Informing conservation and resiliency planning using sea-level rise and storm-surge scenario impact estimates in Corpus Christi Bay

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Prepared by
Dr. Jorge Brenner, and Michael Thompson
The Nature Conservancy
205 N. Carrizo St.
Corpus Christi, TX 78411

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1305 N. Shoreline Blvd., Suite 205
Corpus Christi, TX 78401

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Jorge Brenner, *Ph.D.*
Associate Director of Marine Science

Michael Thompson, *M.Sc.*
Marine GIS Analyst

The Nature Conservancy, Texas Chapter
205 N. Carrizo St.
Corpus Christi, TX 78411
Voice: (361) 882-3584 ext. 104
jbrenner@tnc.org

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Acronyms

ADCIRC – ADvanced CIRCulation Model

CBBEP – Coastal Bend Bays & Estuaries Program

GIS – Geographic Information Systems

GLO – Texas General Land Office

GOMA – Gulf of Mexico Alliance

NOAA – National Oceanic and Atmospheric Administration

NWI - National Wetland Inventory

SLAMM – Sea-Level Affecting Marshes Model

SLR – Sea-level Rise

SoVI - Social Vulnerability Index

TNC – The Nature Conservancy

INTRODUCTION

With millions of people living in vulnerable regions along the United States coastline, the potential impacts of rising sea levels on low-lying coastal communities and infrastructure is becoming a recognized hazard (IPCC, 2007; Karl et al., 2009; Weiss et al., 2011; Parris et al., 2012). The Gulf of Mexico contains about 20,000 km² of land below 1.5 meters in elevation (Titus and Richman, 2001) and is one of the regions in the continental U.S. that is most vulnerable to both sea-level rise (SLR) and storm-surge (Weiss et al., 2011; Thieler and Hammar-Klose, 2000). The impacts of rising sea levels and storm-surge on coastal communities and habitats can vary greatly, both spatially and temporally, with the greatest impacts of inundation occurring in low-elevation areas with little or no topographic relief (Nicholls et al., 2011; Weiss et al., 2011). Areas like these, which include the Corpus Christi region, typically contain coastal communities surrounding habitats like salt marshes, coastal plains, river deltas and barrier islands. The population in these vulnerable areas, especially in Texas, is expected to increase significantly. By 2050 the Texas General Land Office predicts that the population of the 18 coastal counties in Texas will approach 9.3 million people, an increase from 2010 of about 3.2 million new residents (GLO, 2013). As the population continues to grow the pressure being exerted on the fragile wetland habitats like those surrounding Corpus Christi Bay will also increase; but so too will the demand for the services and benefits that they provide.

Local planners and private property owners have generally not decided how they will manage their response to increasing sea levels (Titus et al., 2009) nor have they developed future habitat or shoreline management strategies that take SLR into account (CCSP, 2009). These increasing hazards threaten not only coastal communities and infrastructure, but also natural ecosystems. Coastal wetlands in the northern Gulf of Mexico have experienced significant declines this century (National Ocean Service NOAA, 2011) and accelerated SLR projections are expected to further increase the rate and magnitude of wetland loss (Nicholls, 2004; Parris et al., 2012). Wetlands are among the Gulf's most economically and ecologically important habitats and comprise approximately thirty-one percent (73,483 km2) of land within the U.S. Gulf of Mexico coastal watershed (NOAA, 2006). These wetland habitats provide many benefits for human and natural communities including vital nursery habitat for commercial and recreational fish species, storm-surge protection, erosion prevention, pollutant removal and are an important habitat for a wide diversity of plants and animals (National Ocean Service NOAA, 2011). Harm to these habitats, which degrade their ability to provide these benefits, can increase the cost of storm recovery efforts and damage already stressed natural communities. An example of the economic importance of marsh systems, on which 95% of all recreational and commercially important fish species depend, can be illustrated in the annual economic benefit of saltwater fisheries to the state of Texas, which was estimated to be around $2 billion dollars in 2011 (GLO, 2013).

According to the Climate Change Science Program populations living in low lying coastal communities like Corpus Christi face two broad options when responding to future SLR: 1) shoreline protection; and/or 2) retreat (CCSP, 2009). How affected communities respond to coastal hazards has a lot to do with their environmental and socioeconomic conditions, which influence their overall vulnerability and resiliency. Throughout the five Gulf States it is estimated that 14% of the population that lives within the Gulf Coast Special Flood Hazard area are below the poverty level (National Ocean Service NOAA, 2011).

A recent study by Martinich et al. (2013) found that many socially vulnerable communities located on the US coast are at risk to SLR, more than half of them occurring in the Gulf Coast region. Planning and responding to a global threat such as SLR ultimately falls to regional and local administrators who need critical information on the potential impacts of SLR and storm-surge necessary to support informed decision making and increase community resiliency (Najjar et al., 2000; Nicholls et al., 2007; Nicholls et al., 2008; CCSP, 2009; National Research Council, 2009;). Most state and local coastal hazard risk assessments in the U.S. are focused on current hazard risk, and do not incorporate potential future risks due to climate change impacts such as SLR (Frazier et al., 2010; Shepard et al., 2011a; National Research Council, 2011).

Resource managers and policy makers need access to information on the potential impacts of SLR in order to make the best informed conservation and coastal resiliency decisions. Coastal resiliency involves incorporating natural habitats and their ability to mitigate damages from SLR and storm-surge into development, climate adaptations and risk reduction strategies to reduce the impacts of natural disasters and improve recovery efforts. To ensure that coastal planners consider cost-effective measures for conserving coastal habitats and protecting communities it is essential they have access to data on a range of projected SLR scenarios that are based on credible science (Williams, 2012). We addressed this challenge in Corpus Christi Bay by following a conservation and resiliency analysis methodology designed by the Nature Conservancy (Gilmer et al., 2012) that provides coastal planners, administrators and resource managers with a series of indices and spatial tools to help inform the planning process, protect vulnerable communities, improve coastal resiliency, and conserve/restore important coastal habitats. The methodology focuses on coastal habitats, primarily regularly and irregularly flooded salt marshes, which provide protection and mitigation from SLR and storm-surge impacts.

The framework for TNC's conservation and resiliency analysis came together as part of the scoping process which originally consisted of scientists from the Nature Conservancy, representatives from the Gulf of Mexico Alliance, and regional stakeholders in Texas who identified ongoing and future conservation planning efforts that were best suited to be informed by SLR and storm-surge projections, socioeconomic indicators, and marsh migration scenarios. Through this scoping process the team initially identified four relevant questions pertaining to SLR (shown below) that formed the basis for the development of the analysis framework:

1. *What are the potential impacts of a 1 meter sea level rise to irregularly- and regularly-flooded marshes in the study area?*
2. *Which communities are potentially most at risk to hurricane storm-surge, and how might sea-level rise increase present-day risk to storm-surge?*
3. *Which communities might be most or least resilient to future changes based on socioeconomic indicators, inundation exposure, and marsh viability?*
4. *How might SLR impacts and future marsh habitat distribution inform land acquisition and habitat conservation planning?*

The objective of this project was to assess the implications of scenarios of sea-level rise and storm-surge in the viability of marsh wetland habitat and the resilience of communities along Corpus Christi Bay, Texas. This project used results from the Sea-level Affecting Marshes Model (SLAMM) based sea-level rise assessment conducted by The Nature Conservancy-Florida Program to develop storm-surge scenarios and spatial indicators of social-ecological resilience in Corpus Christi Bay area. The project also published and made available all the resulting scenarios and indicators for download at the Sea-Level Rise Data Platform (www.SLRPortal.org) and Gulf Coastal Resiliency Decision Support Tool (http://maps.coastalresilience.org/gulfmex/). To obtain local input a stakeholder workshop was organized.

STUDY AREA

The project site for this analysis is located on the southwestern coast plain of Texas and includes Corpus Christi Bay, Nueces Bay and the Nueces River delta, and portions of the upper Laguna Madre (Figure 1). Corpus Christi Bay is classified as a semi-tropical bay that has been designated as an estuary of national significance by the Environmental Protection Agency. The project site is located in Nueces and San Patricio counties, next to the city of Corpus Christi which has a population of over 300,000. The Bay itself is separated from the Gulf of Mexico by Padre and Mustang Islands with access to Gulf of Mexico waters through two maintained waterways; the shipping channel in Port Aransas and Packery channel, which separates North Padre Island from Mustang Island. The primary fresh water sources entering Corpus Christi Bay come from the Nueces River and Oso Creek, which enter the bay from its western and southern extensions, Nueces Bay and Oso Bay. Corpus Christi Bay covers approximately 190 sq miles and has an average depth of around 10 feet (3 m). Nueces Bay, which has an average depth of just over 6.6 feet (2 meters), covers an additional 30 sq. miles.

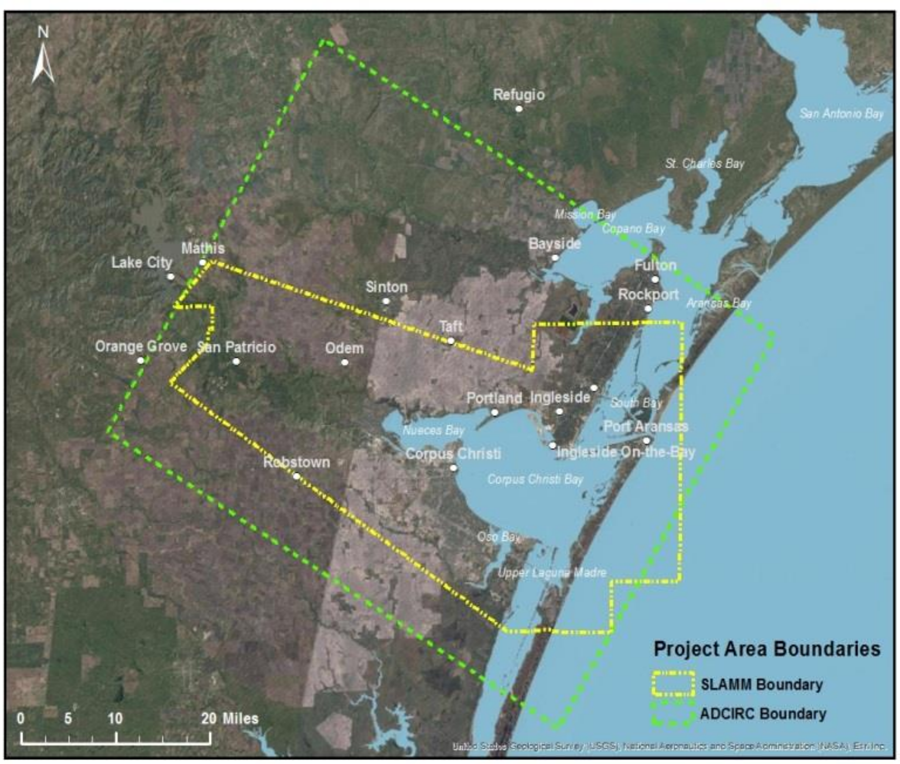

Figure 1: Corpus Christi Bay project site boundaries.

Corpus Christi Bay and the Upper Laguna Madre also contain important sea grass habitats that, along with marshes, supply vital nursery habitat to many fish and invertebrate species. Corpus Christi and the surrounding areas draw a large number of tourists each year and the regions abundance of petroleum and natural gas has attracted considerable industry and infrastructure. Because of its proximity to these industries/facilities and access to the Gulf of Mexico it has also become home to the nation's 5th largest port, with shipping and maintenance facilities located on both the north and south sides of the bay.

These bays are important natural estuaries that support a diverse collection of birds, fish and wildlife. The bay ecosystems and their surrounding marsh lands and islands are home to around 490 species of birds and 234 species of fish. This development has had a significant impact on the salt marsh habitat similar to many other places along the coast of the Gulf of Mexico, which has lost an estimated 257,150 acres of marshland during the period from 2004-2009 (Dahl and Stedman, 2013).

Given the prevalence, sensitivity, and economic and ecological importance of regularly- and irregularly-flooded marshes in the Corpus Christi Bay region, this study focused on these habitats, which collectively cover over around 11,000 acres currently within the 745,136 acre study area. Regularly-flooded marshes experience constant tidal flow and therefore contain higher salinity soils while irregularly flooded marshes typically experience greater salinity and climatic variability. The variability between regularly- and irregularly-flooded marshes create differentiated populations of flora and fauna that are driven by their respective tolerance and dependence on salinity and water table levels. In addition to salt marsh the project site contains over 19,000 acres of fresh marsh habitat, mostly occurring within the Nueces River delta, over 350,000 acres of undeveloped dry land, 67,600 acres of developed land, and estuarine and ocean waters that cover over 183,000 and 86,000 acres of area, respectively.

METHODS

Modelling Approach

The methods used in this study follow 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. The framework for the overall analysis is outlined in Figure 2 and all results assume a eustatic SLR of one meter by 2100. The methods described herein detail our approach in the Corpus Christi Bay region for assessing socioeconomic and ecological risk to 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; while storm-surge events have traditionally caused catastrophic damages and loss of life along the gulf coast. Since SLR can intensify future storm-surge events we also elected to model SLR scenarios into our storm-surge models to provide an additional coastal hazard index. GIS software (ESRI ArcInfo 10.1) 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 15m x 15m and were projected in the Universal Transverse Mercator 14N (NAD 1983) coordinate system.

