Application of the Sea-Level Affecting Marshes Model (SLAMM 5.0) to Cabo Rojo and Laguna Cartagena National Wildlife Refuge

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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 Cabo Rojo and Laguna Cartagena.

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

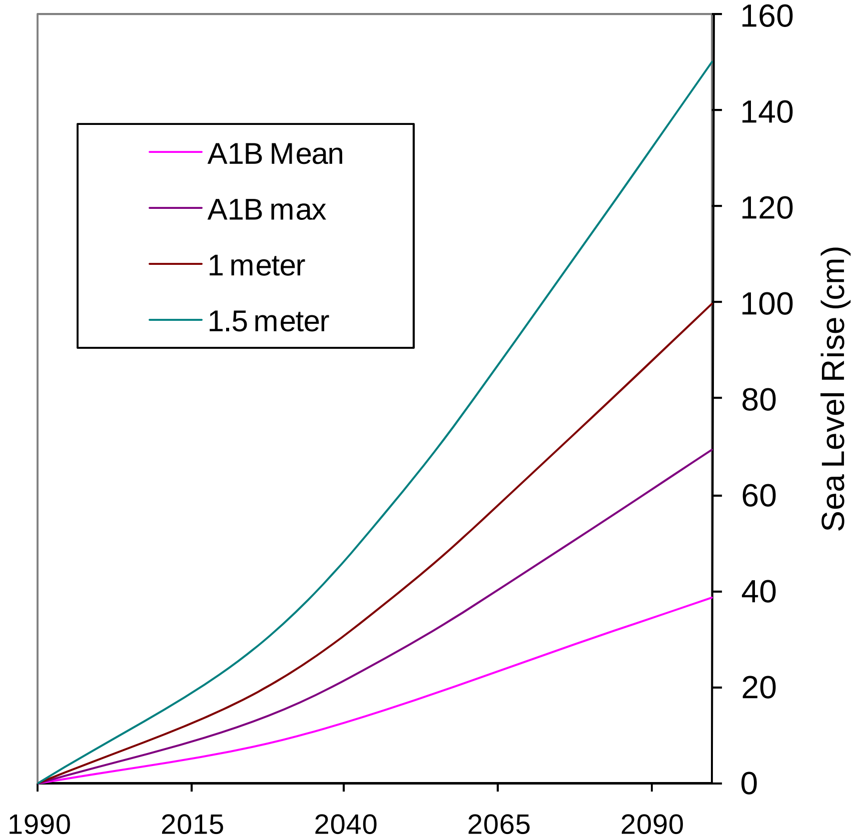
Sea-Level Rise Scenarios

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).

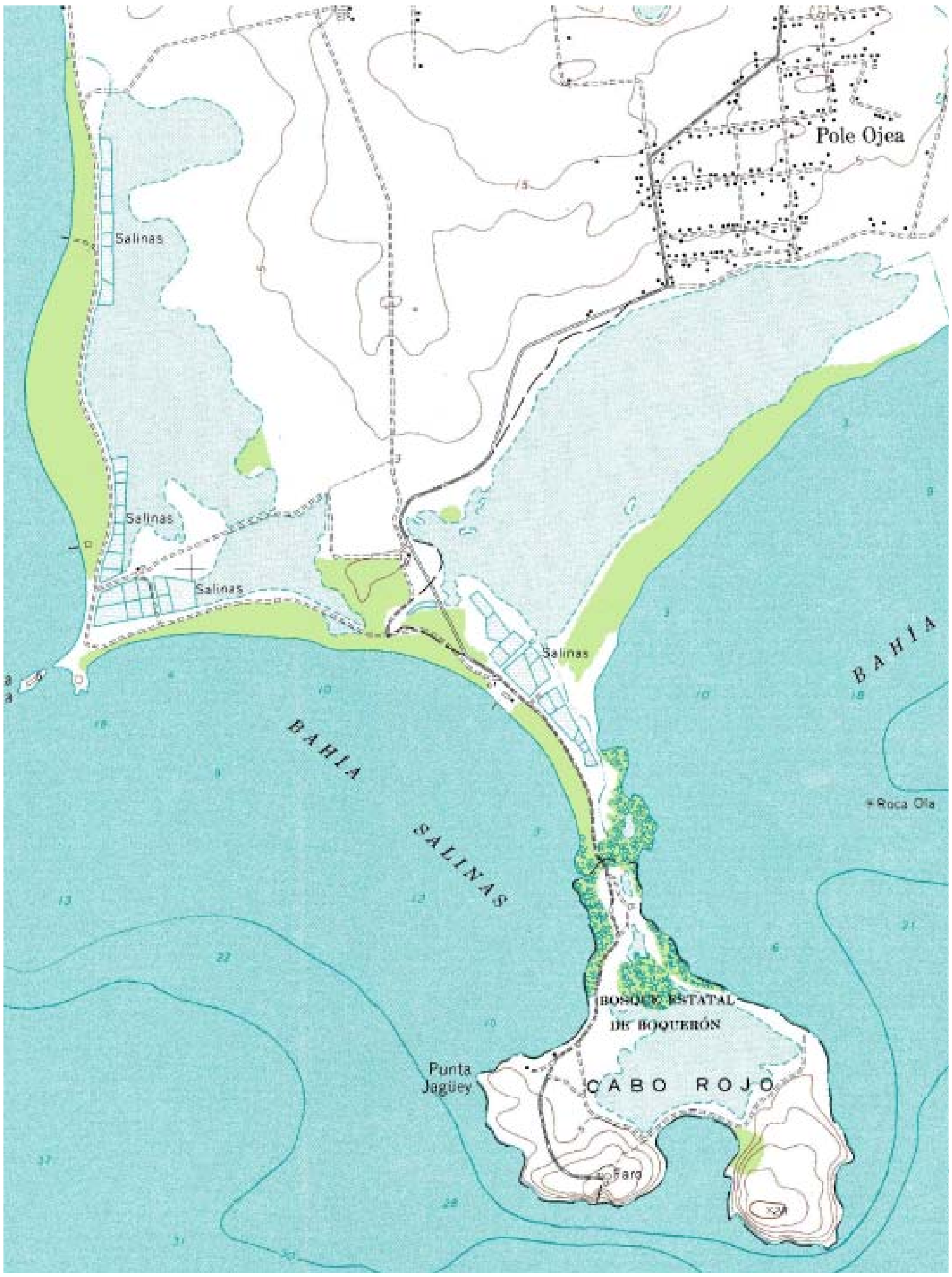
Figure 1: Summary of SLR Scenarios Utilized



Methods and Data Sources

No LIDAR data were found for the Cabo Rojo and Laguna Cartagena NWR so elevation data for Cabo Rojo and Laguna Cartagena are based on the National Elevation Dataset (NED). An examination of the metadata for the NED indicates that it was derived from the 1954 USGS topographic map shown below (Figure 2).

Figure 2: Cabo Rojo Topography from USGS Map.
Contour Interval is 5 meters referenced to Mean Sea Level.



There is considerable uncertainty as to the elevation of lands between mean sea level and the five meter contour.

The digital elevation map and USGS contour map indicate that Laguna Cartagena NWI is located in lands that are at least 10 meters above mean sea level so this refuge is predicted to have negligible effects from global sea level rise.

The National Wetlands Inventory (NWI) for both refuges is based on a photo date of 1983; this date represents the initial condition for this modeling analysis. This NWI survey, when converted to 30 meter cells, suggests that the 1038 acre Laguna Cartagena refuge is composed of dry lands, fresh marsh, and open water (table below). The 2400 acre Cabo Rojo NWR is primarily composed of dry land, and estuarine beach, with some open water and mangrove forest as well. (Acreages are based on approved acquisition boundaries.)

Laguna Cartagena NWI		**Cabo Rojo NWI Survey**	
Dry Land	52.0%	Dry Land	65.2%
Inland Fresh Marsh	43.6%	Estuarine Beach	21.9%
Inland Open Water	4.4%	Estuarine Open Water	10.4%
		Mangrove	1.3%
		Open Ocean	0.6%
		Ocean Beach	0.4%
		Brackish Marsh	0.2%

The historic trend for Sea Level Rise was estimated at 1.35 mm/year based on long term trends measured at Magueyes Island (NOAA station 9759110). This is quite close to the 1.65 mm/year rate measured in San Juan, Puerto Rico (9755371).

There is significant uncertainty relating the elevation data (which is listed as having a vertical datum of NGVD29) to Mean Sea Level for the Caribbean Region. The relationship of a vertical datum to mean tide level is generally available through NOAA but not for the Caribbean region. Some information may be gathered, however, by examining the original USGS topological map that has a vertical datum of mean sea level. My examination of this map compared to NED data indicated that the two were very close with respect to the location of contours and also the height of various peaks within the map. For this reason, no correction between MTL and NGVD29 was utilized in this simulation.

The oceanic tide range was calculated using the average of the two closest NOAA stations, being: Magueyes Island, PR (9751373) and Punta Guanajabo, Mayagues, PR (9751401).

Parameters pertaining to marshes (i.e. accretion rates and erosion rates) are not relevant to this site as there are minimal wetlands identified based on the National Wetlands Inventory, nor are any predicted to occur. Default values are therefore used, though the model will not be sensitive to those choices.

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.

SLAMM INPUT PARAMETERS FOR CABO ROJO AND LAGUNA CARTAGENA

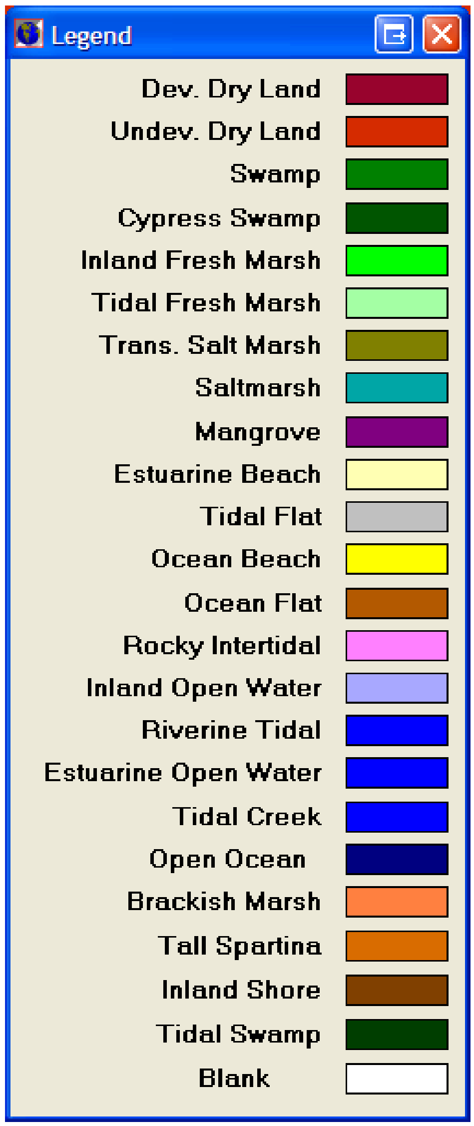
Site	Cabo Rojo	Laguna Cartagena
NED Source Date (yyyy)	1966	1966
NWI_photo_date (yyyy)	1983	1983
Direction_OffShore (N|S|E|W)	W	W
Historic_trend (mm/yr)	1.35	1.35
NGVD29_correction (MTL-NAVD88 in meters)	0	0
Water Depth (m below MLW- N/A)	2	2
TideRangeOcean (meters: MHHW-MLLW)	0.27	0.27
TideRangeInland (meters)	0.27	0.27
Mean High Water Spring (m above MTL)	0.180	0.180
MHSW Inland (m above MTL)	0.180	0.180
Marsh Erosion (horz meters/year)	1.8	1.8
Swamp Erosion (horz meters/year)	1	1
TFlat Erosion (horz meters/year) [from 0.5]	2	2
Salt marsh vertical accretion (mm/yr) Final	3.9	3.9
Brackish March vert. accretion (mm/yr) Final	4.7	4.7
Tidal Fresh vertical accretion (mm/yr) Final	5.9	5.9
Beach/T.Flat Sedimentation Rate (mm/yr)	0.5	0.5
Frequency of Large Storms (yr/washover)	25	25

Results

Results for Laguna Cartagena are insignificant under all scenarios run due to the relatively high elevation of the site. A negligible amount of dry land conversion due to soil saturation is predicted under all scenarios.

