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

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

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warren pinnacle consulting, inc.

PO Box 315, Waitsfield VT, 05673
(802)-496-3476

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Introduction

Tidal marshes are among the most susceptible ecosystems to climate change, especially accelerated sea-level rise (SLR). The 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 pending peer review).

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).

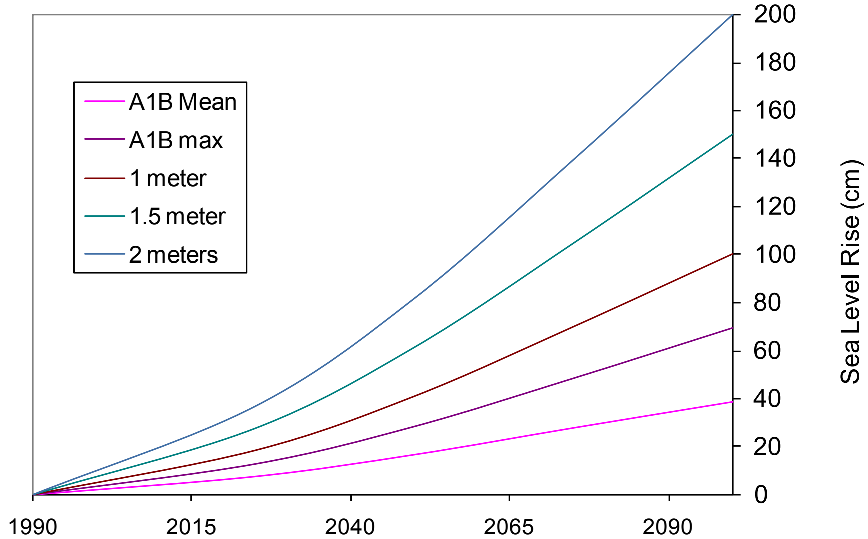

Figure 1. Summary of SLR scenarios utilized

Methods and Data Sources

This study of Breton 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).

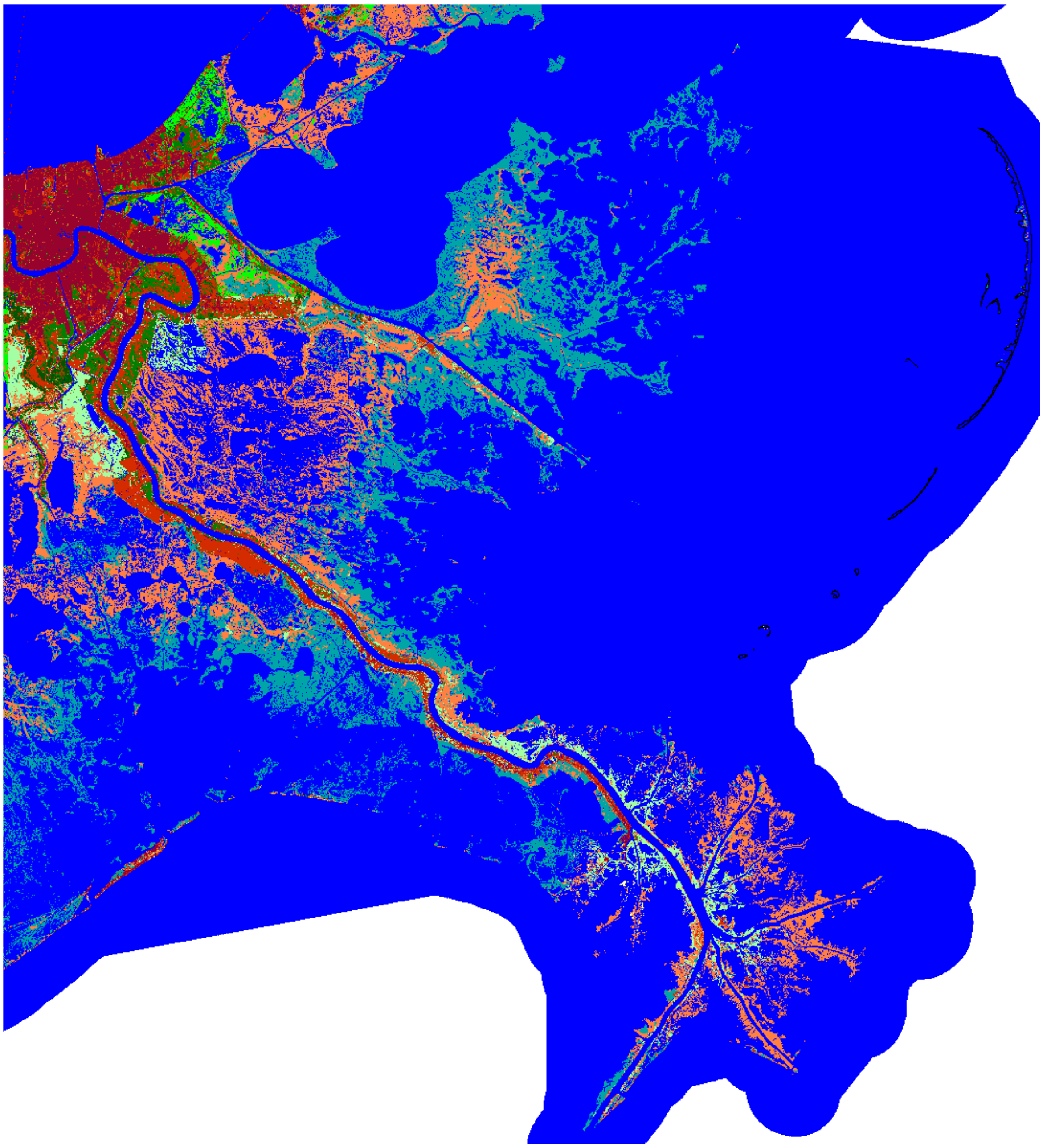

Figure 2. Portion of southeastern Louisiana study area with Breton NWR boundary shown in black

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, 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 7,542 acre refuge (approved acquisition boundary including water) is composed of the following categories:

	Land cover type	Area (acres)	Percentage (%)
	Estuarine Open Water	7,020	93
	Regularly Flooded Marsh	293	4
	Irregularly Flooded Marsh	203	3
	Undeveloped Dry Land	19	< 1
	Estuarine Beach	3	< 1
	Tidal Fresh Marsh	2	< 1
	Inland Fresh Marsh	1	< 1
	Total (incl. water)	**7,542**	**100**

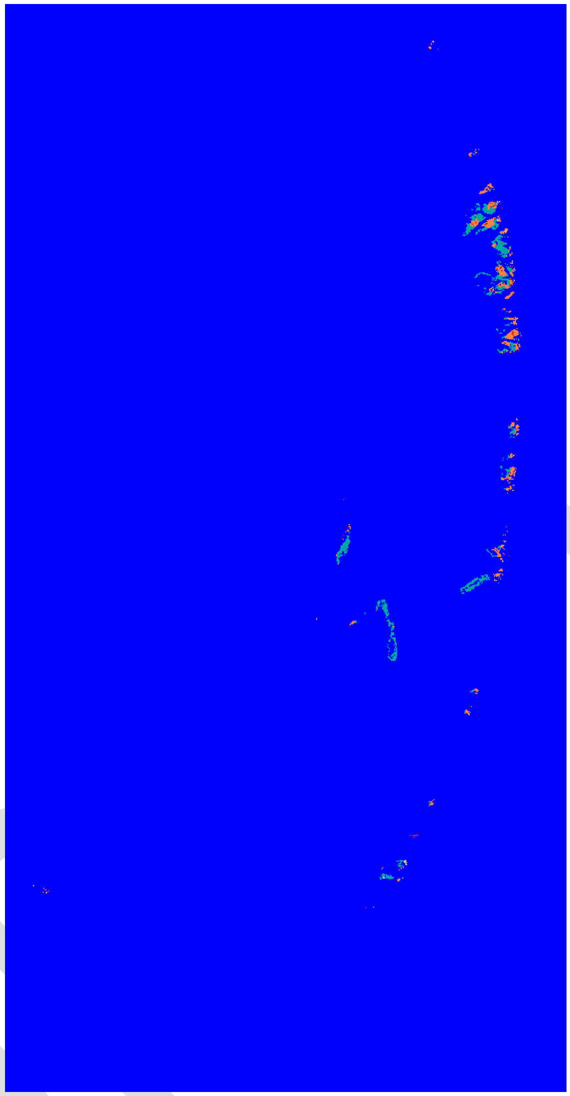

Figure 3. 2004 NWI data layer used for Breton NWR

According to the National Wetland Inventory, there are no diked areas within Breton NWR.

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." Kriging is a method of interpolation that predicts unknown values from data observed at known locations (Lang 2000). The final raster obtained for the Breton NWR area is shown in Figure 4.

[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.

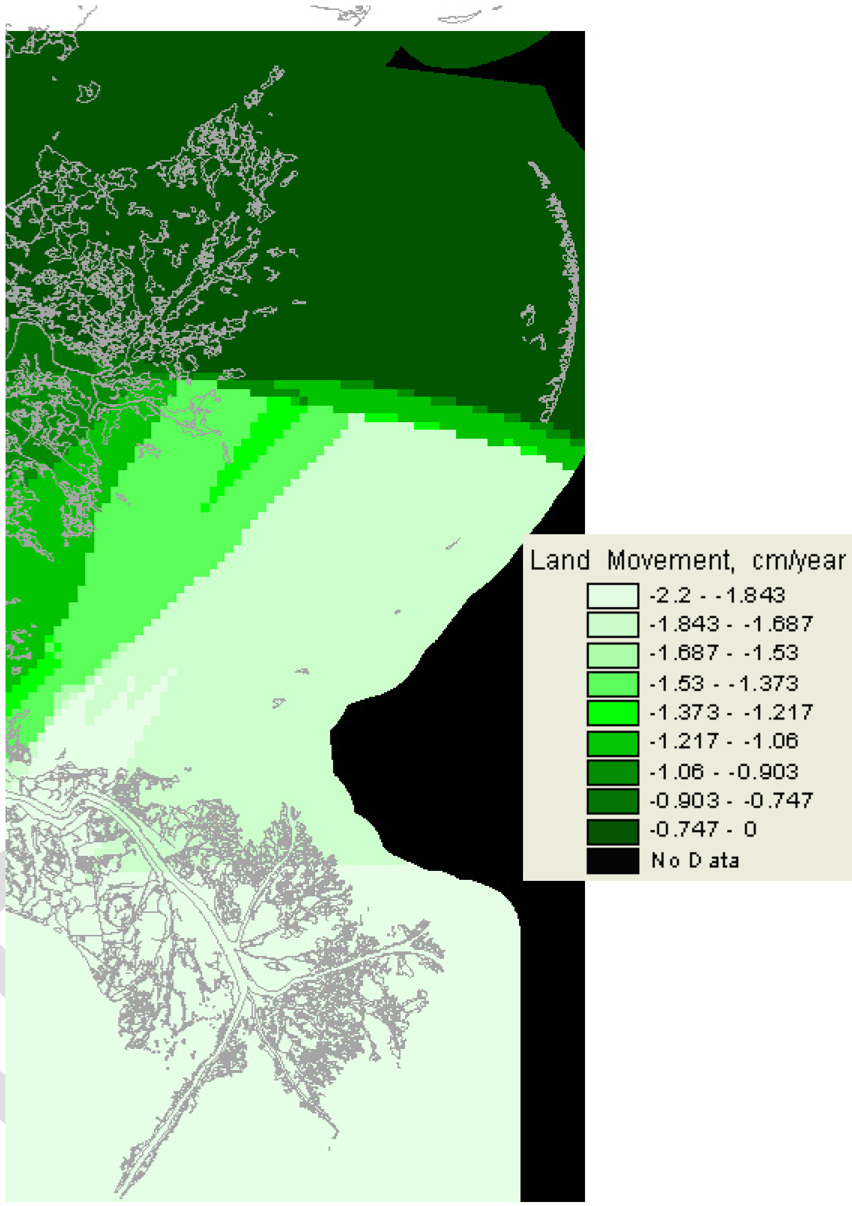

Figure 4. Kriged Subsidence raster from Shinkle and Dokka and long term NOAA tide gauge data

The great diurnal tide range at this site was estimated at 0.45 m using local water level data. This value was determined by averaging the tidal data at the closest NOAA tide prediction values of 0.42 m and 0.49 m shown in Figure 5.

