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INSTITUTE FOR A DISASTER RESILIENT TEXAS

Evaluating the Effects of a Coastal Spine: National-Level Economic Ripple Effects of Storm Surge Events

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Executive Summary

Following Hurricane Ike, scientists, policy makers, and elected officials have been calling for a comprehensive coastal storm surge protection system for the Galveston Bay region. To date, several efforts have estimated benefit/cost ratios of multiple protection solutions—which have focused primarily on the direct economic impacts of a surge-related event in Galveston Bay. Although these results have been critical in demonstrating the effectiveness of a coastal spine from the perspective of avoided damages, other secondary, indirect benefits had yet to be evaluated. The following describes recent analytical efforts to better quantify these indirect benefits through four distinct research areas including: 1) assessing the economic implications of surge-driven damage related to a coastal spine, 2) determining potential changes in the costs of flood insurance, and 3) understanding socioeconomic behavior related to the establishment of a coastal spine. The following provides a brief summary of findings of each of these three areas of research under Texas GLO contract No. 18-159-000-A719.

State-Level Economic Implications

Storm surge impacts that occur without coastal protection could have substantial long-term impacts on the growth of the Texas economy. When evaluating impacts with a coastal spine over a 50-year time frame, the projected economic impact on Texas' Gross State Product (GSP) of storm surge without coastal protection is substantial. The GSP in 2066 will decrease by 8%, corresponding to $863 billion loss. A coastal spine substantially mitigates these economic impacts, which are still estimated to decline but by only 2%. Further, all macroeconomic indicators—except for government expenditures—will also decline, with the value of net exports (value of exports net value of imports) suffering the most profound decline by an estimated 13% corresponding to $160 bilion loss.

Specific state-level impacts on housing and petrochemical sectors include:

- Housing sector output declines by nearly 8% corresponding to $39.5 billion in the sector loss in sales, and related employment and prices also fall by 0.66% and 0.77%, respectively. These estimates are mitigated in the presence of a coastal spine to a 2% decrease in housing sector output and less than 1% decreases in employment and prices.
- Outputs in the petroleum and chemical manufacturing sectors decline by 19%, amounting to $175.4 billions in lost revenues from both sectors. Decreases in these sectors are also mitigated in the presence of a coastal spine to 3% and 5%, respectively.
- Employment and prices in the petroleum sector are the most sensitive to a destructive surge event: jobs in petroleum sector will be 17% lower corresponding to approximately 155,000 in lost jobs and prices on petroleum products will increase by 13%. These estimates are reduced to 1% reduction in employment and 1% increases in prices with a coastal barrier.
- Chemical manufacturing jobs will shrink by 9% (96,000 jobs will be lost) and prices on these goods will increase by 1.6% without coastal protection. Employment figures are reduced to 2% and prices increases decrease to 0.37% with coastal protection.
- Electricity sector prices will be 6% higher by the end of the study period. These increases are reduced to 1.57% with a coastal spine.

National-Level Economic Implications

The impacts of a storm-surge event without coastal protection also have adverse effects on the United States economy. These impacts are, unsurprisingly, smaller in magnitude compared to state level impacts, yet have lasting impacts into the future.

- Following an unprotected, 500-year surge event in Galveston Bay, the U.S. Gross Domestic Product (GDP) is estimated to be 1.1% lower by the end of the forecast period; this corresponds to an estimated $883 billion dollar economic decline.
- The decline in U.S. GDP is reduced to 0.28% following the same event with coastal protection in place.
- U.S. net exports are also estimated to decline by 4% (approximately $166 billion in loss), while investment and household consumption will be 1.14% ($167 billion in loss) and 0.83% lower ($532 billion lower), all relative to the same time period with no surge impacts.
- The immediate and long-term impacts on other states indicate that while some, primarily neighboring states, experience positive GSP, income and welfare growth, 30 states not including Texas will have lower GSP in response to a surge event in Texas.

Coastal Flood Insurance Premiums

- Over 31,000, or 10% of all National Flood Insurance Program policies in Harris and Galveston Counties, would experience a reduction in 100-year storm surge as a result of a coastal spine.
- Areas that would have reduced storm surge with a coastal spine remit over $41 million dollars in annual NFIP premiums and have total flood insurance coverage of over $8 billion dollars.
- Under a 100-year storm surge scenario, over 3,000 coastal 100-year flood insurance policies would be protected to less than 1 foot of inundation.
- An additional 14,149 high-risk flood insurance policies would be protected completely protected from a 100-year storm surge.
- In the most conservative insurance scenario, nearly $5 million dollars in premiums could be saved annually by residents while still maintaining the same flood insurance coverage with the presence of a coastal spine.
- Additional scenarios suggest that total annual premiums in the coastal Houston-Galveston area could be reduced by 21-28% while still maintaining the same flood insurance coverage.

Public Perceptions of Coastal Protection in Texas

- Widespread public support exists for structural and non-structural mitigation to address the risk Texas coastal communities face from natural hazards. Multiple mitigation strategies were evaluated, ranging from levees and elevation to land use regulations, and all of them were supported by over 70% of the respondents in each county.

- There is overwhelming public support for the coastal spine or Ike Dike in the greater Houston-Galveston Region. Approximately 73% of the respondents surveyed said they support the construction of the coastal spine.

- The public prefers shared responsibility for financing the coastal spine. The majority of respondents – 55% - believed that both government and port industries should be responsible for financing the coastal barrier system. Two-thirds of respondents also supported some type of public tax, including sales and hotel tax, to raise revenue to construct the coastal spine.

- Residents believe the coastal spine will reduce risk to homes and provide job security for some. Over 50% of Chambers and Galveston County respondents said they feel their home would be at less at risk if the coastal spine were constructed; 47% of Harris County respondents said the same. Additionally, about 40% of Chambers and Galveston County respondents said their job would be more secure; 33% of Harris County respondents said the same.

- Environmental concerns related to the Ike Dike remain. Over 65% of Chambers County respondents expressed concern about the consequences of the Ike Dike on the environment. About 58% of Galveston County and 50% of Harris County respondents are equally concerned.

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Chapter 1. Evaluating the Effects of a Coastal Spine: National-Level Economic Ripple Effects of Storm Surge Events

Meri Davlasheridze and Qin Fan

Executive Summary

The 2017 North Atlantic hurricane season and the enormity of the impacts they brought to coastal communities have once more heighted private and public concerns about the catastrophic future storms and the ways to mitigate their impacts. Among many alternatives, surge suppression systems have gained particular interest among policy makers, planners and researchers. The Galveston Bay region (herein referred to as the bay) represents one of the most flood- and surge-prone areas in the United States (SURGEDAT 2017). Due to its vulnerability there has been a particular interest in comprehensively assessing a coastal storm surge suppression system (aka coastal spine) proposed as a mitigation strategy after 2008's Hurricane Ike that brought historic surge levels and impacted local economies in the Southeast Texas. The urgency to address this issue has been heighted as there is a growing consensus that surge height could increase in response to an increase in hurricane intensities and sea-level rise (SLR). Some recent studies suggest flood heights of storm surge associated with 1 in every 100 year to become as frequent as one in every four years, and this all due to SLR creating a higher "launch point" for future storm surges (Frumhoff et al. 2007).

Prior research conducted on this topic has focused on quantifying impacts of surge events on property and industrial assets locally (Atoba et al., 2018; Davlasheridze et al. 2018). However, little has been done to view the problem from regional and national perspectives. Nationally strategic assets located in the bay such as petroleum refineries, petro-chemical manufacturing and the Port of Houston all bear merits in presenting the problem in the context of the nation. Understanding the spatial economic spillovers of surge impacts on the larger economy and long-term socioeconomic ramifications are important for economic stability of other states as well as for the nation as a whole, and will further contribute to a better understanding of the scope of economic damages and the economic feasibility of a surge suppression system.

This report presents the results of a nation-wide economic study of storm surge impacts on the three counties along the Galveston Bay (Galveston, Harris and Chambers) and explores how direct impacts on a specific sector(s) in the bay communities propagate through the economy of TX as well economies of other states and the nation as a whole in the long term, while capturing general equilibrium and multiplier effects.

Economic Model

The economic impacts presented in this report are derived from a 23 sector, multi-year state-level Computable General Equilibrium (CGE) Model. By including the national and global economies, and linking them to the Texas economy, the model captures essential economic relationships that influence the economic impacts of storm surge along the gulf coast of Southeast Texas.

The 23 sectors included in the economic model encompass sectors that are of great importance to the Texas state economy and human wellbeing. Specifically, the two surge-sensitive sectors were selected (i) residential housing (referred to as dwelling throughout) and (ii) petroleum refinery and chemical manufacturing sectors. Beyond these major sensitive sectors, aggregation of similar sectors was guided by model calibration and stability of the model results. Because this study examines the economy-wide impacts of storm surge, the economic model captures *general equilibrium*[1] and *multiplier effects*[2] of individual sectoral responses to surge events.

Assessment Period

In this study, the impacts of surge events on the economy are considered for 50-years in the future, starting from the year 2016 and ending with the year 2066. As an extension, we also incorporate surge impacts under the SLR using the SLR projections in 2080. Additional model simulations are also conducted for the ending year 2080. The choice of 50 year time span was guided by two principles: (1) human behavior, the underlying theoretical foundation of the CGE model, and the subsequent evolution of regional economic systems are much more uncertain than is the evolution of surge events (forecast errors in economic modeling increase rapidly with forecast length) and (2) 50 years is a typical time span used to assess the feasibility of flood protection structures in the United States by the US Army Corps of Engineers (USACE), the primary federal agency responsible for the large scale infrastructure projects.

