Application of the Sea-Level Affecting Marshes Model (SLAMM 6) to Dungeness 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 brackish marsh (Park et al. 1991).

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

Model Summary

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

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

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

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

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

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

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

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

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

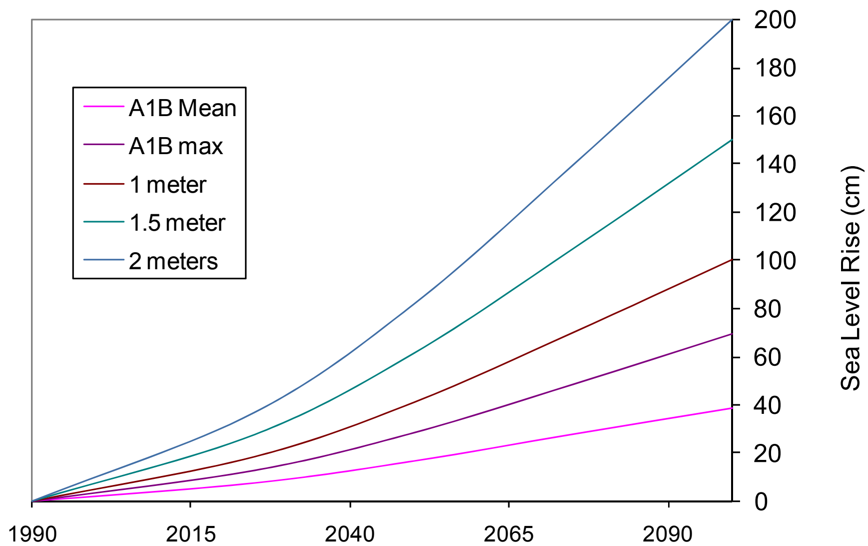
Sea Level Rise Scenarios

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

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

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

Figure 1: Summary of SLR Scenarios Utilized



Methods and Data Sources

The digital elevation map used in this simulation is 1/9 arc second LiDAR derived from the National Elevation Dataset (NED, Figure 1). The data were derived from 2001 "Puget Sound Region" flights. Elevations for tidal flat areas that were not covered with LiDAR data were estimated using the SLAMM elevation pre-processor, and are subject to more uncertainty.

Figure 1: SLAMM-produced elevation map for refuge.
Lightest polygon represents an area with no elevation data.

The wetlands layer for the study area was produced by the National Wetlands Inventory and is based on a 1980 photo date. Converting the NWI survey into 10 meter cells indicates that the approximately one thousand six hundred acre refuge (approved acquisition boundary including water) is composed of the following categories:

Open Ocean	70.3%
Tidal Flat	13.6%
Undeveloped Dry Land	8.7%
Irregularly Flooded Marsh	0.5%
Regularly Flooded Marsh	0.4%
Swamp	0.2%

Dungeness Refuge does not have any impounded wetlands, according to the National Wetland Inventory.

The historic trend for relative sea level rise was estimated at 1.085 mm/year using the average of the two nearest NOAA gages with long-term SLR data (9444900, Port Townsend, WA; 9444090, Port Angeles, WA). The rate of sea level rise for this refuge is lower than the global (eustatic) SLR for the last 100 years (approximately 1.7 mm/year). This estimate is in agreement with several studies that found that the Dungeness NWR region is subject to mild vertical uplift, with higher rates of uplift occurring in lands west of the refuge (Verdonck, 2006. Mitchell, et al., 1994).

The tide range was estimated at 2.14 meters (great diurnal range or GT) using the value from the tide gage at Ediz Hook, WA (9444122).

For accretion values, regularly flooded marsh was set to 3.6 mm/year, irregularly flooded marsh to 3.75 mm/year and tidal fresh marsh to 4 mm/year. These data were based on regional measurements taken by Thom (1992). For erosion values, marshes were set to 2 m/year, swamp to 1 m/year and tidal flat erosion to 0.2 m/year.

An MTL to NAVD correction of 1.21 was used for this model based on the nearest NOAA gage (9444122, Ediz Hook, WA).

Modeled U.S. Fish and Wildlife Service refuge boundaries for Washington 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.

A shift between the NWI and current satellite imagery is apparent due to the roughly 30 year difference between them. The Dungeness Spit has apparently migrated to some extent over this time period. This shift is most visible at certain points along the spit, where it can reach 70 meters (Figure 2 and Figure 4). This offset is also visible in differences between the NWI coverage and the digital elevation map (Figure 3).

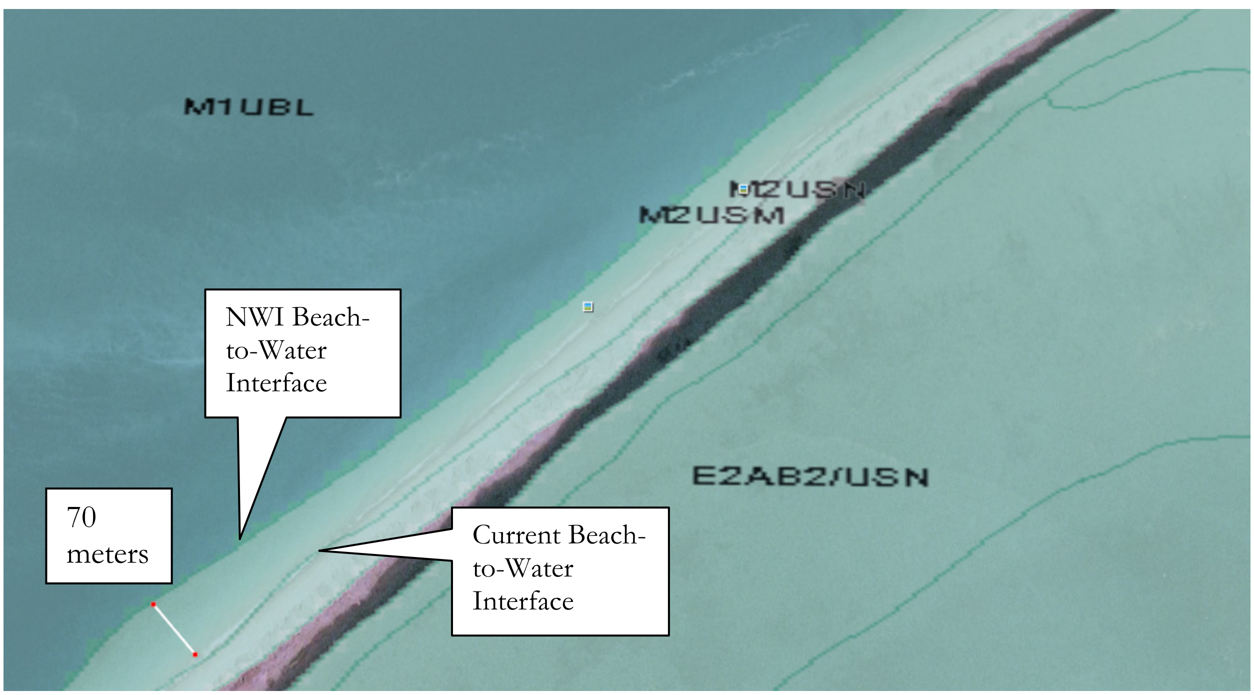


Figure 2: Area Along Western Spit.

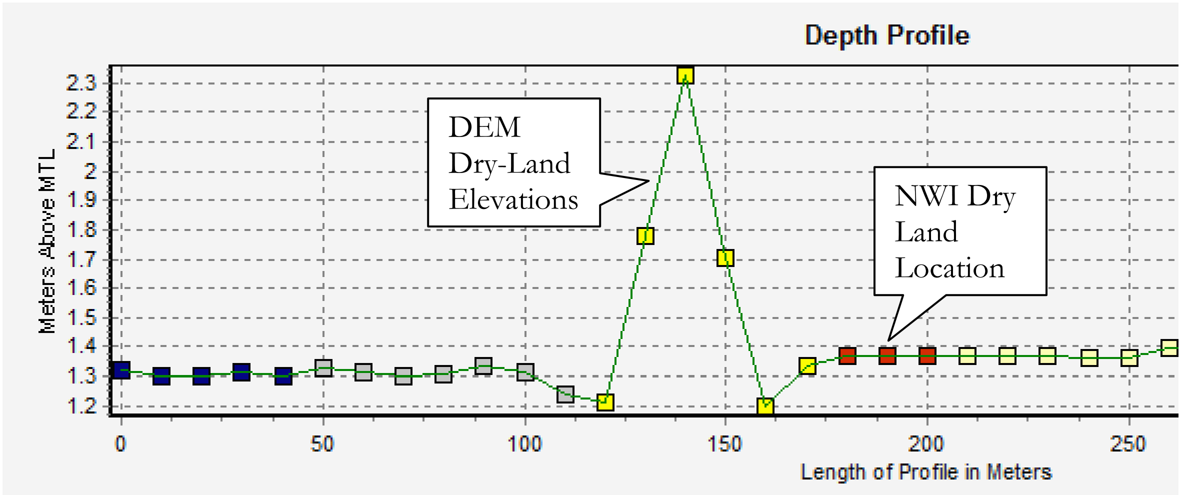


Figure 3: Profile Showing Offset Between DEM and NWI.
Yellow cells are beach cells and red cells are dry land cells (grey is tidal flat and navy blue are open water)

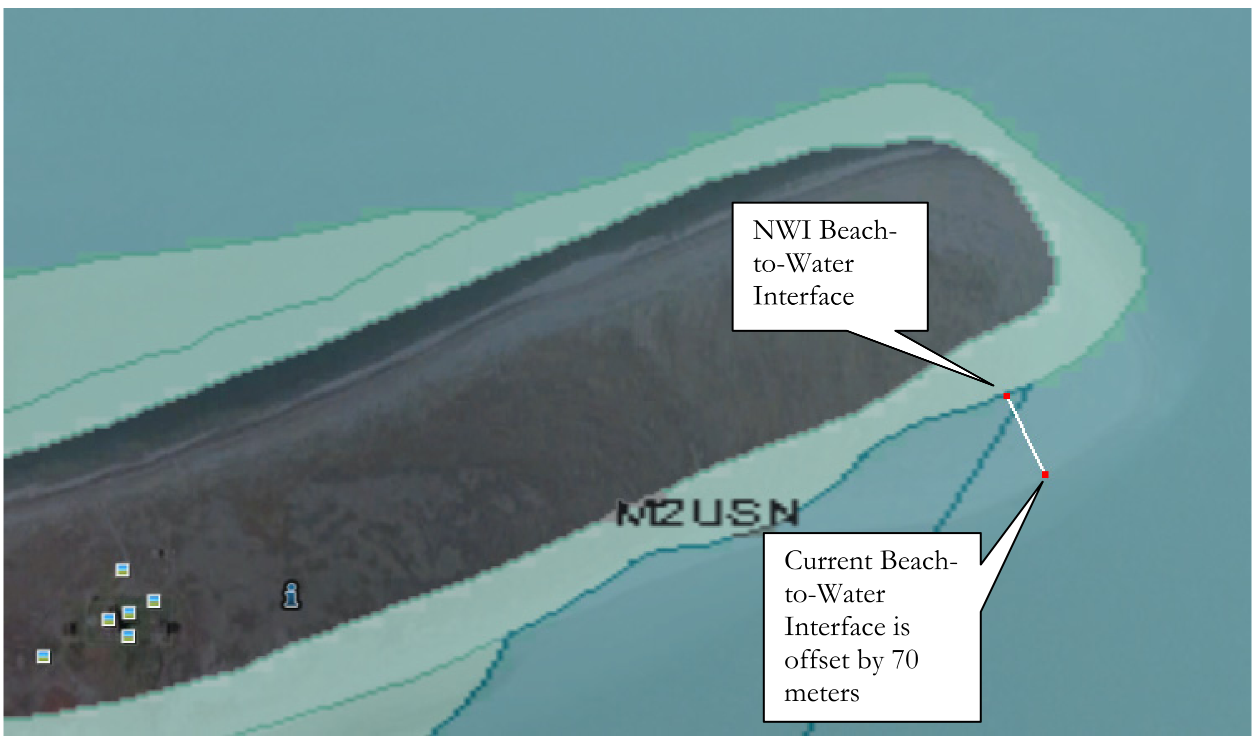


Figure 4: Differences at Eastern Tip of Spit.

SUMMARY OF SLAMM INPUT PARAMETERS FOR DUNGENESS NWR

Parameter	Global	SubSite 1	SubSite 2
Description	Dungeness	SubSite 1	No Elevation Data
NWI Photo Date (YYYY)	1980	1980	1980
DEM Date (YYYY)	2001	2001	2001
Direction Offshore [n,s,e,w]	North	East	South
Historic Trend (mm/yr)	1.085	1.085	1.085
MTL-NAVD88 (m)	1.21	1.21	1.21
GT Great Diurnal Tide Range (m)	2.14	2.14	2.14
Salt Elev. (m above MTL)	1.5	1.5	1.5
Marsh Erosion (horz. m /yr)	2	2	2
Swamp Erosion (horz. m /yr)	1	1	1
T.Flat Erosion (horz. m /yr)	0.2	0.2	0.2
Reg. Flood Marsh Accr (mm/yr)	3.6	3.6	3.6
Irreg. Flood Marsh Accr (mm/yr)	3.75	3.75	3.75
Tidal Fresh Marsh Accr (mm/yr)	4	4	4
Beach Sed. Rate (mm/yr)	0.5	0.5	0.5
Freq. Overwash (years)	0	0	0
Use Elev Pre-processor [True,False]	FALSE	FALSE	TRUE

Results

Dungeness NWR is predicted to be vulnerable to sea level rise (SLR) inundation effects. Between 7% and 90% of refuge tidal flat – which makes up around 13% of the refuge – is predicted to be lost across all SLR scenarios. Refuge dry land – which comprises nearly 10% of the refuge – is predicted to be lost at a rate between 34% and 52% across all SLR scenarios. Irregularly flooded (brackish) and regularly flooded (salt) marshes are only predicted to suffer losses in the most extreme SLR scenarios.

SLR by 2100 (m)	0.39	0.69	1	1.5	2
Tidal Flat	7%	18%	27%	73%	90%
Undeveloped Dry Land	34%	42%	47%	51%	52%
Estuarine Beach	0%	0%	1%	2%	4%
Ocean Beach	-72%	96%	98%	99%	100%
Brackish Marsh	0%	0%	1%	81%	98%
Saltmarsh	-2%	-8%	-59%	-192%	7%
Swamp	0%	0%	0%	1%	1%

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

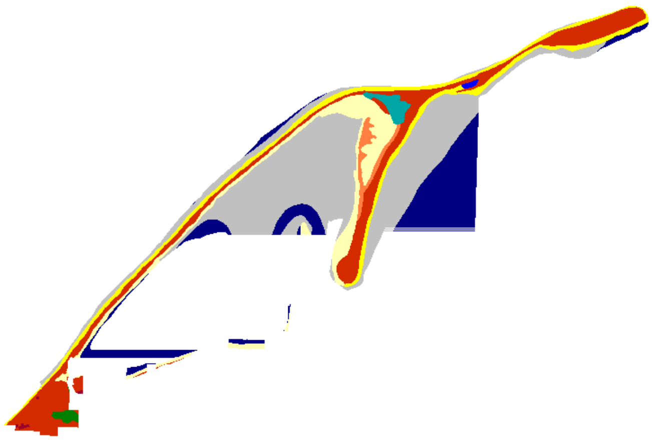
(Positive numbers are losses and negative numbers are gains)

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

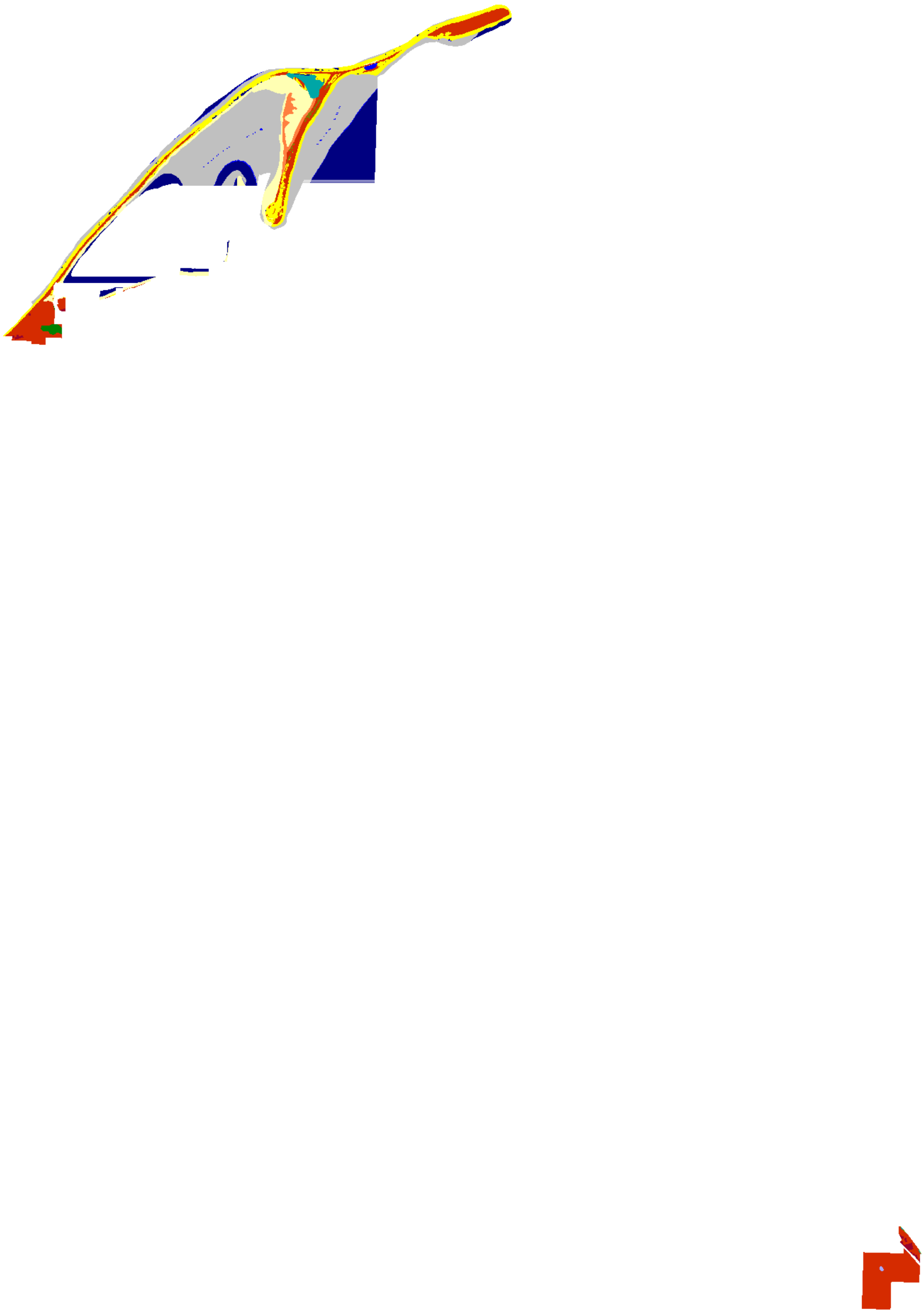
Dungeness Raster
IPCC Scenario A1B-Mean, 0.39 M SLR Eustatic by 2100

Results in Acres

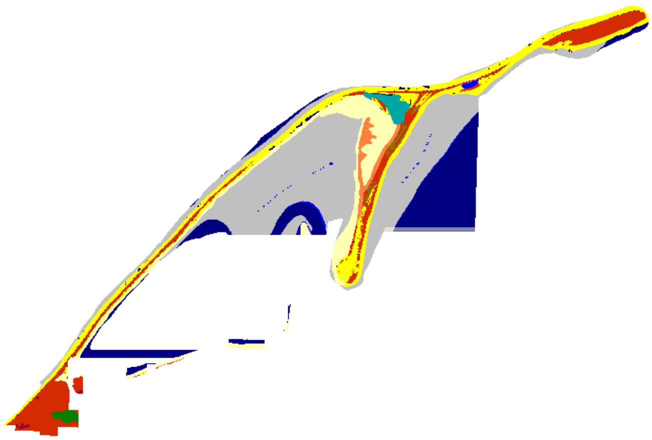
	Initial	2025	2050	2075	2100
Open Ocean	3203.6	3211.1	3221.9	3232.3	3251.1
Tidal Flat	620.9	611.2	604.8	590.2	575.0
Undeveloped Dry Land	394.7	306.1	295.7	277.6	261.5
Estuarine Beach	145.5	146.6	146.5	146.4	146.1
Ocean Beach	130.1	204.0	208.7	216.8	223.7
Brackish Marsh	25.0	25.0	25.0	25.0	25.0
Saltmarsh	18.6	18.9	18.9	18.9	18.9
Swamp	7.8	7.8	7.8	7.8	7.8
Dev. Dry Land	6.8	6.8	6.8	6.8	6.8
Estuarine Open Water	2.5	12.3	10.9	20.0	22.0
Inland Open Water	0.7	0.7	0.7	0.7	0.7
Trans. Salt Marsh	0.0	5.7	8.6	13.7	17.6
Total (incl. water)	**4556.2**	**4556.2**	**4556.2**	**4556.2**	**4556.2**