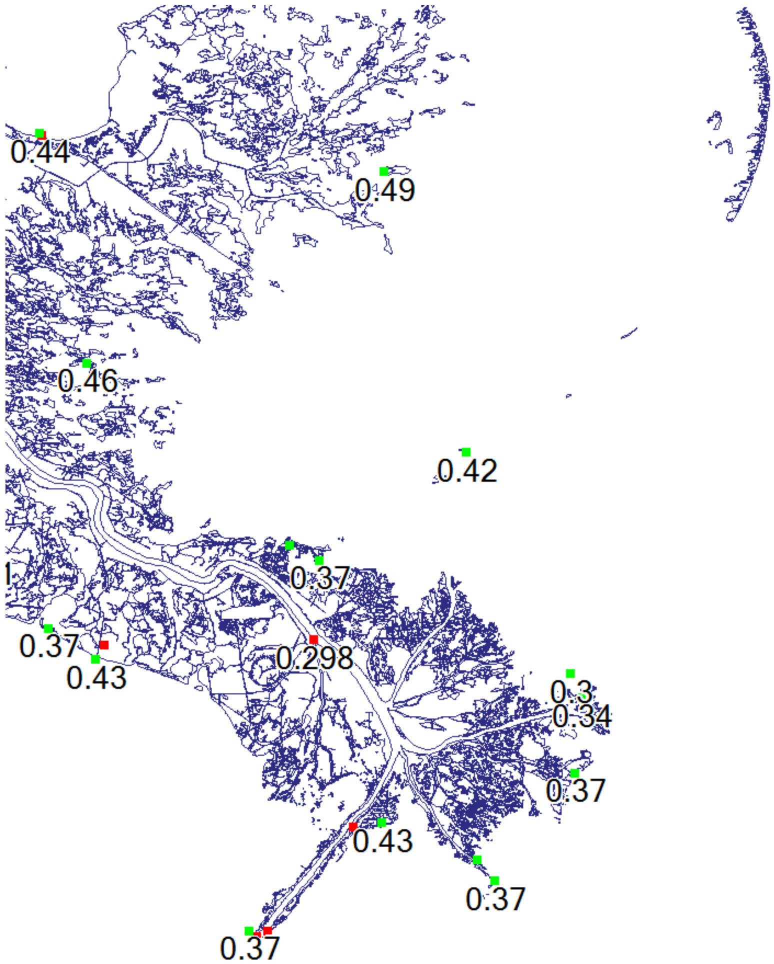

Figure 5. Diurnal tide range values (in meters) for southeastern Louisiana

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 Breton NWR, the salt elevation was designated ad 0.38 m above MTL.

Accretion data for coastal Louisiana were collected from several studies published in peer-reviewed journals (Bryant and Chabreck 1998; Cahoon and Turner 1989; Nyman et al. 1993; Nyman et al. 1990; Nyman et al. 2006). A total of 40 averaged accretion rates were combined to determine the accretion value used in the Louisiana SLAMM model. Each of these data points were based on several cores. The average accretion value for coastal Louisiana SLAMM modeling project was determined to be approximately 8.2 mm/year.

Table 1. Estimate of Site-Specific Accretion Rates from Literature Survey

Marsh Type	Average Accretion, mm/year	Samples
brackish	8.53	21
brackish/saline	9.60	155
fresh	8.03	61
intermediate	6.40	3
saline	9.43	290
unspecified	6.10	474
Grand Total	**8.16**	**1004**

For comparison, the average elevation change calculated from data in the Coastwide Reference Monitoring System (CRMS) database was 8.63 mm/year. From this extensive array of SET tables placed throughout the study area, short term accretion rates were measured. However, this data set had considerable variability (ranging from negative 114 mm/year to positive 60 mm/year). Table 1 shows the accretion rates in the CRMSs data. Analysis of this data set revealed a statistically significant relationship between accretion rates and cell elevations (with accretion rates tending to be higher in areas of lower elevation).

The final model calibration resulted in a maximum accretion rate of 11 mm/yr at the low elevation range and a minimum accretion rate of 6 mm/yr at the top of the tidal frame for each tidal marsh category. This simple relationship between accretion and marsh elevation is illustrated in Figure 6.

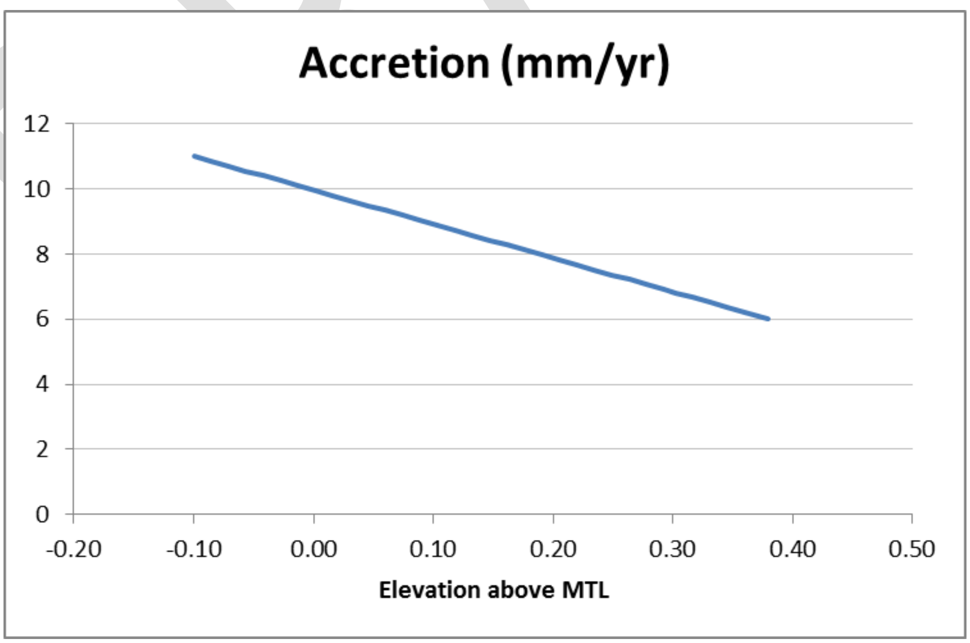

Figure 6. Relationship between predicted accretion rates and elevation used for regularly-flooded marsh

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 Breton NWR study was 0.3 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 2. Summary of SLAMM input parameters for Breton NWR

Subsite Name	SubSite 10
NWI Photo Date (YYYY) Forecast	2007
DEM Date (YYYY)	2009
Direction Offshore [n,s,e,w]	East
MTL-NAVD88 (m)	0.3
GT Great Diurnal Tide Range (m)	0.45
Salt Elev. (m above MTL)	0.38
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 Breton NWR was completed using a SLAMM model that was calibrated to historical data for a project funded by the National Wildlife Federation. This calibrated model predicts that Breton NWR will be severely impacted for all SLR scenarios and wetland types. Table 3 presents the predicted loss of each wetland category by 2100 for each of the five SLR scenarios examined.

A lack of elevation data for parts of the refuge leads to uncertainty in the model results[2]. 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 scenarios of approximately 1.5 m of SLR by 2100 have the potential to completely inundate the refuge. Dry lands in this refuge were particularly subject to this "no elevation data" problem. Because of this, it is difficult to make predictions about the timing of dry-land loss as a consequence of this additional uncertainty.

Table 3. 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**
Regularly Flooded Marsh	-20	-12	-95	-100	-100
Irregularly Flooded Marsh	-20	-80	-100	-100	-100
Undeveloped Dry Land	-10	-10	-10	-10	-10
Estuarine Beach	-100	-100	-100	-100	-100
Tidal Fresh Marsh	-67	-84	-97	-97	-97

[2] Some "speckles" of no-data elevations were present in the final DEM utilized for this project; these areas were not modeled which may result in speckles of permanently resilient wetlands when zooming in very close to spatial maps of model results

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

Results in Acres

		Initial	2025	2050	2075	2100
	Estuarine Open Water	7020	7022	7061	7074	7115
	Regularly Flooded Marsh	293	269	270	239	236
	Irregularly Flooded Marsh	203	184	180	167	162
	Undeveloped Dry Land	19	17	17	17	17
	Estuarine Beach	3	2	1	0	0
	Tidal Fresh Marsh	2	2	1	1	1
	Inland Fresh Marsh	1	1	1	1	1
	Transitional Salt Marsh	0	1	0	0	0
	Tidal Flat	0	44	11	43	10
	Total (incl. water)	**7542**	**7542**	**7542**	**7542**	**7542**

Breton NWR, Initial Condition

Breton NWR, 2025, Scenario A1B Mean

Breton NWR, 2050, Scenario A1B Mean

Breton NWR, 2075, Scenario A1B Mean

Breton NWR, 2100, Scenario A1B Mean

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

Results in Acres

		Initial	2025	2050	2075	2100
	Estuarine Open Water	7020	7023	7064	7088	7167
	Regularly Flooded Marsh	293	269	269	247	258
	Irregularly Flooded Marsh	203	184	180	141	41
	Undeveloped Dry Land	19	17	17	17	17
	Estuarine Beach	3	1	0	0	0
	Tidal Fresh Marsh	2	2	1	1	0
	Inland Fresh Marsh	1	1	1	1	1
	Transitional Salt Marsh	0	1	0	0	0
	Tidal Flat	0	44	9	47	57
	Total (incl. water)	**7542**	**7542**	**7542**	**7542**	**7542**

Breton NWR, Initial Condition

Breton NWR, 2025, Scenario A1B Maximum

Breton NWR, 2050, Scenario A1B Maximum

Breton NWR, 2075, Scenario A1B Maximum

Breton NWR, 2100, Scenario A1B Maximum

Breton NWR
1 m eustatic SLR by 2100

Results in Acres

		Initial	2025	2050	2075	2100
	Estuarine Open Water	7020	7022	7097	7219	7415
	Regularly Flooded Marsh	293	269	275	166	15
	Irregularly Flooded Marsh	203	183	121	5	0
	Undeveloped Dry Land	19	17	17	17	17
	Estuarine Beach	3	2	0	0	0
	Tidal Fresh Marsh	2	2	1	0	0
	Inland Fresh Marsh	1	1	1	1	1
	Transitional Salt Marsh	0	1	0	0	0
	Tidal Flat	0	44	29	133	93
	Total (incl. water)	**7542**	**7542**	**7542**	**7542**	**7542**

Breton NWR, Initial Condition

Breton NWR, 2025, 1 Meter

Breton NWR, 2050, 1 Meter

Breton NWR, 2075, 1 Meter

Breton NWR, 2100, 1 Meter

Breton NWR
1.5 m eustatic SLR by
2100

Results in Acres

		Initial	2025	2050	2075	2100
	Estuarine Open Water	7020	7039	7171	7408	7515
	Regularly Flooded Marsh	293	269	184	11	0
	Irregularly Flooded Marsh	203	165	12	0	0
	Undeveloped Dry Land	19	17	17	17	17
	Estuarine Beach	3	1	0	0	0
	Tidal Fresh Marsh	2	2	0	0	0
	Inland Fresh Marsh	1	1	1	1	1
	Transitional Salt Marsh	0	1	0	0	0
	Tidal Flat	0	47	156	104	8
	Total (incl. water)	**7542**	**7542**	**7542**	**7542**	**7542**

Breton NWR, Initial Condition

Breton NWR, 2025, 1.5 Meters

Breton NWR, 2050, 1.5 Meters

Breton NWR, 2075, 1.5 Meters

Breton NWR, 2100, 1.5 Meters

Breton NWR
2 m eustatic SLR by 2100

Results in Acres

		Initial	2025	2050	2075	2100
	Estuarine Open Water	7020	7063	7229	7452	7523
	Regularly Flooded Marsh	293	271	132	0	0
	Irregularly Flooded Marsh	203	128	1	0	0
	Undeveloped Dry Land	19	17	17	17	17
	Estuarine Beach	3	1	0	0	0
	Tidal Fresh Marsh	2	2	0	0	0
	Inland Fresh Marsh	1	1	1	1	1
	Transitional Salt Marsh	0	1	0	0	0
	Tidal Flat	0	58	162	71	1
	Total (incl. water)	**7542**	**7542**	**7542**	**7542**	**7542**

Breton NWR, Initial Condition

Breton NWR, 2025, 2 Meters

Breton NWR, 2050, 2 Meters

Breton NWR, 2075, 2 Meters

Breton NWR, 2100, 2 Meters

Discussion

Model results for Breton NWR indicate that it is very vulnerable to sea level rise. When rates of sea-level rise exceed measured accretion rates in this region, marshes are predicted to sustain considerable losses.

