Prioritization of Critical Marsh Conservation and Restoration Areas based on Future Sea-level Rise Scenarios in Copano and San Antonio Bays, Texas Area

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Table of Contents

List of Figures

List of Tables

Acronyms

AR	Assessment Report
AOI	Area of Interest
ASCII	American Standard Code for Information Interchange
ANWR	Aransas National Wildlife Refuge
BEG	Bureau of Economic Geology
CMP	Coastal Management Program
CSA	Copano and San Antonio Bays
DEM	Digital Elevation Model
DST	Decision Support Tool
FGDC	Federal Geographic Data Committee
GIS	Geographic Information Systems
GLO	General Land Office
GOMA	Gulf of Mexico Alliance
ICWW	Intra Coastal Water Way
IPCC	Intergovernmental Panel on Climate Change
LiDAR	Light Detection And Ranging
MANERR	Mission-Aransas National Estuarine Research Reserve
MTL	Mean Tide Level
NLCD	National Land Cover Dataset
NOAA	National Oceanic and Atmospheric Administration
NWI	National Wetland Inventory
ORNL	Oak Ridge National Laboratory
SLAMM	Sea-Level Affecting Marshes Model
SLR	Sea-Level Rise
SRES	Special Reports on Emissions Scenarios
SoVI	Social Vulnerability Index
TCMP	Texas Coastal Management Program
T_0	Time zero
TNC	The Nature Conservancy
US	United States

INTRODUCTION

The Nature Conservancy (TNC) has worked for the past six years in implementing its coastal resilience strategy, a program helpful in understanding coastal vulnerabilities and identifying priority areas for future marsh management and restoration efforts. The goal of these research efforts is to reduce the potential risks of sea-level rise (SLR) and storm-surge in Texas by utilizing the Sea-level Affecting Marsh Migration (SLAMM) model and new high-resolution LiDAR data to produce a series of spatial indices for coastal restoration and protection for San Antonio and Copano Bay estuarine systems. These indices are designed to promote healthy coastal ecosystems and identify nature-based solutions to sea-level rise, focusing on marsh habitat viability along the Texas central coast and opportunities for marsh restoration and community adaptation.

Scientific evidence suggests that SLR and related increases in storm-surges will progressively put coastal habitats and populations at risk (Clough and Polaczyk 2011, Maloney and Preston 2014, Parris et al. 2012). Coastal wetland habitats provide numerous benefits to people and other ecosystems, and are amongst the most susceptible ecosystems to SLR impacts. In this project, Coastal Management Program (CMP) funding helped leverage TNC's expertise, as well as the work of numerous related efforts, to develop a continuous view of the potential future impacts of SLR on coastal wetland habitats along the Gulf of Mexico. Using a highly specialized team with experience in similar projects, TNC completed the products and deliverables of this project using a framework designed and utilized by TNC in similar coastal habitats including: Galveston Bay, Jefferson County and Freeport, Texas, as well as multiple locations in Mississippi and Florida (Thompson et al. 2014). TNC's experimental approach for this analysis is based on currently available data, and includes the assessment of habitat risks and vulnerability to coastal hazards by utilizing SLAMM to investigate potential future SLR scenarios. TNC identified ecologically important areas for conservation, with the purpose of informing management and stakeholders of the relative vulnerability of these valuable coastal natural resource areas, and provided a set of spatially explicit products that can be used directly in coastal resilience planning and other decision-making processes.

TNC utilized the results of the new University of Texas Bureau of Economic Geology (BEG) LiDAR acquisitions for San Antonio Bay and Copano Bay, and other available datasets, to produce new SLAMM scenario outputs of the project site. These outputs were used as the basis for the implementation of TNCs' Marsh Conservation and Resiliency framework in the study area. The framework includes four primary analyses - 1) Marsh Change, Migration and Viability, 2) Community Risk, 3) Community Resilience, and 4) Long-term Marsh Management. In addition, a comparative analysis was conducted using new high resolution SLAMM results (16.4 ft/5 m) with those conducted previously with a coarser resolution (98.4 ft/30 m; Warren Pinnacle Consulting 2010); this is an essential analysis given the rapid advancement of LiDAR technology and the need to validate previous SLAMM modeling efforts.

This project was conducted within an 18-month period and included the following: 1) integration of high resolution LiDAR data into SLAMM models; 2) identification of priority conservation areas; 3) comparison of low and high resolution SLAMM models; and 4) dissemination of results through two stakeholder workshops and publication of all project data and deliverables online. Project results will benefit resource managers and planners by providing readily available, spatially explicit model data on coastal habitat change for various projected future SLR scenarios, thereby resulting in data in GIS and map formats which can be directly incorporated into coastal resiliency, conservation and restoration strategies.

Study Area

The project site for this analysis is located on the southwestern coastal plain of Texas and includes Copano Bay, Aransas Bay, San Antonio Bay with Guadalupe River delta and Espiritu Santo Bay (Figure 1). It also overlaps seven Texas counties: Nueces, Aransas, Refugio, Victoria, Matagorda, San Patricio, and Calhoun. Both the Copano Bay and San Antonio Bay regions are known for their rural characteristics, and are home to farming and ranching communities near the Guadalupe Delta. Additionally the bays are home to the Aransas National Wildlife Refuge (ANWR) and Mission-Aransas National Estuarine Research Reserve (MANERR). They are separated from the Gulf of Mexico by San Jose and Matagorda Islands, with access to Gulf of Mexico waters through two maintained waterways: the Intracoastal Waterway (ICWW) to the north near Port O'Connor and the shipping channel in Port Aransas to the south. The primary fresh water sources entering Copano Bay come from the Mission River to the north, Aransas River with Chiltipin Creek from the northwest, and Copano Creek from the east; San Antonio Bay receives its freshwater from the Guadalupe River and San Antonio River from its northern extension, along with the Green Lake/Victoria ship channel (Tremblay and Calnan 2011). The Copano Bay system covers approximately 152,960 acres and has an average depth of around 10 ft. (3 m). San Antonio Bay, which has an average depth of just over 6.6 ft. (2 m), covers approximately 129,280 acres (Moretzsohn et al. 2016).

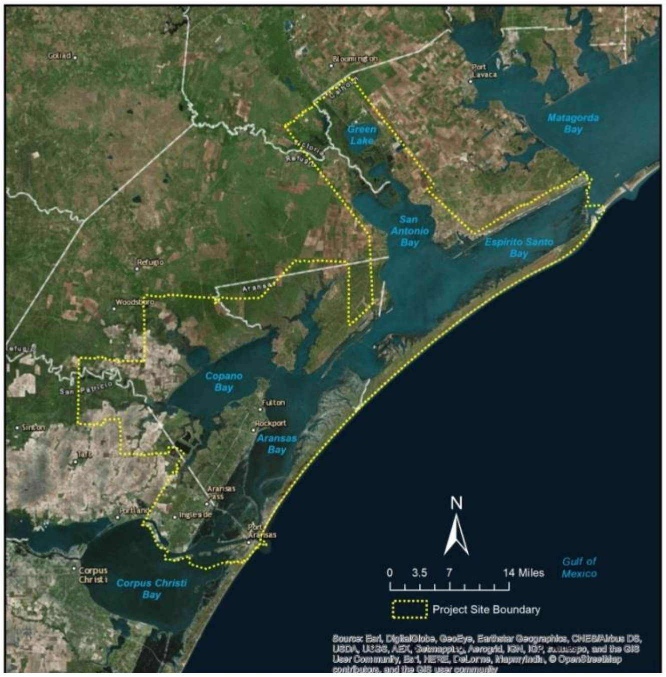

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Figure 1. Copano and San Antonio Bays project site boundary (yellow).

Copano and San Antonio Bays are characterized by a wide range of biodiversity, especially since they house two important federal protected areas: ANWR (including the Matagorda Island Unit) and MANERR. Both management units focus on supporting critical habitats that provide foraging, nesting and resting places to many bird, fish and invertebrate species, including the endangered whooping crane, whose dwindling population of fifteen birds back in 1941 sparked the fire to protect its habitat for generations to come. Moreover, the bay ecosystems and their surrounding marshlands and islands are home to over 400 species of birds and over 200 species of fish (USFWS 2016).

Regularly- and irregularly-flooded marshes in the Copano and San Antonio Bay project areas represent extensive ecological and socio-economic importance to the surrounding communities, but these habitats are also prone to the most sensitive environmental changes and to SLR (GLO 2013). For marsh viability and community resilience, this project study focused on these habitats, which combined cover over 51,797 acres currently within the 778,390-acre study area. Both palustrine and estuarine marshes have been observed over a long period of time by local scientists, who found a dramatic increase in area from 1979 to 2009 due to land subsidence, land management practices, and accelerated SLR (Tremblay and Calnan 2011). In addition to marshes, the project site contains over 19,000 acres of fresh marsh habitat, over 291,500 acres of Undeveloped Dry Land, 16,650 acres of Developed Land, and Estuarine and Ocean Waters that cover over 317,781 acres of area collectively.

METHODS

Modeling Approach

The modeling approach used in this study follows an overarching project framework for informing ongoing and future conservation and resiliency planning efforts through SLR and storm-surge projections, socioeconomic indicators, and marsh migration scenarios as referenced in past projects (Thompson et al. 2014, Geselbracht et al. 2013, Gilmer et al. 2012). The framework for the overall analysis is outlined in Figure 2 and all results utilized a eustatic SLR of 1 m (3.2 ft) by 2100. The methods described herein detail our approach in the Copano and San Antonio Bays region for assessing socioeconomic and ecological risk from SLR and storm-surge, coastal habitats' relation to vulnerable human communities, and management options needed to support conservation and restoration planning for climate-enhanced coastal change.

We chose to use SLR and storm-surge as the main climate-related drivers of change for this analysis because their effects are measurable and can be modeled using established methods. Sea-level rise has many implications to coastal communities, including the loss or gain of wetland habitats and impacts on human infrastructure and resiliency, where storm-surge events have traditionally caused catastrophic damage and loss of life along the gulf coast. Since SLR can intensify future storm-surge events, we also elected to analyze the impacts of storm-surge intensified by SLR to create an additional coastal hazard index. Geographical Information System (GIS) software (ESRI ArcMap 10.2.2) was used to analyze the scenarios in raster and shapefile format. All raster inputs and the resulting GIS data used for this analysis have a spatial resolution of 5 m, and were projected in the Universal Transverse Mercator 14N (NAD 1983) coordinate system.

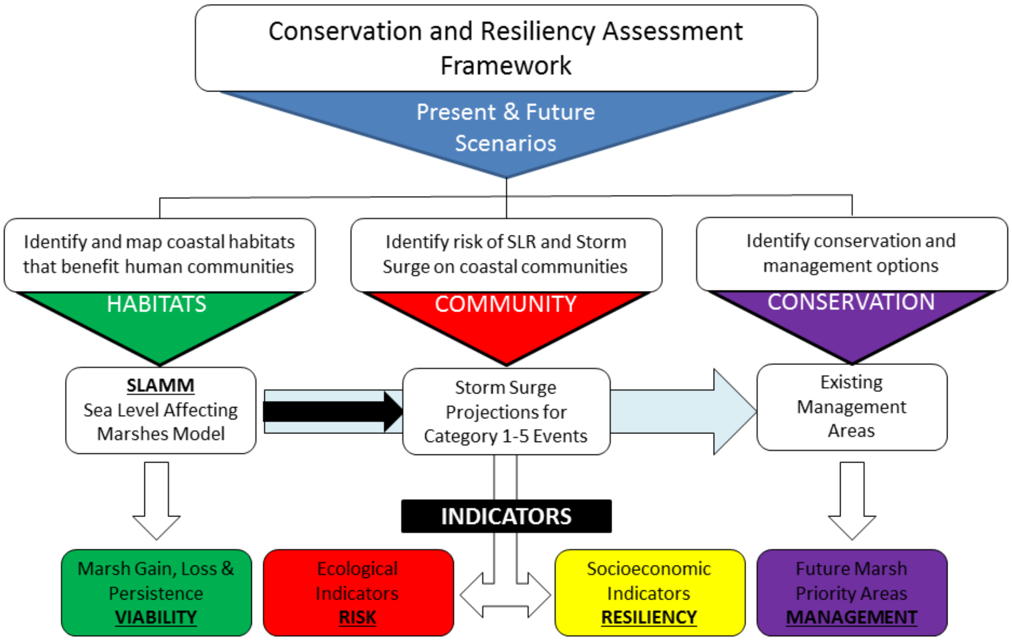

Figure 2. Framework for the Nature Conservancy's conservation and resiliency analysis.

Sea-Level Rise and Marsh Migration Modeling

To prep for prioritization of habitats susceptible to sea-level rise and storm-surge and its changes, the study area was modeled using the Sea-level Affecting Marshes Model (SLAMM 6.2) (Clough et al. 2012). This model 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). SLAMM is used to simulate the effects of SLR on coastal wetland habitats and potential changes in tidal marsh area and other coastal habitat types in response to multiple scenarios of SLR (see Figure 3). SLAMM data was processed by staff at TNC-Alabama Coastal Program using five SLR scenarios that could potentially occur by the year 2100: IPCC A1B-mean (Intergovernmental Panel on Climate Change; 0.39 m), IPCC A1B-maximum (0.69 m), eustatic 1 m, eustatic 1.5 m, and eustatic 2 m[1] . Each SLR scenario was modeled for four time-steps – 2025, 2050, 2075 and 2100 — in order to understand the dynamic and subsequent impacts of SLR over a long period of time. The SLAMM model simulates the changes of wetland habitats and shoreline position at a specific location when it is exposed to SLR by incorporating site-specific information on land elevations, land cover, tide ranges, land subsidence rates, and sedimentation and erosion rates (Clough and Larson 2010). For further analysis of marsh viability and community risk and resiliency, the eustatic 1 m SLR by 2100 was chosen because several recent studies have indicated that rising sea levels are likely to approach 1 m by the year 2100 (Nicolls et al. 2011, Vermeer and Rahmstorf 2009, Martinich et al. 2012, Parris et al. 2012, Williams 2012).

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[1] Equivalent of 1.28, 2.26, 3.28, 4.92, 6.56 ft of SLR, respectively.

SLAMM has been used frequently by federal agencies (e.g., the U.S. Fish and Wildlife Service) and regional entities (Gulf of Mexico Alliance, GOMA) as well as TNC to assist in their planning of conservation activities along the Gulf Coast and other coastal areas that are susceptible to SLR impacts (Titus et al. 1991, Lee et al. 1992, Park et al. 1993, Galbraith et al. 2002, Glick and Clough 2006, Glick et al. 2007, Craft et al. 2009, Clough and Polaczyk 2011, Clough 2011). For a thorough technical description of SLAMM model processes and the underlying assumptions and equations, see Clough and Larson. (2010). In addition, Clough and his team at Warren Pinnacle Consulting, Inc. ran the initial SLAMM modelling in 2010 in the same vicinity (ANWR) as the study area so this project reflects on the differences in using higher resolution LiDAR data with smaller cell size (5 m) versus the Clough's team project that utilized 30 m cell size (lower resolution). It is important to note that the SLAMM model results are subject to uncertainty based on limitations in input data, incomplete knowledge about factors that control the behavior of the system being modeled, data gaps, and simplifications of the system (CREM 2008).

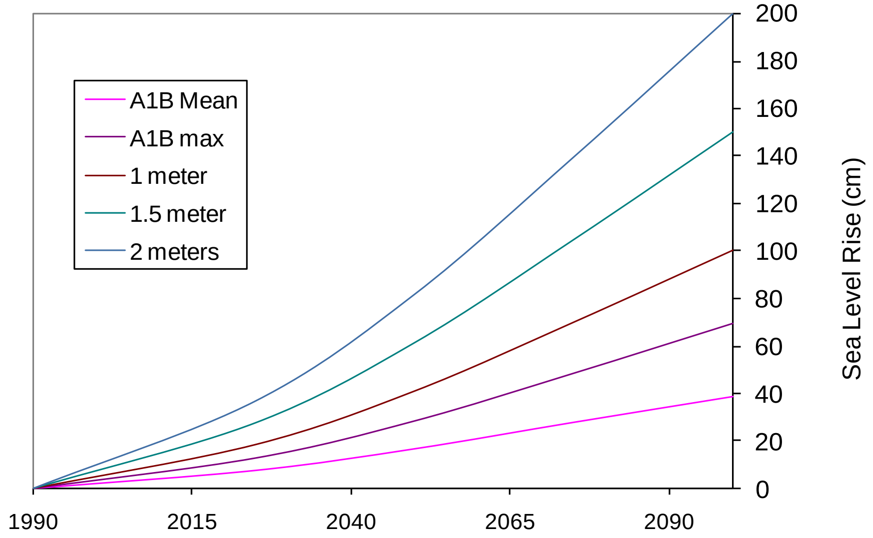


Figure 3. Summary of SLR scenarios adapted from Clough & Larson (2010).

SLAMM requires three inputs to run the model for a specific location. It utilizes ASCII (American Standard Code for Information Interchange) files that are converted from the original format of the inputs. These inputs are: elevation, which is derived from LiDAR (Light Detection and Ranging) data; slope, which is derived from LiDAR data; and vegetation, which is derived from National Wetlands Inventory (NWI) data and National Land Cover Dataset (NLCD). Each of these inputs had to be converted and transformed in ArcMap to be usable in SLAMM.

The BEG provided the LiDAR data for this project. As shown in Figure 4, BEG compiled 1 m high resolution LiDAR data for all shorelines and bay areas within the Copano and San Antonio Bays area between 2013 and 2014. This data was provided to TNC in December 2014. The LiDAR coverage was given in multiple files that were mosaicked together and resampled to 5 m cell size to create one streamlined raster elevation file to assist in a smoother work process. In addition, further map processing had to be conducted as the LiDAR data covering open water areas or inland ponds or any type of open water was not identified with an elevation value. The mosaicked elevation file was reclassified to convert all null values to “0” to reflect elevation at water level. Without reclassifying this value, the SLAMM model would output inaccurate results. Due to the large project area, we trimmed the project site to extend only to the footprint of the LiDAR dataset. After all the modifications were complete to the mosaicked LiDAR file, it was then converted to ASCII for elevation input into SLAMM.

Figure 4. Map of Texas Bureau of Economic Geology LiDAR footprints for Copano and San Antonio Bays.

The mosaicked LiDAR file was converted into the slope input by way of the Spatial Analyst’s Surface’s Slope ArcToolbox processed into an ASCII file for input into SLAMM.

The land cover classes in SLAMM follow the initial habitat classifications defined by the 2008 NWI. A TNC GIS analyst in Florida Chapter provided the Alabama Chapter with a table to help convert the NWI classes into SLAMM categories. The vegetation input for SLAMM required a bit more processing as it involved combining the attributes NWI and NLCD (2011) via map algebra, especially when converting undeveloped lands to developed lands. The wetlands layer for the study area was produced by the NWI and was based on 2008 photo dates. Wetlands were downloaded from the US Fish and Wildlife’s Wetlands Mapper website (http://www.fws.gov/wetlands/Data/Mapper.html) and the NLCD from the US Geological Survey’s Multi-Resolution Land Characteristics Consortium (http://www.mrlc.gov/finddata.php). The wetlands layer was the base layer for vegetation and resampled to 5 m cell size to match the resolution of the elevation and slope files. After finalization of developed areas and classifying open water areas, the vegetation file was then processed into an ASCII file for input into SLAMM.

The SLAMM model is versatile as it allows the user to enter in both general and specific site parameters to develop outputs that can be accurate for the project site. These parameters are listed below in Table 1. Past research from Geselbracht et al. (2013) and Clough and Larson (2010) projects have supplemented the numbers for the general site and subsites for Copano and San Antonio Bays as they both covered the same area. These numbers were then cross-referenced with newer research found to update as necessary. SLAMM parameters for Copano and San Antonio Bays are provided below in Table 3 and Table 2, respectively. In addition, locations of subsites are shown in Figure 5 for San Antonio Bay and Figure 6 for Copano Bay.

The historic trend for sea-level rise in this area was estimated at 5.27 mm/year using the nearest NOAA gage with long-term SLR data (#8774770, Rockport, TX). The rate of sea-level rise for this refuge has been substantially higher than the global average for the last 100 years (approximately 1.7 mm/year, IPCC 2007), and this difference is likely due to land subsidence. SLAMM allows for the differential between local and global rates of sea-level rise as it is projected to continue through the year 2100 within these model simulations.

A number of tide gauges were used to determine tide range for this SLAMM application where tides ranged from 0.11 m to 0.499 m (#8773963, North Matagorda, TX; #8773037, Seadrift, TX; #8774770, Rockport, TX; #8773259, Port Lavaca, TX; #8775270, Port Aransas, H. Caldwell Pier, TX; #8774513, Copano Bay, TX; #8773701, Port O'Connor, TX). The elevation at which estuarine water is predicted to regularly inundate the land (the salt elevation) was estimated based on a frequency of inundation analysis using data from TCOON (Texas Coastal Ocean Observation Network) tide stations at Seadrift (#031) and Port O'Connor (#057) as well as from the Rockport NOAA gage (#8774770, Rockport, TX) (Clough and Larson 2010).

Table 1. List of SLAMM Parameters to run model and can be specified for a particular area.

Description of Parameters		
NWI Photo Date (YYYY)	Marsh Erosion (horz. m /yr)	Mangrove Accr (mm/yr)
DEM Date (YYYY)	Swamp Erosion (horz. m /yr)	Tidal Swamp Accr (mm/yr)
Direction Offshore [n,s,e,w]	T.Flat Erosion (horz. m /yr)	Swamp Accretion (mm/yr)
Historic Trend (mm/yr)	Reg.-Flood Marsh Accr (mm/yr)	Beach Sed. Rate (mm/yr)
MTL-NAVD88 (m)	Irreg.-Flood Marsh Accr (mm/yr)	Freq. Overwash (years)
GT Great Diurnal Tide Range (m)	Tidal-Fresh Marsh Accr (mm/yr)	Use Elev Pre-processor [True,False]
Salt Elev. (m above MTL)	Inland-Fresh Marsh Accr (mm/yr)	

Clough and Larson (2010) were able to acquire a couple of sources for accretion data within the study area. Callaway, Patrick, and DeLaune (1997) reported average accretion rates of 4.4 mm/year with a standard deviation of 1.6 mm/year (from a transect taken east of the Aransas Unit of the ANWR), and they noted that the MANERR had an accretion rate of 4.8 mm/year but it was noted as "incomplete" so the parameter for accretion stayed at 4.4 mm/year. Another report from Feagin and Yeager (2008) found through their observations of temporary variable accretion rates before and after growth faulting (7.8 mm/year before and 1.3 mm/year after faulting). Clough and Larson (2010) noted that when you average the range of accretion values (4.55 mm/year) it ends up being close to the long-term accretion rate (4.4 mm/year) utilized within the modeling and will be applied for Regularly Flooded and Irregularly Flooded Marshes' accretion rates. The MTL (Mean Tide Level) to NAVD88 correction was derived using available data from

NOAA gauges. Behind the barrier island the correction was set to 0.339 m, and the coastal value was set to 0.107 m. The Frequent Overwash (years) was set to “0” per guidance of Warren Pinnacle Consulting, Inc. technical staff as the overwash model is sensitive to high resolution data resulting in incorrect SLAMM outputs.

Table 2. San Antonio Bay subsites and parameters.

Description	Global	Subsite 1	Subsite 2	Subsite 3	Subsite 4	Subsite 5	Subsite 6
NWI Photo Date (YYYY)	2008	2008	2008	2008	2008	2008	2008
DEM Date (YYYY)	2013	2013	2013	2013	2013	2013	2013
Direction Offshore [n,s,e,w]	South	South	South	North	South	West	North
Historic Trend (mm/yr)	5.16	5.16	5.16	5.16	5.16	3.55	3.55
MTL-NAVD88 (m)	0.339	0.339	0.339	0.339	0.107	0.339	0.339
GT Great Diurnal Tide Range (m)	0.111	0.111	0.283	0.131	0.499	0.48	0.2
Salt Elev. (m above MTL)	0.36	0.36	0.48	0.36	0.332	0.58	0.23
Marsh Erosion (horz. m /yr)	0.72	0	1.55	0.84	0	1.09	0.84
Swamp Erosion (horz. m /yr)	0.28	0	0	0.28	0	0.28	0.28
T.Flat Erosion (horz. m /yr)	0.28	0	0	0.84	0	0.28	0.84
Reg.-Flood Marsh Accr (mm/yr)	4.4	4.4	4.4	4.4	4.4	3.81	3.81
Irreg.-Flood Marsh Accr (mm/yr)	4.4	4.4	4.4	4.4	4.4	1.3	1.3
Tidal-Fresh Marsh Accr (mm/yr)	5.9	5.9	5.9	5.9	5.9	4.86	4.86
Inland-Fresh Marsh Accr (mm/yr)	5.9	5.9	2.9	2.9	2.9	2.9	2.9
Mangrove Accr (mm/yr)	7	7	7	7	7	7	7
Tidal Swamp Accr (mm/yr)	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Swamp Accretion (mm/yr)	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Beach Sed. Rate (mm/yr)	0.5	0.5	0.5	0.5	0.5	0.69	0.69
Freq. Overwash (years)	0	0	0	0	0	0	0
Use Elev Pre-processor [True,False]	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE

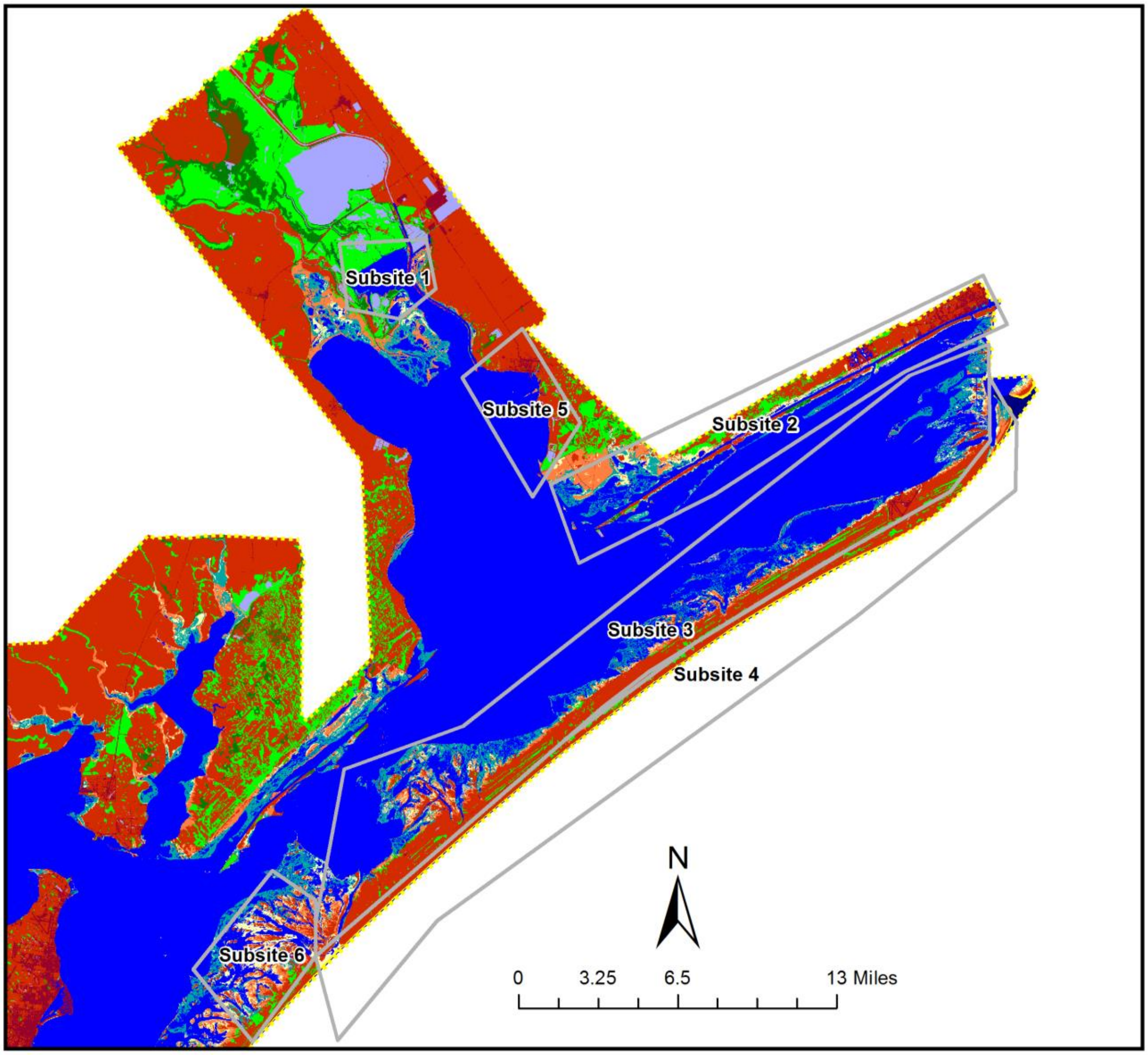


Figure 5. San Antonio Bay input subsites for model application.

Table 3. Copano Bay subsites and parameters.