Scenarios

Selection of scenarios in this report were guided by (i) surge events, (ii) policy responses and (iii) the duration of production cessation for major industrial plants in the area.

Synthetic storms were used to generate exposure of assets relative to water inundation levels. Each storm has different probability of occurrence in a given year and provides the possibility to assess the bandwidth of likely impacts to the states' and national economies associated with storms of different intensities. The most intense and destructive storm is the 500-year storm, with an annual probability of 0.2%, followed by the 100-year (1%) storm surge, 10-year (10%) and an Ike-like storm surge. The selection of the latter was guided by the hurricane Ike, a category 2 hurricane that struck Southeast coast of Texas in 2008 and brought a historic amount of surge levels. Ike remains the most recent hurricane accompanied with major surge event for the bay communities, as Hurricane Harvey in August 2017 for the area was a precipitation event.

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[1] Some economic sectors will be impacted by surge events indirectly because of direct impacts on more sensitive economic sectors within the region (e.g., dwelling and petro products & chemical manufacturing sectors). Hence it is expected the surge impacts on a specific sector(s) will also impact prices of capital, labor, materials, or other production inputs facing producers in another economic sector. Similarly, surge impacts on one sector(s) may also affect output prices received by producers in another sector. The price changes (both outputs and inputs) stimulate substitution away from higher-priced goods and toward lower-priced goods. These phenomena acting through markets and prices are commonly referred to as general equilibrium effects.

[2] Changes in input prices (i.e., prices of labor, capital, energy and materials) can lead to changes in personal income, because in the CGE model individuals are assumed to be owners and suppliers of these inputs. Hence the direct impacts on one sector can generate a chain reaction of additional rounds of indirect effects through the changes in personal income, often referred to as induced effects. The total impact accounts for all rounds of effects on all economic sectors which represents some multiple of the direct impacts, commonly referred to as "multiplier effects".

The surge inundation outputs were modified by factoring in a 17’ coastal spine system, as a surge suppression mitigation strategy proposed for the region. Hence for each surge scenario, economic impacts are assessed with and without the coastal spine.

Direct impacts to petroleum and chemical manufacturing sector are modeled through the lost output value (lost sales/revenues) associated with the cessation of production operation. Without knowing specific causes of shutdown, and relying on past reports and published data, it was assumed that plants shut down for 18, 26 and 33 days either because surge events cause a failure of main electric system or equipment due to a power outage or plants simply close for precautionary purposes. For the sake of brevity, in this report results associated with 33 day shutdown are reported. Other results were built in a companion web-based Atlas for visual presentation (http://www.texascoastalatlas.com/coastalspine/). As an extension, storm surge scenarios that incorporate the SLR in 2080 were also developed without and with the coastal spine system.

Economic Scenarios and Simulations

Economic impacts are calculated as the difference between the value of economic indicators (e.g. prices, output, income, GDP, welfare, consumption, investment, net export) “with” surge events and the values of these indicators “without” the storm surge; the “without” surge values of economic indicators are referred to as the “baseline” values and this scenario is called the Business As Usual (BAU) scenario. Economic indicators in the BAU scenario are derived by simulating the economic model forward in time given projections of key exogenous economic variables (population, working age population, saving rates, depreciation rates, government taxes, rates of productivity growth, and rates of improvement in capital and labor quality). Economic indicators with storm surge are derived by simulating the model forward in time with changes in selected parameters (e.g., for the housing sector capital endowment is reduced by the amount of estimated property damages, for the petroleum and chemical manufacturing sectors total factor productivity growth rates are adjusted until output losses solved in the model matches the estimated losses that correspond to the different shut-down days in the petroleum and chemical manufacturing sectors) as a way to reflect the impacts of surge on underlying economic conditions.

Two types of economic simulations are conducted. One type estimates the impacts of surge events on individual sectors (i.e., housing and petroleum and chemical manufacturing separately). This exercise allows us to disentangle the economic effects of surge from each of the sectors, such as housing, on others, such as petroleum and chemical manufacturing, so as to better understand the direct and sectoral-level effects of surge events. In the second type we estimate the economic impacts when storm surge affects all surge-sensitive sectors simultaneously to fully capture indirect and induced effects on Texas’ own economy as well as economies on other states and the nation as a whole through trade and labor flows across states.

Damage to the Housing Sector

Storm surge is projected to impact the housing (i.e. dwelling) sector negatively by destroying residential property located in inundated areas. The HAZUS-MH model developed by the Federal Emergency Management Agency (FEMA) was updated using parcel-level data available from the county tax assessors’ offices to estimate exposure and direct damages to structures while factoring in structural characteristics of the property such as foundation type, structure age, replacement cost, construction material, and elevation. Using the supplied damage-depth functions, the losses to individual properties were estimated without a coastal spine and one with the coastal spine system. Destruction of property represents the decline of capital endowment to households in the CGE model who are assumed to own factors of production.

Depending on the intensity of the storm, direct property damages in the three counties were estimated in the range of $8.5 billion (associated with 500-year storm), $4.6 billion (with 100-year storm), half a billion (10-year storm), and 3 billion with Ike-like storm without the coastal spine. These figures correspond to negligible shares to the entire state's GDP. For example, the most intense 500-year damages represent only 0.5% of the total state GDP in 2016 prices, however correspond to 11% of the sector's total output in Texas. Notably, the coastal spine mitigates the bulk of residential losses, reducing estimated damages by four times relative to the estimated damages without the surge suppression system.

Petroleum and Chemical Manufacturing

Petroleum and chemical manufacturing sectors are other sensitive sectors that are assumed to be directly impacted by surge events in the region. Based on published reports and data, it was assumed that the destruction of industrial property will have minimal impact on disrupting sector production operation. However, plants may experience substantial output (revenue/sales) losses if they close due to electrical equipment and control room (including Systems and Operating) failure or due to power outages. We assumed plants to be down for as little as 18 days and the maximum shutdown days considered was 33 days. Subsequent revenue losses were calculated for each of the shutdown durations. For the purpose of modeling economy-wide impacts of output losses associated with plant shutdown, it was assumed shutdowns will affect efficiency and intensity of the inputs utilized in production process. Thus, the impact was model through reduction in total factor productivity (TFP) associated with all input factors (i.e. capital, labor, energy, and material) in a corresponding sector (i.e., petroleum and chemical manufacturing sectors).

Total output losses associated with different shutdown durations were estimated in the range of $4.3 – $8 billion associated with the 500-year storm surge event without a coastal spine and only $116 – $213 million when a coastal spine was in place. It should also be noted that industry losses were fully mitigated with spine protection under 10-year and Ike-like storm events. The resultant output loss of 33-day shutdown represents approximately 8% of the total output value of these sectors in Texas in 2016.

Key Results when Storms Impact Dwelling, Petroleum and Chemical Manufacturing Sectors Simultaneously

500-Year Storm Surge

Findings without a Coastal Spine

- Dwelling sector output in Texas in 2066 declines by nearly 8%. Employment and prices in the dwelling sector also fall by 0.66 percent and 0.77 percent, respectively relative to the BAU.
- Outputs in petroleum and chemical manufacturing sectors decline by 19% respectively in Texas in 2066. The employment and prices in the petroleum sector are the most sensitive to a destructive surge event. The number of jobs in petroleum sector will be 17% lower and prices will increase by 13 percent on petroleum products (e.g., gasoline, diesel, and other) in 2066 in Texas. Chemical manufacturing jobs will shrink by 9%, and the prices on these goods will only increase by 1.6% in 2066 relative to the BAU.
- In terms of secondary impacts on other sectors, all aggregate sectors studied will be adversely impacted by surge events and will experience output (revenue) losses that will persist in the long-term.
- The most sensitive indirectly impacted sectors in terms of revenue losses include natural resource mining (e.g., gas, oil and coal) with 15% decline in output in 2066, electricity (-12%), heat & air condition (-9%), and water and sewage (-8%), among others. These are the sectors that either directly use goods produced by petroleum and chemical manufacturing as inputs in their own production processes or are serving residential housing sector (e.g., electricity).
- Electricity sector prices will be 6% higher in 2066, and the prices in other sensitive sectors will also increase, however marginally.

