Application of the Sea-Level Affecting Marshes Model (SLAMM 6) to James River 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

July 26, 2010

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

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

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 most Region 1 refuges. This analysis is designed to assist in the production of comprehensive conservation plans (CCPs) for each refuge along with other long-term management plans.

Model Summary

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

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

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

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

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

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

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

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

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

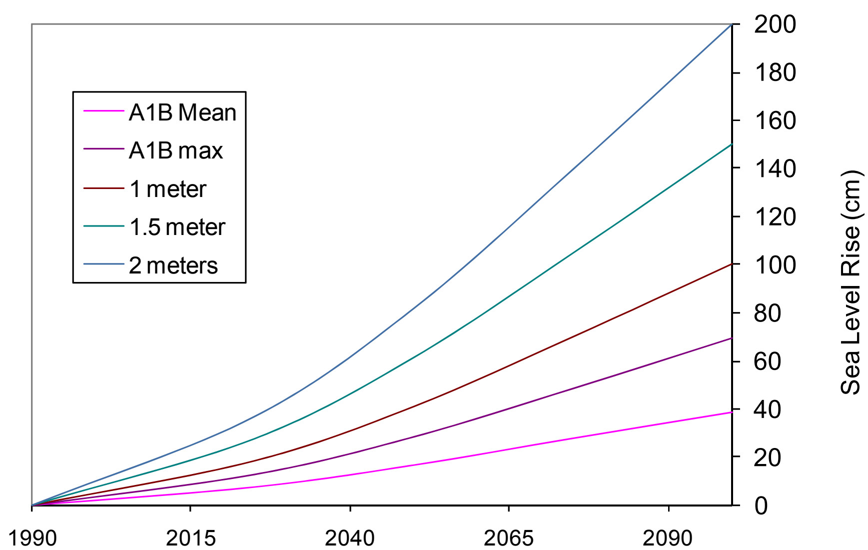
Sea Level Rise Scenarios

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

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

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

Figure 1: Summary of SLR Scenarios Utilized



Methods and Data Sources

The digital elevation map used in this simulation was supplied by Prince George County based on 2-foot contour photogrammetry with a 2006 creation date (Figure 1).

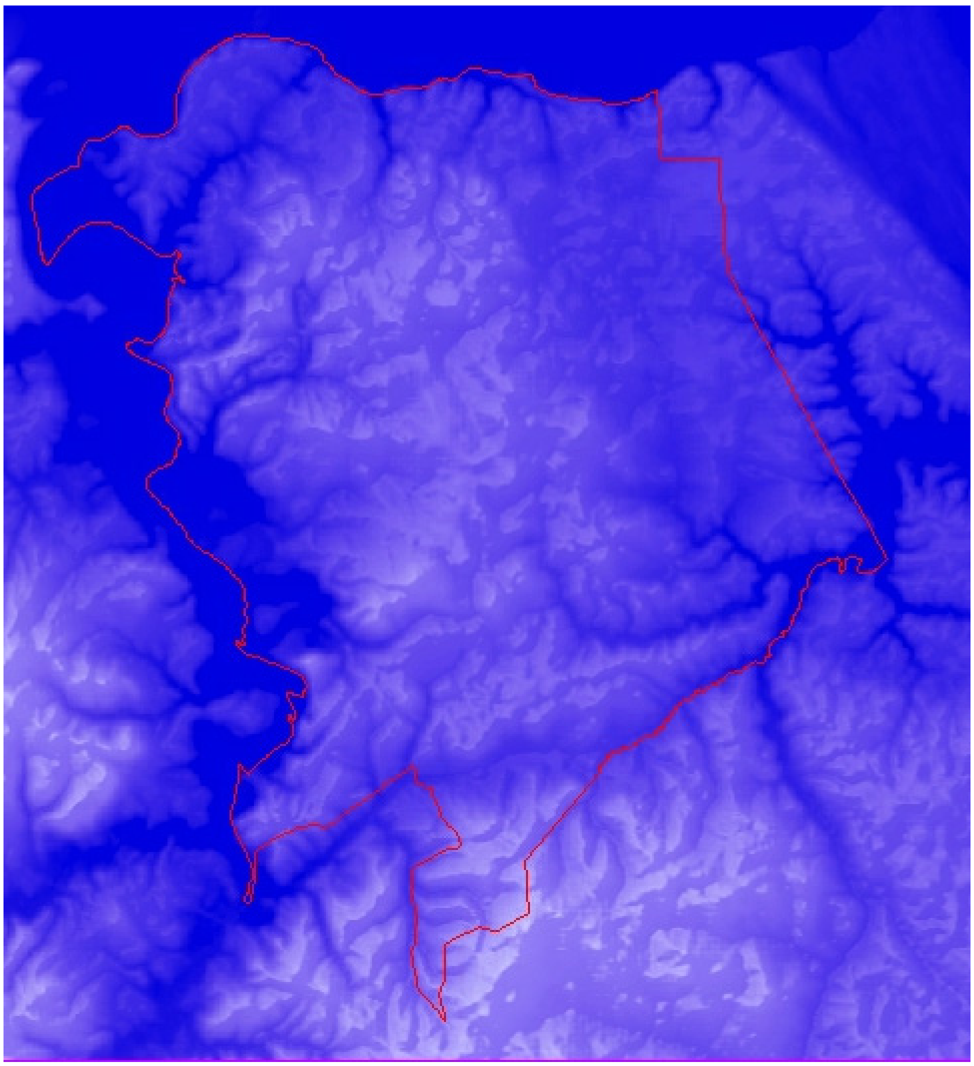


Figure 1: DEM source map for James River NWR (red boundary).

The wetlands layer for the study area was produced by the National Wetlands Inventory and is based on a 1994 photo date. Converting the NWI survey into 10 meter cells indicates that the approximately four thousand five hundred acre refuge (approved acquisition boundary including water) is composed of the following categories:

	Undeveloped Dry Land	82.7%
	Swamp	10.9%
	Tidal Swamp	3.8%
	Tidal Fresh Marsh	1.2%

According to the National Wetland Inventory, only a small fraction of swamp in James River NWR is impounded (Figure 2).

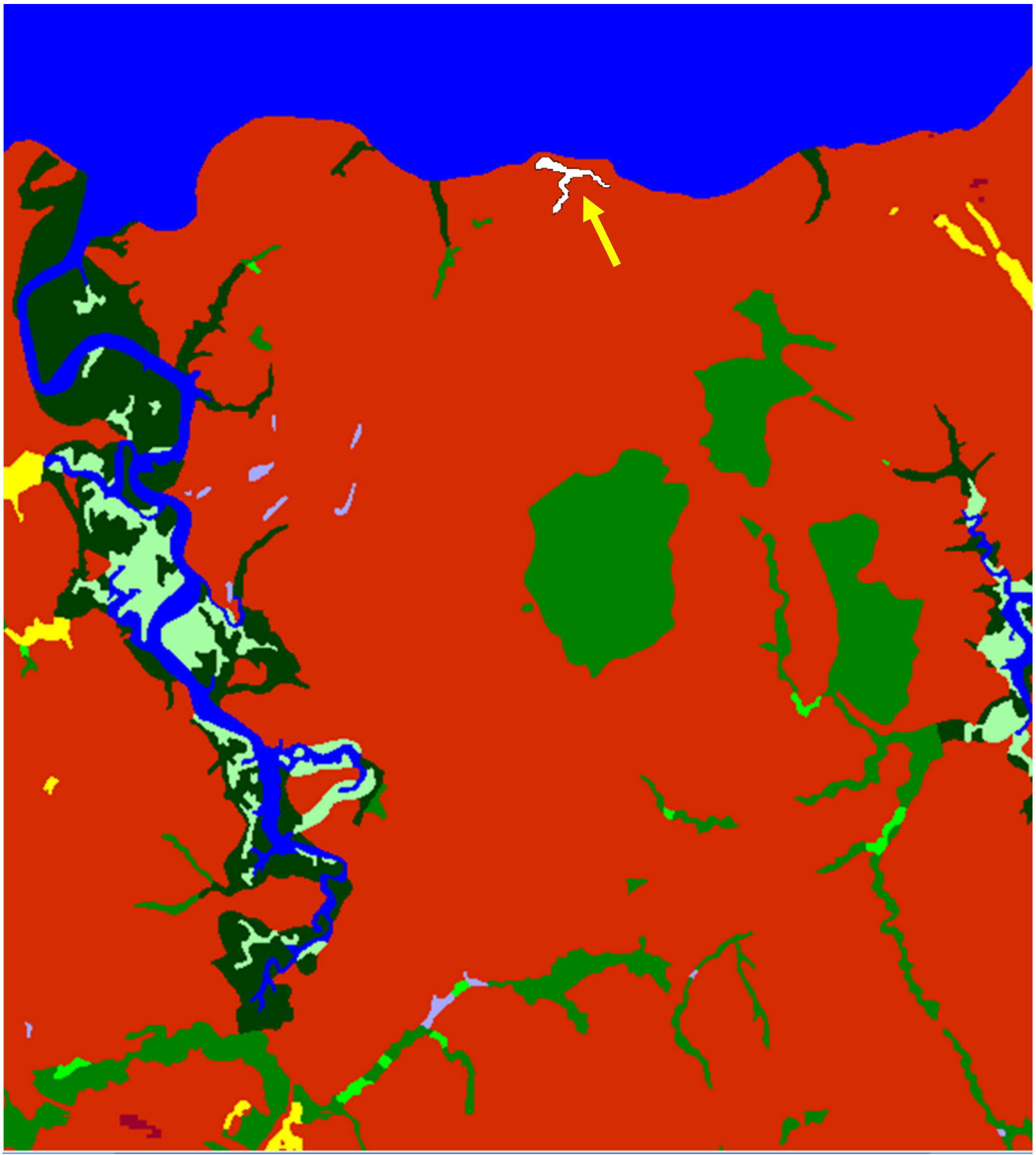


Figure 2: Diked wetland within refuge shown in white (yellow arrow)

The historic trend for sea level rise was estimated at 4.12 mm/year using the average of the two nearest NOAA gages with SLR data (8638610, Sewells Point, VA; 8637624, Gloucestor Point, VA). Based on these data, the rate of sea level rise for this refuge is assumed to be higher that the global average for the last 100 years (approximately 1.7 mm/year, IPCC 2007a). This difference between local and eustatic trends is assumed to continue through 2100.

The tide range was estimated at 0.75 meters (great diurnal range or GT) using the mean of the two nearest NOAA tide table data (8638481, City Point, Hopewell, VA; 8638449, Claremont, James River, VA).

Accretion and erosion data were unavailable for the refuge and the immediate region. The closest recorded accretion rates were from the Blackwater NWR in the northeast Chesapeake Bay region. Accretion rates in regularly flooded marshes were set to 2.65 mm/year based on an accretion study locared within the Blackwater NWR (Stevenson, 1985). Rates for irregularly flooded marshes were set to 5.3 mm/year (n=5) based on three studies: two from Monie Bay and one from Nanticoke River Estuary (Kearney, 1986; Kearney et al., 1991; Ward et al., 1998). Rates for tidal fresh marshes were set to 7.2 mm/year (n=5) based on the means of numerous studies within Maryland (Reed et al., 2008).

The MTL to NAVD88 correction was derived using the NOAA VDATUM product. We used an elevation correction value of 0.018 meters for this study area.

Wetland elevations within the refuge are subject to considerable uncertainty. The majority of tidal swamp and tidal-fresh marsh acreage is located below the lowest contour of our 2-foot contour data (Figure 3). For this reason, wetland elevations were estimated using the SLAMM wetland pre-processor which estimates wetland elevations as a function of the tidal range. However, for tidal swamps and tidal-fresh marshes, the relationship between tide range and marsh range is less clear than for other wetland types, due to the importance and variability of fresh-water flows.

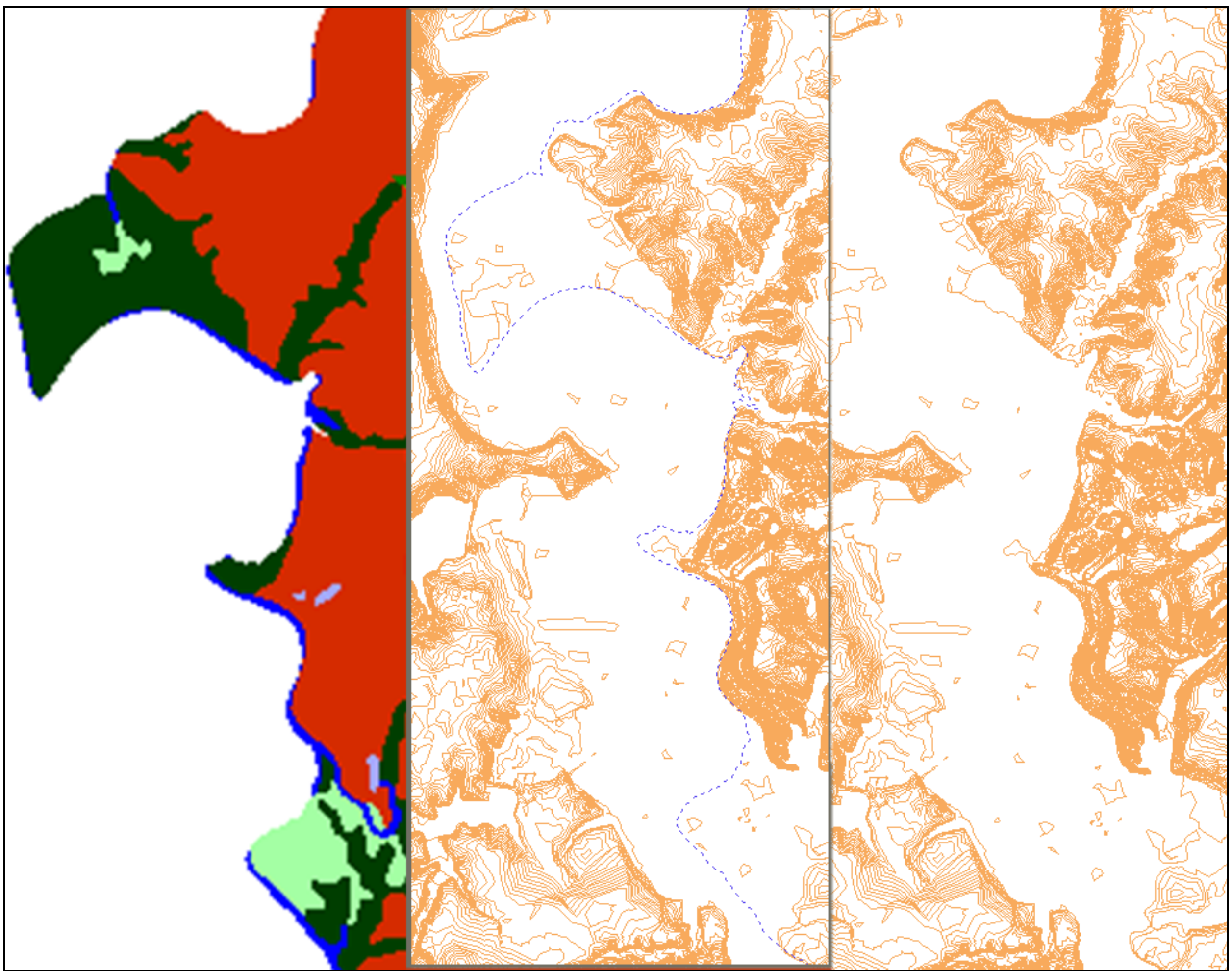


Figure 3: Tidal Swamp and Tidal Fresh Marsh (in dark and light green) compared to elevation contour map. The majority of the swamp and marsh lands fall below the lowest contour.

Modeled U.S. Fish and Wildlife Service refuge boundaries for Virginia are based on Approved Acquisition Boundaries as published on the FWS National Wildlife Refuge Data and Metadata website. The cell-size used for this analysis was 10 meter by 10 meter cells. Note that the SLAMM model will track partial conversion of cells based on elevation and slope.

SUMMARY OF SLAMM INPUT PARAMETERS FOR JAMES RIVER NWR

Parameter	Global	SubSite 1	SubSite 2
Description	James River	SubSite 1	SubSite 2
NWI Photo Date (YYYY)	1994	1994	1994
DEM Date (YYYY)	2006	2006	2006
Direction Offshore [n,s,e,w]	South	North	West
Historic Trend (mm/yr)	4.12	4.12	4.12
MTL-NAVD88 (m)	0.018	0.018	0.018
GT Great Diurnal Tide Range (m)	0.75	0.75	0.75
Salt Elev. (m above MTL)	0.5	0.5	0.5
Marsh Erosion (horz. m /yr)	1.8	1.8	1.8
Swamp Erosion (horz. m /yr)	1	1	1
T.Flat Erosion (horz. m /yr)	6	6	6
Reg. Flood Marsh Accr (mm/yr)	2.65	2.65	2.65
Irreg. Flood Marsh Accr (mm/yr)	5.33	5.33	5.33
Tidal Fresh Marsh Accr (mm/yr)	7.2	7.2	7.2
Beach Sed. Rate (mm/yr)	0.5	0.5	0.5
Freq. Overwash (years)	25	25	25
Use Elev Pre-processor [True,False]	TRUE	TRUE	TRUE

Results

The SLAMM model predicts that James River NWR will be severely impacted by SLR inundation. A majority of refuge tidal swamp and tidal fresh marsh are predicted to be lost by the 1 meter scenario. These results are subject to considerable uncertainty, however, as detailed in the *Discussion* section below. In particular, poor elevation data drives model uncertainties for these categories.

SLR by 2100 (m)	0.39	0.69	1	1.5	2
Undeveloped Dry Land	2%	3%	3%	4%	4%
Tidal Swamp	77%	100%	100%	100%	100%
Tidal Fresh Marsh	0%	39%	94%	100%	100%
Riverine Tidal	59%	72%	76%	81%	85%
Inland Fresh Marsh	0%	0%	0%	3%	13%
Cypress Swamp	0%	0%	0%	0%	1%

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

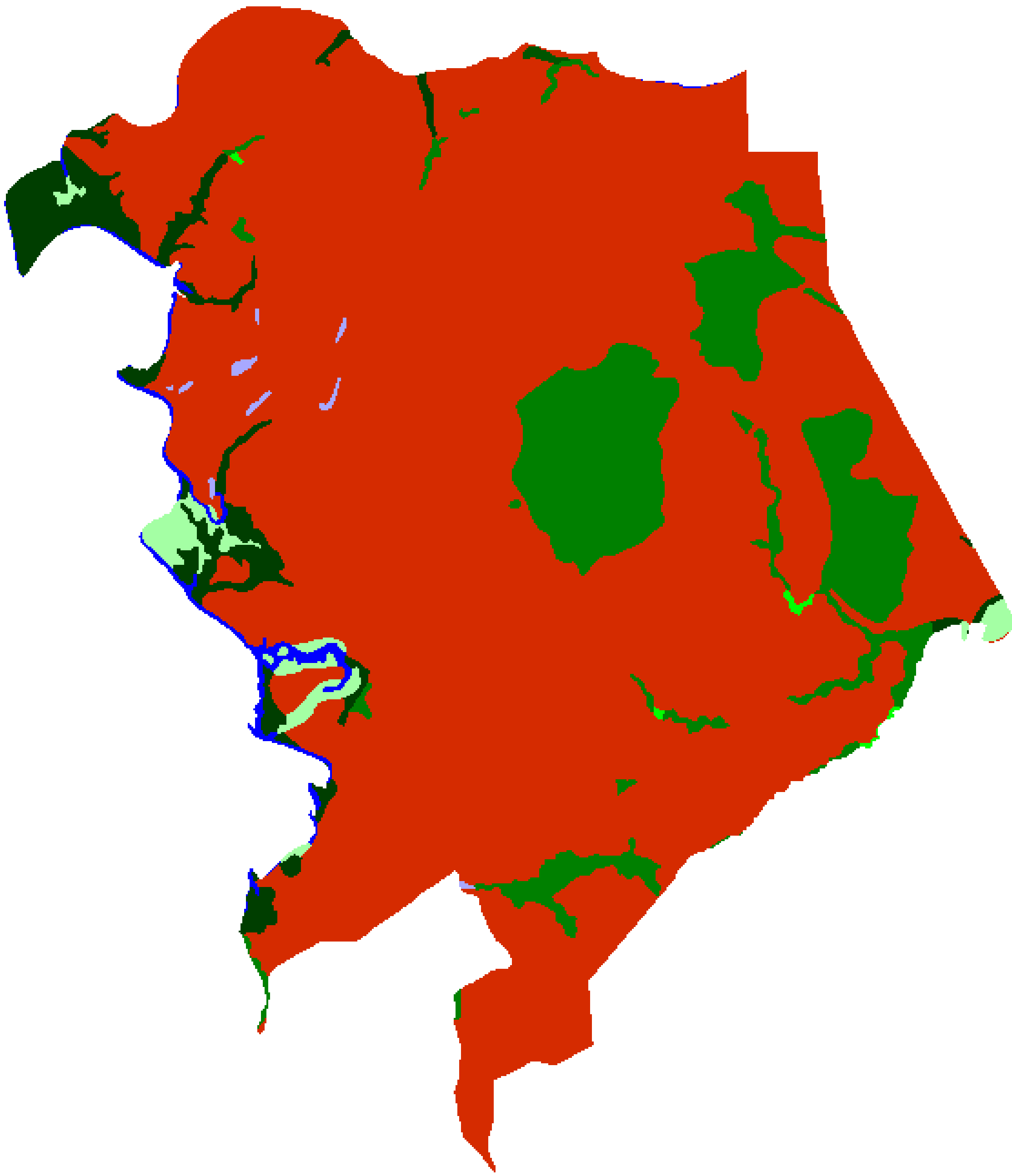
Maps of SLAMM input and output to follow will use the following legend:

Undeveloped Dry Land	
Swamp	
Tidal Swamp	
Tidal Fresh Marsh	
Riverine Tidal	
Inland Open Water	
Inland Fresh Marsh	
Cypress Swamp	
Irregularly Flooded Marsh	
Estuarine Open Water	
Regularly Flooded Marsh	
Transitional Salt Marsh	
Tidal Flat	

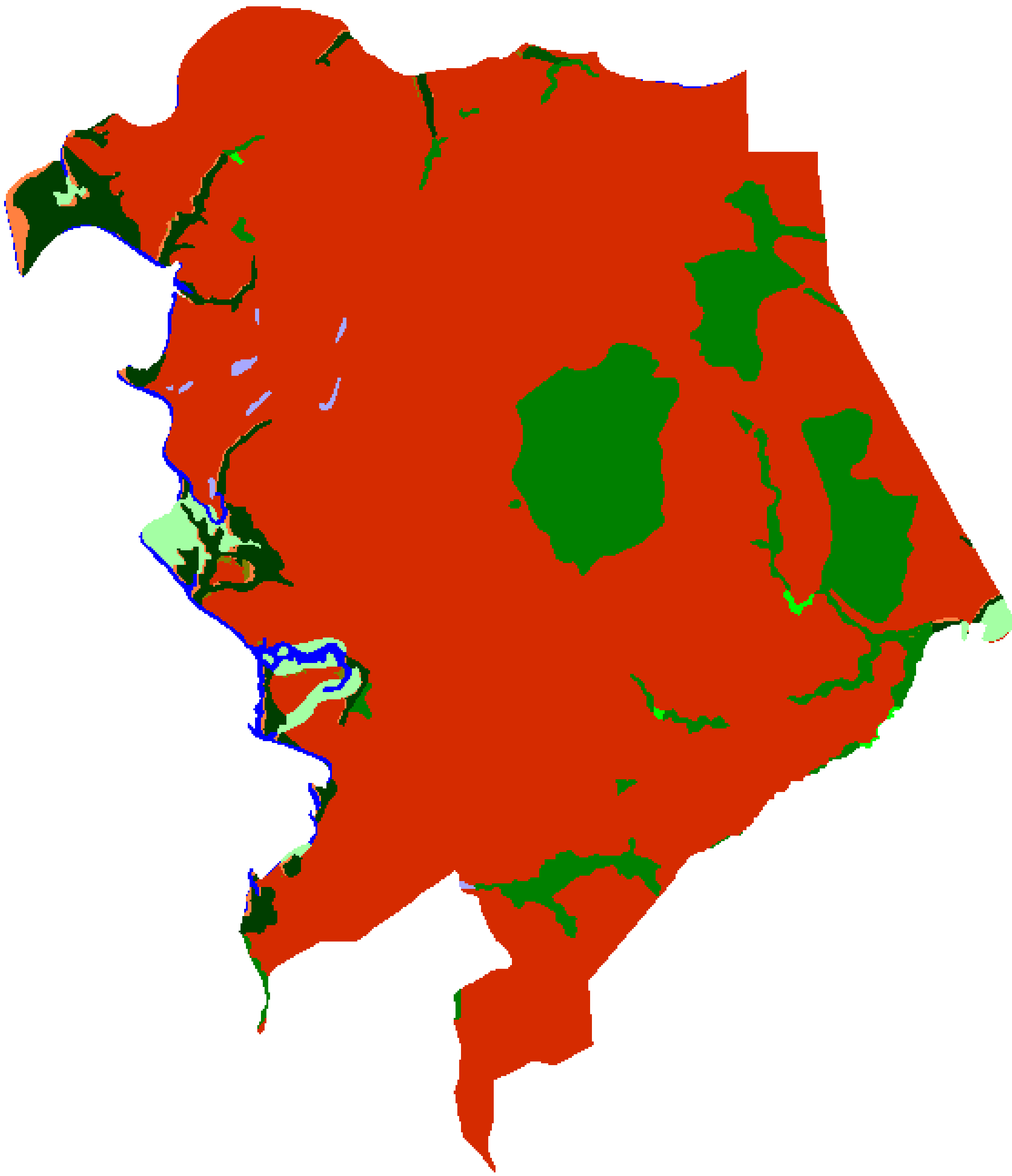
James River Raster
IPCC Scenario A1B-Mean, 0.39 M SLR Eustatic by 2100