A lack of elevation data for parts of the refuge leads to 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. This was especially true for the small quantity of dry lands at this refuge. Therefore, it may be assumed that scenarios of approximately 1.5 m of SLR by 2100 have the potential to completely inundate the refuge.

The Chandeleur Islands that comprise Breton NWR are sensitive to change due to storm events. In this application of SLAMM, the effects of the barrier-island overwash model were applied once every 30 years to islands less than 500 m wide. However, there is uncertainty in the application of this module of the model due to missing elevation data as well as the frequency and magnitude of storm events.

Some of the area surrounding Breton NWR was studied in a previous SLAMM analysis funded by The Nature Conservancy (Glick et al. 2011). Maps of results for the larger study area are presented in the "contextual maps" below.

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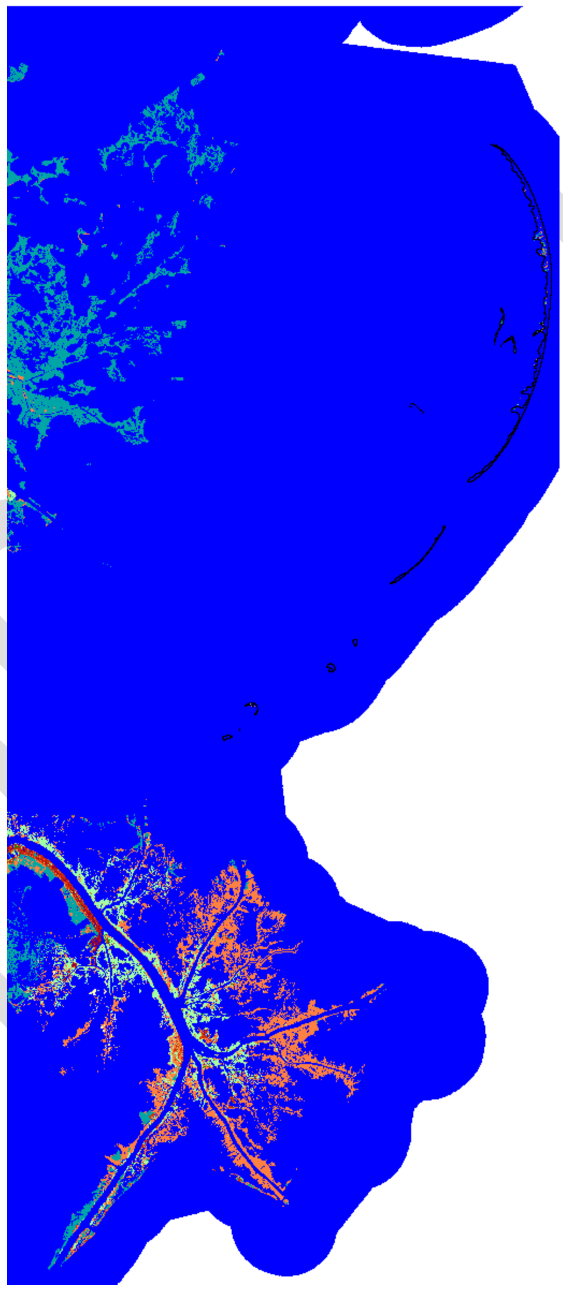
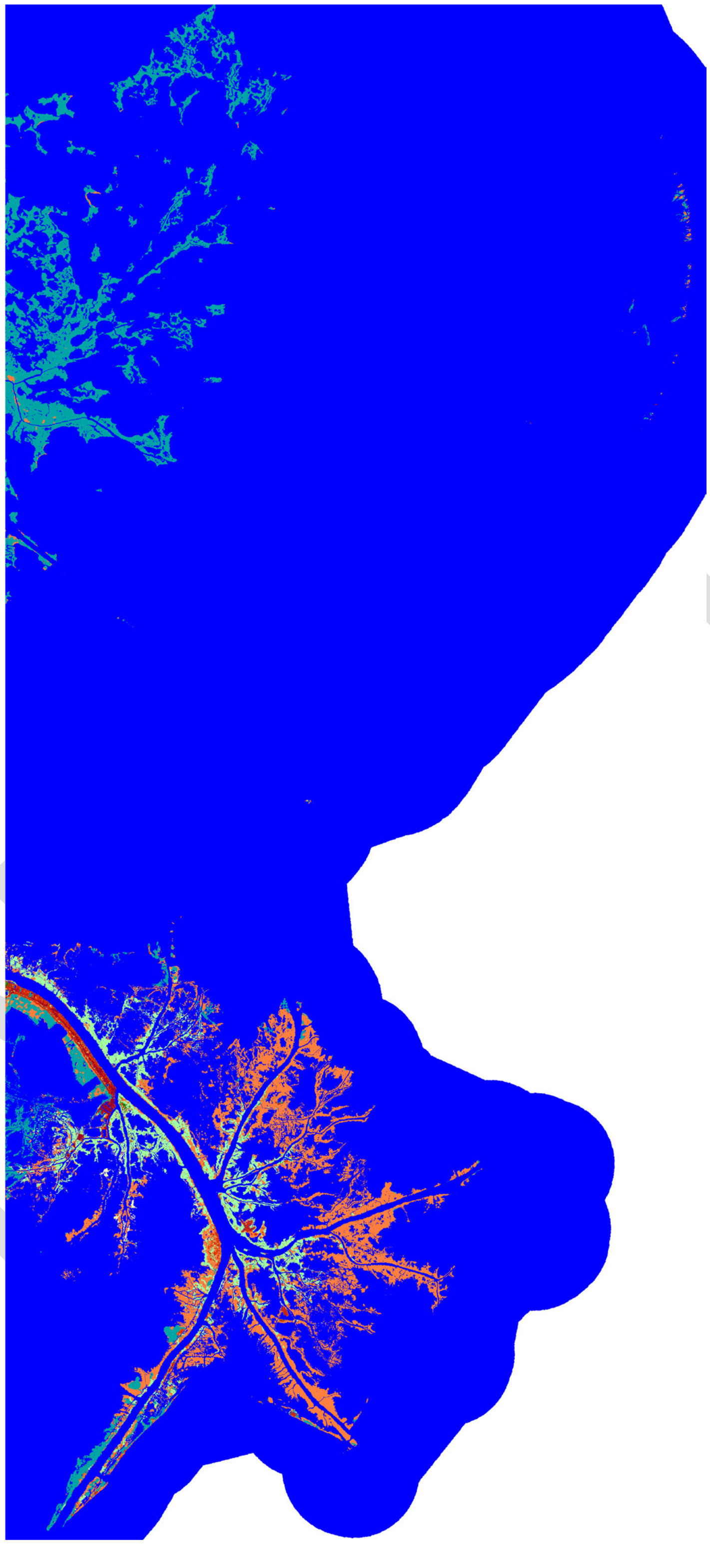
Appendix A: Contextual Results

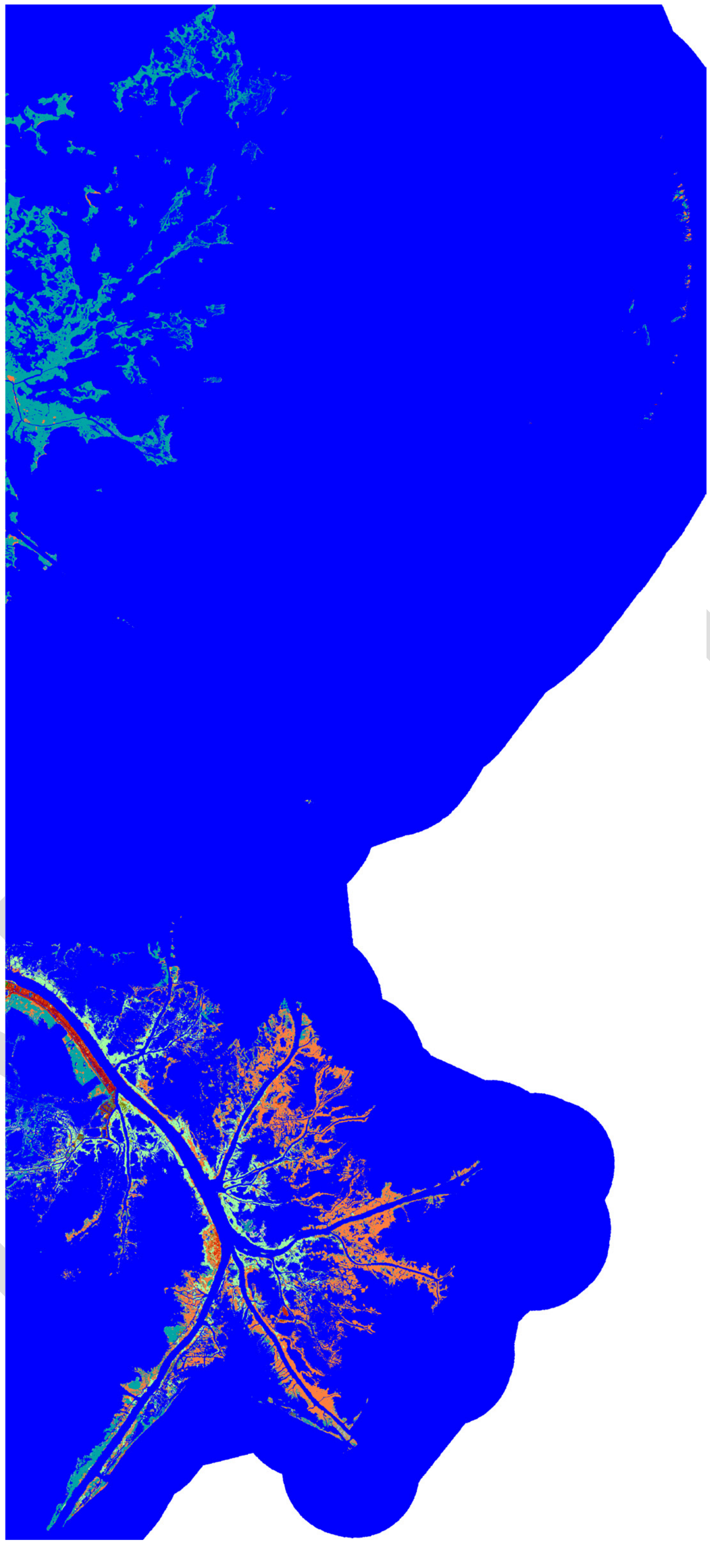
The SLAMM model does take into account the context of the surrounding lands or open water when calculating effects. For example, erosion rates are calculated based on the maximum fetch (wave action) which is estimated by assessing contiguous open water to a given marsh cell. Another example is that inundated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