Description	Global	Subsite 1	Subsite 2	Subsite 3	Subsite 4	Subsite 5	Subsite 6	Subsite 7
NWI Photo Date (YYYY)	2006	2006	2006	2008	2008	2006	2006	2006
DEM Date (YYYY)	2014	2014	2014	2014	2014	2014	2014	2014
Direction Offshore [n,s,e,w]	South	East	West	West	East	East	North	East
Historic Trend (mm/yr)	4.48	3.55	3.55	3.55	3.55	3.55	3.55	3.55
MTL-NAVD88 (m)	0.339	0.339	0.339	0.339	0.339	0.339	0.339	0.339
GT Great Diurnal Tide Range (m)	0.2	0.48	0.2	0.2	0.48	0.2	0.2	0.2
Salt Elev. (m above MTL)	0.23	0.58	0.23	0.23	0.58	0.23	0.23	0.23
Marsh Erosion (horz. m /yr)	1.08	0.28	0.84	0.84	0.28	0.84	0.84	0.84
Swamp Erosion (horz. m /yr)	0.8	0.28	0.28	0.28	0.28	0.28	0.28	0.28
T.Flat Erosion (horz. m /yr)	1.08	0.28	0.84	0.84	0.28	0.84	0.84	0.84
Reg.-Flood Marsh Accr (mm/yr)	4.12	3.81	3.81	3.81	3.81	3.81	3.81	3.81
Irreg.-Flood Marsh Accr (mm/yr)	2.94	1.3	1.3	1.3	1.3	1.3	1.3	1.3
Tidal-Fresh Marsh Accr (mm/yr)	5.41	4.86	4.86	4.86	4.86	4.86	4.86	4.86
Inland-Fresh Marsh Accr (mm/yr)	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9
Mangrove Accr (mm/yr)	7	7	7	7	7	7	7	7
Tidal Swamp Accr (mm/yr)	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Swamp Accretion (mm/yr)	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Beach Sed. Rate (mm/yr)	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69
Freq. Overwash (years)	0	0	0	0	0	0	0	0
Use Elev Pre-processor [True,False]	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE

Description	Subsite 8	Subsite 9	Subsite 10	Subsite 11	Subsite 12	Subsite 13	Subsite 14	Subsite 15
NWI Photo Date (YYYY)	2008	2006	2008	2006	2006	2006	2006	2006
DEM Date (YYYY)	2014	2014	2014	2014	2014	2014	2014	2014
Direction Offshore [n,s,e,w]	South	North	South	South	South	South	East	North
Historic Trend (mm/yr)	5.27	5.27	5.27	5.27	5.27	5.27	5.27	5.27
MTL-NAVD88 (m)	0.339	0.339	0.339	0.339	0.339	0.339	0.339	0.339
GT Great Diurnal Tide Range (m)	0.117	0.117	0.117	0.117	0.117	0.117	0.117	0.117
Salt Elev. (m above MTL)	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36
Marsh Erosion (horz. m /yr)	0.84	1.56	1.68	1	2.29	1.56	1.07	1.88
Swamp Erosion (horz. m /yr)	0.28	1.56	1.68	1	2.29	1.56	1.07	1.88
T.Flat Erosion (horz. m /yr)	0.84	1.56	1.68	1	2.29	1.56	1.07	1.88
Reg.-Flood Marsh Accr (mm/yr)	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4
Irreg.-Flood Marsh Accr (mm/yr)	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4
Tidal-Fresh Marsh Accr (mm/yr)	5.9	5.9	5.9	5.9	5.9	5.9	5.9	5.9
Inland-Fresh Marsh Accr (mm/yr)	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9
Mangrove Accr (mm/yr)	7	7	7	7	7	7	7	7
Tidal Swamp Accr (mm/yr)	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Swamp Accretion (mm/yr)	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Beach Sed. Rate (mm/yr)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Freq. Overwash (years)	0	0	0	0	0	0	0	0
Use Elev Pre-processor [True,False]	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE

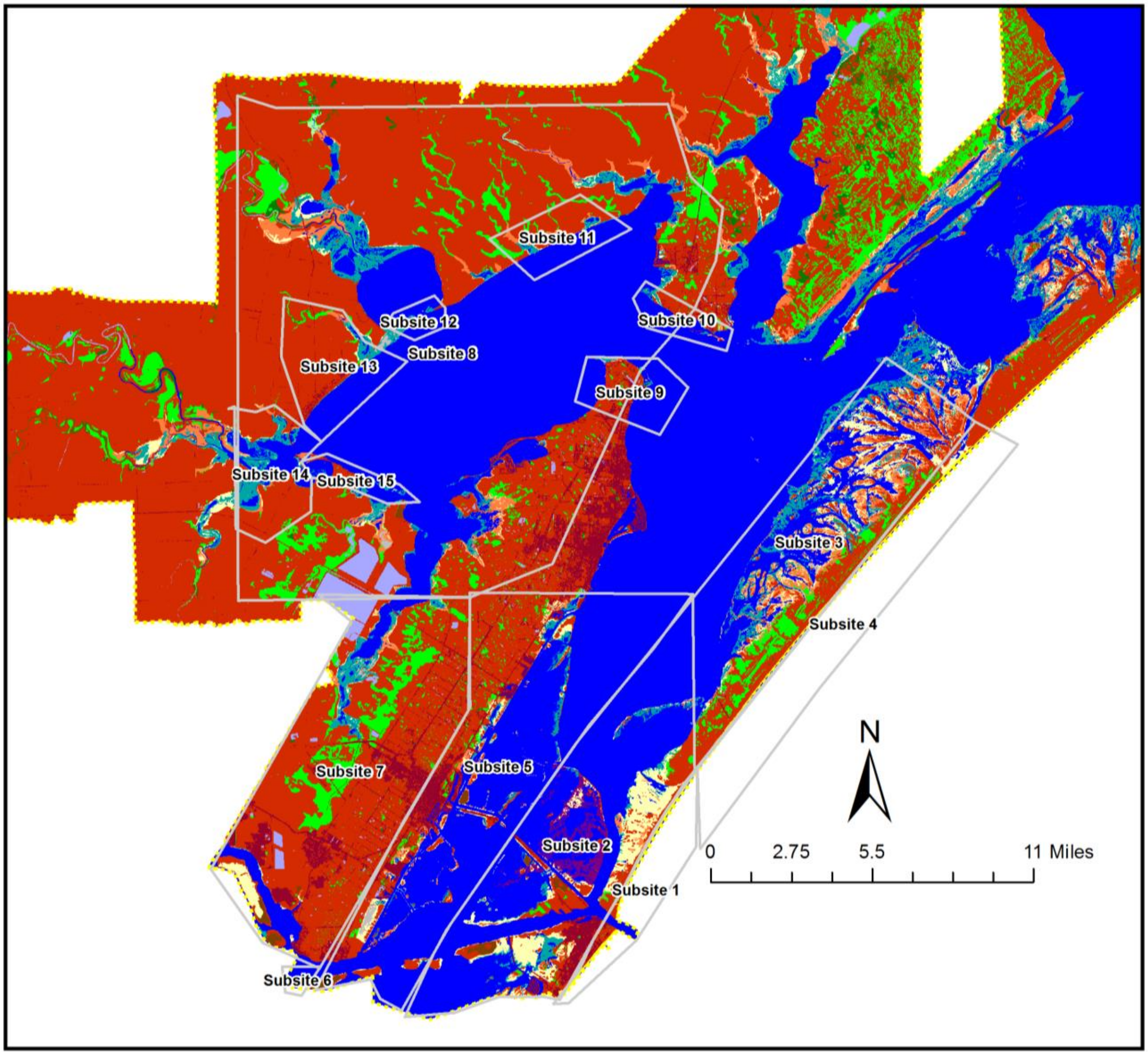


Figure 6. Copano Bay input subsites.

Storm-surge Data

Storm-surge simulation data were acquired by another source, Oak Ridge National Laboratory (ORNL), based on their previous modeling studies of storm-surge under different hurricane intensities and various SLR scenarios along the Texas coast, as well as, other US coasts (Maloney and Preston 2014). This source was chosen as a part of this analysis because of efficiency as we did not have the resources to hire an external contractor to conduct site specific storm-surge scenarios (like the ADvanced CIRCulation model or ADCIRC). With guidance from the data provider, the 0.82 m scenario was selected as it represents the 95th percentile global mean sea-level rise by 2100 under the Special Report on Emissions Scenario (SRES) A1Fi scenario. This estimate comes from the work of Hunter (2010) who was trying to reconcile the IPCC's Assessment Report 4 (AR4) and Assessment Report 3 (AR3) SLR projections in order to enhance comparability. There was no available data for storm-surge exposure for a eustatic 1 m SLR projection across the different hurricane categories; therefore, we decided to utilize the 0.82 m projections as it is relatively close to 1 m projections. Because no recent hurricane has made landfall at the desired location of interest, storm-surge exposure areas for each Saffir-Simpson Hurricane Wind Scale category (1 to 5, positively correlated with intensity) were evaluated. This modeling effort was motivated by the need to provide another perspective of tropical storms and hurricane impacts to TNC and Texas GLO to better understand the effects of SLR and storm-surge within the Copano and San Antonio Bays study area. The products provided as part of this effort will help coastal managers, scientist and the conservation community in identifying the additional threat posed by storm-surge given 1 m of SLR by 2100 in the study area.

Conservation and Resiliency Modeling

The following modeling efforts are based on TNC's previous research and the conservation and resilience framework that resulted from these efforts. It has four main analyses that include: 1) marsh change and viability, 2) community risk, 3) community resilience, and 4) marsh conservation and management (Geselbracht et al. 2013, Gilmer et al. 2012, Thompson et al. 2014). We focus primarily on two of the SLAMM land cover classes, Regularly-flooded and Irregularly-flooded Marsh, because they are important habitats for fisheries, wildlife, and coastal protection (National Ocean Service NOAA 2011).

Marsh Change and Viability Analysis

This analysis identified existing Regularly and Irregularly-flooded Marshes that are most likely to persist over time, and those that are most threatened to be lost to SLR in the future and are reported and summarized per census block. SLAMM model results for Copano and San Antonio bays were used to calculate where these changes might occur and predict where marshes (salt and fresh) might gain, lose or maintain area under a 1 m of SLR scenario for the time period between the initial land cover dataset and 2100.

A marsh viability estimate was determined for each census block (that currently had wetlands in 2008) by summarizing the gain, persistence and loss per marsh. Salt marsh advancement zones, as used in this study, refer to the path through which marshes are predicted to move landward under the 1 m SLR by 2100 scenario.

Additionally, to better relate marsh viability to socioeconomic data in subsequent analyses and to illustrate aggregated marsh viability at the human community level, a marsh viability analysis was also calculated and aggregated at the census block scale. The latter census block level calculation was determined for each block by the marsh area via the following equation:

Marsh Viability = (Marsh Gain – Marsh Loss) + Marsh Persistence/ Initial Marsh Area

Marsh viability was then classified from “Low” to “High” based on a 5-class Natural Breaks classification using ArcMap to help visualize maximum differences in marsh viability per census block. The Natural Breaks classification method is a “binning” method that groups similar values to maximize the differences between classes (de Smith et al. 2009). To normalize results further, we removed outliers that interfered with the Natural Breaks classification group breakdown and to prevent a skewed output.

Community Risk Analysis

Following methods similar to those used in a recent study by Shepard et al. (2011) we identified communities facing the highest risk of storm-surge and SLR. Granger (2003) and Shepard et al. (2011) conceptualize risk as:

Risk(i)= Exposure [Hazard(i) x Elements at Risk(i)] x Vulnerability

To calculate a particular hazard scenario, we utilized the ORNL storm-surge data (+0.82 m A1Fi scenario) combined with our 1 m 2100 SLAMM SLR model results to determine a value to measure the community’s risk to SLR and storm-surge. In this application of this equation “exposure” refers to storm-surge inundation scenarios, which are a function of the *[Hazard x Elements at Risk]* portion of the equation (Granger 2003). We used this conceptual risk framework to identify communities that potentially could face the highest risk to hurricane storm-surge by providing computer model results of how SLR, and its impacts on habitat, can increase risk to storm-surge when factored into future storm scenarios.

Exposure was calculated by classifying all inundated census blocks into “high”, “medium”, and “low” based on the percentage of each census block inundated per storm-surge for the initial conditions (baseline) and for storm-surge with SLR in 2100 (future). Census blocks with less than 5% and more than 0.1% of inundation were classified as “low”; less than 15% and more than 5% were “medium” and greater than 15% were considered to be of “high” exposure (Table4).

Table 4. Inundation and exposure levels for storm-surge and SLR Impacts.

Inundation Percentage	***Exposure Level***
< 0.10%	None
0.09 % to 4.99%	Low
5.00% to 14.99%	Medium
> 15.00%	High

The social vulnerability side of the equation was implemented by using the Social Vulnerability Index (SoVI) data provided by the Hazards and Vulnerability Research Institute at the University of South Carolina at the block group scale. The index synthesizes 31 socioeconomic variables, which the research literature suggests contribute to reduction in a community’s ability to prepare for, respond to, and recover from hazards and has been used extensively by others (Burton and Cutter 2008, Martinich et al. 2013, Schmidtlein et al. 2008, Wood et al. 2010). In this analysis, the project area covered three classes: Medium High, Medium, and Medium Low.

Finally, the community risk index was calculated by classifying the storm-surge exposure index and also SLR exposure index with the SoVI into a conceptual 1 to 5 (low to high) ranking system where blocks groups that experienced high exposure and medium high social vulnerability (e.g. "5"), were considered highest risk, while census blocks with medium exposure and medium social vulnerability were considered medium risk (e.g. "3"), and so forth (see Tables 5 and 6 below).

Table 5. Ranking system for measuring a community's risk to 1 m SLR.

1 m SLR Exposure	SOVI	RANK	Label
Low/None	Medium Low	1	Lowest Risk
Low	Medium	2	Low-Med Risk
Low	Medium High	2	Low-Med Risk
Medium	Medium Low	3	Medium Risk
Medium	Medium	3	Medium Risk
Medium	Medium High	3	Med-High Risk
High	Medium Low	4	Med-High Risk
High	Medium	4	Highest Risk
High	Medium High	5	Highest Risk

Table 6. Ranking system for measuring a community's risk to storm surge.

Storm-surge Exposure	SOVI	RANK	Label
None	Medium Low	0	No Risk
None	Medium	0	No Risk
None	Medium High	0	No Risk
Low	Medium Low	1	Lowest Risk
Low	Medium	2	Low-Med Risk
Low	Medium High	2	Low-Med Risk
Medium	Medium Low	3	Medium Risk
Medium	Medium	3	Medium Risk
Medium	Medium High	4	Med-High Risk
High	Medium Low	4	Med-High Risk
High	Medium	5	Highest Risk
High	Medium High	5	Highest Risk

Community Resilience Analysis

The community resilience analysis utilizes both the community risk analysis and marsh viability analysis as inputs to help identify communities at the census block scale that might be least (or most) resilient based on the community's combined social vulnerability, exposure to storm-surge, and the long-term marsh viability. This analysis assumes that communities are more resilient if they have lower social vulnerability, less exposure to storm-surge inundation, and contain marsh systems that can either maintain or increase in size under the 1 m of SLR by the year 2100 scenario.

The community resilience analysis framework, as outlined in Figure 7, uses an indexing method similar to that which was used in the community risk analysis. The combined marsh viability and community risk indices were classified on a 1-5, low to high, scale using an if-then logic model where communities with low risk and high marsh viability would be considered "most resilient" (e.g. 5) and communities with high risk and low marsh viability would be considered "least resilient" (e.g. 1). It is also important to note that only census blocks that currently contain marsh distribution were considered in this analysis.

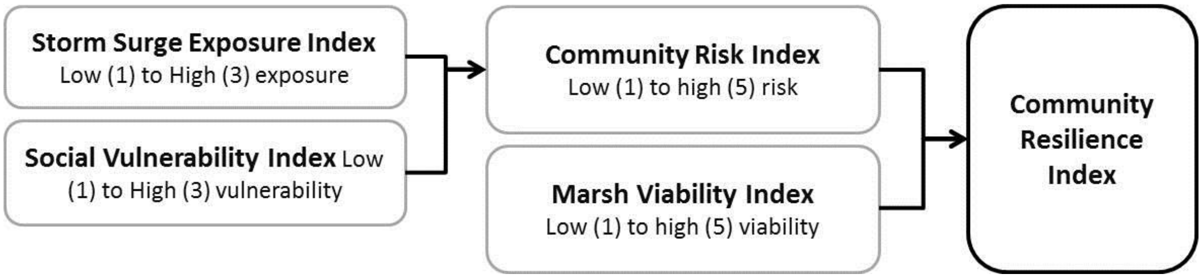


Figure 7. Community resilience analysis framework.

Marsh Conservation and Management Analysis

This conservation gap analysis was designed to better inform existing and future land conservation and protected land management planning and acquisition strategies by analyzing the effects of future SLR on regularly and irregularly flooded salt marsh habitats. First, both federal and state management areas were analyzed using the initial condition SLAMM maps to illustrate current marsh distributions that fall within the jurisdiction of existing management areas. Next, areas in which marsh is predicted to advance by the year 2100, according to the SLAMM model outputs, were identified and characterized as either within or outside of current management boundaries. To better understand if marsh migration is viable, barriers to migration such as developed land were identified within 100 m of existing marsh distributions. While conservation of all marsh habitat is ideal, it is not realistic and thus 3 areas were selected as priority areas for immediate or future conservation efforts based on the spatial relationships between marsh habitat (advancement zone and persistent zones in 2100) and the adjacency to existing management areas or populated areas, as well as, areas where conservation may improve ecosystem function. All analyses were performed with SLAMM outputs from the 1 m by 2100 scenario.

Resolution Analysis

The analysis was split into 3 parts based on the outputs of SLAMM. The first part will address the differences in the initial condition outputs due to the converted resolution of the vegetation layer (land cover). The second part will assess differences in the time zero outputs (baseline) due to the time stamps and resolution of the elevation and slope rasters (derived from LIDAR). The last part discusses the differences in the future habitat outputs under 1 m of SLR in 2100 between the two studies. Most of this analysis was done visually using ArcGIS software.

RESULTS

SLAMM Sea-level Rise Scenarios

To recap the SLAMM output model results, tables and maps are provided for each scenario and timestamp following this paragraph. We ran SLAMM models with protecting Developed Dry Land to focus on the impacts of SLR on the impacts of undeveloped lands and other habitats. Table 7 shows that between 8% and 17% of Undeveloped Dry Land is predicted to be lost in sea-level rise scenarios of up to 1 m by 2100. But with SLR scenarios of 1.5 m and 2 m, the loss of Undeveloped Dry Land increases to 25% and 32%, respectively. Regularly Flooded Marsh has an unusual trend where it loses marsh in A1BMean (0.39 m) and A1B Max (0.69 m) scenarios with percentages of 47% and 46%, respectively, and then increases its acreages with SLR scenarios of 1.5 m with 5% and 2 m with 38%. The remaining coastal habitat types except for Tidal Flats continue to lose their acreages with increase of SLR by 2100. Open Ocean increases significantly with 1.5 m and 2 m SLR scenarios because San Jose and Matagorda Islands would slowly be submerged by the rising water levels and Copano and San Antonio Bays would be more hydrologically connected to the Gulf of Mexico.

When reviewing over the outputs of SLR scenario for 1 m by 2100, Undeveloped Dry Lands, Inland Fresh Marshes and Irregularly Flooded Marshes are expected to significantly decrease between 2008 and 2100, while Transitional Marshes are expected to increase as new land is covered by salt water inundation. Regularly-flooded Marshes begin to decrease in acreages between 2008 and 2050, but in 2075, it slowly builds back its acreages due to inundation converting more land to marsh (Figure 8). The trend of the Regularly-flooded Marshes in the study area begin by decreasing by a significant 47%, a loss of 15,790 acres, between 2008 and 2050, then regains more acreage by a 43% increase between 2050 and 2100 with 25,293 total acres. Irregularly-flooded Marshes are expected to decline during the same period by 89%, and Inland Fresh Marsh habitat is also projected to decrease by more than 40%, from an initial area of 51,061 acres to 30,197 acres. Transitional Salt Marsh and Tidal Flats are the only land cover types that show an increase in habitat with 1 m of SLR through 2100 as Transitional Salt Marsh is projected to gain over 27,000 acres and Tidal Flats gain over 17,500 acres. SLAMM water categories Open Ocean and Estuarine Open Water also significantly gain in overall area with a total increase of about 77,415 acres by 2100. Gains and losses are summarized in Table 7 for the most commonly occurring SLAMM cover categories.

Table 7. Summary of SLAMM results depicting percentages of change for selected categories.

SLAMM Category	SLR by 2100 (m)				
	0.39	0.69	1	1.5	2
Undeveloped Dry Land	-8%	-12%	-17%	-25%	-32%
Swamp	-24%	-31%	-38%	-51%	-63%
Inland Fresh Marsh	-14%	-28%	-41%	-58%	-69%
Tidal Fresh Marsh	-37%	-66%	-85%	-92%	-94%
Regularly-flooded Marsh	-47%	-46%	-24%	5%	38%
Irregularly-flooded Marsh	-41%	-70%	-89%	-98%	-99%
Mangrove	-80%	-85%	-89%	-93%	-95%
Estuarine Beach	-91%	-96%	-97%	-98%	-98%
Tidal Flat	236%	611%	879%	1191%	1522%
Inland Open Water	-31%	-33%	-34%	-37%	-39%
Estuarine Open Water	17%	21%	24%	27%	29%
Open Ocean	33%	60%	82%	167%	310%

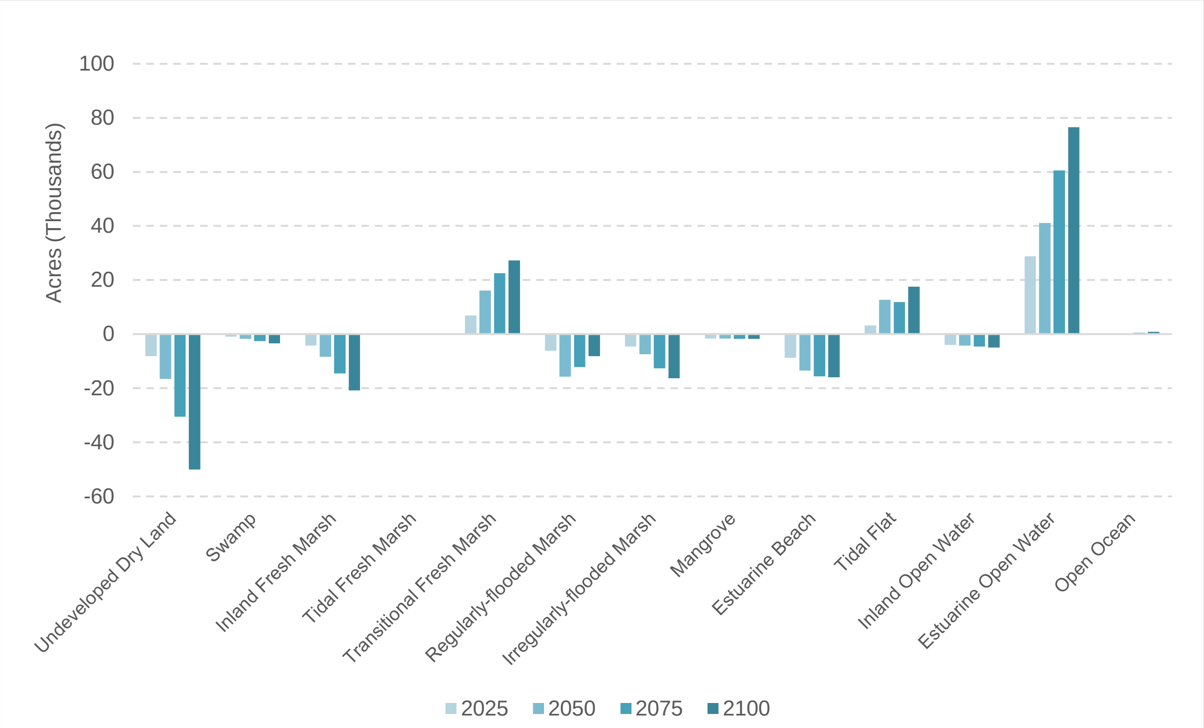


Figure 8. Predicted change in acres of SLAMM land cover classifications in Copano and San Antonio Bays, Texas under a 1 m SLR by 2100 scenario from baseline condition (2008) through 4 time periods – 2025, 2050, 2075 and 2100.

The results below (Tables 9 to 13; Figures 9 to 29) constitute the outputs of the SLAMM model run under each SLR scenario. Maps of SLAMM input (initial) and output (year, scenario) to follow will use the following legend showing the colors of each SLAMM land category (Table 8):

Table 8. SLAMM land category map legend.

Developed Dry Land
Undeveloped Dry Land
Swamp
Inland Fresh Marsh
Tidal Fresh Marsh
Transitional Fresh Marsh
Regularly-flooded Marsh
Mangrove
Estuarine Beach
Tidal Flat
Ocean Beach
Inland Open Water
Riverine Tidal
Estuarine Open Water
Open Ocean
Irregularly-flooded Marsh
Inland Shore
Tidal Swamp

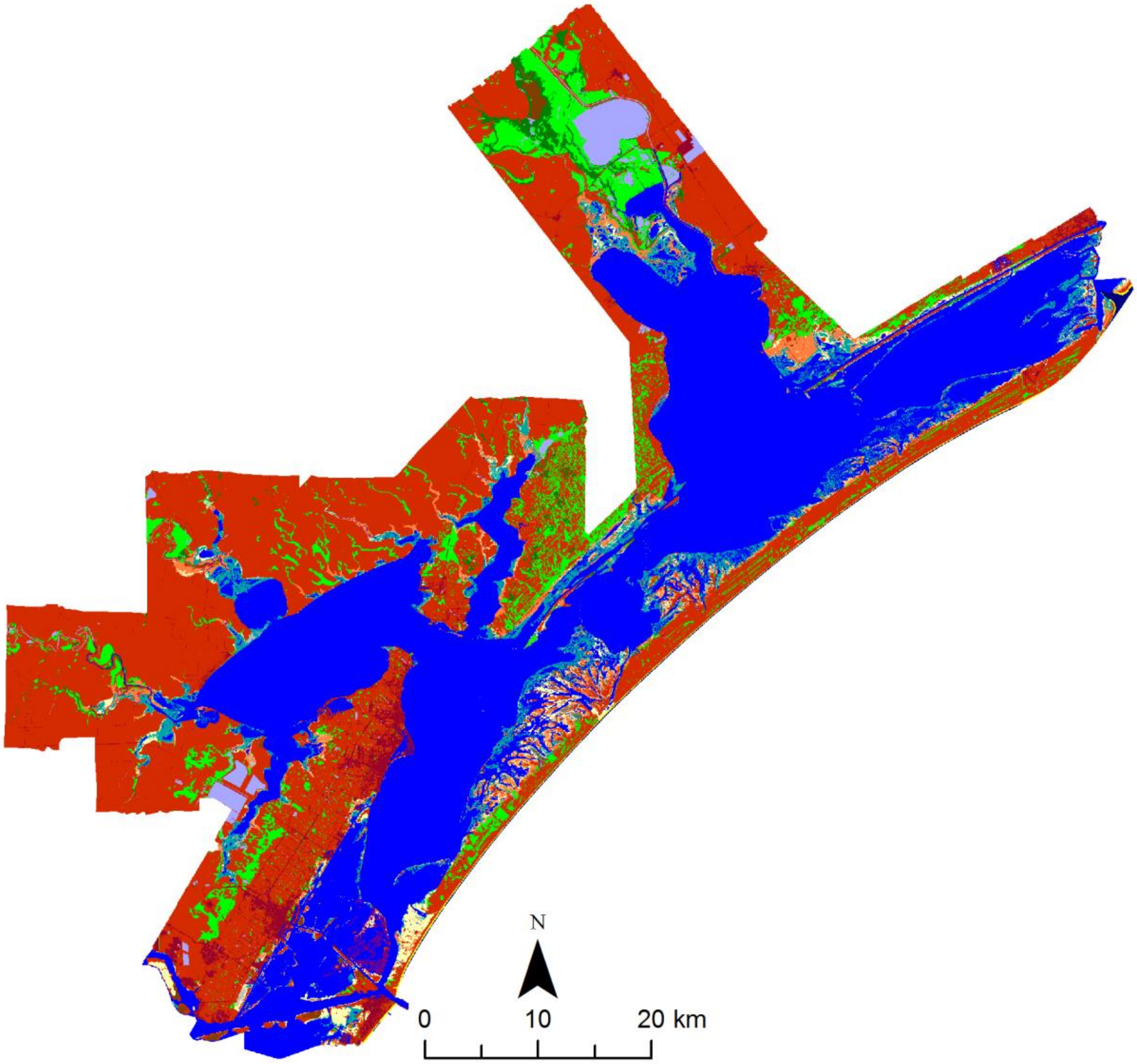


Figure 9. Initial Condition (2008) – this will be the same map for all scenarios.

Table 9. IPCC A1B-Mean, 0.39 m SLR by 2100.

SLAMM Category	Timestamp Results (acres)				
	Initial	2025	2050	2075	2100
Developed Dry Land	16652.7	16652.7	16652.7	16652.7	16652.7
Undeveloped Dry Land	291546.1	284399.4	280763.2	275100.3	268497.1
Swamp	9140.9	8321.7	7844.3	7412.0	6964.7
Inland Fresh Marsh	51061.2	47597.5	46718.7	45309.9	43696.5
Tidal Fresh Marsh	196.6	152.7	147.1	135.3	124.5
Transitional Fresh Marsh	19.1	5683.1	9460.5	14731.4	19367.7
Regularly-flooded Marsh	33485.0	27287.9	22218.0	20796.1	17766.1
Mangrove	1990.2	398.8	398.0	396.2	391.9
Estuarine Beach	16468.4	8257.0	6124.6	3091.9	1529.1
Tidal Flat	1999.1	4422.8	6441.8	3933.5	6707.4
Ocean Beach	1704.3	1637.9	1609.1	1635.0	1682.6
Inland Open Water	14434.7	10478.5	10263.8	10074.1	9898.1
Riverine Tidal	180.2	10.9	7.8	4.9	3.1
Estuarine Open Water	317601.6	345460.2	352781.0	363256.8	370699.0
Open Ocean	1024.9	1134.7	1202.4	1281.2	1364.6
Irregularly-flooded Marsh	18312.4	14178.5	13470.1	12351.2	10879.4
Inland Shore	2347.7	2090.9	2062.1	2003.0	1941.7
Tidal Swamp	2.2	2.1	2.0	1.8	1.2

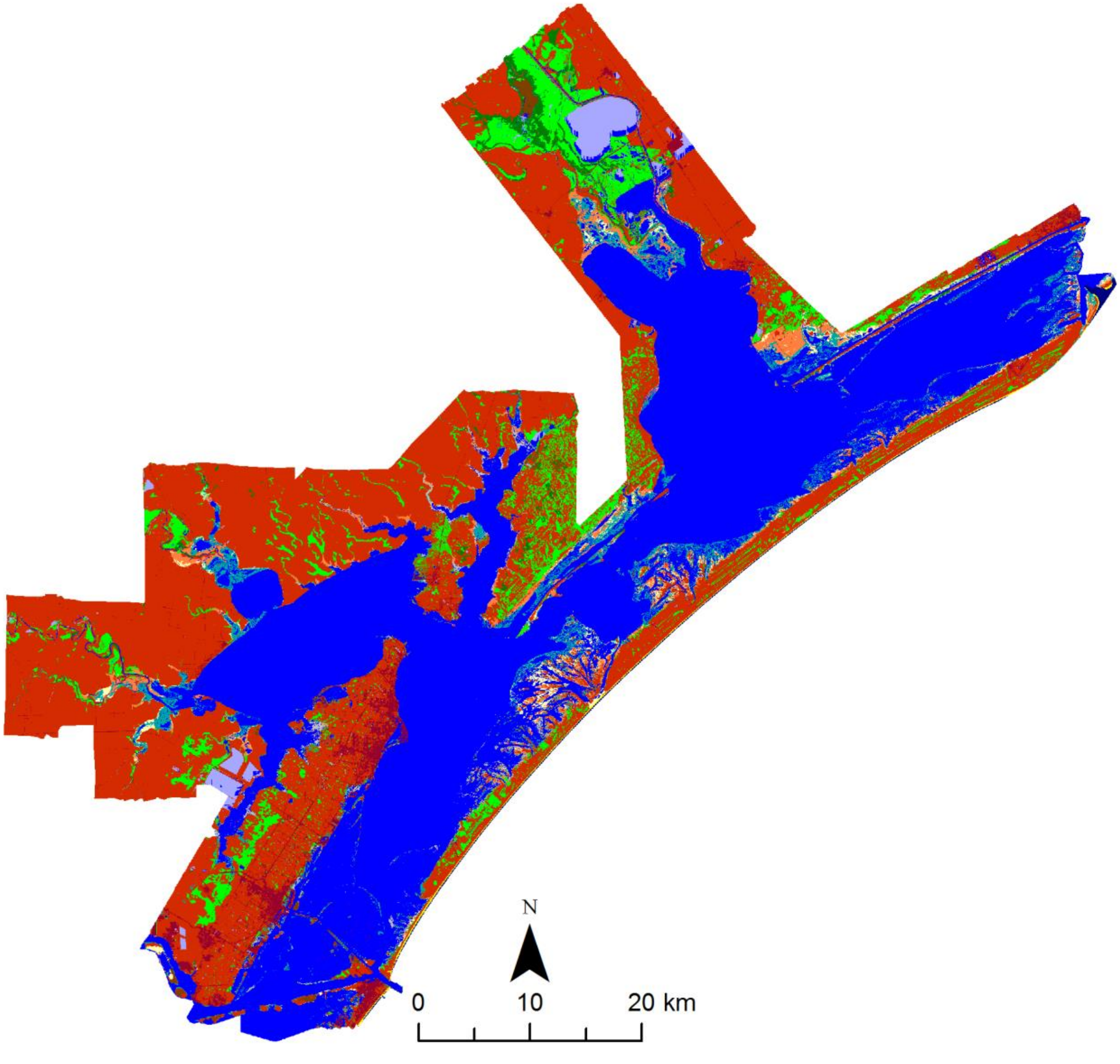


Figure 10. 2025, Scenario A1B Mean.

