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

***REVISED***

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

October 17, 2011

warren pinnacle consulting, inc.
PO Box 315, Waitsfield VT, 05673
(802)-496-3476

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



Funding for model runs and permission for use of model results was provided by The National Wildlife Federation.

# 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 many coastal 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. This analysis is a summary of model runs produced by the National Wildlife Federation (Glick et al. 2011).

# 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 et al. 1992; Park et al. 1993; Galbraith et al. 2002; National Wildlife Federation & Florida Wildlife Federation 2006; Glick et al. 2007; Craft et al. 2009). The first phase of this work was completed using SLAMM 5, while the second phase simulations were run with SLAMM 6.

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 m 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 is used in USFWS simulations 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 et al. 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*

Forecast simulations used 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 m 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 m of global sea level rise by 2100. A1B-maximum predicts 0.69 m 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 m 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." (Clark 2009) 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 m, 1½ m, and 2 m of eustatic sea-level rise by the year 2100. The A1B- maximum scenario was scaled up to produce these bounding scenarios (Figure 1).

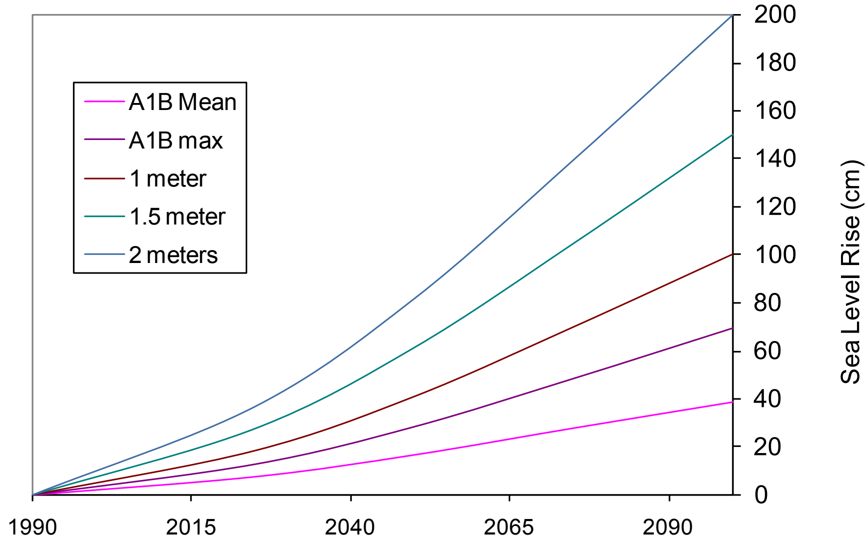



Figure 1: **Summary of SLR scenarios utilized**

## Methods and Data Sources

This study of Delta NWR was derived from a previously conducted project of the National Wildlife Federation to analyze the effects of SLR on southeastern Louisiana (Glick et al. 2011).

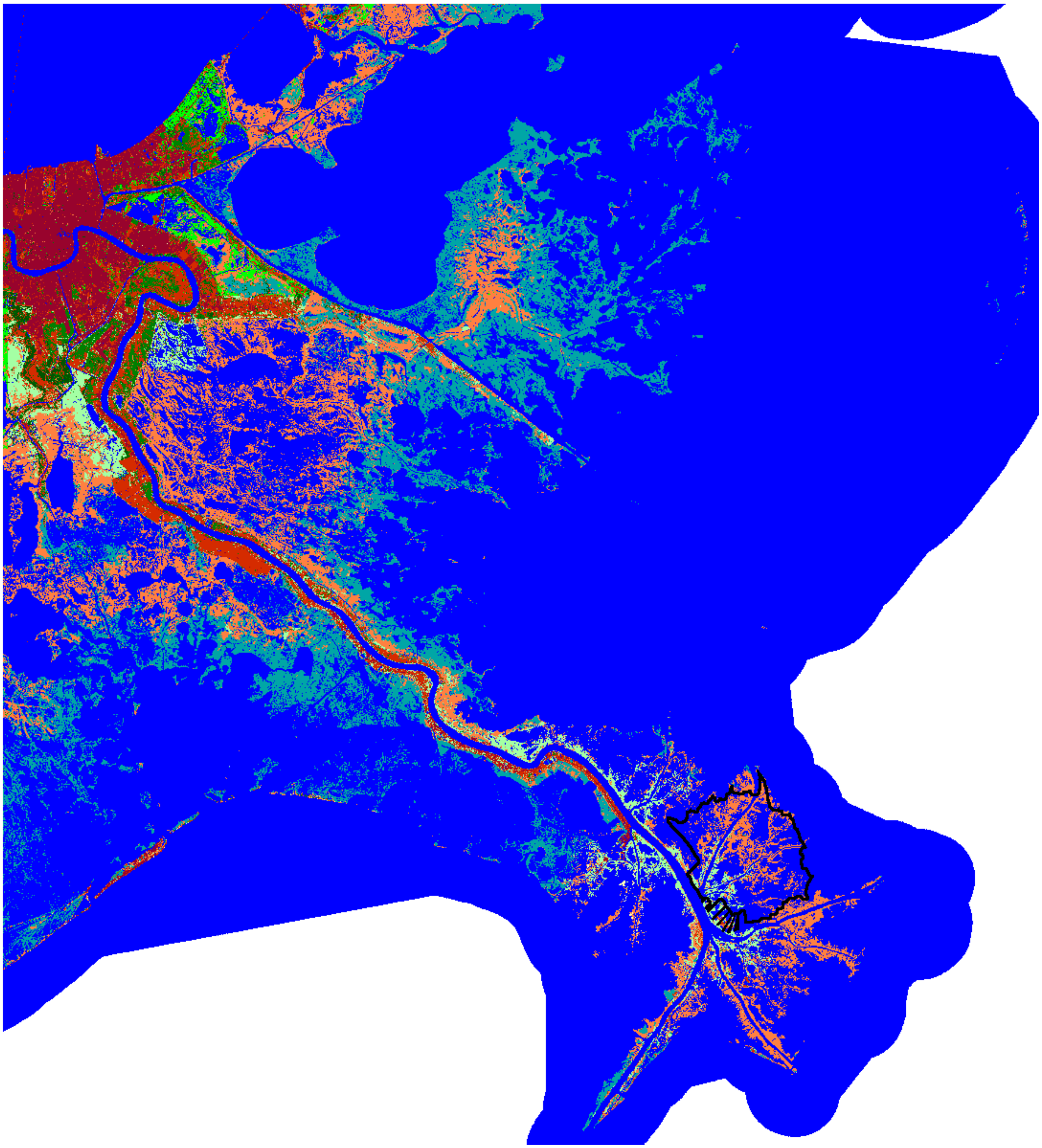


Figure 2. Portion of southeastern Louisiana study area with Delta NWR boundary shown in black

The digital elevation map used in this simulation was provided by Brady Couvillion of USGS (Couvillion, 2010). Since a complete LiDAR dataset was not available, the USGS used a method which draws upon patterns of wetting and drying as discerned in multiple dates of spectral imagery (Landsat band 5), correlated those patterns in areas for which topography data did exist, and then applied those patterns to gaps in the topography data to complete the data. Bare-earth LiDAR data were used preferentially, where available, to produce a spatially continuous DEM. However gaps existed in the elevation model output. Consequently, the use of model-derived elevation data led to uncertainty in the SLAMM results (discussed further in the results and discussion sections).

The USGS utilized a similar modeling process to produce a 2007 wetlands cover layer. This 2007 layer was used both as the basis for the forecast model and also the "observed data" to compare hindcast results against. Again, multiple remote-sensed images were used and a set of algorithms was created by training the model against existing forestry classes. The result provides a "pseudo-NWI" suitable for SLAMM modeling.

Converting the NWI survey into 15 m cells indicated that the approximately 50,753 acre refuge (approved acquisition boundary including water) is composed of the following categories:

| Land cover type | | Area (acres) | Percentage (%) |
|---|---|---|---|
| | Estuarine Open Water | 33748 | 66 |
| | Irregularly Flooded Marsh | 13424 | 26 |
| | Tidal Fresh Marsh | 3002 | 6 |
| | Undeveloped Dry Land | 234 | < 1 |
| | Regularly Flooded Marsh | 163 | < 1 |
| | Swamp | 103 | < 1 |
| | Estuarine Beach | 78 | < 1 |
| | Cypress Swamp | 1 | < 1 |
| | **Total (incl. water)** | **50753** | **100** |

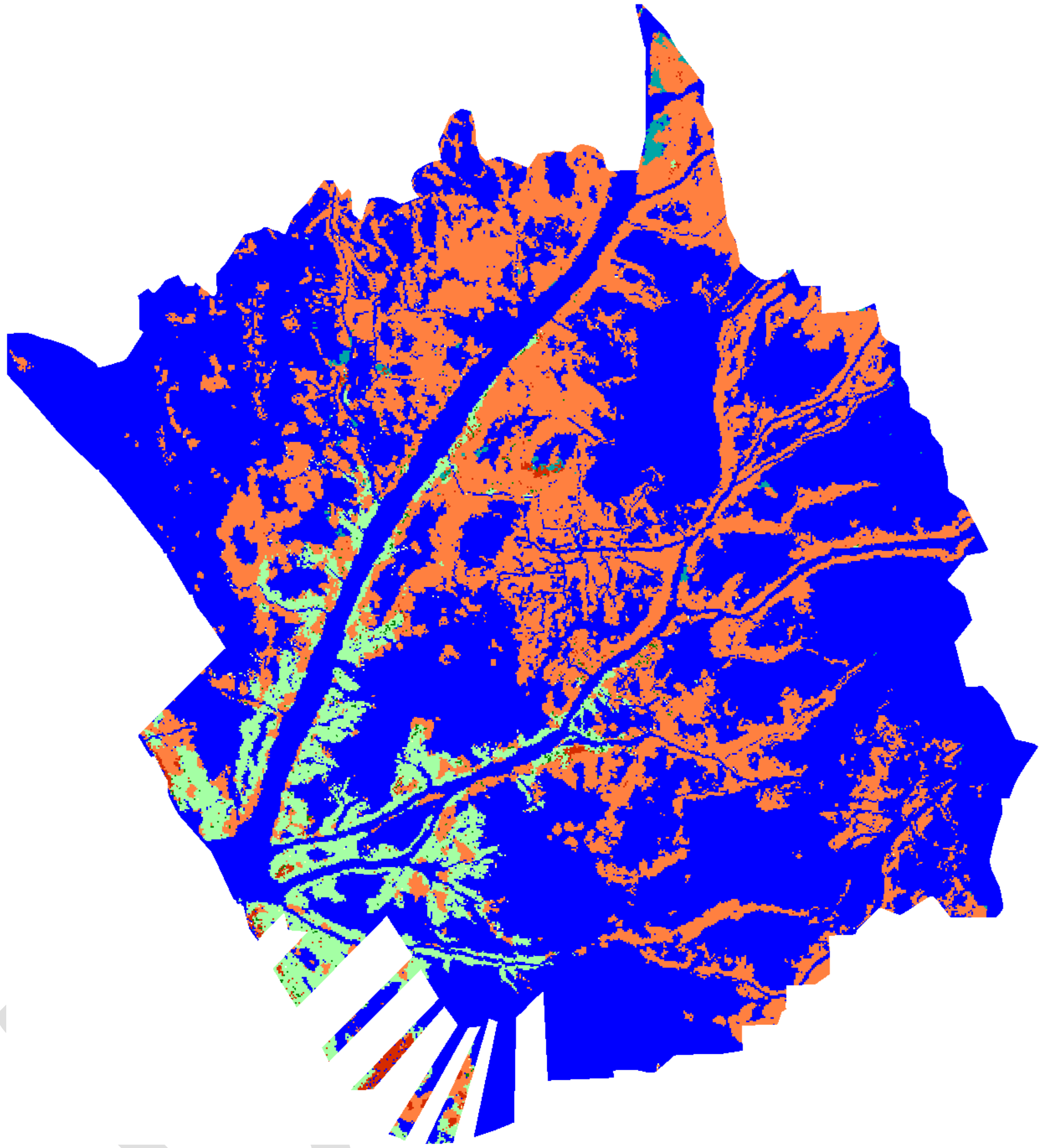


Figure 3. 2004 NWI data layer used for Delta NWR

According to the National Wetland Inventory, there are no diked areas within Delta NWR. Older NWI data suggested that the entire region was diked, thus necessitating this report revision.

Subsidence rates included in the final model runs were estimated from point observations primarily derived from geodetic data (Shinkle and Dokka 2004). These data were added to information obtained from the NOAA tide gauges at Grand Isle (gauge 8761724) and Eugene Island (gauge 8764311)[1]. The full set of points was interpolated to produce a continuous map via "kriging."

[1] Subsidence rates at the Grand Isle and Eugene Island tide gauges were calculated by subtracting the 1.7 mm/yr eustatic SLR trend from the observed at each location, resulting in subsidence rates of 7.5 and 8.0 mm/yr, respectively.

Kriging is a method of interpolation that predicts unknown values from data observed at known locations (Lang 2000). The final raster obtained for the Delta NWR area is shown in Figure 5.

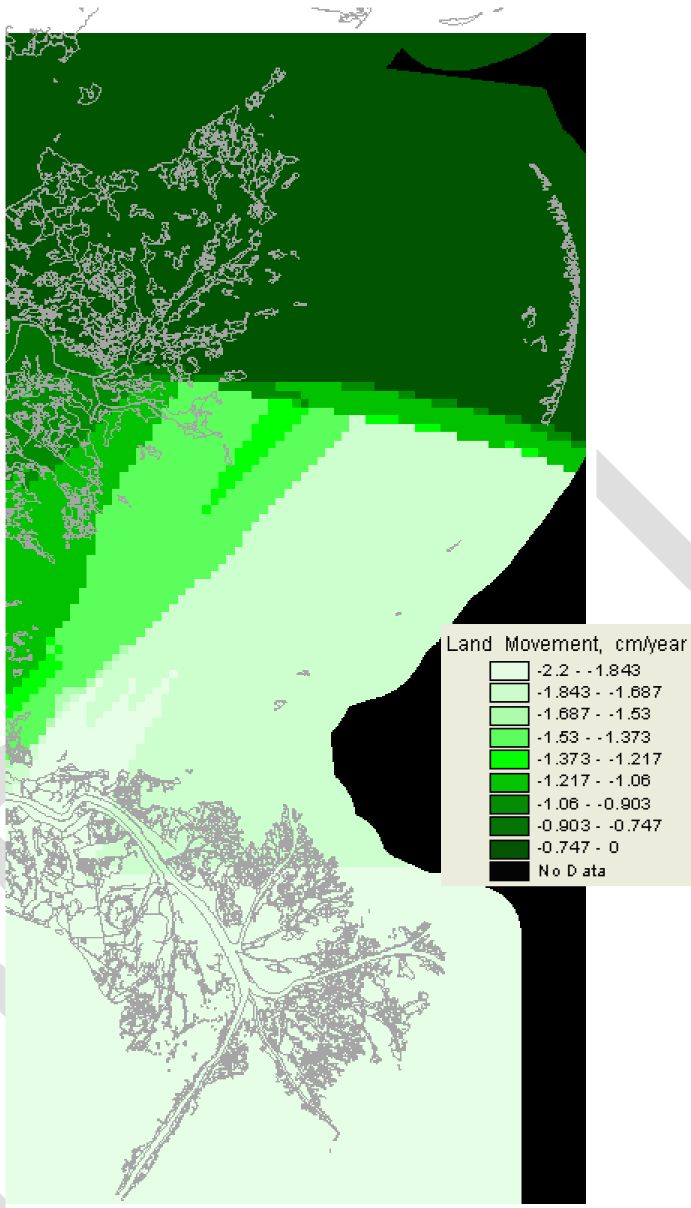



Figure 4. Kriged Subsidence raster from Shinkle and Dokka and long term NOAA tide gauge data

The great diurnal tide range at this site was estimated at 0.42 m using local water level data. This value was determined by averaging the tidal data at the closest NOAA tide prediction values shown in Figure 6.

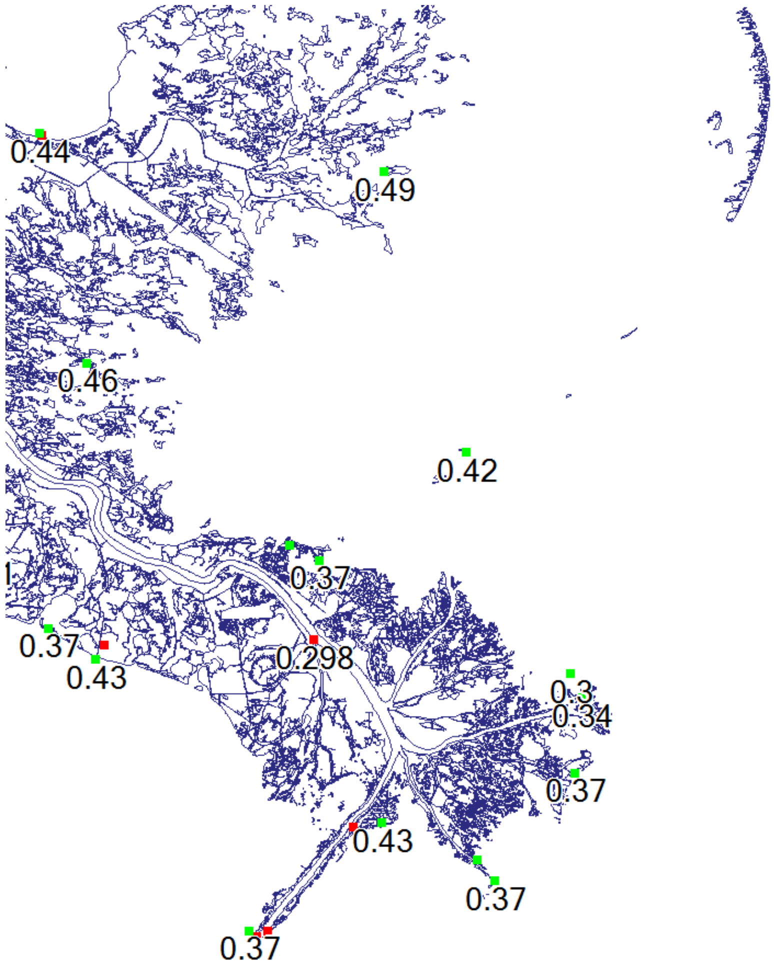



Figure 5. Diurnal tide range values (in meters) for southeastern Louisiana

The "salt elevation" parameter within SLAMM designates the boundary between coastal wetlands and dry lands or fresh water wetlands. An estimate of this elevation may be derived by examining historical tide gauge data to determine how frequently different elevations are flooded with ocean water. Within SLAMM modeling simulations this elevation is usually defined as the elevation over which flooding is predicted less than once in every 30 days. Dry lands and fresh-water wetlands are assumed to be located above that elevation. In this study of Delta NWR, the salt elevation was designated ad 0.36 m above MTL.

Based on information received from Brady Couvillion of the USGS (personal communication, 2011), accretion feedback curves were used to allow marsh accretion rates to range from 12 to 16 mm/yr.

Little or no information about marsh erosion rates within the study area is available in the scientific literature. Therefore, erosion rates applied were the default values for SLAMM. Marsh erosion was set to 1.8 horizontal meters per year, swamp erosion was set to 1 meter per year, and tidal flat erosion to 2 meters per year. It is important to note that erosion only occurs in SLAMM if the land is (1) in contact with open water (2) the maximum wave fetch requirement of 9 km is met (Clough et al. 2010).

Due to the limited spatial variability within these vertical datum transformations in this site, the NAVD88 to MTL correction was applied on a "subsite" basis. The correction value applied to the Delta NWR study was 0.36 m.

Modeled U.S. Fish and Wildlife Service refuge boundaries for Louisiana 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 15 m by 15 m cells. Note that the SLAMM model will track partial conversion of cells based on elevation and slope.

Table 1. Summary of SLAMM input parameters for Delta NWR

| | |
|---|---|
| NWI Photo Date (YYYY) Forecast | 2007 |
| DEM Date (YYYY) | 2009 |
| Direction Offshore [n,s,e,w] | South |
| MTL-NAVD88 (m) | 0.36 |
| GT Great Diurnal Tide Range (m) | 0.42 |
| Salt Elev. (m above MTL) | 0.36 |
| Marsh Erosion (horz. m /yr) | 1.8 |
| Swamp Erosion (horz. m /yr) | 1 |
| T.Flat Erosion (horz. m /yr) | 2 |
| Reg. Flood Marsh Accr (mm/yr) | 8.5 |
| Irreg. Flood Marsh Accr (mm/yr) | 8.5 |
| Tidal Fresh Marsh Accr (mm/yr) | 9.8 |
| Beach Sed. Rate (mm/yr) | 1 |
| Freq. Overwash (years) | 30 |
| Use Elev Pre-processor [True,False] Forecast | FALSE |
| Reg Flood Use Model [True,False] | TRUE |
| Reg Flood Max. Accr. (mm/year) | 11 |
| Reg Flood Min. Accr. (mm/year) | 6 |
| Reg Flood Elev a coeff. (cubic) | 0 |
| Reg Flood Elev b coeff. (square) | 0 |
| Reg Flood Elev c coeff. (linear) | 1 |
| Irreg Flood Use Model [True,False] | TRUE |
| Irreg Flood Max. Accr. (mm/year) | 11 |
| Irreg Flood Min. Accr. (mm/year) | 6 |
| Irreg Flood Elev a coeff. (cubic) | 0 |
| Irreg Flood Elev b coeff. (square) | 0 |
| Irreg Flood Elev c coeff. (linear) | 1 |
| Tidal Fresh Use Model [True,False] | TRUE |
| Tidal Fresh Max. Accr. (mm/year) | 11 |
| Tidal Fresh Min. Accr. (mm/year) | 6 |
| Tidal Fresh Elev a coeff. (cubic) | 0 |
| Tidal Fresh Elev b coeff. (square) | 0 |
| Tidal Fresh Elev c coeff. (linear) | 1 |

# Results

This simulation of the Delta NWR was completed using a SLAMM model that was calibrated to historical data for a project funded by the National Wildlife Federation (Glick et al. 2011). Table 2 presents the predicted loss of each wetland category by 2100 for each of the five SLR scenarios examined. Results suggest that Delta NWR will be significantly impacted by sea-level rise even at the lowest SLR scenarios examined in this study.

An important feature of the results shown in Figure 2 is that the losses of some categories reach a maximum percentage loss that is less than 100%. This result is a consequence of missing elevation data in the refuge. Because the elevation data does not exist, SLAMM cannot predict when lands without elevation data may be lost.

Table 2. Predicted Change Rates of Land Categories by 2100 Given Simulated Scenarios of Eustatic Sea Level Rise. *Negative values indicate losses and positive indicate gains.*

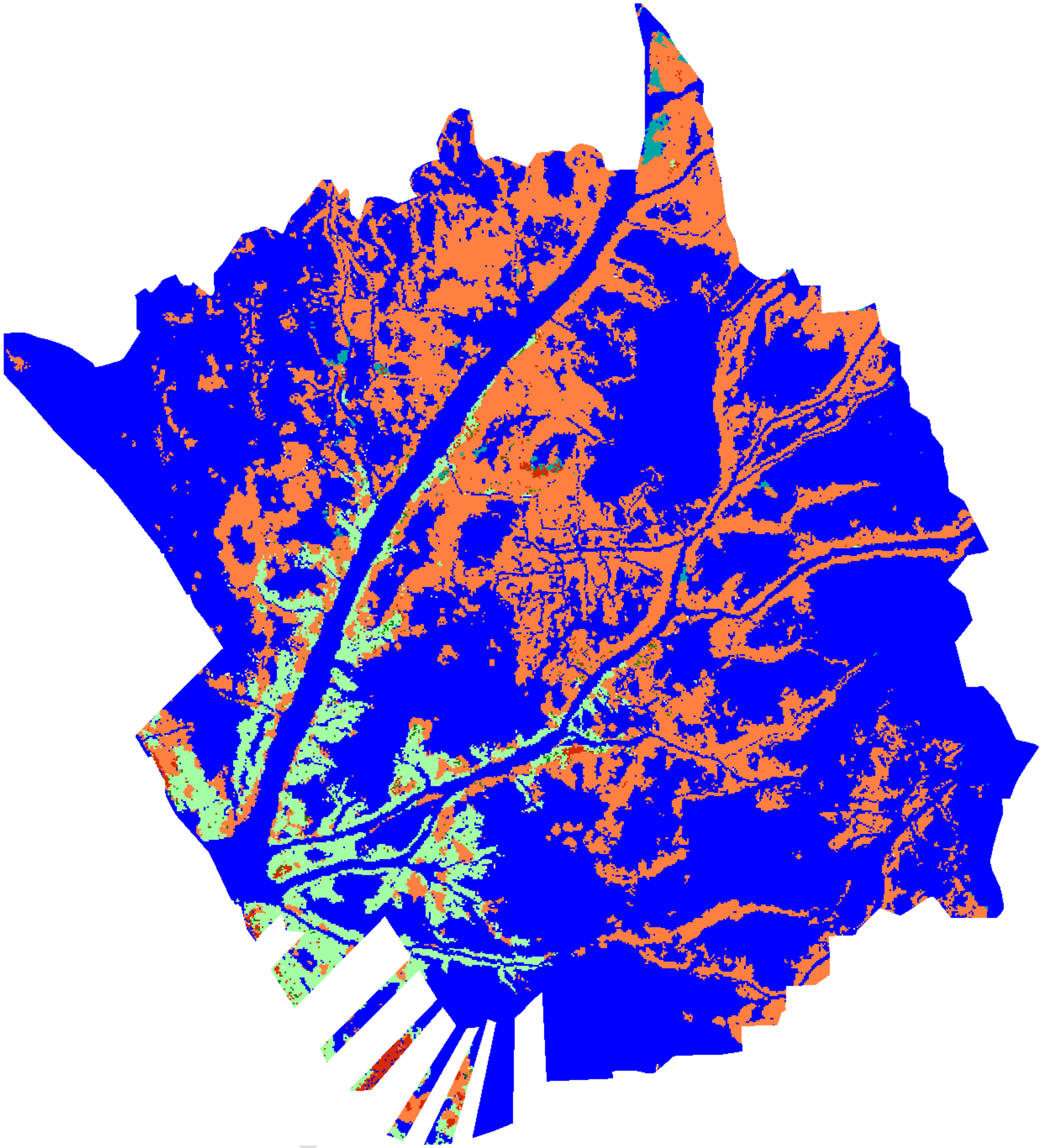
| Land cover category | Land cover change by 2100 for different SLR scenarios (%) | | | | |
|---|---|---|---|---|---|
| | 0.39 m | 0.69 m | 1 m | 1.5 m | 2 m |
| Irregularly Flooded Marsh | -99 | -100 | -100 | -100 | -100 |
| Tidal Fresh Marsh | -99 | -100 | -100 | -100 | -100 |
| Undeveloped Dry Land | -96 | -96 | -96 | -96 | -96 |
| Regularly Flooded Marsh | -18 | -51 | -69 | -86 | -93 |
| Swamp | -97 | -97 | -97 | -97 | -98 |
| Estuarine Beach | -100 | -100 | -100 | -100 | -100 |
| Cypress Swamp | -80 | -80 | -80 | -80 | -80 |

Delta NWR is primarily composed of irregularly-flooded and tidal fresh marsh. Both of these wetland categories are predicted to be lost by 99% at 0.39 m of SLR by 2100 and 100% lost at higher SLR scenarios. Although these categories reach 100% loss, the maps presented below suggest some irregularly-flooded marsh to persist in 2100. These marsh cells appear on maps due to missing elevation data, as discussed above.

