# Application of the Sea-Level Affecting Marshes Model (SLAMM 5.0) to Bayou Teche NWR

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# Introduction

Tidal marshes are among the most susceptible ecosystems to climate change, especially accelerated sea level rise (SLR). Sea level is predicted to increase by 30 cm to 100 cm by 2100 based on the International Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) (Meehl et al. 2007). 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. A CCP is a document that provides a framework for guiding refuge management decisions. All refuges are required by law to complete a CCP by 2012.

# 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 Bayou Teche 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

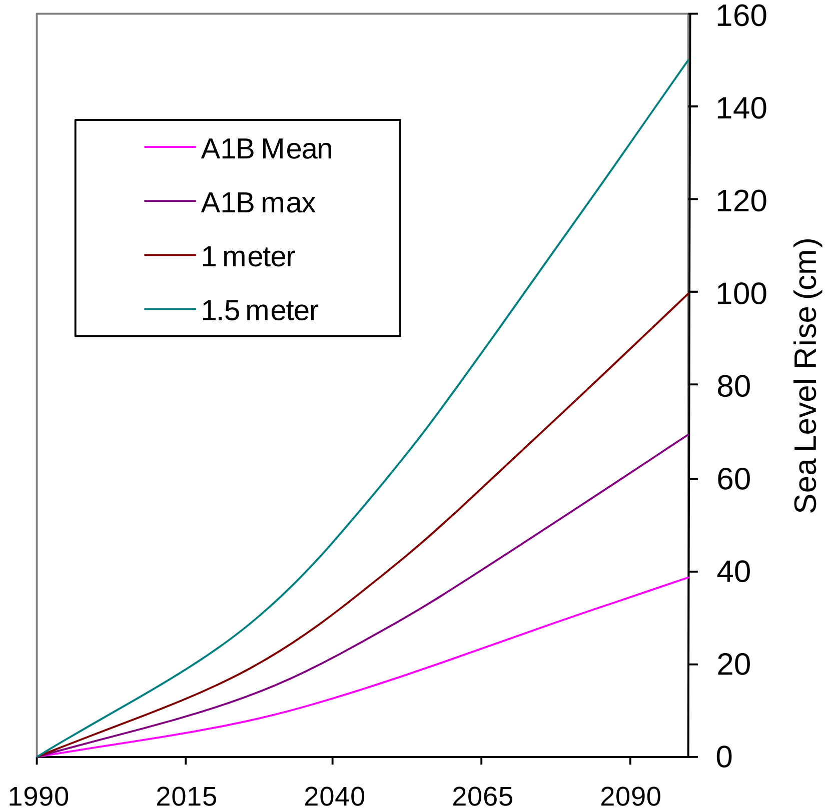
## *Sea-Level Rise Scenarios*

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 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 might be 50 to 140 cm. 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

High-resolution LIDAR data are available for Bayou Teche NWR based on a 2004 flight-date. These elevation data are available through the National Elevation Dataset (NED) that was updated to reflect this high quality data. The error in vertical resolution for LIDAR data can be as low as 5-10 cm.

The National Wetlands Inventory for Bayou Teche is based on a photo date of 1989. This survey, when converted to 30 meter cells, suggests that on that date, the approximately thirty-six thousand acre refuge (approved acquisition boundary) was composed of the categories as shown below:

| | |
|---|---|
| Cypress Swamp | 40% |
| Dry Land | 28% |
| Swamp | 19% |
| Inland Fresh Marsh | 6% |
| Tidal Swamp | 3% |
| Riverine Tidal | 1% |
| Inland Open Water | 1% |
| Tidal Fresh Marsh | 1% |

The historic trend for Sea Level Rise was estimated at 9.8 mm/year using the average of the long term trends measured on Grand Isle, Louisiana (NOAA station 8761724) and Eugene Island, Louisiana (8764311). This historic trend is dramatically higher than the global average for the last 100 years (approximately 1.5 mm/year) indicating that significant land subsidence is occurring in this region. When estimating the local effects of eustatic sea level rise in this region, this rate of subsidence (approximately 8.3 mm/year) is projected to continue over the period of projection.

The oceanic tide range was estimated at 0.343 meters using the average of the two closest NOAA stations (Tesoro Marine Terminal, Atchafalaya River, La, 8764044 and Weeks Bay, La, 8765148).

There were no stations within 25 miles of the study area that relate the NED vertical datum of NAVD88 to mean tide level. To be conservative, the lower range of several of the nearest stations was used (0.155). Using the low end of this range means that land elevations are set to higher levels as compared to mean tide level and predicted effects will be minimized as a result of this uncertainty.

| Station | Site Name | MTL-NAVD88 (m) |
|---|---|---|
| 8771510 | GALVESTON PLEASURE PIER | 0.155 |
| 8771450 | GALVESTON PIER 21 | 0.200 |
| 8761826 | CHENIERE CAMINADA, CAMINADA PASS | 0.331 |
| 8747437 | BAY WAVELAND YC, BAY ST. LOUIS | 0.164 |
| 8746819 | PASS CHRISTIAN YC, MISS. SOUND | 0.155 |
| 8761426 | GREENS DITCH, LAKE ST. CATHERINE | 0.217 |

Accretion rates were set based on an analysis of five studies of vertical accretion in Louisiana (Cahoon et al. 1994, Cahoon et al. 1995, Cahoon et al., 1999, Stevenson et al. 1986, White et al. 2002). Measured accretion rates for each marsh-type were averaged and are summarized in the table below. Accretion rates in Louisiana tend to be higher than those measured in other states.

| Marsh Type | Accretion Rate (mm/yr) | |
|---|---|---|
| Freshwater | 7.73 | n=2 |
| Brackish | 7.67 | n=5 |
| Saline | 9.75 | n=6 |

Modeled U.S. Fish and Wildlife Service refuge boundaries are based on Approved Acquisition Boundaries as received from Kimberly Eldridge, lead cartographer with U.S. Fish and Wildlife Service, and are current as of June 2008.

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.

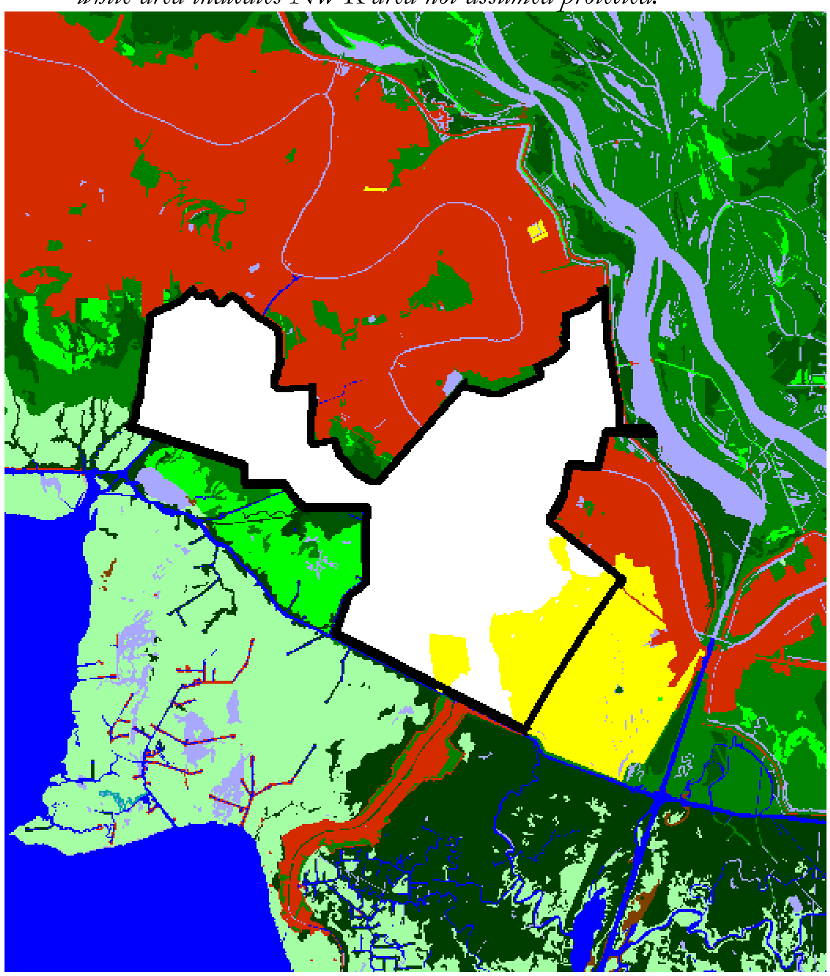
**Geographic Location of Dikes**

The region of Bayou Teche is extensively surrounded by dikes complicating the model's setup. The SLAMM model accepts, as a model input, a map of lands that are assumed to be protected by existing dikes. The model assumes that those lands protected by dikes are not subject to inundation but could still be subject to soil saturation due to pressure on the water table from sea level rise.

The National Wetlands Inventory does demarcate some lands as protected by dikes, but experience with this data-set indicates that it does not effectively capture all protected lands. The NWI dike coverage is shown here.

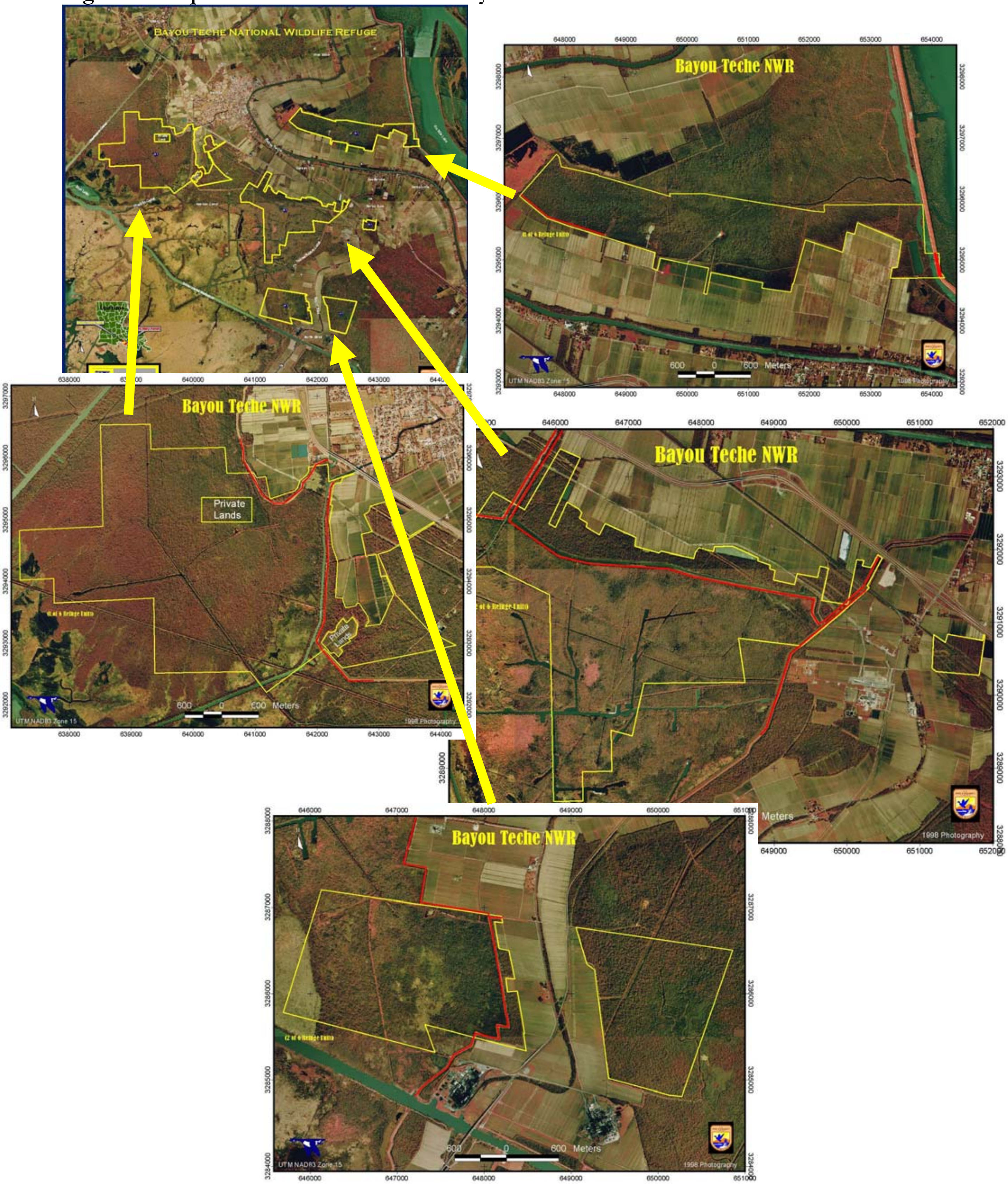
**Figure 2: Bayou Teche with NWI designated "Diked/Impounded" Modifier**

*Boundary outline is in black, areas designated as diked are in yellow, white area indicates NWR area not assumed protected.*



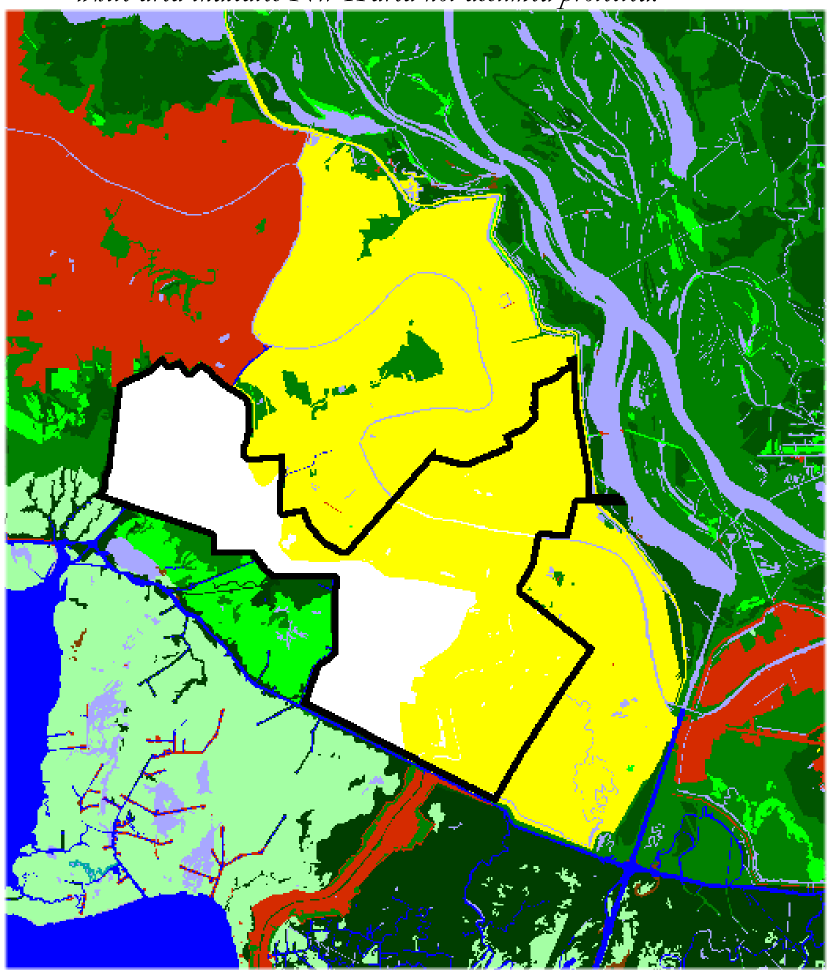
To help refine this estimate of diked areas, U.S. FWS project managers forwarded the following maps indicating the location of dikes within the Bayou Teche boundaries:

**Figure 3: Maps of Dikes Located within Bayou Teche. Dikes are indicated with red lines**



Based on examination of these maps, examination of USGS topological maps which include information about the location of dikes, and examination of the NED elevation data set (in which dikes were often visible as elevated ridges), the following map of "lands protected by dikes" was derived and used in the modeling of Bayou Teche.

**Figure 4: Final Map of Regions assumed Protected By Dikes in Bayou Teche**
*Boundary outline is in black, areas assumed to be protected by dikes are in yellow, white area indicates NWR area not assumed protected.*



A conversation with Ken Litzenberger, the U.S. Fish and Wildlife Service project manager for Bayou Teche occurred in June of 2008. He stated that, to his knowledge, there are no site-specific erosion, wetland inventory, or accretion data better than the data cited above. He also was helpful in arranging for delivery of the levee maps as shown above.

## SUMMARY OF SLAMM INPUT PARAMETERS FOR BAYOU TECHE

| Site | | Bayou Teche |
|---|---|---|
| NED Source Date (yyyy) | , | 2002 |
| NWI_photo_date (yyyy) | , | 1989 |
| Direction_OffShore (N\|S\|E\|W) | , | S |
| Historic_trend (mm/yr) | , | 9.795 |
| NAVD88_correction (MTL-NAVD88 in meters) | , | 0.155 |
| *Water Depth (m below MLW- N/A)* | , | 2 |
| TideRangeOcean (meters: MHHW-MLLW) | , | 0.343 |
| TideRangeInland (meters) | , | 0.343 |
| Mean High Water Spring (m above MTL) | , | 0.228 |
| MHSW Inland (m above MTL) | , | 0.228 |
| Marsh Erosion (horz meters/year) | , | 1.8 |
| Swamp Erosion (horz meters/year) | , | 1 |
| TFlat Erosion (horz meters/year) [from 0.5] | , | 2 |
| Salt marsh vertical accretion (mm/yr) Final | , | 9.75 |
| Brackish March vert. accretion (mm/yr) Final | , | 7.67 |
| Tidal Fresh vertical accretion (mm/yr) Final | , | 7.73 |
| Beach/T.Flat Sedimentation Rate (mm/yr) | , | 0.5 |
| Frequency of Large Storms (yr/washover) | , | 25 |
| Use Elevation Preprocessor for Wetlands | , | FALSE |

# Results

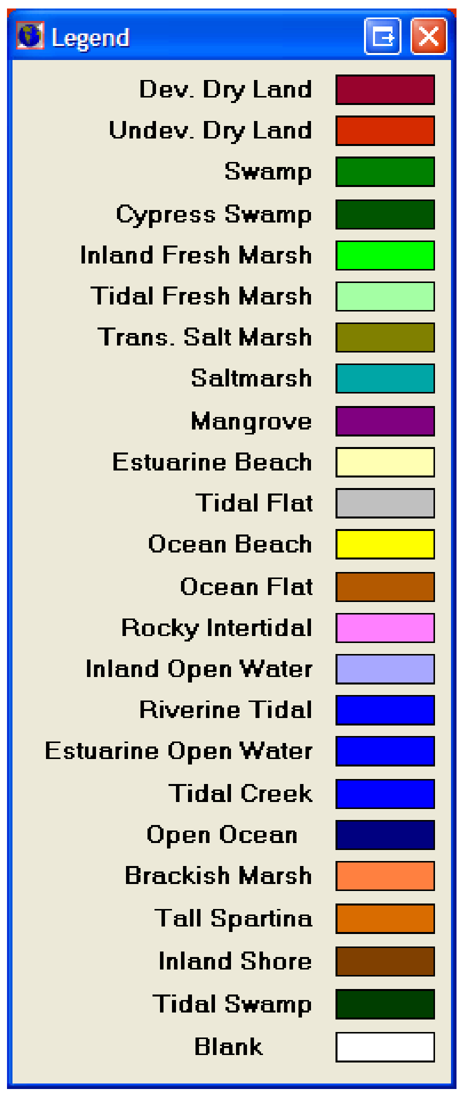
Model results suggest that Bayou Teche is subject to dramatic changes as a result of global sea level rise. The combination of global sea level rise and local subsidence results in predictions of salt water intrusion with significant effects.

Cypress swamps are subject to significant loss under all scenarios run. High resolution elevation data indicate that cypress swamps are located just above the saline boundary at present date and additional saline intrusion is predicted. SLAMM assumes that inundated cypress swamps will convert into open water.

Most dry land is considered to be protected by dikes, but dry land that is not will be lost under most scenarios. Even dry land that is protected by dikes is predicted to suffer some effects from soil saturation under all scenarios of sea level rise. This suggests, at the least, a need for increased pumping of waters off of cultivated and developed lands in addition to dike maintenance costs.