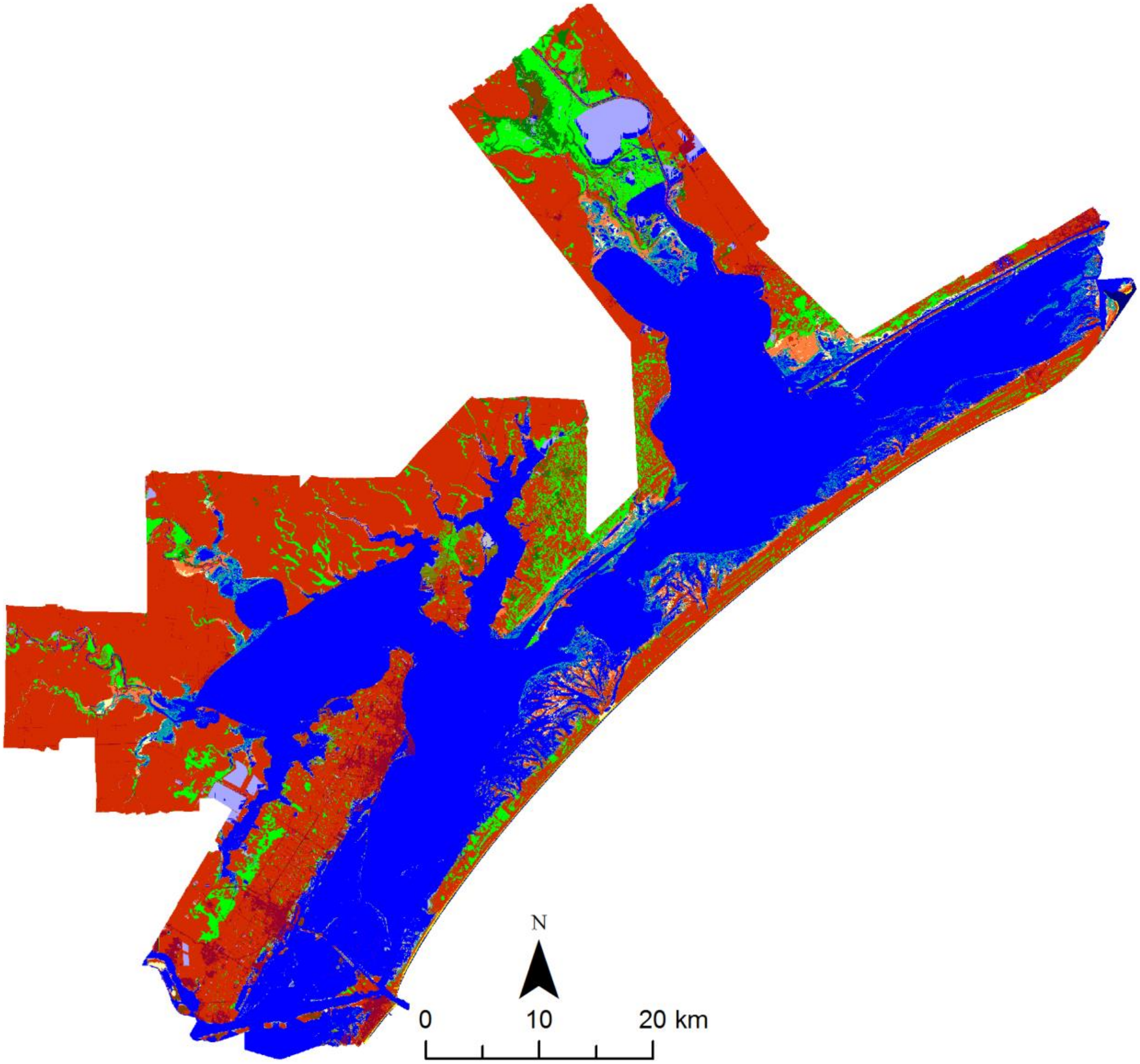


Figure 11. 2050, Scenario A1B Mean.

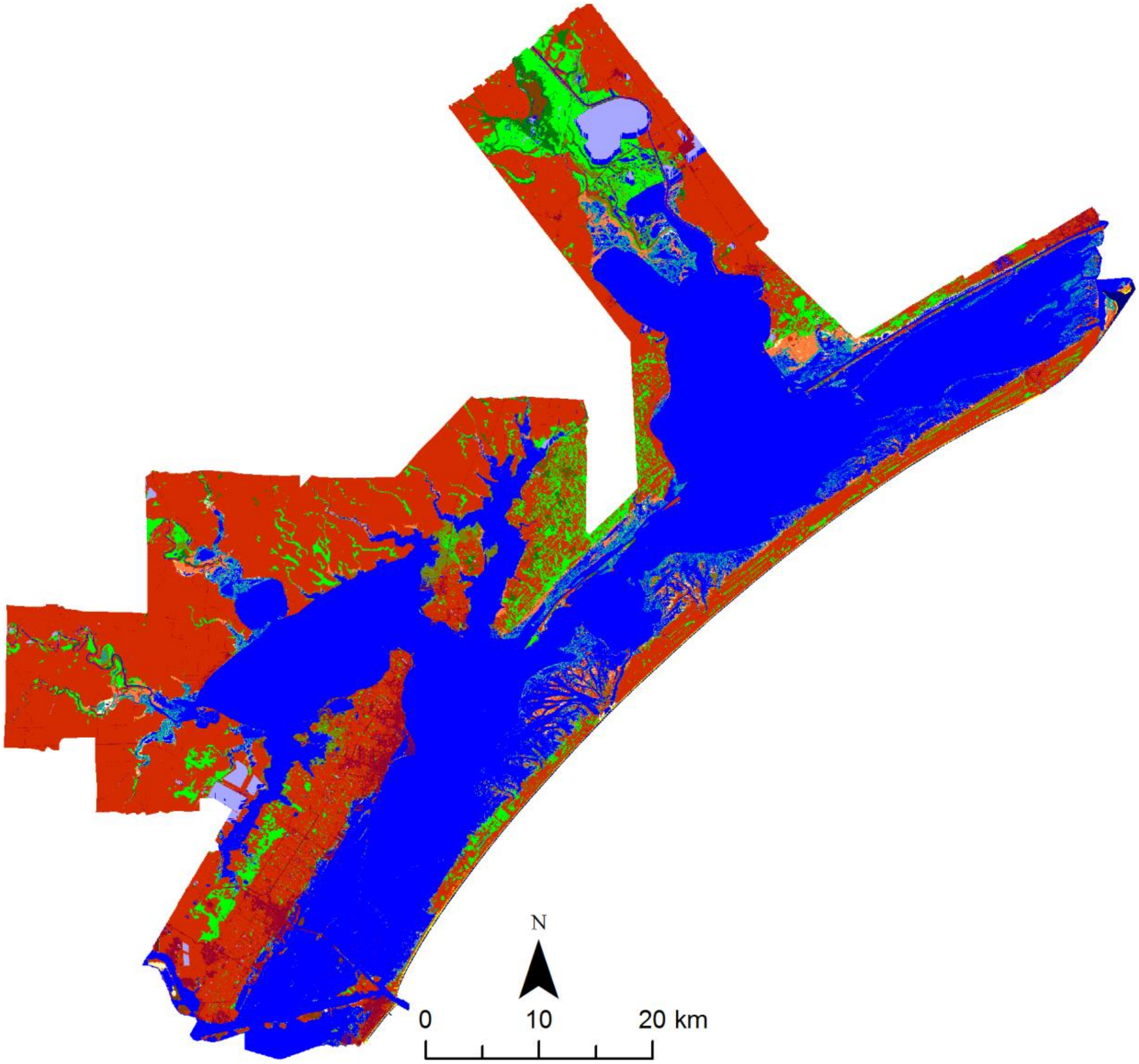


Figure 12. 2075, Scenario A1B Mean.

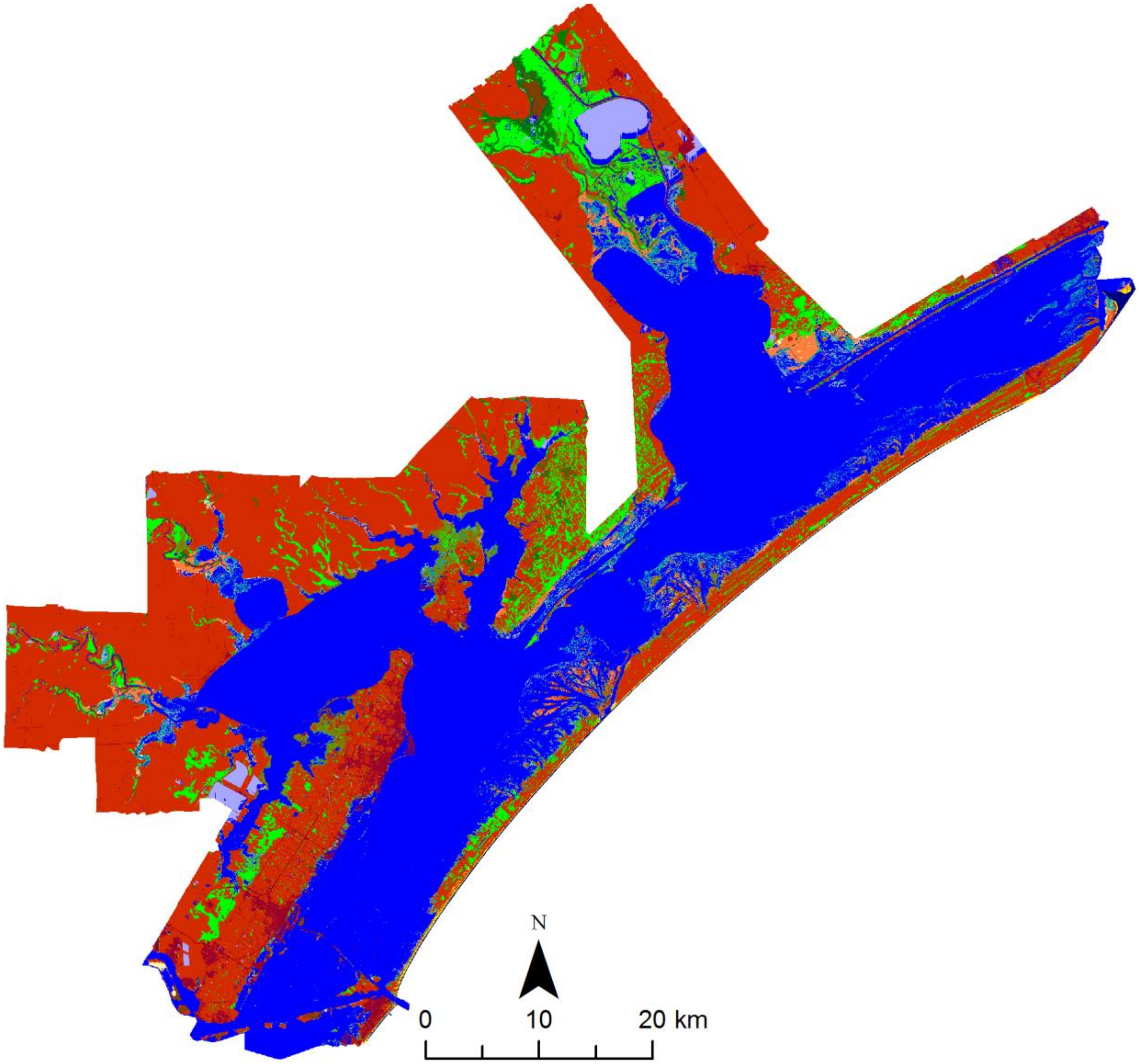


Figure 13. 2100, Scenario A1B Mean.

Table10. IPCC A1B-Max, 0.69 m SLR by 2100.

SLAMM Category	Timestamp Results (acres)				
	Initial	2025	2050	2075	2100
Developed Dry Land	16652.7	16652.7	16652.7	16652.7	16652.7
Undeveloped Dry Land	291546.1	283896.7	278178.3	268588.5	256380.7
Swamp	9140.9	8247.5	7646.4	6986.0	6285.5
Inland Fresh Marsh	51061.2	47264.8	44995.9	41062.1	36775.0
Tidal Fresh Marsh	196.6	147.1	128.1	97.0	66.8
Transitional Fresh Marsh	19.1	6253.5	12626.8	18646.6	22833.3
Regularly-flooded Marsh	33485.0	27354.4	20184.3	17830.4	17975.5
Mangrove	1990.2	391.6	388.2	343.3	299.2
Estuarine Beach	16468.4	8001.1	4427.2	1515.4	626.7
Tidal Flat	1999.1	4705.1	9759.3	11943.3	14209.5
Ocean Beach	1704.3	1641.6	1654.3	1719.7	1710.4
Inland Open Water	14434.7	10453.0	10194.6	9924.2	9675.2
Riverine Tidal	180.2	10.6	6.8	3.8	1.6
Estuarine Open Water	317601.6	345941.6	355635.2	370655.3	385720.6
Open Ocean	1024.9	1135.3	1205.4	1335.9	1643.8
Irregularly-flooded Marsh	18312.4	13981.9	12448.3	8923.2	5497.6
Inland Shore	2347.7	2086.8	2033.4	1938.5	1813.0
Tidal Swamp	2.2	2.1	2.0	1.1	0.0

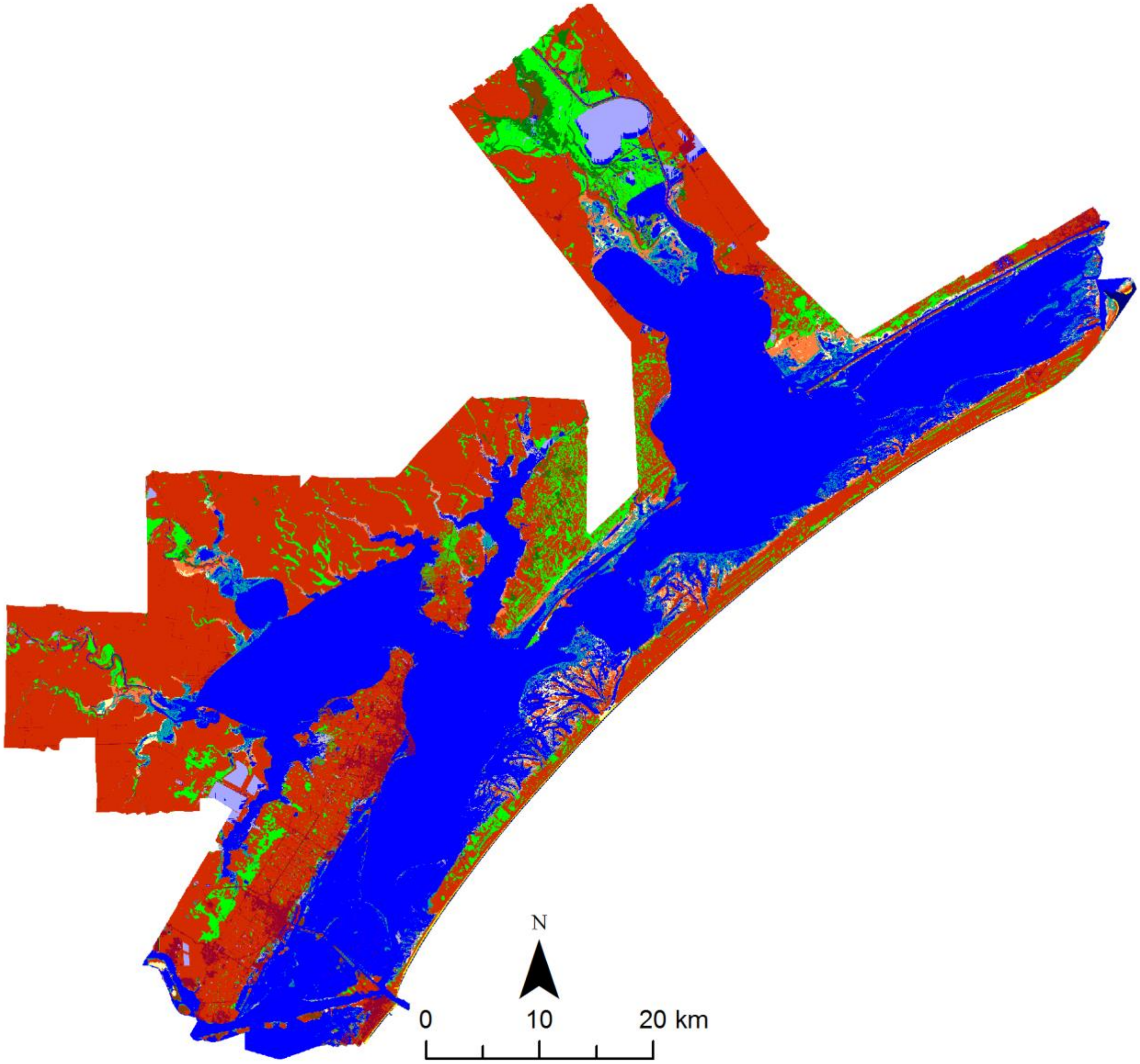


Figure 14. 2025, Scenario A1B Max.

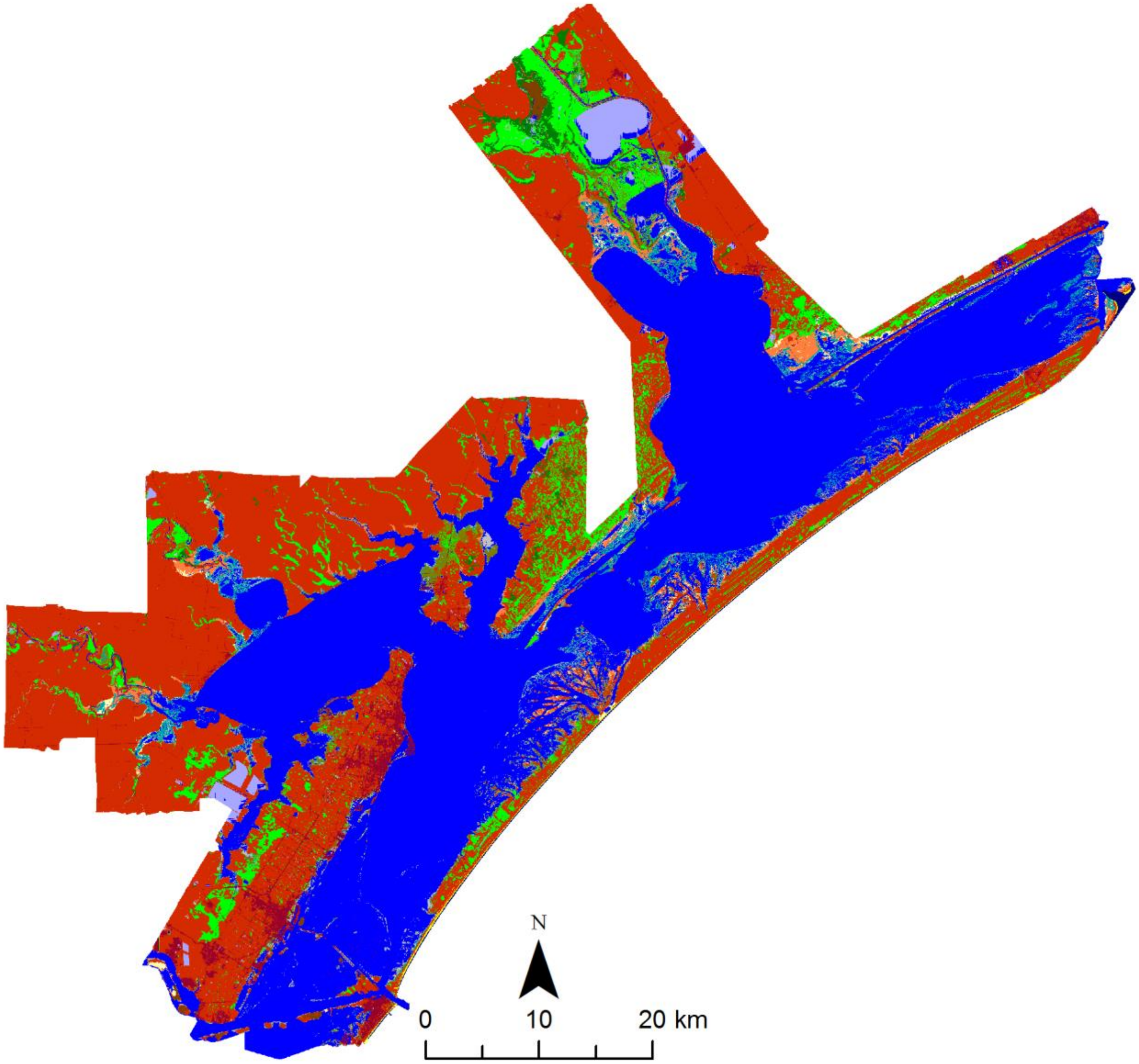


Figure 15. 2050, Scenario A1B Max.

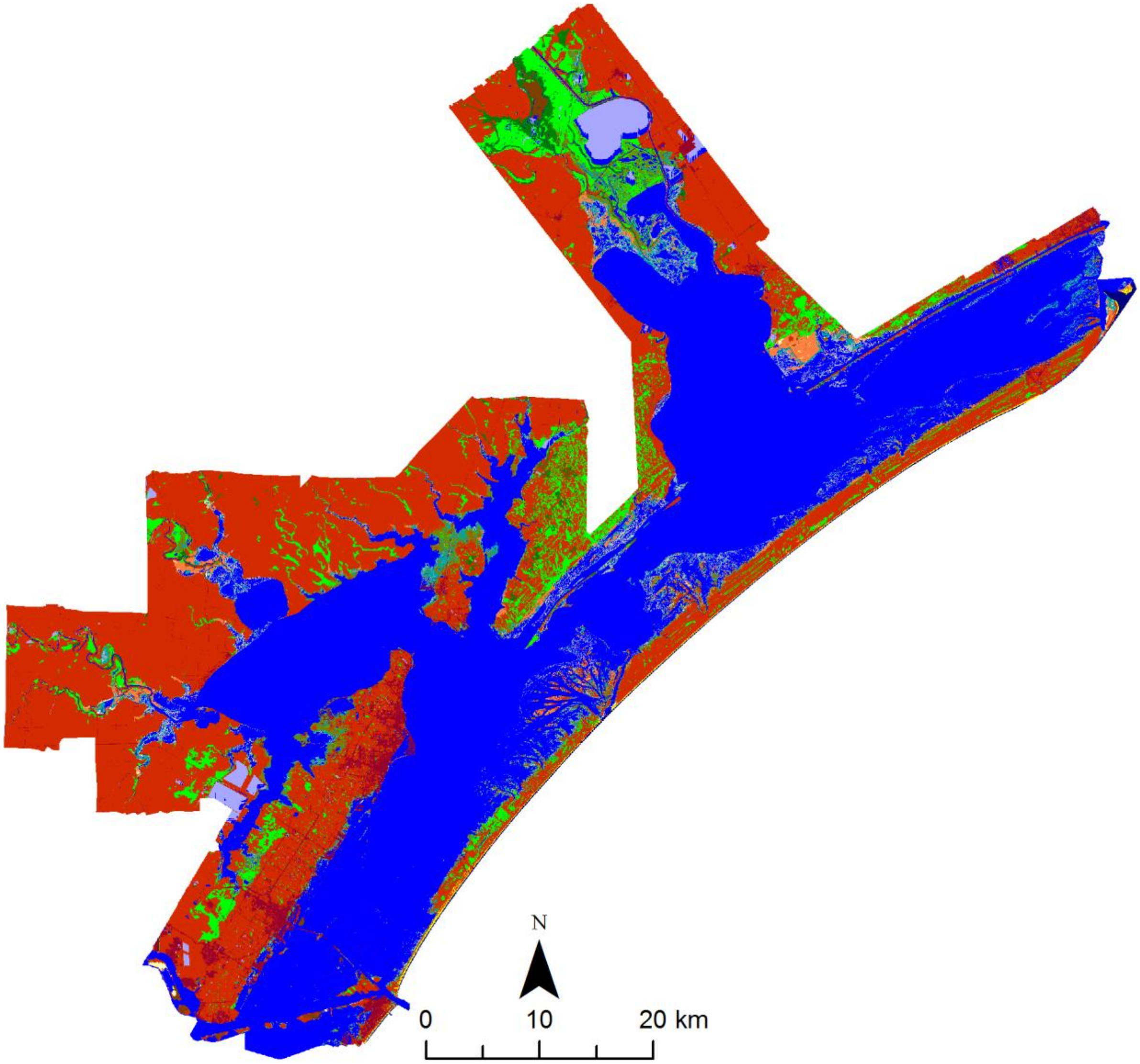


Figure 16. 2075, Scenario A1B Max.

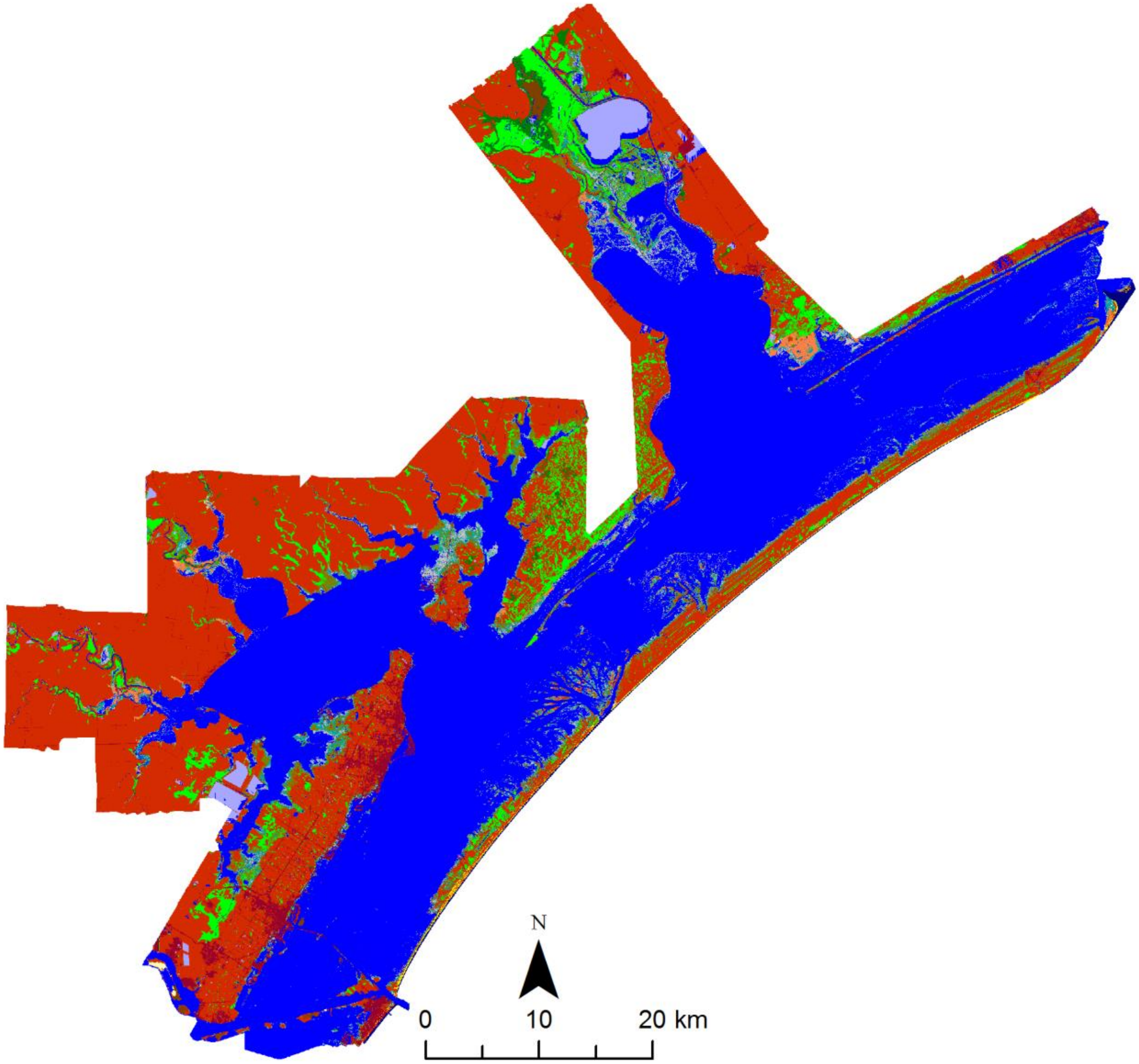


Figure 17. 2100, Scenario A1B Max.

Table 11. 1.0 m SLR by 2100.

SLAMM Category	Timestamp Results (acres)				
	Initial	2025	2050	2075	2100
Developed Dry Land	16652.7	16652.7	16652.7	16652.7	16652.7
Undeveloped Dry Land	291546.1	283358.8	275000.8	261043.8	241459.7
Swamp	9140.9	8162.6	7425.2	6541.3	5697.8
Inland Fresh Marsh	51061.2	46859.5	42667.5	36519.3	30197.1
Tidal Fresh Marsh	196.6	143.1	106.4	61.0	29.5
Transitional Fresh Marsh	19.1	6887.1	16086.1	22548.1	27274.4
Regularly-flooded Marsh	33485.0	27340.1	17694.7	21277.4	25293.3
Mangrove	1990.2	390.5	335.1	274.1	222.2
Estuarine Beach	16468.4	7665.1	2991.6	794.6	430.7
Tidal Flat	1999.1	5206.6	14643.6	13838.3	19574.3
Ocean Beach	1704.3	1646.4	1708.6	1696.7	2075.9
Inland Open Water	14434.7	10426.6	10127.3	9793.9	9464.2
Riverine Tidal	180.2	10.2	6.0	2.5	1.2
Estuarine Open Water	317601.6	346455.7	358684.7	378138.1	394179.8
Open Ocean	1024.9	1136.0	1217.1	1536.0	1864.2
Irregularly-flooded Marsh	18312.4	13742.2	10817.7	5602.5	2032.6
Inland Shore	2347.7	2081.9	2000.5	1846.9	1717.7
Tidal Swamp	2.2	2.1	1.8	0.2	0.0

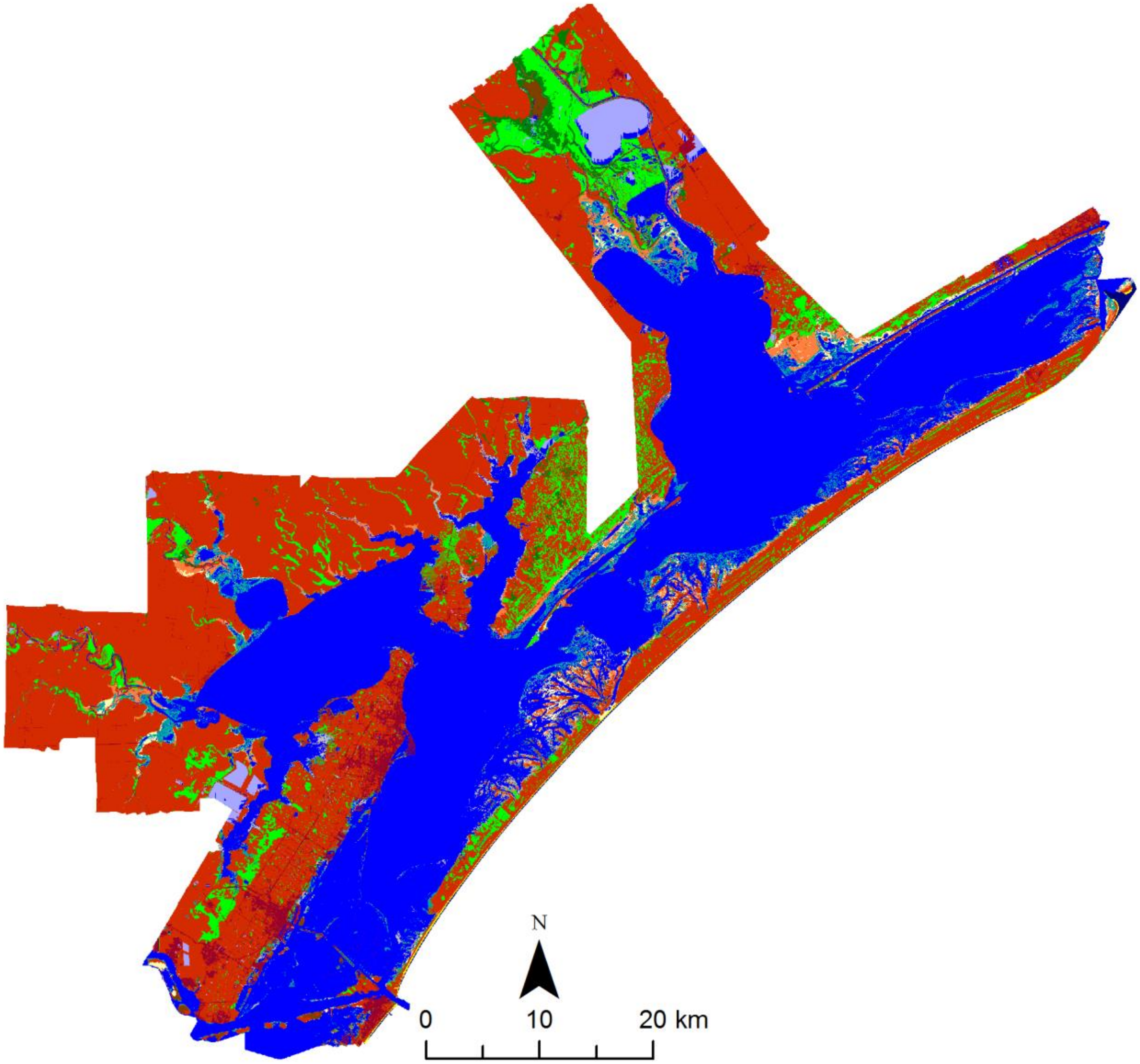


Figure 18. 2025, Scenario 1 m.