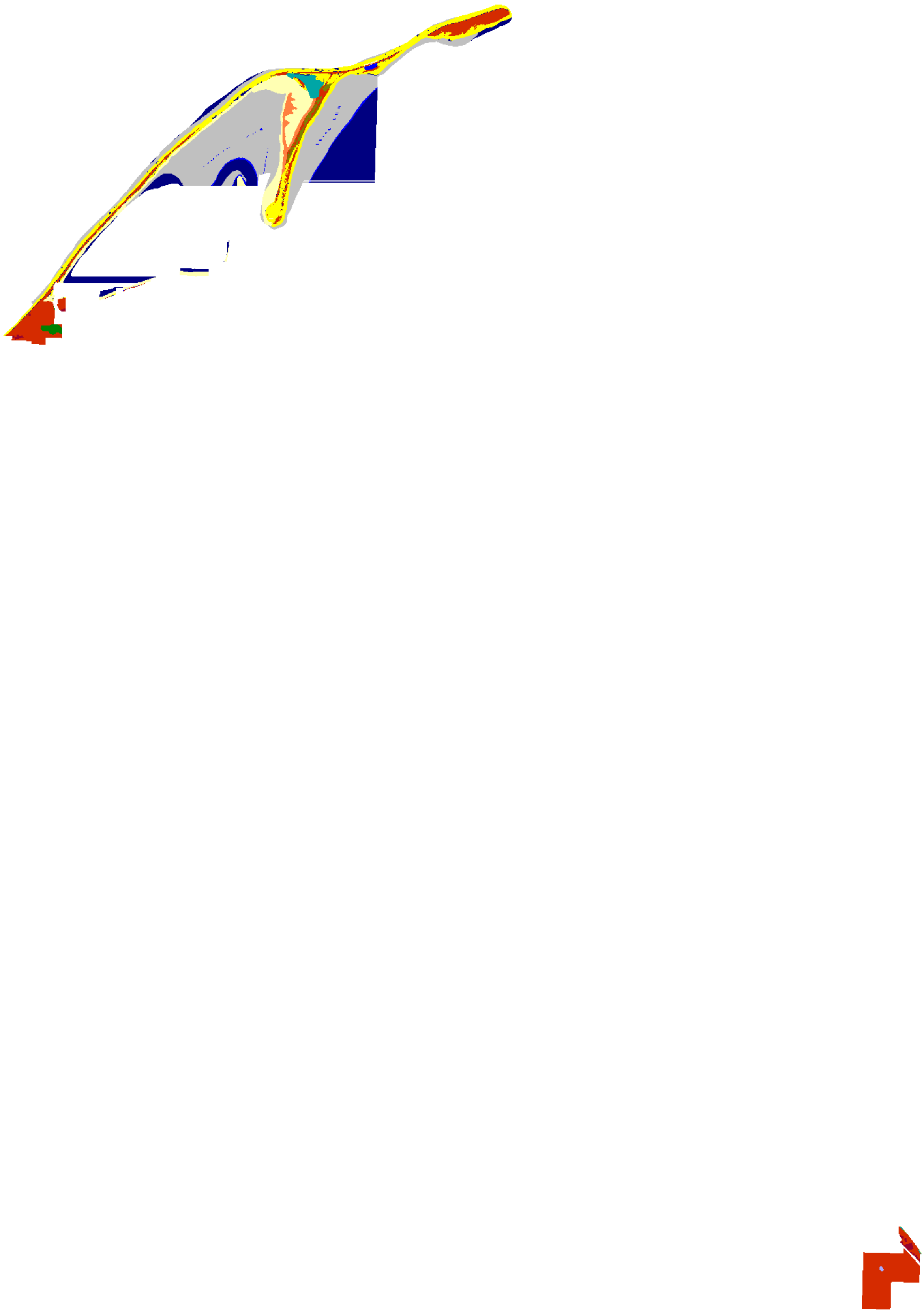
Dungeness NWR, Initial Condition



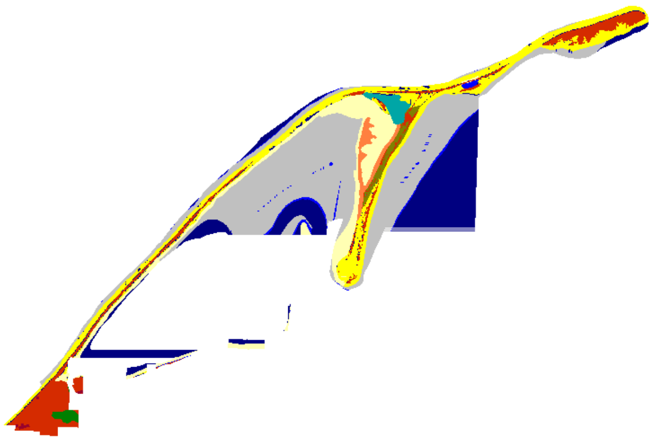
Dungeness NWR, 2025, Scenario A1B Mean



Dungeness NWR, 2050, Scenario A1B Mean



Dungeness NWR, 2075, Scenario A1B Mean

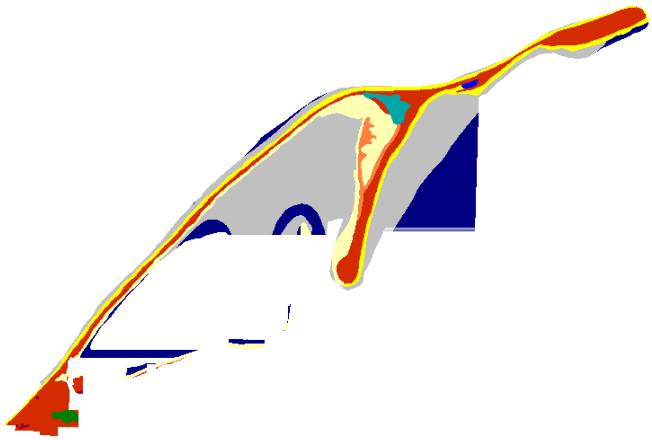


Dungeness NWR, 2100, Scenario A1B Mean

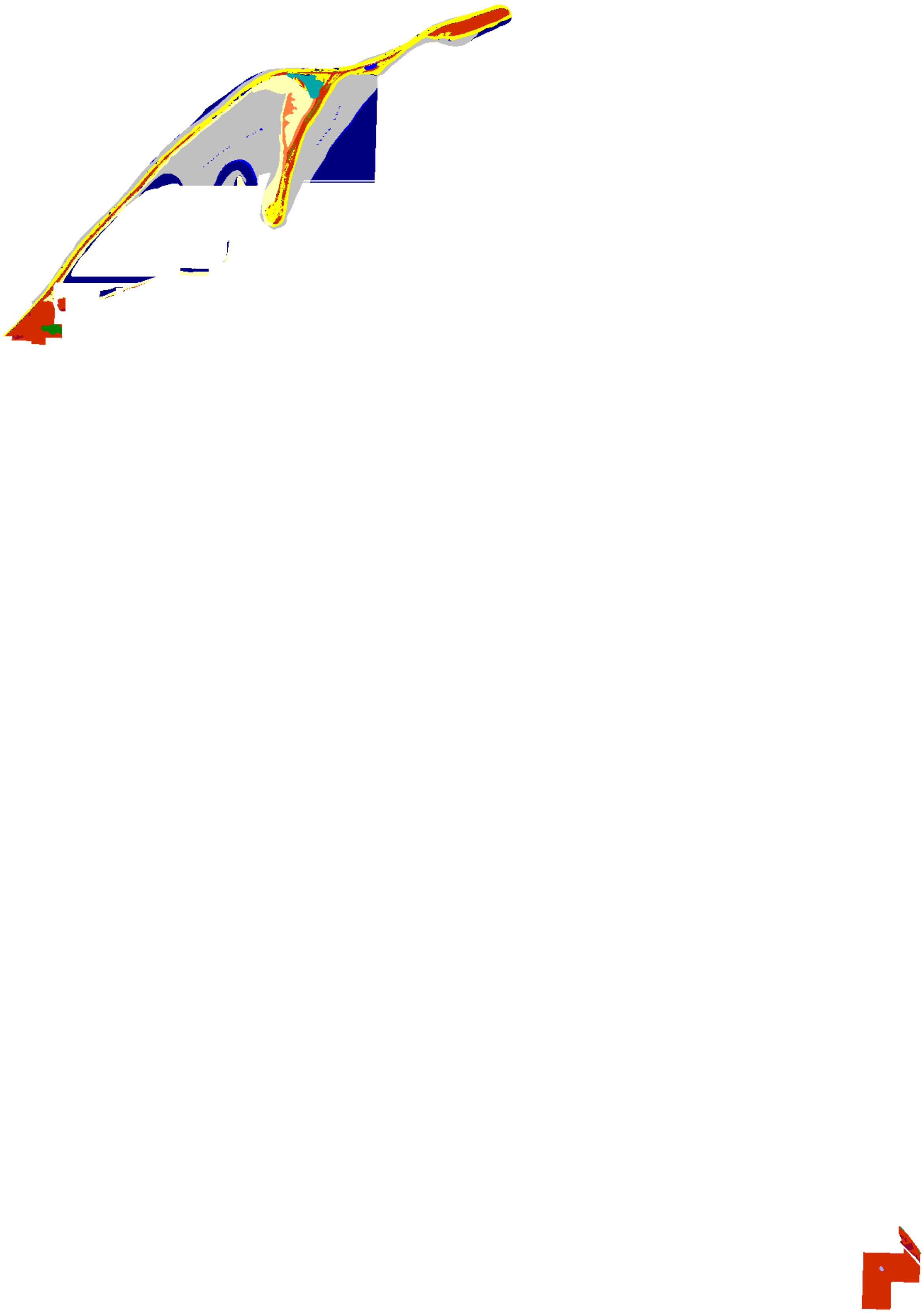
Dungeness Raster
IPCC Scenario A1B-Max, 0.69 M SLR Eustatic by 2100

Results in Acres

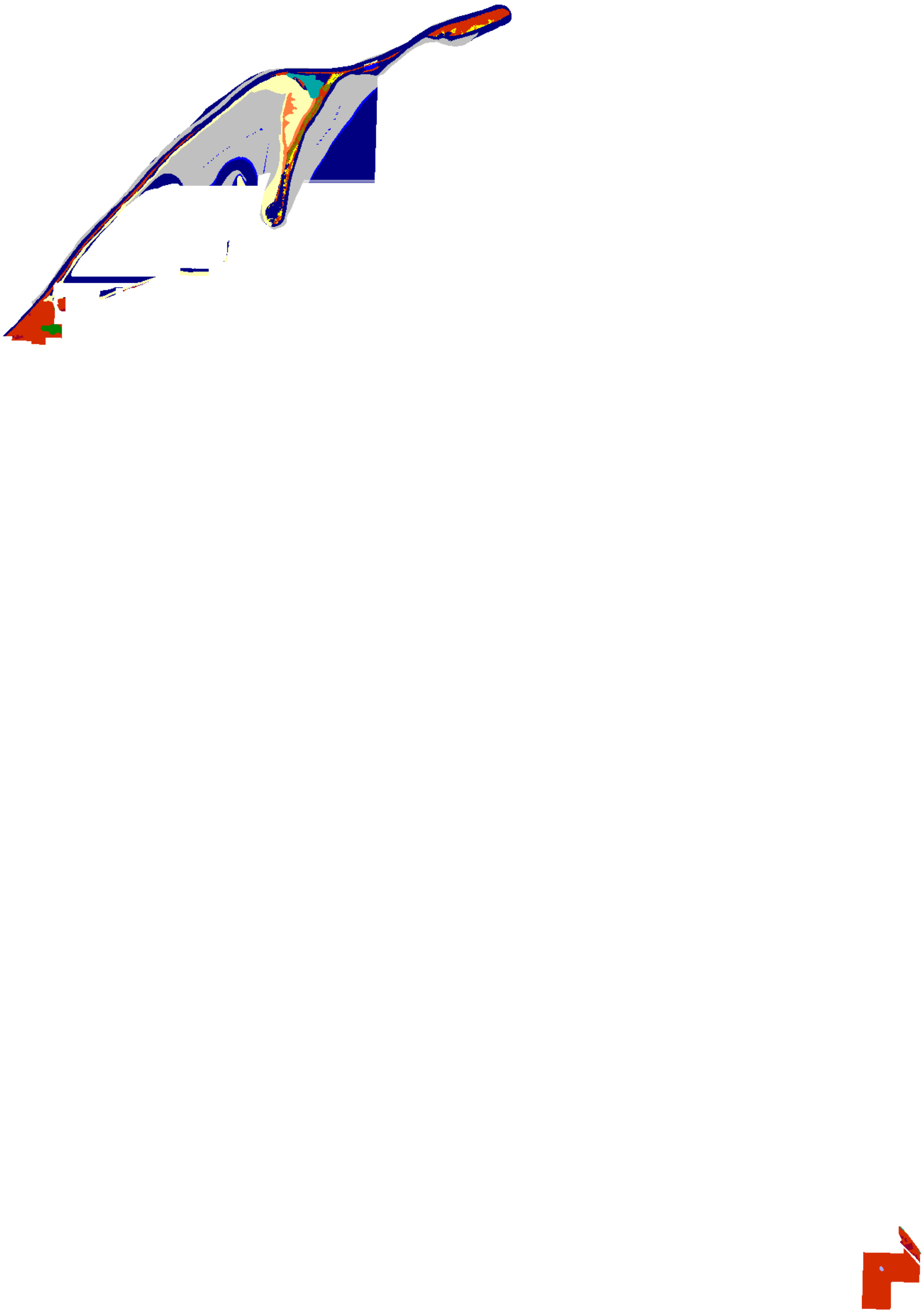
	Initial	2025	2050	2075	2100
Open Ocean	249.8	296.4	435.6	531.9	583.2
Tidal Flat	620.9	606.5	587.0	554.1	511.5
Undeveloped Dry Land	394.7	299.3	272.5	248.0	228.9
Estuarine Beach	145.5	146.5	146.2	145.7	145.1
Ocean Beach	130.1	170.1	62.1	8.0	4.7
Brackish Marsh	25.0	25.0	25.0	25.0	25.0
Saltmarsh	18.6	19.0	19.1	19.4	20.2
Swamp	7.8	7.8	7.8	7.8	7.8
Dev. Dry Land	6.8	6.8	6.8	6.8	6.8
Estuarine Open Water	2.5	17.0	24.8	40.4	54.7
Inland Open Water	0.7	0.7	0.7	0.7	0.7
Trans. Salt Marsh	0.0	7.3	14.7	14.5	13.9
Total (incl. water)	**1602.4**	**1602.4**	**1602.4**	**1602.4**	**1602.4**



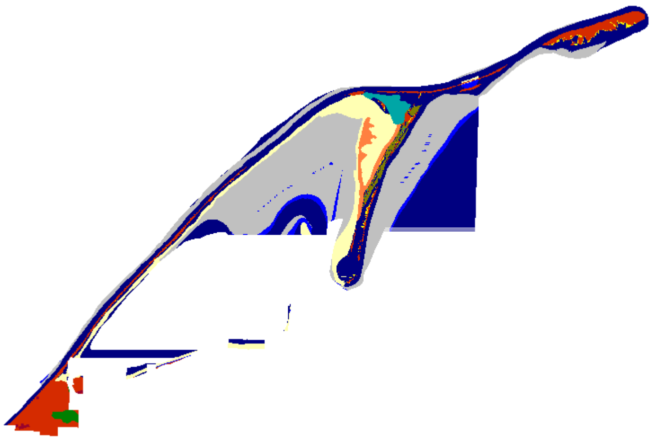
Dungeness NWR, Initial Condition



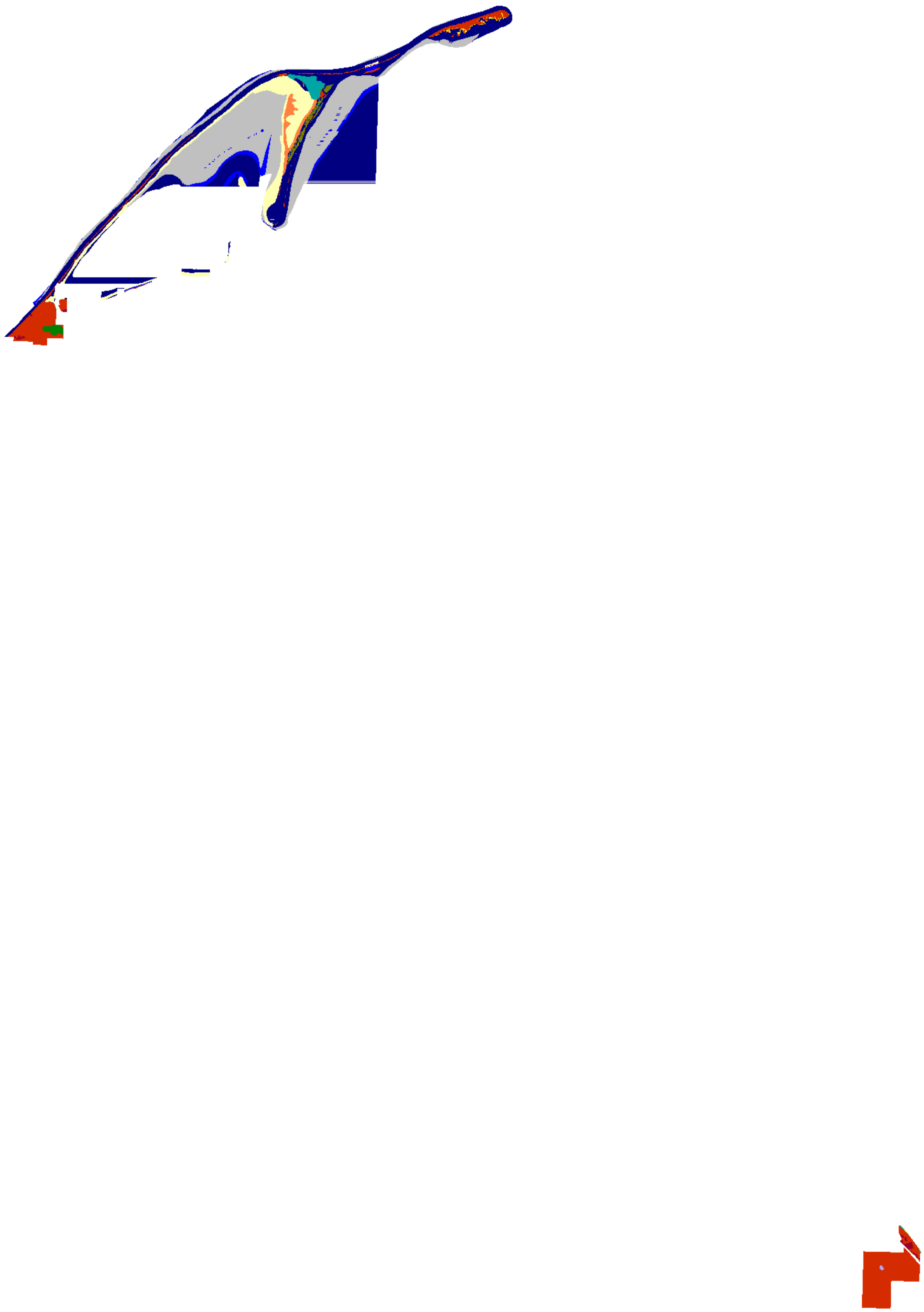
Dungeness NWR, 2025, Scenario A1B Maximum



Dungeness NWR, 2050, Scenario A1B Maximum



Dungeness NWR, 2075, Scenario A1B Maximum

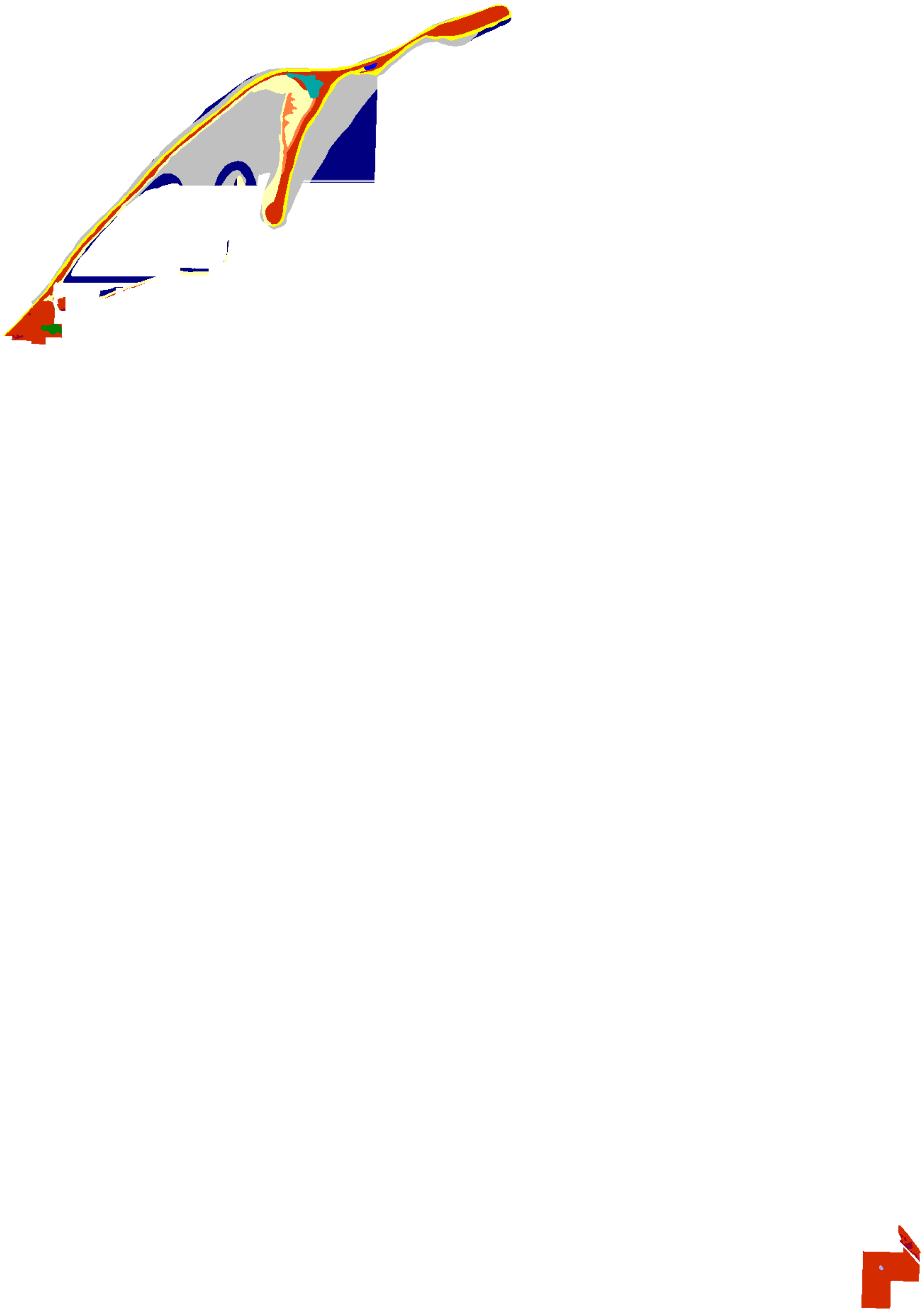


Dungeness NWR, 2100, Scenario A1B Maximum

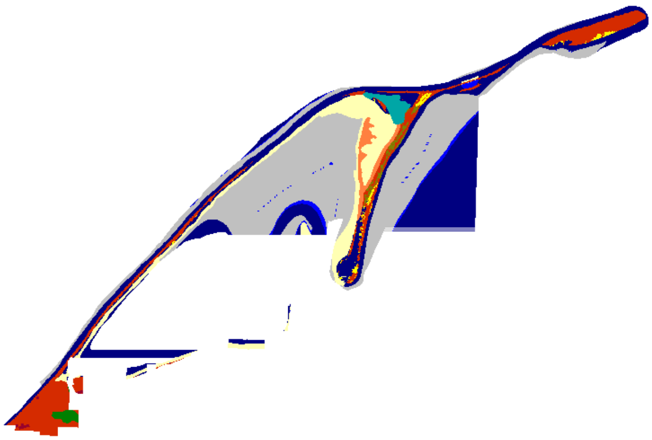
Dungeness Raster
1 Meter Eustatic SLR by 2100