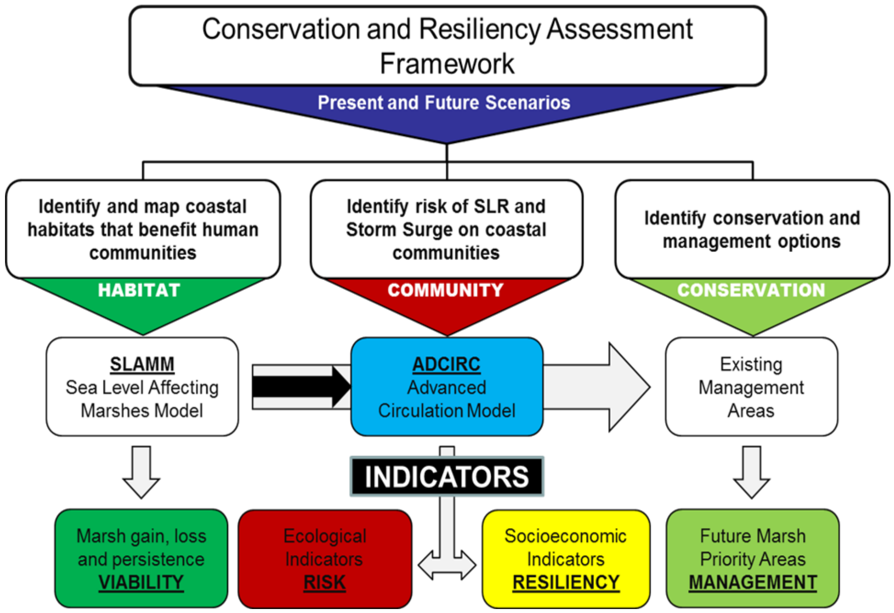

Figure 2: Framework for the Nature Conservancy's Conservation and Resiliency Analysis.

Sea-Level Rise and Marsh Migration Modeling

To simulate the effects of SLR on coastal wetland habitats the Sea-Level Affecting Marshes Model was employed as a model input to simulate potential changes in tidal marsh area and other coastal habitat types in response to SLR (see Figure 2, above). These SLAMM inputs were created by staff at TNC-Florida Program using a 1 meter SLR by the year 2100 scenario and occur over four time steps –2025, 2050, 2075 and 2100 (Geselbracht et al., 2013). This rate of SLR was chosen because several recent studies have indicated that rising sea levels are likely to approach 1 meter (3.3 ft) by the year 2100 (Nicolls et al., 2011; Vermeer and Rahmstorf, 2009; Martinich et al., 2012; Parris et al., 2012; Williams, 2012). SLAMM modeling accounts for the dominant processes involved in wetland conversion and shoreline modifications during long-term SLR by incorporating information on land elevations, land cover, tide ranges, land subsidence rates, sedimentation and erosion rates, and SLR scenarios to model the future spatial distribution of marsh and other habitats (Clough et al., 2010).

The land cover classes used by SLAMM are based on initial habitat classifications defined by the 2006 National Wetland Inventory (NWI). An initial raster land cover map was created for the year 2006 and then modeled using SLAMM for each of the four time step using 1 meter of SLR by 2100. We focus primarily on two of the SLAMM land cover classes, regularly-flooded and irregularly-flooded marsh, because they are all important habitats to fisheries, wildlife and coastal protection (National Ocean Service NOAA, 2011) but have also included fresh marsh in this analysis as mentioned earlier.

Federal agencies, including the US Fish and Wildlife service, and regional entities including the Gulf of Mexico Alliance (GOMA) have utilized SLAMM and recognize the validity of this model, which has been used to estimate the impacts of sea level rise on National Estuary Research Reserves and coasts all over the U.S. (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, 2011a,b,c,d). For a thorough technical description accounting of SLAMM model processes and the underlying assumptions and equations, see Clough et al. (2010).

Storm-surge Modeling

Storm-surge simulations were generated by an external contractor, ARCADIS US, Inc. using the Advanced Circulation (ADCIRC) hydrodynamic model to generate storm-surge inundation predictions based on a simulated storm event chosen by the project team, CBBEP, and the manager of the Emergency Management Systems of the City of Corpus Christi (see ARCADIS 2013 report for more details). ADCIRC is an integrated system of computer programs that model time dependent, free surface circulation and transport in water bodies utilizing a finite element method with unstructured grids (www.ADCIRC.org). It was chosen as a part of this analysis because of its ability to predict storm-surge and flooding by considering habitat related forcing conditions including surface stress boundary conditions (i.e. – Manning's *n* coefficient).

This modeling effort was motivated by the need to provide a series of technical tools to The Nature Conservancy (TNC) and Coastal Bend Bays & Estuaries Program to better understand the effects of sea level rise (SLR) and storm surge within the Corpus Christi Bay area. The present implementation of the Advanced Circulation model for SLR analysis complements the information produced by previous studies conducted by The Nature Conservancy. 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 one meter of SLR by 2100 in the study area. This project has been funded through a grant from the Coastal Bend Bays & Estuaries Program.

The intent of this project is to utilize the future vegetation conditions predicted by the SLAMM model to generate ADCIRC model friction parameters representative of future conditions. In this way the ADCIRC model can be used to analyze the effects of future landscapes and SLR on storm surge. Future scenarios include changes in land cover type in the area. The land cover changes are implemented by utilizing the available SLAMM output information to derive appropriate hydrodynamic friction parameters. A SLR rate of one meter by 2100 is analyzed for this study for 2050 and 2100 conditions. Because no recent hurricane has made landfall at the desired location of interest, a hypothetical storm scenario was selected as the representative storm scenario in this study area.

The hypothetical storm used here was originally derived as part of a U.S. Army Corps of Engineers (USACE) and Federal Emergency Management Agency (FEMA) flood insurance study (FIS) of the Texas coastline (USACE, 2011). Storm 343 from the 2011 FEMA storm suite was applied for this effort to approximate a high intensity category 1 storm moving from south-southeast to north-northwest and making first landfall near Padre Balli Park. Storm 343 has a peak wind speed of 90 miles per hour (mph) in the Gulf and approximately 65 mph at landfall, a forward speed of 6 knots (6.9 mph), and a minimum central pressure of 960 millibar (mb). The track for Storm 343 is shown in Figure 3. The initial landfall location is 97.207291 W, 27.604974 N. Additionally, note that ADCIRC simulations do not include rainfall in the analysis; only storm surge and nearshore waves are considered in this analysis.

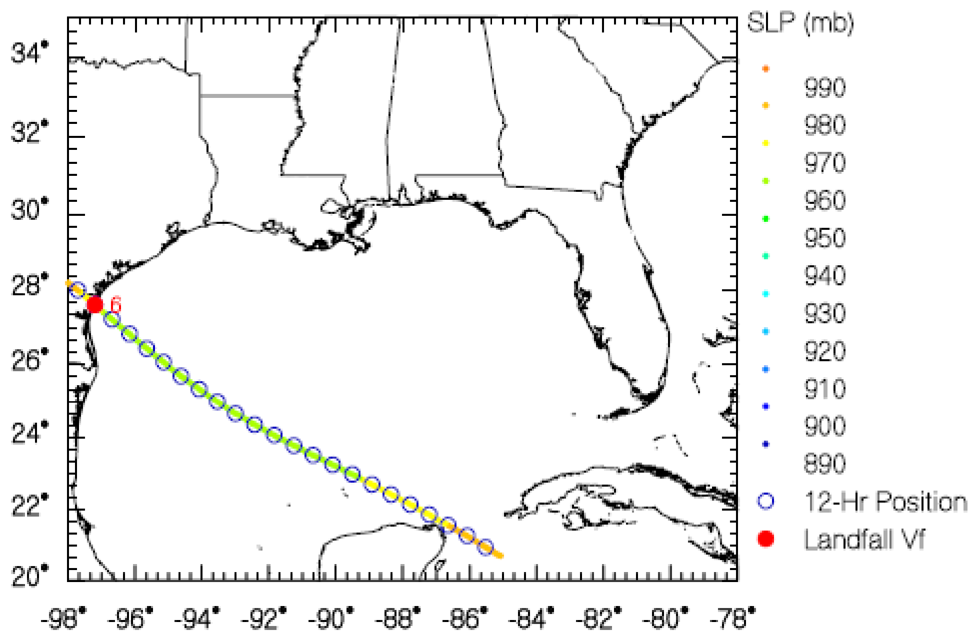

Figure 3: Theoretical Storm Track Applied for the Study.

ADCIRC model results for Corpus Christi include current and future predictions for 2050 and 2100 using the SLAMM landcover maps and the 1 meter of SLR by 2100 scenario as primary model inputs. In addition to the standard 1m SLR scenario models another ADCIRC model was run utilizing the 2006 baseline SLAMM modeled land cover with all salt marsh habitat removed. This model was run to investigate the roles that marsh habitats play on coastal protection and to measure the effects that marsh habitats have on surge attenuation. All ADCIRC results are referenced to the NAVD88 vertical datum and are offset to the local mean sea level for Corpus Christi, Texas is 1.18 foot (0.36 m). For more information on the methodology and results of these simulations, see ARCADIS (2013).

Stakeholder Workshop

On August 27, 2013 scientists from the Corpus Christi office of TNC met with 20 representatives from state, county and city offices, resource managers, city planners and researchers to discuss preliminary SLAMM and ADCIRC model results. During this meeting the analysis framework was discussed and suggestions were solicited from the various stakeholders on what they would like to see in addition to the analyses already included in the framework. The results of this workshop, in terms of additional questions the participants would like to see addressed, can be summarized in the following questions:

1. How does SLR impact fresh marshes in around Corpus Christi Bay?
2. How might rising sea level impact the health of Seagrass beds?
3. Identify marsh migration paths and their relation to development?

Once we identified which spatial indices were the most relevant to answer these questions we used spatially-explicit computer simulation models to explore the potential impacts and risks of SLR and storm-surge inundation. Using previously modeled results of marsh migration under a projected 1 meter by 2100 SLR scenario we assess how SLR and storm-surge might impact coastal communities, including those most socially vulnerable. Indices for marsh viability, community risk, community resiliency and marsh management were formulated based on our spatially-explicit model outputs in order to score the potential impacts of SLR on coastal communities and marsh habitats. Additional questions were also identified during the workshop including the suggestion to evaluate flood insurance rates in inundation areas and questions about the process of marsh migration and transition that were outside the scope of our current investigation.

Conservation and Resiliency Modeling

The following modeling efforts are based on the Nature Conservancy's previous research and the conservation and resilience framework that came from these efforts. It has four main analyses which include 1) Marsh change and viability, 2) Community Risk, 3) Community Resilience and 4) Marsh conservation and management.

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 in two geographic units 1) per existing marsh polygon and 2) summarized per census block group. SLAMM model results for Corpus Christi Bay were used to calculate where these changes might occur and predict where marshes (salt and fresh) might gain, lose or maintain area under a 1m of SLR scenario for the time period between the initial land cover dataset and 2100.

A marsh viability estimate was determined for each existing salt marsh (polygon) 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 meter 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 group scale. The latter block group level calculation was determined for each block by the marsh area via the following equation:

$$\textit{Marsh Viability} = (\textit{Marsh Gain} - \textit{Marsh Loss}) + \textit{Marsh Persistence} / \textit{Initial Marsh Area}$$

Marsh viability was then classified from "Low to High" based on a 5-class Natural Breaks classification using ESRI's ArcGIS 10 software to help show maximum differences in marsh viability per census block group. The Natural Breaks classification method is a “binning” method that groups similar values that maximize the differences between classes (de Smith et al., 2009).

In addition to looking at salt marsh we included some analysis on fresh marsh based on suggestions from the participants at our Corpus Christi SLAMM workshop. These included analyzing the gains, losses and persistence of fresh marsh within the study area based on the 1 meter of sea-level rise scenario. Because the SLAMM models do not predict fresh marsh migration a viability analysis was not conducted as no new marsh is created in the future scenarios. Another analysis that was added from input at the workshop was an evaluation of where seagrass might migrate to given the 1 meter SLR scenario. In this analysis we use maps of where sea grass beds currently occur within the project boundaries and evaluated them based on a digital elevation model to determine the range of depth where they currently occur. To predict where they might migrate to in the future we shifted the mean water level based on the 1 meter SLR scenario and identified areas in the future that would meet the same depth requirements in the bay based on the elevation model.

Community Risk Analysis

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

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

where (i) is a particular hazard scenario, in this case the ADCIRC storm-surge predictive models which integrate SLR. 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 block groups into “high”, “medium”, and “low” based on the percentage of each block group inundated per storm-surge for the initial conditions (baseline) and for storm-surge with SLR scenarios in 2050 and 2100 (future). Block groups 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.

The social vulnerability side of the equation was implemented by using the Social Vulnerability Index (SoVI) data that was 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; Schmidtlein et al., 2008; Martinich et al., 2013; Wood et al., 2010).

In this analysis, “High” social vulnerability was categorized as the top 20% and “Low” as the lowest 20%, while “Medium” is the middle 60%. Finally, the Community Risk index was calculated by classifying the exposure index with the SoVI into a conceptual 1-5 (low to high) ranking system where blocks groups that experienced high exposure and high social vulnerability (e.g. “5”), were considered highest risk, while block groups with medium exposure and medium social vulnerability were considered medium risk (e.g. “3”), and so forth.

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 block group 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 meter of SLR by the year 2100 scenario.

The Community Resilience Analysis framework, as outlined in Figure 4, 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 block groups that currently contain marsh distribution were considered in this analysis.

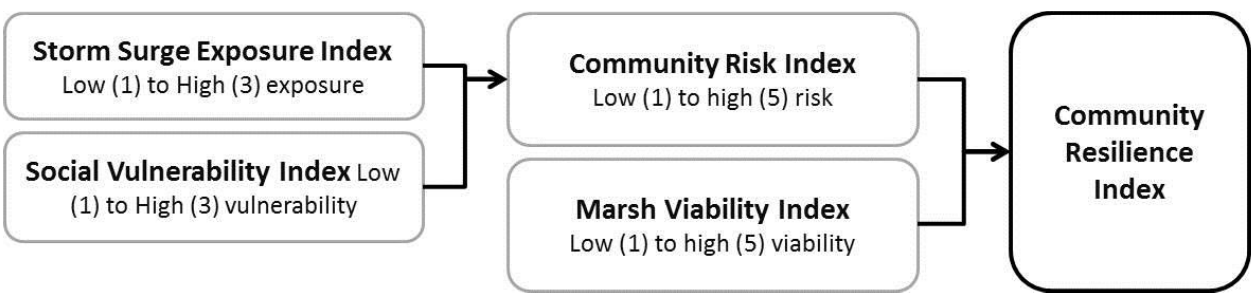

Figure 4: Community resilience analysis framework.