Swamps, fresh marshes, and tidal marshes are all subject to dramatic losses under all scenarios examined. In most of the scenarios run, salt marsh migrates into the Bayou Teche wildlife refuge by the year 2100.

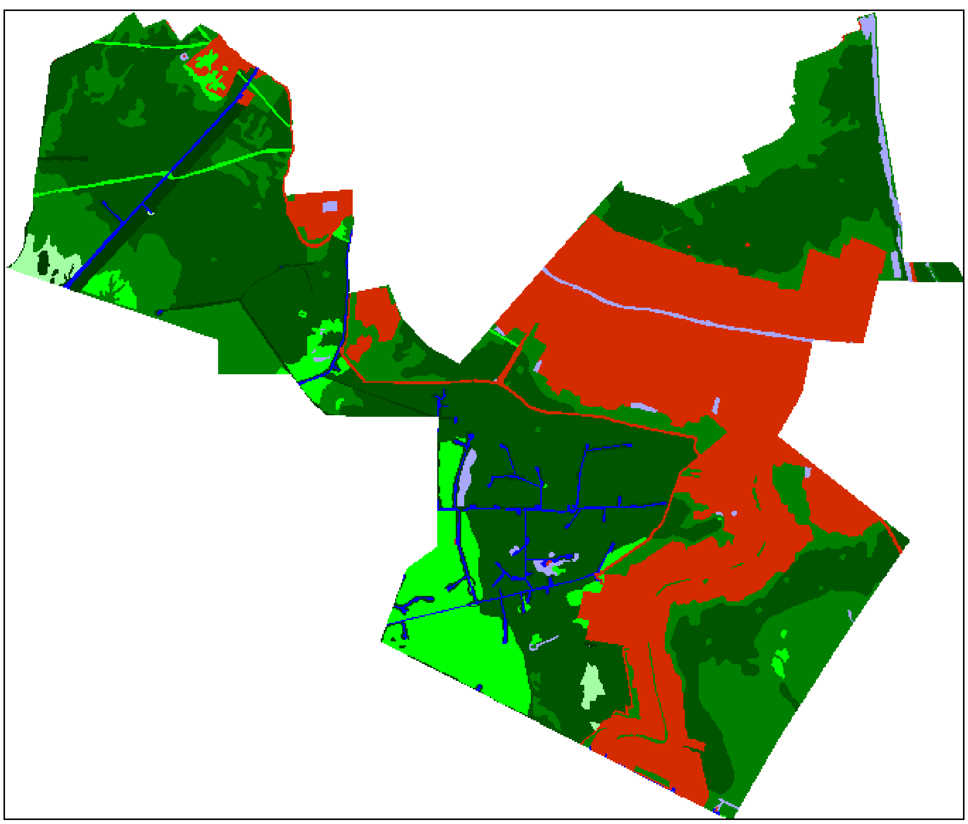
Maps of SLAMM input and output to follow will use the following legend:



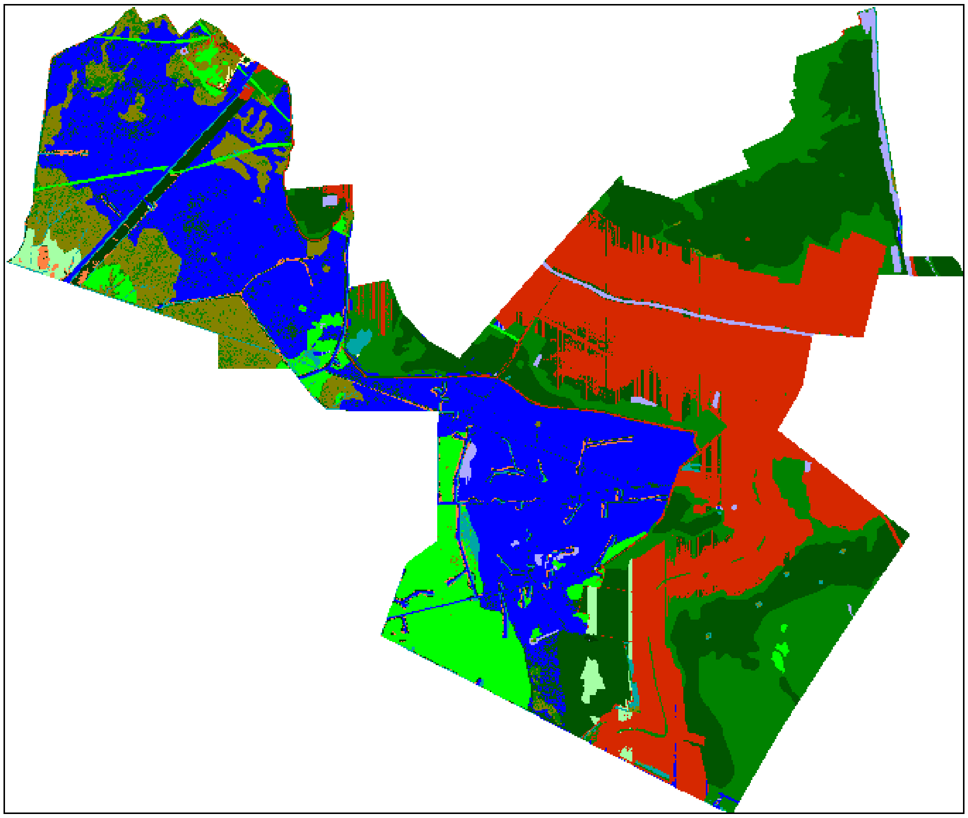
Bayou Teche
IPCC Scenario A1B-Mean, 0.39 M SLR Eustatic by 2100

Results in Acres

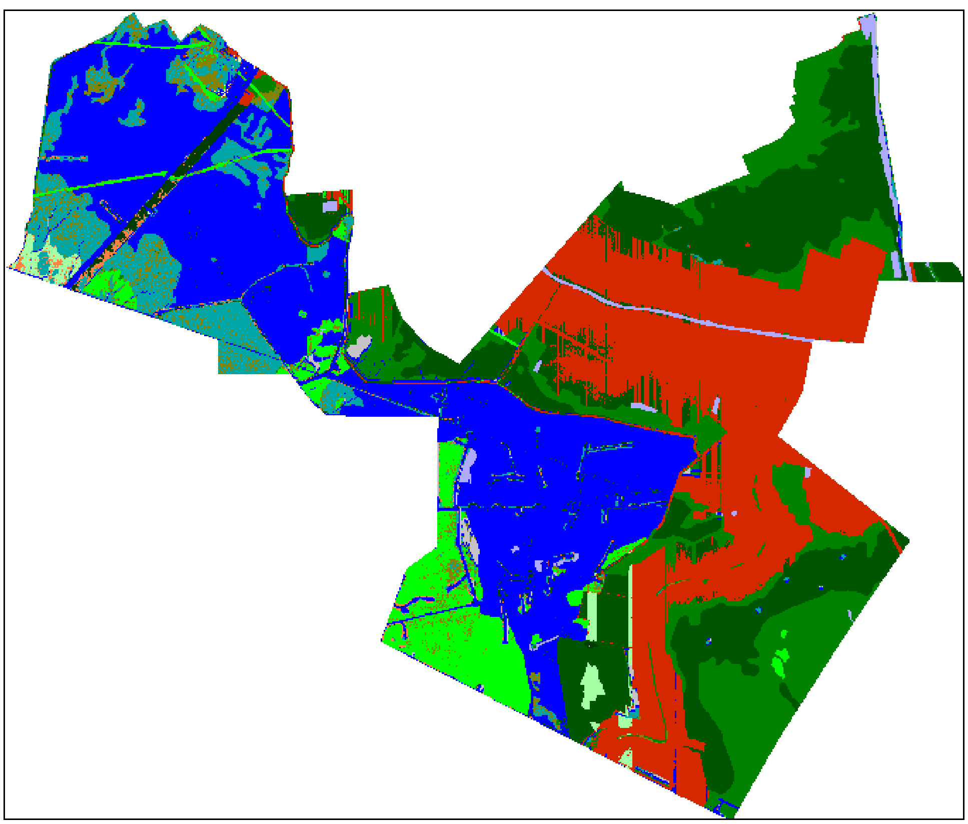
| | Initial | 2025 | 2050 | 2075 | 2100 |
|---|---|---|---|---|---|
| Cypress Swamp | 14730.3 | 7342.5 | 6742.0 | 6660.6 | 6385.8 |
| Dry Land | 10194.3 | 8483.4 | 8327.5 | 8244.1 | 8194.7 |
| Swamp | 6952.0 | 5100.1 | 4598.9 | 4530.4 | 4404.5 |
| Inland Fresh Marsh | 2365.8 | 2237.1 | 2001.1 | 1298.8 | 802.5 |
| Tidal Swamp | 941.2 | 457.5 | 306.2 | 194.7 | 121.8 |
| Riverine Tidal | 484.8 | 241.9 | 190.5 | 158.2 | 145.3 |
| Inland Open Water | 476.1 | 417.4 | 401.2 | 394.1 | 389.4 |
| Tidal Fresh Marsh | 252.9 | 371.0 | 348.8 | 271.8 | 249.2 |
| Saltmarsh | 0.0 | 524.7 | 2327.0 | 1393.7 | 1141.2 |
| Estuarine Open Water | 0.0 | 8892.4 | 9961.9 | 11220.5 | 13530.8 |
| Brackish Marsh | 0.0 | 273.2 | 213.8 | 212.8 | 112.3 |
| Trans. Salt Marsh | 0.0 | 2038.0 | 802.5 | 772.4 | 544.4 |
| Tidal Flat | 0.0 | 0.0 | 168.0 | 1032.6 | 370.9 |
| Estuarine Beach | 0.0 | 18.2 | 8.1 | 12.8 | 4.8 |
| **Total (incl. water)** | 36397.4 | 36397.4 | 36397.4 | 36397.4 | 36397.4 |



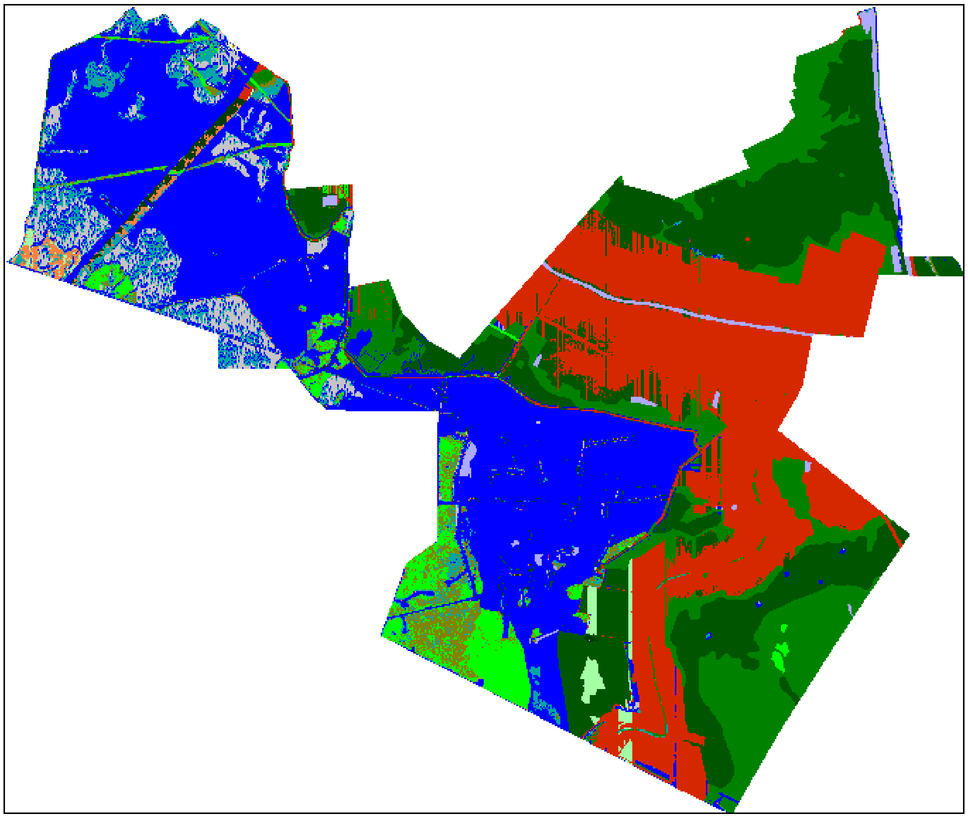
Bayou Teche NWR Initial Condition



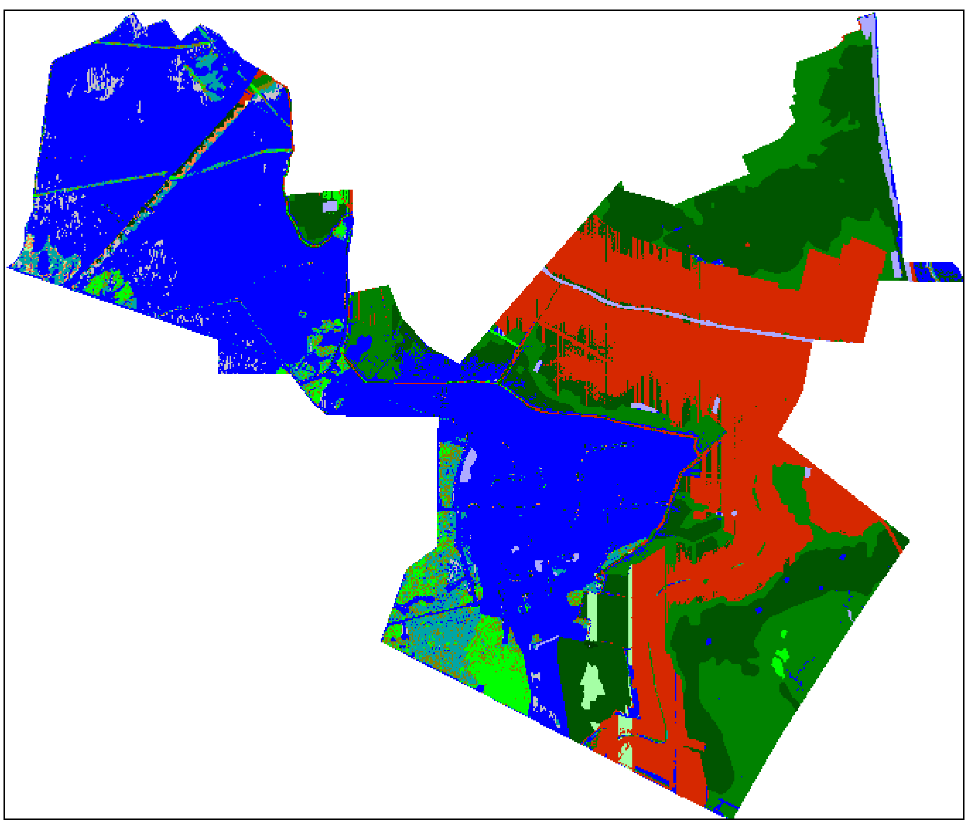
Bayou Teche NWR, 2025 IPCC Scenario A1B-Mean



Bayou Teche NWR, 2050 IPCC Scenario A1B-Mean



Bayou Teche NWR, 2075 IPCC Scenario A1B-Mean

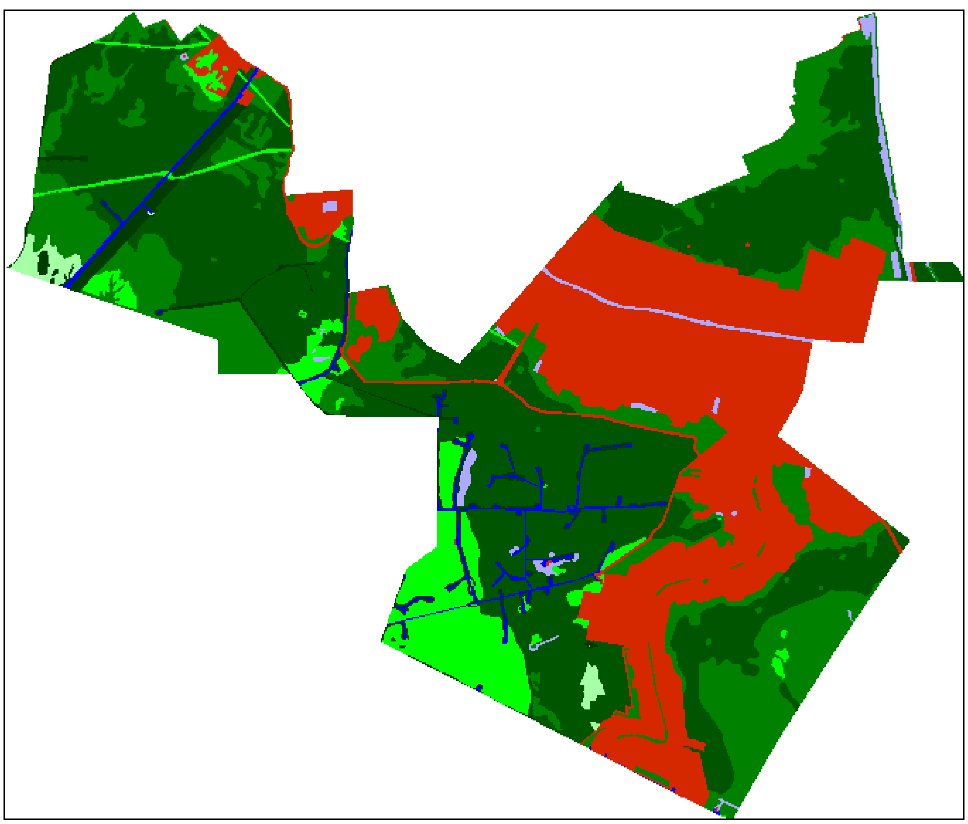


Bayou Teche NWR, 2100 IPCC Scenario A1B-Mean

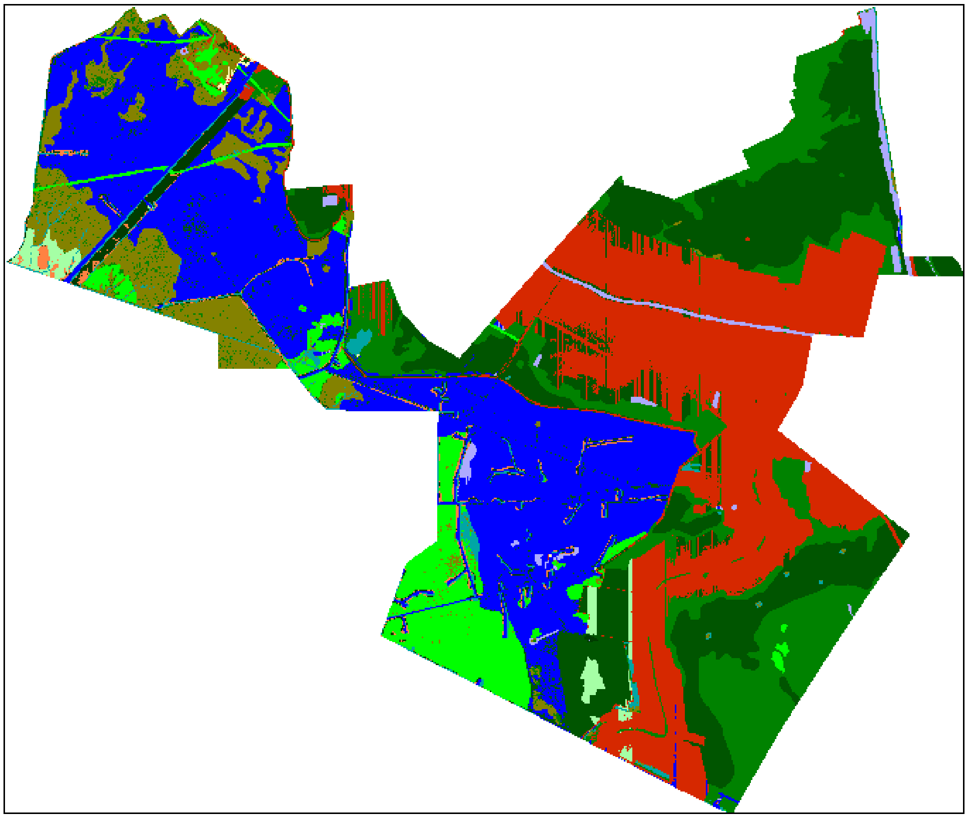
Bayou Teche
IPCC Scenario A1B-Max, 0.69 M SLR Eustatic by 2100