At Cabo Rojo, dry land is predicted to withstand, for the most part, all simulated scenarios of sea level rise. This prediction is, of course, subject to the uncertainty of the elevation data set utilized.

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



Cabo Rojo
IPCC Scenario A1B-Mean, 0.39 M SLR Eustatic by 2100

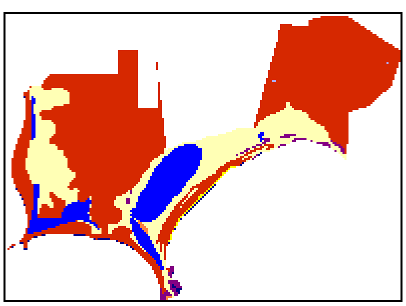
Results in Acres

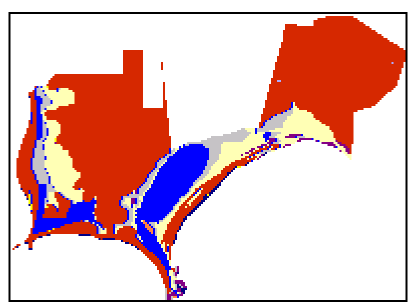
	Initial	2025	2050	2075	2100
Dry Land	1565.2	1554.3	1539.2	1520.6	1509.5
Estuarine Beach	525.7	315.8	103.9	13.9	11.1
Estuarine Open Water	249.7	318.9	543.6	791.8	802.5
Mangrove	31.1	27.3	27.1	26.1	24.7
Open Ocean	14.9	22.8	26.8	32.8	40.0
Ocean Beach	9.1	5.0	5.1	6.1	5.8
Brackish Marsh	4.0	3.6	3.6	3.3	3.3
Inland Open Water	0.7	0.7	0.7	0.7	0.7
Tidal Flat	0.0	152.1	150.6	5.2	2.9
Total (incl. water)	**2400.5**	**2400.5**	**2400.5**	**2400.5**	**2400.5**

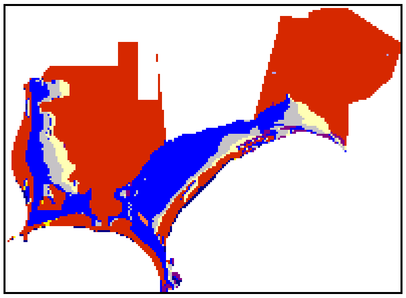
Laguna Cartagena
IPCC Scenario A1B-Mean, 0.39 M SLR Eustatic by 2100

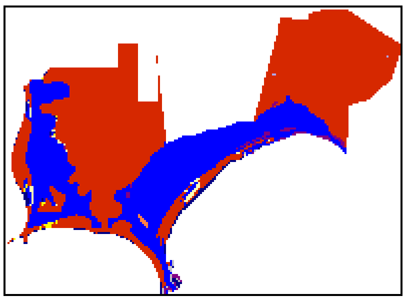
Results in Acres

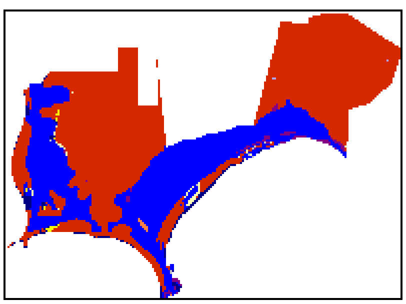
	Initial	2025	2050	2075	2100
Dry Land	539.1	527.3	526.4	525.8	525.3
Inland Fresh Marsh	452.8	464.5	465.5	466.1	466.6
Inland Open Water	45.8	45.8	45.8	45.8	45.8
Total (incl. water)	**1037.7**	**1037.7**	**1037.7**	**1037.7**	**1037.7**

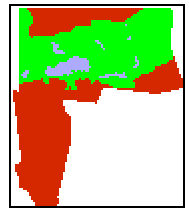

Cabo Rojo, Initial Condition

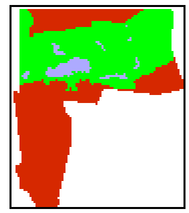

Cabo Rojo, 2025, Scenario A1B Mean


Cabo Rojo, 2050, Scenario A1B Mean

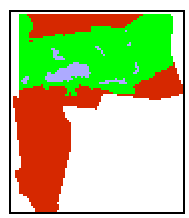

Cabo Rojo, 2075, Scenario A1B Mean

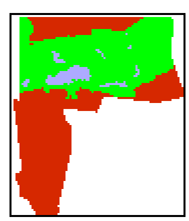

Cabo Rojo, 2100, Scenario A1B Mean


Laguna Cartagena, Initial Condition


Laguna Cartagena, 2025, Scenario A1B Mean


Laguna Cartagena, 2050, Scenario A1B Mean


Laguna Cartagena, 2075, Scenario A1B Mean


Laguna Cartagena, 2100, Scenario A1B Mean

Cabo Rojo
IPCC Scenario A1B-Max, 0.69 M SLR Eustatic by 2100

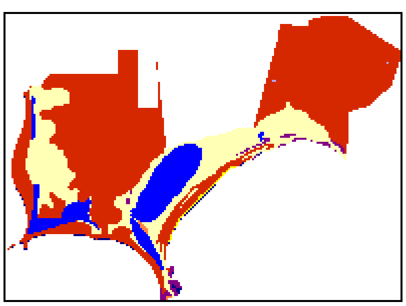
Results in Acres

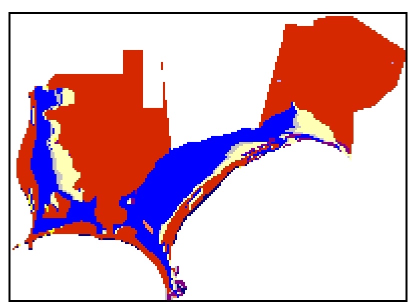
	Initial	2025	2050	2075	2100
Dry Land	1565.2	1545.2	1519.4	1501.2	1489.5
Estuarine Beach	525.7	161.9	16.0	8.6	5.4
Estuarine Open Water	249.7	581.3	795.1	811.6	804.8
Mangrove	31.1	28.6	29.1	26.4	27.9
Open Ocean	14.9	25.5	29.6	41.0	70.2
Ocean Beach	9.1	3.9	5.8	4.2	0.8
Brackish Marsh	4.0	3.6	3.6	2.4	0.0
Inland Open Water	0.7	0.7	0.7	0.7	0.7
Tidal Flat	0.0	50.0	1.3	4.4	1.2
Total (incl. water)	**2400.5**	**2400.5**	**2400.5**	**2400.5**	**2400.5**

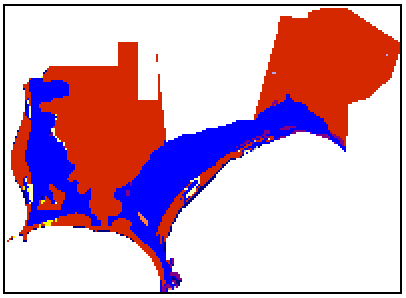
Laguna Cartagena
IPCC Scenario A1B-Max, 0.69 M SLR Eustatic by 2100

Results in Acres

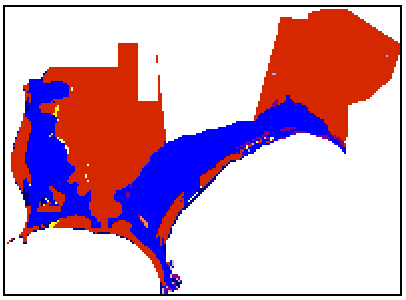
	Initial	2025	2050	2075	2100
Dry Land	539.1	527.3	526.4	525.8	525.3
Inland Fresh Marsh	452.8	464.5	465.5	466.1	466.6
Inland Open Water	45.8	45.8	45.8	45.8	45.8
Total (incl. water)	**1037.7**	**1037.7**	**1037.7**	**1037.7**	**1037.7**


Cabo Rojo, Initial Condition

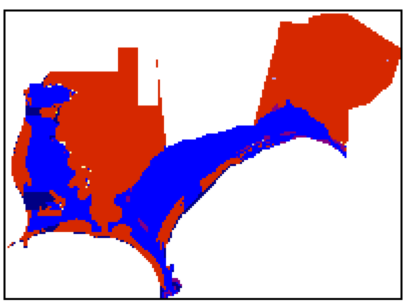

Cabo Rojo, 2025, Scenario A1B Maximum



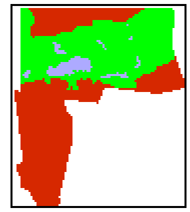
Cabo Rojo, 2050, Scenario A1B Maximum



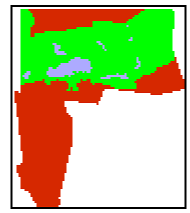
Cabo Rojo, 2075, Scenario A1B Maximum



Cabo Rojo, 2100, Scenario A1B Maximum

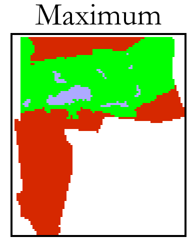


Laguna Cartagena, Initial Condition

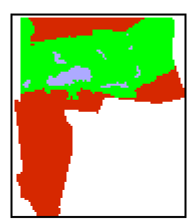


Laguna Cartagena, 2025, Scenario A1B Maximum

Laguna Cartagena, 2050, Scenario A1B Maximum



Laguna Cartagena, 2075, Scenario A1B Maximum



Laguna Cartagena, 2100, Scenario A1B Maximum

Cabo Rojo
1 Meter Eustatic SLR by 2100

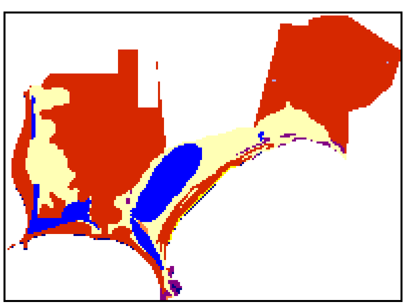
Results in Acres

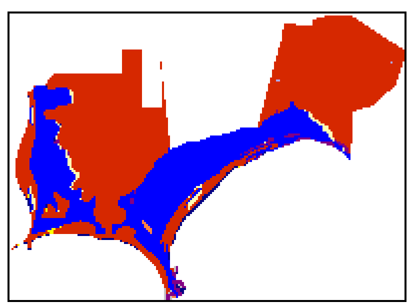
	Initial	2025	2050	2075	2100
Dry Land	1565.2	1535.8	1507.1	1489.3	1478.0
Estuarine Beach	525.7	32.7	12.3	8.6	5.1
Estuarine Open Water	249.7	760.9	802.7	812.5	814.0
Mangrove	31.1	32.3	32.7	30.2	18.5
Open Ocean	14.9	26.5	35.5	54.8	81.2
Ocean Beach	9.1	4.5	5.0	1.4	0.7
Brackish Marsh	4.0	3.6	0.6	0.0	0.0
Inland Open Water	0.7	0.7	0.7	0.7	0.7
Tidal Flat	0.0	3.6	3.9	3.1	2.3
Total (incl. water)	**2400.5**	**2400.5**	**2400.5**	**2400.5**	**2400.5**