Marsh 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. Marsh advancement zones located immediately adjacent to existing management areas were then selected as priority protection areas; which we consider to be areas where existing conservation management areas could be more readily expanded to include these advancement zones and allow for the uninterrupted landward migration of marsh habitats that is modeled occur under the 1m SLR by 2100 scenario.

RESULTS

SLAMM Sea-level Rise Scenarios

Regularly and Irregularly flooded marshes are expected to significantly decrease between 2006 and 2100, while transitional salt marshes are expected to increase as new land is covered by salt water inundation. SLAMM predicts land cover changes to be less severe between 2006 and 2050, with more drastic changes in landcover occurring between 2050 and 2100. Regularly-flooded marshes in the study area are predicted to change considerably, decreasing by almost 45%, (3,585 acres) between 2009 and 2100 while irregularly-flooded marshes are expected to decline during the same period by 78%, or 2,306 acres. Inland fresh marsh habitat is projected to also decrease by more than 12%, from an initial area of 19,871 acres to 17,437 acres. Transitional salt marsh is the only marsh land cover type that shows an increase in habitat with 1 meter of SLR through 2100 as it is projected to gain over 290 percent (4,431 acres). Meanwhile, the only other SLAMM land cover category that gains in overall area is the estuarine waters of Corpus Christi Bay, which are expected to increase in area by 20,737 acres, an 11.33 percent change.

The full results for the SLAMM analysis are detailed in Geselbracht et al. (2013) and gains and losses are summarized in Figure 5 below for the most commonly occurring land cover types.

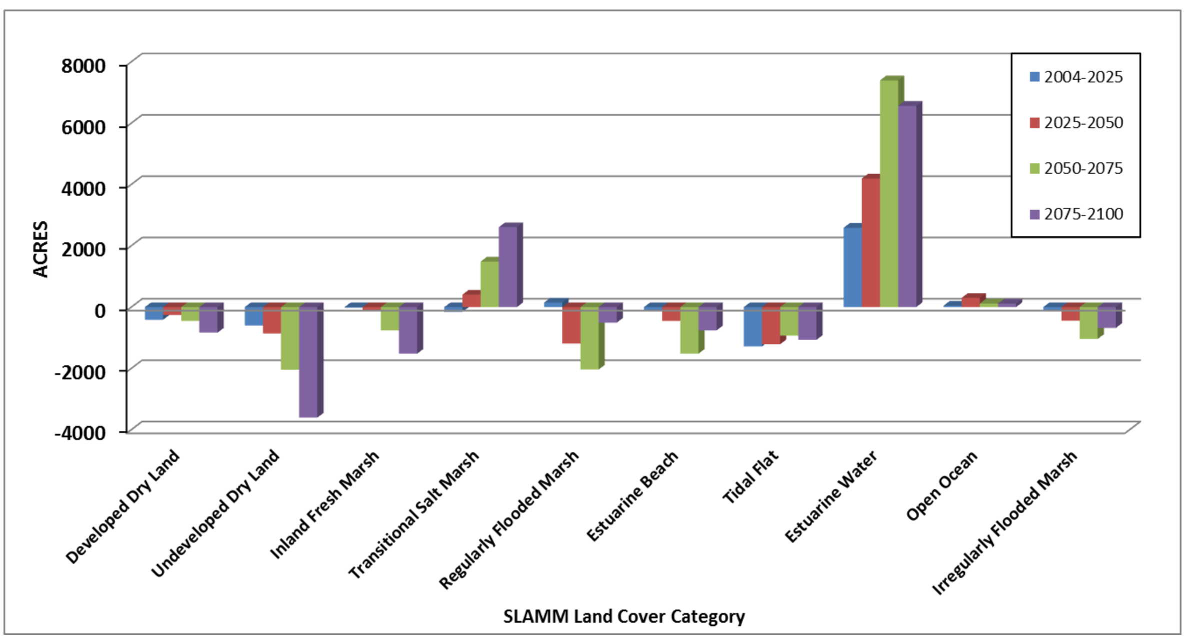

Figure 5: Predicted change in acres of SLAMM land cover classifications in Corpus Christi Bay, Texas under a 1 meter SLR by 2100 scenario from baseline condition (2006) through 4 time periods – 2025, 2050, 2075 and 2100.

ADCIRC Storm-surge Models

The storm-surge inundation extents for Corpus Christi, modeled on a simulated Category 1 hurricane, as taken from ARCADIS (2013), for current land cover (2006) and future (2050 and 2100) land cover predictions are shown in Figure 6 (below). The storm-surge analysis found that the 2006 storm-surge scenario inundated an estimated 74,880 acres of land around the bay of Corpus Christi. The 2050 and 2100 storm-surge scenarios, which include 1 meter of SLR by 2100, are predicted to inundate an estimated 84,988 and 106,505 acres, respectively. This constitutes an increase of over 42% percent from the 2006 baseline scenario through 2100, indicating that 1 meter of SLR can increase near term storm-surge exposure by a considerable factor. More details regarding the predicted storm-surge impacts can be found in the ADCIRC report on Corpus Christi Bay completed by ARCADIS (2013).

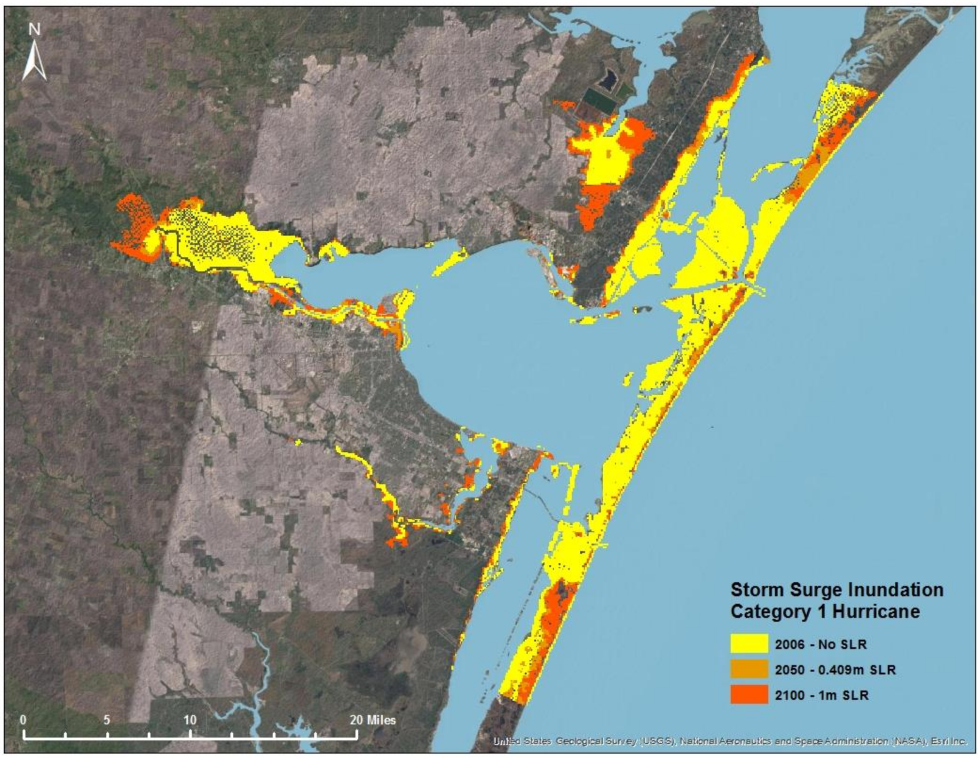

Figure 6: Predicted storm inundation extents for Corpus Christi Bay region from 2006 through 2100.

In addition to the storm surge models that include all the SLAMM land cover categories another model was run for the year 2006 using the same category 1 hurricane simulation that had the entire salt marsh habitat removed. This analysis was conducted to determine the attenuation effects that marshes have on storm surge and how they play a role in coastal protection and community resilience. The results of this analysis indicate that without marshes the potential impacts of storm surge would increase within the study area covering 75, 831 acres, or an additional 951 acres of land inundated in the no marsh scenario (Figure 7). Figure 8 (below) shows the results of the ADCIRC model in storm surge elevations for the study area. Based on the category 1 hurricane used for the simulation the maximum storm surge potential within the study area is below 8 feet.

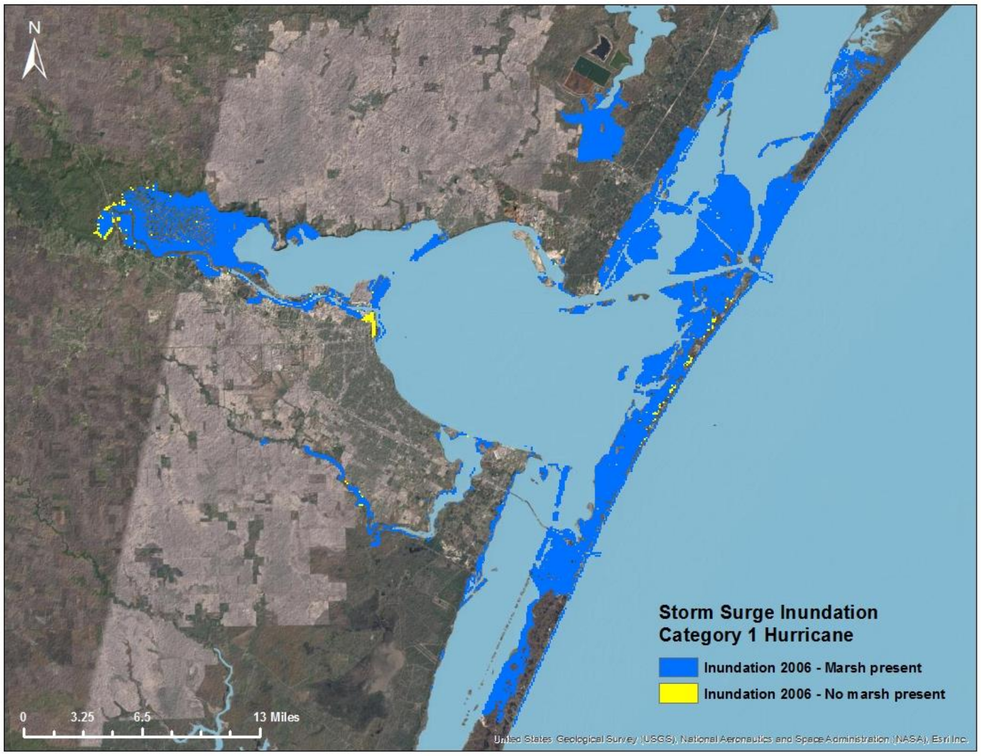

Figure 7: Predicted storm inundation extents without marsh present for Corpus Christi Bay region from 2006 through 2100.

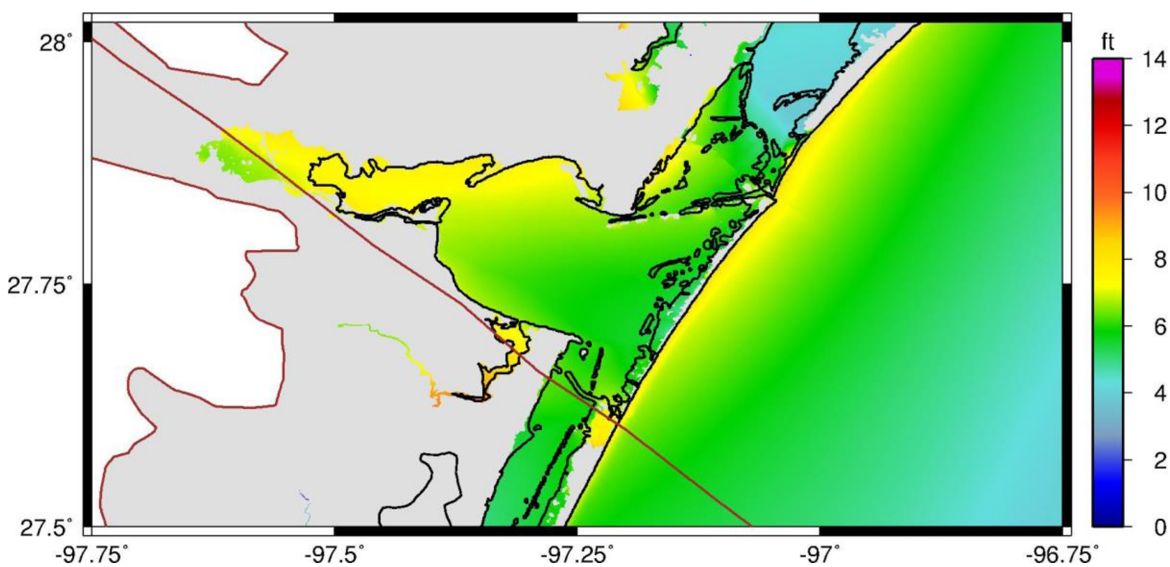

Figure 8: Predicted storm surge elevation (feet) for Corpus Christi Bay region under a category 1 hurricane event (storm track is shown as solid line).

Conservation and Resilience Analyses

Marsh Change and Viability Analysis

Initial salt marsh distribution, which includes both regularly and irregularly flooded marshes, around Corpus Christi Bay in 2006 was calculated to be 10,958 acres while fresh marshes, which include inland and tidal fresh marsh, covered an area of 19,878 acres, primarily in the Nueces river delta region. Over the time period from 2006 through 2100 assuming a 1m SLR rise a large portion of salt marshes within the project site are predicted to disappear with only an estimated 5,066 remaining, a change of over 53% (Figure 9).