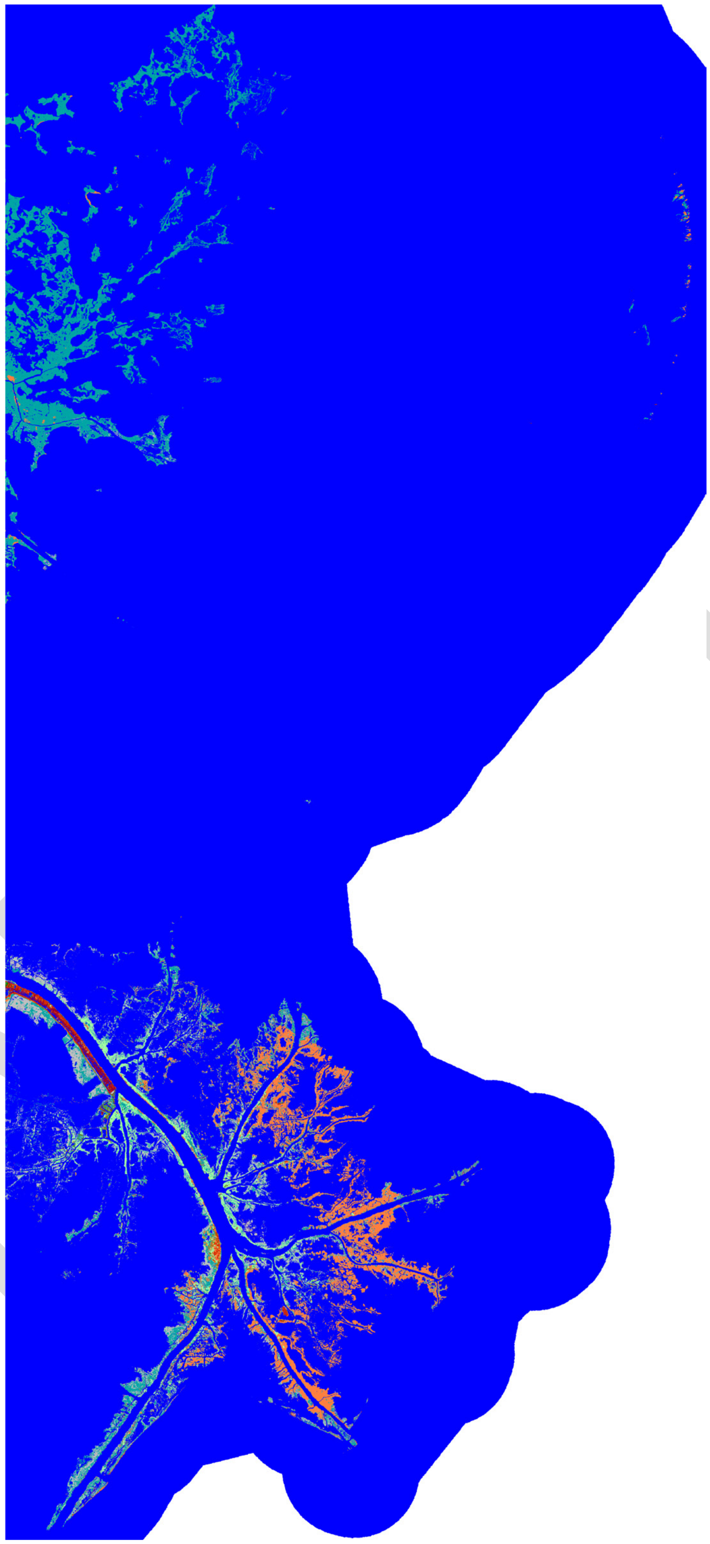
Breton National Wildlife Refuge (outlined in black) within simulation context



Breton Context, Initial Condition



Breton Context, 2025, Scenario A1B Mean



