Application of the Sea-Level Affecting Marshes Model (SLAMM 5.0) to Great Bay NWR

Prepared For: Dr. Brian Czech, Conservation Biologist

U. S. Fish and Wildlife Service
National Wildlife Refuge System
Division of Natural Resources and Conservation Planning
Conservation Biology Program
4401 N. Fairfax Drive - MS 670
Arlington, VA 22203

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

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Introduction

Tidal marshes are among the most susceptible ecosystems to climate change, especially accelerated sea level rise (SLR). The 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. Pfeffer et al. (2008) suggests that 200 cm by 2100 is at the upper end of plausible scenarios due to physical limitations on glaciological conditions. Rising sea level 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 4 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 5.0) 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.

SLAMM Version 5.0 is the latest version of the SLAMM Model, developed in 2006/2007 and based on SLAMM 4.0. SLAMM 5.0 provides the following refinements:

- The capability to simulate fixed levels of sea-level rise by 2100 in case IPCC estimates of sea-level rise prove to be too conservative;
- Additional model categories such as "Inland Shore," "Irregularly Flooded (Brackish) Marsh," and "Tidal Swamp."
- *Optional.* In a defined estuary, salt marsh, brackish marsh, and tidal fresh marsh can migrate based on changes in salinity, using a simple though geographically-realistic salt wedge model. This optional model was not used when creating results for Great Bay NWR.

Model results presented in this report were produced using SLAMM version 5.0.1 which was released in early 2008 based on only minor refinements to the original SLAMM 5.0 model. Specifically, the accretion rates for swamps were modified based on additional literature review. For a thorough accounting of SLAMM model processes and the underlying assumptions and equations, please see the SLAMM 5.0.1 technical documentation (Clough and Park, 2008). 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).

Sea-Level Rise Scenarios

The primary set of eustatic (global) sea level rise scenarios used within SLAMM was derived from the work of the Intergovernmental Panel on Climate Change (IPCC 2001). SLAMM 5 was run using the following IPCC and fixed-rate scenarios:

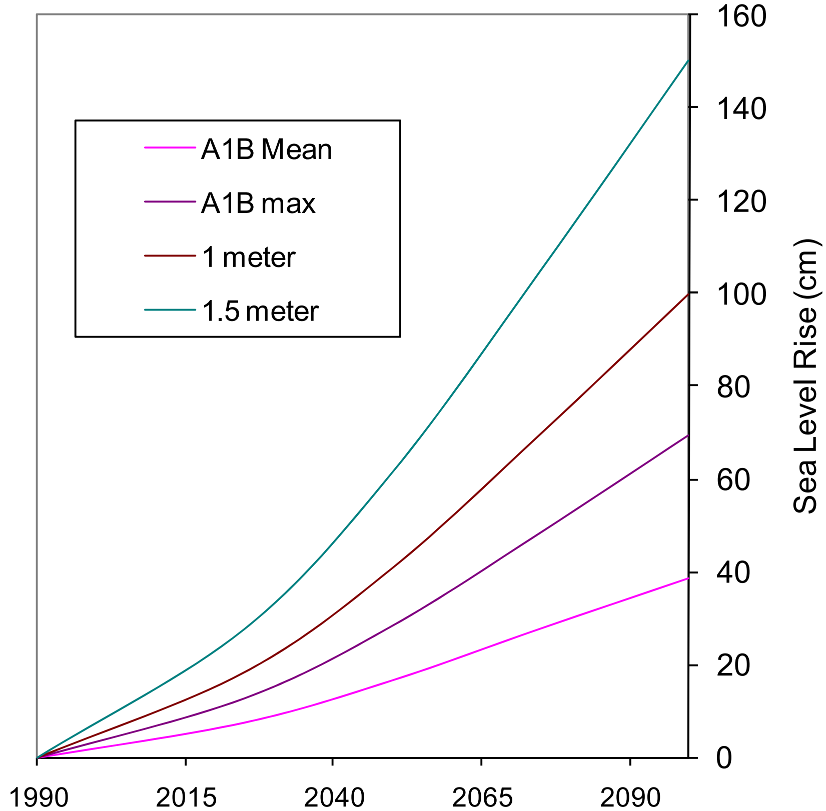
Scenario	Eustatic SLR by 2025 (cm)	Eustatic SLR by 2050 (cm)	Eustatic SLR by 2075 (cm)	Eustatic SLR by 2100 (cm)
A1B Mean	8	17	28	39
A1B Max	14	30	49	69
1 meter	13	28	48	100
1.5 meter	18	41	70	150

Recent 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 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. 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)

To allow for flexibility when interpreting the results, SLAMM was also run assuming 1 meter, 1½ 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

Elevation data used are based on National Elevation Dataset (NED). The NED was derived from a 1956 survey as illustrated within USGS topographic map shown below (Fig. 2). The contour intervals in this map are twenty feet. The elevation of lands between the shoreline and the twenty foot contour is subject to considerable uncertainty. Because of this, wetlands elevations were estimated as a function of tidal range.

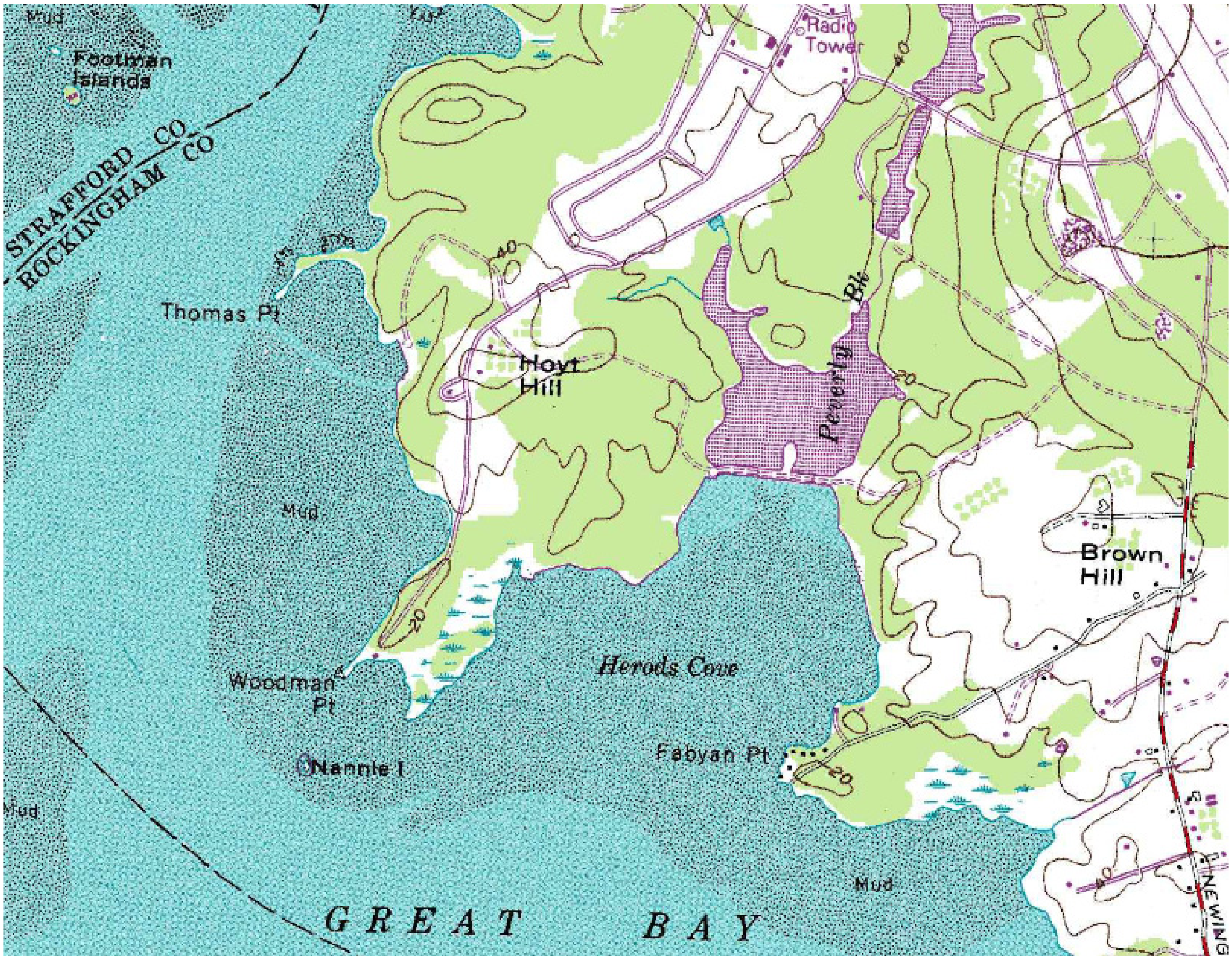


Figure 2: Great Bay Excerpt from USGS Map.

The National Wetlands Inventory for Great Bay is based on a photo date of 2004. An examination of the NWI map overlaid on recent satellite photos indicates no changes since the inventory was taken.

Converting the NWI survey into 30 meter cells indicates that the approximately one thousand acre refuge (approved acquisition boundary including water) is primarily composed of the categories as shown below:

Dry Land	87.6%
Inland Open Water	6.6%
Brackish Marsh	2.6%
Swamp	1.0%
Inland Fresh Marsh	0.8%

Based on the NWI coverage, there are a few diked and impounded wetlands within the Great Bay NWR (Fig. 3). The most prominent diked region within the refuge is an area of inland open water. Areas demarcated as protected by dikes were, however, assumed to be protected in this modeling analysis.

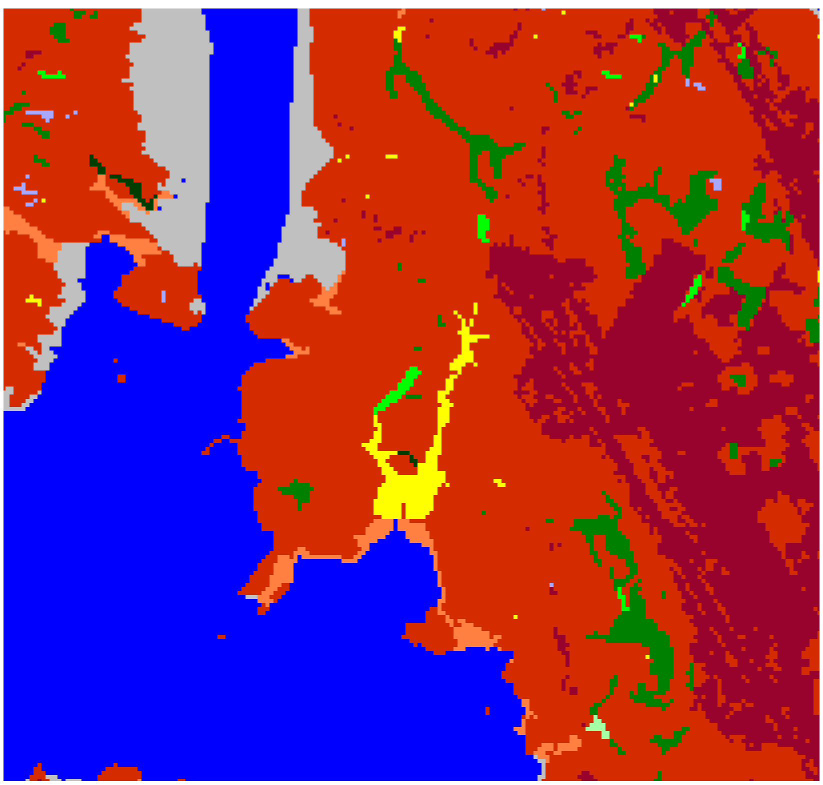


Figure 3: Diked Areas Marked in Yellow

The historic trend for sea level rise was estimated at 1.76 mm/year using the closest station (8419870, Seavey Island, ME). This measured rate is similar to the global average for the last 100 years (approximately 1.5-2.0 mm/year). Any effects of isostatic rebound that have affected this region for the last 100 years have been measured within that historic trend and the same rate of isostatic rebound is projected forward into the next 100 years.

The tide range used for this site was estimated at 2.5 meters, and was estimated using the closest NOAA oceanic gage (8419870, Seavey Island, ME).

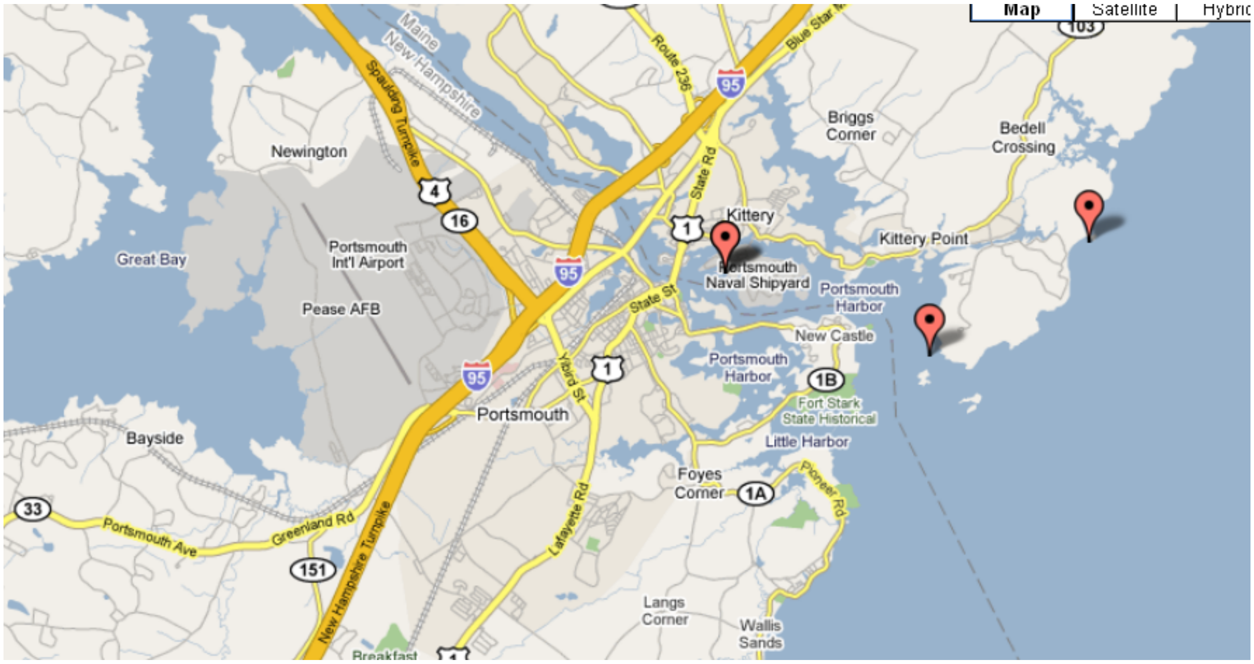


Figure 4: NOAA Gages Relevant to the Study Area.