Results in Acres

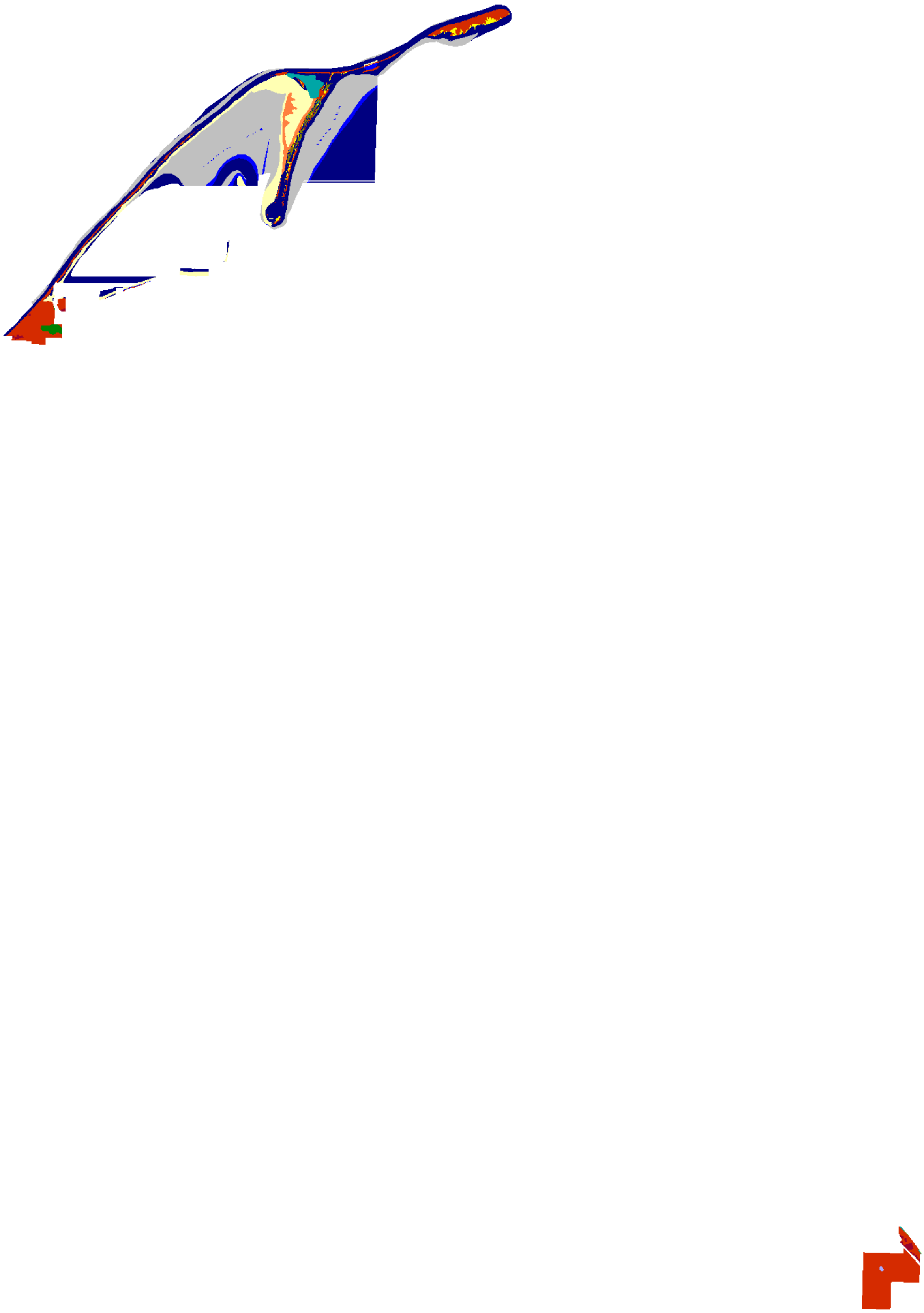
	Initial	2025	2050	2075	2100
Open Ocean	249.8	411.9	514.8	576.9	647.4
Tidal Flat	620.9	598.7	565.8	508.0	453.0
Undeveloped Dry Land	394.7	287.6	255.0	227.4	209.6
Estuarine Beach	145.5	146.4	145.9	145.0	144.3
Ocean Beach	130.1	62.9	11.9	6.7	2.8
Brackish Marsh	25.0	25.0	25.0	25.0	24.8
Saltmarsh	18.6	19.0	19.6	22.8	29.5
Swamp	7.8	7.8	7.8	7.8	7.8
Dev. Dry Land	6.8	6.8	6.8	6.8	6.8
Estuarine Open Water	2.5	25.1	39.1	68.3	75.1
Inland Open Water	0.7	0.7	0.7	0.7	0.7
Trans. Salt Marsh	0.0	10.5	10.1	7.1	0.6
Total (incl. water)	**1602.4**	**1602.4**	**1602.4**	**1602.4**	**1602.4**



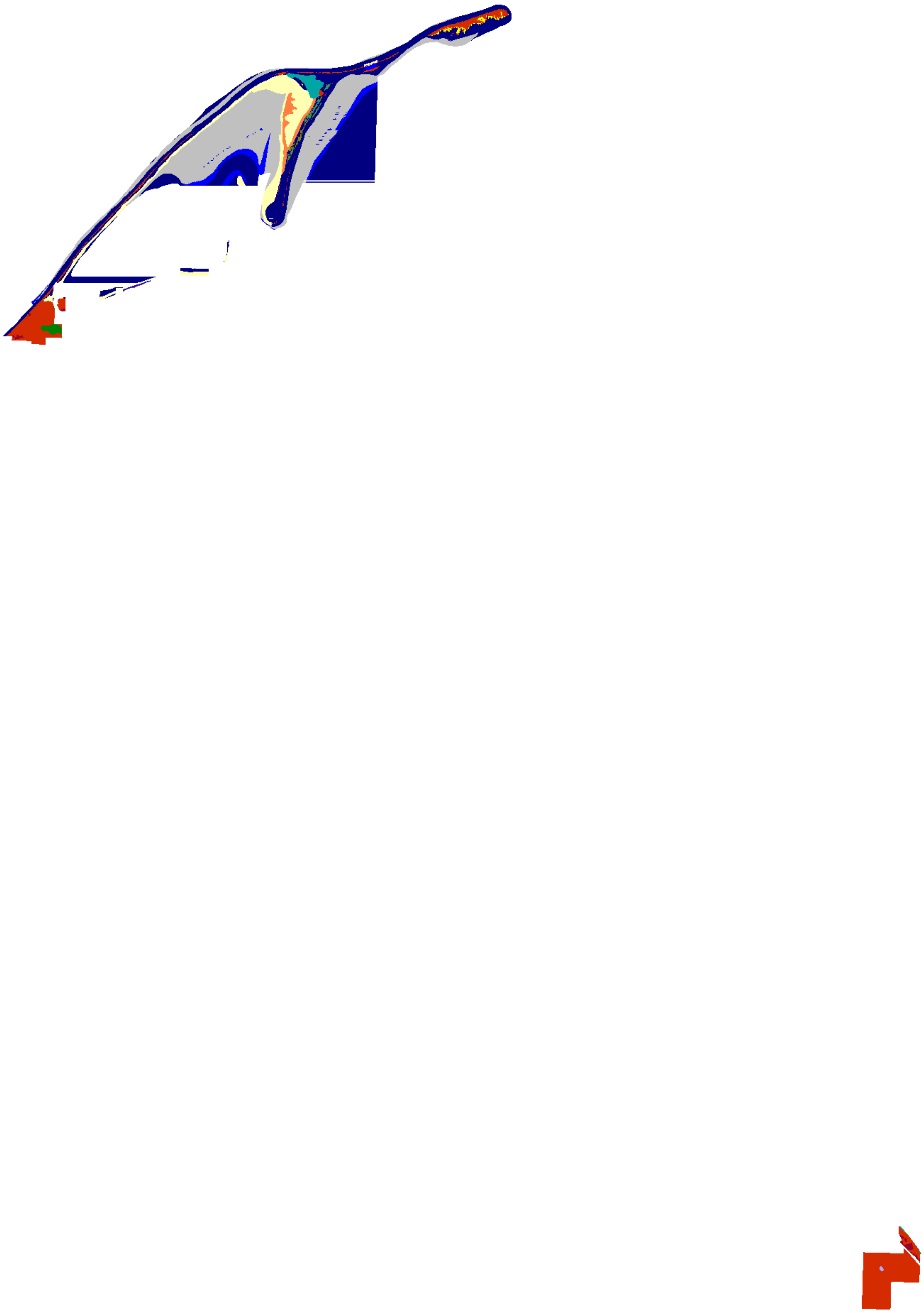
Dungeness NWR, Initial Condition



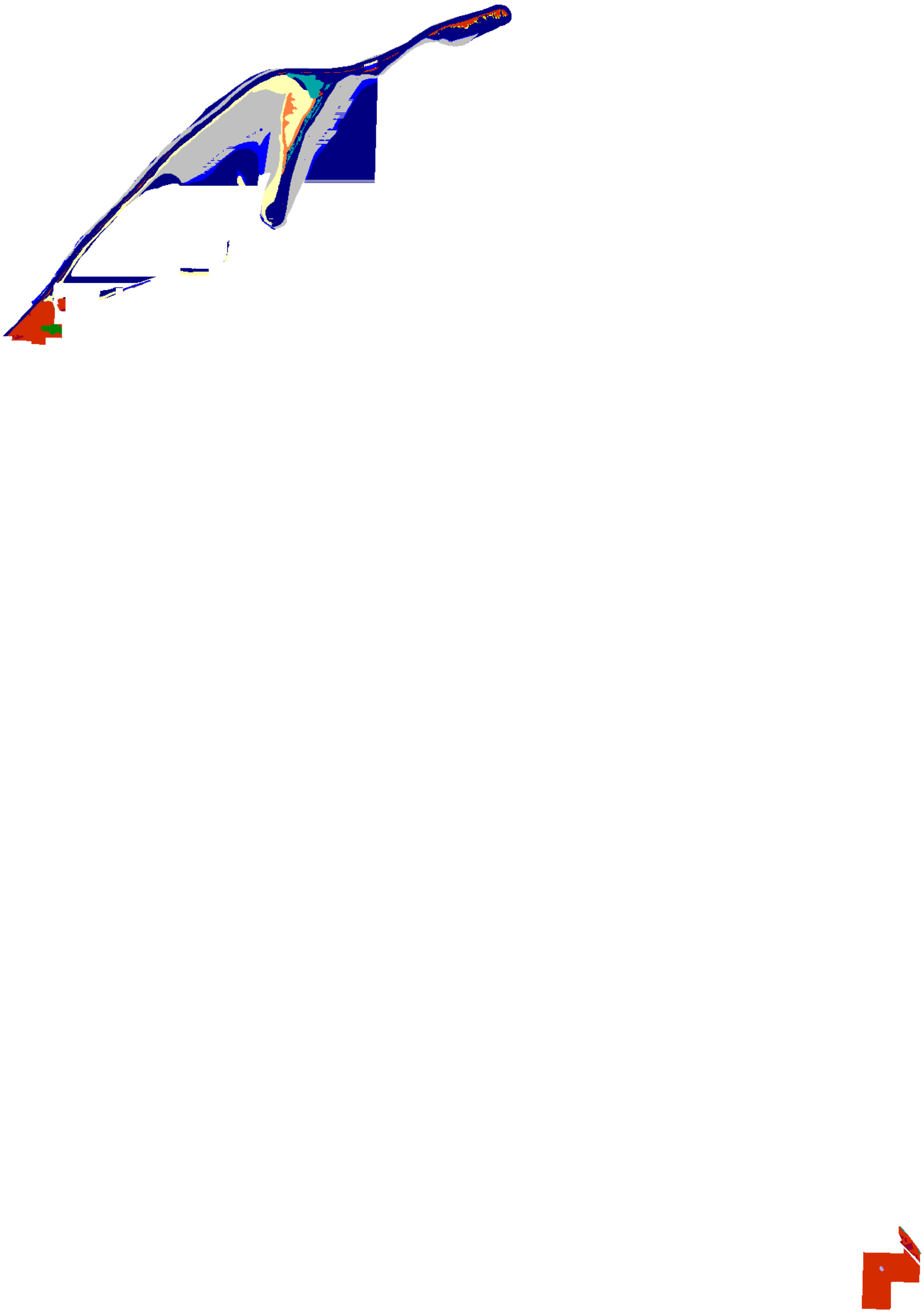
Dungeness NWR, 2025, 1 meter



Dungeness NWR, 2050, 1 meter



Dungeness NWR, 2075, 1 meter

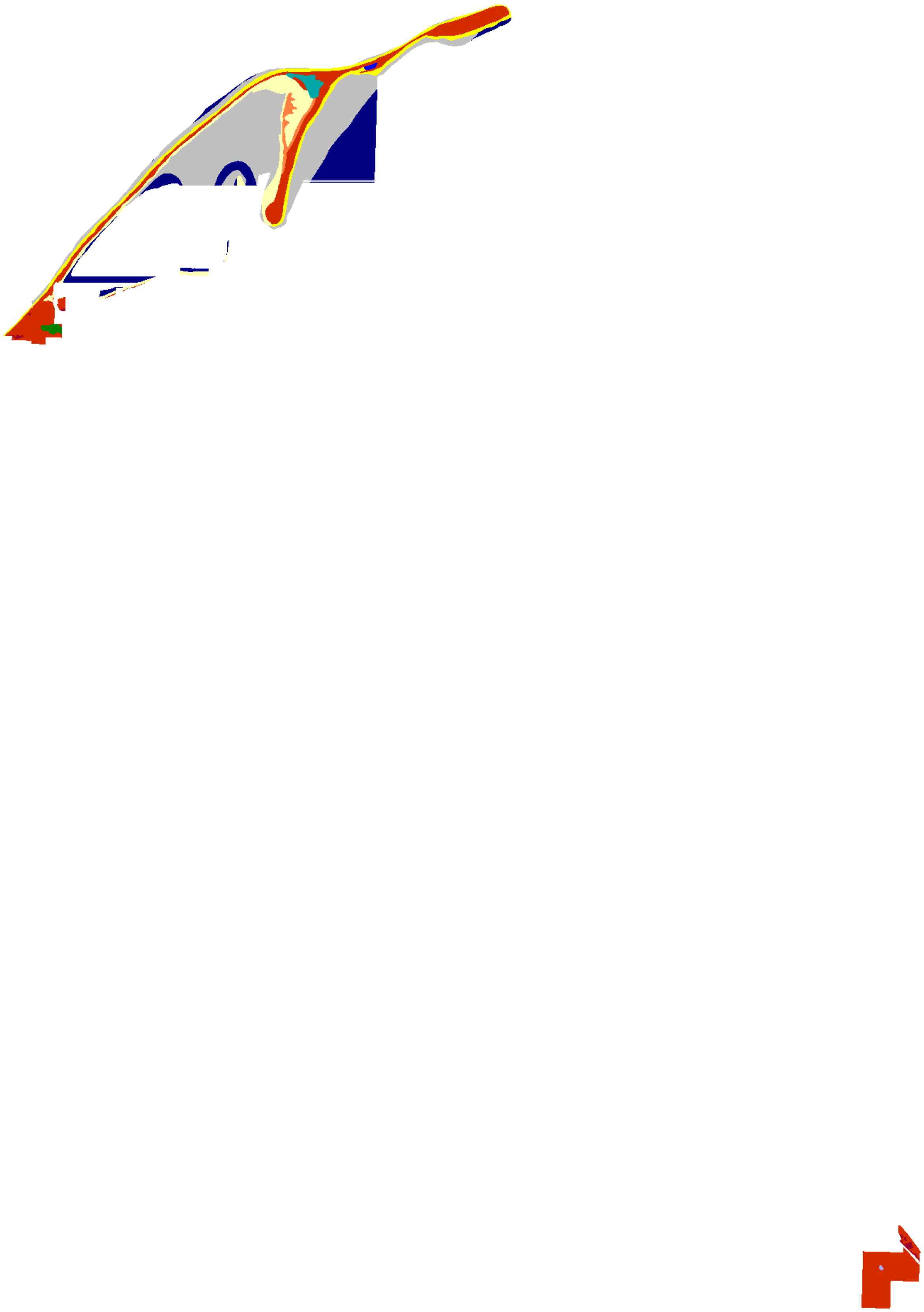


Dungeness NWR, 2100, 1 meter

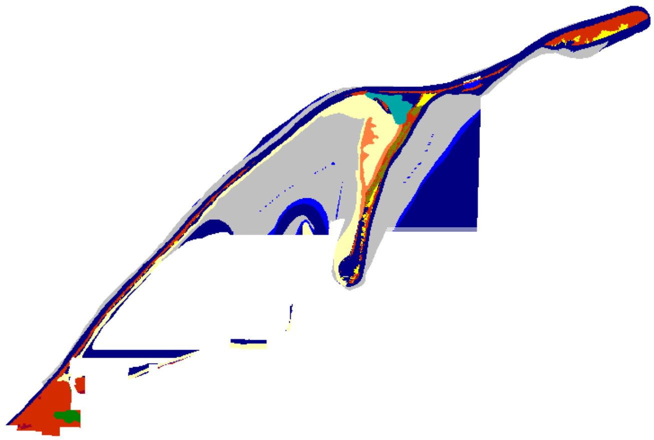
Dungeness Raster
1.5 Meters Eustatic SLR by 2100

Results in Acres

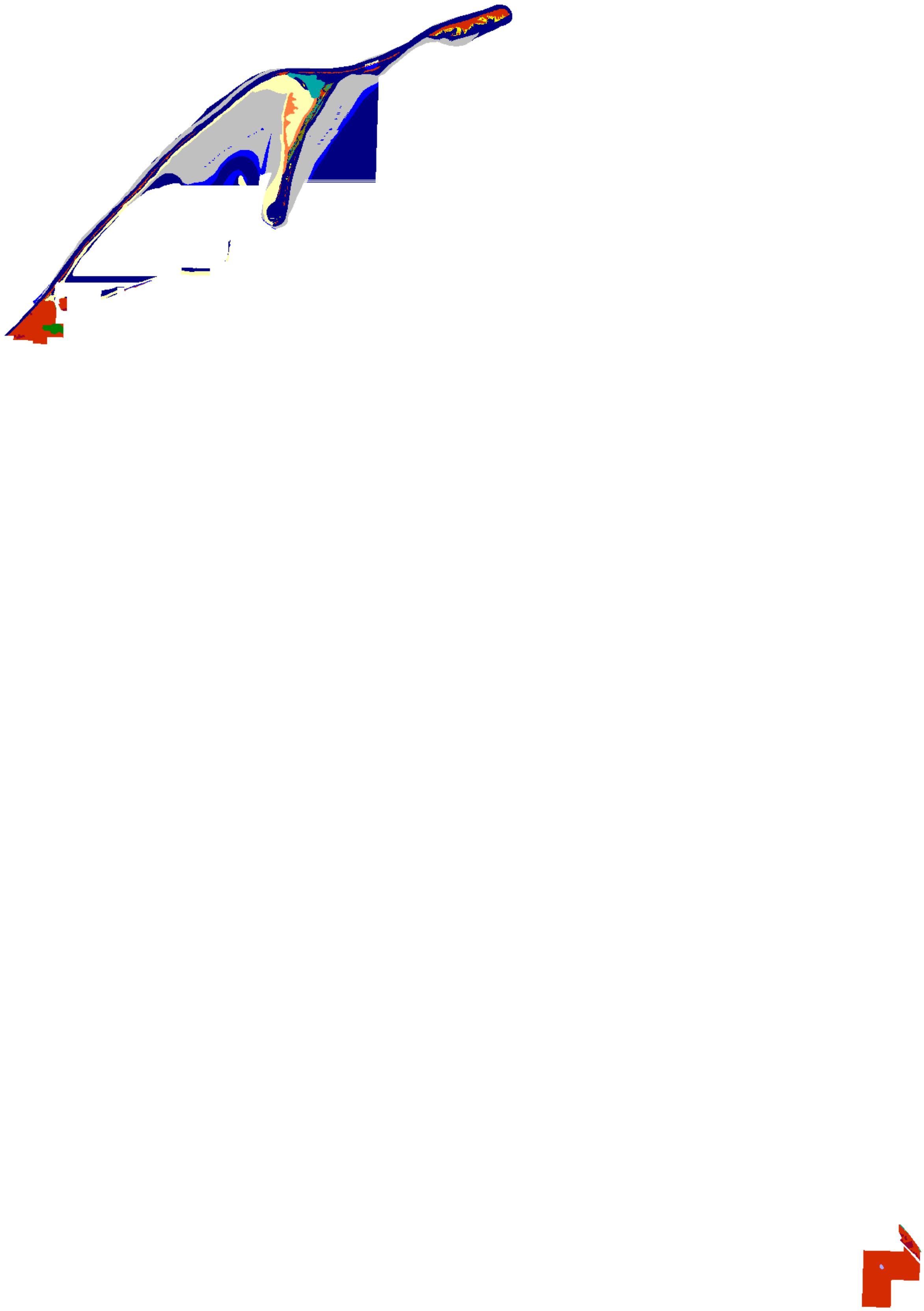
	Initial	2025	2050	2075	2100
Open Ocean	249.8	469.9	548.4	634.2	714.5
Tidal Flat	620.9	584.2	520.4	442.3	167.6
Undeveloped Dry Land	394.7	271.1	233.0	206.7	191.6
Estuarine Beach	145.5	146.2	145.2	144.3	142.6
Ocean Beach	130.1	16.7	8.6	3.4	1.3
Brackish Marsh	25.0	25.0	25.0	24.7	4.7
Saltmarsh	18.6	19.2	23.7	34.4	54.4
Swamp	7.8	7.8	7.8	7.8	7.7
Dev. Dry Land	6.8	6.8	6.8	6.8	6.8
Estuarine Open Water	2.5	39.9	72.1	96.6	310.0
Inland Open Water	0.7	0.7	0.7	0.7	0.7
Trans. Salt Marsh	0.0	15.0	10.7	0.5	0.6
Total (incl. water)	**1602.4**	**1602.4**	**1602.4**	**1602.4**	**1602.4**