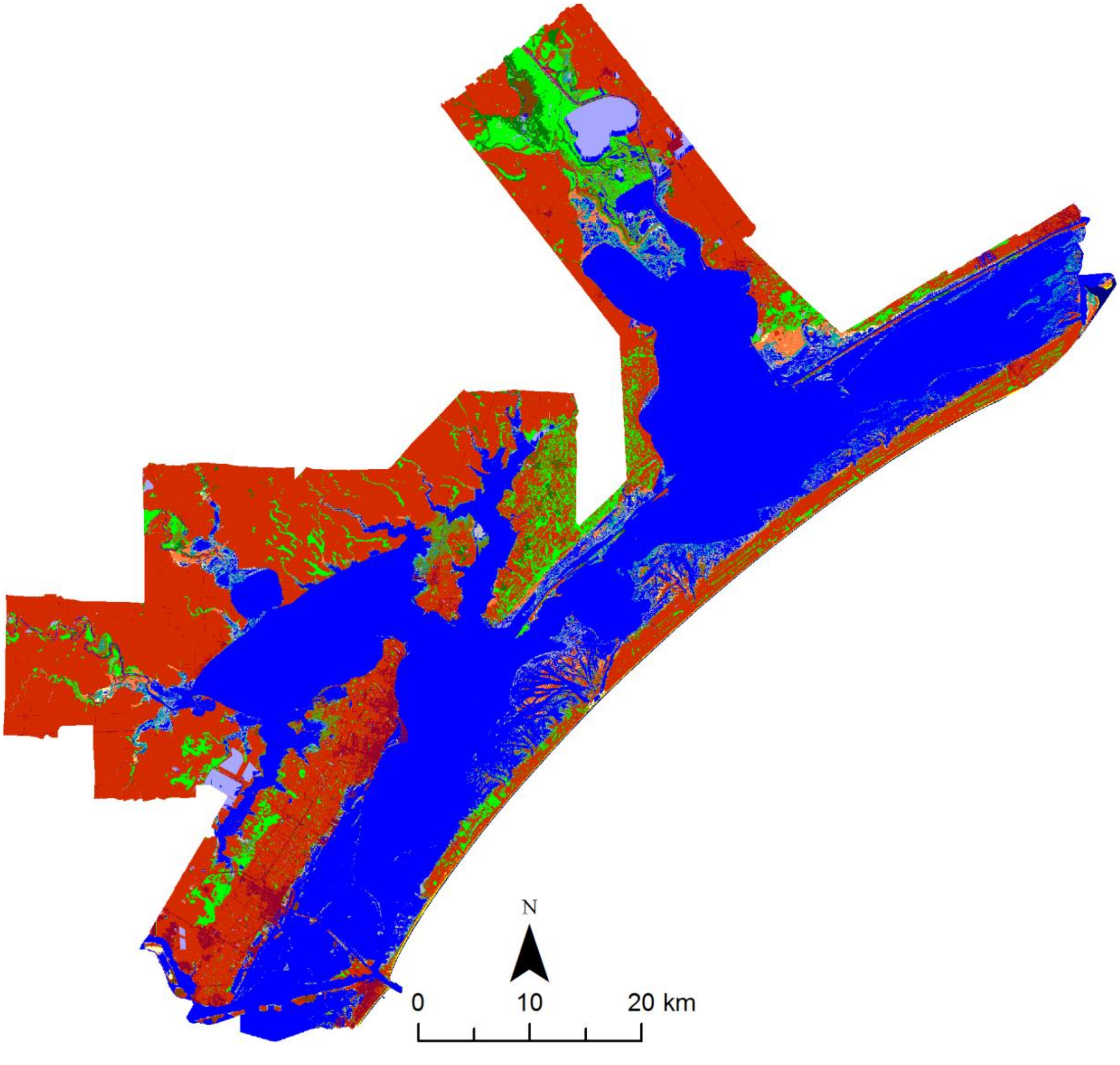


Figure 19. 2050, Scenario 1 m.

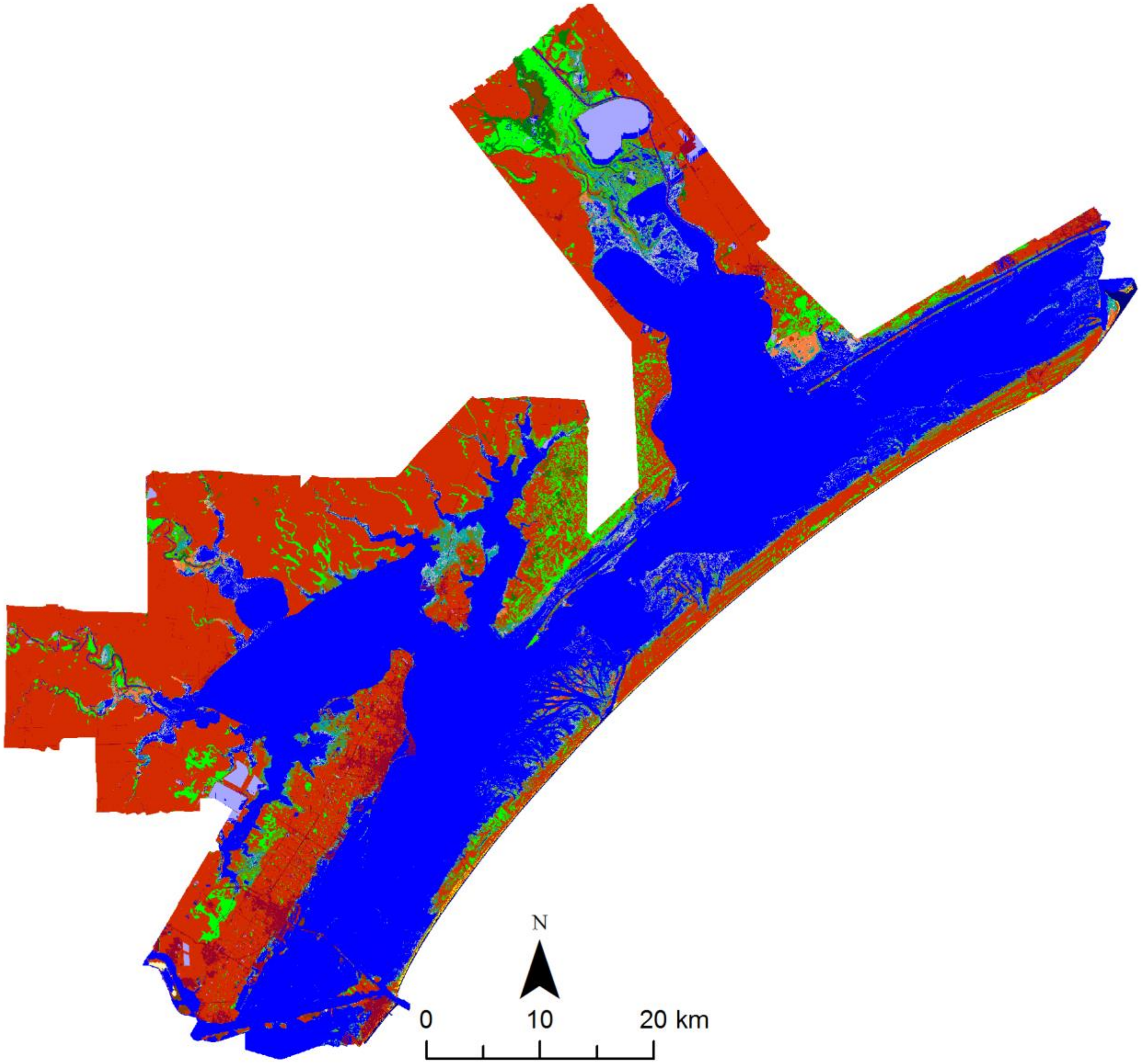


Figure 20. 2075, Scenario 1 m.

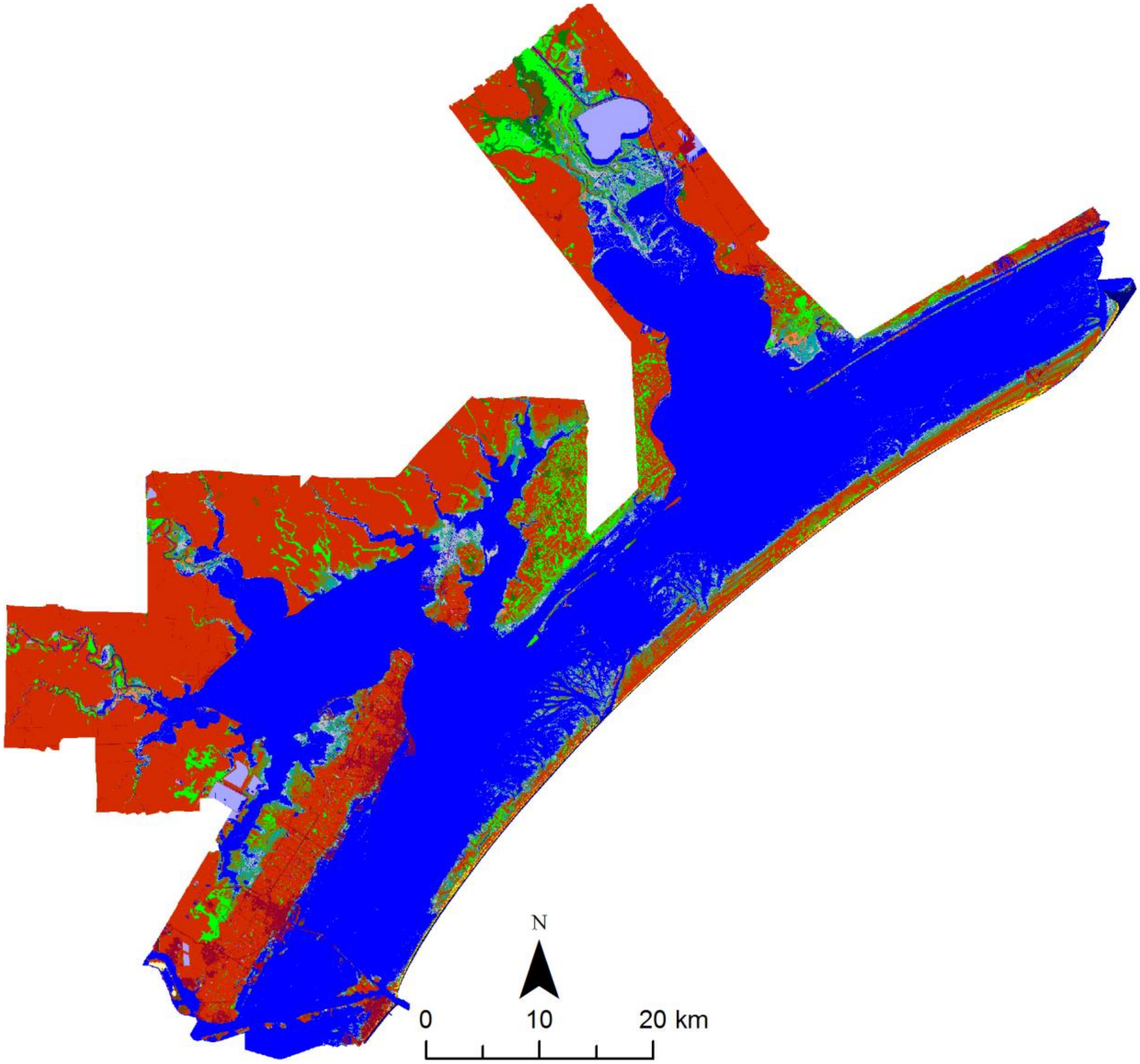


Figure 21. 2100, Scenario 1 m.

Table 12. 1.5 m SLR by 2100.

SLAMM Category	Timestamp Results (acres)				
	Initial	2025	2050	2075	2100
Developed Dry Land	16652.7	16652.7	16652.7	16652.7	16652.7
Undeveloped Dry Land	291546.1	282363.5	274860.6	245892.2	217917.9
Swamp	9140.9	8028.5	7068.0	5845.6	4474.1
Inland Fresh Marsh	51061.2	45970.3	40637.5	29413.1	21514.7
Tidal Fresh Marsh	196.6	132.6	73.6	25.3	15.6
Transitional Fresh Marsh	19.1	8300.5	19287.1	33532.4	35402.6
Regularly-flooded Marsh	33485.0	27097.2	18971.9	26882.9	35152.6
Mangrove	1990.2	360.3	360.5	204.4	142.8
Estuarine Beach	16468.4	6894.2	2692.9	447.0	390.9
Tidal Flat	1999.1	6403.0	19323.1	15961.6	25806.8
Ocean Beach	1704.3	1629.3	1671.5	1907.0	2720.0
Inland Open Water	14434.7	10389.2	10669.2	9601.5	9140.4
Riverine Tidal	180.2	9.5	115.8	1.3	0.6
Estuarine Open Water	317601.6	347406.1	354357.9	386384.3	404664.0
Open Ocean	1024.9	1164.9	1204.9	1806.4	2734.2
Irregularly-flooded Marsh	18312.4	13290.2	8182.2	1870.8	307.9
Inland Shore	2347.7	2073.3	2036.6	1738.8	1129.4
Tidal Swamp	2.2	2.1	1.2	0.0	0.0

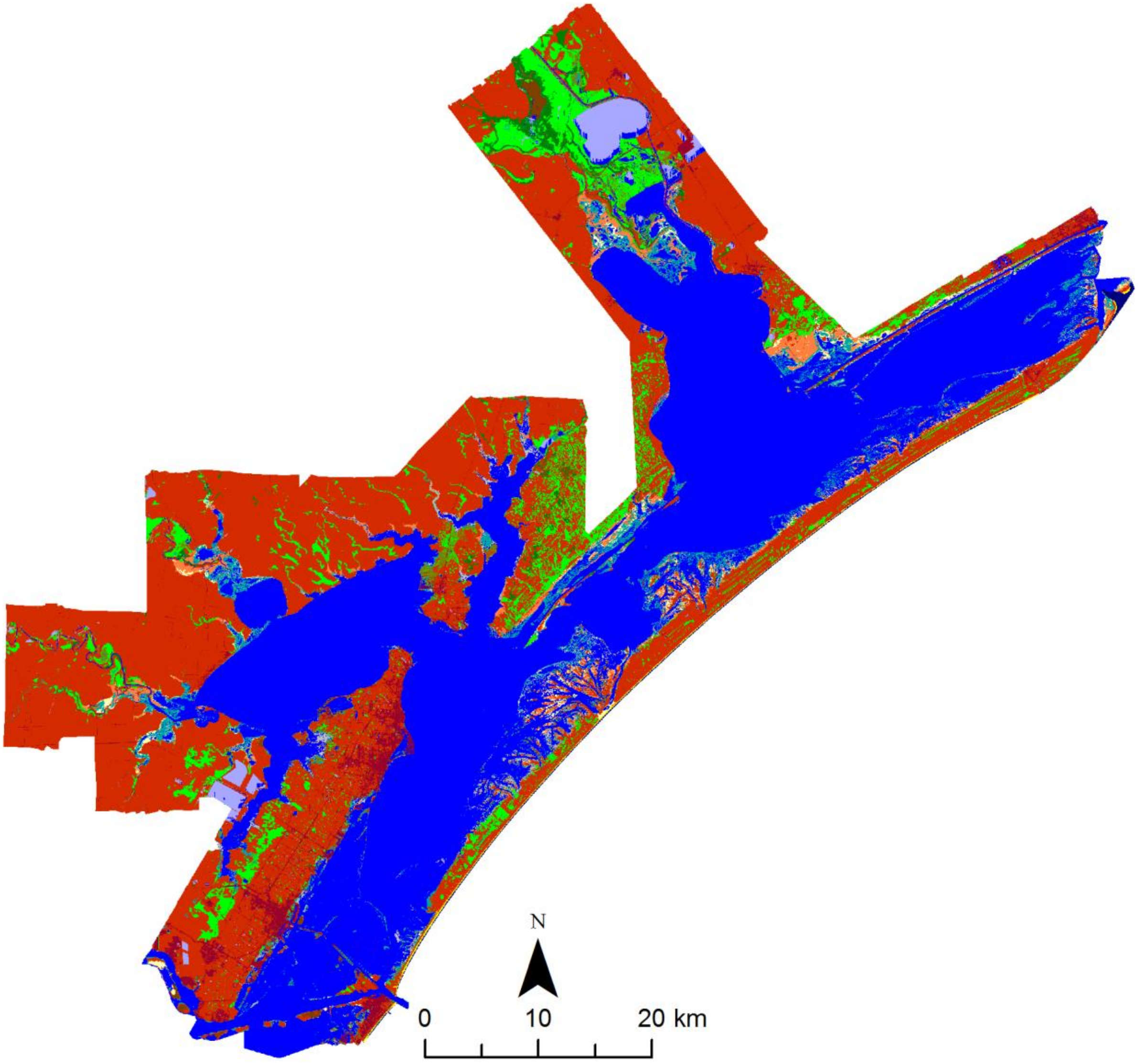


Figure 22. 2025, Scenario 1.5 m.

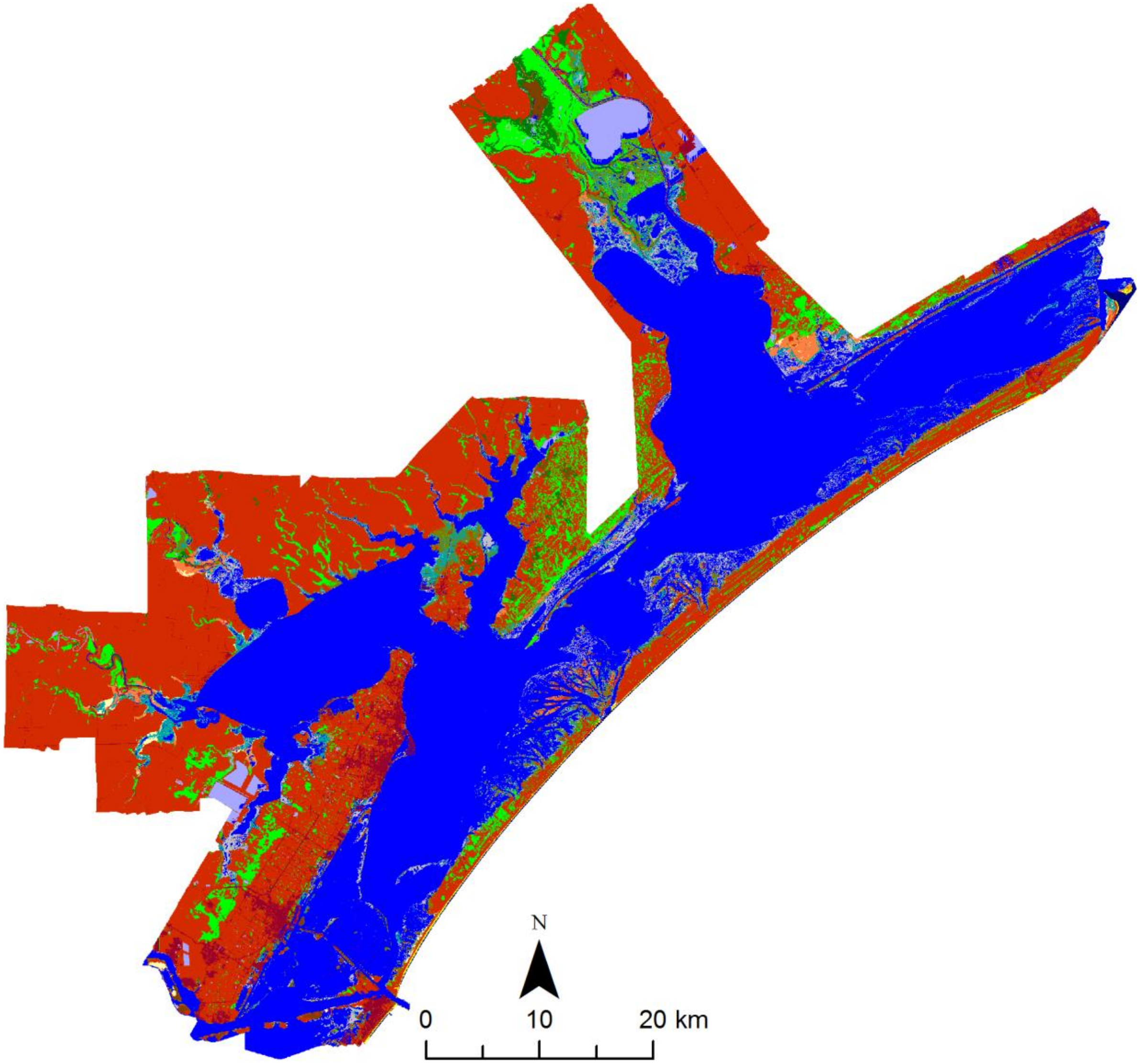


Figure 23. 2050, Scenario 1.5 m.

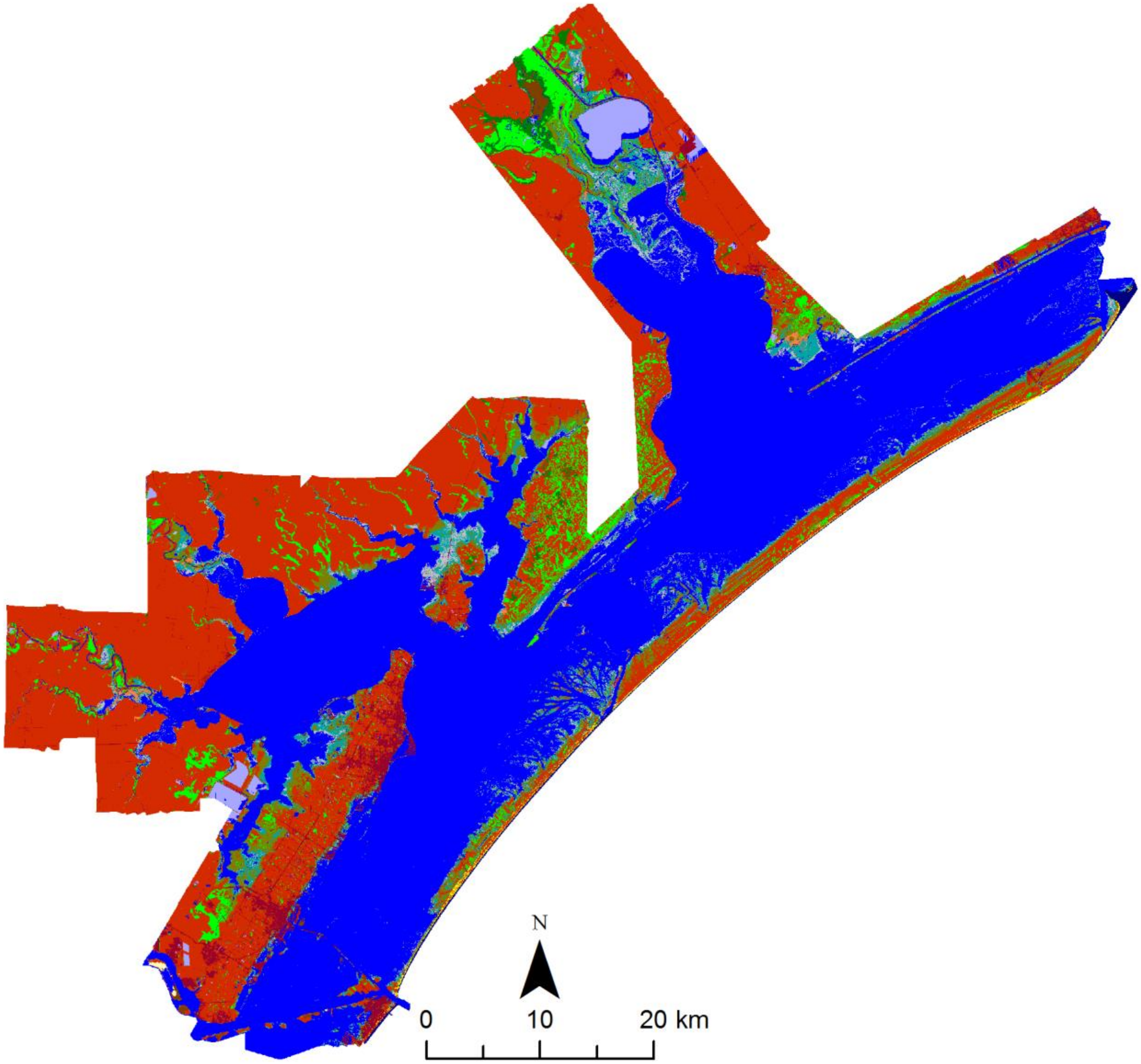


Figure 24. 2075, Scenario 1.5 m.

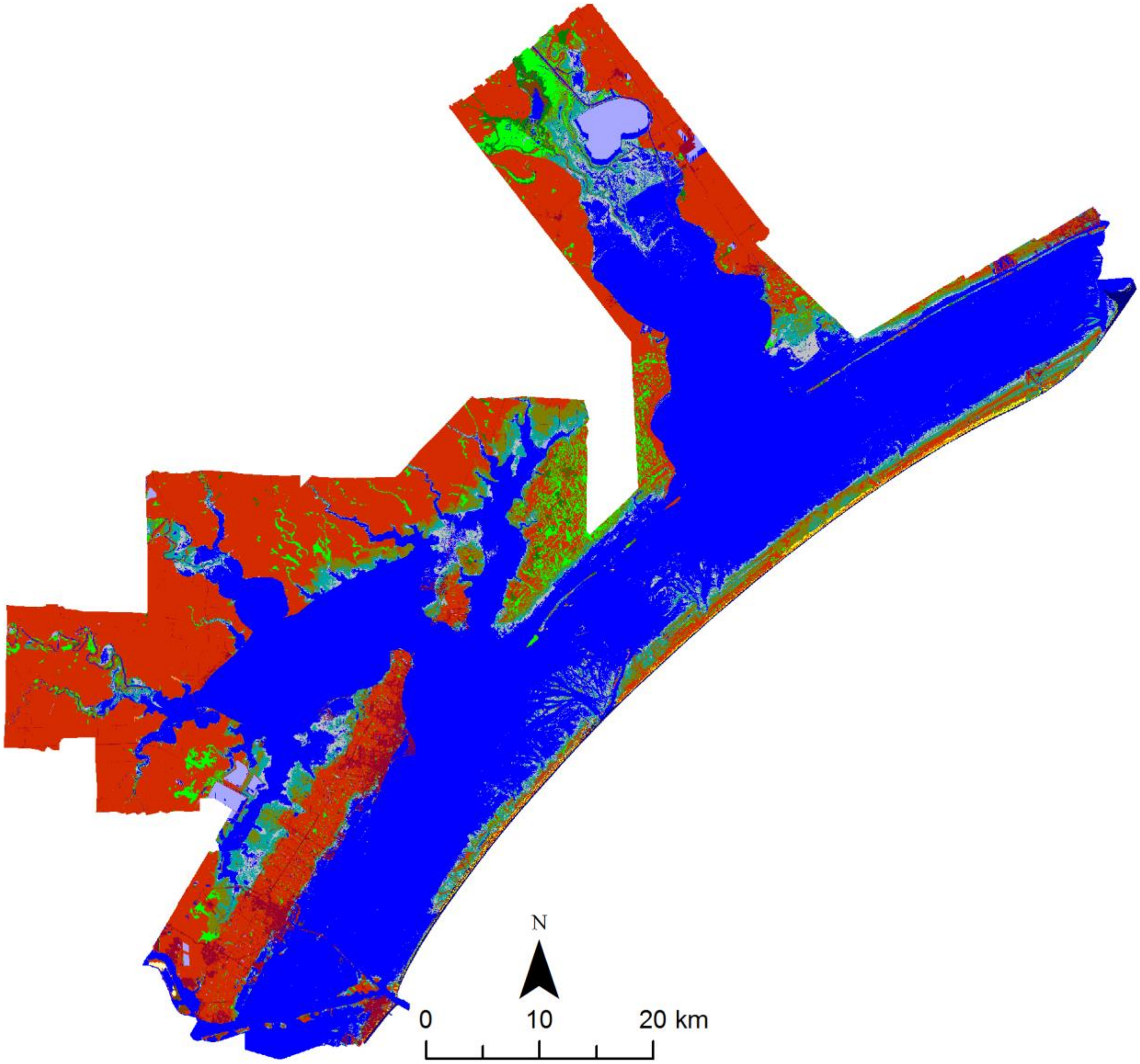


Figure 25. 2100, Scenario 1.5 m.

Table 13. 2.0 m SLR by 2100.