Accretion rates in salt and brackish marshes were set to 2.58 mm/year, and the rates in tidal fresh marshes to 5.9 mm/year. The values for salt and brackish marshes are from a seventeen year study measuring accretion rates of Maine salt marshes (J.E. Goodman et al., 2006). No site-specific accretion studies were found as part of this research.

Modeled U.S. Fish and Wildlife Service refuge boundaries are based on Approved Acquisition Boundaries as published on the FWS "National Wildlife Refuge Data and Metadata" website. The modeling team contacted Refuge Manager Graham Taylor to ensure model parameters were consistent with local knowledge.

The cell-size used for this analysis was 30 meter by 30 meter cells. However, the SLAMM model does track partial conversion of cells based on elevation and slope.

SUMMARY OF SLAMM INPUT PARAMETERS FOR GREAT BAY

Description	Great Bay
DEM Source Date (yyyy)	1956
NWI_photo_date (yyyy)	2004
Direction_OffShore (N|S|E|W)	W
Historic_trend (mm/yr)	1.76
NAVD88_correction (MTL-NAVD88 in meters)	-0.063
Water Depth (m below MLW- N/A)	2
TideRangeOcean (meters: MHHW-MLLW)	2.5
TideRangeInland (meters)	2.5
Mean High Water Spring (m above MTL)	1.663
MHSW Inland (m above MTL)	1.663
Marsh Erosion (horz meters/year)	1.8
Swamp Erosion (horz meters/year)	1
TFlat Erosion (horz meters/year) [from 0.5]	0.5
Salt marsh vertical accretion (mm/yr) Final	2.58
Brackish March vert. accretion (mm/yr) Final	2.58
Tidal Fresh vertical accretion (mm/yr) Final	5.9
Beach/T.Flat Sedimentation Rate (mm/yr)	0.5
Frequency of Large Storms (yr/washover)	50
Use Elevation Preprocessor for Wetlands	TRUE

Results

Great Bay National Wildlife Refuge is predicted to be resilient to the effects of sea level rise. Dry land, which comprises the great majority of this NWR, is predicted to lose a very small amount even in the most extreme scenario. (The majority of dry land at this site is located above the 20 foot USGS contour.) Brackish marsh, although it comprises a relatively small amount of the refuge, is expected to succumb to the effects of sea level rise.

SLR by 2100 (m)	0.39	0.69	1	1.5
Dry Land	3%	4%	4%	5%
Brackish Marsh	21%	59%	83%	98%
Tidal Swamp	5%	12%	18%	20%

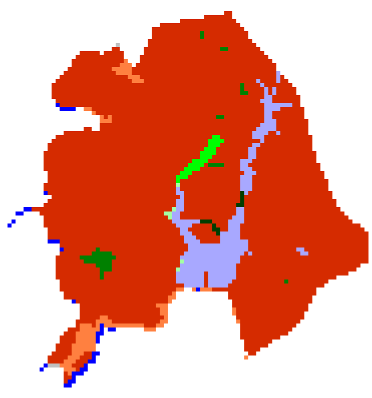
Predicted Loss Rates of Land Categories by 2100 Given Simulated Scenarios of Eustatic Sea Level Rise

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

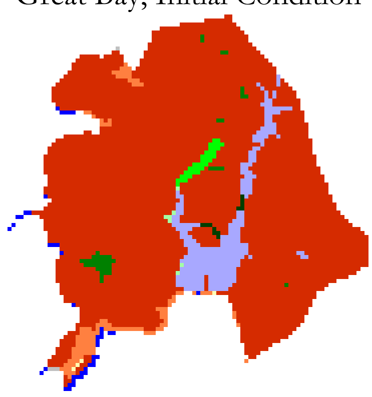
Great Bay
IPCC Scenario A1B-Mean, 0.39 M SLR Eustatic by 2100

Results in Acres

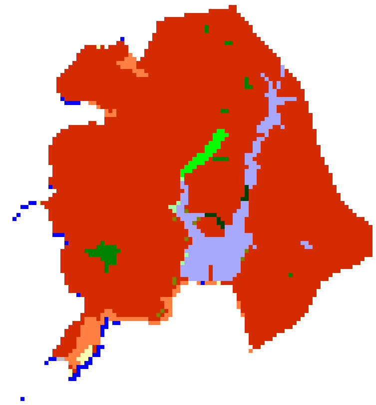
	Initial	2025	2050	2075	2100
Dry Land	923.8	921.8	916.2	907.9	900.5
Inland Open Water	69.2	69.2	69.2	69.2	69.2
Brackish Marsh	27.6	27.6	26.4	23.8	21.8
Swamp	10.2	10.2	10.2	10.2	10.2
Estuarine Open Water	10.0	10.2	10.4	10.5	10.6
Inland Fresh Marsh	8.5	8.5	8.5	8.5	8.5
Tidal Swamp	2.7	2.7	2.6	2.6	2.5
Tidal Fresh Marsh	1.6	1.6	1.6	1.6	1.6
Tidal Flat	0.9	0.7	0.5	0.4	0.3
Trans. Salt Marsh	0.0	1.1	4.0	8.9	13.6
Estuarine Beach	0.0	0.9	3.6	7.0	9.8
Saltmarsh	0.0	0.0	1.2	3.9	5.9
Total (incl. water)	**1054.4**	**1054.4**	**1054.4**	**1054.4**	**1054.4**



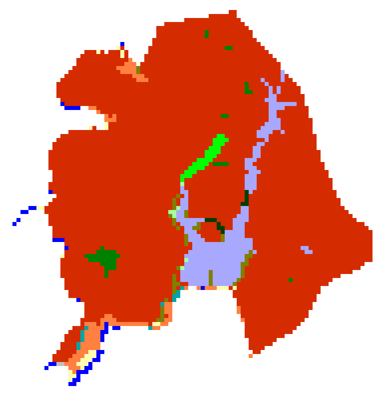
Great Bay, Initial Condition



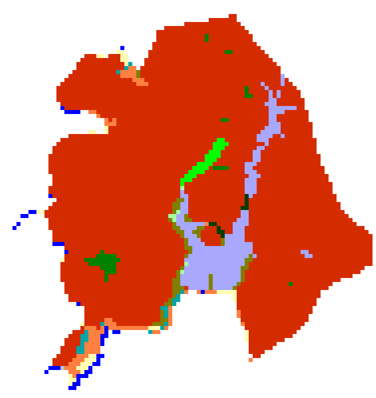
Great Bay, 2025, Scenario A1B Mean



Great Bay, 2050, Scenario A1B Mean



Great Bay, 2075, Scenario A1B Mean

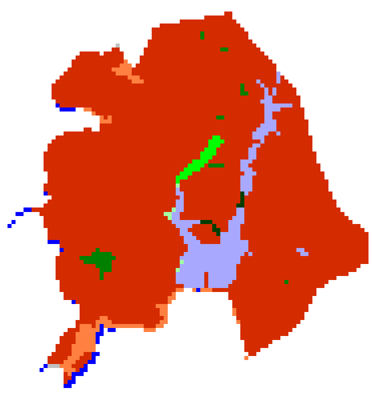


Great Bay, 2100, Scenario A1B Mean

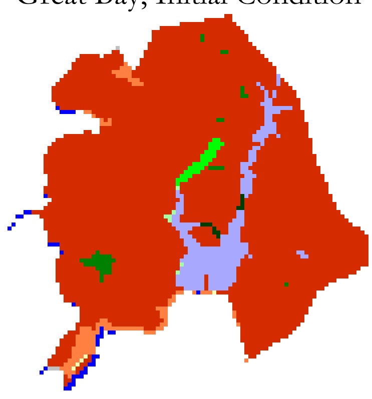
Great Bay
IPCC Scenario A1B-Max, 0.69 M SLR Eustatic by 2100

Results in Acres

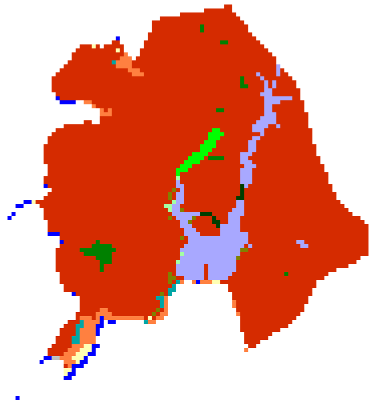
	Initial	2025	2050	2075	2100
Dry Land	923.8	920.1	909.6	896.8	890.9
Inland Open Water	69.2	69.2	69.2	69.2	69.2
Brackish Marsh	27.6	26.5	22.0	16.6	11.3
Swamp	10.2	10.2	10.2	10.2	10.2
Estuarine Open Water	10.0	10.2	10.4	10.5	10.6
Inland Fresh Marsh	8.5	8.5	8.5	8.5	8.5
Tidal Swamp	2.7	2.6	2.6	2.5	2.3
Tidal Fresh Marsh	1.6	1.6	1.6	1.6	1.6
Tidal Flat	0.9	0.7	0.5	0.3	0.3
Trans. Salt Marsh	0.0	1.9	7.9	15.9	17.2
Estuarine Beach	0.0	1.8	6.3	11.1	14.1
Saltmarsh	0.0	1.1	5.7	11.1	18.3
Total (incl. water)	**1054.4**	**1054.4**	**1054.4**	**1054.4**	**1054.4**



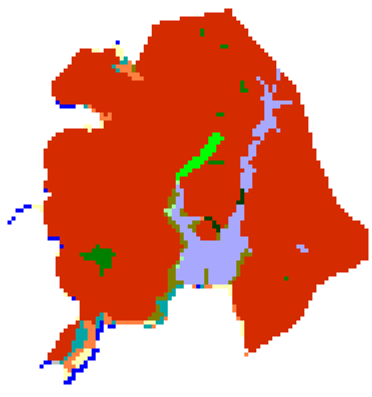
Great Bay, Initial Condition



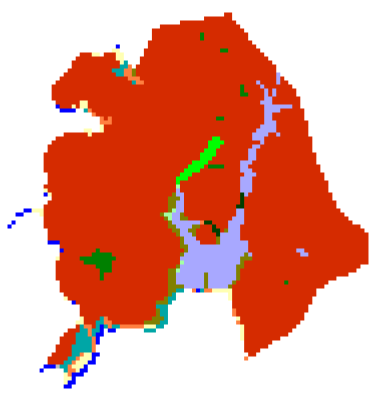
Great Bay, 2025, Scenario A1B Maximum



Great Bay, 2050, Scenario A1B Maximum



Great Bay, 2075, Scenario A1B Maximum

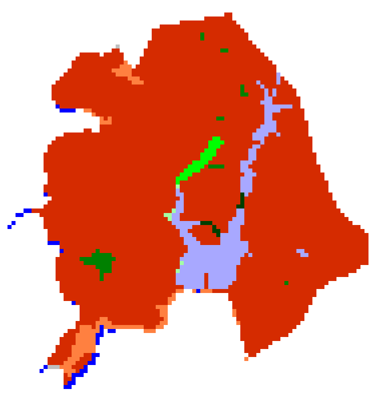


Great Bay, 2100, Scenario A1B Maximum

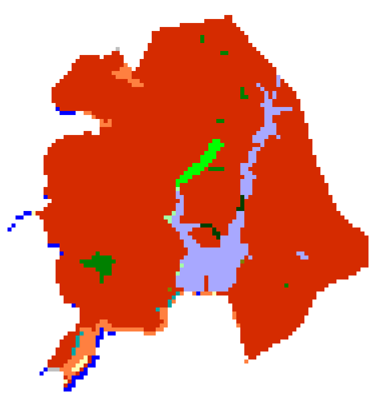
Great Bay
1 Meter Eustatic SLR by 2100

Results in Acres

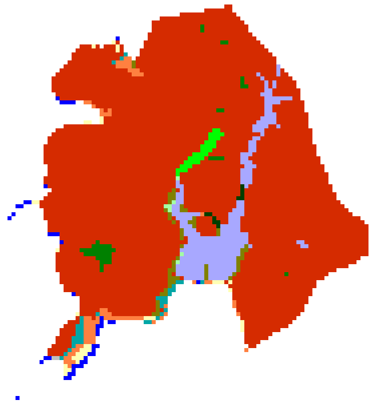
	Initial	2025	2050	2075	2100
Dry Land	923.8	918.2	902.5	891.3	886.7
Inland Open Water	69.2	69.2	69.2	69.2	69.2
Brackish Marsh	27.6	24.9	18.2	9.8	4.7
Swamp	10.2	10.2	10.2	10.2	10.2
Estuarine Open Water	10.0	10.2	10.4	10.5	12.8
Inland Fresh Marsh	8.5	8.5	8.5	8.5	8.5
Tidal Swamp	2.7	2.6	2.5	2.3	2.2
Tidal Fresh Marsh	1.6	1.6	1.6	1.6	1.6
Tidal Flat	0.9	0.7	0.5	0.3	1.8
Trans. Salt Marsh	0.0	2.9	12.2	15.8	6.7
Estuarine Beach	0.0	2.8	9.1	13.9	16.4
Saltmarsh	0.0	2.7	9.5	21.0	33.7
Total (incl. water)	**1054.4**	**1054.4**	**1054.4**	**1054.4**	**1054.4**