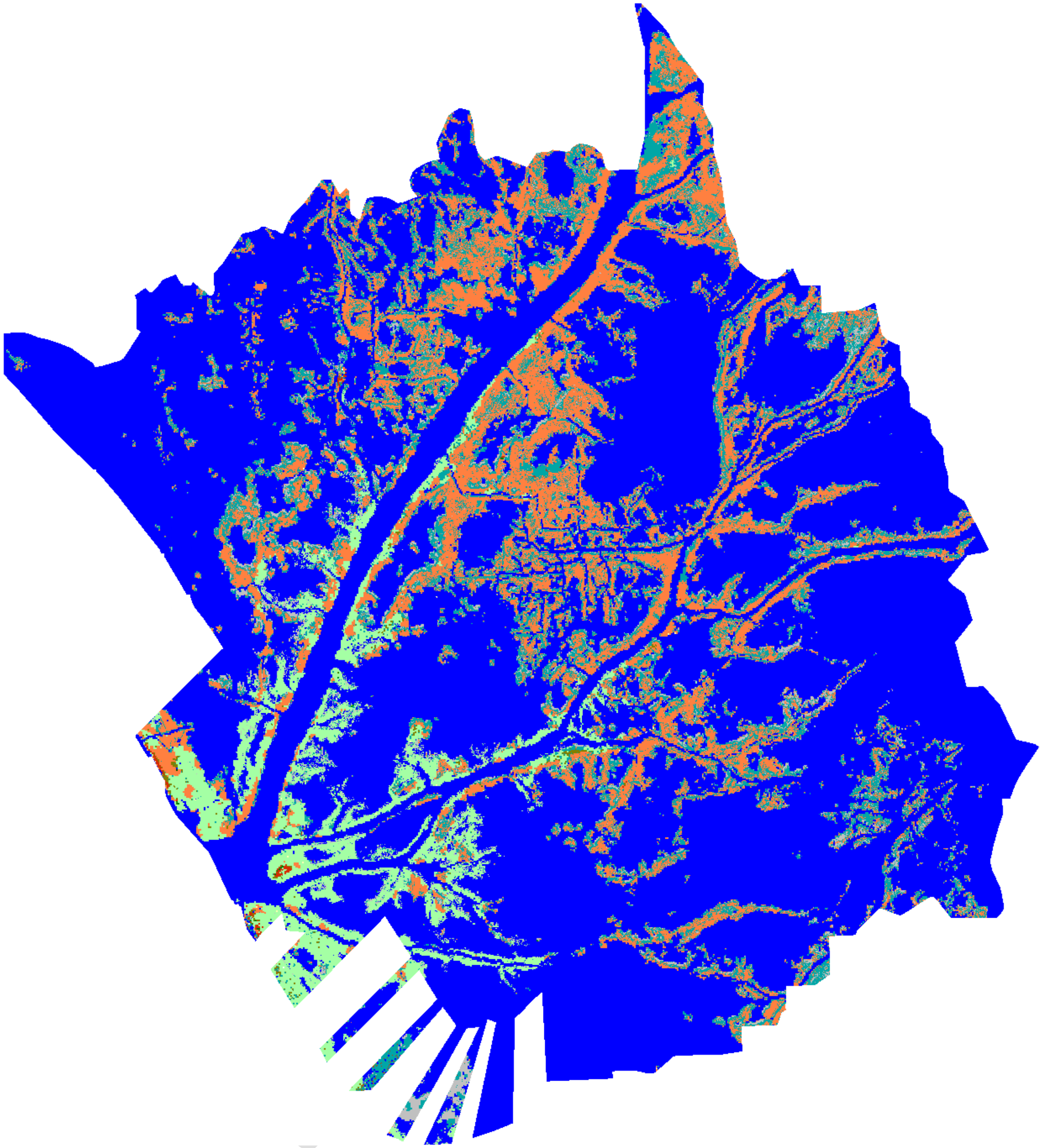
IPCC Scenario A1B-Mean, 0.39 m SLR eustatic by 2100

Results in Acres

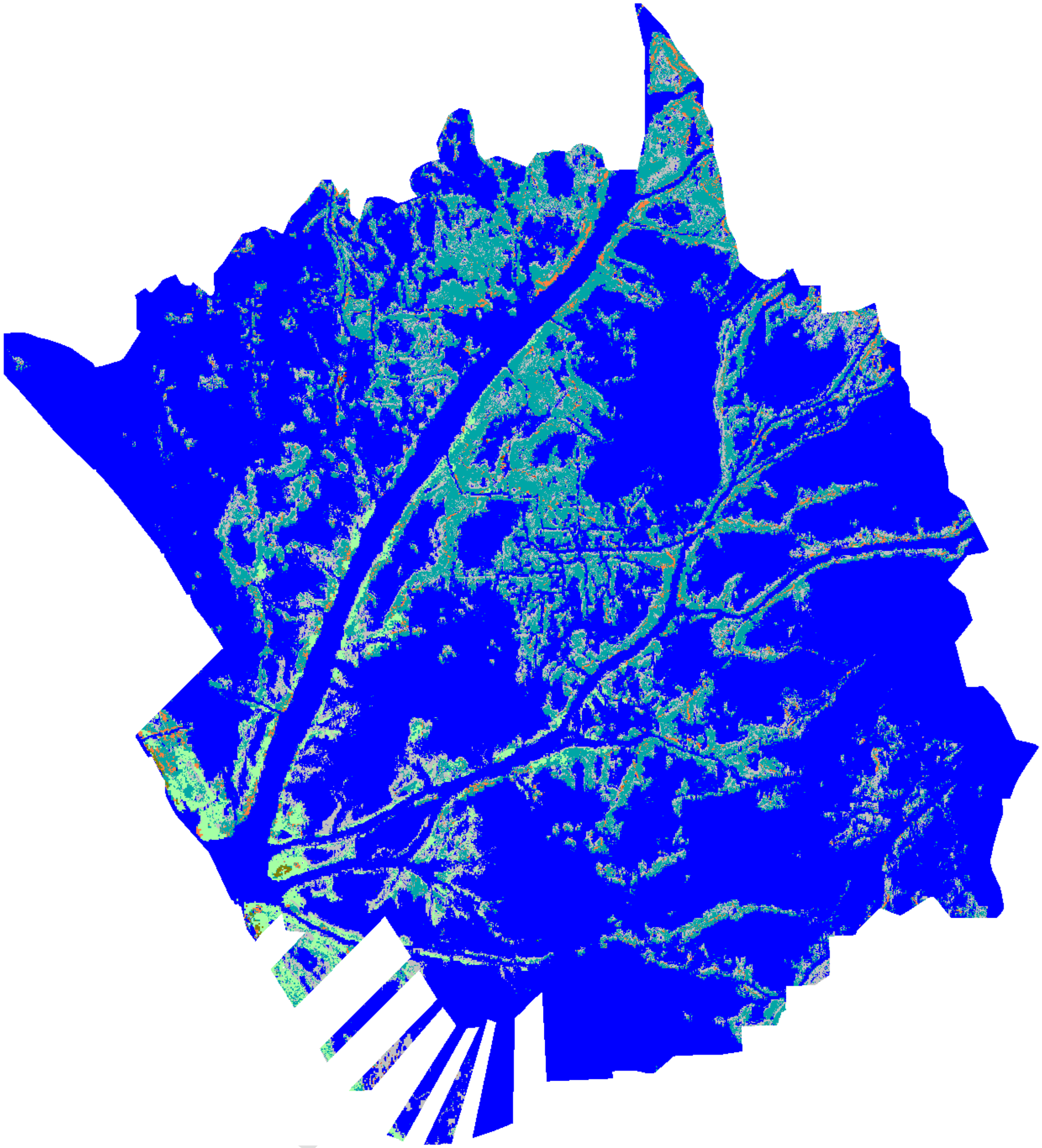
| | | Initial | 2025 | 2050 | 2075 | 2100 |
|---|---|---|---|---|---|---|
| | Estuarine Open Water | 33748 | 34347 | 37149 | 43837 | 49998 |
| | Irregularly Flooded Marsh | 13424 | 7113 | 949 | 237 | 124 |
| | Tidal Fresh Marsh | 3002 | 2320 | 973 | 95 | 31 |
| | Undeveloped Dry Land | 234 | 32 | 11 | 9 | 9 |
| | Regularly Flooded Marsh | 163 | 5390 | 7281 | 834 | 133 |
| | Swamp | 103 | 7 | 3 | 3 | 3 |
| | Estuarine Beach | 78 | 20 | 1 | 0 | 0 |
| | Cypress Swamp | 1 | 1 | 0 | 0 | 0 |
| | Transitional Salt Marsh | 0 | 67 | 25 | 2 | 0 |
| | Tidal Flat | 0 | 1456 | 4360 | 5735 | 454 |
| | **Total (incl. water)** | **50753** | **50753** | **50753** | **50753** | **50753** |



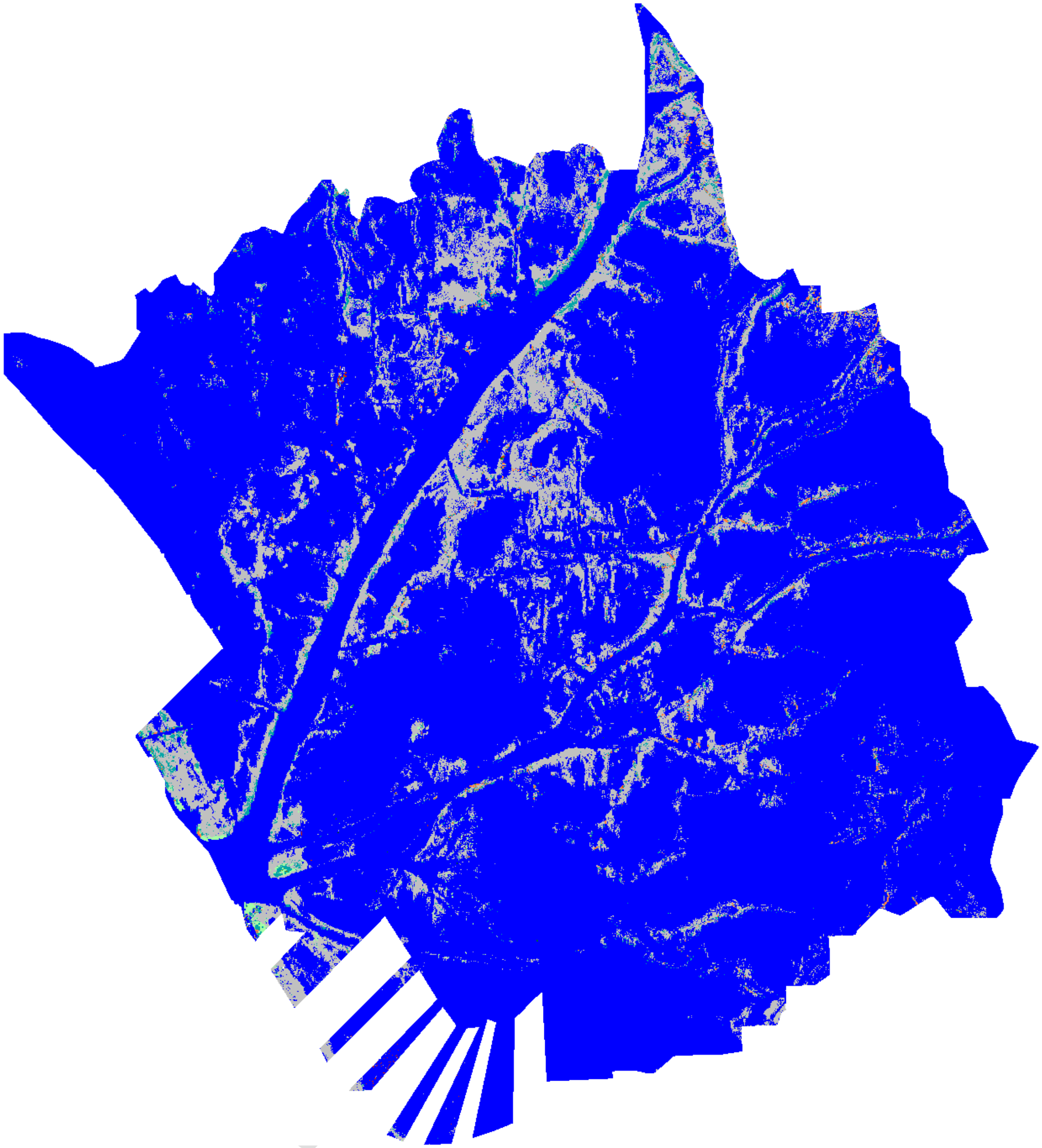
Delta NWR, Initial Condition



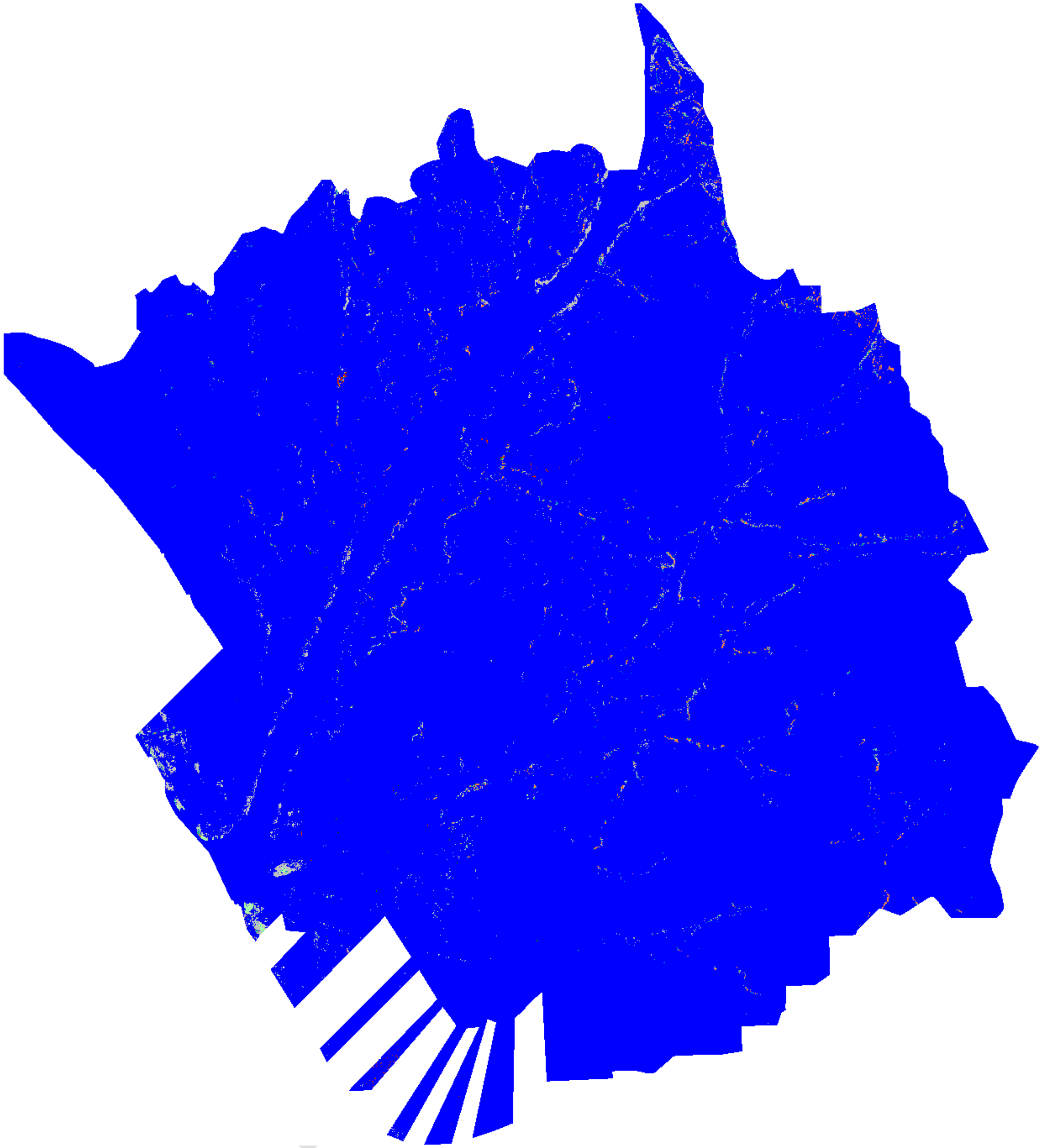
Delta NWR, 2025, Scenario A1B Mean



Delta NWR, 2050, Scenario A1B Mean



Delta NWR, 2075, Scenario A1B Mean

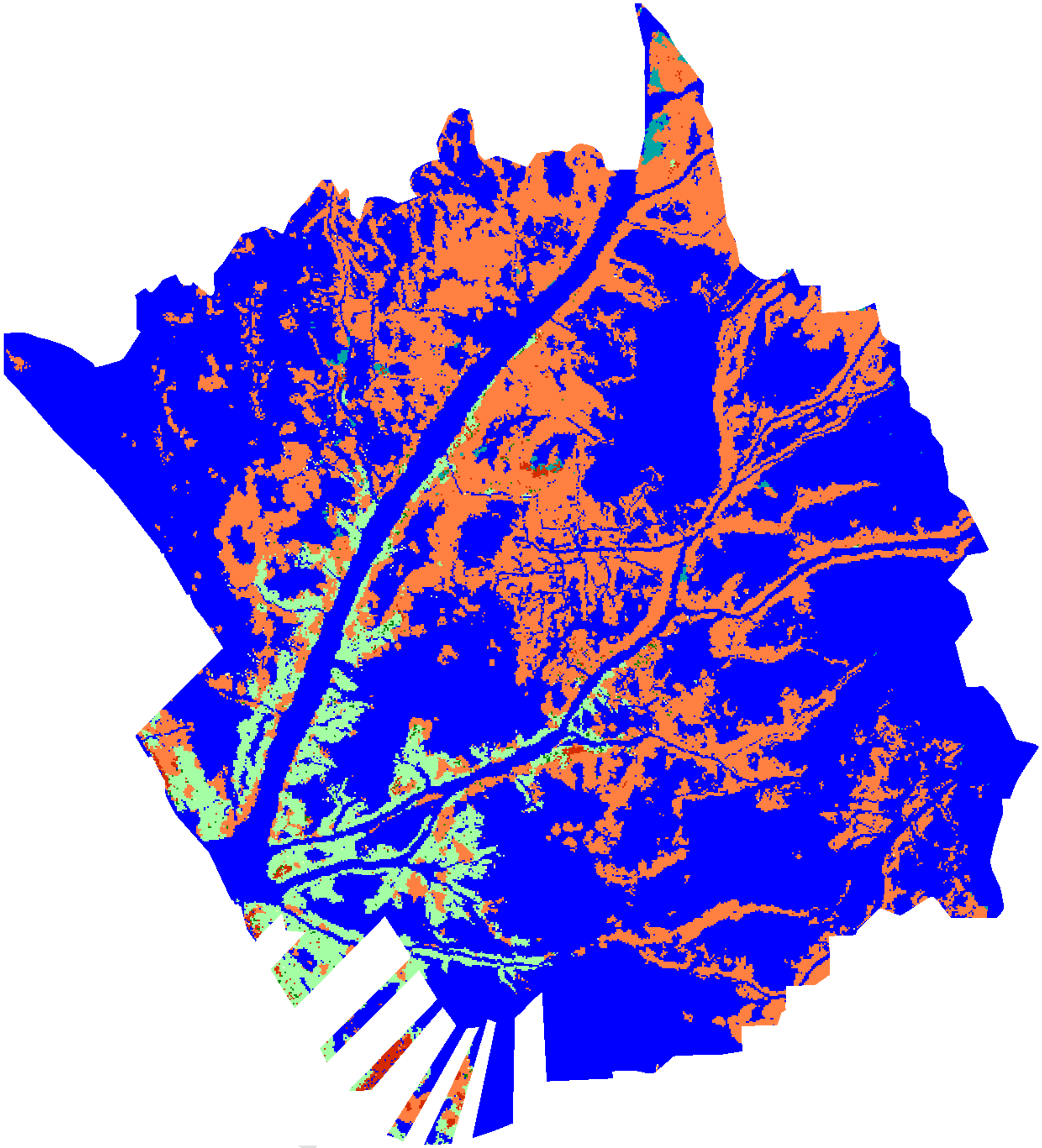


Delta NWR, 2100, Scenario A1B Mean

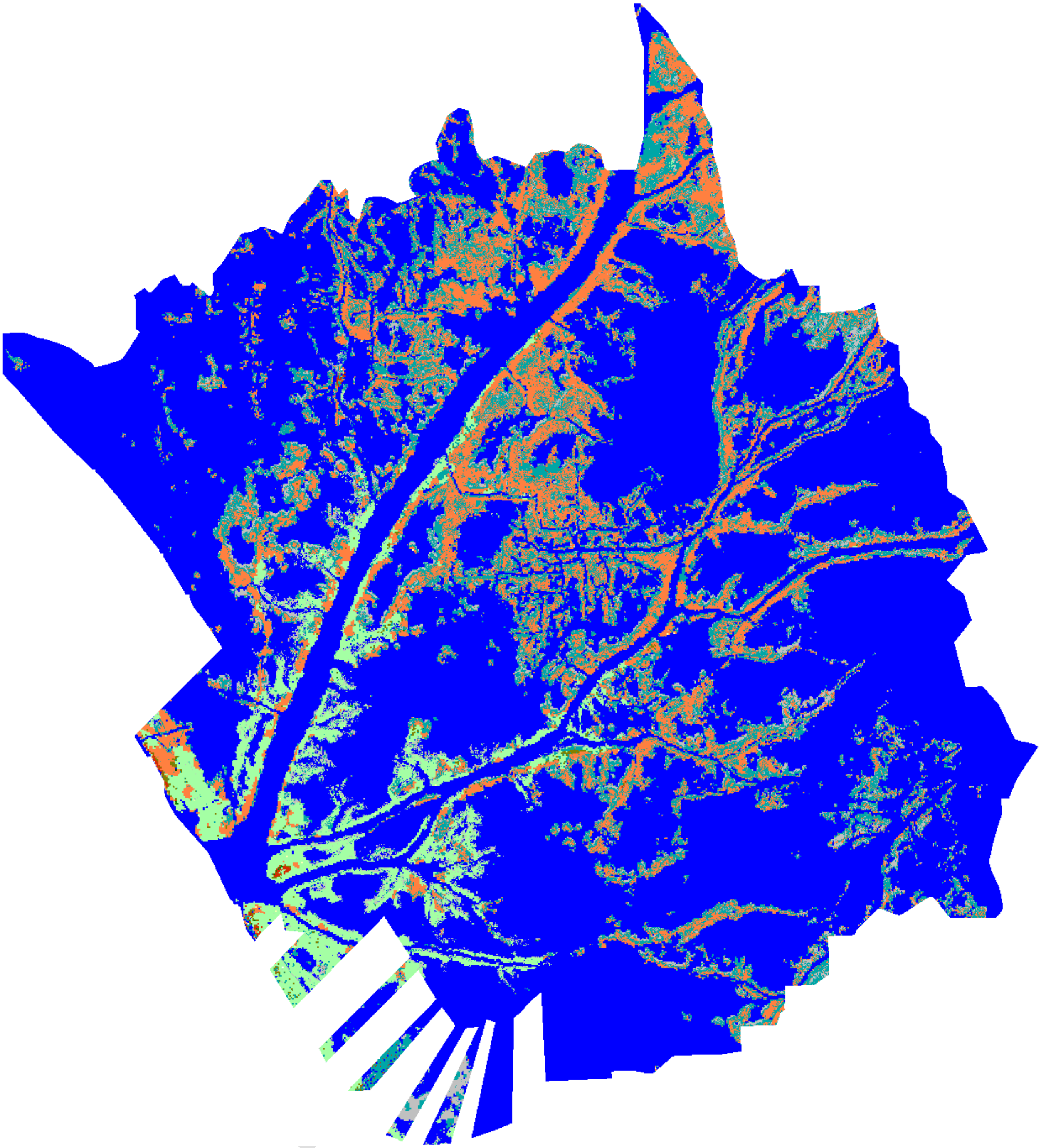
IPCC Scenario A1B-Max, 0.69 m SLR eustatic by 2100

Results in Acres

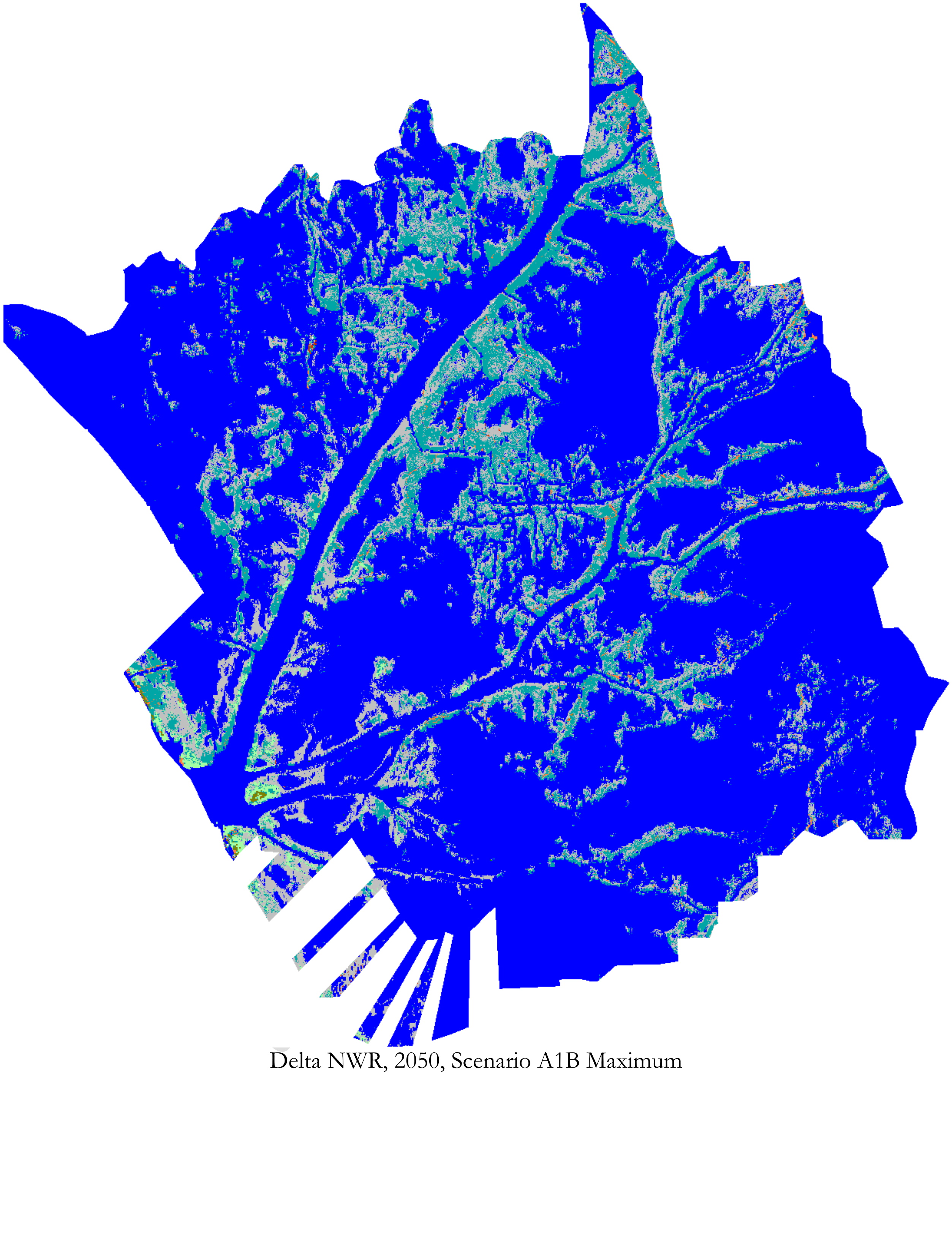
| | | Initial | 2025 | 2050 | 2075 | 2100 |
|---|---|---|---|---|---|---|
| | Estuarine Open Water | 33748 | 34429 | 38154 | 46024 | 50416 |
| | Irregularly Flooded Marsh | 13424 | 5982 | 432 | 141 | 61 |
| | Tidal Fresh Marsh | 3002 | 2180 | 360 | 38 | 11 |
| | Undeveloped Dry Land | 234 | 30 | 10 | 9 | 9 |
| | Regularly Flooded Marsh | 163 | 6162 | 5771 | 316 | 81 |
| | Swamp | 103 | 7 | 3 | 3 | 3 |
| | Estuarine Beach | 78 | 18 | 1 | 0 | 0 |
| | Cypress Swamp | 1 | 1 | 0 | 0 | 0 |
| | Transitional Salt Marsh | 0 | 69 | 24 | 1 | 0 |
| | Tidal Flat | 0 | 1875 | 5998 | 4221 | 171 |
| | **Total (incl. water)** | **50753** | **50753** | **50753** | **50753** | **50753** |