SLAMM Category	Timestamp Results (acres)				
	Initial	2025	2050	2075	2100
Developed Dry Land	16652.7	16652.7	16652.7	16652.7	16652.7
Undeveloped Dry Land	291546.1	281329.0	263157.0	228911.8	199014.6
Swamp	9140.9	7911.7	6662.3	5222.2	3339.9
Inland Fresh Marsh	51061.2	45006.6	35101.5	23318.5	15946.2
Tidal Fresh Marsh	196.6	123.6	48.7	17.0	11.4
Transitional Fresh Marsh	19.1	9961.4	28931.6	45892.4	37012.1
Regularly-flooded Marsh	33485.0	26308.5	19297.0	33407.9	46332.0
Mangrove	1990.2	338.5	244.5	151.9	95.3
Estuarine Beach	16468.4	6175.0	905.1	392.5	350.2
Tidal Flat	1999.1	8026.1	21977.4	18248.9	32424.8
Ocean Beach	1704.3	1643.3	1715.6	2611.3	2534.7
Inland Open Water	14434.7	10359.5	9929.9	9421.8	8868.2
Riverine Tidal	180.2	9.0	3.6	1.0	0.4
Estuarine Open Water	317601.6	348312.2	365296.8	389792.7	410583.0
Open Ocean	1024.9	1166.2	1473.1	2079.2	4198.0
Irregularly-flooded Marsh	18312.4	12778.3	4909.0	527.4	98.5
Inland Shore	2347.7	2063.7	1860.9	1517.8	705.3
Tidal Swamp	2.2	2.0	0.4	0.0	0.0

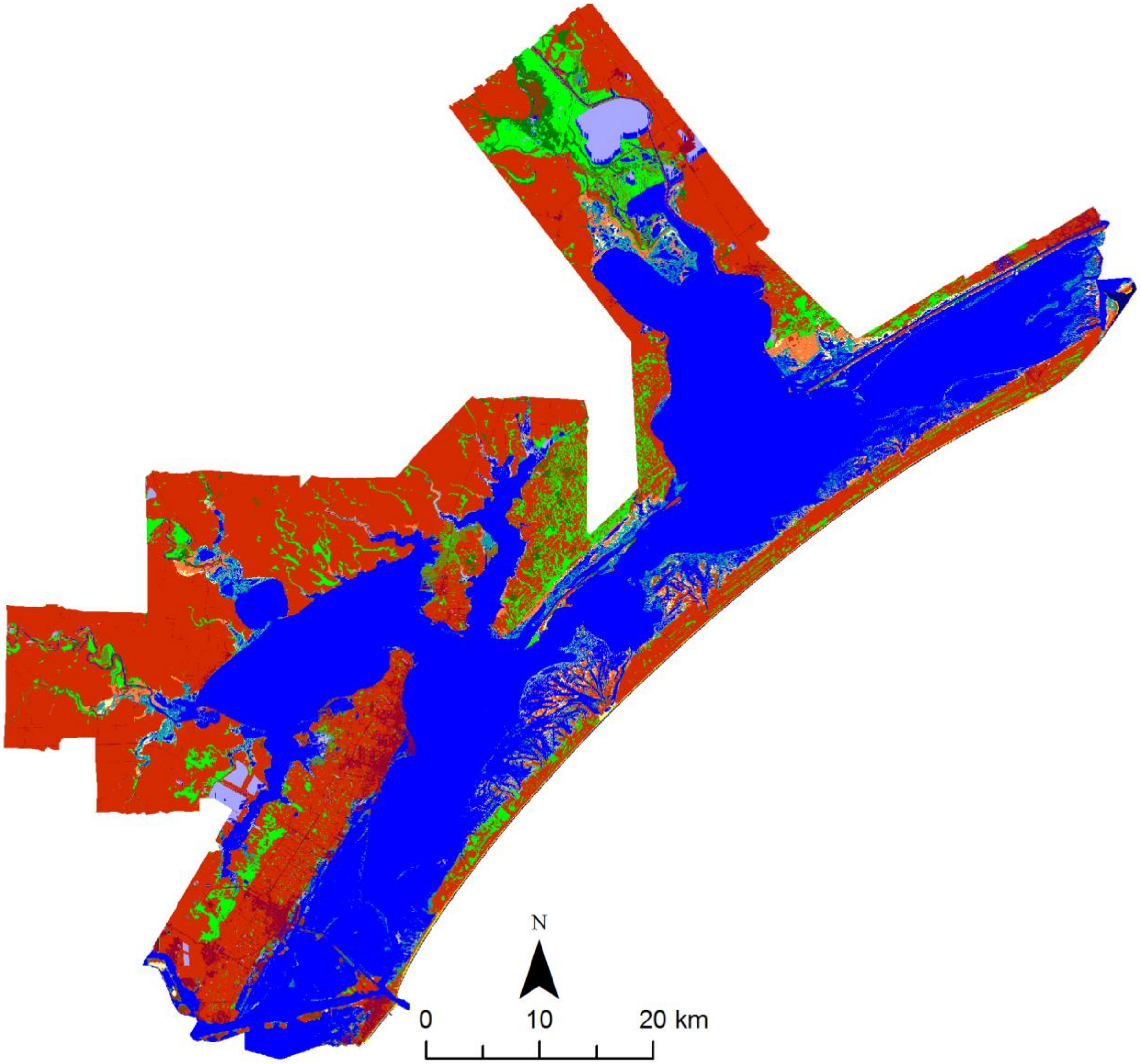


Figure 26. 2025, Scenario 2 m.

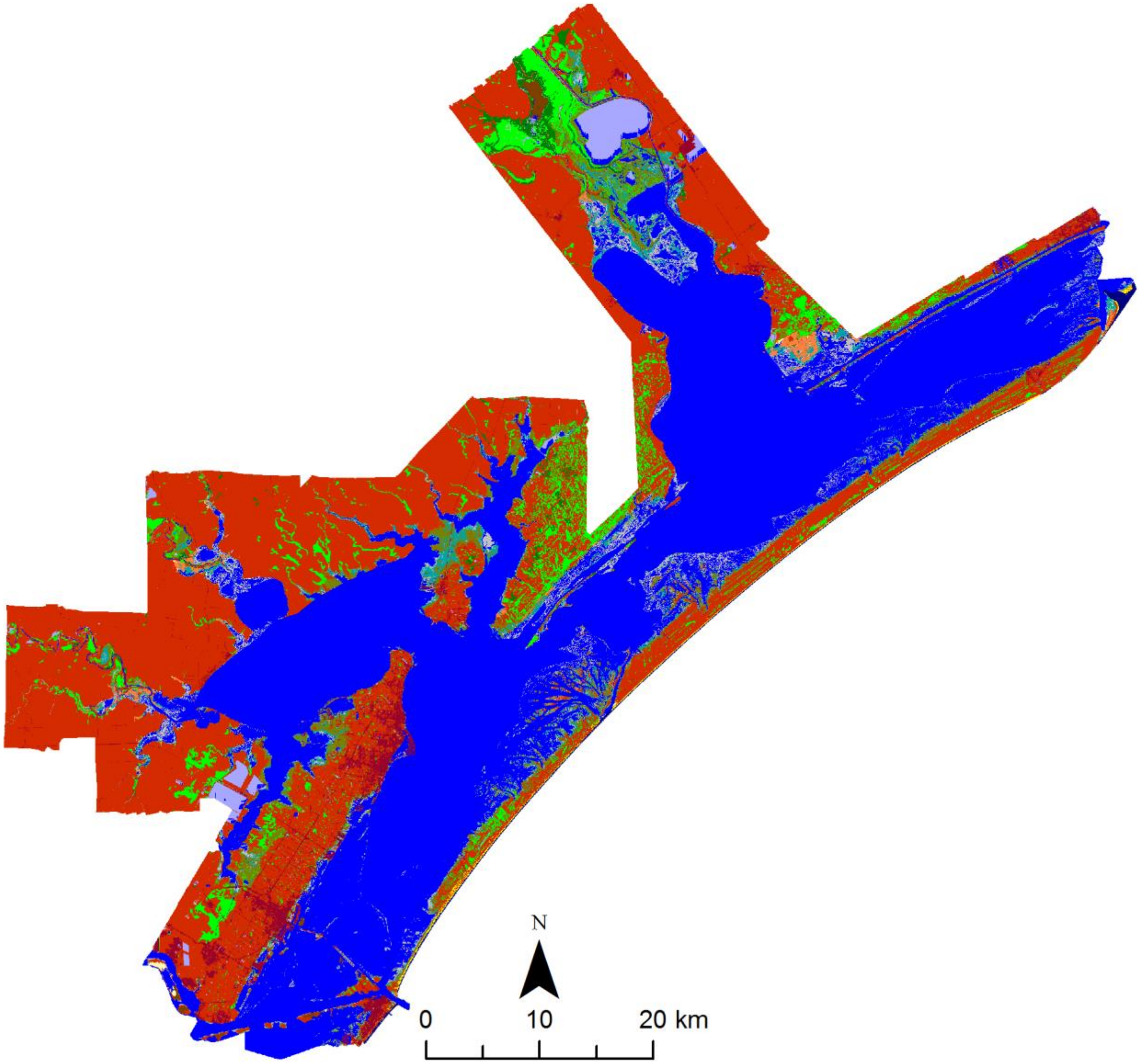


Figure 27. 2050, Scenario 2 m.

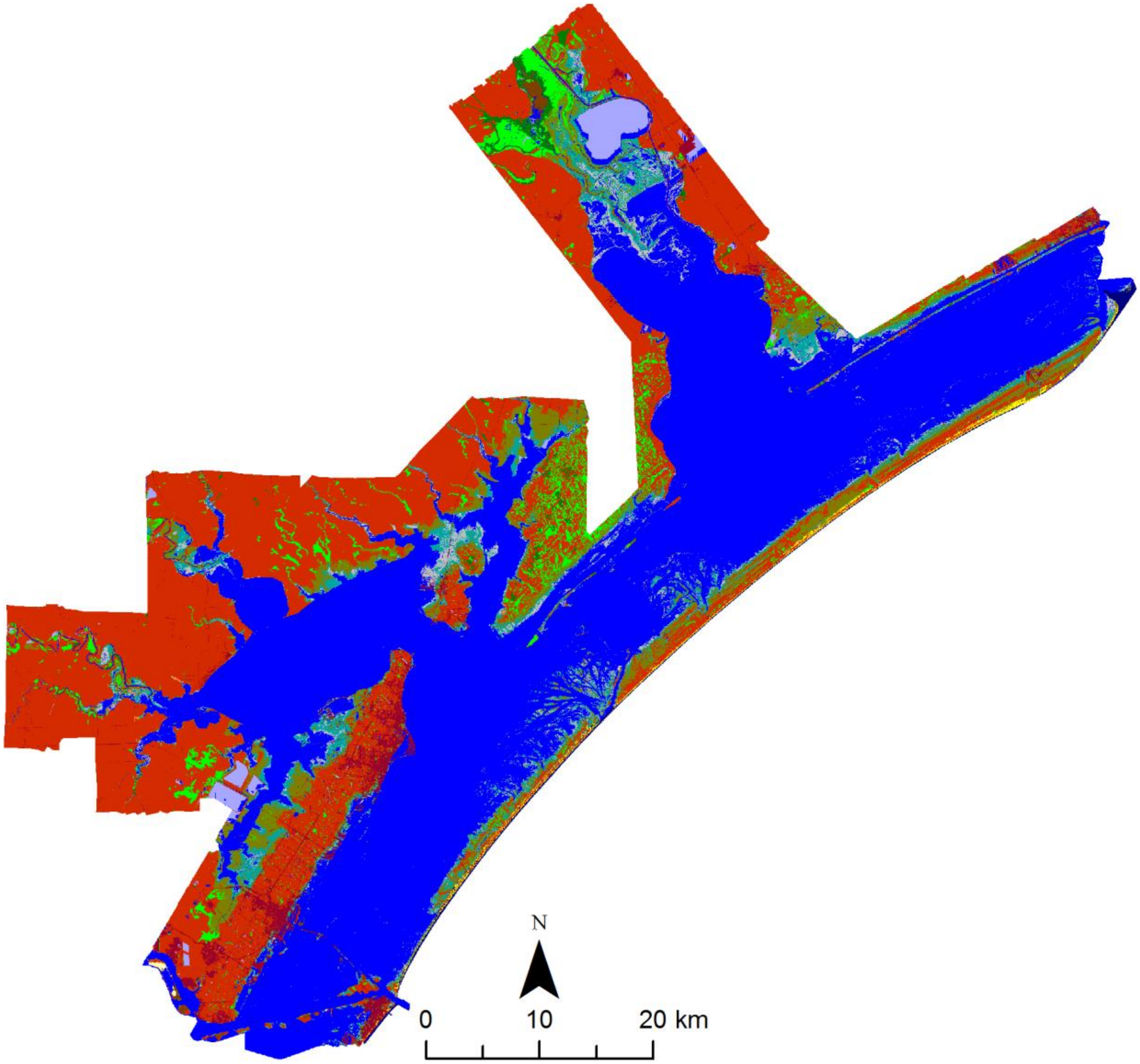


Figure 28. 2075, Scenario 2 m.

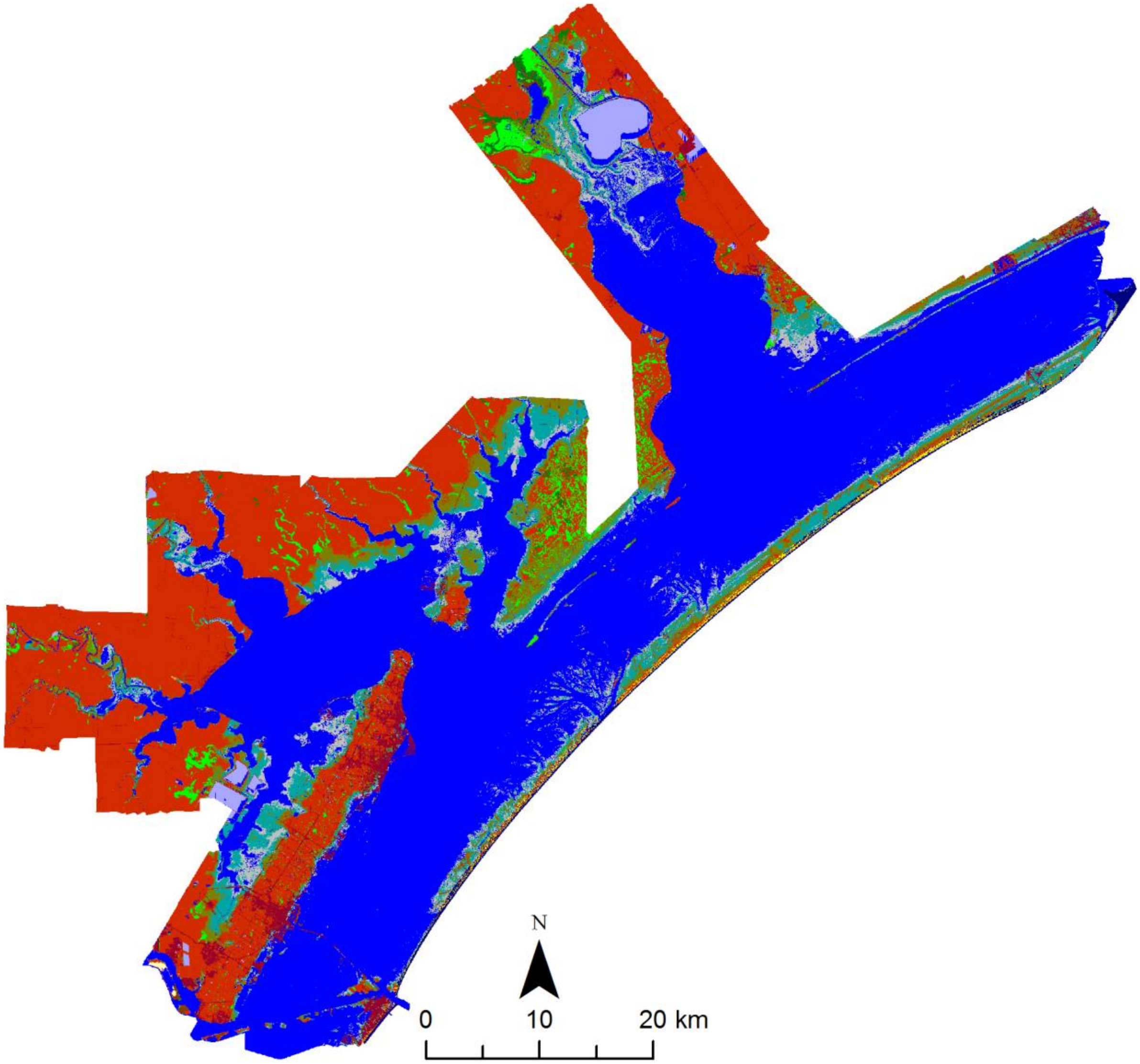
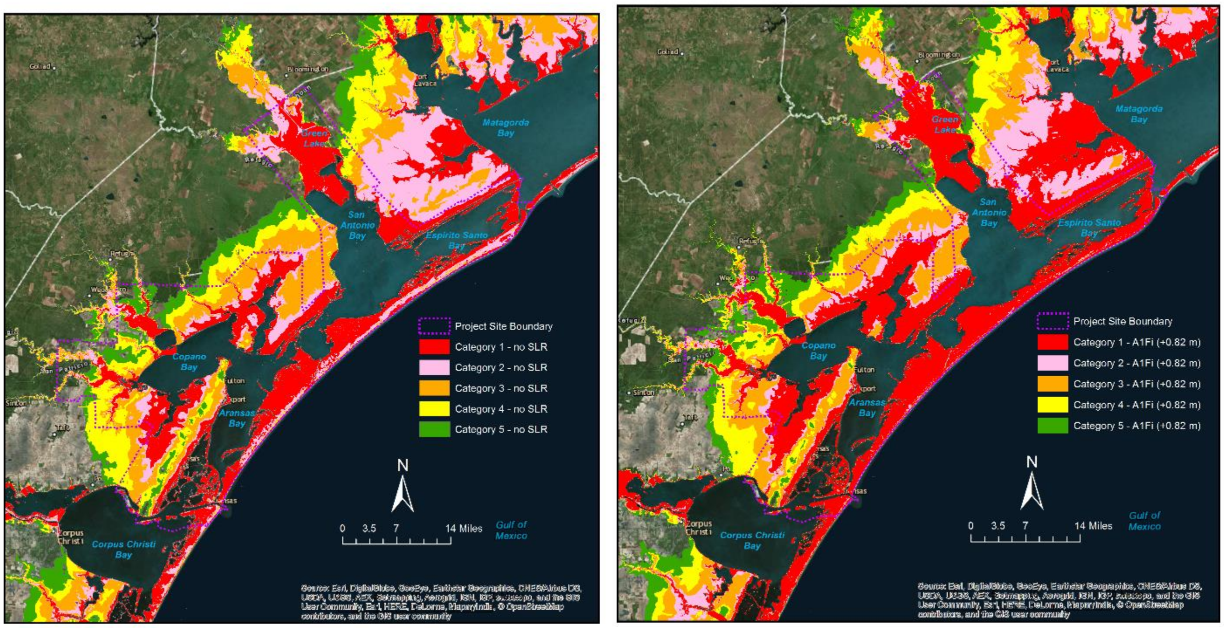


Figure 29. 2100, Scenario 2 m.

Storm-surge Exposure

The storm-surge exposure areas were developed by ORNL who modeled a simulation for both base (2008) and 0.82 m (2100) A1Fi SLR scenario for each Saffir-Simpson category event, see Figure 30 below. Using Category 3 storm event for comparison, the storm-surge analysis found that the 2008 storm-surge scenario inundated an estimated 360,798 acres of land around Copano and San Antonio Bay system. The 2100 storm-surge scenarios, which include 0.82 m of SLR by 2100, are predicted to inundate an estimated 389,924 acres. This constitutes an increase of 8% percent from the 2008 baseline scenario through 2100, which is not a significant change and indicates that the landscape of the project area is considerably low elevation that is already susceptible to SLR and storm-surge inundation associated with tropical storms and Category 1 storms.



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community, Esri, HERE, DeLorme, MapmyIndia, © OpenStreetMap contributors, and the GIS user community

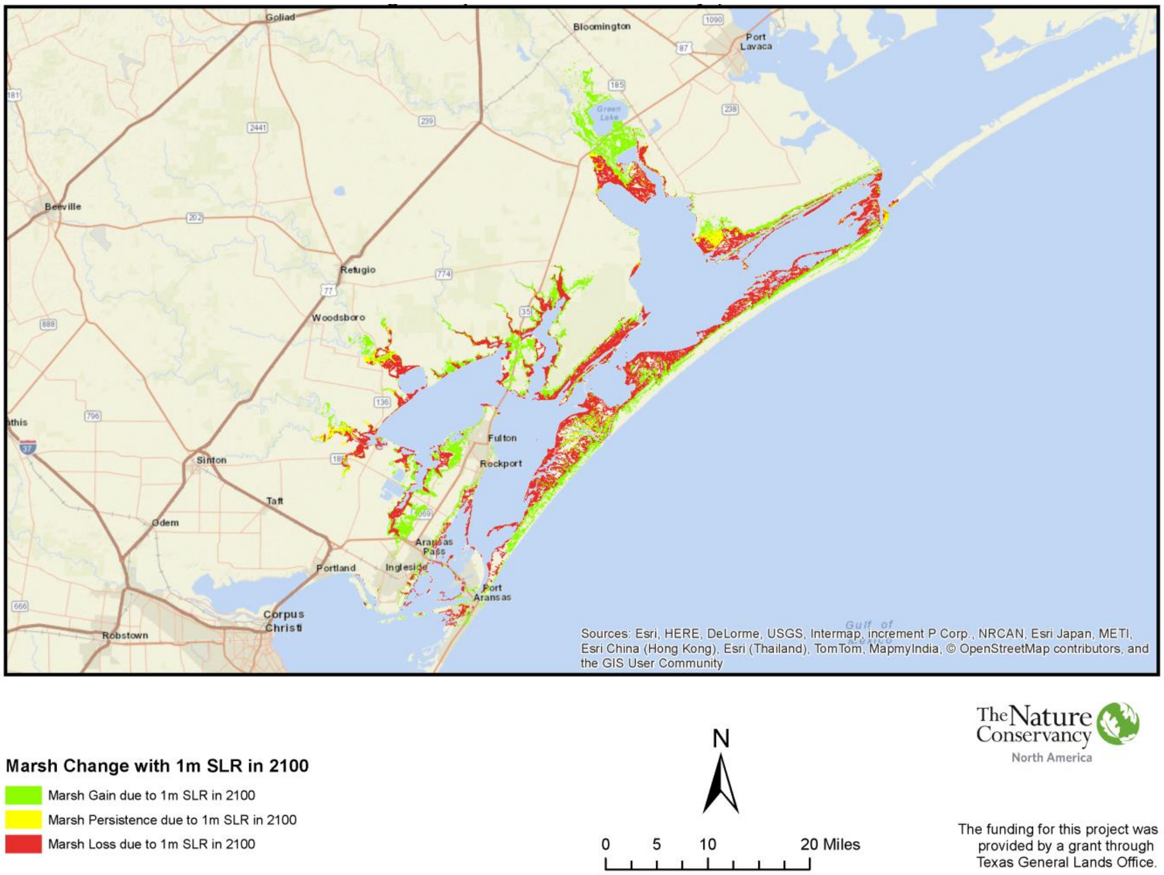
Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community, Esri, HERE, DeLorme, MapmyIndia, © OpenStreetMap contributors, and the GIS user community

Figure 30. Storm Surge Exposure areas for Saffir-Simpson Category 3 event: (left) base year (2008); (right) A1Fi (0.82 m) scenario (2100).

Conservation and Resilience Analyses

Marsh Change and Viability Analysis

Initial salt marsh distribution, which includes both Regularly and Irregularly Flooded Marshes, around Copano and San Antonio Bays in 2008 was calculated to be 51,797 acres while Fresh Marshes, which include Inland and Tidal Fresh Marsh, covered an area of 51,277 acres, primarily in the Guadalupe River delta region. Over the time period from 2008 through 2100 assuming a 1 m SLR rise a large portion of salt marshes within the project site are predicted to disappear with only an estimated 27,326 acres remaining, a change of over 47% (Figure 31). Fresh marshes within the region are projected to increase their area through 2100, especially Transitional Fresh Marshes, with 57,501 acres projected by the SLAMM model throughout the time period.



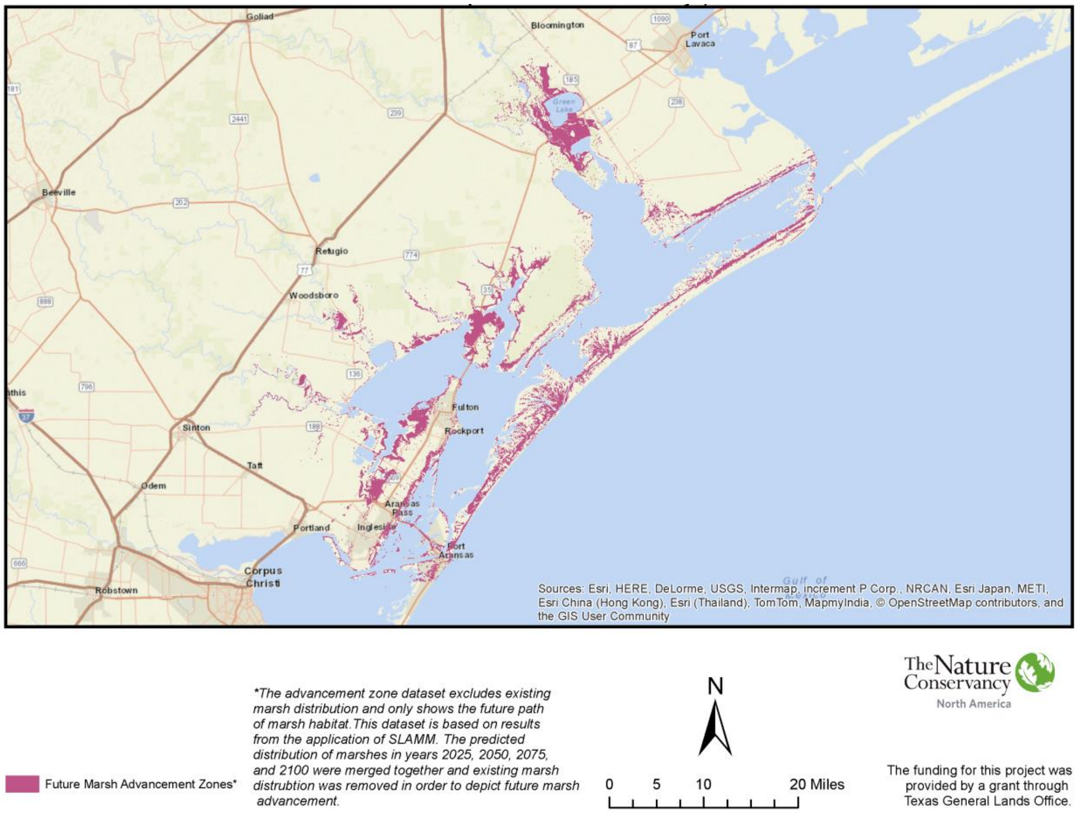
Sources: Esri, HERE, DeLorme, USGS, Intermap, increment P Corp., NRCAN, Esri Japan, METI, Esri China (Hong Kong), Esri (Thailand), TomTom, MapmyIndia, © OpenStreetMap contributors, and the GIS User Community

The funding for this project was provided by a grant through Texas General Lands Office.

Figure 31. Gains, losses and persistence of salt marsh in Copano and San Antonio Bays in 2100 with 1 m of SLR.

The total salt marsh advancement zone (the landward path beyond existing marsh through which marshes are predicted to move) under a 1 m SLR scenario from 2008 to 2100 is projected to total over 44,377 acres (Figure 32). Importantly, the marsh advancement zone does not include existing marsh and is only a calculation of projected marsh advancement beyond the initial marsh distribution. These results indicate that land areas beyond the current marsh footprint need to be managed to provide land for marshes to migrate and persist into the future; for comparison, the area of the predicted salt marsh advancement zone is roughly 86% of the size of existing salt marsh distribution throughout the study site.

Overall, the viability of salt marshes across the census blocks of Copano and San Antonio Bays in 2100 with 1 m of SLR is majorly low (Figure 33). The most viable marsh systems were usually found within developed dry land areas as these areas were protected in SLAMM modeling. There is one large census block located within the ANWR that resulted in being viable with 1 m SLR by 2100, which shows that the refuge is significant and has prime value for protecting marshes from SLR and storm-surge. Marsh systems on San Jose and Matagorda Islands were least viable along with those that border Copano, San Antonio, Aransas and Espiritu Santo Bays. Overall Regularly-Flooded and Irregularly-flooded Marshes decrease significantly between 2008 and 2100 resulting in 24,471 acres of marsh habitat lost due to 1 m of SLR, which amounts to a net change of -47%.



Sources: Esri, HERE, DeLorme, USGS, Intermap, increment P Corp., NRCAN, Esri Japan, METI, Esri China (Hong Kong), Esri (Thailand), TomTom, MapmyIndia, © OpenStreetMap contributors, and the GIS User Community

*The advancement zone dataset excludes existing marsh distribution and only shows the future path of marsh habitat. This dataset is based on results from the application of SLAMM. The predicted distribution of marshes in years 2025, 2050, 2075, and 2100 were merged together and existing marsh distrubtion was removed in order to depict future marsh advancement.

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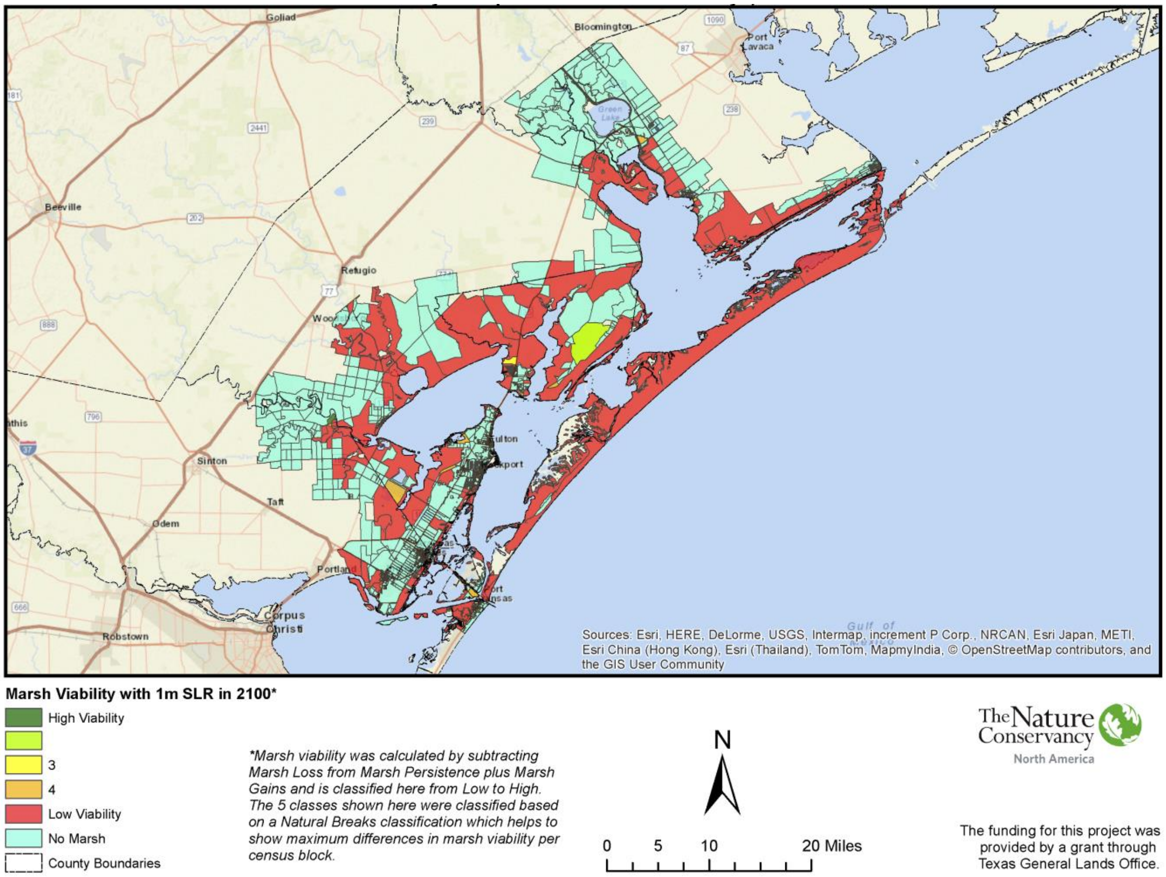
Figure 32. Future marsh advancement zones in Copano and San Antonio Bays through 2100 with 1 m of SLR.



