Quantification of Hurricane Surge Damage in Coastal Bays as a function of Dune and Wetland Characteristics with Application to Restoration and Climate Change

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Final Report

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Introduction to Report

Hurricanes pose one of the largest natural threats to communities along the Texas coast, as was demonstrated when Hurricane Ike made landfall in Galveston in September 2008. While it is widely acknowledged that coastal natural resource areas (CNRAs), such as beach and barrier island dunes and coastal wetlands, provide some level of protection against hurricane damage, the exact role that wetland and dune restoration and degradation play in changing inundation and property damage is not fully understood.

We investigated the impact of two CNRAs, coastal dunes and wetlands, on mitigating hurricane impacts. We used calibrated physics-based numerical models (hydrodynamics [ADCIRC1] and barrier island morphodynamics [XBeach2]) and a geographic information system (GIS) framework for the City of Corpus Christi, as characteristic of many coastal communities on the Texas coast, to achieve the following objectives:

1. Quantify the effect of spatial dune parameters (e.g., dune height, width, alongshore extent) on surge inundation and property damage by hurricanes.
2. Quantify the effect of the presence of wetlands and their spatial parameters (e.g., elevation [low, high marsh, etc.], aerial extent, frictional resistance) on surge inundation and property damage by hurricanes.
3. Quantify the relative effect of dune and wetland degradation on hurricane inundation and damage by, for example, climate change (e.g., sea level rise) and, conversely, the effect of dune and wetland restoration by manmade efforts. Parametric models will be developed using the outcomes of objectives 1 and 2.

This project supported one Ph.D. student and PI time to supervise additional students contributing to its outcomes. The format of this report is in the form of final progress report, published journal papers and a draft of a paper to be submitted. Specifically, the following items make up this report:

- **Part 1:** Final Progress Report
- **Part 2:** Irish, J.L., A.E. Frey, J.D. Rosati, F. Olivera, L.M. Dunkin, J.M. Kaihatu, C.M. Ferreira and B.L., Edge,. *Potential Implications of global warming and barrier island degradation on future hurricane inundation*, **Ocean and Coastal Management**, Vol. 53, 645-657, 2010.
- **Part 3:** Ferreira, C; Irish, J. Olivera, F *"The influence of coastal wetlands on hurricane surge in Corpus Christi, TX."* (in preparation)

- **Part 4:** Ferreira, C. M., Irish, J.L., Olivera, F. 2011. “Hurricane storm surge online viewer.” Available at: http://people.tamu.edu/~celsomoller/gis/flexviewer/index.html

PROGRESS REPORT

(Project Name) Quantification of Hurricane Surge Damage in Coastal Bays as a function of Dune and Wetland Characteristics with Application to Restoration and Climate Change

(GLO Contract No.) 10-051-000-3747

(Reporting Period) Final Report, July 2011

Task 1: (Quantify Existing Dune and Wetland Parameters in Corpus Christi, TX)

- In this task, existing topography, aerial imagery, CNRA maps, water level data, information available in the literature, and elevation and horizontal position data and photographs gathered during two site visits to Corpus Christi will be reviewed to identify existing dune and wetland characteristics along the barrier islands fronting and within Corpus Christi Bay, respectively. Spatial information will be imported and analyzed within an existing Geographic Information System (GIS) framework developed by the PIs to quantify and determine the alongshore variability in the following dune parameters: dune height, dune width, barrier island height, beach width, and beach berm height. Similarly, the following wetland parameters will be determined by GIS analysis: spatial extent and location of existing wetland regions, characterization of wetland type (e.g., high or low marsh), and wetland condition (degree of degradation). To complete this task, a survey total station has been purchased.

  The project contract did not commence until November 30, 2009. Due to this contracting delay, we anticipate a two-month slip in completion of all tasks and deliverables. Other than the abovementioned contracting delay, there was only one delay for this task: the site visit was delayed. The site visit has been conducted on September 20th to 22nd with the aim of verifying the parameterization of the hydrodynamic model regarding wetland characteristics based on the sensitivity analyses already concluded (enhance our capacity to represent hydrodynamic bottom friction according to wetland type). A second site visit was not needed because much of the required coastal data were obtained based on geospatial data.

  Our revised deliverables timeline for this task is:

1. Purchase of survey total station	Feb 2009
2. Site visits conducted	Feb 2011
3. Topography, imagery, and other data collected and analyzed	Jun 2010

  Light Detection And Ranging (LiDAR) data for city locations outside of the barrier islands, collected by the City of Corpus Christi were requested. However, the Texas Engineering Experiment Station and the City of Corpus Christi could not come to an agreement on the liability statement for data usage. Thus, these data was not available for our study.

  The other GIS data are already collected and included in a project geodatabase, including high resolution topography data (LiDAR) for the barrier island (agreement with Dr. Jim Gibeaut at Texas A&M Corpus Christi), the wetland national dataset and imagery for the study area.

  The dune parameters to quantify alongshore variability (dune height, dune width, barrier island height, beach width and beach berm high) were determined from the 10-meter DEM developed by the USGS.

The wetland parameters (spatial extent, location, type and condition) were determined using the National Wetlands Inventory (wetland areas mapped by the U.S. Fish and Wildlife Service's National Wetlands Inventory based on 1992-93 photography). These parameters were validated in the summer 2010 site visit.

All GIS data collected are organized in a geodatabase including metadata for the validation datasets, which is the geospatial framework to support tasks 2 and 3.

The proposed deliverables for this task are concluded.

Task 2: (Identify Restored and Degraded Dune and Wetland Conditions)

- In this task, hypothetical restored and degraded dune and wetland configurations were developed based on review of previous hurricane surge and storm morphodynamic simulations with ADCIRC1 and XBeach2 by the PIs, and of the outcomes of Task 1. Emphasis in developing these restored and degraded conditions will be based on how best to quantify the surge response as a function of dune and wetland parameters (elevation, spatial extent, frictional resistance, etc.). As such, the identified alternate dune and wetland systems (scenario for entire Corpus Christi area) will span a range from highly degraded to optimally restored. A minimum of three hypothetical dune systems and three hypothetical wetland systems were developed.

The project contract did not commence until November 30, 2009. Due to this contracting delay, we anticipate a two-month slip in completion of all tasks and deliverables. Our revised deliverables timeline for this task is:

1. Existing hurricane simulations reviewed to identify relevant dynamics	Apr 2010
2. Hypothetical dune systems for Corpus Christi area identified	Jul 2010
3. Hypothetical wetland systems for Corpus Christi area identified	Nov 2010

Review of existing hurricane simulations was completed and information from task 1 (dune and wetland parameters) was used to cross-check the ADCIRC grid information regarding topography and roughness coefficients. This information was used to generate the hypothetical dune and wetland systems.

The scenario considering a lower elevation dune at the island has already been simulated. A research paper presenting these results has been published in *Ocean and Coastal Management*.

We also conducted sensitivity analyses regarding hydrodynamic parameterization of wetland characteristics (Manning’s N, surface canopy and surface roughness) including information from: 1) National Land Cover Dataset (NLCD) 2001 and 1992; 2) National Wetlands Inventory (NWI) 2001; and 3) a hypothetical scenario with a very high and a very low Manning’s N. The calibrated hydrodynamic model was used to simulate Hurricane Bret (1999) to calculate storm surge for each scenario. Comparison of storm surge extent and magnitude under the different conditions will be submitted for publication in a research paper under development that will show the importance of correctly determining friction factors related to coastal wetlands for hurricane surge estimation in Corpus Christi.

We developed hypothetical scenarios that represent wetland modifications for the study area including the following: 1) Updated land use map from the City of Corpus Christi; 2) Wetland composition and Manning's N friction factor representing the comprehensive development master plan proposed by the city for 2050. We also identified the following additional scenarios: 1) Future wetland sensitivity resulting from sea level rise; 2) Hypothetical restoration projects; 3) Hypothetical degradation areas. The updated land use map and the comprehensive development plan for the city of Corpus Christi were digitized and integrated into our GIS geodatabase. The products of this task were included in the current hydrodynamic simulations and the additional scenarios were the last simulations to be completed.

The proposed deliverables for this task are concluded.

Task 3: (Simulate Hurricane Hydrodynamics and Morphodynamics)

- In this task, the existing physics-based hydrodynamic and morphological modeling framework (ADCIRC and XBeach) for the Corpus Christi area, developed by the PIs, was used to simulate the surge response from one historical hurricane (Bret). This existing modeling framework included baseline grid topography, bottom friction, and numerical calibration. ADCIRC is a finite-element hydrodynamic model which solves the shallow-water equations to predict water levels and currents. Here, we applied the two-dimensional depth-integrated version of this model. ADCIRC model input includes wind and barometric pressure fields generated with a Planetary Boundary Layer (PBL) model and wave radiation stress forcing generated with the spectral wave model SWAN (SWAN results from prior work were used in this study). The XBeach model is a physics-based, three-dimensional finite difference morphological model which simultaneously solves nearshore wave and surge propagation, sediment transport, and the resulting morphological change. XBeach model input will include hurricane water level and wave condition time histories generated with ADCIRC and SWAN, respectively. A second ADCIRC simulation was performed where the ADCIRC barrier island topography is pre-conditioned using the storm-induced morphological changes predicted with the XBeach model. Hurricane morphodynamics and surge were simulated for 21 scenarios: three hurricanes using the existing dune and wetland layouts as identified in Task 1 plus three hurricanes on the six dune and wetland layouts identified in Task 2. Wetlands will be represented by areas of increased bottom friction with appropriate topographic elevation change (e.g., high or low marsh) while dunes will be represented by topographic elevation change.

The project contract did not commence until November 30, 2009. Due to this contracting delay, we anticipated a two-month slip in completion of all tasks and deliverables. Our revised deliverables timeline for this task is:

1. Initial ADCIRC simulations completed	Jul 2010
2. XBeach simulations completed	Mar 2011
3. Final ADCIRC simulations completed	Apr 2011

Simulations of barrier island wetland scenarios have been completed.

To accomplish the study objectives it was deemed more appropriate to consider Hurricane Bret instead of three historical hurricanes as initially proposed, and hypothetical hurricanes scenarios to cover a broader range of storm surges.

Initial wetland sensitivity analyses, for Hurricane Bret, which compare wetland parameters developed from NLCD and NWI datasets with four hypothetical wetland scenarios considering very high and low Manning's n and wind stress (surface canopy) values suggest that: (1) for areas inside Nueces Bay, the maximum storm surge could vary up to four times depending on the parameter selection, (2) for areas inside Corpus Christi Bay, the maximum storm surge varied around three times, and (3) behind the barrier island the maximum storm surge variation was less than three times.

We have successfully implemented the coupled version of the hydrodynamic model (ADCIRC) and the wave model (SWAN) to run on the Texas A&M supercomputers (EOS and HYDRA) allowing the simultaneous processing of both models, resulting in a more realistic calculation of flood elevations. We have concluded a set of preliminary test runs using the coupled model and we are now adopting the coupled version for the project hydrodynamic simulations.

The simulations using the coupled ADCIRC/UNSWAN were concluded for the current wetland scenarios (NLCD2001 and NLCD 1992) and we have also repeated the sensitivity analyses using the coupled version. We have performed the simulations for the climate changed future wetland scenarios. We have also included the wetland databases provided by the NOAA C-CAP analyses and the National Wetlands Inventory (NWI)

The proposed deliverables for this task are concluded.

Task 4: (Quantify Inundation and Property Damages as a Function of Dune and Wetland Parameters)

- In this task, the simulated surges determined in Task 3 were integrated into the GIS framework for Corpus Christi previously developed by the PIs. Using spatial data analysis, inundated area and property damages were quantified for each of the 21 simulated scenarios. Statistics on the number of homes and buildings flooded and particular geographic regions, within the City of Corpus Christi, impacted were also determined. These storm impact statistics were correlated with the relevant dune and wetland parameters identified during Tasks 1 and 2 (e.g., dune height, dune width, wetland type, wetland spatial extent) to develop parametric tools for quantifying the benefits of dune and wetland restoration or, conversely, for quantifying the risk posed by dune and wetland degradation by natural (e.g., climate change) and manmade (e.g., public use) actions.

The project contract did not commence until November 30, 2009. Due to this contracting delay, we anticipate a two month slip in completion of all tasks and deliverables. Our revised deliverables timeline for this task is:

1. Inundation and damage maps and statistics developed May 2011
2. Parametric tools relating dune and wetland characteristics with hurricane impacts developed Jun 2011

We have collected spatial data for the Nueces County and San Patricio County that will add more resolution and information to the HAZUS database. This geospatial data was organized in a geodatabase to support the damage analyses using the water levels from Task 4. The final damage analyses was based on a composite database reflecting the best available data from the City of Corpus Christi parcel data, the Counties databases and HAZUS.

We have also included business data provided by the Reference USA that included more than 30.000 business establishments for the area. This data was converted to a geodatabase and also considered in the damage analyses.

The damage analysis was performed using 27 depth-damage relationships and a classification scheme for the business analyses. The geospatial results were summarized in county level analyses. The relation between wetlands and potential damage was established for each scenario considered.

The proposed deliverables for this task are concluded.

Task 5: (Develop and Provide Public and Professional Outreach)

- In this task, the web-based primer on hurricane surge being developed under contract # 08-009-000 will be expanded to include a quantitative discussion of how dunes and wetlands change the surge response and damages during hurricanes. The new components of this hurricane surge primer will describe, in an easy-to-read manner, how hurricane surge at the coast is modulated by wetlands and dunes. The primer will include written text along with appropriate graphics for concept visualization. Near the conclusion of the study, a technical seminar was conducted which will be open to any interested local, state, or federal agency. At this seminar, the final outcome of this research was presented.

  The project contract did not commence until November 30, 2009. Due to this contracting delay, we anticipate a two month slip in completion of all tasks and deliverables. Our revised deliverables timeline for this task is:

  1. Primer content developed and integrated with existing on-line primer Jun 2011
  2. Technical seminar completed Jun 2011

  A web based GIS application was developed using the ESRI Flex Viewer API to display the project results to provide public outreach. This application is currently available online at:

  http://people.tamu.edu/~celsomoller/gis/flexviewer/index.html

  A technical seminar was presented at the GLO office in July 6th where the major research findings were presented to the GLO staff and invited researchers.

  The proposed deliverables for this task are concluded.

Task 6: (Disseminate Research Findings)

- In this task, a report was prepared summarizing this research undertaking. This report describes how dunes and wetlands influence storm surge along the Texas coast and discuss the applicability of the developed parametric tools for decision-making regarding the preservation and restoration of these CNRAs. Instructions on accessing the on-line primer for public outreach are available online. Based on the study's technical findings, one or more publications in peer-reviewed scientific journals will be prepared. Geospatial information in ArcGIS format developed as part of this research, along with appropriate metadata files as documented in Content Standard for Digital Geospatial Metadata will be made available to interested local, state, and federal agencies upon request.

The project contract did not commence until November 30, 2009. Due to this contracting delay, we anticipate a two month slip in completion of all tasks and deliverables. Our revised deliverables timeline for this task is:

1. Final report completed	Jun 2011
2. Journal publication(s) submitted	Jun 2011

Journal papers published:

- Irish, J.L., A.E. Frey, J.D. Rosati, F. Olivera, L.M. Dunkin, J.M. Kaihatu, C.M. Ferreira and B.L., Edge,. *Potential Implications of global warming and barrier island degradation on future hurricane inundation*, **Ocean and Coastal Management**, Vol. 53, 645-657, 2010

Journal paper in preparation:

- Ferreira, C; Irish, J. Olivera, F *"The influence of coastal wetlands on hurricane surge in Corpus Christi, TX."* (in preparation)

The proposed deliverables for this task are concluded.

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Potential implications of global warming and barrier island degradation on future hurricane inundation, property damages, and population impacted

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ABSTRACT

Hurricane flooding is a leading natural threat to coastal communities. Recent evidence of sea level rise coupled with potential future global warming indicate that sea level rise will accelerate and hurricanes may intensify over the coming decades. In regions fronted by barrier islands, the protective capacity of these islands may diminish as they are degraded by rising sea level. Here we present a hydrodynamic and geospatial analysis of the relative role of barrier island degradation on potential future hurricane flooding. For the City of Corpus Christi, Texas, USA, hurricane flooding is projected to rise between 20% and 70% by the 2030s, resulting in an increase in property damages and impacted population. These findings indicate that adaptive management strategies should be developed and adopted for mitigating loss of natural barrier islands when these islands act as protective features for populated bayside communities. Finally, this study illustrates a method for applying models to forecast future storm protection benefits of barrier island restoration projects.

1. Introduction

Inundation by storm surge from hurricanes and other tropical cyclones is one of the leading natural threats to coastal communities. Since 2004, the United States of America (USA) has experienced some of its highest hurricane surges on record with the surges generated by Hurricanes Ike, Rita, Katrina, and Ivan matching or exceeding previous measurements [1–3]. Possible acceleration of sea level rise (SLR) and intensification of hurricanes as a consequence of global warming [4,5] can lead to increased hurricane flooding and damages. In regions protected by natural barrier islands, this potential acceleration in hurricane inundation with global warming is expected to be amplified, as the barrier islands themselves are vulnerable to degradation from SLR. This potential escalation in hurricane flooding inundation can lead to an increased land area threatened by storm surge, potentially increasing hurricane-induced economic damages, the number of evacuees prior to landfall of a hurricane, and demand on resources for post-storm recovery, among other factors. Thus, it is prudent to quantify the potential impact of global warming on future hurricane flooding to improve and develop adaptive engineering, planning, and evacuation strategies for communities at the coast.

In this paper, we investigate the potential implications of global warming on future hurricane inundation and damages with emphasis on the relative role of future degradation, with SLR, of protective barrier islands. Here we present a generalized method for assessing these potential implications at any worldwide location exposed to coastal storms. Our analysis for the City of Corpus Christi, Texas, located on the northern Gulf of Mexico, USA, shows that, if future global warming scenarios are realized and if protective barrier islands degrade over time, hurricane flooding inundation and associated damages will increase during the next century.

Below, we discuss recent climatic research on global warming with an emphasis on those factors with the potential to increase hurricane inundation, and we discuss barrier island processes and the potential for natural barrier island degradation with SLR. The numerical modeling and geographic information methods used for evaluating the potential rise in future hurricane inundation, damages, and population affected are then introduced. Finally, we

Abbreviation: ADCIRC, ADvanced CIRculation model; IPCC, Intergovernmental Panel on Climate Change; MSL, mean sea level; MSL_{2000s}, present-day mean sea level; $MSL_{2030s\text{-}high}$, high projection of 2030s mean sea level; $MSL_{2080s\text{-}middle}$, mid-range projection of 2080s mean sea level; NOAA, National Oceanic and Atmospheric Administration; SLR, sea level rise; SRF, surge response function; SST, sea surface temperature; SWAN, Simulating WAves nearshore.

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present our results and conclusions regarding future hurricane inundation as a consequence of potential barrier island degradation, sea level rise, and hurricane intensification.

2. Background

The hurricane flooding probability and damage risk assessment that forms the basis for much coastal engineering and planning depends on climate statistics including hurricane track, frequency, and intensity and mean sea level. Since these climate statistics can vary on short (decadal) and long-term time scales [6], it is important to understand how the coastal landscape and flooding responses change as a result of climate variability. Here, we will focus on the implications of long-term global warming projections.

The climate projections presented by the Intergovernmental Panel on Climate Change (IPCC) [4] indicate that sea surface temperature (SST) over the next century will rise between 1.1 °C and 6.4 °C. In this analysis, to span a range of future climate possibilities, we consider three of the IPCC future global warming scenarios:

1) B1, which assumes a low rate of greenhouse gas emissions,
2) A1B, which assumes a moderate rate of greenhouse gas emissions, and
3) A1FI, which assumes a high rate of greenhouse gas emissions and represents the highest emission scenario considered by the IPCC [7].

By assuming that the expected global change in sea level rise and the expected hurricane intensification are correlated with SST rise, each of these warming scenarios can be used to project future sea level rise and hurricane intensification.

2.1. Potential sea level rise with global warming

Observed mean sea level (MSL) data over time show a net rise in global, or eustatic, sea level [4,8–10]. Observed eustatic SLR rates over the last century are between 0.17 and 0.18 cm/year [4]; however, these observations also indicate an acceleration in SLR over the last couple of decades, with an SLR rate of 0.30 cm/year [4]. Global climate projections made by the IPCC also indicate a future acceleration in SLR, with respect to historical observations, projecting rates as high as 60 cm over the next century for the three climate scenarios listed above [4,11]. Other researchers suggest eustatic SLR over the next century may be as much as 1 m if major ice-sheet melting occurs [12–14].

2.2. Potential hurricane intensification with global warming

The historical hurricane record and climate projections both suggest that major hurricanes (Category 3 to 5 on the Saffir–Simpson scale [15]) may become more intense with SST rise [5,16–19]. By evaluating several convective parameterizations [20–22] and considering thermodynamic impacts, Knutson and Tuleya [16,23] estimated that, on average, a hurricane's central pressure would increase 8% per 1 °C of SST rise:

$$p_{\Delta SST} = p_o - 0.08(\Delta SST)\left(p_{far} - p_o\right) \quad (1)$$

where:

$p_{\Delta SST}$ is the future projected hurricane central pressure,
p_o is the present-day (2000s) hurricane central pressure,
ΔSST is the sea surface temperature change in °C, and
p_{far} is the far-field barometric pressure, and all pressure parameters are in consistent units.

Because Eq. (1) does not account for wind shear, among other factors, it should be considered representative of possible hurricane central pressure change with SST change for a future tropical system, if that tropical system develops fully.

2.3. Potential barrier island degradation with sea level rise

To understand the potential changes to barrier island morphology with increasing sea level, we first considered how barrier islands have formed and evolved over the past 3000 to 7000 years. Barrier islands were able to form during this period because the eustatic sea level rise rate was relatively slow (~0.1–0.2 cm/year) [24]. Prior to this time, eustatic sea level rise was rapid (1–2 cm/year) and barrier islands were unable to form because the destructive processes of erosion and overwash were greater than constructive processes such as a net influx of long shore sand transport, Aeolian transport and dune building, and onshore transport.

Over the past 100-years, for example, barrier islands in Louisiana have experienced a relative SLR of approximately 1 m (rate of 1 cm/year). Morphologic response of these islands to this rapid rise has been to form breaches, islets, permanent inlets, resulting in island break up and drowning in place [25]. A similar response has been documented in the geologic record offshore of Fire Island, New York, whose islands formed 9000 years ago were drowned in place as sea level rose rapidly. These islands were overstepped as new islands formed in a more landward position [26,27]. Based on this long-term evidence, we infer that a future rise in relative sea level exceeding 1–2 cm/year would likely break up and drown barrier islands fronting Corpus Christi Bay.

With relatively slow rates of relative sea level rise, natural barrier islands can respond in two ways: (1) with sufficient supply of littoral sand, barrier islands can be stable or migrate landward through inundation and overwash processes; or (2) without sufficient supply of sand, islands can either drown in place, which will occur with extremely rapid relative SLR, and break up or disintegrate, forming islets and breaches as occurred in the Isle Dernieres, Louisiana [25].

The Bruun Rule [28] is the simplest model for long-term evolution of the shoreface. It predicts equilibrium shoreface retreat given the rate of relative SLR and the vertical and horizontal extents of the active beach and nearshore profile. The relationship is formulated by equating the volume eroded by an increase in relative sea level to the sediment required to increase the elevation of the active profile, and the profile retreats parallel to itself. Dean and Maurmeyer [29] modified the Bruun Rule for barrier islands, including terms relating the active extent of the lagoon (or bay) in the vertical and horizontal dimensions. Dean and Maurmeyer [29] noted that if the zone of active cross-shore movement of sediment is equal for both the ocean and bay (e.g., same active depth), there would be no potential for building up of the island during landward migration and the barrier island would narrow, essentially drowning in place.