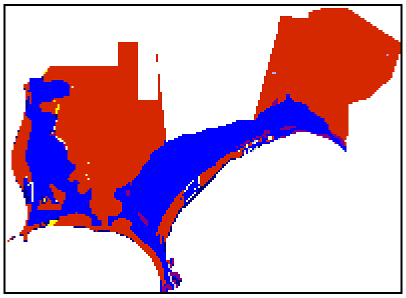
Laguna Cartagena
1 Meter Eustatic SLR by 2100

Results in Acres

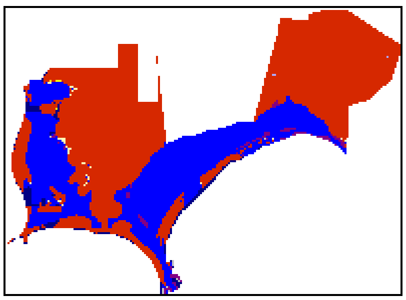
	Initial	2025	2050	2075	2100
Dry Land	539.1	527.3	526.4	525.8	525.1
Inland Fresh Marsh	452.8	464.5	465.5	466.1	466.8
Inland Open Water	45.8	45.8	45.8	45.8	45.8
Total (incl. water)	**1037.7**	**1037.7**	**1037.7**	**1037.7**	**1037.7**


Cabo Rojo, Initial Condition

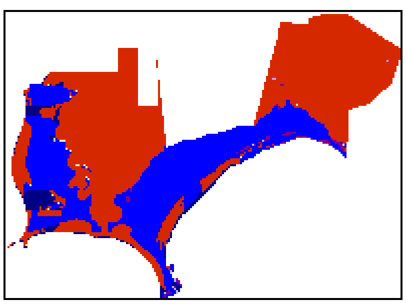

Cabo Rojo, 2025, 1 meter eustatic SLR by 2100



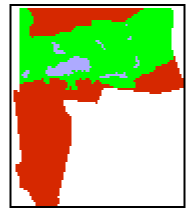
Cabo Rojo, 2050, 1 meter eustatic SLR by 2100



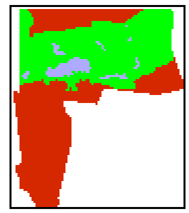
Cabo Rojo, 2075, 1 meter eustatic SLR by 2100



Cabo Rojo, 2100, 1 meter eustatic SLR by 2100

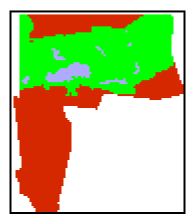


Laguna Cartagena, Initial Condition

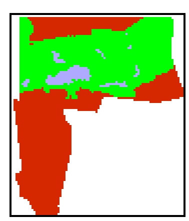


Laguna Cartagena, 2025, 1 meter eustatic SLR by 2100

Laguna Cartagena, 2050, 1 meter eustatic SLR by 2100



Laguna Cartagena, 2075, 1 meter eustatic SLR by 2100



Laguna Cartagena, 2100, 1 meter eustatic SLR by 2100

Cabo Rojo
1.5 Meters Eustatic SLR by 2100

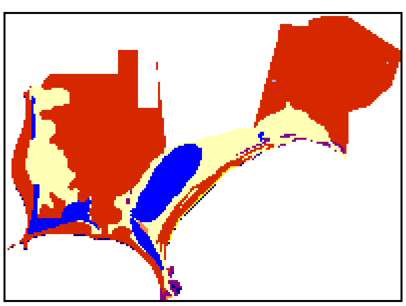
Results in Acres

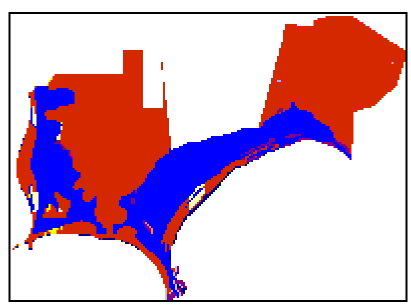
	Initial	2025	2050	2075	2100
Dry Land	1565.2	1519.9	1493.2	1476.8	1462.9
Estuarine Beach	525.7	20.4	13.8	8.5	4.3
Estuarine Open Water	249.7	782.6	816.3	838.0	838.4
Mangrove	31.1	36.3	28.8	1.3	0.0
Open Ocean	14.9	28.4	41.6	74.4	92.1
Ocean Beach	9.1	5.7	1.4	0.7	1.2
Brackish Marsh	4.0	0.9	0.0	0.0	0.0
Inland Open Water	0.7	0.7	0.7	0.7	0.7
Tidal Flat	0.0	5.7	4.7	0.0	0.0
Total (incl. water)	**2400.5**	**2400.5**	**2400.5**	**2400.5**	**2400.5**

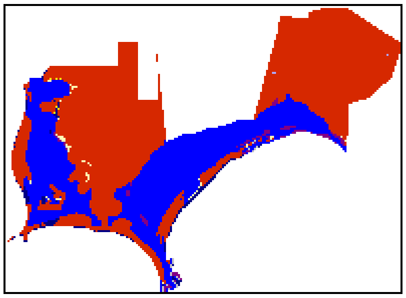
Laguna Cartagena
1.5 Meters Eustatic SLR by 2100

Results in Acres

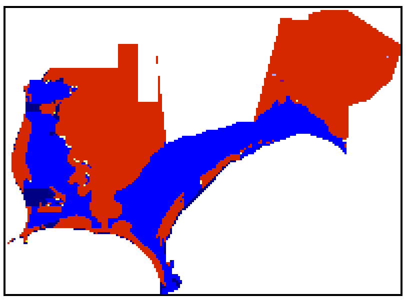
	Initial	2025	2050	2075	2100
Dry Land	539.1	527.3	526.4	525.6	525.1
Inland Fresh Marsh	452.8	464.5	465.5	466.3	466.8
Inland Open Water	45.8	45.8	45.8	45.8	45.8
Total (incl. water)	**1037.7**	**1037.7**	**1037.7**	**1037.7**	**1037.7**


Cabo Rojo, Initial Condition

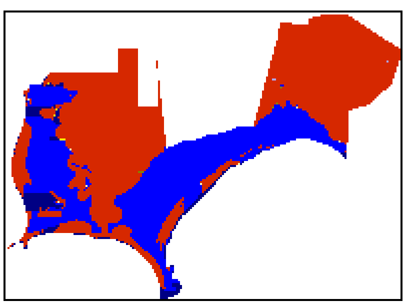

Cabo Rojo, 2025, 1.5 meters eustatic SLR by 2100



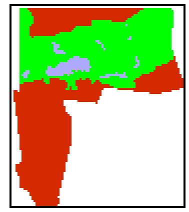
Cabo Rojo, 2050, 1.5 meters eustatic SLR by 2100



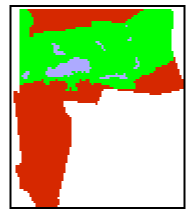
Cabo Rojo, 2075, 1.5 meters eustatic SLR by 2100



Cabo Rojo, 2100, 1.5 meters eustatic SLR by 2100

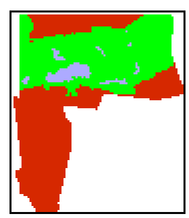


Laguna Cartagena, Initial Condition

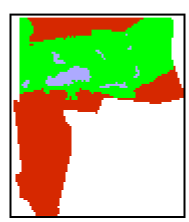


Laguna Cartagena, 2025, 1.5 meters eustatic SLR by 2100

Laguna Cartagena, 2050, 1.5 meters eustatic SLR by 2100



Laguna Cartagena, 2075, 1.5 meters eustatic SLR by 2100



Laguna Cartagena, 2100, 1.5 meters eustatic SLR by 2100

Discussion:

Predicted dry-land effects are minor for both refuges. Cabo Rojo is predicted to lose 7% of its dry land under the extreme 1.5 meter scenario of sea level rise. This result is uncertain due to the five-meter contour interval of the elevation data set. However, even at this contour interval, many contours appear in the Cabo Rojo map indicating significant vertical relief at this site.

At Cabo Rojo, the salt-pond regions (inland regions of estuarine beach) are predicted to be lost-- converted to tidal flats and eventually open water-- under all scenarios of sea level rise. However, the initial elevations of these areas are, again, quite uncertain due to the low vertical resolution of the input data.

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

Clough, J.S. and R.A. Park, 2007, *Technical Documentation for SLAMM 5.0.1* February 2008, Jonathan S. Clough, Warren Pinnacle Consulting, Inc, Richard A. Park, Eco Modeling. 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

Galbraith, H., R. Jones, R.A. Park, J.S. Clough, S. Herrod-Julius, B. Harrington, and G. Page. 2002. Global Climate Change and Sea Level Rise: Potential Losses of Intertidal Habitat for Shorebirds. *Waterbirds* 25:173-183.

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

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.

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.

Meehl GA, Stocker TF, Collins WD, Friedlingstein P, Gaye AT, Gregory JM, Kitoh A, Knutti R, Murphy JM, Noda A, Raper SCB, Watterson IG, Weaver AJ and Zhao ZC. 2007. Global climate projections. Pp. 747-845. In: Solomon S, Qin, D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor, M and Miller HL, (eds.) *Climate change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK: Cambridge University Press.

Monaghan, A. J. *et al,* 2006 "Insignificant Change in Antarctic Snowfall Since the International Geophysical Year" *Science* 2006 313: 827-831.

Moorhead, KK and Brinson MM. 1995. Response of wetlands to rising sea level in the lower coastal plain of North Carolina. *Ecological Applications* 5: 261-271.

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

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.

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

Rodriguez, E., C.S. Morris, J.E. Belz, E.C. Chapin, J.M. Martin, W. Daffer, S. Hensley, 2005, *An assessment of the SRTM topographic products*, Technical Report JPL D-31639, Jet Propulsion Laboratory, Pasadena, California, 143 pp.

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.