Results in Acres

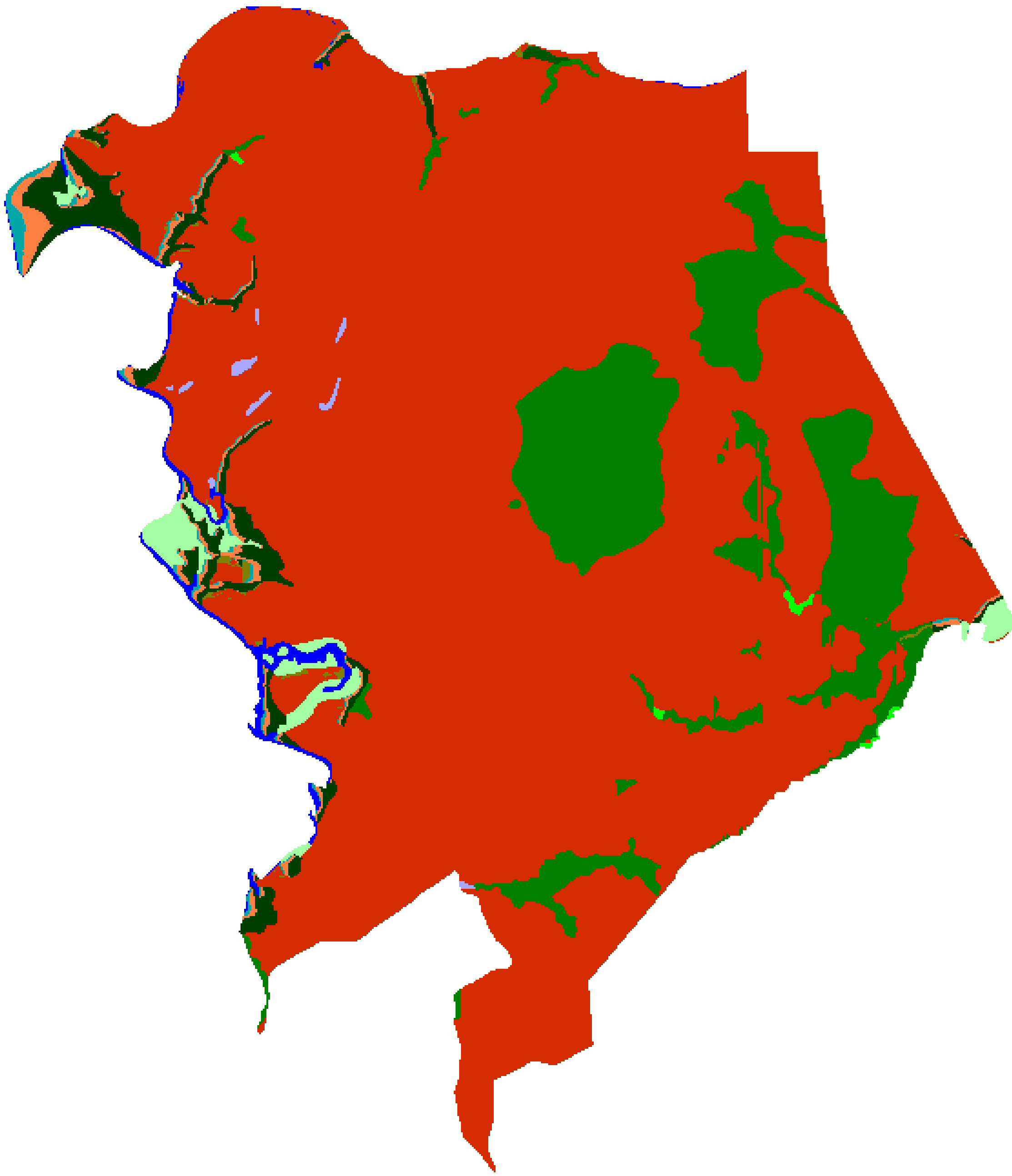
	Initial	2025	2050	2075	2100	Legend
Undeveloped Dry Land	3695.5	3691.4	3637.3	3626.7	3618.4	
Swamp	487.5	487.2	534.5	539.0	539.8	
Tidal Swamp	170.2	145.5	111.4	72.0	38.5	
Tidal Fresh Marsh	55.1	55.1	55.1	55.1	55.1	
Riverine Tidal	42.0	42.0	23.2	18.8	17.2	
Inland Open Water	8.2	8.2	7.8	7.8	7.7	
Inland Fresh Marsh	4.9	4.9	4.9	4.9	4.9	
Cypress Swamp	3.0	3.0	3.0	3.0	3.0	
Irregularly Flooded Marsh	0.0	24.7	39.0	39.6	33.9	
Estuarine Open Water	0.0	0.0	21.1	26.1	32.2	
Regularly Flooded Marsh	0.0	0.0	20.0	61.1	73.7	
Transitional Salt Marsh	0.0	4.4	9.0	11.8	14.5	
Tidal Flat	0.0	0.0	0.0	0.5	27.5	
Total (incl. water)	**4466.4**	**4466.4**	**4466.4**	**4466.4**	**4466.4**	



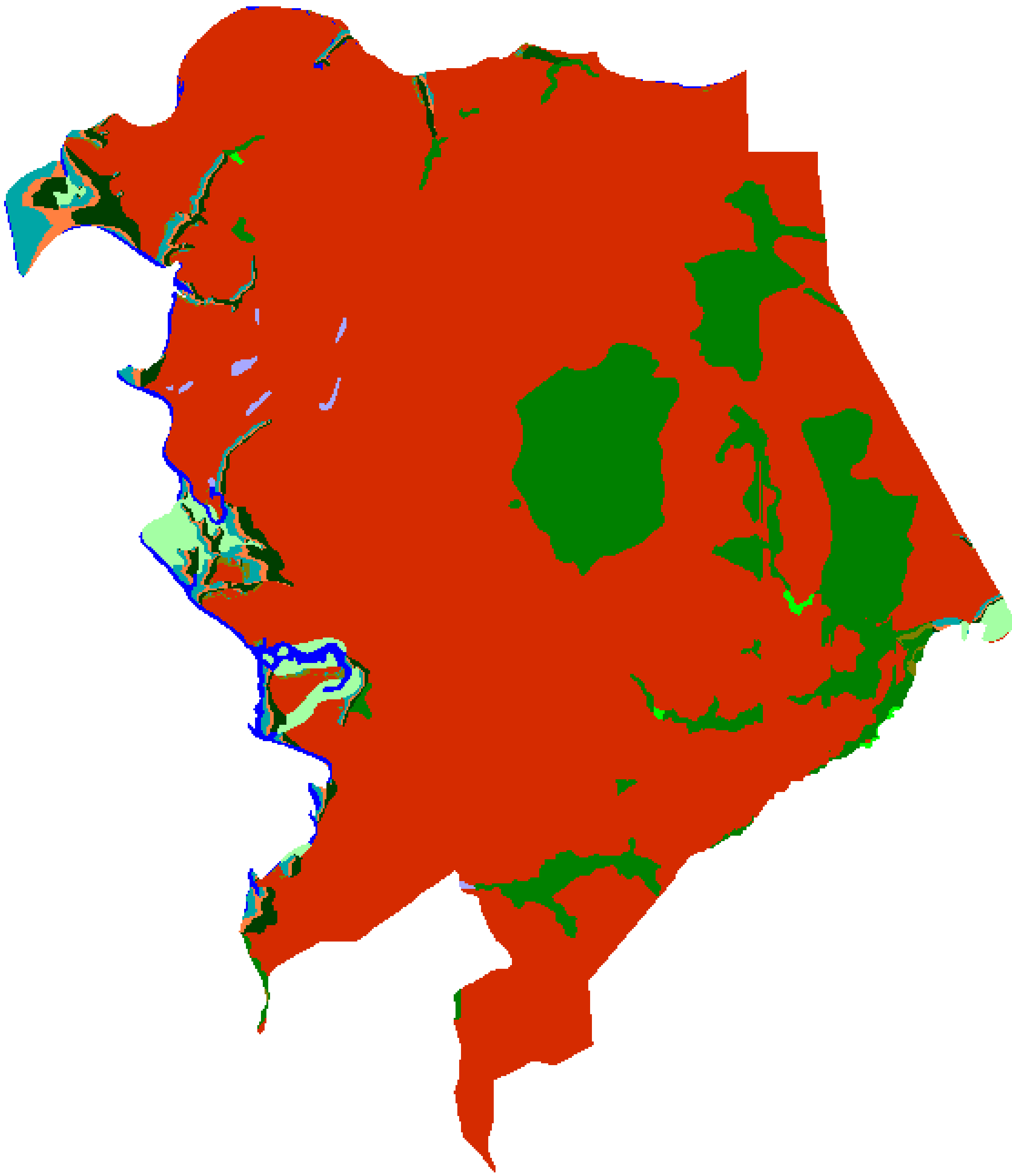
James River NWR, Initial Condition



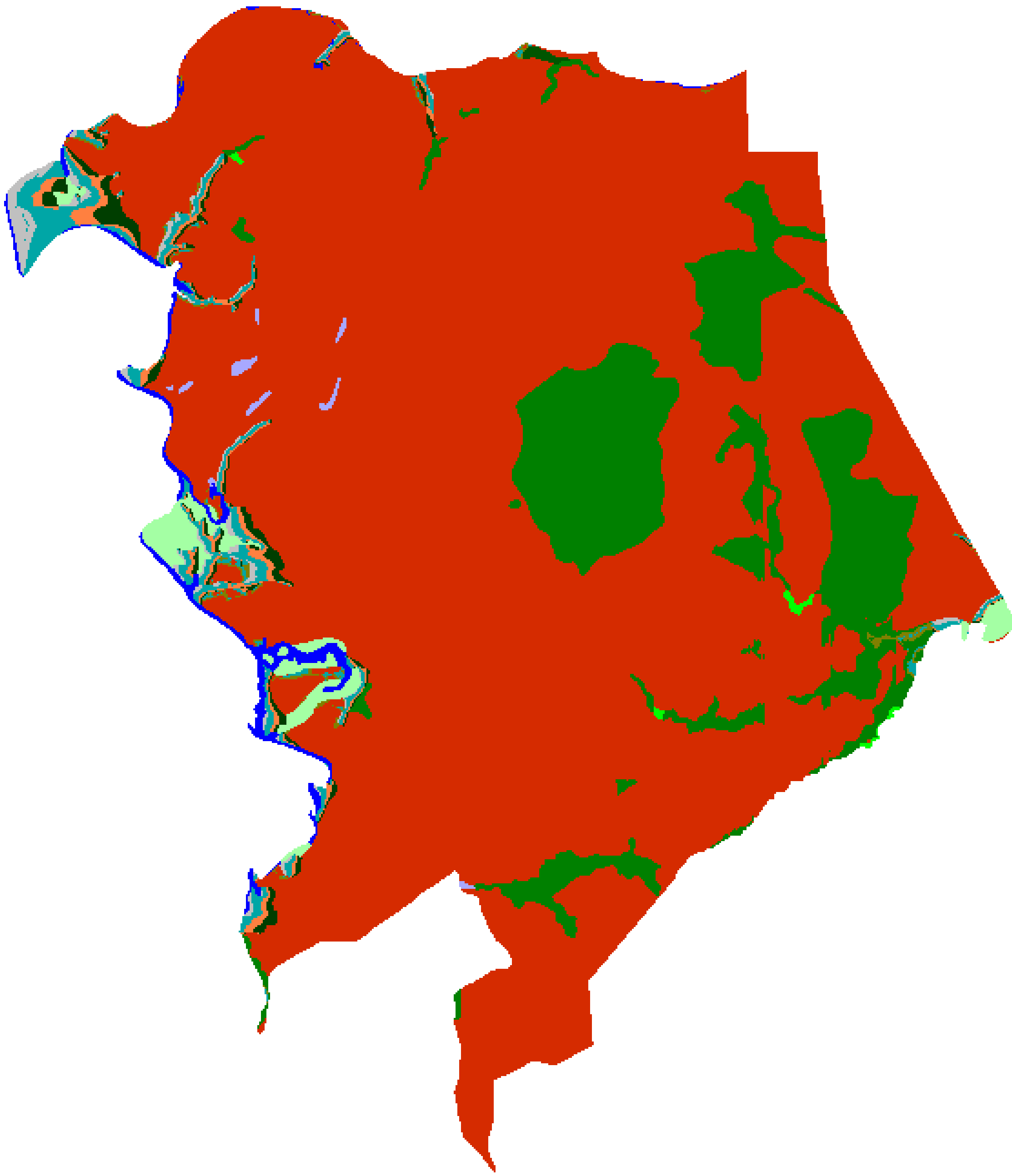
James River NWR, 2025, Scenario A1B Mean



James River NWR, 2050, Scenario A1B Mean



James River NWR, 2075, Scenario A1B Mean

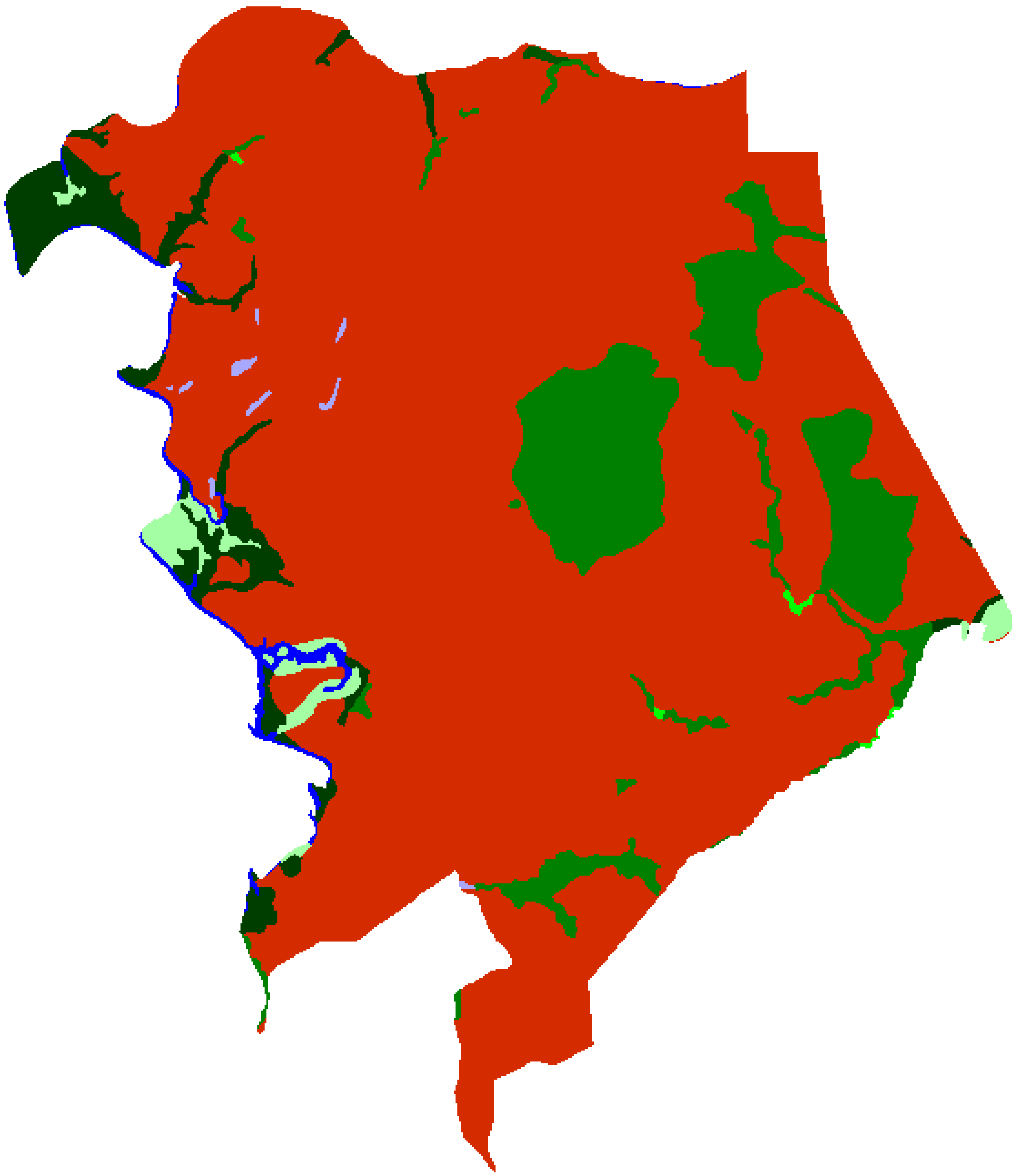


James River NWR, 2100, Scenario A1B Mean

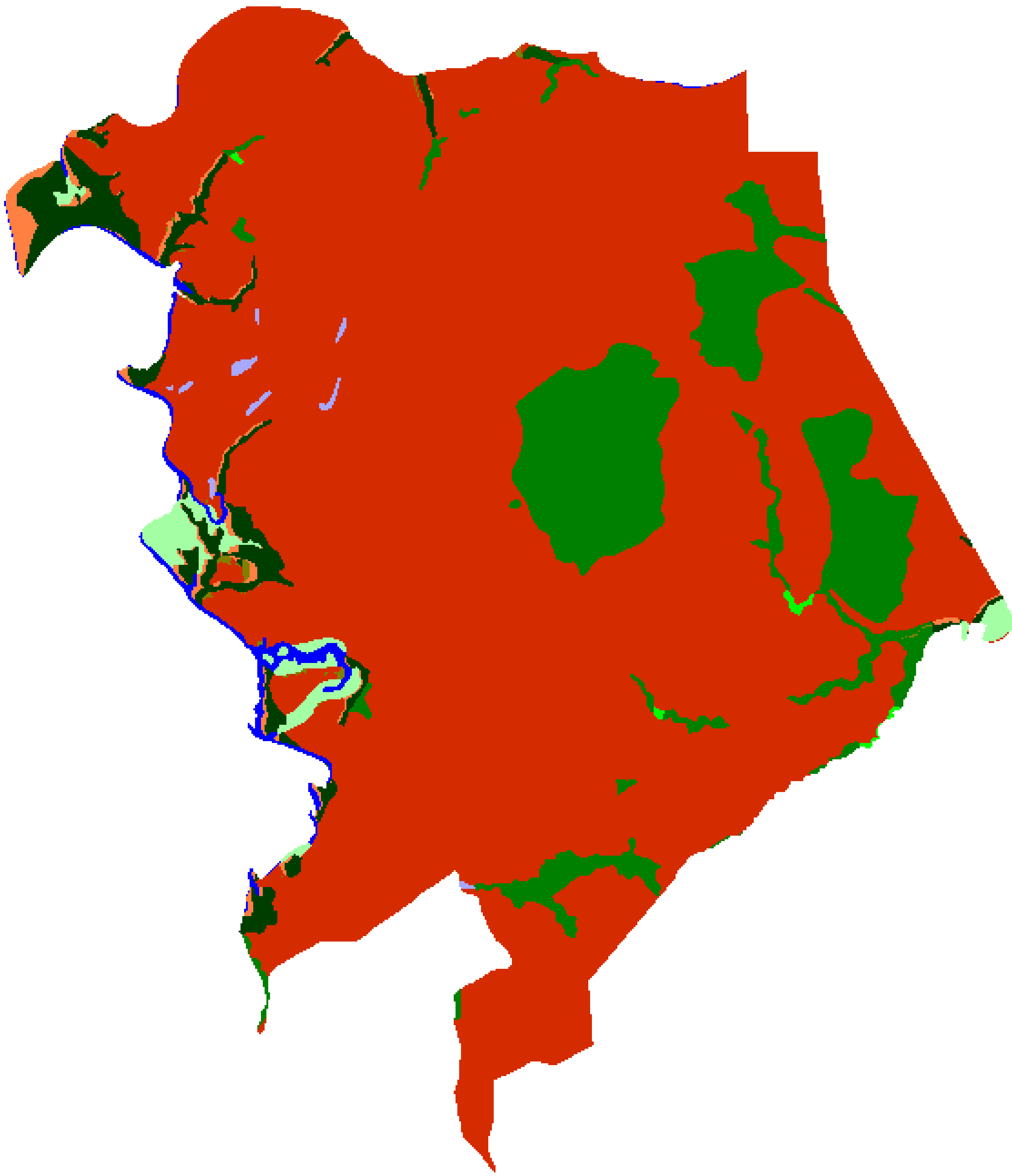
James River Raster
IPCC Scenario A1B-Max, 0.69 M SLR Eustatic by 2100

Results in Acres

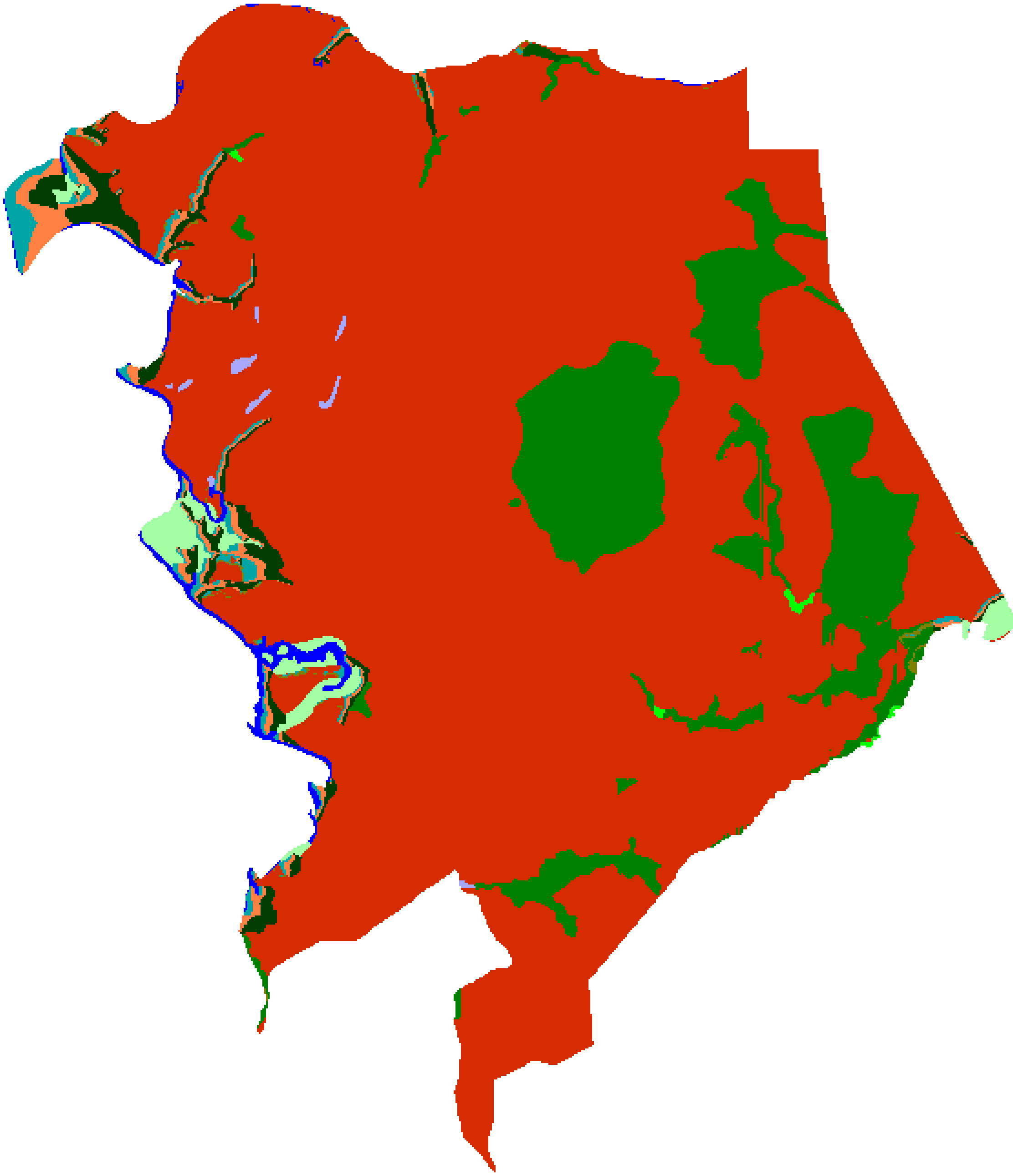
	Initial	2025	2050	2075	2100	Legend
Undeveloped Dry Land	3695.5	3689.8	3630.8	3617.1	3598.1	
Swamp	487.5	487.1	537.0	540.0	546.6	
Tidal Swamp	170.2	133.1	80.2	25.4	0.0	
Tidal Fresh Marsh	55.1	55.1	55.0	45.4	33.4	
Riverine Tidal	42.0	42.0	20.7	16.7	11.9	
Inland Open Water	8.2	8.2	7.8	7.7	7.6	
Inland Fresh Marsh	4.9	4.9	4.9	4.9	4.9	
Cypress Swamp	3.0	3.0	3.0	3.0	3.0	
Irregularly Flooded Marsh	0.0	37.1	53.1	64.3	37.4	
Regularly Flooded Marsh	0.0	0.0	41.9	66.5	81.8	
Estuarine Open Water	0.0	0.0	23.1	32.6	56.3	
Transitional Salt Marsh	0.0	6.1	9.0	10.9	12.7	
Tidal Flat	0.0	0.0	0.0	31.6	72.6	
Total (incl. water)	**4466.4**	**4466.4**	**4466.4**	**4466.4**	**4466.4**	