Fresh marshes within the region are projected to maintain most of their area through 2100, losing around 12%, or 2,440 acres of their initial cover and are not predicted to gain any area by the SLAMM model throughout the time period (Figure 10).

The total salt marsh advancement zone (the landward path beyond existing marsh through which marshes are predicted to move) under a 1 meter SLR scenario from 2006 to 2100 is projected to total over 6,500 acres (Figure 11). Importantly, the marsh advancement zone does not include existing marsh and is only a calculation of projected marsh advancement beyond the 2006 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 60% of the size of existing marsh distribution throughout the study area.

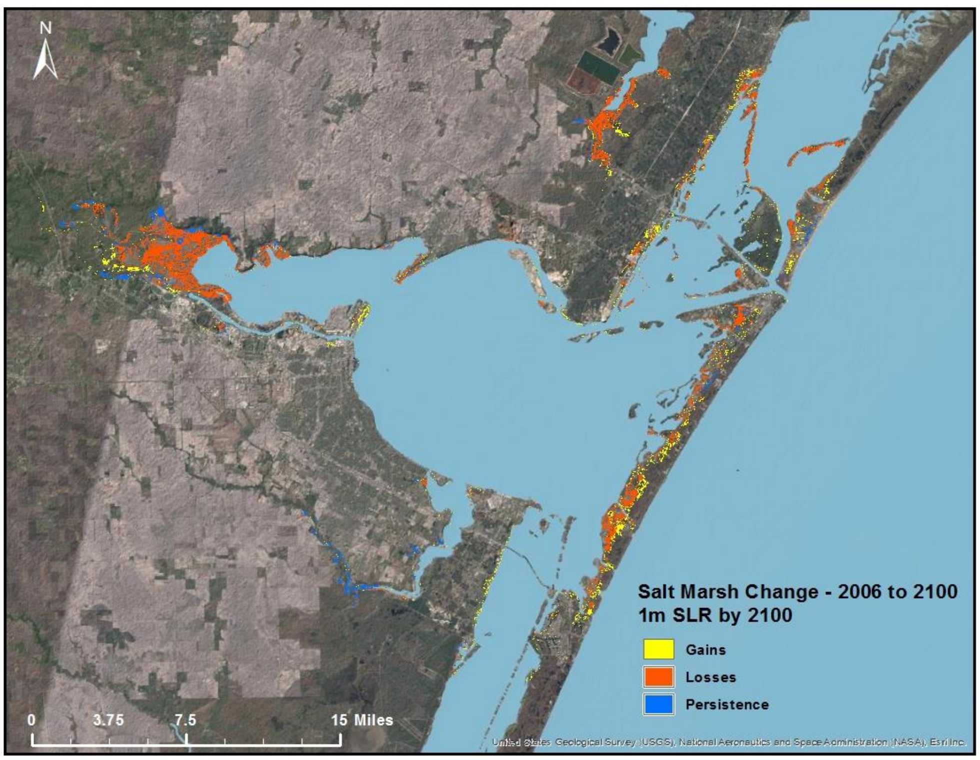

Figure 9: Gains, loses and persistence of salt marsh in Corpus Christi Bay through 2100 with 1m of SLR.

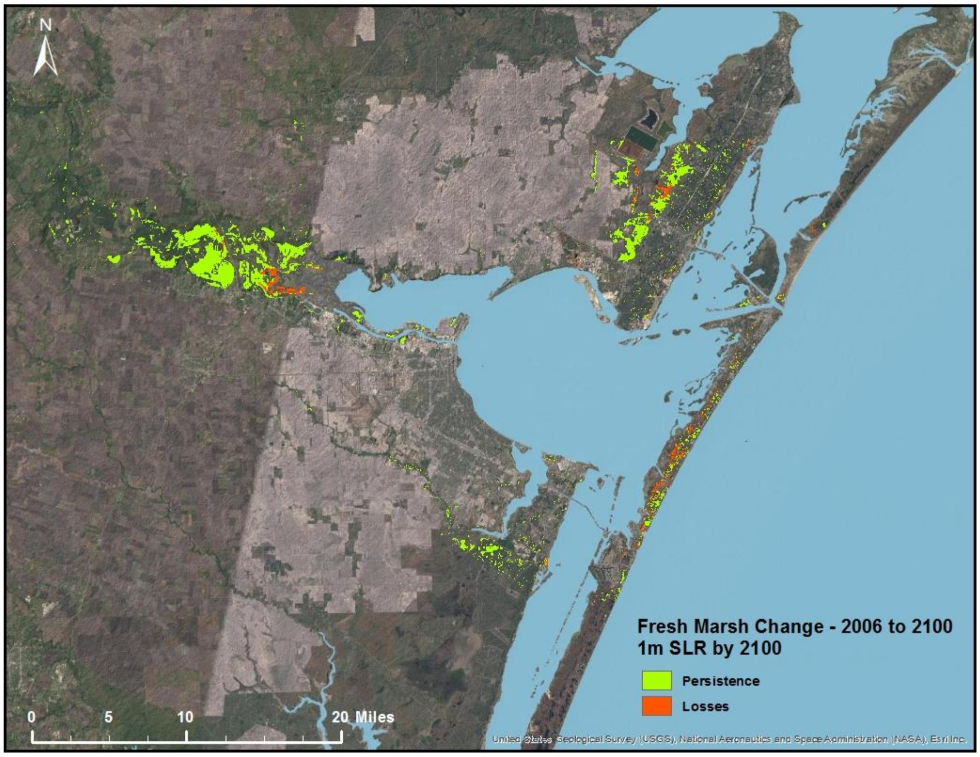

Figure 10: Gains, loses and persistence of fresh marsh in Corpus Christi Bay through 2100 with 1m of SLR.

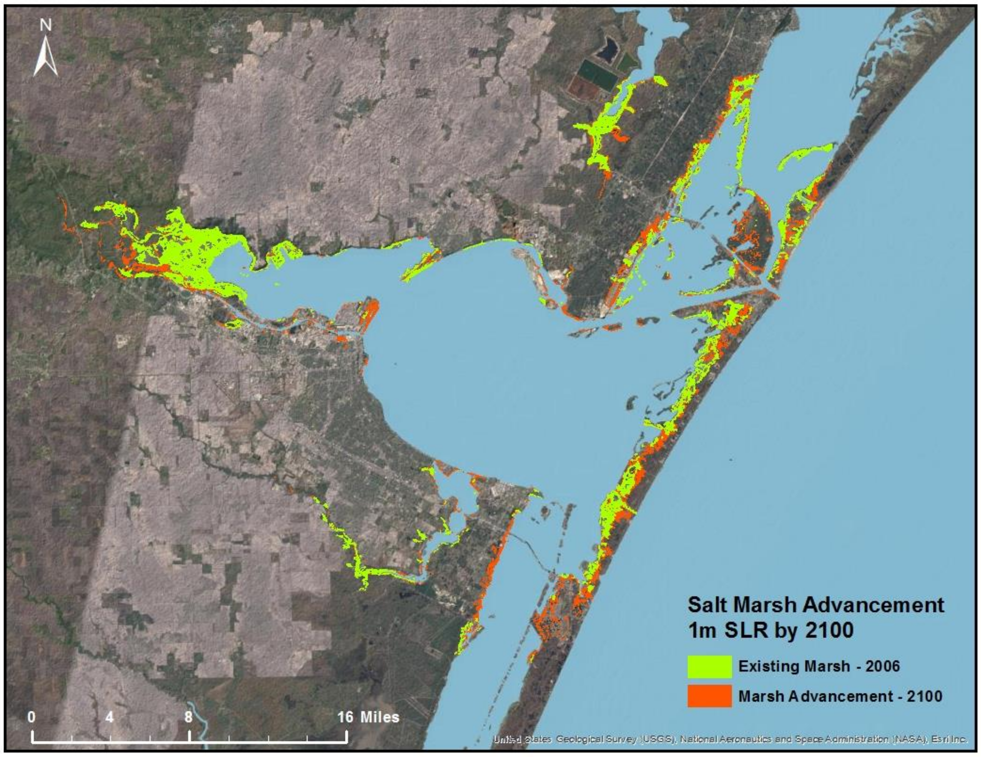

Figure 11: Salt marsh advance zones in Corpus Christi Bay through 2100 with 1m of SLR.

The viability of salt marshes in Corpus Christi Bay in 2100, assuming one meter of SLR, is overall low (Figure 12). Viability for individual marsh complexes was determined by looking at the amount of marsh that remains in the initial marsh footprint through 2100. The most viable marsh systems were largely found on San Jose Island and in the upper reaches of the Nueces River delta and Oso Bay. The vast majority of marshes in the initial SLAMM land cover maps, almost 80%, will not contain any marsh in their original footprints, while the remaining marshes will suffer losses of 56% or more.

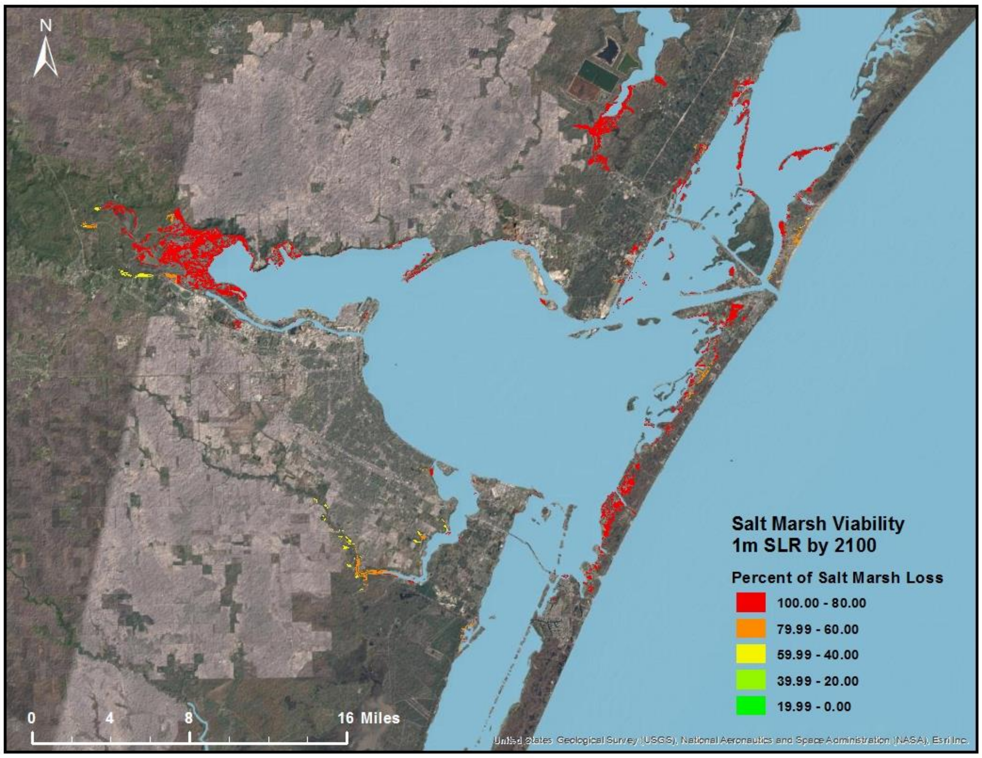

Figure 12: Salt marsh viability of marsh complexes in Corpus Christi Bay through 2100 with 1m of SLR.

At the block group community scale marsh systems on San Jose and St. Joseph Islands, surrounding Ingleside, north of Aransas Pass, and in the Nueces Bay region were least viable. The most viable marshes at the block group scale are found in a small area south of Aransas pass fronting Red Fish Bay, on North Padre island in the Laguna Madre, and at the entrance to Nueces Bay (Figure13). Overall marsh change between 2004 and 2100 results in 5,891 acres of marsh habitat lost due to 1m of SLR, which amounts to a net change of -54%.

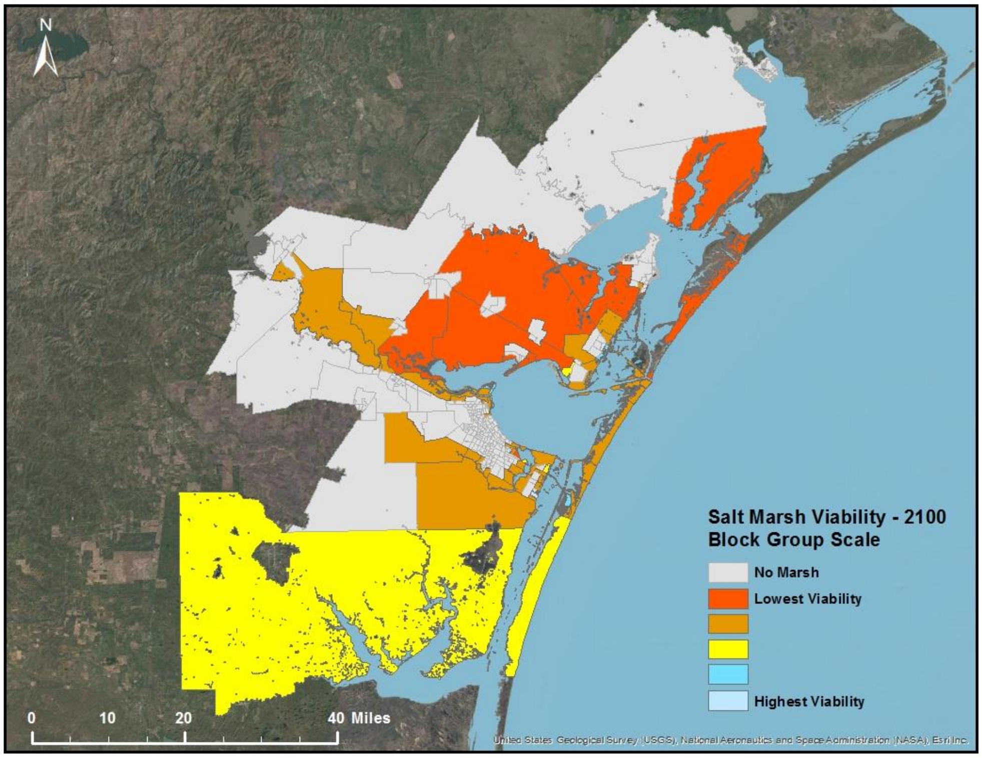

Figure 13: Marsh viability at the census block group scale for Corpus Christi Bay.