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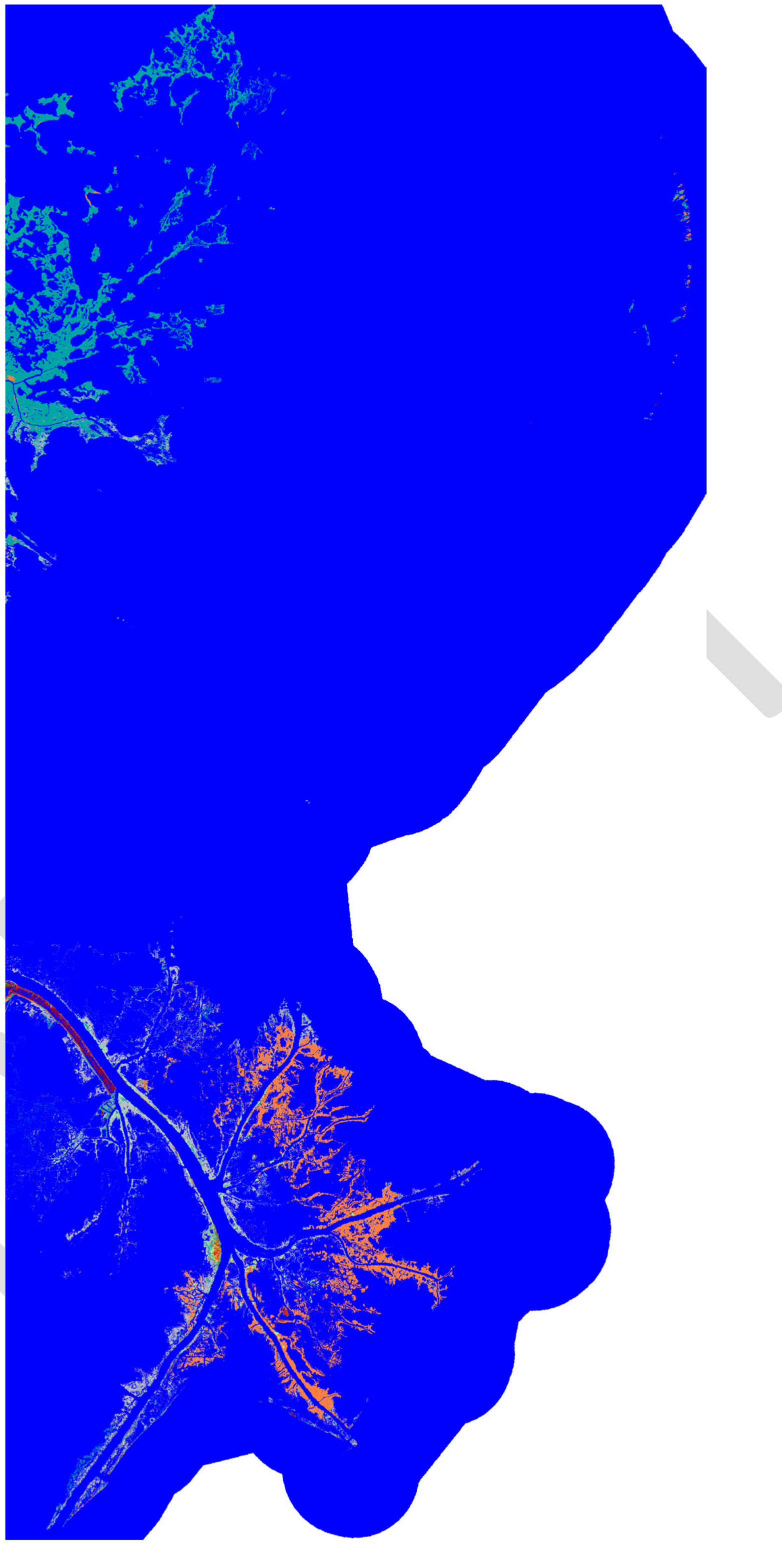
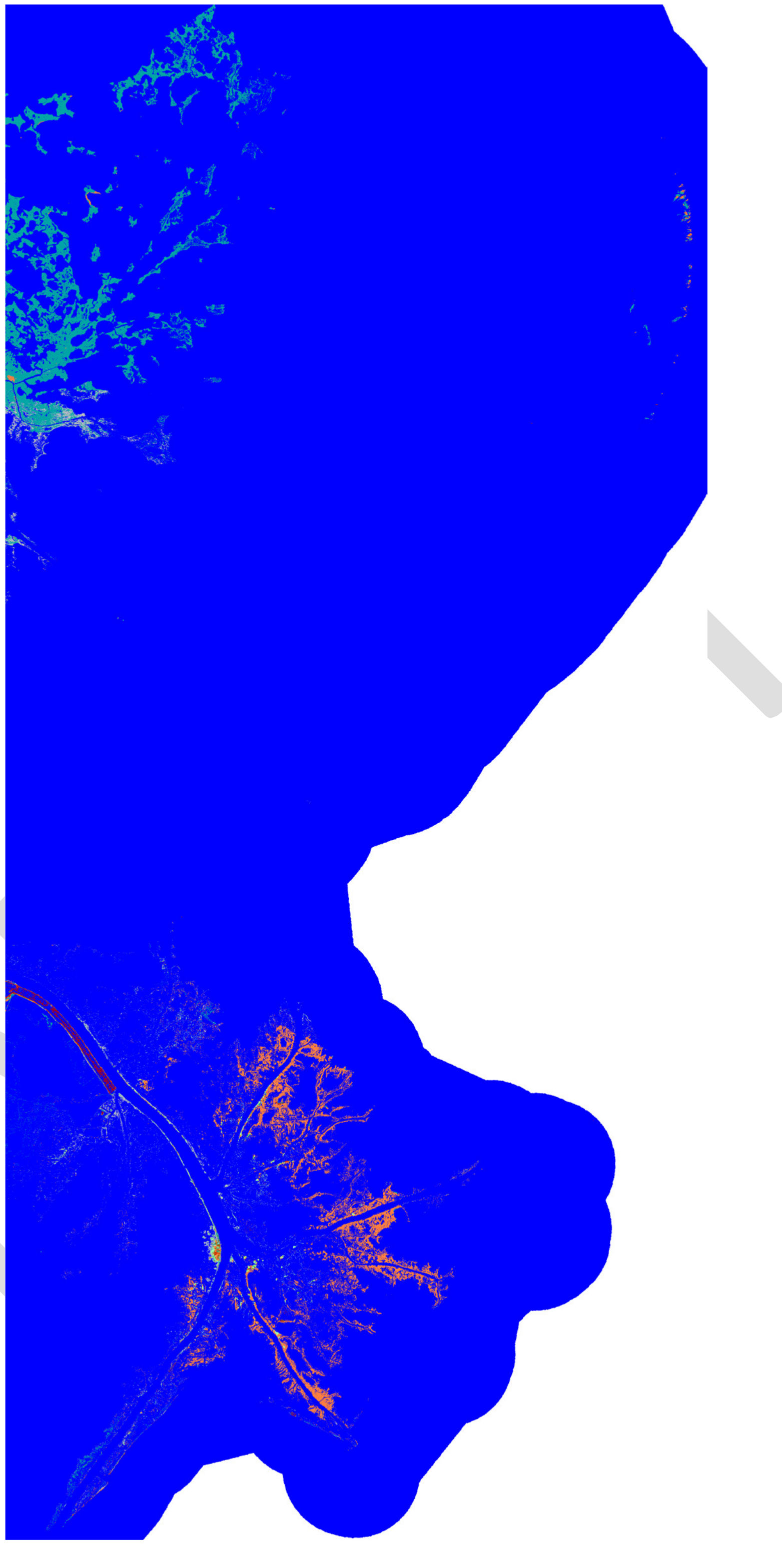
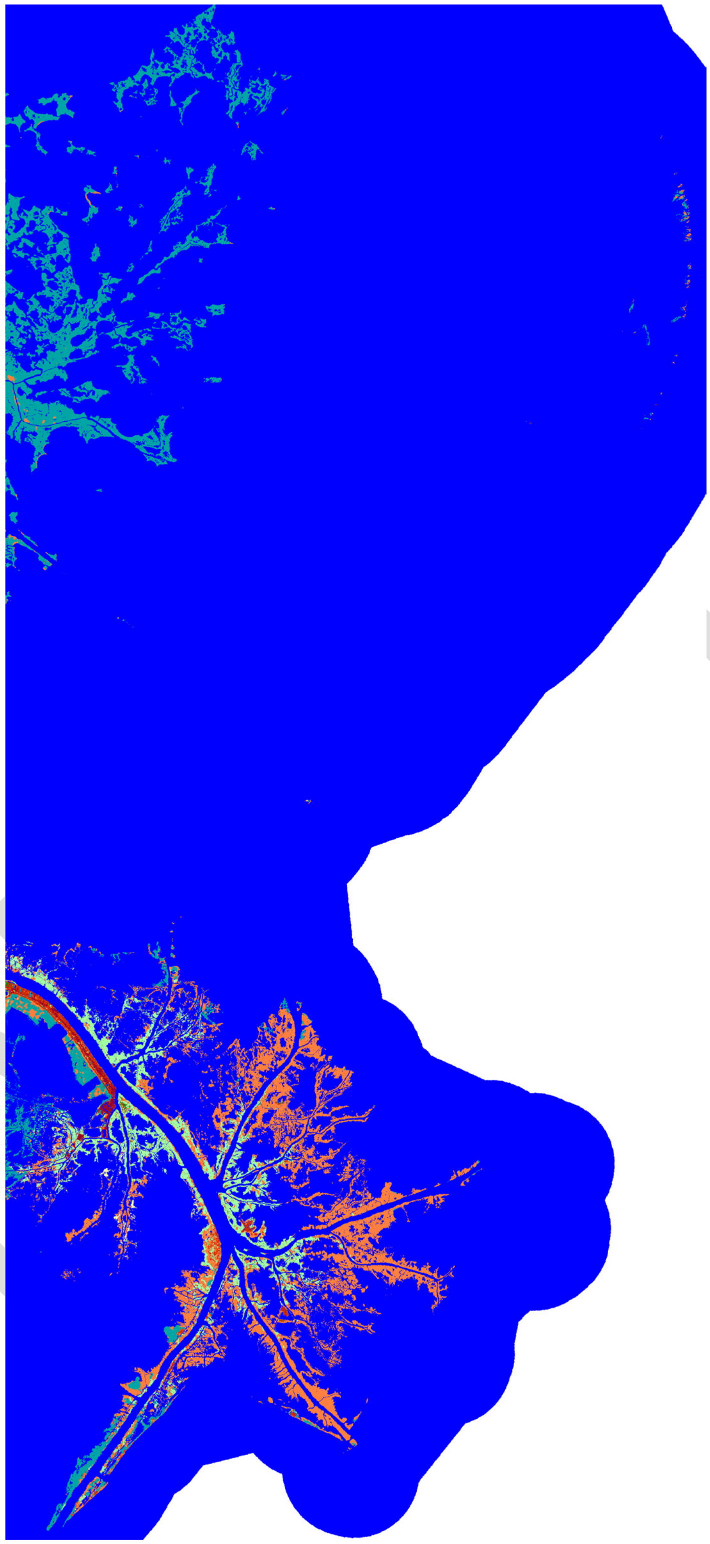
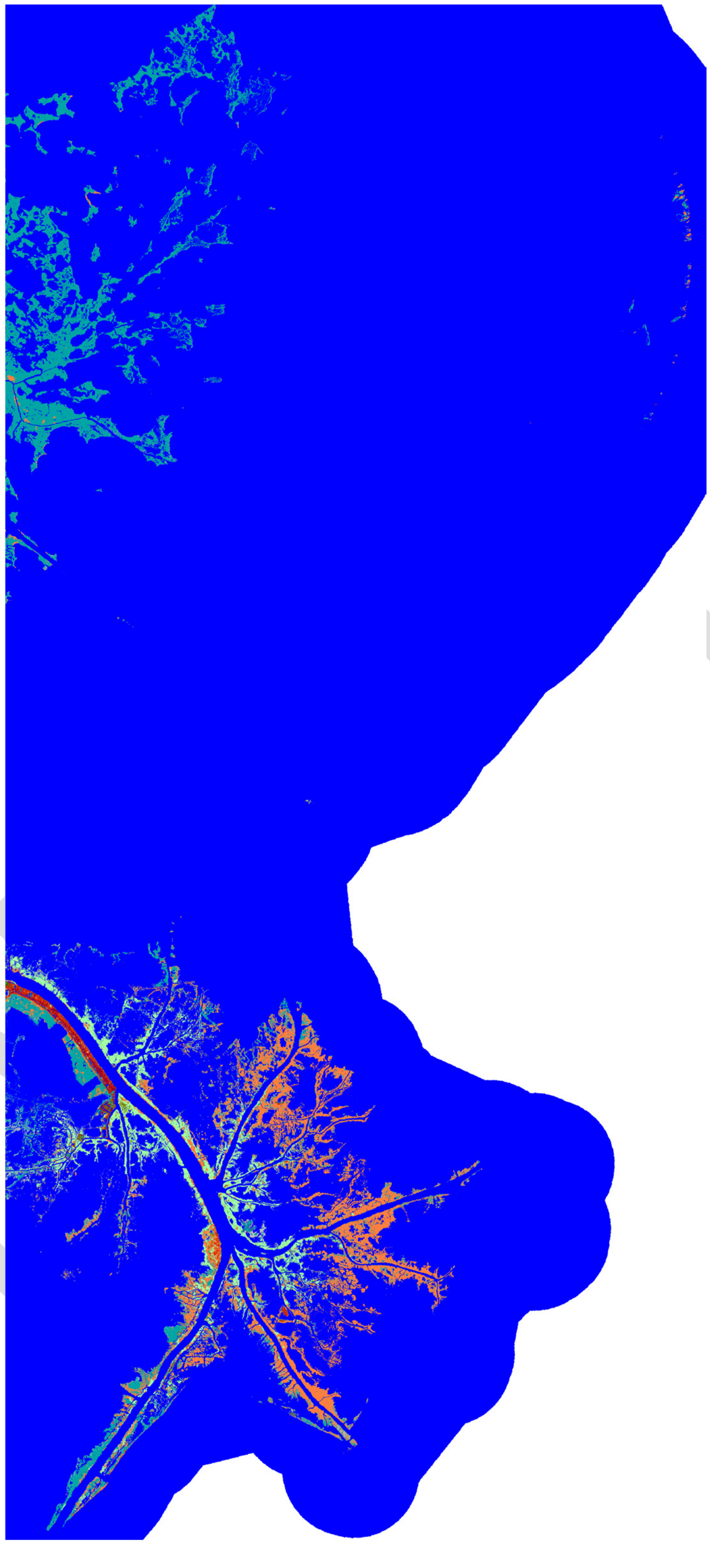