Results in Acres

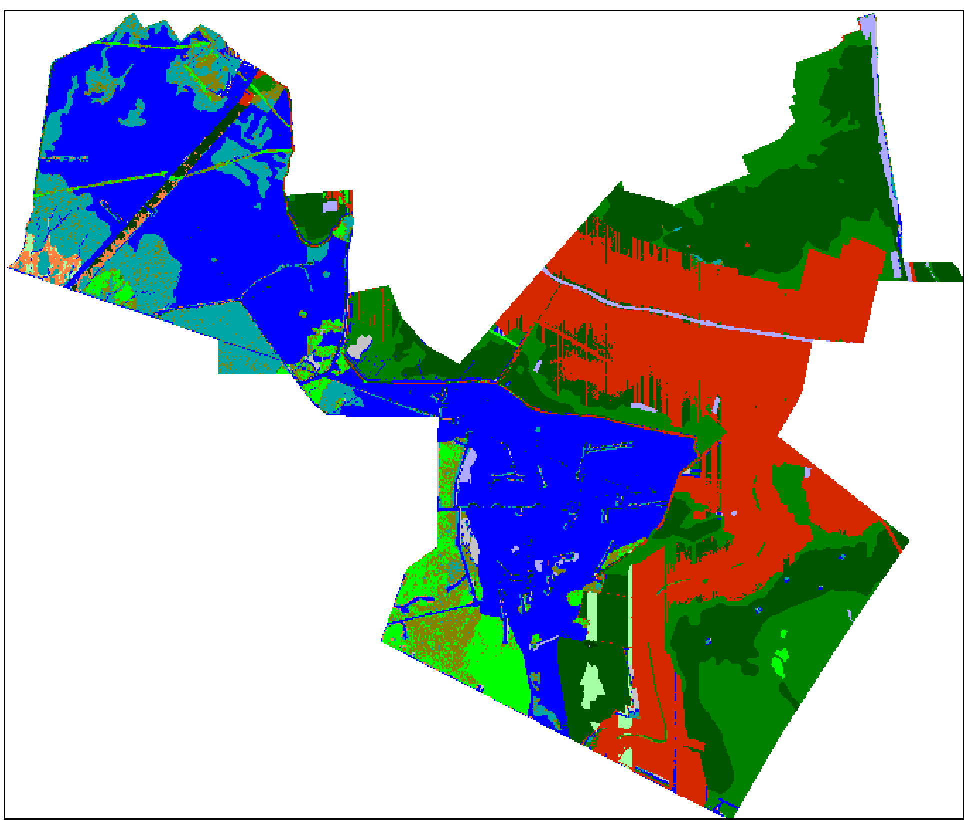
| | Initial | 2025 | 2050 | 2075 | 2100 |
|---|---|---|---|---|---|
| Cypress Swamp | 14730.3 | 7087.6 | 6804.9 | 6626.3 | 6099.3 |
| Dry Land | 10194.3 | 8370.2 | 8186.8 | 8082.0 | 8003.0 |
| Swamp | 6952.0 | 4859.0 | 4580.6 | 4467.8 | 3630.7 |
| Inland Fresh Marsh | 2365.8 | 2181.8 | 1341.7 | 558.7 | 194.1 |
| Tidal Swamp | 941.2 | 420.2 | 258.7 | 138.6 | 81.5 |
| Riverine Tidal | 484.8 | 241.2 | 174.1 | 149.6 | 136.7 |
| Inland Open Water | 476.1 | 417.4 | 398.8 | 391.2 | 387.9 |
| Tidal Fresh Marsh | 252.9 | 366.7 | 271.7 | 237.1 | 215.4 |
| Saltmarsh | 0.0 | 543.7 | 2647.4 | 1453.4 | 1010.5 |
| Estuarine Open Water | 0.0 | 9241.1 | 10079.3 | 11434.4 | 15568.0 |
| Brackish Marsh | 0.0 | 295.6 | 267.6 | 159.2 | 64.6 |
| Trans. Salt Marsh | 0.0 | 2351.5 | 1185.9 | 851.2 | 404.3 |
| Tidal Flat | 0.0 | 0.0 | 191.7 | 1839.2 | 596.3 |
| Estuarine Beach | 0.0 | 21.4 | 8.3 | 8.7 | 5.2 |
| **Total (incl. water)** | 36397.4 | 36397.4 | 36397.4 | 36397.4 | 36397.4 |



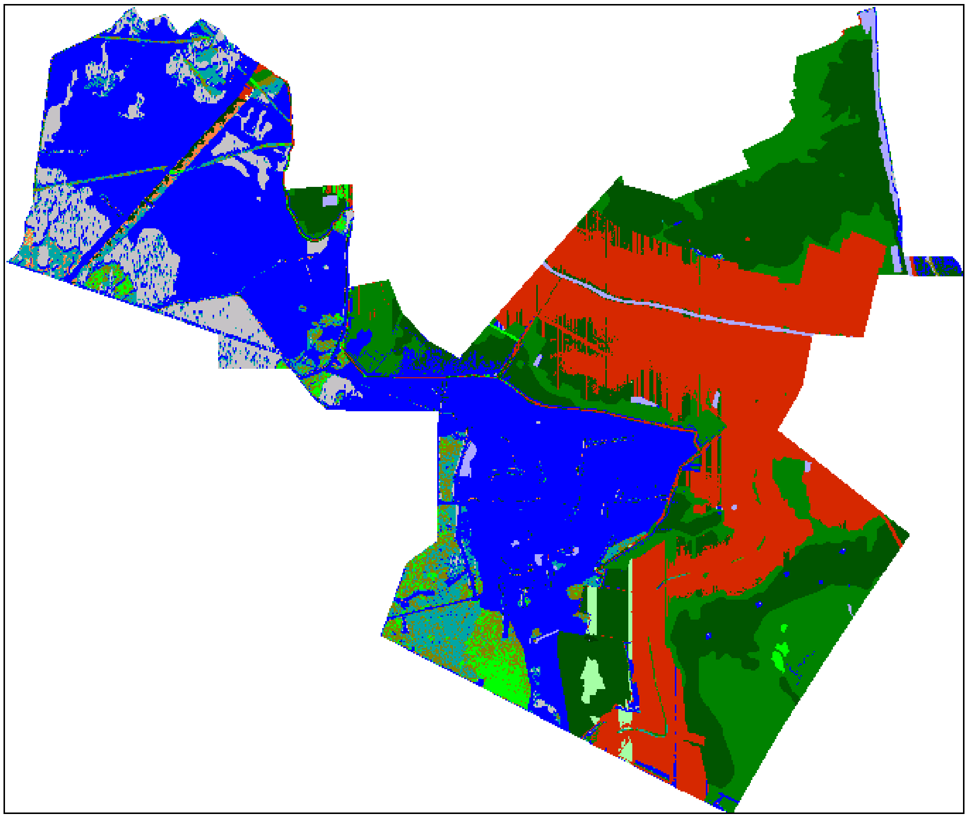
Bayou Teche NWR Initial Condition Scen_A1B_Maximum



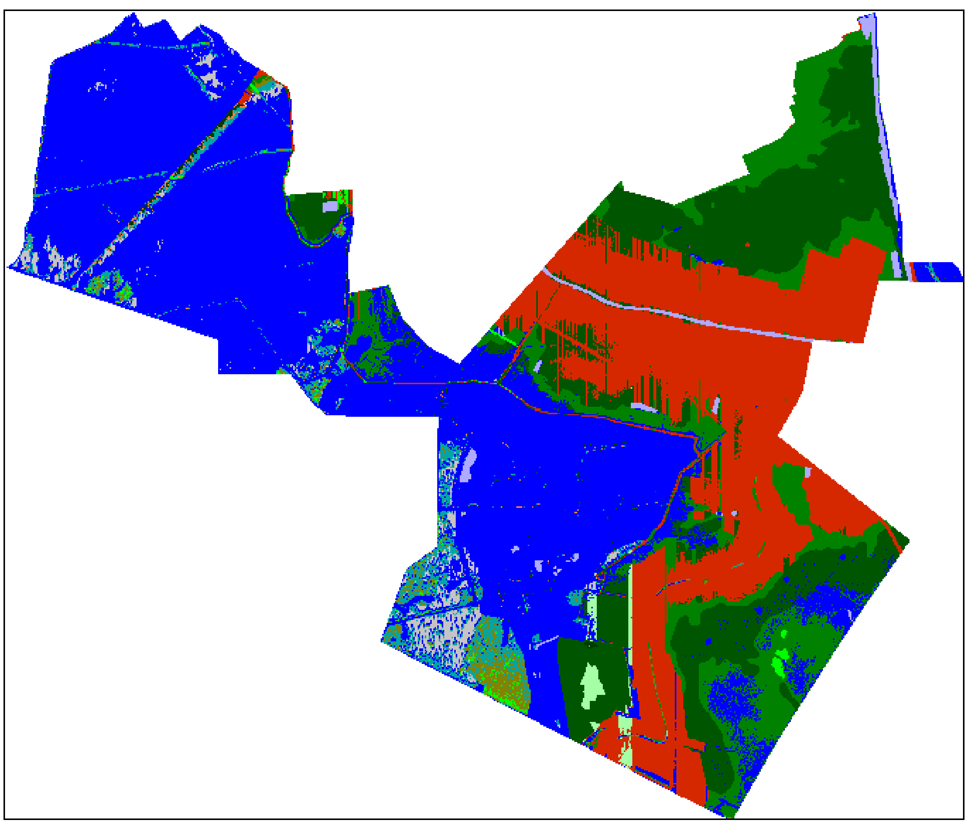
Bayou Teche NWR, 2025 IPCC Scenario A1B-Maximum



Bayou Teche NWR, 2050 IPCC Scenario A1B-Maximum



Bayou Teche NWR, 2075 IPCC Scenario A1B-Maximum

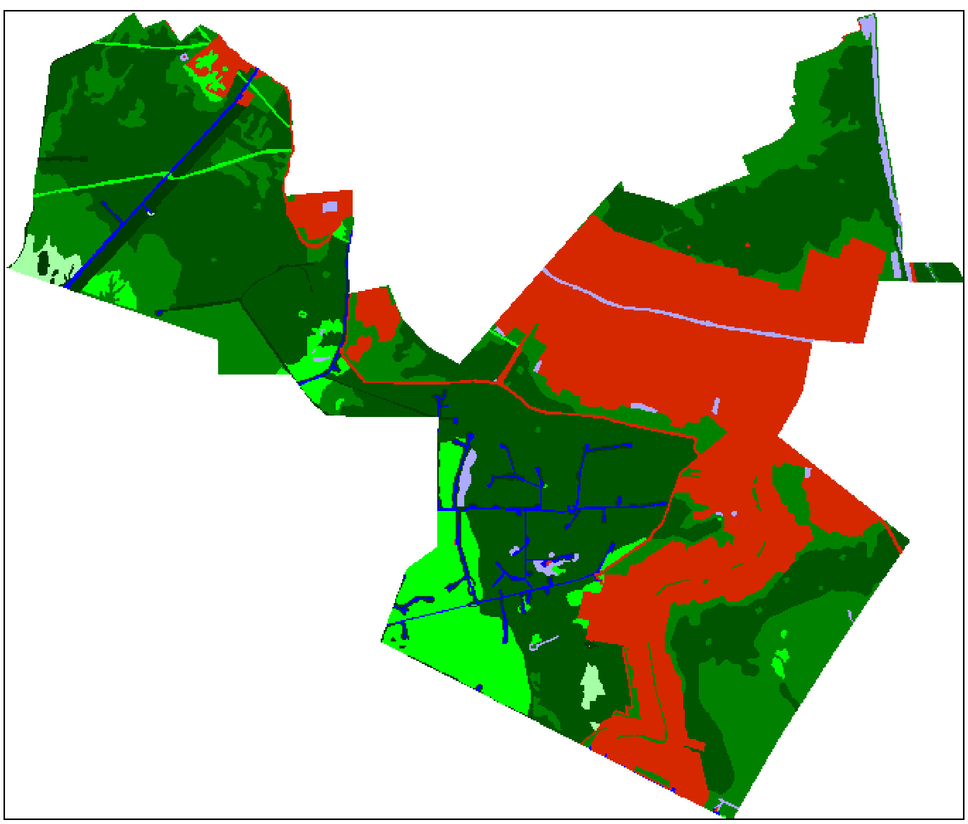


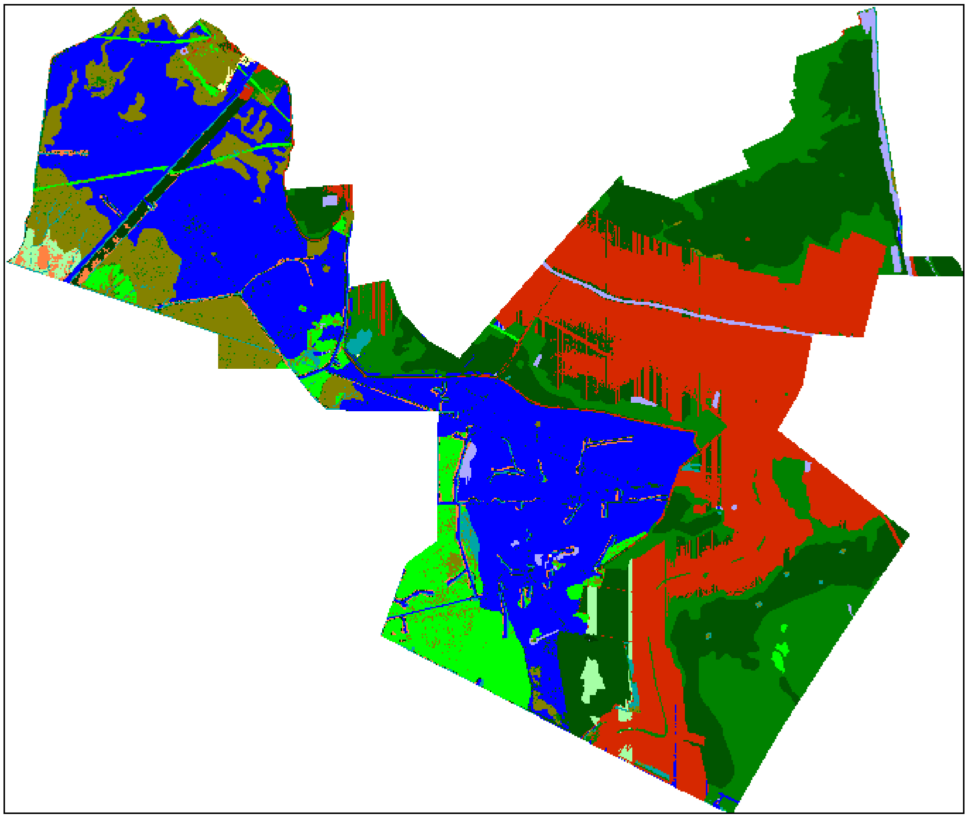
Bayou Teche NWR, 2100 IPCC Scenario A1B-Maximum

Bayou Teche
1 Meter Eustatic SLR by 2100

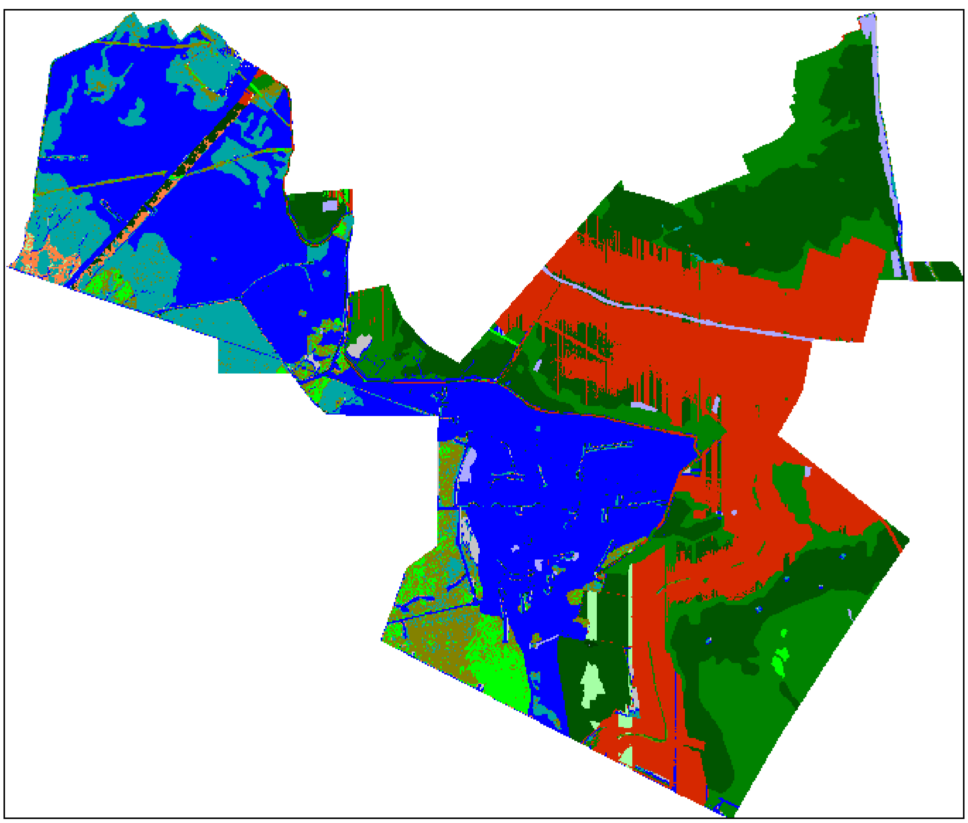
Results in Acres

| | Initial | 2025 | 2050 | 2075 | 2100 |
|---|---|---|---|---|---|
| Cypress Swamp | 14730.3 | 7034.6 | 6888.5 | 6541.4 | 4847.7 |
| Dry Land | 10194.3 | 8256.9 | 8031.7 | 7880.7 | 7772.5 |
| Swamp | 6952.0 | 4723.0 | 4568.0 | 4375.3 | 2204.7 |
| Inland Fresh Marsh | 2365.8 | 1973.4 | 809.7 | 199.9 | 60.7 |
| Tidal Swamp | 941.2 | 385.9 | 211.3 | 101.3 | 53.8 |
| Riverine Tidal | 484.8 | 241.5 | 166.2 | 145.3 | 135.3 |
| Inland Open Water | 476.1 | 416.8 | 394.1 | 390.1 | 387.4 |
| Tidal Fresh Marsh | 252.9 | 342.6 | 244.1 | 228.4 | 179.2 |
| Saltmarsh | 0.0 | 543.7 | 3068.8 | 1666.1 | 799.7 |
| Estuarine Open Water | 0.0 | 9385.7 | 10149.1 | 11858.1 | 18944.8 |
| Brackish Marsh | 0.0 | 356.5 | 282.8 | 127.6 | 49.9 |
| Trans. Salt Marsh | 0.0 | 2712.2 | 1383.4 | 672.1 | 144.1 |
| Tidal Flat | 0.0 | 0.0 | 191.9 | 2204.7 | 812.7 |
| Estuarine Beach | 0.0 | 24.6 | 7.9 | 6.4 | 4.9 |
| **Total (incl. water)** | 36397.4 | 36397.4 | 36397.4 | 36397.4 | 36397.4 |