Findings with a Coastal Spine

- Coastal spine mitigates bulk of detrimental impacts on Texas economy as well as on economies of other states and the nation.
- Dwelling sector output in 2066 will decline by only 2%. Employment and prices in the dwelling sector will also decline but negligibly by 0.09% relative to the BAU.
- Outputs in petroleum and chemical manufacturing sector decline by 3% and 5% respectively in Texas in 2066. The number of jobs in petroleum sector will be 1% lower and prices will increase by 1% on petroleum products in 2066 in Texas. Chemical manufacturing jobs will only decline by 2%, and the prices on these products will increase by 0.37% in 2066 relative to the BAU.
- Although lesser in magnitude, all other sectors will also experience decline in output value. The most sensitive indirectly impacted sectors are still electricity, natural resource mining (e.g., gas, oil and coal), heating and air conditioning, and water and sewage.
- Electricity sector prices will be 1.57% percent higher in 2066 and the prices in other sensitive

Overall Impacts

The overall projected economic impact of storm surge without the spine system on Texas' Gross State Product (GSP) during the assessment period is substantial. The GSP in 2066 will decrease by 8% corresponding to $863 billion loss in GSP. All macroeconomic indicators except for government expenditure in the state will decline in 2066, with the value of net exports (exports – imports) suffering with the most profound decline by an estimated 13%. The social welfare will be 8% lower, while total investment and consumption will decline by 1% and 6.9% respectively, likely due to higher prices on some of the important consumption goods (electricity and gasoline). Total government expenditures will increase in response to surge events and will be 1% higher in 2066. Surge impacts will also have adverse socioeconomic implications nation-wide in the long term, however estimated declines are smaller in magnitude. The U.S. GDP is estimated to be 1.1% lower in 2066, corresponding to an estimated $883 billion in decline. U.S. net exports will decline by 4%, investment and household consumption will be 1.14% and 0.83% lower in 2066, and overall social welfare will decline by 0.92% , all relative to the BAU.

The CGE model results indicate that while some states (primarily neighboring) will experience positive GSP, income and welfare growth due to potential substitution of inputs of production and labor outmigration, 30 states, not including Texas itself, will have a lower GSP in response to a surge event in Texas. In terms of social welfare, with the exception of a handful of states, the majority will experience welfare loss in 2066 if the coastal spine is not constructed in the bay.

The coastal spine substantially mitigates impacts on Texas' GSP, which is estimated to still decline in 2066 but by only 2%. All macroeconomic indicators except for government expenditures in Texas show a decrease in 2066. The impact reflected on net export (exports – imports) is reduced four times. Similar mitigating effects are observed for social welfare, total investment and consumption. Government expenditures will increase, but only by 0.19%. Impacts on national accounts are mitigated substantially. Although major macroeconomic indicators will still exhibit declines in 2066, the rates of decrease are relatively small. For example, U.S. GDP will be 0.28% lower and social welfare will decline by only 0.24% if the 500-year surge event disrupts housing and major petroleum and chemical manufacturing sectors in the three counties along the Southeastern Gulf Coast of Texas.

Ike-Like Storm Surge

Findings

- Impacts of an Ike-like storm are relatively smaller compared to the impacts generated by the 500-year storm surge event.
- The chemical manufacturing sector output will decline by 5.9% without protection and outputs will only drop by 0.27% with coastal spine protection, relative to the BAU in 2066.
- Electricity sector output is the second most impacted, shrinking by 4.45% if no coastal protections is provided.
- Prices also increase in storm sensitive sectors. For example, electricity product prices will be 2% higher in 2066 without coastal protection, and petroleum product prices will increase by 1%.
- Coastal protection fully mitigates the impacts on petroleum and chemical manufacturing, and all residual impacts (which are estimated to be minimal) on other sectors under the protection scenario are due to the impacts on dwelling sector.
- Texas GSP will be 2.7% in 2066, welfare will drop by 2%, and net export will fall by 4% in comparison to their projected levels in the BAU, if no coastal protection is provided.

- Impacts as reflected on national accounts are relatively smaller under no protection. For example, the U.S. GDP declines by 0.29% and net exports fall by 1.12%in 2066. However, coastal protection almost fully mitigates impacts on the U.S. economy. This is partially because petroleum and chemical manufacturing sectors do not sustain damages when a coastal spine is factored into direct damage assessment.

500-Year Storm Surge that Incorporates Sea-Level Rise (SLR) in 2080

Findings

- With SLR Texas' GSP decreases by 4.5% without the spine in 2080.
- This impact is mitigated to -0.63% with protection.
- The coastal spine substantially mitigates negative impact on consumption, per capita income, and net exports as well.
- The national impact is generally small without protection. Net exports will experience the largest decline (-3%) in a single year, compared to the BAU scenario without SLR in the year 2080.

Introduction

In recent years, there has been a particular interest in the comprehensive assessment of a coastal storm surge suppression system, also referred to as a coastal spine, which has been proposed as a mitigation strategy for the Galveston Bay region. The idea of the spine emerged after 2008's Hurricane Ike that brought historic surge levels and impacted local economies in Southeast Texas (TAMUG 2017), and has again received the revived interest after hurricane Harvey in 2017 (Rebuild Texas 2017).

Prior studies and efforts have focused on delineating hazard exposure of structures and industries (Atoba et al., 2018; Burleson et al., 2015) as well as quantifying the benefits of a spine realized in terms of avoided direct damages (Davlasheridze et al., 2018). However, other second-order impacts of destructive surge events and the subsequent benefits of a surge mitigation system have not been well demonstrated. Large surge events may trigger a variety of indirect effects including disruption of supply linkages and commodity shipments, temporary cessation of production operation, and cascading adverse effects across interdependent economic systems. Disruption of some of the important and strategic assets located in the bay area (e.g., oil refineries, petro-chemical manufacturing, etc.) could reverberate throughout not only the local or regional economy, but may also have significant economic and social implications for other states and the nation, and may also impact their economies in the long term (Kousky 2014; Cavallo & Noy 2011; MacKenzie, Santos, & Barker 2012; Norio et al. 2011).

Understanding the spatial economic spillovers of surge impacts on the larger economy and long-term socioeconomic ramifications are important for the economic stability of other states as well as for the nation as a whole, and will further contribute to a better understanding of the scope of economic damages and the economic feasibility of a surge suppression system.

This study builds on and further extends previous research on this subject by developing a nation-wide economic model using the framework of the Computable General Equilibrium Model (CGE). The CGE model allows for modeling economic impact at the sector level, and explores how direct impacts on a specific sector(s) propagate through the economy as a whole while capturing general equilibrium and multiplier effects. The CGE model has a rigorous theoretical foundation and has been widely used by scholars and policy makers to model economic impacts associated with policy changes at the sector level (Bohringer et al., 2003; Bergman, 1991; Shoven and Whalley, 1992; Sue Wing 2009) as well as the economy-wide implications of extreme events (Rose and Guha, 2004; Rose and Liao, 2005; Rose, Oladosu, & Liao, 2007; Sue-Wing, Rose and Wein, 2015) and climate change (Abler et al., 2009; Hsiang et al., 2017). The details of the model are provided in the subsequent sections.

Second-order (indirect and induced impacts) are modeled through direct impacts on the two primary sectors that are the most surge-sensitive: (i) the dwelling sector and (ii) petroleum refinery and chemical manufacturing sectors. Direct impacts through property losses are estimated by integrating outputs from the Advanced CIRCulation Model (ADCIRC) that generates water inundation associated with different intensity storms with the Federal Emergency Management Agency's (FEMA) US Multi-Hazard (Hazus-MH) model. The same ADCIRC inundation outputs are also used to identify petroleum refinery and chemical manufacturing plant hazard exposures and integrated with Chemplant data to estimate output losses associated with production cessation due to a storm surge. As such, the modeling framework integrates three models, ADCIRC, HAZUS-MH and Computable General Equilibrium (CGE) models, along with assumptions related to plant-shut down durations, to estimate state- industry- and nation-wide macroeconomic impacts of surge events effecting the Galveston Bay region in Texas. The impact scenarios are built around the intensity of storms and also factor in the mitigating effects of a coastal spine. Hence, the impact estimates with and without a coastal spine protection are generated.

Impacted Area

The study area covers Galveston, Harris and Chambers counties located in the southeastern part of Texas Gulf coast, surrounding Galveston and Trinity bays (see Figure 1). The three counties, hereafter referred to asreferred the Houston Galveston Area (HGA) region covers 2,727 square miles and is one of the most populous regions in the U.S. According to the 2010 census, its population is approximately 4.42 million. The Houston metropolitan area, which is part of Harris County is the third most populated metro area in the U.S. and accounts for approximately 93% of total population of the HGA. The most recent report by the Houtson-Galveston Area Council indicates that the population will surpass 6.3 million by 2040 (HGAC, 2017).

The Galveston Bay region, often referred to as petrochemical capital of the U.S., houses one-third of the petroleum refineries in the U.S. and represents the second largest petro-chemical complexes in the world. In addition to these strategic assets, the HGA is a home of the Port of Houston, which is largest port in the U.S. in terms of import and export tonnage (Port of Houston 2017). The region contributes approximately a quarter of the Texas Gross State Product (GSP) with an estimated GSP value of $341 billion, and employs over 60% of the state's total population (MIG 2012).

The HGA is also one of the most flood- and surge-prone areas in the U.S. (SURGEDAT 2017) and on average, experiences a major hurricane once every 15 years (Parisi and Lund 2008). The area's geography and local climate, coupled with population and economic exposure, make this region particularly vulnerable to damaging storms. While Hurricane Harvey in 2017 was the most damaging hurricane for the region, the bulk of these damages were due to heavy rainfall and abnormal precipitation. The most recent surge event was generated by the 2008's Hurricane Ike, which spurred the initial policy discussion around the coastal spine system (i.e. Ike Dike) as a mitigation alternative to address surge-induced impacts regionally (TAMUG 2017). It is envisioned that the spine will be a complex system connecting seawalls and fortified dunes/levees along the coastline to retractable gates located at the mouth of Galveston Bay and San Luis Pass (see Figure 1).