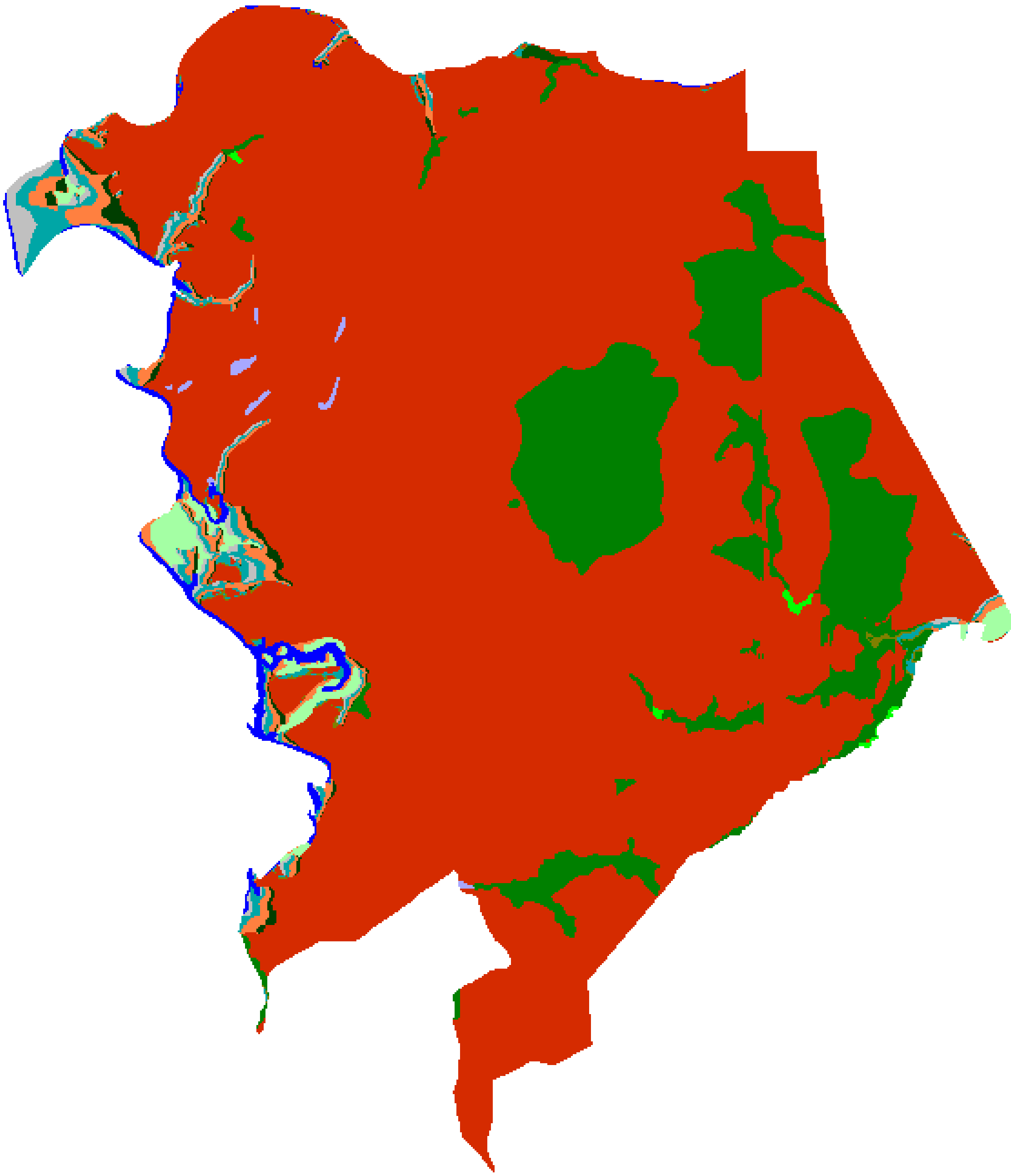
James River NWR, Initial Condition



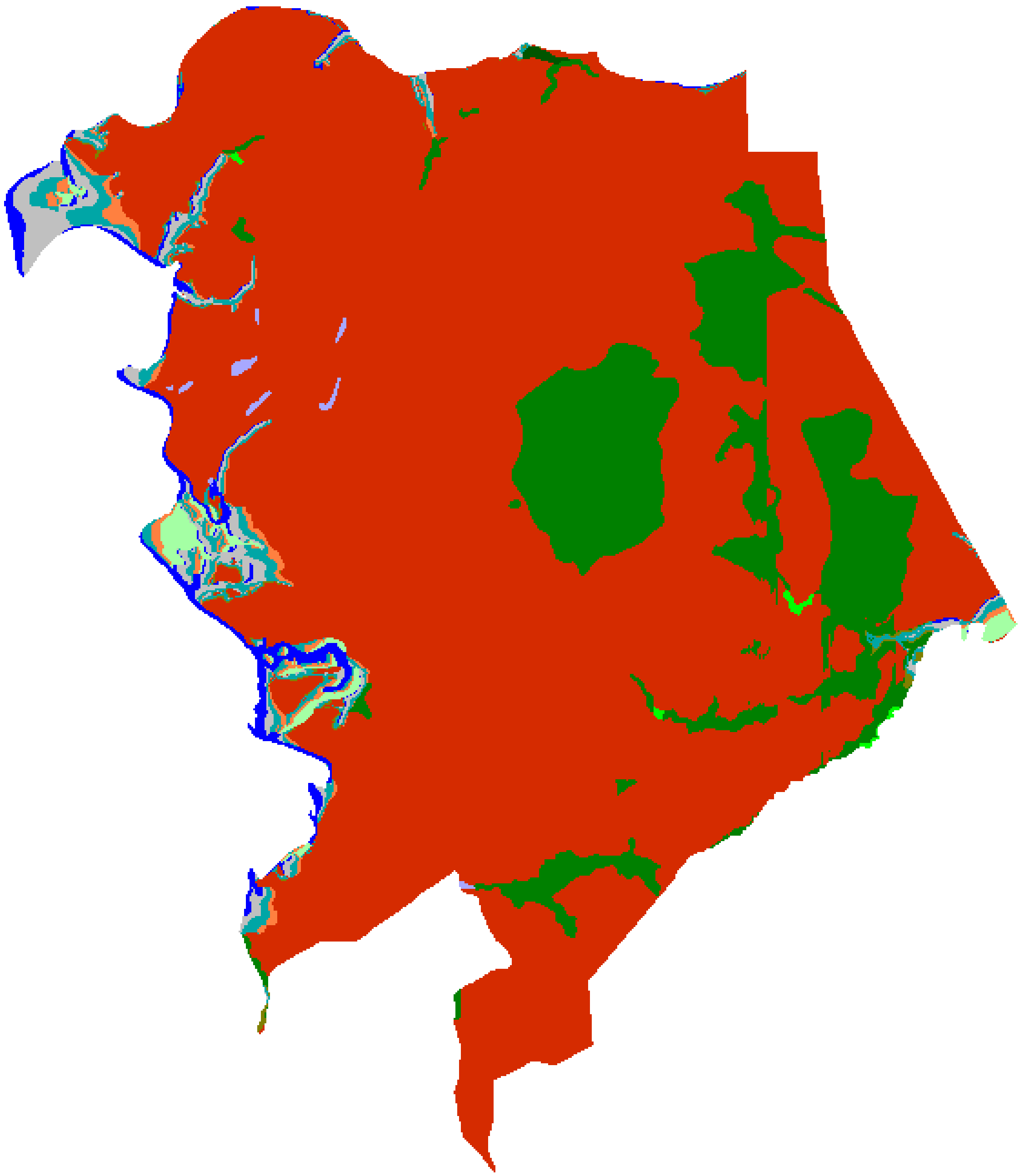
James River NWR, 2025, Scenario A1B Maximum



James River NWR, 2050, Scenario A1B Maximum



James River NWR, 2075, Scenario A1B Maximum

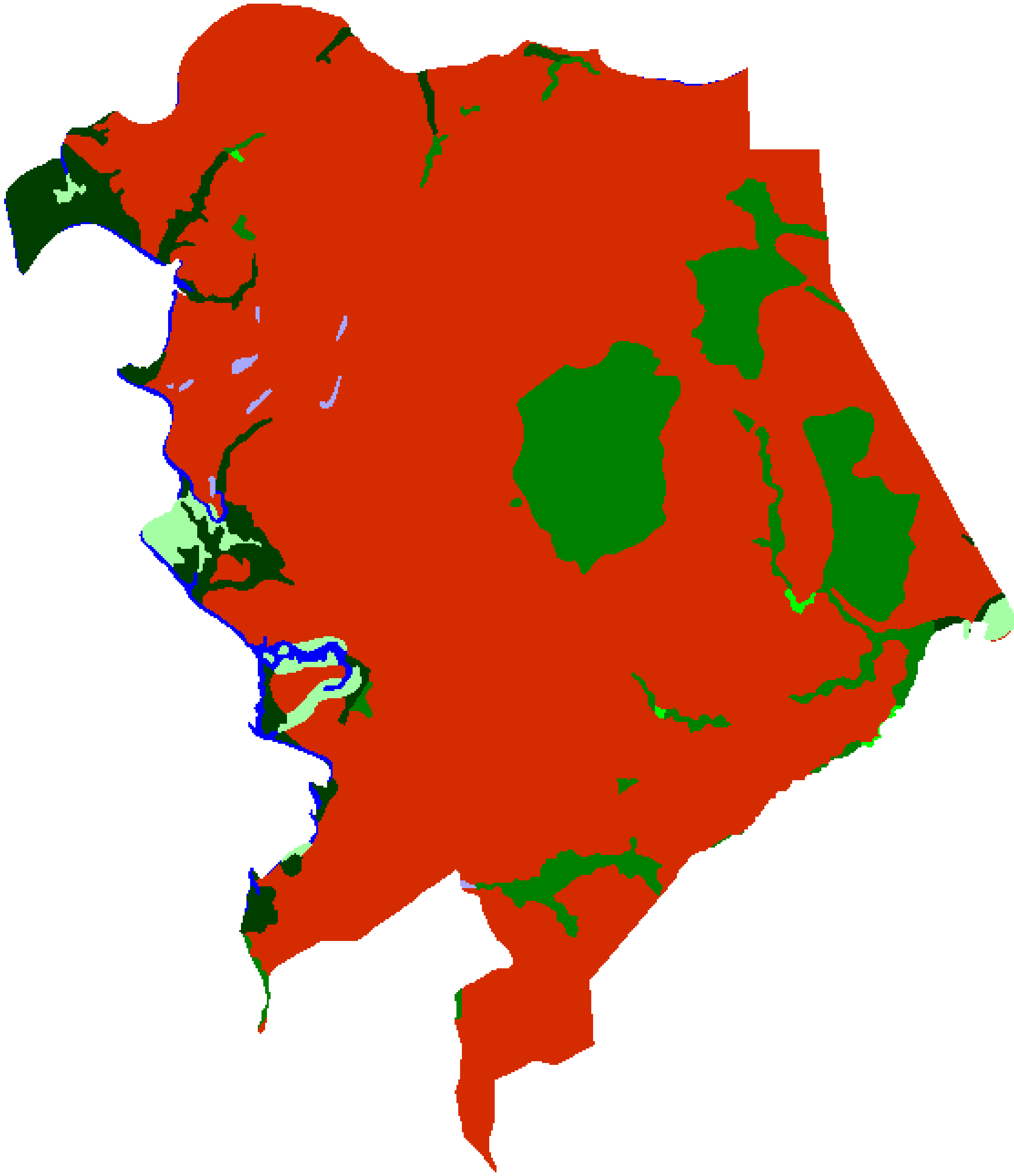


James River NWR, 2100, Scenario A1B Maximum

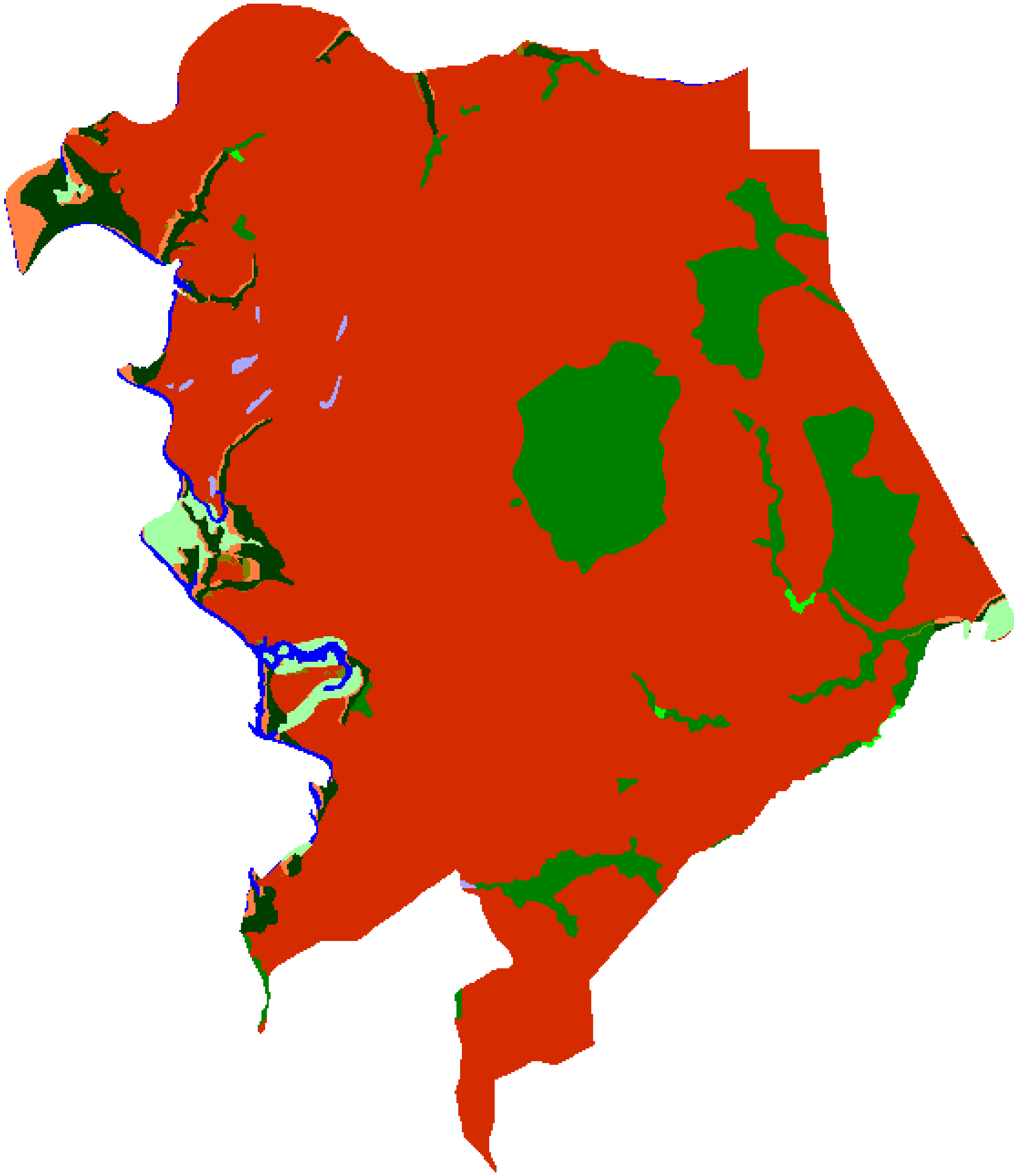
James River Raster
1 Meter Eustatic SLR by 2100

Results in Acres

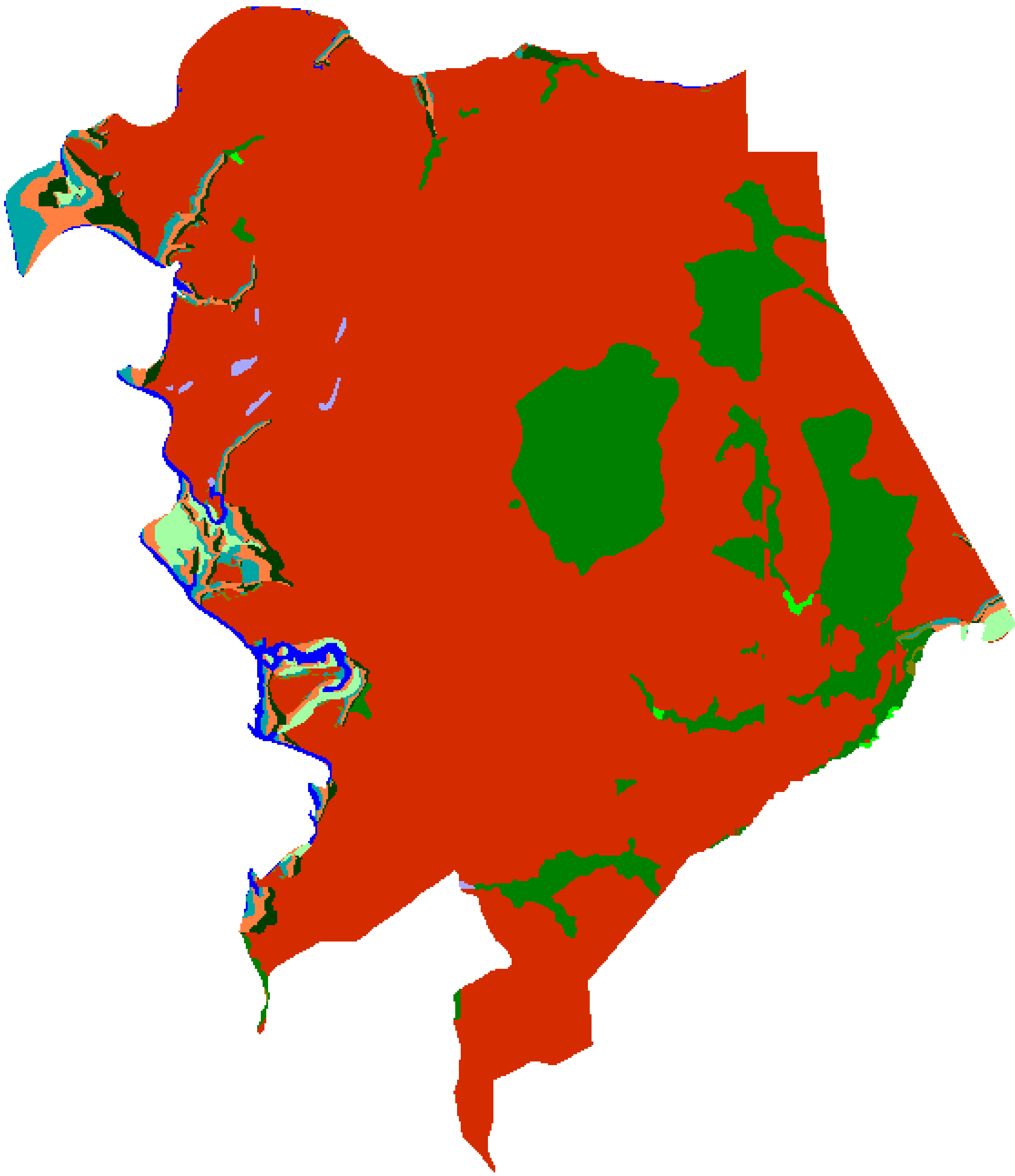
	Initial	2025	2050	2075	2100	Legend
Undeveloped Dry Land	3695.5	3688.4	3624.9	3605.2	3579.7	
Swamp	487.5	486.8	539.3	542.2	549.4	
Tidal Swamp	170.2	119.2	51.8	0.0	0.0	
Tidal Fresh Marsh	55.1	53.8	40.4	19.2	3.4	
Riverine Tidal	42.0	42.0	13.8	12.0	10.2	
Inland Open Water	8.2	8.2	7.8	7.7	7.6	
Inland Fresh Marsh	4.9	4.9	4.9	4.9	4.9	
Cypress Swamp	3.0	3.0	3.0	3.0	3.0	
Irregularly Flooded Marsh	0.0	52.2	80.9	73.0	15.8	
Regularly Flooded Marsh	0.0	0.0	59.9	92.8	90.1	
Estuarine Open Water	0.0	0.0	29.5	37.9	93.2	
Transitional Salt Marsh	0.0	7.7	10.3	17.0	18.6	
Tidal Flat	0.0	0.0	0.0	51.5	90.5	
Total (incl. water)	**4466.4**	**4466.4**	**4466.4**	**4466.4**	**4466.4**	