In addition to the marsh viability analysis we also conducted an analysis that came out of the Corpus Christi workshop in order to determine where sea grass habitat might migrate into the future given 1 meter of SLR by 2100. The first map (Figure 14) shows where the current distribution of seagrass occurs, based on data from the Ken Dunton lab at the University of Texas (which can be found at http://www.texasseagrass.org/) within the bay and overlayed on the depth range that seagrasses currently occur within the bay. Figure 15 shows the current DEM range of seagrass in warm colors (red/yellow) and the same depth range in 2100 given a one meter sea level rise. As you can see by the images that the amount of suitable habitat, based on the depth ranges at which seagrasses are found currently, shrinks significantly by 2100 indicating that SLR will have a detrimental effect on seagrass abundance in the future.

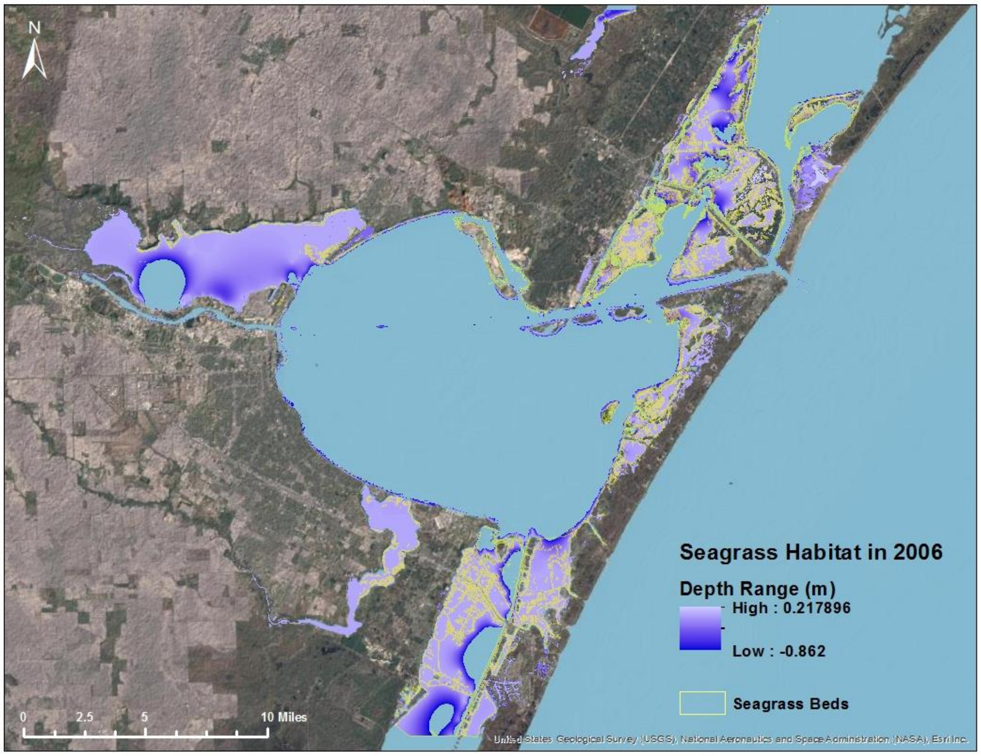

Figure 14: Current seagrass distribution in the Corpus Christi Bay project area and the depth ranges at which they occur.

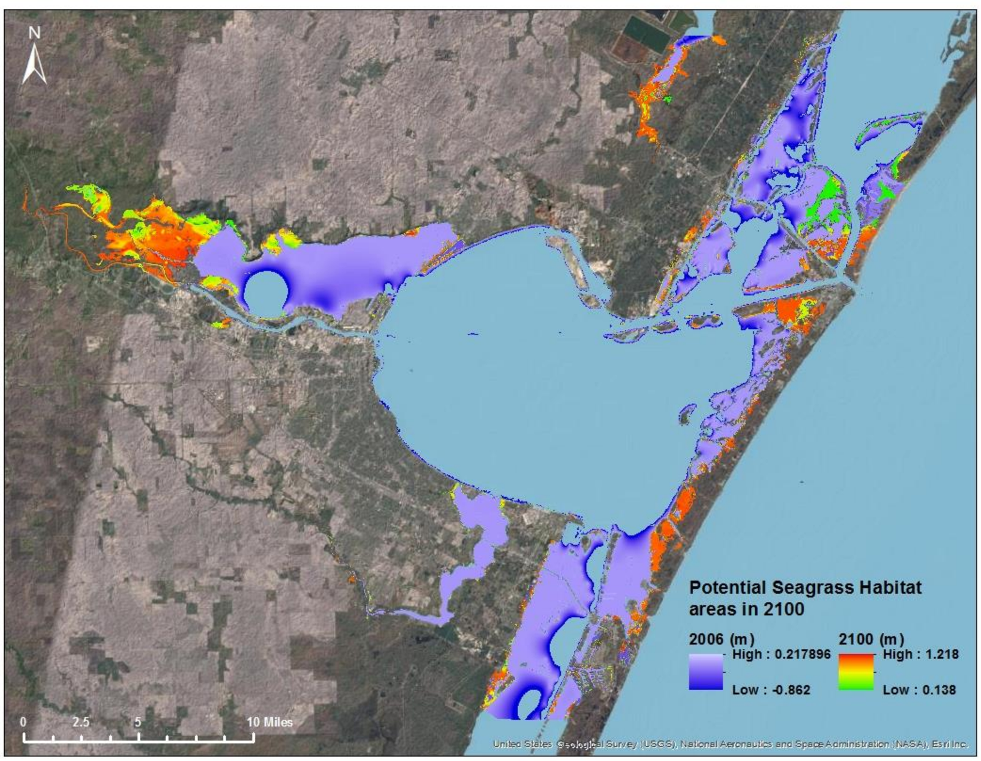

Figure 15: Predicted sea grass suitable habitat areas in 2100 (warm colors) in the Corpus Christi Bay project area and the depth ranges at which they occur mapped against suitable habitat in 2006 (cool colors).

Community Risk Analysis

The Social Vulnerability Index (Figure 16) illustrates that some of the most vulnerable human communities in the Corpus Christi Bay region were found around the Nueces River Delta, in Flour Bluff, within the City of Corpus Christi and in the Rockport-Fulton area. Within the study area, 55 block groups were found to be of high social vulnerability, followed by 191 that were classified as medium vulnerability, and 59 were of low social vulnerability.

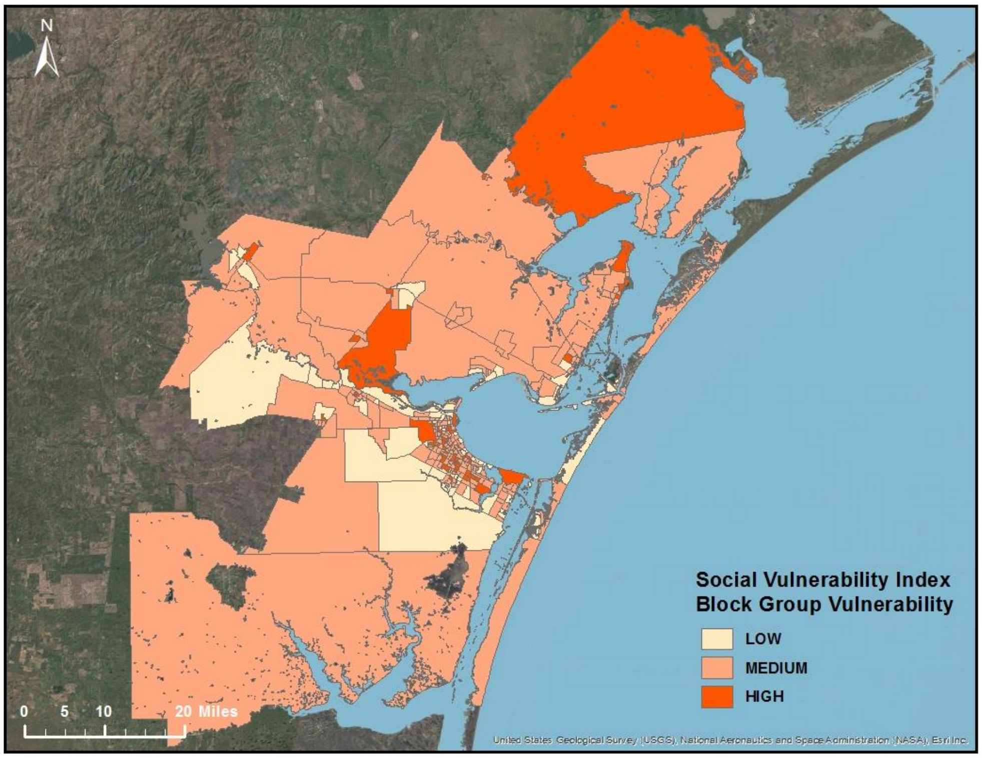

Figure 16: Social vulnerability Index (SoVI) at the census block group scale for Corpus Christi Bay.

The next figures show the percentage of each block group 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 4 blocks experience inundation greater than 25% while 276 block group within the project region are projected to face between 1 to 5 % inundation, with only 1 block group experiencing over 40% inundation by this simulated storm scenario (Figure 17). As seen in Figure 18, 10 block groups are projected to face between 75 and 100% inundation under a Category 1 hurricane surge scenario with 1 meter of SLR, compared with no block groups that face the same risk under the simulated storm alone in 2006, without SLR factored in (Figure 19). Mustang Island, North Padre Island, the Oso Bay region, Ingleside and the Nueces River delta are the most exposed block groups under all three scenarios with 17 block groups experiencing over 50% inundation by 2100 under the SLR plus storm-surge scenario.

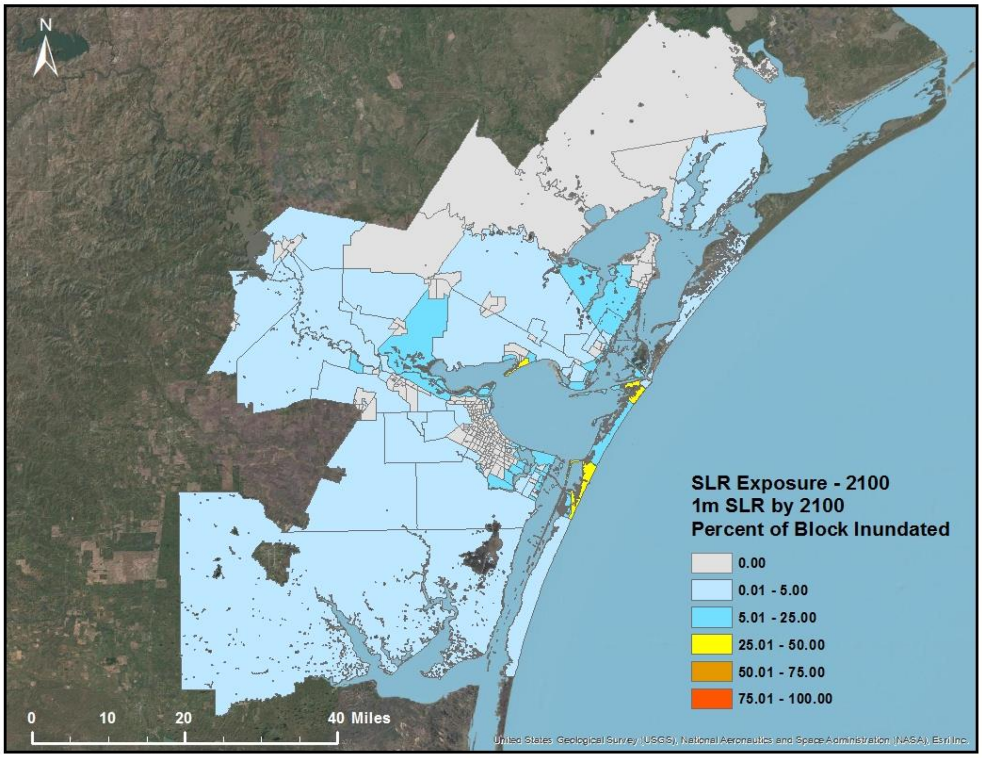

Figure 17: Exposure to inundation (%) to 1 meter of SLR by 2100 for census block groups in the Corpus Christi Bay region.