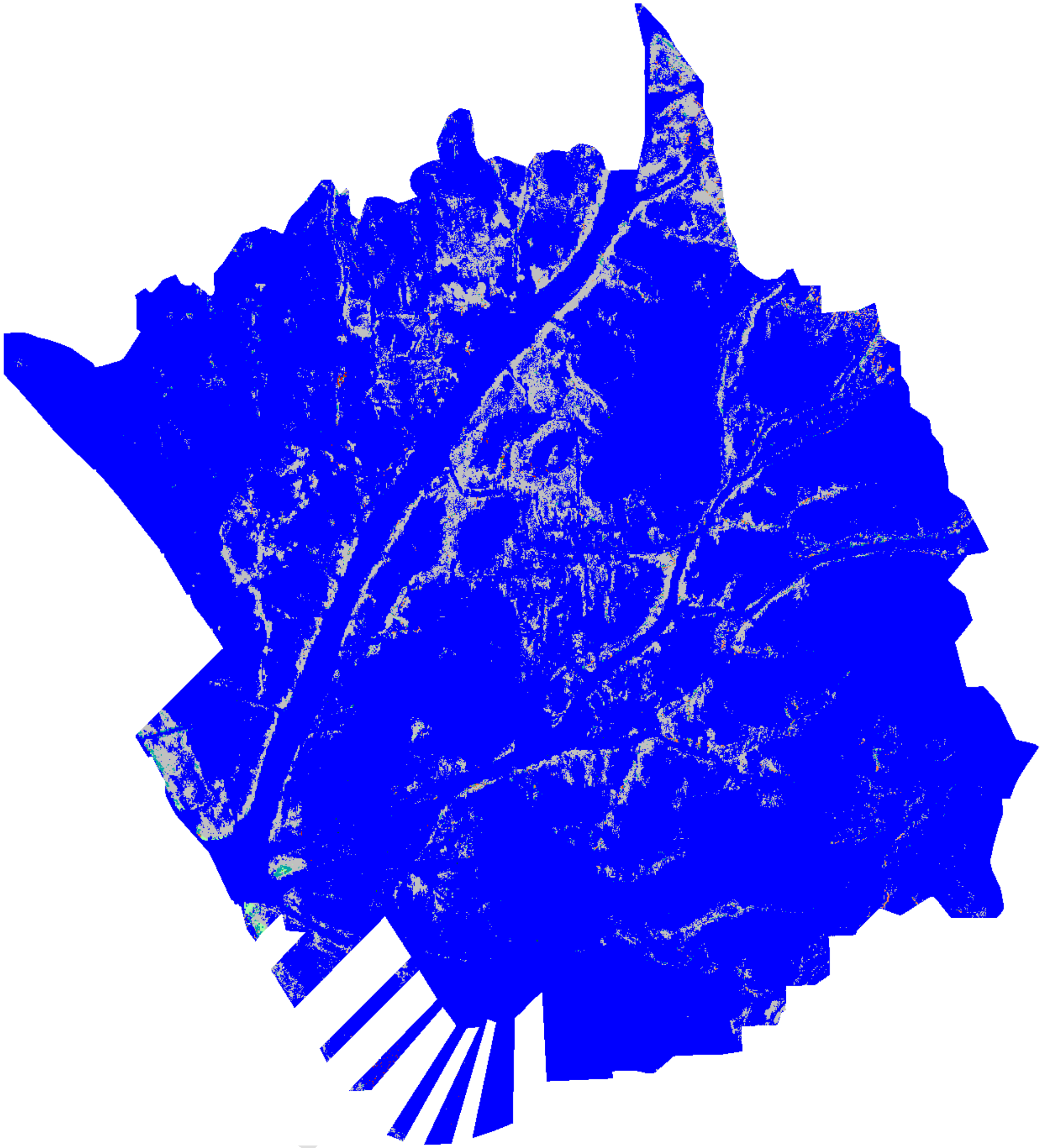
Delta NWR, Initial Condition



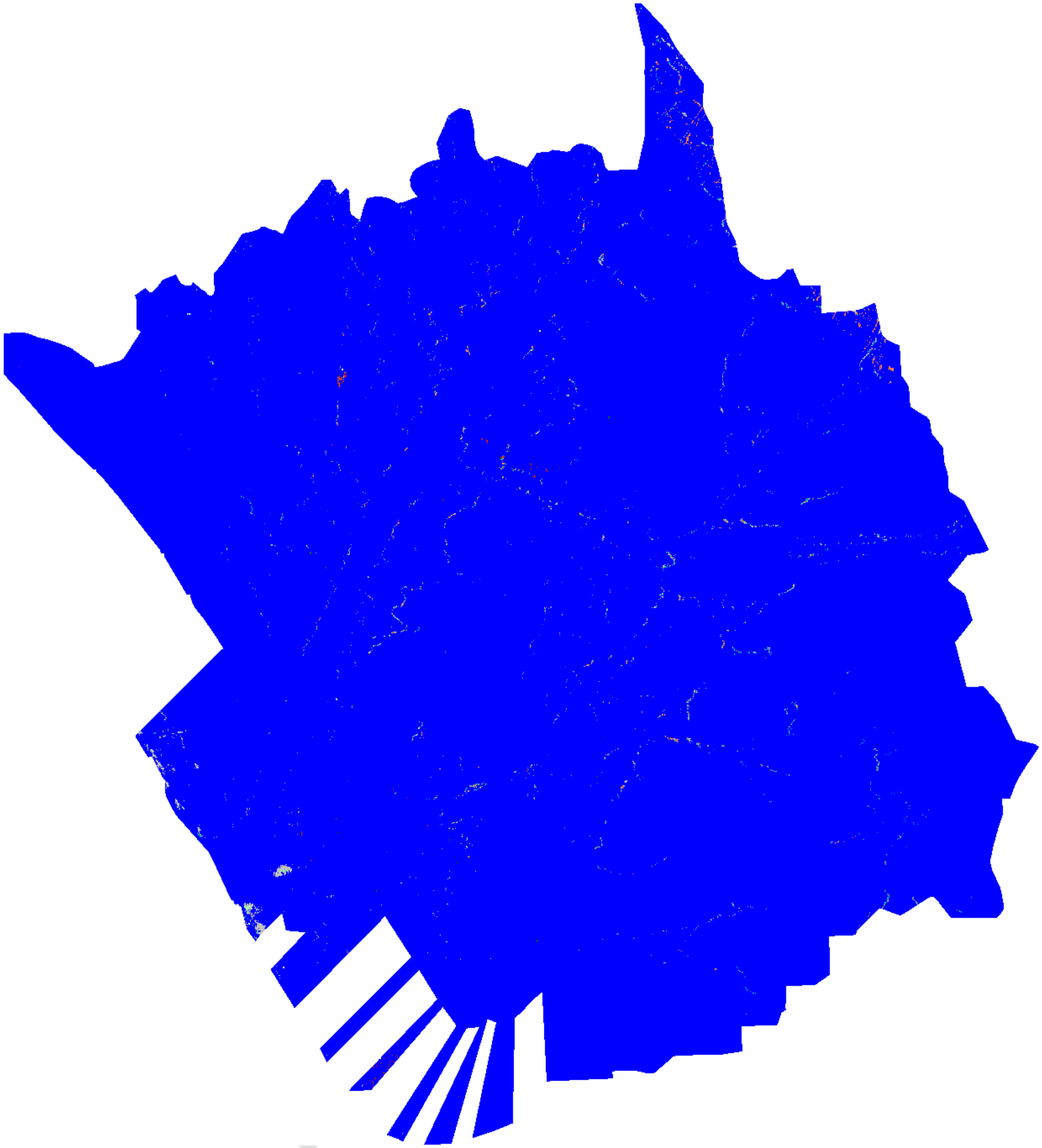
Delta NWR, 2025, Scenario A1B Maximum



Delta NWR, 2050, Scenario A1B Maximum



Delta NWR, 2075, Scenario A1B Maximum

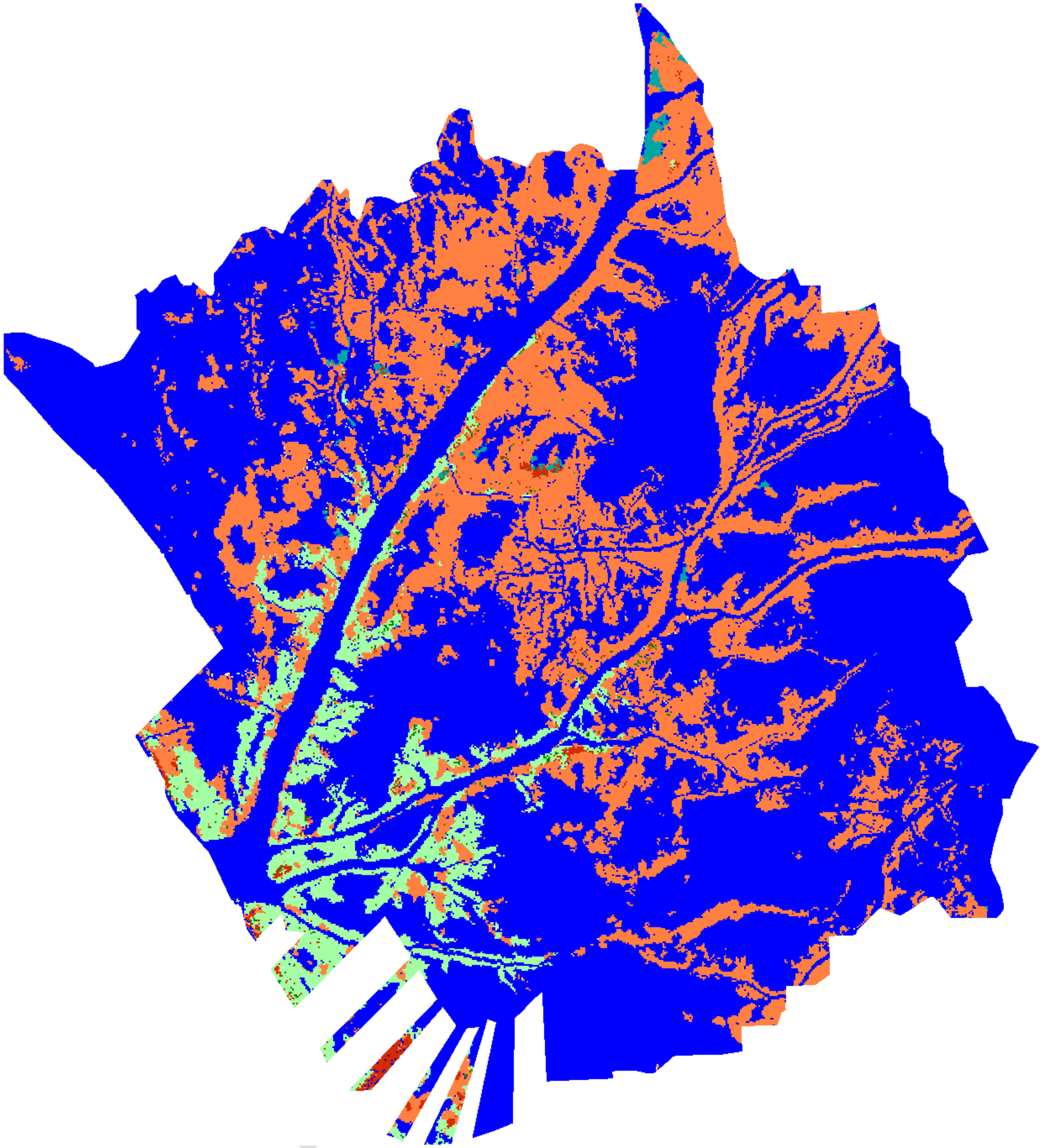


Delta NWR, 2100, Scenario A1B Maximum

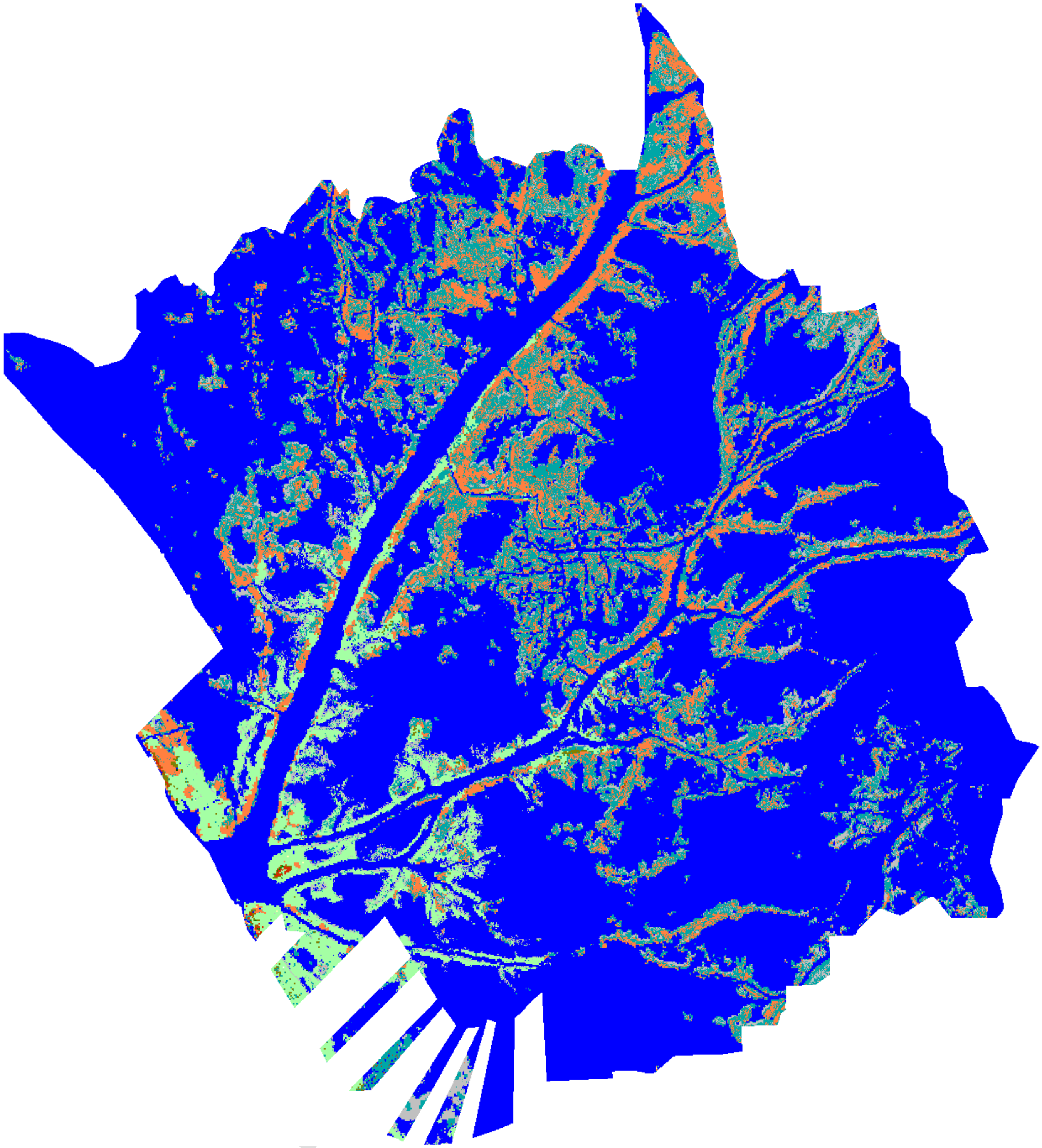
1 m eustatic SLR by 2100

Results in Acres

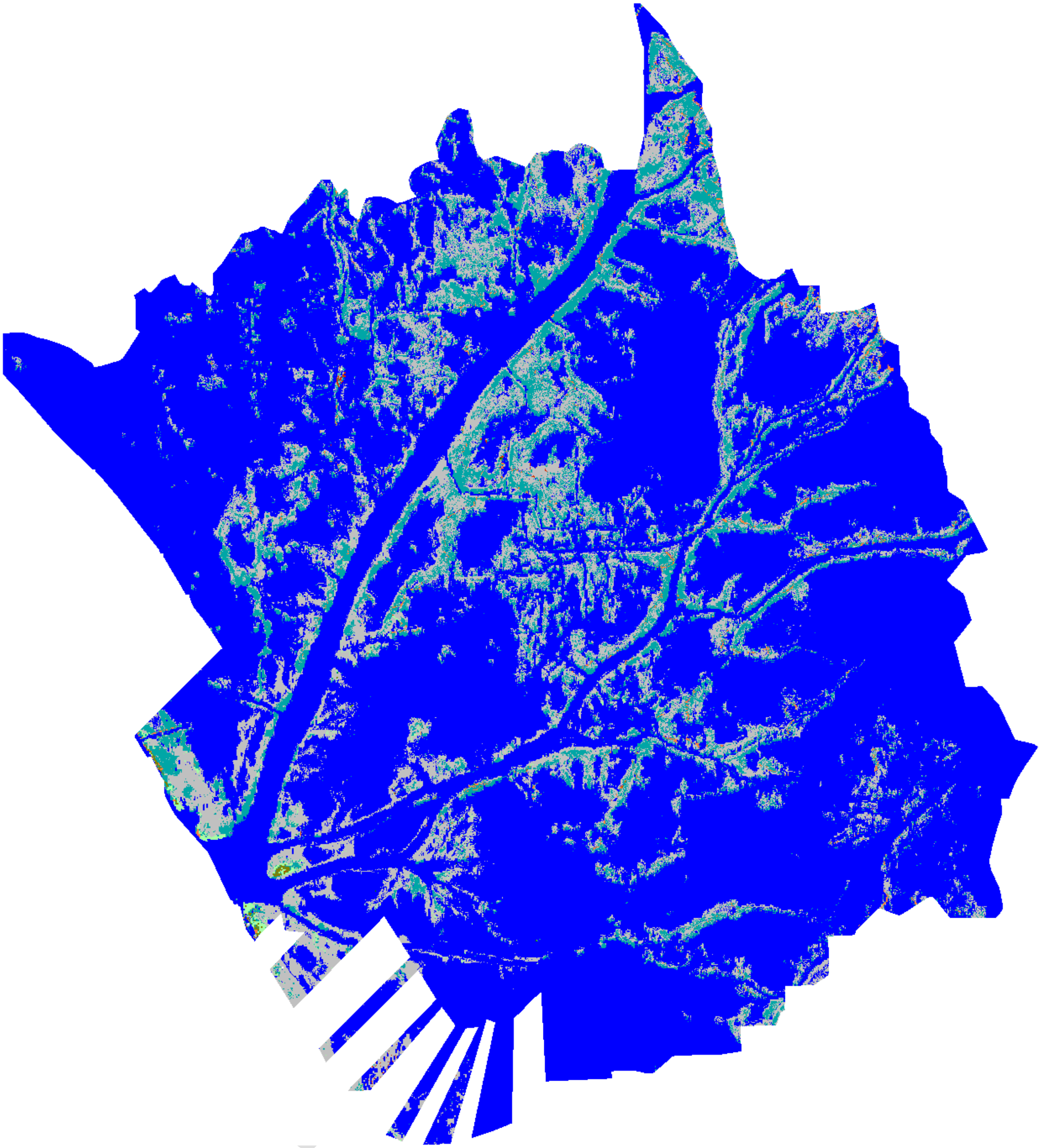
| | | Initial | 2025 | 2050 | 2075 | 2100 |
|---|---|---|---|---|---|---|
| | Estuarine Open Water | 33748 | 34535 | 39067 | 47401 | 50532 |
| | Irregularly Flooded Marsh | 13424 | 4610 | 261 | 88 | 37 |
| | Tidal Fresh Marsh | 3002 | 2017 | 128 | 19 | 5 |
| | Undeveloped Dry Land | 234 | 28 | 10 | 9 | 9 |
| | Regularly Flooded Marsh | 163 | 7045 | 4459 | 194 | 51 |
| | Swamp | 103 | 7 | 3 | 3 | 3 |
| | Estuarine Beach | 78 | 15 | 0 | 0 | 0 |
| | Cypress Swamp | 1 | 1 | 0 | 0 | 0 |
| | Transitional Salt Marsh | 0 | 71 | 22 | 1 | 0 |
| | Tidal Flat | 0 | 2423 | 6802 | 3038 | 115 |
| | **Total (incl. water)** | **50753** | **50753** | **50753** | **50753** | **50753** |