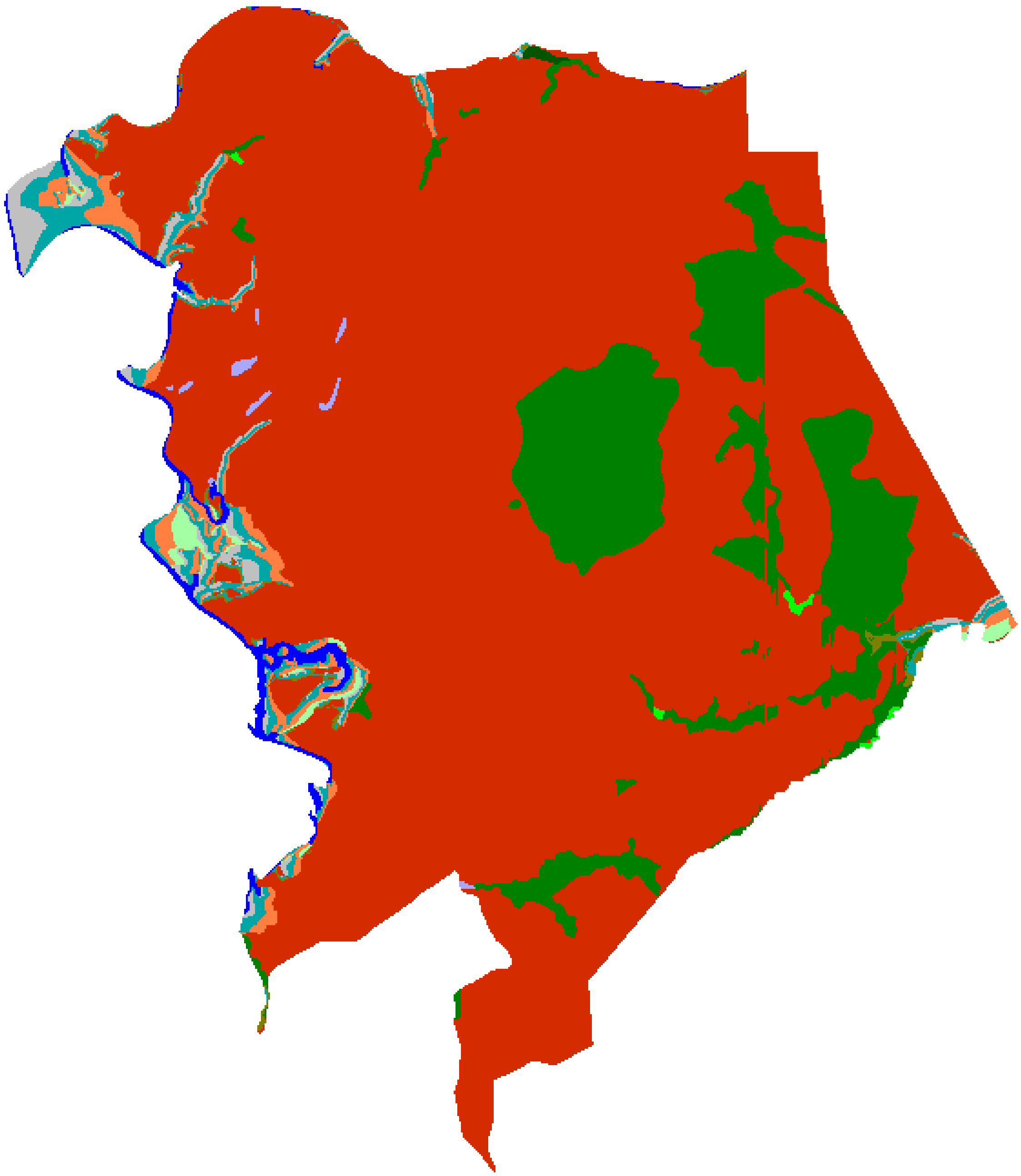
James River NWR, Initial Condition



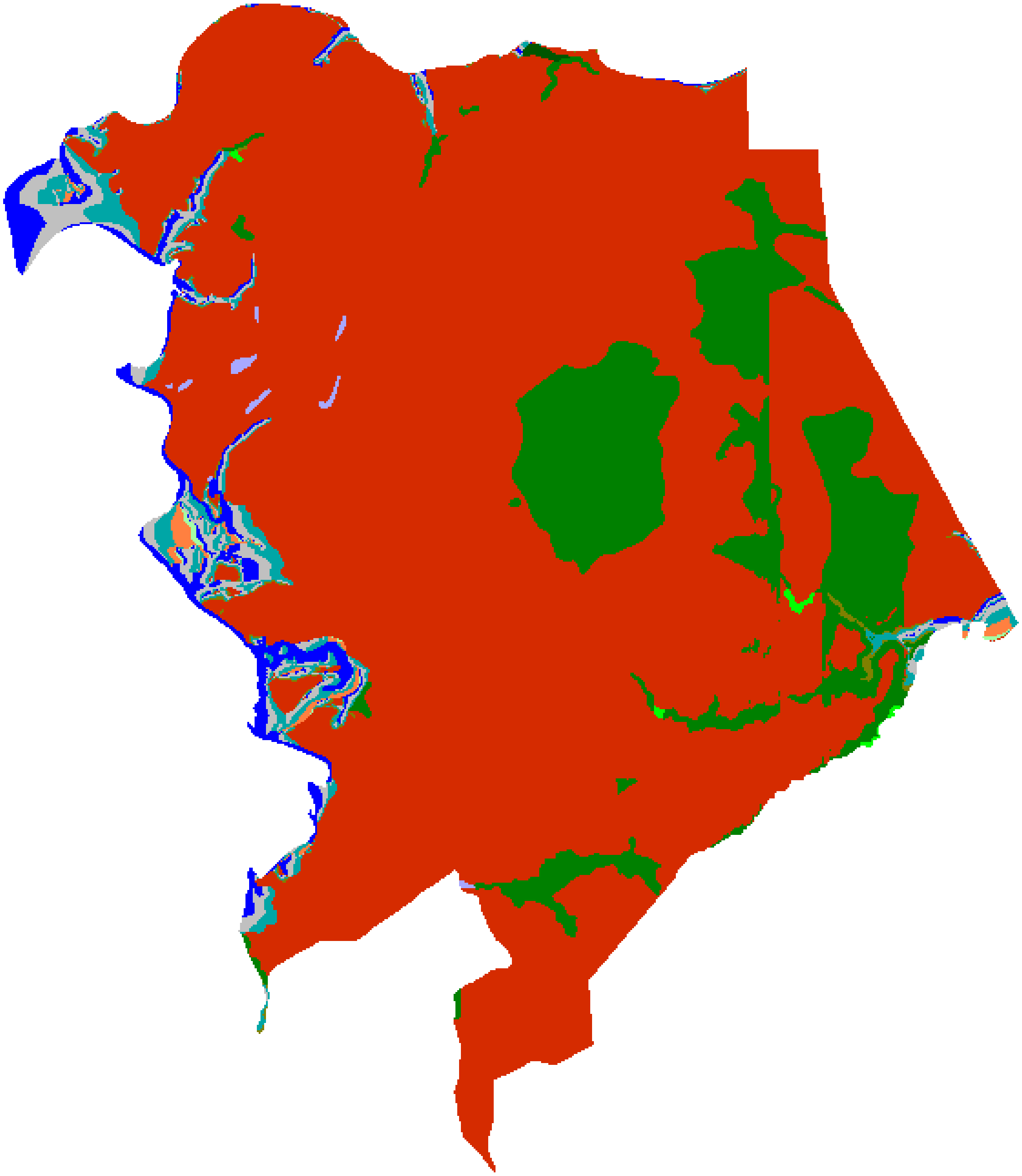
James River NWR, 2025, 1 meter



James River NWR, 2050, 1 meter



James River NWR, 2075, 1 meter

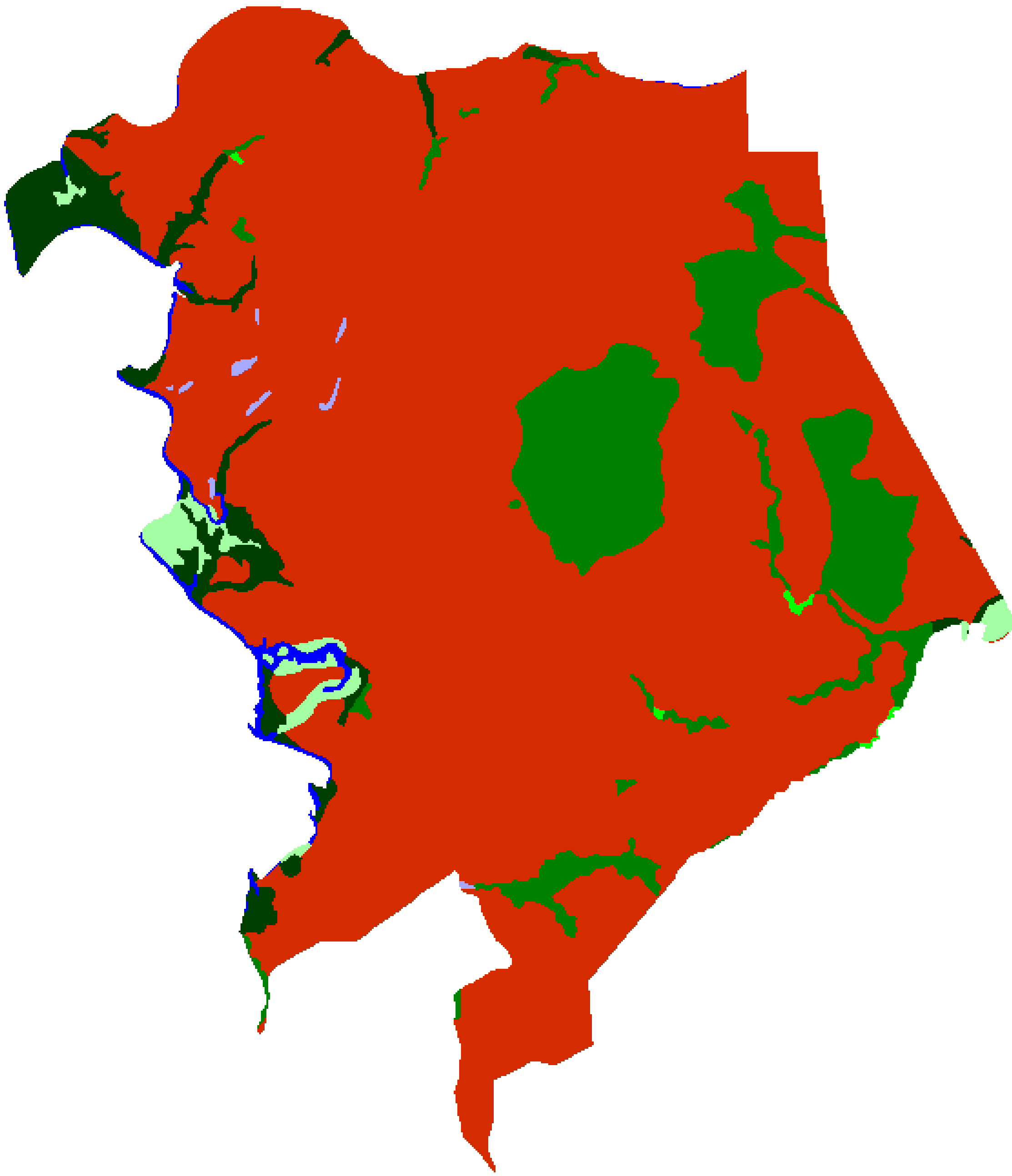


James River NWR, 2100, 1 meter

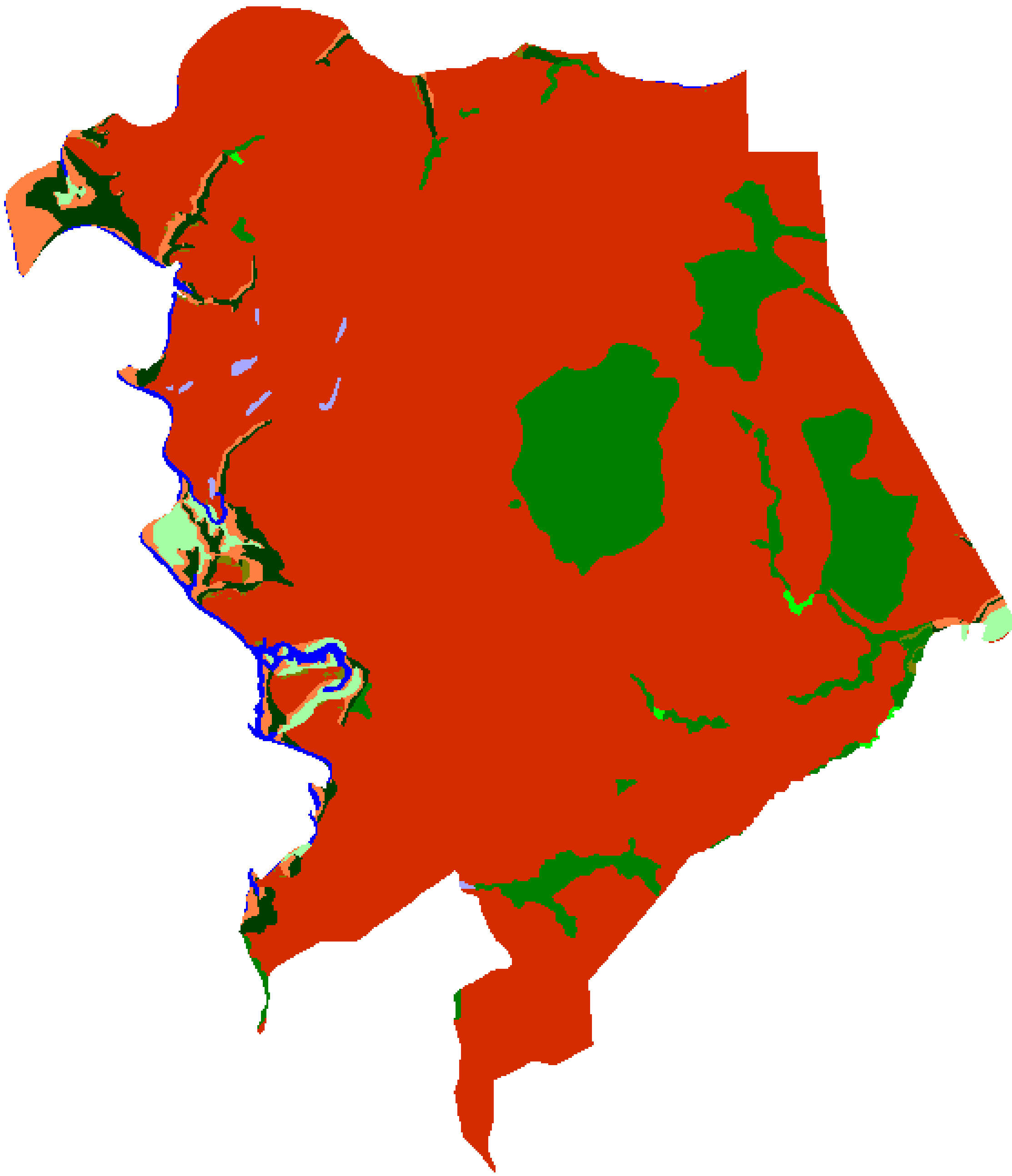
James River Raster
1.5 Meters Eustatic SLR by 2100

Results in Acres

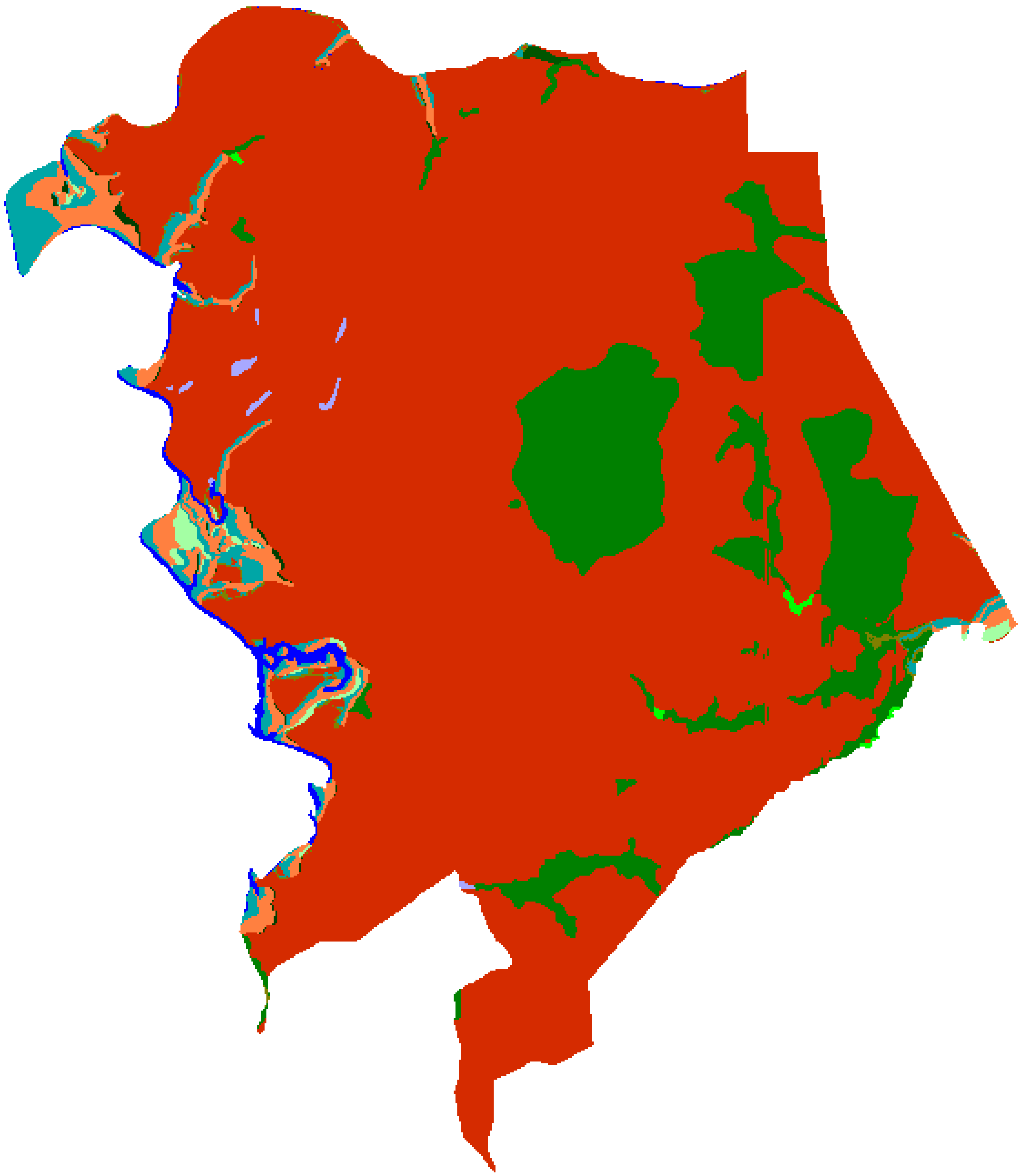
	Initial	2025	2050	2075	2100	Legend
Undeveloped Dry Land	3695.5	3686.3	3616.5	3581.9	3558.5	
Swamp	487.5	485.6	539.2	548.4	543.8	
Tidal Swamp	170.2	96.2	9.2	0.0	0.0	
Tidal Fresh Marsh	55.1	43.5	16.9	0.0	0.0	
Riverine Tidal	42.0	42.0	12.4	10.1	7.8	
Inland Open Water	8.2	8.2	7.7	7.6	7.5	
Inland Fresh Marsh	4.9	4.9	4.9	4.9	4.7	
Cypress Swamp	3.0	3.0	3.0	3.0	3.0	
Irregularly Flooded Marsh	0.0	85.5	113.7	26.0	0.0	
Regularly Flooded Marsh	0.0	0.0	96.6	129.6	51.5	
Estuarine Open Water	0.0	0.0	30.5	41.0	133.7	
Transitional Salt Marsh	0.0	11.1	15.9	25.6	28.5	
Tidal Flat	0.0	0.0	0.0	88.3	127.3	
Total (incl. water)	**4466.4**	**4466.4**	**4466.4**	**4466.4**	**4466.4**	



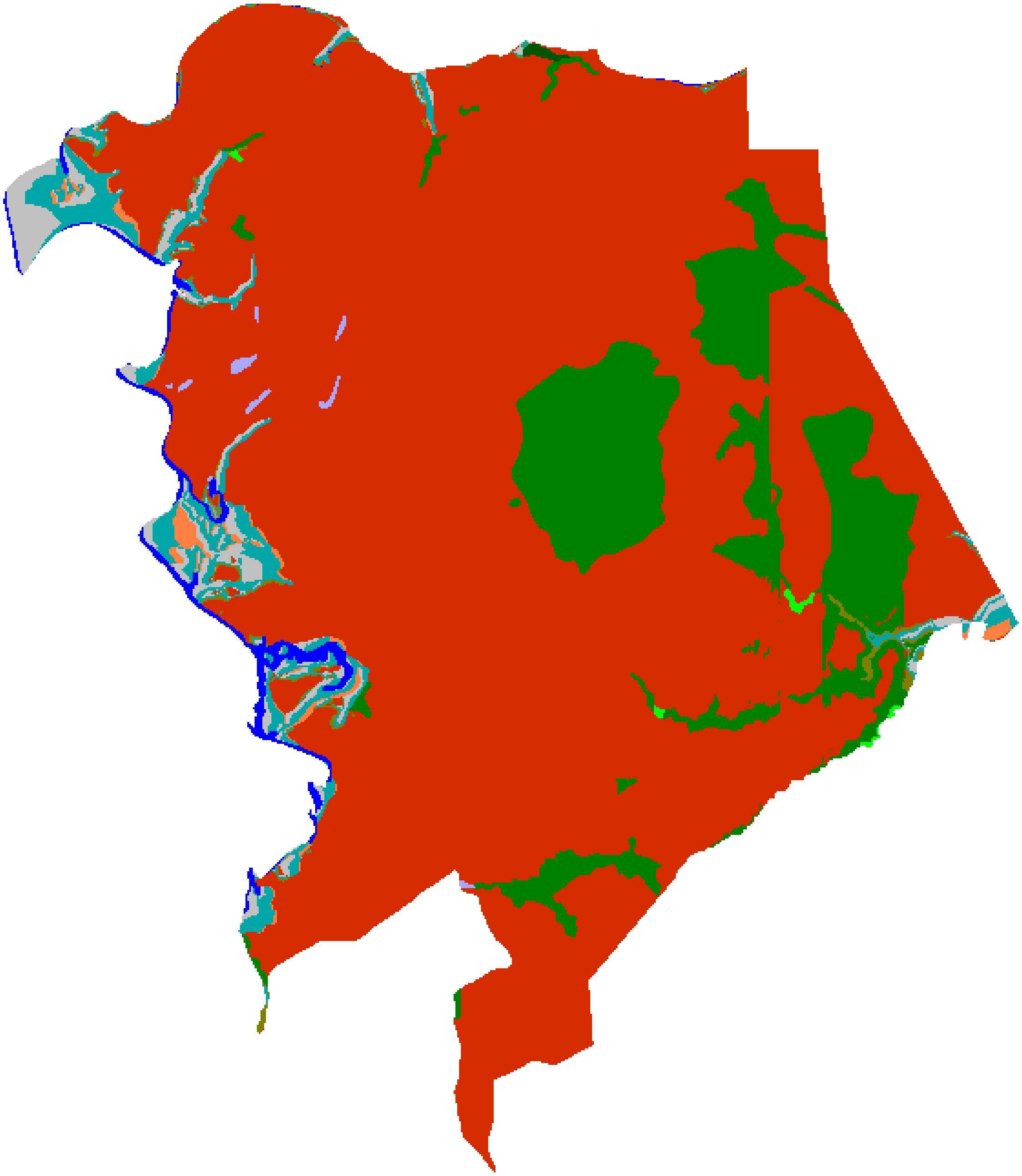
James River NWR, Initial Condition



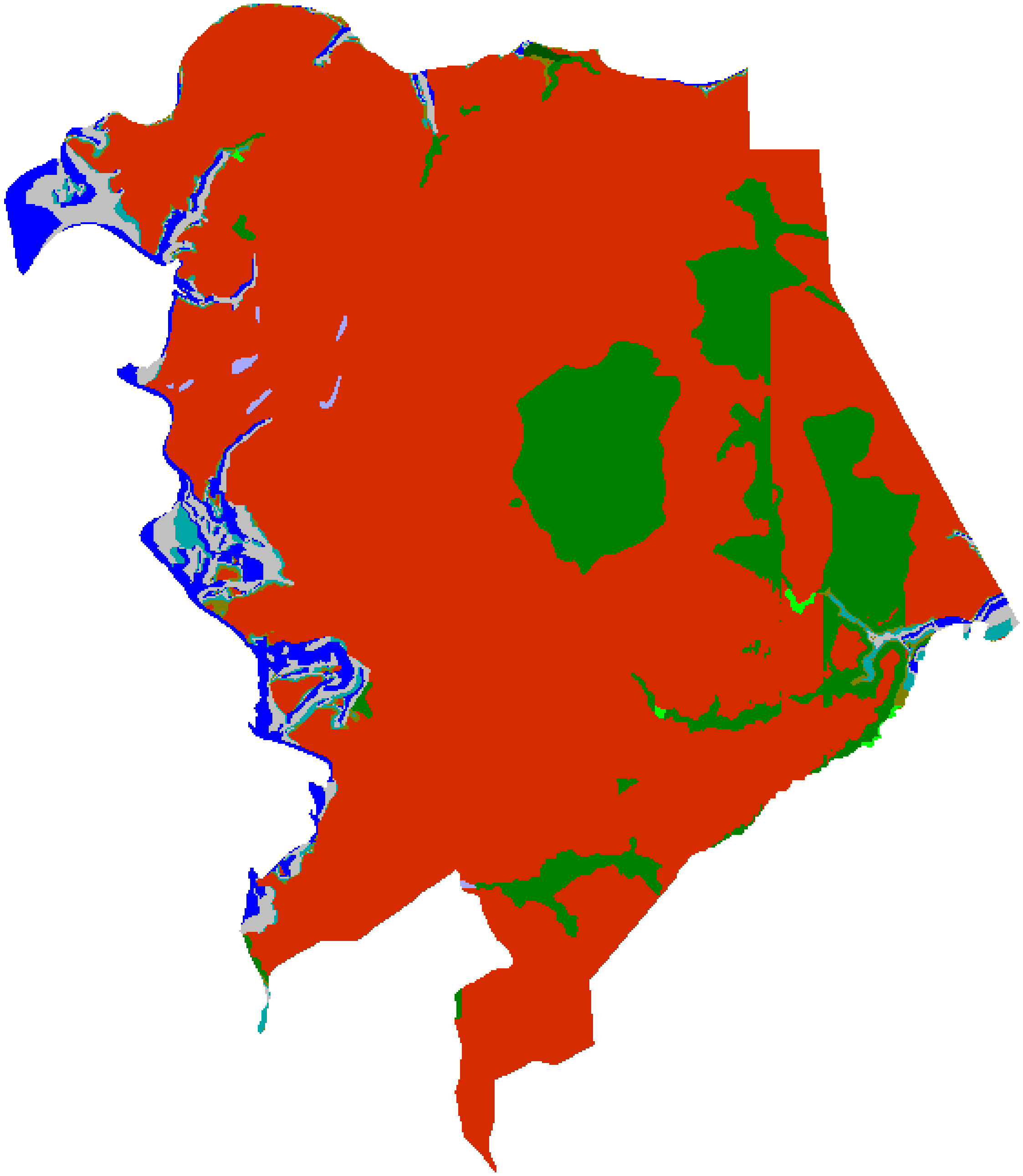
James River NWR, 2025, 1.5 meter



James River NWR, 2050, 1.5 meter



James River NWR, 2075, 1.5 meter

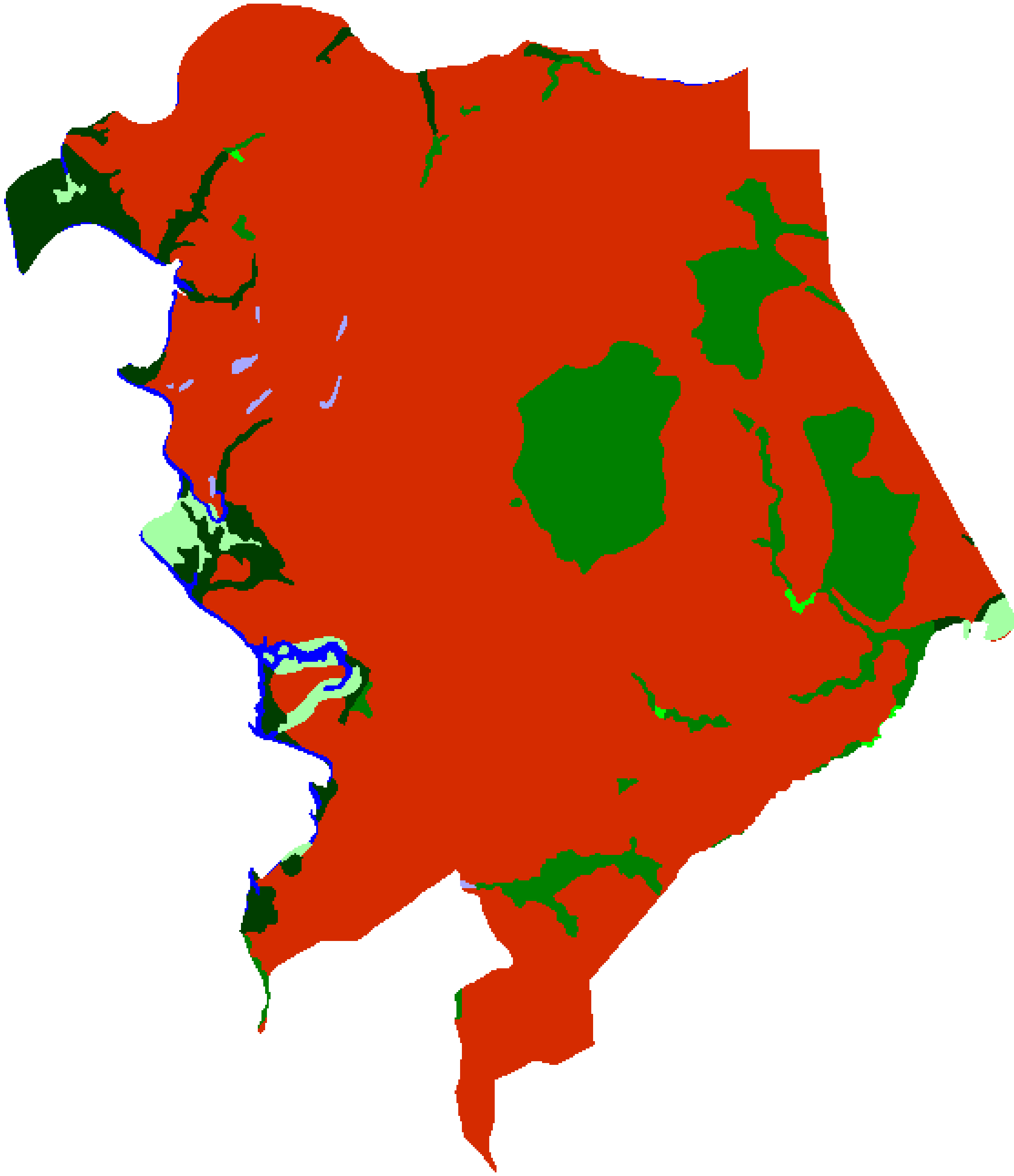


James River NWR, 2100, 1.5 meter

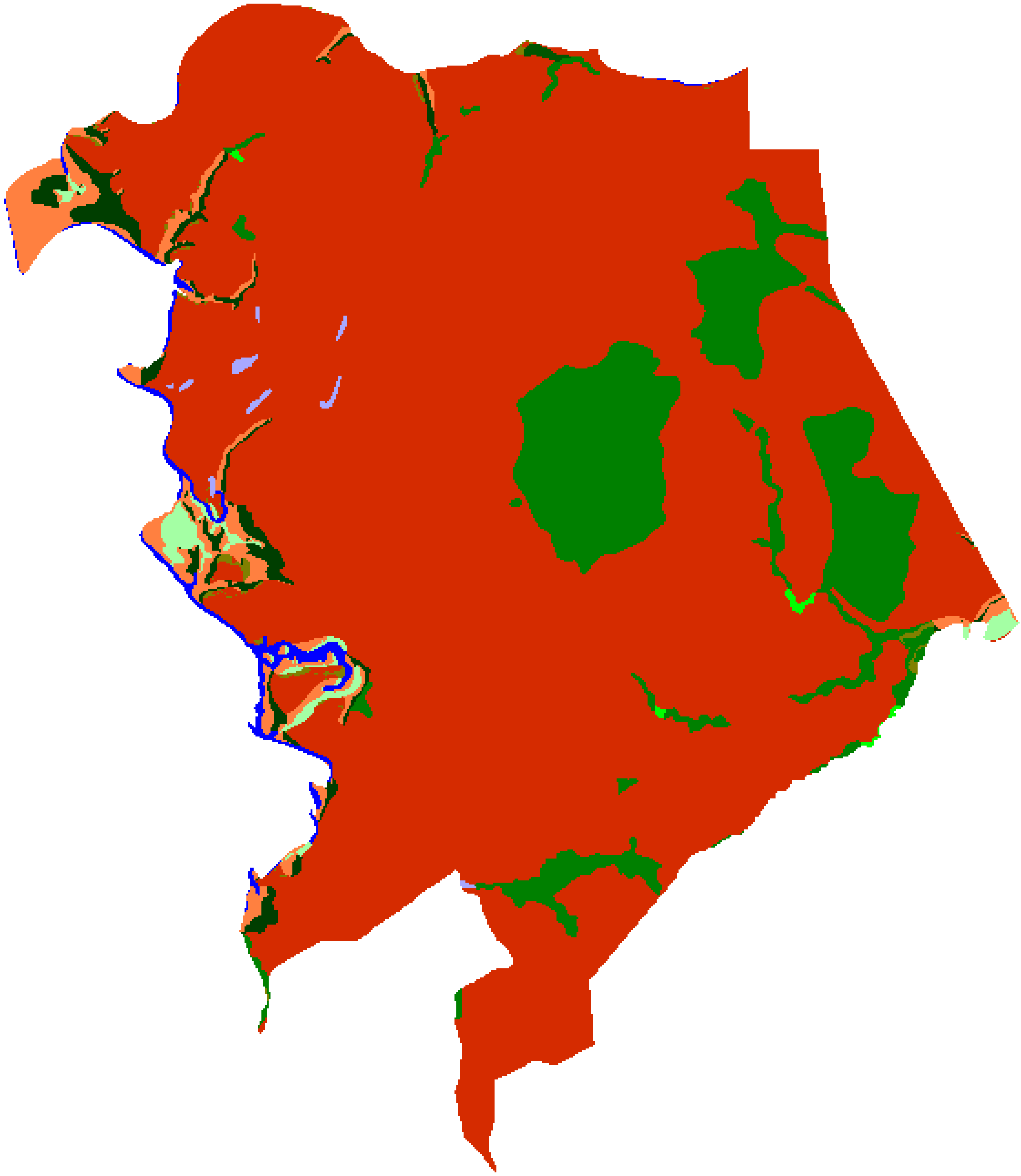
James River Raster
2 Meters Eustatic SLR by 2100