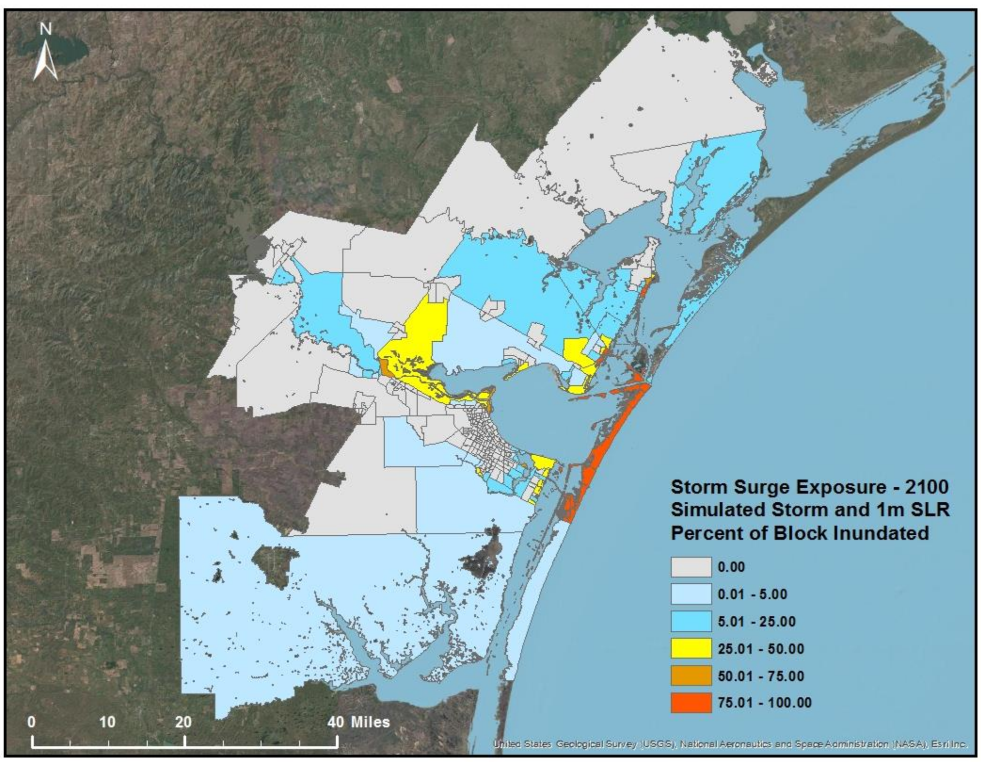

Figure 18: Exposure to storm-surge inundation (%) in 2100 by a Category 1 hurricane with 1 meter of SLR for census block group scale for Corpus Christi Bay.

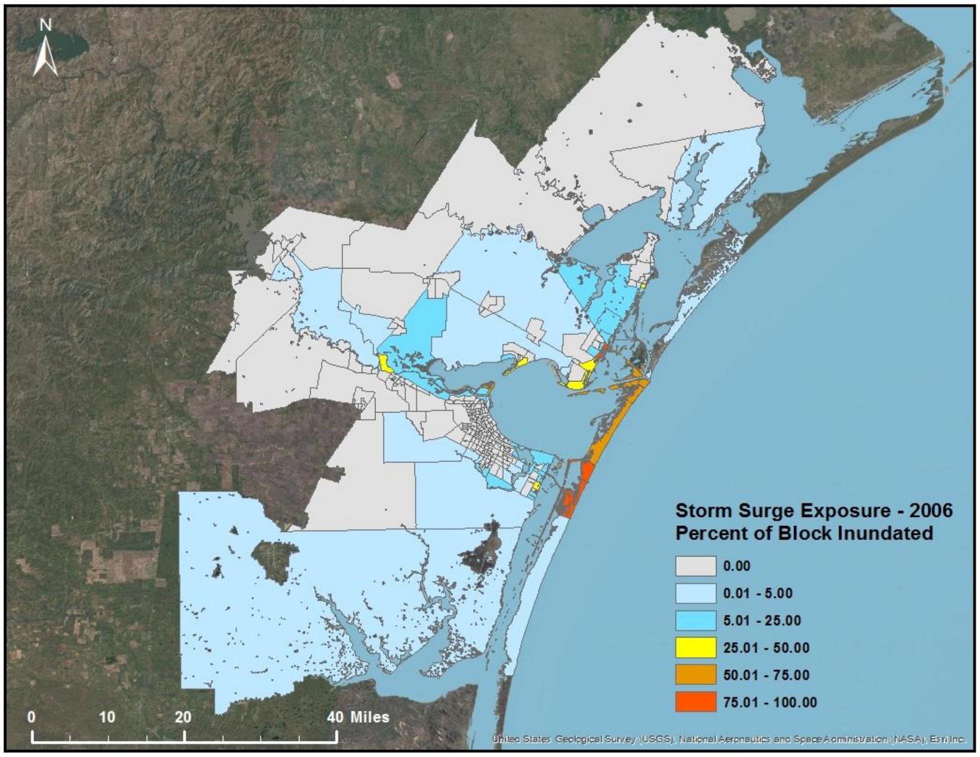

Figure 19: Exposure to storm-surge inundation (%) in 2006 by a Category 1 hurricane for census block group scale for Corpus Christi Bay.

The Community Risk Indexes can be seen in Figures 20, 21, and 22. Some of the most at-risk communities to a 1 meter SLR scenario are found on Mustang and North Padre Island, south of Port Aransas, in Flour Bluff and around the Nueces River delta (Figure 20). Storm surge risk in 2006 under a simulated category 1 storm without SLR (Figure 21) shows that communities like Port Aransas on Mustang and on North Padre Islands are at higher risk as well as communities that are in the Nueces River delta. Figure 22 shows the impact of SLR in increasing storm-surge risk throughout the study area. Notably, several communities in the downtown region of Corpus Christi that are at low risk to a 1 meter 2100 SLR scenario, face the highest risk to storm-surge under both the 2006 and 2100 storm-surge scenarios while those communities at risk in 2006 are at much greater risk in 2100 with SLR factored in.

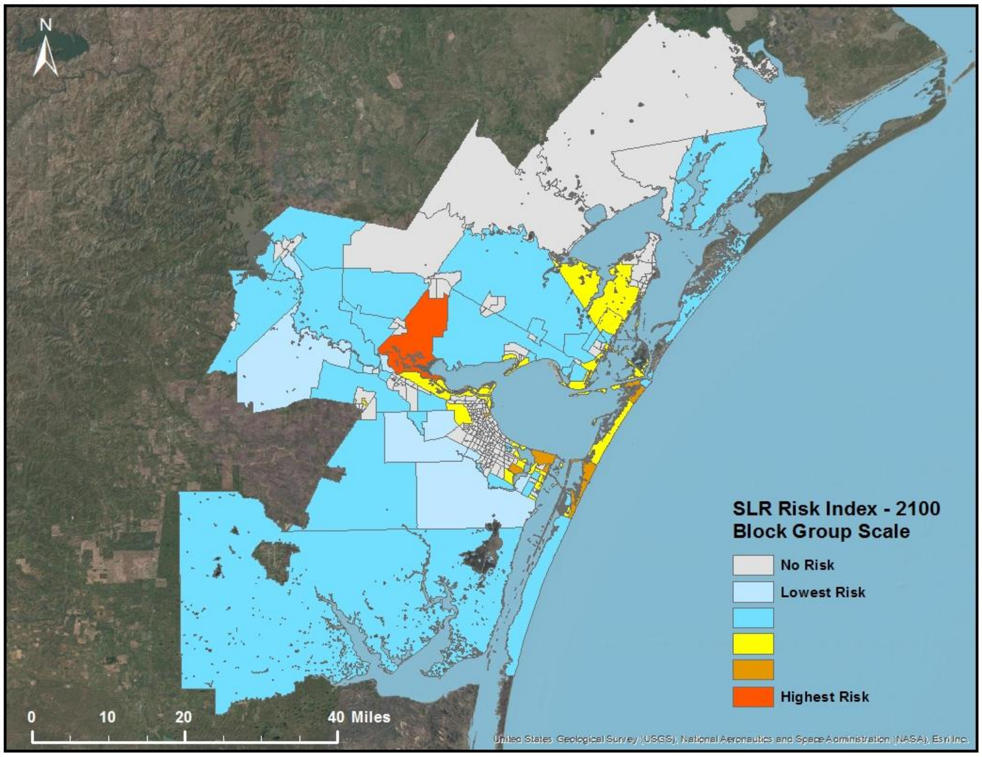

Figure 20: Risk exposure to inundation by 1 meter of SLR by 2100 for census block group scale for Corpus Christi Bay.

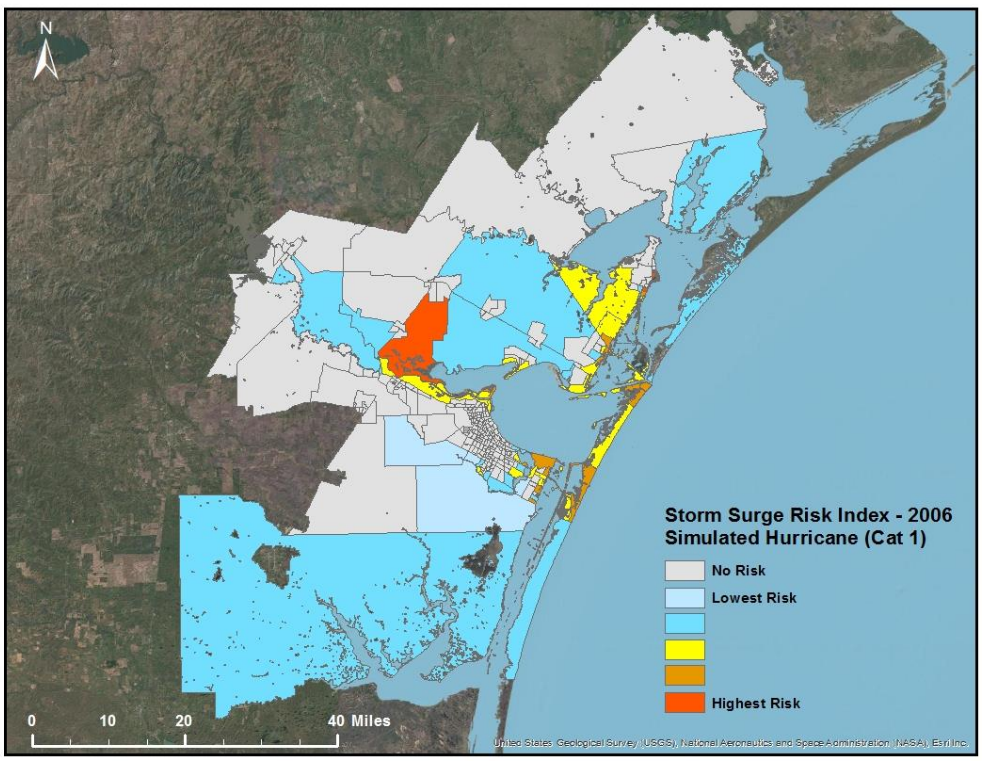

Figure 21: Risk exposure to inundation by a category 1 hurricane event in 2006 for census block group scale for Corpus Christi Bay.

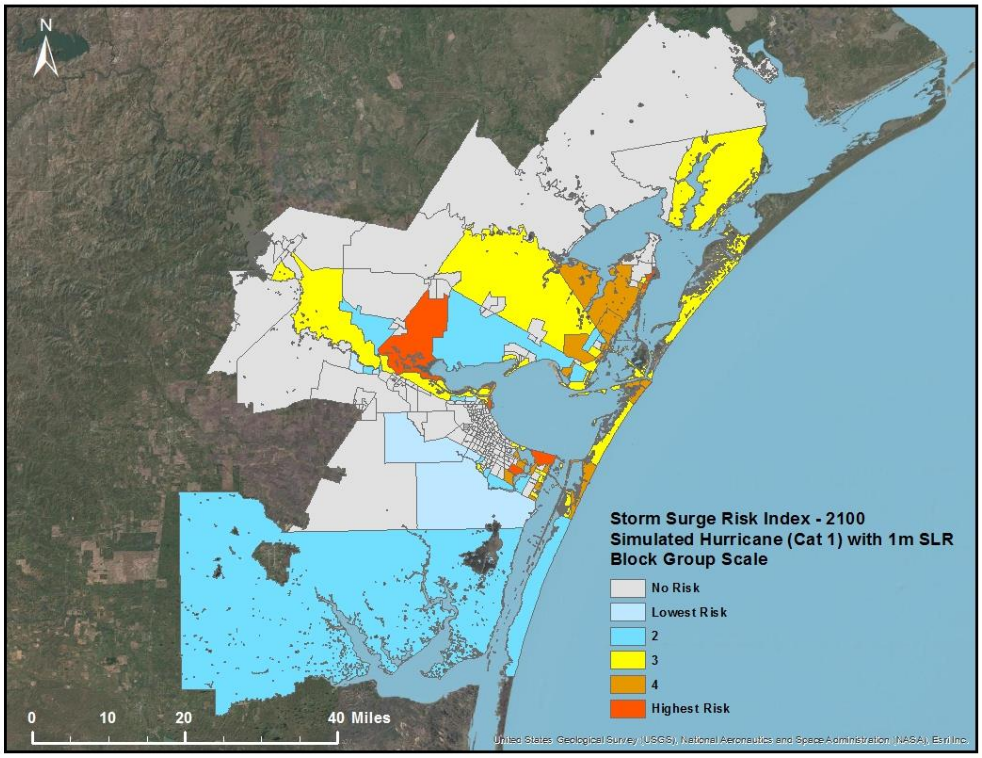

Figure 22: Risk exposure to inundation by a category 1 hurricane event and 1 meter of SLR in 2100 for census block group scale for Corpus Christi Bay.

Community Resilience Analysis

Areas that were projected to experience substantial marsh loss under the 1 meter 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 23). Conversely, those communities that contained more viable marshes, lower social vulnerability and less exposure to storm-surge, were found to be most resilient. Only 56 block groups were considered for this analysis, as the other 249 block groups did not contain marsh distribution in 2006. Of these 56 block groups, 1 was found to be least resilient, while the remaining 55 blocks were ranked between medium and least resilient, with no block groups found to be "resilient" due to the high amount of marsh loses, the extent of storm-surge inundation and moderate to high social vulnerability that are found in this region. Out of these block groups 16 are categorized as "medium" and the remaining 27 are classified as medium-high in resiliency. In particular, the Community Resilience Analysis found that the areas which are on the barrier islands, surrounding Oso bay and on the shores surrounding Nueces Bay are among the least resilient communities in the study area, while some of the more resilient communities are in located on the south side of along Oso creek and on North Padre Island facing the Laguna.