Sources: Esri, HERE, DeLorme, USGS, Intermap, increment P Corp., NRCAN, Esri Japan, METI, Esri China (Hong Kong), Esri (Thailand), TomTom, MapmyIndia, © OpenStreetMap contributors, and the GIS User Community

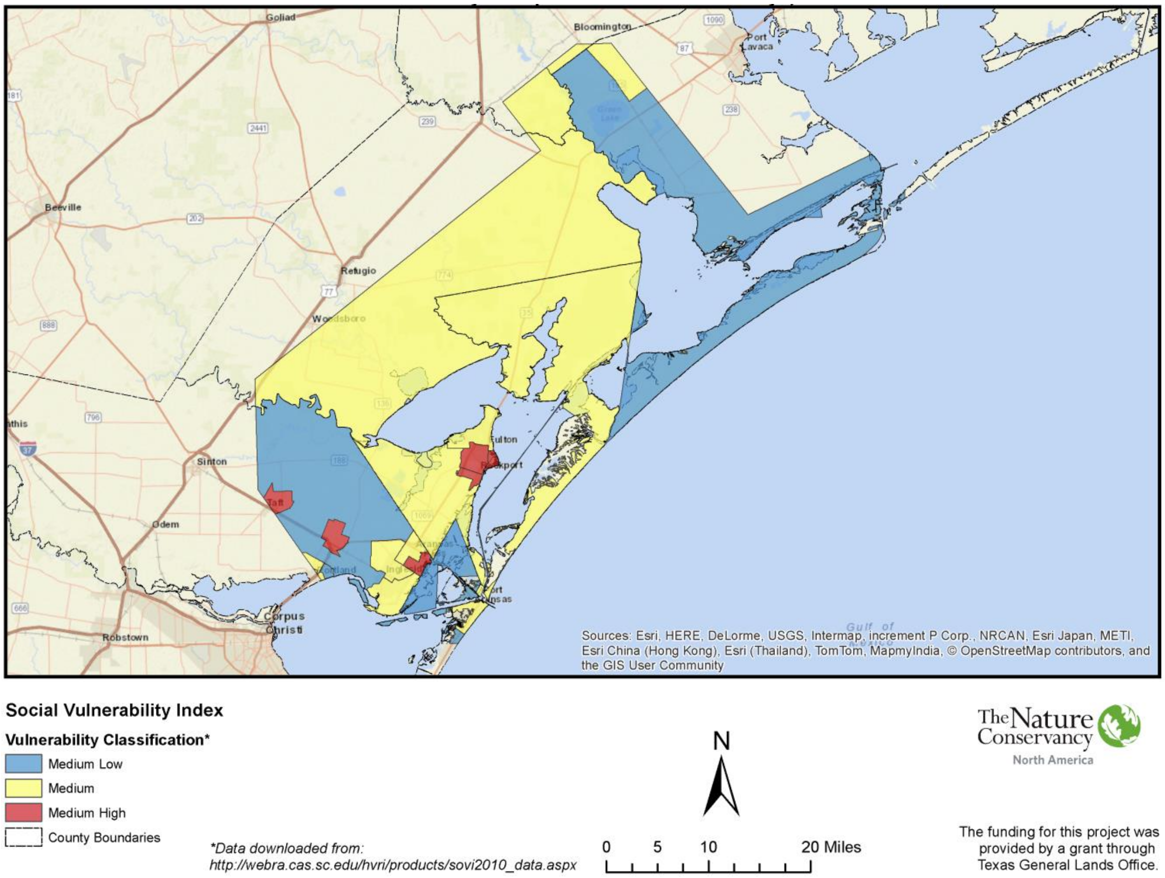
*Marsh viability was calculated by subtracting Marsh Loss from Marsh Persistence plus Marsh Gains and is classified here from Low to High. The 5 classes shown here were classified based on a Natural Breaks classification which helps to show maximum differences in marsh viability per census block.

The funding for this project was provided by a grant through Texas General Lands Office.

Figure 33. Marsh viability at the census block scale for Copano and San Antonio Bays.

Community Risk Analysis

The Social Vulnerability Index (SoVI; Figure 34) illustrates that Copano and San Antonio Bays study area ranked from Medium High to Medium Low, primarily due to this area being relatively rural and less populated like its neighboring cities of Corpus Christi and Galveston. Within the study area, 736 census blocks were found to be of medium high social vulnerability, followed by 1,750 census blocks that were classified as medium vulnerability, and 945 census blocks were of medium low social vulnerability.



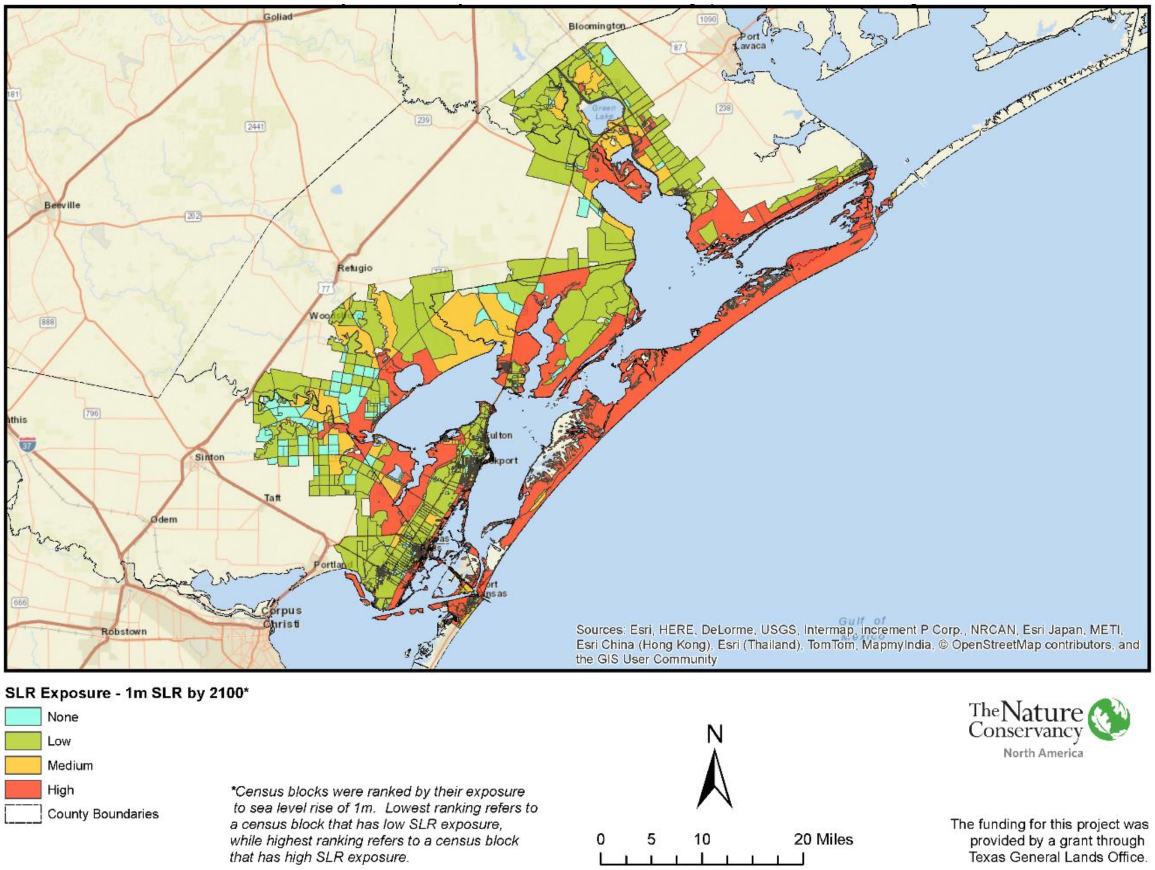
Sources: Esri, HERE, DeLorme, USGS, Intermap, increment P Corp., NRCAN, Esri Japan, METI, Esri China (Hong Kong), Esri (Thailand), TomTom, MapmyIndia, © OpenStreetMap contributors, and the GIS User Community

*Data downloaded from: http://webra.cas.sc.edu/hvri/products/sovi2010_data.aspx

The funding for this project was provided by a grant through Texas General Lands Office.

Figure 34., Social vulnerability Index (SoVI) for Copano and San Antonio Bays.

The following figures show the exposure of each census block inundated under each scenario, in addition to the compounding impacts of SLR onto a present-day storm-surge exposure. The SLR-only inundation scenario for 2100 found that only 196 blocks experience inundation 5 to 10% while 739 blocks within the study area are projected to face between 0.1 to 5% inundation, with 682 census blocks experiencing over 15% inundation by this simulated scenario (Figure 35). With a Category 1 hurricane storm-surge scenario without SLR, 1,376 census blocks (40%) are projected to be highly exposed, mainly because the study area is primarily open water and there is a large ratio of perimeter of waterbodies to its area leaving the communities who reside along the bays highly potential to be impacted by hurricanes of the lower tier (Figure 36). Only 118 blocks are projected as lower exposed to Category 1 hurricane storm-surge scenario with SLR, compared with 132 census blocks that face the same level of exposure under the simulated storm alone in 2008, without SLR factored in (Figure 37). The difference between the two years is due to some of the lower exposed blocks in 2008 being more vulnerable to SLR with storm-surge exposure in 2100. Additional maps for Category 2 through5 hurricane scenarios are available on Gulf Sea Level Rise (www.gulfsealevelrise.org) and located within its GIS Data Platform.

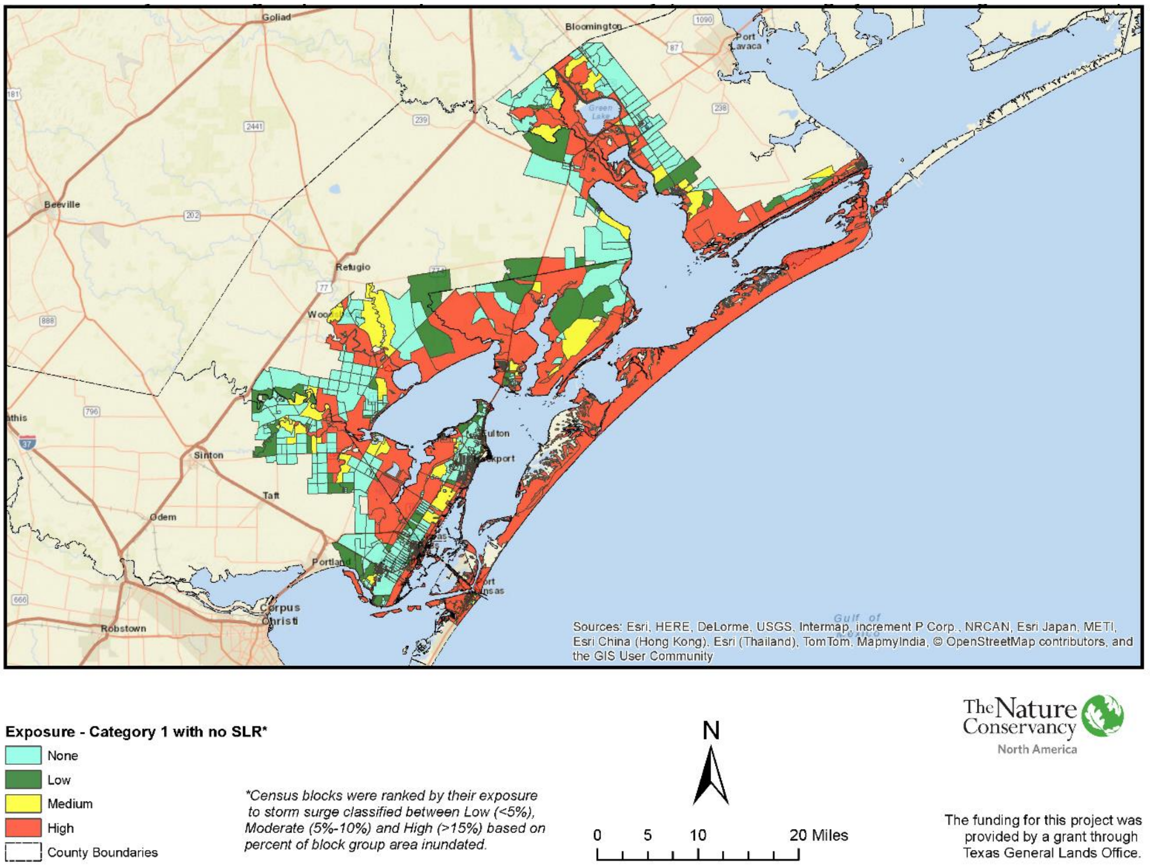


Sources: Esri, HERE, DeLorme, USGS, Intermap, increment P Corp., NRCAN, Esri Japan, METI, Esri China (Hong Kong), Esri (Thailand), TomTom, MapmyIndia, © OpenStreetMap contributors, and the GIS User Community

*Census blocks were ranked by their exposure to sea level rise of 1m. Lowest ranking refers to a census block that has low SLR exposure, while highest ranking refers to a census block that has high SLR exposure.

The funding for this project was provided by a grant through Texas General Lands Office.

Figure 35. Exposure to SLR in 2100 with no hurricanes in Copano and San Antonio Bays.

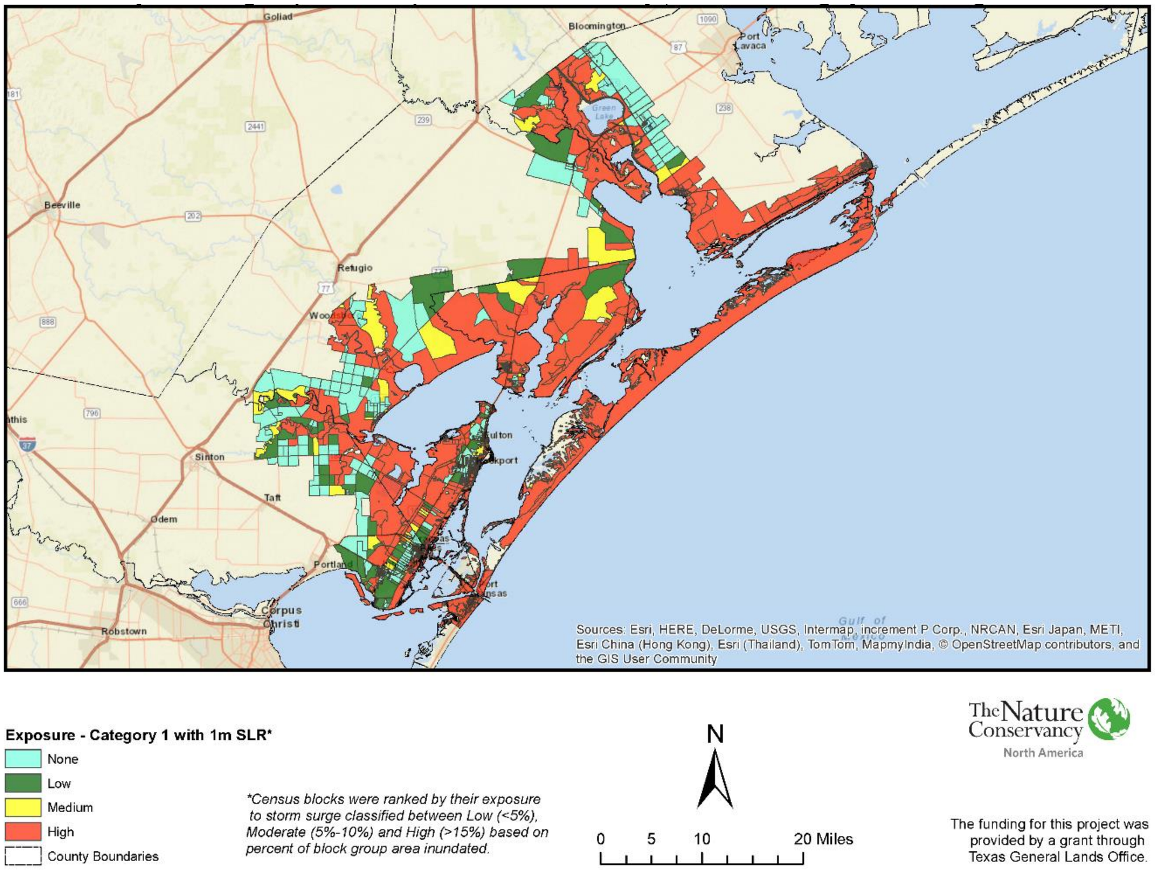


Sources: Esri, HERE, DeLorme, USGS, Intermap, increment P Corp., NRCAN, Esri Japan, METI, Esri China (Hong Kong), Esri (Thailand), TomTom, MapmyIndia, © OpenStreetMap contributors, and the GIS User Community

*Census blocks were ranked by their exposure to storm surge classified between Low (<5%), Moderate (5%-10%) and High (>15%) based on percent of block group area inundated.

The funding for this project was provided by a grant through Texas General Lands Office.

Figure 36. Exposure to storm-surge inundation in 2008 by a Category 1 hurricane with no SLR in Copano and San Antonio Bays.



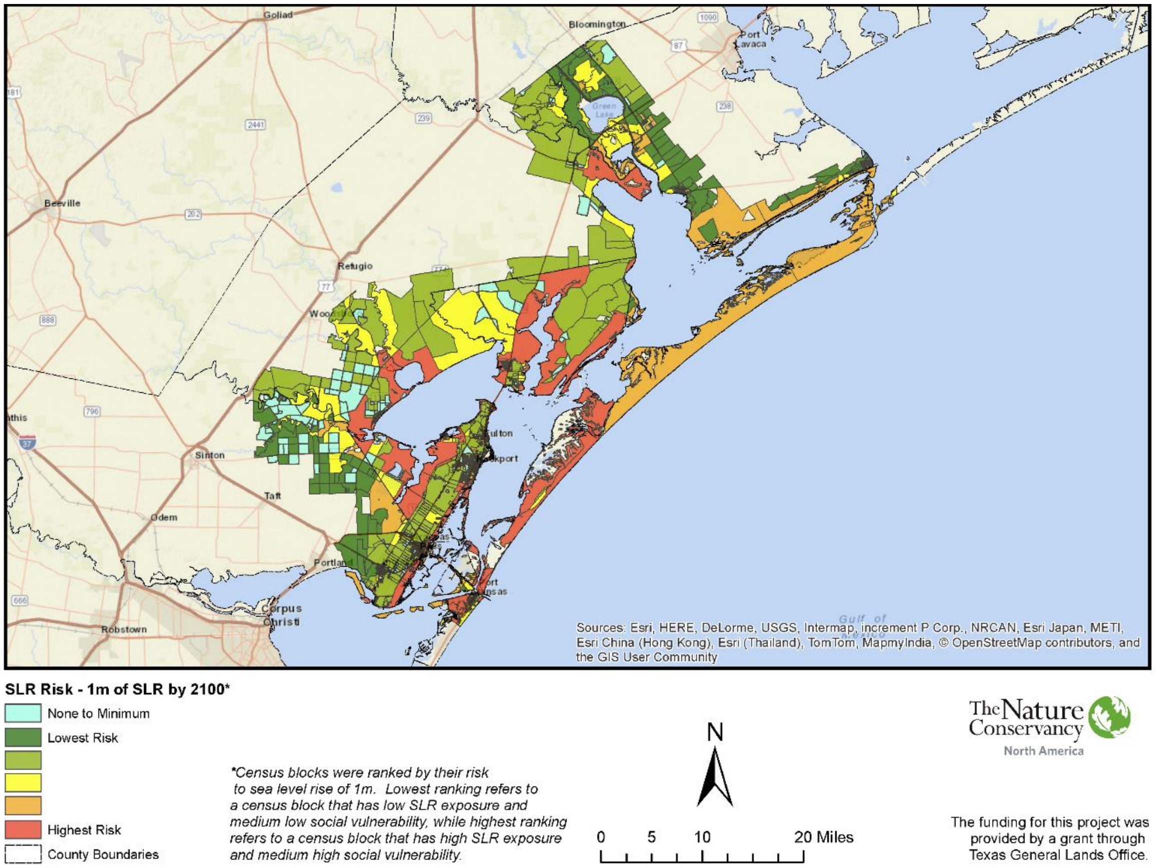
Sources: Esri, HERE, DeLorme, USGS, Intermap, increment P Corp., NRCAN, Esri Japan, METI, Esri China (Hong Kong), Esri (Thailand), TomTom, MapmyIndia, © OpenStreetMap contributors, and the GIS User Community

*Census blocks were ranked by their exposure to storm surge classified between Low (<5%), Moderate (5%-10%) and High (>15%) based on percent of block group area inundated.

The funding for this project was provided by a grant through Texas General Lands Office.

Figure 37. Exposure to storm-surge inundation in 2008 by a Category 1 hurricane with SLR in Copano and San Antonio Bays

The Community Risk Indexes are shown in Figures 38, 39 and 40. The communities most at risk to a 1 m SLR scenario are found on San Jose and Matagorda Islands, southern Copano Bay, St. Charles Bay, and Guadalupe River delta (Figure 38). Storm-surge risk in 2008 under a simulated Category 1 storm without SLR (Figure 39) shows communities in Guadalupe River delta, San Jose and Matagorda Islands, and multiple blocks along Copano Bay and St. Charles Bay are at risk with inundation. Figure 40 shows the combination of SLR impact with Category 1 storm-surge increases the risk of almost all of the communities that reside within the study area, especially those that are waterfront. More maps are available at Gulf Sea Level Rise website (www.gulfsealevelrise.org).



Sources: Esri, HERE, DeLorme, USGS, Intermap, increment P Corp., NRCAN, Esri Japan, METI, Esri China (Hong Kong), Esri (Thailand), TomTom, MapmyIndia, © OpenStreetMap contributors, and the GIS User Community

**Census blocks were ranked by their risk to sea level rise of 1m. Lowest ranking refers to a census block that has low SLR exposure and medium low social vulnerability, while highest ranking refers to a census block that has high SLR exposure and medium high social vulnerability.*

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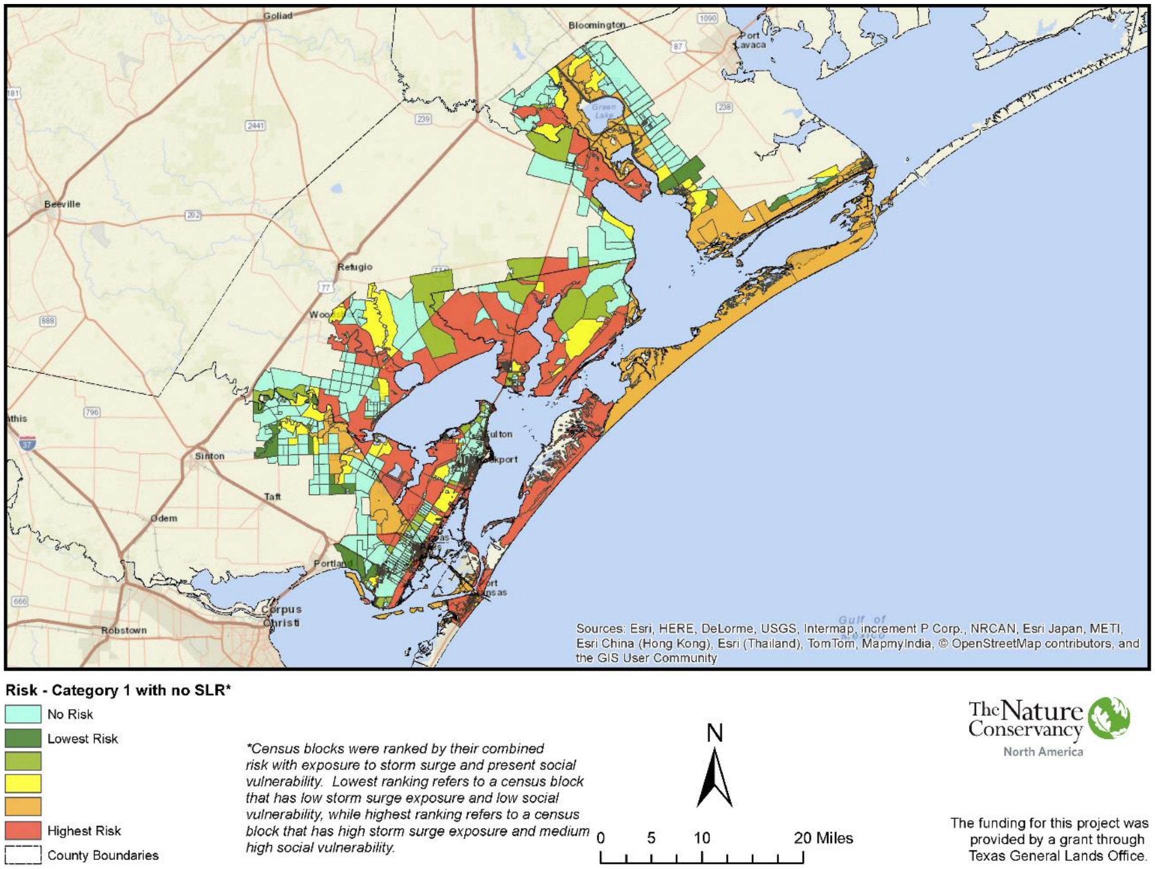
The funding for this project was provided by a grant through Texas General Lands Office.

Figure 38. Risk exposure to inundation by 1 m of SLR by 2100 for census block scale for Copano and San Antonio Bays.



Sources: Esri, HERE, DeLorme, USGS, Intermap, increment P Corp., NRCAN, Esri Japan, METI, Esri China (Hong Kong), Esri (Thailand), TomTom, MapmyIndia, © OpenStreetMap contributors, and the GIS User Community

*Census blocks were ranked by their combined risk with exposure to storm surge and present social vulnerability. Lowest ranking refers to a census block that has low storm surge exposure and low social vulnerability, while highest ranking refers to a census block that has high storm surge exposure and medium high social vulnerability.

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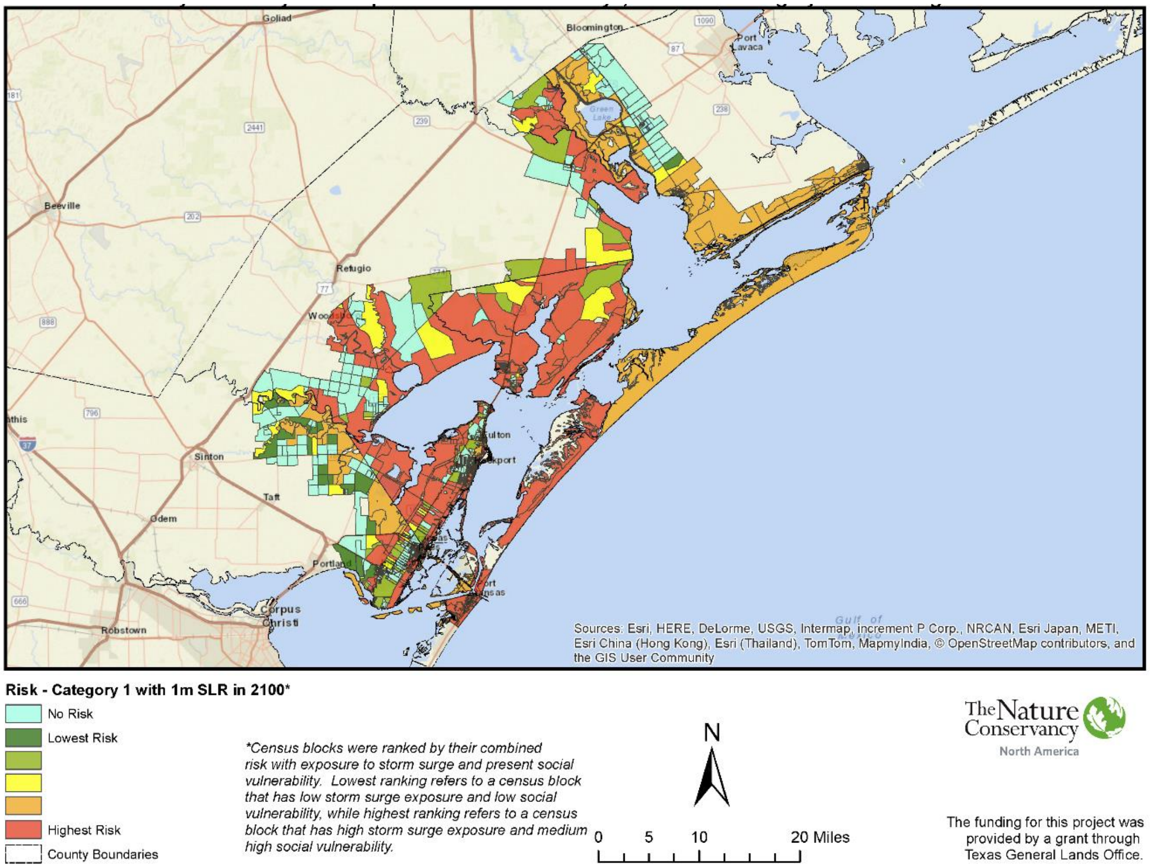
The funding for this project was provided by a grant through Texas General Lands Office.

Figure 39. Risk exposure to inundation by a Category 1 hurricane event in 2008 for census block scale for Copano and San Antonio Bays.



Sources: Esri, HERE, DeLorme, USGS, Intermap, increment P Corp., NRCAN, Esri Japan, METI, Esri China (Hong Kong), Esri (Thailand), TomTom, MapmyIndia, © OpenStreetMap contributors, and the GIS User Community

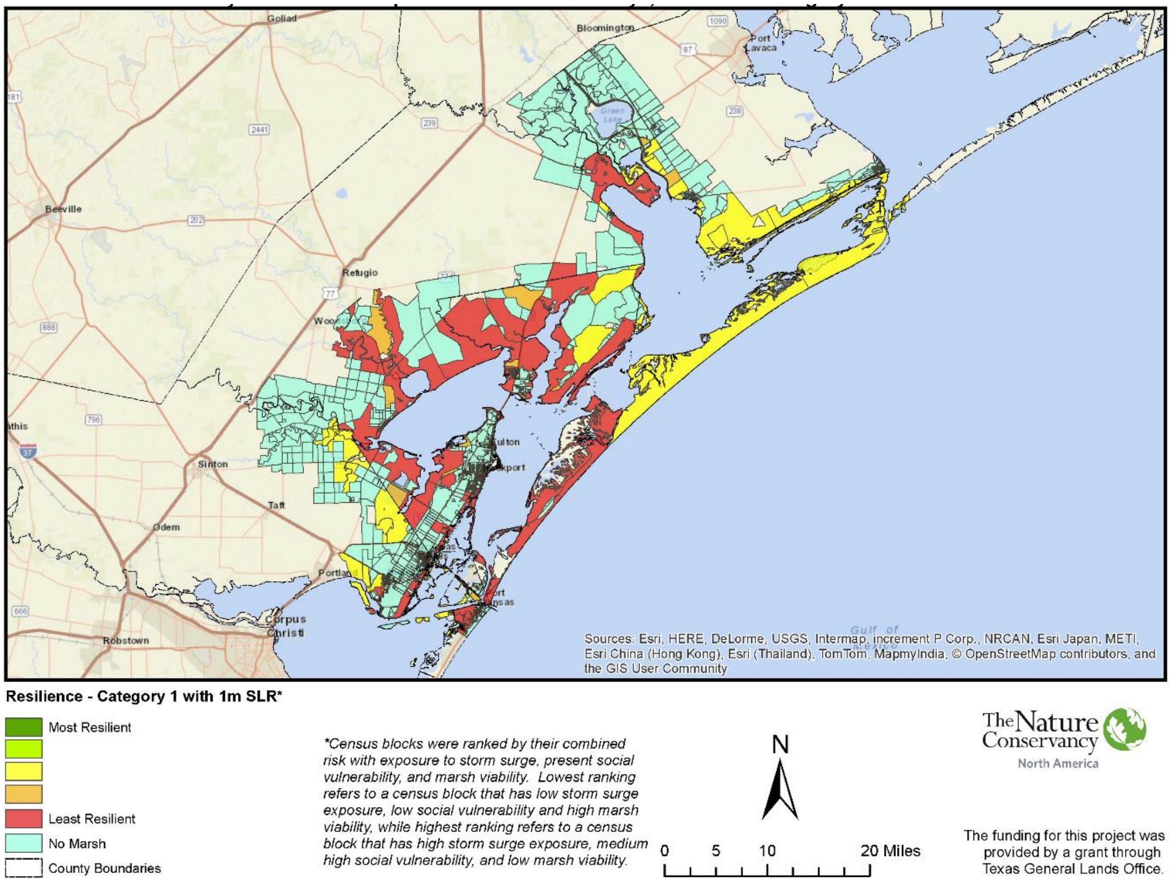
*Census blocks were ranked by their combined risk with exposure to storm surge and present social vulnerability. Lowest ranking refers to a census block that has low storm surge exposure and low social vulnerability, while highest ranking refers to a census block that has high storm surge exposure and medium high social vulnerability.

The funding for this project was provided by a grant through Texas General Lands Office.

Figure 40. Risk exposure to inundation by a category 1 hurricane event and 1 m of SLR in 2100 for census block scale for Copano and San Antonio Bays.