Results in Acres

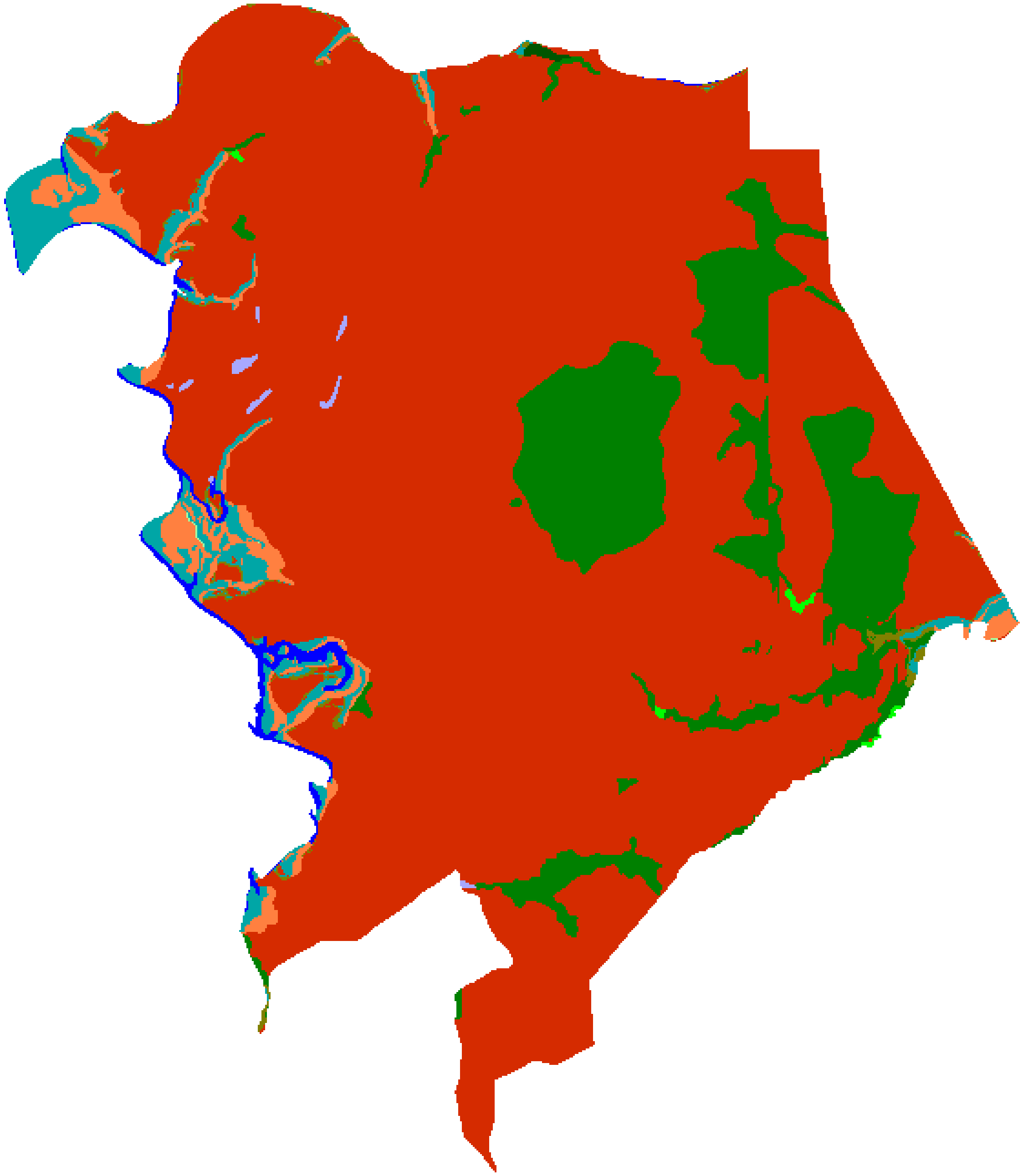
	Initial	2025	2050	2075	2100	Legend
Undeveloped Dry Land	3695.5	3684.4	3603.2	3566.9	3536.9	
Swamp	487.5	484.9	542.8	543.5	539.5	
Tidal Swamp	170.2	74.1	0.0	0.0	0.0	
Tidal Fresh Marsh	55.1	32.6	0.9	0.0	0.0	
Riverine Tidal	42.0	42.0	11.5	8.4	6.3	
Inland Open Water	8.2	8.2	7.6	7.5	7.5	
Inland Fresh Marsh	4.9	4.9	4.9	4.7	4.3	
Cypress Swamp	3.0	3.0	3.0	3.0	3.0	
Irregularly Flooded Marsh	0.0	118.5	105.8	1.0	0.0	
Regularly Flooded Marsh	0.0	0.0	132.3	128.9	37.0	
Estuarine Open Water	0.0	0.0	31.2	43.0	170.3	
Transitional Salt Marsh	0.0	13.8	23.1	36.0	34.6	
Tidal Flat	0.0	0.0	0.0	123.4	127.2	
Total (incl. water)	**4466.4**	**4466.4**	**4466.4**	**4466.4**	**4466.4**	



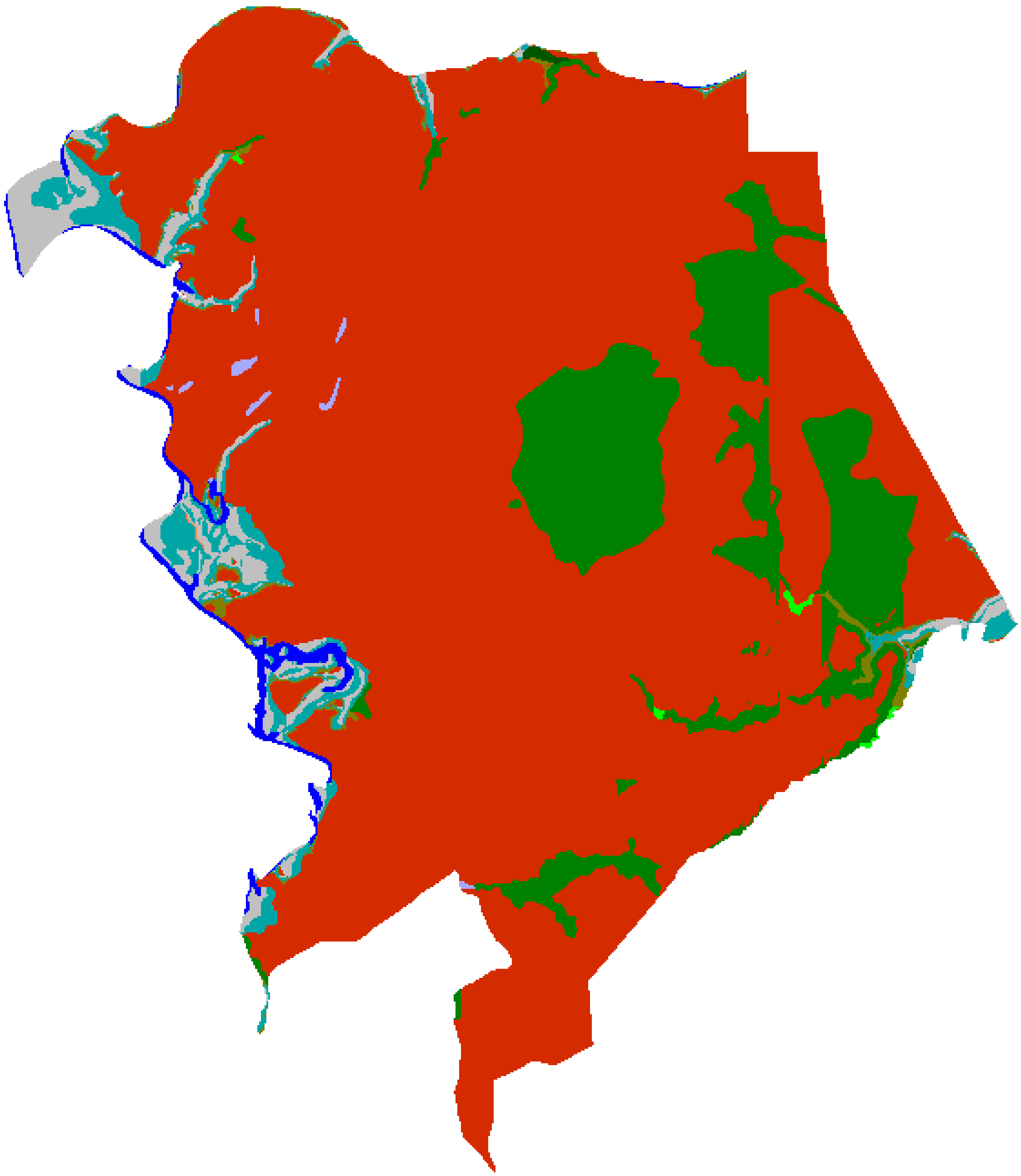
James River NWR, Initial Condition



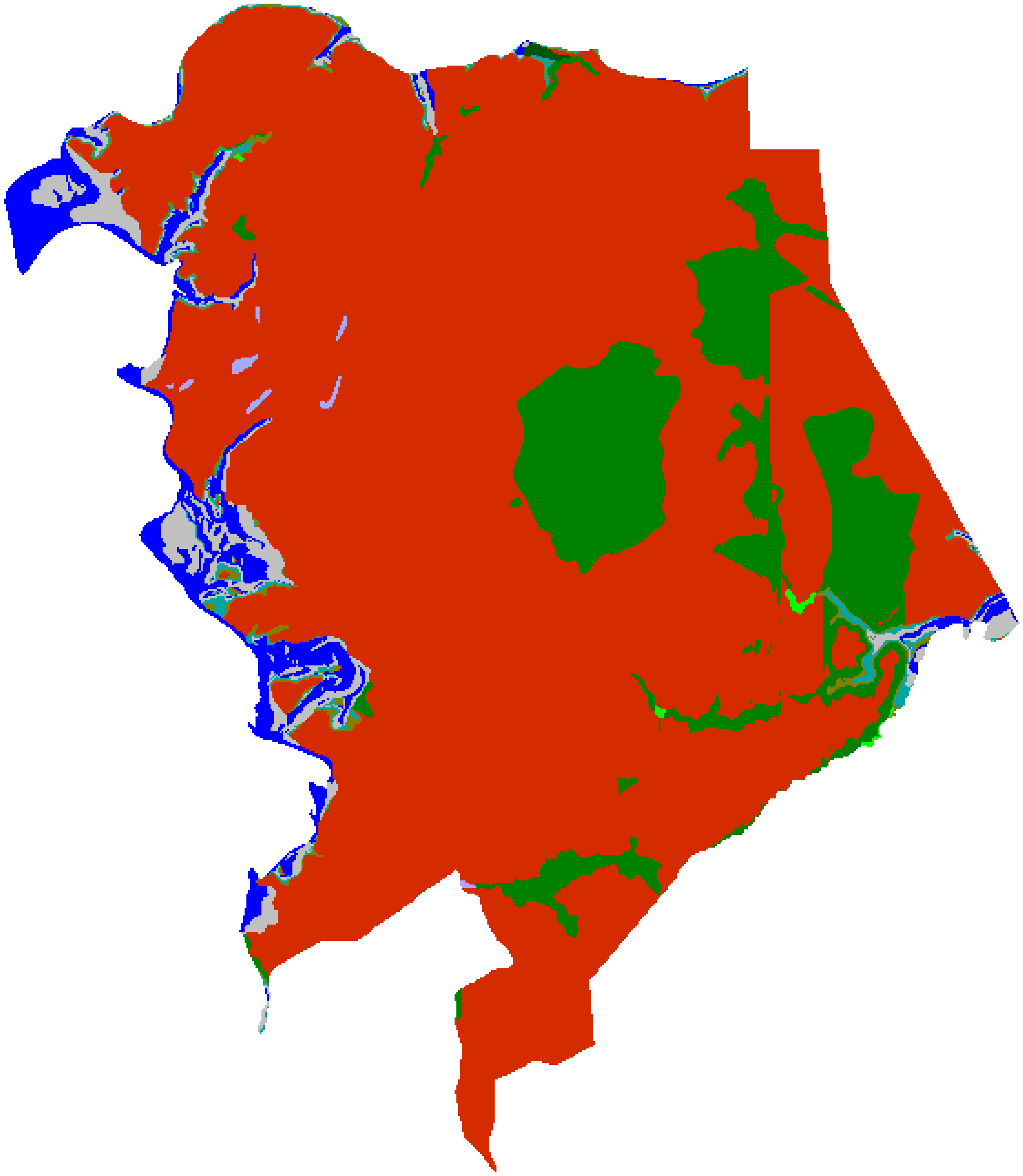
James River NWR, 2025, 2 meters



James River NWR, 2050, 2 meters



James River NWR, 2075, 2 meters



James River NWR, 2100, 2 meters

Discussion

Dry lands, inland-fresh marshes, and non-tidal swamps are predicted to be relatively resilient to sea-level rise at James River refuge. Initial-condition elevations for these categories place them above the predicted effects of inundation in nearly all future scenarios of sea-level rise.

On the other hand, tidal-fresh marsh and tidal swamps are predicted to sustain significant losses. It must be noted that SLAMM predictions regarding tidal fresh marsh and tidal swamps at this site carry a significant amount of uncertainty. Nearly all of the tidal swamp and tidal fresh marsh lie below the first contour of the elevation data source, so there is essentially no elevation data for these wetland categories (Figure 3 on page 6). To compensate for this lack of elevation data, the elevations in these areas were estimated as a function of tide-range. As noted above, this process is subject to considerable uncertainty, especially for these particular wetland categories. Future SLAMM simulations of the region would considerably benefit from high vertical-resolution LiDAR data.

SLAMM uses a default tidal-swamp accretion rate of 1.1 mm/year based on data taken in GA swamps (Craft et. al, 2009). Considering that vulnerable areas of this refuge consist extensively of tidal swamp, future simulations would benefit from additional measurements of tidal-swamp accretion rates.

References

Cahoon, D.R., J. W. Day, Jr., and D. J. Reed, 1999. "The influence of surface and shallow subsurface soil processes on wetland elevation: A synthesis." *Current Topics in Wetland Biogeochemistry*, 3, 72-88.

Chen, J. L., Wilson, C. R., Tapley, B. D., 2006 "Satellite Gravity Measurements Confirm Accelerated Melting of Greenland Ice Sheet" *Science* 2006 0: 1129007

Clark, J. S. and W. A. Patterson III. 1984. Pollen, Pb-210 and sedimentation in the intertidal environment. Journal of Sedimentary Petrology 54(4):1249-1263.

Clough, J.S. Park, R.A. and R. Fuller, 2010, *SLAMM Technical Documentation, Release 6.0 beta, Draft,* January 2010, http://warrenpinnacle.com/prof/SLAMM

Craft C, Clough J, Ehman J, Guo H, Joye S, Machmuller M, Park R, and Pennings S. Effects of Accelerated Sea Level Rise on Delivery of Ecosystem Services Provided by Tidal Marshes: A Simulation of the Georgia (USA) Coast. *Frontiers in Ecology and the Environment.* 2009; 7, doi:10.1890/070219

Council for Regulatory Environmental Modeling, (CREM) 2008. *Draft guidance on the development, evaluation, and application of regulatory environmental* models P Pascual, N Stiber, E Sunderland - Washington DC: Draft, August 2008

Erwin, RM, GM Sanders, DJ Prosser, and DR Cahoon. 2006. High tides and rising seas: potential effects on estuarine waterbirds. Pages 214-228 in: Terrestrial Vertebrates of Tidal Marshes: Evolution, Ecology, and Conservation (R. Greenberg, J. Maldonado, S. Droege, and M.V. McDonald, eds.). Studies in Avian Biology No. 32, Cooper Ornithological Society.

Glick, Clough, et al. *Sea-level Rise and Coastal Habitats in the Pacific Northwest An Analysis for Puget Sound, Southwestern Washington, and Northwestern Oregon* July 2007 http://www.nwf.org/sealevelrise/pdfs/PacificNWSeaLevelRise.pdf

Hawaii Office of State Planning, Coastal Zone Management Program, 1992, Aerial Photography Analysis of Coastal Erosion on the Islands of Kauai, Molokai, Lanai, Maui, and Hawaii, June 1991, Prepared by Makai Ocean Engineering, Inc and Sea Engineering, Inc.

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* [Houghton, J.T.,Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K.Maskell, and C.A. Johnson (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 881pp.

IPCC, 2007. *Climate Change 2007 - The Physical Science Basis: Contribution of Working Group I to the Fourth Assessment Report of the IPCC. Cambridge: Cambridge University Press.* ISBN 978 0521 88009-1.

Lee, J.K., R.A. Park, and P.W. Mausel. 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. *et al,* 2006 "Insignificant Change in Antarctic Snowfall Since the International Geophysical Year" *Science* 2006 313: 827-831.

National Wildlife Fed 'n et al., *An Unfavorable Tide: Global Warming, Coastal Habitats and Sportfishing in Florida* 4, 6 (2006). http://www.targetglobalwarming.org/files/AnUnfavorableTideReport.pdf

Pakenham, Anna. (2009). Patterns of Sediment Accumulation in the Siletz River Estuary, Oregon (Dissertation). Oregon State University.

Park, R.A., J.K. Lee, and D. Canning. 1993. Potential Effects of Sea Level Rise on Puget Sound Wetlands. *Geocarto International* 8(4):99-110.

Park, R.A., M.S. Trehan, P.W. Mausel, and R.C. Howe. 1989a. The Effects of Sea Level Rise on U.S. Coastal Wetlands. In *The Potential Effects of Global Climate Change on the United States: Appendix B - Sea Level Rise,* edited by J.B. Smith and D.A. Tirpak, 1-1 to 1-55. EPA-230-05-89-052. Washington, D.C.: U.S. Environmental Protection Agency.

Park, RA, JK Lee, PW Mausel and RC Howe. 1991. Using remote sensing for modeling the impacts of sea level rise. *World Resources Review* 3:184-220.

Pfeffer, Harper, O'Neel, 2008. Kinematic Constraints on Glacier Contributions to 21st-Century Sea-Level Rise. *Science*, Vol. 321, No. 5894. (5 September 2008), pp. 1340-134

Rahmstorf, Stefan 2007, "A Semi-Empirical Approach to Projecting Future Sea-Level Rise," *Science* 2007 315: 368-370.

Reed, D.J., D.A. Bishara, D.R. Cahoon, J. Donnelly, M. Kearney, A.S. Kolker, L.L. Leonard, R.A. Orson, and J.C. Stevenson, 2008: "Site-Specific Scenarios for Wetlands Accretion in the Mid-Atlantic Region. Section 2.1" in *Background Documents Supporting Climate Change Science Program Synthesis and Assessment Product 4.1: Coastal Elevations and Sensitivity to Sea Level Rise*, J.G. Titus and E.M. Strange (eds.), EPA430R07004, Washington, DC: U.S. EPA. http://www.epa.gov/climatechange/effects/downloads/section2_1.pdf

Stevenson and Kearney, 2008, "Impacts of Global Climate Change and Sea-Level Rise on Tidal Wetlands" Pending chapter of manuscript by University of California Press.

Titus, J.G., R.A. Park, S.P. Leatherman, J.R. Weggel, M.S. Greene, P.W. Mausel, M.S. Trehan, S. Brown, C. Grant, and G.W. Yohe. 1991. Greenhouse Effect and Sea Level Rise: Loss of Land and the Cost of Holding Back the Sea. *Coastal Management* 19:2:171-204.

United States Fish and Wildlife Service, Federal Highway Administration Western Federal Lands Highway Division. 2009. Environmental Assessment for the Ni-les'tun Unit of the James River National Wildlife Refuge Restoration and North Bank Land Improvement Project

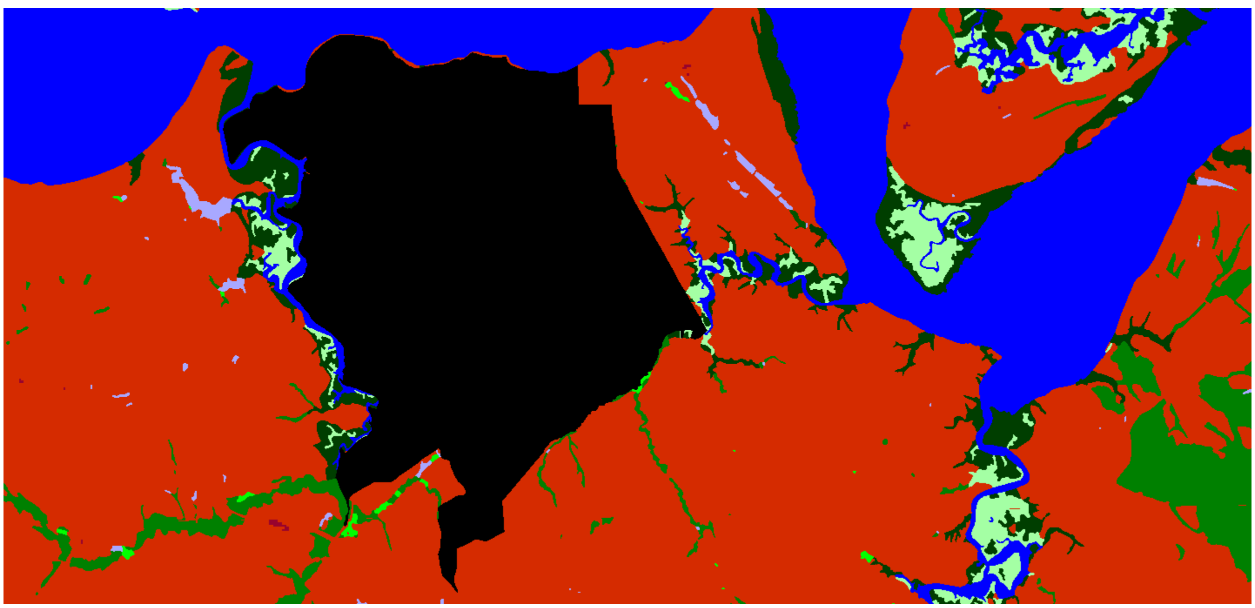
Vermeer, M., and Rahmstorf, S. 2009. Global sea level linked to global temperature. *Proceedings of the National Academy of Sciences*, 2009; DOI: 10.1073/pnas.0907765106.