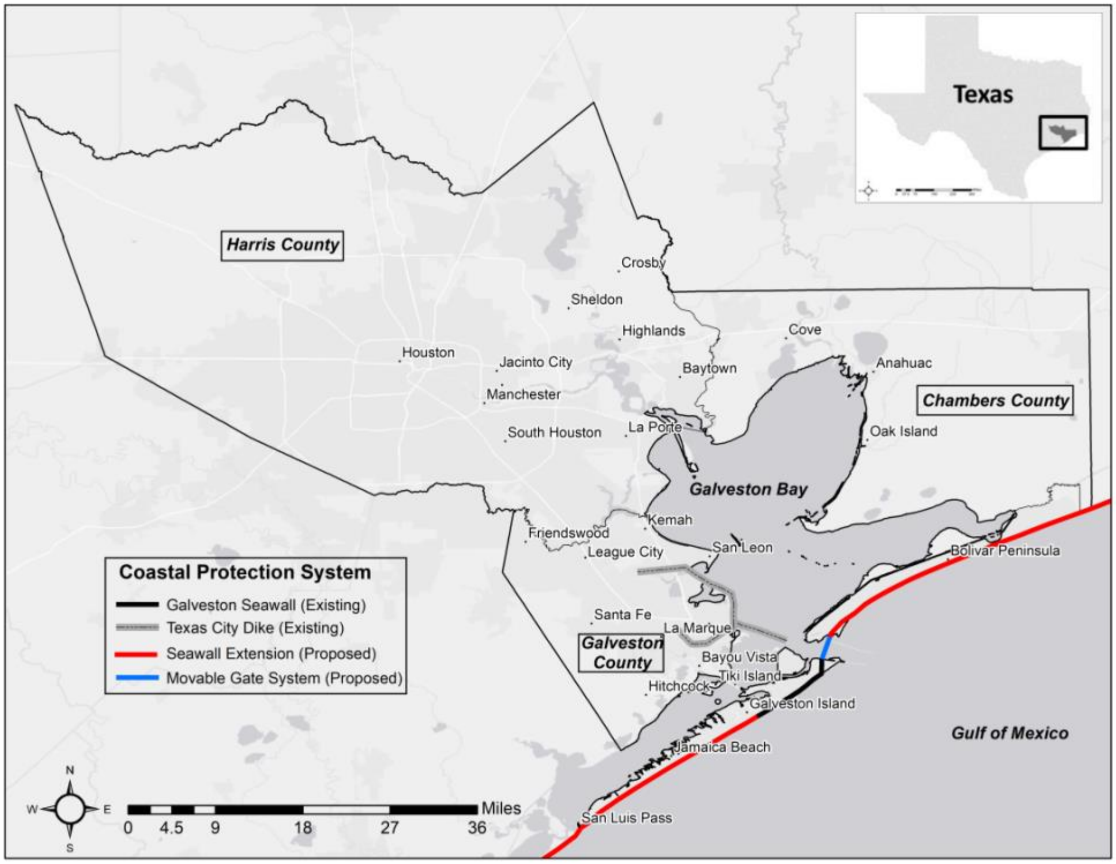

Figure 1: Impacted/Study Area.

Notes: The figure shows the HGA region covering Galveston, Harris and Chambers County and also indicates the location of the suggested coastal spine system, which will connect the existing Galveston seawall with the proposed extensions and a retractable gate system, covering approximately a 57-mile long barrier along the Galveston bay. Source: Davlasheridze et al. (2018).

Methodology Overview

The steps in this assessment of storm surge impacts on the state and national economy include (1) assessing surge impacts on housing and petroleum refinery and chemical manufacturing sectors with different intensity storms, with and without coastal spine protection; (2) developing a multi-year, multi-sector economic model for impact analysis; and (3) modeling surge impacts on the overall economy. The following summarizes key elements of these procedures. More details pertinent to direct loss estimation in particular are provided in Davlasheridze et al. (2018) and Atoba et al. (2018).

Synthetic Proxy Storms

Three proxy (500-year, 100-year, 10-year) and Ike-like storms were generated using the Advanced CIRCulation (ADCIRC) model. ADCIRC is a coupled wave and storm surge model that simulates the movement of water and storm surge forced by the effects of a hurricane (wind and atmospheric pressure gradients, and surface wind waves) (Westerink et al. 1992, Hope et al., 2013). ADCIRC outputs (e.g., peak surge-height) were used to assess and delineate hazard exposure of residential and petro-chemical plants for the HGA region. Differences in return probabilities in these proxy storms allowed us to examine exposure and impacts at different intensity levels. Of the three proxy storms, the 500-year is the strongest with a return probability of one in every 500 years, or a storm with 0.2% chance of occurrence in any given year. Characteristics of the proxy storms are reported in Table 1.

Table 1: Storm Characteristics.

Storm Type	Landfall	Central Pressure	Forward Speed	Rmax
10-year Proxy	San Luis Pass	975 mb	6 kts	17.7 – 25.7 n mi
100-year Proxy	San Luis Pass	930 mb	11 kts	25.8 – 37.4 n mi
500-year Proxy	San Luis Pass	900 mb	11 kts	21.8 – 31.6 n mi

Source: The Coastal Hazards Center of Excellence, Jackson State University; Authors.

Modeling Property Losses

The ADCIRC model outputs (e.g., peak surge-height maps) were input into the HAZUS-MH model to generate losses to building stock by block group, which were then aggregated to generate residential property losses for the three counties. HAZUS-MH is an engineering model developed by the Federal Emergency Management Agency (FEMA) for modeling impacts from flood, hurricanes or earthquake hazards. The model generates estimates of economic losses to general building stock, lifelines, utilities, debris and the associated social impacts, as well as the resultant avoided loss from mitigation (Scawthorn et al. 2006a; 2006b; Ding et al. 2008). The HAZUS-MH default building inventory is based on Census block group-level data containing extensive sets of information such as population demographics, structural characteristics of buildings (e.g. square footage), numbers and locations of critical infrastructure (e.g. bridges, hospitals, utility lifelines, schools, etc.). The Comprehensive Data Management System (CDMS) permits users to update and manage default datasets utilized in HAZUS-MH analyses with more detailed and accurate data specific to a location of interest. For this study, the HAZUS-MH default building inventory was updated using parcel-level information for the three counties (Galveston, Harris and Chambers), such as building improvement year, amounts spent on improvement, building materials, structural cost, and square footage. Relevant water depth-damage curves from the U.S. Army Corps of Engineers (USACE) Galveston District and the Federal Insurance Administration (FIA) were then employed to estimate the direct loss to residential property. These detailed block-group level property loss estimates were then aggregated to the HGA level, to derive the most accurate proxy for the direct impact to residential housing sector. Impacts were estimated with and without a coastal spine system by factoring in the spine system during ADCIRC model runs. For illustration, in Figure 2 we depict the map of loss avoidance with coastal protection in a 500-year storm surge event.

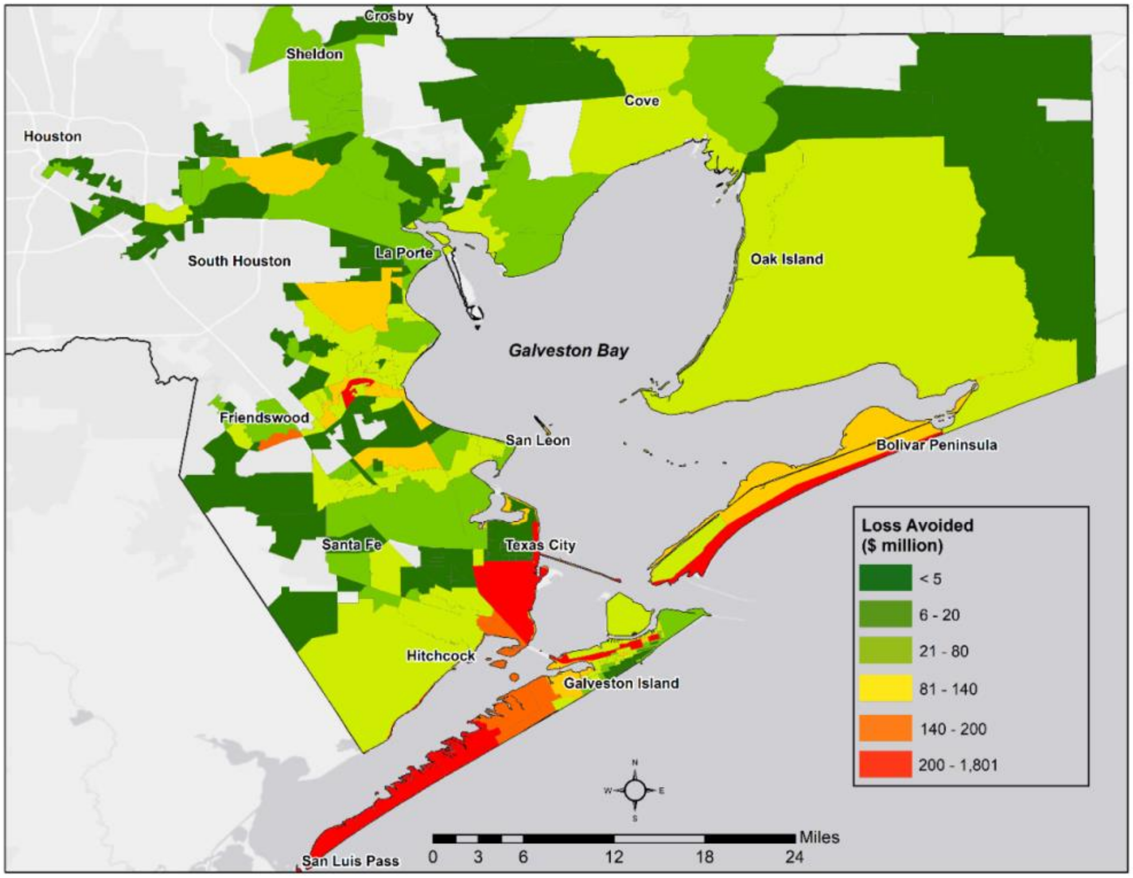

Figure 2: Property Loss Avoidance Associated with a Coastal Spine for a 500-year Surge Event.
Source: Davlasheridze et al. (2018).