List et al. [30] examined the applicability of the Bruun Rule to predict shoreline response due to relative SLR for 150 km of Louisiana coastline west of the Mississippi River. The authors eliminated approximately half the profiles that did not maintain an equilibrium form over the 50- to 100-year period considered. For the remaining profiles tested, the authors assumed between 31% sand (for deltaic shorelines) and 100% sand (for sand spits) to calculate volumetric losses of fine sediment as the beach retreated. The Bruun Rule could not accurately predict shoreline response in a hindcast evaluation for the Louisiana coast. Long-term massive redistribution of sediment in the nearshore and on the shoreface was used as evidence of changes to the long-term regional sediment budget that decreased applicability of the Bruun Rule. Also, relative SLR has increased the size of the bays behind barrier islands, thus increasing the tidal prism of adjacent inlets and their associated ebb and flood tidal deltas. As the barrier retreats, the redistribution of sand into the deeper bay, as well as into deltas, suggest that the barrier islands cannot maintain their subaerial form.

There is an exacerbating response to an increase in sea level for barrier islands that protect a bay or estuary, for cases in which the bay area can increase. As relative sea level increases, the bay area and tidal prism increase, causing an increase in adjacent inlet area. With larger tidal prism and inlet area, ebb and flood shoals become larger, removing sand from the barrier island beaches. Thus, sea level affects the barrier island sand budget in three ways: apparent retreat of the shoreline because of higher water level; migration of the island itself because of an increased propensity for overwash; and an increased sink for sand in formation of the tidal shoals. FitzGerald et al. [31–33] presented a conceptual model of barrier island evolution with relative SLR, for the case in which a sufficient source of sediment is not available. This model shows the break up of a barrier island fronting a bay as relative water level increases, bay area increases, and sand in the littoral budget is transported to meet the demand of the newly-forming inlet shoals. The response of a barrier island to the additional loss of sand to the inlet shoals is to erode, followed by an increase in overwash and formation of small breaches or islets. For the situation in which sufficient sand is available to maintain a subaerial barrier island, migration of the island into the bay may reduce the bay area to some degree, and may offset the otherwise increase in bay area, tidal prism, inlet area, and shoal volume.

2.4. Potential implications of global warming on coastal communities

Hurricanes over the last decade have resulted in widespread damages and loss of life. For example, Hurricane Katrina in 2005 devastated the northern Gulf of Mexico coastline, from Louisiana through Alabama, resulting in more than 1500 deaths and $81 billion in damages [34]. If potential acceleration in SLR and potential hurricane intensification with global warming occur, such hurricane events will result in more severe impacts at the coast.

Several recent studies have considered the effect of SLR on hurricane flooding probability in the USA. For example, Cooper et al. [35] concluded that 1%–3% of New Jersey could be permanently inundated within a century, and a moderately high 0.61-m rise in sea level, based on IPCC projections [4], could result in the present-day 100-year flood level increasing in likelihood to a 30- to 40-year flood level. Kleinosky et al. [36] considered SLR of 30, 60, and 90 cm in Hampton Roads, Virginia. The authors found that the flooding probability zones for major hurricanes (Category 3 and higher) increased between 7% and 28%, while the flooding probability zones for critical facilities (hospitals, schools, etc) increased between 1% and 19%. In a case study for New York City, Gornitz et al. [37] determined that the return period of the present-day 100-year storm flood could increase in likelihood to between 19 and 68 years by the 2050s and to between 4 and 68 years by the 2080s. The authors also found that the 100-year flood would increase from 2.96 m, today, to between 3.0 and 3.5 m by the 2020s and up to 4.2 m by the 2080s.

Among studies of sites in the USA, Frey et al. [38] and Frey [39] are the only studies to consider the combined impact of SLR and hurricane intensification. Frey et al. [38] considered both acceleration in SLR and hurricane intensification in quantifying potential increases in property damage and population affected by hurricane inundation under several IPCC global warming scenarios. Frey et al. [38] reported that if the highest greenhouse gas emission scenario reported by the IPCC is realized, by the 2080s, property damages by hurricane inundation could increase by more than 250% per hurricane event. Under this same high rate of warming scenario, by the 2080s this study showed that population impacted would increase by more than 200% per event.

Church et al. [40] considered tropical cyclone intensification and SLR in Australia. They found that in Cairns, the 100-year storm event increases in elevation from 2.5 m to 2.9 m by 2050 and the average return interval for the 2.5 m event increases in likelihood from a 100-year event to a 40-year event as a result of SLR and tropical cyclone intensification. Karim and Mimura [41] recently studied the effects of tropical cyclone intensification and SLR from climate change on coastal Bangladesh, and showed that flooded area increases by 13% when the SST increases 2 °C and that flooded area increases by 25% when the SST increases by 4 °C. Ali [42,43] also conducted a similar study in Bangladesh and found that a 2 °C SST rise and an SLR of 0.3 m resulted in a 20% increase in flooding, while a 4 °C SST rise and an SLR of 1.0 m resulted in a 40% increase in flooding.

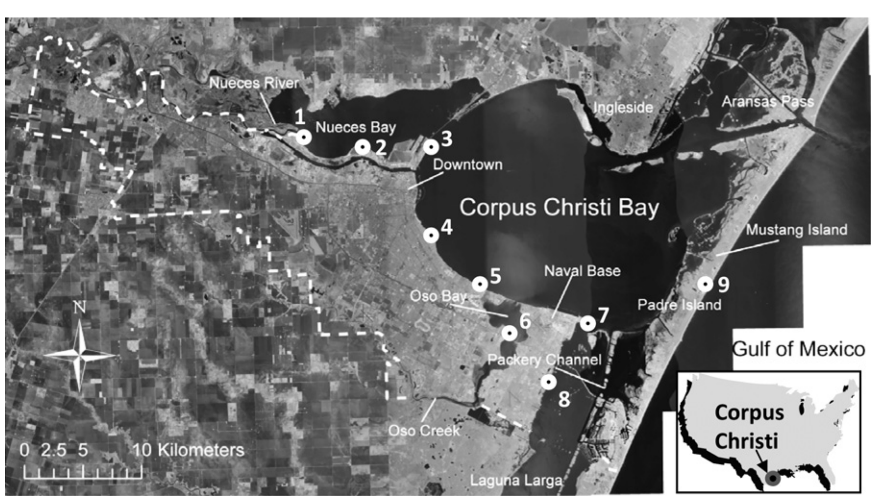

Fig. 1. Location map for Corpus Christi, Texas USA (aerial imagery from U.S. Geological Survey [67]). Dashed line represents the City of Corpus Christi boundary, and numbered circles are selected locations for surge results discussion (Section 5.2).

While the potential implications of global warming on coastal storm impacts is evidenced in the literature discussed above, it is worth noting that none of these studies considered the potential implications of future barrier island degradation on future storm impacts. Yet, barrier islands are known to provide some level of protection against hurricane surge and wave action (e.g., [44]). Because barrier islands can act as natural surge barriers, their potential degradation with SLR can result in higher flood elevations within coastal bays. As an example, Canizares and Irish [45] showed that for coastal storms in Long Island, New York, surge waters passing over the barrier islands during hurricanes can raise flood levels on the order of 1 m within coastal bays. In this paper, we focus on the role of barrier island degradation on future hurricane flooding.

3. Study area

The City of Corpus Christi, along the Texas, USA Gulf of Mexico coastline (Fig. 1) was selected for evaluating the potential impacts of global warming and barrier island degradation on hurricane inundation and its relation to population affected and economic damages. This region of the Texas coast is regularly subjected to high hurricane surges, and the population of Corpus Christi is vulnerable to hurricane damage because of the extensive coastal infrastructure serving tourism, commerce, and energy. More than 275,000 people reside on both the mainland and the barrier islands, this urban community supports a strong tourism industry, multiple oil refineries, the Corpus Christi Naval Air Station, the Port of Corpus Christi, and Texas A&M University – Corpus Christi.

3.1. Historical sea level rise

Historical observations of relative SLR in this region include substantial contributions from both eustatic rise and land subsidence. Based on water level observations reported by the National Oceanic and Atmospheric Administration (NOAA) near Corpus Christi, historical relative SLR in this region is 0.46 cm/year [46]. Using the abovementioned historical eustatic SLR rates, observed land subsidence due to fluid withdrawal and soil consolidation (e.g., [47]) is estimated to contribute 0.29 cm/year to the historical relative SLR. Studies of land subsidence in Texas [48–50] indicate that subsidence rates for this region have slowed somewhat in recent decades, most likely in response to reduced groundwater extraction [51]. However, land subsidence is projected to accelerate in many locations around the world as demands on groundwater increase with population growth [52]. Due to the uncertainty in projecting such processes as groundwater extraction, it is assumed here that land subsidence in Corpus Christi will continue into the future at its average historical rate of 0.29 cm/year. However, if fluid extraction in the future slows or ceases due to mitigation measures, land subsidence may decrease correspondingly. Conversely, if fluid extraction increases as is likely with population growth, land subsidence may increase correspondingly; the United Nations projects the U.S. population to increase 18% by the 2030s [53].

3.2. Hurricane history

Ten major hurricanes (Category 3 or higher) have made landfall along the Texas coastline since 1950 [54]. Of these storms, Hurricanes Beulah (1967), Allen (1980), and Bret (1999) generated high flood levels at Corpus Christi. Observed maximum flood levels along the open coast for these three hurricanes were between 1 m and 3 m [55–57]. It is worth noting that while Hurricane Ike (2008), which made landfall about 300 km to the north of Corpus Christi, generated more than 1 m of surge at Corpus Christi [46], this storm made landfall as a Category 2 hurricane and thus is not classified as a "major hurricane."

3.3. Role of barrier islands for surge protection

The City of Corpus Christi is divided into two geographic sections: a mainland portion, situated on Corpus Christi Bay, and a barrier island portion, Mustang and Padre Islands, which separates Corpus Christi Bay from the Gulf of Mexico. The natural barrier island system fronting Corpus Christi Bay acts as a natural surge barrier to mainland Corpus Christi and other bayside communities. If surge overtopping of the barrier islands is limited, flood levels along mainland Corpus Christi are generated predominantly by locally generated wind surge within Corpus Christi Bay and by ocean flood waters passing through Aransas Pass at the northeastern end of the Bay. Much of this barrier island system is low-lying (Fig. 2), however, with long stretches of elevations as low as 1.25 m above present-day (2000s) mean sea level (MSL_{2000s}) and some areas with elevations between 0 and 0.5 m above MSL_{2000s}. During major hurricane flooding events, ocean flood waters flow over these low-lying portions of this barrier island system,

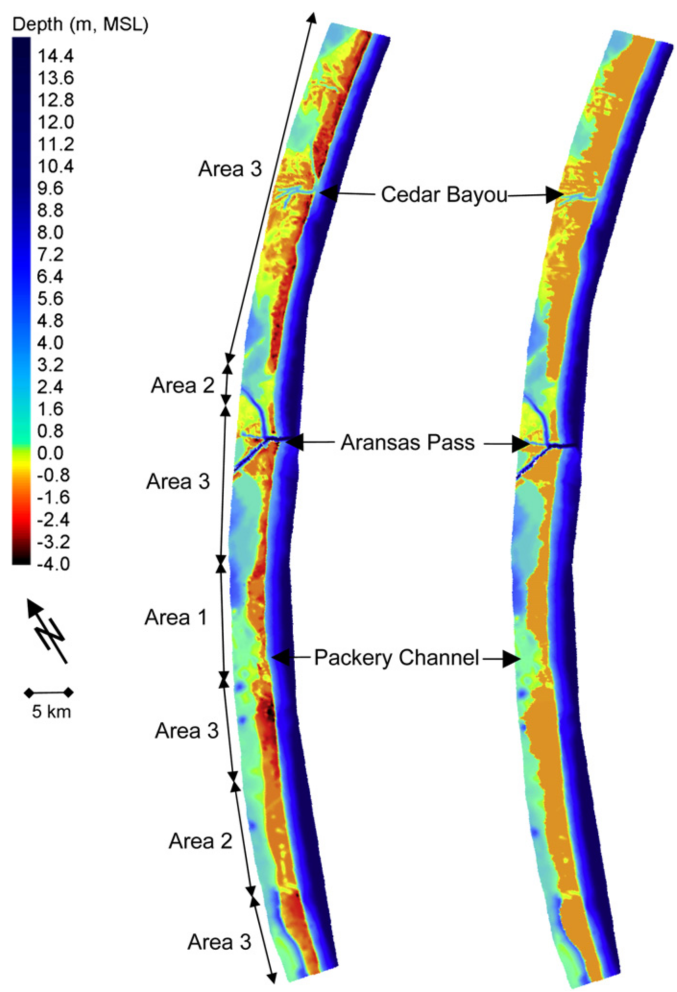

Fig. 2. Padre, Mustang, and San Jose Island topography in the vicinity of Corpus Christi. Left pane shows present-day (2000s) topography while right pane shows a possible future degraded condition, where the entire barrier island system has an elevation no higher than 1 m with respect to MSL during the time period of interest. Areas 1, 2, and 3 indicate morphological reach designation for idealized XBEACH simulations.

oftentimes generating overwash and breach areas which more effectively convey flood waters into Corpus Christi Bay. For example, numerical simulations of hurricane flooding by Hurricane Beulah (1967) indicate widespread barrier island overflow into Corpus Christi Bay [58] occurred during this event. With future SLR and no anthropogenic action, it is expected that this protective barrier island system will degrade, ultimately allowing more storm overflow into Corpus Christi Bay during hurricane surge events.

4. Methods

A combined numerical simulation and geographic information analysis approach was used to evaluate the potential impact of global warming and barrier island degradation on hurricane inundation, damages, and population impacted. The sections below summarize the selection and development of future scenarios with global warming, potential future degraded barrier island conditions, the numerical modeling scheme used to estimate hurricane flood levels, and the geographic information methods used to quantify potential changes in property damages and population impacted. In this analysis, we neglect the impacts of direct wave action, wind, and inland precipitation on damages and consider only those damages directly related to static flooding caused by storm surge induced by wind and barometric pressure, by wave setup, and by SLR. The approach outlined below, with modifications for local conditions, is designed to be applicable for assessing the potential impacts of global warming on tropical cyclone flooding at any worldwide location exposed to coastal storms.

4.1. Future global warming scenarios

To evaluate the combined impact of hurricane intensification, sea level rise, and barrier island degradation on hurricane inundation in the future, climate projections for SST change and eustatic SLR were developed using the climate model MAGICC/SCENGEN [59]. Specifically, two future periods were assessed, the 2030s and the 2080s, by assuming a base year of 1990. For each period, the three abovementioned IPCC carbon-dioxide emission rate scenarios B1, A1B, and A1FI were used, in which three carbon-dioxide doubling sensitivities were considered for each scenario (cool [2.0 °C], average [3.0 °C], and warm [4.5 °C]) [38,58,60]. In total, 27 climate projections were developed using MAGICC/SCENGEN for each period.

Projected rates of SST rise and eustatic SLR ranged from 0.01 °C/year to 0.06 °C/year and 0.24 cm/year to 0.72 cm/year, respectively (Fig. 3). For our analysis, relative SLR in the 2030s and 2080s was taken as the sum of the eustatic rise projected with the climate model plus an estimate of land subsidence. Here, future land subsidence in the Corpus Christi area was assumed to continue at the historical measured rate of 0.29 cm/year. Thus, relative SLR is projected to range from 0.53 cm/year to 1.01 cm/year. Land subsidence makes up 25%–55% of the projected relative SLR at Corpus Christi, depending on climate projection. Under the greatest greenhouse gas emissions scenario considered here, A1FI, the relative SLR rate approximates the minimum of our inferred critical barrier island drowning criteria of 1–2 cm/year (see Section 2.3).

In this paper, we consider potential future hurricanes similar to the historical Hurricane Bret. Of the three major hurricanes impacting Corpus Christi since 1950, Hurricane Bret generated the smallest surge, on the order of 1 m along the open coast. Numerical hurricane flooding simulations for this storm indicate minimal barrier island overwash and breaching occurred during the historical occurrence of this event, as the ocean side flood elevation was very similar to the lowest barrier island elevations [38]. As such, we expect that flood elevations within Corpus Christi Bay will

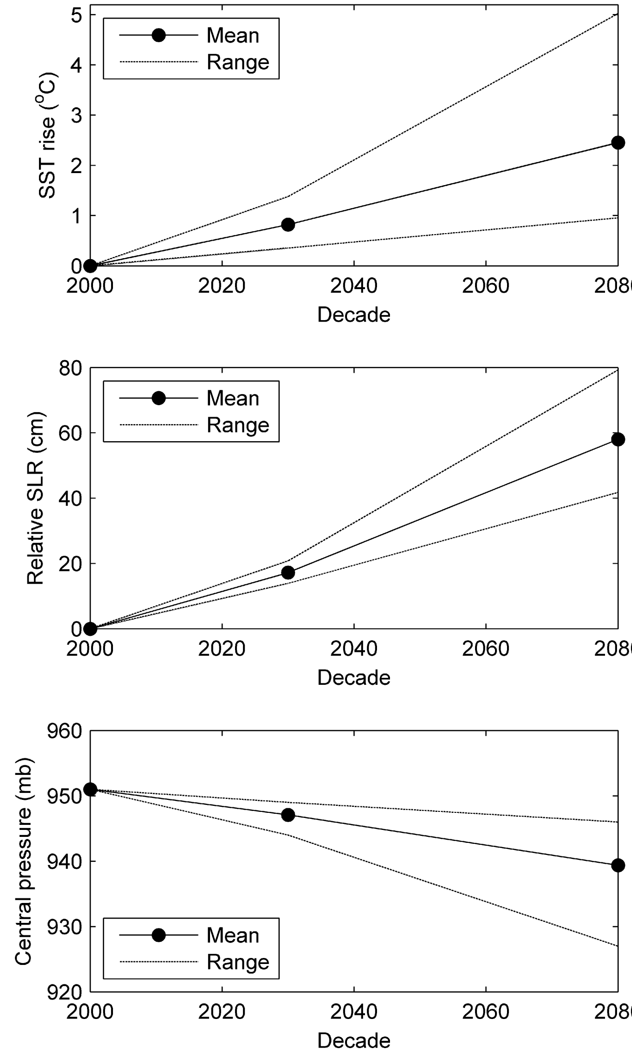

Fig. 3. Projected future sea surface temperature (SST, top pane) rise, relative sea level rise (SLR, center pane), and hurricane intensification for hurricanes like Hurricane Bret (bottom pane). Modified from Mousavi et al. [60].

be sensitive to possible future barrier island degradation. Thus, this storm is highly suitable for evaluating the potential implications of future barrier island degradation on back-bay hurricane flooding. Future hurricanes similar to Hurricane Bret were developed by holding the historical hurricane's track, size, and forward speed

Table 1
Future global warming projections applied to Hurricane Bret for evaluation (modified from Frey et al. [38]).

Future scenario	SST rise (°C)	Landfall central pressure (mb)	Sea level rise (cm)		
			Eustatic SLR	Subsidence	Total relative SLR
Present-day	0	951	0.0	0.0	0.0
A1FI (cool, 2 °C sensitivity) – 2030s	0.36	949	7.6	6.4	14.0
B1 (warm, 4.5 °C sensitivity) – 2030s	1.38	944	14.4	6.4	20.8
A1B (middle, 3 °C sensitivity) – 2080s	2.51	939	36.9	20.9	57.8
A1FI (warm, 4.5 °C sensitivity) – 2080s	5.02	927	58.4	20.9	79.3

constant while varying the hurricane's central pressure. For each climate scenario, the hurricane's central pressure was intensified based on Eq. (1). These projections indicate that this hurricane condition intensifies between 0.1 and 0.3 mb/year (Fig. 3). Table 1 presents the future climate projections selected for detailed hurricane inundation, property damage, and population analysis.

4.2. Future barrier island conditions

The relative SLR projections introduced above suggest that the already low-lying barrier island system fronting Corpus Christi Bay will degrade over time, if no anthropogenic action is taken. However, the relative SLR rates considered here do not indicate that significant barrier island break up and drowning will occur. Our intent in this paper is to evaluate the relative sensitivity of hurricane flooding under future warming scenarios if future degradation of the barrier islands occurs, with respect to no barrier island degradation. Here, we consider one potential degraded barrier island scenario. Our assumptions in creating future barrier island morphology for the modeling herein was to decrease the elevation of the islands to an elevation representative of long-term overwash processes, where no natural or anthropogenic elevation recovery has occurred. As such, the elevations above 1 m along the entire barrier island system were lowered to an elevation of 1 m relative to MSL during the periods of interest (e.g., 2000s, 2030s, or 2080s). Fig. 2 (right pane) shows this degraded barrier island condition. As this figure shows, the majority of the barrier island is represented by a uniform elevation, with the exception being the region just to the north of Aransas Pass, where elevations lower than 1 m above MSL have been maintained. In developing this degraded barrier island scenario, sediment volume removed from the island was deposited into the bay in the form of overwash fans, thereby increasing the width of the low-lying islands. With the above degraded barrier islands scenario, we assume that the amount of sediment deposited in the bay as overwash fans is not eroded away by bayside processes. While the above scenario does not consider all possible future degraded conditions, for example, one in which the barrier island drowns or is further divided by new inlet formation, this scenario can be used to give an indication of the relative role of future barrier island degradation on hurricane flooding. During hurricane simulation, additional barrier island erosion is allowed to occur. Finally, due to the level of degradation considered here, in our analysis we assume that the barrier island is uninhabited in the 2030s and 2080s; therefore, all inundation, damages, and population calculations and results, including those for present-day (2000s), only considering relative impacts to the mainland portion of Corpus Christi (Fig. 1). As such, these calculations are conservative (low).

4.3. Simulation of hurricane flooding

Hurricane inundation was simulated using the finite-element, depth-integrated, hydrodynamic model ADCIRC (ADvanced CIRCulation) [61]. For this investigation, ADCIRC, which solves the shallow-water equations for mass and momentum conservation, was forced with winds, barometric pressure, and wave radiation stress force. Mean sea level within the ADCIRC model was adjusted in order to evaluate future sea level conditions. Hurricane wind and pressure fields were developed with a planetary boundary layer model [62], while wave radiation stress force was developed using the spectral wave model SWAN [63]. Astronomical tidal range at the study location is 40 cm along the open coast to about 10 cm within the bays [46]. Tide level at the time of peak hurricane surge will impact the exact flood elevation and associated inundation and damages. However, since our study objective is to evaluate the relative role of barrier island configuration on bay flooding, we neglect tidal variation in this analysis. All flood levels are based on a mean tide condition. To account for barrier island erosion during hurricane passage, the XBEACH morphological model [64] was employed, and results for dune erosion were used to pre-condition the ADCIRC computational grid. Fig. 4 presents the numerical modeling strategy. Application of the XBEACH model is discussed below, while details of other aspects of the numerical modeling approach are described in Mousavi et al. [60] and Frey [39].