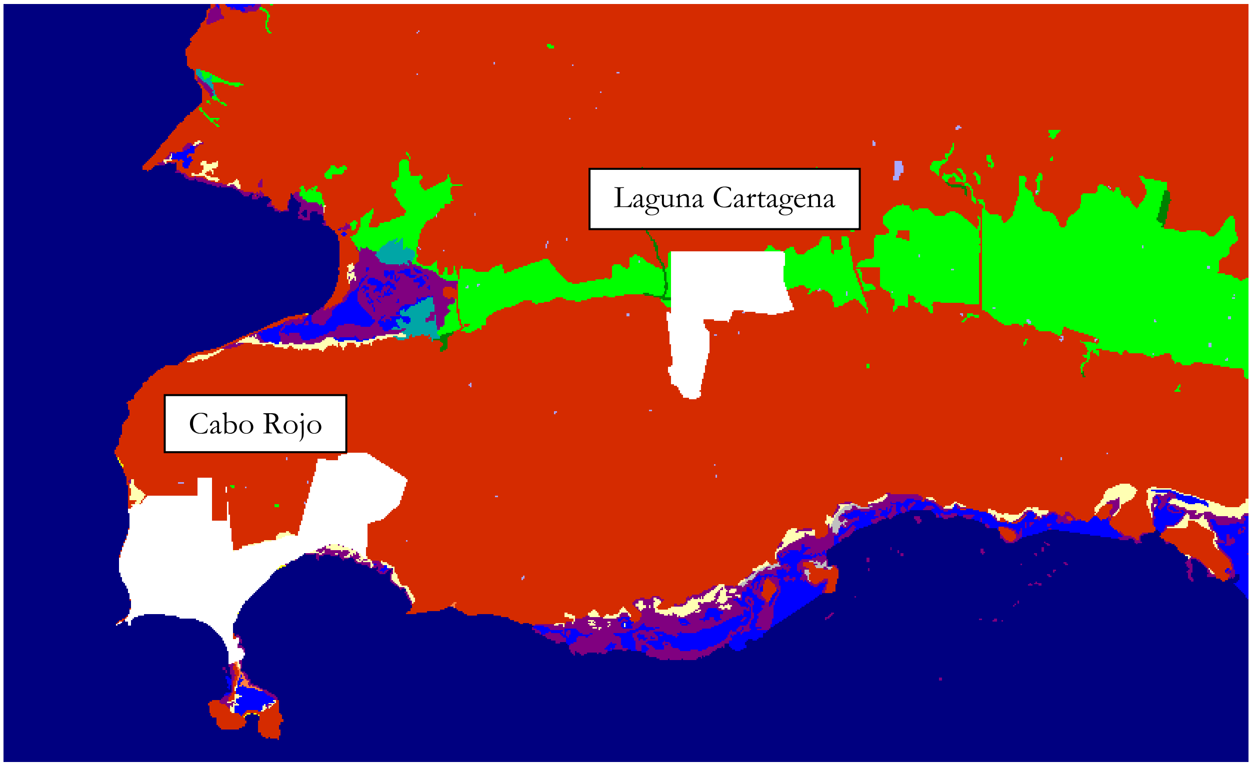
Titus, J.G., R.A. Park, S.P. Leatherman, J.R. Weggel, M.S. Greene, P.W. Mausel, M.S. Trehan, S. Brown, C. Grant, and G.W. Yohe. 1991. Greenhouse Effect and Sea Level Rise: Loss of Land and the Cost of Holding Back the Sea. *Coastal Management* 19:2:171-204.

Appendix A: Contextual Results

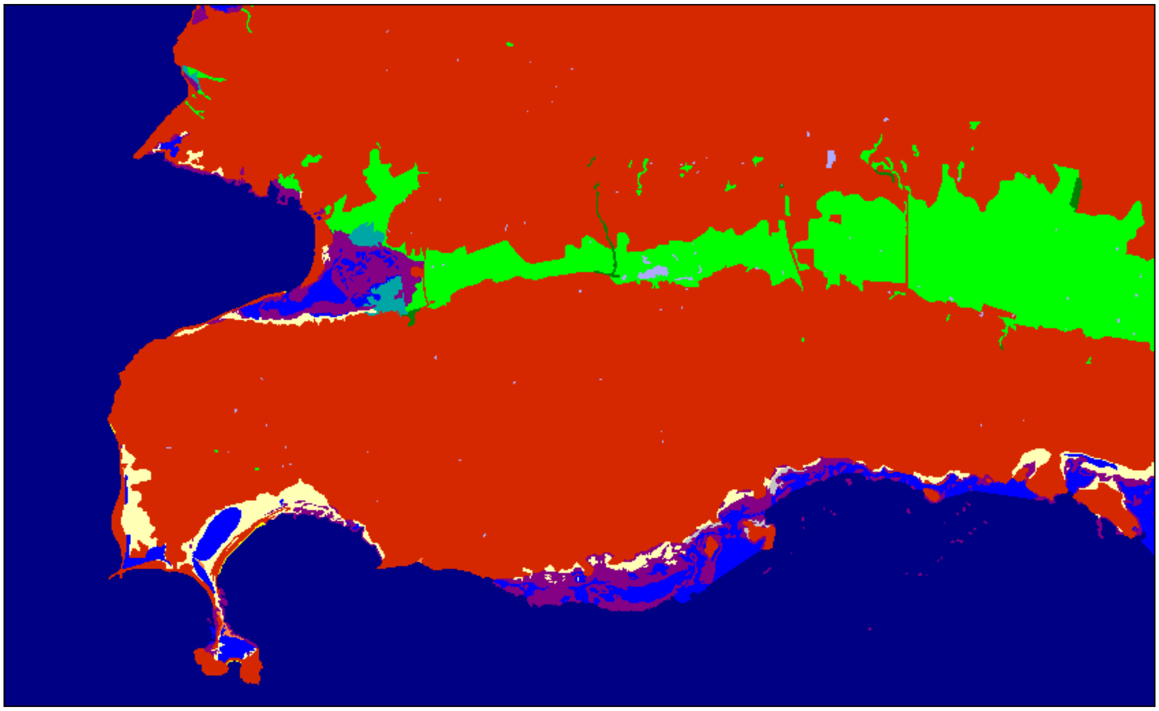
The SLAMM model does take into account the context of the surrounding lands or open water when calculating effects. For example, erosion rates are calculated based on the maximum fetch (wave action) which is estimated by assessing contiguous open water to a given marsh cell. Another example is that inundated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

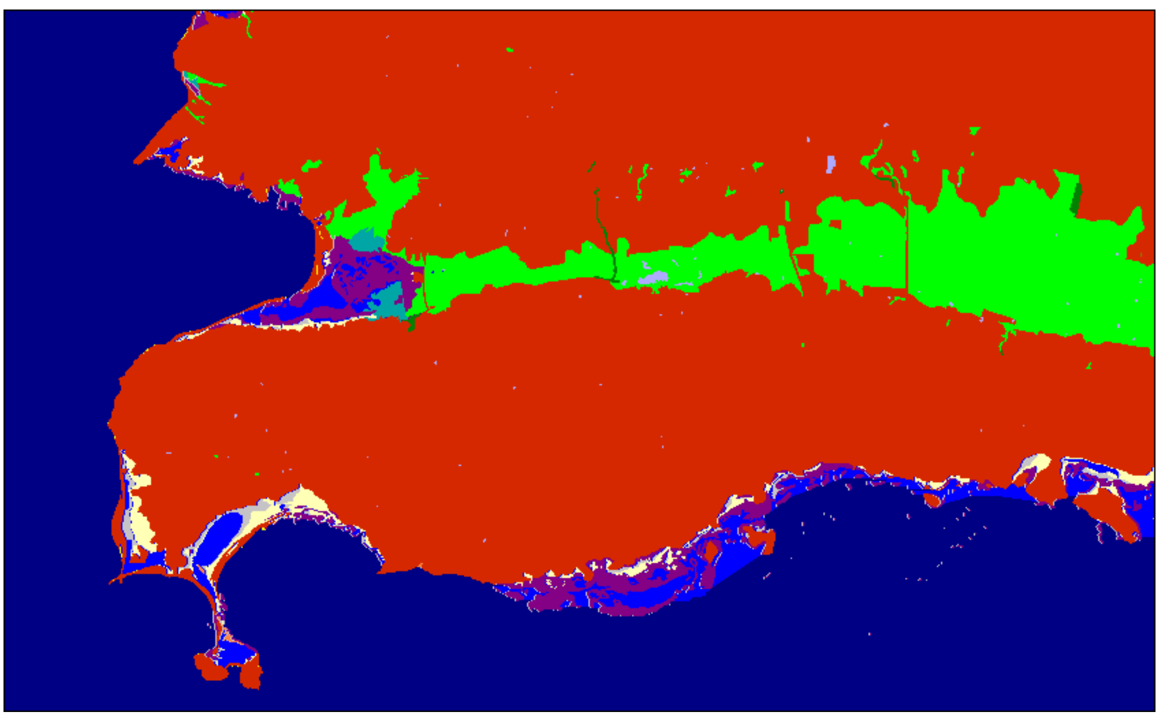
- Results were closely examined (quality assurance) within USFWS refuges but not closely examined for the larger region.
- Site-specific parameters for the model were derived for USFWS refuges whenever possible and may not be regionally applicable.
- Especially in areas where dikes are present, an effort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



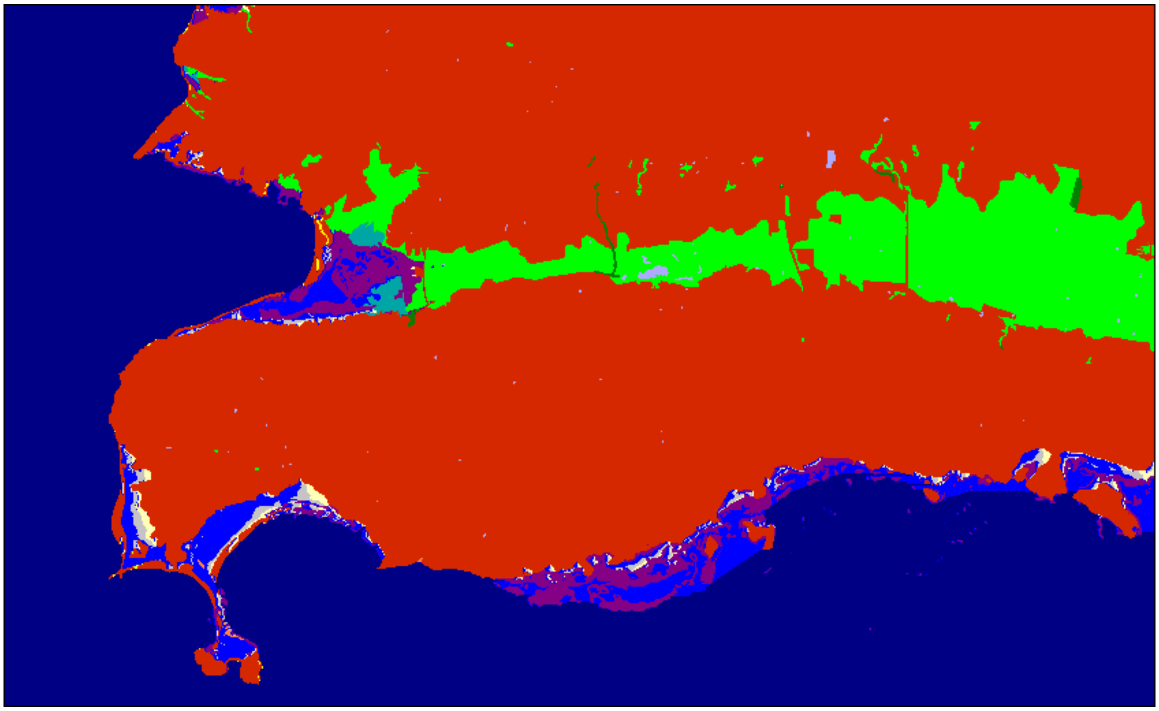
Location of Cabo Rojo and Laguna Cartagena (white areas) within Puerto Rico Contextual Simulation