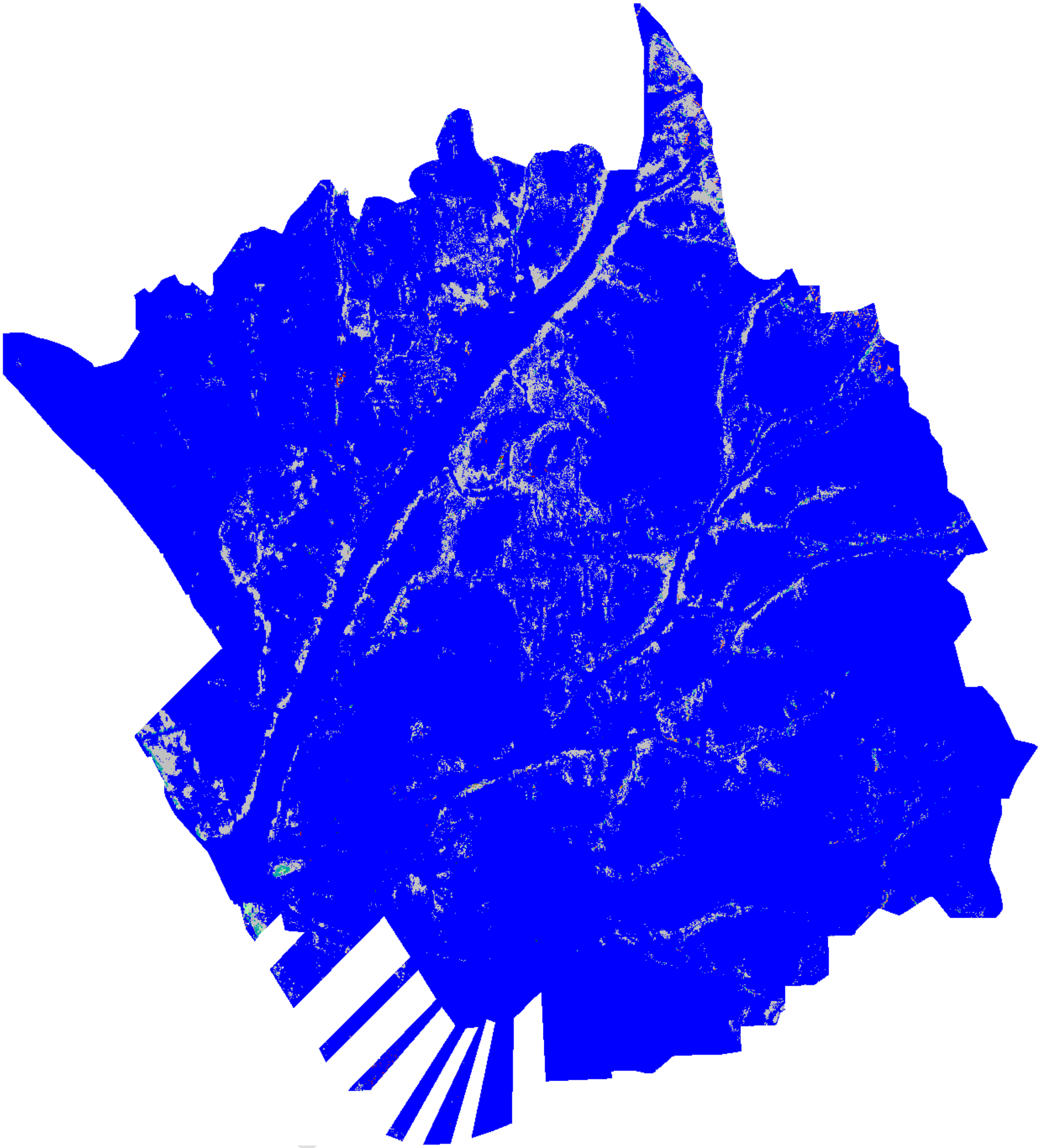
Delta NWR, Initial Condition



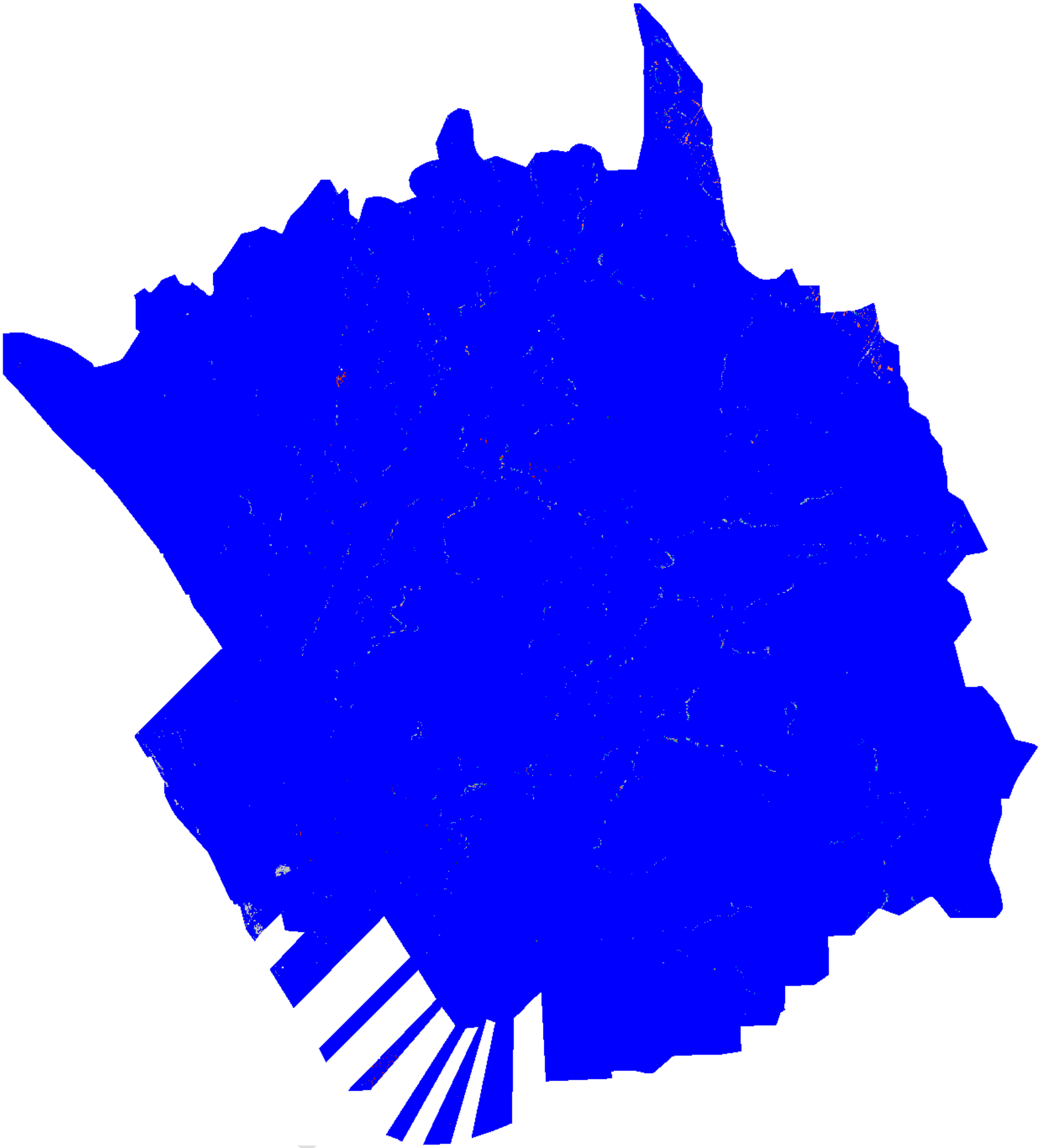
Delta NWR, 2025, 1 Meter



Delta NWR, 2050, 1 Meter



Delta NWR, 2075, 1 Meter

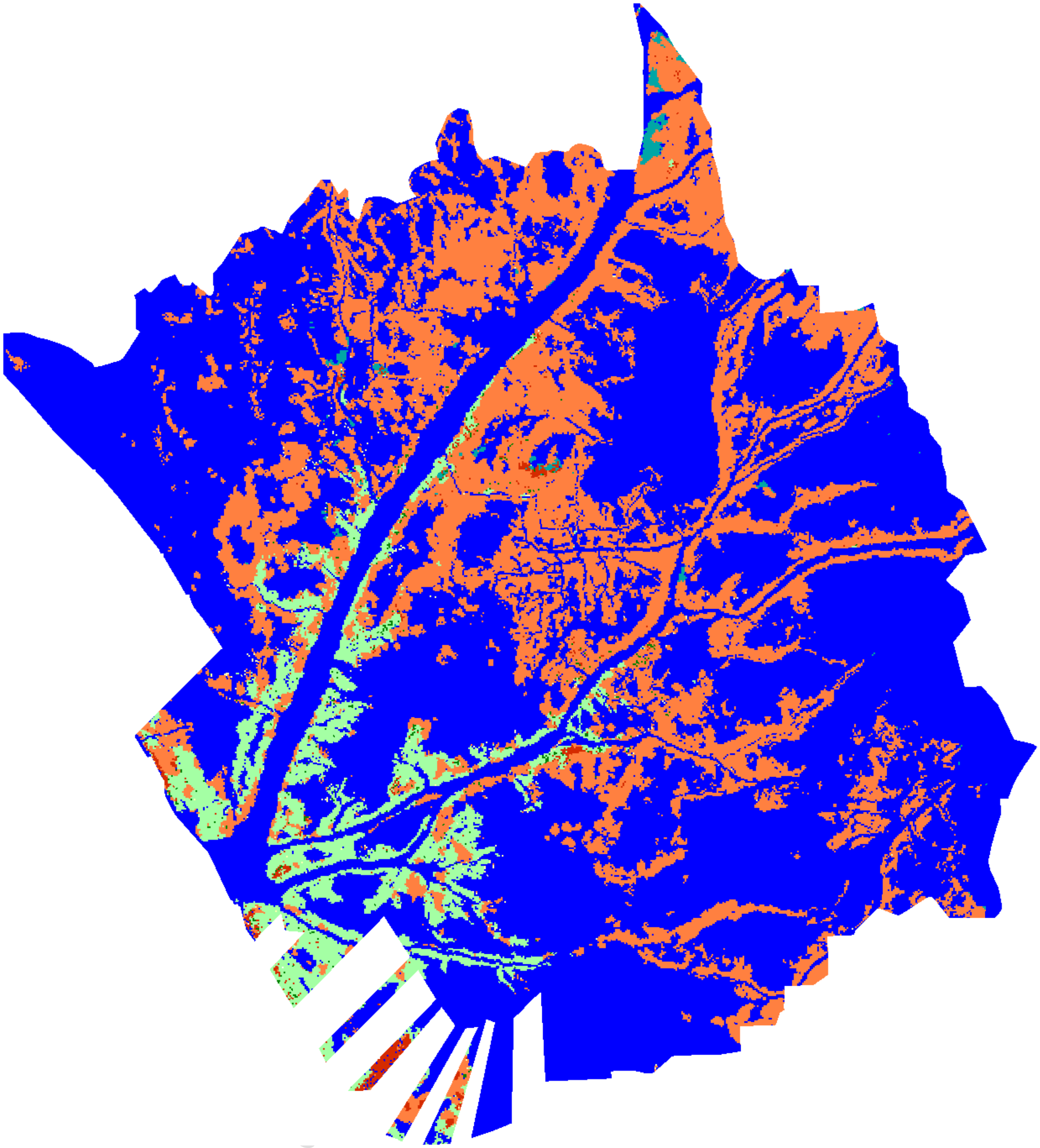


Delta NWR, 2100, 1 Meter

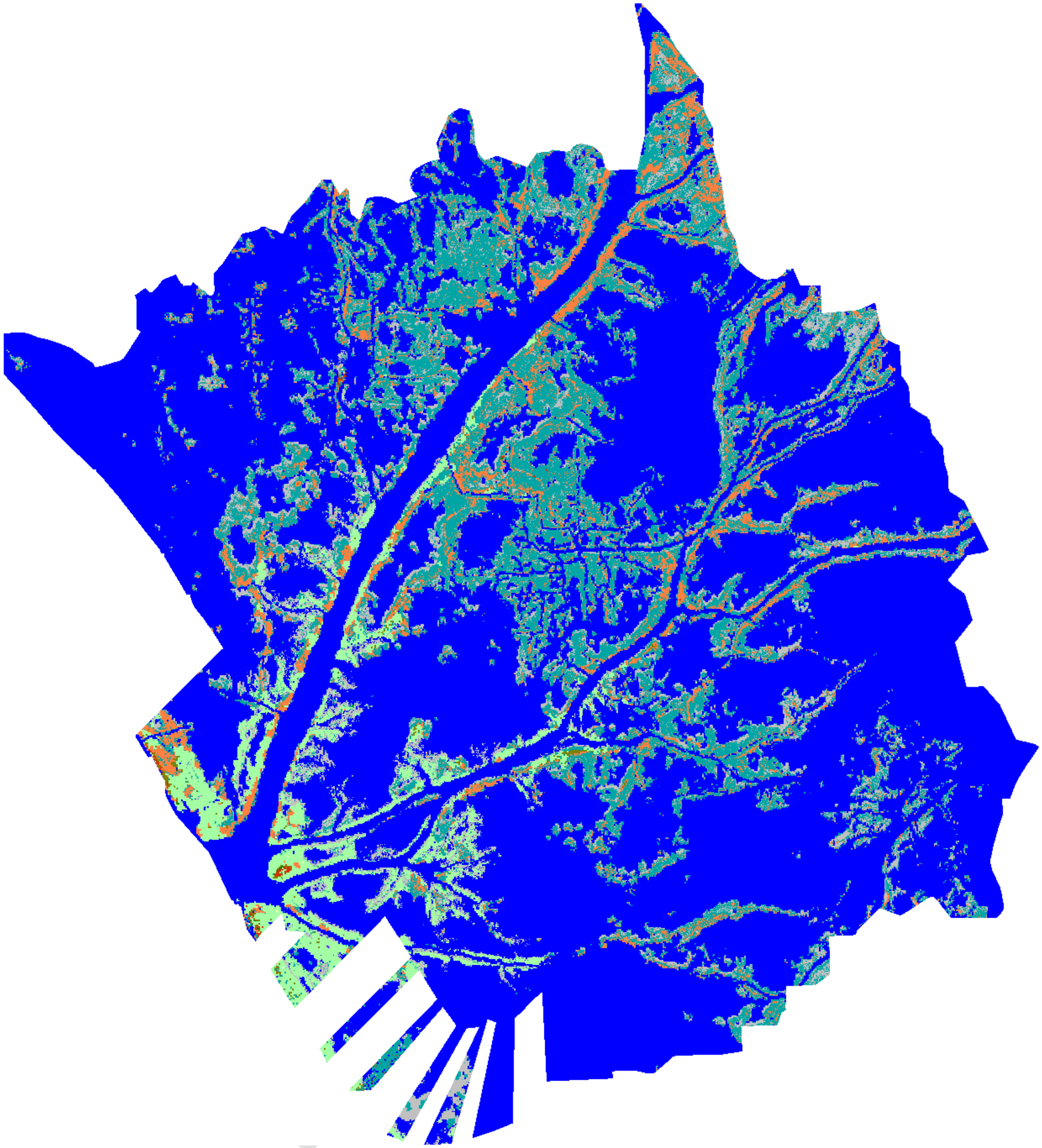
1.5 m eustatic SLR by 2100

Results in Acres

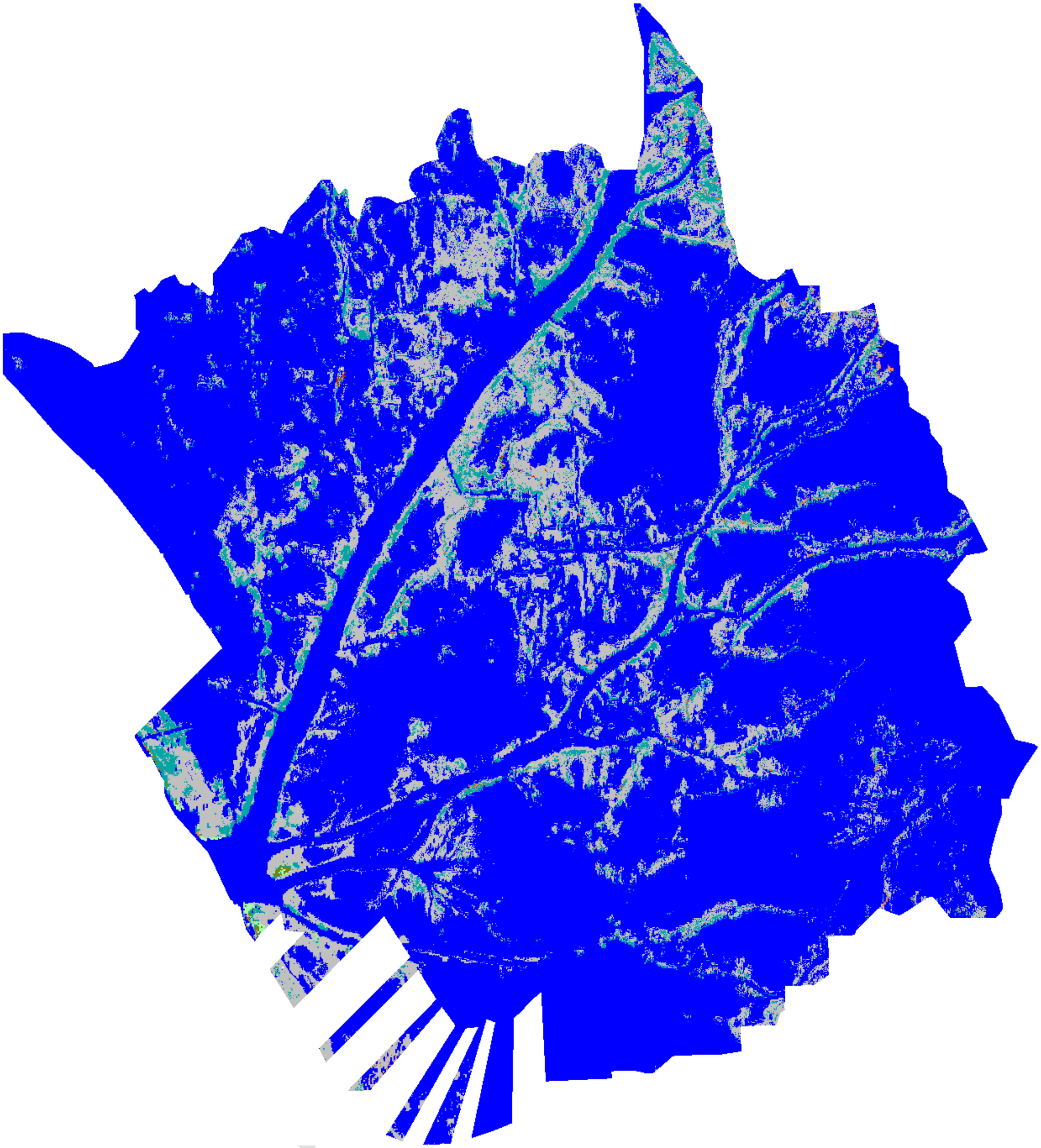
| | | Initial | 2025 | 2050 | 2075 | 2100 |
|---|---|---|---|---|---|---|
| | Estuarine Open Water | 33748 | 34755 | 40576 | 48919 | 50615 |
| | Irregularly Flooded Marsh | 13424 | 2643 | 170 | 48 | 24 |
| | Tidal Fresh Marsh | 3002 | 1738 | 54 | 7 | 1 |
| | Undeveloped Dry Land | 234 | 25 | 10 | 9 | 9 |
| | Regularly Flooded Marsh | 163 | 7996 | 2554 | 139 | 23 |
| | Swamp | 103 | 6 | 3 | 3 | 3 |
| | Estuarine Beach | 78 | 12 | 0 | 0 | 0 |
| | Cypress Swamp | 1 | 1 | 0 | 0 | 0 |
| | Transitional Salt Marsh | 0 | 74 | 19 | 1 | 0 |
| | Tidal Flat | 0 | 3503 | 7367 | 1626 | 76 |
| | **Total (incl. water)** | **50753** | **50753** | **50753** | **50753** | **50753** |



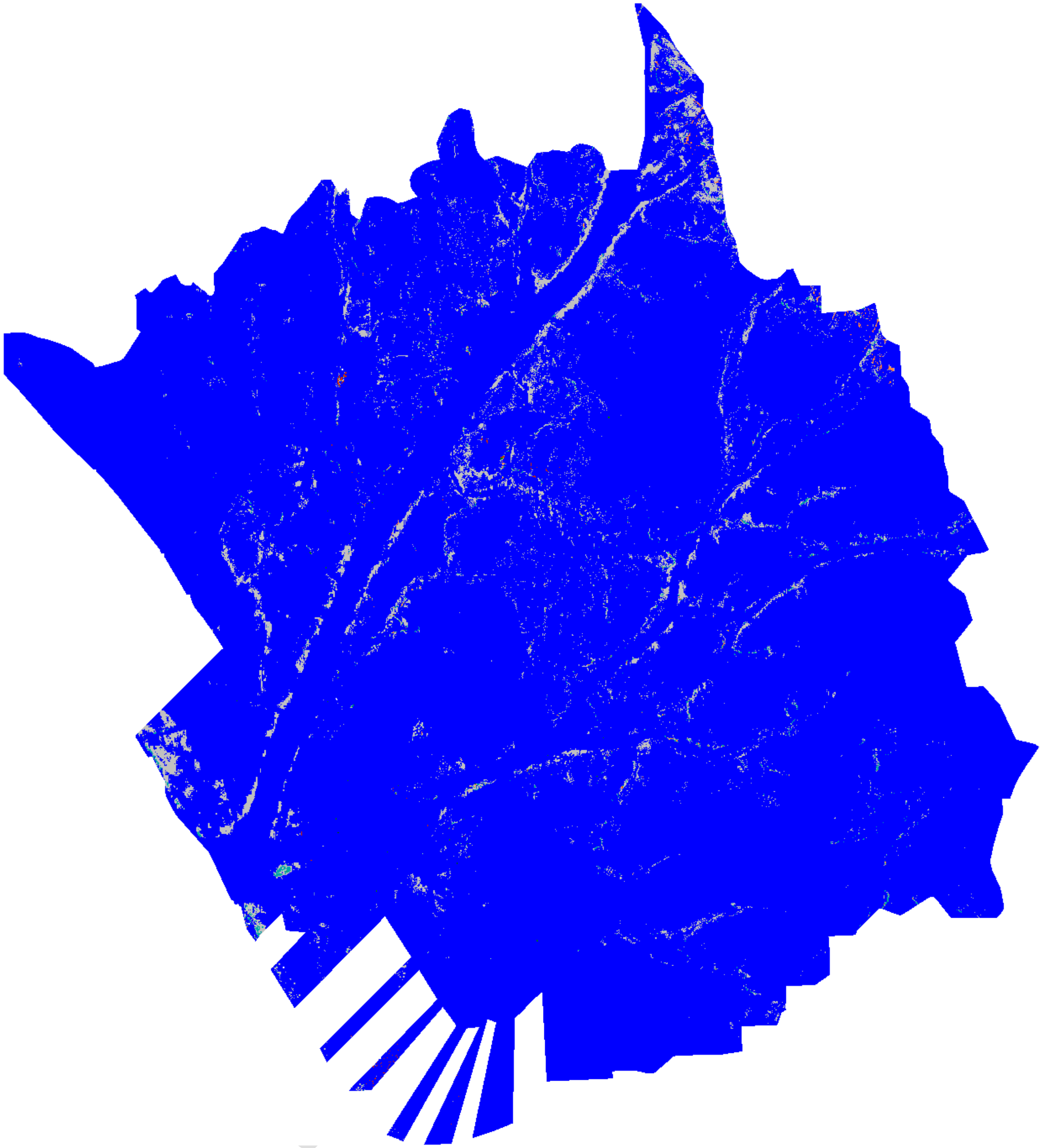
Delta NWR, Initial Condition



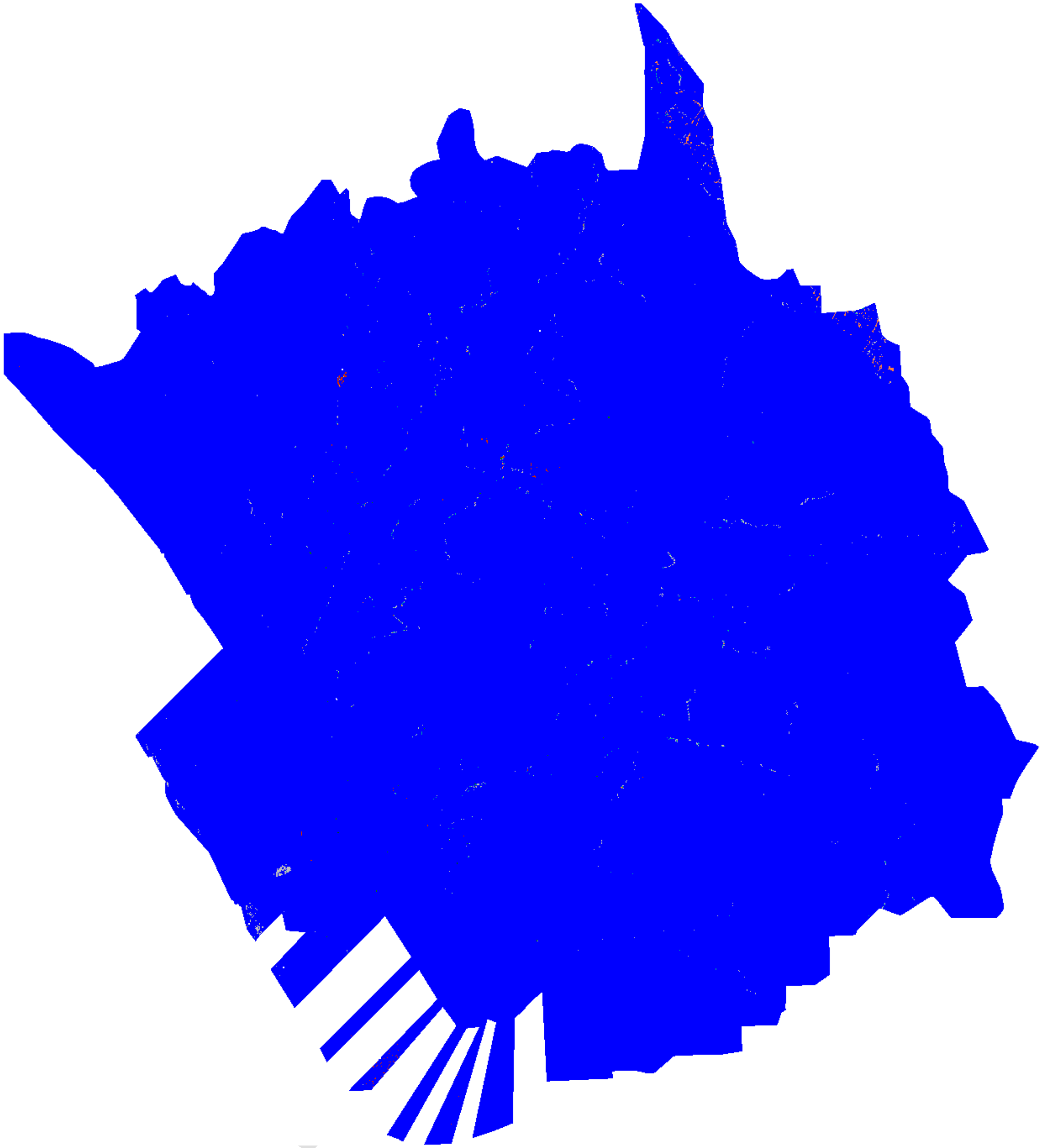
Delta NWR, 2025, 1.5 Meters



Delta NWR, 2050, 1.5 Meters



Delta NWR, 2075, 1.5 Meters

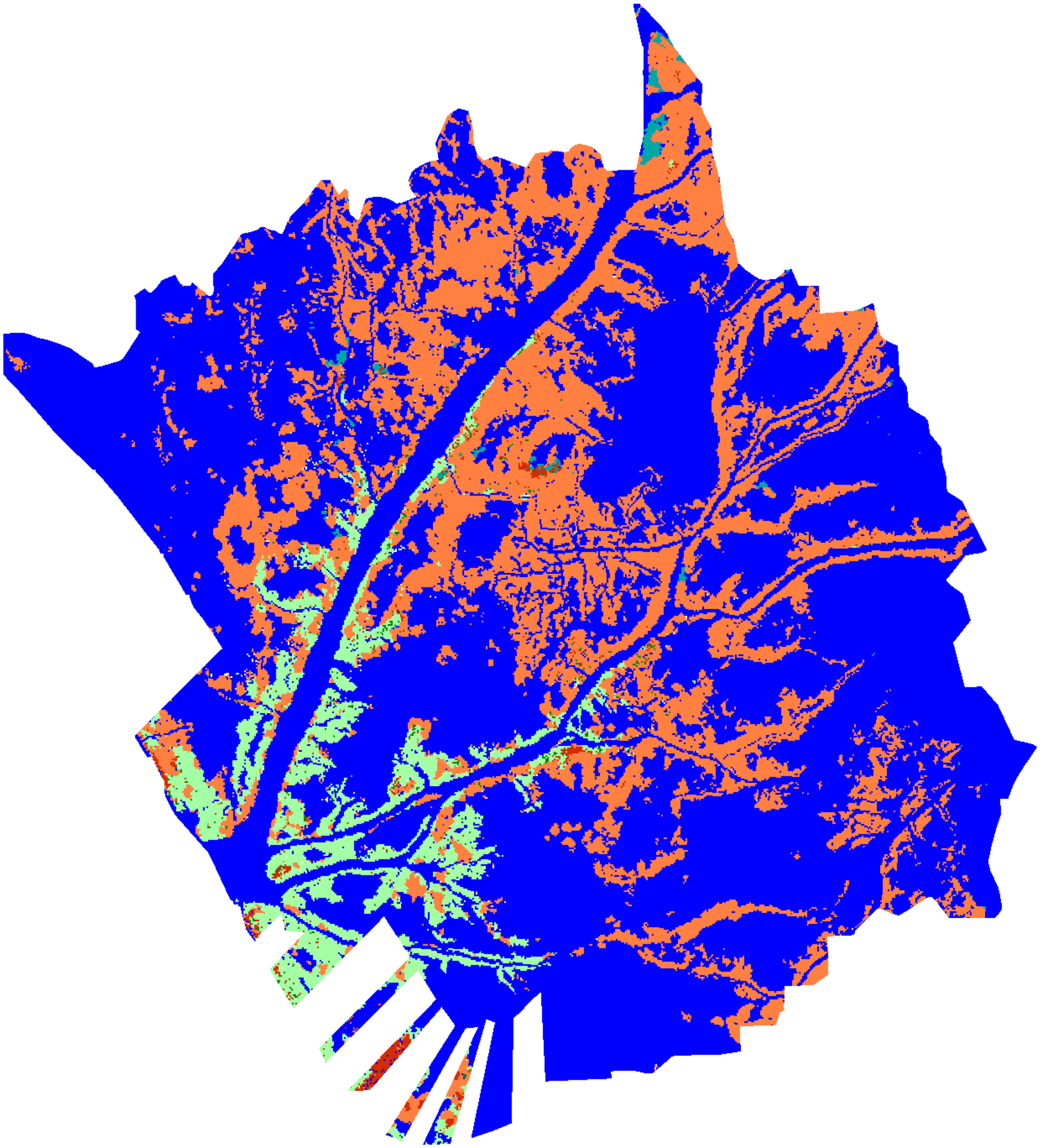


Delta NWR, 2100, 1.5 Meters

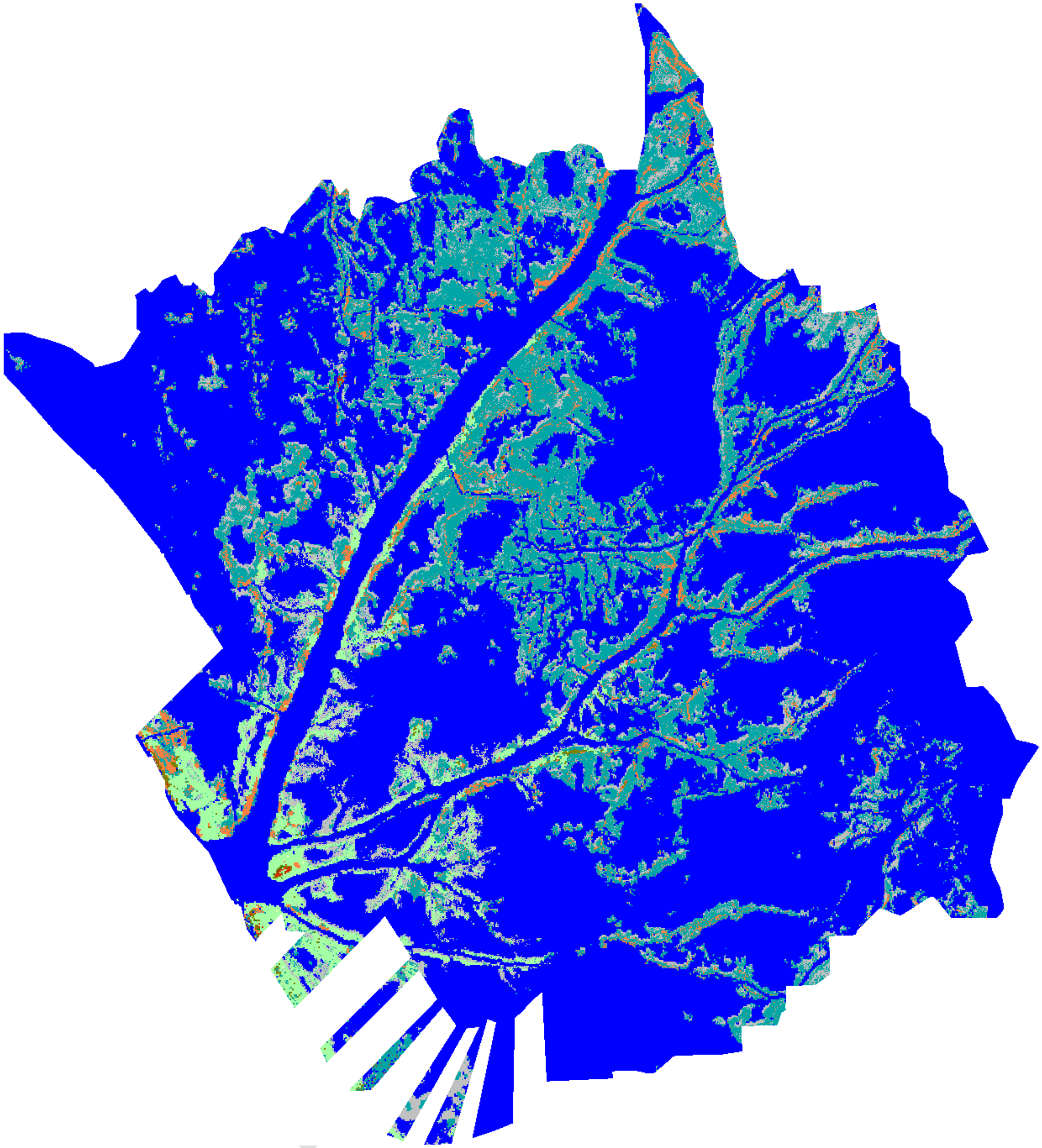
2 m eustatic SLR by 2100

Results in Acres

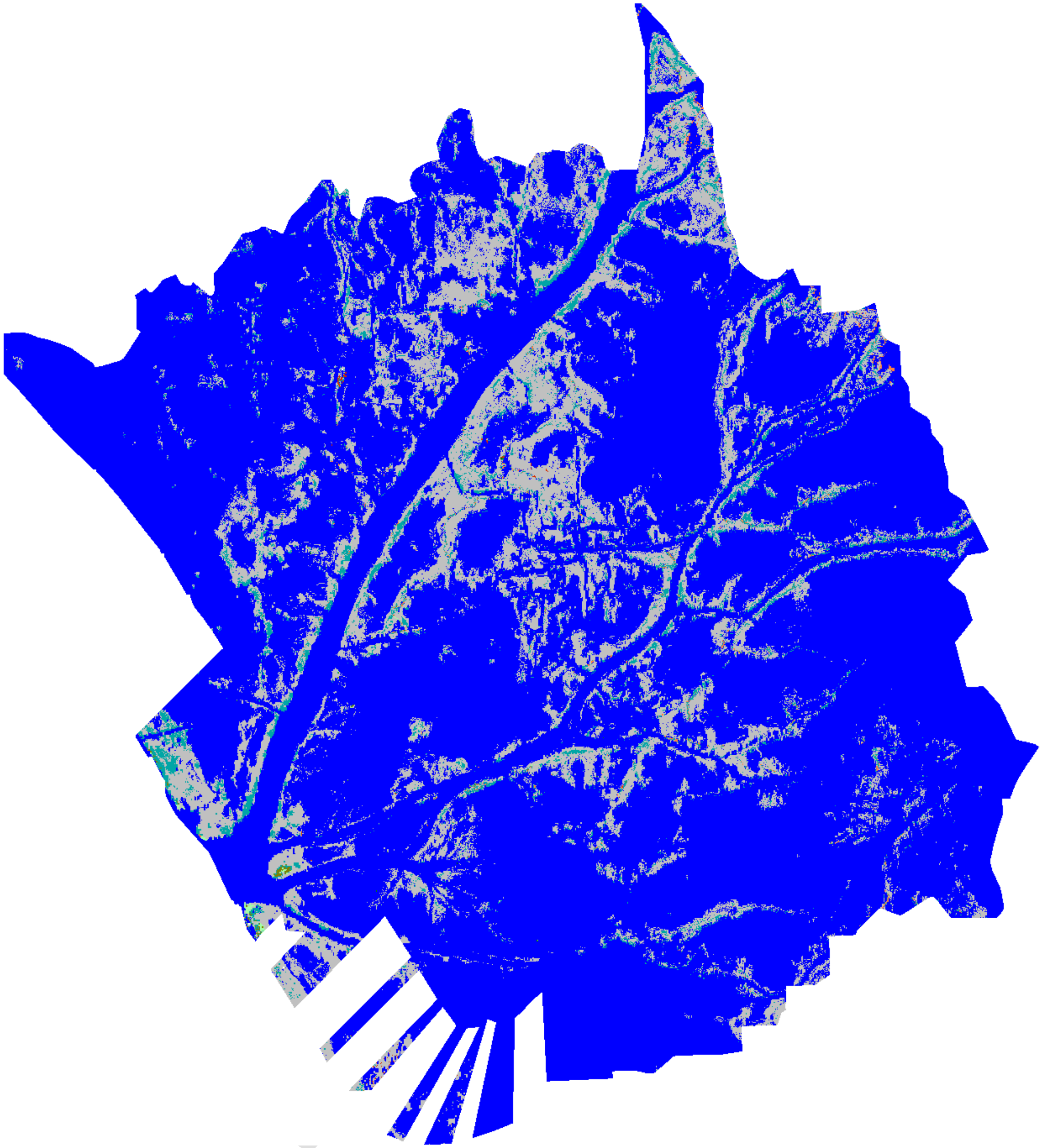
| | | Initial | 2025 | 2050 | 2075 | 2100 |
|---|---|---|---|---|---|---|
| | Estuarine Open Water | 33748 | 34821 | 41181 | 49663 | 50655 |
| | Irregularly Flooded Marsh | 13424 | 1539 | 119 | 32 | 20 |
| | Tidal Fresh Marsh | 3002 | 1455 | 30 | 3 | 0 |
| | Undeveloped Dry Land | 234 | 22 | 9 | 9 | 9 |
| | Regularly Flooded Marsh | 163 | 8956 | 1502 | 99 | 11 |
| | Swamp | 103 | 6 | 3 | 3 | 2 |
| | Estuarine Beach | 78 | 9 | 0 | 0 | 0 |
| | Cypress Swamp | 1 | 1 | 0 | 0 | 0 |
| | Transitional Salt Marsh | 0 | 78 | 15 | 0 | 0 |
| | Tidal Flat | 0 | 3867 | 7893 | 942 | 54 |
| | **Total (incl. water)** | **50753** | **50753** | **50753** | **50753** | **50753** |