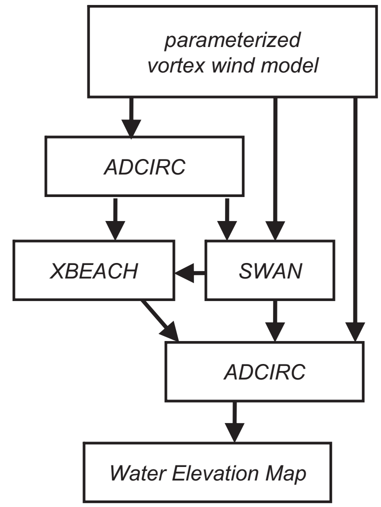

Fig. 4. Schematic of numerical modeling approach for simulating hurricane flooding.

4.4. Simulation of storm-induced barrier island erosion

To account for additional flooding and damages induced by overtopping and breaching of the barrier islands, barrier island lowering and erosion were incorporated into ADCIRC simulations by first estimating storm-induced barrier island erosion, then pre-conditioning the ADCIRC grid prior to flood level simulation. To determine barrier island erosion, the XBEACH morphological model was used [64,65]. XBEACH is a physics-based finite-difference numerical model which simulates morphological change induced by rising water levels and irregular waves; it accounts for erosion due to intermittent dune run up and overtopping by waves as well as erosion due to quasi-steady barrier island inundation. Sediment transport was computed in XBEACH using an advection-diffusion scheme using the Soulsby-van Rijn transport formula [66]. A median grain diameter of 0.217 mm was specified based on beach

Table 2
Present-day (2000s) characteristics of morphological reaches used in XBEACH simulations.

	Area 1		Area 2		Area 3	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
Barrier island width (m)	1765	1765	740	3095	1765	3423
Dune height (m, MSL)	2.7	9.0	0.1	1.25	2.6	6.1

sand samples collected in May 2008 [39]. The model includes an avalanching algorithm, which allows for modeling the slumping of sediment when the bottom slope becomes very steep.

To overcome the high computational expense of running a detailed morphological model, a series of idealized simulations with XBEACH were performed to determine dune lowering as a function of initial dune conditions and storm hydrodynamic conditions. Four idealized storm surge and wave conditions were used to span the range of hydrodynamic conditions characterized by the storms in Table 1 [39].

The barrier island system in the vicinity of Corpus Christi was divided into three morphologically-similar areas (see Fig. 2), with some of them were further sub-divided for morphological simulation to better characterize individual areas along the barrier island system. For each area, morphological characteristics including dune height and barrier island width, were determined for existing conditions using the U.S. Geological Survey [67] 10-m Digital Elevation Model (DEM) (Table 2). For the future degraded condition considered here, the maximum barrier island elevation within all XBEACH simulations was specified uniformly as 1.00 m above MSL, as given by the climate scenario considered, everywhere except in the very low area to the north of Aransas Pass. For future degraded conditions, the barrier island width varied from 740 to 3900 m. In total, six idealized topography scenarios were constructed to represent both the present-day (2000s) and future (2030s and 2080s) pre-storm barrier island conditions [39]. For morphological reaches with minimal variation in dune height and barrier island width, the XBEACH grid is uniform in the alongshore direction. For morphological reaches with measurable variation in dune height or width, the grid topography varies alongshore. In these cases, the model topography was organized to allow for a weak location (low dune elevation and/or barrier island width) at the alongshore center of the computational grid to account for the possibility of severe overwash and breaching. The simulated morphological responses indicate regions of erosion that remain above mean sea level (overwash) as well as regions of significant erosion to elevations to below mean sea level (breaching).

Changes in dune elevation were extracted profile-wise from each XBEACH simulation, and barrier island elevations in the ADCIRC grid were lowered. The amount of dune lowering applied to the ADCIRC grid was determined by weighted averaging between the actual hydrodynamic conditions (surge and wave) and the idealized hydrodynamic conditions. To conserve sediment mass when lowering the ADCIRC grid elevations, sediment removed from the dunes was translated landward. All final ADCIRC simulations were performed using the respective lowered barrier island grid configuration.

4.5. Estimation of inundated area, property damages, and population impacted

For each hurricane-climate scenario analyzed here, inundated area, property damages, and population impacted were quantified within a geographic information system (GIS) framework [38,39]. To form the basis for geospatial calculations, three datasets within the city limits of Corpus Christi were used: (1) a 10-m resolution digital elevation model (DEM) [67], (2) land parcel data which contained property value among other information [68], and (3) U.S. Census Bureau [69] population data for 2000 by census tract. Simulated flood elevations were intersected with the DEM, and inundated area was computed. Damages to the structure on each parcel due to static flood level were estimated by determining the mean flood depth within each land parcel, then by using the property damage versus flood depth relationships reported by the Federal Emergency Management Agency [70] (equivalent to those relationships integrated in the HAZards United States [HAZUS] system). All property damage values are given with respect to 2009 US dollar value. Finally, the spatial distribution of inundated area

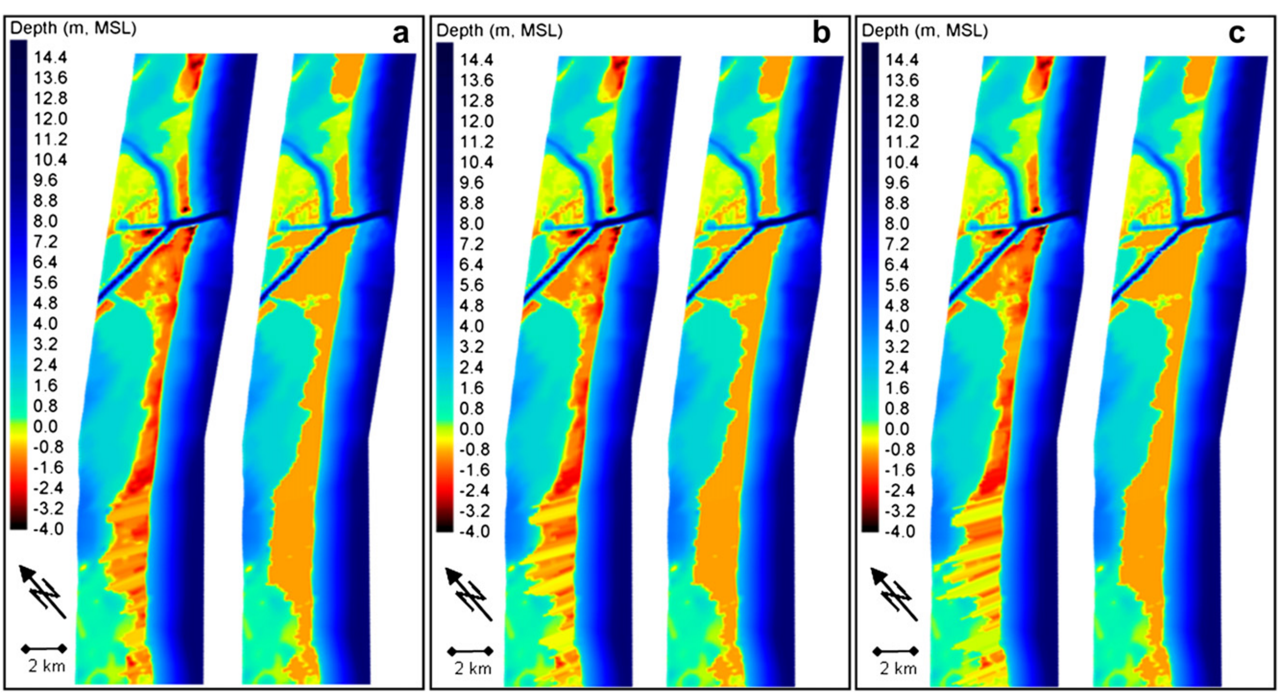

Fig. 5. Estimated storm-induced barrier island erosion on Mustang and Padre Islands: (a) under present-day (2000s) Hurricane Bret conditions when no hurricane intensification or relative SLR is assumed (left pane, MSL datum is MSL_{2000s}); (b) after 1.38 °C of SST rise, representing the 2030s B1 (warm, 4.5 °C sensitivity) scenario (center pane, MSL datum is $MSL_{2030s\text{-}high}$); and (c) after 2.51 °C of SST rise, representing the 2080s A1B (middle, 3 °C sensitivity) scenario (right pane, MSL datum is $MSL_{2080s\text{-}middle}$). In each pane, post-storm topography when no future barrier island degradation is assumed is on left, while post-storm topography when future barrier island degradation is assumed is on right. Area shown extends from Packery Channel to just north of Aransas Pass (see Figs. 1 and 2).

and flood depth were intersected with the population census data to determine the number of people impacted during each hurricane-climate scenario. Here, the population within each census tract was assumed to be evenly distributed throughout the parcel areas of the tracts. In this analysis, population affected reflects only to people living in the flooded areas according to census data but does not include all others affected by loss of jobs, overall slowdown of the economy in the broader area and other social impacts. The above method was executed for the mainland portion of Corpus Christi; as mentioned previously, here we assume that the barrier island would be uninhabited under the future degraded condition considered. Finally, the points of comparison used in the results and discussion are inundated area, property damage, and population impacted on the mainland evaluated for the case in which the barrier island was assumed to retain its present-day (2000s) condition (i.e., no-degradation assumed), where barrier island elevations were assumed to rise correspondingly with future SLR [38,39].

5. Results

5.1. Storm-induced overwash and breaching of Mustang and Padre islands

Under present-day (2000s) conditions, simulated flood elevation on the ocean side of Mustang Island (station 9 on Fig. 1) is 1.0 m, MSL_{2000s}. For the case of no barrier island degradation, post-storm simulation results for the present-day (2000s) hurricane scenario indicate some overwash of Mustang and Padre Islands. Specifically, near Packery Channel, elevations were generally lowered to about 1 m above MSL_{2000s} due to wave-induced erosion, and some narrow channels of slightly lower elevation, about 0.8 m above MSL_{2000s} were predicted (Fig. 5, left pane). For discussion purposes, Fig. 5 (left pane) also shows the predicted post-storm topography under present-day (2000s) conditions when the degraded barrier island condition is specified. Here, predicted storm-induced erosion of the degraded barrier island is negligible.

It is worth noting that with this degraded condition, no alongshore variability is predicted over the large region specified at a uniform 1-m elevation. This is a limitation of the methodology adopted here for estimating dune and barrier island lowering. For the degraded barrier island case, alongshore uniformity has been assumed during the majority of XBEACH simulations, the exception being the region just to the north of Aransas Pass. It is expected that under some real future condition, small perturbations in barrier island elevation would indeed induce channelized overwash areas.

Two additional comparative examples of the predicted storm-induced erosion response are shown in Fig. 5. The center pane shows the predicted response for the 2030s high climate estimate, when SST rise is 1.38 °C (B1 [warm, 4.5 °C sensitivity]), while the right pane shows the predicted response for the 2080s average climate estimate, when SST rise is 2.51 °C (A1B [middle, 3 °C sensitivity]). For the 2030s scenario shown, simulated flood elevation on the ocean side of Mustang Island is 1.2 m, MSL_{2000s}, or 1.0 m with respect to MSL for this 2030s projection ($MSL_{2030s\text{-}high}$). For the case of no barrier island degradation, this flood elevation inundates the lowest-lying sections of the barrier island. Storm morphology estimation indicates overwash of the barrier island in the region north of Packery Channel to elevations on the order of 0.9 m above $MSL_{2030s\text{-}high}$. A shallow breach, with a depth of 0.1 m below $MSL_{2030s\text{-}high}$, is predicted in the region to the north of Aransas Pass. For the case of the degraded barrier island condition, the ocean side flood elevation is on the order of the maximum barrier island elevation of 1.0 m above $MSL_{2030s\text{-}high}$, indicating the entire barrier island system is inundated during the peak of the storm. However, storm erosion predictions

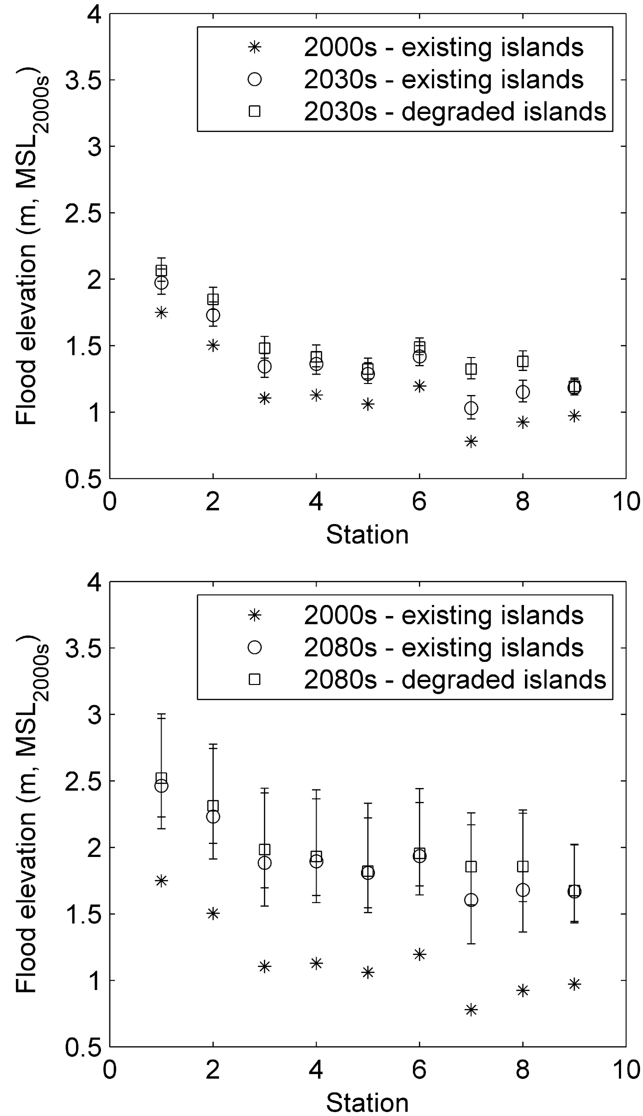

Fig. 6. Flood elevation projections at selected locations (see Fig. 1 for station locations). Symbols indicate mean of all projections while error bars indicate the upper and lower limits of the projections.

show minimal change to the barrier island landscape. These predictions indicate minimal overwash in the narrowest parts of the barrier island, between Packery Channel and Aransas Pass. As with the no-degradation case, predictions for the degraded barrier island case also show the same shallow breach formation in the region to the north of Aransas Pass.

For the 2080s scenario shown, simulated flood elevation on the ocean side of Mustang Island is 1.7 m, MSL_{2000s}, or 1.1 m with respect to MSL for this 2080s projection ($MSL_{2080s\text{-}middle}$). For the no-degradation case, overwash and breaching trends are similar to that for the 2030s scenario. In the 2080s case, somewhat more erosion is predicted to the north of Packery Channel, and the breach to the north of Aransas Pass is deeper, on the order of 0.2 m below $MSL_{2080s\text{-}middle}$, and wider. For the degraded barrier island case, the entire barrier island system is inundated for a short period around the peak of the storm, causing very slight overwash between Packery Channel and Aransas Pass. As with the no-degradation case, the predictions for the degraded barrier island case also indicate the development of a shallow breach to the north of Aransas Pass.

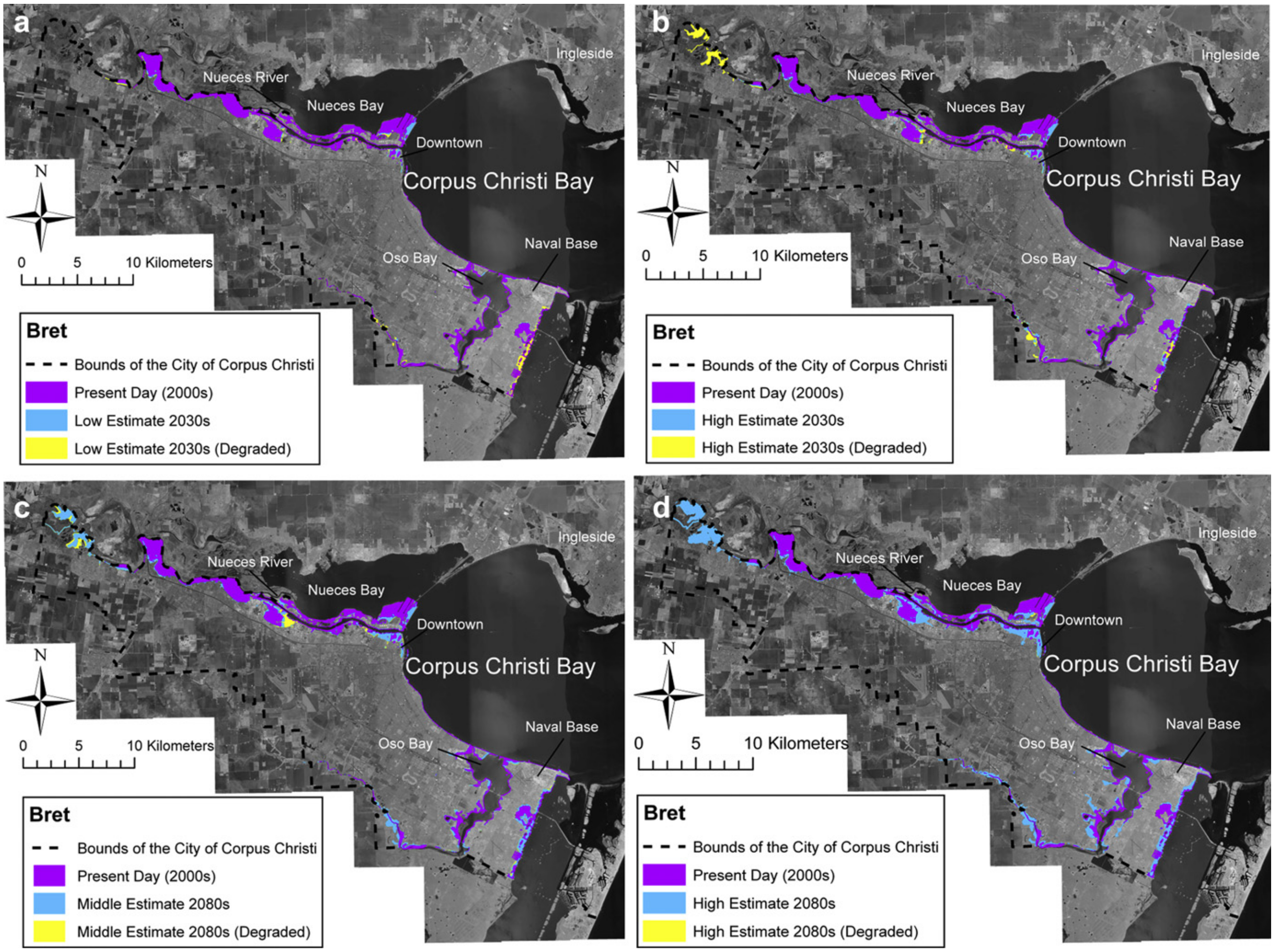

Fig. 7. Projected inundated area maps for mainland Corpus Christi for future storms similar to Hurricane Bret (a) after 0.36 °C of SST rise, representing the 2030s A1FI (cool, 2 °C sensitivity) scenario (top left pane); (b) after 1.38 °C of SST rise, representing the 2030s B1 (warm, 4.5 °C sensitivity) scenario (top right pane); (c) after 2.51 °C of SST rise, representing the 2080s A1B (middle, 3 °C sensitivity) scenario (bottom left pane); and (d) after 5.02 °C of SST rise, representing the 2080s A1FI (warm, 4.5 °C sensitivity) scenario (bottom right pane).

While the predicted morphological response is more dramatic for the case of no barrier island degradation, it will be shown below that the relatively larger volume of water which passes over the uniformly low barrier islands in the degraded case causes flood elevations to rise within Corpus Christi Bay.

5.2. Flood elevations and inundated area on mainland Corpus Christi

Fig. 6 shows the mean and range of flood elevations predicted at selected locations (see Fig. 1), based on the full suite of 27 climate projections per time period for the cases in which no future barrier island is assumed and in which a uniformly degraded barrier island is assumed. By the 2030s, the mean flood elevation prediction, when no barrier island degradation is assumed, is between 0.2 and 0.3 m higher than the present-day (2000s) flood elevation at all locations along the mainland of Corpus Christi. When future barrier island degradation is assumed, the difference between the 2030s mean prediction and the present-day (2000s) flood elevation becomes larger and exhibits more variation along the mainland coastline of Corpus Christi. For example, in Laguna Larga (stations 7 and 8), the difference between the mean predicted 2030s flood elevation and the present-day (2000s) flood elevation is about 0.5 m, and is more than twice the difference predicted for the no-degradation case. In Nueces Bay (stations 1 and 2), the 2030s flood elevation predictions are about 0.1 m higher for the degraded barrier island case with respect to the no-degradation case.

However, in Corpus Christi Bay, between the downtown and Oso Bay (stations 4 and 5), there is little difference between the 2030s projections with and without barrier island degradation. This lack of change in flood elevations can be explained by the relative change in free surface gradient within Corpus Christi [60]. Because Corpus Christi Bay is relatively shallow, with mean depth on the order of 3.5 m, the relative increase in mean depth induced by barrier island overflow during the storm results in relatively less locally generated wind setup and setdown during the degraded barrier island cases. Because of their location, the relative rise in mean flood depth within Corpus Christi Bay during the degraded barrier island condition is balanced by a relative reduction in wind setup [60].

As expected, the relative rise in flood elevation for the 2030s cases when barrier island degradation is assumed, with respect to the no barrier island degradation cases, results in relatively more inundated area in mainland Corpus Christi (Fig. 7, top panes). For the low 2030s estimate (A1FI [cool, 2 °C sensitivity]), additional inundation is predicted along the Laguna Larga shoreline and along Oso Creek and the Nueces River; some additional inundation is also

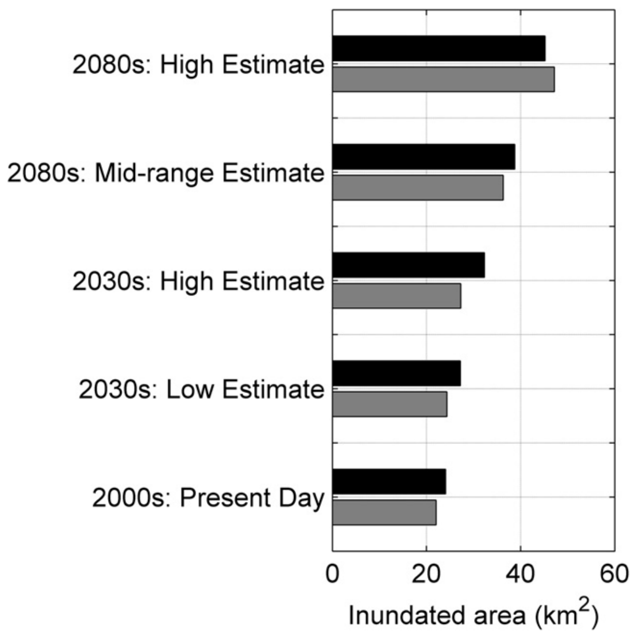

Fig. 8. Projected inundated area on mainland Corpus Christi. Projections when no barrier island degradation is assumed are shown in gray while projections when barrier island degradation is assumed are shown in black. The 2080s: High Estimate shown for the degraded barrier island case is as given by the numerical simulation output and GIS analysis. The difference between this result and that for the no-degradation condition indicates the inherent error in using a uniformly degraded barrier island and is assumed to represent a convergence between the two barrier island conditions.

predicted in the downtown. For the high 2030s estimate (B1 [warm, 4.5 °C sensitivity]), the most significant additional inundation is along the Nueces River. Fig. 8 shows that, for the 2030s projections, the area inundated on mainland Corpus Christi increases between 10% and 20% under degraded barrier island conditions, with respect to no-degradation conditions.