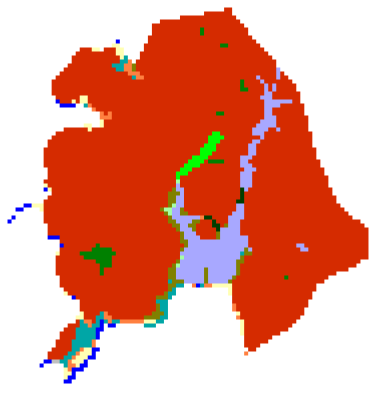
Great Bay, Initial Condition



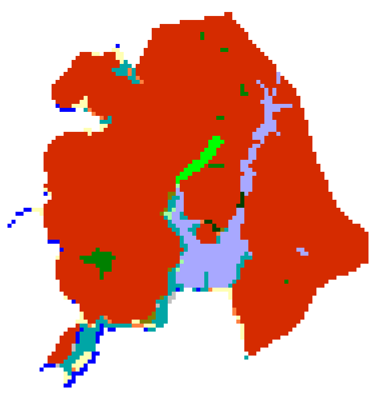
Great Bay, 2025, 1 meter



Great Bay, 2050, 1 meter



Great Bay, 2075, 1 meter

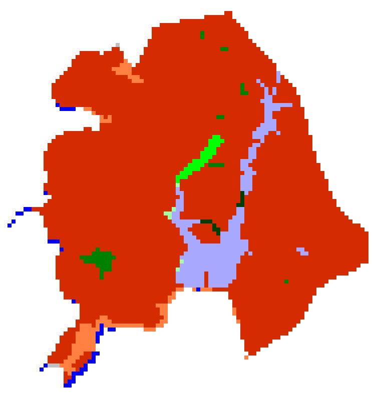


Great Bay, 2100, 1 meter

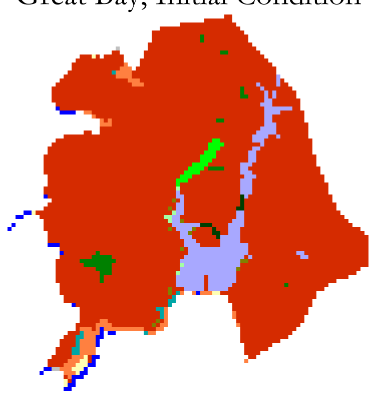
Great Bay
1.5 Meters Eustatic SLR by 2100

Results in Acres

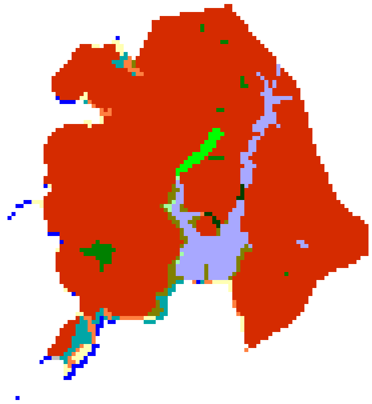
	Initial	2025	2050	2075	2100
Dry Land	923.8	914.8	893.9	886.7	879.1
Inland Open Water	69.2	69.2	69.2	69.2	69.2
Brackish Marsh	27.6	22.3	12.1	3.7	0.5
Swamp	10.2	10.2	10.2	10.2	10.2
Estuarine Open Water	10.0	10.2	10.4	13.2	16.7
Inland Fresh Marsh	8.5	8.5	8.5	8.5	8.5
Tidal Swamp	2.7	2.6	2.4	2.2	2.1
Tidal Fresh Marsh	1.6	1.6	1.6	1.6	1.6
Tidal Flat	0.9	0.7	0.5	4.1	14.7
Trans. Salt Marsh	0.0	4.9	16.8	5.0	3.6
Estuarine Beach	0.0	4.2	12.4	16.4	20.7
Saltmarsh	0.0	5.3	16.5	33.7	27.6
Total (incl. water)	**1054.4**	**1054.4**	**1054.4**	**1054.4**	**1054.4**



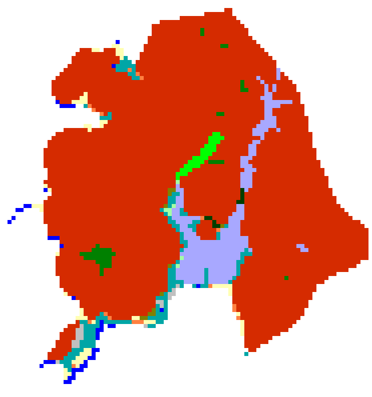
Great Bay, Initial Condition



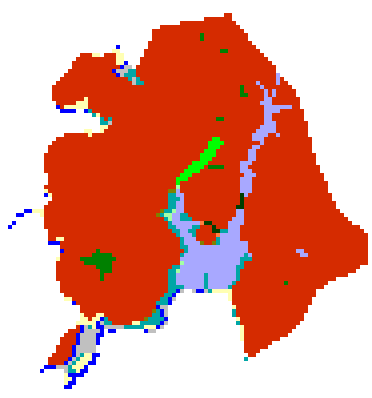
Great Bay, 2025, 1.5 meter



Great Bay, 2050, 1.5 meter



Great Bay, 2075, 1.5 meter



Great Bay, 2100, 1.5 meter

Discussion:

Model results for Great Bay indicate that dry land will be fairly resilient to the effects of sea level rise. Loss of dry land is predicted to be minimal. Loss of dry land between the shoreline and the twenty foot contour (figure 2) is subject to considerable uncertainty, however.

Alternatively, loss of irregularly flooded marsh (brackish marsh) is predicted to be severe. In moderate scenarios, frequency of inundation of these marshes is predicted to increase, converting the marsh to regularly flooded marsh (saltmarsh). Flooding in the higher scenarios is predicted to convert most of the irregularly flooded marsh into tidal flats and open water.

Accretion rates for marshes at this location were derived from regional measurements, and were assumed to remain constant over time in this simulation, which is an additional source of model uncertainty. Another source of model uncertainty stems from the lack of high resolution LiDAR data, in addition to the fact that the DEM used in this model is over 50 years old. A future study of the area would benefit from such data.

The SLAMM model accounts for the local effects of isostatic rebound by taking into account the historical sea level rise for each site. The historical rate of land movement is predicted to continue through the year 2100 (i.e. the rate of isostatic rebound is assumed to remain constant).

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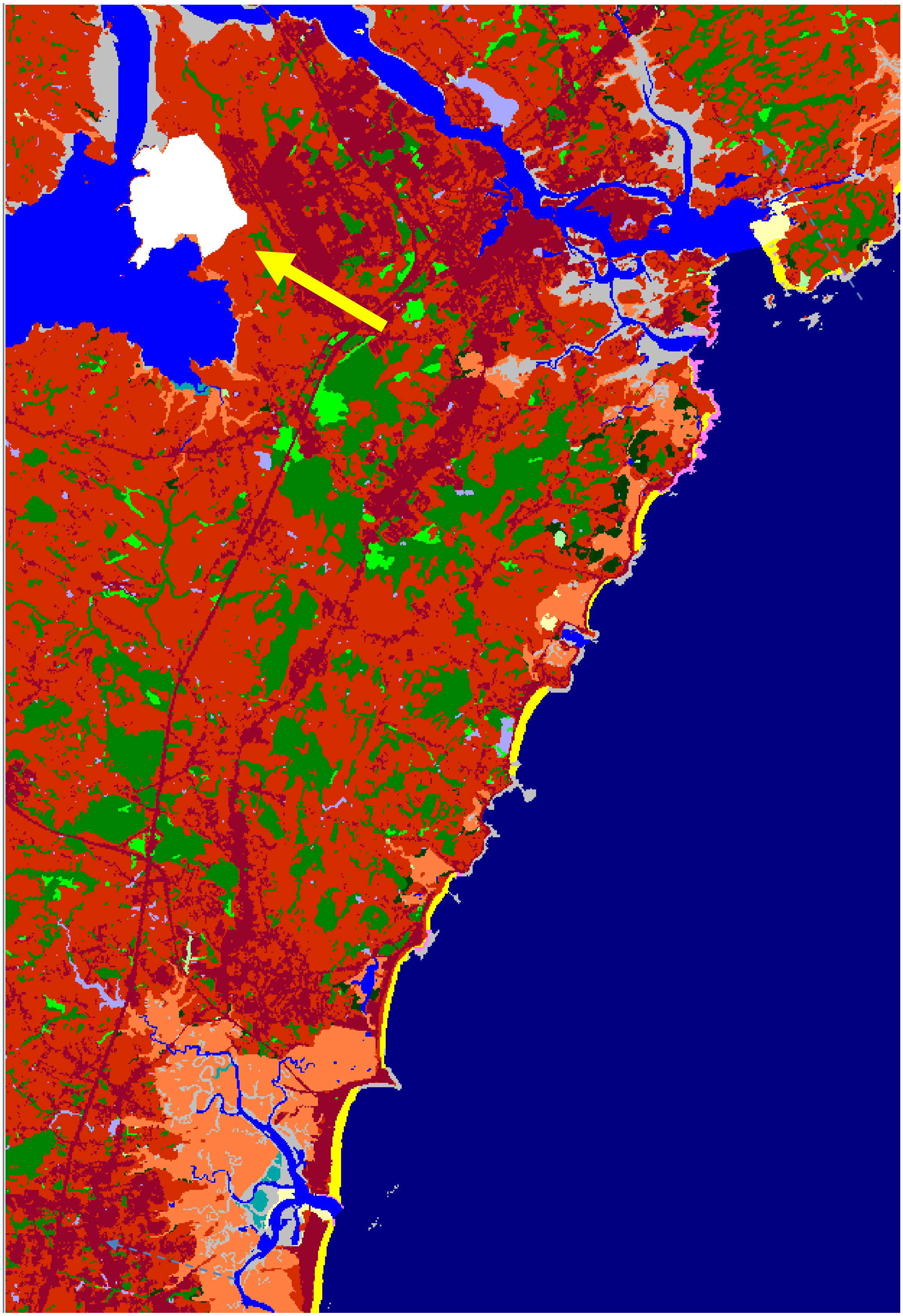
Appendix A: Contextual Results

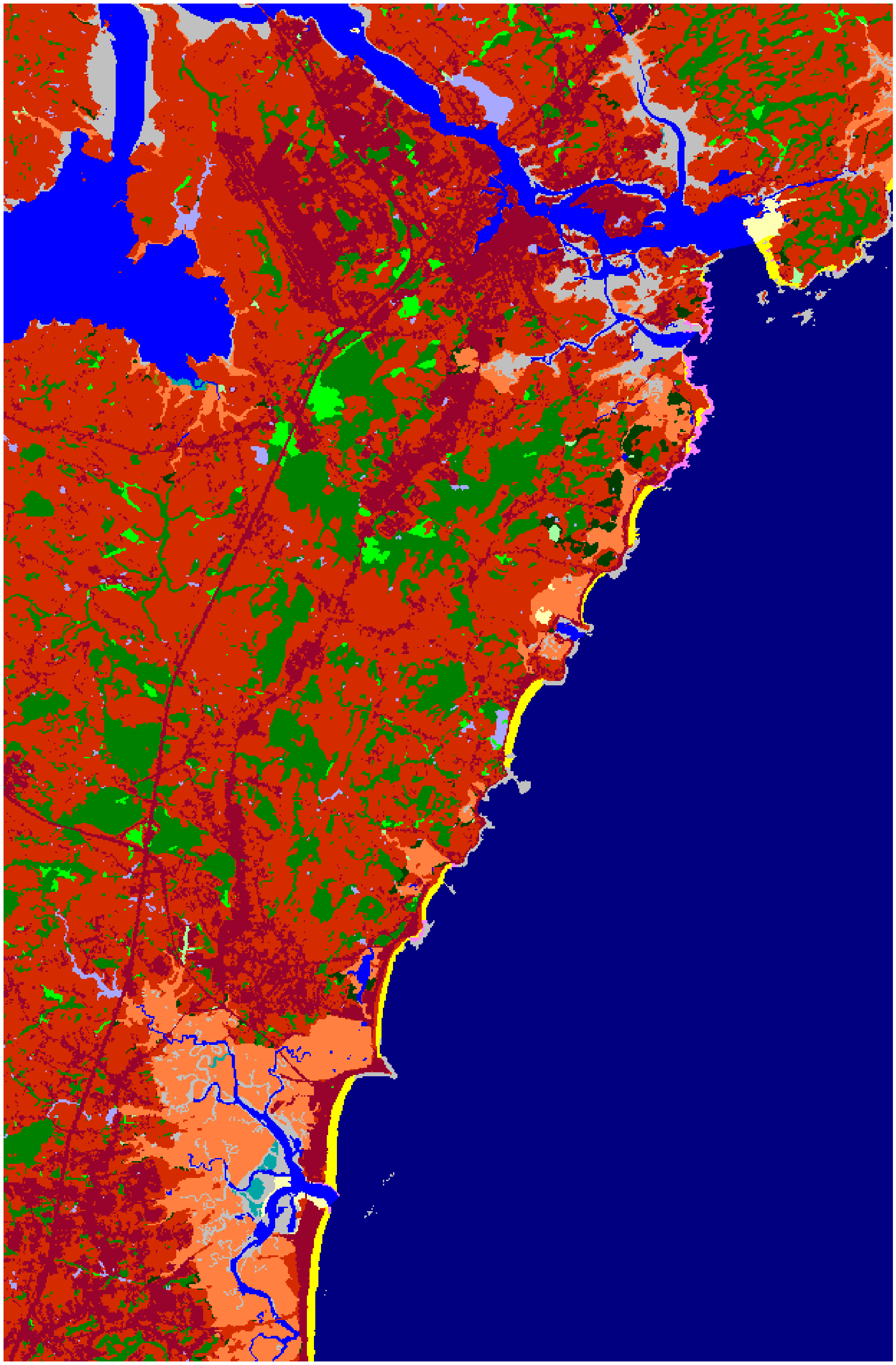
The SLAMM model does take into account the context of the surrounding lands or open water when calculating effects. For example, erosion rates are calculated based on the maximum fetch (wave action) which is estimated by assessing contiguous open water to a given marsh cell. Another example is that inundated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