Output Losses for Petroleum Refinery and Chemical Manufacturing Sectors

To estimate direct economic losses for each petroleum refinery and petro-chemical plant sectors, commonly classified by the North American Industry Classification System (NAICS) codes, several assumptions highlighted below were made. For large-scale manufacturing operations, while property losses may be negligible,[3] there could be sizeable losses associated with plant shutdowns due to electrical equipment and control room (including systems and operating) failure (Hydrocarbon Publishing Company 2016) or simply power outages (U.S. Department of Energy 2009). According to U.S. Department of Energy estimates, these two causes have constituted over 80% of electrical problems in U.S. refineries during 2009-2013, of which 14% were caused by inclement weather incidents (i.e. hurricanes, winds, thunderstorms).

[3] During super storm Sandy, Phyllips 66's Bayway in New Jersey reported economic losses approximately $ 706 million, of which $56 million (7.9%) was the cost of damaged equipment (capital loss) and the remaining $650 million was the output loss associated with 24 days shut-down due to power outage (Hydrocarbon Publishing Company 2016).

Hence, rather than modeling industrial property losses, we calculated total value of production output loss for each industrial plant and aggregated them at the sectoral level. In Appendix Table B1 we report NAICS codes and names for all sectors aggregated in petro- and chemical- manufacturing sectors for CGE modeling purposes. In order to generate the value of production output losses as described in Davlasheridze et al. (2018) we employed petrochemical refinery and manufacturing plant-level data from Chemplants[4] and the 2012 Census of Manufacturers. The Chemplants database reports NAICS classifications of petroleum refinery and chemical plants and their physical street addresses and employment, while the Census of Manufacturers gives information about the total number of establishments (EST), number of employees (EMP), annual payrolls, total cost of materials, total value of shipment and receipts for services, value added (VA), total capital expenditure and total output (OUT) for NAICS classified (2-6 digit) industries at a zip code level.

The physical plant addresses from the Chemplant database were geocoded in ArcGIS to match them with the NAICS relevant digits of the Census of Manufacturers at a zip-code level. For every zip-code and relevant NAICS industries, two different types of average production output values were calculated: (a) establishment averages (e.g., average establishment output, calculated as $\frac{\mathrm{OUT}_{\mathrm{NAICS,zip}}}{\mathrm{EST}_{\mathrm{NAICS,zip}}}$), and (b) averages per employee (e.g., average employee output, calculated as $\frac{\mathrm{OUT}_{\mathrm{NAICS,zip}}}{\mathrm{EMP}_{\mathrm{NAICS,zip}}}$). It was assumed output values were proportional to plant employment levels. Specifically for every plant *I* (a) if Chemplants provided plant *I* employment estimates $(\mathrm{EMP}_{\mathrm{NAICS,i}})$, the estimated output values were calculated by multiplying the U.S. Census industry per employee averages with the number of plant employees $(\mathrm{e.g.}, \left[\frac{\mathrm{OUT}_{\mathrm{NAICS,zip}}}{\mathrm{EMP}_{\mathrm{NAICS,zip}}}\right] \times \mathrm{EMP}_{\mathrm{NAICS,i}})$; (b) in cases where no plant employment was available from Chemplants, missing plant level indicators were replaced by the U.S. Census' industry establishment averages $(\mathrm{e.g.}, \left[\frac{\mathrm{OUT}_{\mathrm{NAICS,zip}}}{\mathrm{EST}_{\mathrm{NAICS,zip}}}\right])$.

As an illustration, in Figures 3 and 4 we depict plant exposure for the 500-year proxy storm without and with coastal protection along with their respective inundation levels.

[4] Available at www.chemplants.com

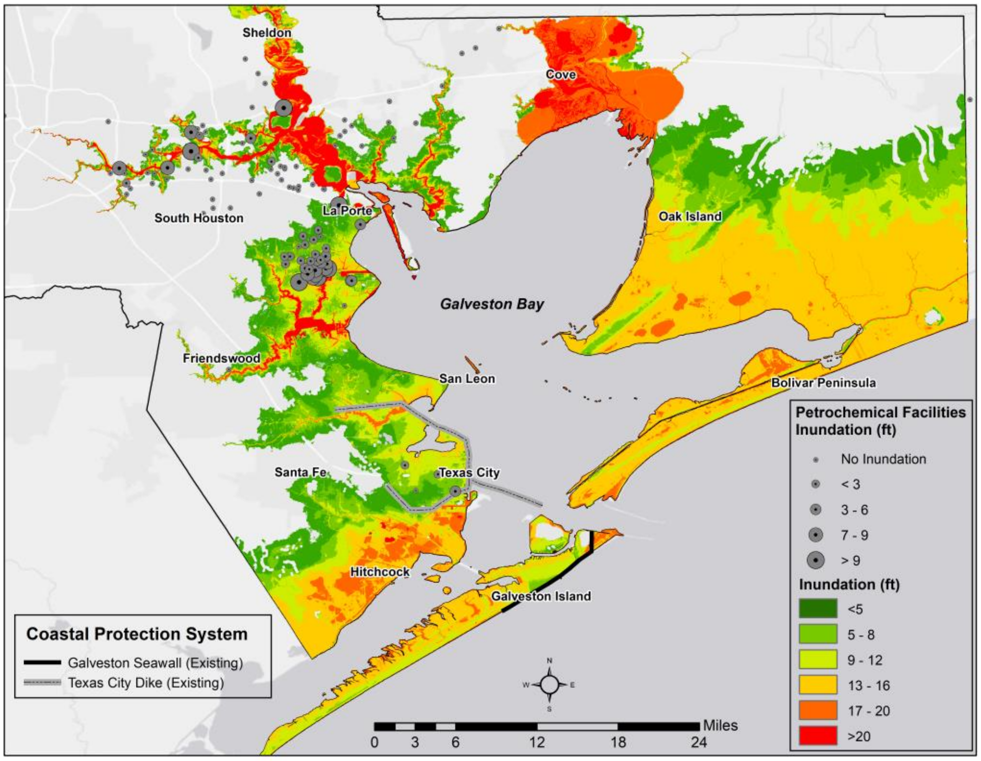

Figure 3: Petro and Chemical Plant Exposure to 500-year Inundation without Protection.
Source: Davlasheridze et al. (2018).

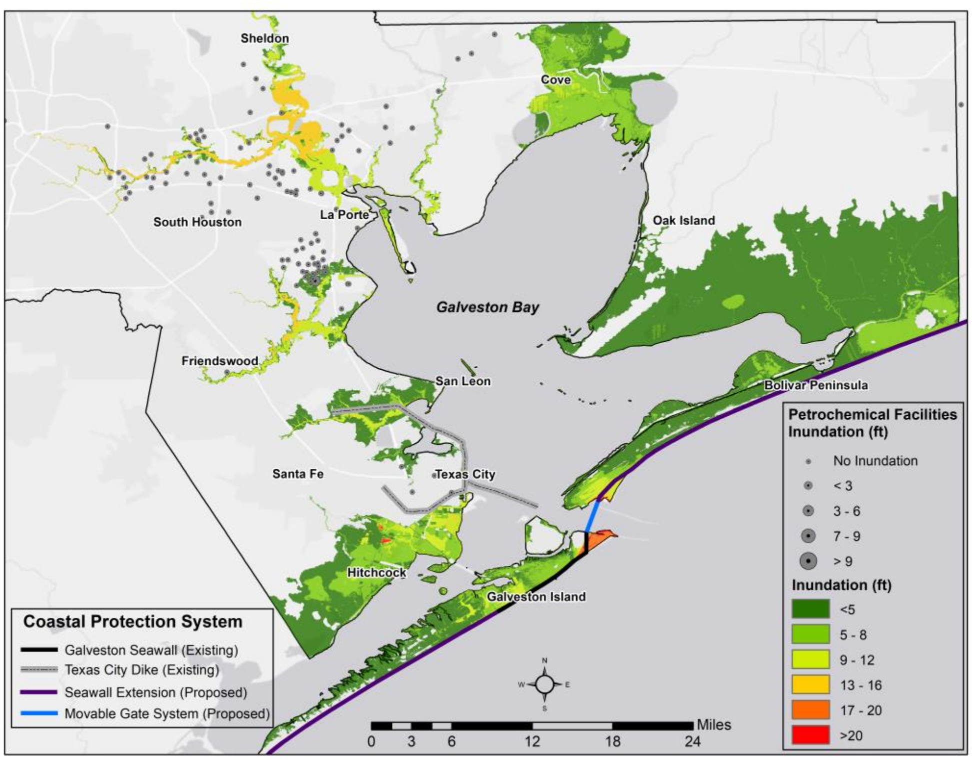

Figure 4: Petro and Chemical Plant Exposure to 500-year Inundation with Protection.
Source: Davlasheridze et al. (2018).