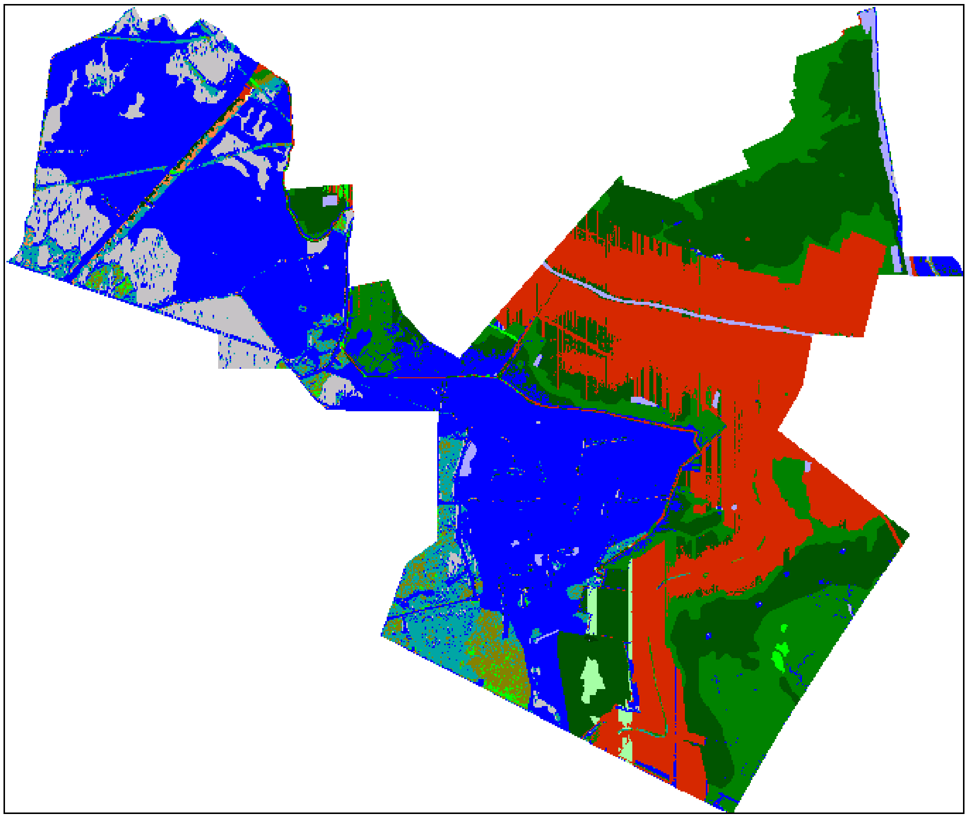

Bayou Teche NWR Initial Condition 1 meter Eustatic by 2100



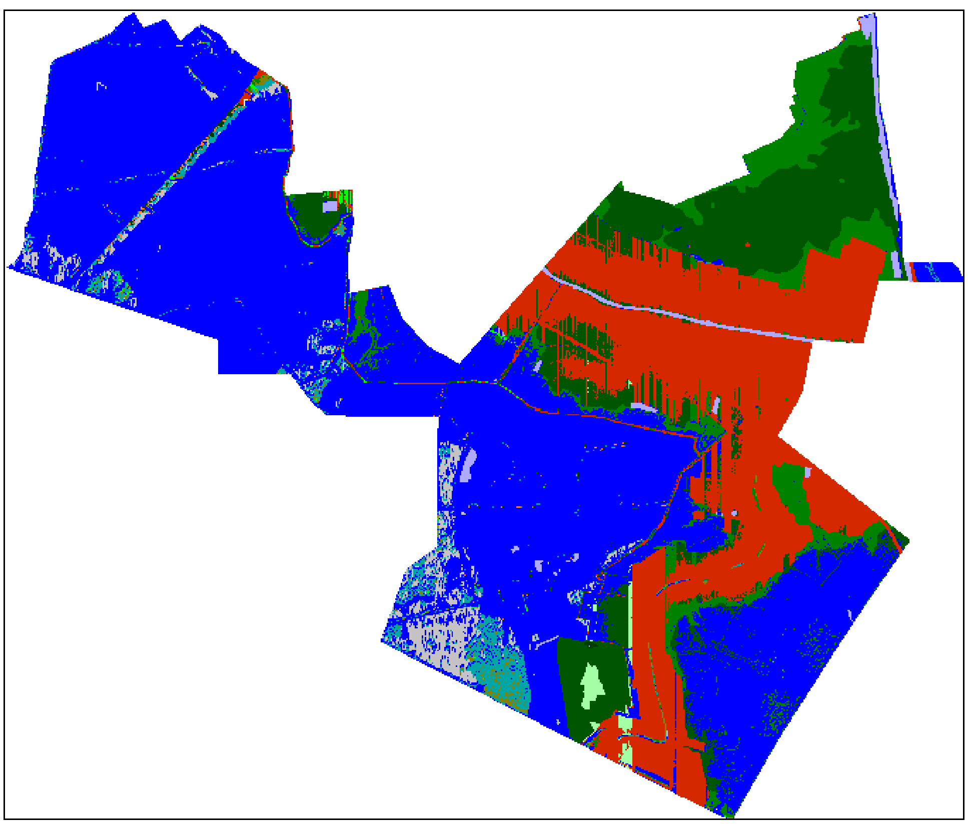
Bayou Teche NWR, 2025_1 meter Eustatic by 2100



Bayou Teche NWR, 2050_1 meter Eustatic by 2100



Bayou Teche NWR, 2075_1 meter Eustatic by 2100

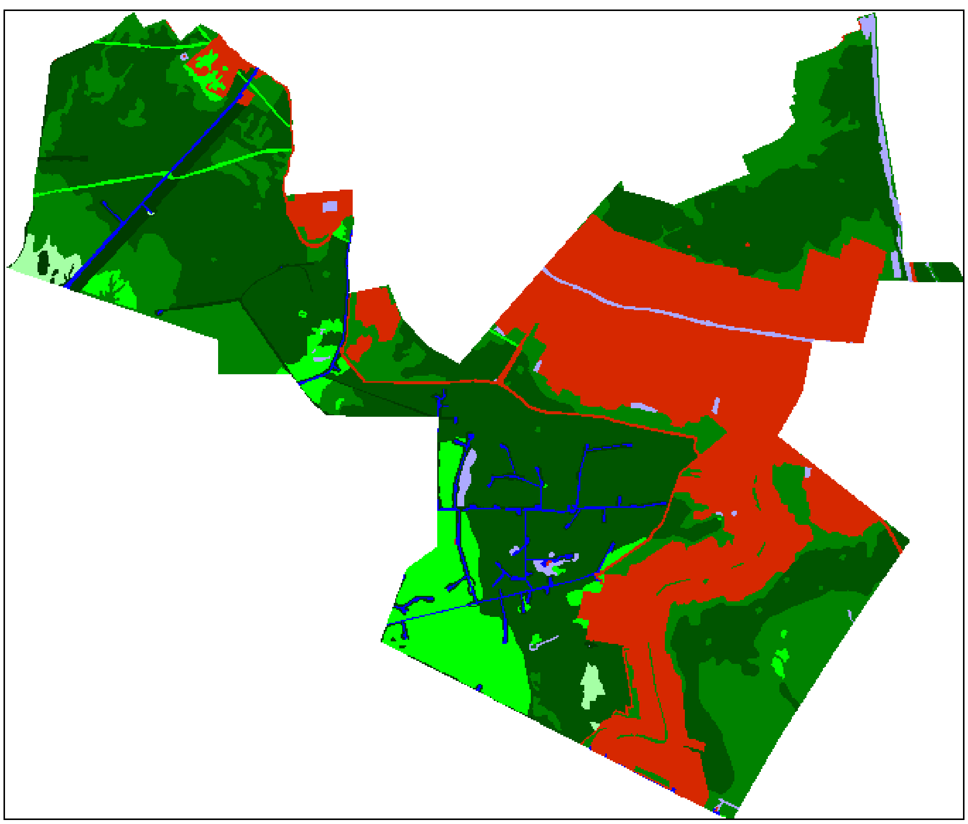


Bayou Teche NWR, 2100_1 meter Eustatic by 2100

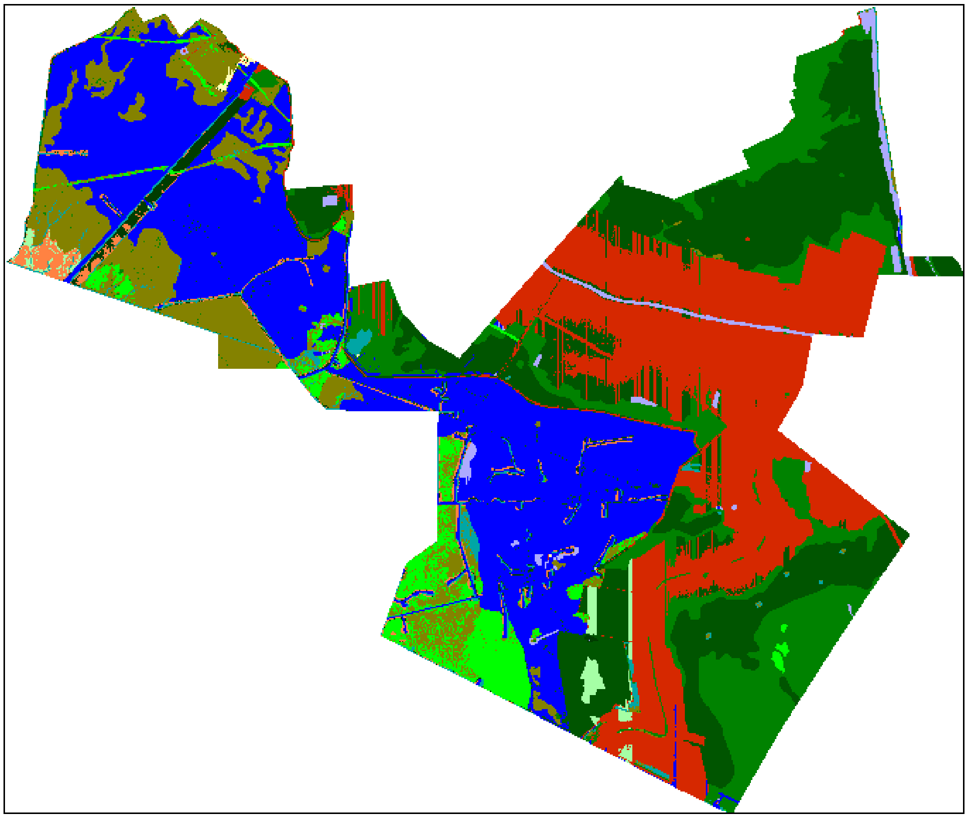
Bayou Teche
1.5 Meters Eustatic SLR by 2100

Results in Acres

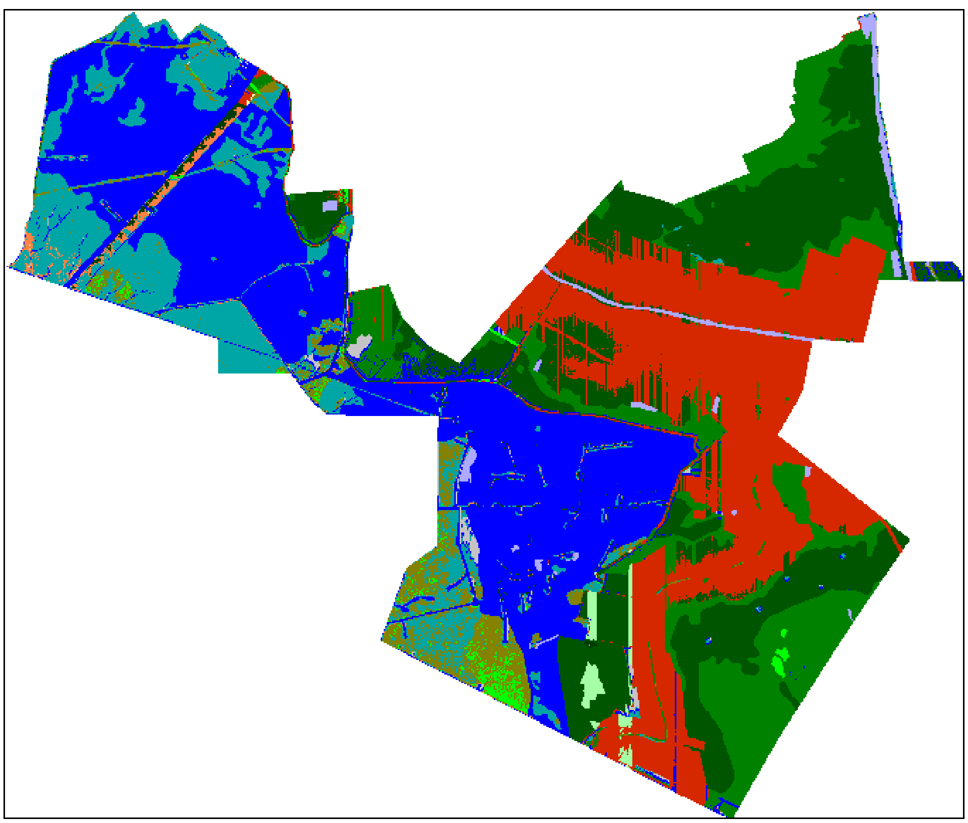
| | Initial | 2025 | 2050 | 2075 | 2100 |
|---|---|---|---|---|---|
| Cypress Swamp | 14730.3 | 7095.5 | 7009.8 | 5877.2 | 3560.6 |
| Dry Land | 10194.3 | 8073.7 | 7763.6 | 7519.4 | 7246.4 |
| Swamp | 6952.0 | 4636.9 | 4546.3 | 2929.1 | 1222.8 |
| Inland Fresh Marsh | 2365.8 | 1453.7 | 310.8 | 64.3 | 24.5 |
| Tidal Swamp | 941.2 | 338.5 | 150.1 | 65.2 | 23.0 |
| Riverine Tidal | 484.8 | 241.9 | 160.6 | 141.3 | 135.4 |
| Inland Open Water | 476.1 | 416.8 | 392.1 | 387.9 | 387.4 |
| Tidal Fresh Marsh | 252.9 | 277.1 | 227.3 | 186.0 | 132.2 |
| Saltmarsh | 0.0 | 543.7 | 3812.2 | 1521.8 | 375.2 |
| Estuarine Open Water | 0.0 | 9480.1 | 10303.6 | 14512.7 | 22452.5 |
| Brackish Marsh | 0.0 | 473.6 | 243.2 | 88.6 | 41.4 |
| Trans. Salt Marsh | 0.0 | 3338.6 | 1278.6 | 286.6 | 42.2 |
| Tidal Flat | 0.0 | 0.0 | 191.8 | 2811.0 | 748.4 |
| Estuarine Beach | 0.0 | 27.2 | 7.5 | 6.4 | 5.4 |
| **Total (incl. water)** | 36397.4 | 36397.4 | 36397.4 | 36397.4 | 36397.4 |



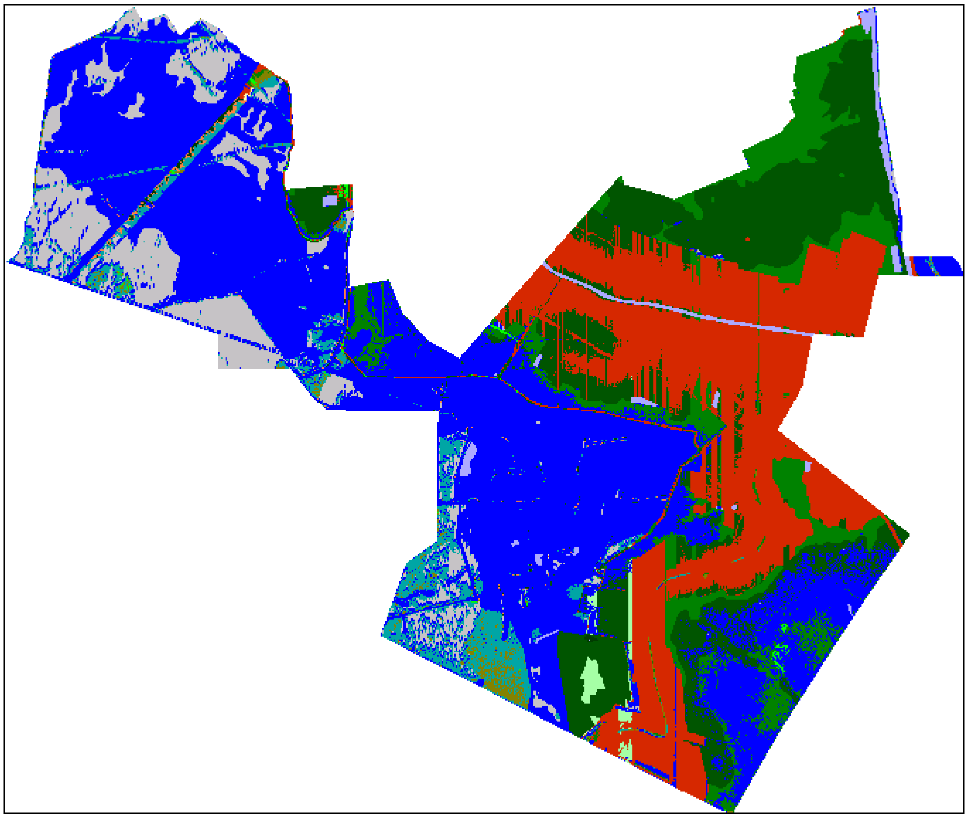
Bayou Teche NWR Initial Condition 1.5 meter Eustatic by 2100

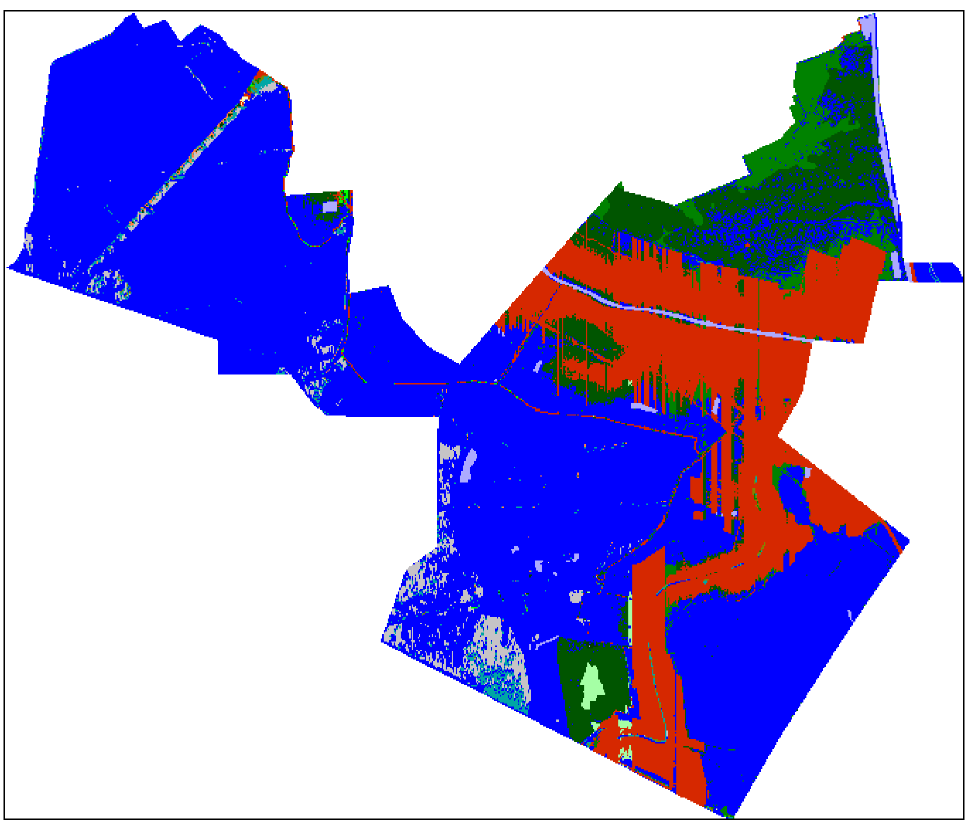


Bayou Teche NWR, 2025_1.5 meter Eustatic by 2100



Bayou Teche NWR, 2050_1.5 meter Eustatic by 2100


Bayou Teche NWR, 2075_1.5 meter Eustatic by 2100


Bayou Teche NWR, 2100_1.5 meter Eustatic by 2100

# Discussion:

The high resolution elevation data for this site indicate that much of the fresh water habitat in Bayou Teche is quite close to the salt boundary (vertically). Therefore, additional sea level rise combined with the continuation of local subsidence is predicted to have a dramatic effect at this site.

The assumptions of which lands are protected by dikes were based on a weight-of-evidence approach as described above and are subject to additional uncertainty.

The SLAMM assumption that cypress swamps, when inundated by salt water, will convert to open water, produces dramatic results for this site. This assumption was based on the professional judgment of the model developers based on witnessing the effects of cypress swamp inundation. However, following the conversion of cypress swamp, there may be some land mass maintained as salt marshes or tidal flats. To further refine model results at this site, this assumption could be examined more closely and refined.

Nonetheless, cypress swamps that are subject to saline inundation will be significantly impacted. The prediction that cypress swamps are in jeopardy of such inundation may be more important than the exact fate of those swamps following inundation.