By the 2080s, the mean flood elevation prediction, when no barrier island degradation is assumed, is between 0.8 and 1.1 m higher than the present-day (2000s) flood elevation at all locations along the mainland of Corpus Christi (Fig. 6). When barrier island degradation is assumed, mean flood elevation predictions for the 2080s rise by less than 0.1 m to about 0.3 m with respect to the no-degradation case. The most dramatic difference, about 0.3 m, between the no-degradation and degraded cases is observed in Laguna Larga, immediately behind the barrier island (stations 7 and 8). Predicted inundated area for the middle 2080s scenario (A1B [middle, 3 °C sensitivity]) under the degraded barrier island case is predicted to increase 7% (Fig. 8), with respect to the no-degradation case, primarily along the Nueces River and in the downtown area (Fig. 7, lower left pane).

For the highest 2080s global warming scenario analyzed here (A1FI [warm, 4.5 °C sensitivity]), the simulations indicate slightly more flooding under the no-degradation case than under the degraded case; flood elevation differences are much less than 0.1 m in most locations (Fig. 6, upper limit) while percent change in inundated area is less than 4% (Fig. 7 [lower right pane] and 8). This result is an artifact of the uniformly degraded barrier island assumption, which limits breach formation. As discussed previously, it is expected that natural variability in barrier island elevation would induce breach formation. However, the exact location and extent of these breach formations are not known. Thus, we interpret the results for this 2080s upper limit to indicate the inherent error in the above approach and to represent a convergence between the two barrier island conditions. In other words, for more extreme surge events, the exact barrier island configuration is expected to have minimal impact on bay flooding. In the damage and population impacted discussion below, we assume that results for the degraded barrier island case equal the results for the no-degradation case for this high 2080s global warming estimate.

5.3. Damages to homes and other buildings on mainland Corpus Christi

Property damage estimates for homes and other buildings on mainland Corpus Christi due to static flooding for only selected future climate scenarios are given in Fig. 9. As this figure shows, property damages increase measurably when future barrier island degradation is considered. Property damage projections for the 2030s indicate that under the degraded barrier island case, expected damages increase by more than 50% with respect to the no-degradation case. This corresponds to an overall increase in damages on mainland Corpus Christi between $5 million and $10 million (2009 values) per storm event. Under the no-degradation case, property damage to buildings in the downtown area for the 2030s global warming projections are estimated to be between about $10,000 and $130,000. When future barrier island degradation is considered, damages in the downtown more than double, rising between $25,000 and $300,000 (2009 values) for the 2030s projections. Property damages to homes and buildings in the residential areas outside of the downtown under the no-degradation case are estimated to be between $10 million and $20 million (2009 values) for the 2030s projections, where damages are projected to rise an additional $5 million to $9 million (2009 values) under a degraded barrier island condition.

Projections for the 2080s indicate that property damages under a degraded barrier island case will increase by 25% under a middle-range climate scenario, with respect to damage predictions for the no-degradation case. Under the degraded barrier island case,

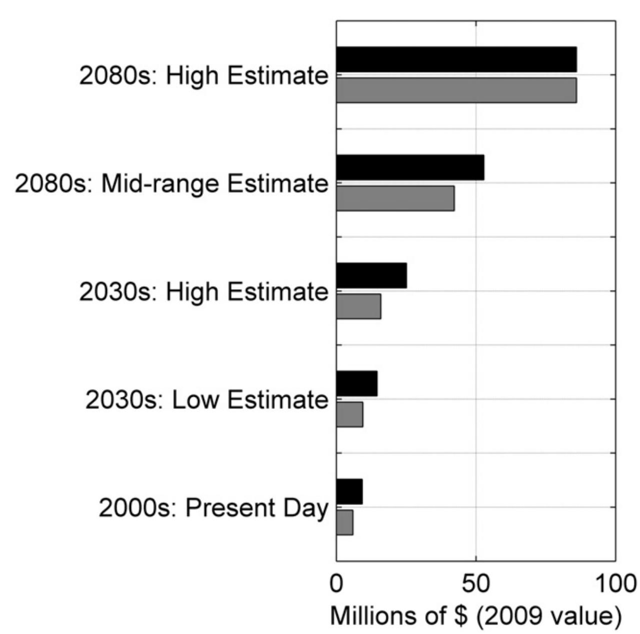

Fig. 9. Projected property damage to homes and other buildings on mainland Corpus Christi. Projections when no barrier island degradation is assumed are shown in gray while projections when barrier island degradation is assumed are shown in black. The 2080s: High Estimate shown for the degraded barrier island case is specified by assuming convergence with the no-degradation condition.

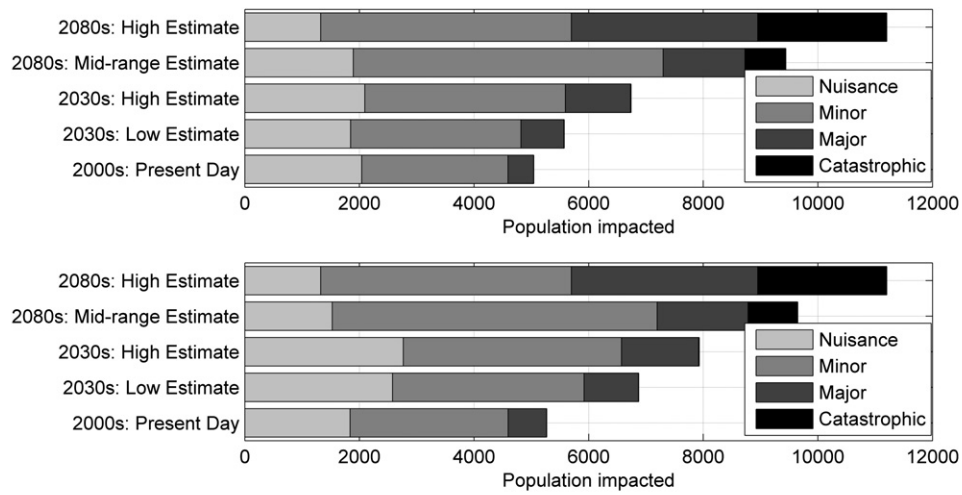

Fig. 10. Projected population impacted on mainland Corpus Christi. Results when no barrier island degradation is assumed are in top pane while results when barrier island degradation is assumed are in bottom pane; populations are segmented by degree of flooding (Nuisance, Minor, Major, or Catastrophic). The 2080s: High Estimate shown for the degraded barrier island case is specified by assuming convergence with the no-degradation condition.

property damages increase over damage values for the no-degraded case by about $2 million (2009 values) in the downtown and by about $8 million (2009 values) in other mainland residential areas for this middle-range 2080s projection. However, under higher warming scenarios for the 2080s, additional damages induced by a low barrier island configuration, with respect to no-degradation, are expected to diminish.

5.4. Population impacted on mainland Corpus Christi

For the selected climate scenarios in Table 1, projections of population impacted are given in Fig. 10. If a storm like Hurricane Bret were to occur today, it is estimated that about 5000 people on mainland Corpus Christi would be directly impacted by inundation to their property. Projections for the 2030s indicate that an additional 500 to 1700 people (about a 10%–30% rise) would be directly impacted by SLR and hurricane intensification, when no barrier island degradation is assumed. For the case of future barrier island degradation, population impacted rises an additional 1000 to 1300 over the no-degradation estimates, representing a 15–25% increase over the no-degradation case. Projections for the 2080s when no barrier island degradation is assumed indicate that an additional 4400 to 6100 people (about a 90%–120% rise) are directly impacted, with respect to present-day (2000s) conditions. This analysis indicates that potential future barrier island degradation has minimal impact on 2080s projections of total population impacted. Here, differences between the no-degradation and degraded cases give less than a 3% (200 people) increase in population impacted.

To infer the degree to which people are impacted by a given hurricane-climate scenario, changes with initial barrier island conditions, the population data were evaluated based on degree of flooding as defined below:

- Nuisance Flooding: Flooding of the area, but below home or building foundation elevation (<0 m flood depth, with respect to foundation elevation). People in this category are assumed to evacuate, but be able to return home shortly after the hurricane event.
- Minor Flooding: Flooding to depths between 0 and 0.9 m above the foundation elevation. People in this category are assumed to evacuate, but minor property damages will preclude immediate return to their home after the hurricane event.
- Major Flooding: Flooding to depths between 0.9 and 1.5 m above the foundation elevation. People in this category are assumed to evacuate and be displaced from their home, due to major property damage, for some period of time following the hurricane event.
- Catastrophic Flooding: Flooding to depths more than 1.5 m above the foundation elevation. People in this category are assumed to evacuate and experience catastrophic levels of damage to their homes. It is assumed that these people would be either displaced from their home for a significant period of time following the hurricane event or displaced permanently.

Fig. 10 shows that under present-day (2000s) conditions, most people directly impacted by a hurricane like Hurricane Bret experience Nuisance or Minor Flooding. Assuming no barrier island degradation, by the 2030s, relatively more people are impacted by Minor Flooding than by Nuisance Flooding. Inclusion of future barrier island degradation in the 2030s projections, substantially increases (by 30%–40%) the number of people experiencing Nuisance Flooding but has less of an impact on the number of people experiencing Minor Flooding (increasing 8%–12%). The 2030s projections for people experiencing Major Flooding increases by 18%–26% when barrier island degradation is considered, with respect to the no-degradation case. For the middle 2080s projection, while changes in overall population impacted are small, the number of people falling into Minor Flooding or more severe categories rises by 13% when barrier island degradation is considered. For higher 2080s projections, little change is predicted between the no-degradation and degraded barrier island cases.

6. Discussion and conclusions

Based on the above simulations and geospatial analysis, we conclude that potential future barrier island degradation with SLR can have a significant impact on future hurricane flooding, inundation, damages, and population impacted at the coast. However, the results also indicate that the relative sensitivity of bay flooding to exact barrier island geometry diminishes for larger hurricane surge events. Based on the results presented above, we conclude that if future global warming scenarios are realized and barrier islands undergo natural degradation with SLR, flooding by moderate hurricane surge events, such as the Hurricane Bret scenarios considered here, may rise between 20% and 70% by the

2030s, with respect to present-day (2000s) estimates. This rise in flood elevation by the 2030s is projected to increase property damages by 150% to more than 300% and increase population impacted by 230%–290%.

The methodology presented in this paper is transparent to location. It can be readily applied to any location where adequate property and topographic data are available. The surge and wave analysis from the different scenarios presented can be easily transferred to alternate destinations worldwide. Without adequate property data, HAZUS or similar data could be employed. The local sea level projections may also need to be modified based on local relative SLR. The examples of similar analyses by Church et al. [40] for Sydney, Australia, Cooper [35] for the populated coast of New Jersey, and Gornitz et al. [37] for New York City clearly illustrate typical major urban areas that would be impacted by relative SLR and climate change. The methodology is also suitable for application in areas prone to SLR and non-tropical storms such as Europe (e.g., Venice) and the Nile Delta region of Egypt.

Possibly more susceptible to adverse impacts of SLR and climate change are those coastal communities in developing countries. For example, more than 25,000 km^2 of coastal land (from 0 to 3 m MSL) in Central America, Mexico, and the Caribbean are vulnerable to hurricane activity. In India and Bangladesh about 13,000 km^2 of coastal land is subjected to tropical cyclones while about 6000 km^2 is vulnerable on the island of Madagascar. Existing infrastructure, current management strategies, and lack of resources in these regions means that these regions will not likely be able to withstand even small incremental changes in SLR and tropical cyclone climate. Furthermore, population density and projected growth in some of these regions is high. For example, population density in India is projected to increase from a very dense 369 people per km^2 in 2010–465 people per km^2 in 2035, a 20% rise [53]. Population density in Central America is projected to rise about 40% by the 2030s while population in Madagascar is projected to rise by more than 70% by the 2030s [53]. This population growth amplifies the impact of increased flood probability with SLR and climate change in that the relative increase in risk to lives and livelihoods will be higher in areas of higher population growth, with respect to areas with little or declining (e.g., Australia) growths [53]. This suggests the clear importance of the need to consider the broad probabilities of occurrence to bring focus to the risk in these areas where the consequences are very high.

It is not possible, however, to always associate areas prone to hurricane damages to poor and marginalized segments of the coastal populations. Even though that has been observed; for example, in the case of Hurricane Katrina, the devastating impact of hurricane flooding might have been associated more to lack of property insurance or of resources to respond to the event than to the severity of the flood itself. In addition to the direct property damage presented here, flood damage also involves other social and economic impacts, which were not discussed here because they were considered beyond the scope of this paper despite being of critical importance. The analysis presented here also considers only one highly simplified possible future degraded barrier island scenario and considers only damage due to wind- and pressure-generated surge, wave setup, and SLR. If very high rates of SLR are realized over the coming years, such as those that could result if major ice-sheet melting occurs (e.g., [12]) or if groundwater extraction increases with population growth, more severe barrier island degradation scenarios, including inlet and islet formation, could develop. Such severe changes in the barrier island landscape may result in higher flood elevations and associated impacts than those reported here.

Conversely, if adaptive management strategies are adopted through engineering and planning activities such as beach nourishment, these protective barrier islands may be maintained. Other engineering and planning strategies to limit coastal flooding and strengthen the resilience of barrier islands to climate change and relative SLR include:

- Implementing setbacks;
- Using sand fencing and active planting of grasses on barrier island dunes to capture Aeolian sand transport and increase island elevation;
- Using measures to reduce trampling of dunes and vegetation through dune and beach walkovers;
- Eliminating sand and gravel mining of beaches and river systems within the regional littoral system;
- Constructing living vegetated shorelines on the bayside of barrier islands to capture wash over sand within the subaerial island and to build a platform onto which the island can migrate;
- Eliminating subsurface fluid withdrawal;
- Eliminating vessel wakes that erode bay shorelines; and
- Mandating placement of beach-quality sediment that is dredged within the littoral zone, whether trapped behind dams or dredged from navigation channels.

Such engineering and management activities on the barrier islands, when coupled with flood management strategies on the mainland, have the capacity to minimize the potential impacts of global warming on future hurricane flooding.

In conclusion, the results of this study indicate that the potential implications of global warming on hurricane flooding are severe when protective barrier islands are left to degrade naturally. It is thus prudent to consider adaptive management strategies to preserve and restore these island features in populated coastal regions. For example, expenditures for future beach nourishment activities should be measured against the benefit such activities provide in terms of reduced flooding and damages in light of SLR and increased hurricane surge probability. Future research and planning when considering the potential implications of global warming and barrier island degradation should also consider human demographic trends of the coastal population such as degradation of the critical infrastructure including protective ecosystems, as well as additional physical damages induced by wind, direct wave action, and inland precipitation.

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The influence of coastal wetlands on hurricane surge in Corpus Christi, TX

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1. Introduction

Hurricanes pose one of the largest natural threats to communities along the Texas coast, as was demonstrated when Hurricane Ike made landfall in Galveston this September. While it is widely acknowledged that coastal natural resource areas (CNRAs), such as beach and barrier island dunes and coastal wetlands, provide some level of protection against hurricane damage, the exact role that wetland and dune restoration and degradation play in changing inundation and property damage is not fully understood.

It is believed that coastal wetlands might reduce the impact of the storm surge on coastal areas, acting as a natural protection against hurricane flooding. The potential of wetlands in reducing storm surge in Louisiana was investigated by Wamsley *et al.* (2010), and the studies carried out by Loder *et al.* (2009) demonstrated the importance of correctly representing wetlands on storm surge calculations. Also, hurricane related storm surge hazards generally occur when the storm surge floods areas where the infrastructure is not well designed or the society is not prepared for it. Thus, it is crucial to evaluate the potential protection provided by wetlands against storm surges, especially in relation to demographics, infrastructure and economic activities.

The objective of this research is to quantify the effect of wetlands, described by their physical parameters (e.g., elevation, aerial extent, frictional resistance), on surge inundation, considering their adjustment to new climate conditions.

2. Background

2.1 Effects of wetlands on hurricane surge modeling

As the datasets of historical extreme events are too short to calculate reliable statistical predictions of coastal flood levels, numerical analysis is an important instrument for predicting and simulating the flooding extent and magnitude in coastal areas. In recent years, improvements in the understanding of the physics of storm surges have led to the development of physically based numerical models capable of reasonably representing the storm surges caused by hurricanes (e.g., Resio and Westerink, 2008).

There is a wide variety of numerical models that simulate hurricane storm surges, for example: the Sea, Lake, and Overland Surge from Hurricane (SLOSH) (Jelesnianski et al. 1992); the Advanced Circulation (ADCIRC) model (Luettich and Westerink, 2004); the Eulerian-Lagrangian circulation (ELCIRC) (Zhang et al. 2004); and the fully non-linear Finite Volume Coastal Ocean Model (FVCOM) (Chen et al., 2003).

Many studies investigated storm surges using numerical models (Irish et al., (2005); Mattocks and Forbes (2010) Rego and Li (2010); Westerink et al., (2008); and Ebersole et al., (2010); Xu et al., (2010)) and many authors are investigating the effect of wind waves to storm surge modeling (Chen et al., (2007); Huang et al., (2010); Dietrich, et al. (2010); Bunya et al., (2010) and Dietrich et al., (2011)).

The effect of wetlands on storm surges was evaluated by the United States Army Corps of Engineers (USACE, 1963) for southern Louisiana. Although the report suggests a simplified rule of thumb stating that the storm surge is attenuated by one meter for each 14.5 km of marsh as the surge propagates inland, Resio and Westerink (2008) pointed out that this phenomenon is more complex than this linear relation and the propagation of the storm surge inland depends on many factors such as momentum balance, storm track, size, duration, forward speed, waves, bathymetry, topography, local surface roughness and geometries. Experimental studies carried out by Nepf (1999) supported the development of a model to represent drag, diffusion and turbulence of flow through emergent vegetation.

Previous research, considering hypothetical wetland formation in an idealized bathymetry, carried out by Loder *et al.* (2009), evaluated the sensitivity of water levels to marsh bottom friction, marsh elevation and marsh continuity using six storms and found that these parameters have a definite effect on peak surge levels. Wamsley *et al*. (2010) found that, for the Louisiana coast, the effectiveness of wetlands in attenuating the storm surge is primarily dependent on the surrounding landscape and storm characteristics. The effectiveness of wetlands restoration and degradation to reduce storm surge was also investigated by Wamsley *et al.* (2009) for the southern Louisiana coast.

The impact of climate change and respective sea level rise (SLR) on wetlands and coastal marshes has been investigated by Chu-Agor *et al.* (2011), Craft *et al*. (2009) and Galbraith *et al.* (2002). More specifically, Smith *et al.* (2010) investigated the impact of SLR on hurricane storm surges along the coast of Louisiana incorporating wetlands change from SLR and Mousavi *et al.* (2011) used a method to infer hurricane intensity from global warming scenarios and investigated its effects on storm surge in Corpus Christi, TX.

2.2 Hurricane flooding damage assessment

A catastrophic event is most likely to be remembered by its social impacts and the damages it causes rather than by its return period, flood intensity or magnitude. Location matters when determining the impact of a hurricane or its risk, which is the product of the probability of flooding times the damage (Jonkman *et al.,* 2008). The flood damages are usually classified as tangible (easily evaluated in economic terms), or intangible (difficult to express in economic terms), and direct (caused by physical contact with the water), and indirect losses (economic and social impact caused by the flood).

A common method for evaluating flood damage from flooding is by using depth-damage functions. These functions usually relate flood water stages to percent damage for a given structure and are derived from post-event surveys, analyses of insurance claims, and historical flood data analyses (Nadal *et al.*, 2010).

An application for damage estimation in the United States is HAZUS-MH (Hazards US Multi Hazard) developed by the Federal Emergency Management Agency (FEMA) in 2004 (Schneider *et al.*, 2006). It includes modulus to evaluate damages caused by winds, earthquakes and floods. A validation of the HAZUS-MH model is presented by Ding *et al.* (2008) for a watershed in

Harris County, TX, where they concluded that a HAZUS Level 2 analyses (enhanced national inventories with local information) provided a reliable analyses compared to the data of the Federal Flood Control Project. Longenecker (2009) investigated the validation of the HAZUS methodology with Hurricane Katrina surveyed damage data.

Duta *et al.* (2003) developed a mathematical framework that combines distributed hydrological modeling and damage assessment, also using depth-damage curves, to evaluate damage in Japan. Wood *et al.* (2005) also used a depth-damage approach to evaluate damage on the coastal UK, and Seifert *et al.* (2010) developed the application FLEMOcCS to estimate flood losses specifically to the commercial sector.

Several applications of the above mentioned methods can be found in the literature (Schiller, 2011; Jonkman *et al.*, 2008; Frey *et al.*, 2010; Brody *et al.*, 2007; Elmer *et al.*, 2010). Newly proposed methods are incorporating different factors to calculate flood damage; for example, Jonkman *et al.* (2008) proposes a comprehensive methodology to evaluate loss of lives during a flood event, and Nadal *et al.* (2010) proposed a method to infer damage to building structures considering water velocity, wave action, debris impact and foundation scour.

2.3 Study Area

A case study was developed for the counties of San Patricio and Nueces in Texas. The city of Corpus Christi is located in Nueces County and has faced a number of episodes of hurricanes (i.e., Beulah in 1967, Bret in 1999 and, most recently, Alex in 2010). Both counties are located on the margins of Corpus Christi Bay and Nueces Bay, which are connected to the ocean water through inlets on the barrier island that protect the bays.

Figure 1: Nueces and San Patricio Counties along the Gulf of Mexico Texas coast.

3. Methodology

The effects of wetlands on storm surge was analyzed using different wetland databases (historical, current and expected future) and quantified using numerical simulation forced by historical and hypothetical hurricanes. A framework was developed to integrate hydrodynamic modeling of storm surges and GIS. Using this framework, we performed a damage assessment analyses that quantified the benefits/losses caused by different wetlands compositions. The overall research framework is presented in Figure 2.

3.1 Wetland characterization

To characterize the wetland type and define its spatial distribution along the coast, we used three different land use databases: 1) the National Land Cover Dataset (NLCD) for 1992 and 2001 (Vogelmann *et al*., 1992 and Homer *et al.,* 2004); 2) the National Wetlands Inventory (NWI) for 1993; and 3) the Coastal Change Analysis Program (C-CAP) for 1996, 2001, 2006 (NOAA).

