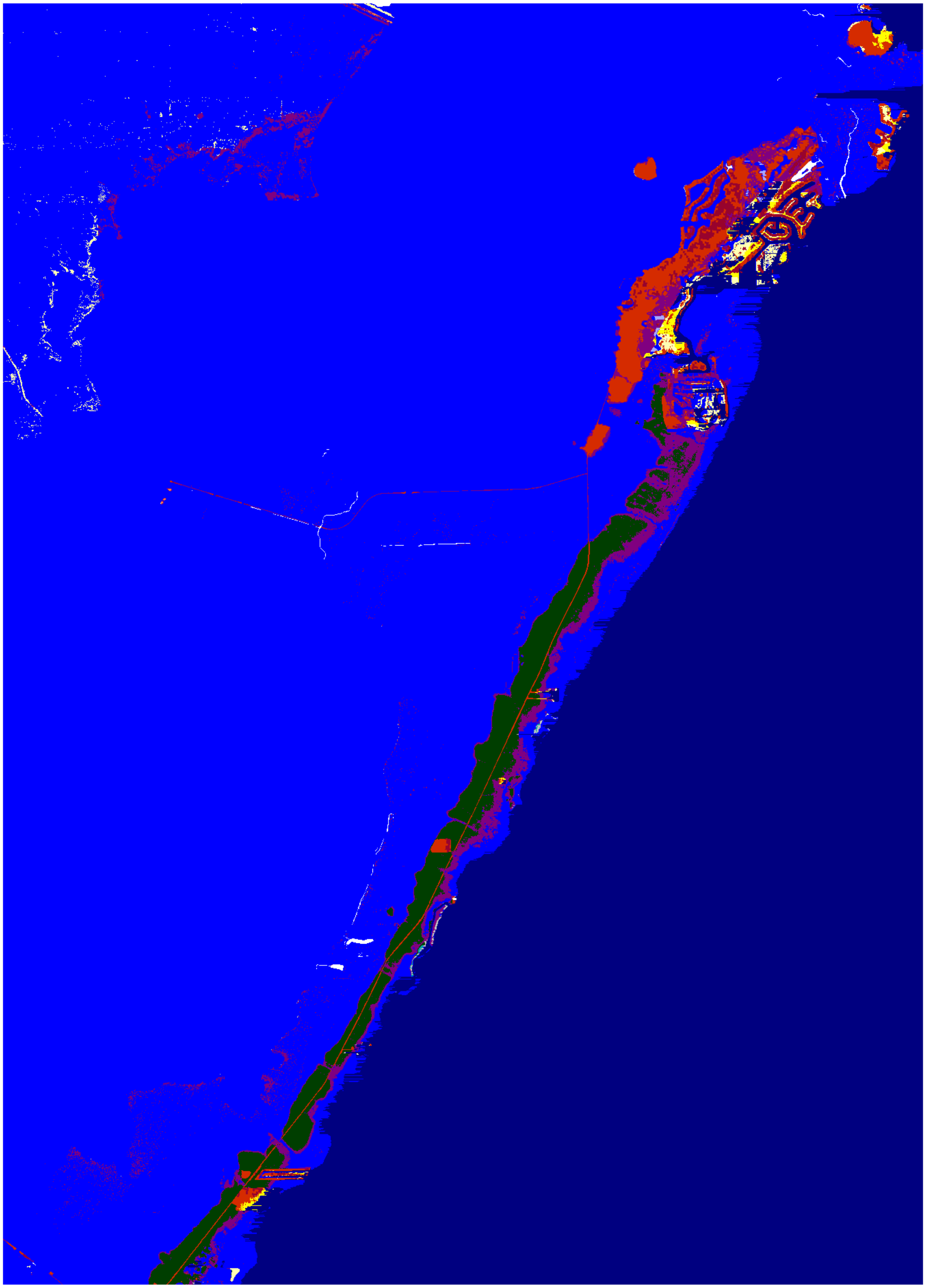
Crocodile Lake Context, Initial Condition