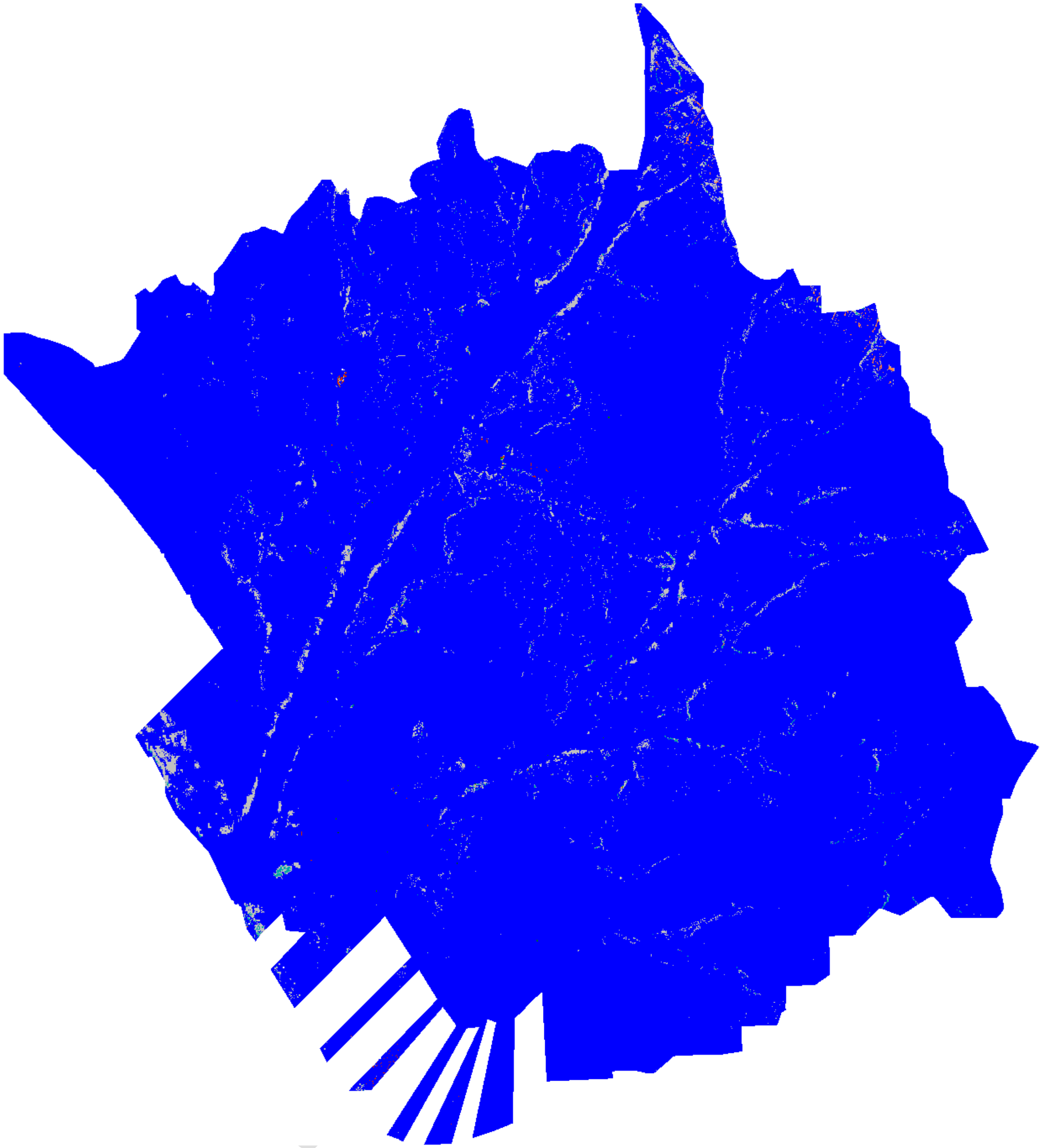
Delta NWR, Initial Condition



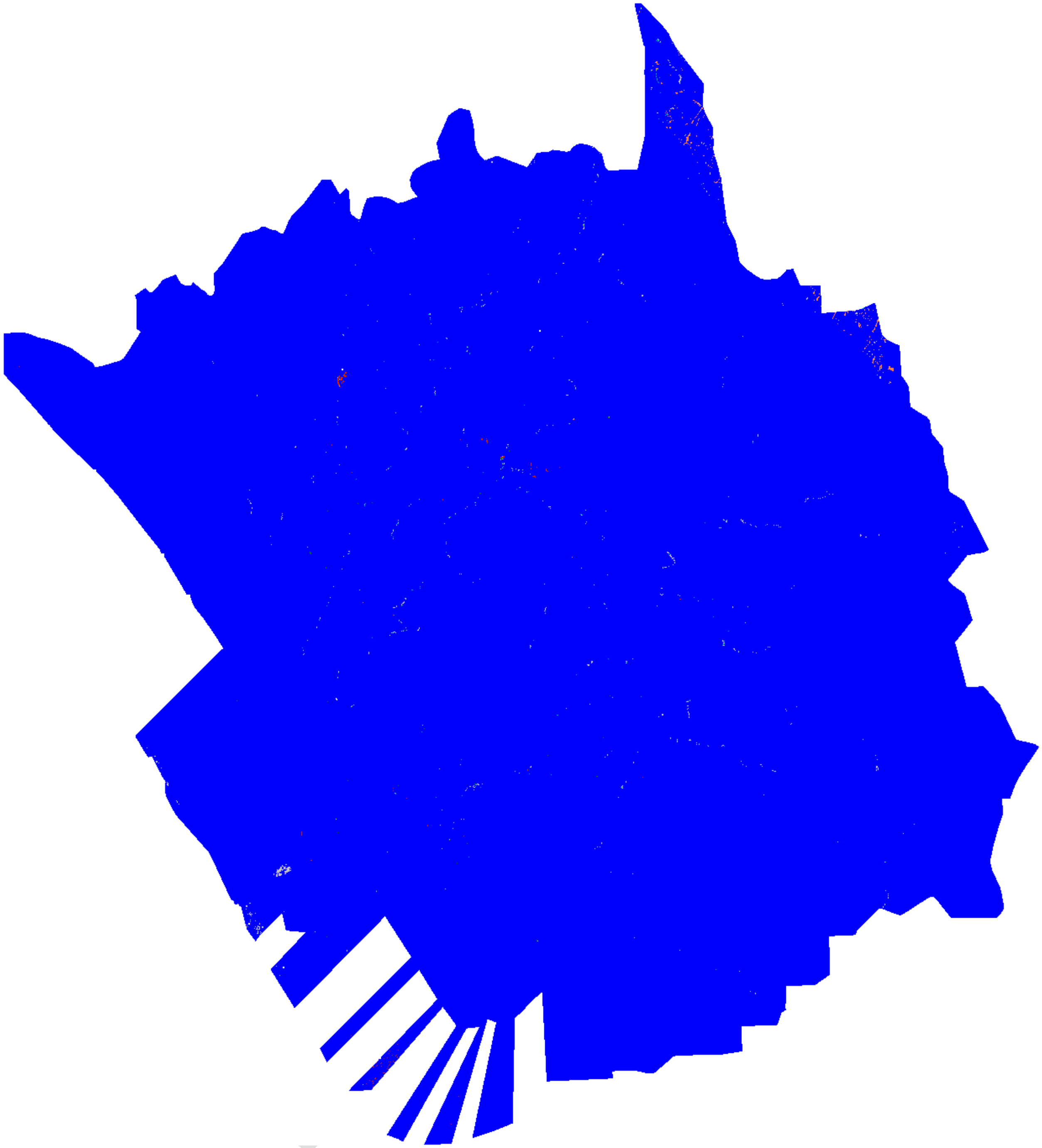
Delta NWR, 2025, 2 Meters



Delta NWR, 2050, 2 Meters



Delta NWR, 2075, 2 Meters



Delta NWR, 2100, 2 Meters

# Discussion

Model results for Delta NWR indicate that it is completely vulnerable to sea level rise by 2100. At the lowest SLR scenario run (the A1B mean scenario, or 0.39 m of SLR by 2100) near all of the irregularly-flooded marsh, tidal-fresh marsh, and swamp is predicted to be lost.

However, there are several sources of uncertainty in these model results. A major contributing factor to these losses is a high predicted rate of subsidence in the bird's foot delta of the Mississippi River, which leads to the prediction of significant losses of wetlands under all SLR scenarios examined. Direct measurements of subsidence in the bird's foot delta itself were not available and these subsidence rates are extrapolated from nearby measurements on dry land (Shinkle and Dokka 2004).

Accretion feedback curves were used as a function of cell elevation to allow marsh accretion rates to range from 12 to 16 mm/yr. However, these accretion rates did not vary spatially, whereas extremely high rates of accretion may be occurring at the interface between distributaries and open water thus resulting in small pockets of more resilient wetlands in these locations. As a consequence, results of model calibration (conducted for the National Wildlife Federation) suggested the model may overpredict losses in the immediate interface between river distributaries and open water.

A lack of elevation data for a small fraction of the refuge leads to some additional uncertainty in the model results. The small amount of land that is predicted to persist at the higher SLR scenarios does so only because the elevations of these lands are unknown. Therefore, it may be assumed that SLR scenarios as low as the IPCC mean SLR by 2100 (0.39 m SLR by 2100) have the potential to completely inundate the refuge.

The area surrounding Delta NWR was studied in a previous SLAMM analysis funded by the National Wildlife Federation (Glick et al. 2011). This model application report was distilled from that larger report. Maps of results for a larger portion of the study area are presented in the "contextual maps" below.

# References


Bryant, J. C., and Chabreck, R. H. (1998). "Effects of Impoundment on Vertical Accretion of Coastal Marsh." *Estuaries*, 21(3), 416.

Cahoon, Donald R., and Turner, R. E. (1989). "Accretion and Canal Impacts in a Rapidly Subsiding Wetland II. Feldspar Marker Horizon Technique." *Estuaries*, 12(4), 260.

Chen, H., and Pontius, R. G. (2010). "Sensitivity of a Land Change Model to Pixel Resolution and Precision of the Independent Variable." *Environmental Modeling & Assessment*.

Chen, J. L., Wilson, C. R., and Tapley, B. D. (2006). "Satellite Gravity Measurements Confirm Accelerated Melting of Greenland Ice Sheet." *Science*, 313, 1958-1960.

Clark, P. U. (2009). *Abrupt Climate Change: Final Report, Synthesis and Assessment Product 3. 4*. DIANE Publishing.

Clough, J. S., Park, R. A., and Fuller, R. (2010). "SLAMM 6 beta Technical Documentation."

Council for Regulatory Environmental Modeling. (2008). *Draft guidance on the development, evaluation, and application of regulatory environmental models*. Draft, Washington, DC.

Couvillion, B. (2010). Personal Communication. "DVD Delivery."

Craft, C., Clough, J. S., Ehman, J., Joye, S., Park, R. A., Pennings, S., Guo, H., and Machmuller, M. (2009). "Forecasting the effects of accelerated sea-level rise on tidal marsh ecosystem services." *Frontiers in Ecology and the Environment*, 7(2), 73-78.

Darnell, A. R., Tate, N. J., and Brunsdon, C. (2008). "Improving user assessment of error implications in digital elevation models." *Computers, Environment and Urban Systems*, 32(4), 268-277.

Galbraith, H., Jones, R., Park, R., Clough, J., Herrod-Julius, S., Harrington, B., and Page, G. (2002). "Global Climate Change and Sea Level Rise: Potential Losses of Intertidal Habitat for Shorebirds." *Waterbirds*, 25(2), 173.

Glick, P., Clough, J., and Nunley, B. (2007). *Sea-level Rise and Coastal Habitats in the Pacific Northwest: An Analysis for Puget Sound, Southwestern Washington, and Northwestern Oregon*. National Wildlife Federation.

Glick, P., Clough, J., Polaczyk, A., and Nunley, B. (2011). *Sea-Level Rise and Coastal Habitats in Southeastern Louisiana: An Application of the Sea Level Affecting Marshes (SLAMM) Model*. Draft Technical Report. National Wildlife Federation.

Grinsted, A., Moore, J. C., and Jevrejeva, S. (2009). "Reconstructing sea level from paleo and projected temperatures 200 to 2100 AD." *Climate Dynamics*, 34(4), 461-472.

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*. Cambridge University Press, Cambridge, United Kingdom, 881.

IPCC. (2007). *Climate Change 2007: The Physical Science Basis*. Cambridge University Press, Cambridge, United Kingdom.

Lang, C.-yi. (2000). "Kriging Interpolation." (Jan. 11, 2011).

Lee, J. K., Park, R. A., and Mausel, P. W. (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.

Monaghan, A. J., Bromwich, D. H., Fogt, R. L., Wang, S.-H., Mayewski, P. A., Dixon, D. A., Ekaykin, A., Frezzotti, M., Goodwin, I., Isaksson, E., Kaspari, S. D., Morgan, V. I., Oerter, H., Van Ommen, T. D., Van der Veen, C. J., and Wen, J. (2006). "Insignificant Change in Antarctic Snowfall Since the International Geophysical Year." *Science*, 313(5788), 827-831.

Moorhead, K. K., and Brinson, M. M. (1995). "Response of Wetlands to Rising Sea Level in the Lower Coastal Plain of North Carolina." *Ecological Applications*, 5(1), 261-271.

National Wildlife Federation and Florida Wildlife Federation. (2006). *An Unfavorable Tide: Global Warming, Coastal Habitats and Sportfishing in Florida.*

Nyman, J. A, DeLaune, R. D., Roberts, H. H., and Patrick Jr, W. H. (1993). "Relationship between vegetation and soil formation in a rapidly submerging coastal marsh." *Marine ecology progress series. Oldendorf*, 96(3), 269–279.

Nyman, J. A., Delaune, R. D., and Patrick, W. H. (1990). "Wetland soil formation in the rapidly subsiding Mississippi River Deltaic Plain: Mineral and organic matter relationships." *Estuarine, Coastal and Shelf Science*, 31(1), 57-69.

Nyman, John A., Walters, R. J., Delaune, Ronald D., and Patrick, J. (2006). "Marsh vertical accretion via vegetative growth." *Estuarine, Coastal and Shelf Science*, 69(3-4), 370-380.

Park, R. A., Trehan, M. S., Mausel, P. W., and Howe, R.C. (1989). "The Effects of Sea Level Rise on U.S. Coastal Wetlands." *The Potential Effects of Global Climate Change on the United States: Appendix B - Sea Level Rise*, U.S. Environmental Protection Agency, Washington, DC, 1-1 to 1-55.

Park, R. A., Lee, J. K., Mausel, P. W., and Howe, R. C. (1991). "Using remote sensing for modeling the impacts of sea level rise." *World Resources Review*, 3, 184-220.

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

Pfeffer, W. T., Harper, J. T., and O'Neel, S. (2008). "Kinematic Constraints on Glacier Contributions to 21st-Century Sea-Level Rise." *Science*, 321(5894), 1340-1343.

Rahmstorf, S. (2007). "A Semi-Empirical Approach to Projecting Future Sea-Level Rise." *Science*, 315(5810), 368-370.

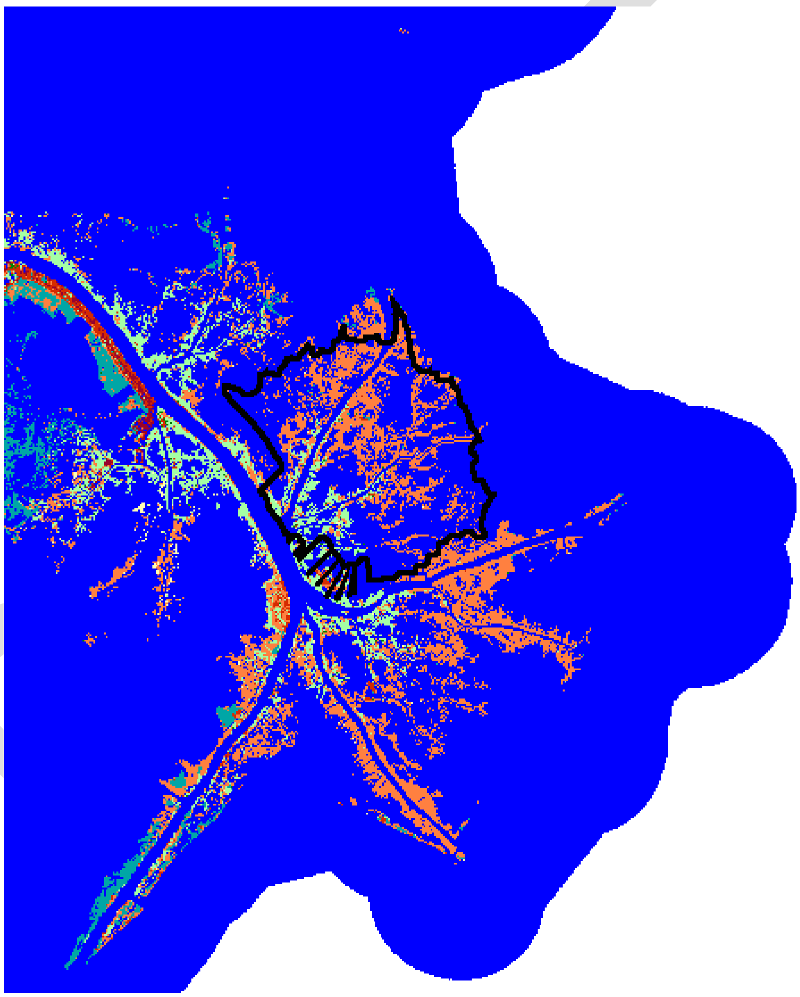
Shinkle, K. D., Dokka, R. K., and (US), N. G. S. (2004). *Rates of vertical displacement at benchmarks in the lower Mississippi Valley and the northern Gulf Coast*. US Dept. of Commerce, National Oceanic and Atmospheric Administration, National Ocean Service,[National Geodetic Survey.

Titus, J. G., Park, R. A., Leatherman, S. P., Weggel, J. R., Greene, M. S., Mausel, P. W., Brown, S., Gaunt, C., Trehan, M., and Yohe, G. (1991). "Greenhouse effect and sea level rise: the cost of holding back the sea." *Coastal Management*, 19(2), 171–204.

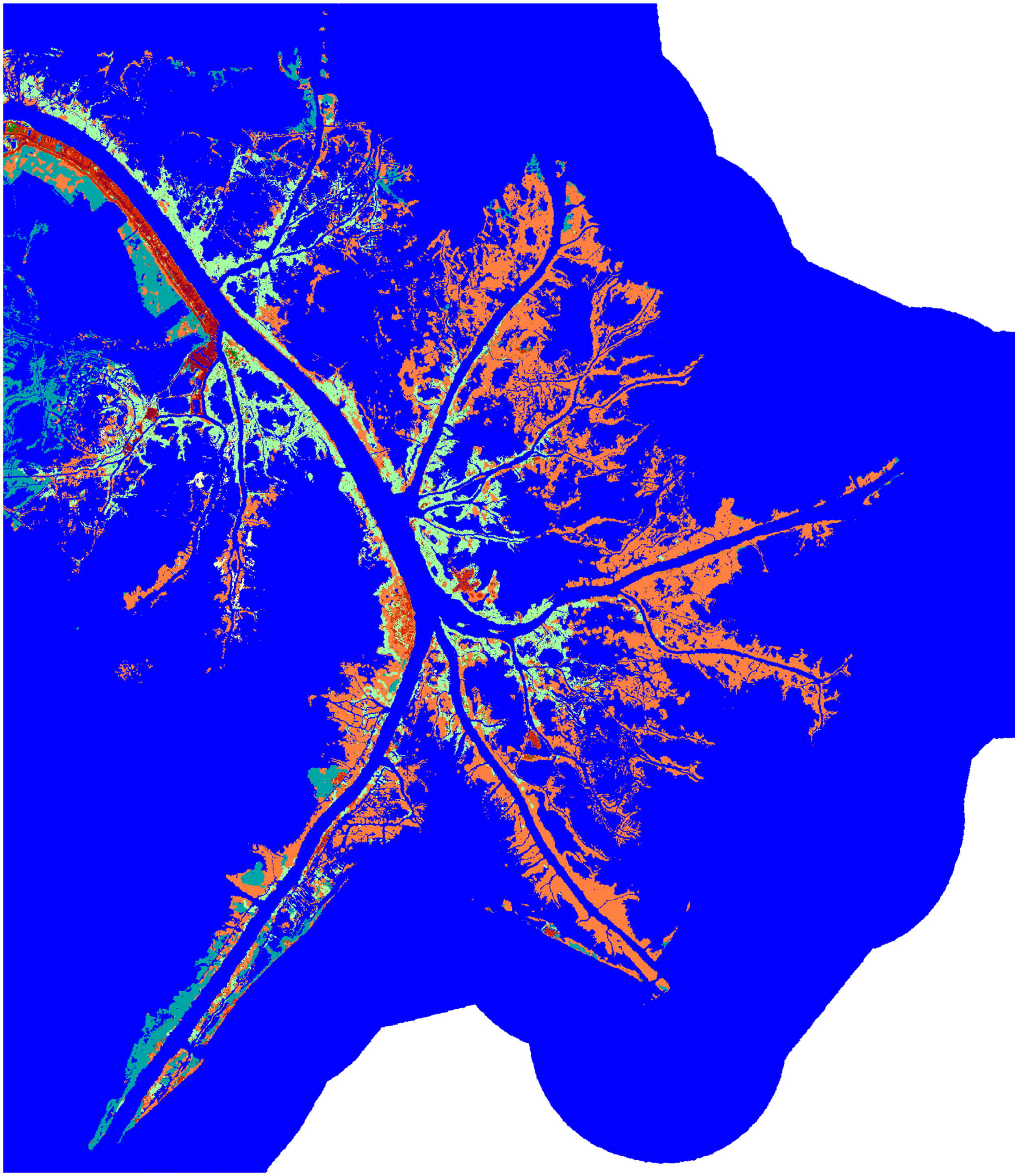
Vermeer, M., and Rahmstorf, S. (2009). "Global sea level linked to global temperature." *Proceedings of the National Academy of Sciences*, 106(51), 21527.

# Appendix A: Contextual Results

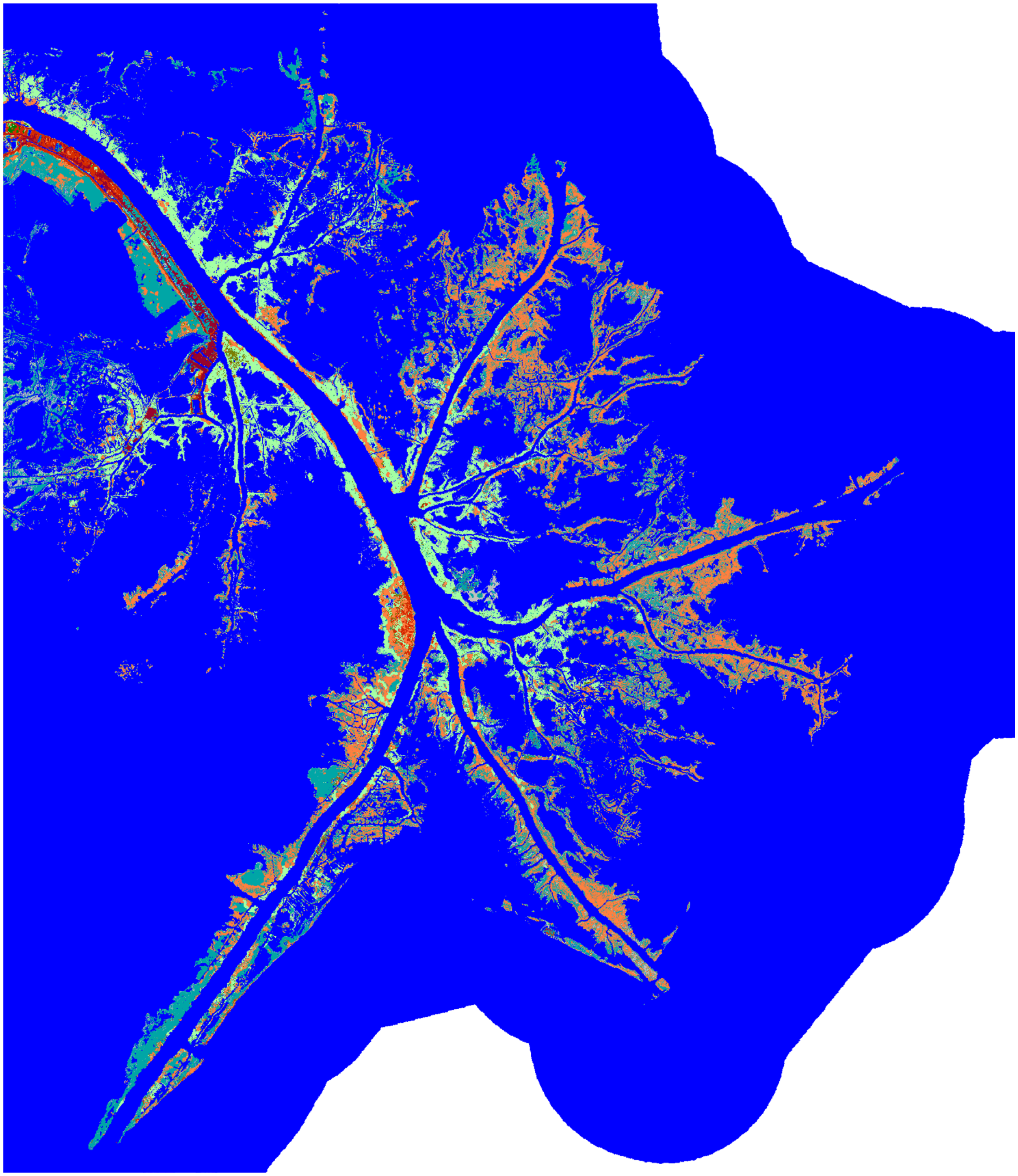
The SLAMM model does take into account the context of the surrounding lands or open water when calculating effects. For example, erosion rates are calculated based on the maximum fetch (wave action) which is estimated by assessing contiguous open water to a given marsh cell. Another example is that inundated 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. A full analysis of this study area was funded by the National Wildlife Federation. It is important to note that the developed dry lands (dark red in the following maps) was considered protected and is not affected by the SLR examined in these scenarios.