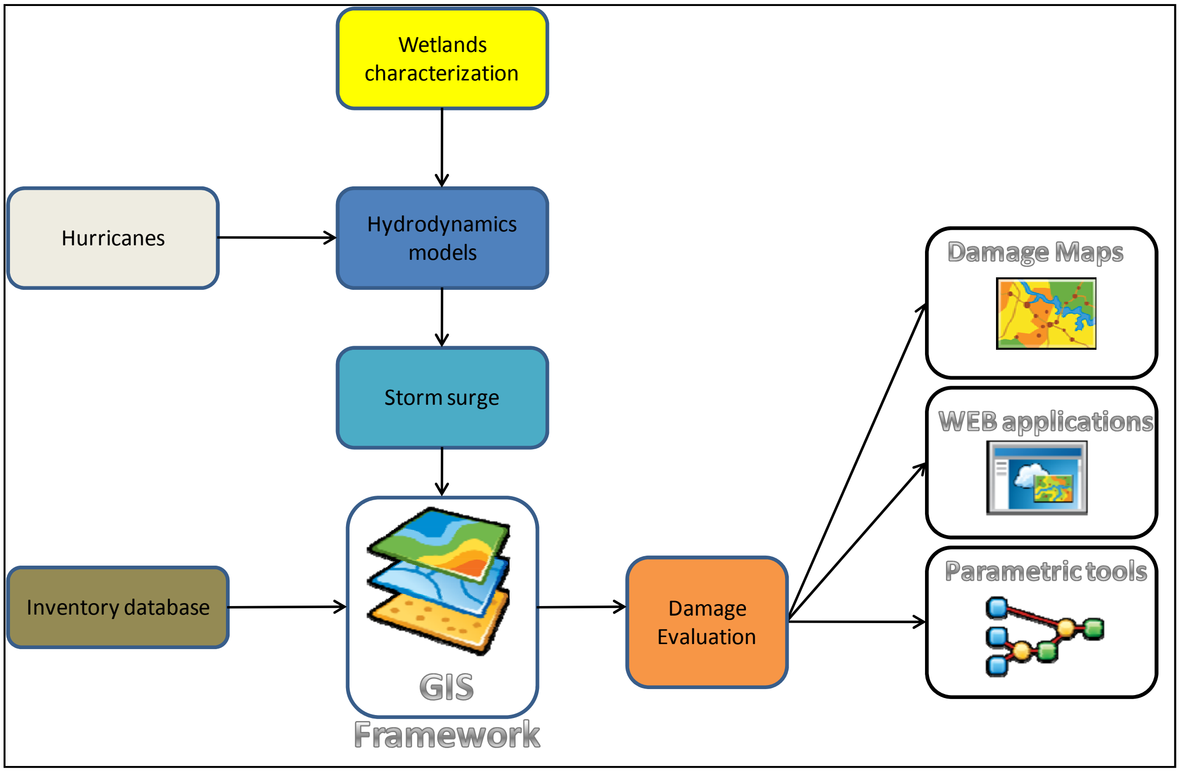


Figure 2: Overall research methodology. Wetlands are characterized within the hydrodynamic model force by hurricane wind and pressure to calculate storm surge. An infrastructure inventory database is used for damage evaluation. The results are presented in damage maps and damage analyses

Wetlands are represented in the numerical model through its influence on the frictional resistance properties. Both the bottom friction stress and the surface wind stress are represented in the numerical analyses. The bottom stress is accounted for by using a non-linear bottom drag coefficient as a function of the Manning's *n* of the surface roughness (Equation 1). The surface stress caused by the wind is represented by the surface canopy coefficient, which symbolizes a blocking factor to wind stress over the water surface according to the wetlands structure.

$$\overrightarrow{\tau_b} = \frac{C_f \vec{U}|\vec{U}|}{h} \qquad (1)$$

where C_f is a function of the Manning's *n* friction coefficient.

The conversion from the wetland classification to the respective Manning's *n* coefficient is based on the relationship proposed by Leuttich and Westerink, (2004) and Tsihrintz and Madiedo (2000), and implemented using a Geographical Information System (GIS) scheme to convert the wetlands information to the numerical model grid node. The same methodology is used to estimate the surface canopy coefficient (Figure 3).

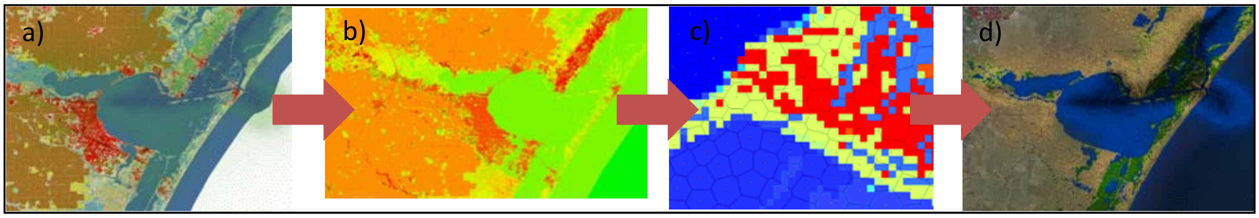


Figure 3: Representation of the conversion of Land Cover database to friction forces. a) Land cover dataset; b)Bottom Friction coefficient; c)Finite Element Grid conversion; d)Updated Finite Element Grid.

3.2: Climate change scenarios

The climate change and sea level rise analyses is based on three factors: 1) Hurricane intensification based on sea surface temperate increase; 2) wetlands alterations based on sea level rise; and 3) future land use for the City of Corpus Christi.

We considered three emissions scenarios defined by the Intergovernmental Panel for Climate Change (IPCC, 2007) to evaluate climate change for year 2080: 1) B1 low rate of green house gas emissions; 2) A1B mid range emissions scenario; and 3) A1FI highest emissions scenario (IPCC, 2007).

The hurricane intensification parameterization is based on recent climatic research (e.g.: Knutson and Tuleya (2004, 2005), Knutson *et al.* (2000, 2007), and Elsner *et al.* (2008)) and on previous research carried out by our research group (Mousavi et. al., 2011), in which a relationship between sea surface temperature increase and change in hurricane central pressure was developed for the above mentioned scenarios.

The effects of sea-level rise on wetlands was quantified using a geospatial analyses based on a simplified approach of the habitat model Sea Level Affecting Marshes Model (SLAMM 5). Using a geospatial wetlands database (e.g., C-CAP 1996) as a initial condition, we estimated the ultimate wetlands spatial distribution and composition for the three different climate scenarios, by considering only the dominant process involved in wetlands conversion, inundation (curves for depth variation / predominant wetland type), In this study we neglected erosion, overwash and accretion.

The projected land use based on the City of Corpus Christi Future Master Plan developed to guide the city planning for 2050 (City of Corpus Christi, 2010) was merged with the hypothetical wetlands scenarios developed on the previous step and used to update the friction parameters of the hydrodynamics model.

The effects of SLR are taken into account within the hydrodynamics model by increasing the base water level above the current mean sea level for the entire model domain. The surge is then calculated considering only the water levels above the mean sea level at the time of the storm. The effects of SLR on surge take into effect only the variation after the increase in the mean sea level not considering the SLR itself. The flood level calculation takes into consideration the total water level with respect to the NAVD88 vertical datum (Figure 4).

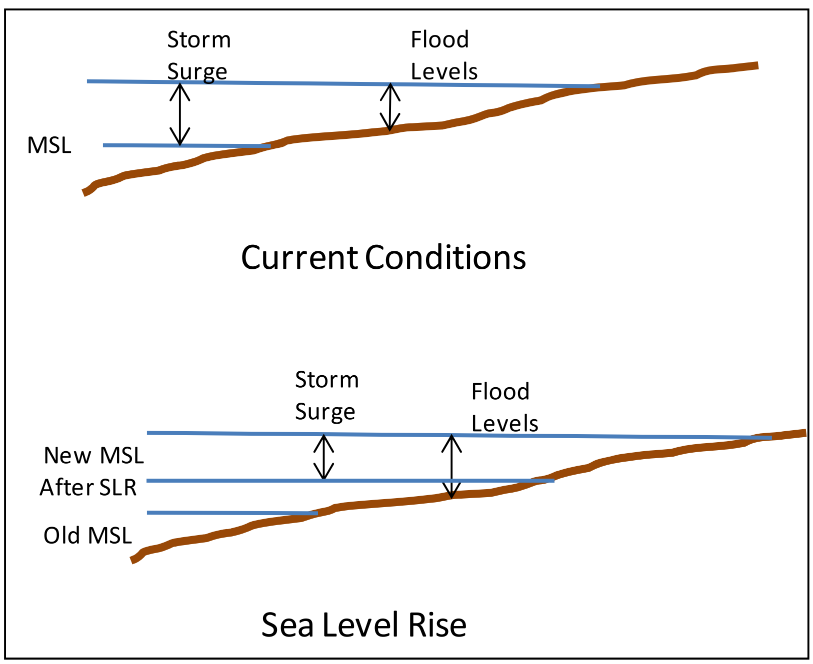


Figure 4: Conceptual model defining storm surge and flood levels.

3.3: Numerical modeling

FEMA recommended the coupling of hydrodynamics models with wave models to decrease uncertainty in determining water levels for coastal flooded areas. One preeminent coupling of surge and wave numerical models is the coupling of the Advanced Circulation (ADCIRC) model and the wave model SWAN (Dietrich *et al.*, 2011).

The ADCIRC model (Luettich and Westerink, 2004) is a physically based, continuous-Galerkin, finite element, shallow water model that solves for water levels and currents at a range of scales and is widely used for storm surge modeling (e.g.: Ebersole *et al.*, 2010). SWAN is a third generation spectral wave model that computes random, short crested wind-generated waves in coastal regions and inland waters (Booij *et al.*, 1999). The SWAN model has recently been updated to support the use of unstructured grids (UNSWAN).

We used the two dimensional depth integrated (2DDI) version that solves the Generalized Wave Continuity Equation (GWCE) (Eq. 2) and the vertically integrated momentum equations (Eq. 3). The surface stresses are represented in the momentum equation as τs due to winds, τw due to waves, and τb due to bottom friction.

$$\frac{\partial h}{\partial t} + \nabla_h(\vec{U}h) = 0 \tag{2}$$

$$\frac{\partial \vec{U}}{\partial t} + (U \bullet \nabla_h)\vec{U} = -g\nabla_h\left(\zeta + \frac{p(x,y)}{g\rho}\right) + f\,\hat{k} \times \vec{U} + \frac{\vec{\tau_s}}{h\rho} - \frac{\vec{\tau_b}}{h\rho} + \frac{\vec{\tau_w}}{h\rho} \tag{3}$$

The coupled version of ADCIRC and UNSWAN uses the same unstructured finite element numerical grid for both models. The wave model is forced by wind, and the surge model is forced by wind and pressure fields. Tides and river inflow are not considered in the analyses. The general framework for modeling storm surge using ADCIRC+UNSWAN is presented in Figure 5.

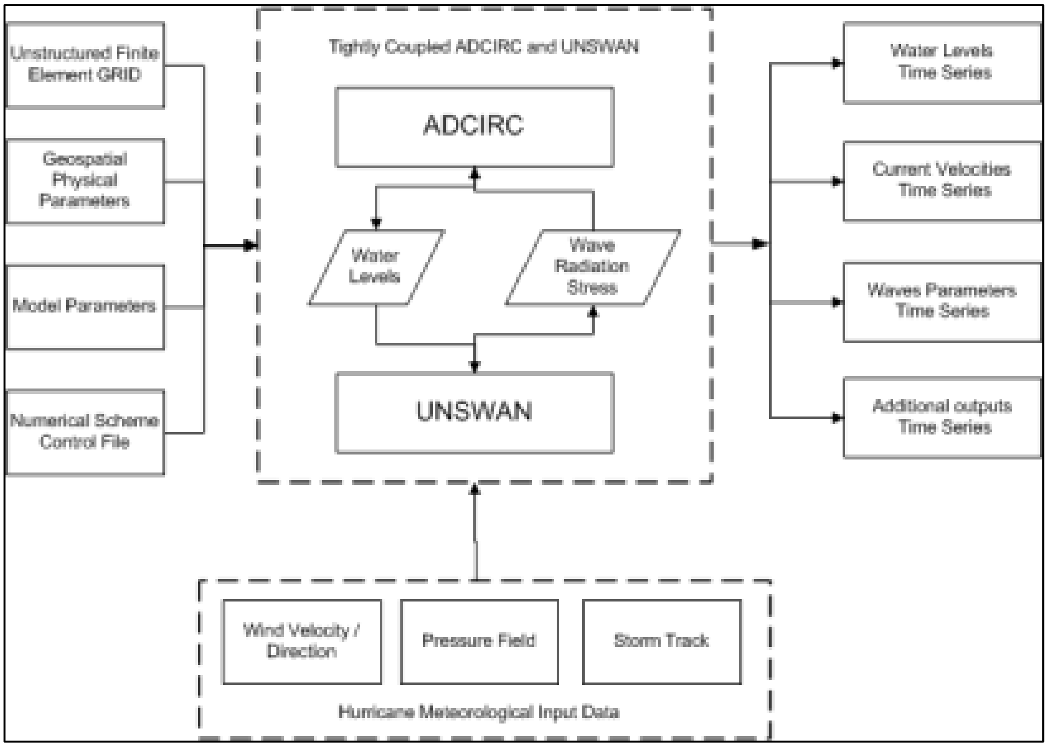


Figure 5: Numerical simulation framework.

3.4 Hurricane forcing

Wind and pressure are the main forcing components in hurricane storm surge simulations. Cardone and Cox (2009) investigated the application of wind and pressure fields for ADCIRC forcing. In this study, the Planetary Boundary Layer Model (PBL) developed by Thompson and Cardone (1996) is used to generate wind and pressure fields representing the physical properties of historical hurricane Bret. The storm track of Hurricane Bret considered here is presented in Figure 6. Also, we incorporated the parameters developed by Knutson and Tuleya (2008) representing hurricanes modified by climate change for the region of Corpus Christi (Figure 7).

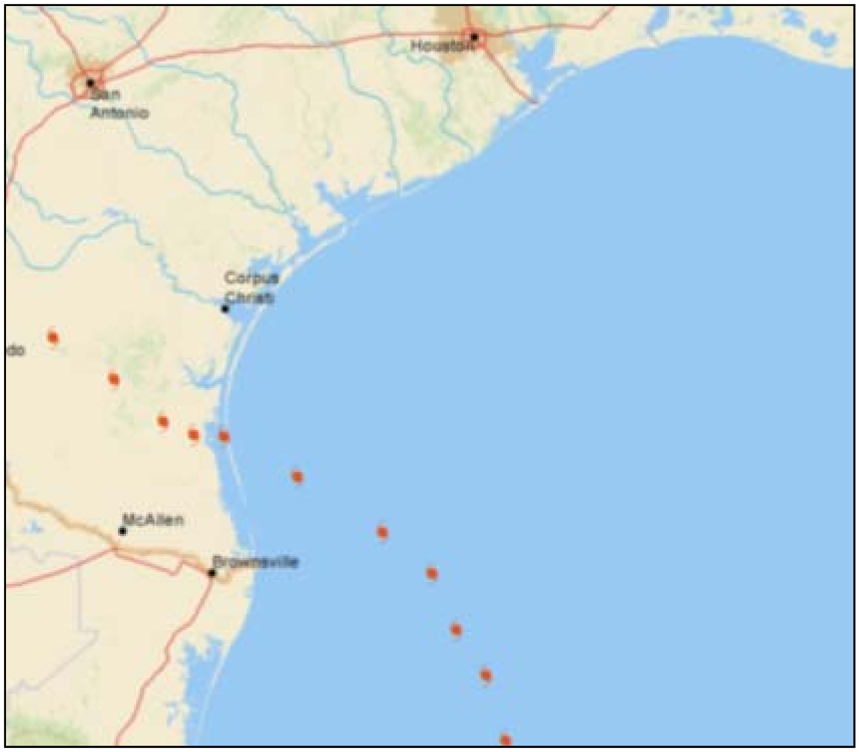


Figure 6: Hurricane Bret storm track

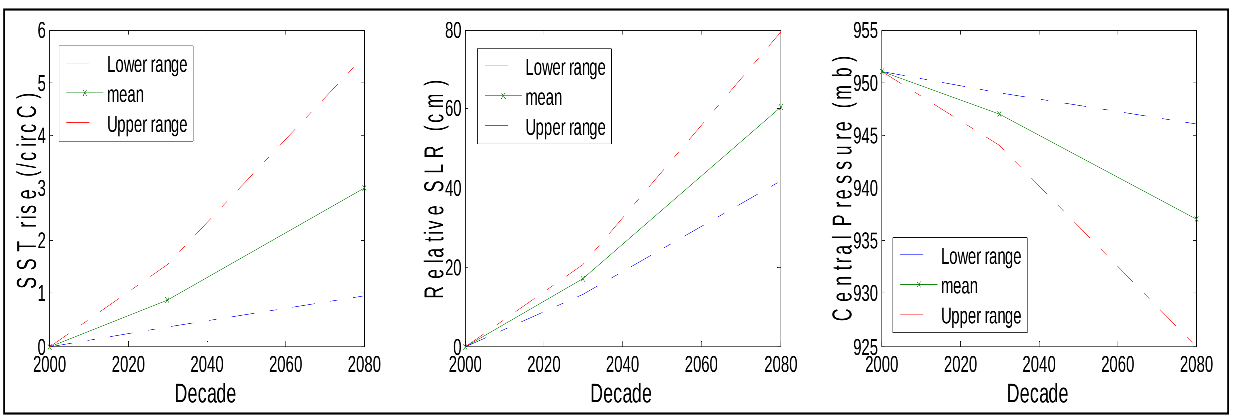


Figure 7: Projected Sea Surface Temperature (SST) change, relative Sea Level Rise (SLR) and predicted Hurricane Bret central pressure intensification

3.5 Hurricane surge damage assessment

We evaluated damage based on the depth-damage functions approach. This approach consists of relating water depth at a given location to a percentage of damage. A Geospatial analysis was used to relate spatially the flood depth with facilities.

The damage evaluation was carried out programmatically using PYTHON, FORTRAN and ArcObjects in a GIS framework built upon the basic functionality of HAZUS.

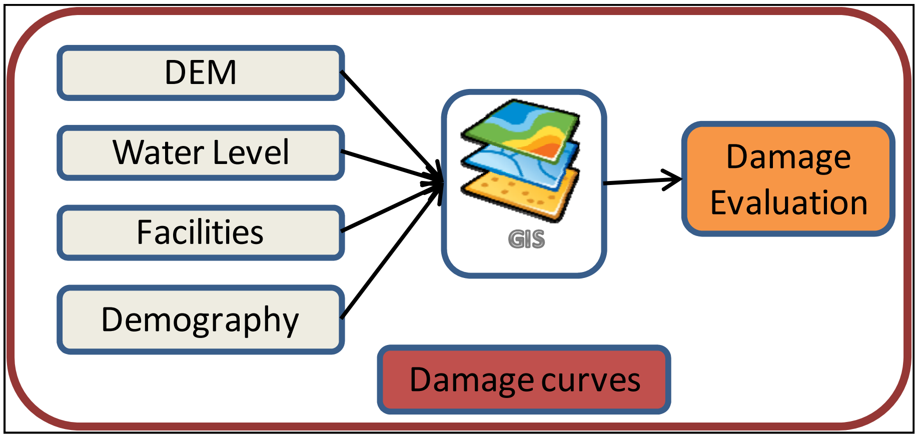


Figure 8: Overall methodology for damage assessment

The hydrodynamic modeling of storm surge calculates water levels for every node in the numerical model. We used GIS to convert water levels to water depths spatially distributed within the study area. We are considering three sources of topographic data to calculate water depth. The first source is the model topography/bathymetry itself developed for the FEMA floodmap studies. These data have the advantage that it matches the original data used in the hydrodynamic calculation but they are sparsely distributed in points over the study area. The second source of topographic data was the USGS 10-meter DEM of the counties. The third and more detailed data used is the LiDAR data already gathered for most of the area. The final DEM was developed based on the three sources and defined as the best available data.

The built-environment inventory was taken from the HAZUS-MH geodatabase. These data was organized by census block and tracts and provides information of buildings, including their use (e.g., residential, commercial, industry), agriculture areas, churches, educational centers, emergency response units, essential facilities (hospitals, police, fire department), high potential loss facilities (dams, nuclear plants, etc), transportation systems (roads, bus, train, ports, etc), services systems (water, waste water, oil, etc), vehicles and also its modules for social and economical analyses that are based on the previously calculated facilities damages.

Figure 9: HAZUS Geodatabase for Nueces and San Patricio County

An enhanced geodatabase was developed including the county parcel databases with more detailed data for the building stock. Also, commercial data were incorporated from the Reference USA database that provides data on economic activities within the county, with the exact location of each business and it revenue and other economic information (Figure 10).

The building value was estimated as the difference of the property total current assessed value and the current assessed land value for each parcel. The parcels with no data for any of the other fields were excluded from the analyses.

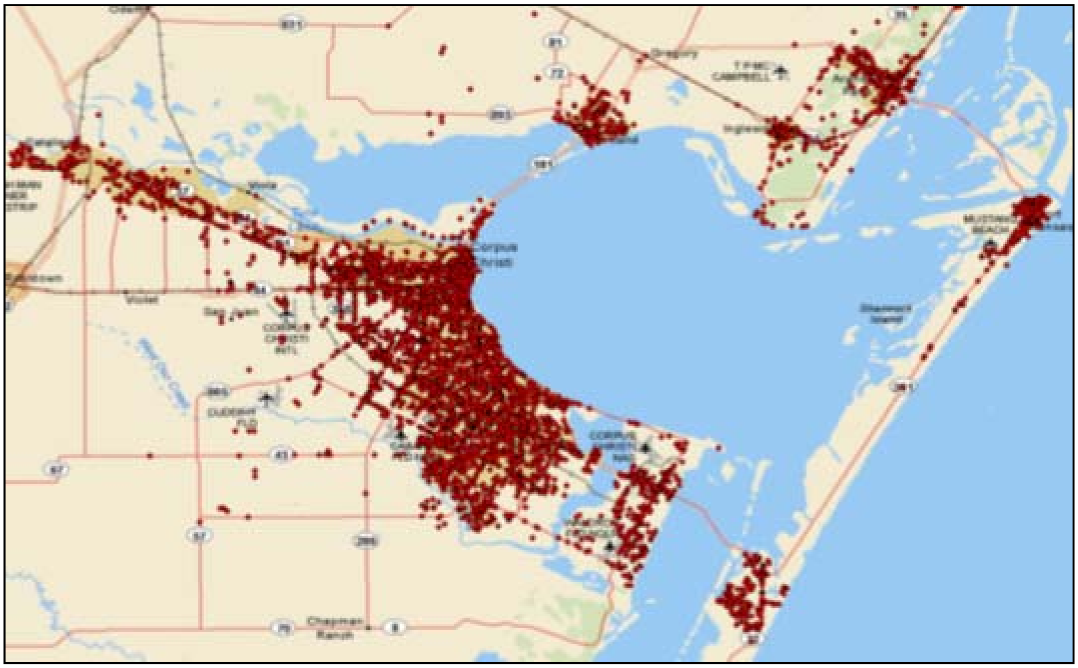


Figure 10: Overall research methodology

The damage curves were selected from the Federal Insurance Administration (FIA) fragility weighted curves and also from various U.S. Army Corps of Engineers (USACE) previously defined curves (Scawthorn *et al.*, 2006). An example set of these functions is plotted in Figure 11.

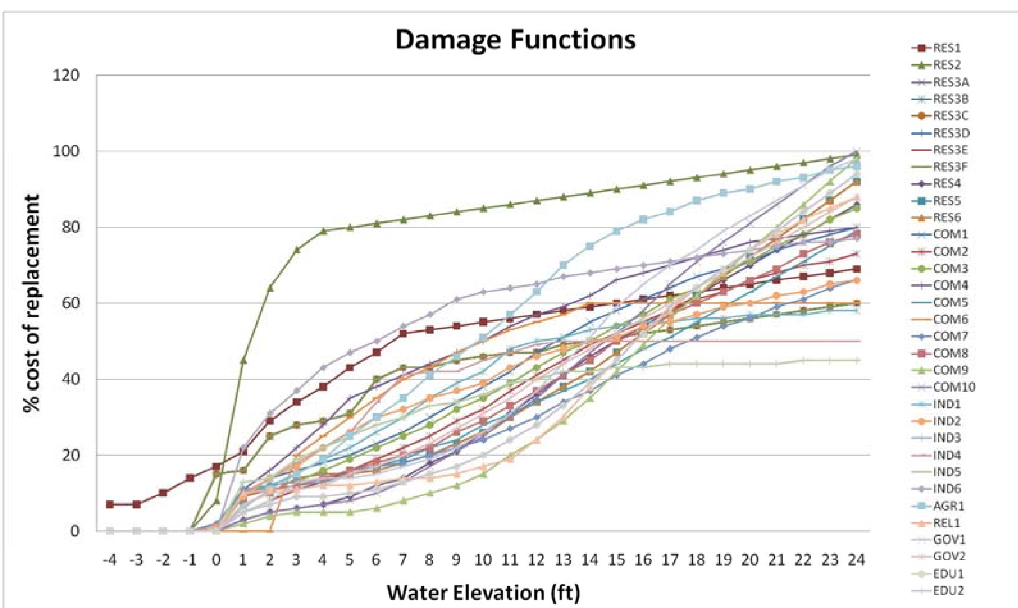


Figure 11: Selected depth-damage curves

The business damage was based on a subjective classification scheme that represented the severity of the flooding at a given point. The classification is used to infer the total number of businesses affected between ranges of flood heights. Table 1 presents the relation between water levels and the flood index.