Appendix A: Contextual Results

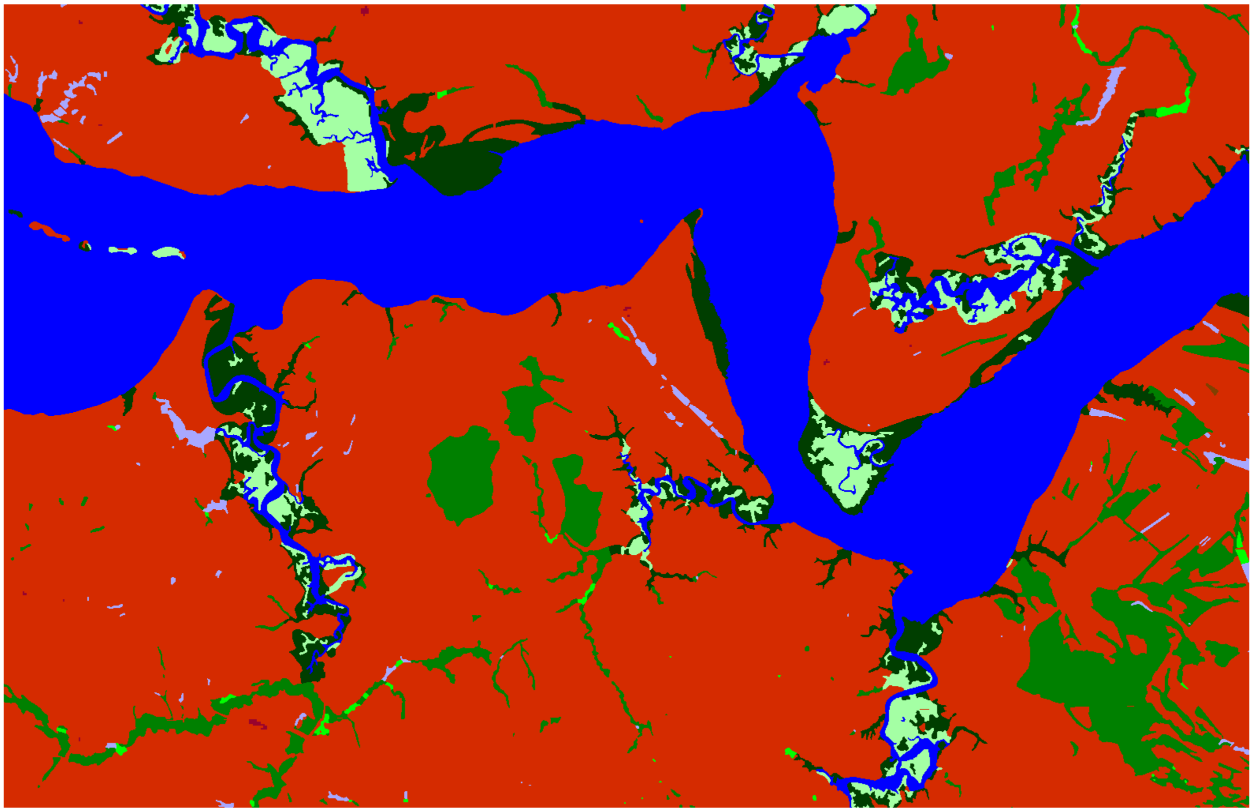
The SLAMM model does take into account the context of the surrounding lands or open water when calculating effects. For example, erosion rates are calculated based on the maximum fetch (wave action) which is estimated by assessing contiguous open water to a given marsh cell. Another example is that inundated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

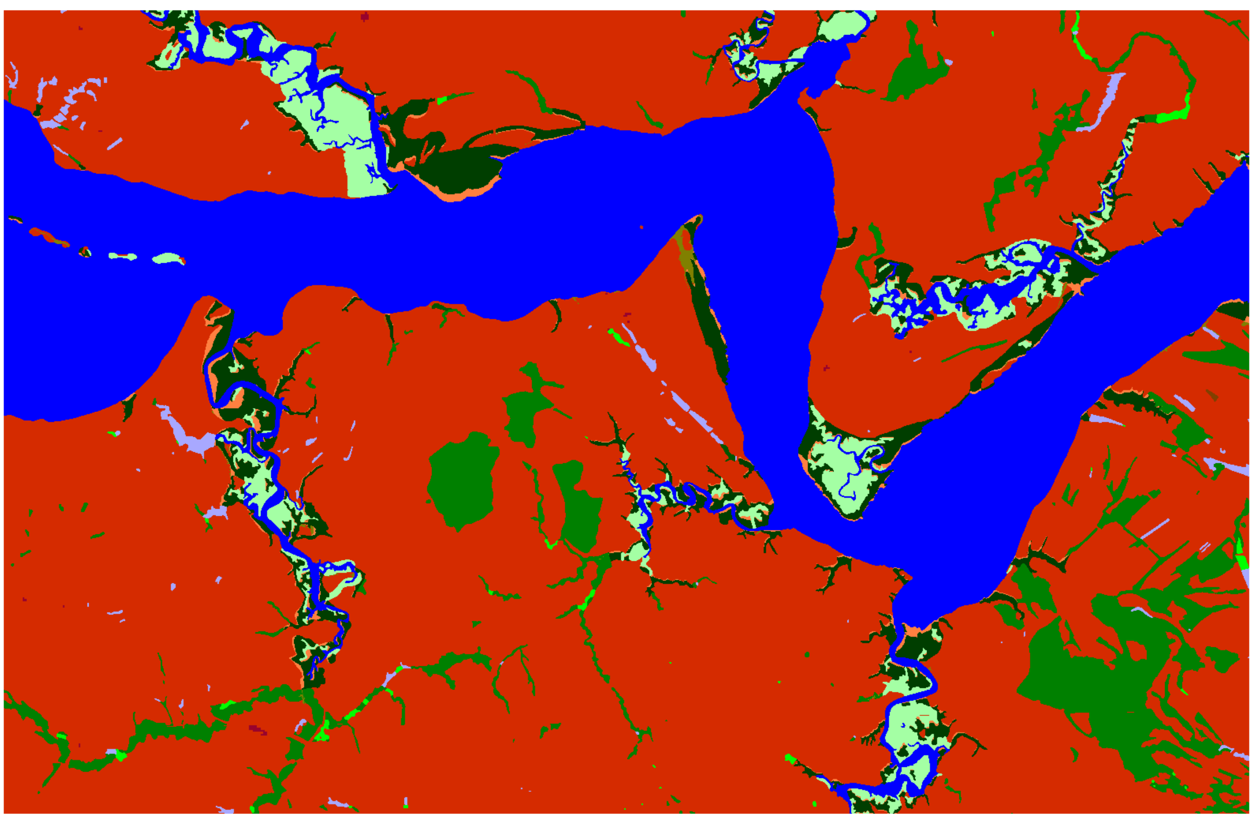
- Results were closely examined (quality assurance) within USFWS refuges but not closely examined for the larger region.
- Site-specific parameters for the model were derived for USFWS refuges whenever possible and may not be regionally applicable.
- Especially in areas where dikes are present, an effort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



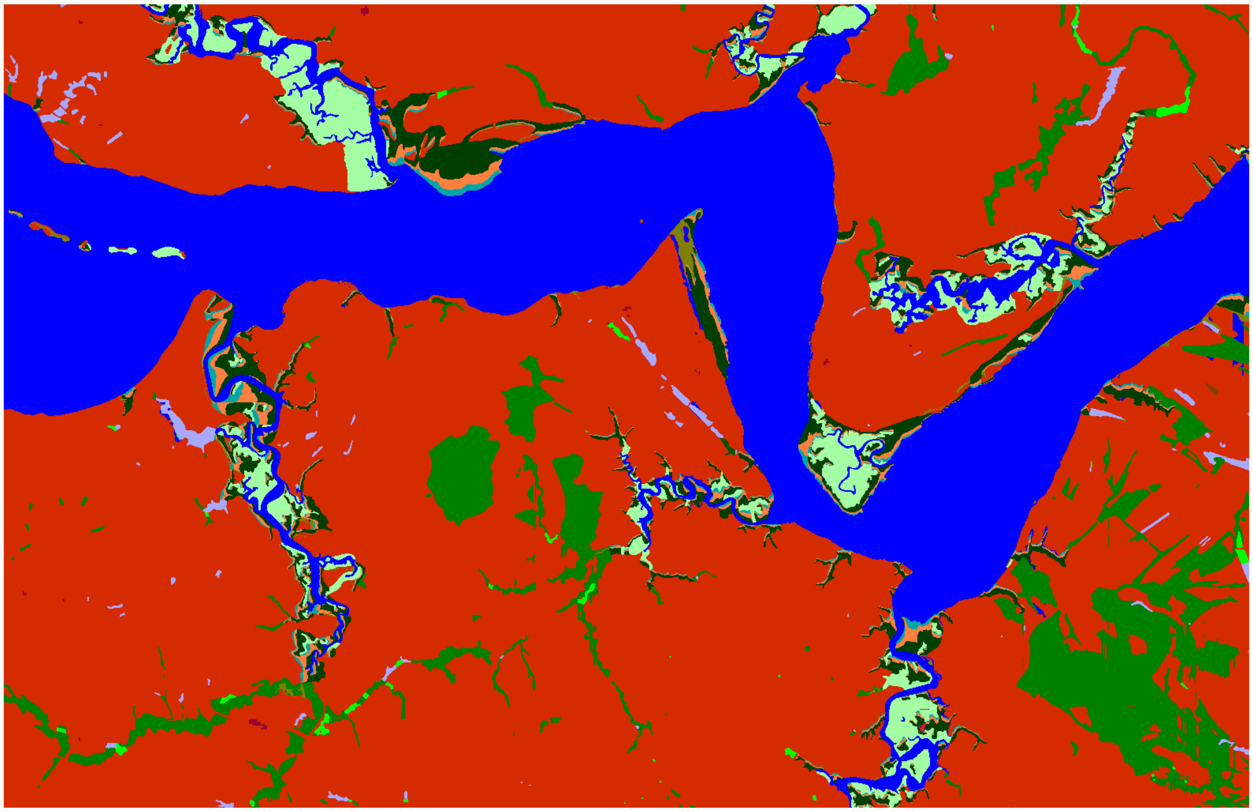
James River National Wildlife Refuge within simulation context (black).



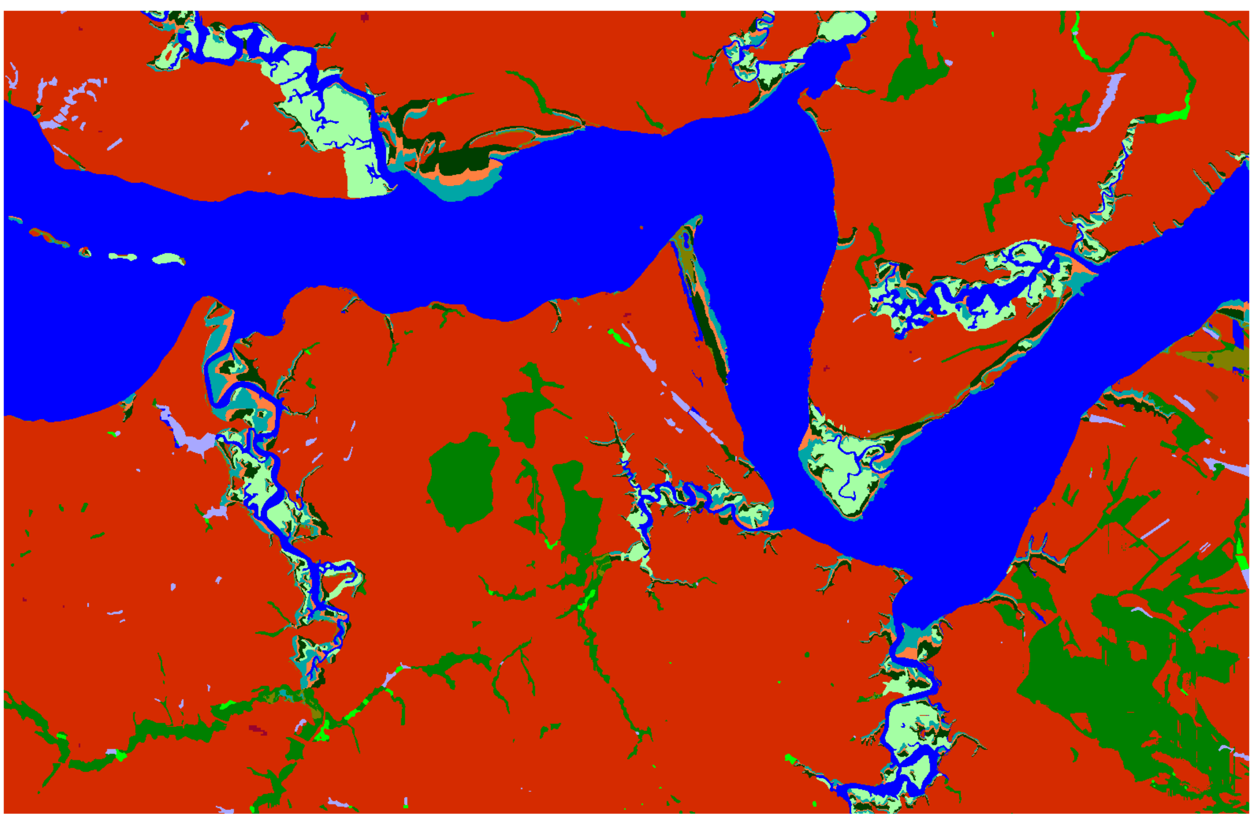
James River Context, Initial Condition



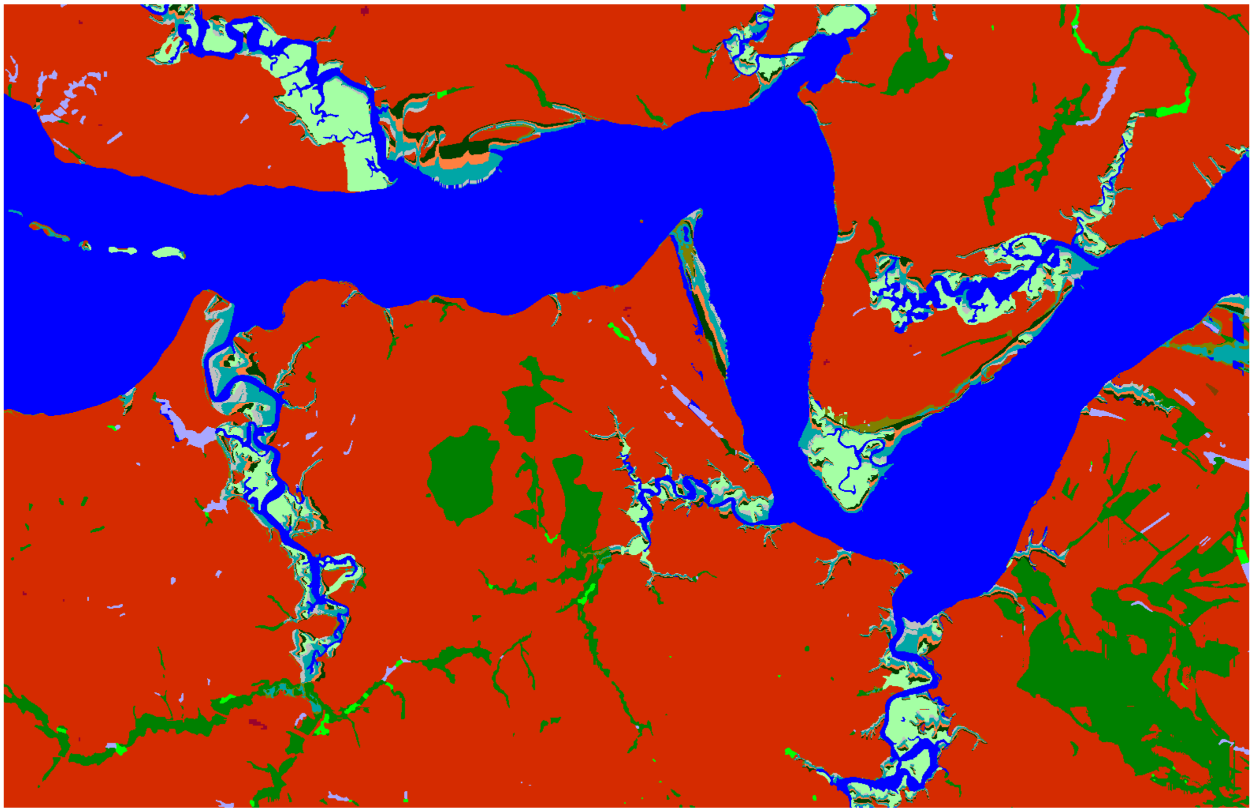
James River Context, 2025, Scenario A1B Mean



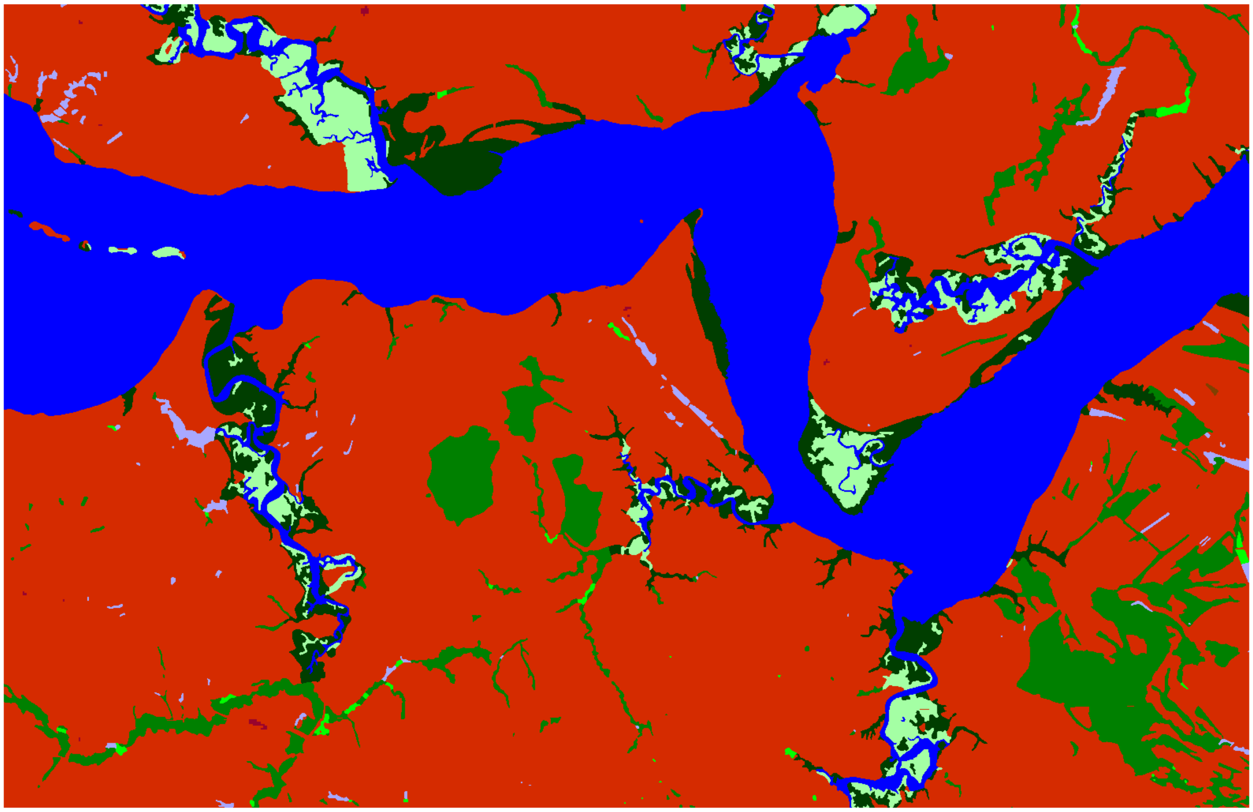
James River Context, 2050, Scenario A1B Mean



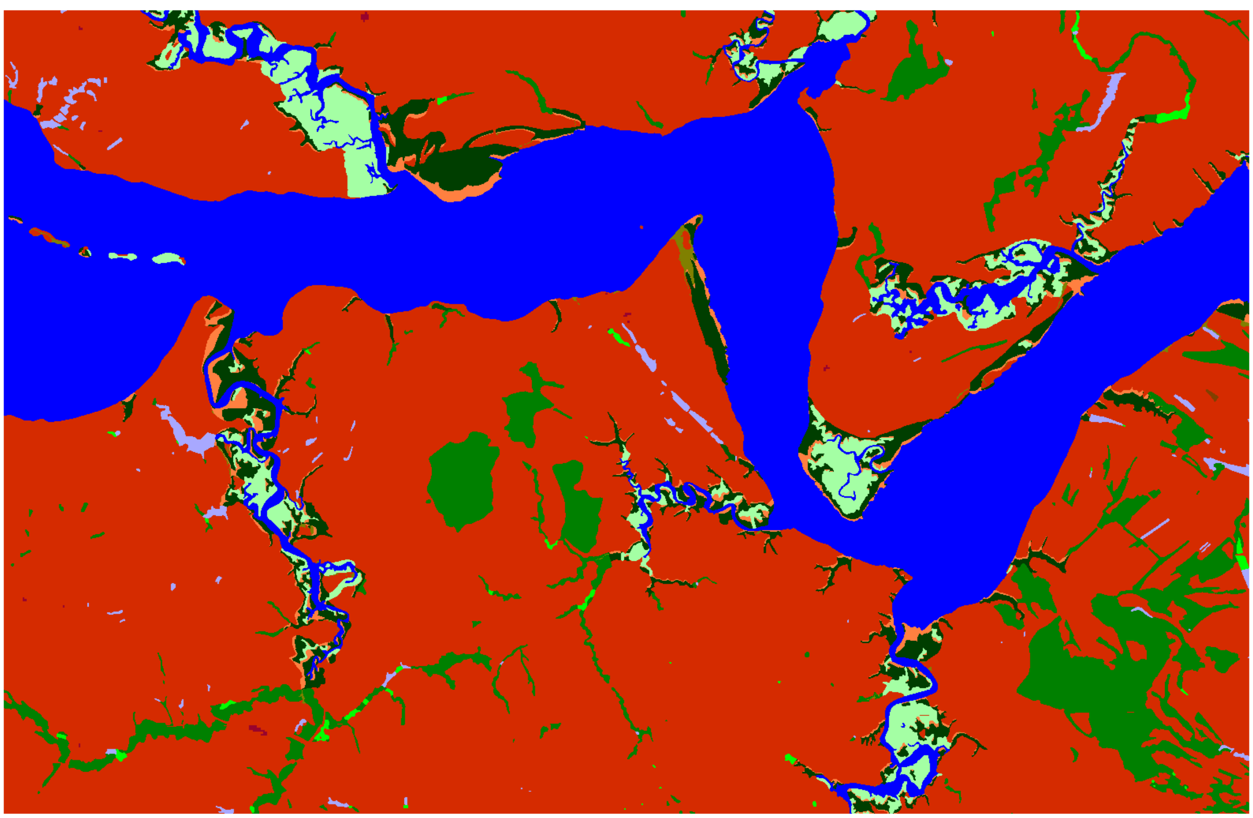
James River Context, 2075, Scenario A1B Mean



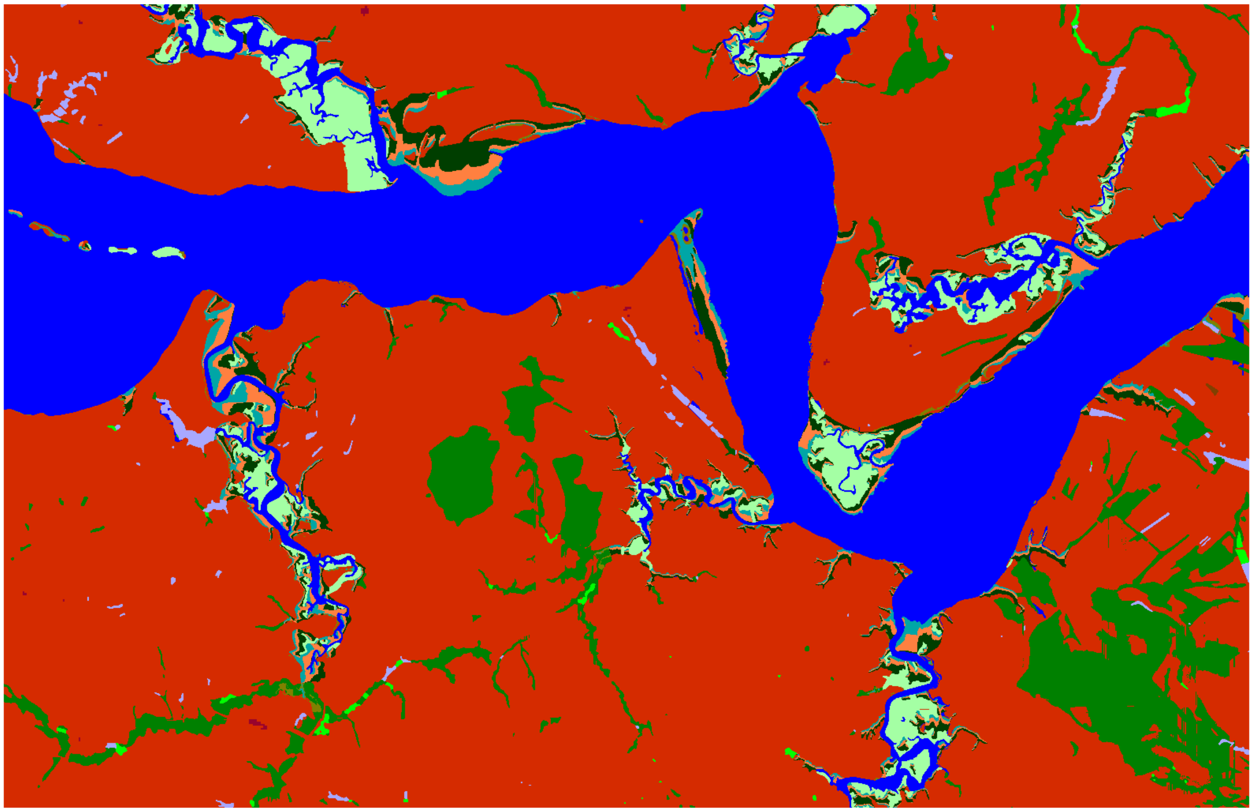
James River Context, 2100, Scenario A1B Mean