Shut-Down Duration Scenarios

To create plausible plant shut-down duration scenarios, we used U.S. Department of Energy (2009) reported plant level shut-downs, restarting days and the number of days during which refineries were operated at partial capacity in response to 2005 and 2008 hurricanes, respectively.[5] Three different shut-down scenarios were considered: (1) 18 days – corresponding to the average number of shut-down and restarting days in 2005; (2) 26 days – the average number of shut-down and restarting days in the sample; and (3) 33 days – the average number of shut-down and restarting days in 2008. For each of the shut-down periods, relevant output value losses were calculated using the daily output value (based on calculations described above) for all relevant firms multiplied by the total number of days plants were assumed to be down.[6] Individual plant level output losses were then aggregated up to NAICS industry for each county.

Output losses for petro- and chemical-manufacturing sectors along with residential losses (structure and contents) to the dwelling sector in the CGE model associated with different storm surge and plant shut-down scenarios were converted to 2016 dollars using Urban Consumer Price Index (presented in Table 2).

Table 2: Residential Loss (structure and contents) and Industry Output Losses Associated with Different Scenarios (millions of 2016 dolllars).

	Without protection (18)	With protection (18)	Without Protection (26)	With Protection (26)	Without Protection (33)	With Protection (33)
Panel A: 500-year						
Chemical	1,469.72	65.55	2,122.92	94.68	2,694.48	120.18
Petro-products	2,839.14	50.61	4,100.98	73.1	5,205.08	92.79
Dwelling	8,495.92	2,469.16				
Panel B: 100-year						
Chemical	173.88	4.23	251.16	6.1	318.79	7.75
Petro-products	920.8	50.61	1,330.04	73.1	1,688.13	92.79
Dwelling	4,608.76	1,404.05				
Panel C: 10-year						
Chemical	5.92	0	8.55	0	10.85	0
Petro-products	24.49	0	35.37	0	44.9	0
Dwelling	558.88	110.49				
Panel D: Ike-like storm						
Chemical	7.12	0	128.09	0	185.01	0
Petro-products	16.41	0	295.48	0	426.80	0
Dwelling	3,148.99	143.91				

Note: Petrochemical and chemical manufacturing sectors were aggregated to one sector, called "chemical" in the table above. Numbers in parenthesis in column headings correspond to a plant shut-down duration measured in days. Residential losses do not vary by the number of shut-down days.

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[5] In Appendix Table B2 we report the full list of Texas plants and corresponding shutdown/partial capacity days experienced as a consequence of the 2005 and 2008 hurricanes.

[6] It was assumed that plants inundated at any positive flood depth would constitute to exposed plants to different storm-surge scenarios.

The economic impacts simulated in the CGE model are based on the losses presented in Table 2 above. It is important to emphasize that losses to the dwelling sector dominate the total direct impacts associated with all different synthetic storm surge events, making up more than half of damages. In the scenario where plants only shut down for 18 days, the dwelling sector suffers more than 66% of all total direct losses locally. Importantly, direct losses to industrial sectors are fully mitigated with coastal spine under 10-year and Ike-like storm, while the residential housing sector still sustains damages, albeit substantially smaller relative to a scenario where no coastal protection is provided.

CGE Model

Model Overview

The CGE model captures economic interactions of consumers, producers, government and the trade sector. Consumers in this model are endowed with a supply of labor and capital. Firms employ labor and capital as input factors of production and pay wages and profits (factor rents) respectively. These factors are used in the production process to generate commodities that are consumed as factors of production (i.e. intermediate input) by firms, or by households as final consumption goods. Government collects taxes and uses tax revenues to purchase goods and services. The model also covers both the domestic (i.e. intra-national) and international trade assuming domestic and imported goods are imperfect substitutes.

The CGE model is based on the premise of the three governing principles of General Equilibrium theory, namely (1) supply equals demand (i.e. all markets clear), (2) producers cannot earn excess profit (i.e. zero profit condition) and (3) consumers exhaust all income (i.e. purchase commodities based on their budget, which equals total income net savings). The model specifies a consumer utility function and a production function as well as elasticities of substitution among input factors and simulates economic impacts using these three principles as guides.

Consumers

Consumers (i.e. households) are endowed with a supply of labor and capital, which represent factors of production for firms. Households receive income from firms who employ these production inputs (i.e. wages are paid for labor and profits are paid for capital), and allocate this income for consumption of goods and services and savings. Households maximize their utility that measures their level of satisfaction through purchasing a bundle of goods and services (e.g. food, housing, energy and others) given their budget constraints (i.e. income minus savings). In the CGE model consumer utility is modeled using a nested constant elasticity of substitution (CES) utility function. The CES function allows different rates of substitutions (i.e. elasticities of substitution[7]) across different commodities (i.e. a food composite good, a housing composite good, an energy composite good, and 11 other non-food, non-house and non-energy goods) within the same utility function. For example, the elasticity of substitution between food and housing is different from the elasticity of substitution between food and energy goods.

[7] The elasticity of substitution measures the degree of substitutability of different goods. The larger the magnitude of the elasticity of substitution, the easier it is to substitute one good with another product.

Producers

Producers, representing different industries, are assumed to be profit maximizers who transform factors of production (i.e. labor, capital, energy and materials) into commodities using specified production technologies. Similar to consumers, the functional form for production technology (a nested Cobb-Douglas-constant elasticity of substitution function is used in the CGE model) accounts for different elasticities of substitution between factors of production within the same production function. For example, the elasticity of substitution between energy and materials can take on a different value than that for capital and labor. Commodities produced by producers are purchased by households and governments as final consumption goods or other firms as intermediate goods.

Government

In the CGE model, the government has two primary roles, it collects taxes and purchases commodities using tax revenues. Government chooses commodities produced by 23 aggregated production sectors specified in Table 3 by maximizing a utility function, and the spending is constrained by the amount of public revenues. In the model, we use a Cobb-Douglas utility function, where the consumption shares across commodities are derived from benchmark data.

Trade Sector

Trade is assumed to happen both domestically as well as internationally, and the trade flows are modeled using the Armington approach where imported goods are considered to be imperfect substitutes for domestic goods. The model is described in detail in Appendix A.

Definition of Major Macroeconomic Indicators Generated by the CGE Model

Gross Domestic (State) Products (GDP/GSP) ($ billions)

The GSP measures the value of the goods and services produced annually in each state and in the United States. It is an important economic indicator and measures how the economy is doing from one year to another. More: https://www.bea.gov/sites/default/files/2018-04/GDP-Education-by-BEA.pdf

Per Capita Income ($)

The average income earned per person in a given year, including wages and salaries earned from participating as laborers in production, earnings from owning a home or unincorporated business, from the ownership of financial assets, and from government (e.g., social security payments and other government transfers) and business (interests and dividends) in the form of transfer receipts. It includes income from domestic sources as well as from the rest of the world. Personal income, however does not include capital gains from changes in stock prices.

Social Welfare ($ billions)

The Social Welfare measure is grounded on the theoretical notion of Hicksian Equivalent Variation (EV), which captures an individual's willingness to pay to avoid price changes due to policy change or external shocks (e.g., surge event). Hicksian EV is measured by (extra/less) income required to reach the final utility level (e.g., resultant due to surge events) at the original prices. In the model a utility index represents the income-weighted sum of individual EVs, and is measured as an aggregate expenditure of the representative agent on consumption.

Relative Prices
Relative prices are aggregate sector composite prices relative to a price of a numeraire good, which is assumed to be prices of all international goods. The numeraire is set at unity. The relative prices are also relative to a base year, for which prices are again assumed to be unity. Hence, the percent change in relative price relative to BAU is the most intuitive measure to capture the price changes associated with surge events.

Output by industry ($ billions)
Output by industry corresponds to the value of production by industry in a calendar year. Alternatively, it can be described as annual revenues (sales) made by each industry plus net inventory change.

Employment ($ millions)
Employment represents full and part-time annual average jobs for both employees and self-employed workers by sector. It does not indicate the number of hours worked per day.

Net export ($ billions)
The net export is the total value of exported goods net imported goods.

Total Consumption ($ billions)
The households' total expenditure on private expenditure (money spend on private consumption goods) and government expenditure (money spent on taxes).

Total Government Consumption ($ billions)
The total government expenditure on domestic and imported commodities.

Investment ($ billions)
The total annual amount of household investment measured in U.S. dollars.