Table 1: Classification scheme for business flooding

Water Depth (meters)	Definition
Below Foundation	Nuisance Flooding
0 ~ 0.9	Minor Flooding
0.9 ~ 1.5	Major Flooding
Greater than 1.5	Catastrophic Flooding

4. RESULTS AND DISCUSSION

The results section is sub divided into an analysis of the sensitivity of the surge calculations to the choice wetland databases, an evaluation of the impact of climate change on storm surge and damage, and an analysis of hypothetical restoration projects. The results were analyzed for 121 monitoring points along the study area as shown in Figure 12.

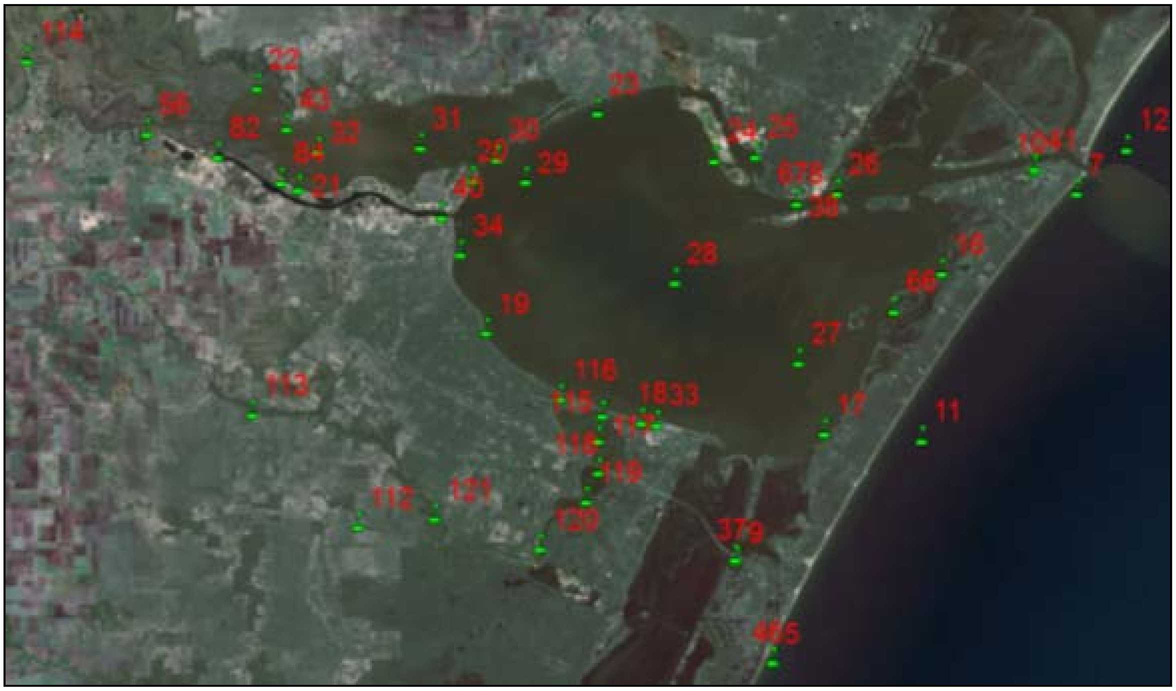


Figure 12: Monitoring points for recording simulated water levels.

4.1 Sensitivity of Wetlands Databases

We repeated the storm surge simulations using the same numerical and meteorological conditions for every wetland database. In general, the choice of wetland database did not affect significantly the water levels, but the sensitivity analyses (very high and low frictions) demonstrated the importance of representing well this parameter within the storm surge model.

An example of the temporal variation of bottom friction, directly related to land use changes, can be observe in Figure 13, where we plotted the spatial difference in friction between the NLCD databases for 1992 and 2001. The greater difference is found in the urbanized areas and some altered coastal ecosystems.

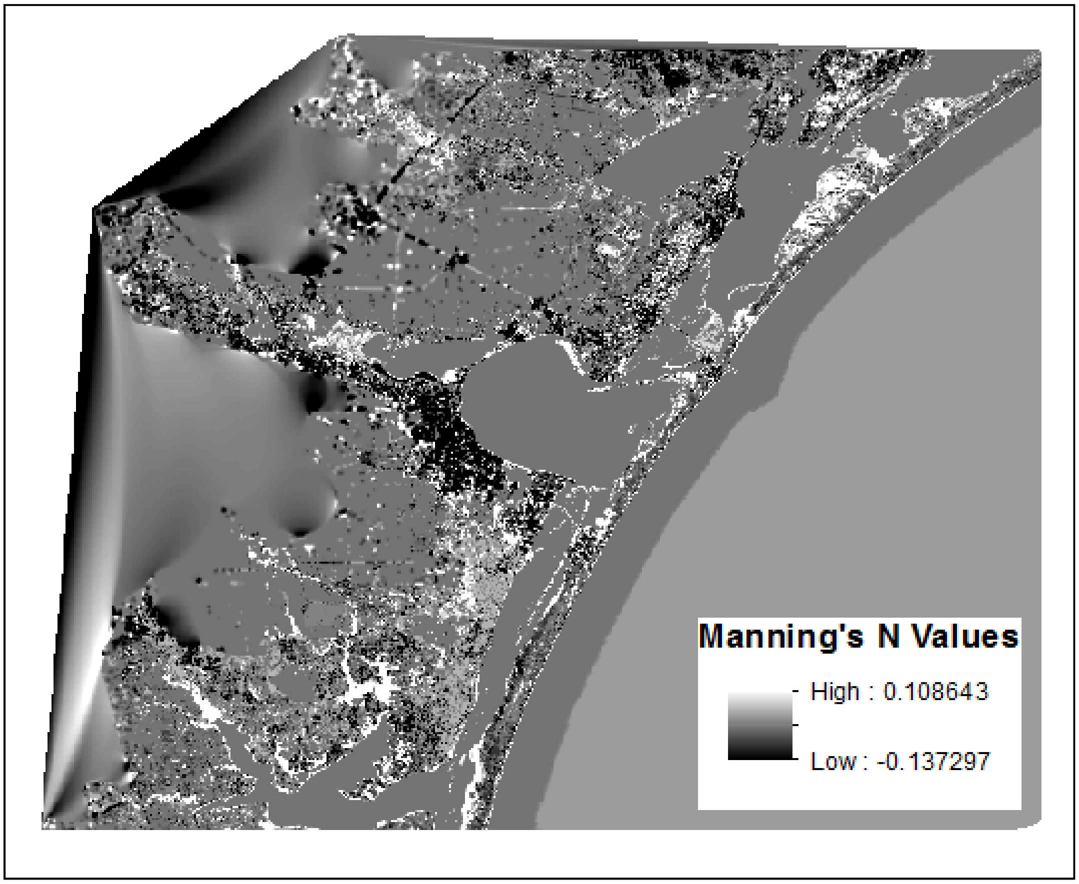


Figure 13: Difference in bottom friction represented by Manning's comparing the National Land Cover dataset from 1992 and 2001.

Considering the sensitivity analyses results (very high and low friction coefficients), at the margins of Nueces Bay, which is the most inland part of the bay system, the storm surge was more influenced by the Manning's n coefficient selection, especially regarding the very high and low values. The maximum water level varied from 0.5 meters to 1.9 meters at the same location for very high and very low friction coeficients. As expected, very high friction coefficients resulted in low surges at the margins of Nueces Bay, as the surge propagation encountered considerable amount of friction along its way. That also produced a lag in time causing a delay in the beginning of the water rise. At the margins of Corpus Christi Bay, less time delay was observed even in the high Manning's n scenario and the maximum water levels varied from 0.6 meters to 1.5 meters.

The differences between the scenarios using the NLCD, C-CAP and NWI datasets were almost negligible at most monitoring points. Behind the barrier island, the high friction coefficients resulted in almost no surge, and the other scenarios presented trends very similar to each other apart from the hypothetical very high and low friction scenarios (Figure 14).

The wind stress analyses presented trends similar trend to the bottom friction but with lower surge variation. Considering the very high and very low surface canopy coefficients, inside Nueces bay, the lower water level was 0.4 meters and the higher water level for the same monitoring point (number 20) was 1.2 meters. At the monitoring points behind the barrier island the water levels varied from 0.8 meters to 0.4 meters.

The choice of wetlands dataset also did not affect significantly the surge results considering the wind stress parameterization.

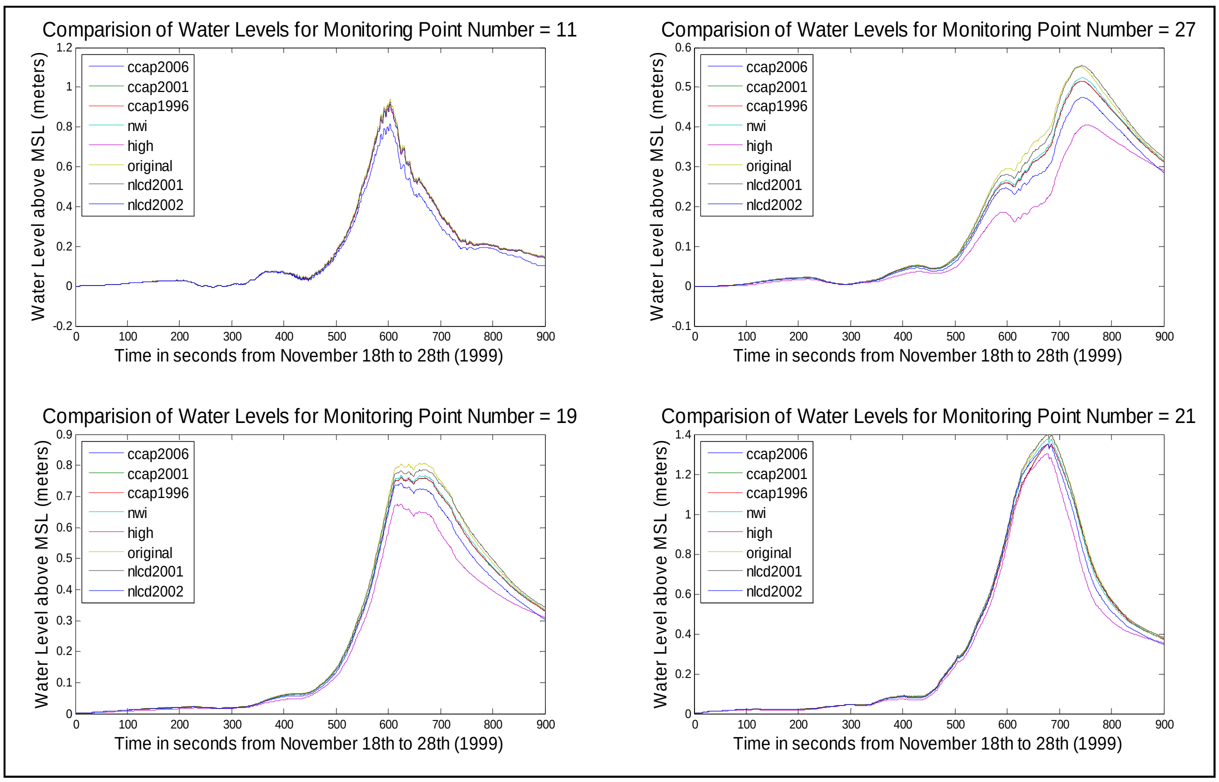


Figure 14: Water levels at selected monitoring station for the wetland databases tested

4.2 Impact of Climate Change on Storm Surge

The impact of climate change was analyzed by considering the effects of SLR and a hypothetical intensification of Hurricane Bret. Those effects were first analyzed separately and then together.

The long-term effect of SLR on wetlands was spatially simulated before the hurricane storm surge simulation. The newly created friction maps were then used as an input for the hydrodynamics model. An example of the results of the SLR wetland simulation is presented on Figure 15 for the C-CAP database.

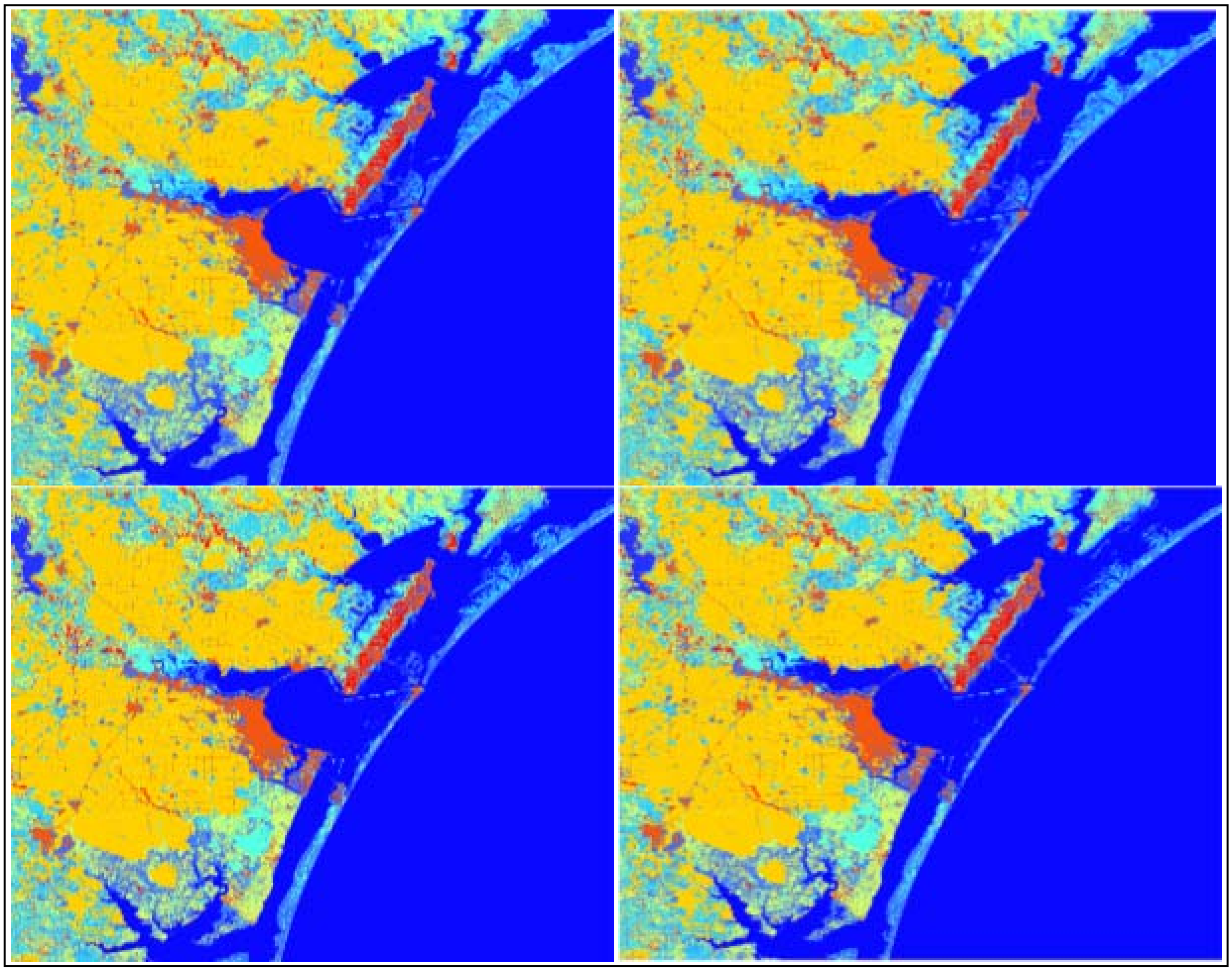


Figure 15: Impact of Sea Level Rise on wetlands considering the C-CAP 2006 database. a) SLR of 0.14 meters; b) SLR of 0.208 meters; c) SLR of 0.578 meters; d) SLR of 0.793 meters

The total loss of wetlands from the present conditions to the highest SLR scenario is presented in Figure 16. It can be observed that the higher losses were at the delta of the Nueces River and around Port Aransas. The areas behind the barrier island were also highly impacted by the SLR.

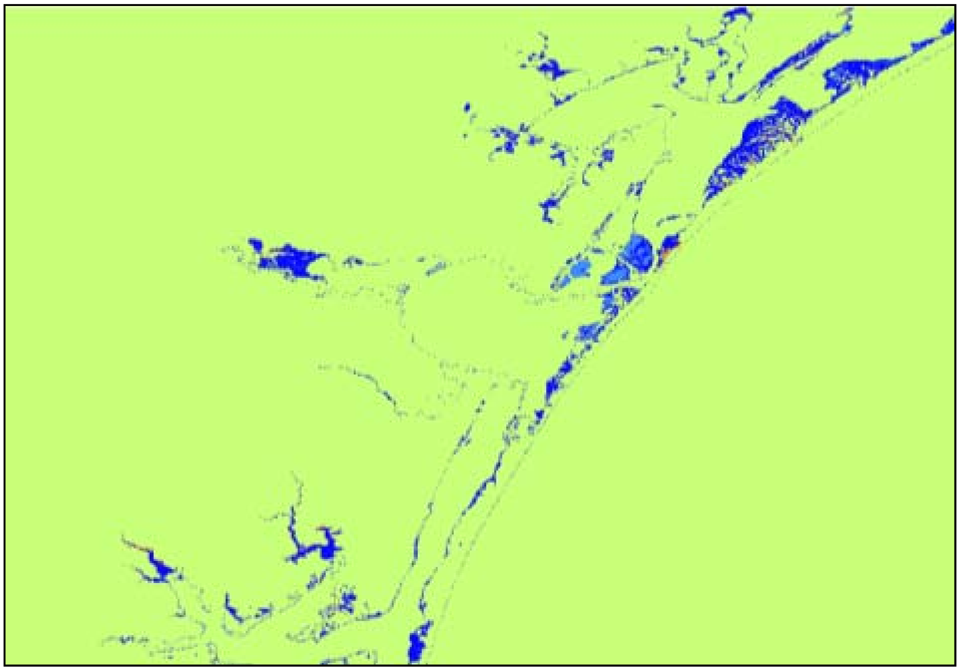


Figure 16: Example of wetland losses caused by SLR comparing present conditions and a SLR of 0.793 meters for the C-CAP (2006) database. Blue colors indicate losses of wetlands.

Considering the scenarios with only central pressure intensification, we found increases in storm surge. Every station included in the analyses presented an increase in the maximum water level as the sea surface temperature increased, thus the central pressure decreased. In figure 17, we present the results for selected stations representing location just behind the barrier island, and inside Corpus Christi and Nueces Bays. The maximum water levels increased up to 0.5 meters at these stations from the present day to the highest scenario considered.

This increasing in maximum water level trend can be easily observed in Figure 18 showing maximum peak surges for selected stations according to the SST scenario considered.

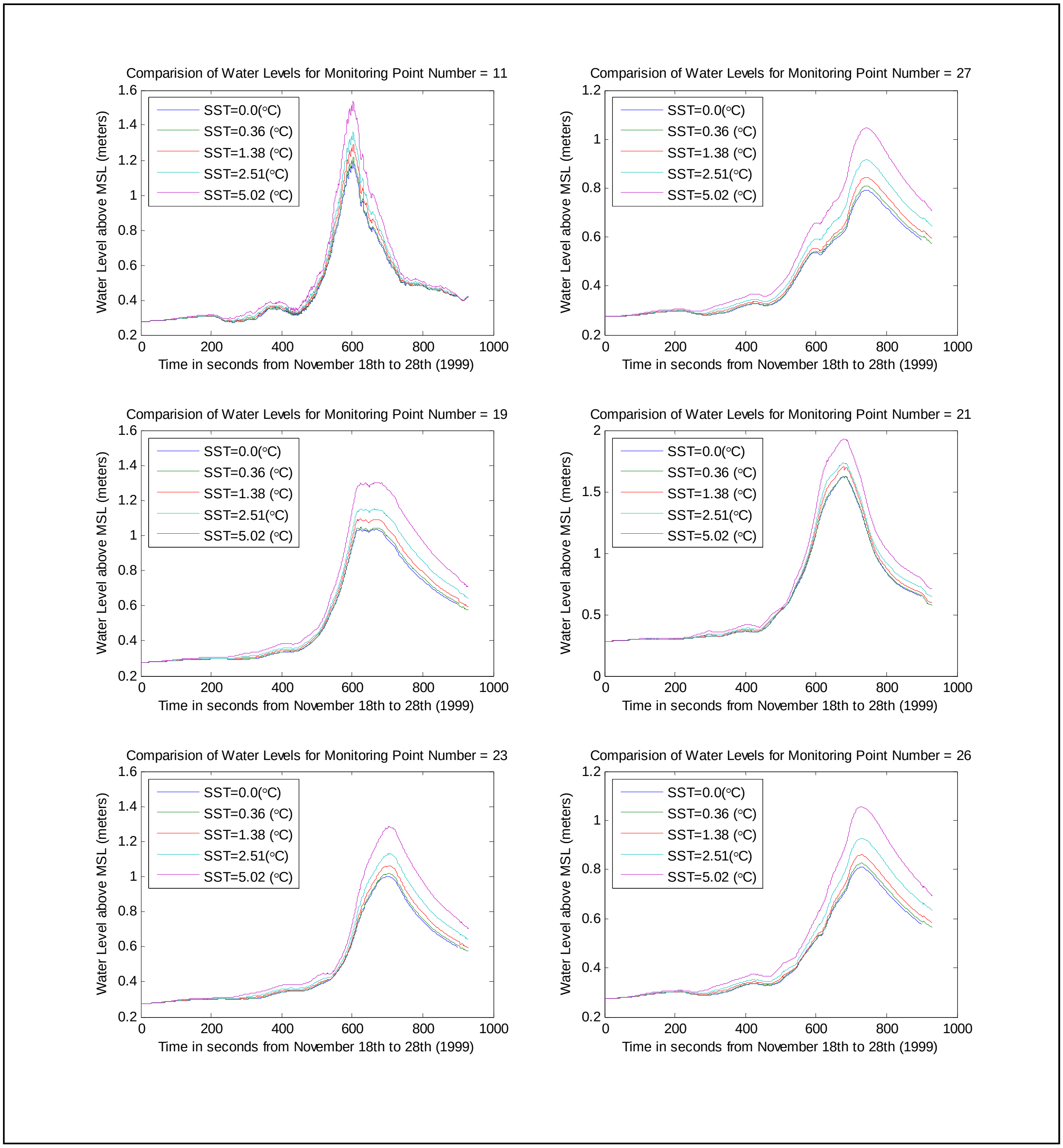


Figure 17: Effects of Hurricane Central Pressure Intensification on water levels for selected stations considering the IPCC scenarios.