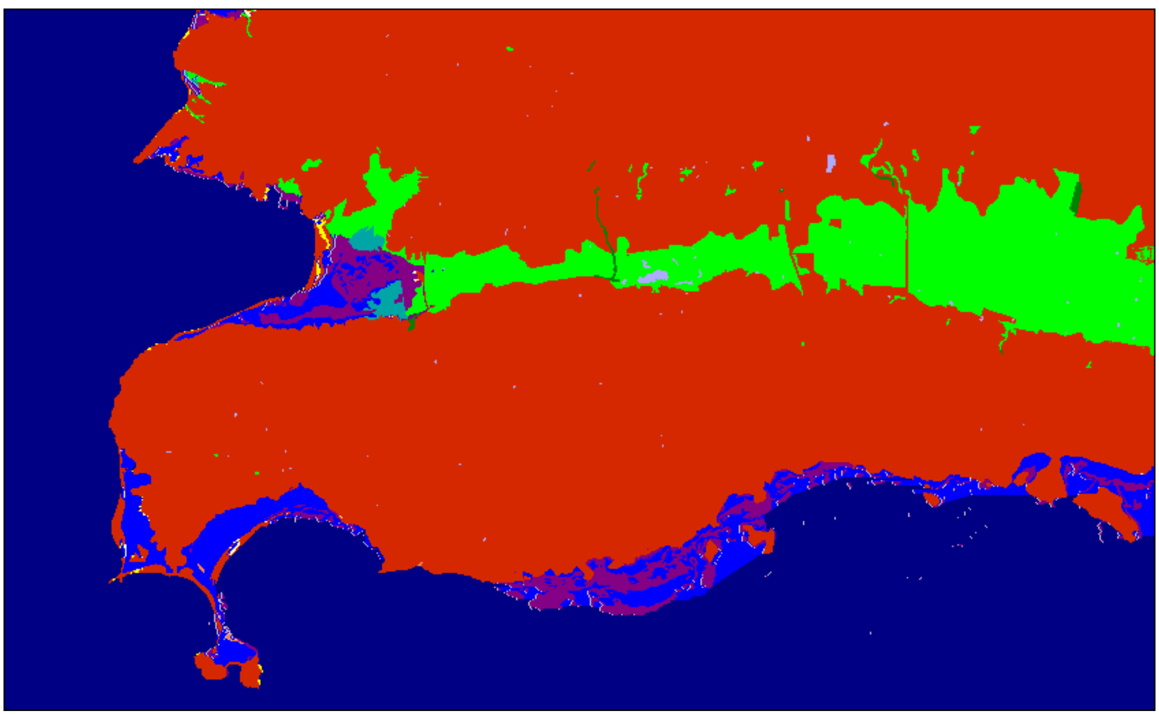
Puerto Rico, Initial Condition



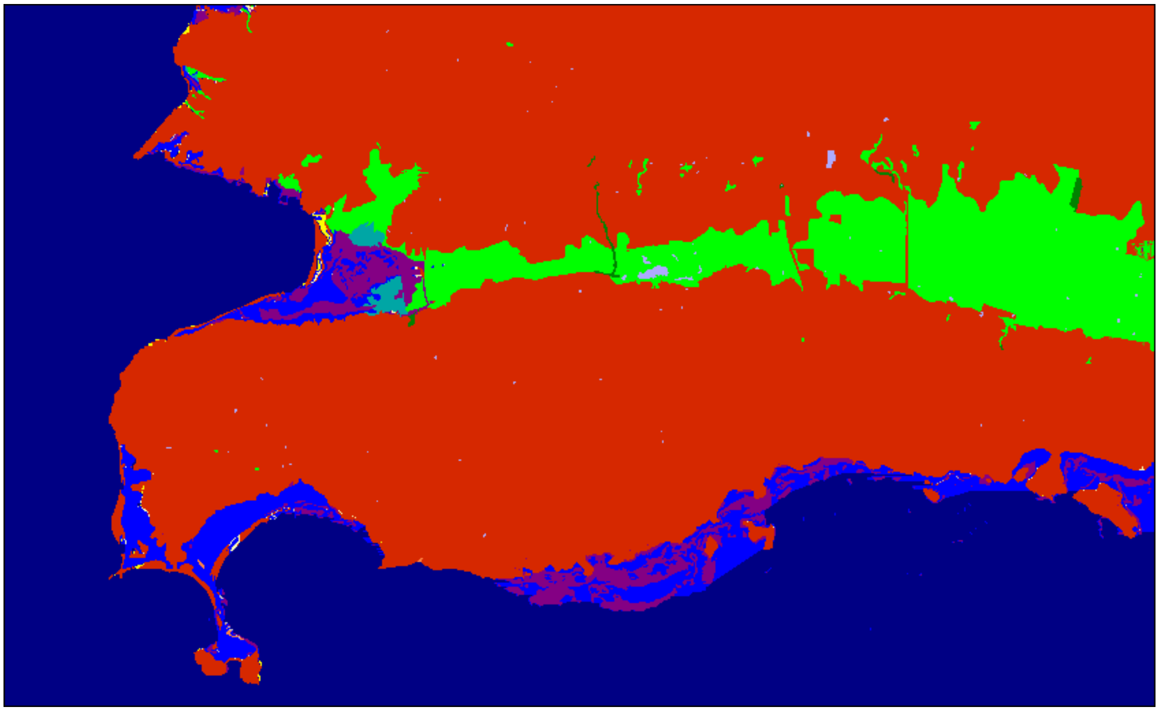
Puerto Rico, 2025, Scenario A1B Mean



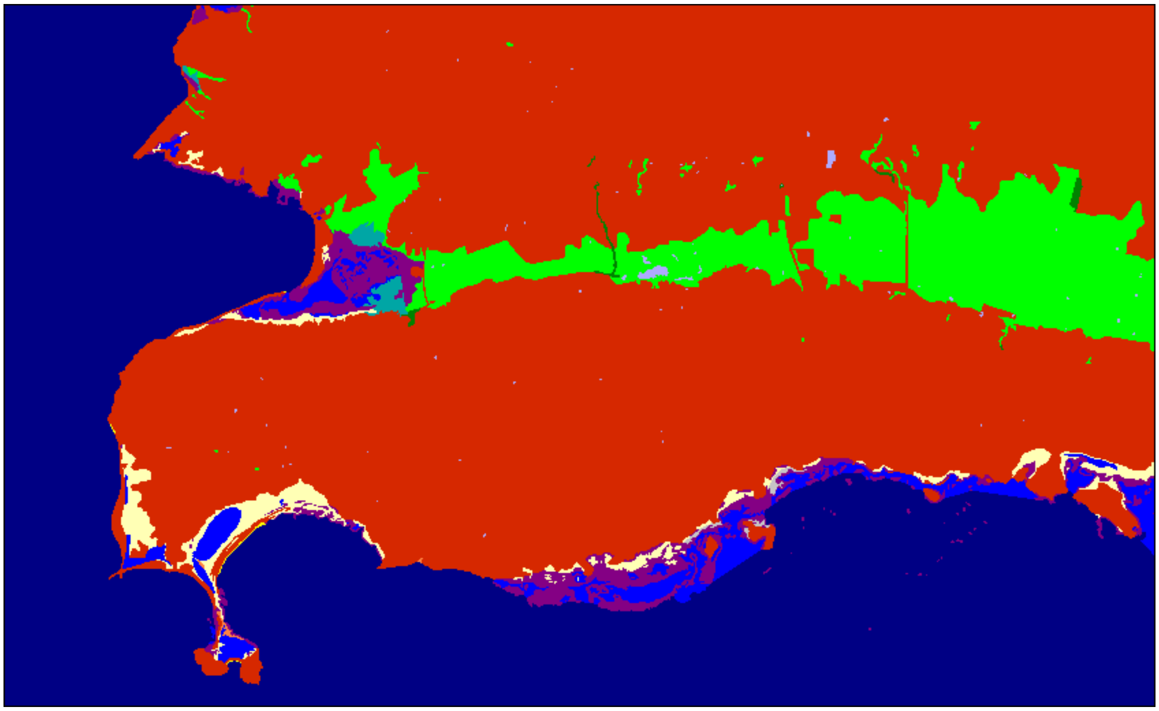
Puerto Rico, 2050, Scenario A1B Mean



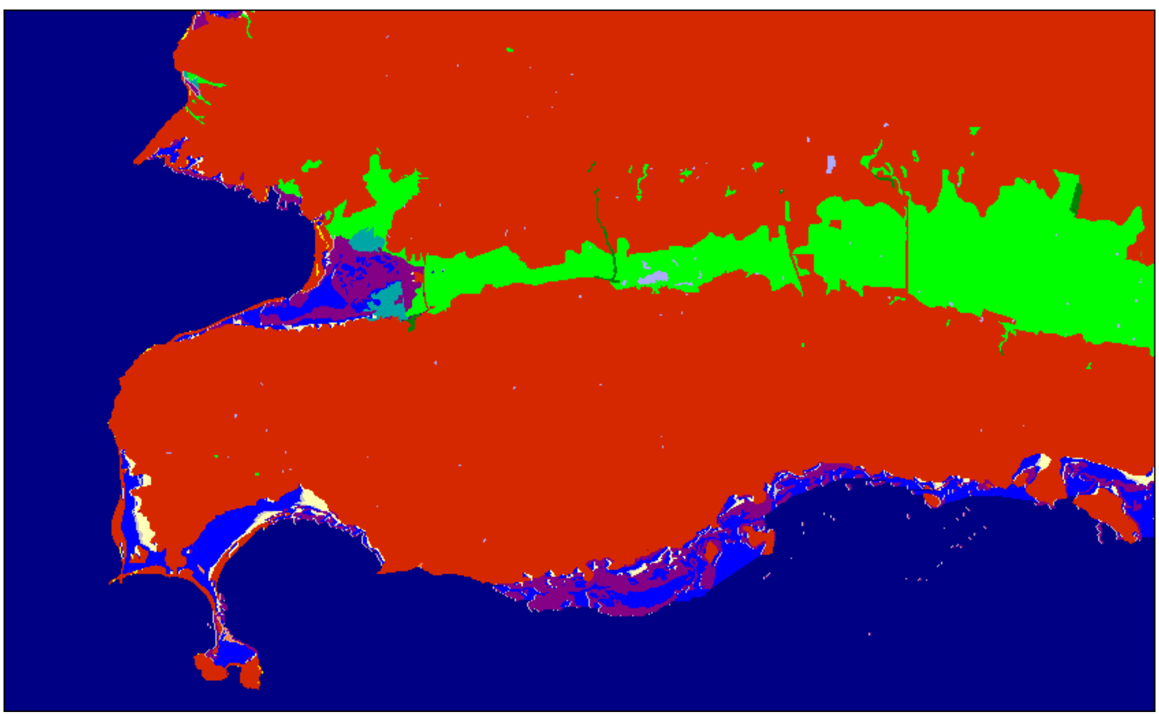
Puerto Rico, 2075, Scenario A1B Mean



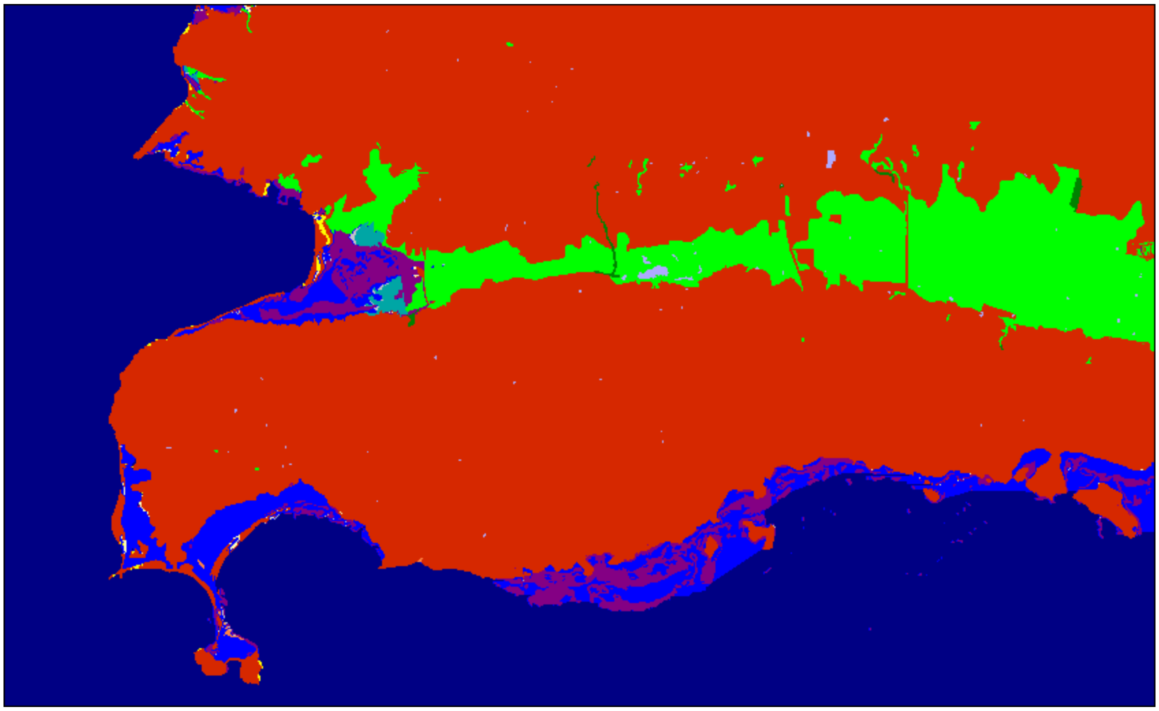
Puerto Rico, 2100, Scenario A1B Mean



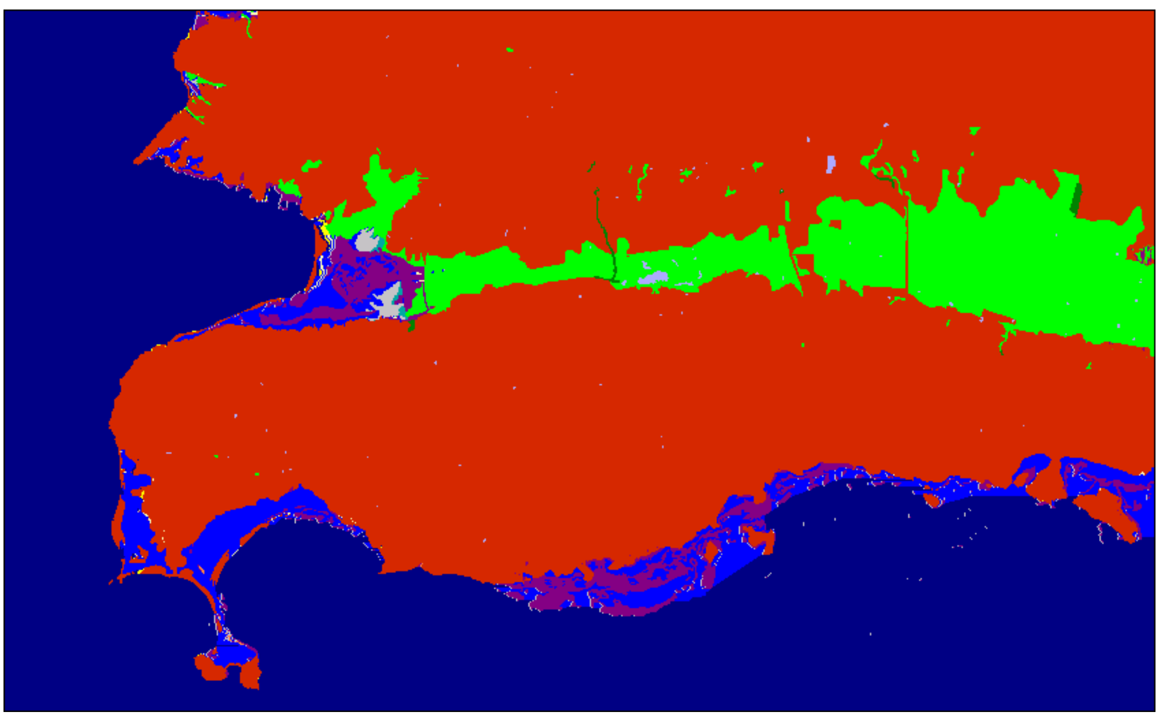
Puerto Rico, Initial Condition Scenario A1B Maximum