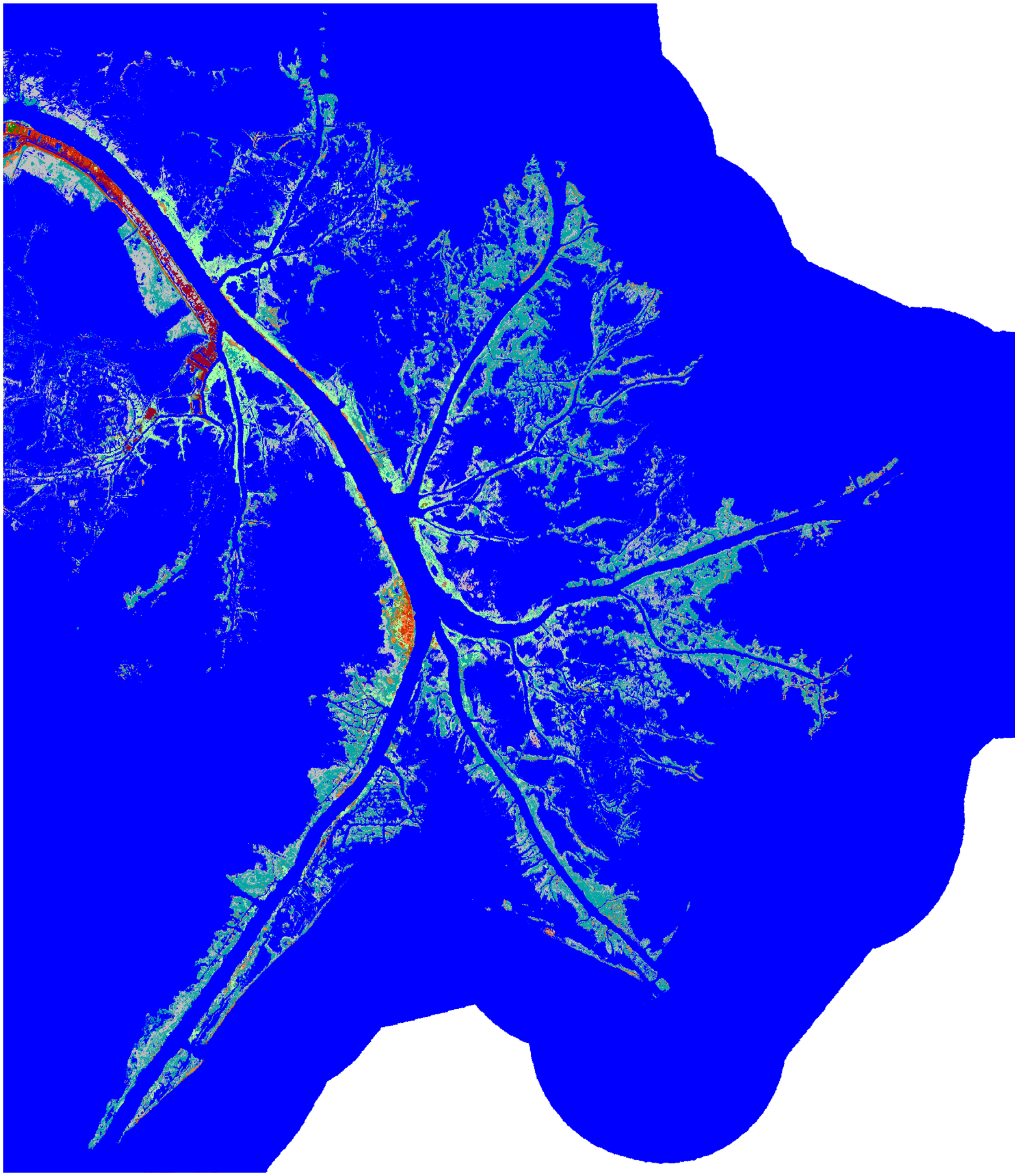
Delta National Wildlife Refuge (outlined in black) within simulation context



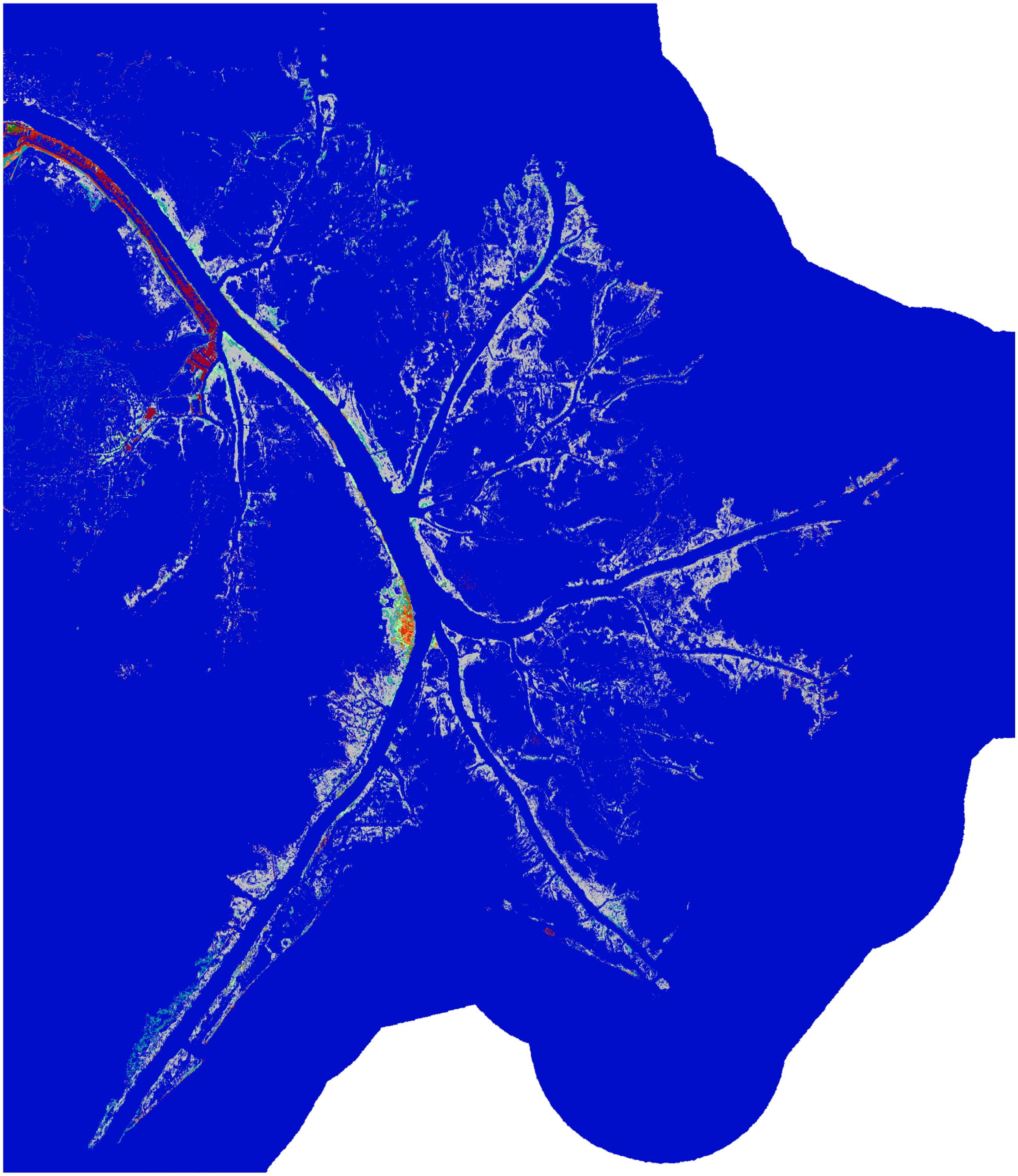
Delta Context, Initial Condition



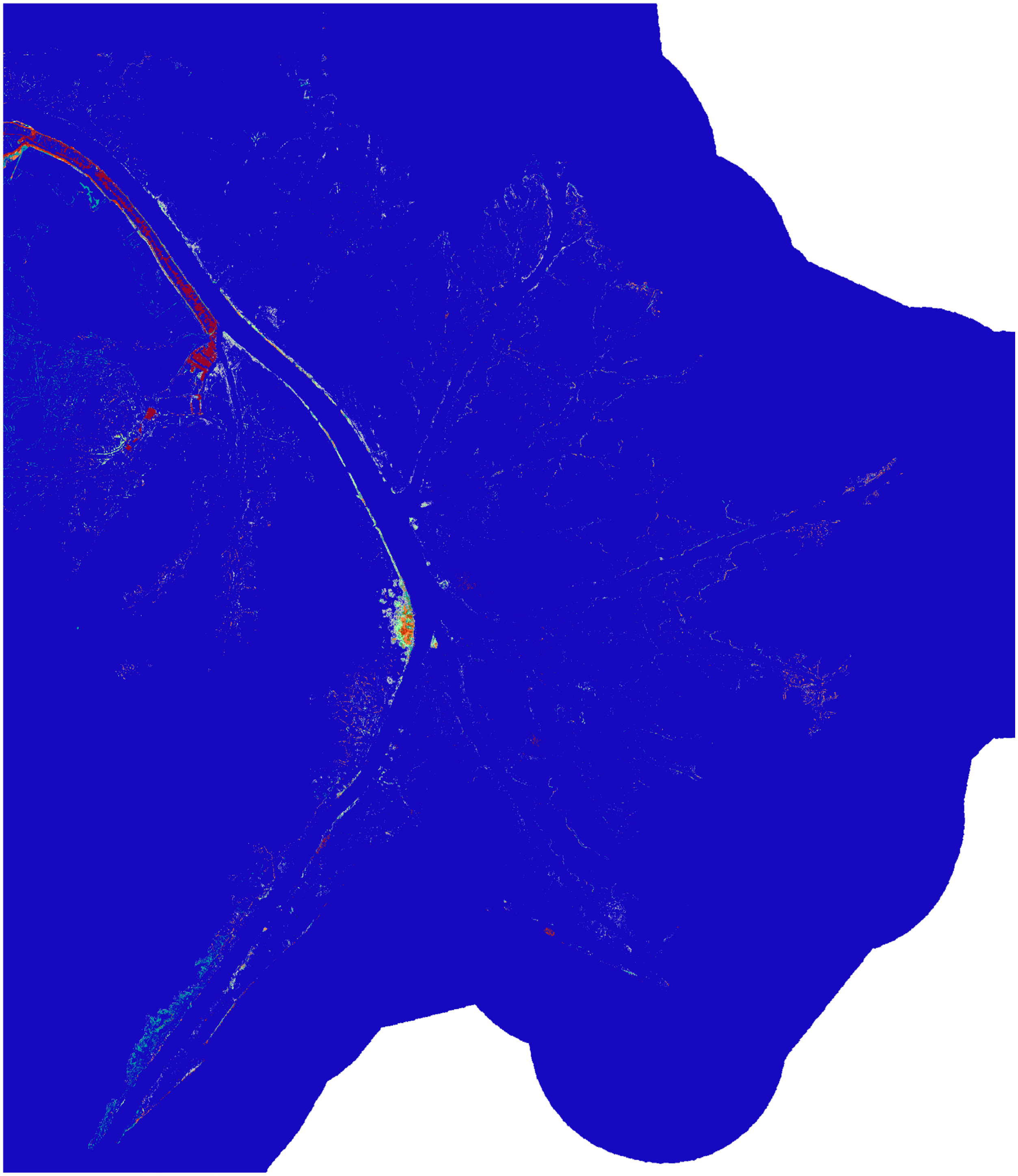
Delta Context, 2025, Scenario A1B Mean



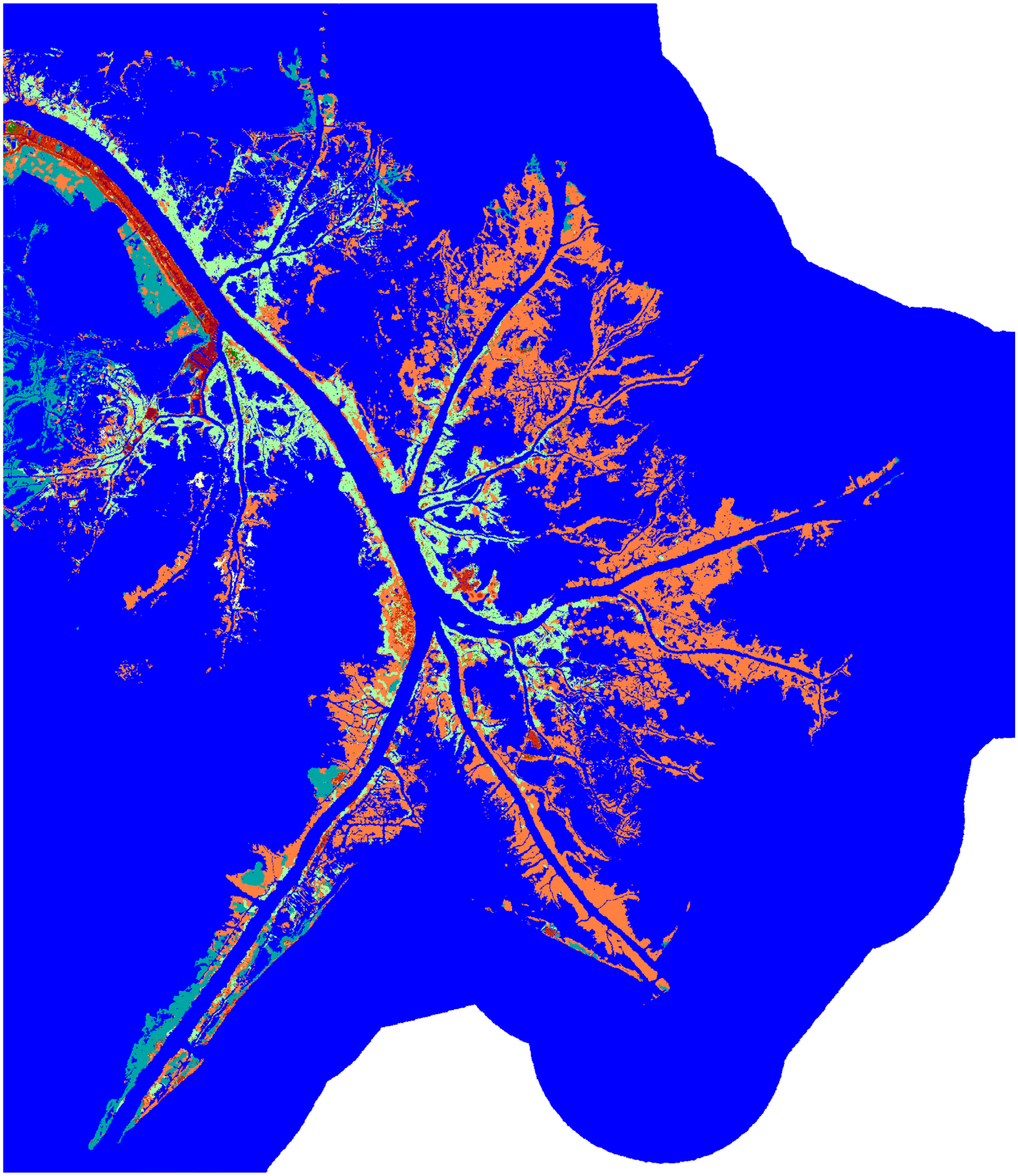
Delta Context, 2050, Scenario A1B Mean



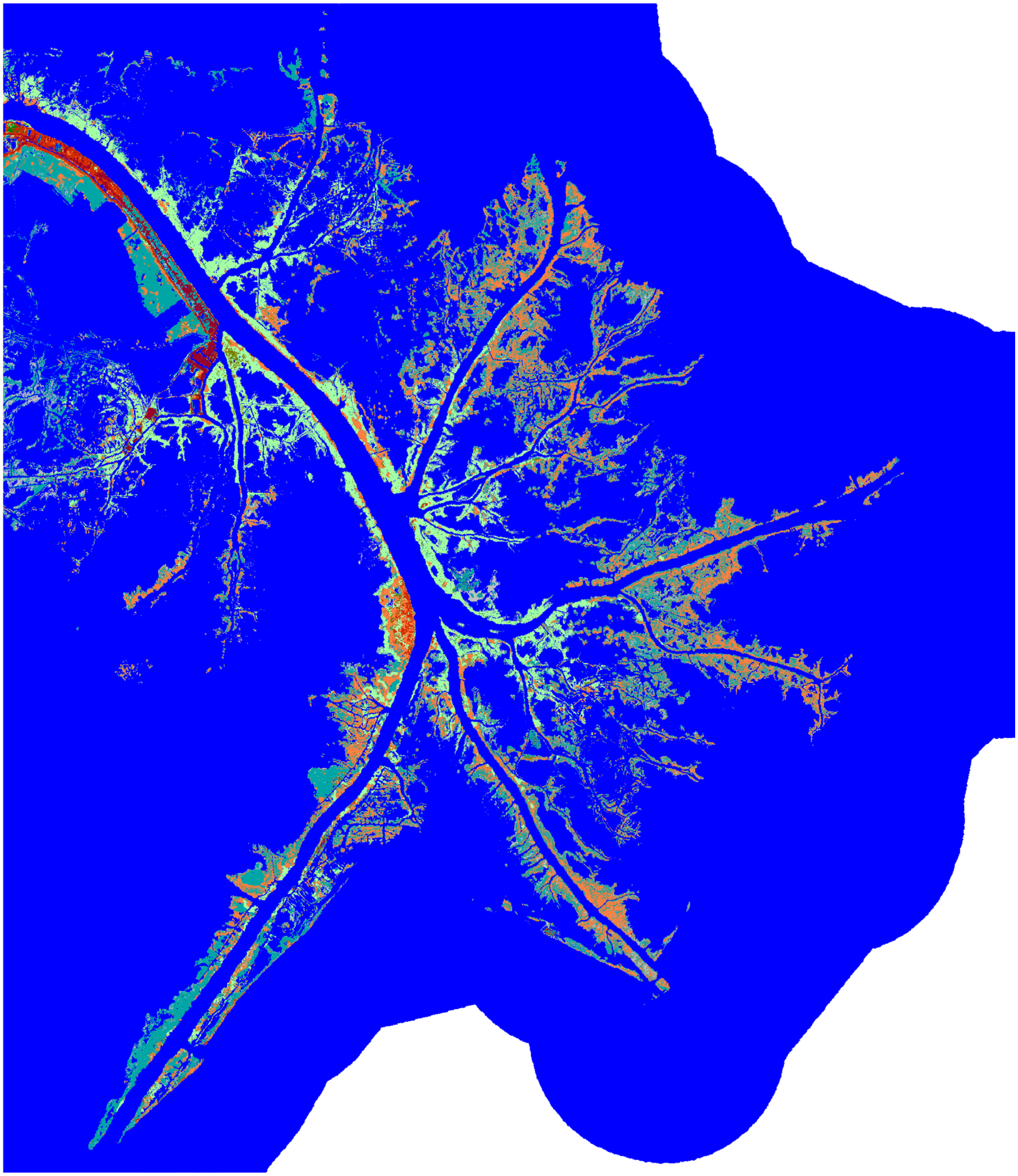
Delta Context, 2075, Scenario A1B Mean



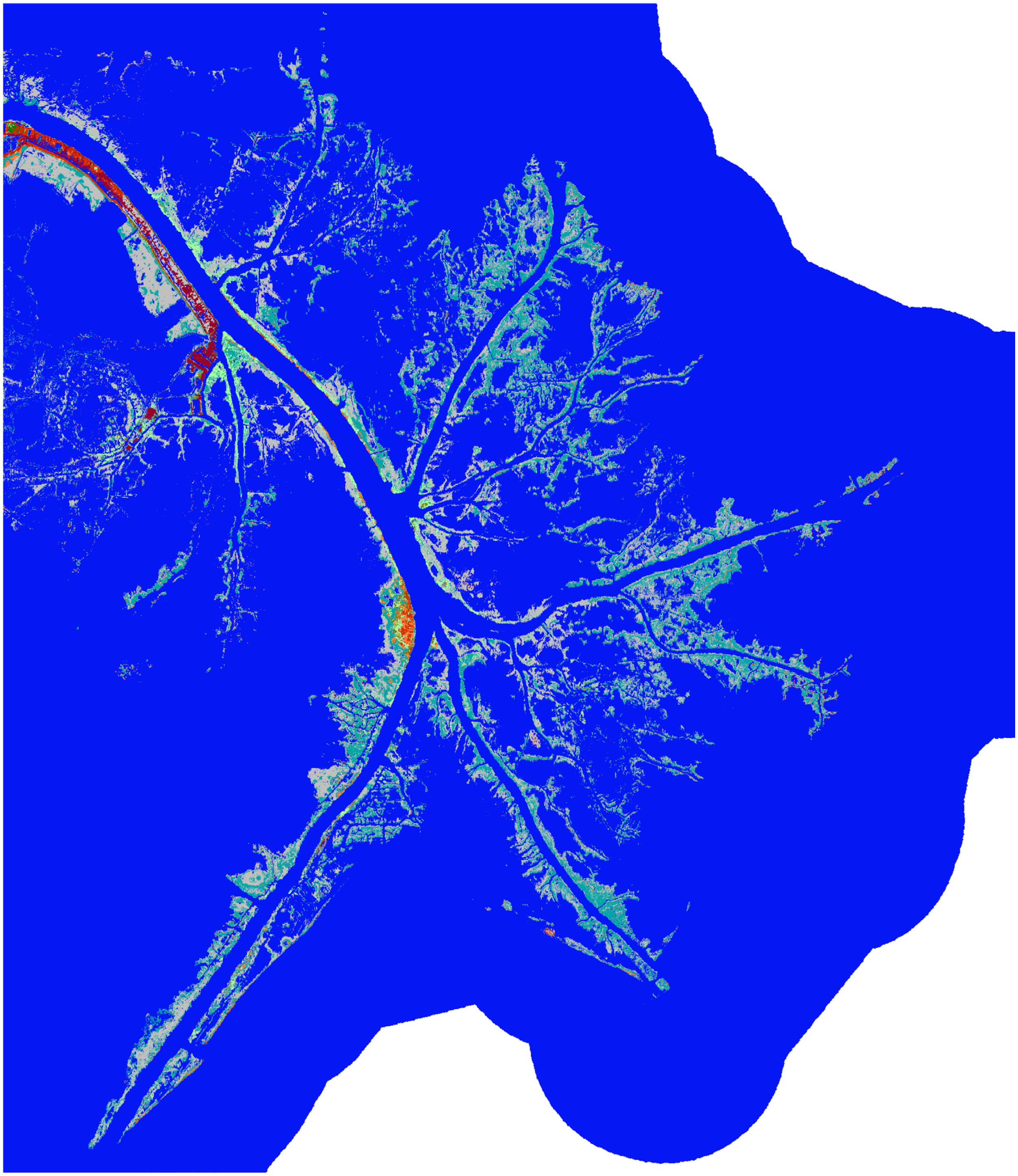
Delta Context, 2100, Scenario A1B Mean



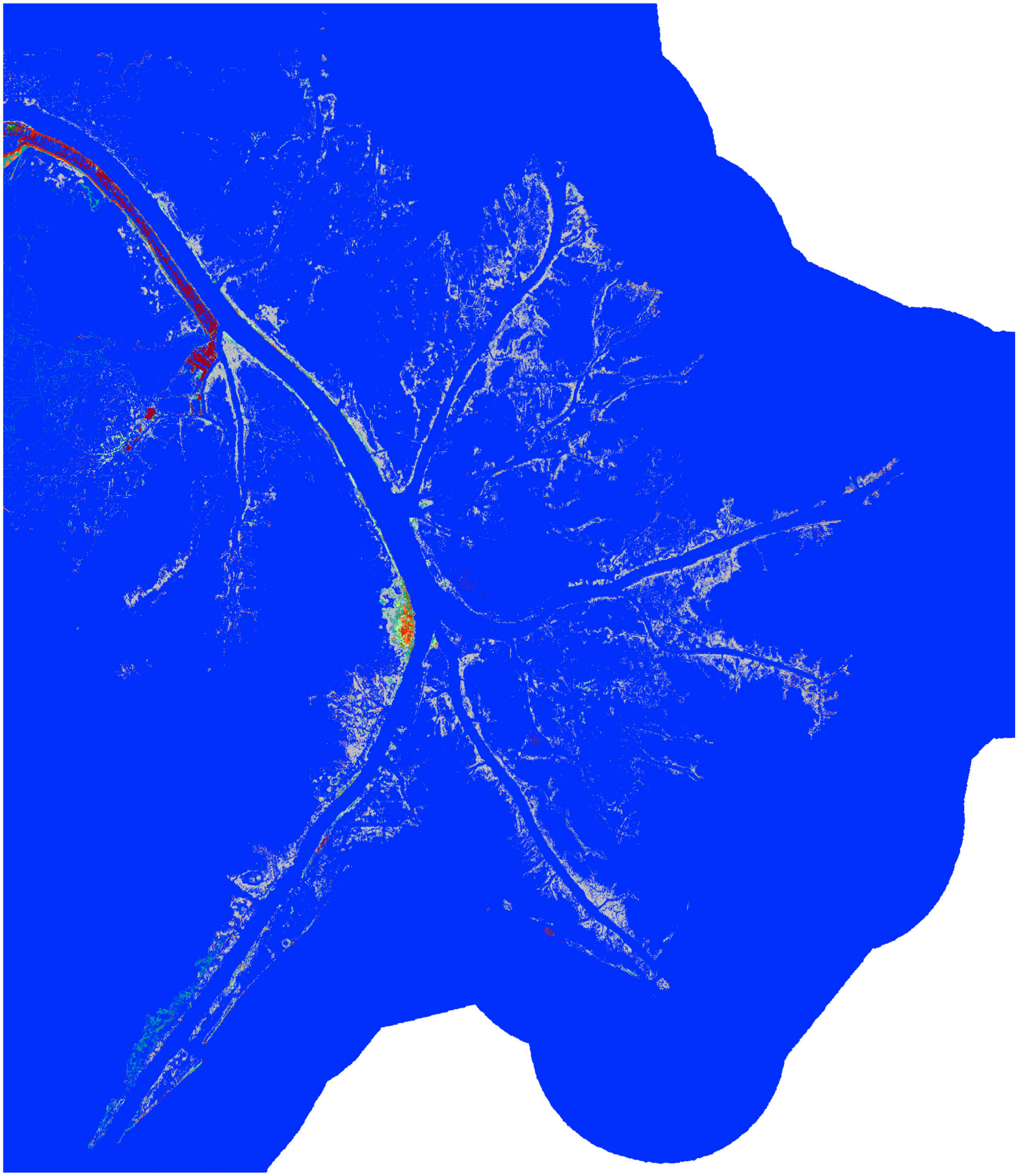
Delta Context, Initial Condition



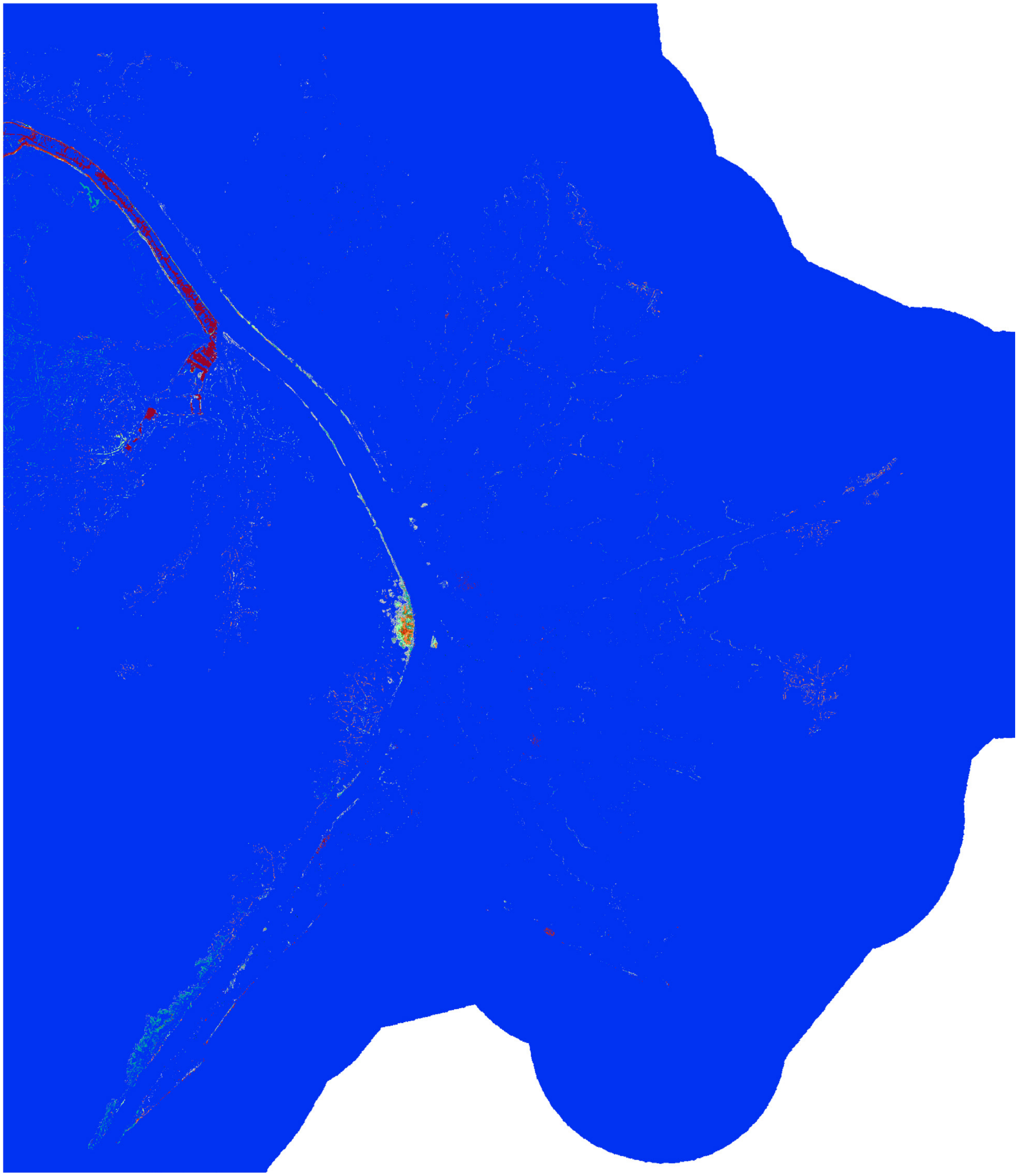
Delta Context, 2025, Scenario A1B Maximum