Breton Context, 2075, Scenario A1B Mean

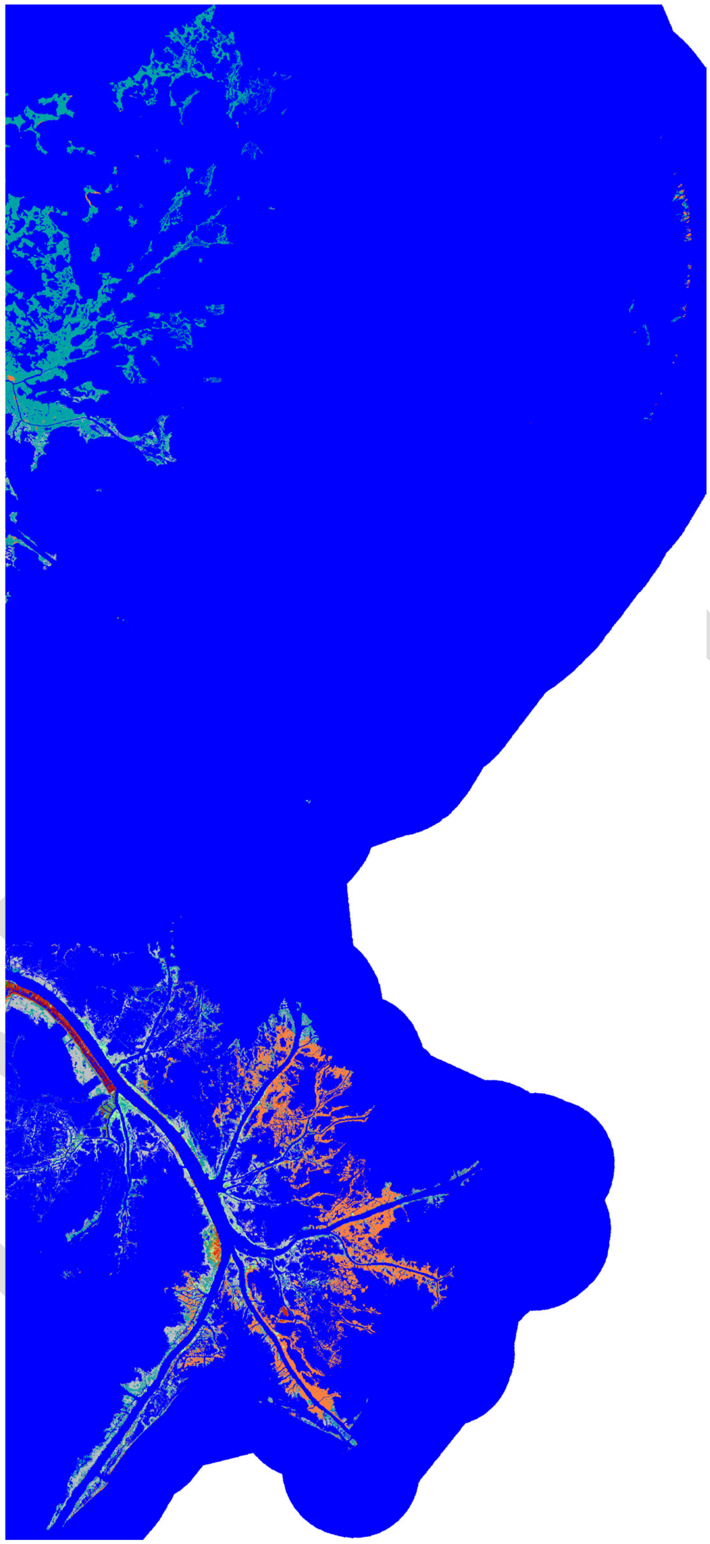

Breton Context, 2100, Scenario A1B Mean



Breton Context, Initial Condition



Breton Context, 2025, Scenario A1B Maximum



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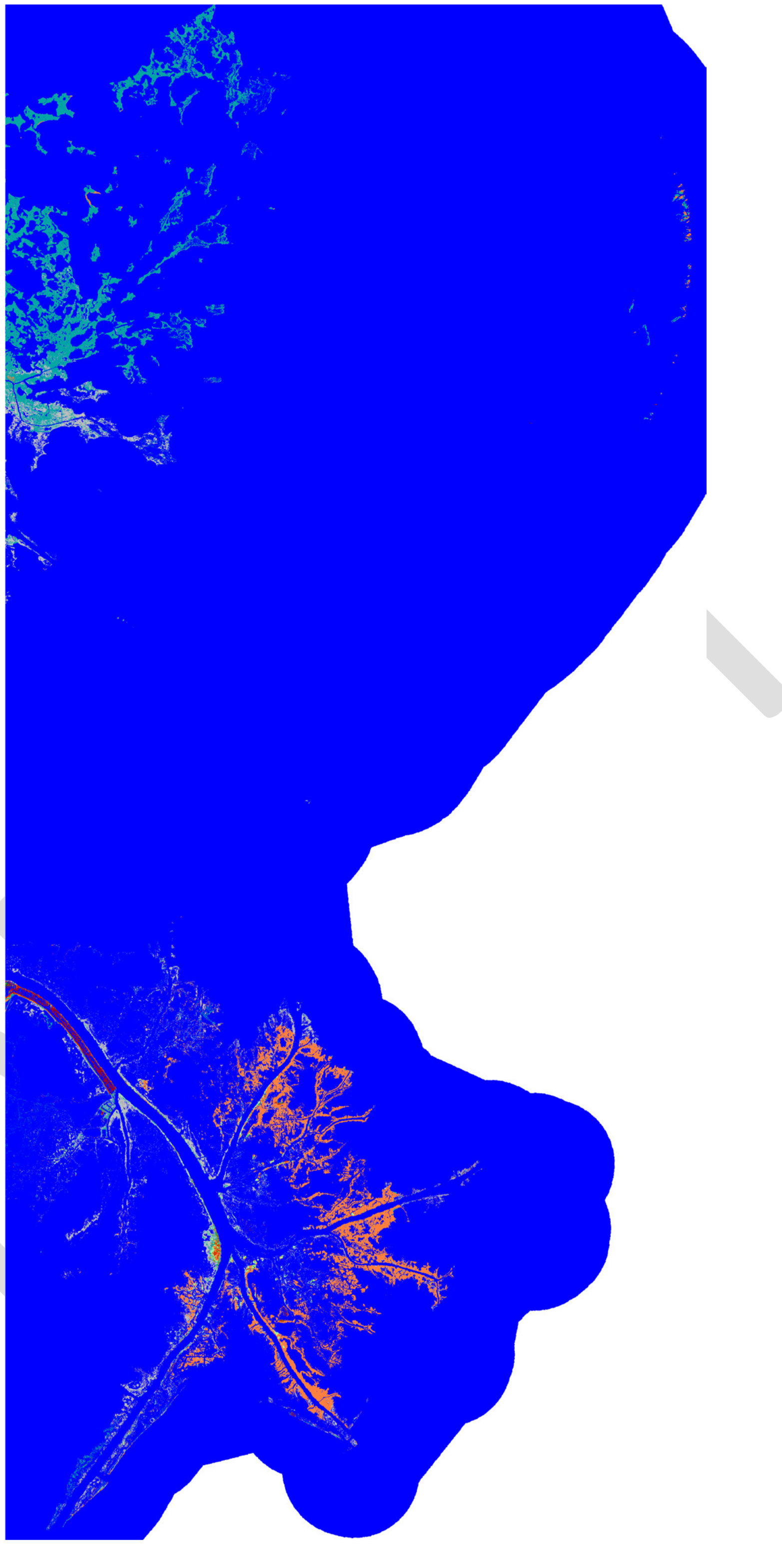
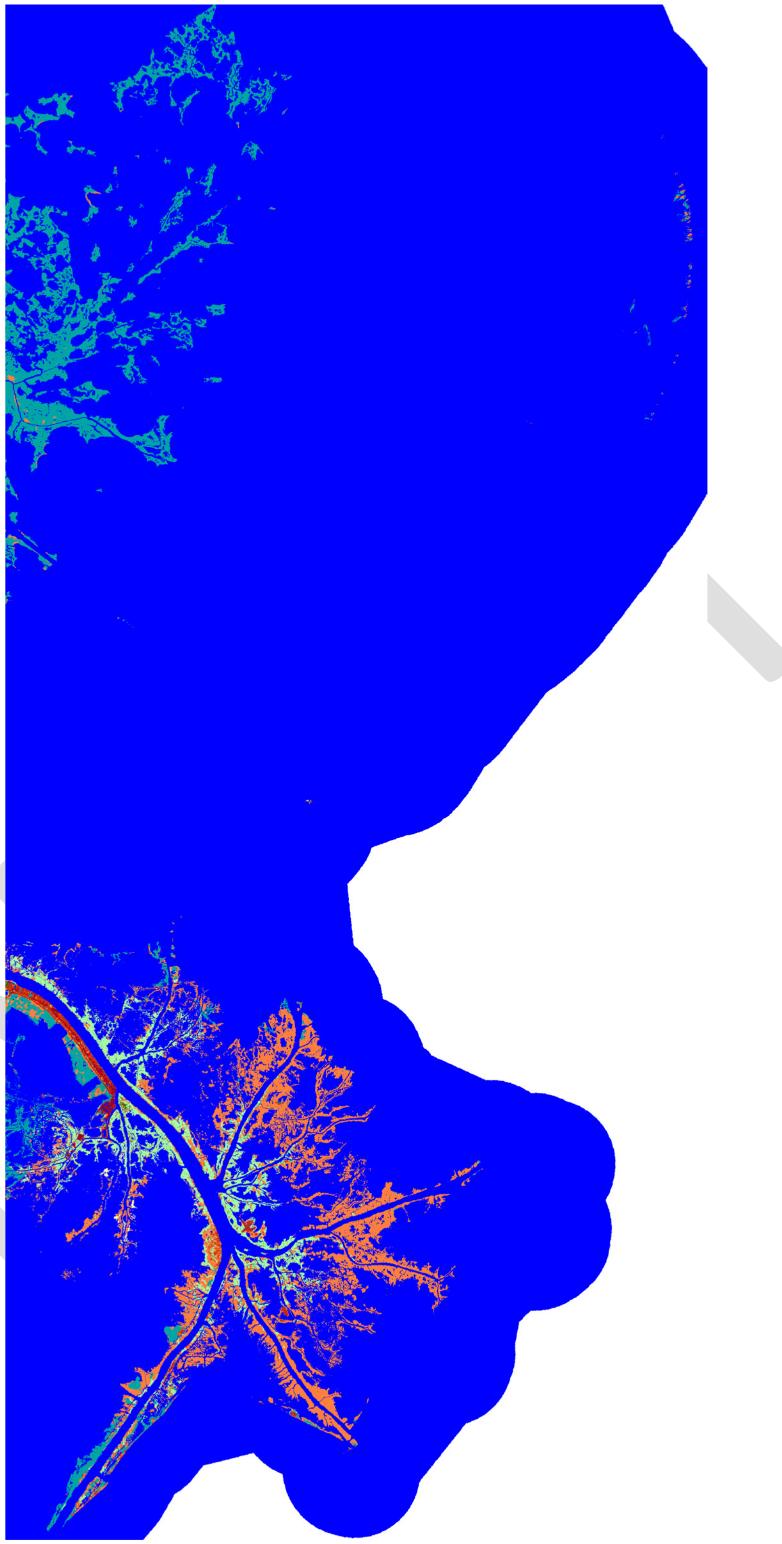
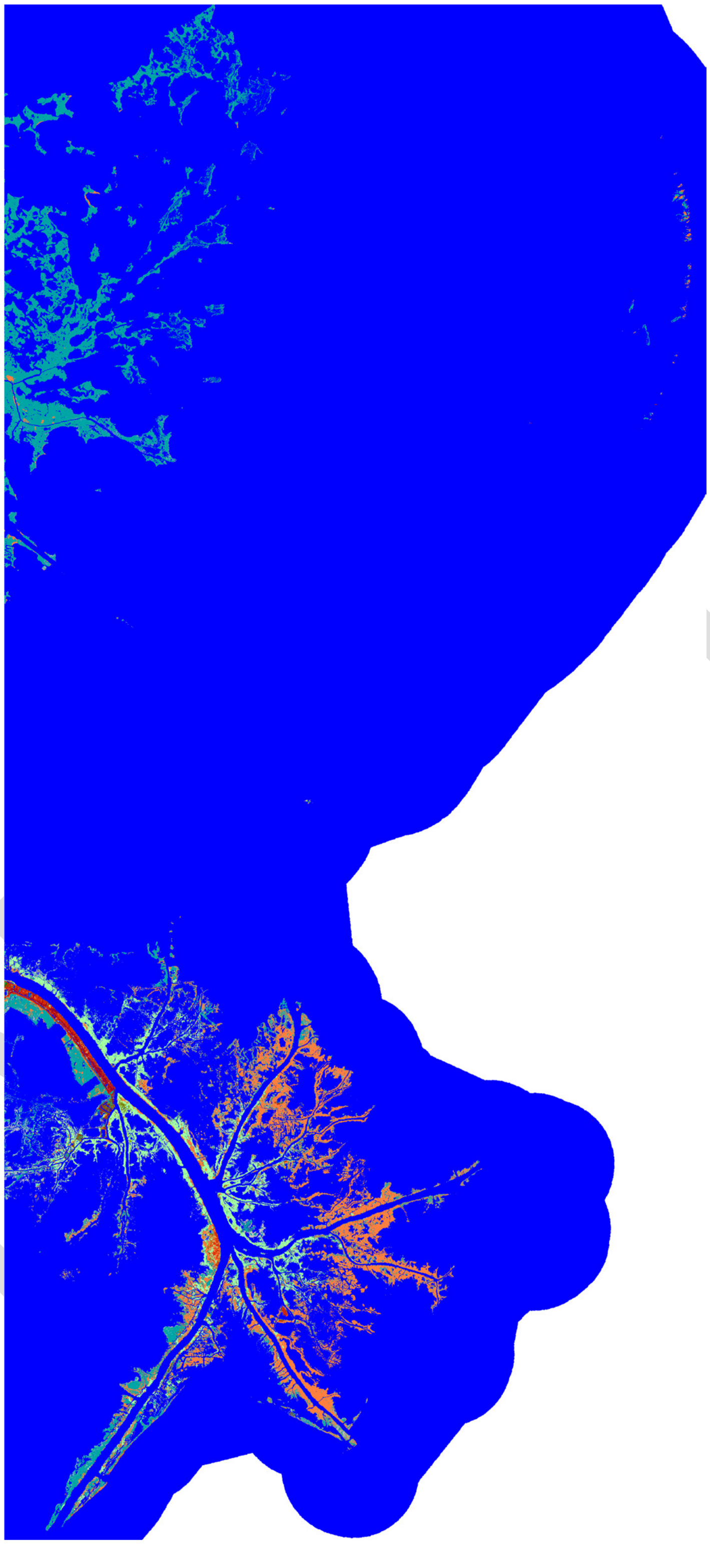