The Model Calibration and Data Sources
A recursive dynamic inter-state CGE model developed for this study is based on the modeling framework presented in Rausch and Rutherford (2008) and Sue Wing (2007). The model is calibrated to the IMPLAN state-level social accounting matrices (SAMs). These SAMs are constructed using data primarily from sources such as the Bureau of Economic Analysis (BEA), the Bureau of Labor Statistics (BLS) and the U.S. Census Bureau. The database includes SAMs covering 536 industrial sectors for 50 states and Washington D.C. for the year 2016. Different from an input-output (IO) table that shows the relationship between inputs and outputs among factors of production, consumption, government, investment, export, and import, a SAM is an expanded version of an IO table and shows the entire monetary flow of the economy. For example, a SAM contains detailed information about payments arising from different sources such as ownership of certain assets, direct taxes on corporations and households, pensions, and transfers. The basic structure of the SAM is based on the following transactions and transfers in the economy: 1) production requires intermediate goods and factor of production such as labor, capital, energy, and materials; 2) these factor endowments are contributed by institutions such as households, firms, government, and foreign entities, which in turn receive factor payments (e.g., wage, rent, and profits), called value-added (VA). Therefore, a SAM shows the interrelationship between value-added and final expenditure. A balanced SAM shows an exact correspondence between rows and columns, which indicates the following relationship: 1) supply equals demand for all goods and factors; 2) tax payments equal tax receipts; 3) zero profits in production; 4) the value of each household expenditure

equals the value of factor income plus transfers; 5) the value of government tax revenue equals the value of transfers.

Sector Aggregation

The IMPLAN 536 finer-scale sectors were aggregated to 23 industrial sectors (see Table 3) including the key sectors of interest such as petroleum refineries (i.e. petro products), chemical manufacturing (including petrochemicals), and dwelling (residential housing) sectors. The IMPLAN source data presents substantial challenges for calibrating the model due to large numbers of small coefficients in the source data. These coefficients represent economic flows that are negligible share of overall economic activity for some sectors, but cause significant computational burdens during matrix factorization. Thus, similar sectors, especially those with small accounts, were aggregated.

Table 3. Production Sectors included in the Model.

Aggregated Commodities[8]	23 Industrial Sectors
Food	Fruits, vegetables, and nuts
	Other animal production
	Other agricultural products
	Food related
Energy commodity	Petro products
	Electricity
	Natural gas, oil, and coal
Housing	Construction
	Wood products
	Furniture
	Insurance
	Dwelling
Others (non-energy, non-food, and non-housing)	Pulp and paper
	Water and sewage
	Chemicals
	Other mining
	Food and tobacco
	Rubber and plastics
	Nonmetallic metals
	Primary metals
	Heat and air-conditioning
	Other manufacturing
	Services

Source: Authors.

[8] These aggregated commodities are used in the nested CES utility function.

Parameters, Exogenous Variables and Data Sources

State-level SAMs representing the flow of commodities and payments across all sectors of the state economies correspond to a benchmark year 2016. From SAMs we derived labor and capital incomes, tax revenue by type of tax, and expenditures on specific commodities by the household, government and foreign sectors. To construct compensation rates for labor and capital employed in each sector, payments to capital and labor were combined with employment and capital input data. The tax rates were derived by dividing public revenues by the related denominator—i.e., value of industry output, and capital and labor payments.

Key exogenous economic variables[9] of the model include total population, depreciation rate, saving rates, government taxes, rates of productivity growth, and rate of improvement in capital and labor quality. Parameters define growth in multifactor, labor and energy productivity.

Population growth trajectories were taken from historical data. Savings rates are calibrated by household and region using base year (2016) data. The assumed values of these parameters and variables are presented in Table 4 and more details are provided in the subsection 3.7 below.

Table 4. Parameters, Exogenous Variables and Data Sources in the CGE Model.

Variable Names	Parameters	Data Sources
State-level SAMs for 2016	SAMs for 536 industries, 9 types of households by income levels, governments, and trade sectors.	Minnesota IMPLAN group (MIG)
Average depreciation rate for all type of asset (2016)	0.05	Bureau of Economic Analysis
Multifactor productivity annual growth rate (2016)	0.025	U.S. Bureau of Labor Statistics
Labor productivity growth rate	0.025	Abler et al. (2009)
Autonomous energy efficiency improvement (AEEI) annual growth rate (2016)	0.02	Energy Information Administration (EIA)
Population	In millions of persons	U.S. Census Bureau

Economic Impacts of Storm Surge

Surge Sensitive Sectors

Sudden surge events will destroy physical capital (productive capital, buildings and other infrastructure). The dwelling sector is the most sensitive to surge events as it encompasses the residential property sector which is directly hit by damaging storms. While petroleum and chemical manufacturing sectors may also experience on-site property damages, the losses to major equipment or a system failure may have a more pronounced impact on this sector because these causes potentially lead to a plant closure and loss of output, as suggested by published reports and assessments, and discussed above in subsection 3.3.

[9] Exogenous variables are variables that are not determined by the model.

General Equilibrium Impacts
Some economic sectors are largely insulated from surge events in terms of their own production processes and are yet affected indirectly by other, more sensitive economic sectors within the region (e.g., dwelling and petro products & chemical manufacturing sectors). Hence it is expected the surge impacts on a specific sector(s) will also impact prices of capital, labor, materials, or other production inputs facing producers in another economic sector. Similarly, surge impacts on one sector(s) may also affect output prices received by producers in another sector. The price changes (both outputs and inputs) stimulate substitution away from higher-priced goods and toward lower-priced goods. These phenomena acting through markets and prices are commonly referred to as general equilibrium effects.

Multiplier Impacts
Changes in input prices (i.e., prices of labor, capital, energy and materials) can lead to changes in personal income, because in the CGE model individuals are assumed to be owners and suppliers of these inputs. Hence the direct impacts on one sector can generate a chain reaction of additional rounds of indirect effects through the changes in personal income, often referred to as induced effects. The total impact accounts for all rounds of effects on all economic sectors which represents some multiple of the direct impacts (referred to as ”multiplier effects”).

Furthermore, Texas' economy is interconnected with other states, especially with economies of surrounding states and regions, and the rest of the world. The ripple effects on economies of other states are captured through exports, imports, inflows and outflows of capital, and in-migration and out-migration of labor across states. Changes in the input and output prices of goods and services produced in surge-sensitive sectors in Texas, in particular in petro and chemical manufacturing sectors that produce tradable goods, will also impact prices and inputs of different sectors in other states and will result in changes in cost of production, productivity, input and output prices. For some states, in particular for those relying on goods and services produced by these surge-sensitive sectors, these changes could be detrimental, while other states may benefit from surge events in Texas because of the substitution possibility among inputs and goods.

The impacts described above are those that influence the economy through the market mechanisms (supply equals demand for all traded goods and services). Hence, the impacts generated by the CGE represent the market impacts of surge events. While storm surge can destroy valuable ecosystem services that are not traded in markets, reduced quality of life, human health and more, they are not captured in this study. The multi-year, multi-sector economic models are best used for the purpose of capturing economic impacts through market and are not generally capable of nonmarket impacts analysis.

Baseline Economic Conditions

The economic impacts analysis presented in this report involves comparing economic conditions without and with surge events. The economy without a storm surge incident is the reference economy and is referred to as the Business As Usual (BAU) economy. Generating the BAU scenario requires consideration of potential economic conditions in the future. We use 50-year time span for simulation given projections of state-level population and key exogenous parameters such as annual growth rates of multi-factor productivity and annual rate of improvement in labor quality.

Labor supply in the model is the product of working age population and labor quality. Population data were obtained from the U.S. Census using 2016 data. In the baseline scenario, the steady population growth rate was assumed over time based on average annual growth rate in the past. To capture the changes of the work force over time, in the model we adjusted the labor quality parameter. The underlying assumption is that the quality of the labor force changes due to education, experience and age. Given the expectation of higher educational attainment in the future, we assumed that labor quality grows at 2.5 percent per year initially, falling to a growth rate of 0.5 percent per year by the end of the modeling period.

Similarly, capital quality changes in the model. This change indicates the shift in the composition of capital towards assets with shorter life. Similar to labor quality, we assumed that capital quality will rise by 2.5 percent per year initially, falling to a growth rate of 0.5 percent by the end of the modeling period.

In addition to growth in capital stocks, population growth, and labor and capital quality improvements over time, economic growth in the model is driven by improvements in total factor productivity (TFP). An improvement in TFP implies that fewer inputs are required to produce a unit of output. Sectoral TFP improvements in the model were chosen to generate estimates of growth in output and employment that replicate published state-level projections by industry from sources such as the Bureau of Economic Analysis (BEA). The model also assumes improvements in autonomous energy efficiency of 2 percent per year over the modeling period, consistent with published forecasts. Table 4 above lists these parameters along with data sources. Finally, an important parameter for the growth of economy is the household savings rate, which is calibrated by household and region using base year (2016) data and is set constant over time.

Impact Scenarios

Economic indicators with storm surge events are derived by also simulating the model forward in time with changes in selected parameters (e.g. sector productivity growth rates and endowment of capital stock) to reflect the impacts of surge events on underlying economic conditions.

The plant shut-down affects how efficiently and intensively the inputs are utilized in production. Thus, we change the scaling parameter that affects total factor productivity (TFP) associated with all input factors (i.e. capital, labor, energy, and material) in a corresponding sector (i.e., petro and chemical manufacturing sectors). The scaling parameter is adjusted to reflect the output losses as shown in Table 2 above. For example, the output loss in the petro products sector for the 33-day shutdown associated with 500-year surge event without coastal protection is estimated at $5.2 billion. This output loss corresponds to a decline in output value in the sector relative to the output value in the BAU scenario. Hence, the scaling parameter associated with TFP for petro products sector is adjusted until the output loss matches the estimated losses as shown in Table 2. Similarly, we adjust the scaling parameter of TFP associated with all input factors for chemical manufacturing sector to match the estimated direct output loss in this sector.