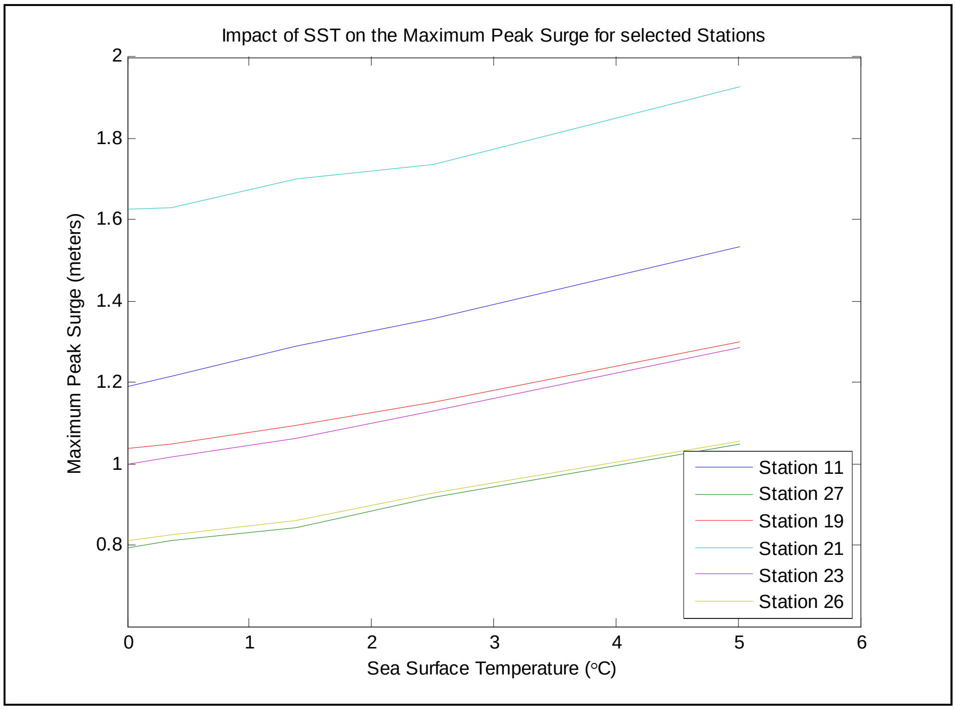


Figure 18: Effects of Hurricane Central Pressure Intensification on water levels for selected stations considering the IPCC scenarios.

Differently from the intensification scenarios, the simulations considering only SLR resulted in very similar surges (water levels above the mean sea level at the time of the storm) as the historical simulation and no significant increase trend was found in this scenarios. The surge results for selected stations are showed in Figure 18 where for the most part, the water levels are very similar for every SLR scenario. At monitoring station number 27, which is located just behind the barrier island and is very susceptible to changes in wetlands, we can verify differences in the peak surge in the order of 0.20 meters, the same is also true for station number 26 which is located inside Nueces Bay.

The plots on Figure 20 demonstrate the trend on the peak surge for the simulated scenarios. While stations 26, 27, 19 and 23 had a slight increase of peak surge, stations 21 and 11 maintained the peak surge with the SLR scenarios constant or even had a decrease.

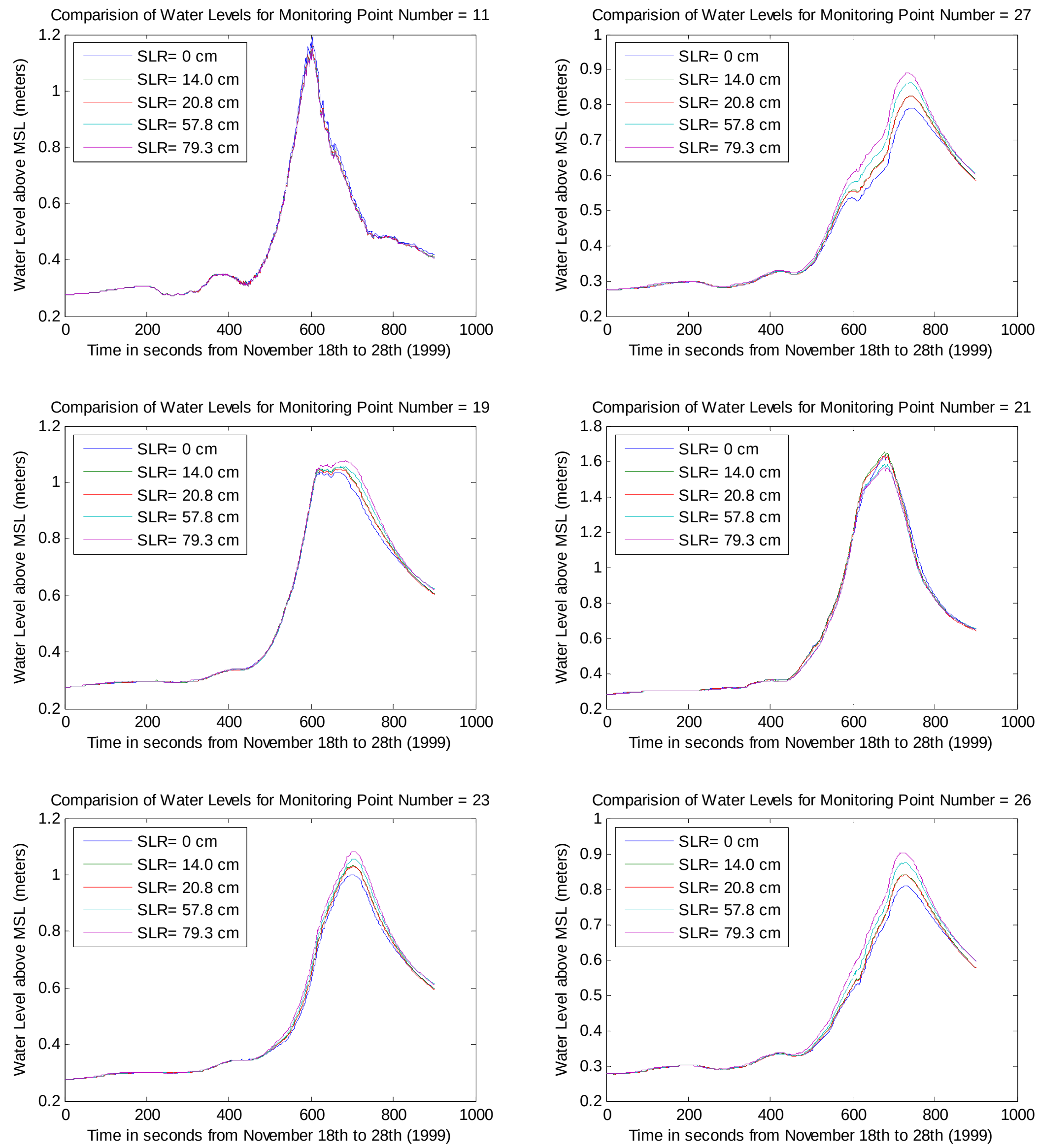


Figure 19: Effects of SLR on water levels for selected stations considering the IPCC scenarios.

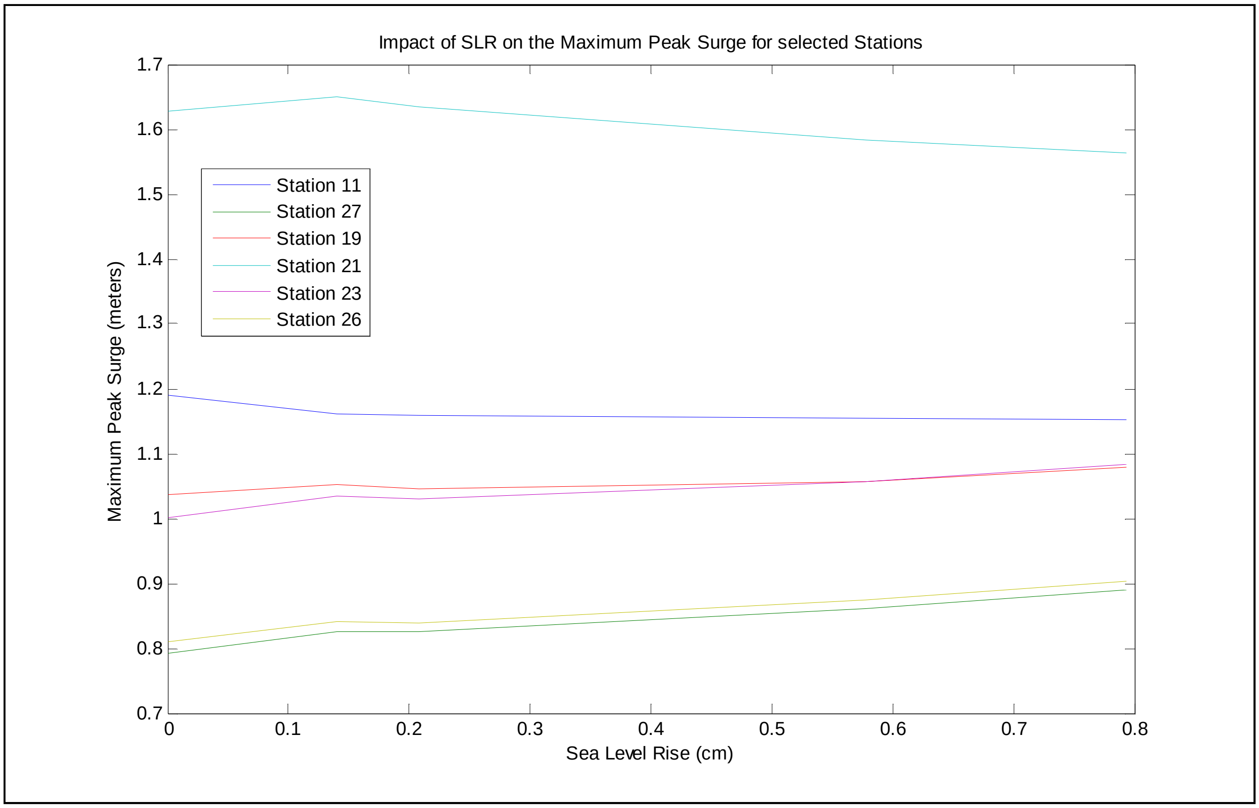


Figure 20: Effects of SLR on water levels for selected stations considering the IPCC scenarios.

The analyses considering both SLR and central pressure intensification resulted in trends similar to the intensification scenarios. The results for selected stations are presented in Figure 21 where we can observe a clear increase in peak surges for all stations with the increase in temperature and SLR. The peak surges were actually greater in the combined simulations than in the intensification only scenarios. Even when considering SLR alone, we did not find significant increases in surges. The final trend for climate change impact for the scenarios analyzed is presented for selected stations in Figure 23.

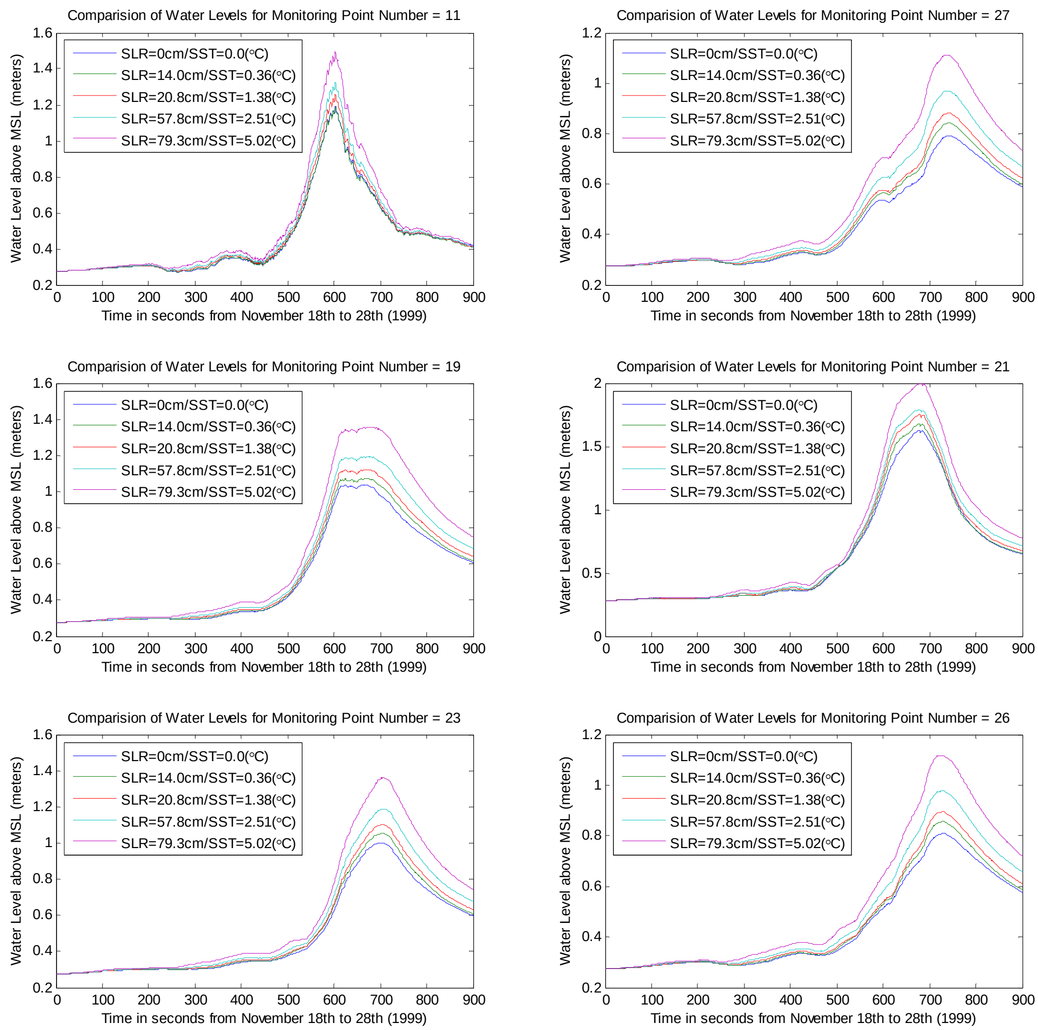


Figure 22: Effects of combined SLR and Hurricane Central Pressure Intensification on water levels for selected stations considering the IPCC scenarios.

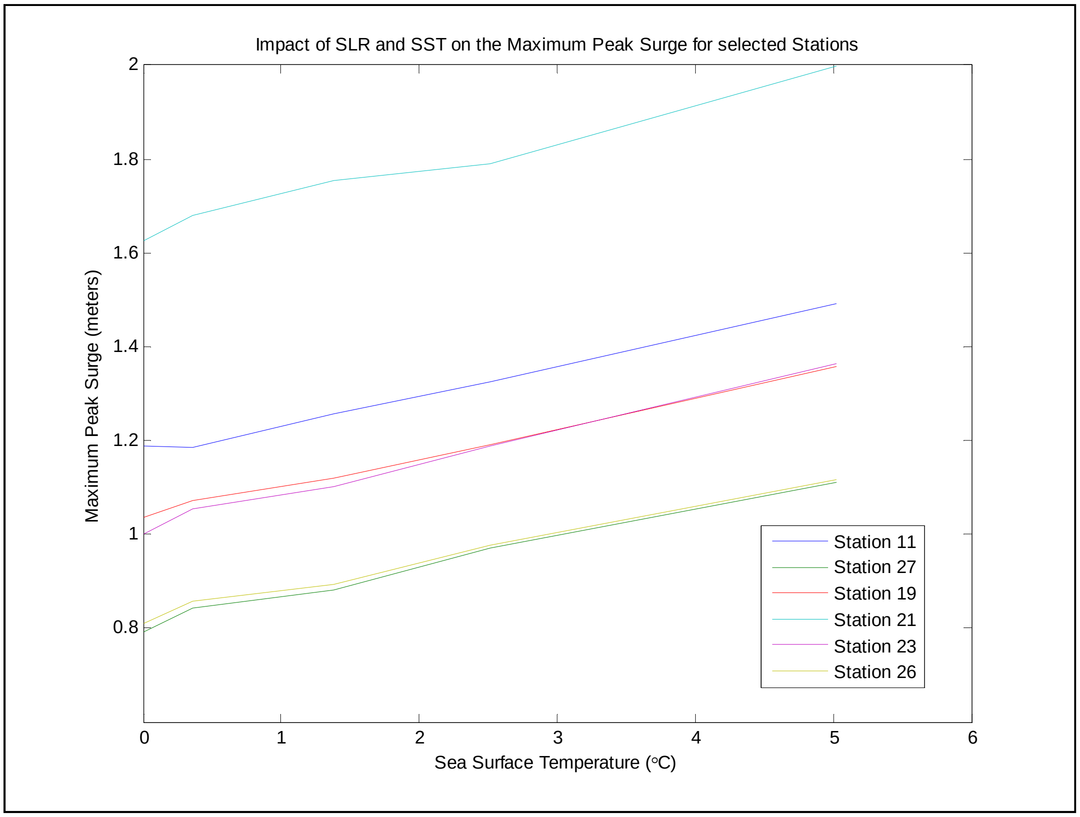


Figure 23: Effects of combined SLR and Hurricane Central Pressure Intensification on water levels for selected stations considering the IPCC scenarios.

4.3 Impact of Climate Change on Potential Infrastructure Damage

We calculated potential damage considering a combined database that included the HAZUS information at the block level and the county information at the parcel level, when existent. We also performed an independent analysis considering businesses from the Reference USA database. The results are spatially distributed and were aggregated to the county level. Figure 24 illustrates the results of a geospatial damage analyses for a given scenario.

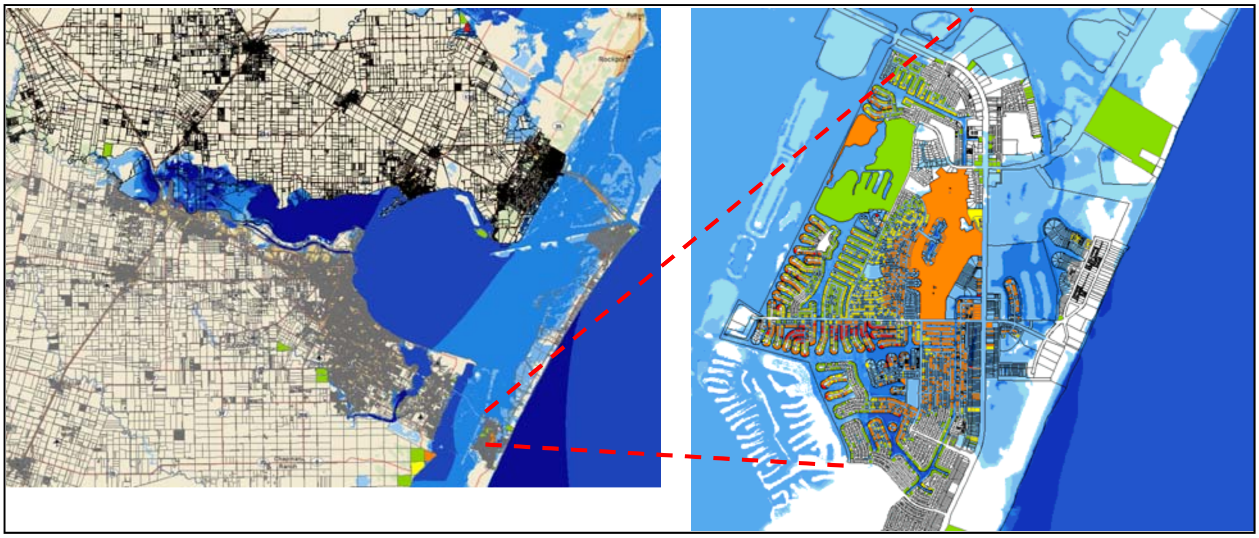


Figure 24: Example of geospatial damage analyses for a given hurricane simulation. Color coded blocks indicates the amount in dollars of damaged infra structure.

The total estimated damage for each county is presented in Figure 25 and represents the sum of all localized damage for each climate scenario simulated, considering the combined effect of SLR and hurricane intensification. Given the uncertainty within the damage analyses, the numbers presented are more suitable for relative comparison analyses than to exact quantification of real damage values.

The damage potential in Nueces County increased considerably from the 2030 to the 2080 scenarios, increasing by more than 10 times the total damage (25 million to 240 million dollars). In San Patricio County the damage increased from approximately 5 million dollars (2030) to 30 million dollars (2080).

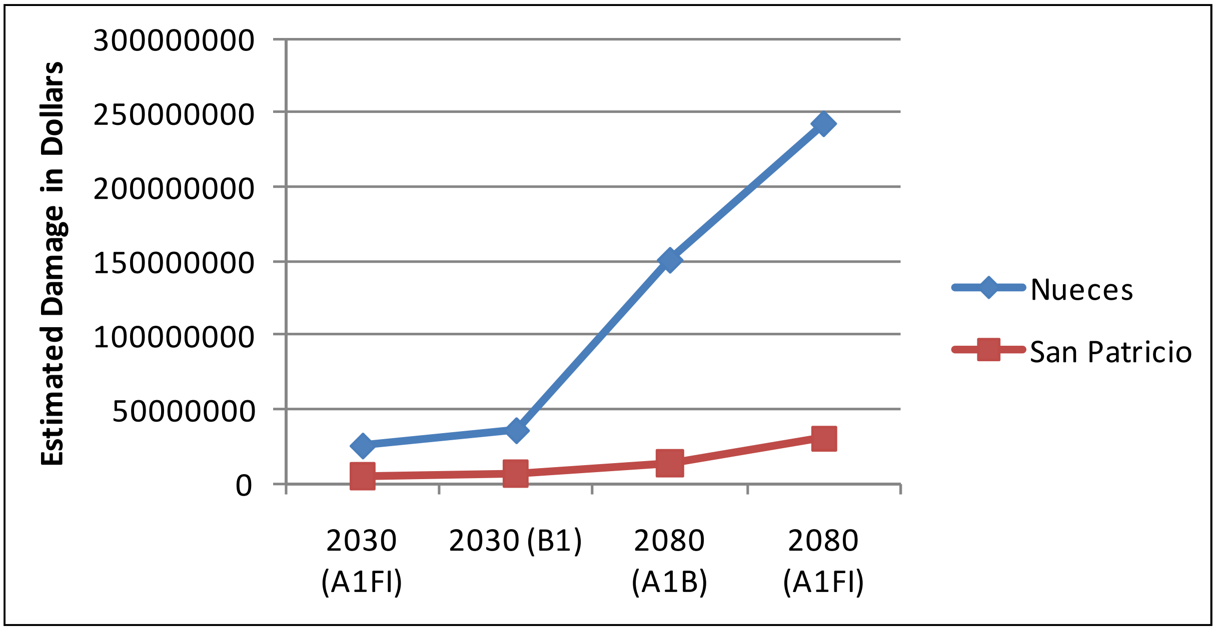


Figure 25: Total estimated damage for each county.

We also evaluated the amount of estimated damage in comparison with the assessed total value of the properties with the county. The results were analyzed by considering only SLR, only hurricane intensification and both SLR and intensification. Although Nueces County had much higher estimated damage than San Patricio, the damage values represented only 2.3 % of the existing infrastructure value; In San Patricio, damages could rise up to 10% of the county infrastructure in the 2080 (A1FI) scenario.