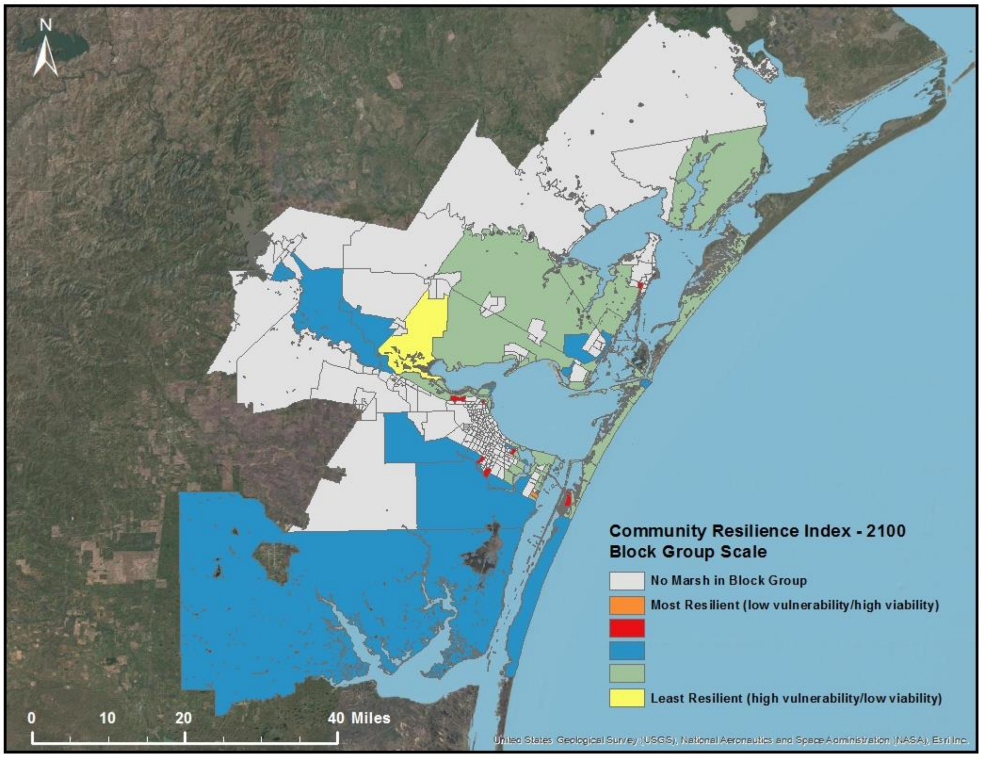

Figure 23: Community resilience index for census block groups under a 1 meter of SLR by 2100 scenario for Corpus Christi Bay region based on storm-surge exposure, marsh viability and social vulnerability.

Marsh Conservation and Management Analysis

Based on the SLAMM model outputs regularly-flooded and irregularly-flooded marsh systems in and around Corpus Christi Bay, under the 1 meter SLR scenario, are showing significant decreases as sea levels rise through 2100. Marsh is migrating and advancing into new areas during this period as seen from the marsh viability analysis; however, losses are greater than gains for both marsh types. Federal, state and TNC management areas within the project site boundaries are shown in Figure 24. The long-term marsh management analysis found that the vast majority of these marsh advancement zones are outside of management areas (Figure 25). Our results predict that approximately 803 acres of existing salt marsh distribution in 2006 were found to be within current management areas while 10,154 acres fell outside of these areas. For fresh marsh, which does not migrate under the SLAMM models, a total of 1,081 acres were inside and 18,795 acres were outside of current management areas (Federal, State and TNC). Under a 1 meter SLR scenario by 2100 only 366 acres of salt marsh will exist within the current management areas while the remaining 4,700 acres of salt marsh will fall outside of their jurisdiction. Fresh marsh also loses area inside management zones with only 776 acres of fresh marsh remaining within side management areas and 16,661 outside.

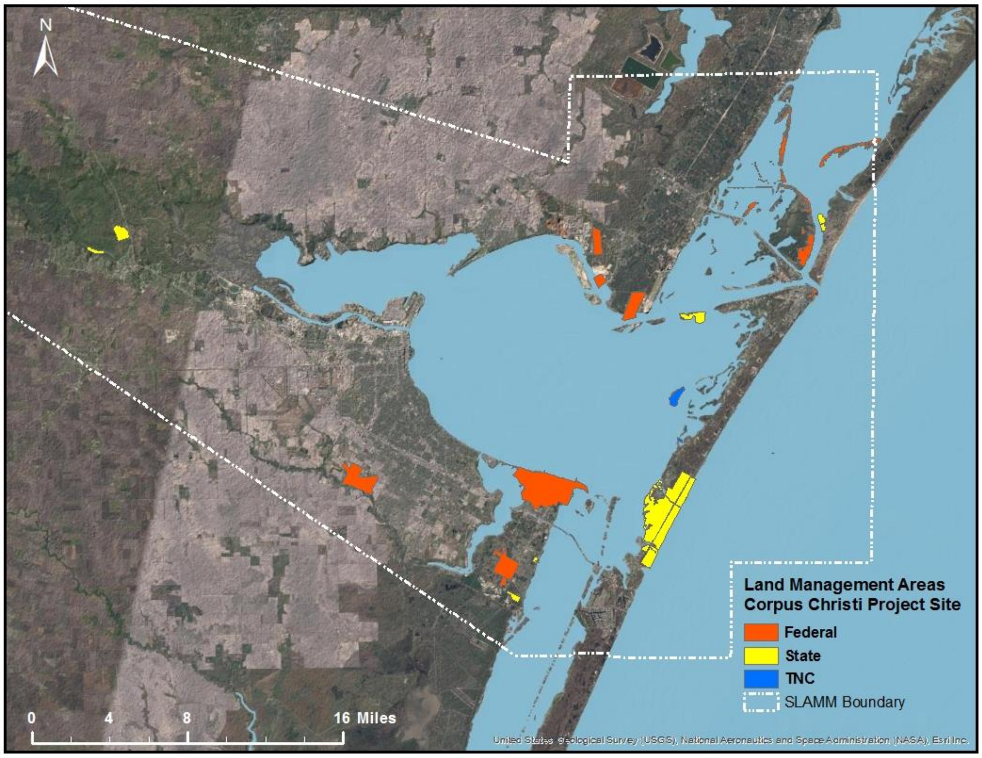

Figure 24: Marsh management areas in the Corpus Christi Bay region in 2013 including all federal, state and TNC lands.

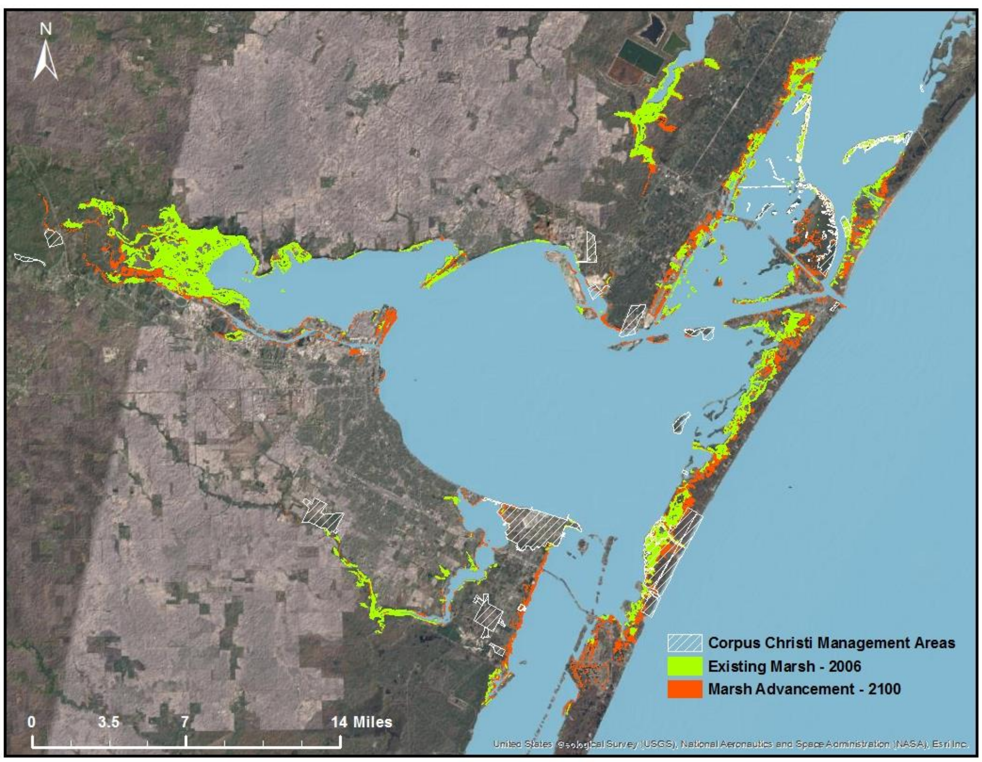

Figure 25: Marsh management areas in the Corpus Christi Bay region with existing and future salt marsh areas.

Importantly, only just over 7% of future marsh advancement zones are within existing management areas, while over 90% of marsh existing in 2100 will remain outside of currently existing management areas. Several key land acquisition or conservation management areas could be expanded to account for future marsh distribution, and these recommended areas are illustrated in Figure 26. Federal management areas that could be expanded include the Mission-Aransas National Estuarine Research Reserve and the areas around the naval air station properties on Flour Bluff, which contain marsh habitat. State management areas that are most critical for expansion include Mustang Island State park, which will have newly developed salt marsh along its borders in the future scenarios. The Nature Conservancy's (and partners) management areas, which include the Cone Nature Preserve, on Mustang Island, and Shamrock Island Preserve, located in Corpus Christi Bay behind Mustang Island, are not projected to have new marsh created in their vicinities.

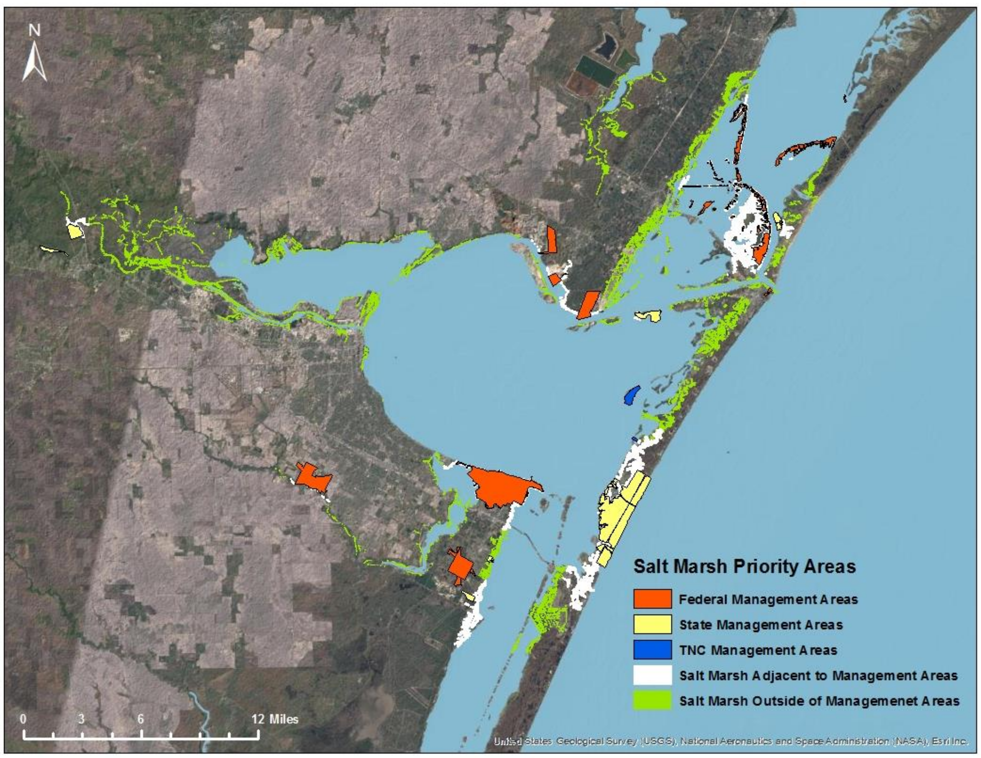

Figure 26: Future marsh management priority areas – areas adjacent to existing federal, state and TNC management areas.

In our final images you can see where salt and fresh marsh predicted to occur in 2100 in relation to the developed land around Corpus Christi Bay (Figure 27) and where developed land is less than 100 meters away from regularly and irregularly-flooded marshland, obstructing further marsh migration in that area (Figure 28). As you can see in the image marsh migration, for both fresh and salt marsh, are impeded by development in many areas around the bay including to the south of the Nueces River delta and in the Aransas Pass area. Development located on North Padre Island and around the town of Port Aransas will also impede the migration of marsh as sea levels rise in the future.