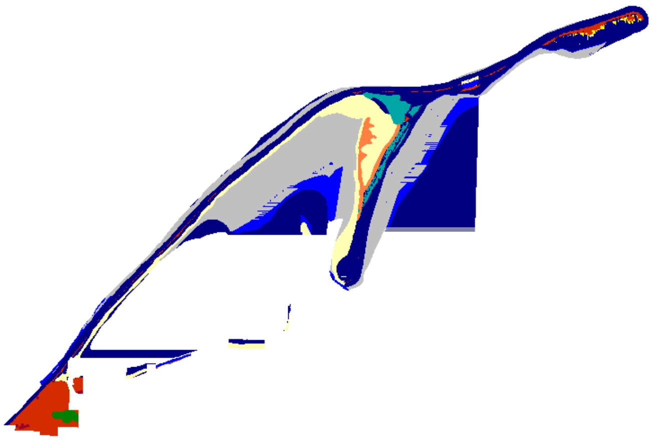
Dungeness NWR, Initial Condition



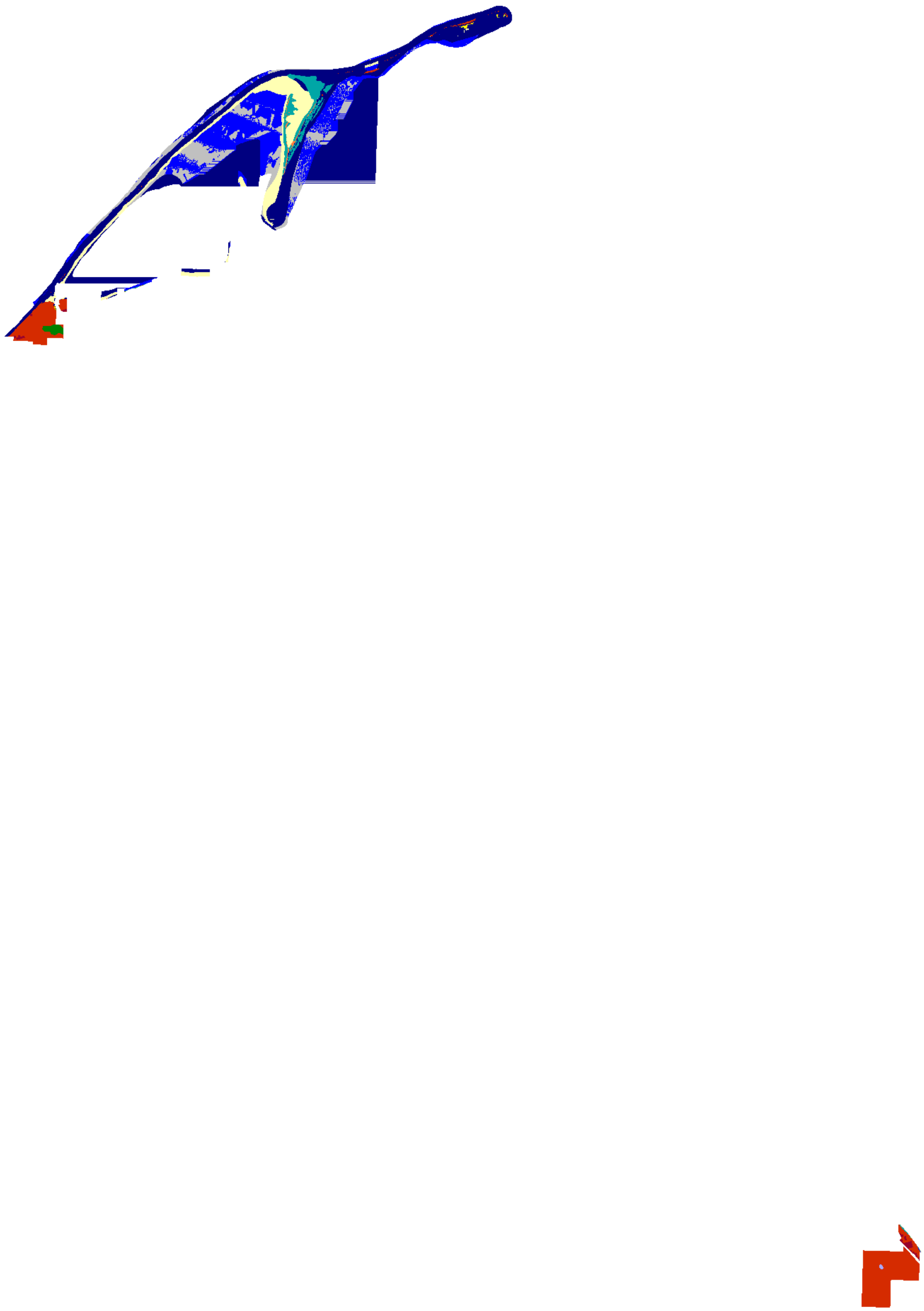
Dungeness NWR, 2025, 1.5 meter



Dungeness NWR, 2050, 1.5 meter



Dungeness NWR, 2075, 1.5 meter

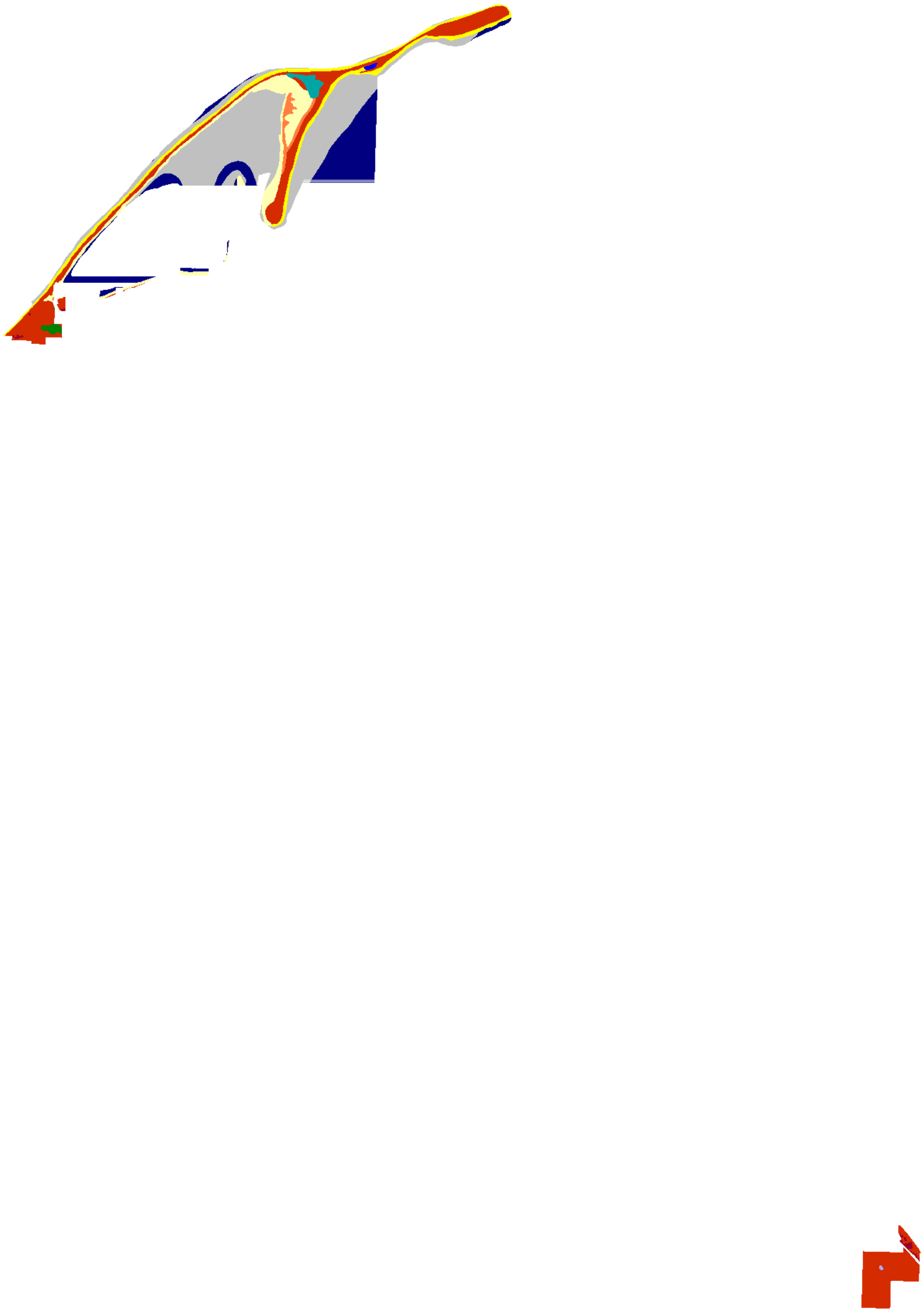


Dungeness NWR, 2100, 1.5 meter

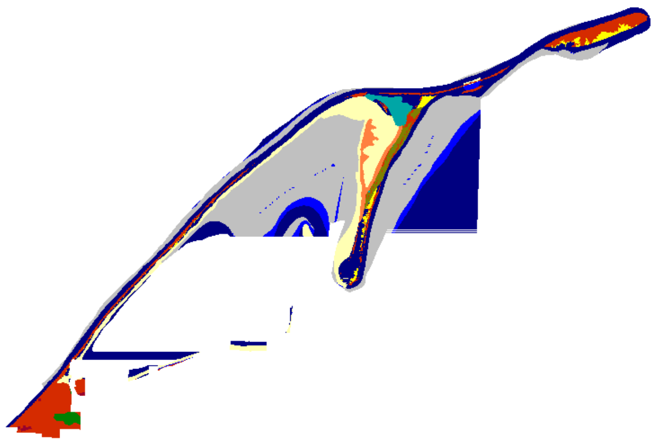
Dungeness Raster
2 Meters Eustatic SLR by 2100

Results in Acres

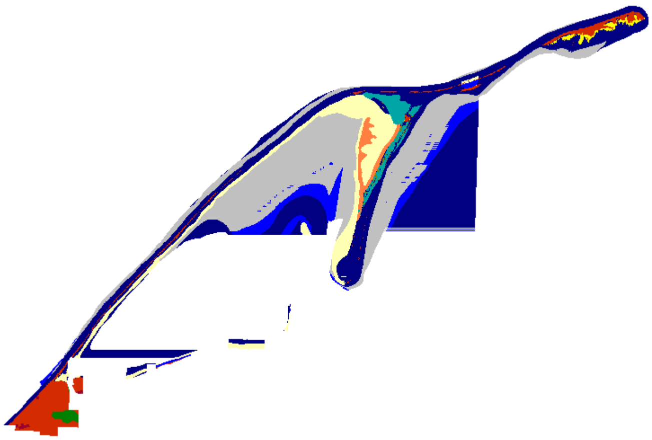
	Initial	2025	2050	2075	2100
Open Ocean	249.8	476.8	573.7	675.4	752.6
Tidal Flat	620.9	568.4	483.0	352.3	62.7
Undeveloped Dry Land	394.7	258.0	218.1	193.5	187.7
Estuarine Beach	145.5	145.9	144.5	142.8	139.8
Ocean Beach	130.1	19.6	8.9	2.2	0.0
Brackish Marsh	25.0	25.0	24.8	4.6	0.4
Saltmarsh	18.6	19.5	34.3	57.7	17.3
Swamp	7.8	7.8	7.8	7.8	7.8
Dev. Dry Land	6.8	6.8	6.8	6.8	6.8
Estuarine Open Water	2.5	55.9	96.3	158.2	426.3
Inland Open Water	0.7	0.7	0.7	0.7	0.7
Trans. Salt Marsh	0.0	18.1	3.6	0.5	0.3
Total (incl. water)	**1602.4**	**1602.4**	**1602.4**	**1602.4**	**1602.4**



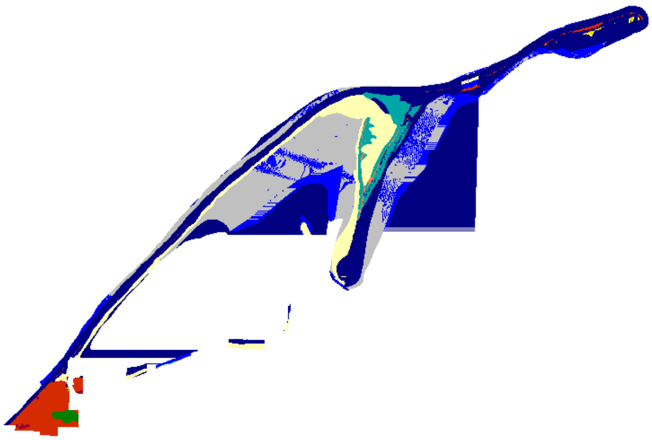
Dungeness NWR, Initial Condition



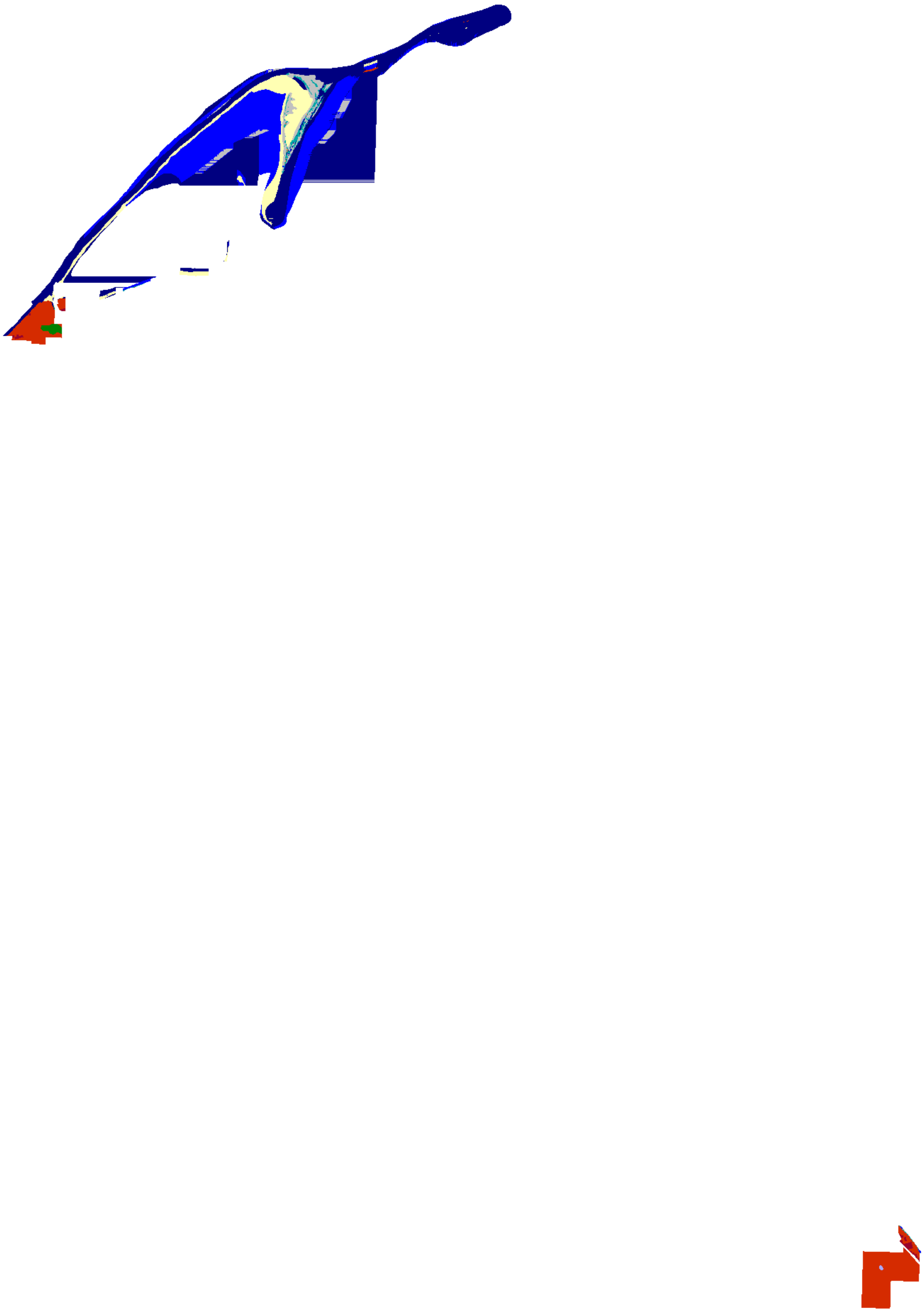
Dungeness NWR, 2025, 2 meters



Dungeness NWR, 2050, 2 meters



Dungeness NWR, 2075, 2 meters



Dungeness NWR, 2100, 2 meters

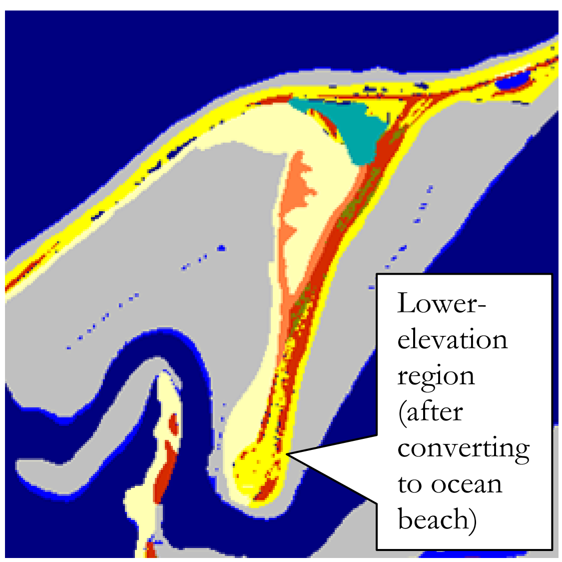
Discussion

The majority of Dungeness NWR is comprised of low-elevation spits of dry land and beach, making these areas particularly vulnerable to SLR.

There is some model uncertainty due to horizontal changes in the spit's location. The spit has apparently migrated in the time between the NWI land cover photo (1980) and the elevation data flights (2001, see Figure 3). Areas that were dry land in the NWI photo but that have open-water elevations now will immediately convert to open water within SLAMM simulations. However, SLAMM does not create beach or dry land when open water has dry land elevations. This means that the horizontal migration of the spit likely causes results to be overstated.

Dry land on the spit is also subject to conversion to ocean beach when it becomes regularly inundated. SLAMM then predicts that the majority of ocean beach will be lost above the 0.39 meter SLR scenario. *Ocean* beach loss in SLAMM is calculated using the Bruun rule, a simple algorithm for determining horizontal erosion rates based on SLR. A considerable amount of uncertainty, therefore, is attached to SLAMM ocean-beach loss rates at this site.

The southern portion of the Dungeness spit has lower elevations in the center of the peninsula. This makes this portion of the spit convert immediately to ocean beach and be subject to erosion following that conversion.



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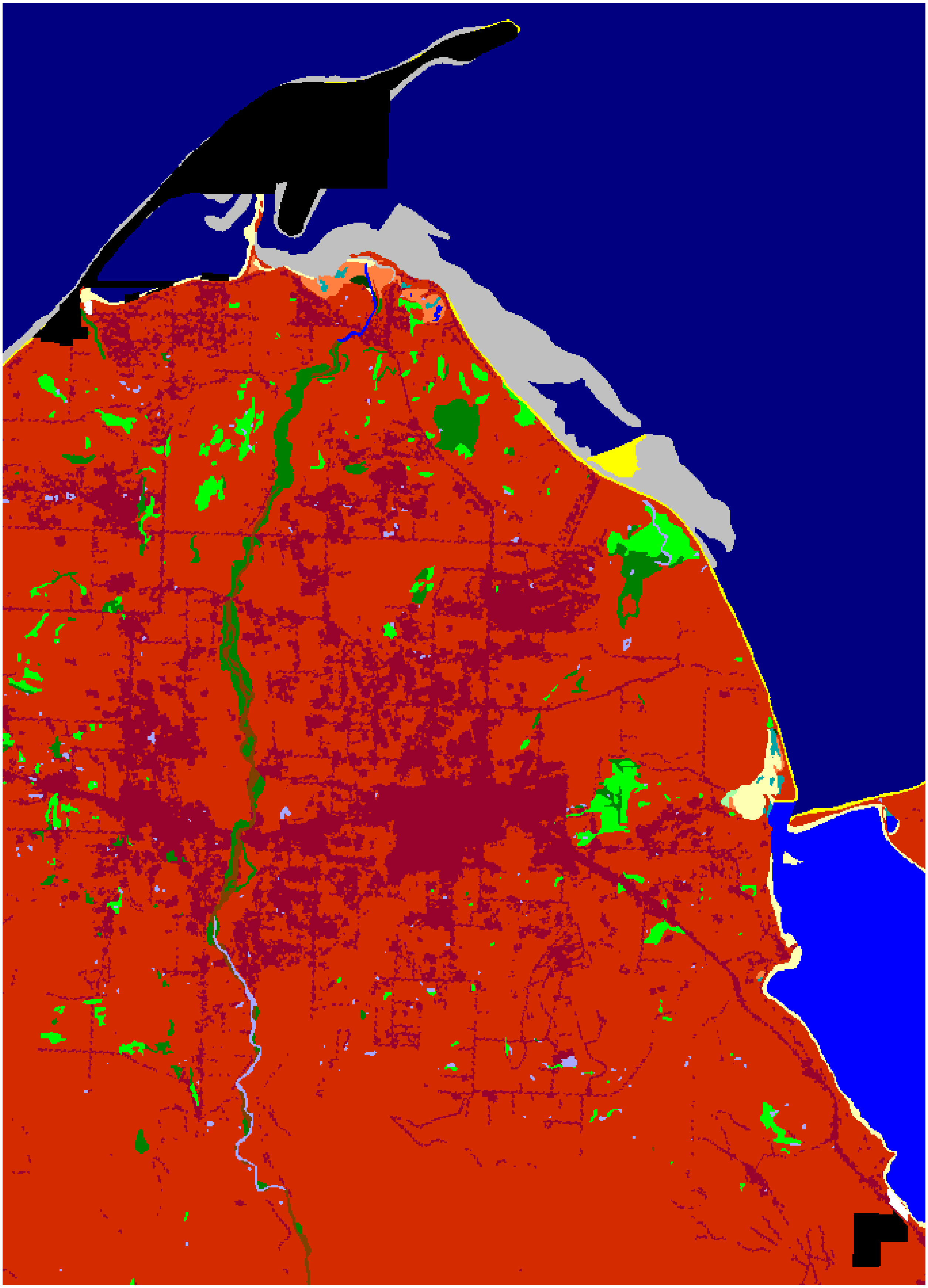
Appendix A: Contextual Results

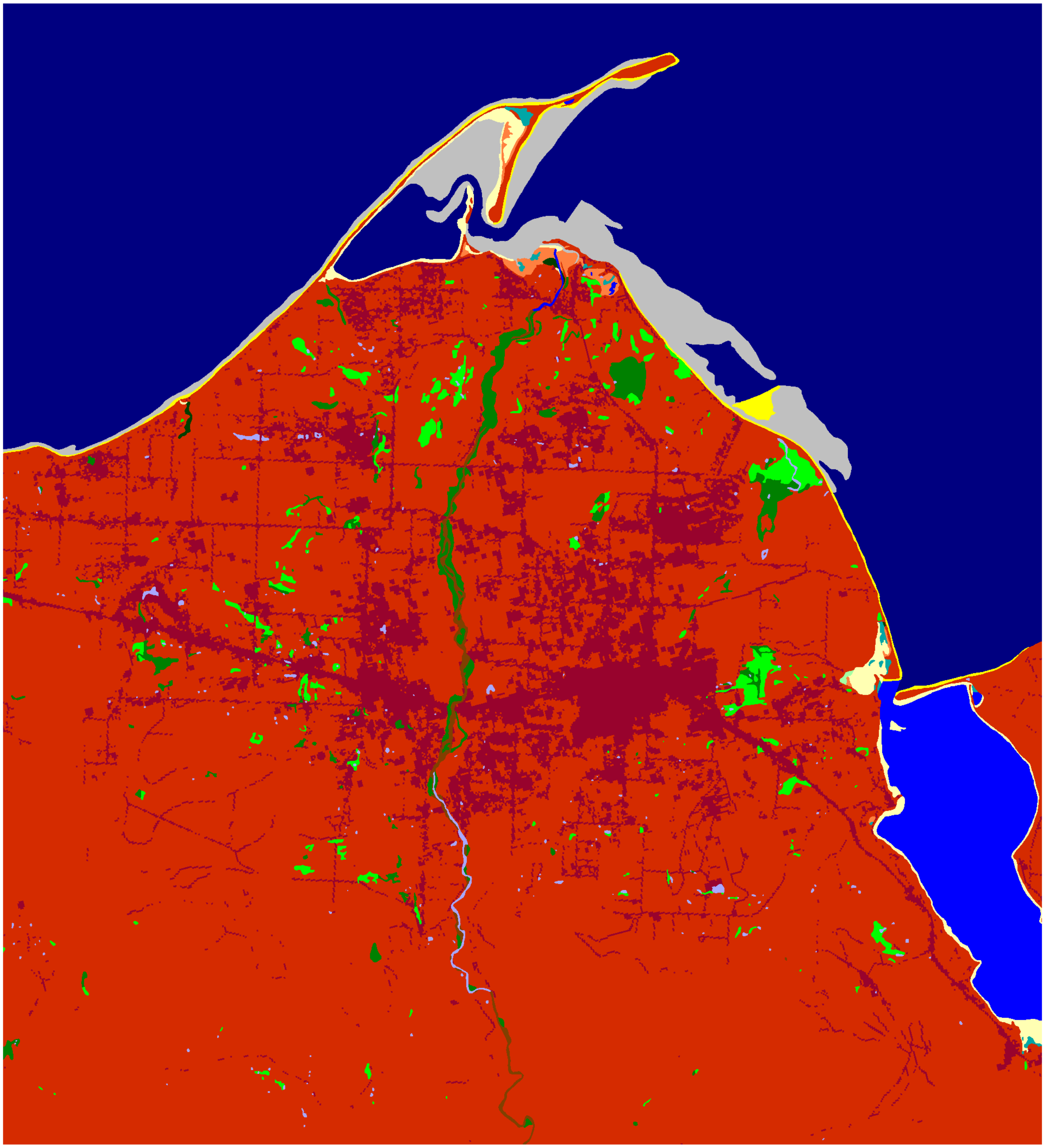
The SLAMM model does take into account the context of the surrounding lands or open water when calculating effects. For example, erosion rates are calculated based on the maximum fetch (wave action) which is estimated by assessing contiguous open water to a given marsh cell. Another example is that inundated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