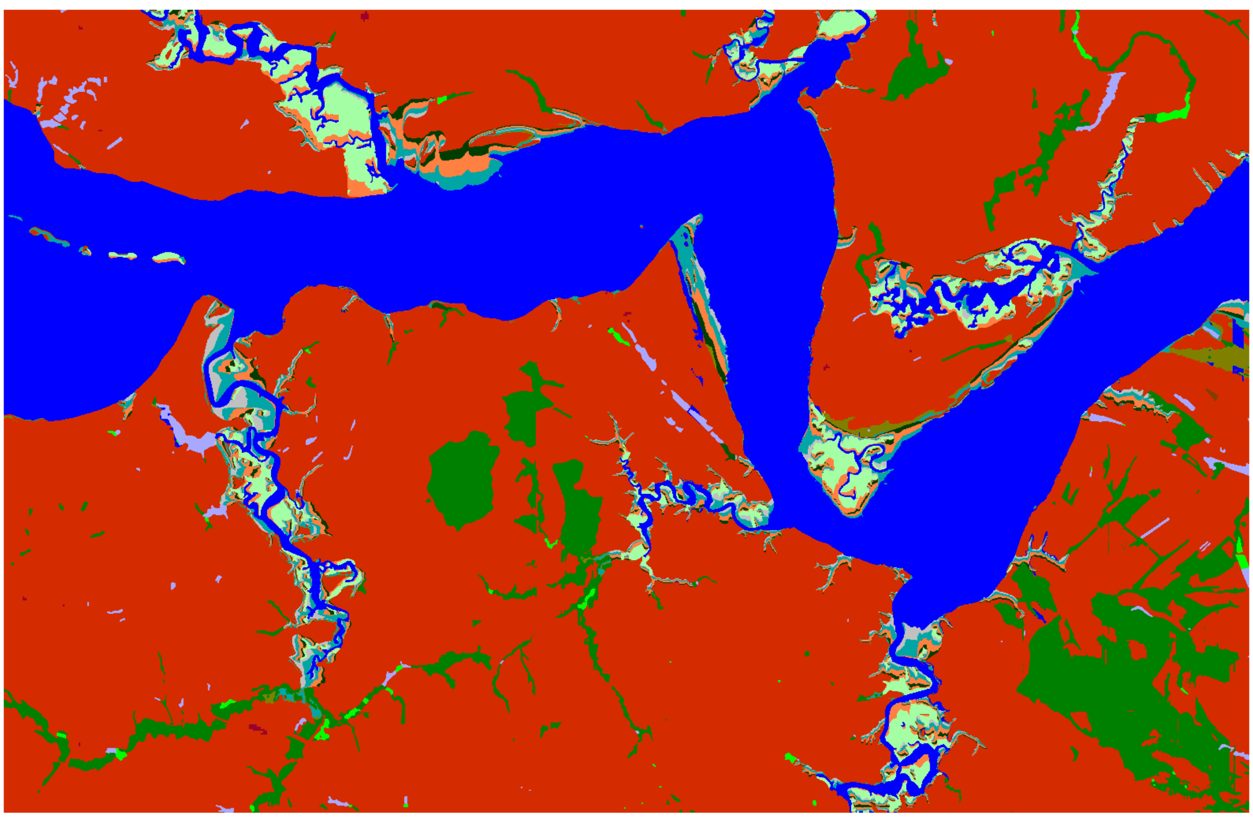


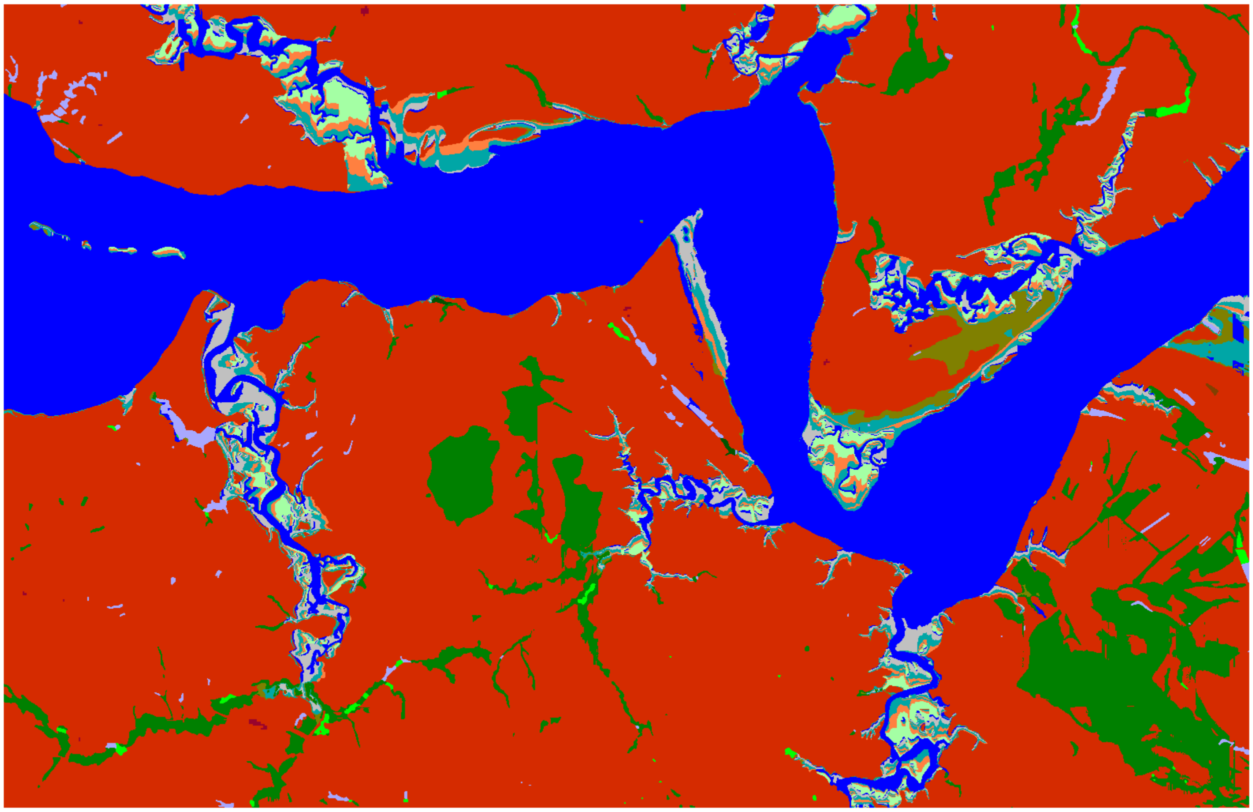
James River Context, Initial Condition



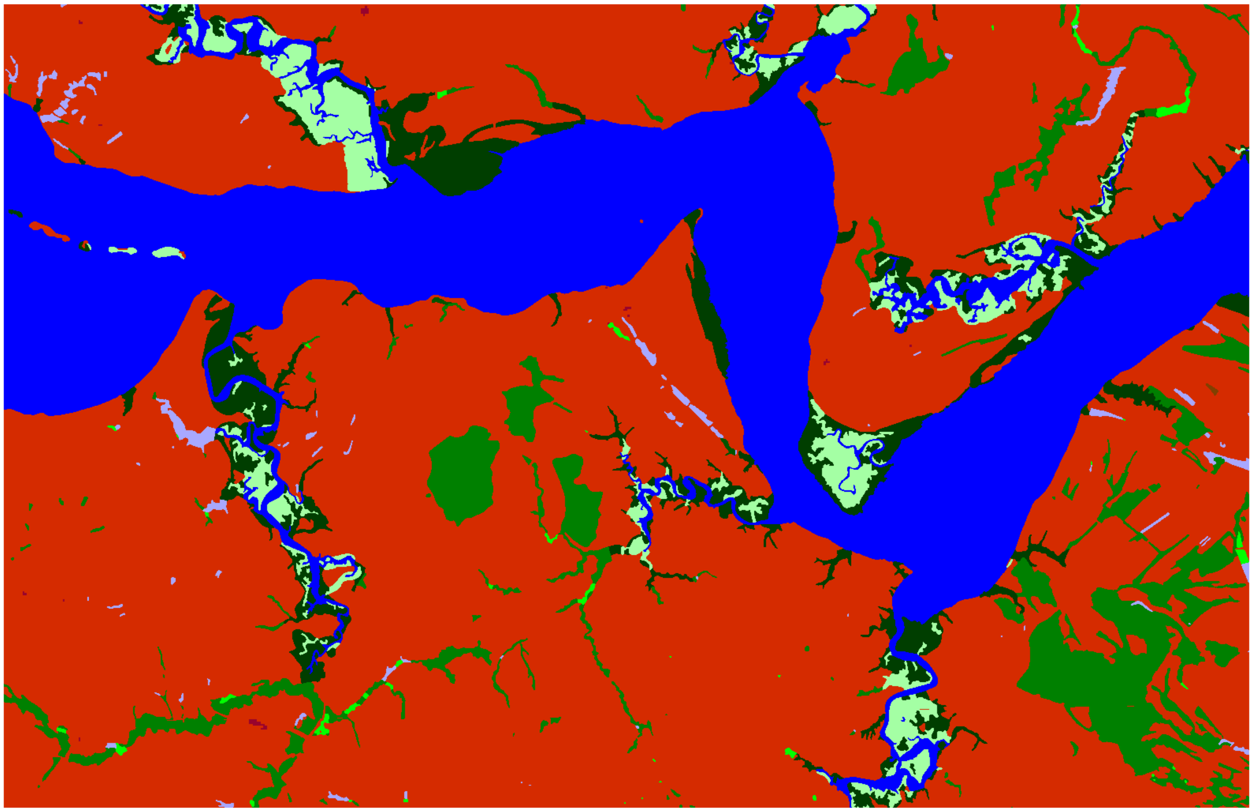
James River Context, 2025, Scenario A1B Maximum


James River Context, 2050, Scenario A1B Maximum

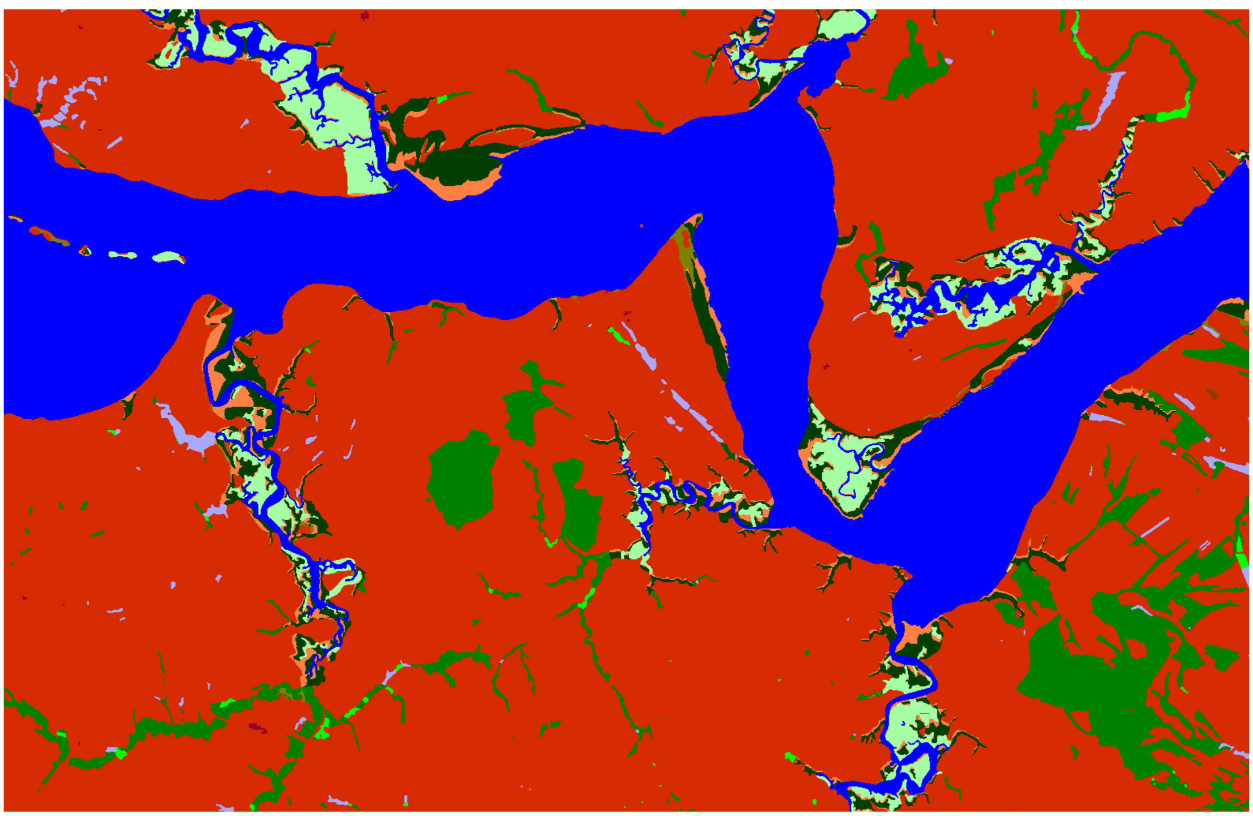

James River Context, 2075, Scenario A1B Maximum



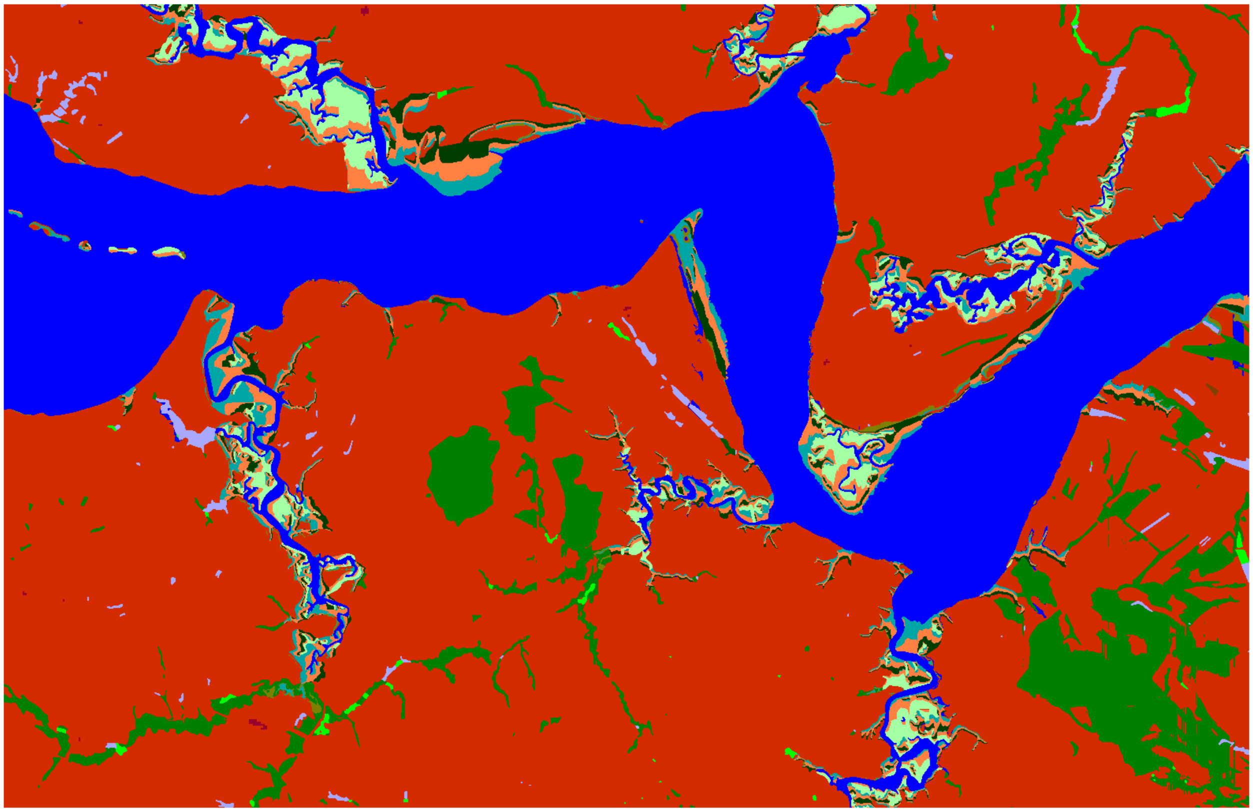
James River Context, 2100, Scenario A1B Maximum