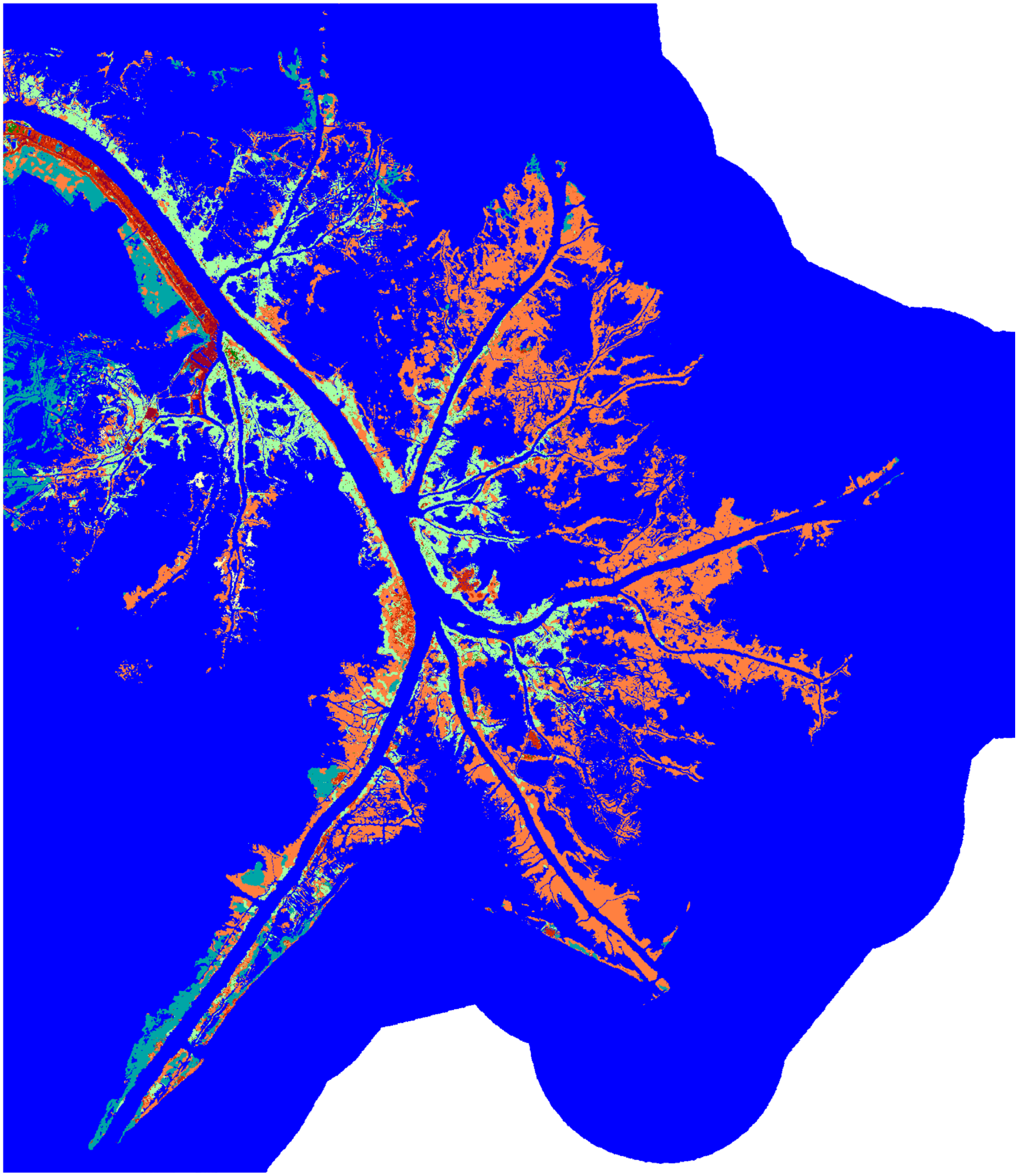
Delta Context, 2050, Scenario A1B Maximum



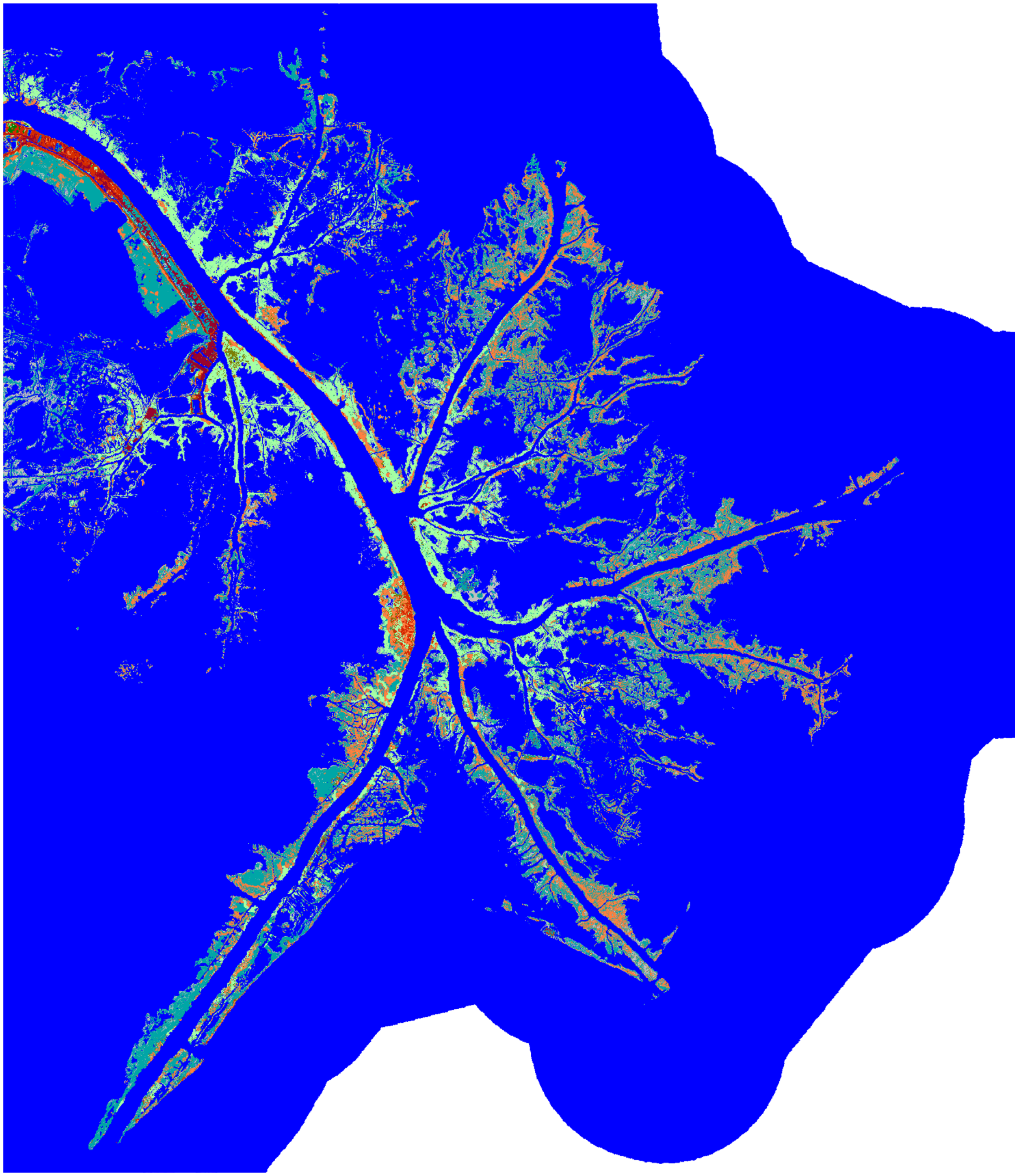
Delta Context, 2075, Scenario A1B Maximum



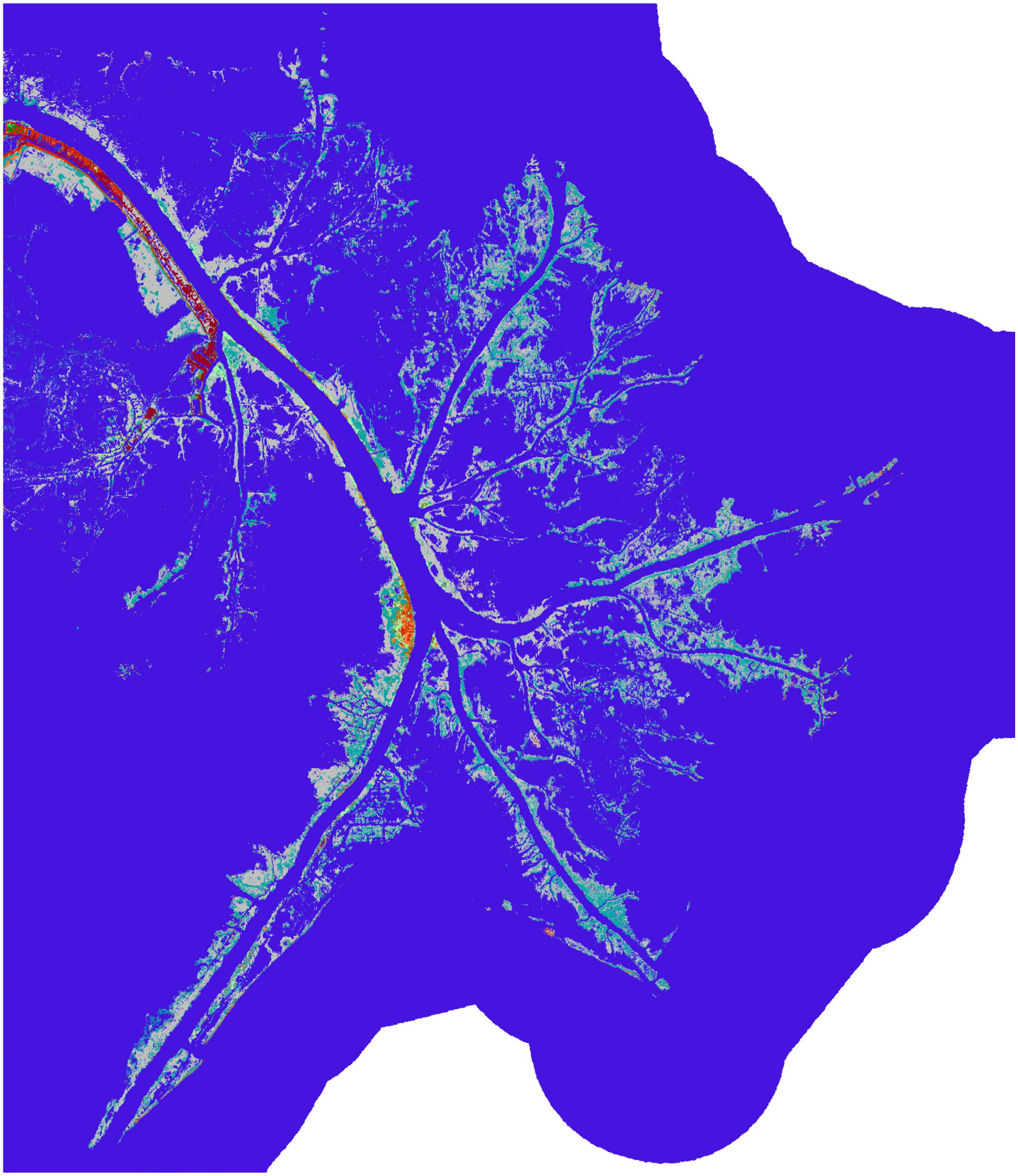
Delta Context, 2100, Scenario A1B Maximum