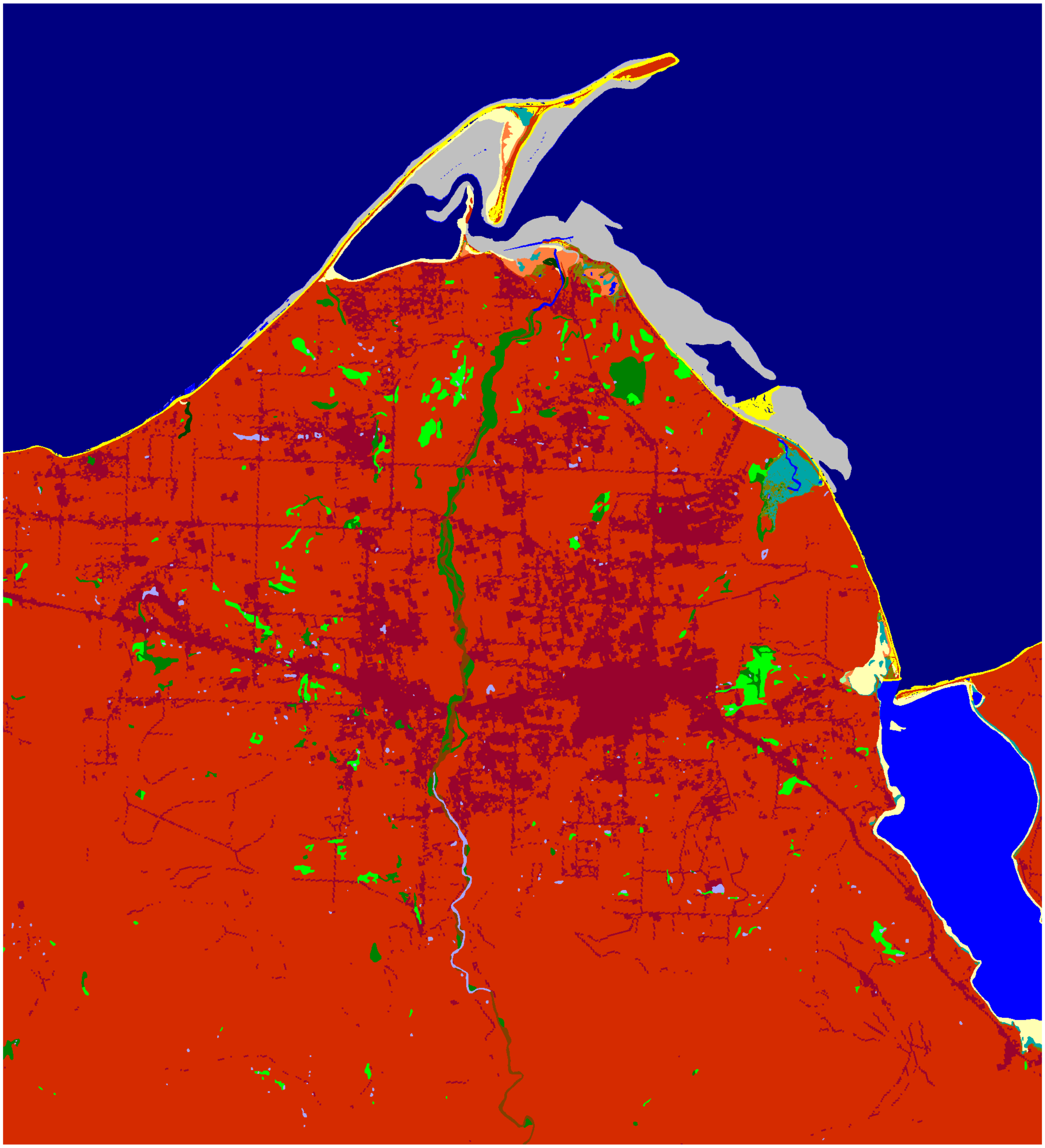
- Results were closely examined (quality assurance) within USFWS refuges but not closely examined for the larger region.
- Site-specific parameters for the model were derived for USFWS refuges whenever possible and may not be regionally applicable.
- Especially in areas where dikes are present, an effort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



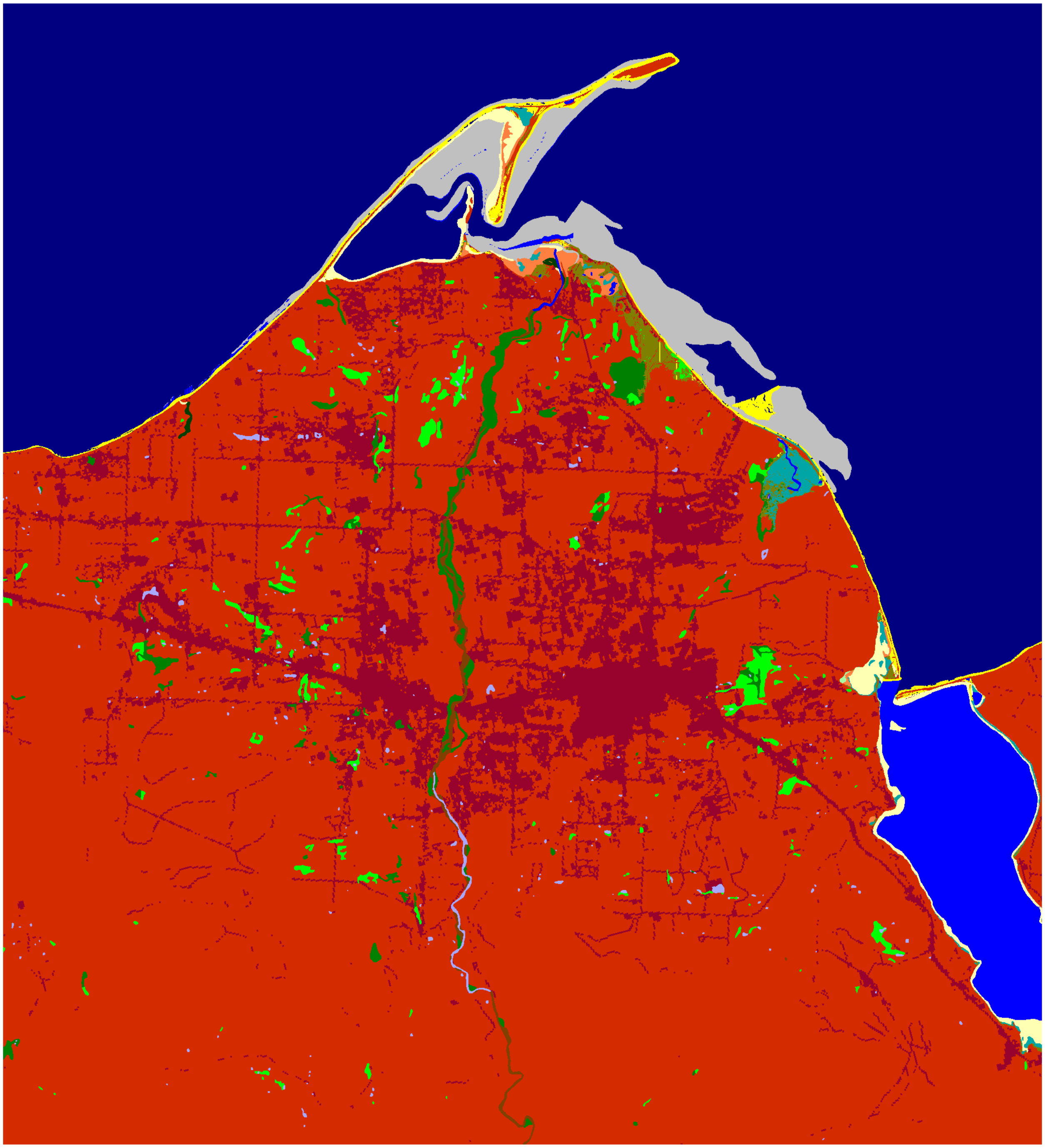
Dungeness National Wildlife Refuge within simulation context (black).



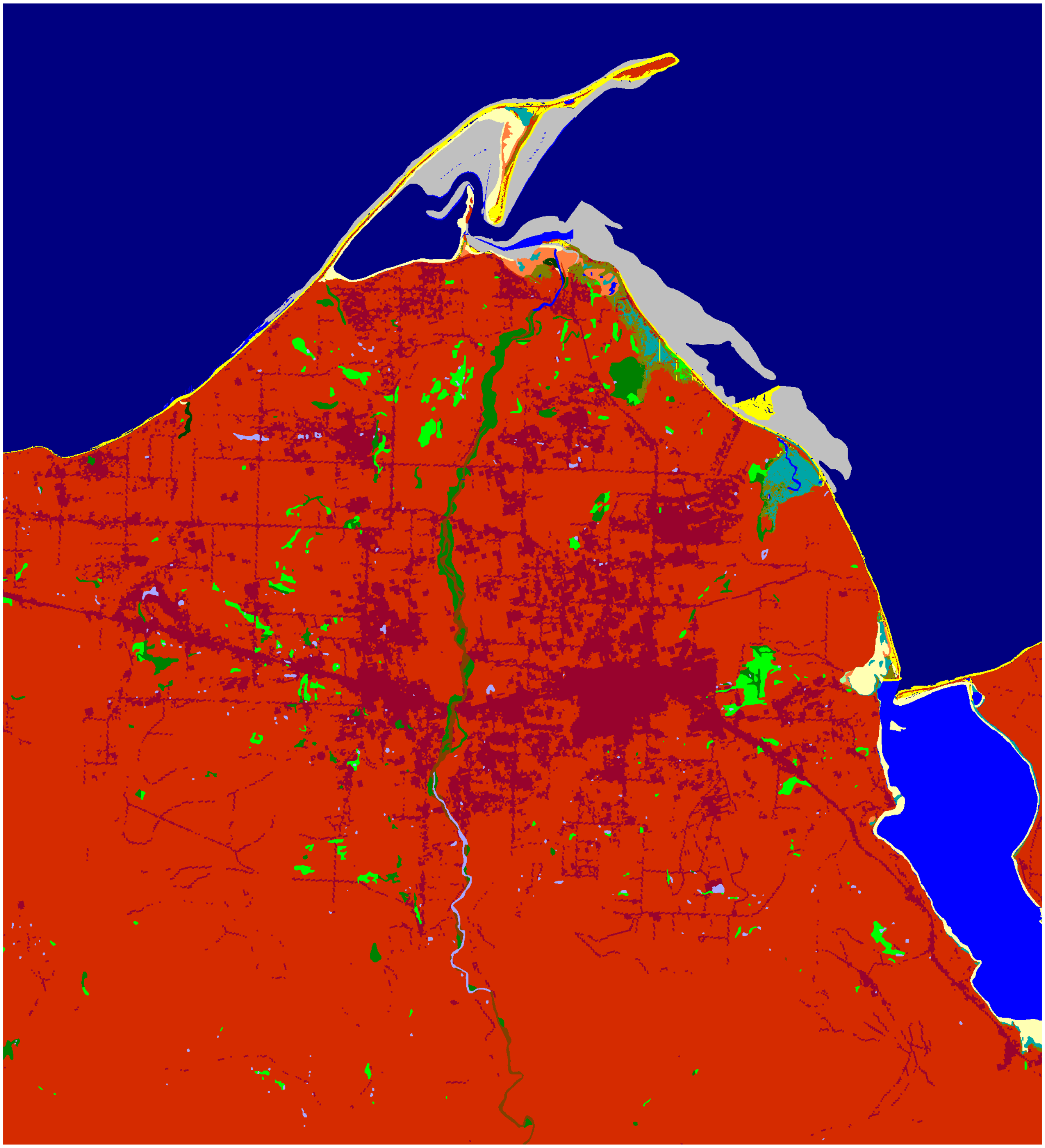
Dungeness Context, Initial Condition



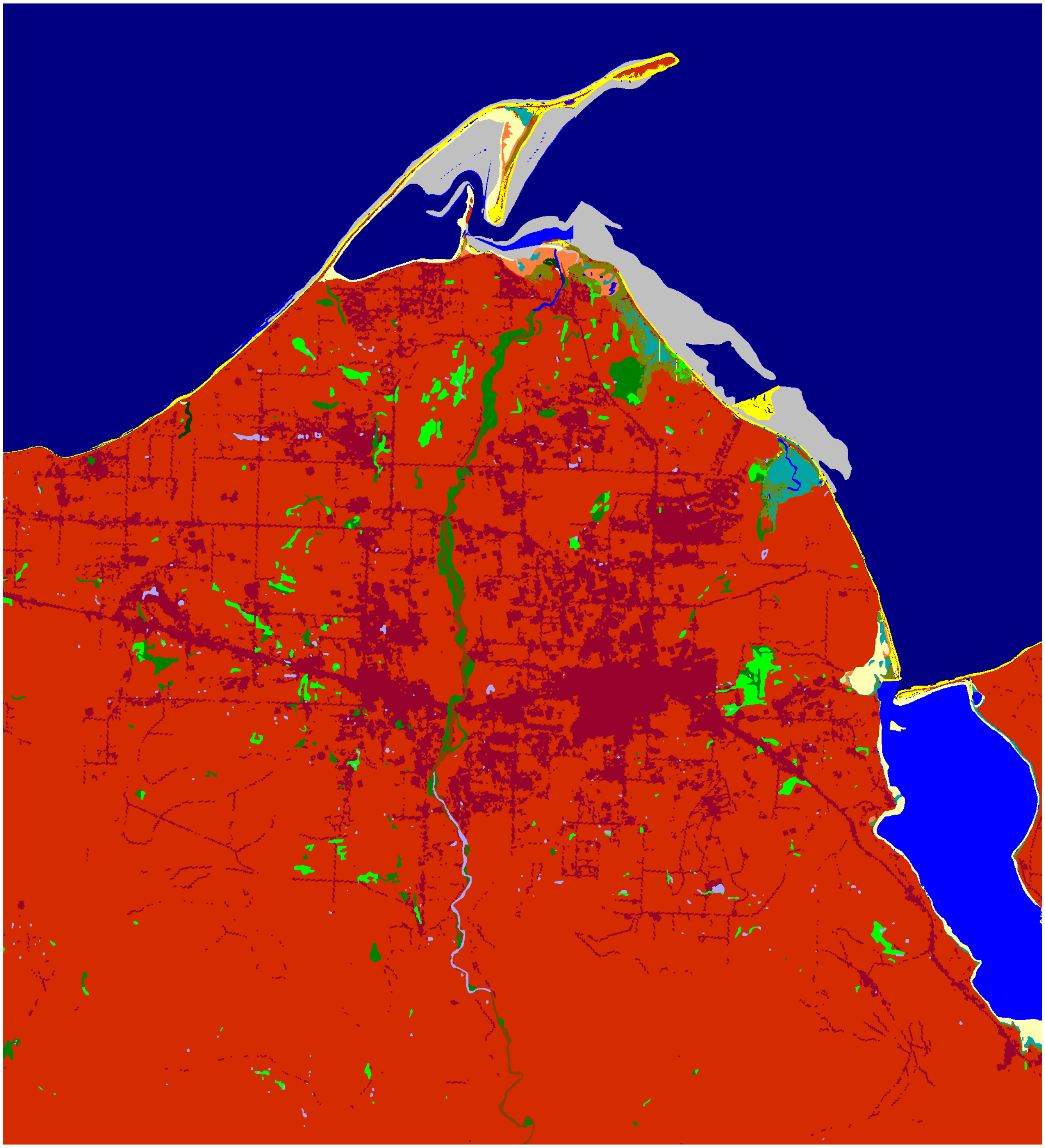
Dungeness Context, 2025, Scenario A1B Mean



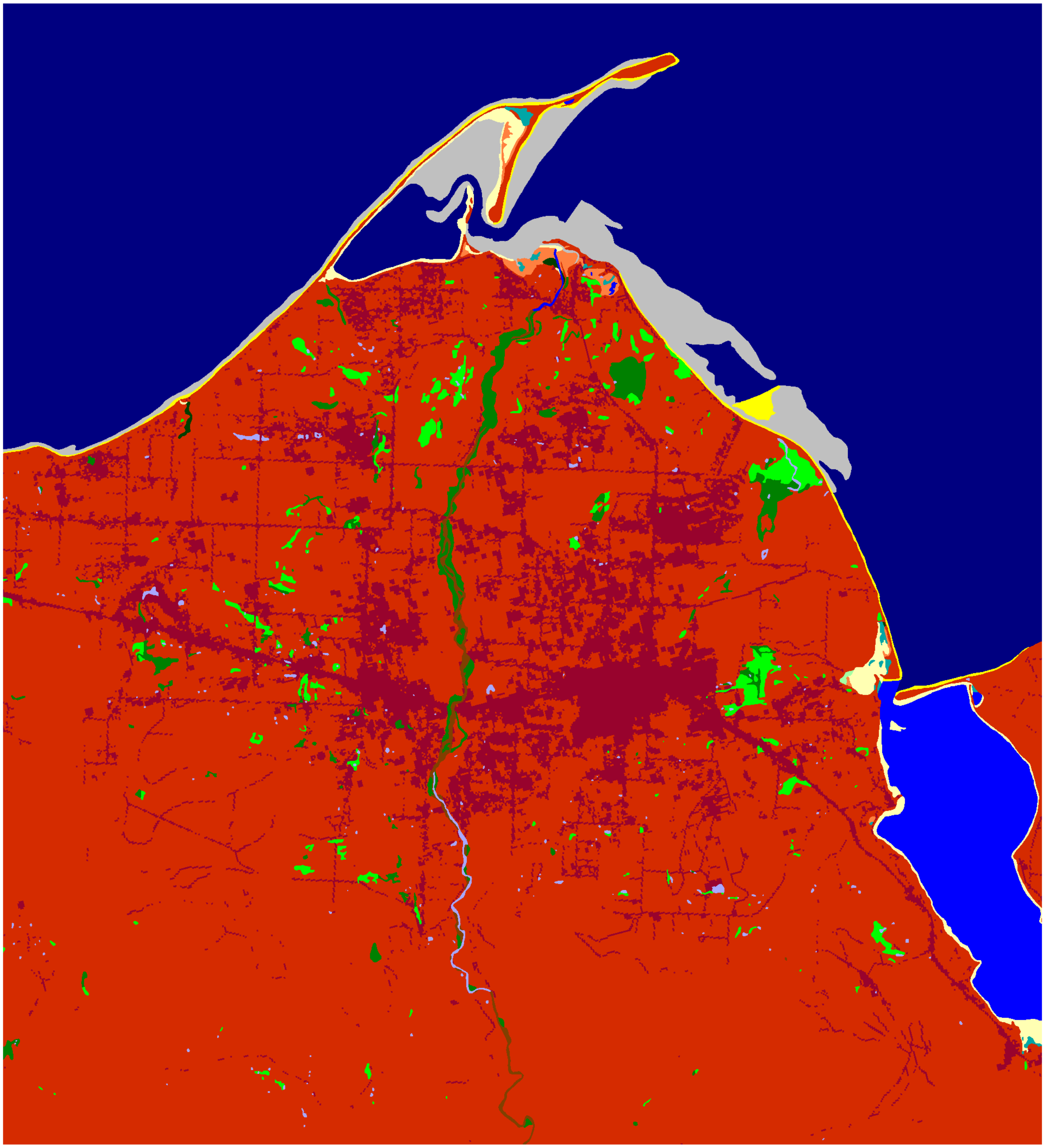
Dungeness Context, 2050, Scenario A1B Mean



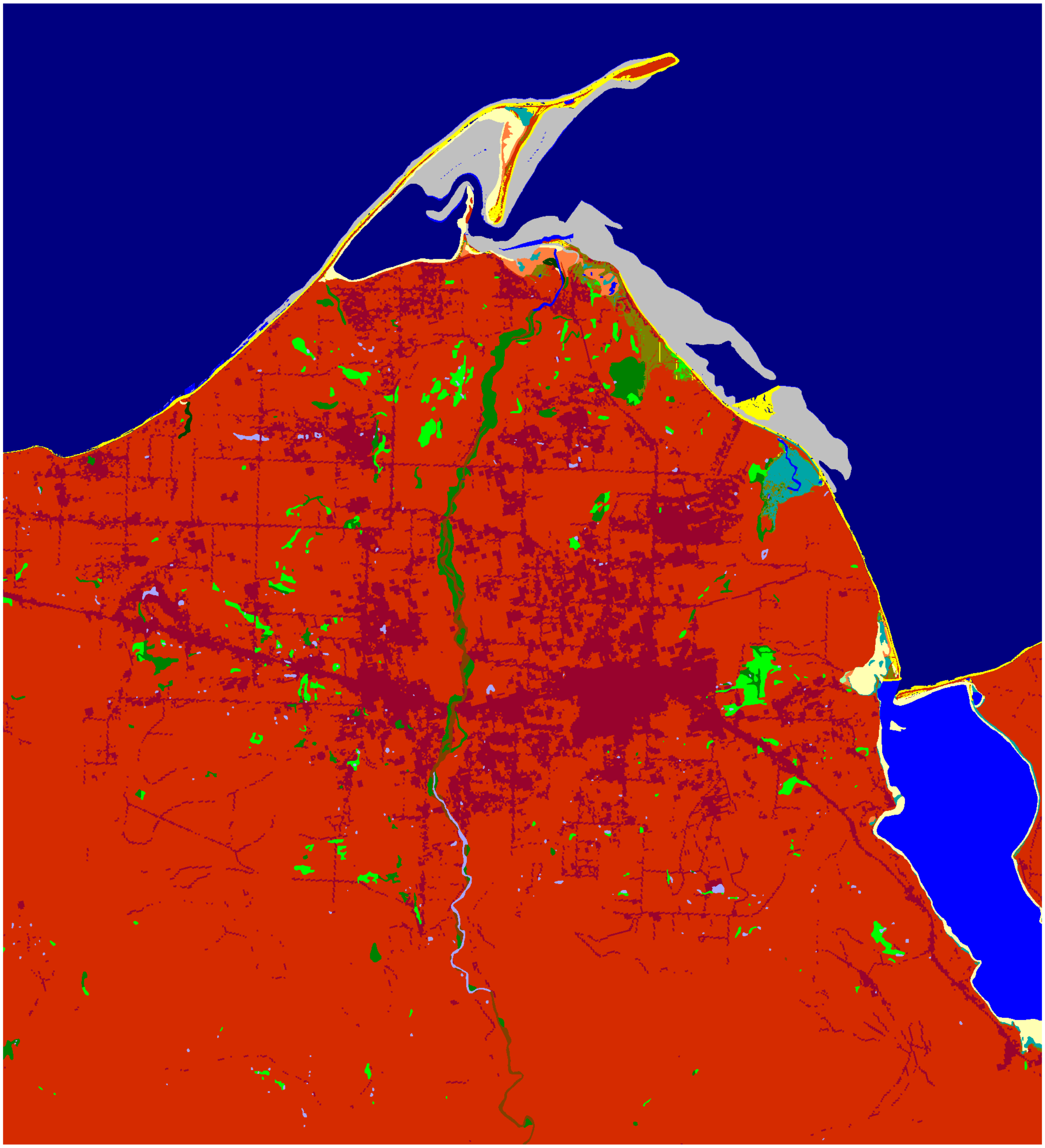
Dungeness Context, 2075, Scenario A1B Mean