Community Resilience Analysis

Areas that were projected to experience substantial marsh loss under the 1 m SLR scenario, had high social vulnerability, and faced high exposure to a Category 1 hurricane storm-surge simulation were found to be least resilient in the community resilience analysis (Figure 41). Conversely, those communities that contained more viable marshes, lower social vulnerability and less exposure to storm- surge, were found to be most resilient. Only 478 blocks out of the 3,431 blocks for the study area were considered for this analysis, as the remaining blocks did not contain marsh distribution in 2008. Of these 478 blocks, only 1 was found to be close to most resilient, while the remaining blocks were ranked between medium and least resilient, with no census blocks found to be "most resilient" due to the high amount of marsh loses, the extent of storm-surge inundation and medium social vulnerability that are found in this region. In particular, the Community Resilience Analysis found that the areas on San Jose and Matagorda Islands, surrounding St. Charles Bay and on the shores of Copano Bay are among the least resilient communities in the study area, while some of the more resilient communities are nestled within the developed areas.



Sources: Esri, HERE, DeLorme, USGS, Intermap, increment P Corp., NRCAN, Esri Japan, METI, Esri China (Hong Kong), Esri (Thailand), TomTom, MapmyIndia, © OpenStreetMap contributors, and the GIS User Community

*Census blocks were ranked by their combined risk with exposure to storm surge, present social vulnerability, and marsh viability. Lowest ranking refers to a census block that has low storm surge exposure, low social vulnerability and high marsh viability, while highest ranking refers to a census block that has high storm surge exposure, medium high social vulnerability, and low marsh viability.

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The funding for this project was provided by a grant through Texas General Lands Office.

Figure 41. Community resilience index for census blocks under a 1 m of SLR by 2100 scenario for Copano and San Antonio Bays based on storm-surge exposure, marsh viability and social vulnerability.

Marsh Conservation and Management Analysis

Based on the SLAMM model outputs, Irregularly-flooded Marsh systems within the Copano and San Antonio Bays system, under the 1 m SLR scenario, are showing significant decreases as sea-levels rise through 2100, but Regularly-flooded Marsh systems react differently in a way where they decrease in size until 2050 and then increase afterwards. Marshes are migrating into new areas during this period as seen from the marsh viability analysis; losses are greater than gains for both marsh types. Federal, state and local management areas within the project site boundaries are shown in Figure 42. The long- term marsh management analysis found that the vast majority of these marsh advancement zones are outside of management areas. Our results predict that approximately 17,167 acres of existing salt marsh distribution in 2008 were found to be within current management areas while 34,630 acres fell outside of these areas. By 2100, following the 1 m SLR scenario, only 1,438 acres of salt marsh will persist within the current management areas. Approximately 57,329 acres of new marsh (marsh advancement zone) will develop through 2100, of which only 26% are within existing management areas (14,842 acres) leaving over 70% of potential marsh habitat unprotected.

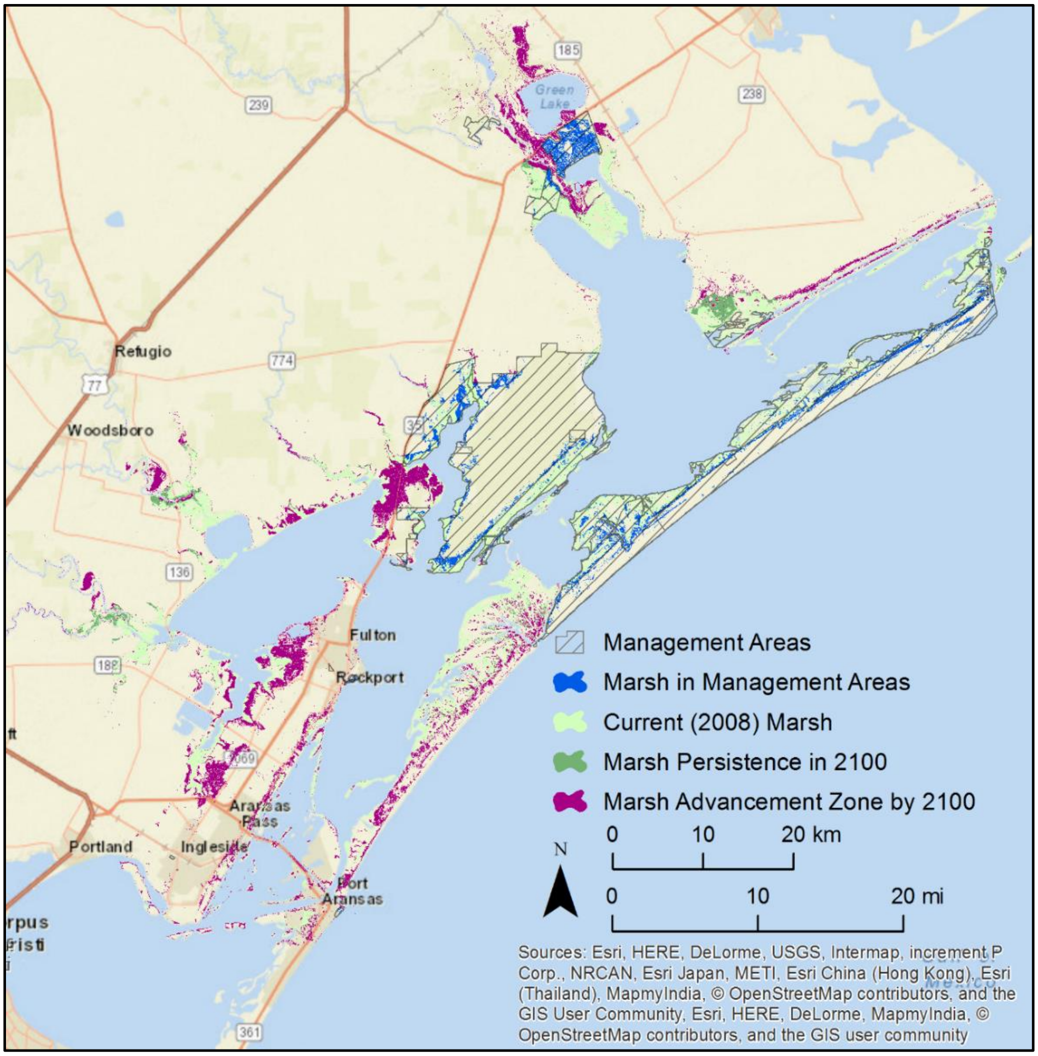

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Figure 42. Future marsh habitat within management areas in the Copano and San Antonio Bays area. This includes federal and state lands. The “Marsh in Management Areas” layer refers to marshes that exist in 2100.

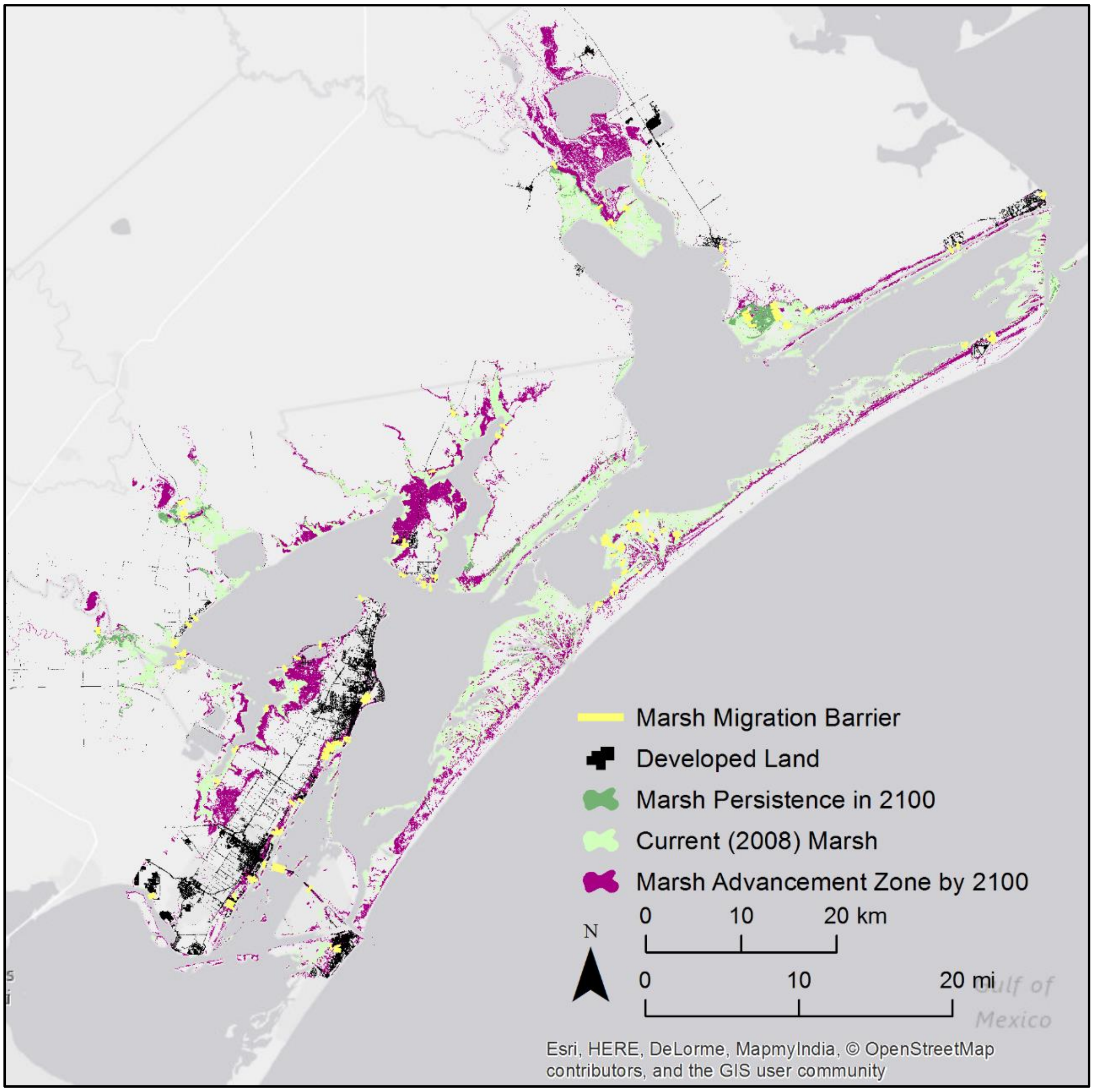

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Figure 43. Current and future marsh habitat shown in relation to developed areas. Developed areas that encroach closer than 100 m of current marsh habitat (2008) act as barriers (yellow) to marsh migration.

While the model results show that marshes have the ability to migrate landward, migration is only possible if there is suitable land to migrate towards without barriers such as roads or other development. Figure 43 shows where marshes are predicted to occur in 2100 in relation to developed land, and where developed land is within 100 m of the current extent of marshes, obstructing future marsh migration (barriers). This figure gives an overview of where current development can become an obstruction to marshes, but also gives insight as to where land should be set aside and protected from development (or further development).

Several key land acquisitions or expanded management areas could help account for future marsh distribution and conservation. Priority areas are identified as those that lie outside management areas (protected) and that have the potential for future marsh migration. An example of these priority areas are illustrated in Figure 44. By visually examining where marshes currently exist and where they are likely to exist in 2100 due to 1 m of SLR, we selected 3 areas that may be critical in marsh conservation and ecosystem functioning[2]. While these areas are not exclusive in their conservation value, they do highlight some different views of conservation strategies and goals.

- AOI (Area of Interest) 1 or “Rockport West” has large potential for marsh expansion. Since this area near development and populated areas, protecting land for marsh expansion may not only preserve ecosystem function but also ecosystem services for the Rockport/Fulton area. Some of these services include fisheries, wave attenuation from storm-surge, and erosion control.
- AOI 2 or “North Holiday Beach” also serves the same purpose of AOI 1 (ecosystem services to communities) but also could be viewed as an expansion of an already protected area, the ANWR. Expanding existing management areas increases habitat connectivity, potentially increasing the effectiveness of conservation efforts.

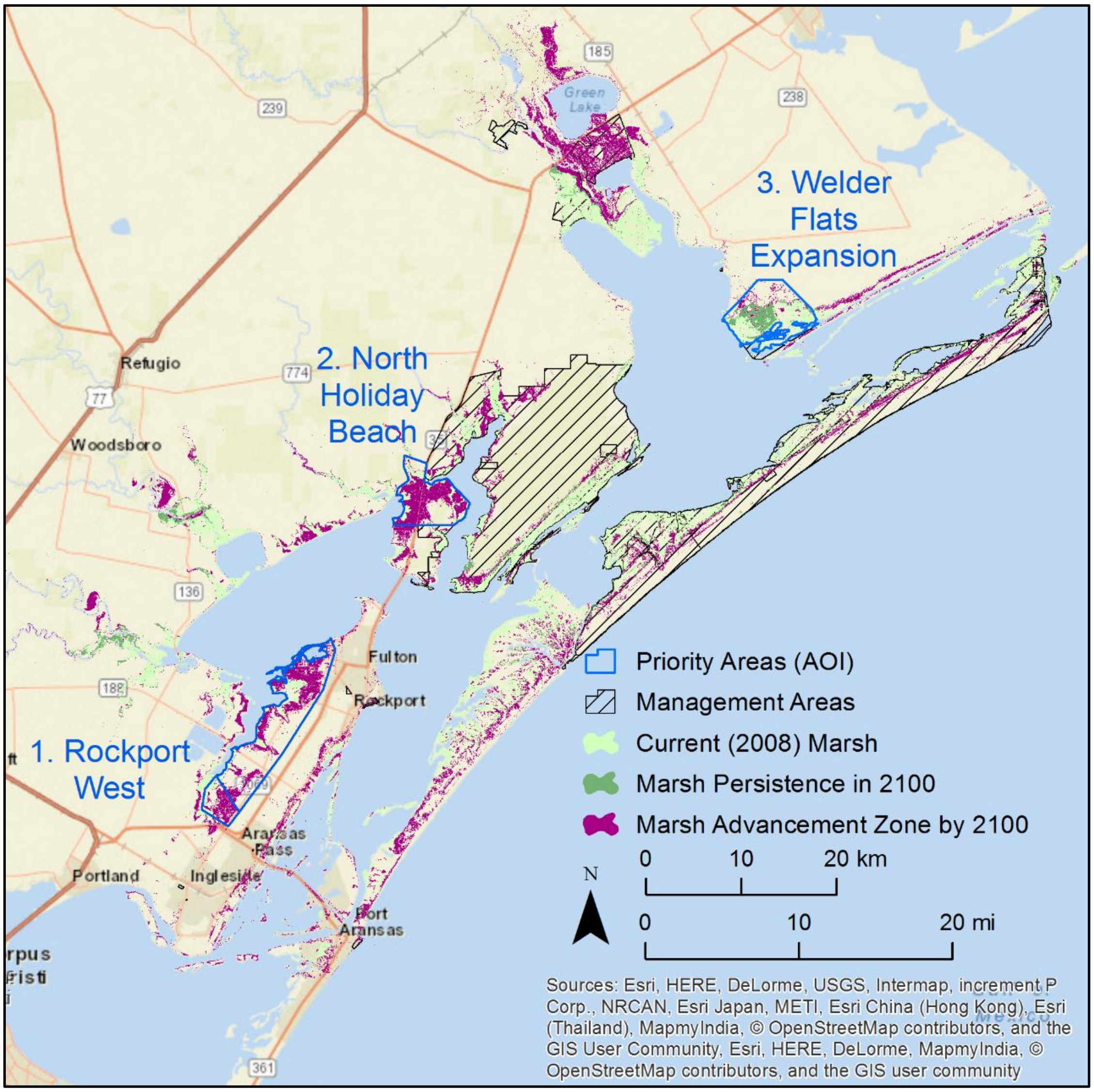

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Figure 44. Areas of interest (AOI) for conservation of marsh habitats with 1 m of SLR by 2100.

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[2] These areas are just a sampling of candidate areas that could be critical for marsh preservation. Other areas include: Aransas River Delta, Mission River Delta (northwest of Mission Lake), San Jose Island, extension of Guadalupe Delta WMA, Intracoastal Waterway mainland shoreline near Espiritu Santo Bay.

- AOI 3 or "Welder Flats Expansion" would be similar to AOI 2 in that it expands an existing management area, but it is also the only area in the study boundaries that has a substantial amount of currently existing marsh that is projected to persist through 2100 (persistence). Protecting persistent marsh also preserves ecosystem services that may not be readily observable such as carbon storage in soils and sediment (Chmura 2013).

Resolution Analysis

In 2010, a 30 m resolution SLAMM was completed for ANWR (Clough and Larson 2010). The SLAMM in this study has a resolution of 5 m in order to determine the efficacy of using higher resolution DEM to predict future habitat in the Copano and San Antonio Bays area (CSA), the two studies were analyzed in respect to one another.

As previously mentioned, SLAMM utilizes 3 raster files to predict future habitat: DEMs, slope (derived from the DEM), and vegetation. Both studies are directly comparable in reference to the vegetation layer used to represent the initial conditions of wetland habitats in the study areas. The vegetation raster files were created from the NWI dataset with reference dates of 2008. The National Land Cover Dataset (NCLD-USGS) was also used to add impervious surfaces to the vegetation rasters, but the CSA study used the 2011 NCLD. The end result is a land cover layer with vegetation and impervious surfaces (impervious surfaces were further classified as "Developed Dry Land") classified into SLAMM land cover categories. Both studies used LiDAR point data to derive a DEM and slope layers. The ANWR study used LiDAR data sets from 2006 whereas the CSA used LiDAR data sets from 2013 and 2014. Differences are expected in elevation and slope in addition to the resolution of the DEM due to geomorphological processes such as erosion, accretion, subsidence, and uplift that could have occurred over 7 to 8 years. Additionally, relative sea-level rise has been rising at 5.27 mm/year in the Rockport area (2014) so there is potential for land elevations present in 2006 to be zero or not present in 2014[3]. Thus differences in the DEM base line will make the projections of future habitat from SLAMM for both studies not directly comparable in a quantitative way.

The analysis was split into 3 parts based on the outputs of SLAMM. The first part will address the differences in the initial condition outputs due to the converted resolution of the vegetation layer (land cover). The second part will assess differences in the time zero outputs (baseline) due to the time stamps and resolution of the elevation and slope rasters (derived from LiDAR). The last part discusses the differences in the future habitat outputs under 1 m of SLR in 2100 between the two studies.

Part 1. Initial Conditions

Visually assessing the ANWR SLAMM (30 m resolution) vs. CSA SLAMM (5 m resolution), the CSA SLAMM is able to preserve smaller habitats or land cover classes due to the finer resolution. The resolution differences were quantified by comparing the rasterized 2008 NWI layer with the initial condition output of each study. The initial condition layer was chosen to minimize error between the two studies caused by differing elevation models. Since the ANWR SLAMM and TNC SLAMM study areas are not exact, a polygon was created in an area where the studies overlapped. This polygon or

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[3] https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?stnid=8774770

AOI was used create a directly comparable area between the 3 shapefiles (NWI, ANWR, CSA) by clipping each shapefile to the AOI extent. The following equation was used to quantify the error between the NWI and the initial condition output from each SLAMM study:

$$Percent\ Error = \left|\frac{T - E}{T}\right| \times 100$$

T represents the theoretical "correct" value, which in this case is the NWI, and the *E* represents the experimental value, which is the SLAMM output. Since the ANWR SLAMM is 30 m resolution, it is expected that smaller habitats are lost and a more generalized land cover surface is produced.

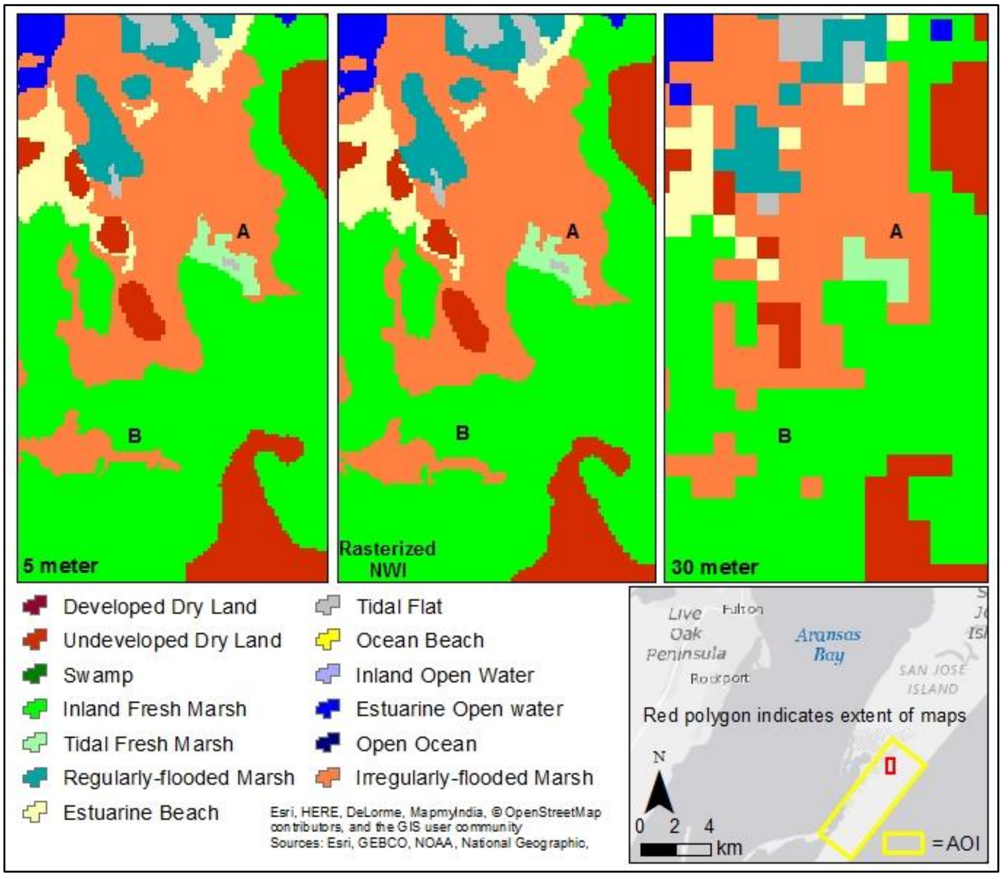
The conversion of irregularly shaped habitats to square cells leads to some error regardless of resolution. However, the size of the resolution may influence the accuracy of the interpretation. Overall, the finer resolution SLAMM (CSA) proved to have less error and thus, higher accuracy in land cover classes compared to the NWI (Table 14). Tidal Fresh Marsh shows the largest difference between the two studies in this AOI suggesting that Tidal Fresh Marsh is better depicted with higher resolutions. The same is true for the other land cover categories.

Table 14. Percent error of initial condition output from SLAMM and rasterized 2008 NWI in the San Jose Island AOI. CSA=2015 Copano Bay & San Antonio Bay SLAMM; ANWR=2010 Aransas National Wildlife Refuge, Greater Aransas SLAMM. *Some land cover categories were removed due to spatial extent of studies.

*SLAMM categories**	*% Error*	
Land Cover	CSA	ANWR
Swamp	0.39	4.23
Inland Fresh Marsh	0.01	0.17
Tidal Fresh Marsh	2.39	14.74
Irregularly-flooded Marsh	0.19	0.41
Regularly-flooded Marsh	1.97	2.99
Estuarine Beach	0.14	1.19
Tidal Flat	0.03	1.12
Inland Open Water	0.15	4.96
Estuarine Open Water	1.71	1.78

Land cover classes that do not cover large areas or have “thin” footprints may be difficult to detect using coarser resolution land cover maps and therefore artificially “lost” in future habitat models. In Figure 45 we highlight two areas where habitat is not detected in the 30 m resolution, but present in the 5 m resolution. “A” indicates the loss of a tidal flat and “B” represents the loss of Irregularly-flooded Marsh in the 30 m resolution. Additionally, B demonstrates the habitat fragmentation that occurs when using coarser resolution. While this may not have large implications for the modeling of future habitats, it may influence policy decisions on what areas are prioritized for conservation (i.e. fragmented habitat areas may be dismissed as high priority areas).

Another way in which differences in resolution can be investigated is through reference points of stationary objects with known measurements, like developed land. On San Jose Island there is a private airport that has been there since 1972 with an airstrip width of 18 m[4]. In this case, the airstrip is almost completely lost using 30 m resolution (Figure 46).



Esri, HERE, DeLorme, MapmyIndia, © OpenStreetMap contributors, and the GIS user community
Sources: Esri, GEBCO, NOAA, National Geographic,

Figure 45. Initial conditions of 5 m (CSA), NWI, and 30 m (ANWR) vegetation layers on San Jose Island (left to right). A) Loss of tidal flat habitat and B) loss of irregularly flooded marsh due to coarser resolution. The inset map (bottom right) shows the area of interest (AOI, yellow) and the subset area shown in the top 3 maps (red). NWI resolution is 1:10,000 or effectively 5 m.

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[4] https://skyvector.com/airport/XS67/San-Jose-Island-Airport

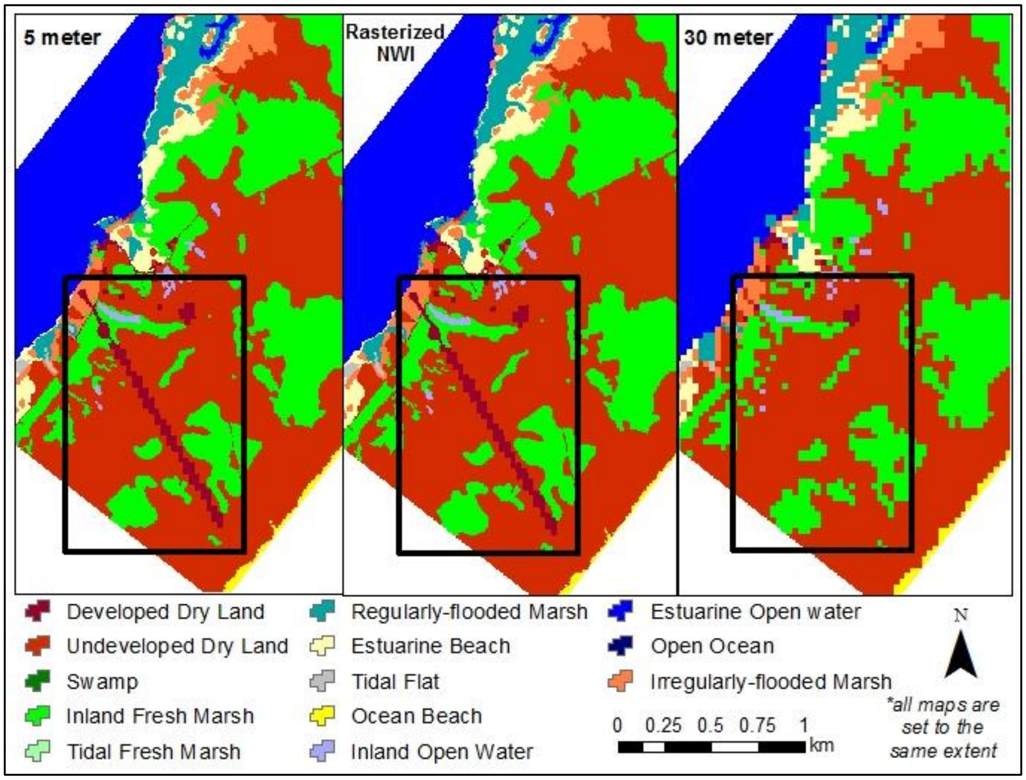

Figure 46. Initial conditions of 5 m (CSA), NWI + developed land, and 30 m (ANWR) vegetation layers on San Jose Island (left to right). The location of the San Jose Island Airport's airstrip is indicated by the black box in each data frame. The 30 m resolution data loses this feature.

Part 2. Time Zero

At time zero (T_0) SLAMM predicts the changes in land cover based on specified tide ranges, the elevation data, and the land cover data. Resolution aside, the two studies use different LiDAR photo dates (2006 vs. 2013/2014) which is probably the main basis for the differences seen between T_0 outputs. By using a more recent elevation data source with an older NWI, SLAMM is able to predict how the habitats from the vegetation layer have changed based on the current elevation. For example, if wetlands from the 2008 NWI are classified as Regularly-flooded Marsh, more current elevation data (that would decrease the elevation since the NWI was collected) may indicate that the area is probably now a Tidal Flat. Figure 47 shows San Jose Island AOI at T_0 for both studies and the vegetation layer used in the CSA SLAMM. Since the elevation data in the ANWR study more closely coincides to the NWI date, the two layers closely reflect each other. On the other hand, the CSA T_0 output reflects the habitat changes that likely occurred between 2008 and 2013/2014 based on elevation. In this case, we see that Regularly-flooded Marsh has transitioned to a tidal flat.

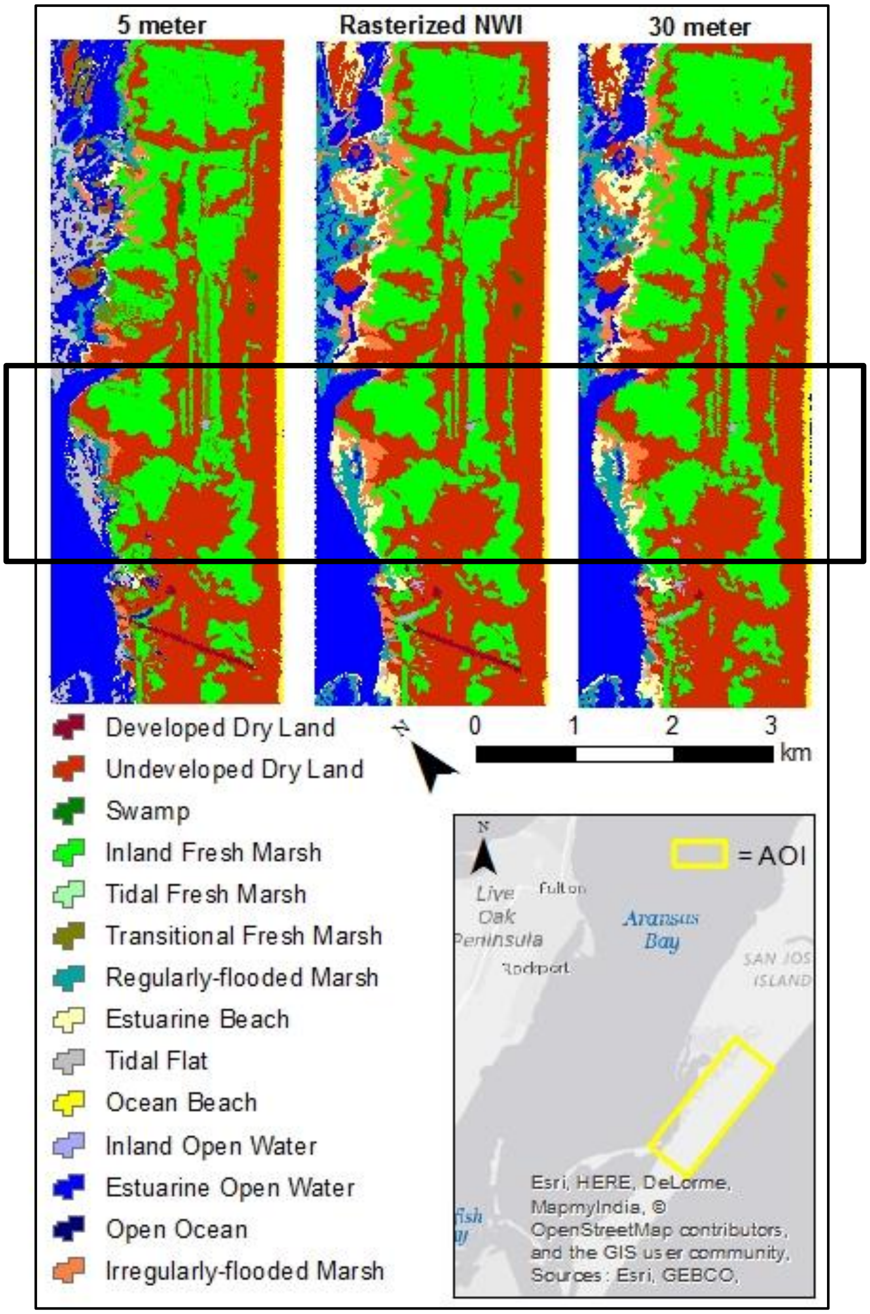

Figure 47**.** Time zero (T_0) for San Jose Island area of interest (AOI). CSA 5 m resolution SLAMM (left) compared to ANWR 30 m resolution SLAMM (right) with reference to land cover input (middle). Highlighted area exemplifies how the elevation data set influences the model (black box). Inset shows location of AOI on San Jose Island.