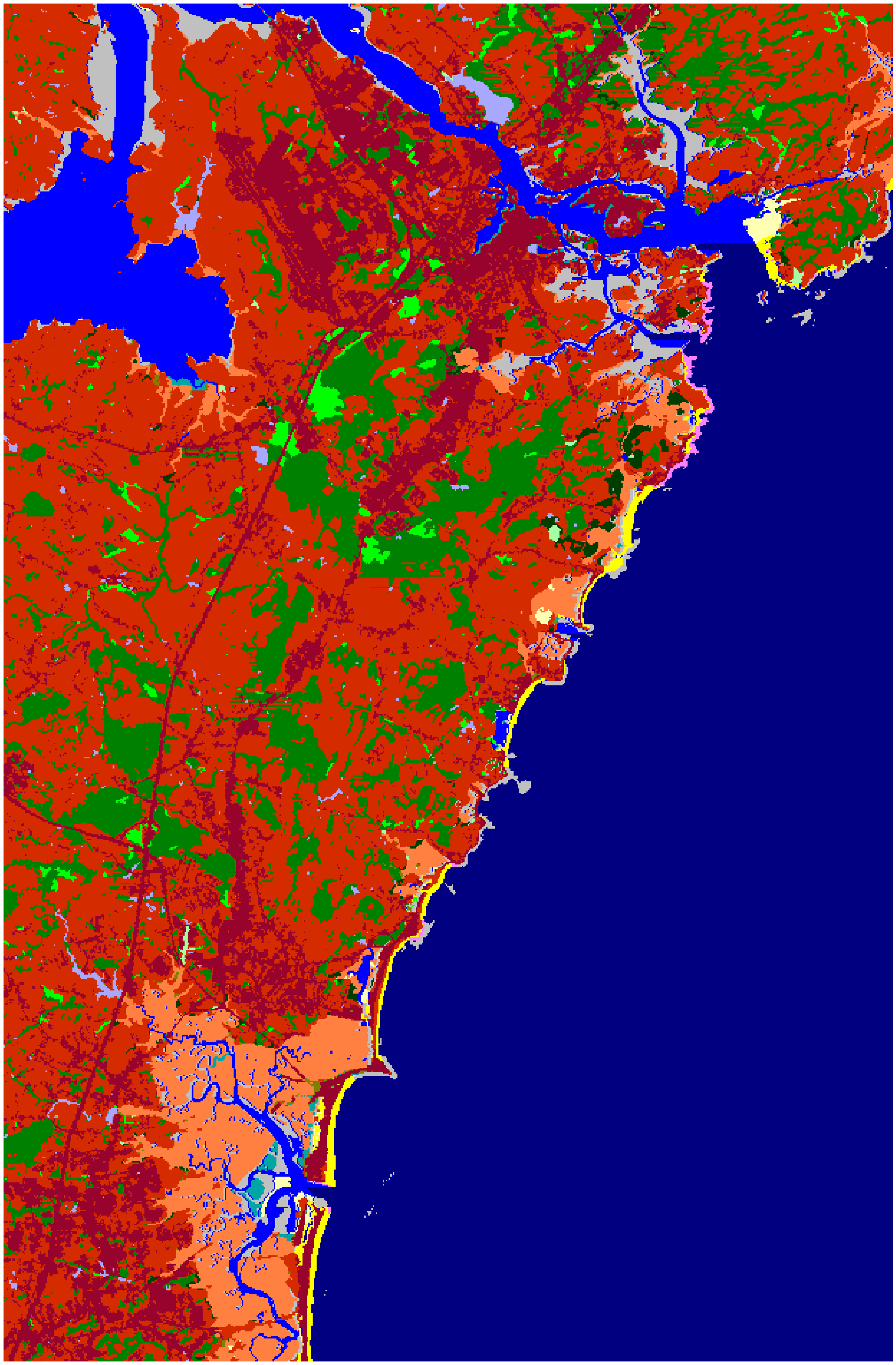
- Results were closely examined (quality assurance) within USFWS refuges but not closely examined for the larger region.
- Site-specific parameters for the model were derived for USFWS refuges whenever possible and may not be regionally applicable.
- Especially in areas where dikes are present, an effort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



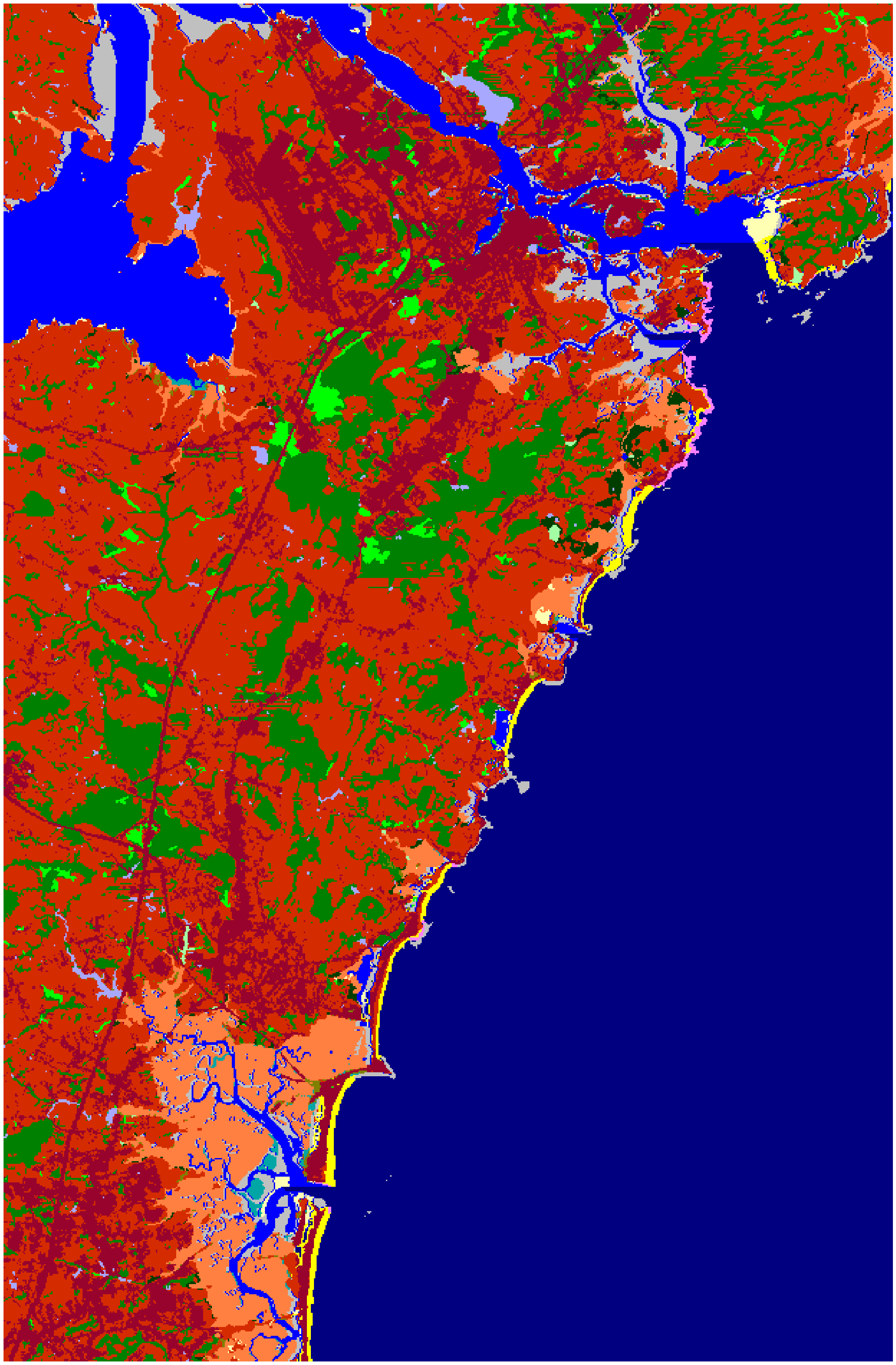
Location of Great Bay National Wildlife Refuge (white) within simulation context



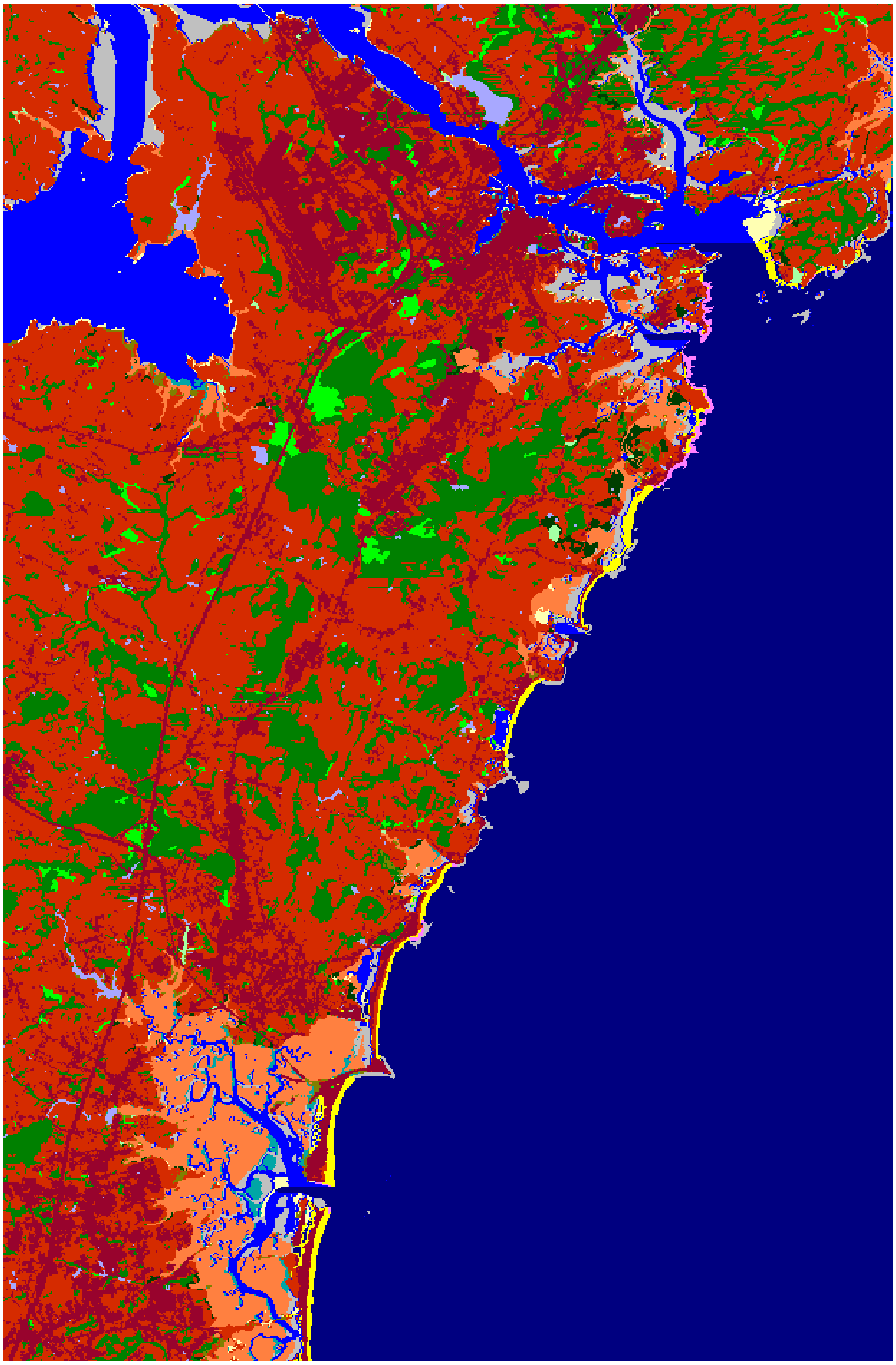
Great Bay Context, Initial Condition



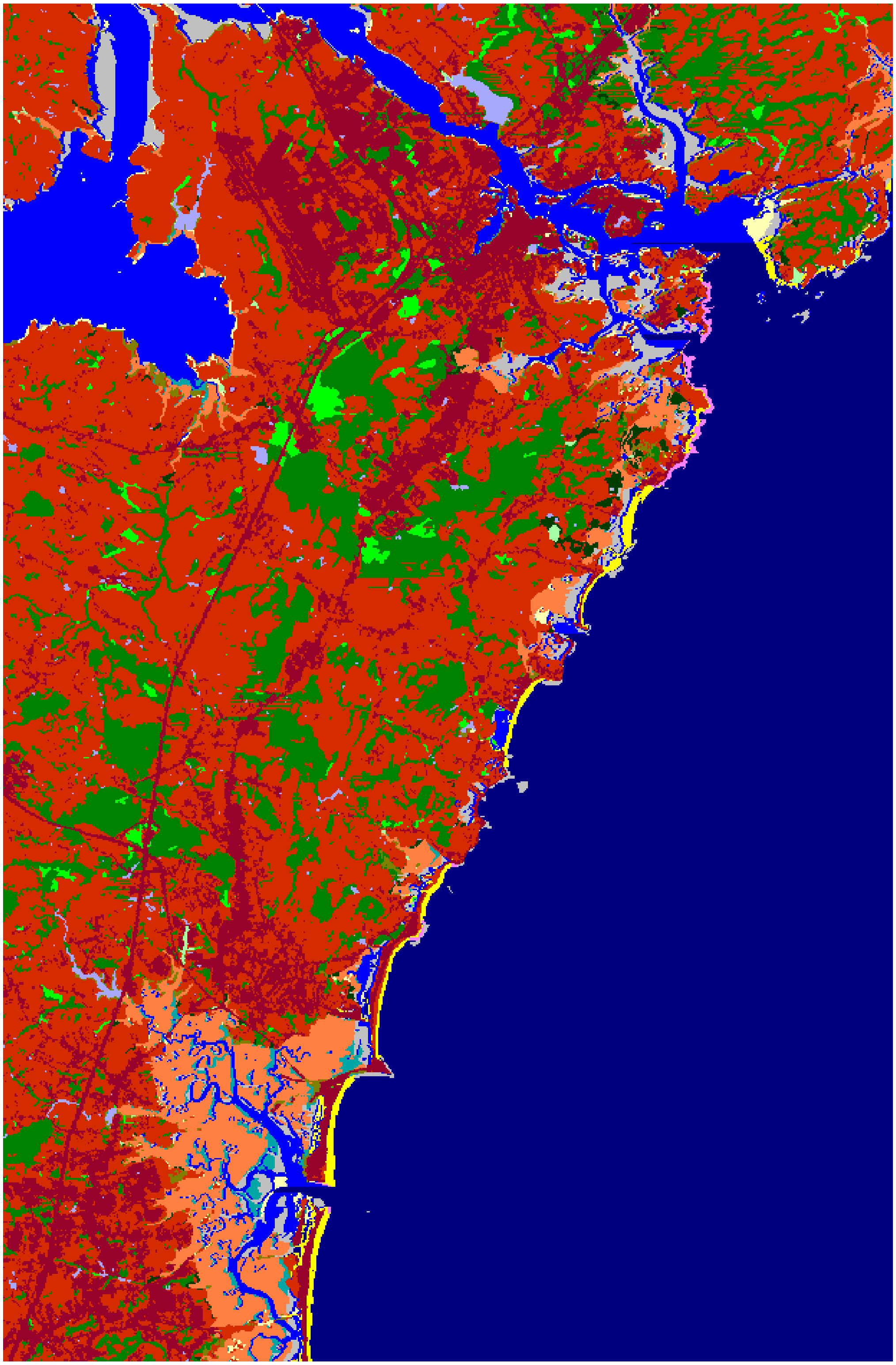
Great Bay Context, 2025, Scenario A1B Mean