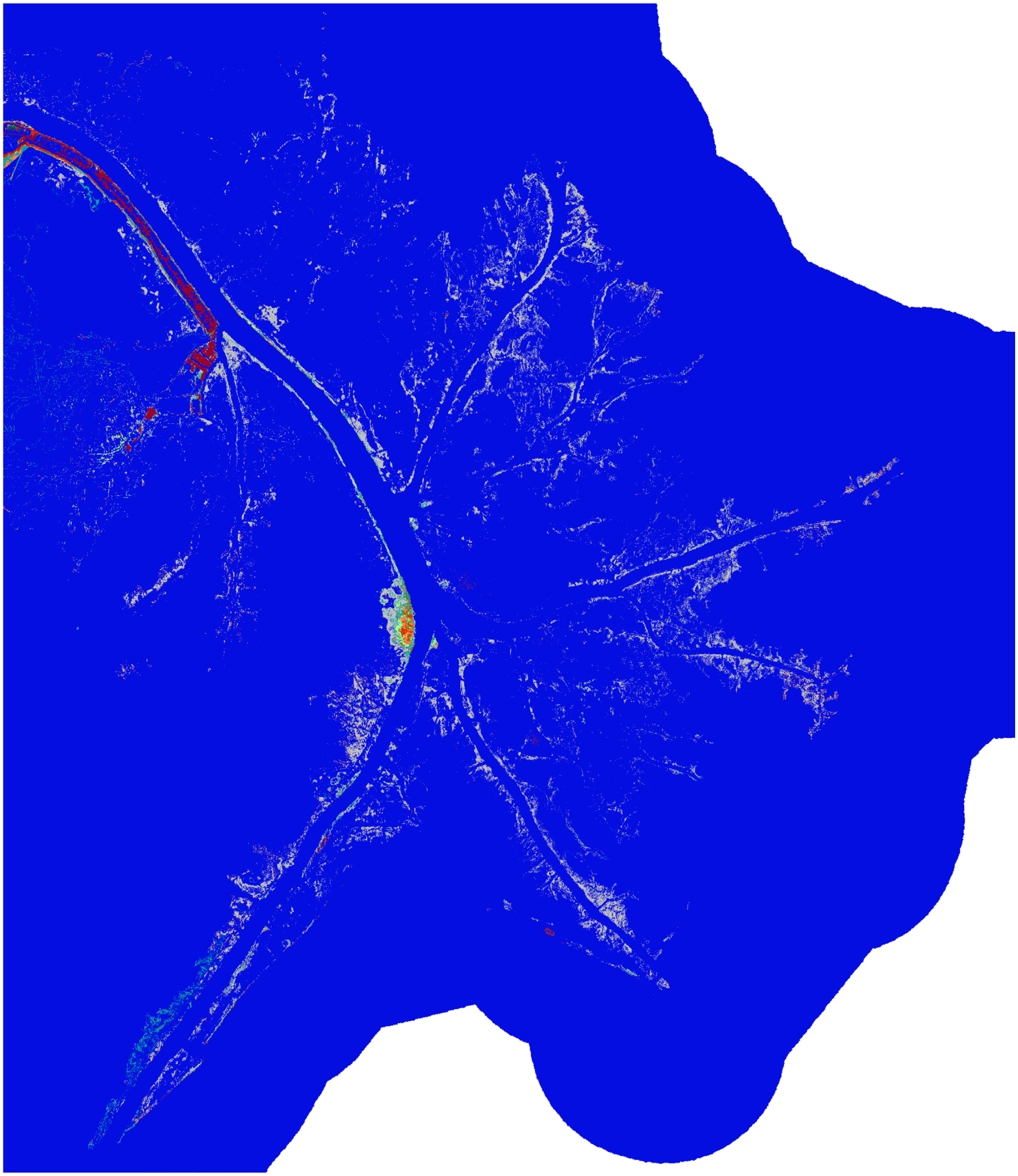
Delta Context, Initial Condition



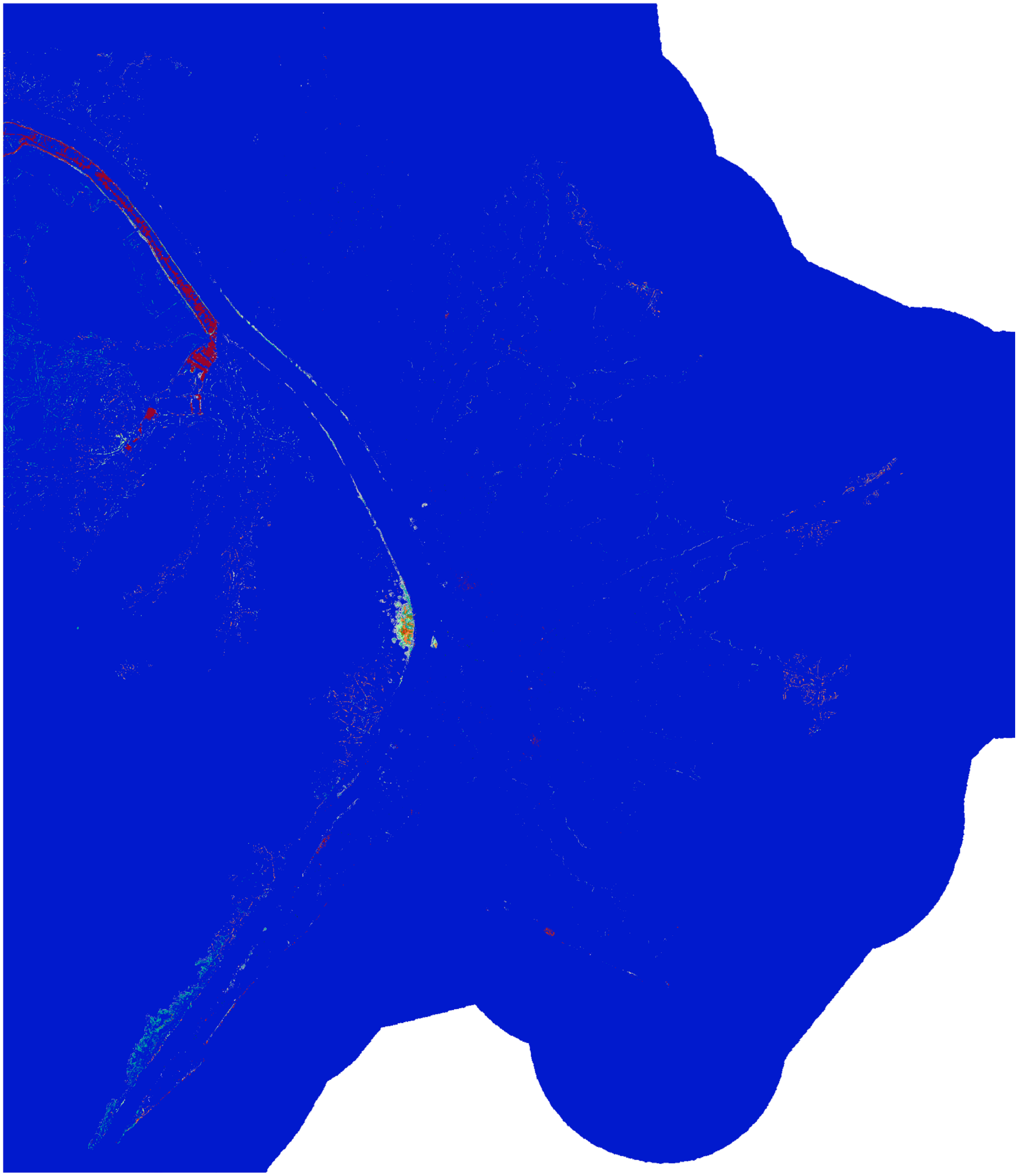
Delta Context, 2025, 1 m



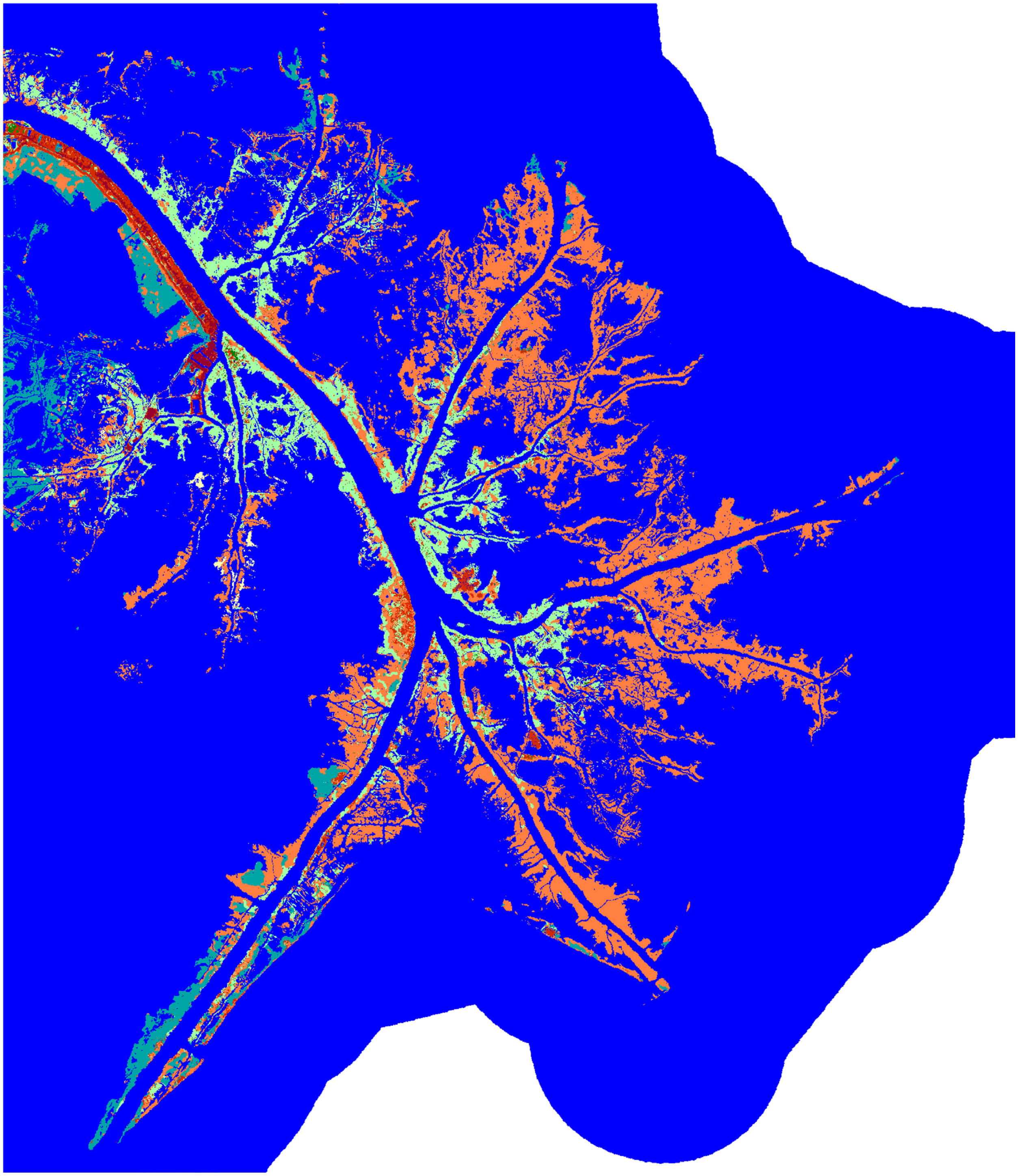
Delta Context, 2050, 1 m



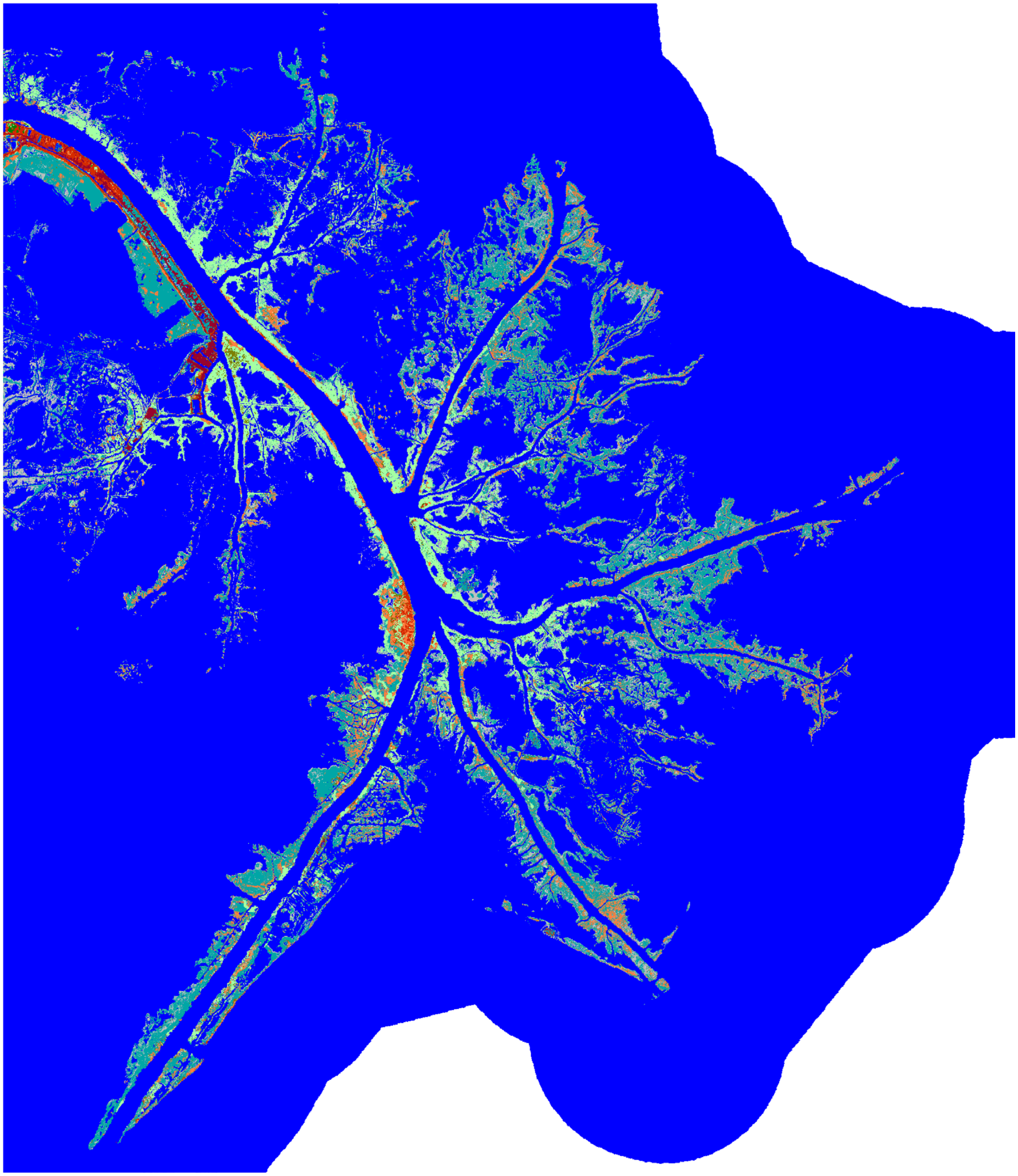
Delta Context, 2075, 1 m



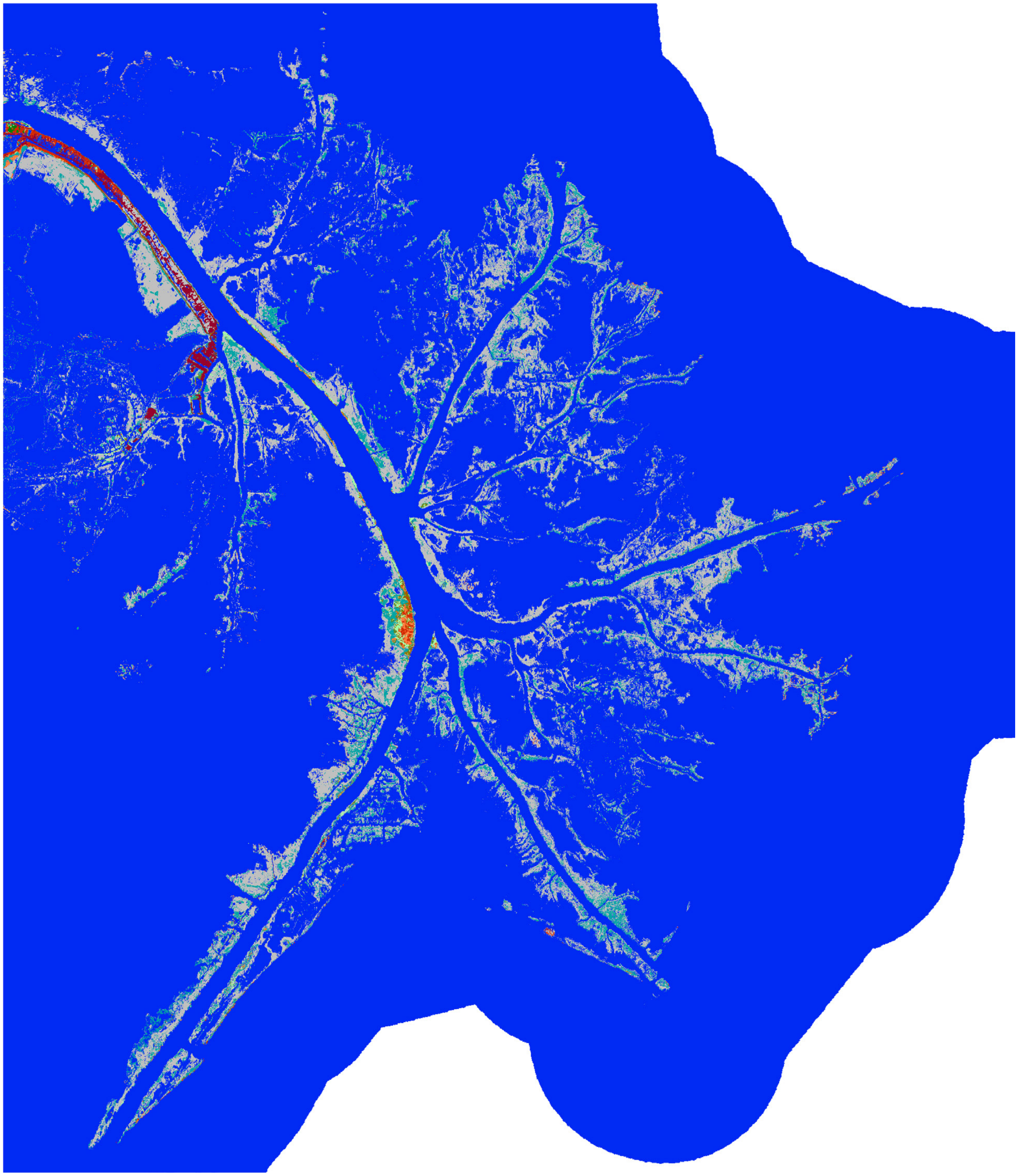
Delta Context, 2100, 1 m



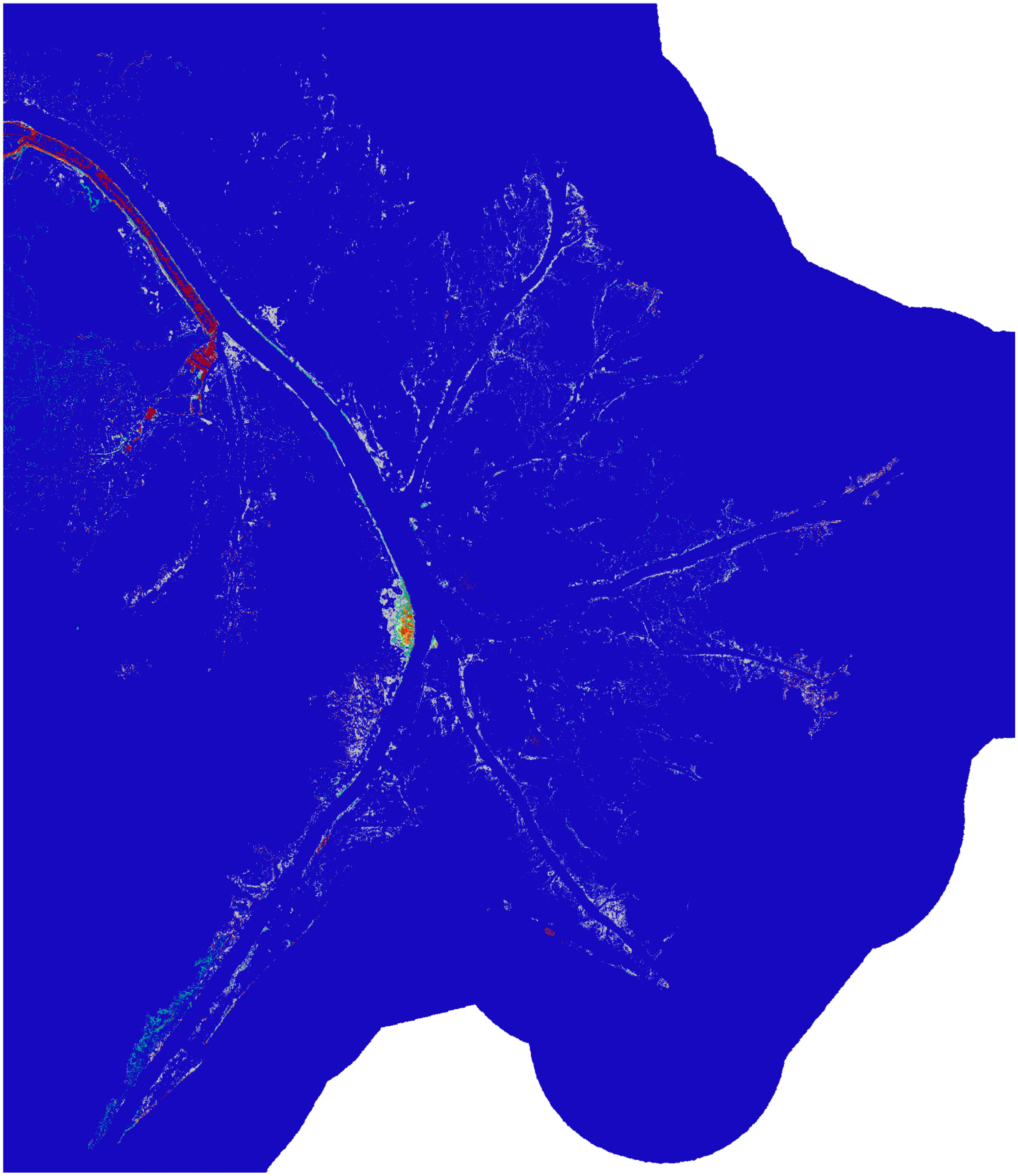
Delta Context, Initial Condition



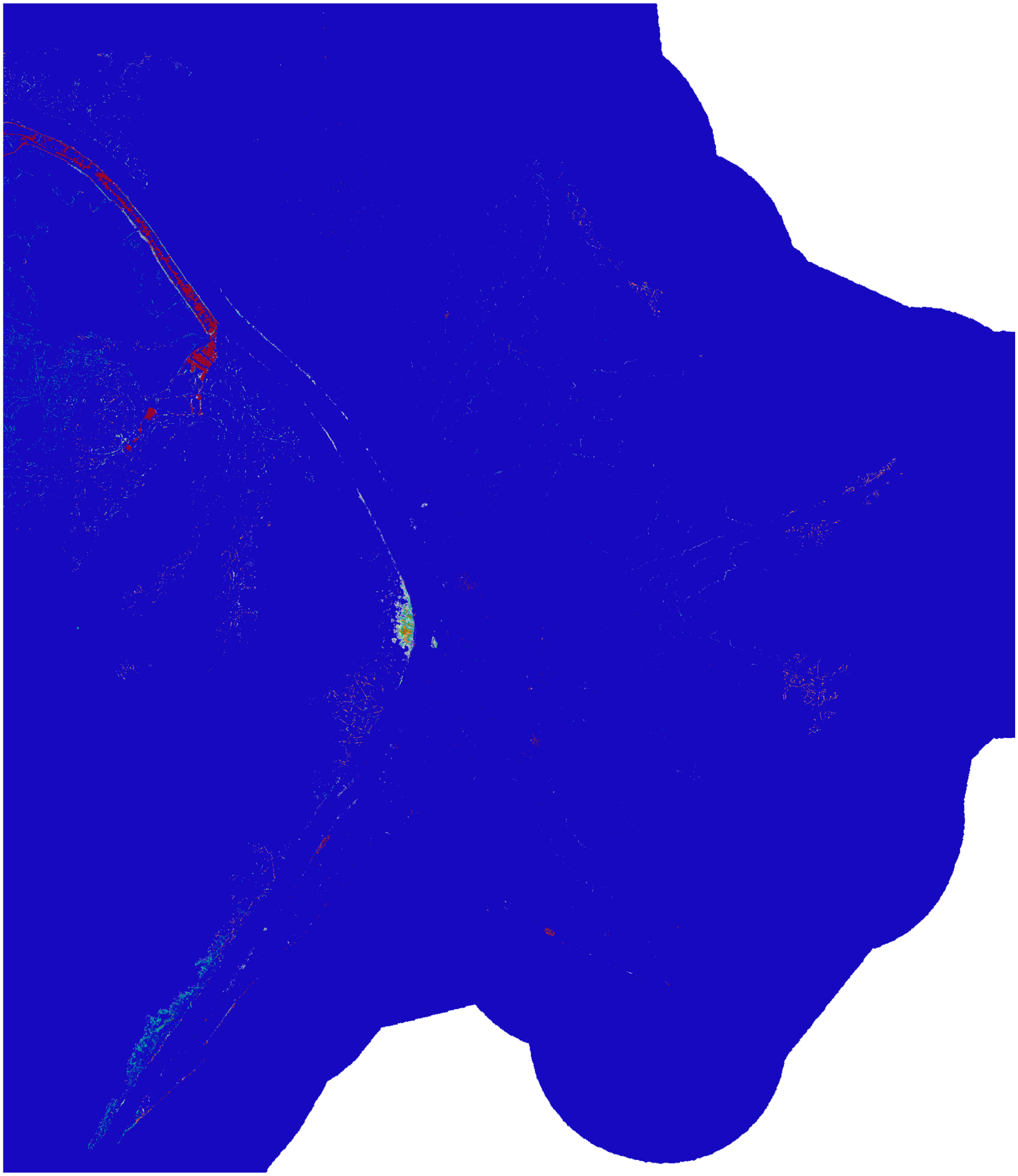
Delta Context, 2025, 1.5 m



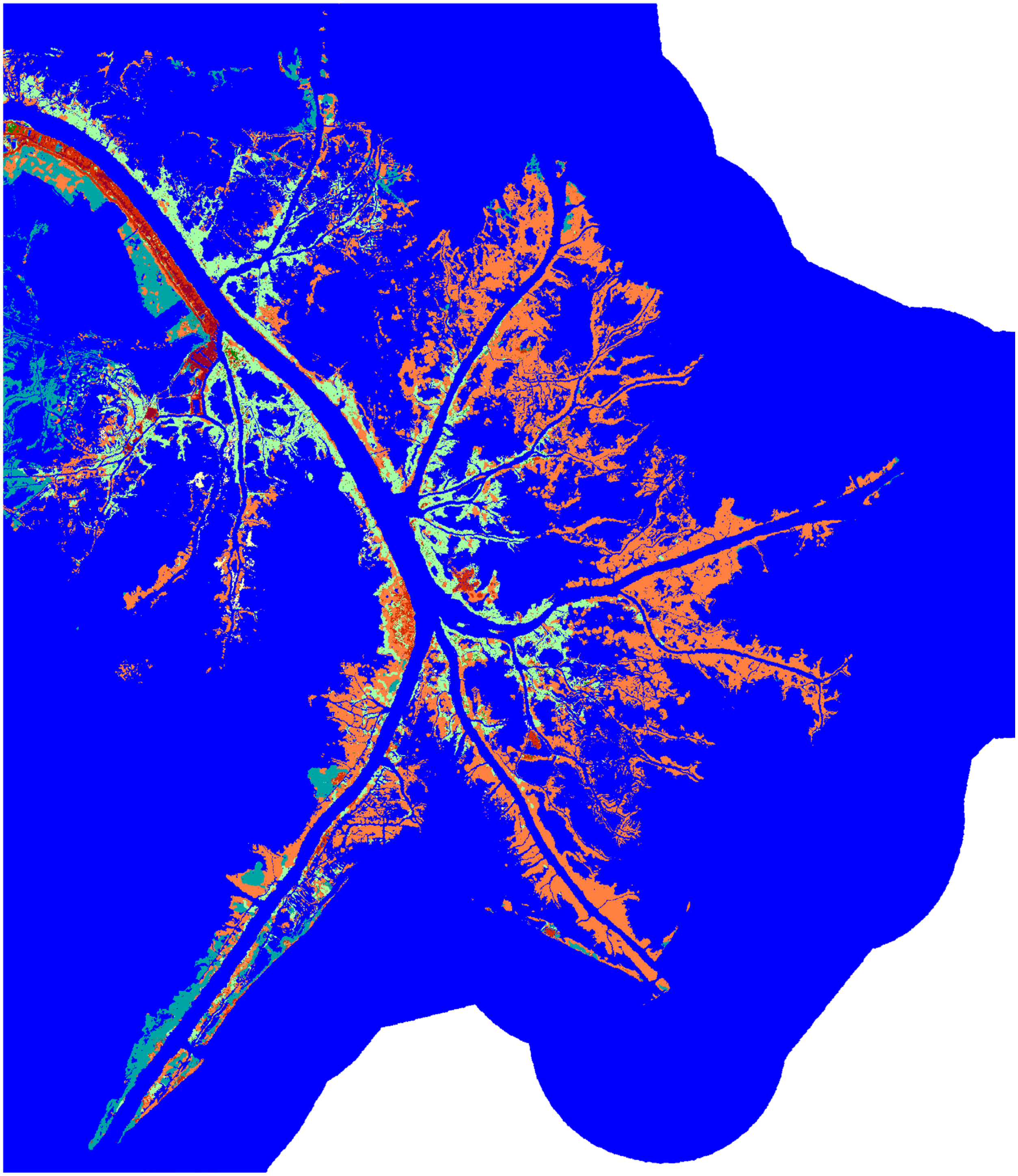
Delta Context, 2050, 1.5 m



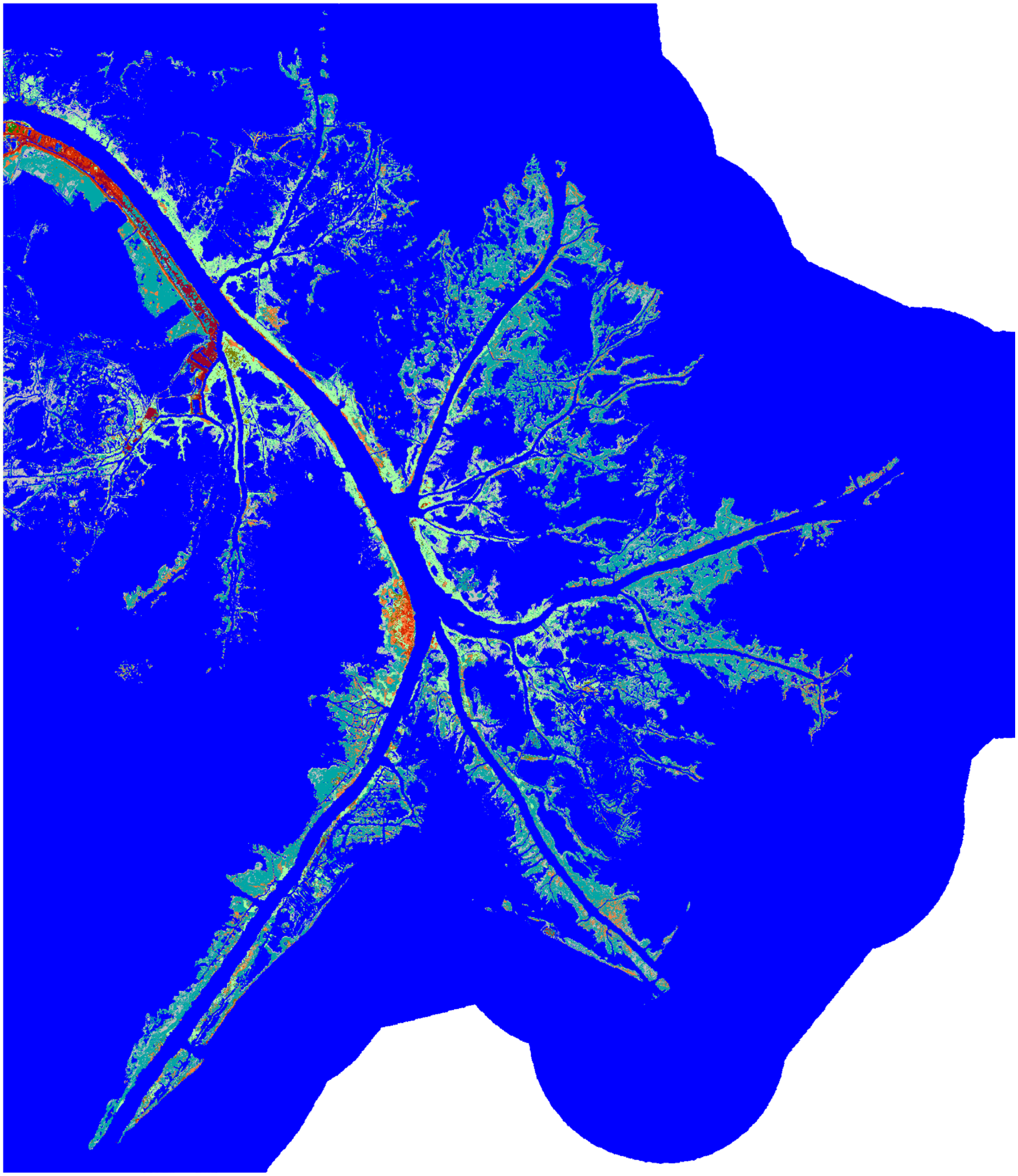
Delta Context, 2075, 1.5 m



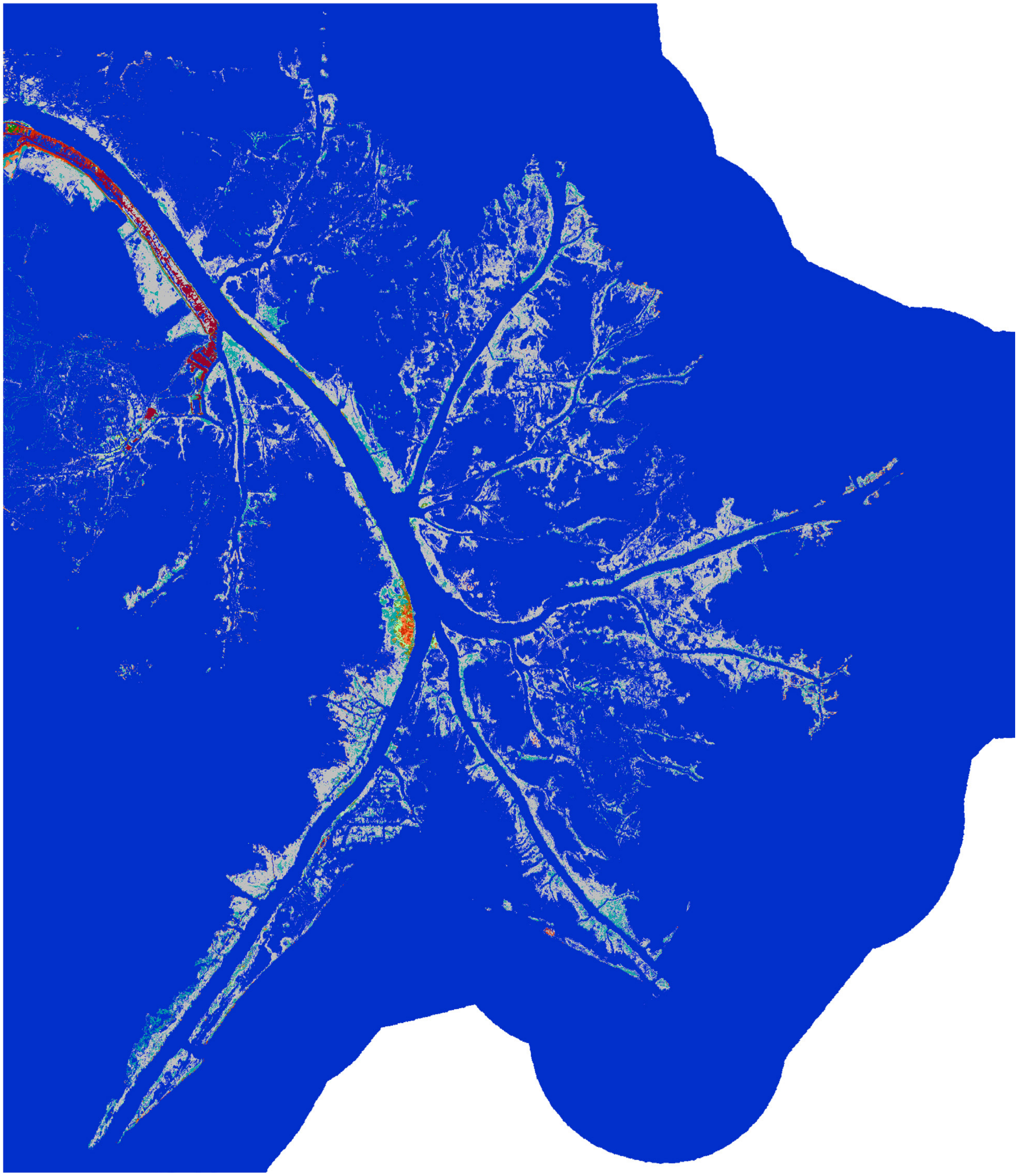
Delta Context, 2100, 1.5 m



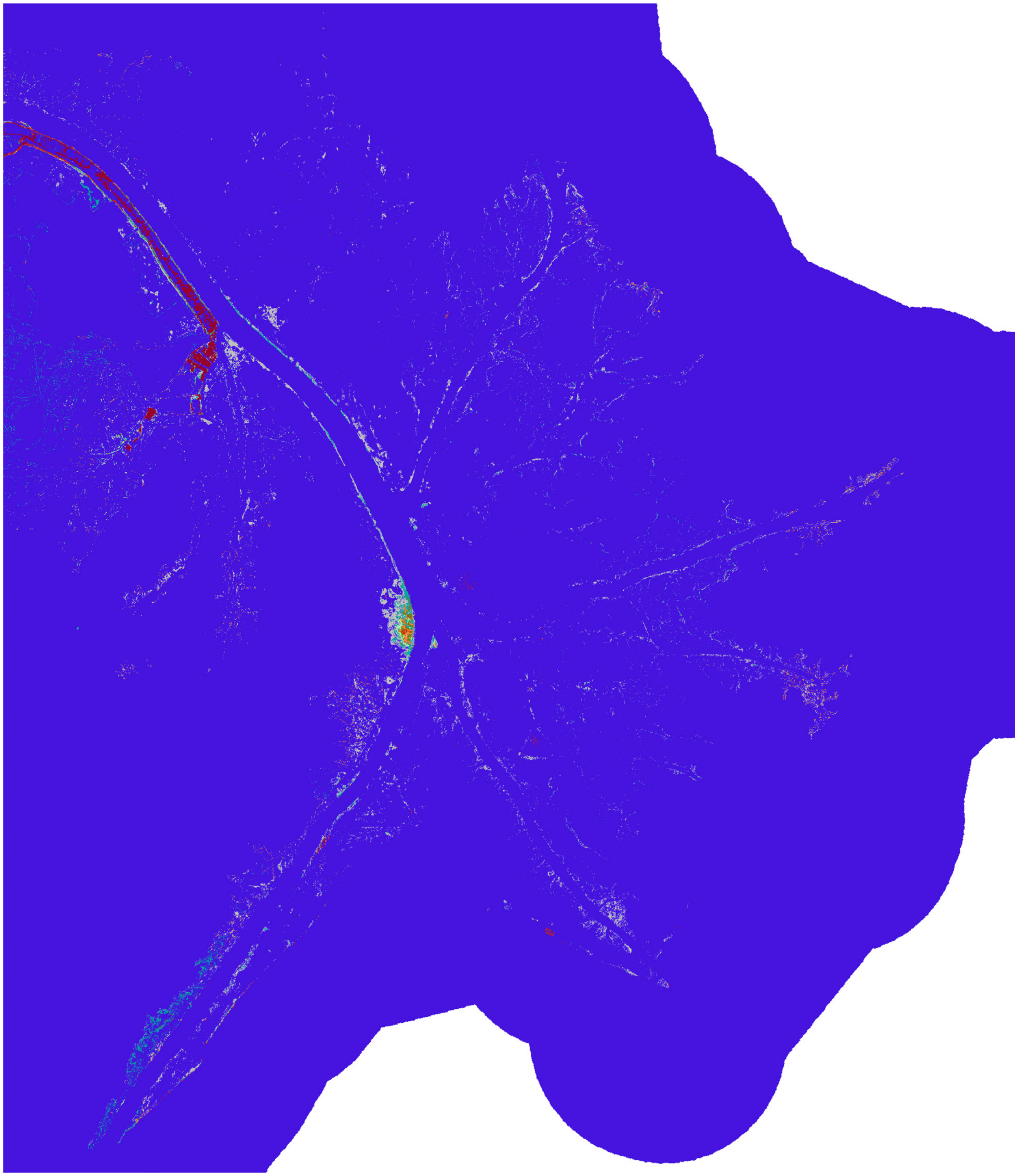
Delta Context, Initial Condition



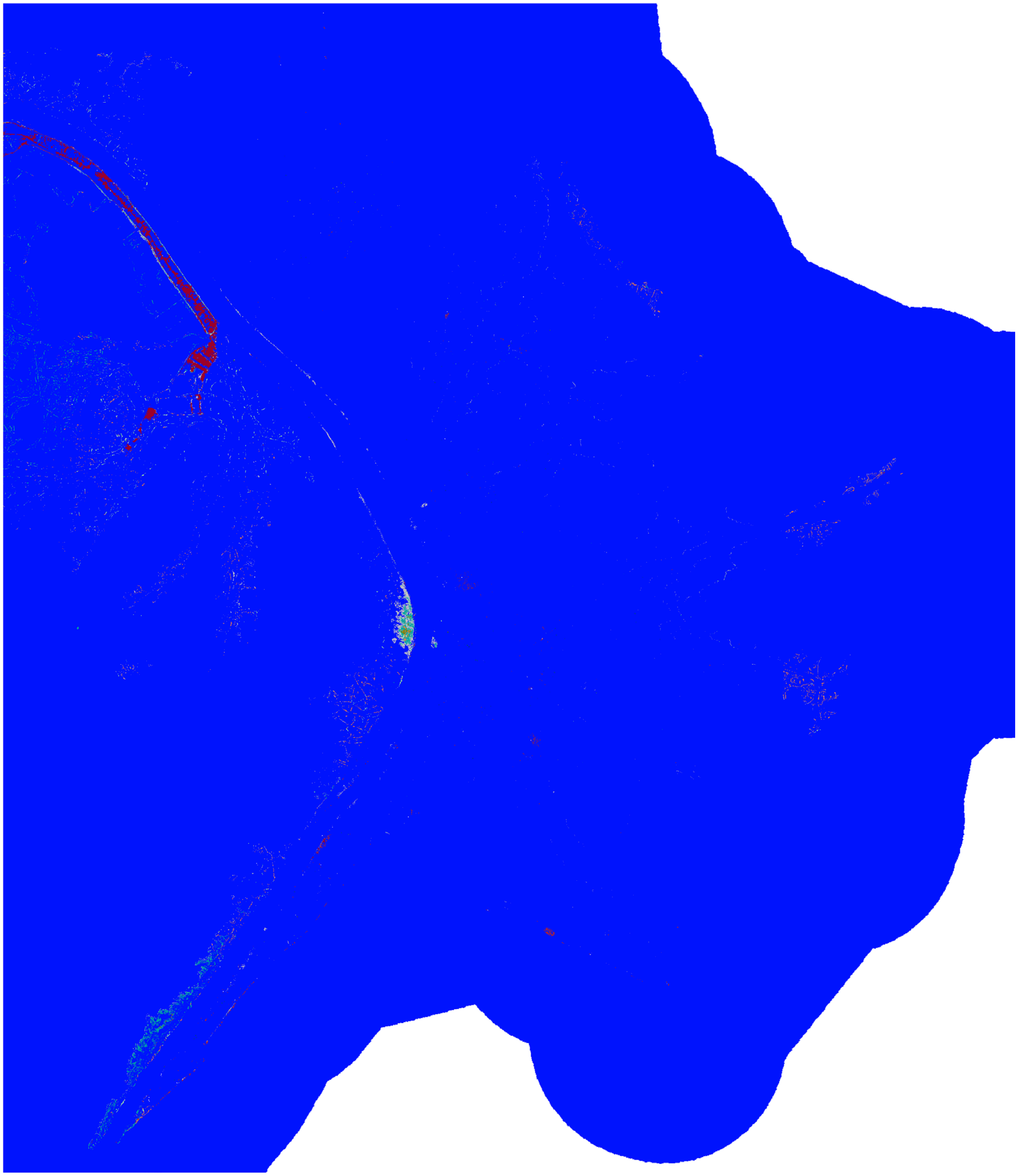
Delta Context, 2025, 2 m



Delta Context, 2050, 2 m



Delta Context, 2075, 2 m



Delta Context, 2100, 2 m