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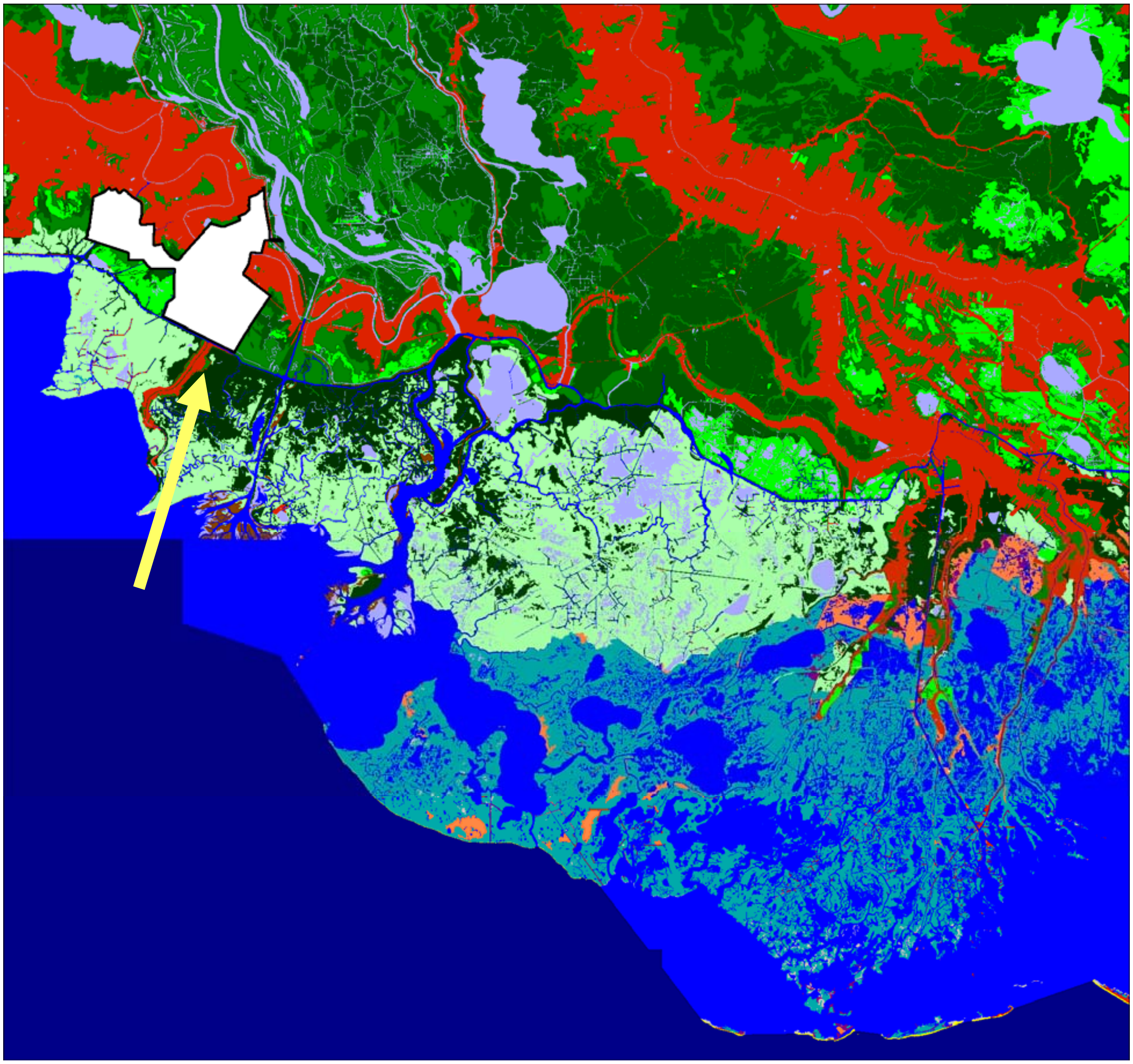
# Appendix A: Contextual Results

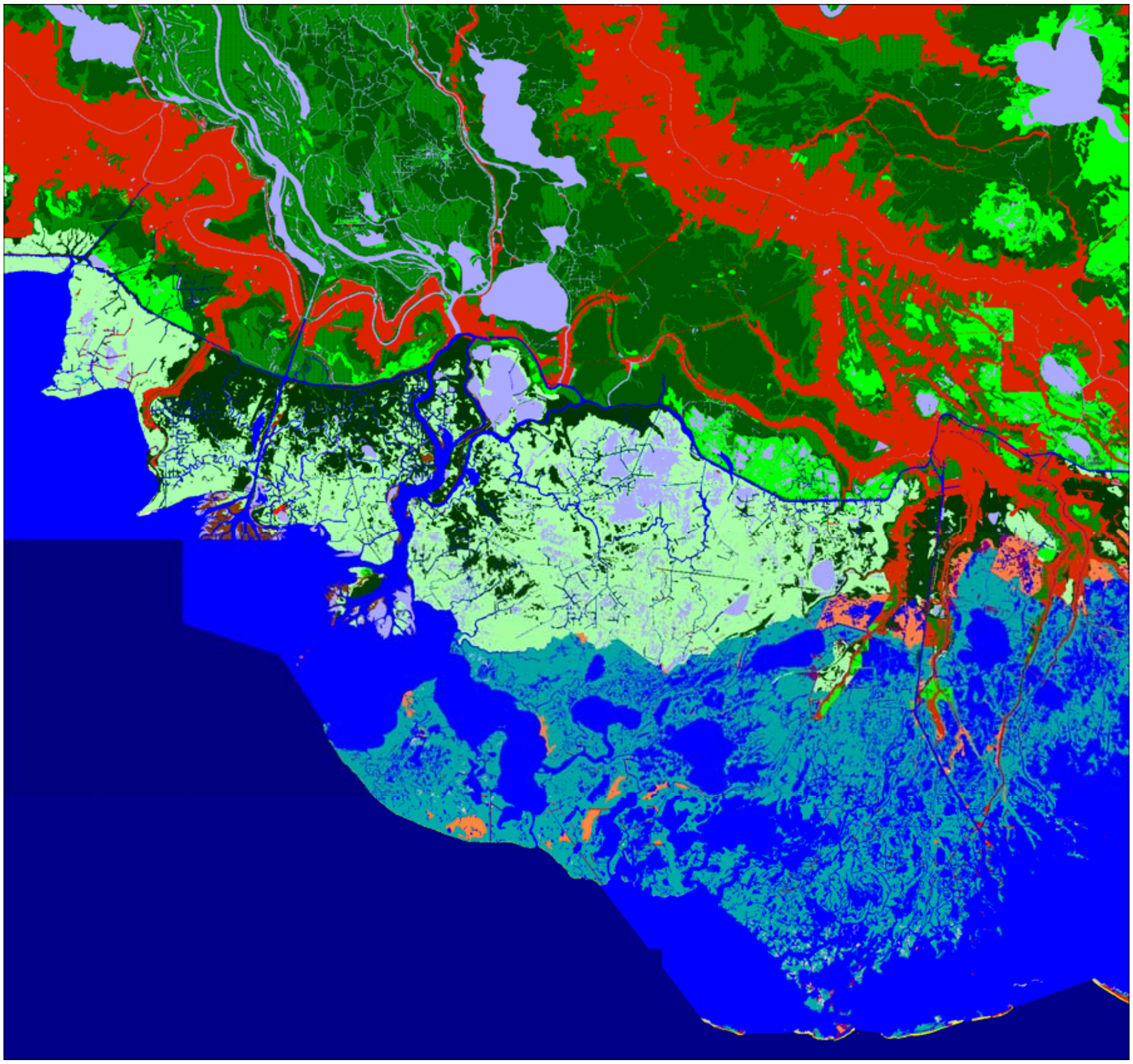
The SLAMM model does take into account the context of the surrounding lands or open water when calculating effects. For example, erosion rates are calculated based on the maximum fetch (wave action) which is estimated by assessing contiguous open water to a given marsh cell. Another example is that inundated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

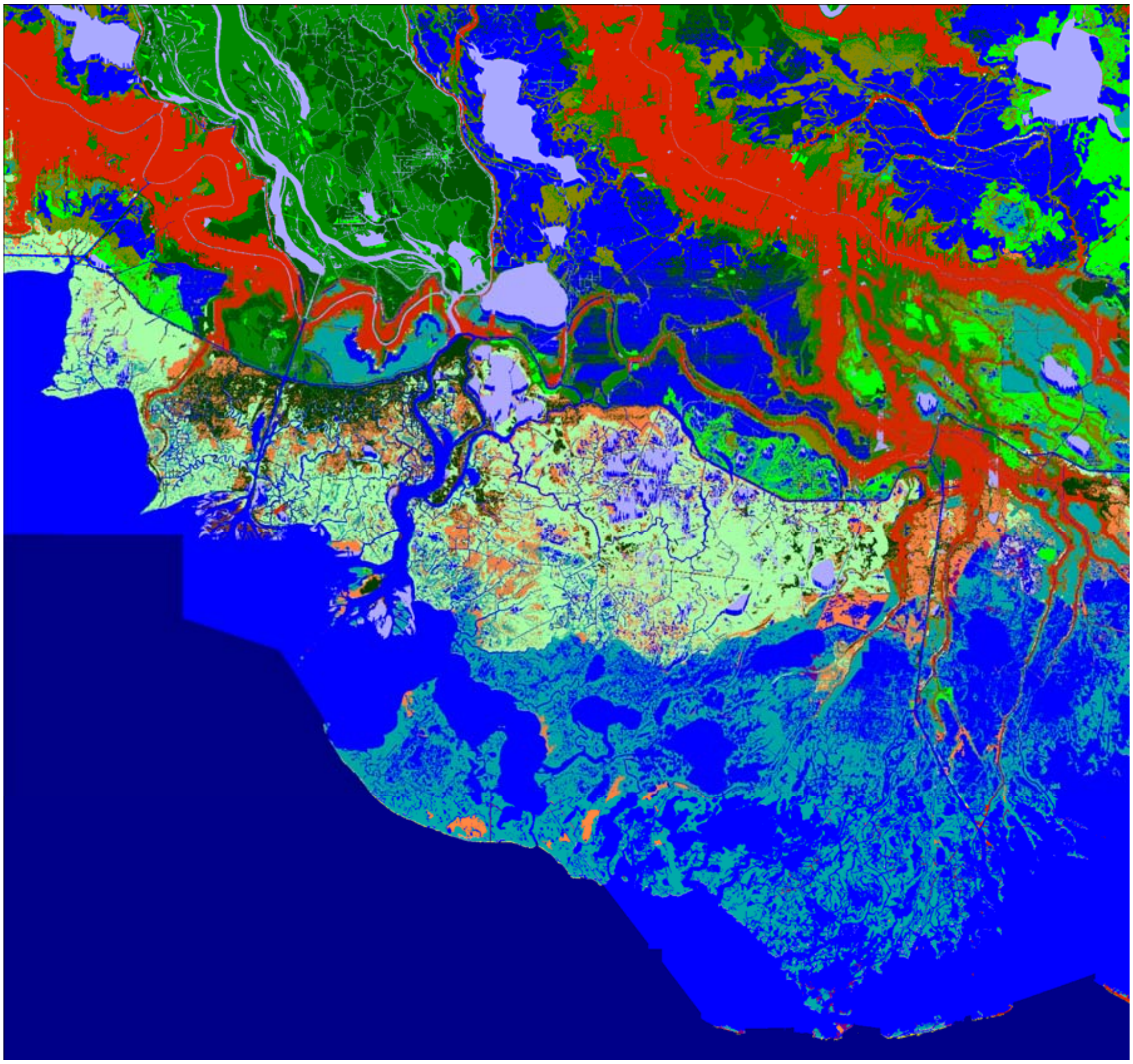
- Results were closely examined (quality assurance) within USFWS refuges but not closely examined for the larger region.
- Site-specific parameters for the model were derived for USFWS refuges whenever possible and may not be regionally applicable.
- Especially in areas where dikes are present, an effort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



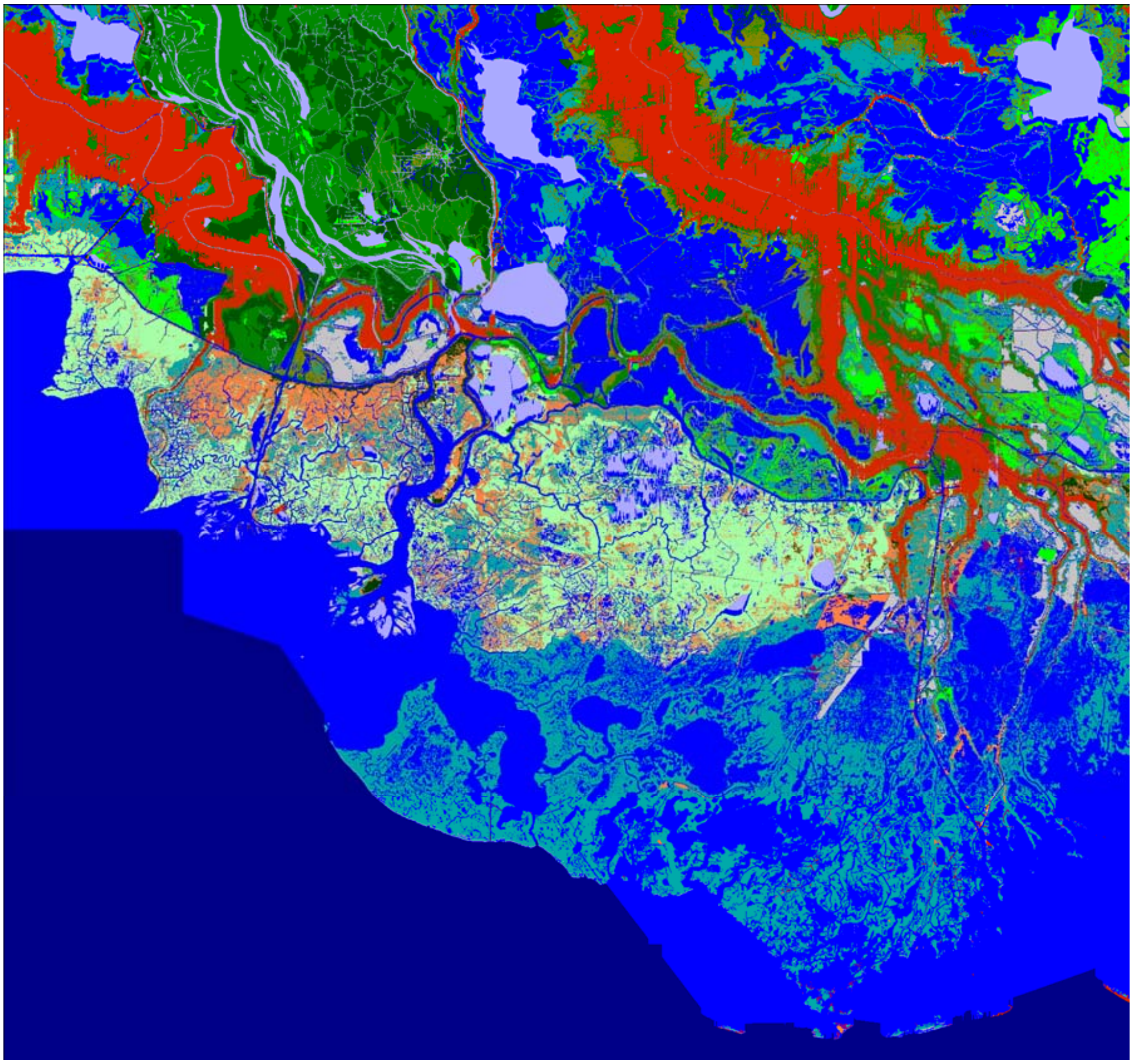
Location of Bayou Teche National Wildlife Refuge (white area with black boundary) within Louisiana simulation context