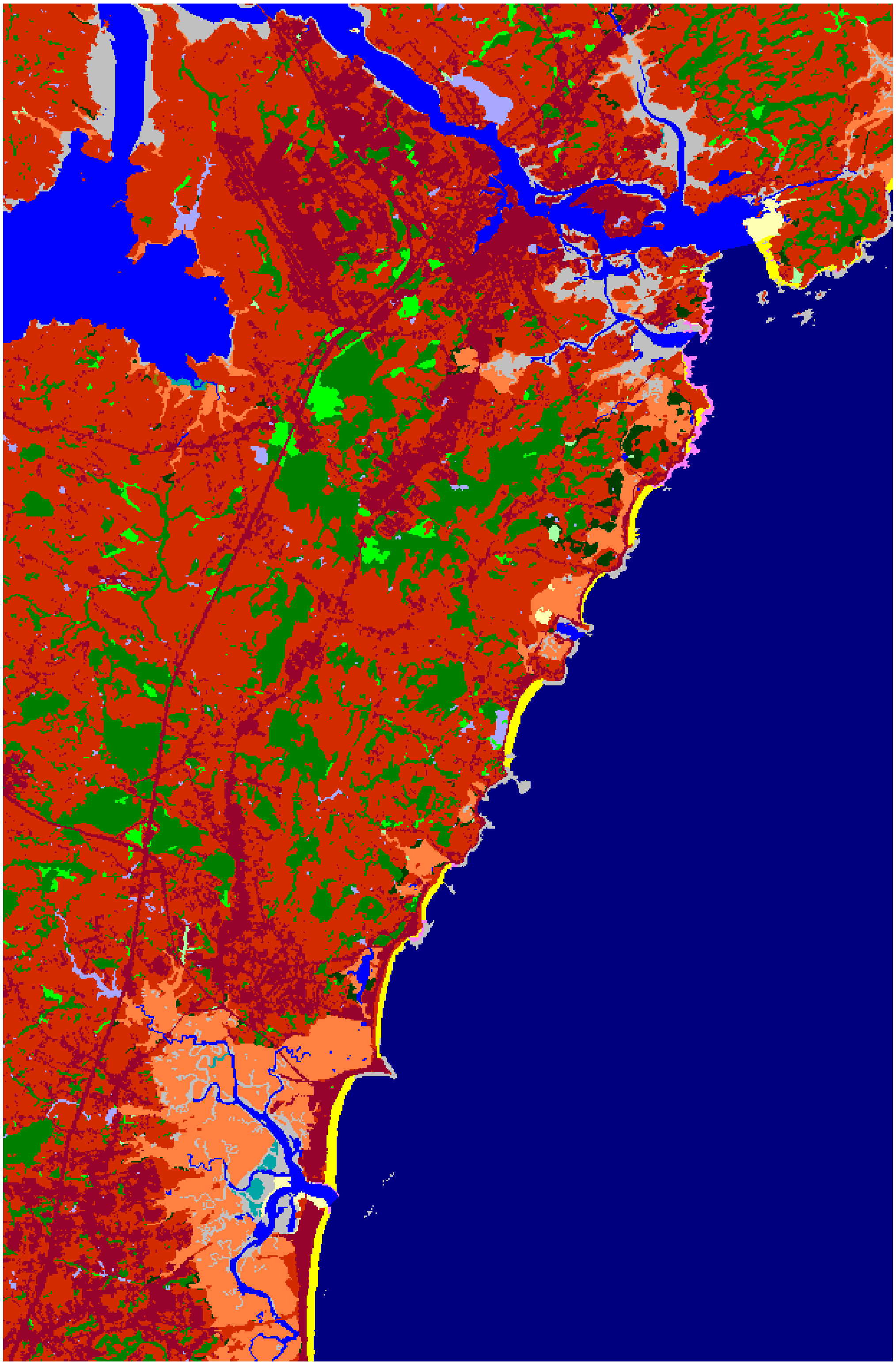
Great Bay Context, 2050, Scenario A1B Mean



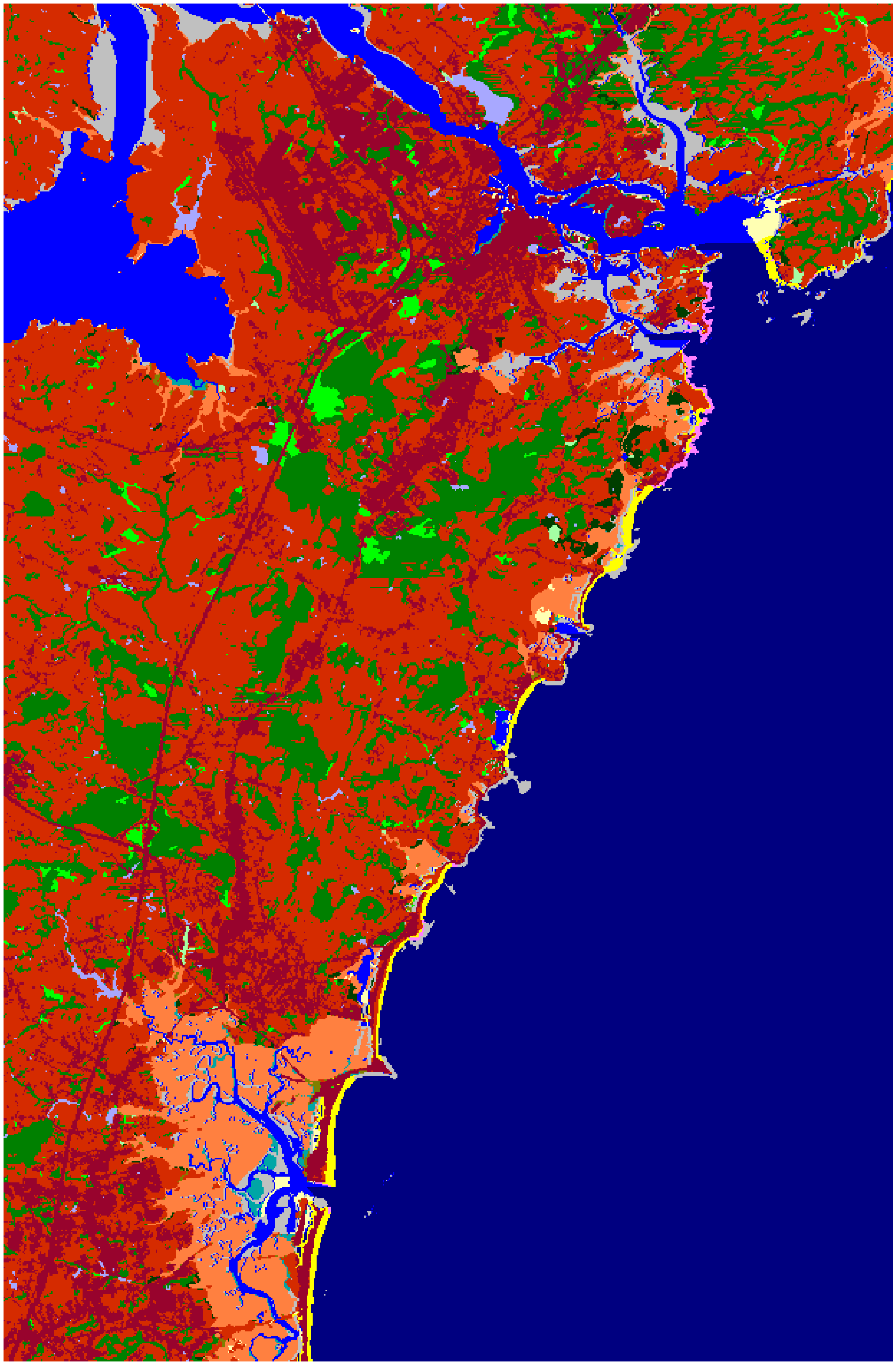
Great Bay Context, 2075, Scenario A1B Mean



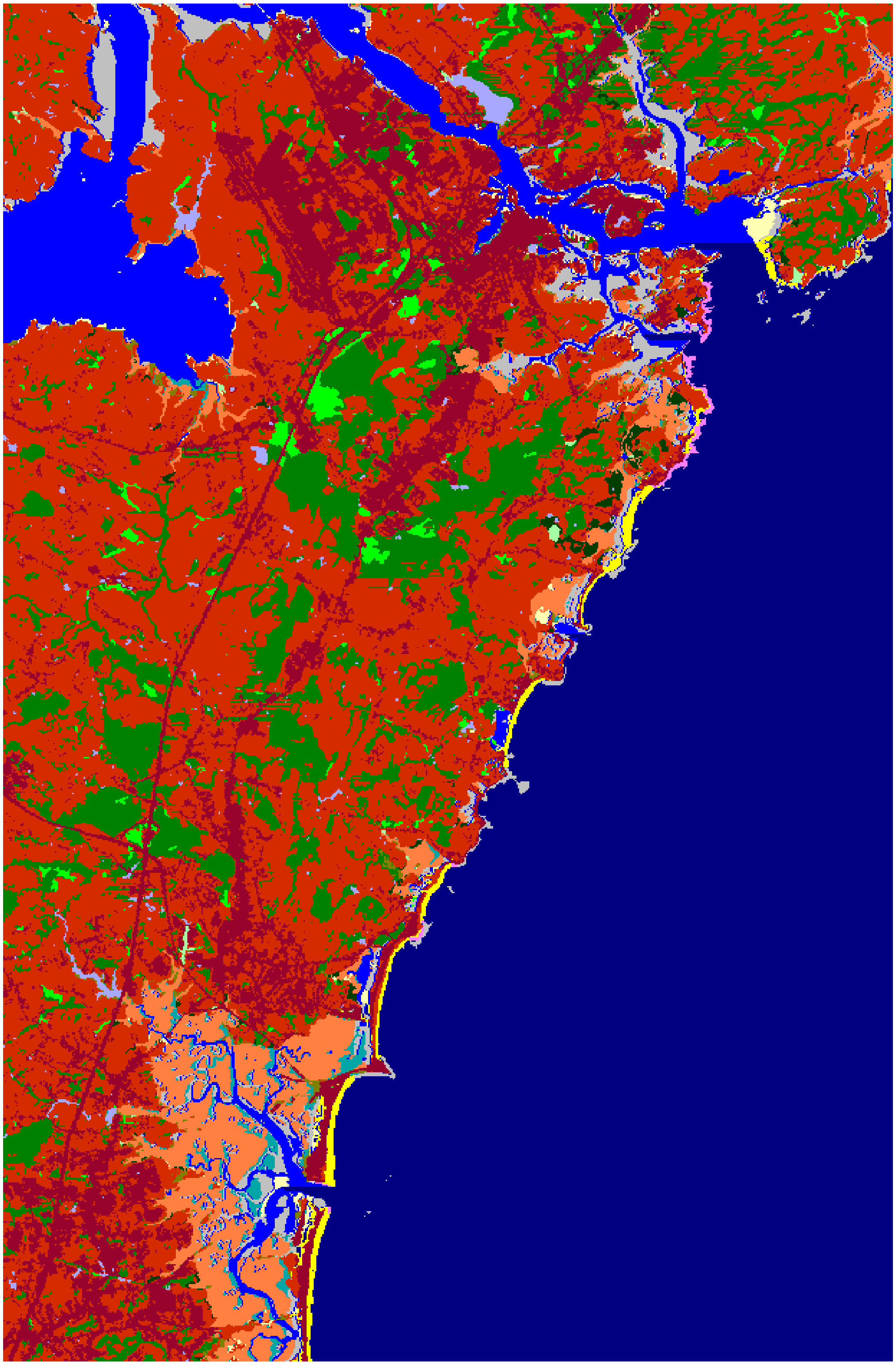
Great Bay Context, 2100, Scenario A1B Mean