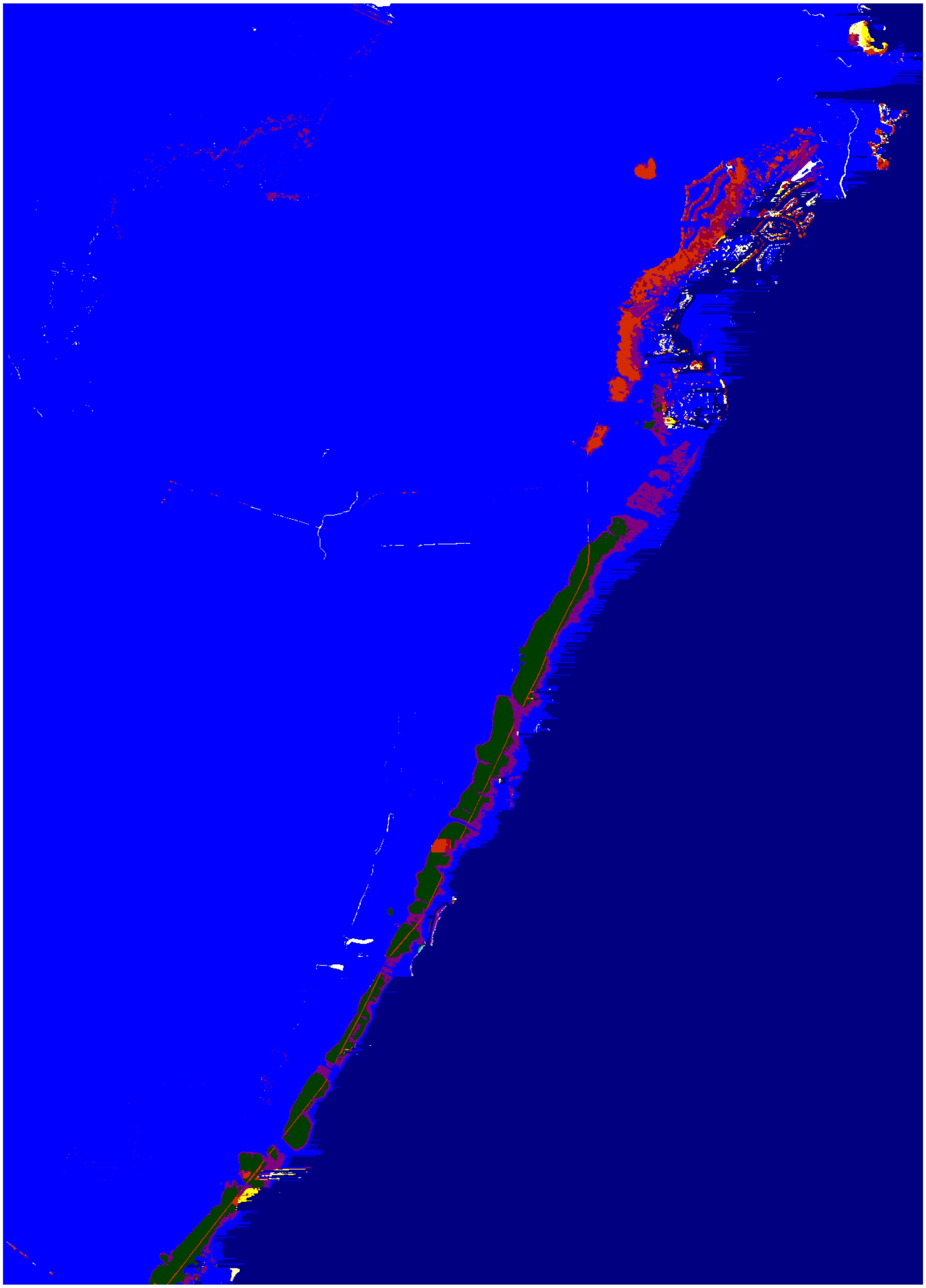
Crocodile Lake Context, 2025, 2 meter



Crocodile Lake Context, 2050, 2 meter



Crocodile Lake Context, 2075, 2 meter



Crocodile Lake Context, 2100, 2 meter