Breton Context, 2075, Scenario A1B Maximum

Breton Context, 2100, Scenario A1B Maximum



Breton Context, Initial Condition

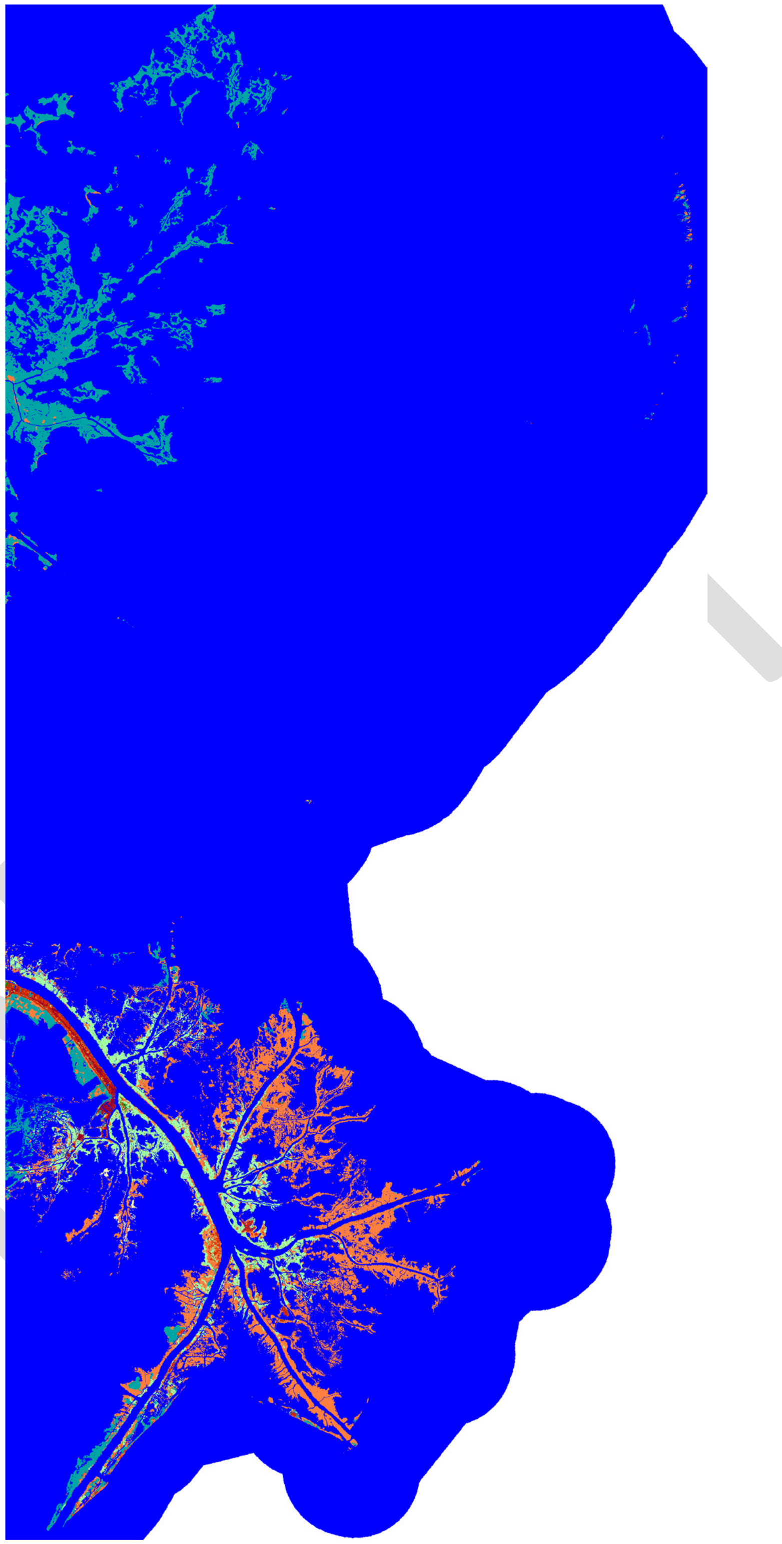


Breton Context, 2025, 1 m

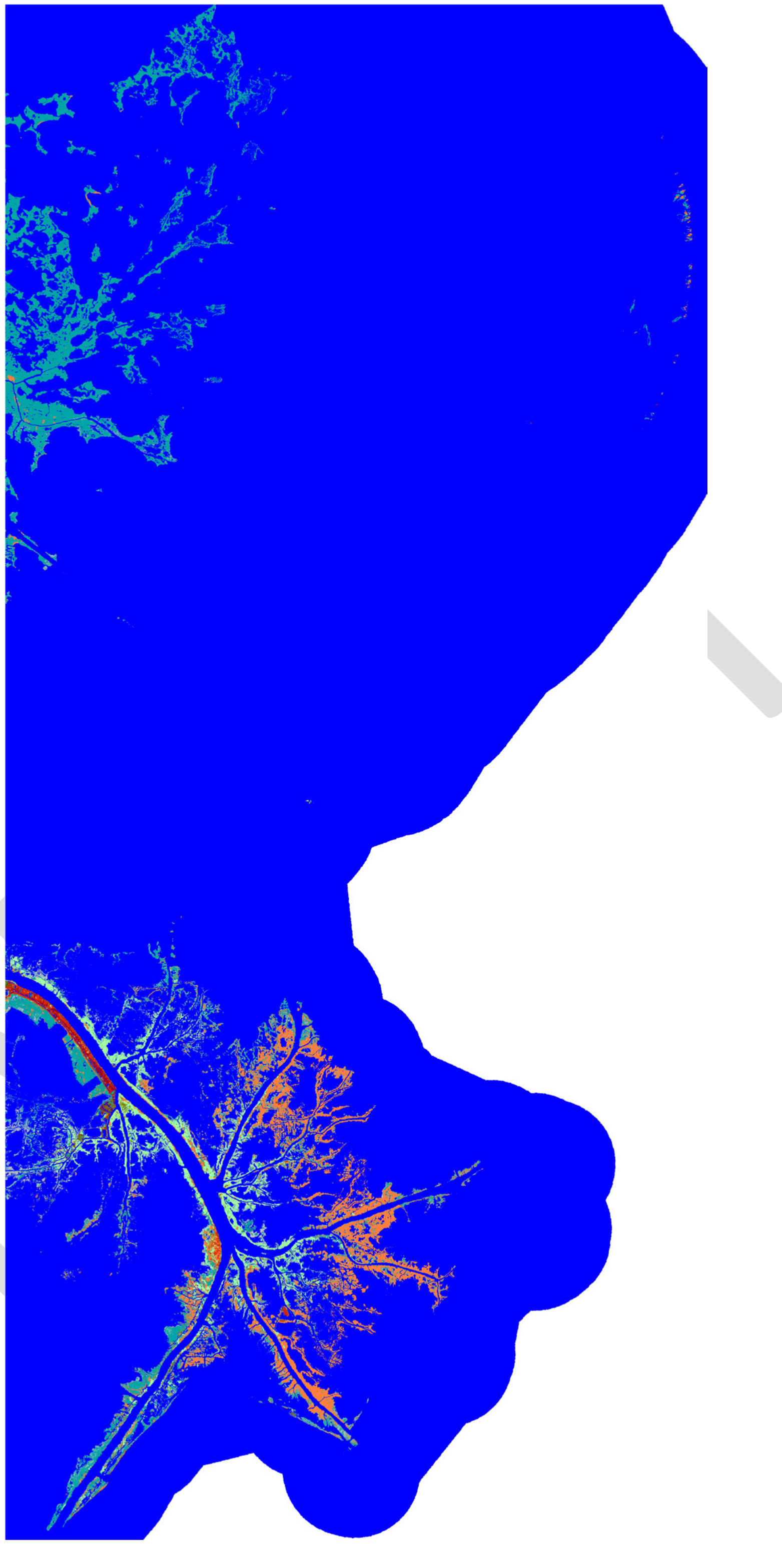
Breton Context, 2050, 1 m

Breton Context, 2075, 1 m

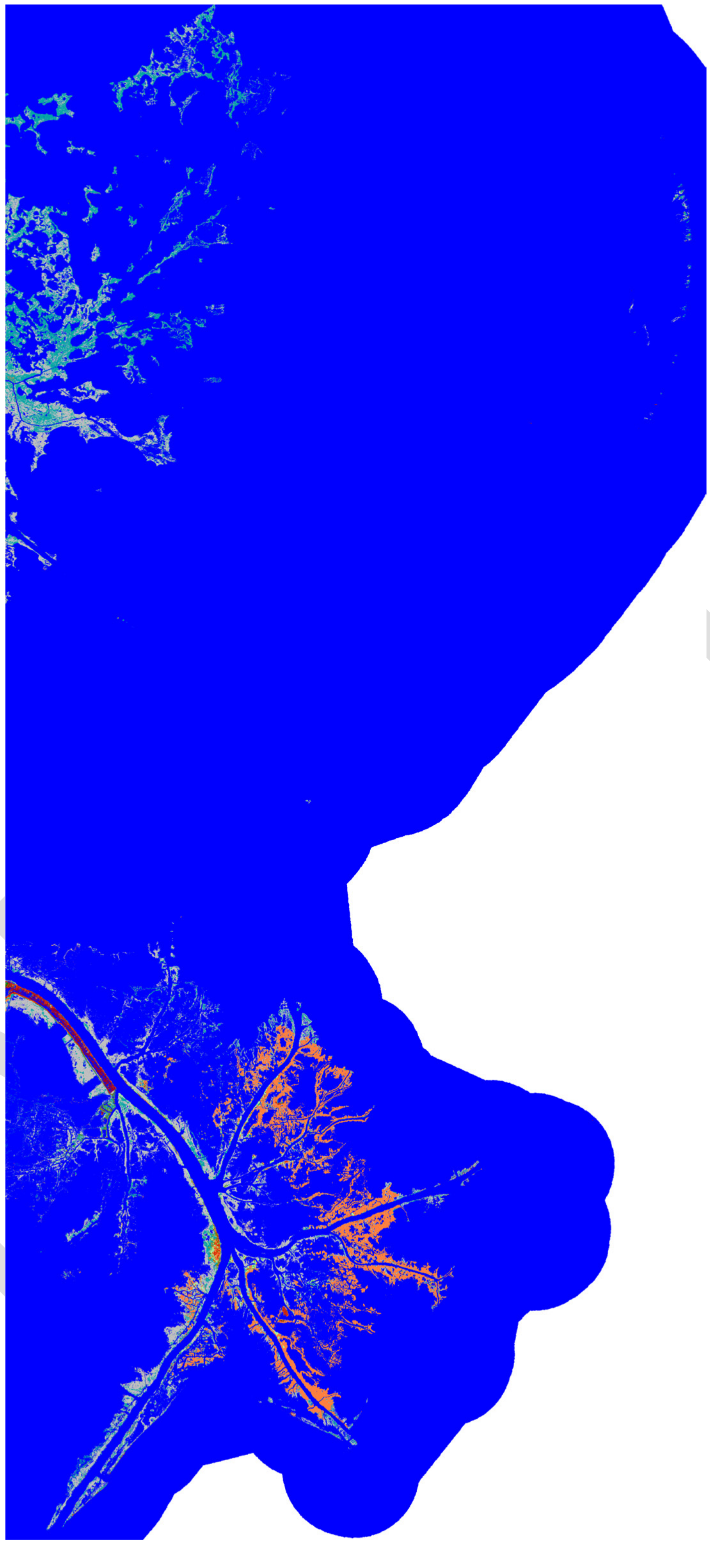
Breton Context, 2100, 1 m



Breton Context, Initial Condition

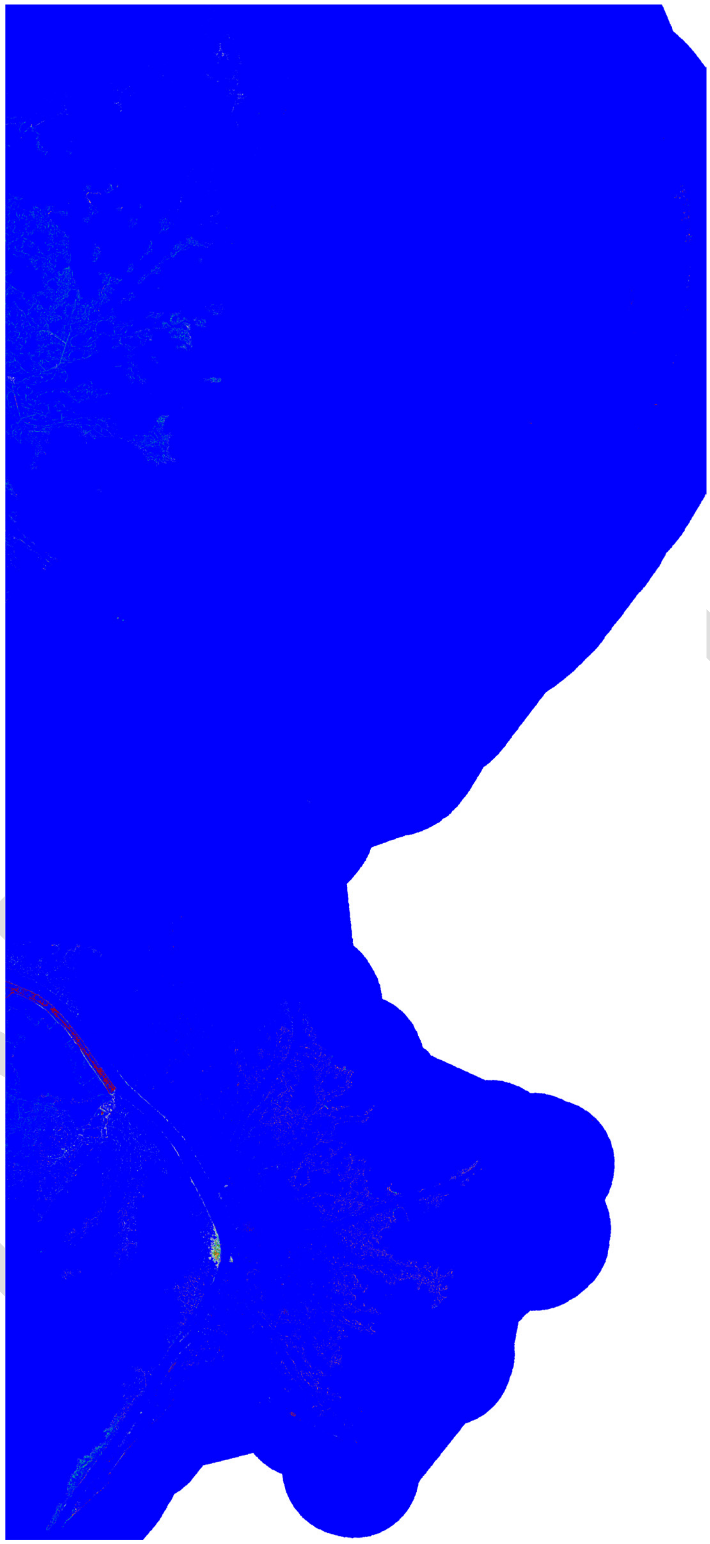