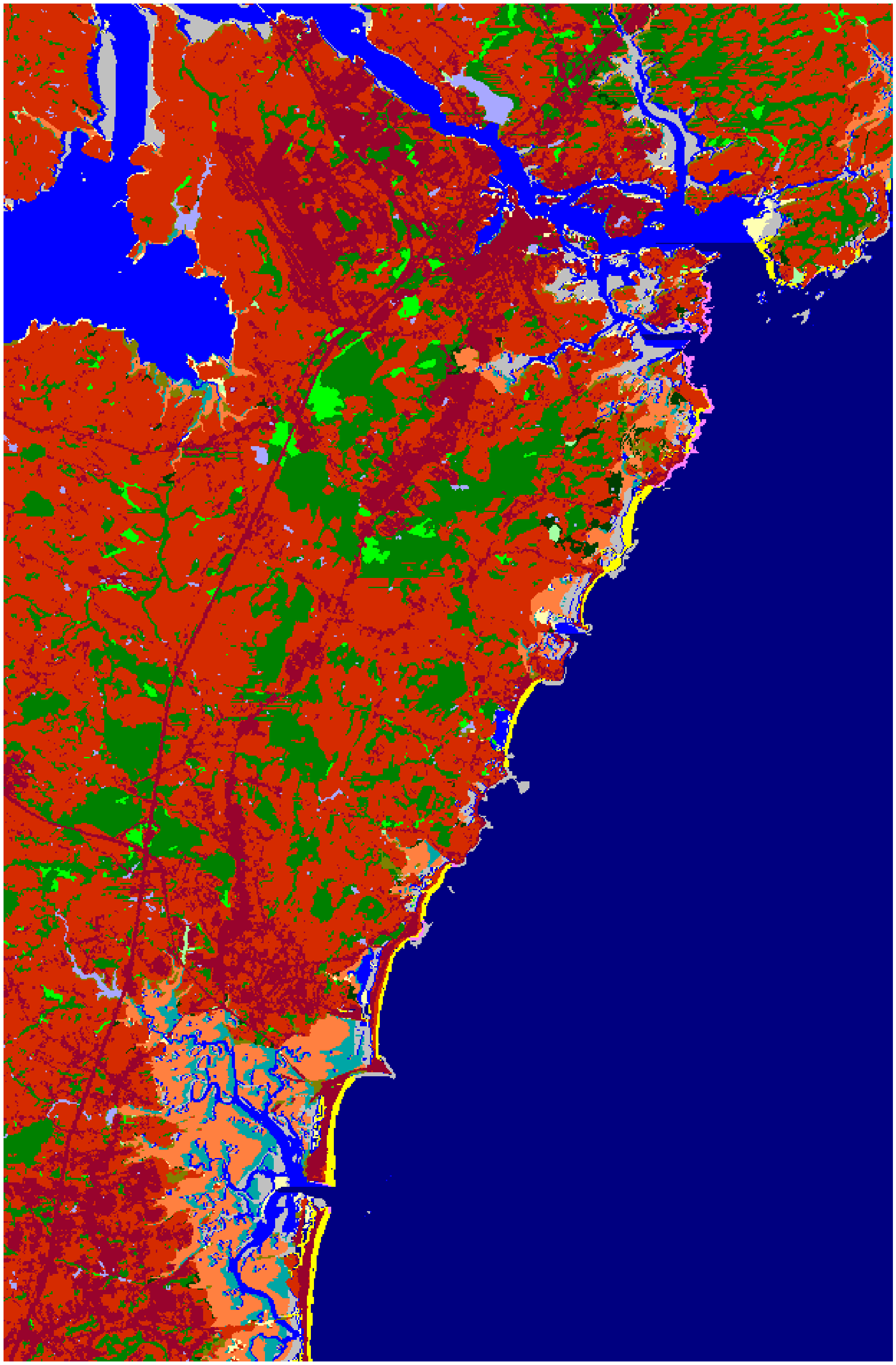
Great Bay Context, Initial Condition



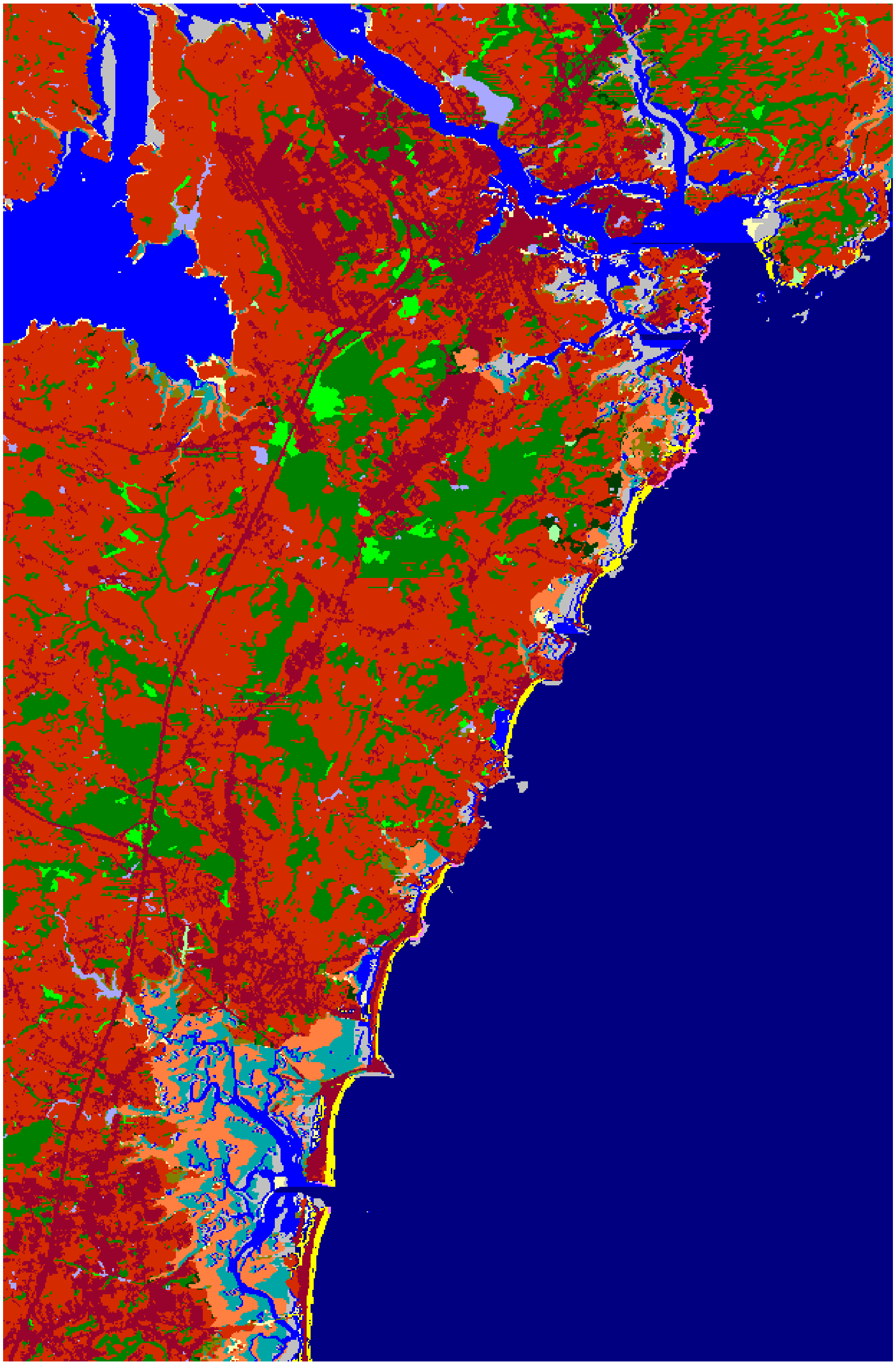
Great Bay Context, 2025, Scenario A1B Maximum



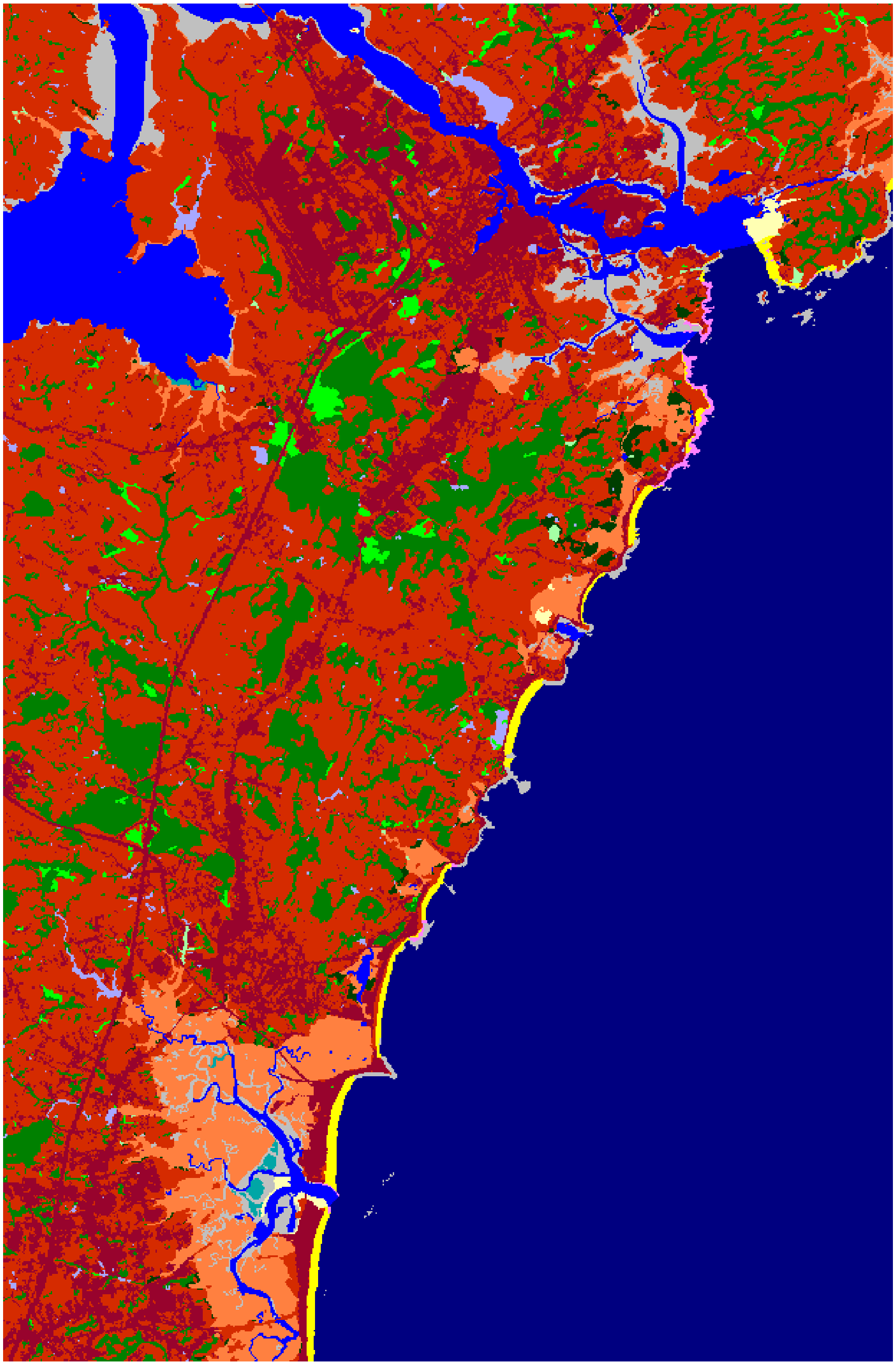
Great Bay Context, 2050, Scenario A1B Maximum



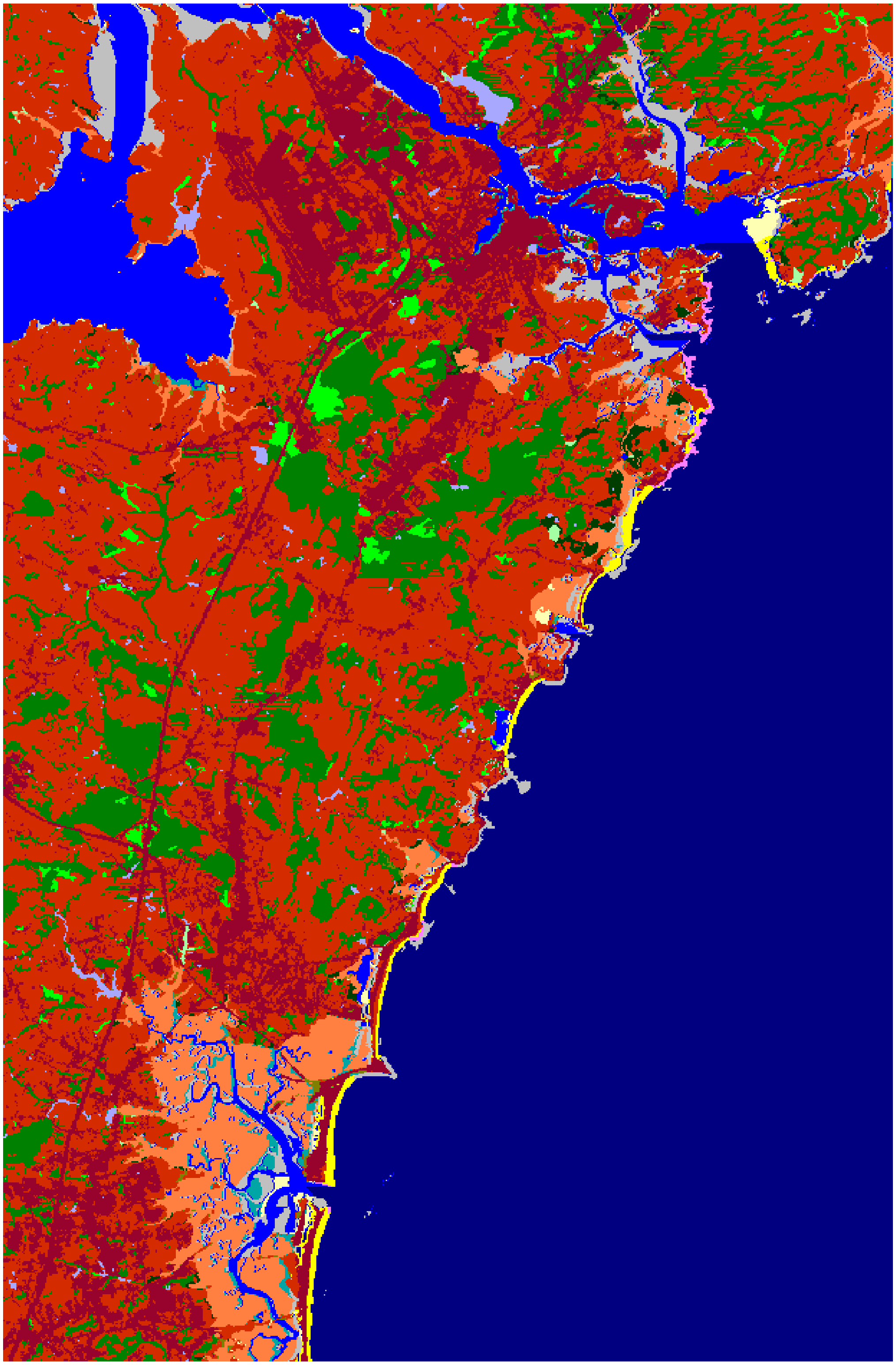
Great Bay Context, 2075, Scenario A1B Maximum



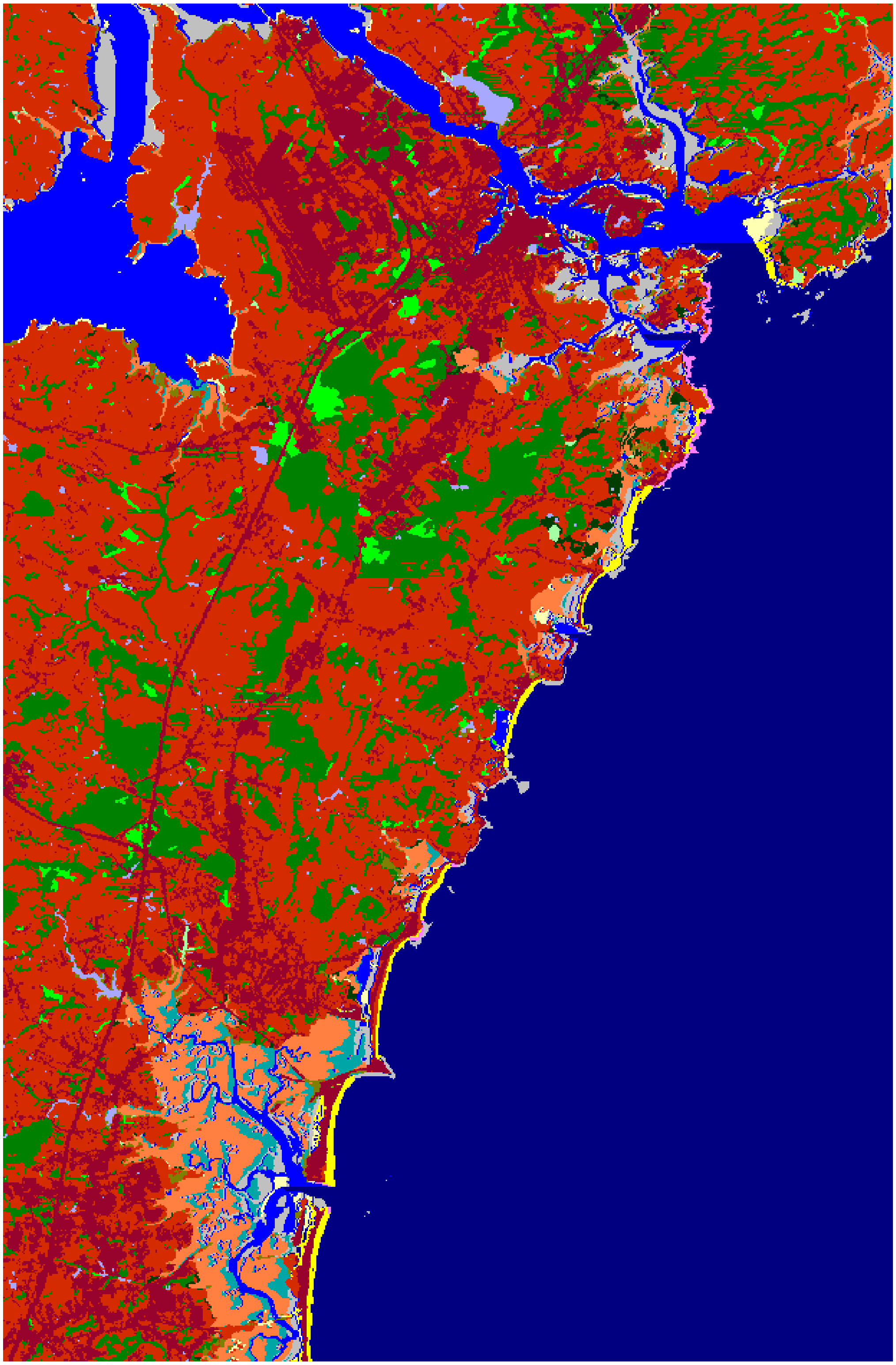
Great Bay Context, 2100, Scenario A1B Maximum