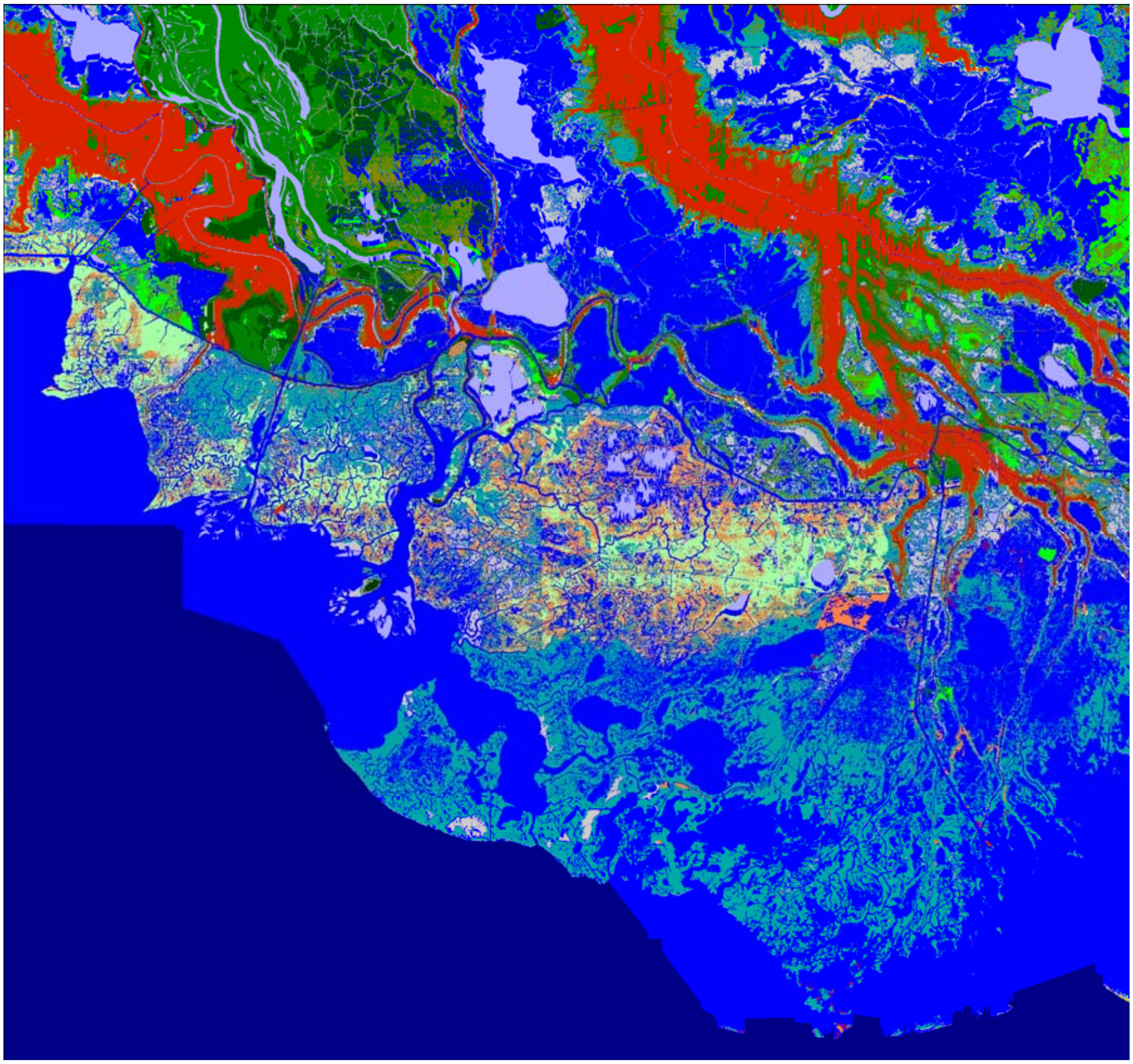
Louisiana Initial Condition



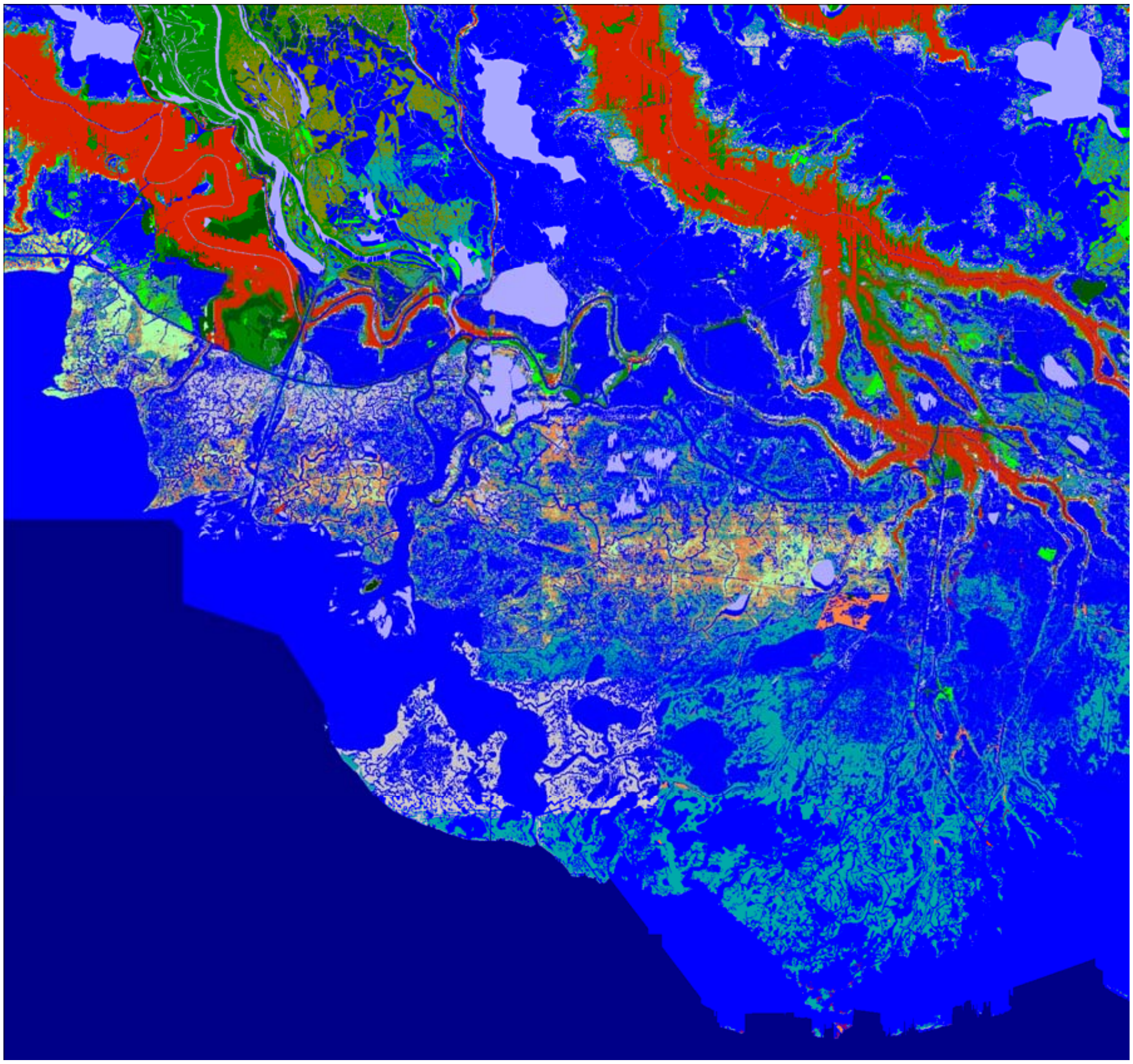
Louisiana 2025 IPCC Scenario A1B-Mean



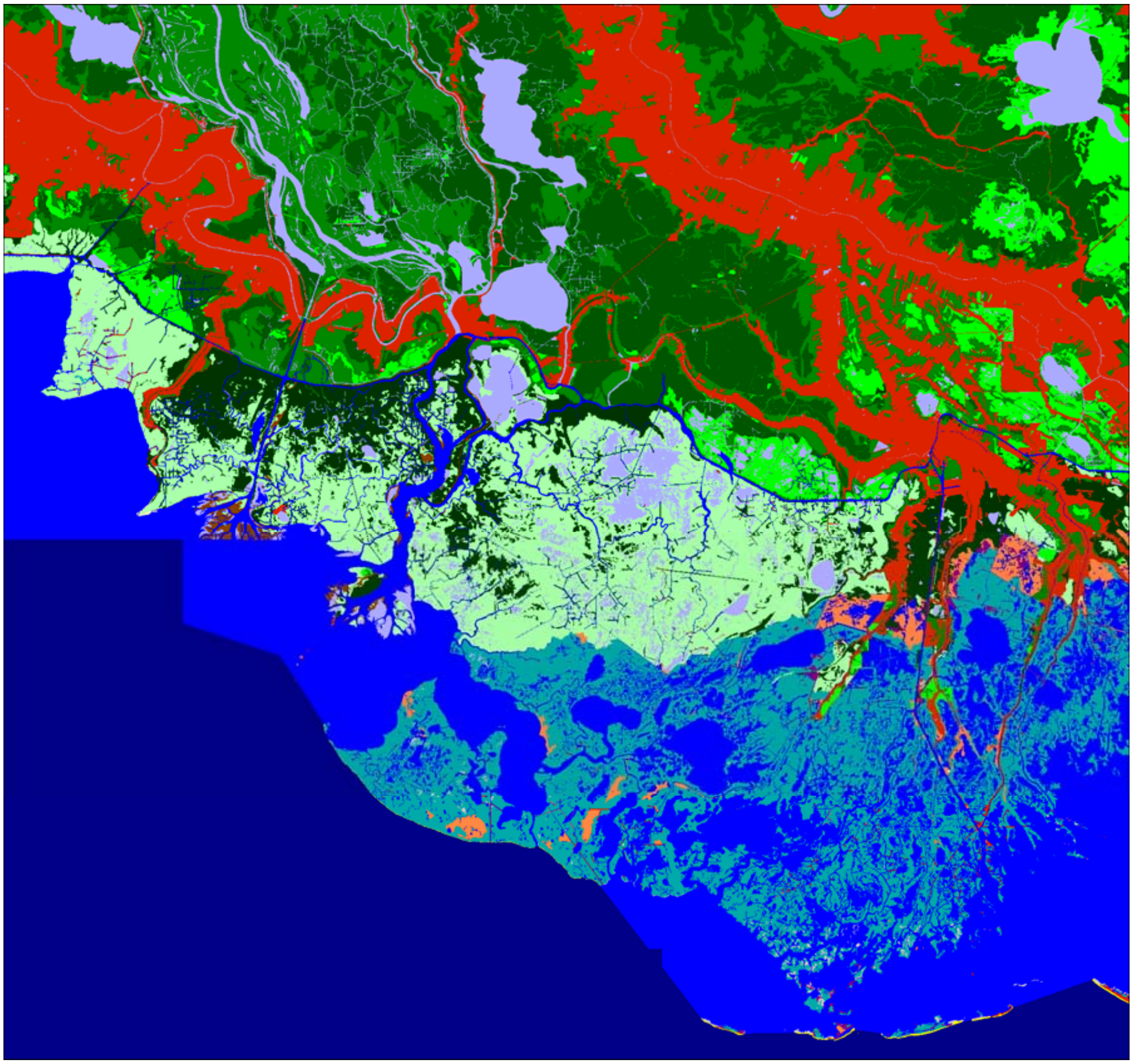
Louisiana 2050 IPCC Scenario A1B-Mean



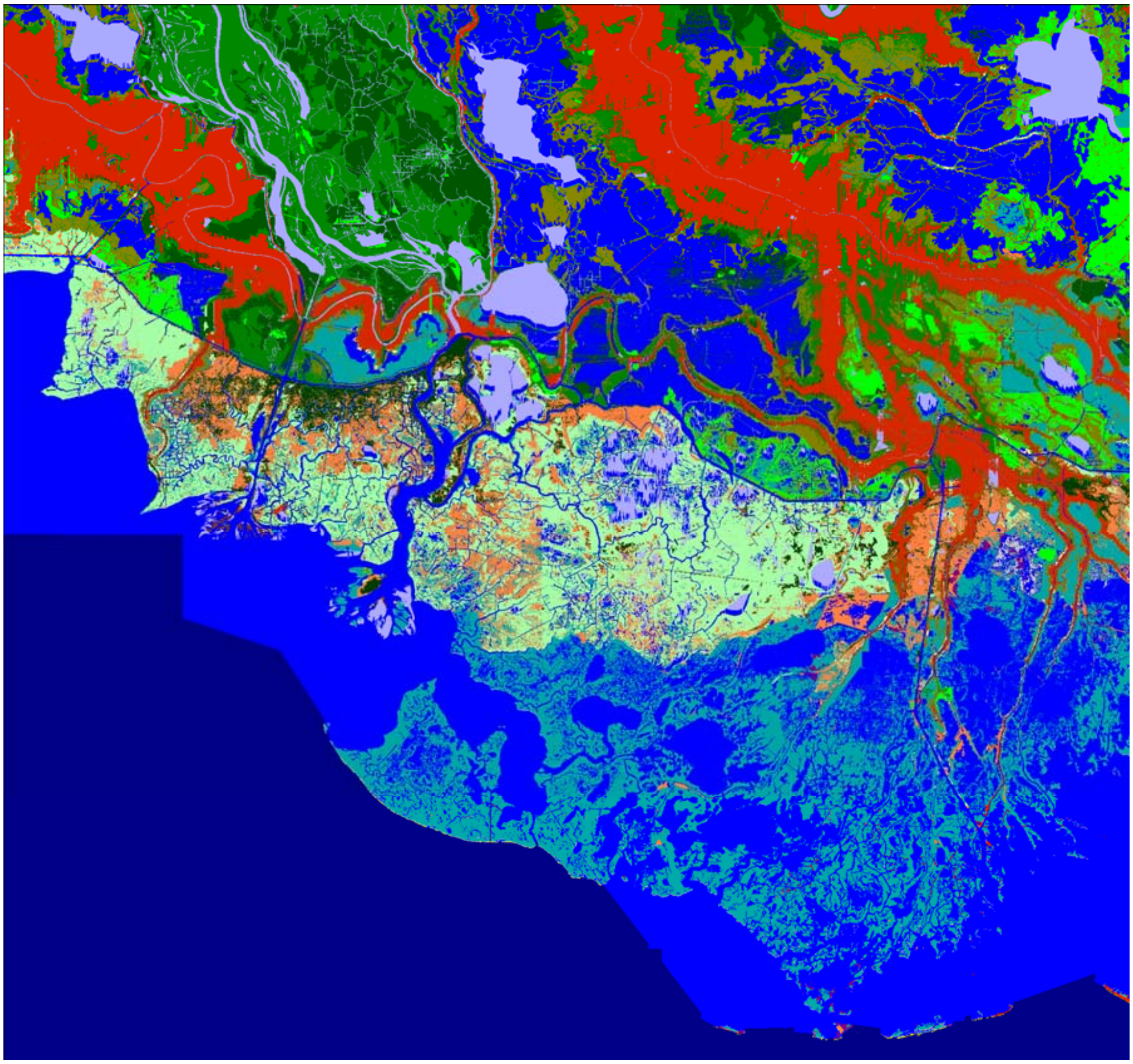
Louisiana 2075 IPCC Scenario A1B-Mean



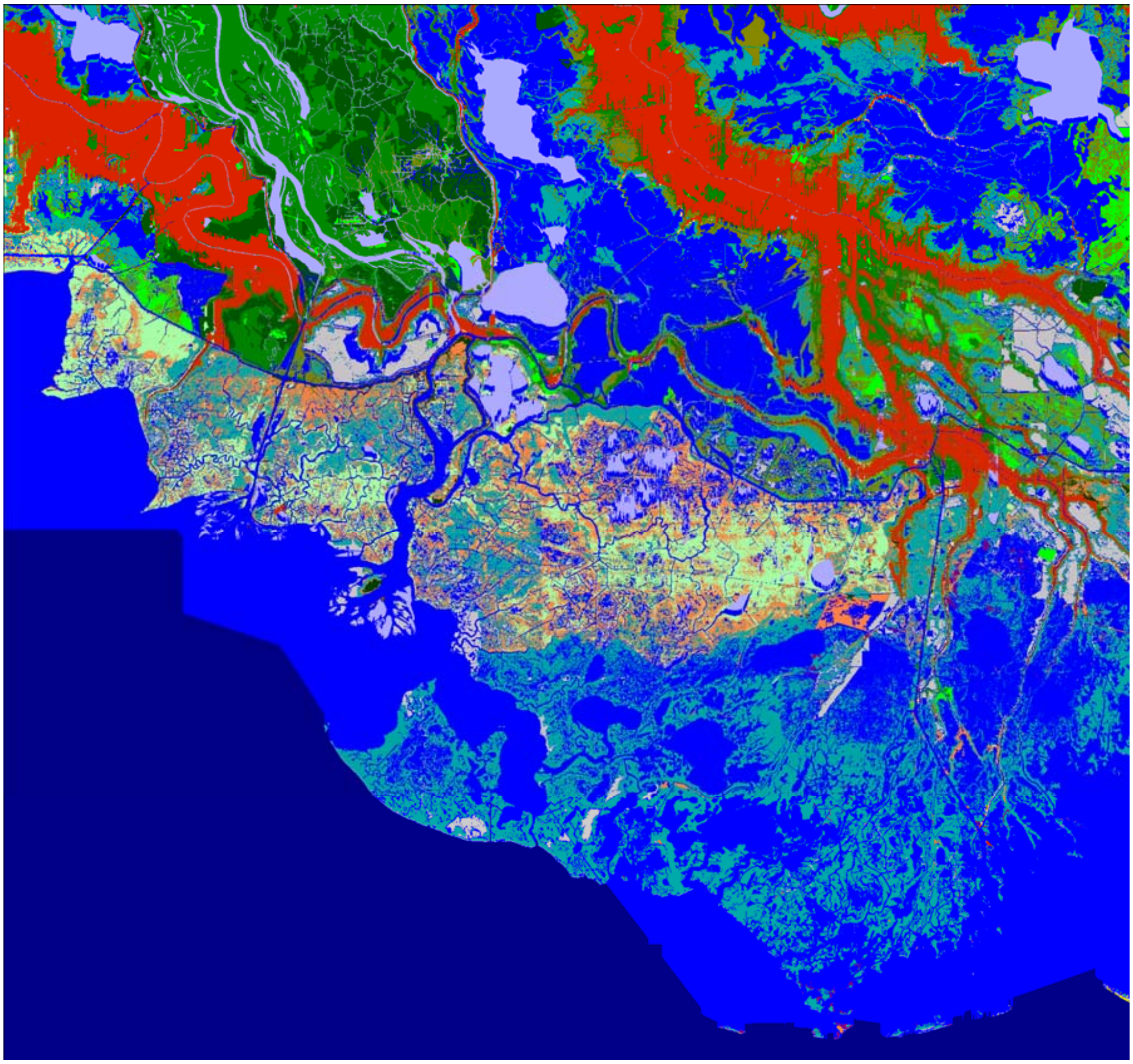
Louisiana 2100 IPCC Scenario A1B-Mean



Louisiana Initial Condition



Louisiana 2025 IPCC Scenario A1B-Maximum



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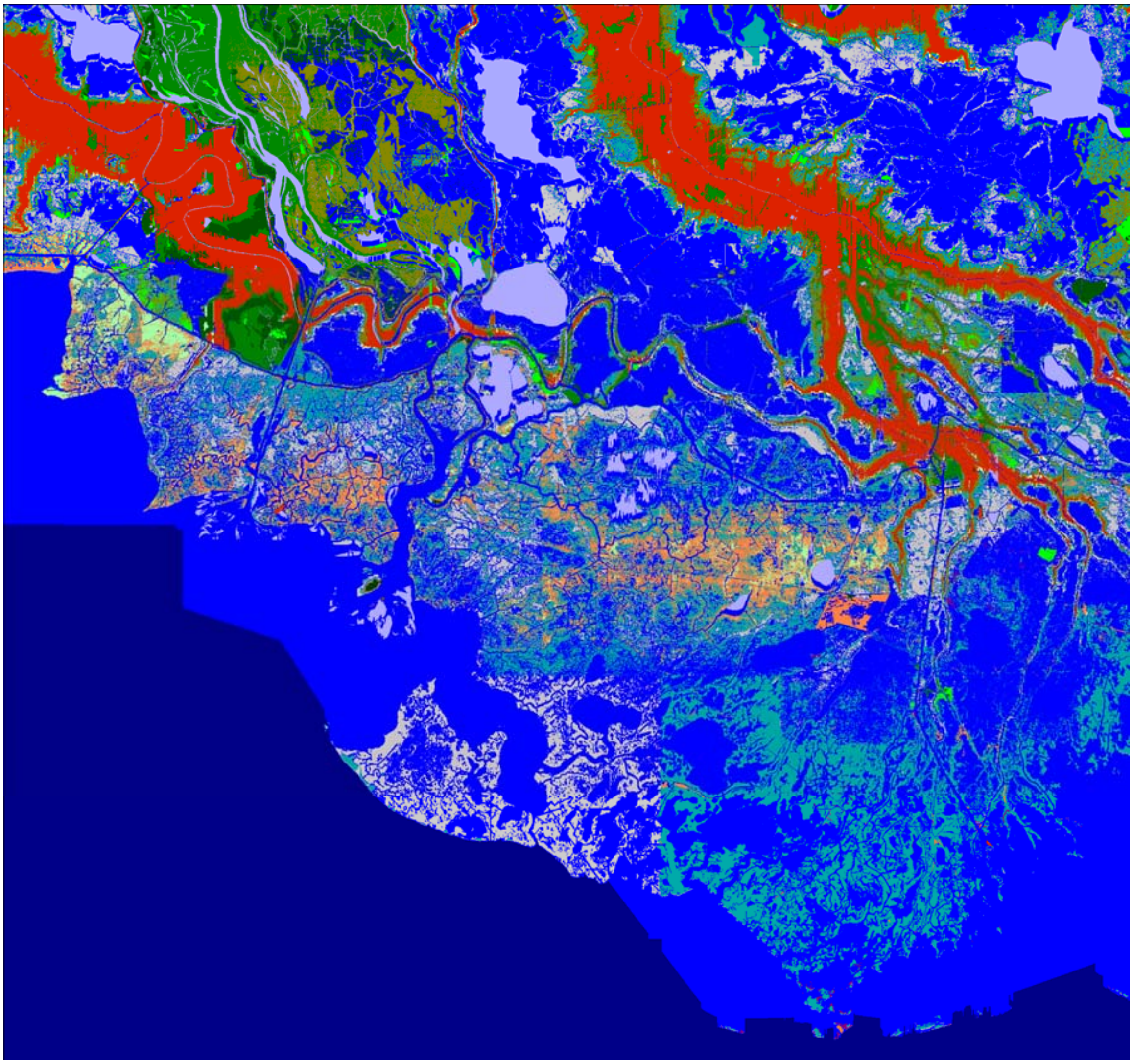