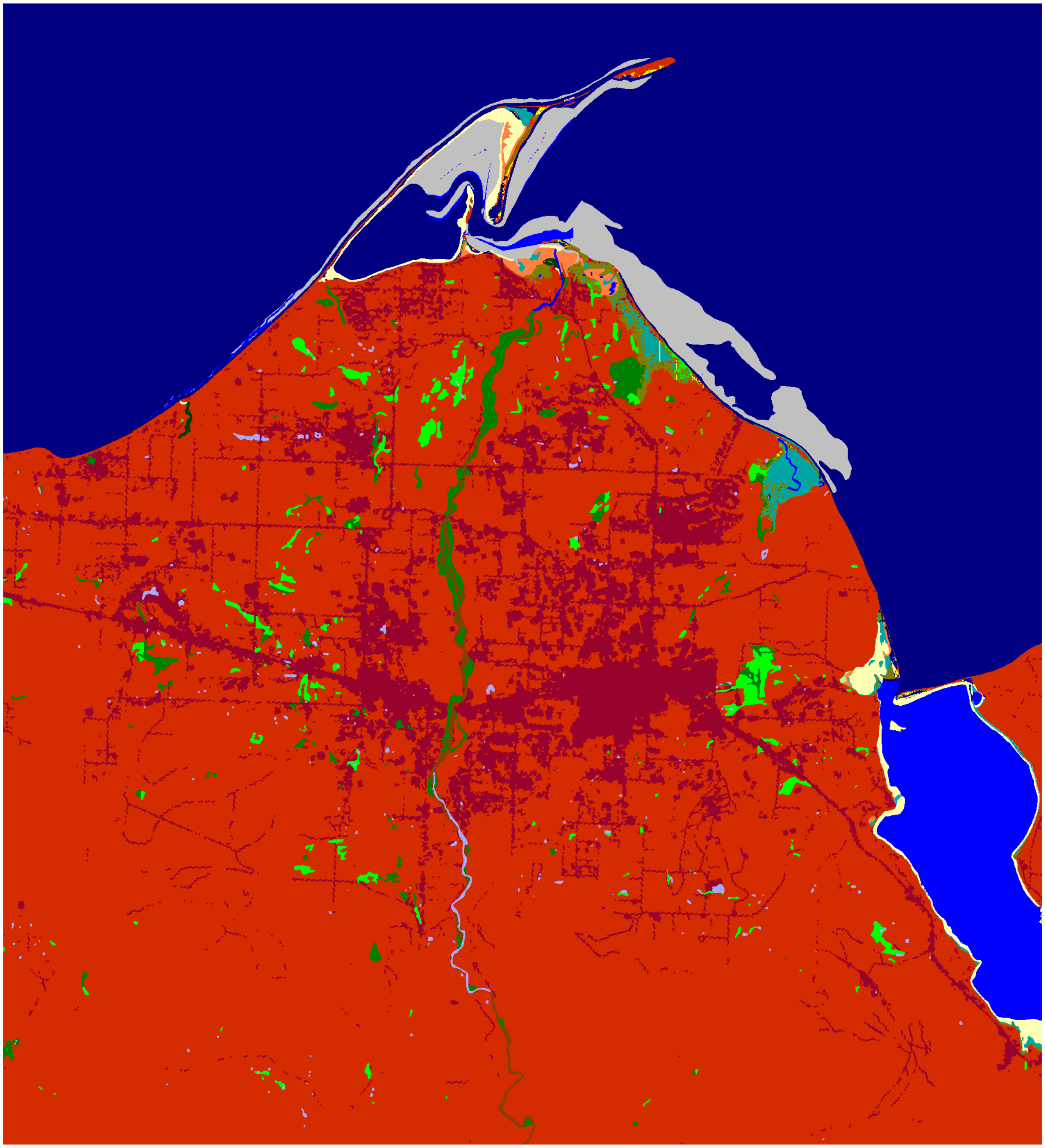


Dungeness Context, 2100, Scenario A1B Mean

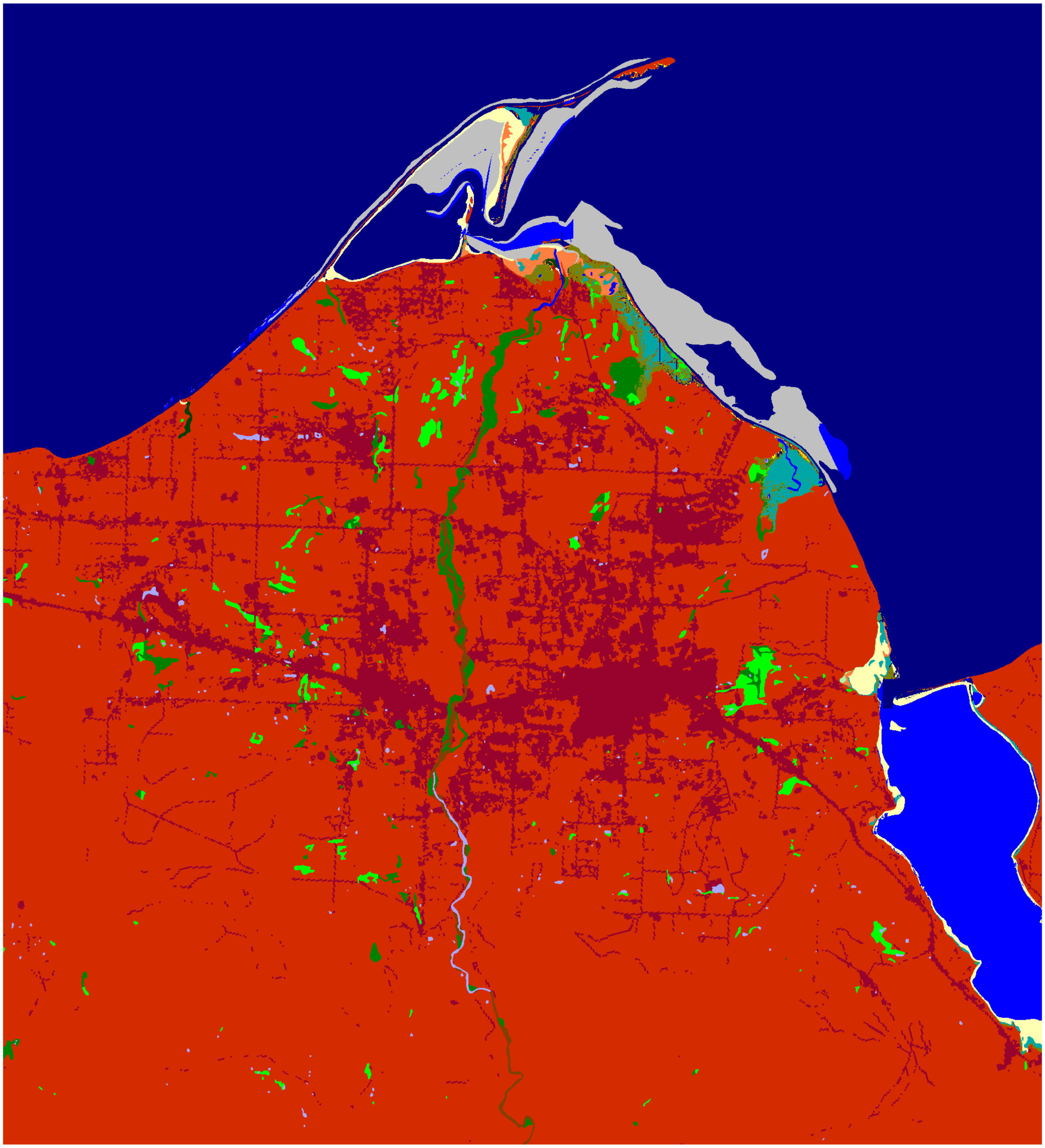


Dungeness Context, Initial Condition

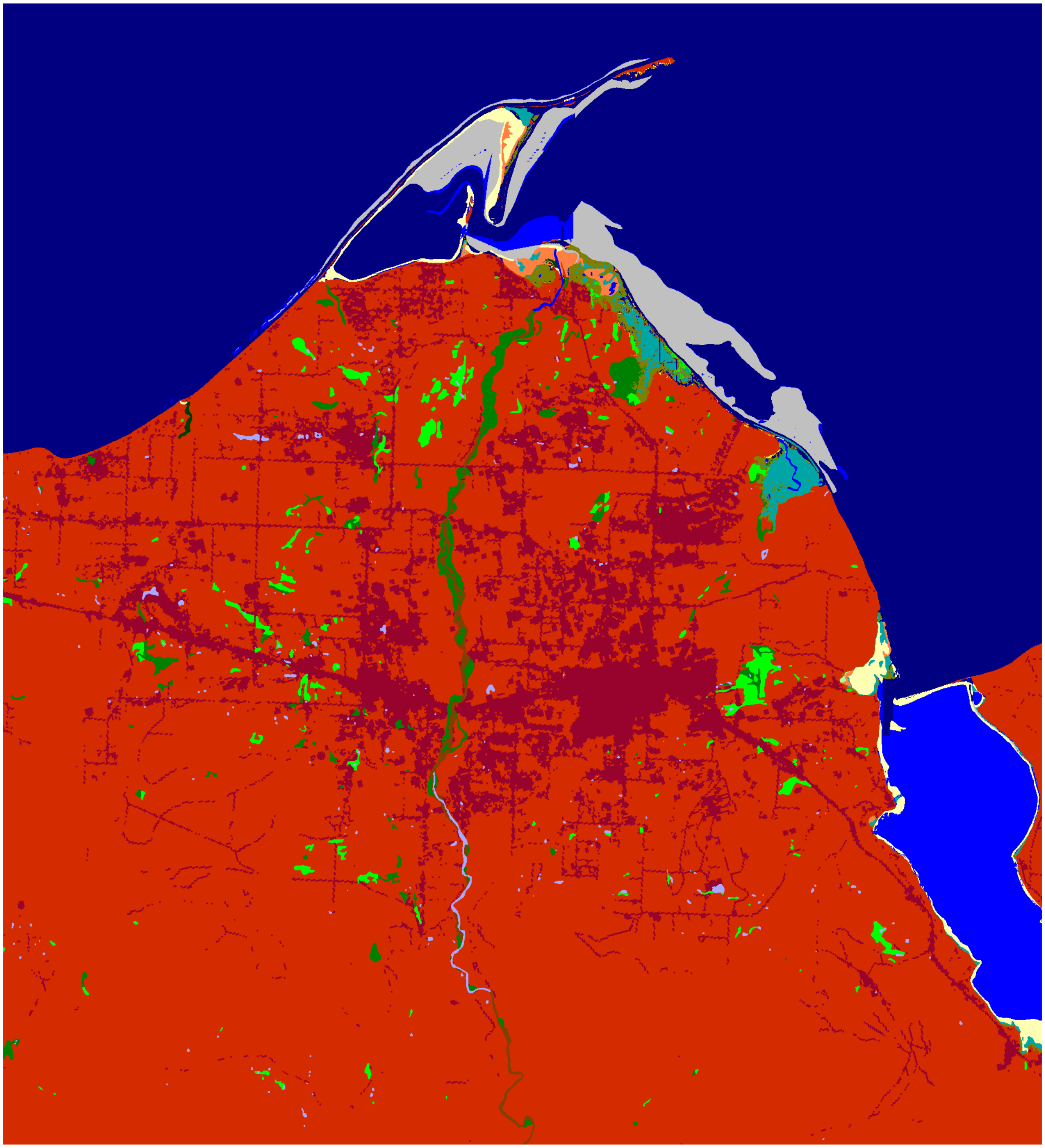

Dungeness Context, 2025, Scenario A1B Maximum



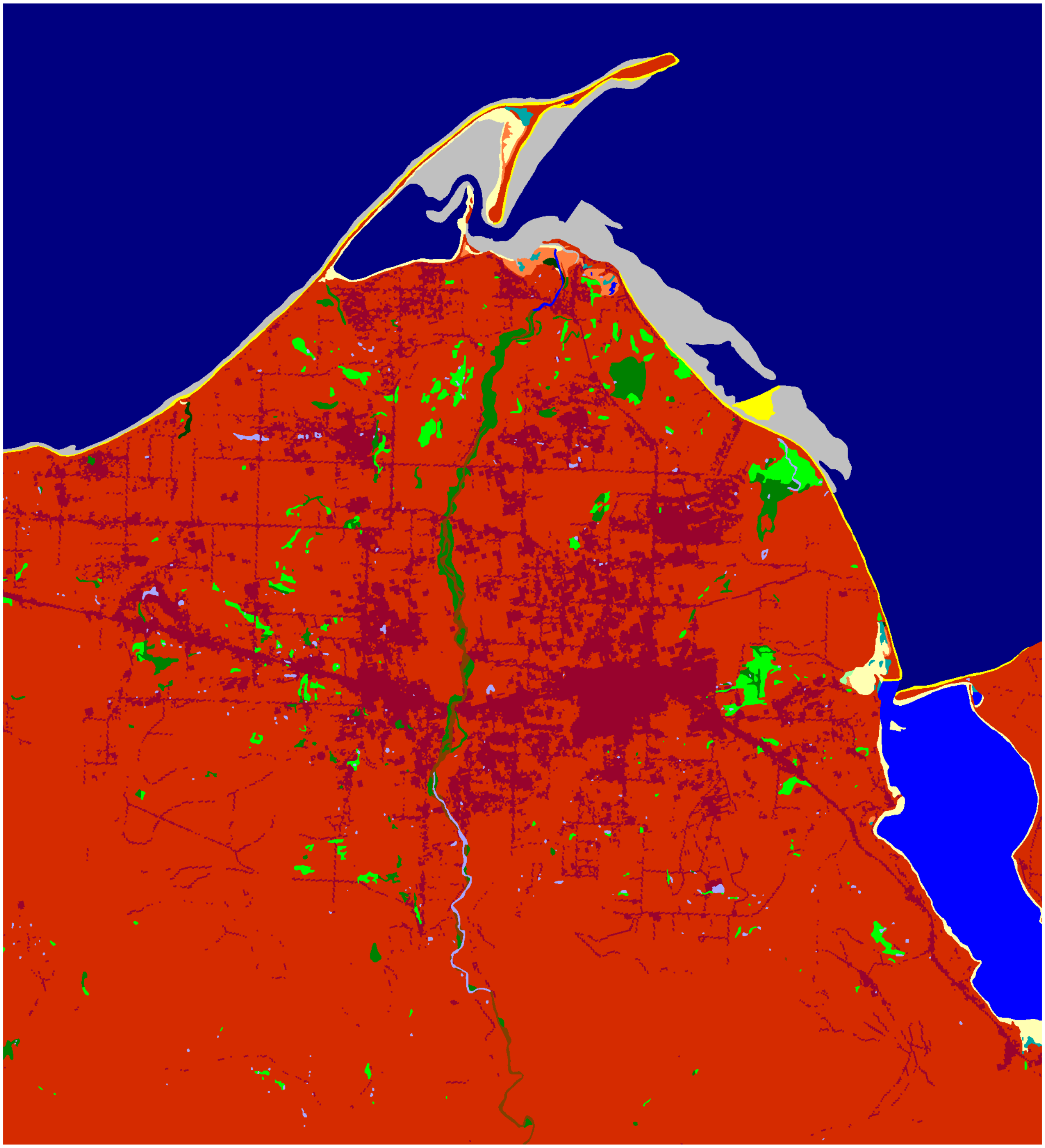
Dungeness Context, 2050, Scenario A1B Maximum



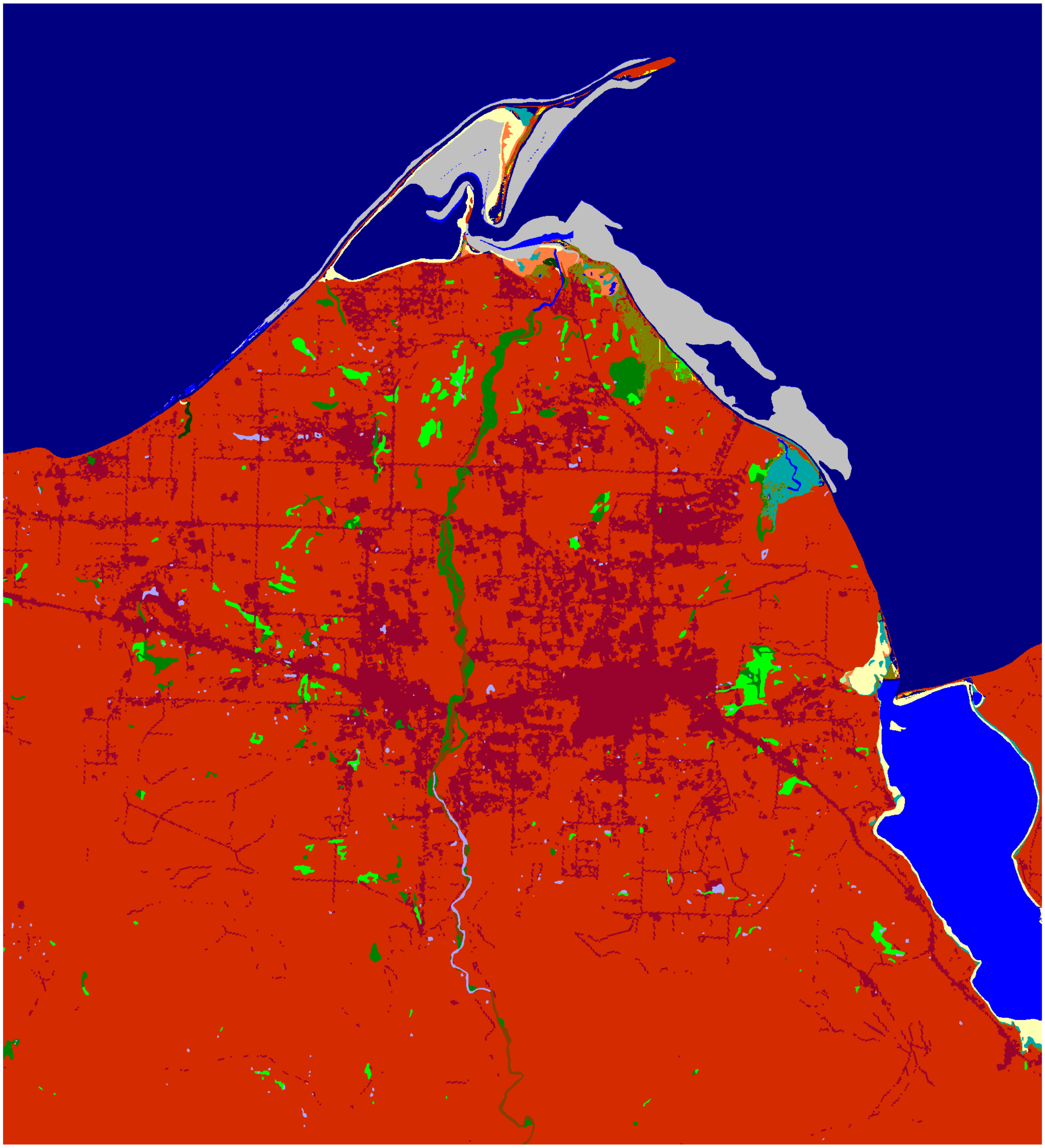
Dungeness Context, 2075, Scenario A1B Maximum



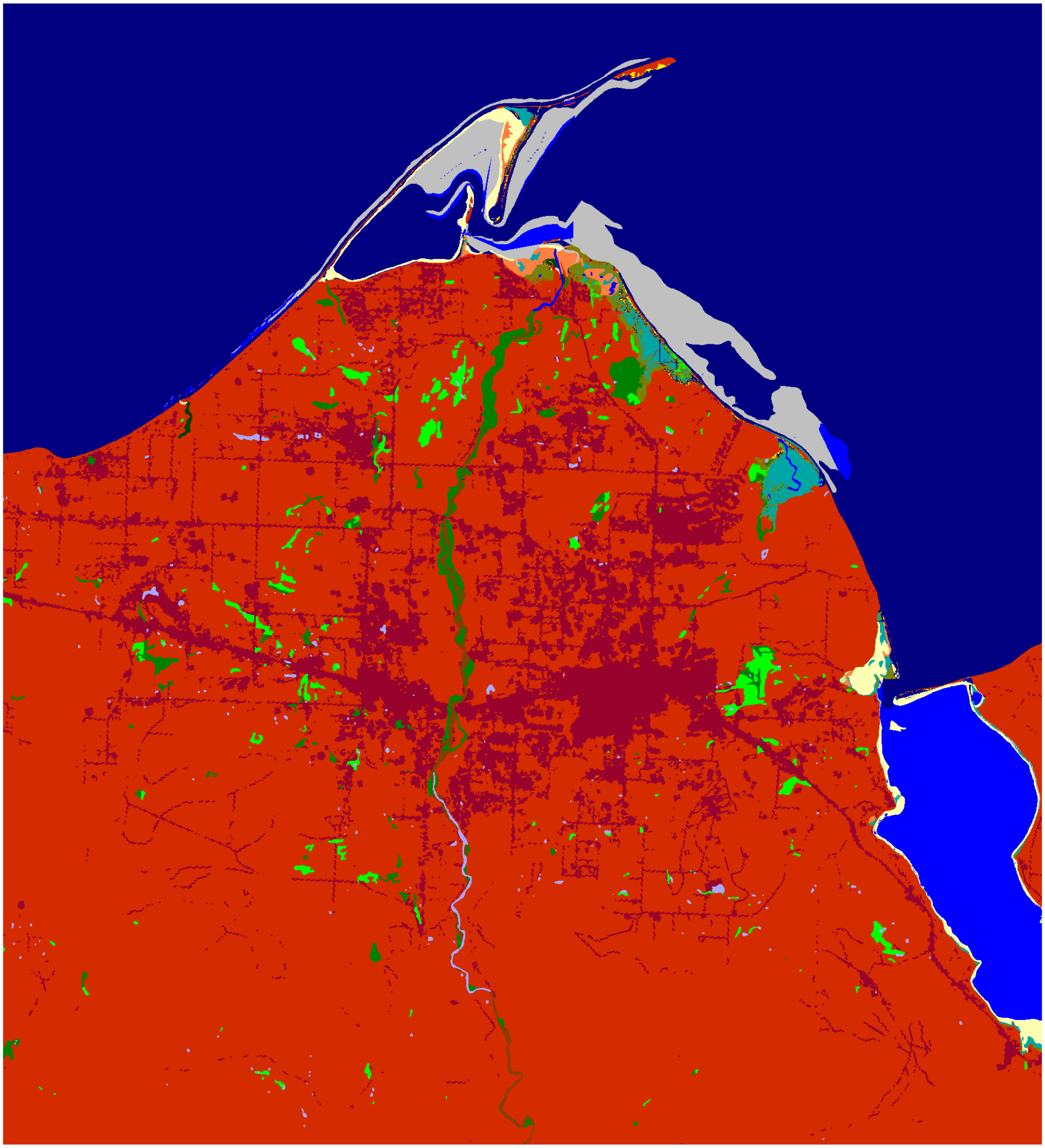
Dungeness Context, 2100, Scenario A1B Maximum