Part 3. SLAMM SLR 1 m by 2100

The 1 m SLR by 2100 SLAMM outputs are fairly different between the two studies. This is largely due to the different starting points (T_0) from which the model is run. Since the projected habitat from two studies are not directly comparable due to the difference in photo dates of the elevation layer, this analysis will also be qualitative and hypothesize the benefits of using finer resolution data when available. The first observation is that the 5 m resolution better reveals the succession of one habitat type to another with rising sea-levels. For example, it clearly shows the conversion of Inland Fresh Marsh to Transitional Fresh Marsh to Regularly-flooded Marsh (Figure 48). Understanding habitat dynamics will be key in protecting key resources and critical for community development under rising sea-levels.

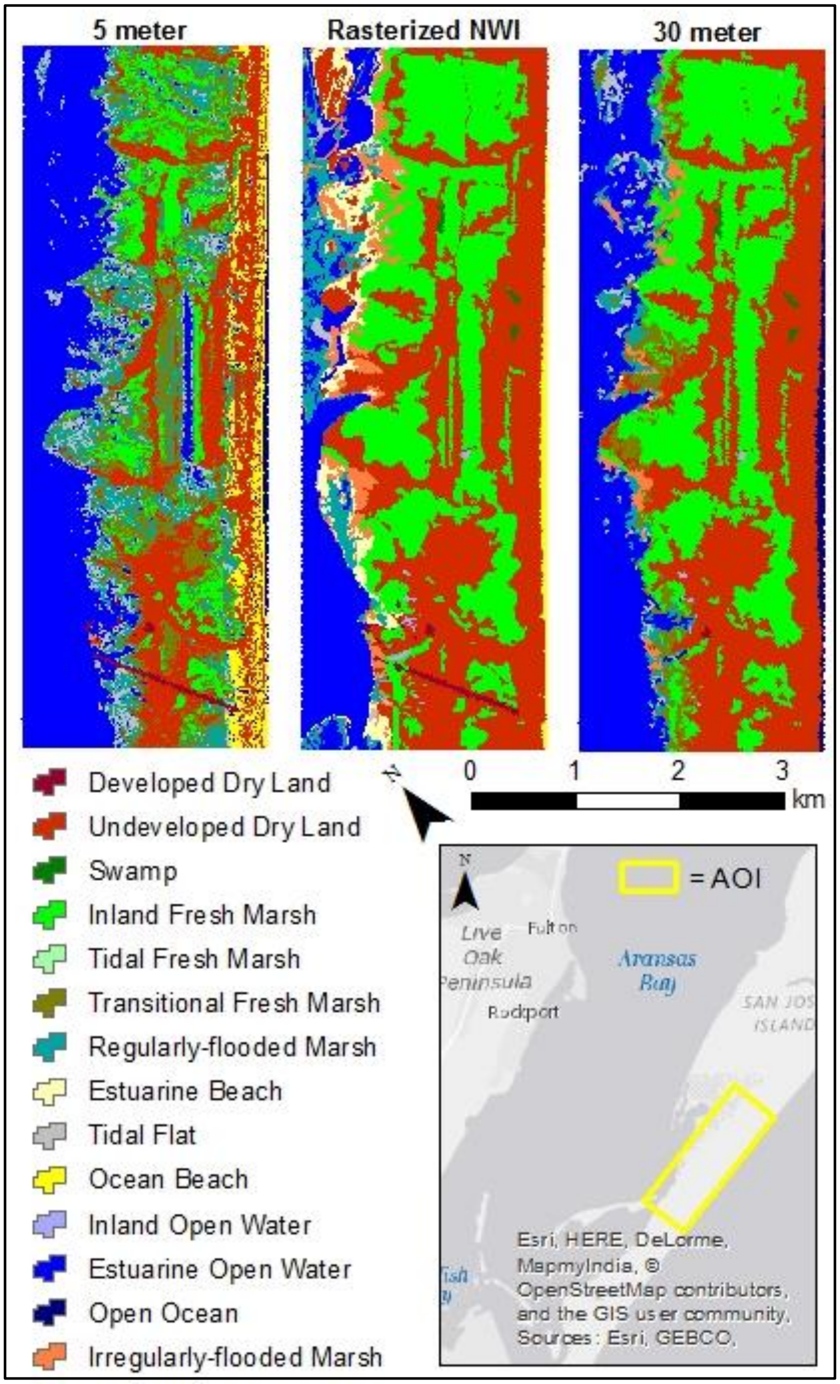

Figure 48. Year 2100 for San Jose Island area of interest (AOI). CSA 5 m resolution SLAMM (left) compared to ANWR 30 m resolution SLAMM (right) with reference to land cover input (middle). Inset shows location of AOI on San Jose Island.

Additionally, the 5 m resolution SLAMM showcases how the finer resolution elevation data permits fine-scale habitat change. For instance, in Figure 48 Ocean Beach moves landward in the 5 m resolution output but the habitat is completely missing from the 30 m resolution SLAMM. The coarser resolution could have potentially underrepresented this habitat type resulting in its loss to sea-level rise.

By comparing the two studies we are not trying to point to which study is more “correct” or “better”, but instead are highlighting the qualities that finer resolution DEMs present in future habitat modeling. Finer resolution is able to detect smaller habitat types (Figures 45, 48), as well as, predict small-scale change (Figure 48) which may be essential for conservation efforts. As resolution of the SLAMM inputs increase (DEM, NWI, NLCD) or as more current inputs are produced, habitat modeling could be re-run to ensure interested parties have the clearest and up to date picture for understanding the impacts future sea-level rise may have on these critical habitats.

STAKEHOLDERS WORKSHOP

The assessment of sea-level rise and opportunities to build coastal resilience in the Texas central coast region would not be completed without the input of local communities. We conducted two stakeholder workshops to gather their input for enhancement of the SLAMM scenarios and their interest for adaptation actions to reduce their vulnerability and increase their resilience.

San Antonio Bay and Copano Bay Sea-level Rise Workshop

On September 15, 2015 TNC partnered with the San Antonio Bay Foundation to organize the “San Antonio and Copano Bay Sea-level Rise Workshop” at the Falcon Point Ranch in Seadrift, Texas. The workshop focused on 1) disseminating the SLAMM scenarios of sea-level rise and gather their input for enhancement, 2) disseminate TNC’s coastal resilience approach and methods used in the coastal vulnerability assessment, and 2) gathering the input of participants about strategies for adapting to climate related coastal hazards and building resilience.

During this half–day workshop the project team presented to and discussed with the local stakeholders of the San Antonio Bay area their ideas and concerns to overcome the risks and build resilient communities along the coast. The workshop had nine participants, representing non-governmental organizations (San Antonio Bay Foundation and TNC), resource management agencies (Texas Parks and Wildlife Department and U.S. Fish and Wildlife Service), and engineering firms (Freese & Nichols, Inc.). Presentations of the workshop included: introduction to The Nature Conservancy model of coastal resilience, SLAMM model parametrization and products available and geomorphological resilience of the Texas coast.

After the presentations and answering the questions of the audience, the group discussed their input for the SLAMM scenarios, and their needs and ideas for adaptation strategies that could bind resilience in the area. These aspects have been integrated into the following topics:

Review and discussion of SLAMM scenarios of sea-level rise:

- Scenarios were mentioned to be informative and useful by participants.
- No specific comments were made to modify the scenarios.
- Scenarios were asked to be shared with the Aransas National Wildlife Refuge staff to be used in a conservation and acquisition analysis that is under development at the moment. [Completed]

- Scenarios were asked to be shared with the group before their official publication in www.SLRPortal.org by the end of year. [Completed]

Coastal resiliency discussion: needs and adaptation strategies:

- Potential for land acquisitions to help with Marsh Migration.
- River sustainability, delta changes.
- Evolution of SA bay.
- Important to look up dynamics of San Antonio Bay Delta and river flow.
- Green Lake/SABAY delta: river flows from NW to SE and sometimes cuts across delta to NE.
- Need to map protected and wildlife management areas and overlay with SLR scenarios. [Completed]
- Delta: estuarine dependency for shrimp and juvenile finfish, ecologically important, and tourism.
- Hydrological modelling would be ideal to understand more the dynamics of the delta.
- Living shoreline proposal of San Antonio Bay Foundation for southern tip of delta. Norman mentioned it's subsiding a bit and erosion is observed.
- Shorelines changes over time: gently sloped versus more acute sloped.
- SE Delta: southeast predominant wind direction.
- In future project combine SLR maps with other modelling efforts for planning of SA bay.
- Check out San Antonio Bay's plan. [Completed]
- Municipalities being affected, tourism is high in San Antonio Bay – need to check into NRDA's tourism impact scale.
- ANWR is looking to expand boundary and would like to use the SLAMM scenarios for this plan.
- Products to be showcased www.coastalresilience.org. [Completed]

Next steps:

- TNC will share the link to access the 1 m by 2100 scenarios with the Director of the ANWR and the rest of the participants. Additionally, the ESRI Grids (GIS layers) were made available. [Completed]
- TNC will distribute the presentations and list of participants after the workshop. [Completed]
- TNC will keep the organizer and participants informed of the availability of the resiliency analysis (maps) and the final report early next year.

Coastal Bend Climate Change Vulnerability and Resiliency Workshop

On December 15, 2015 TNC conducted the "Coastal Bend Climate Change Vulnerability and Resilience Workshop" at the MANERR in Port Aransas, Texas. Since the intent of this project aligns with the NOAA Coastal resilience initiatives to assess climate change vulnerabilities, develop adaptation strategies, and engage and educate stakeholders, the goals of the workshop focused on: 1) disseminating the SLAMM scenarios of sea-level rise and gather their input for enhancement, 2) disseminate TNC's coastal resilience approach and methods used in the coastal vulnerability assessment, and 2) gathering the input of participants about strategies for adapting to climate related coastal hazards and building resilience.

During this half–day workshop the project team presented to and discussed with the local stakeholders of the Texas Coastal Bend their ideas and concerns to overcome the risks and build resilient communities along the coast. The workshop had 26 participants representing counties and cities (27%), state and federal agencies (42.3%), academia (7.7%), and non-for-profits and firms (23%). Presentations of the workshop included: introduction to The Nature Conservancy model of coastal resilience and the coastal vulnerability assessment, vulnerability assessment in the Mission-Aransas estuary, review of the SLAMM-based sea-level rise scenarios for Copano and San Antonio Bay, and tidal datums and stillwater level flooding frequencies at the Bob Hall Pier, Texas. The complete agenda, list of participants and presentations can be obtained and downloaded from the workshop webpage: http://missionaransas.org/coastal-bend-vulnerability-and-resiliency-workshop-0.

After the presentations and answering the questions of the audience, the group discussed their concerns about the climate-related risks for their communities, natural resources and infrastructure, and ideas about how to become more resilient by reducing their vulnerabilities. These aspects have been integrated into the following topics:

Aspects that reduce vulnerability and support adaptation:

- Work on educating people in Texas to change their perception (resistance and reactions) to the climate change word and issues. The ultimate goal is to be resilient and therefore the Coastal Resilience Index could help identify the initial issues and concerns along communities.
- County-level plans tied in with local emergency managers are needed in 2017
- Protect critical facilities along the entire coastal zone and build new facilities away from floodplains.
- Factor in local to regional subsidence as it is a huge issue along Texas coast.
- Identify the areas where marsh habitat will be able to migrate due to sea-level rise and where marsh conservation is needed to reduce community vulnerability. Also identify areas of concern where vulnerability could increase due to marsh loss.
- Protect sand dunes – e.g., Kleberg County. Factor in Erosion Response Plan, dune permitting plan and focus on our beach profile. Setbacks are not straight lines, they change because you need to avoid critical dunes that migrate inland and other important features.
- Conduct better and more frequent surveys to assess the changes in barrier islands. Due to the high concentration of people and activities on these features, having surveys more frequent than every five years (as the Texas General Land Office does currently) would be beneficial for plans and to take action. Unmanned aerial vehicle technology may make this more affordable, perhaps annually.

Big gaps in building resilience:

- Allow planners, managers and public to access to more complex models that integrate sea-level rise, storm-surge, temperature and precipitation stress, and urban growth to enhance our predictive capacity and understand coastal complex processes and their impacts in communities (e.g., Advanced Circulation Model and CHARM Model).
- Identify realistic scenarios for the Texas coast that support focused planning efforts and resources for adaptation. Potentially develop 'near term' scenarios, e.g., 2050 to aid focusing planning efforts, will help focus the efforts in planning window.
- Add economics to this type of assessment to grab peoples and decision-makers' attention. Education component and economic impact needed – package these aspects together and it is a huge opportunity.
- Make more data, tools, scenarios and assessments freely available to planners, academia, and decision-makers – e.g., use http://www.coastalresilience.org to support mitigation projects and

guide when sea-level rise needs to be a factor – think about impacts of changing coastal prairie to marsh.

Future aspects:

- Conduct a follow up survey to identify needs moving forward as there are lots of great plans in the region, but local government uses FEMA plans, so Hazard Mitigation Plans are key for hazard mitigation.

PRODUCTS

Naming conventions

All files have a basic naming convention that is based on location and a description of the file. Most of the descriptors start with the analysis type followed by the scenario (i.e. location_analysis_scenario). The location prefixes for files in this project are either 'gulfmex_TX_CSA'_ or 'TX_CSA'. For SLAMM results, 'SLAMM' is used as the analysis type followed by the timestamp and SLR scenario. For SLAMM results of 1 m SLR by 2100 the user would look for *TX_CSA_SLAMM_2100_1m*. File descriptions for spatial data can always be found in the file's metadata which follows Federal Geographic Data Committee (FGDC) standards[5].

SLAMM

Twenty ASCII files resulted from running SLAMM with 5 SLR scenarios: IPCC A1B Mean (0.39m), IPCC A1BMax (0.69), 1 m, 1.5 m, 2 m across 4 timestamps: 2025, 2050, 2075, 2100. Two additional files result from running SLAMM: an initial conditions file which is essentially the vegetation/landcover input layer, and a baseline (or time zero) file which uses the digital elevation model (DEM) photo date to try and reconcile the differences due to time between the DEM and vegetation/landcover publication date. These 22 files were converted to raster format using ESRI ArcGIS software

Conservation and resiliency analysis

The conservation analysis resulted in 6 shapefiles: marsh loss in 2100, marsh advancement zones in 2100 (advance), where marshes will be managed in 2100, marsh viability per census block in 2100, marsh migration barriers, and priority areas that are not currently managed. For the resiliency analysis, 22 shapefiles were produced based on a community's exposure and risk to SLR and storm-surge. These shapefiles plus the marsh viability shapefile were used to analyze the community's overall resilience to storm-surge in the year 2100, resulting in 5 shapefiles (i.e. there are 5 categories of hurricane that would produce storm-surge).

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[5] *https://www.fgdc.gov/*

STORAGE AND AVAILABILITY

The Box

All deliverables are available for viewing and/or download on the cloud-based, secure, file sharing website, https://tnc.box.com/s/nrzfenq2qbr07iwdo4rg56054u4025sd. Data management of this project is split among 3 main folders as depicted below in Figure 49.

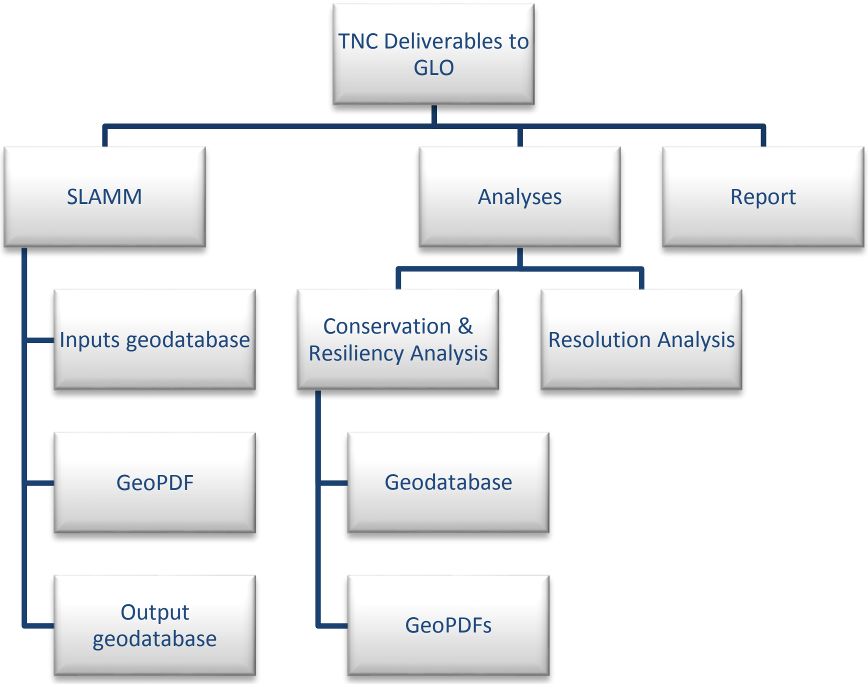


Figure 49. Storage structure of project files found on box.com.

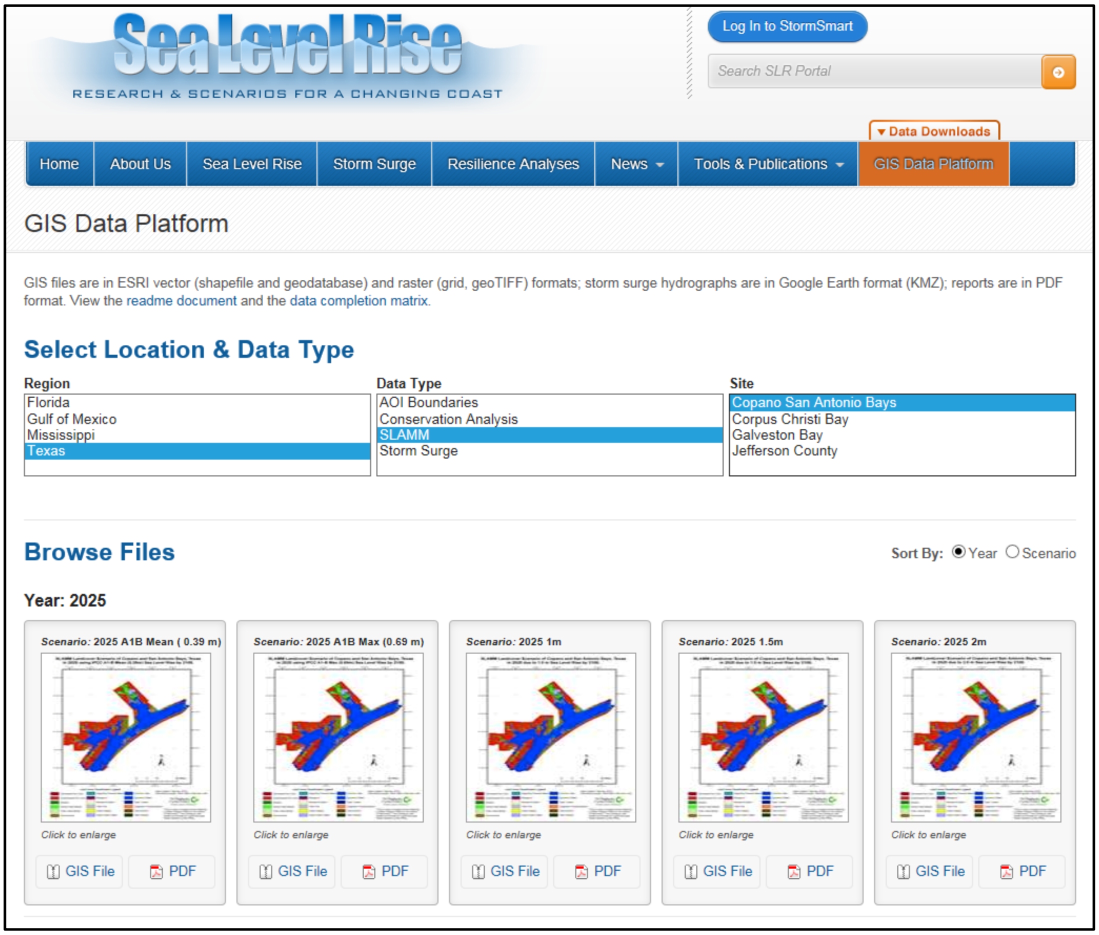
The **SLAMM** folder has 3 subfolders which contain 1) a spatial database of the inputs required to run SLAMM, 2) geospatial PDFs of SLAMM results, and 3) a spatial geodatabase of SLAMM results. The **Analyses** folder has 2 subfolders which contain the resolution analysis and the conservation and resiliency analysis. The resolution analysis subfolder contains a pdf document comparing the 5 m SLAMM results of this study to a coarser resolution SLAMM conducted for the Aransas National Wildlife Refuge (30 m; Clough and Larson 2010). The conservation analysis folder has 2 subfolders that deliver results of the conservation and resiliency analysis in two formats: a spatial geodatabase and geospatial PDFs. The **Report** folder contains the final deliverable that synthesizes the project purpose, methods, analyses, and conclusions into a single report.

All spatial products were produced in ESRI's ArcGIS software (v 10.x). The geodatabases enable the entire project to be recreated, further analyses using SLAMM results, or the creation of new maps (i.e. focusing on an area of interest). Products in the geodatabases include DEM, SLAMM results in raster format, boundary layers (e.g. study area, protected lands, census blocks, etc.), spatial layers derived from the conservation and resiliency analysis, etc. Geospatial PDFs were created for each SLAMM result (22 items) and each conservation and resiliency analysis product (34 items). Geospatial PDFs enable a user to interact with the map and extract georeferenced information without GIS software.

The products from this project are also hosted and available for download on Sea-level Rise Research and Scenarios for a Changing Coast - a web interface focusing on SLR located at http://slrportal.org. In addition, a few of the results will be made available through TNC's Gulf of Mexico Coastal Resilience Decision Support Tool (http://maps.coastalresilience.org/gulfmex/).

SEA-LEVEL RISE DATA PLATFORM

The purpose of www.slrportal.org is to host a data platform that stores and delivers all data generated by TNC and partners related to SLAMM and other coastal resilience projects in a well- organized format that allows the user to easily access and navigate to data of interest, as well as, make the data freely available to public (Figure 50). The data platform consists of a user interface, spatial databases, and file libraries. The portal also gives users an overview of coastal hazards such as sea-level rise, model descriptions, coastal resilience, and other helpful online tools.



GIS Data Platform

GIS files are in ESRI vector (shapefile and geodatabase) and raster (grid, geoTIFF) formats; storm surge hydrographs are in Google Earth format (KMZ); reports are in PDF format. View the readme document and the data completion matrix.

Select Location & Data Type

Region	Data Type	Site
Florida	AOI Boundaries	Copano San Antonio Bays
Gulf of Mexico	Conservation Analysis	Corpus Christi Bay
Mississippi	SLAMM	Galveston Bay
Texas	Storm Surge	Jefferson County

Browse Files

Sort By: ● Year ○ Scenario

Year: 2025

Scenario: 2025 A1B Mean (0.39 m)

Scenario: 2025 A1B Max (0.69 m)

Scenario: 2025 1m

Scenario: 2025 1.5m

Scenario: 2025 2m

Figure 50. The sea-level rise data platform hosted on www.slrportal.org. The interface allows users to easily navigate to data of interest.

COASTAL RESLIENCE DECISION SUPPORT TOOL

The purpose of the Gulf of Mexico Coastal Resilience Decision Support Tool (DST) is to help communities understand their vulnerability from coastal hazards using a variety of applications that are hosted on the online, free mapping portal. Data on this site comes from a variety of conservation practitioners enabling cross-over of information to guide nature-based adaptation solutions (i.e. oyster data from NOAA can be visualized with coastal flooding frequency to investigate the ecosystem services oysters produce). For this project, two apps were utilized to present data in a useful format: ***Community Planning*** and ***Future Habitat***.

The resiliency analysis and conservation analysis is viewable in the "Community Planning" app (Figure 51). SLAMM results for 4 SLR scenarios (IPCC A1B Max, IPCC A1B Mean, 1 m, 1.5 m, 2 m) at all timestamps will be available for viewing in the "Future Habitat" app (Figure 51). Additionally, habitat of interest (e.g. Marsh, Beaches and Flats, and Forested Wetlands) can be filtered out and viewed separately from the entire SLAMM result. The data can also be visualized quantitatively through graphical representation on the "Results & Chart" and "Compare & Chart" tabs.

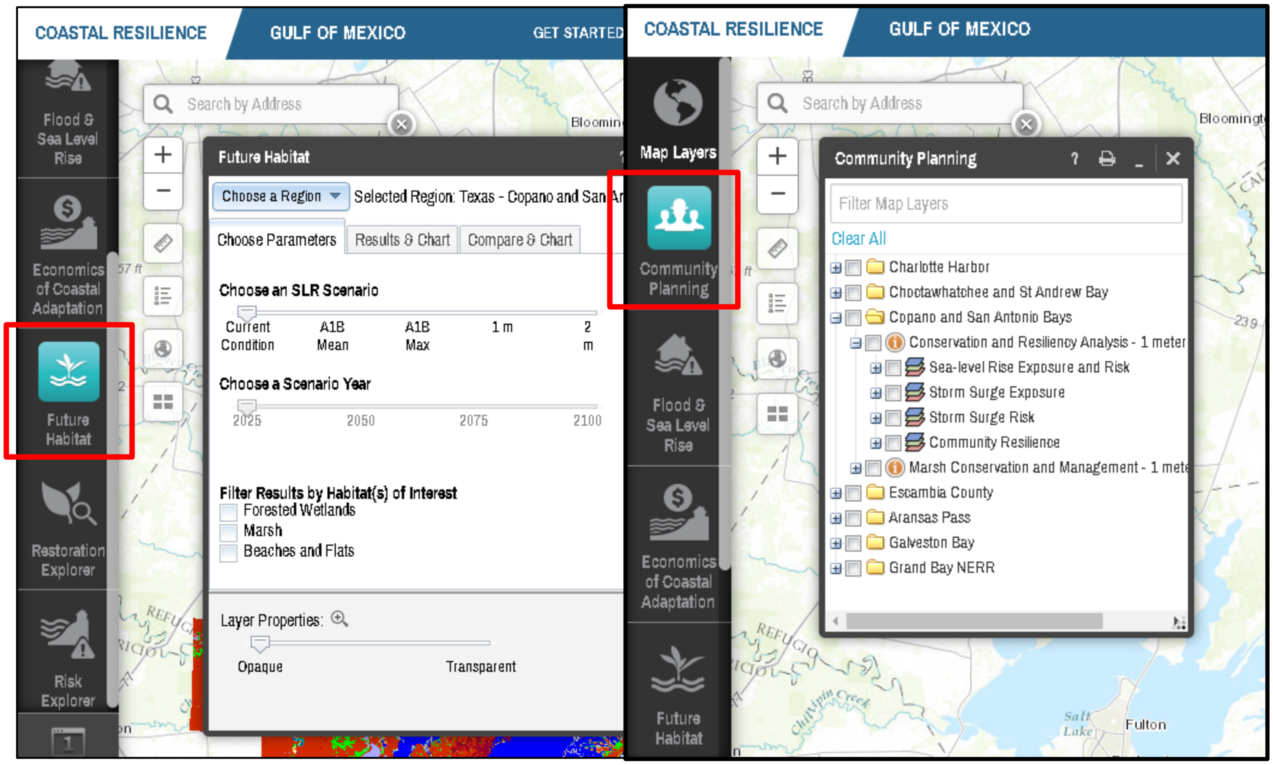


Figure 51. The Nature Conservancy's Coastal Resilience Decision Support Tool (DST) found at www.coastalresilience.org. The Future Habitat app (left) displays model results of future habitat under different SLR scenarios. The Community Planning app (right) helps communities visualize the risks they and the surrounding natural habitat may face due to coastal hazards.

PROJECT HIGHLIGHTS, CHALLENGES AND RECOMMENDATIONS FOR FUTURE RESEARCH

Highlights

This project yields multiple key pieces of information that will help us increase our understanding of the potential impacts of SLR and storm-surge along Copano and San Antonio Bays. It addressed SLR issues by developing local assessments using the best available models and data, publishing the results in a spatial data platform to make the gathered knowledge publicly available, and used the scenarios to address management and conservation issues that would promote socio-ecological resilience in the study area.

Products were developed to serve a variety of users and needs to understand and communicate the potential impacts of SLR and its effects on the natural environment and communities. The two online tools used to distribute the results and products, the SLR portal and Coastal Resilience DST, provide streamlined mapping platforms for a wide range of users-from beginners to those with advanced skillsets to download and utilize the data and information for their own planning needs.

The high resolution LiDAR and respective DEM used in the study allowed us to capture structural aspects of the habitats modeled, increasing the capacity to assess the migration of marshes over time in conjunction with SLR. We consider that the products made available through this project constitute an enhancement of SLR assessments for this area of the central Texas coast.

Challenges

As with any project that involves data gathering and modeling, there is bound to be challenges. One in particular was modification of the BEG LiDAR files that were heavy in data (1 GB per area) and 23 files that had to be mosaicked together to create one DEM file for the study area. In addition, the study area consisted mainly of water bodies and the LiDAR data did not provide depth measurement for open water areas, which is required by SLAMM modeling. Extra time and effort was taken to resolve the issue of assigning a value to those open water areas so that SLAMM models would be able to incorporate the areas in measuring the marsh migration trend across the SLR scenarios and timestamps.

Recommendations for Future Research

A couple recommendations for future research or even further analyses of the produced results involve gathering input from the stakeholders and asking for their insight as to what is important to them in understanding the risks of SLR and its long-term effects. For our products to be effective in community planning, it should be interpreted or portrayed in a way that is relevant for the community to utilize in their comprehensive plan or in their emergency evacuation plan. By personalizing the SLR outputs and the marsh and conservation analyses, it may serve even better the intended users. More frequent hands-on stakeholder workshops with maps may prompt more feedback about how the products should be developed and what other critical habitats are needed to be taken into consideration.

The parameter “Frequent Overwash”, which refers to barrier islands less than 500 m in width which may be subjected to overwash of sediments depositing on the leeward side of the island and converting wetlands, was not functional for this project. With the overwash parameter active, the model inputs’ resolution proved to be too small to achieve accurate results which caused streaking effects in the results of initial model runs It was advised by Warren Pinnacle Consulting, Inc. (WPC) to avoid this parameter due to the characteristics of our study and current limitations of SLAMM software. Future plans would be to work with WPC to reevaluate this parameter and incorporate it back into the SLAMM modeling as the study area consists of Matagorda Island and San Jose Island, the two main island complexes, which have a suite of associated smaller barrier islands and these structures would be affected by an overwash event.

One final recommendation is to motivate future SLAMM implementations in Texas to continue integrating similar high resolution-based DEMs. As the assessment of the impacts of SLR over coastal vegetation depends on the specific aspects of the micro-topography, the high resolution terrain models provide the specific local structure need by SLAMM to tell us if and where marshes could migrate as water level increases.

CONCLUSIONS

In a perfect world, healthy and thriving salt marshes would be allowed to migrate naturally with rising sea-levels and continuously provide non-structure flood control for coastal and human protection, reduce coastal erosion, act as a buffer to storm surge inundation, and provide the ecological structure needed to maintain additional coastal habitats, including seagrass beds, freshwater marshes, and coastal prairies. By focusing primarily on the potential impacts of SLR on marsh migration processes and how changes in habitat (lost or gained) might impact future storm events, our research makes the connection between our changing coastal environment and its ability to provide benefits (i.e. storm protection) to surrounding communities. A recent study by Martinich et al. (2013) echoes our intentions for the results pertaining to the impacts of SLR on socially vulnerable populations, where we try grasp a better picture of how communities are directly affected by SLR and what are the potential social and economic impacts outside of ecological concerns. This valuable information can be applied at national, regional and local levels aiding in community planning for a dynamic future.

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