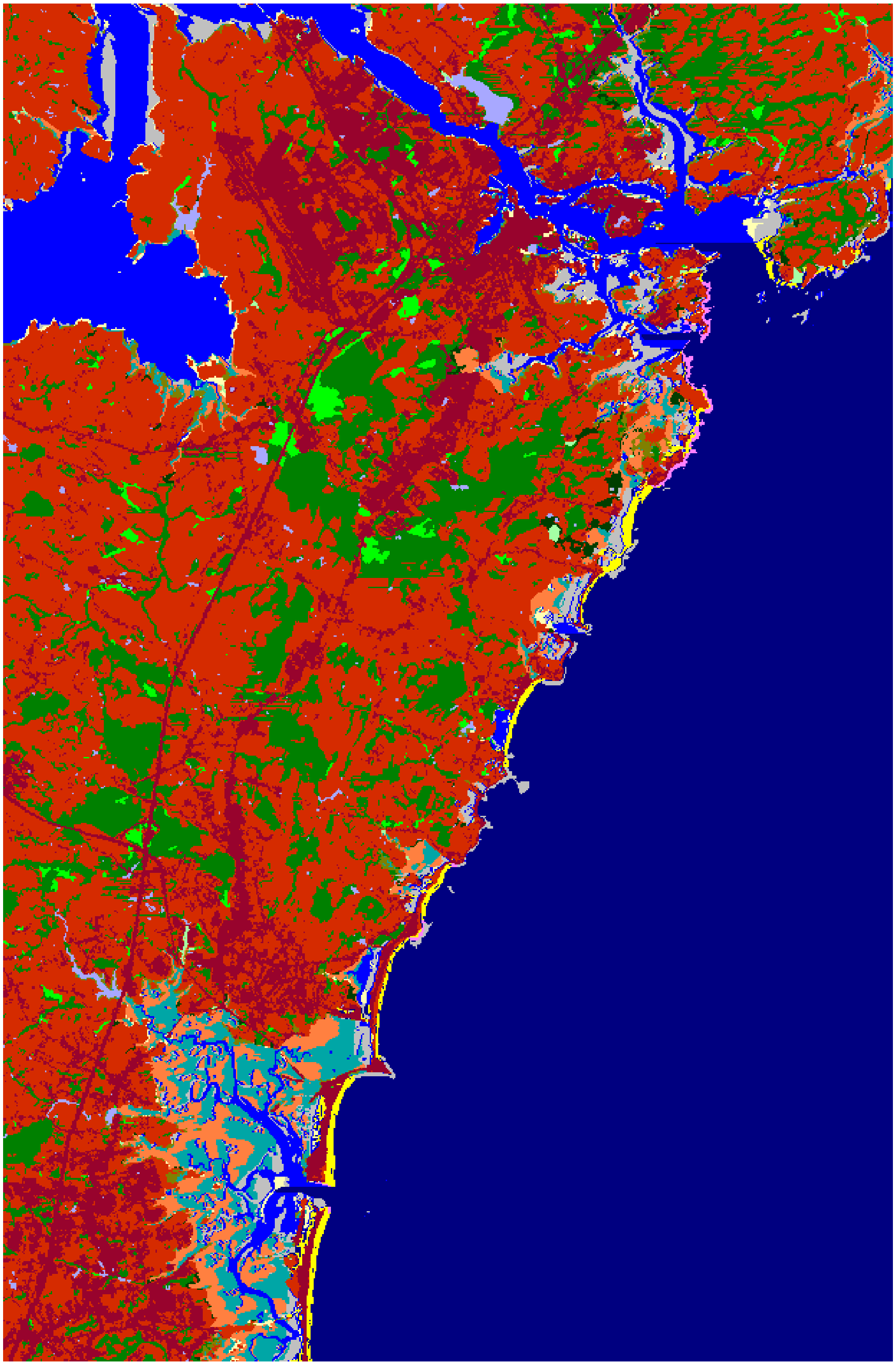
Great Bay Context, Initial Condition



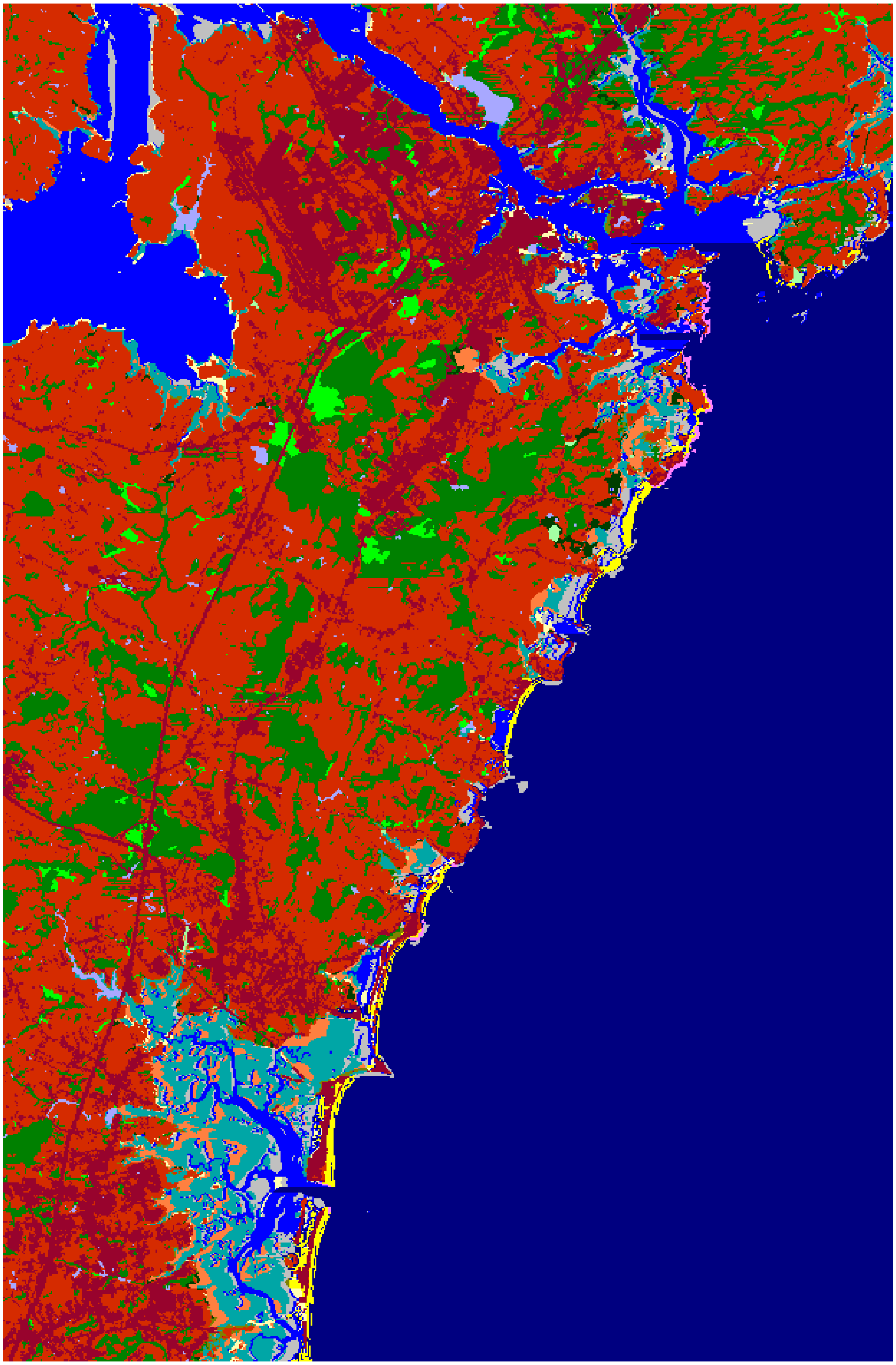
Great Bay Context, 2025, 1 meter



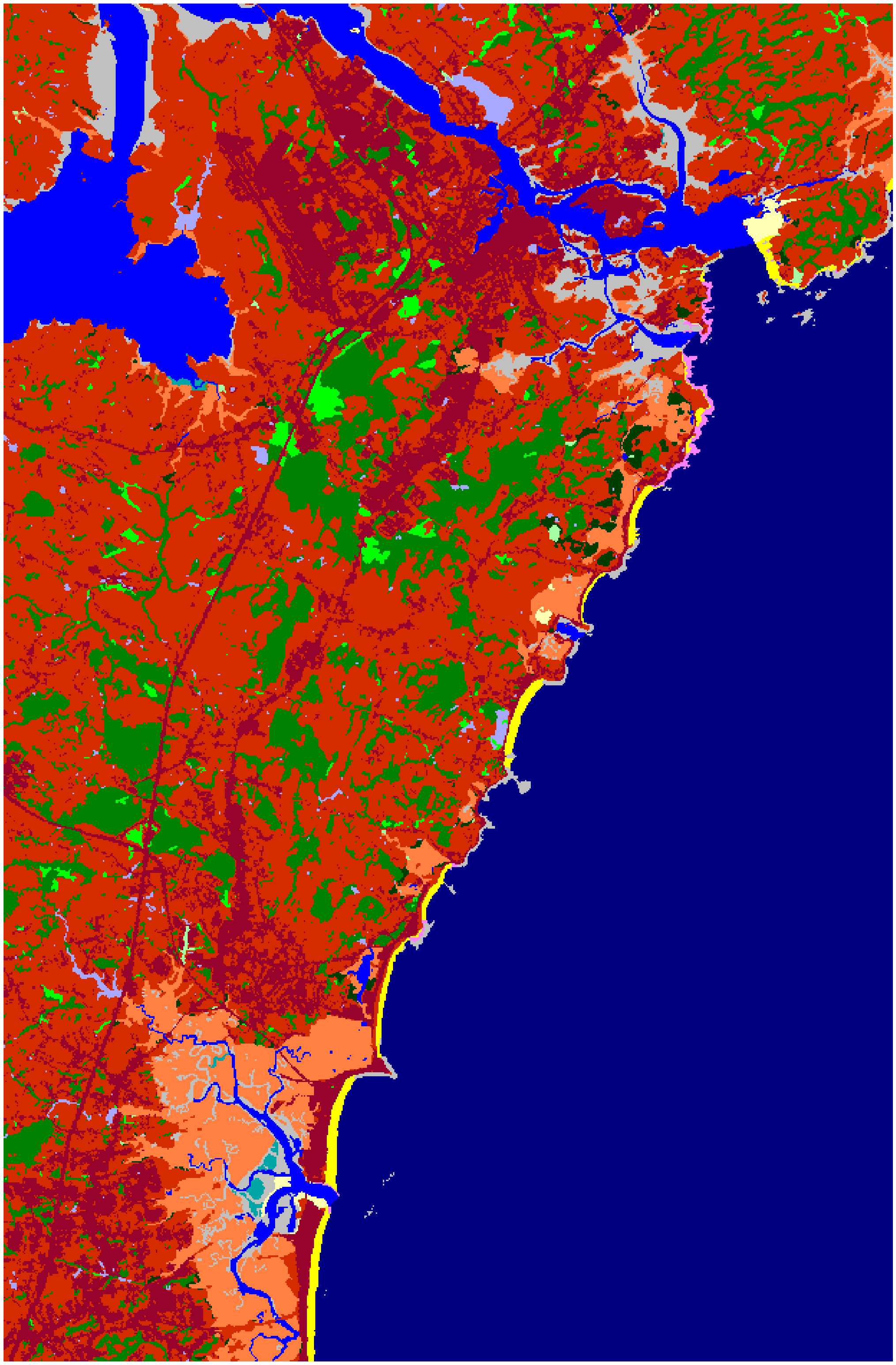
Great Bay Context, 2050, 1 meter



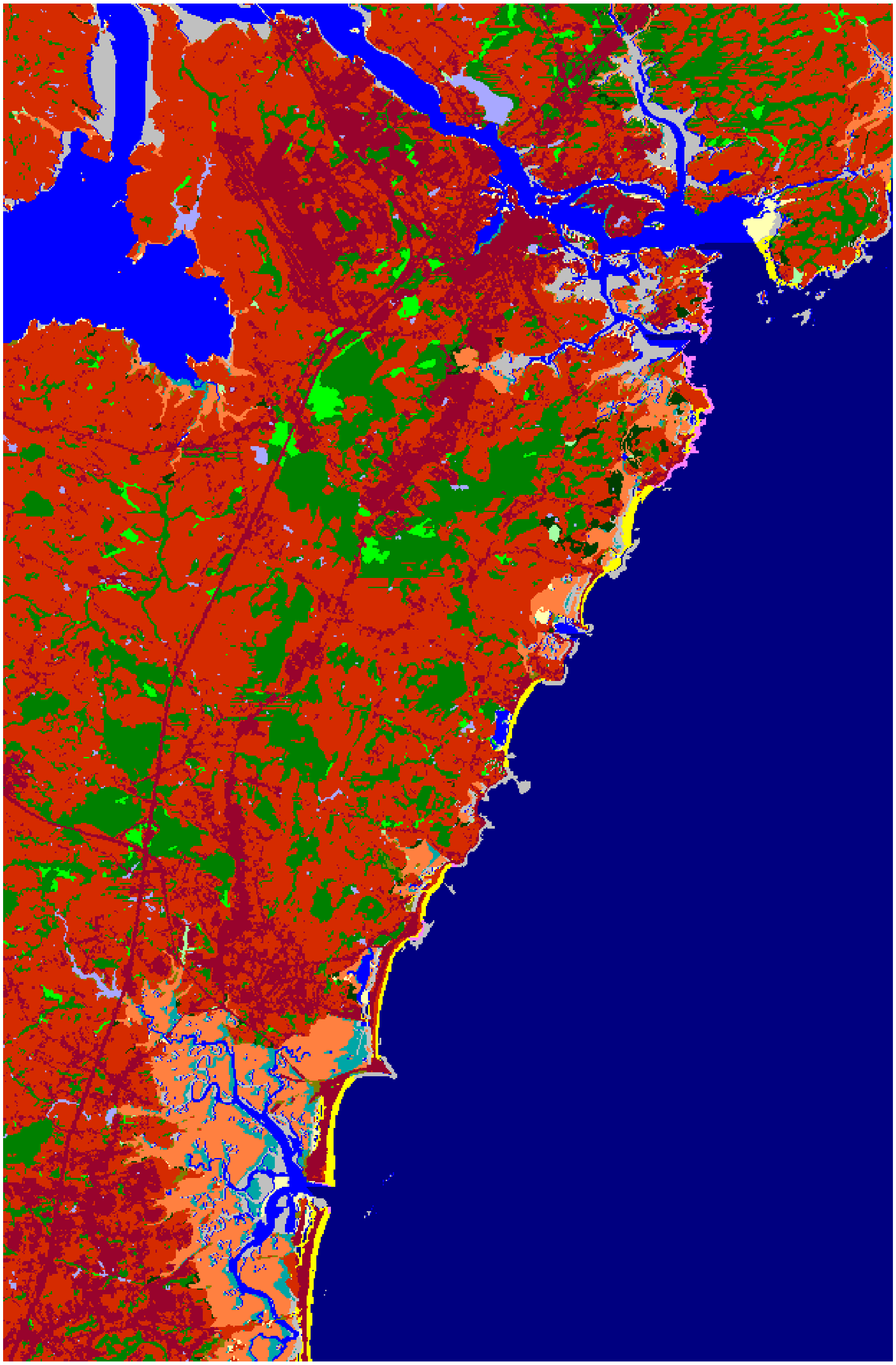
Great Bay Context, 2075, 1 meter