Dungeness Context, Initial Condition



Dungeness Context, 2025, 1 meter



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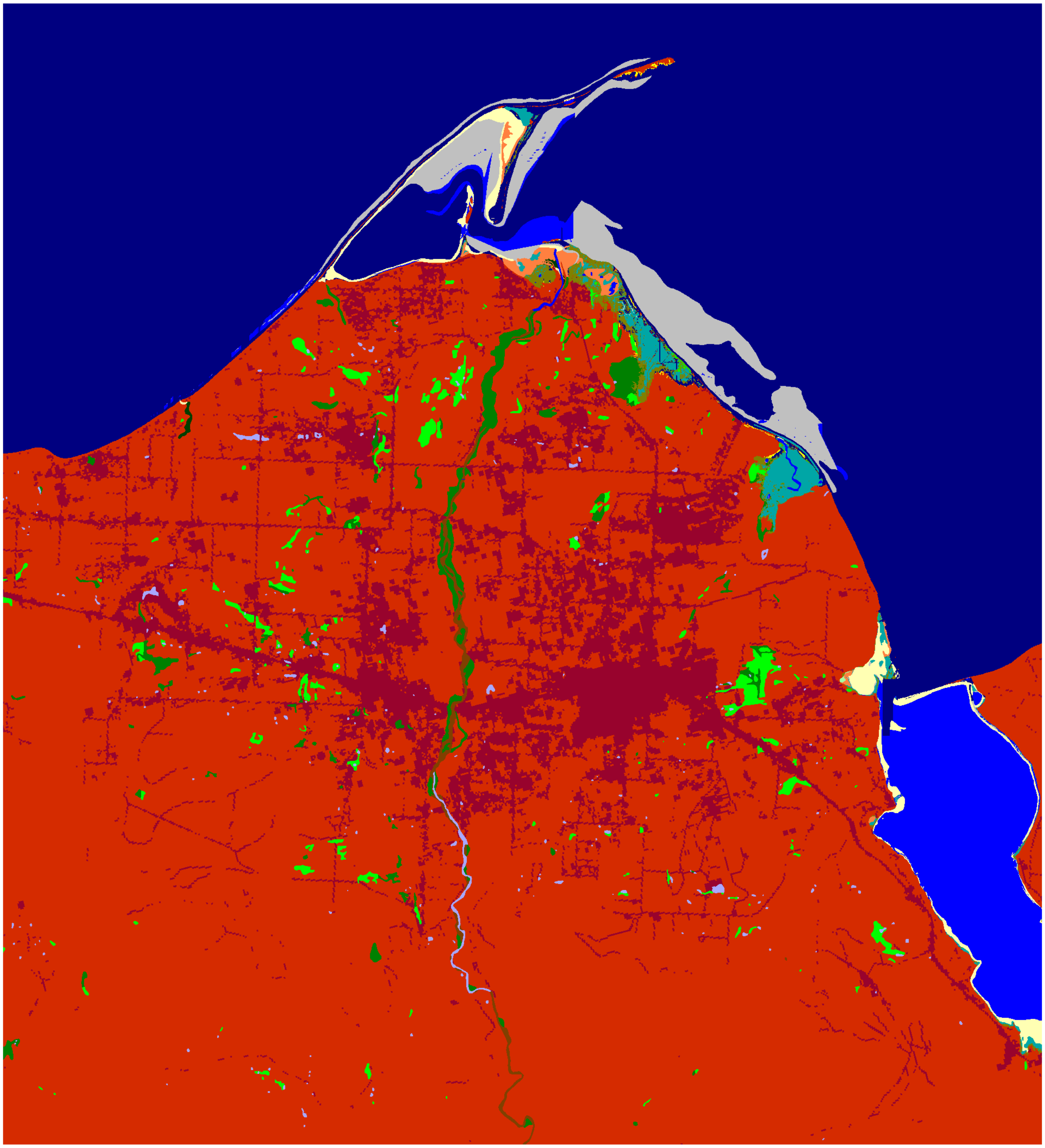

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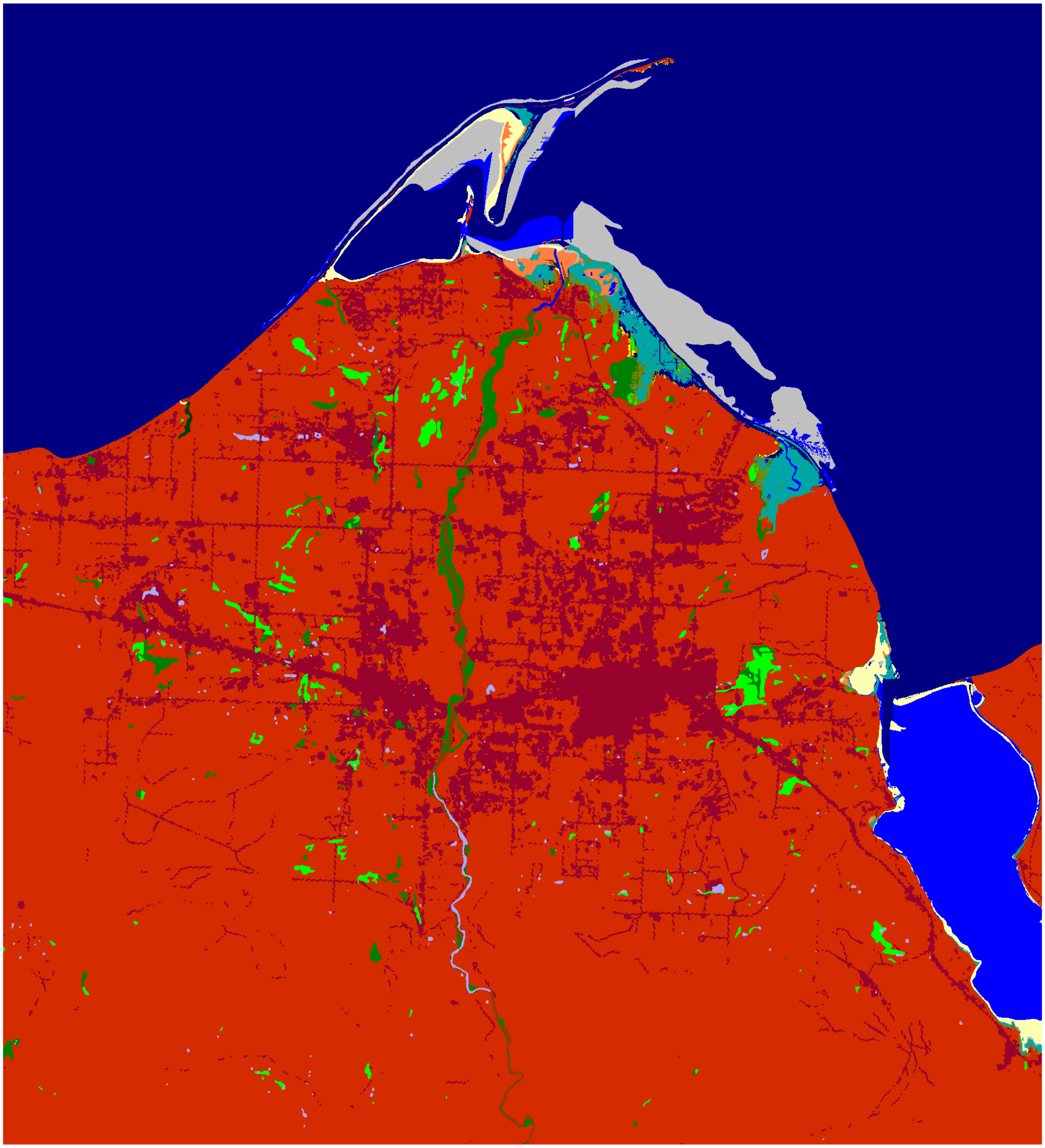
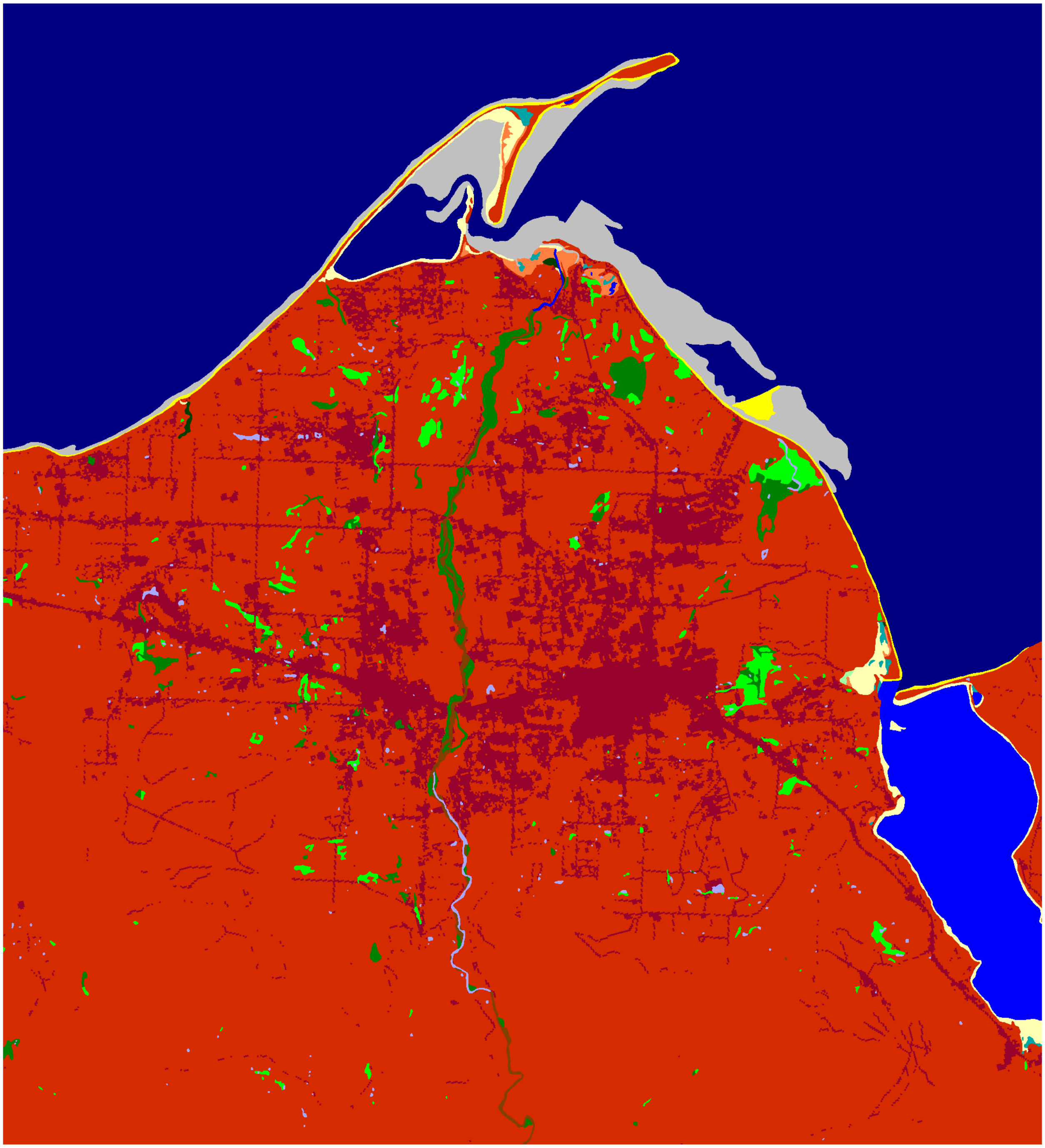
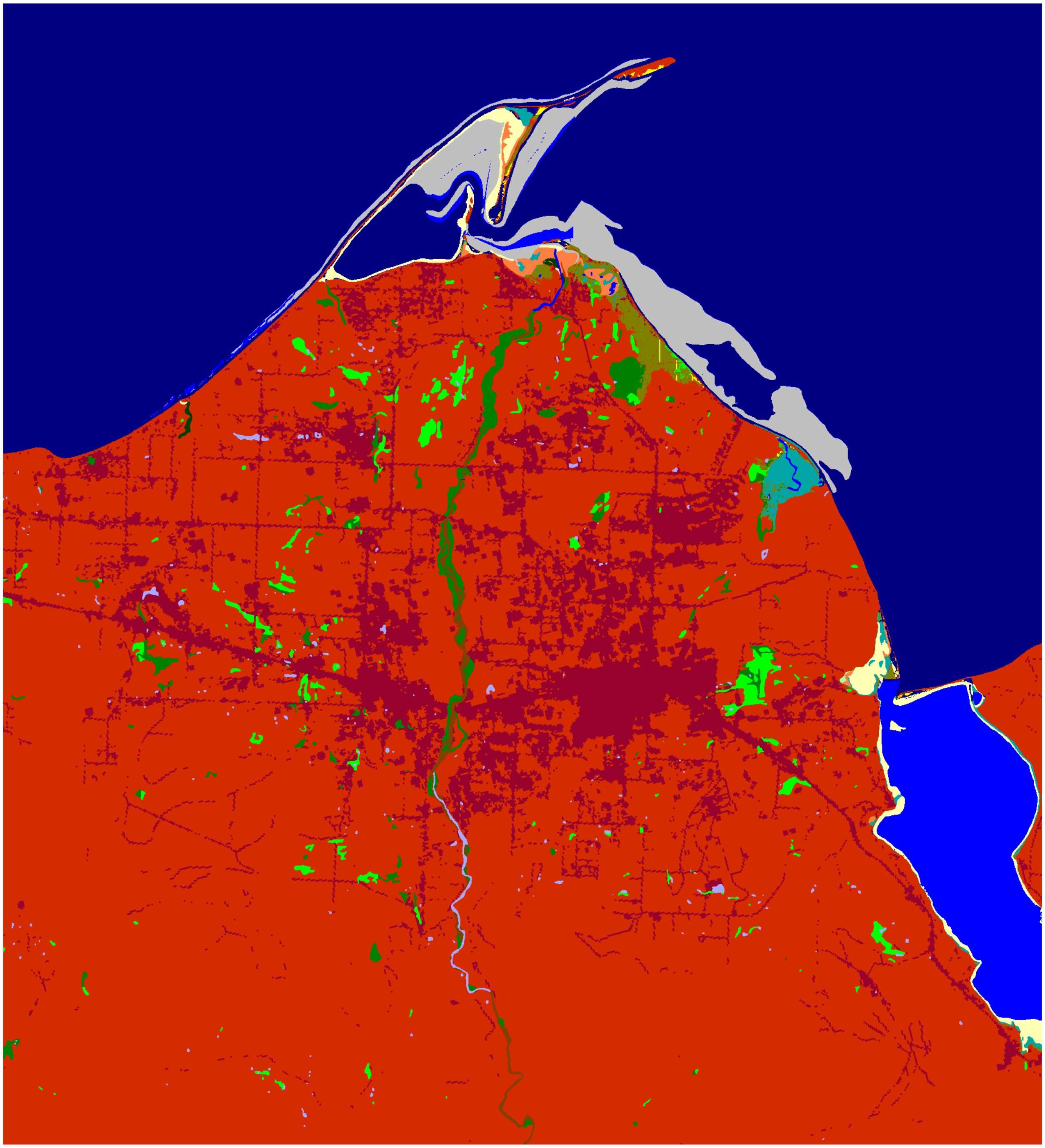