Breton Context, 2025, 1.5 m

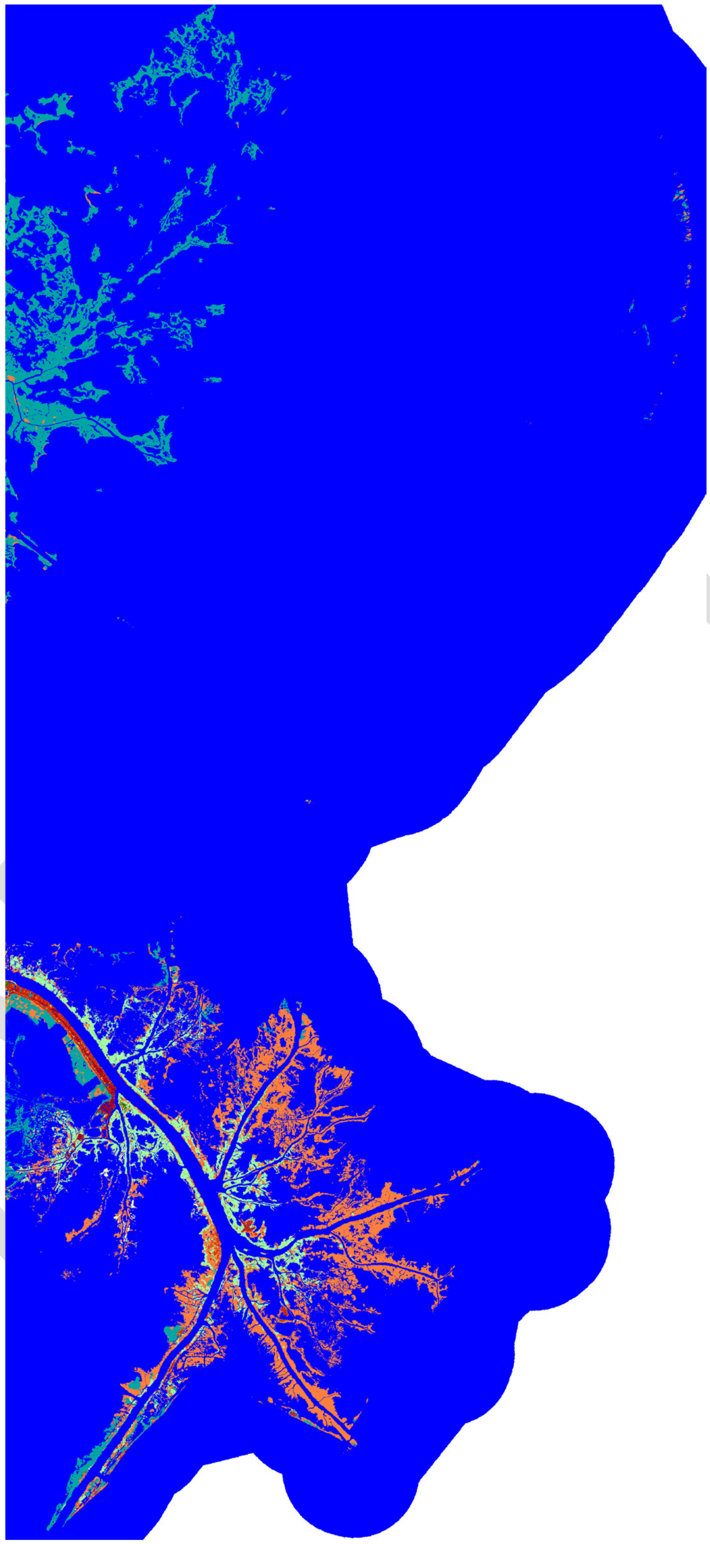


Breton Context, 2050, 1.5 m

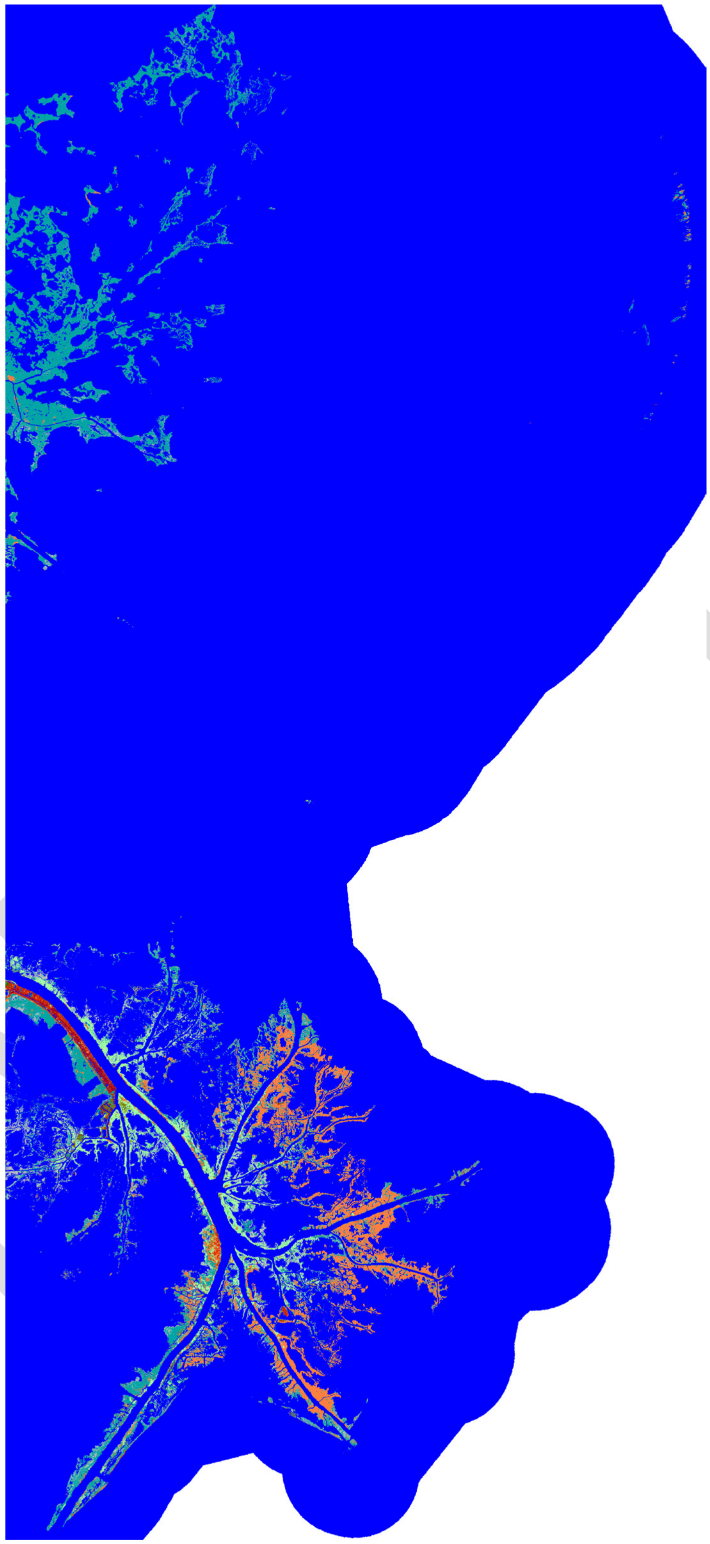
Breton Context, 2075, 1.5 m



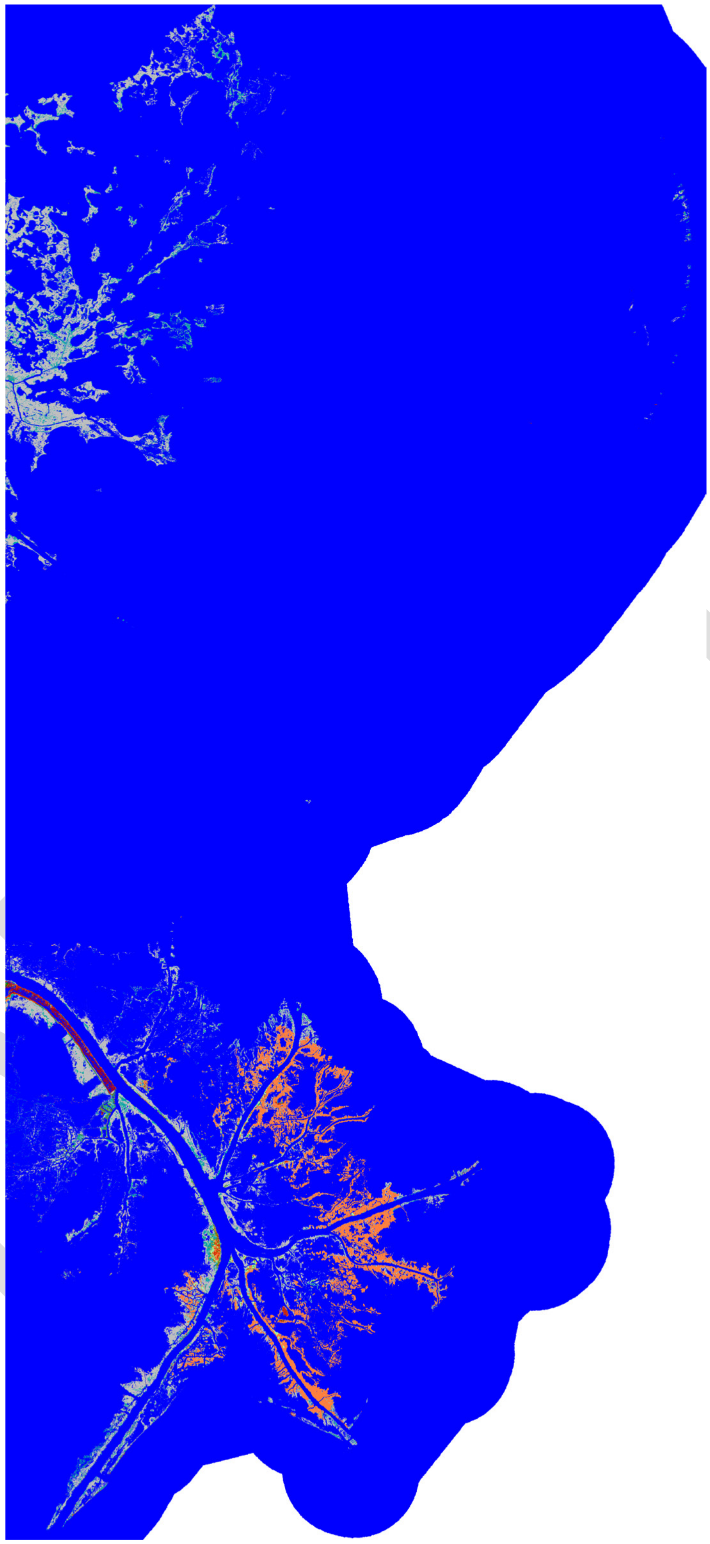
Breton Context, 2100, 1.5 m



Breton Context, Initial Condition

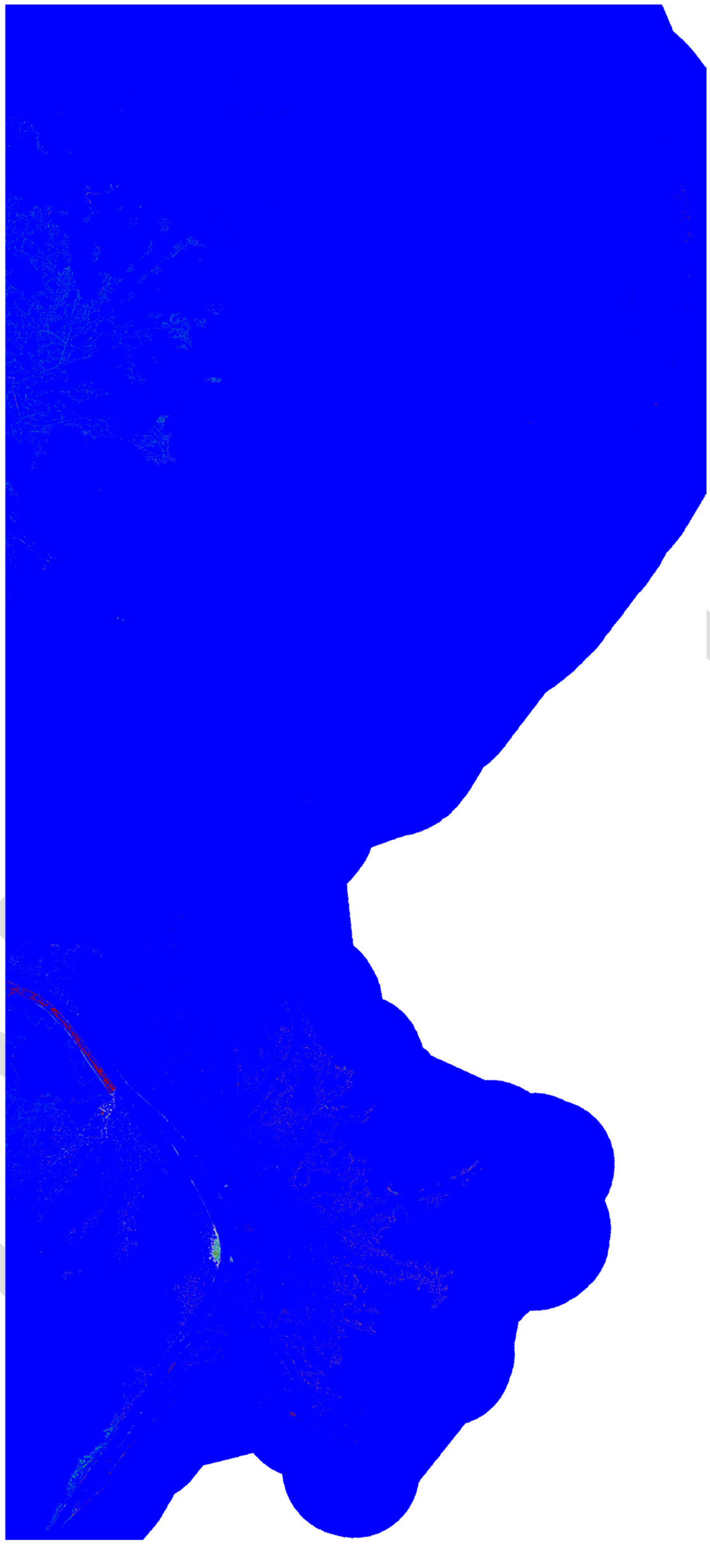


Breton Context, 2025, 2 m



Breton Context, 2050, 2 m

Breton Context, 2075, 2 m



Breton Context, 2100, 2 m