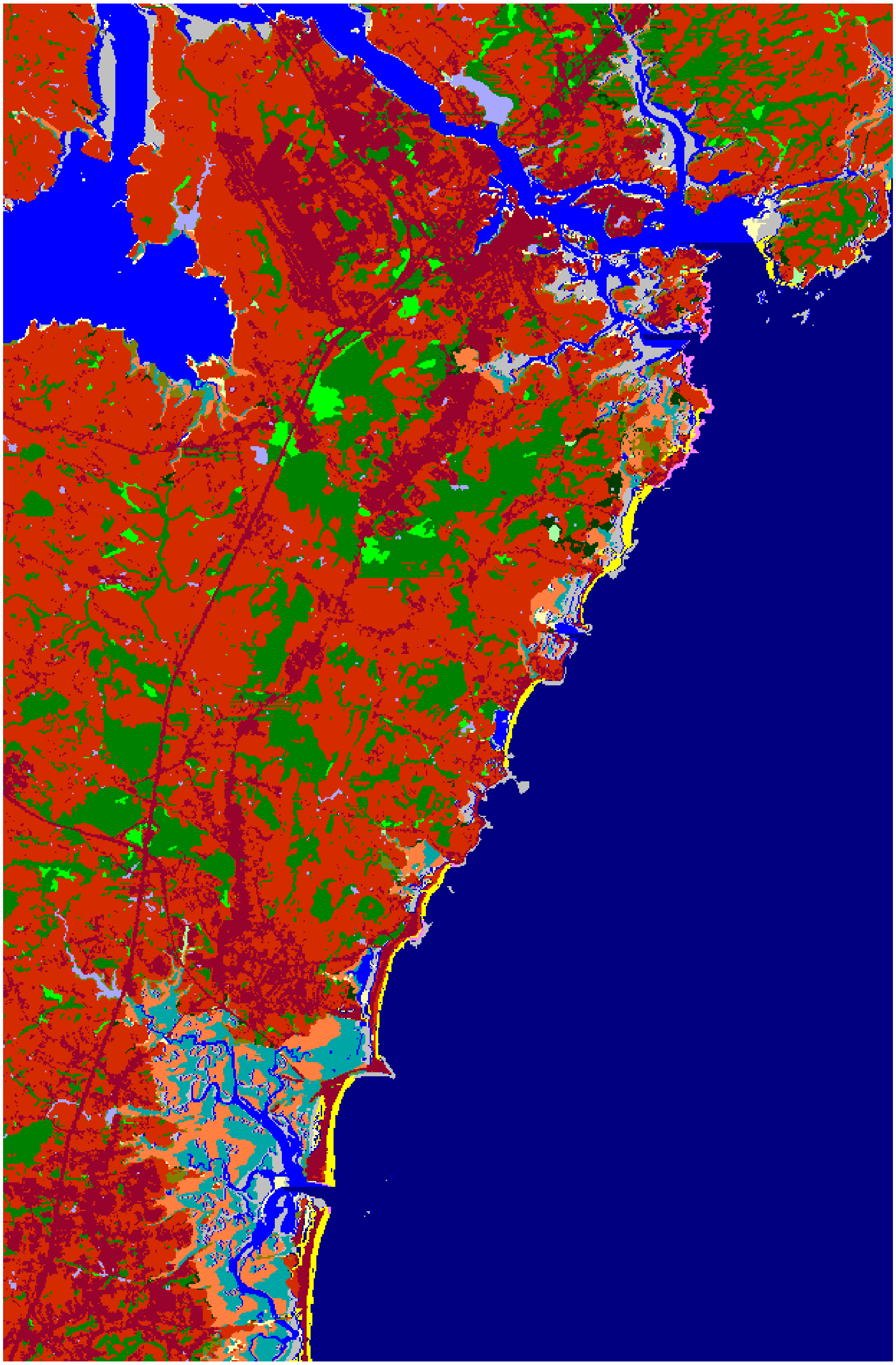
Great Bay Context, 2100, 1 meter



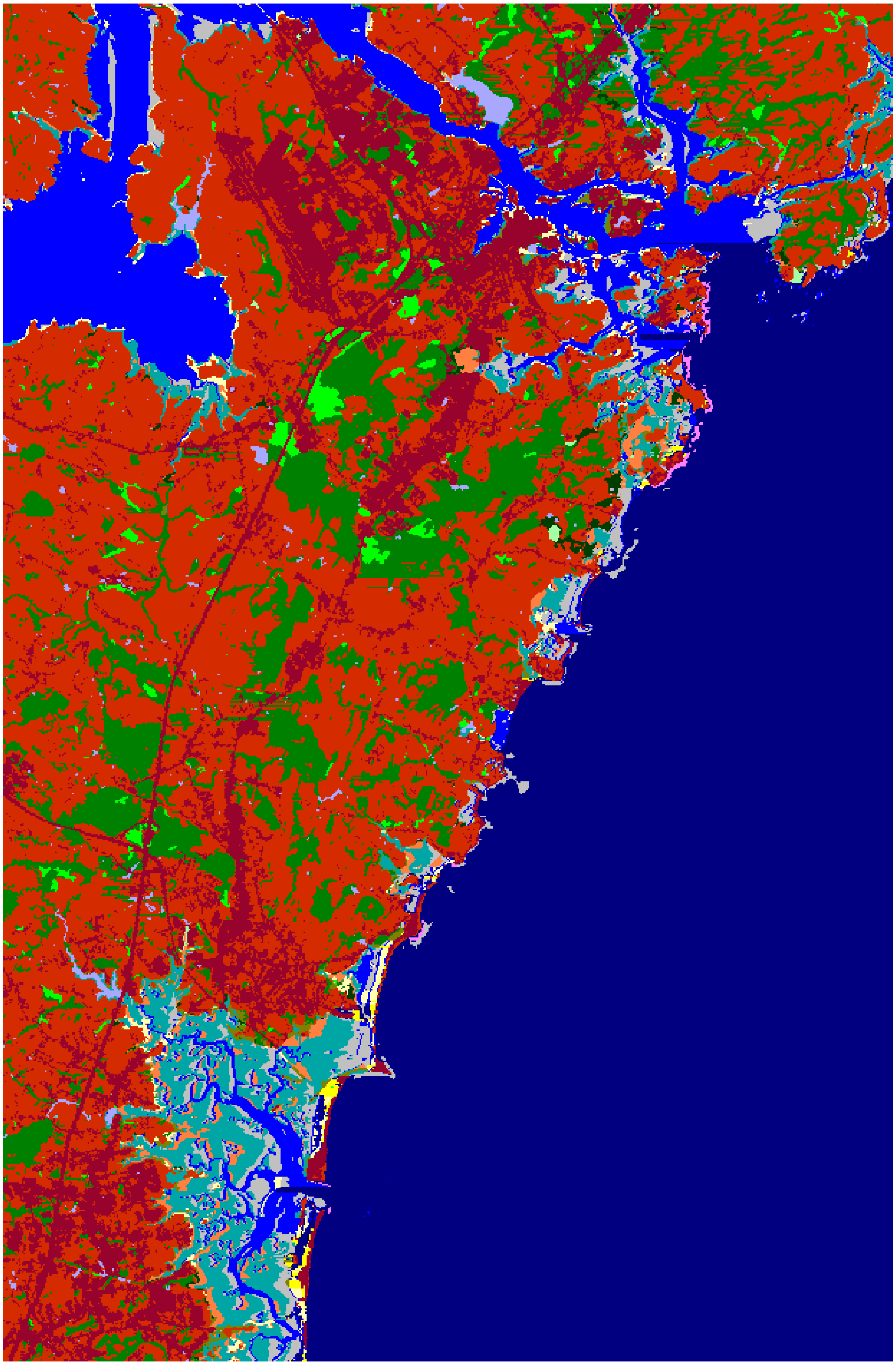
Great Bay Context, Initial Condition



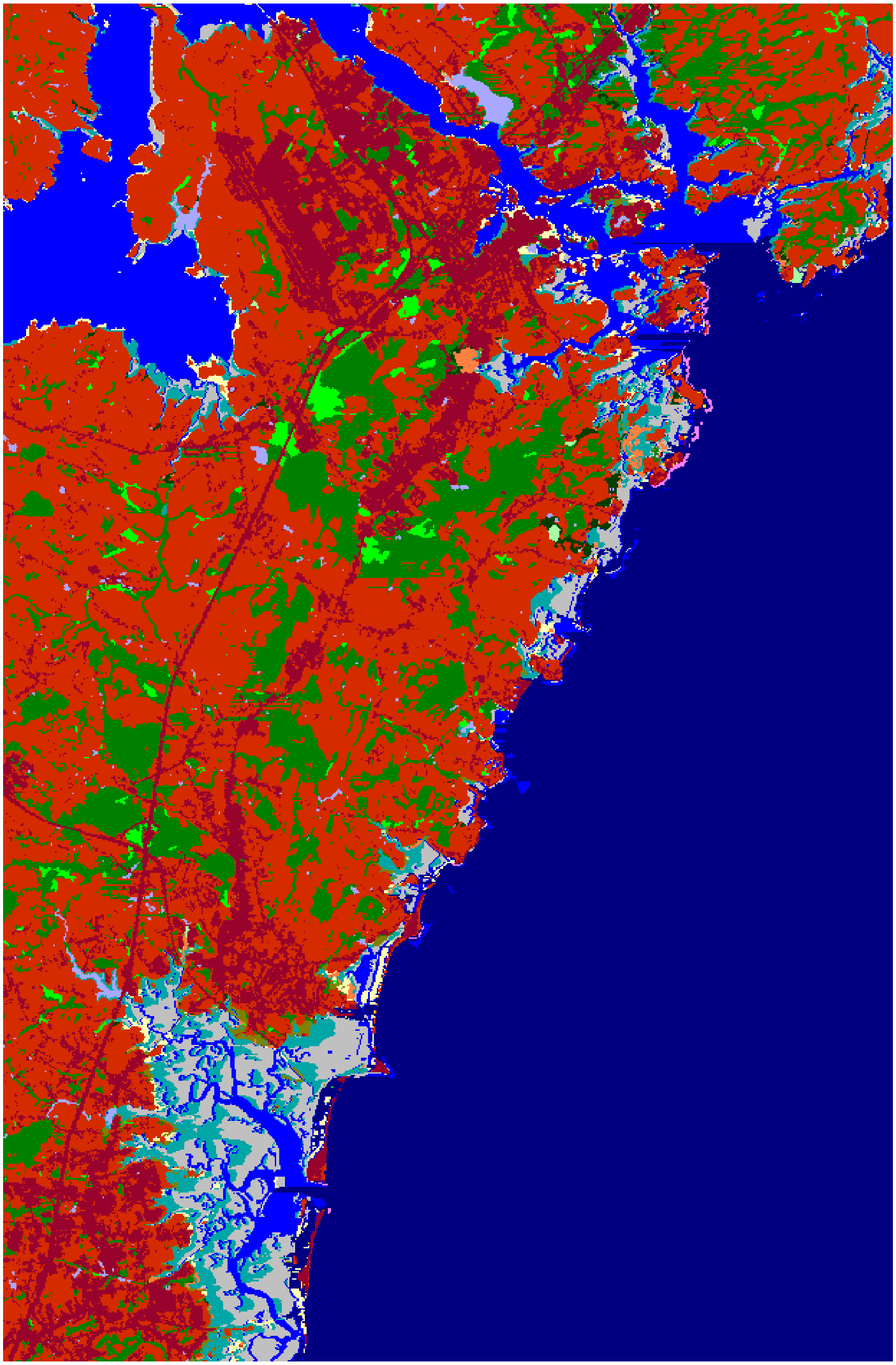
Great Bay Context, 2025, 1.5 meter



Great Bay Context, 2050, 1.5 meter



Great Bay Context, 2075, 1.5 meter



Great Bay Context, 2100, 1.5 meter