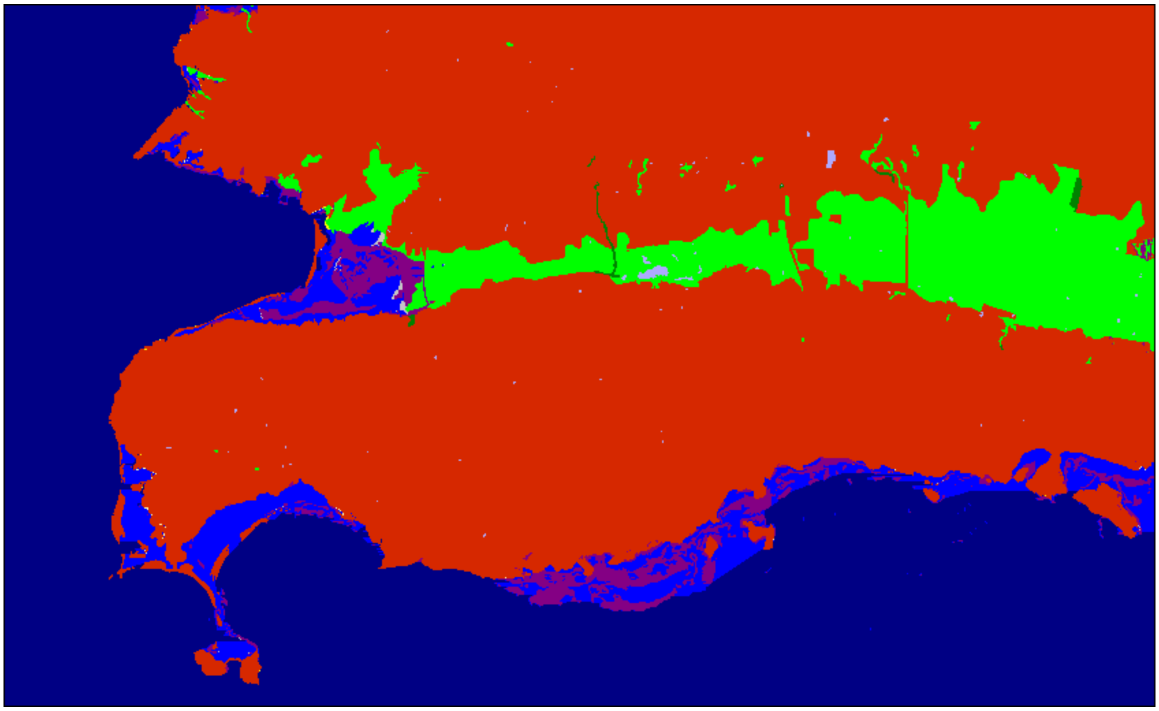
Puerto Rico, 2025, Scenario A1B Maximum



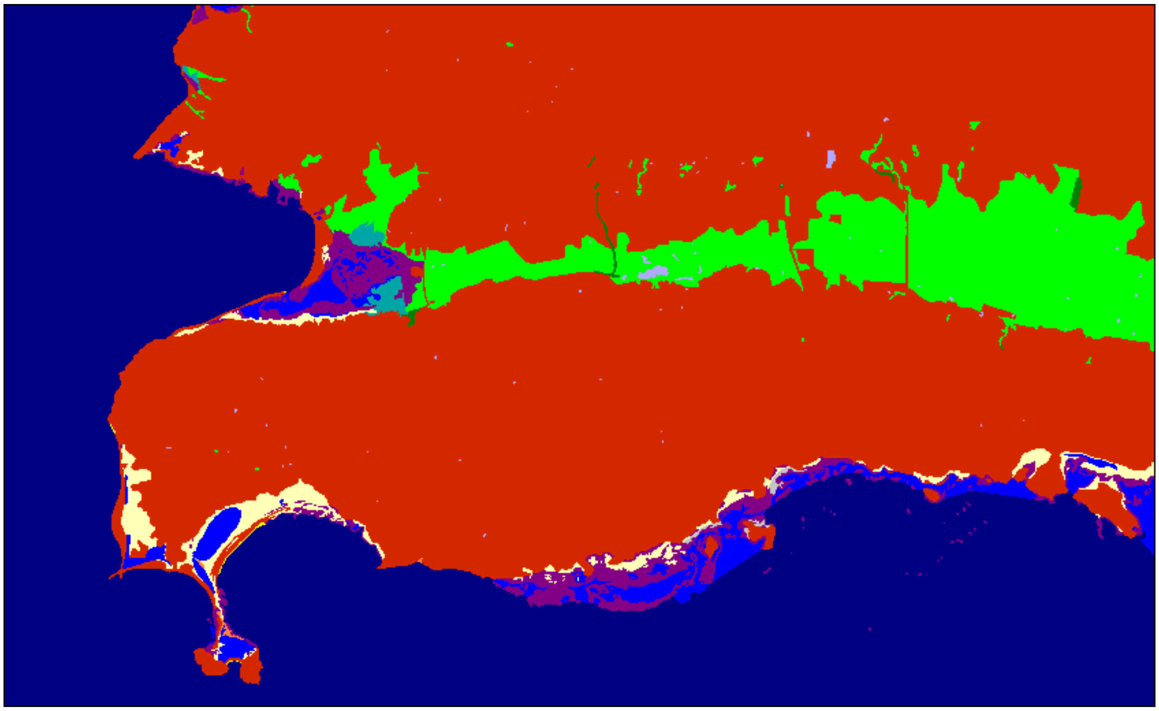
Puerto Rico, 2050, Scenario A1B Maximum



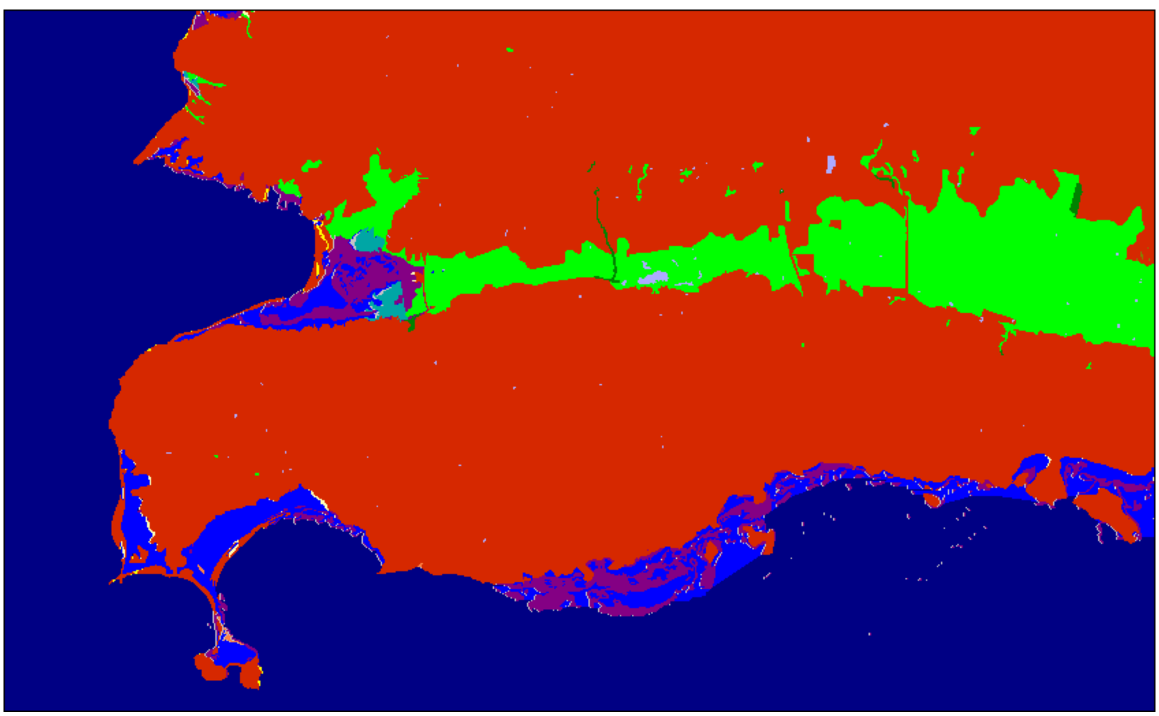
Puerto Rico, 2075, Scenario A1B Maximum



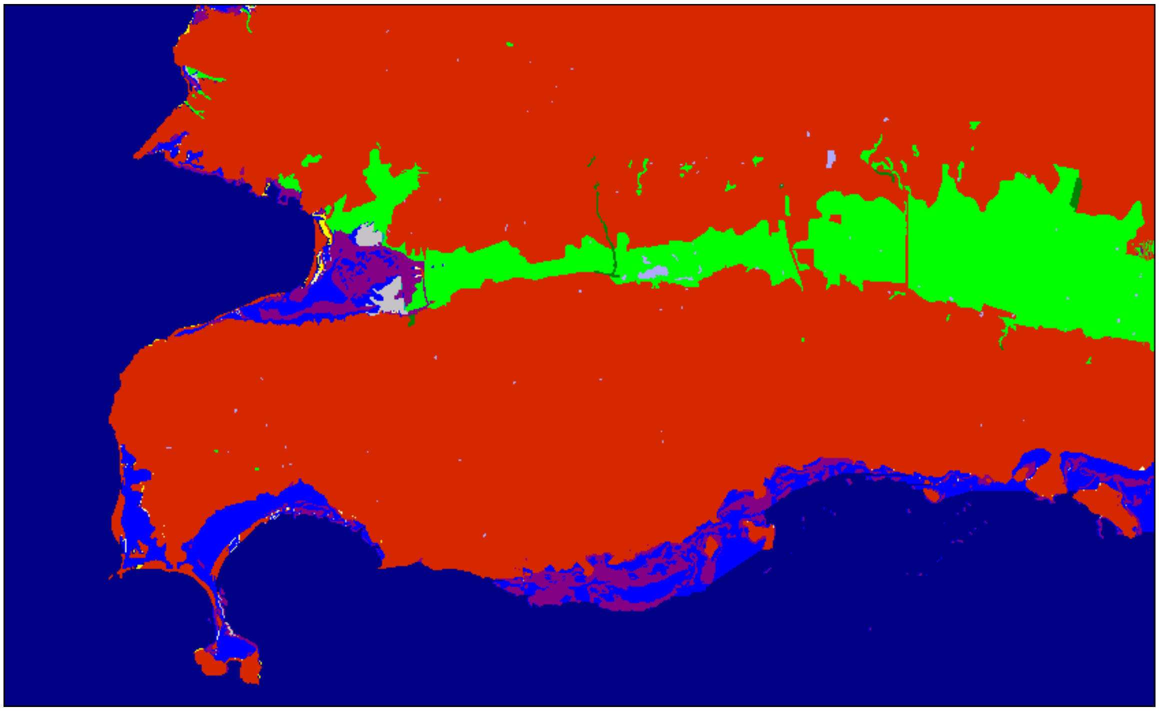