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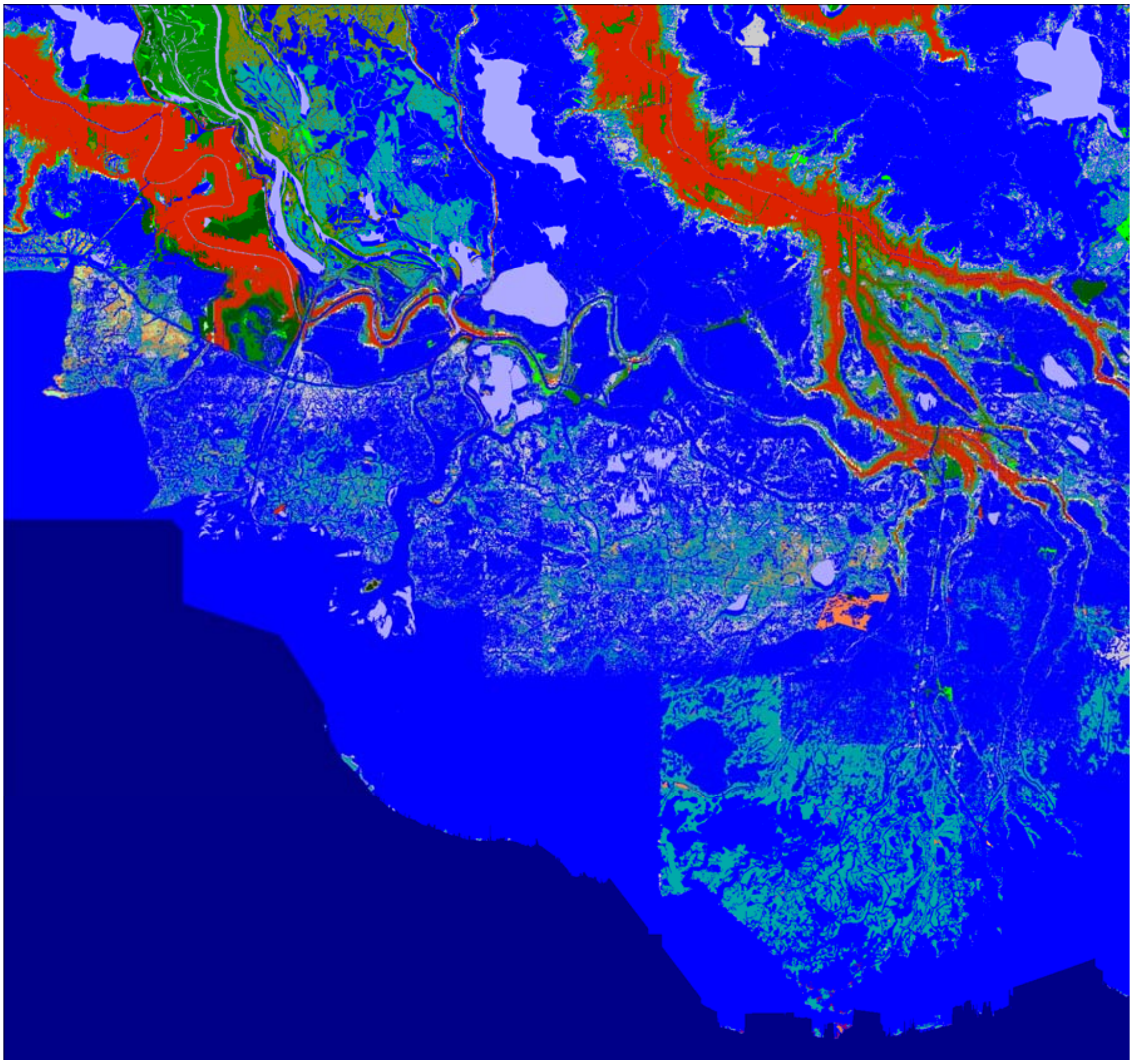
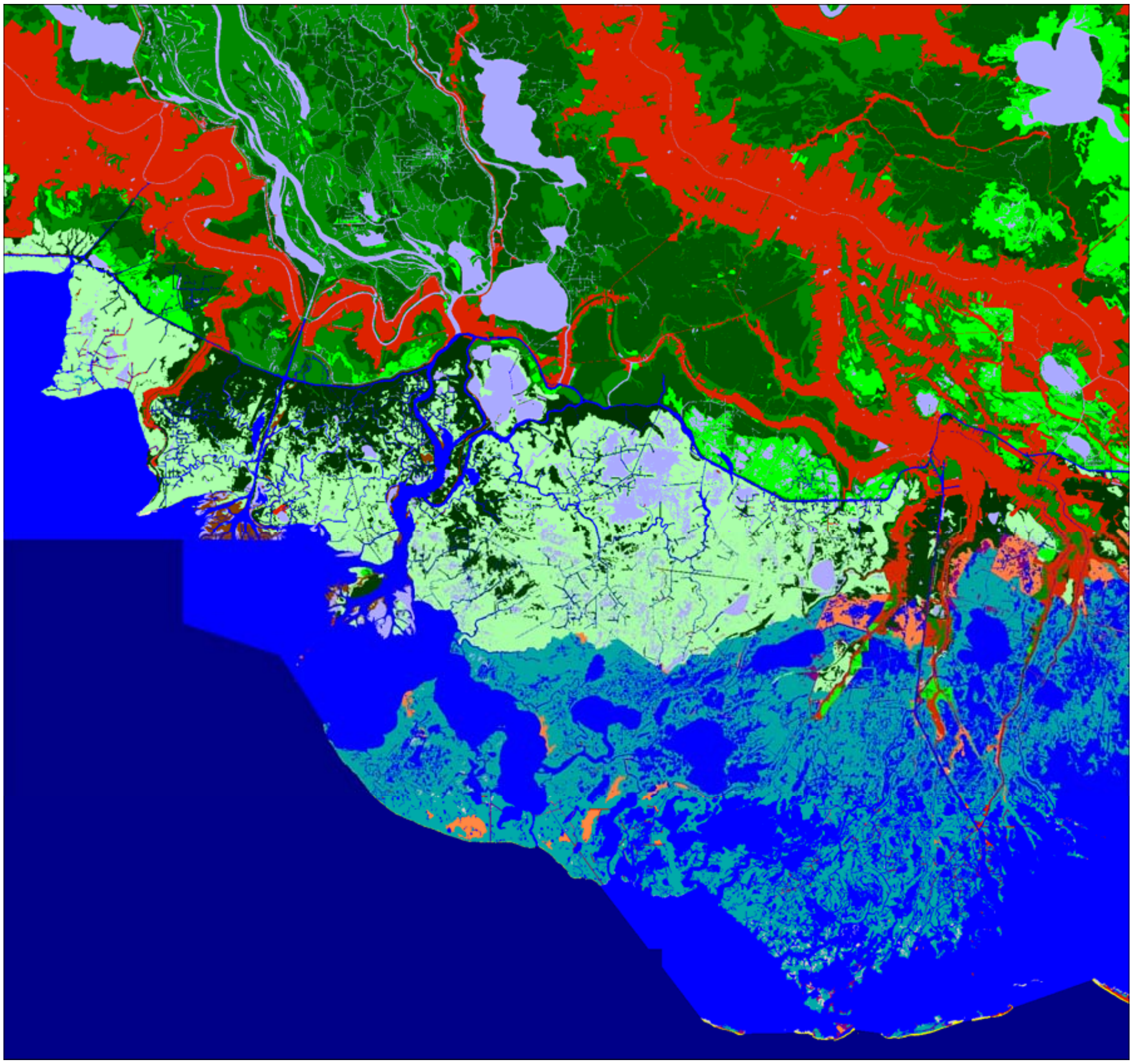
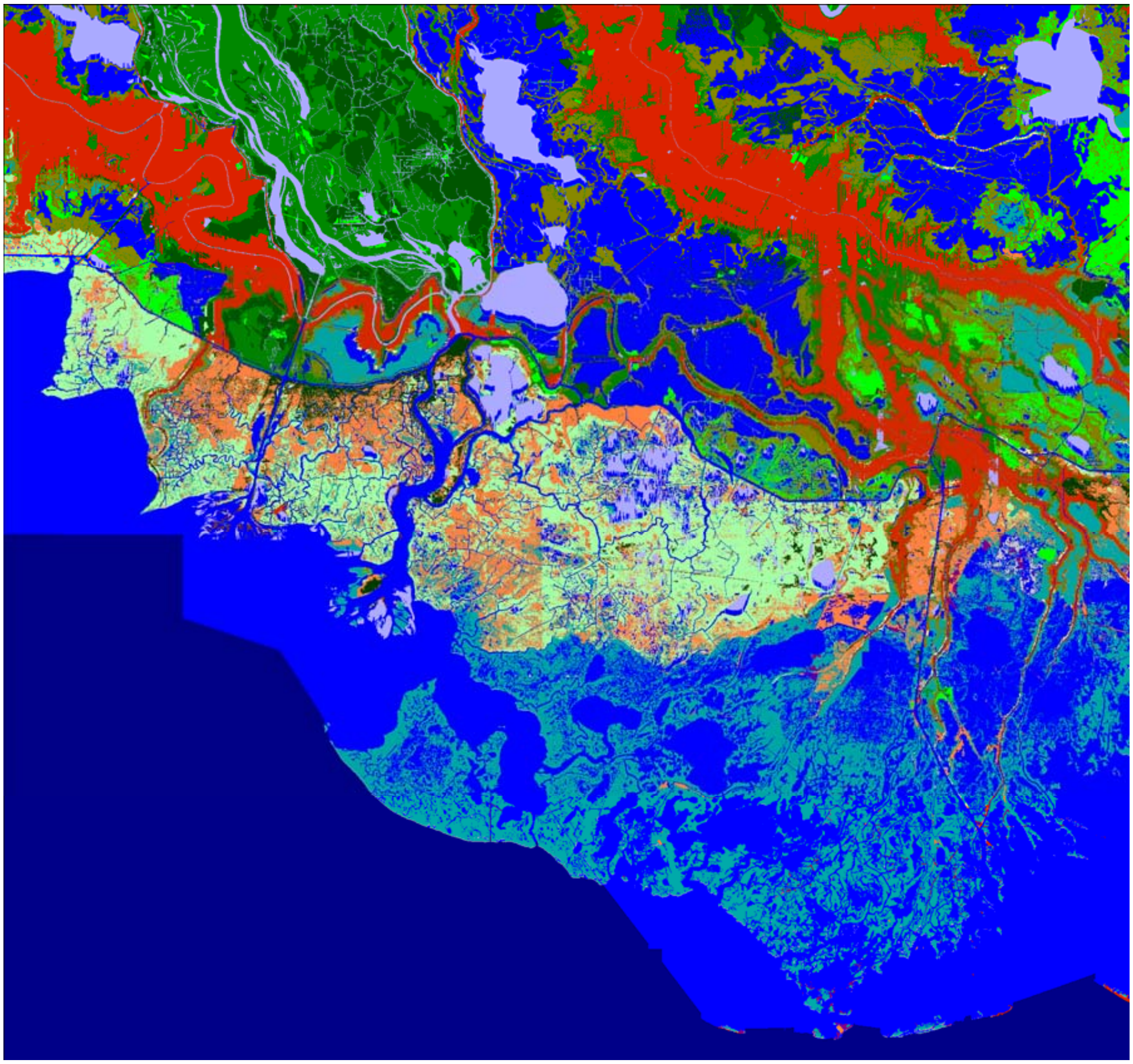


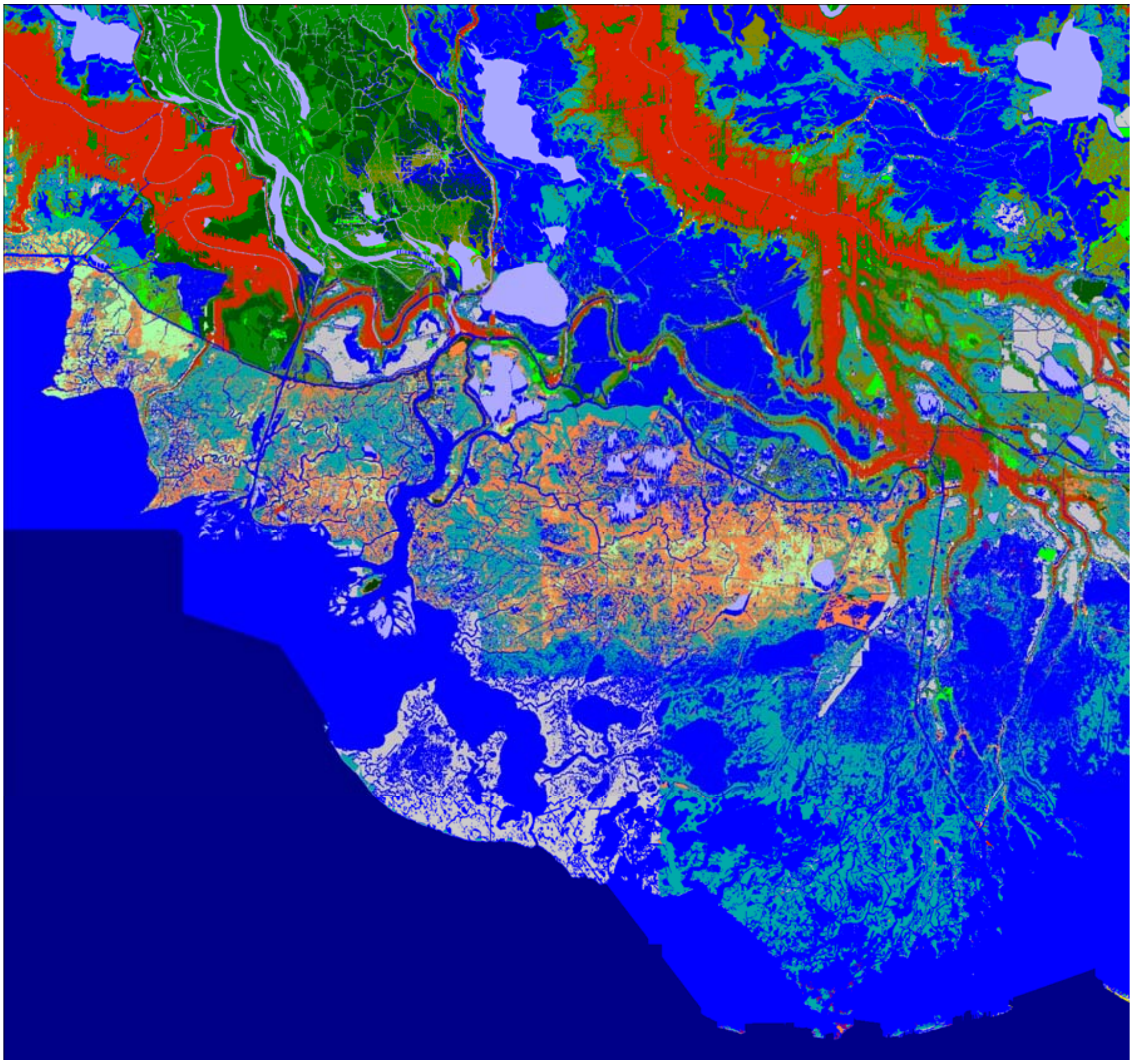
Louisiana 2100 IPCC Scenario A1B-Maximum



Louisiana Initial Condition



Louisiana 2025, 1 meter Eustatic by 2100



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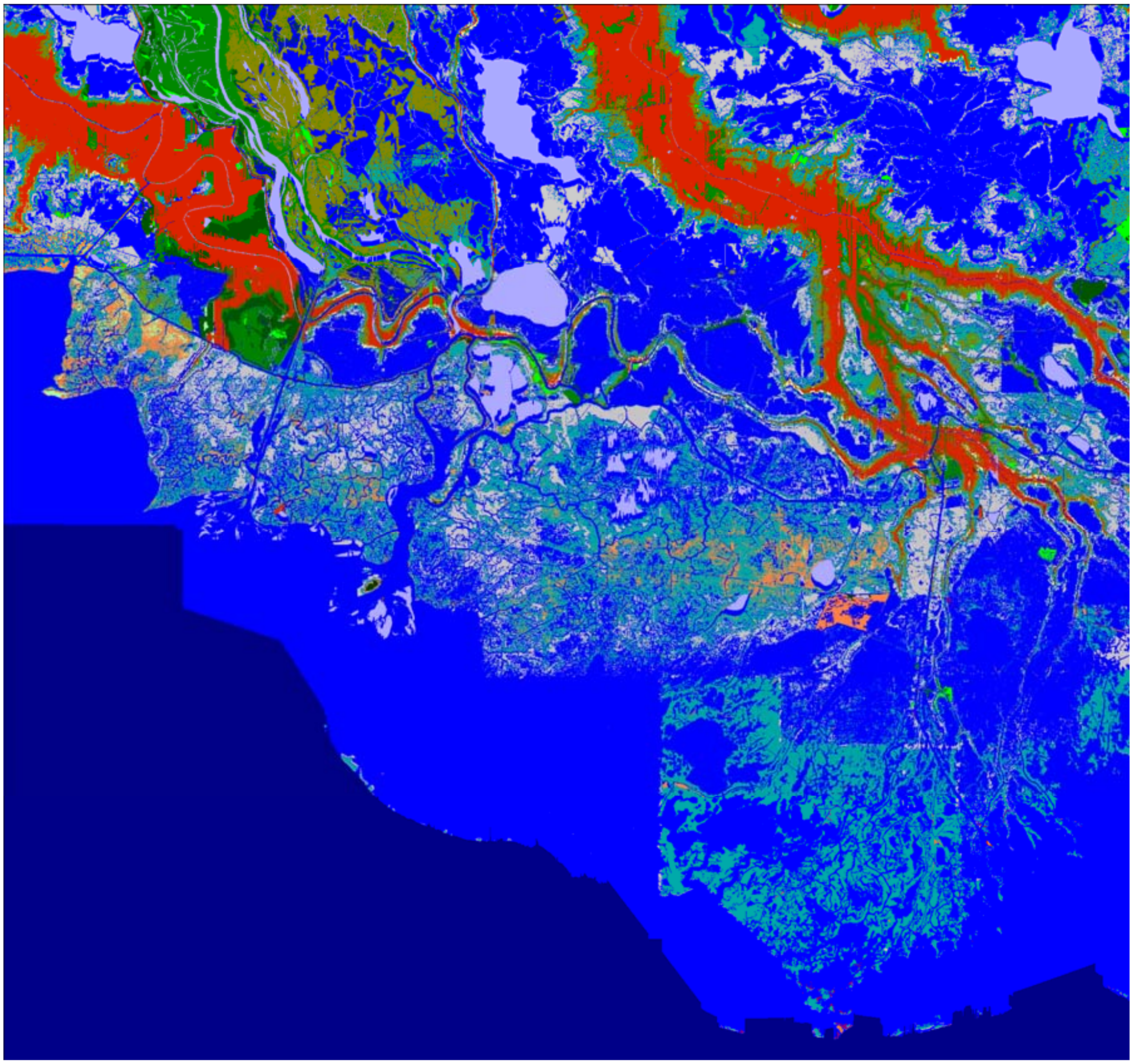
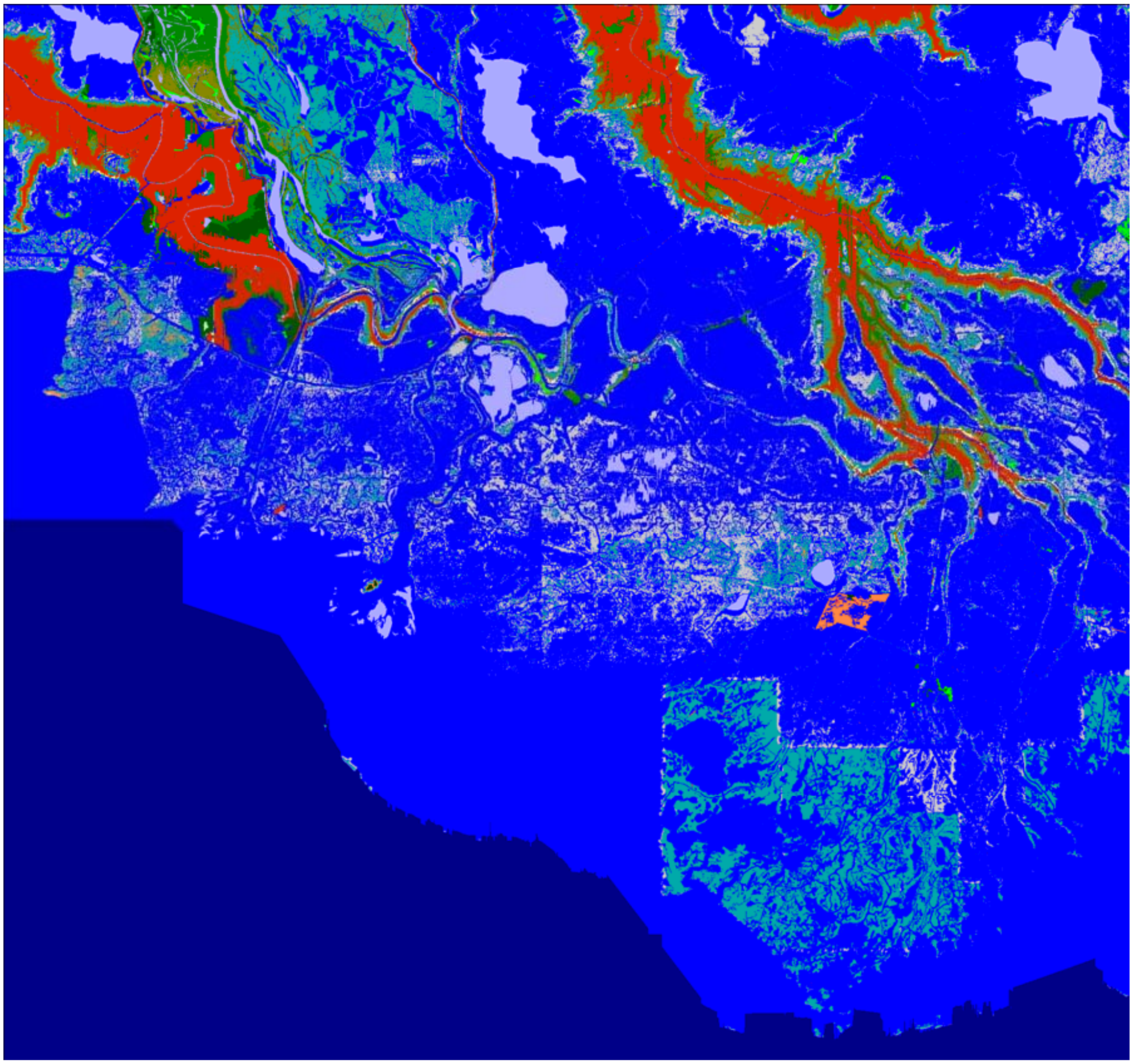
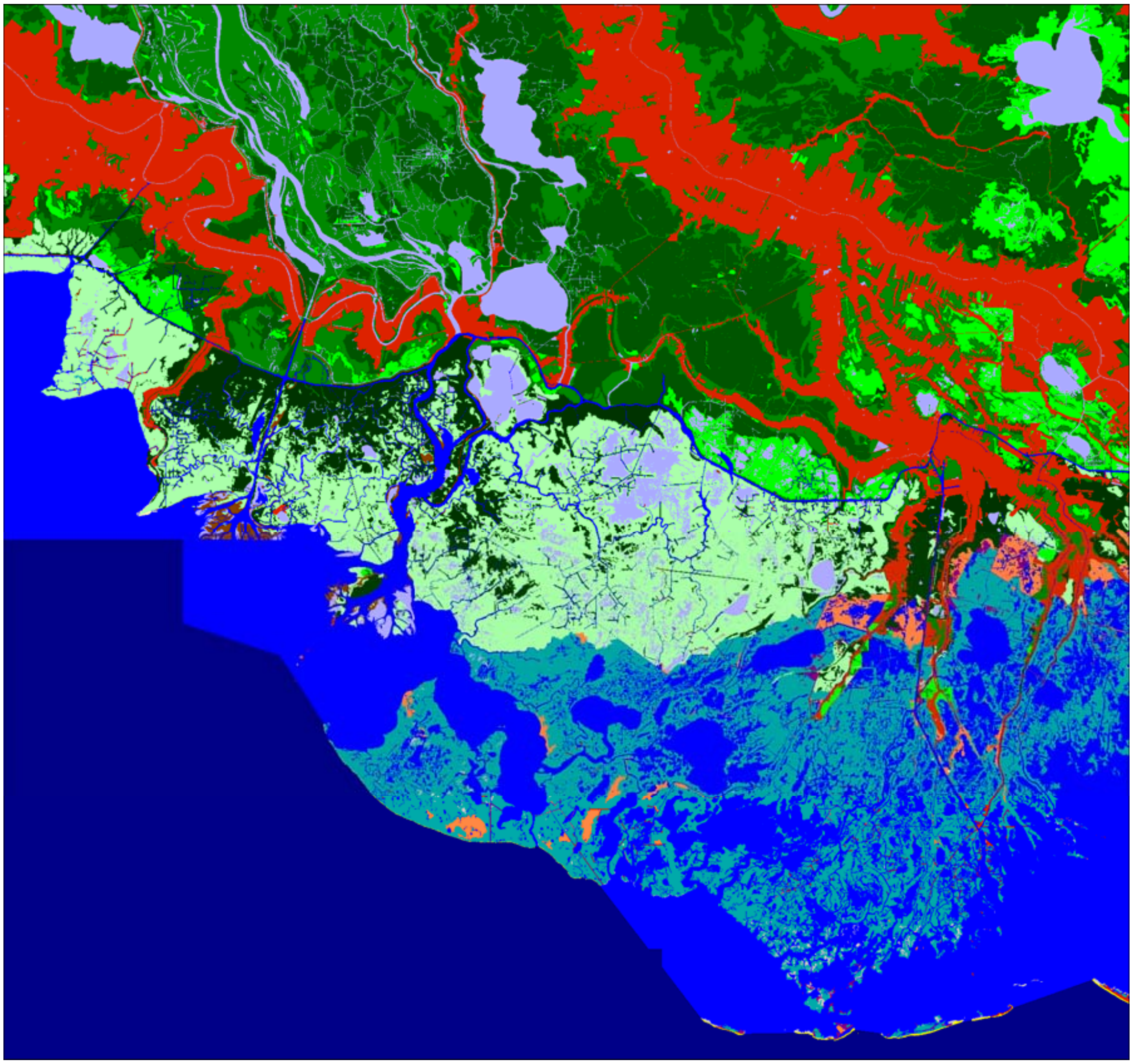