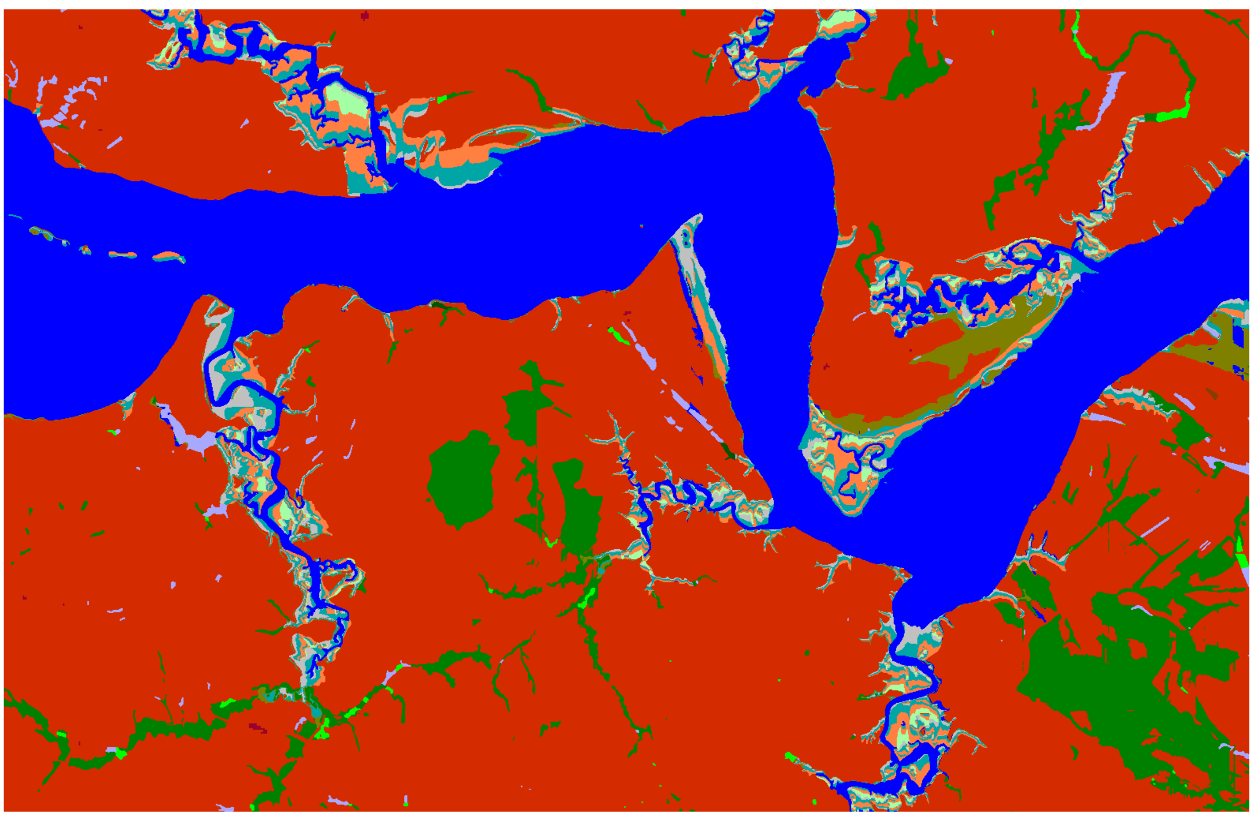
James River Context, Initial Condition



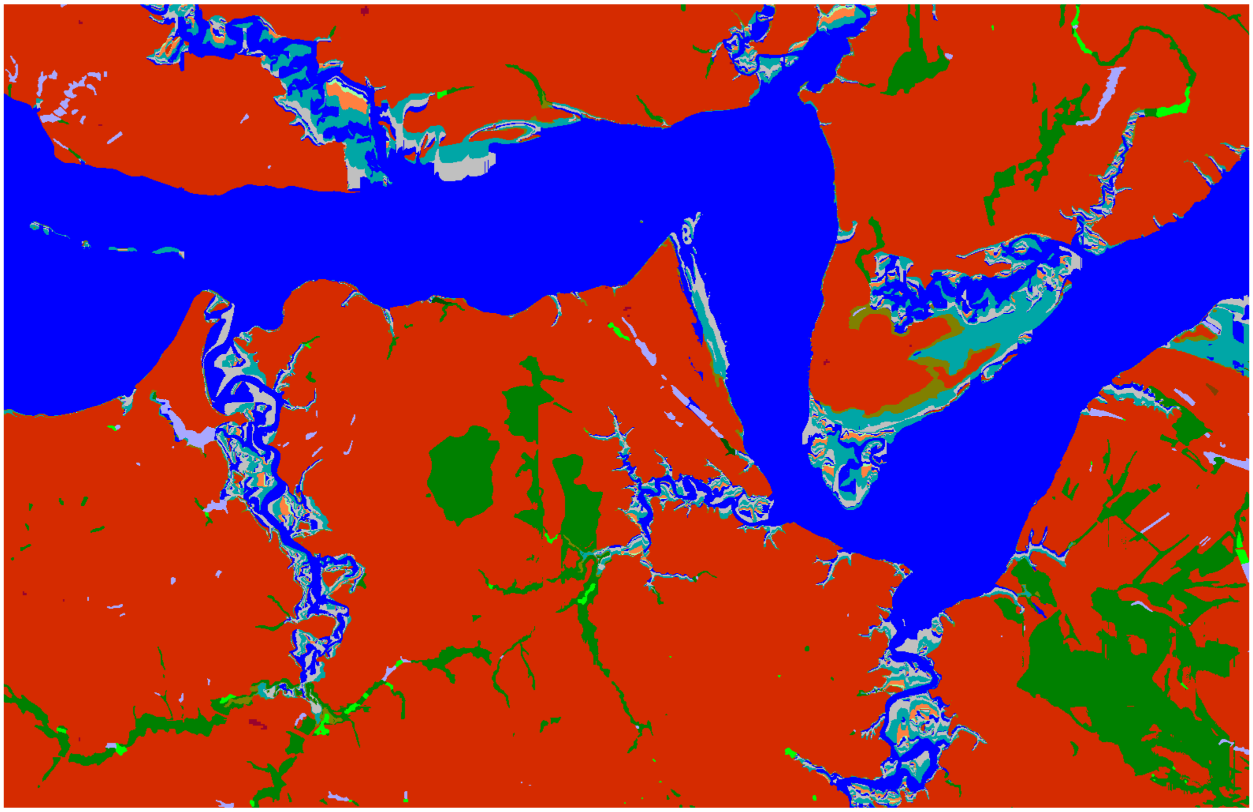
James River Context, 2025, 1 meter



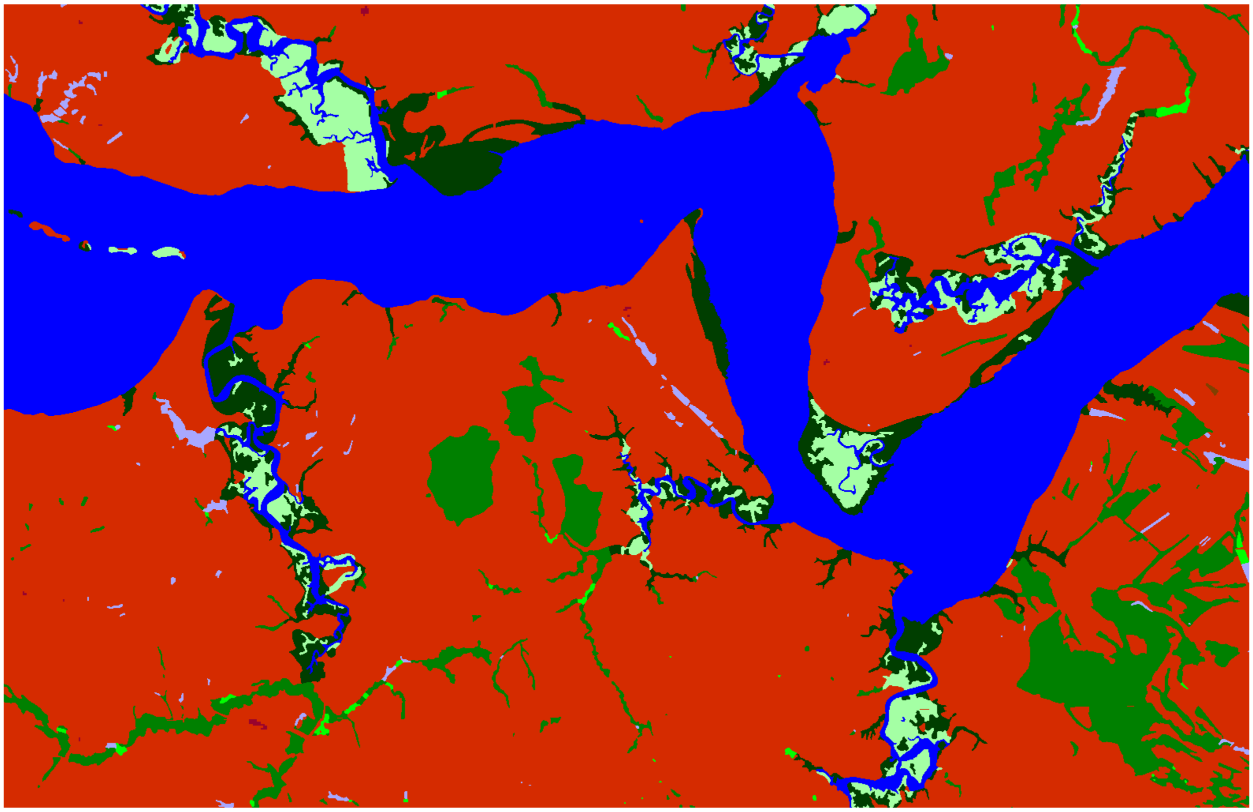
James River Context, 2050, 1 meter



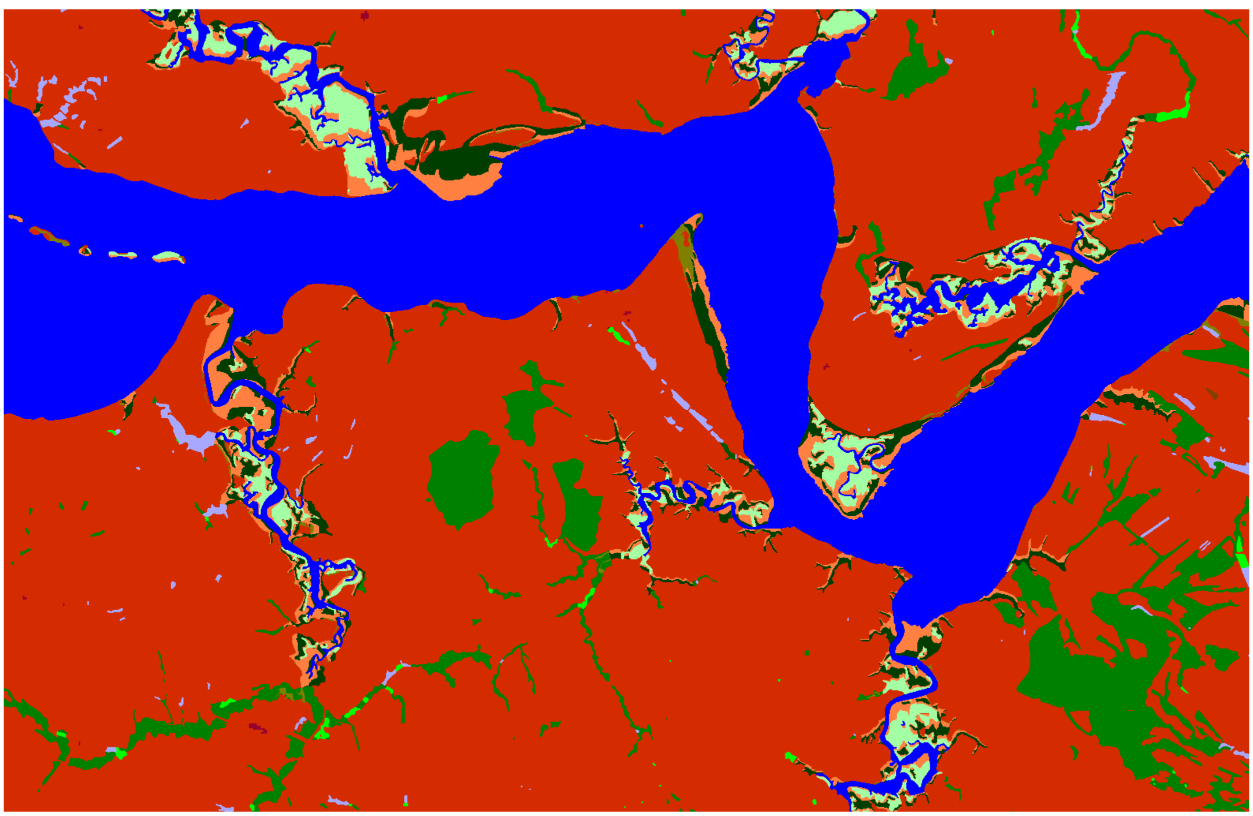
James River Context, 2075, 1 meter



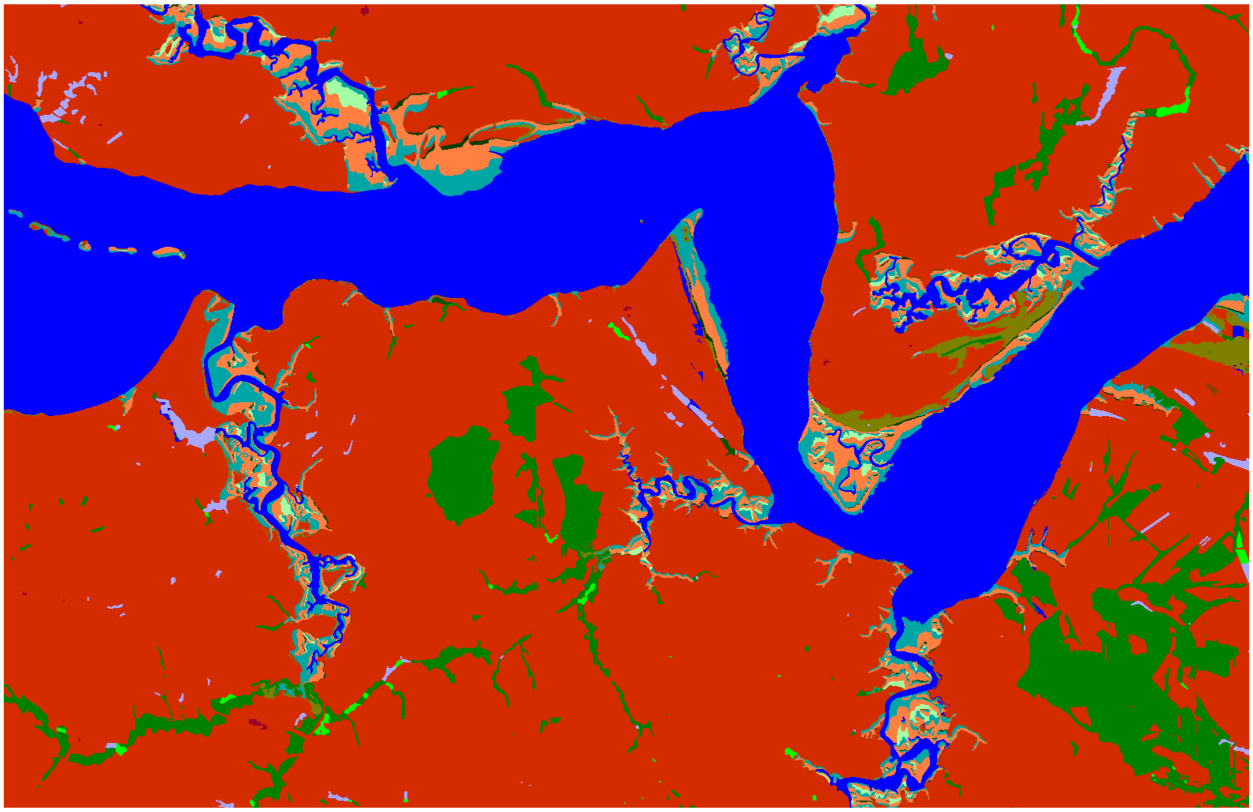
James River Context, 2100, 1 meter



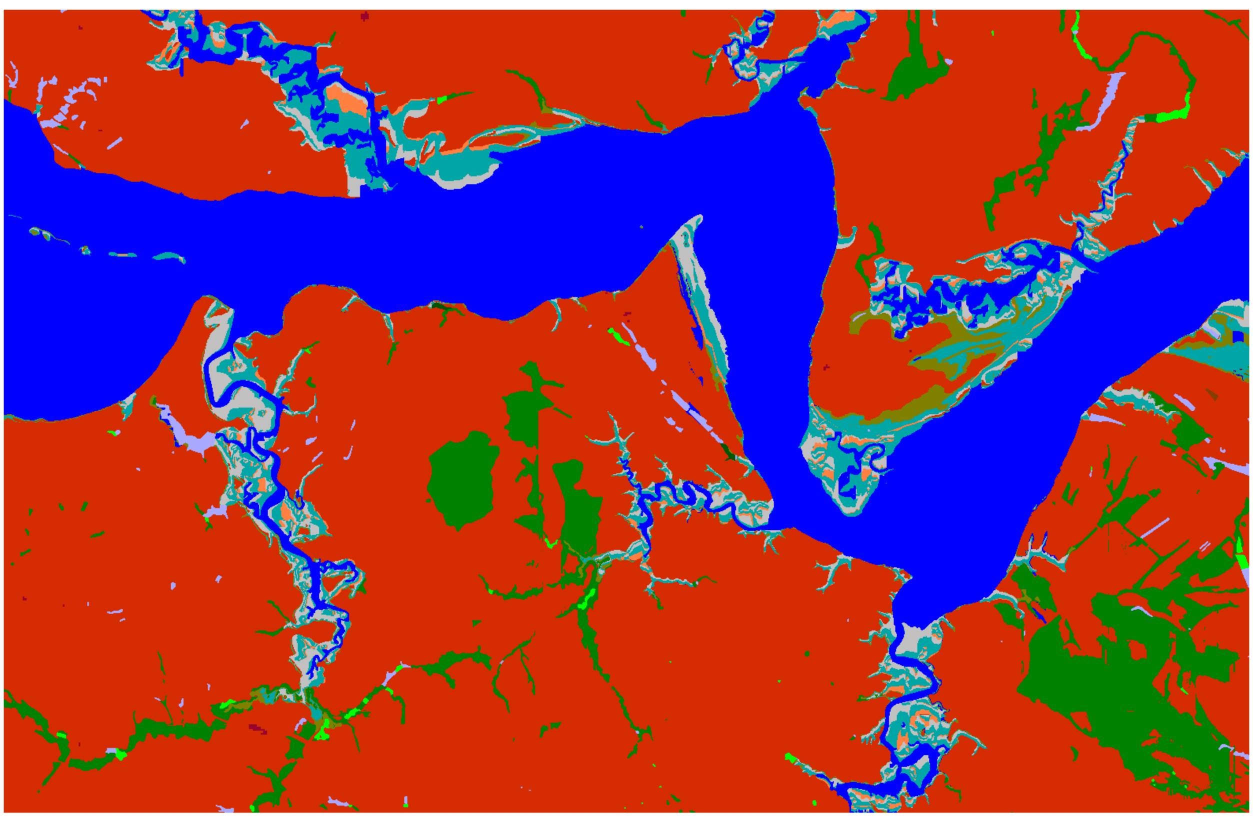
James River Context, Initial Condition



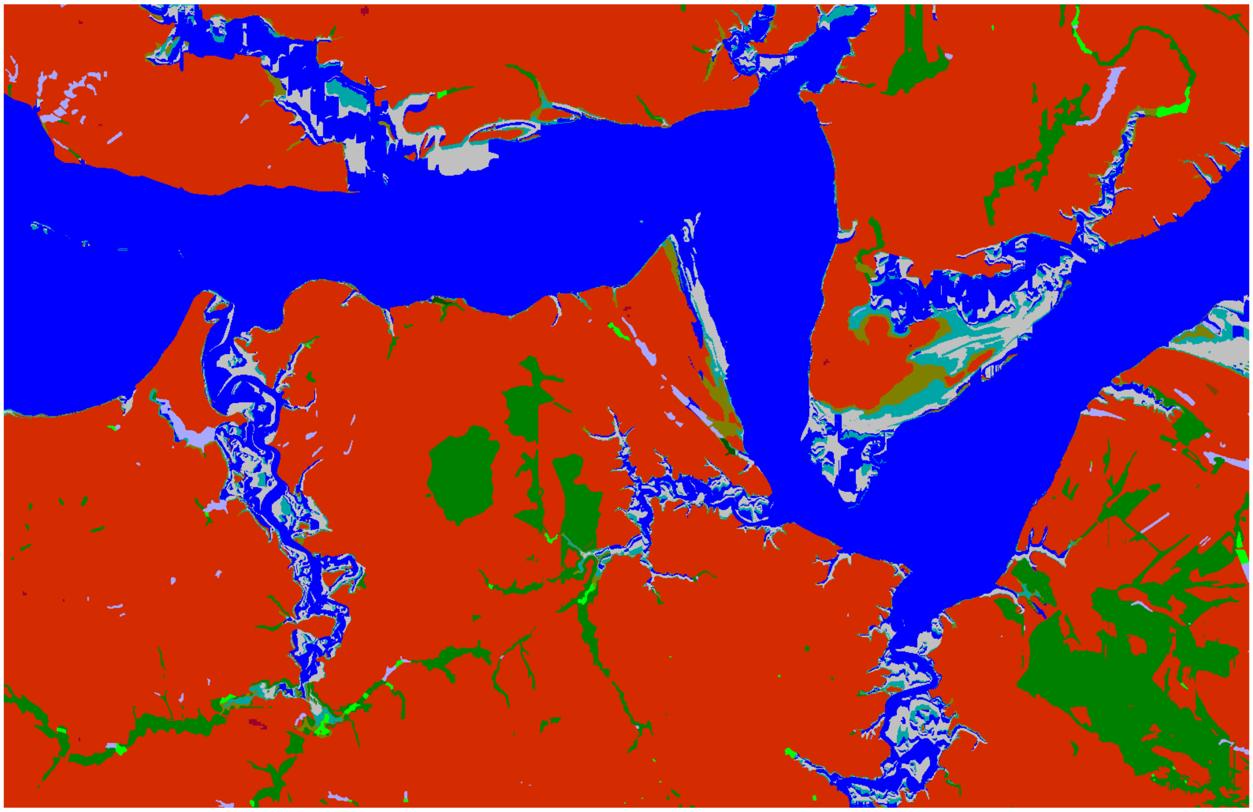
James River Context, 2025, 1.5 meter



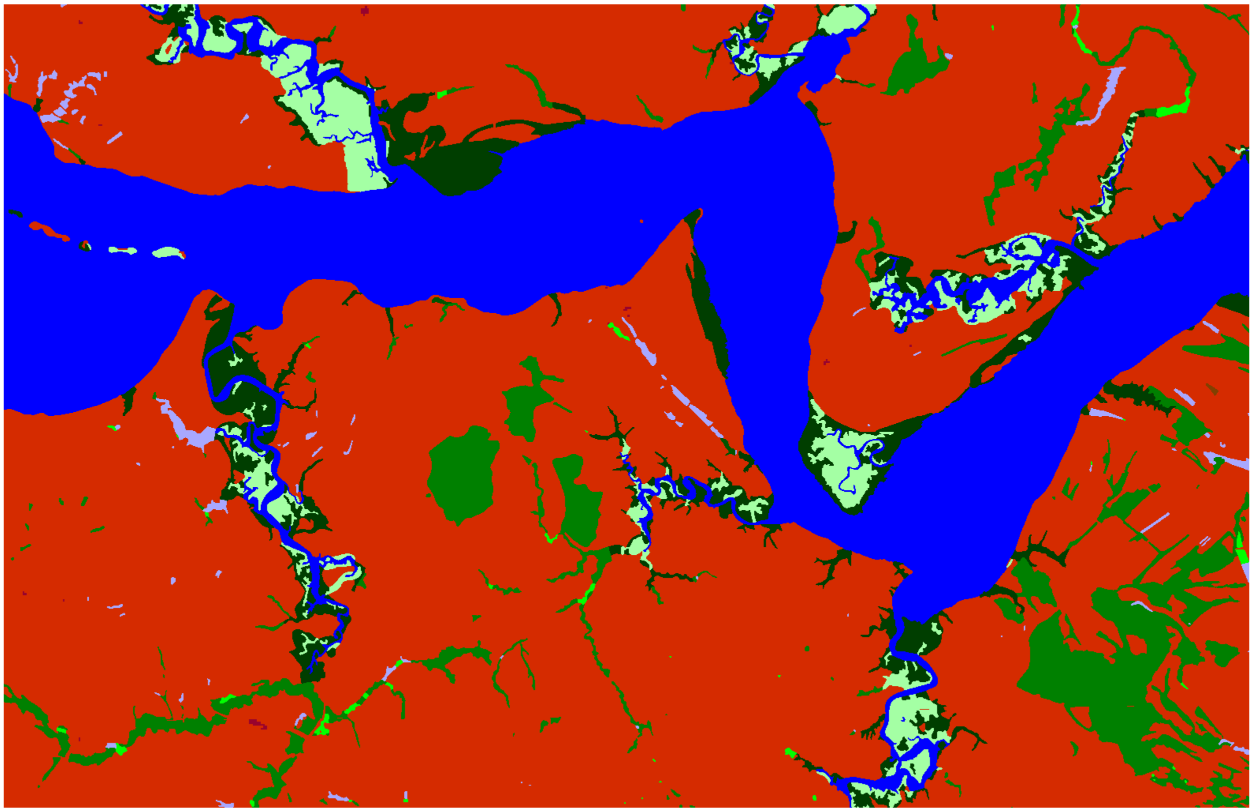
James River Context, 2050, 1.5 meter



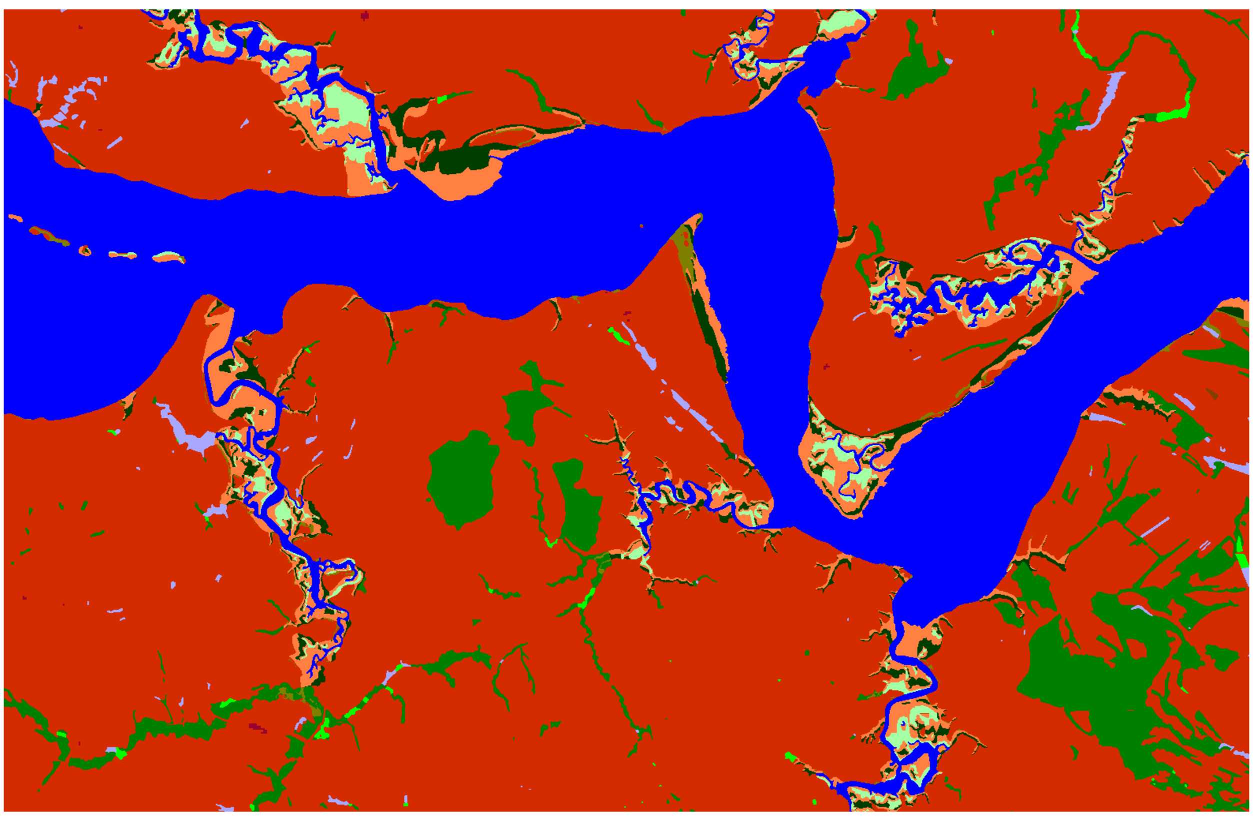
James River Context, 2075, 1.5 meter



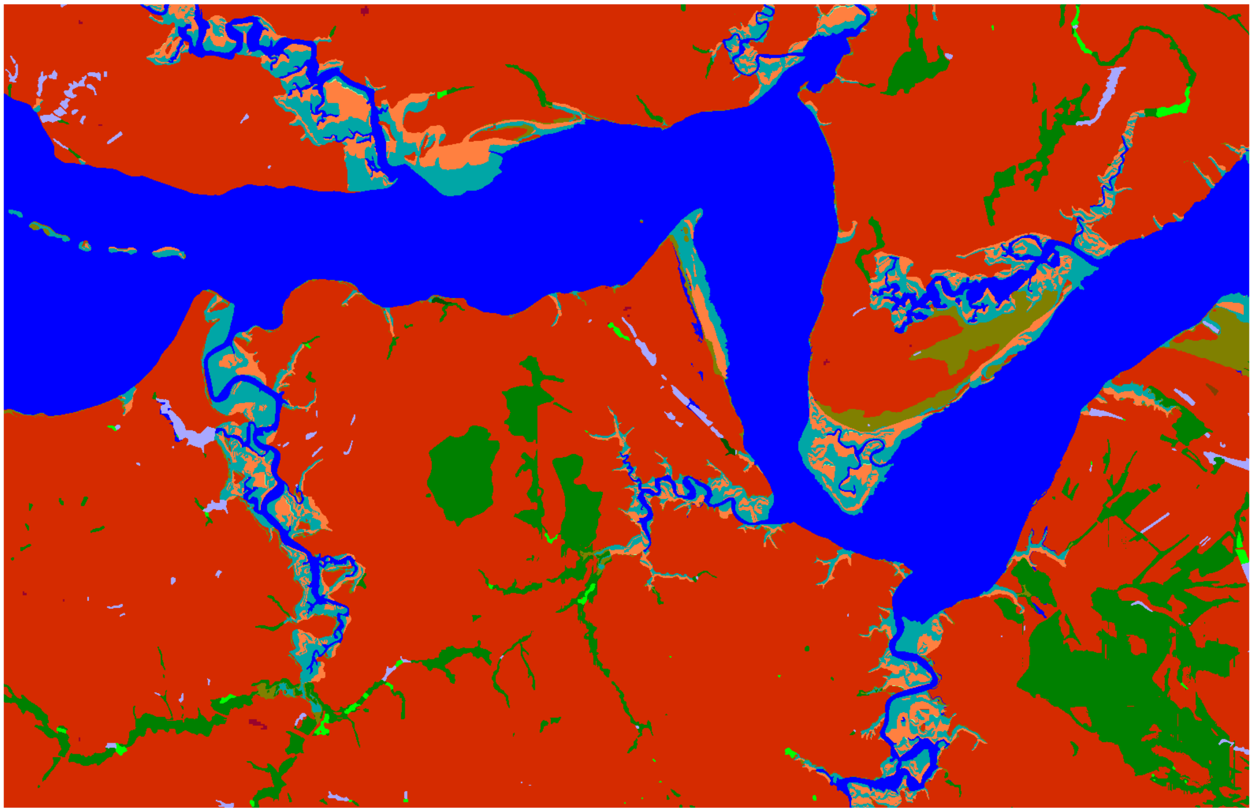
James River Context, 2100, 1.5 meter



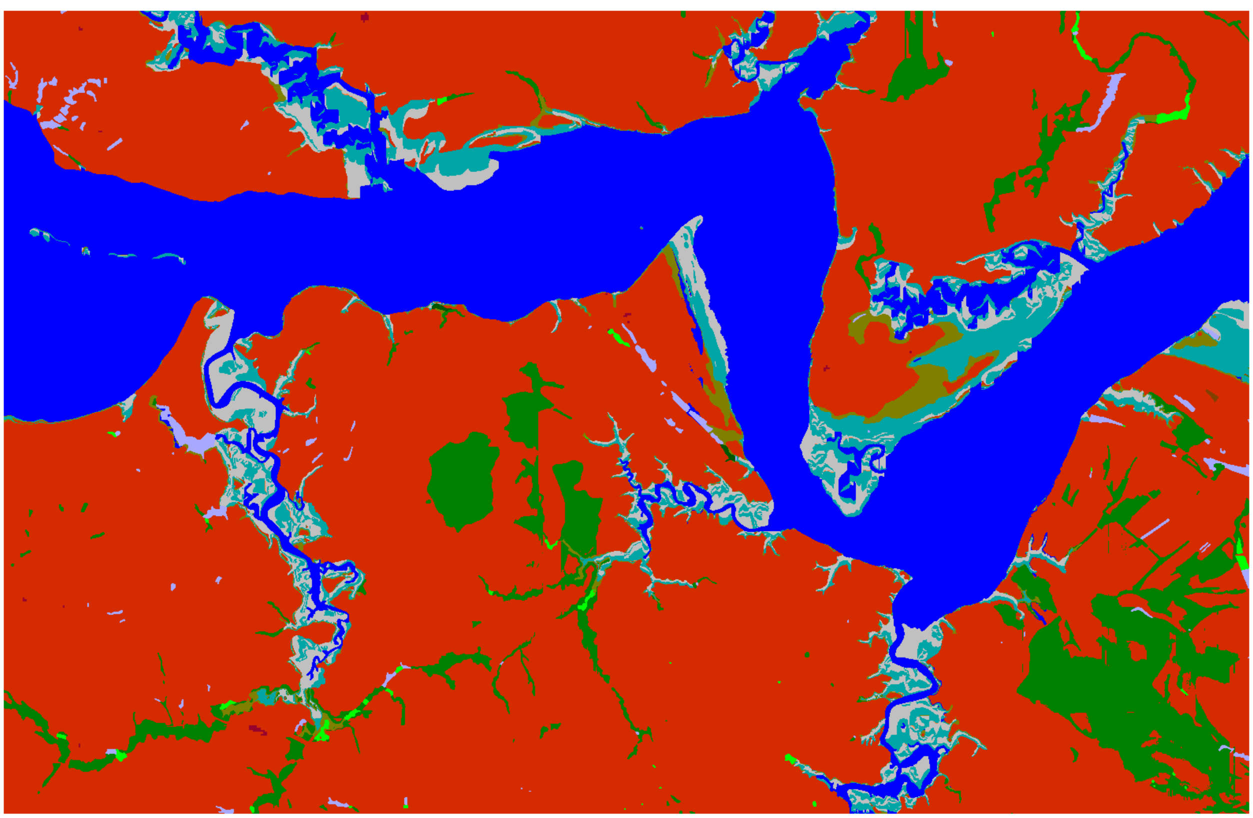
James River Context, Initial Condition



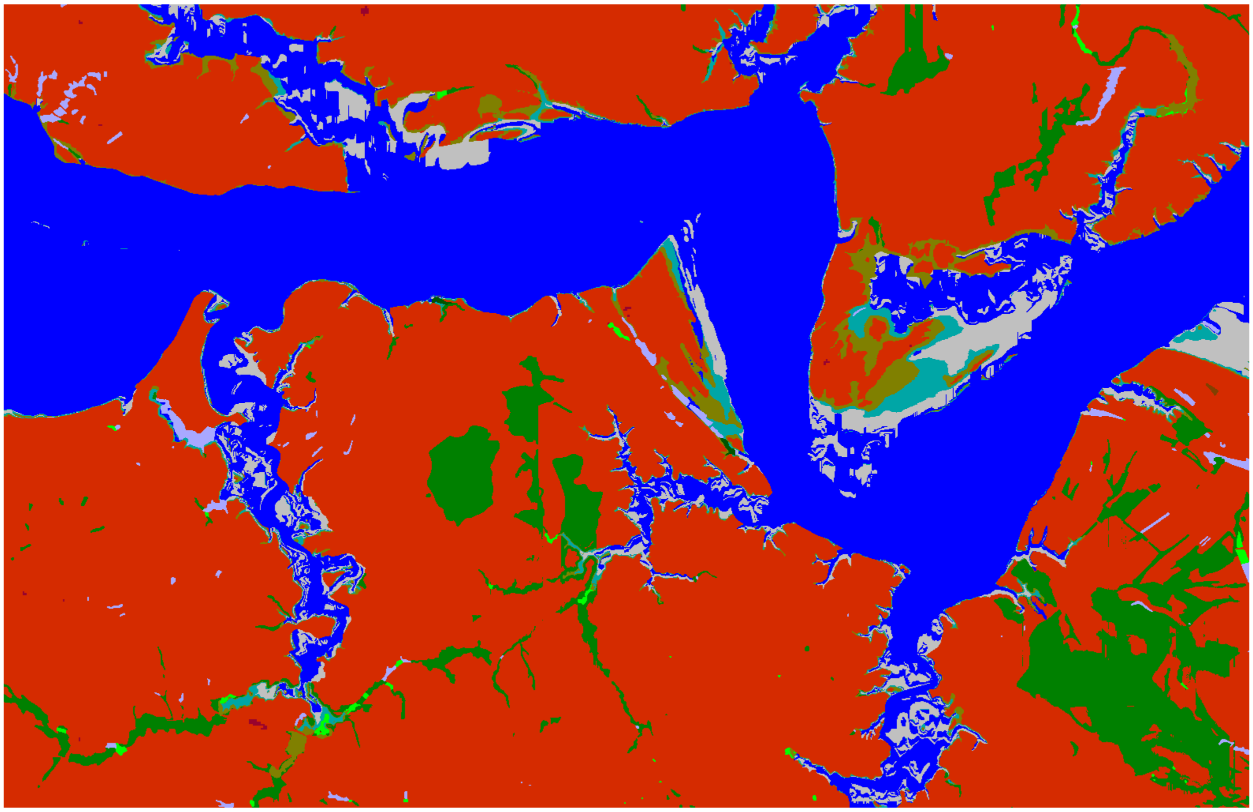
James River Context, 2025, 2 meter



James River Context, 2050, 2 meter



James River Context, 2075, 2 meter



James River Context, 2100, 2 meter