Puerto Rico, 2100, Scenario A1B Maximum



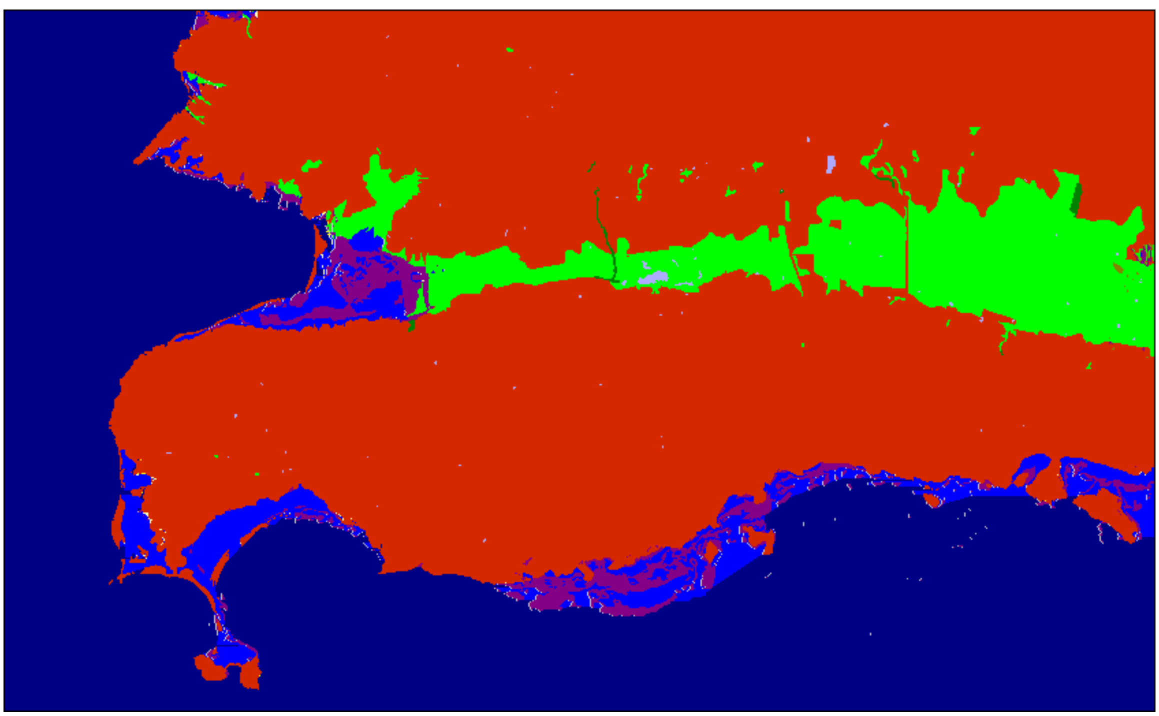
Puerto Rico, Initial Condition



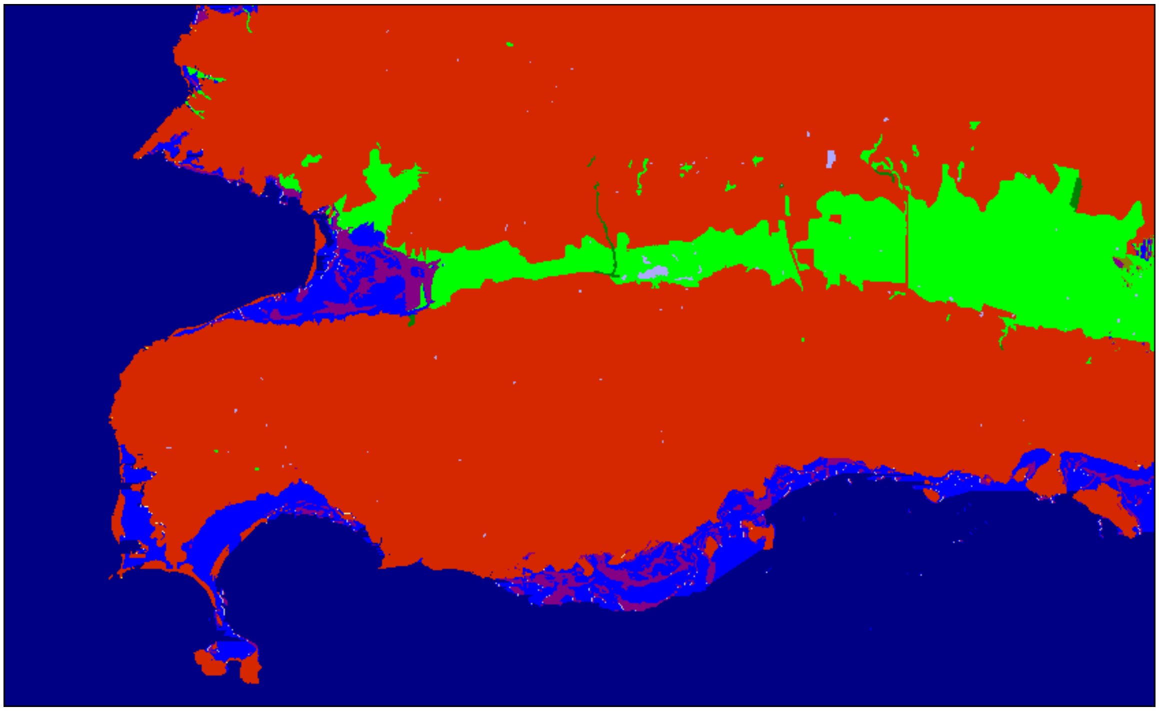
Puerto Rico, 2025, 1 meter eustatic SLR by 2100



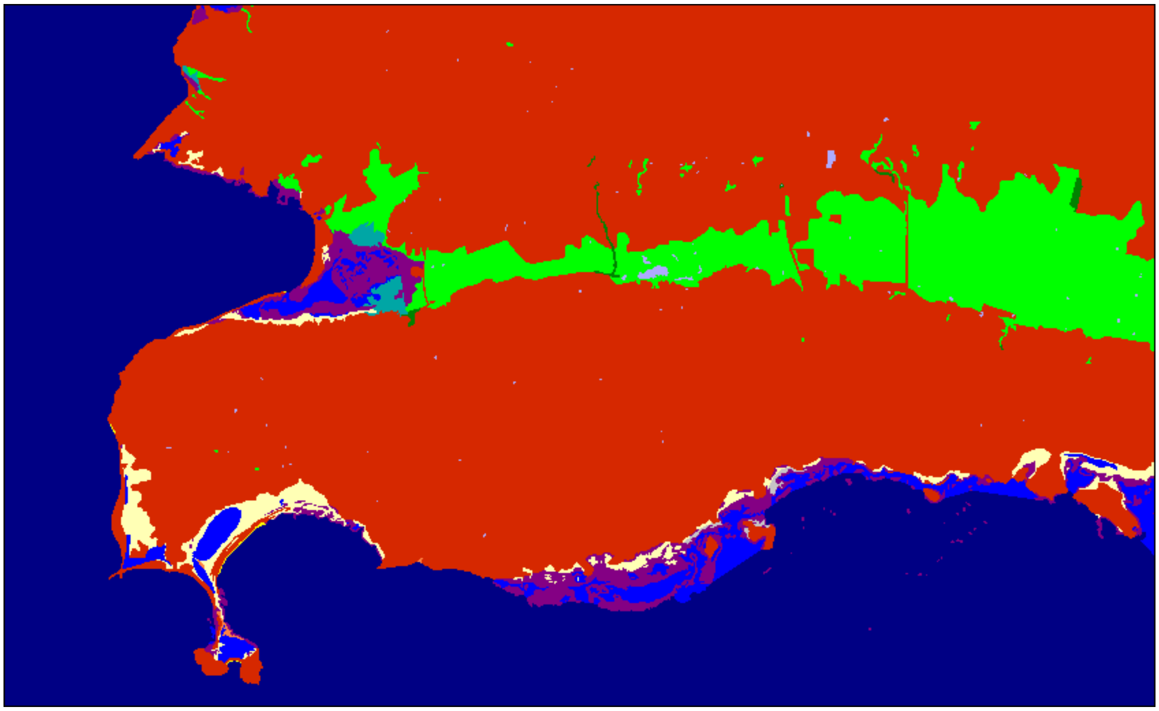
Puerto Rico, 2050, 1 meter eustatic SLR by 2100