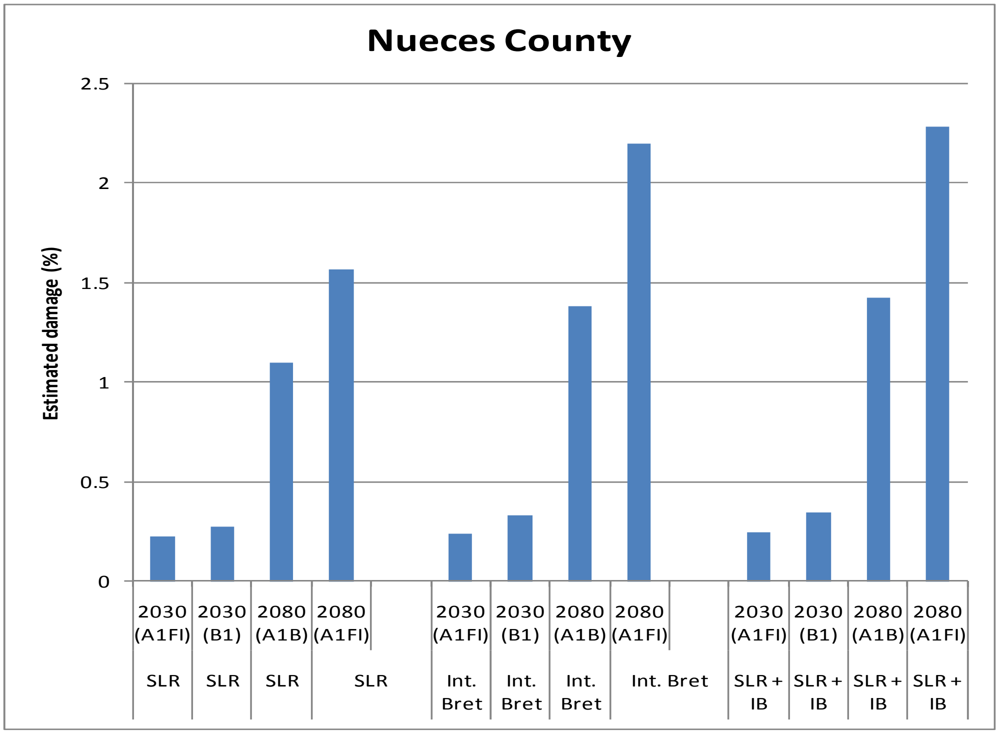


Figure 26: Estimated damage considering SLR, Intensification of Hurricane Bret and both combined for Nueces County.

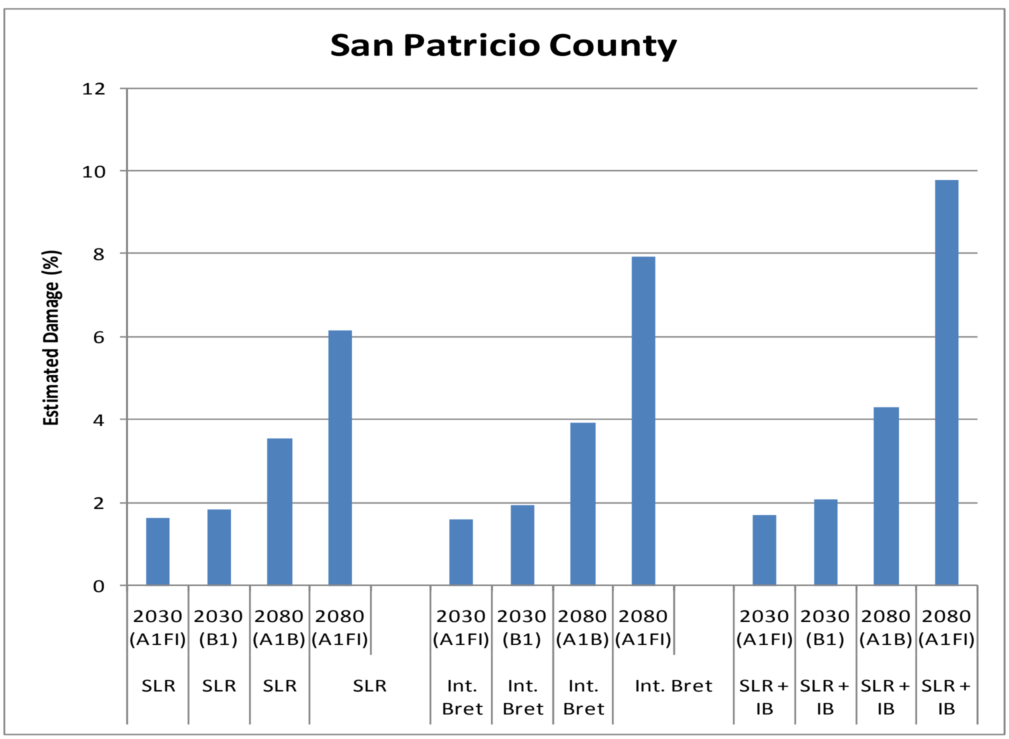


Figure 27: Estimated damage considering SLR, Intensification of Hurricane Bret and both combined for Nueces County.

The business damage estimation using the Reference USA database is based on a point location that represents the location of a given business. The map in Figure 28 illustrates the damage caused by hurricane Bret considering the A1FI scenario for 2080.

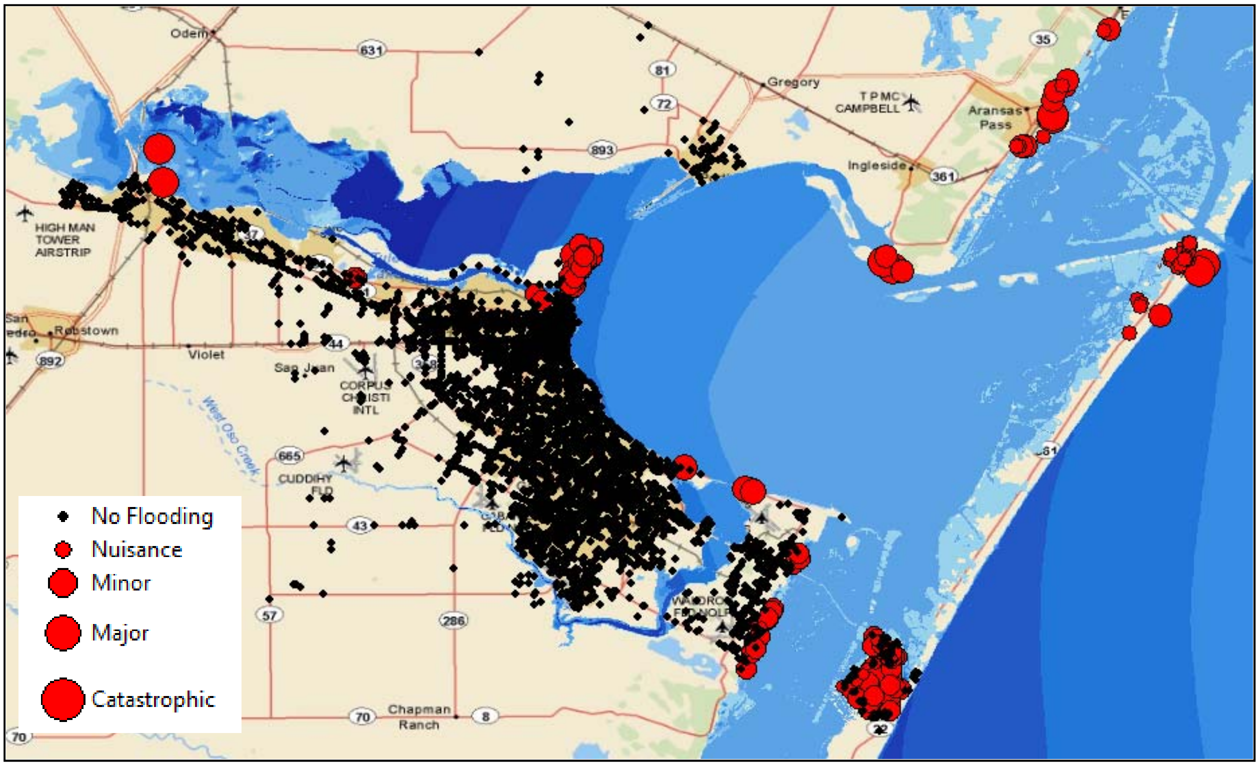


Figure 28: Business damage estimation for a given simulation scenario. The points represent businesses locations and due to the figure scale overlap each other.

The damage associated with businesses for Hurricane Bret on a present day climate conditions is negligible with almost no businesses affected. The results for A1F1 for 2030 also resulted in very minor impacts for both counties. In Nueces County, more than 50 businesses would be under minor flooding for the B1 scenario for 2030, and those numbers are significantly higher for the 2080 scenarios. With the A1B simulations, 250 businesses would be under nuisance or minor flooding and for A1FI this number goes up to 400 with around 50 businesses under major flooding. For San Patricio County, only the 2080 A1FI scenario presented a significant threat with around 150 businesses under nuisance or minor flooding and a few under major flooding. In all cases considered, we found at least one business that would be under catastrophic conditions.

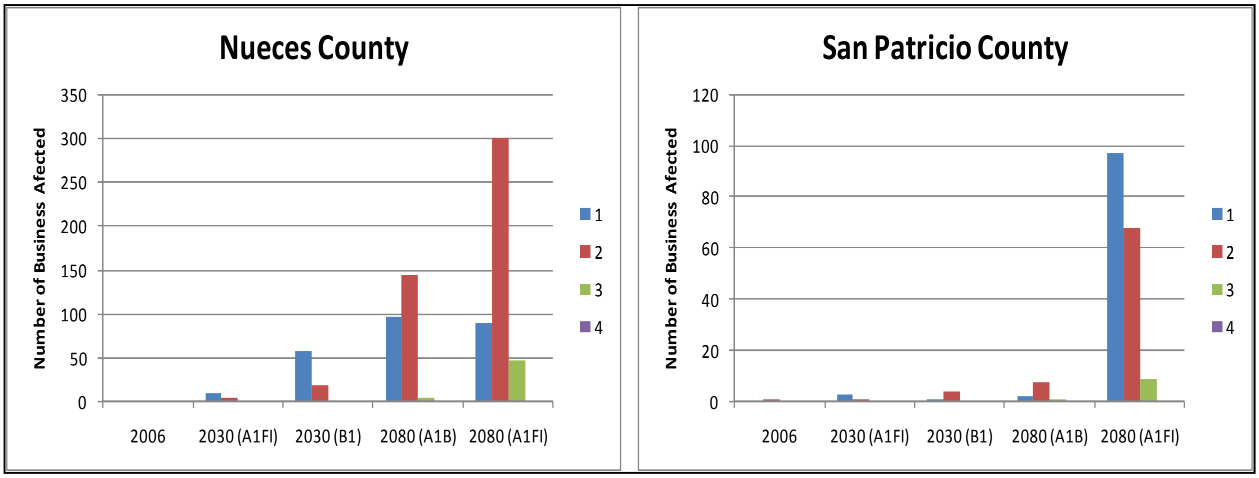


Figure 29: Potential damage by number of business. 1) Nuisance flooding; 2)Minor flooding; 3)Major flooding; 4)Catastrophic flooding

4.4 Simulations of Wetlands restoration projects

The hypothetical wetland restoration projects layout is presented in Figure 30. Those projects are highlighted on the aerial image and reflect the areas where the bottom, wind friction and the bathymetry were altered to reflect the artificially created ecosystems.

Figure 30: a) Example of wetland restoration project: Alcoa Superfund site / Lavaca Bay. Source: Texas General Land Office, 2011. b) Layout view of the hypothetical wetlands projects tested.

The water levels presented high variations along the monitoring stations reflecting the changes applied to the numerical model setup. As a result of these changes, we found both increases and decreases in water levels, depending on the specific simulations and location. Due to a backwater effect, an increase on the water levels, just in front of the restoration projects, was noted. We present the water levels for selected stations representing the simulation of the original model set up with Hurricane Bret, and scenarios with SLR and hurricane intensification (Figure 31).

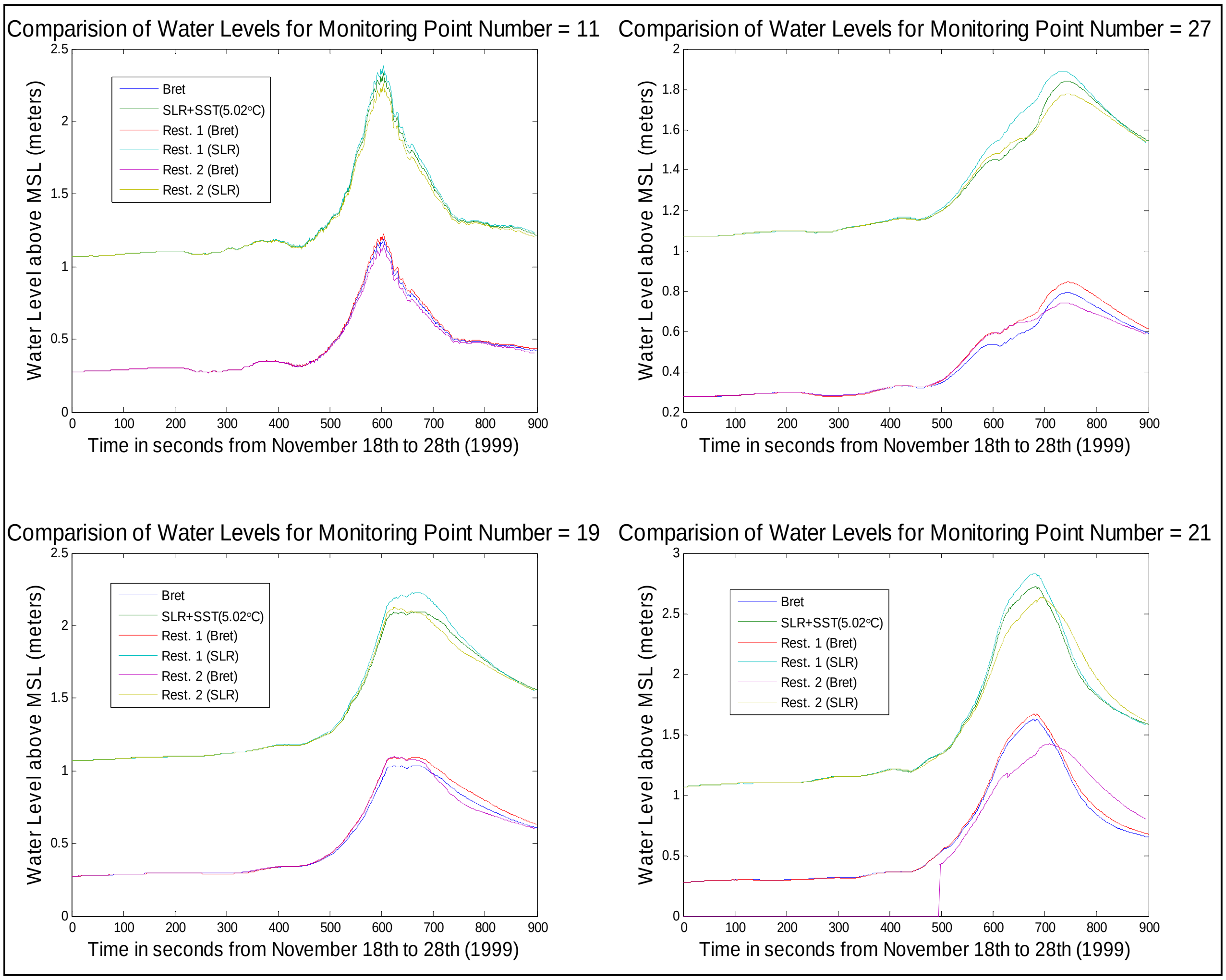


Figure 31: Simulations results including hypothetical wetland restoration projects for selected monitoring points.

The damage analyses was determined to be a more appropriate metric to analyze the effectiveness of the restoration projects, with respect to localized water levels variations.

For Nueces County, the restoration project caused a reduction of $1.3 million in damage when compared to the present day simulation and $9.5 million when compared to the 2080 simulation. Those results demonstrate the effectiveness of the restoration project if created in the correct location for a given storm. As this represents only one storm condition (Bret), the results here are expected to vary greatly under different meteorological conditions. In San Patricio County, the reduction was only $0.23 million for the present day conditions and $1.7 million for the A1FI scenario in 2080.

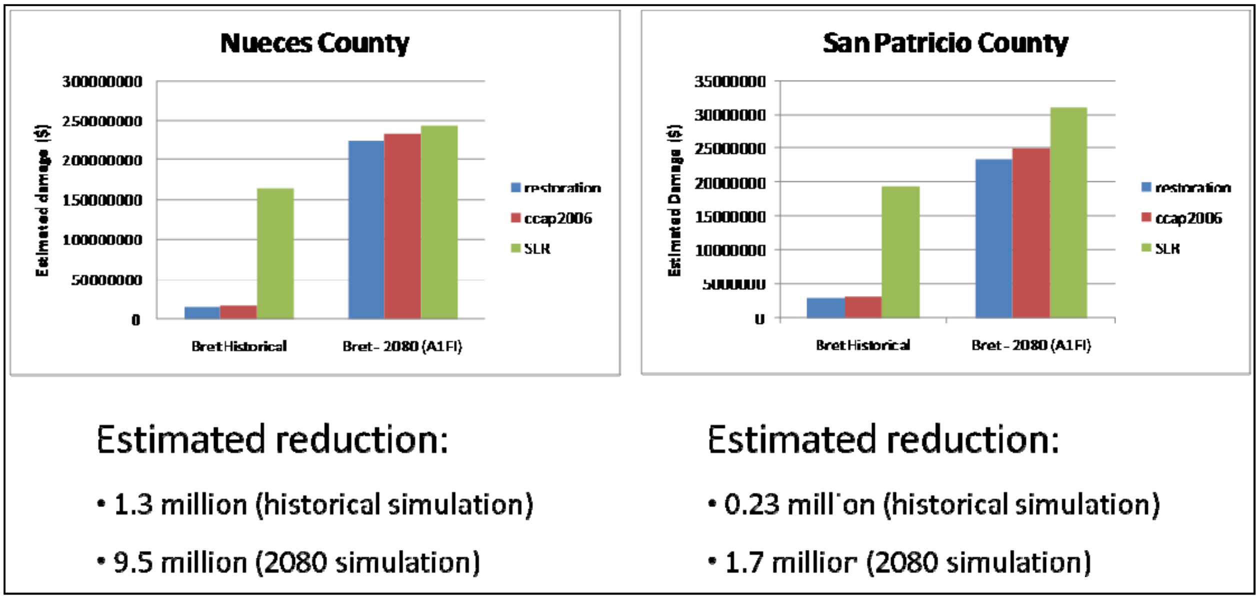
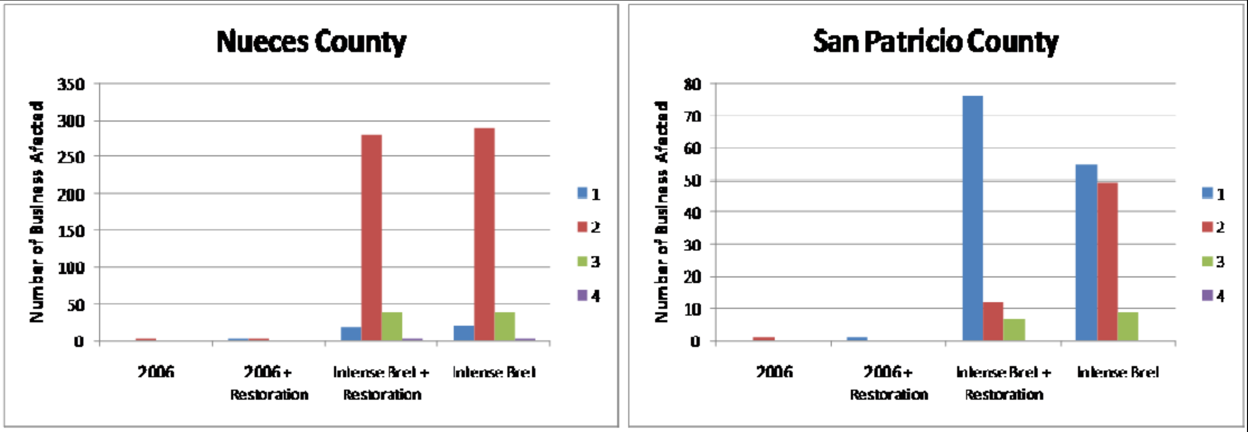


Figure 32: Damage analyses using the general database for the restoration project considering the historical hurricane Bret and the A1FI scenario for 2080.

When looking at the number of businesses affected, the additional protection provided by this restoration project was considerably low in Nueces County, with only 14 businesses in total benefiting from flood reduction. In San Patricio County, a higher number of businesses benefited from the restoration project, where 21 establishments went from nuisance flooding to no flooding, 27 from minor flooding to nuisance flooding and 2 from major flooding to minor flooding.



Estimated reduction:

- 3 Class 1
- 10 Class 2
- 1 Class 3

Estimated reduction:

- 21 Class 1
- 37 Class 2
- 2 Class 3

Figure 33: Damage analyses using the business database for the restoration project considering the historical hurricane Bret and the A1FI scenario for 2080.

5. CONCLUSIONS

Hurricanes are a costly natural disaster along the US Gulf of Mexico coast. It is believed that wetlands might act as a natural barrier to help prevent floods caused by storm surges. In this study, we applied a framework combining physics-based numerical models and GIS to investigate the potential of surge reduction by wetlands in Corpus Christi, Texas. This framework is composed of wind and pressure, hydrodynamic and wave models and GIS for damage analyses.

We have evaluated the sensitivity of flood water levels resulting from storm surge modeling to the wetlands database choice to represent bottom friction, wind blocking effects and bathymetry. The results showed that the differences between the National Land Cover Dataset, the National Wetlands Inventory (NWI) and the Costal Change Analyses Program (C-CAP) did not affect the final surge calculation significantly. On the other hand, very high and very low bottom friction factors resulted in differences varying from 0.5 to almost 2.0 meters for selected locations.

The impacts of sea level rise were evaluated simulating future wetland conditions due to the rise in the mean sea level according to IPCC climate change scenarios and also incorporating hurricane intensification due to the increase in the sea surface temperature. The intensification scenarios resulted in flood levels up to 0.5 meters higher in selected locations considering the H1FI scenario for 2080 (worst case). The Sea level rise by itself did not affect significantly the surge (removing the initial SLR from the calculated flood) but contributed to the increase of the flood levels when analyzed combined with the hurricane intensification.

The damage analyses considered the estimated value from the parcels database and businesses. From the Reference USA database, the estimation of potential damage for Nueces County considering the comparison from the present day scenario to the worst case scenario (A1FI, 2080) resulted in a damage increase of 10 times the initial estimation. In San Patricio County, the damage increase from present day to the 2080 (A1FI) scenario was in the order of 2.5 times.

The proposed hypothetical wetlands restoration scenarios resulted in a reduction of potential damage to around 14 businesses in Nueces County and 60 businesses in San Patricio County and an estimated relative reduction of 1.3 million dollars considering the historical conditions and 9.5 million dollars considering the conditions for 2080 in Nueces County and a relative reduction of 0.2 million dollars for historical conditions and 1.7 million dollars for the 2080 scenario in San Patricio.

In conclusion, the choice of wetlands database did not greatly influenced the calculated surge for the modeled conditions, but the model is sensitive to high and low friction coefficients. The intensification of hurricanes (lower central pressure) resulted in a greater impact to the storm surges than the SLR, although the flood levels were also high for the SLR cases. Worst flood levels were found considering both SLR and intensification combined. The wetland restoration project demonstrated ability to reduce storm surge at specific locations with an impact on reducing flood damages at these locations.

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