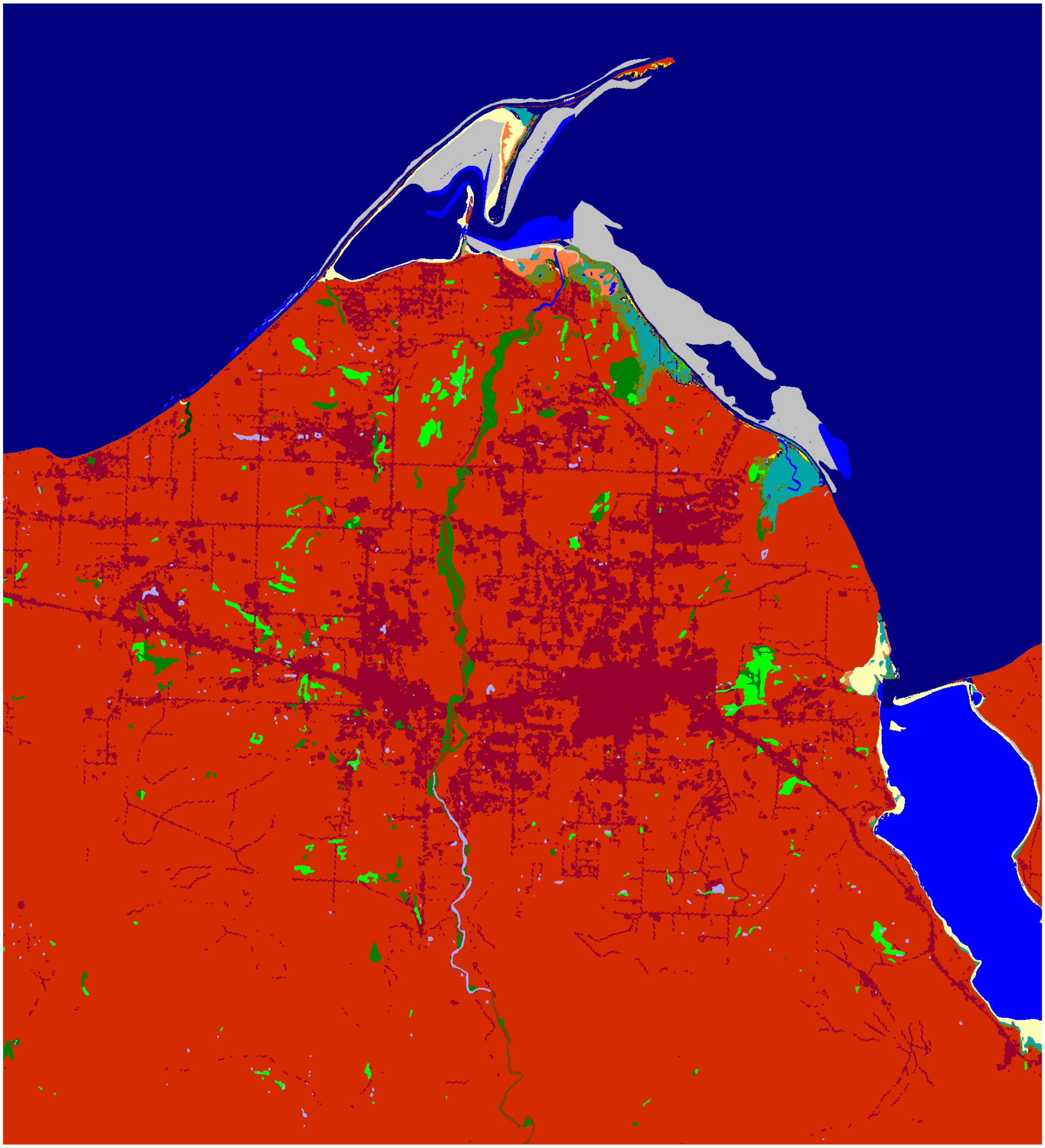
Dungeness Context, 2100, 1 meter



Dungeness Context, Initial Condition



Dungeness Context, 2025, 1.5 meter



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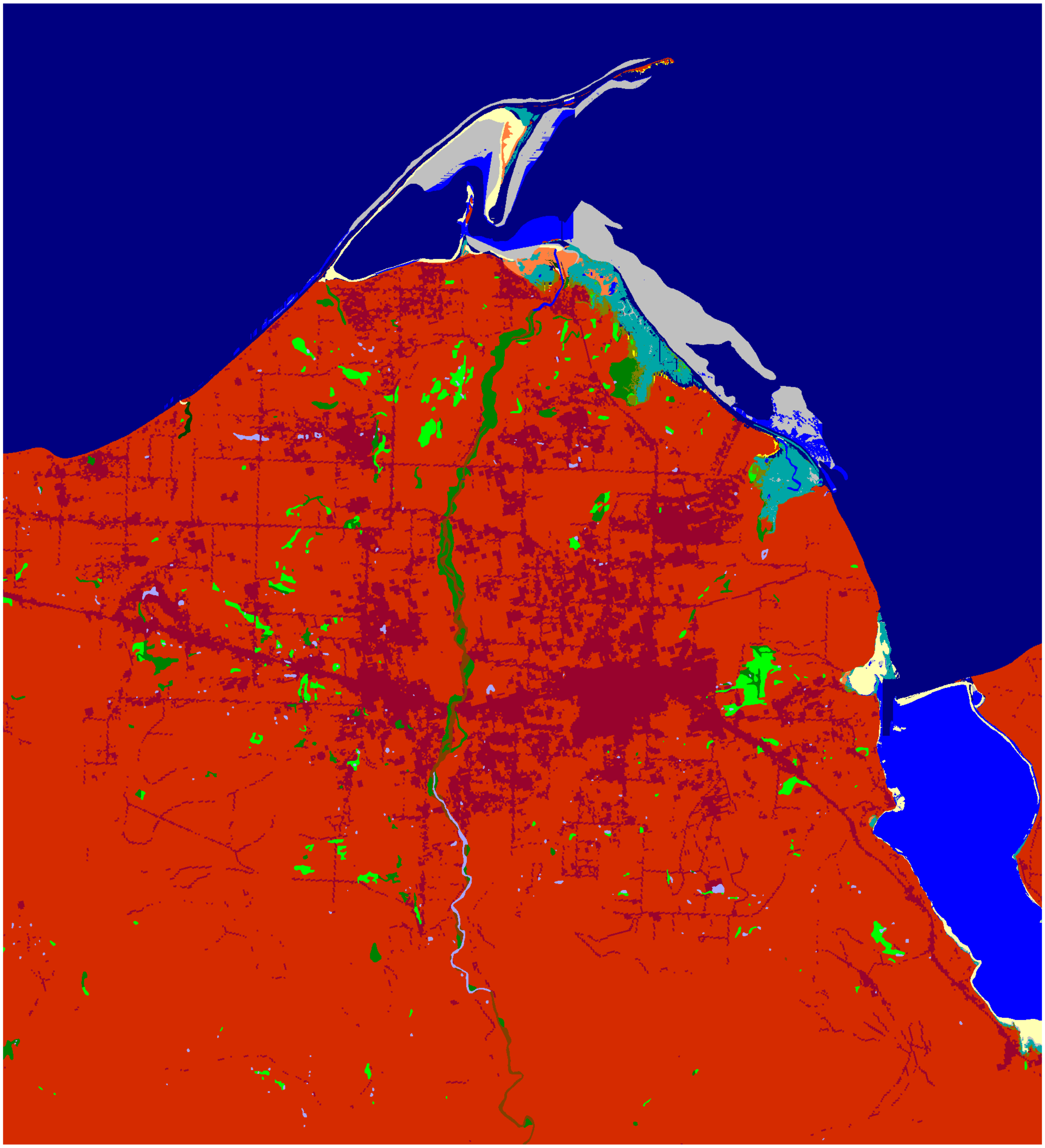
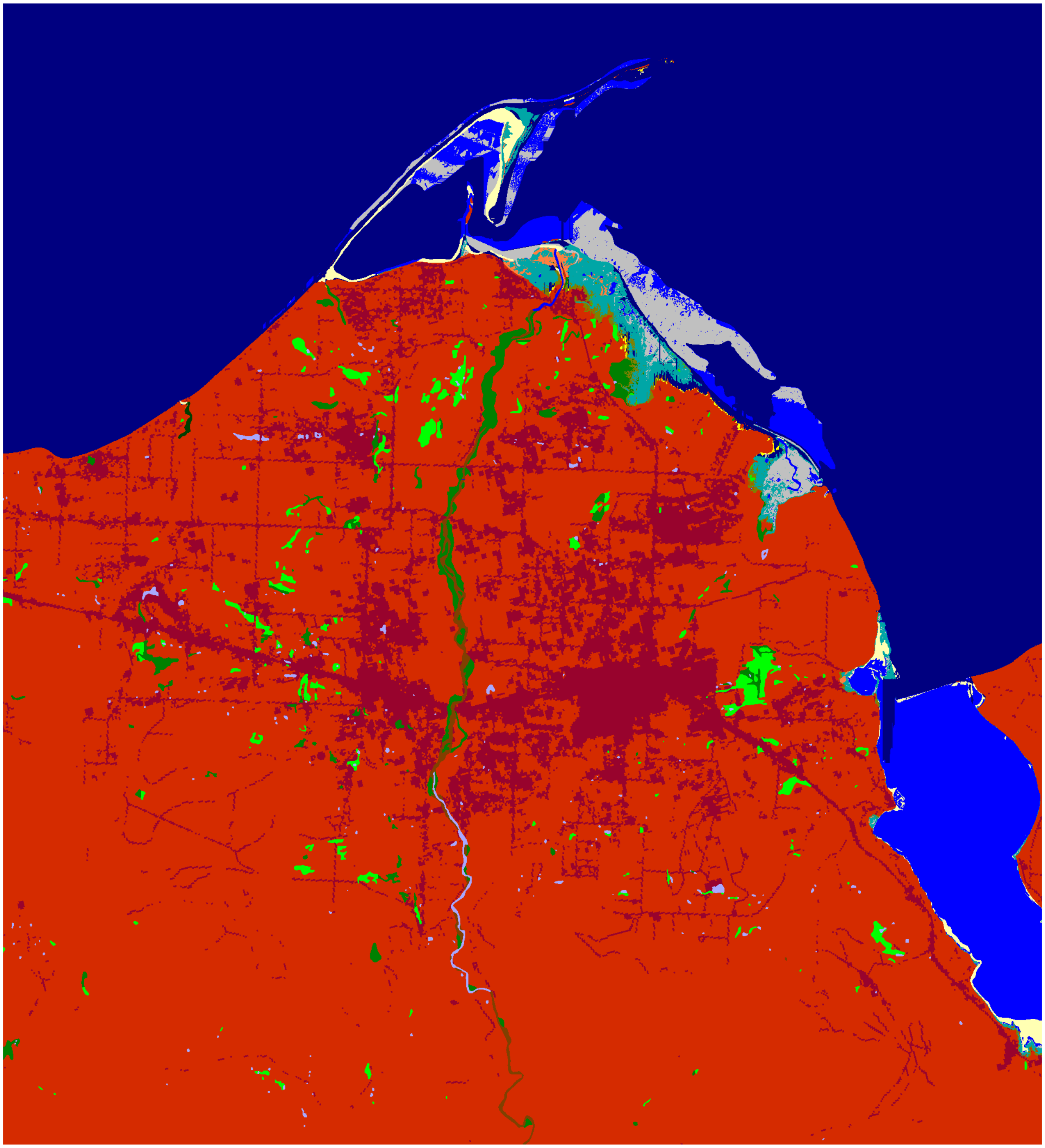
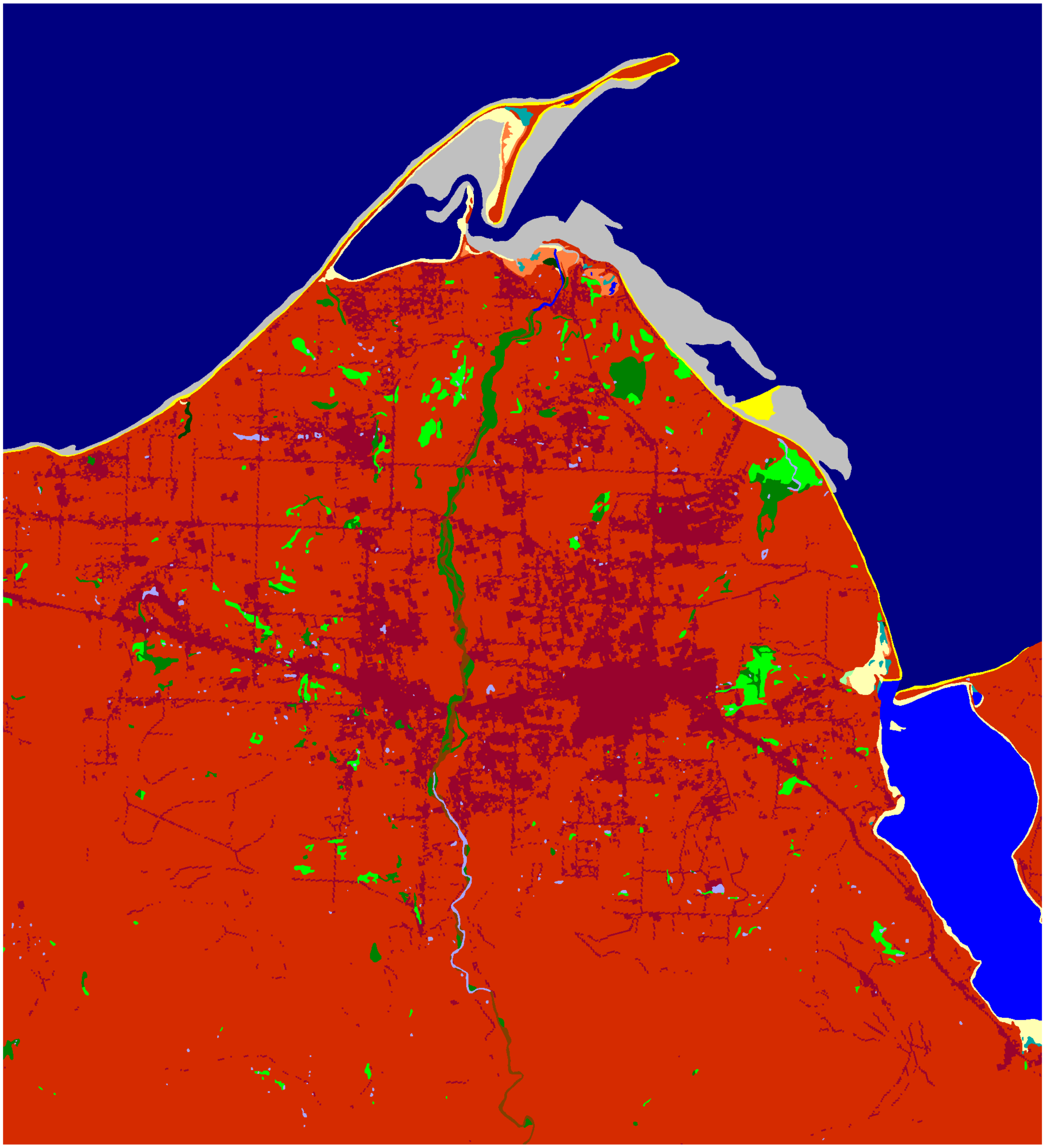


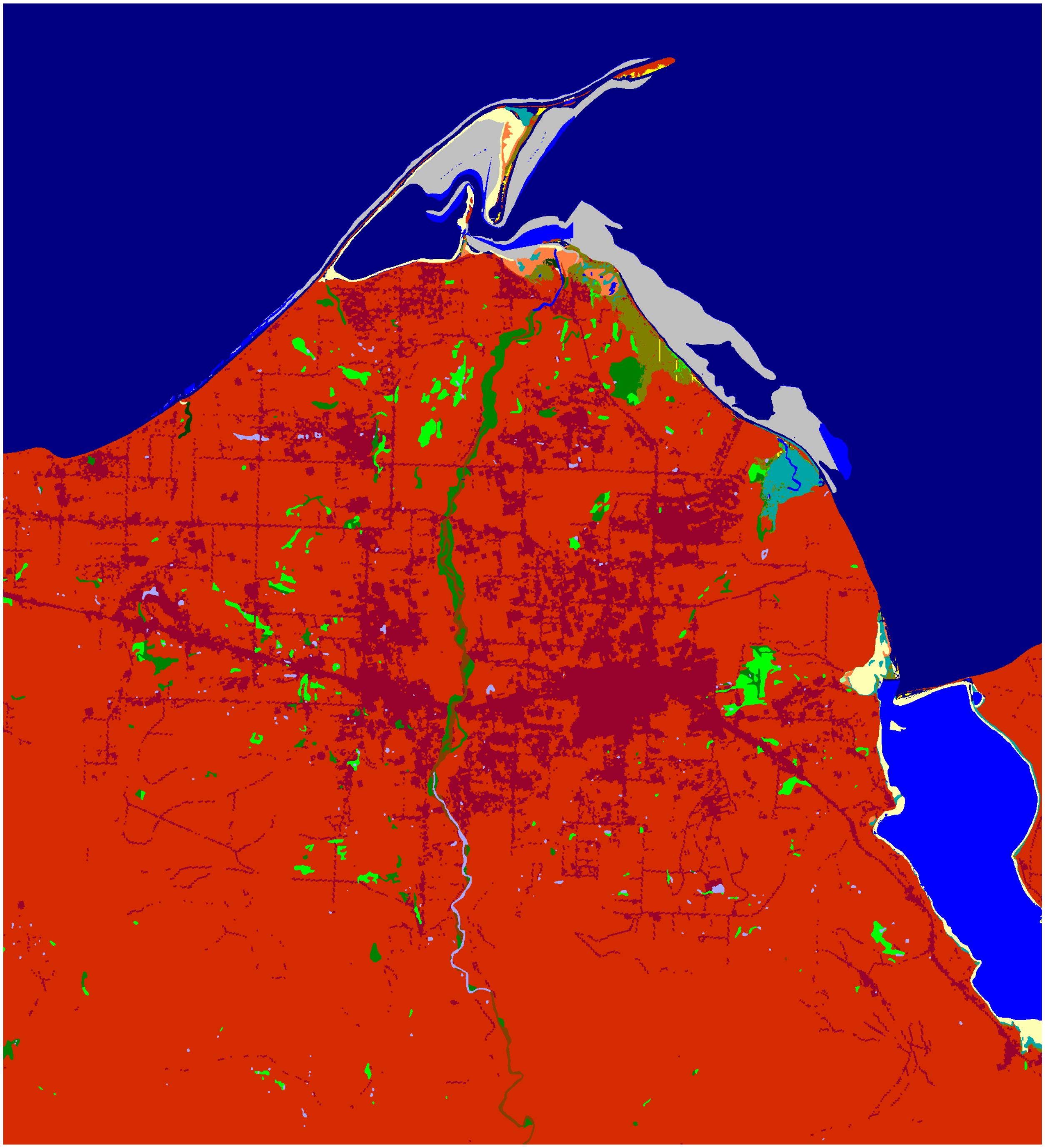
Dungeness Context, 2075, 1.5 meter



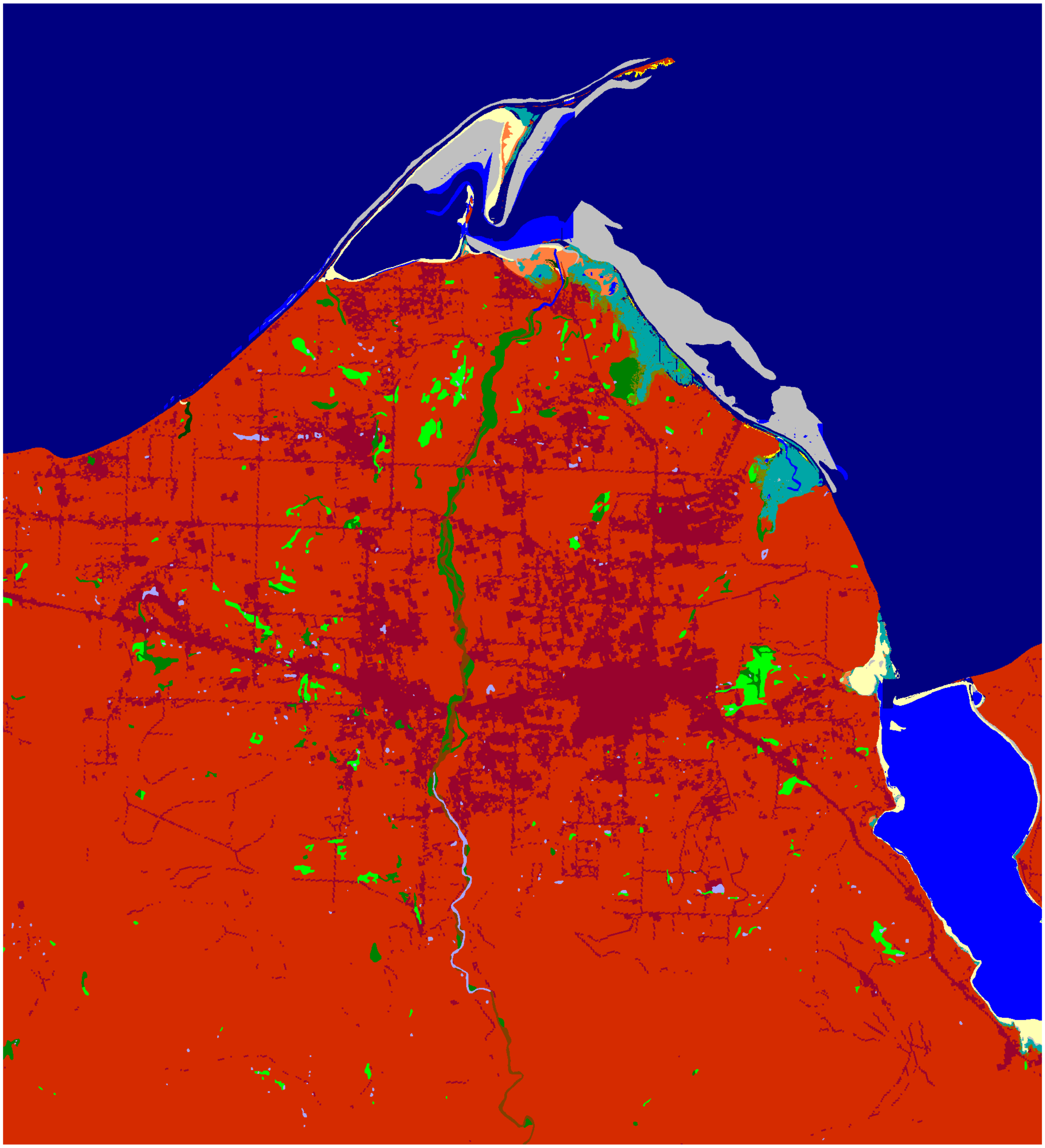
Dungeness Context, 2100, 1.5 meter



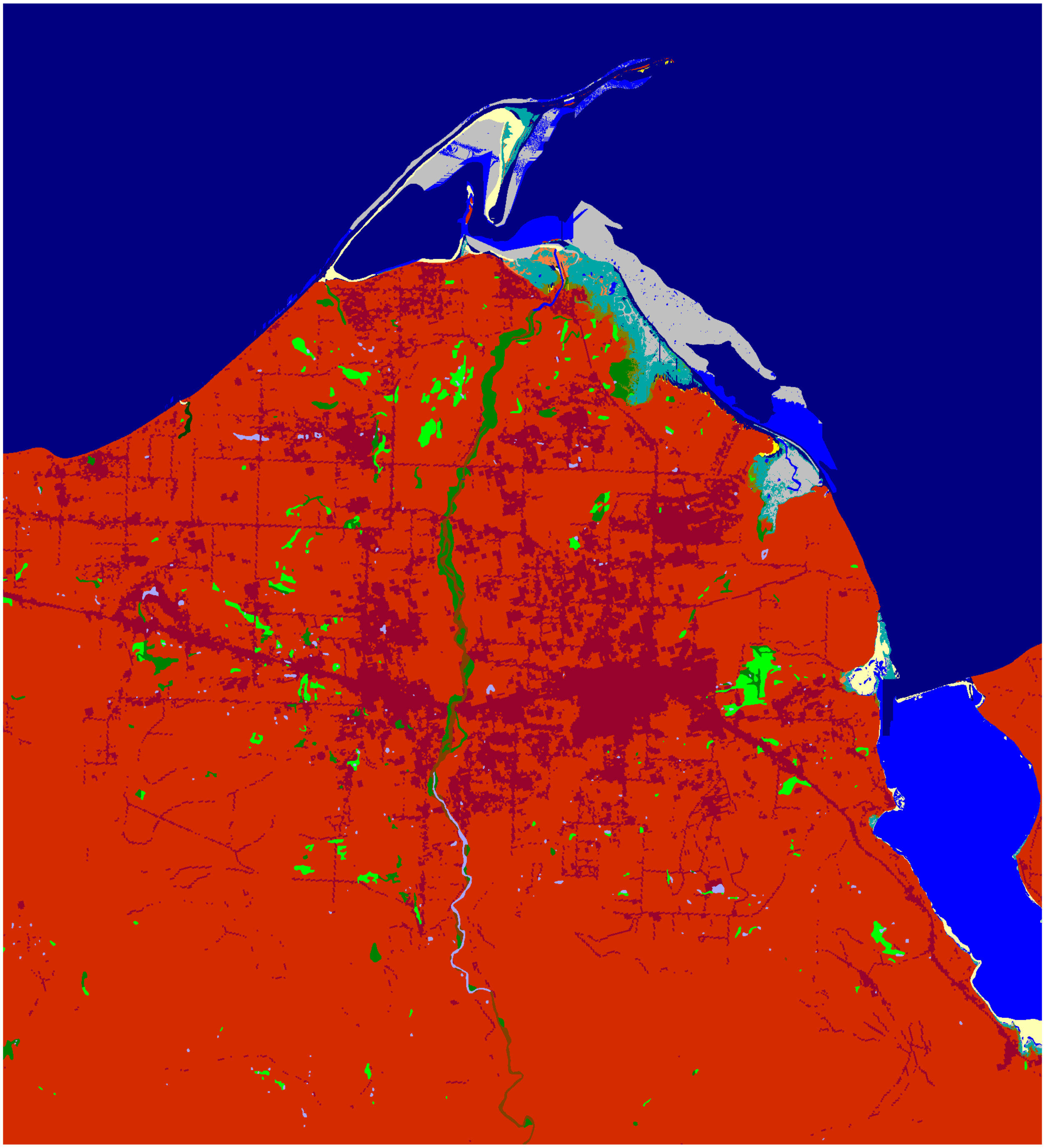
Dungeness Context, Initial Condition



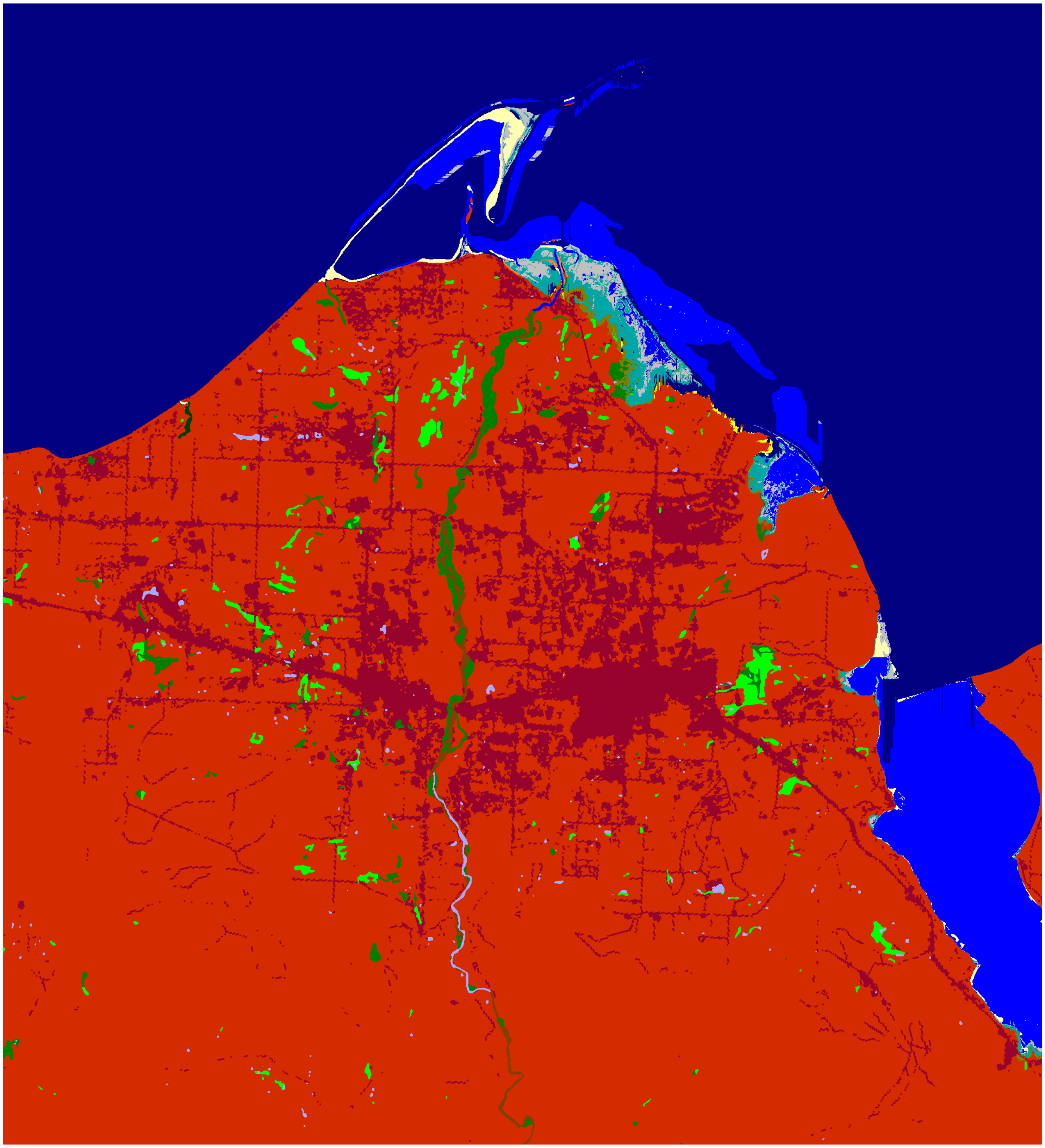
Dungeness Context, 2025, 2 meter



Dungeness Context, 2050, 2 meter



Dungeness Context, 2075, 2 meter



Dungeness Context, 2100, 2 meter