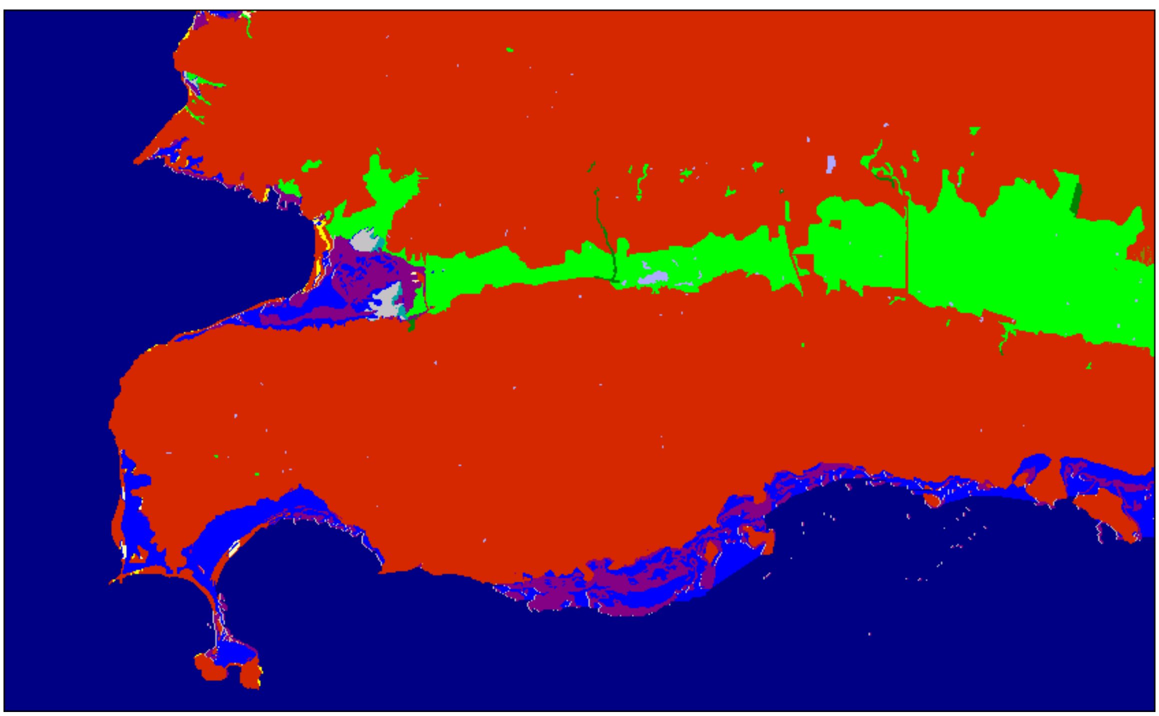
Puerto Rico, 2075, 1 meter eustatic SLR by 2100



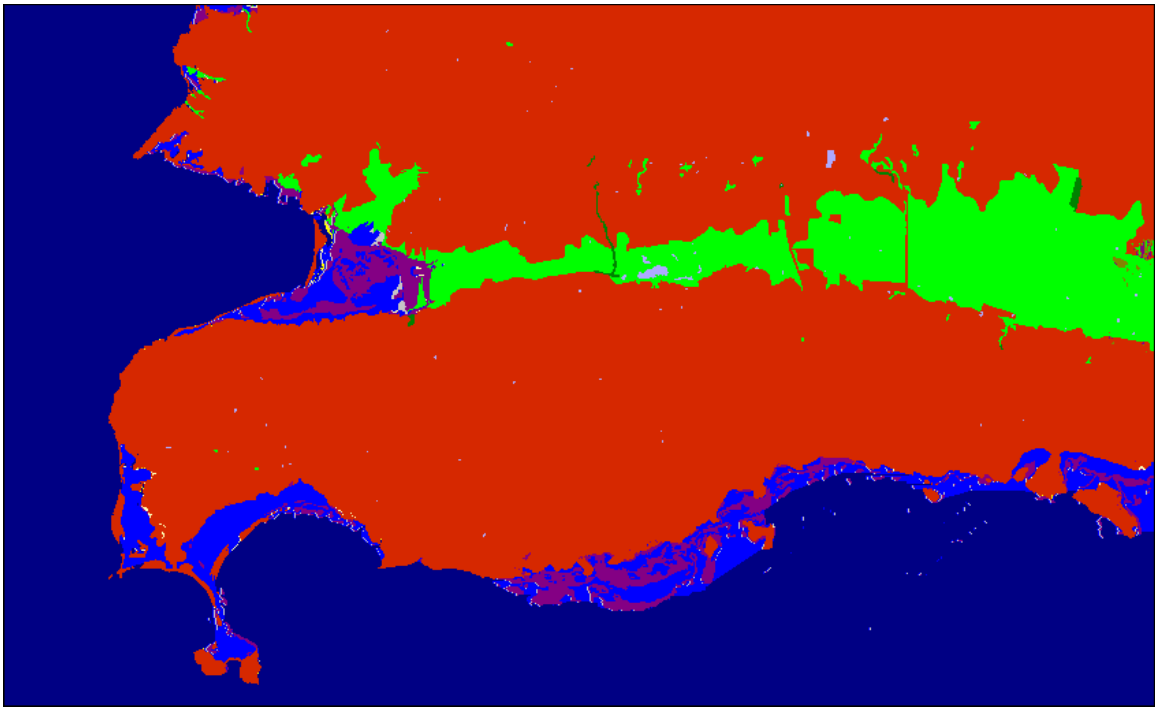
Puerto Rico, 2100, 1 meter eustatic SLR by 2100



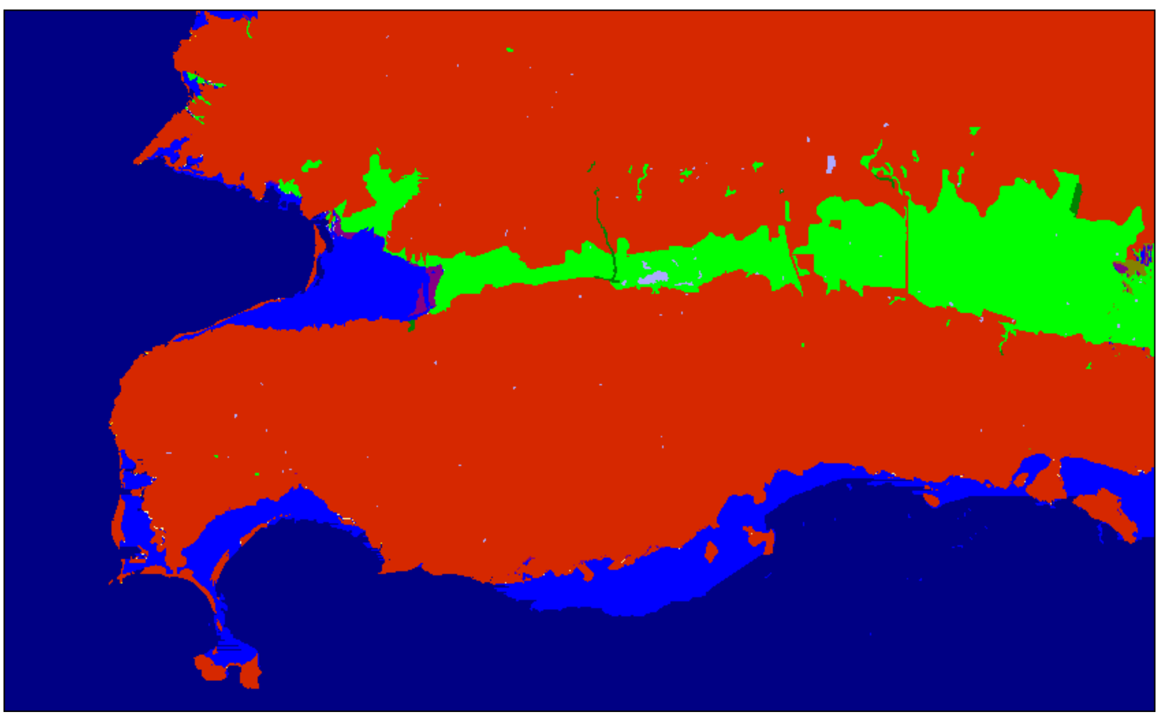
Puerto Rico, Initial Condition



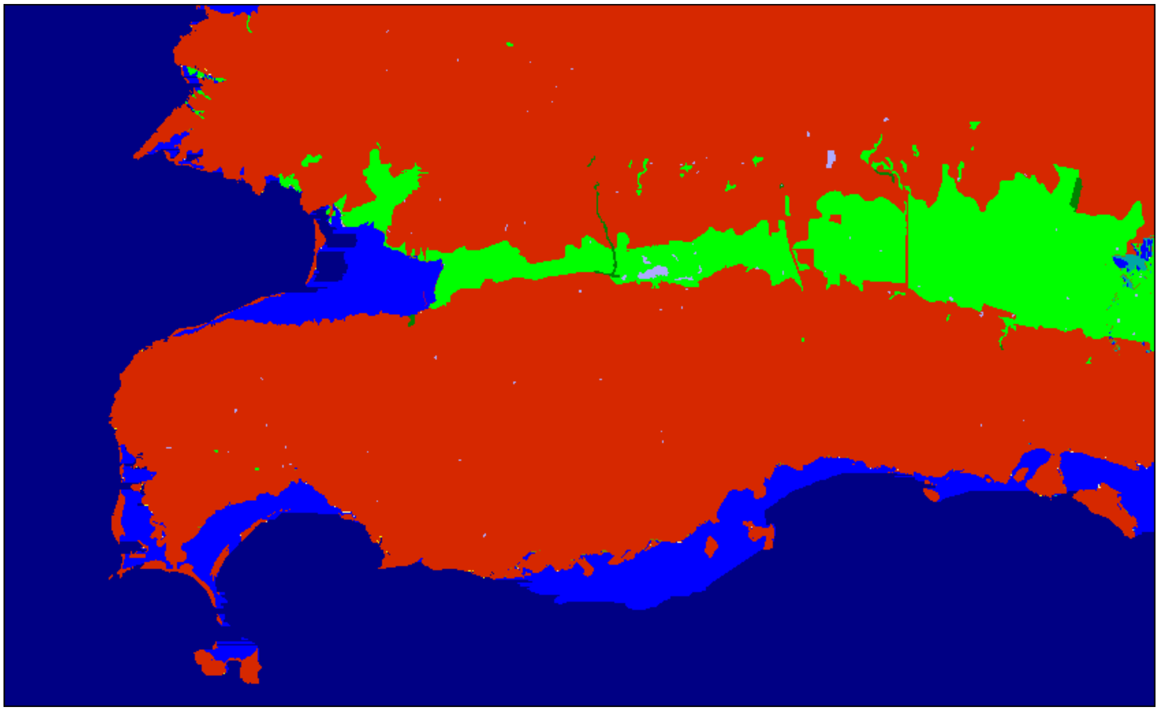
Puerto Rico, 2025, 1.5 meters eustatic SLR by 2100



Puerto Rico, 2050, 1.5 meters eustatic SLR by 2100



Puerto Rico, 2075, 1.5 meters eustatic SLR by 2100



Puerto Rico, 2100, 1.5 meters eustatic SLR by 2100