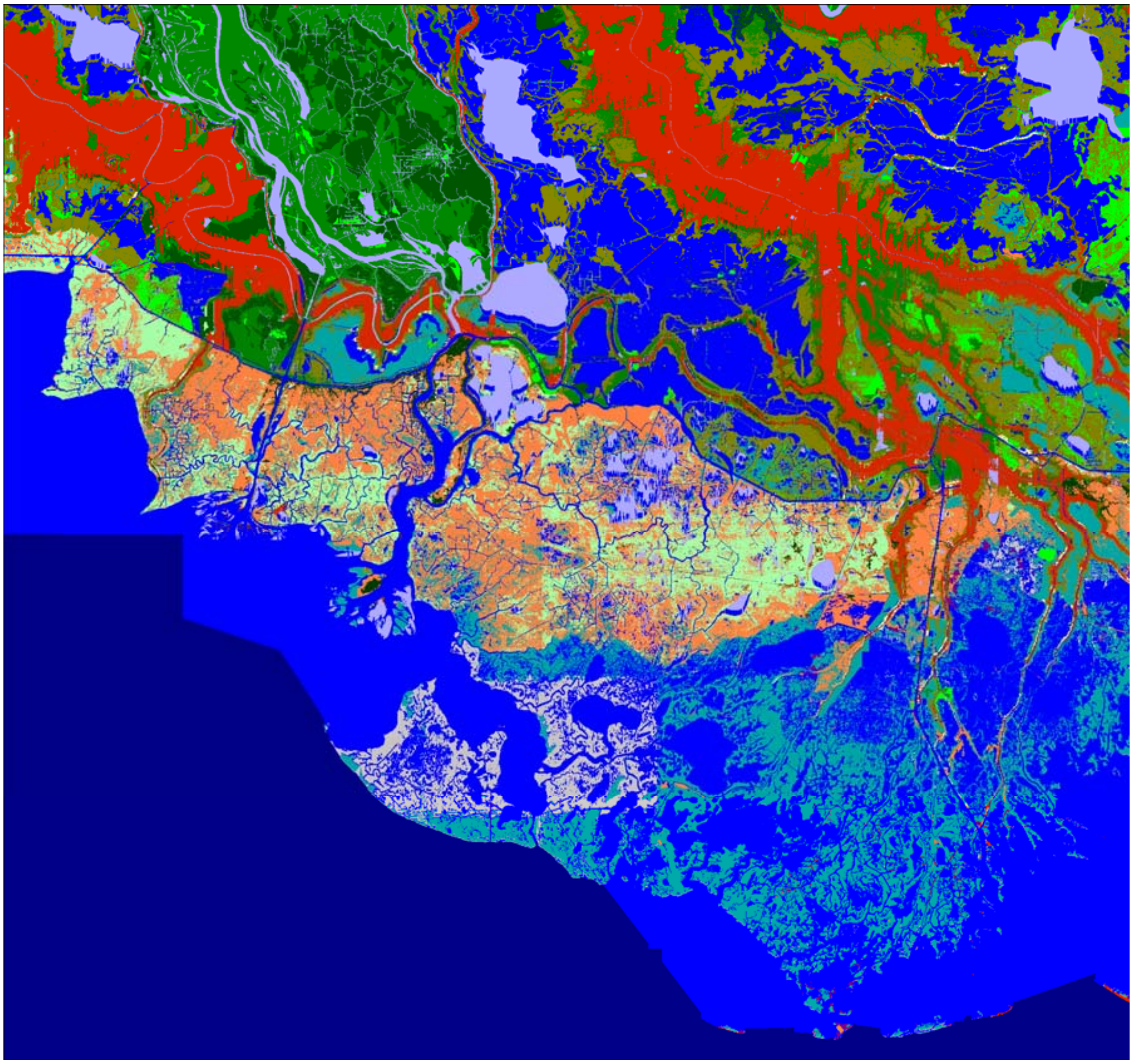
Louisiana 2075, 1 meter Eustatic by 2100



Louisiana 2100, 1 meter Eustatic by 2100



Louisiana Initial Condition



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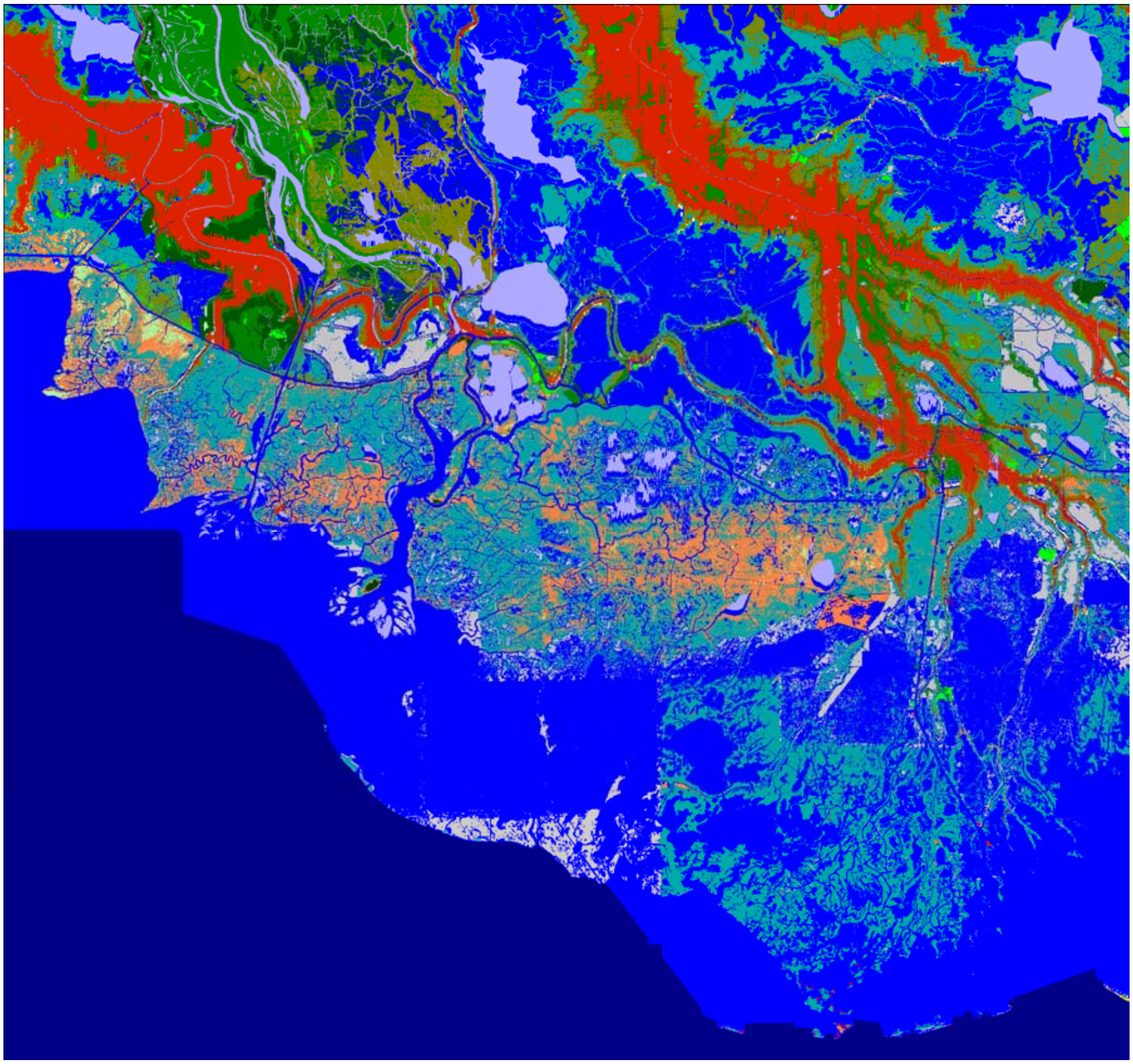

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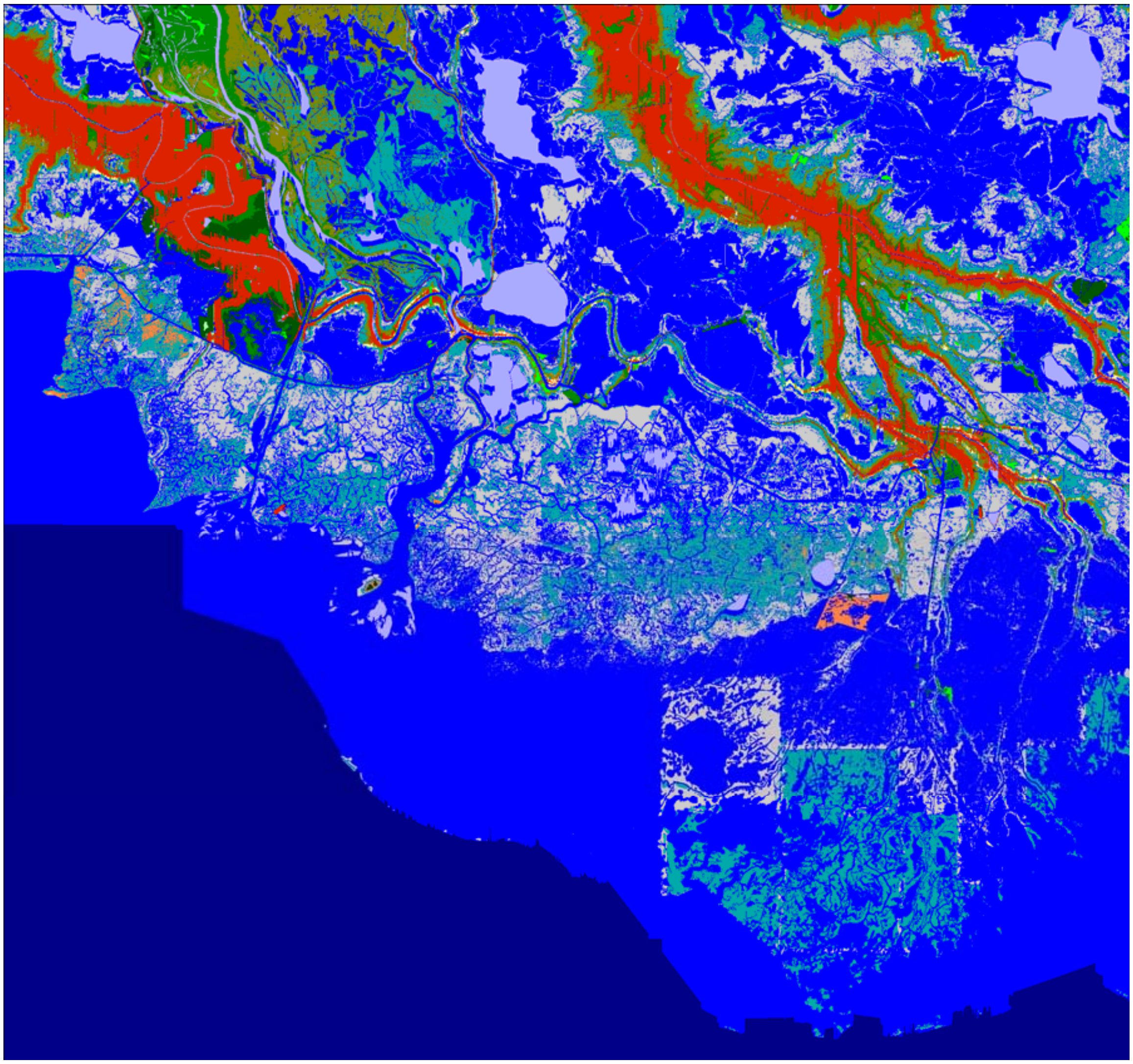

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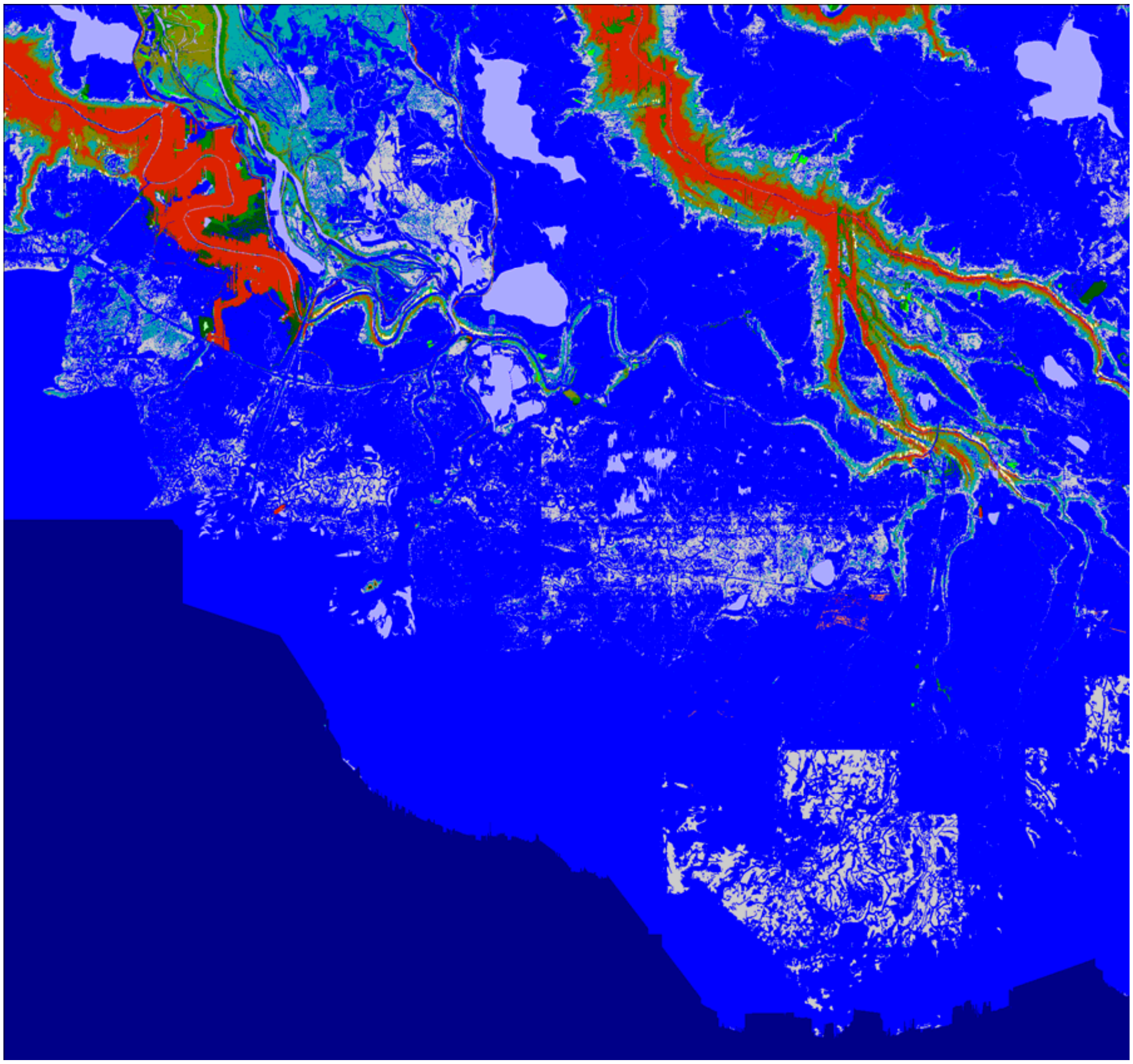

Louisiana 2100, 1.5 meter Eustatic by 2100