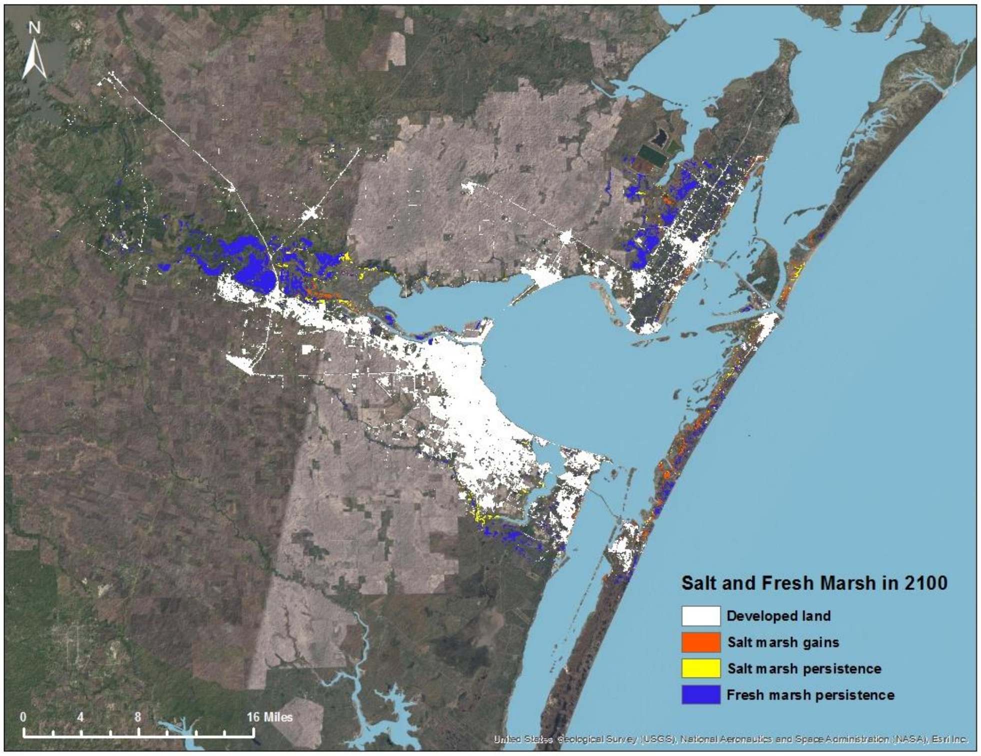

Figure 27: Future salt and fresh marsh habitat in 2100 shown in relation to currently developed land around Corpus Christi Bay.

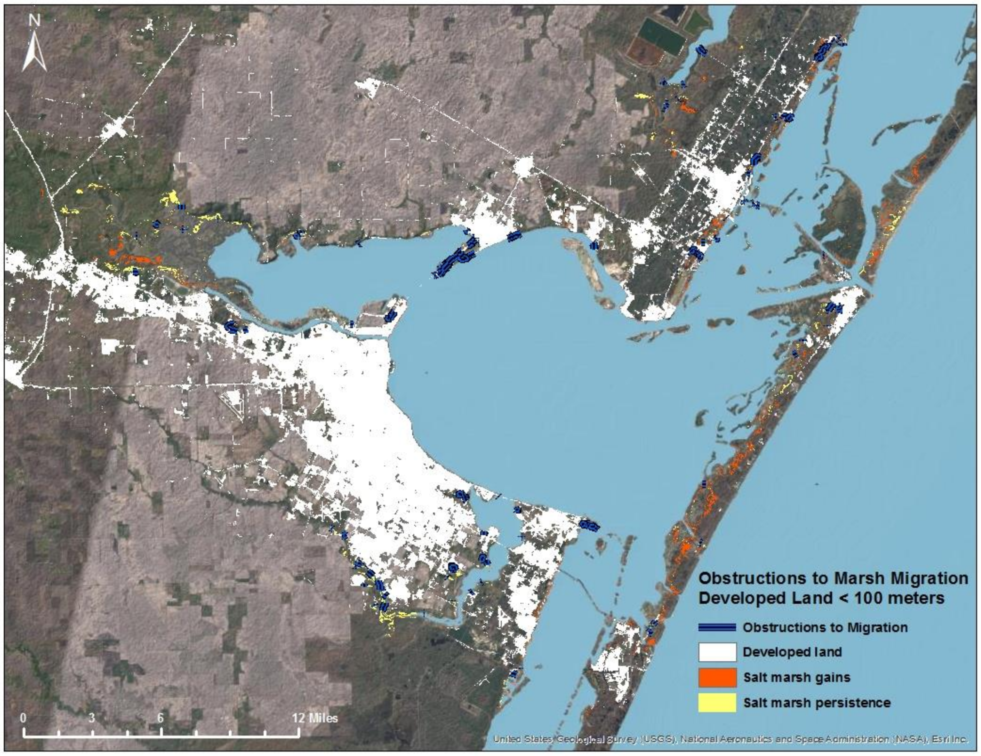

Figure 28: Barriers to marsh migration are identified where developed land encroaches closer than 100 meters to marshland in 2006 - shown in relation to future salt marsh habitat in 2100 around Corpus Christi Bay.

SEA LEVEL RISE DATA PLATFORM

The purpose of the data platform for the Sea-Level Rise Assessment and Conservation Data Platform of the Gulf of Mexico Project is to store and deliver to users all data related to the project 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. The data platform consists of a spatial database, a user interface, online tools, and offline components for viewing the data within ESRI ArcGIS software and GeoPDF documents. The online user interface consists of HTML documents, which are essentially webpages that introduces the user to the coastal hazards, models used, project sites, provide descriptions of the models, project sites and samples of results. The online tools for the data platform consists of the SLAMM View and the Gulf of Mexico Restoration and Resilience Decision Support Tool websites that allows the general public to visualize a sampling of the products created by the project. The Gulf of Mexico Restoration and Resilience Decision Support Tool is integrated into the data platform web pages.

The outputs of the conservation and resiliency analysis which include GIS data, maps and reports will be hosted and available for download on Sea Level Rise Research and Scenarios for a Changing Coast - a newly developed web interface focusing on SLR at located at http://slrportal.org. In addition, the results will be made available through the Nature Conservancy's Gulf of Mexico Decision Support Tool (http://maps.coastalresilience.org/network/).

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 Corpus Christi Bay. It addressed the SLR issues of by developing the technical assessments using the best available models and data, creating a spatial data platform to organize all the knowledge, and used the scenarios to address management and conservation issues that would promote socio-ecological resilience in the study areas. Furthermore, the project accomplished developing online tools to make most of the key results available through a group of tools, such as geo-viewers and web pages that will help users to access, visualize and communicate the findings.

The development of the project followed a multidisciplinary approach by integrating some of the results from the SLAMM-based sea level rise modeling component of The Nature Conservancy in Florida into the process of informing management needs/questions for the coastal socio-ecological systems – i.e. natural habitats and coastal communities. To implement this approach the concept of coastal resilience was applied to identify the future viability of marshes to move as SLR progresses as well as the capacity of these marshes to help coastal communities to adapt. The multidisciplinary philosophy was also embedded in the team that was composed by managers, analysts, planners, and web developers. Additionally an engineering consulting firm supported the development by bringing specific relevant expertise to address some of the key aspects of this project.

The technical developments were approached by identifying, developing and implementing the best available data, models, analysis frameworks and tools needed to enhance the understanding of the potential impacts of SLR in the Gulf region. Different data models and data management tools were used in the implementation of the data platform but the common denominator was the spatial data layers needed to create a series of geographic products that will serve different users to integrate the SLR, storm-surge and conservation outputs into their own plans and assessments. The spatial geodatabase was created and implemented in ESRI's ArcGIS desktop software. ArcGIS is not only the GIS standard for most robust geographic systems applications, but the most common spatial tool among the GIS users in the northern Gulf (several personal communications with stakeholders between 2011 and 2013).

Data was gathered or created to build the base line information needed to integrate the conservation and resilience analyses in this project, as well as a large variety of potential applications that the different audiences could develop using the data platform at www.SLRPortal.org. This online data platform constitutes the first comprehensive SLR spatial data platform in the Gulf of Mexico region. Although several other from Federal to local initiatives have been successful in providing key pieces of information that have substantially contributed to our current understanding of the potential impacts of SLR and other climate-related coastal hazards, the SLR data platform serves not only as a data repository but also as a framework for spatial-based analysis, and a tool to use the existing communication materials or develop ad hoc products at the case by case basis. The database includes from SLAMM-based SLR and ADCIRC-based storm-surge scenarios, to marsh conservation spatial indicators and other environmental data.

The user interface of the SLR data platform provides the capacity to discover, access, visualize and communicate most of the products developed by this project. These include data, snapshots of results, reports and links to other sources of information organized by project site, and model and analysis type. This online interface was designed to provide practical access to these products and support the communication and outreach of the goals pursued in this project. The user interface will help all levels of users understand the scope of the project and the data platform, as well as provide dynamic access to key elements relevant in communicating the potential impacts of SLR in the sites and region. A new web site, based on our prior efforts, has recently been developed and tested which improves the user interface and data accessibility and can be found at http://slrportal.org. It officially came online in March 2013 and is hosted through the StormSmart.org web portal (http://stormsmart.org).

Products of this project were designed to serve a variety of users and needs to understand and communicate the potential impacts of SLR. It was clear since the initial design of the SLR data platform that not all needs and users will require the same complexity and capacity provided by the most robust data management tools used as part of this project. Therefore, this project made also available a series of concrete and straight forward materials for the practical communication of the key messages of this project. Examples of these are the 1-pager documents (flyers) that explain what we know now about the potential impacts of SLR in each project site, the PDF maps that constitute a state-of-the-art interactive no-GIS alternative to show specific details of the potential impacts in a digital map, and the capacity of anybody with a smartphone or Tablet to look at the greatest details in each of the scenarios, even side-by-side, in the field while standing in a part of the coast that could probably be inundated in the future. In the same lines, this project provides in several cases multiples online access points to data, reports and visualizations to provide a safe redundant access to these results at the same time that increases the exposure of these materials.

Challenges

There were several challenges in successfully completing this project, which contributed to the lessons learned by the entire team in developing a data-intensive initiative, such as the SLR data platform. From the project management perspective these challenges followed under different aspects, including gathering and standardizing data and models and the conceptualization of the data platform. Granting and grant project management institutions were always supportive and facilitated the transition through these steps. A successful project, results and data platform was the result of a solid effort made in the development of this project.

Models represent usually streamline analysis frameworks whose relevance and applicability depend highly on the data feeding the process. SLR models used in this project implemented the modeling framework and criteria developed by the Habitat and Conservation and Restoration Team of GOMA for the implementation of SLAMM. The enhanced SLAMM-based framework used in this project included several additional steps and components to the classical implementation of a sea level rise project elsewhere – e.g. storm-surge scenarios assimilate SLAMM outputs as new lad cover layers. Although models in this project used best available databases available, there were multiple cases in which the specific data pieces were not accessible and compromises were made. However, none of these had relevant implications in the quality and availability of results, but constitute mere re-configurations of the workflow. Some of the specific challenges were mostly to make strong positions at times needed to include visions and elements in the process of understanding the SLR process and analyzing the issue with the tools of this project. At several occasions we had to make reference to the fact that SLR is not a concept that may impact people's lives at some point, but a gradual process that has been quantified with precise sensors for at least the past two decades in the Gulf.

Recommendations for Future Research

We divided the recommendations for future research in each of the four main assessments conducted.

SLAMM-base sea level rise

- Since SLAMM assumes management and infrastructure remains in the same location and amount/size thought out the entire modeling horizon (e.g. by 2100), we suggest that future studies should integrate scenarios of development into SLAMM runs. This can be achieved by researching future scenarios of urban expansion and other infrastructure types in existing local and regional development plans and incorporating the planned infrastructure and urban areas into future scenario development and subsequent model runs.
- We recommend that SLAMM implementations along the Texas coast integrate into the model separate estimates for SLR and local subsidence annual rates. Although SLR rates have been relatively constant as shown by the local time series, subsidence constitutes a

much variable process that depend on local geology and resource use (mostly water and hydrocarbons) which can vary largely over small to medium time scales. Therefore influencing the model of fixed subsidence rates that have been computed over short periods of time are used.

- Finally we suggest that future SLAMM implementations use the new SLAMM 6.2 version that integrates variables of mangrove vegetation erosion and accretion in their simulations. These improvements in the model support the development of more realistic scenarios in areas where mangroves are becoming more abundant and contributing to the community marsh-mangrove community shifts but also shoreline stabilization.

CONCLUSIONS

Viable and healthy salt marshes, which are allowed to migrate naturally with rising sea levels, provide non-structure flood control for coastal and human protection, reduce coastal erosion and provide the ecological structure needed to maintain additional coastal habitats, including seagrass beds, fresh water marshlands and even coastal prairie grasslands. All of which are important factors that influence coastal resiliency. 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), which examined the impacts of SLR on socially vulnerable populations, supported our decisions by concluding that spatially mapping SLR risks can potentially be used for a variety of applications at national, regional and local levels and that storm-surge events and coastal habitat modeling should be incorporated into future scenario development.

Our study suggests that SLR impacts should be incorporated into ongoing conservation planning and management activities within the Corpus Christi Bay region. Specifically, key parcels of land adjacent to existing management areas could be acquired and/or sustainably managed to allow for the landward migration of vulnerable marsh habitats. Between 2004 and 2100, over 17,000 acres of land are predicted to contain critical salt and fresh marsh refuge. These areas should be prioritized for conservation and/or acquisition and we highlight priority areas that are adjacent to existing federal and state management areas.

This analysis also shows that human communities throughout the Corpus Christi Bay region face risks to SLR and storm surge, and that storm surge impacts from “today’s” hurricane will be substantially amplified by climate-enhanced SLR and storm surge in the future. It also indicates the marsh provide a valuable ecosystem service by protecting the coast against storm damages by attenuating storm surge and waves and that the absence of salt marshes can amplify the impacts of storm surge and increase the damages potentially suffered in future storm events. Our study also suggests that infrastructure and land use development planning should factor in the impacts of SLR and storm surge as many developable lands, based on SLR and storm surge projections, and building regulations are predicted to be at risk of permanent inundation due to SLR. Furthermore, this study suggests that all land use planning decisions should not only factor in future inundation zones, but also critical marsh advancement zones and their relation to socially vulnerable communities, for which these ecosystems provide a myriad of services ranging from shoreline protection to fish nurseries for nearby human communities.

The analyses and results presented here are intended to inform decision makers within the Corpus Christi Bay region of the potential impacts of SLR and storm surge and to support current and future conservation planning and management decisions within the region. Through a participatory stakeholder process, the project team and stakeholders identified key management questions and employed spatial analyses to illustrate how future changes can be factored into near-term and ongoing planning activities to allow them to better account for future changes. Our study identifies vulnerable coastal ecosystems and human communities and the potential impacts of SLR and storm surge in the Corpus Christi region to allow decision makers to more easily develop adaptation strategies that foster coastal resilience in the face of a changing climate.

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