Different from the impact of industrial output losses, losses to the dwelling sector directly affect a household's capital endowment in the state. The ratio of property damages to the value of output of the dwelling sector in the CGE BAU scenario for each region is calculated using the dwelling losses reported in Table 2 divided by the value of dwelling output in the BAU scenario. This parameter is then incorporated into the CGE model as a coefficient of capital endowment for households by region. The impacts of storm surge on property damages are modeled as exogenous negative shocks to household capital endowments.

The CGE Model is simulated assuming both the dwelling and petro products and chemical manufacturing sectors are impacted simultaneously by surge events; we also consider scenarios when the surge impacts individual sectors such as (i) dwelling and (ii) petro and chemical manufacturing sectors. This exercise allows us to disentangle the economic effects of storm surge from each of the sectors, so as to better understand the sectoral level effects of storm surge.

As an extension, the scenarios from storm surge incorporating the SLR in 2080 were also developed. Subsequently, direct impacts were assessed assuming projected growth in housing units and production output growth for petroleum and chemical manufacturing plants. The CGE modeling framework discussed above were adopted to explore regional and national impacts of surge events coupled with the SLR in the year 2080.

CGE Model Results

Storm Surge Impact on Texas and U.S. Economies

Storm surge generates substantial economic tolls for Texas Economy as seen throughout by declines in major economic indicators such as GSP, per capita income, welfare, value of output for main economic sectors, value of net export and more. Notably, adverse impacts linger over the long-term, with significant socioeconomic ramification across other states and the nation as a whole.

For the sake of brevity and ease of exposition, we present results associated with the 500-year storm without and with the coastal spine protection, as well as briefly preview results generated under the Ike-like storm. **One type** of results estimates the impacts of surge events on individual sectors assuming the surge does not directly affect other sectors. This exercise allows us to abstract from the economic effects of storm surge in any one sector, such as dwelling, petro products and chemical manufacturing sectors, so as to better understand the direct effects of surge events on the sector. In the **second type** of results we estimate the economic impacts when storm surge affects all surge-sensitive sectors simultaneously to fully capture indirect and induced effects on the economy as a whole. The first sets of result are presented for the State of Texas only, while the second type of estimates are presented for the entire country.

Impacts on Dwelling Sector Only

The damage to dwelling sector as reported in Table 2 is estimated at about $8.5 billion in 2016 prices, which corresponds to only a small fraction (0.07%) of the state GSP in 2016 and approximately 11% of the total output value of the sector. While the share of damages to GSP is small, it generates substantial decline in the state's major macroeconomic indicators. As reported in Table 5, the state's GSP declines by 7.10% in 2066 if no coastal spine protection is considered, which is mitigated to -2.04% (albeit still indicating a decline) when the coastal spine is factored in damage assessment. Net export (export-import) falls substantially, initially indicating a sudden decline by 54%. While the gap reduces over time, in 2066 the net export still remains 10% lower than the projected net export in the BAU scenario. Social welfare also declines in the state and is estimated at approximately 7% lower without protection as opposed to 2% with protection, both relative to the BAU in 2066. Both the total consumption and investment will drop notably by approximately 6.5% in 2066. Per capita personal income and government consumption are the only two indicators experiencing positive growth in the state, however income growth is only temporal and lasts for the first decade, after which it starts to decline and remains 2% lower in 2066 relative to the income level in the BAU without a coastal spine. This is consistent with findings of Deryugina et al. (2018) suggesting that New Orleans residents earn more than those living in similar unaffected cities a few years after Hurricane Katrina. Income declines only modestly (by 0.66%) with a coastal spine. Government consumption is increasing across all years presented, indicating expanding spending on different goods and services post-incident.

Table 5: CGE Results for Selected Decades for the Texas Economy, Dwelling Sector Impacts Associated with 500-Year Storm Surge Event.

	2017	2026	2036	2046	2056	2066
Panel A: No Protection Relative to BAU						
Per Capita Income	0.80%	0.05%	-0.74%	-1.34%	-1.75%	-2.01%
GDP	-4.35%	-5.03%	-5.75%	-6.34%	-6.78%	-7.10%
Real Total Consumption	-4.43%	-5.06%	-5.66%	-6.07%	-6.30%	-6.45%
Total Investment	-4.46%	-5.14%	-5.80%	-6.24%	-6.48%	-6.64%
Government Consumption	0.00%	0.10%	0.23%	0.37%	0.51%	0.63%
Net Export	-54.02%	-17.96%	-12.57%	-10.98%	-10.49%	-10.24%
Welfare	-4.36%	-5.05%	-5.74%	-6.25%	-6.59%	-6.83%
Panel B: Protection Relative to BAU						
Per Capita Income	0.19%	-0.02%	-0.24%	-0.41%	-0.52%	-0.60%
GDP	-1.23%	-1.43%	-1.64%	-1.81%	-1.94%	-2.04%
Real Total Consumption	-1.25%	-1.44%	-1.61%	-1.73%	-1.80%	-1.84%
Total Investment	-1.26%	-1.46%	-1.65%	-1.78%	-1.85%	-1.90%
Government Consumption	0.00%	0.03%	0.07%	0.11%	0.15%	0.18%
Net Export	-15.33%	-5.12%	-3.60%	-3.16%	-3.03%	-2.96%
Welfare	-1.24%	-1.44%	-1.64%	-1.79%	-1.89%	-1.96%

Notes: Economic-wide impacts are presented associated with the 500-year storm surge impact on dwelling sector with and without coastal spine protection. Source: Authors.

In terms of sectoral impacts in the state, the adverse shock of surge events lingers in the long term and as seen in Table 6 negatively impacts production output in all sectors. The largest decline (15.7%) is experienced by the chemical sector, followed by the electricity, other mining, natural gas, oil and coal mining, petro products, and the heat and air conditioning sectors. As output shrinks, the prices rise in these surge-sensitive sectors. While chemical sector experiences largest drop in output value, the prices in the sector rise by only 1.23%; electricity prices are the most responsive to this shock and increase by 5.8%; the prices of petro products also rise by 3% in 2066. Prices increase, albeit modestly by less than 1%, for the sectors directly related to dwelling sector including water and sewage, heat and air conditioning and insurance goods and services sectors (see Table 6a). In terms of employment, our simulation results indicate reduced employment numbers in the majority of the sectors that experience decline in production output. The most sensitive sectors include chemical, petro products, electricity, other mining, and heat and air conditioning. We should also note that while in terms of output all sectors experience decline in 2066 associated with the direct impact of surge on the dwelling sector, employment increases in some of the sectors potentially due to the shift of labor force and the substitution effects. For example, we observe employment growth in forestry, furniture, services, insurances and other agricultural goods relative to the BAU, along with fruits, vegetables and nuts sectors. The coastal spine alleviates the sectoral shock and while all primary sectors grow slower than the projected trajectories in the BAU, the declines in output are less pronounced, as seen in Table 6b.

Table 6a: Sectoral Impact of 500-year Storm Surge without Protection vs. BAU (year 2066).

Sector	Output	Employment	Prices
Fruits, Vegetables, Nuts	-5.26%	0.95%	-0.14%
Other Animal Production	-8.32%	-0.99%	-0.01%
Forestry	-0.19%	4.03%	-1.48%
Other Agriculture	-4.69%	1.60%	-0.89%
Other Mining	-10.12%	-2.02%	0.52%
Electricity	-11.96%	-2.42%	5.79%
Natural Gas, Oil, Coal	-9.90%	-0.70%	-0.86%
Water and Sewage	-7.56%	0.35%	1.25%
Construction	-5.77%	-0.12%	-1.21%
Food, Tobacco	-8.15%	-0.74%	0.25%
Wood Products	-3.11%	2.04%	-0.61%
Pulp Paper	-6.12%	0.61%	-0.12%
Petroleum Products	-9.62%	-3.31%	3.07%
Chemicals	-15.72%	-6.41%	1.23%
Rubber Plastics	-8.86%	-1.74%	0.36%
Non-metallic Metals	-7.29%	-0.17%	0.29%
Primary Metals	-3.94%	2.40%	-0.28%
Heating, Air-conditioning	-9.26%	-2.02%	0.25%
Other Manufacturing	-6.70%	0.15%	-0.01%
Furniture	-1.40%	4.47%	-0.37%
Services	-5.94%	0.28%	-0.65%
Insurance	-7.04%	0.14%	0.39%
Dwelling	-6.99%	-0.28%	-0.26%

Notes: In red are highlighted the top ten most sensitive sectors in terms of the indirect impacts of the direct shock of surge on a dwelling sector. Source: Authors.

Table 6b: Sectoral Impact of 500-year Storm Surge with Protection vs. BAU (year 2066).

Sector	Output	Employment	Prices
Fruits, Vegetables, Nuts	-1.49%	0.27%	-0.04%
Other Animal Production	-2.38%	-0.27%	0.00%
Forestry	-0.06%	1.10%	-0.41%
Other Agriculture	-1.32%	0.45%	-0.25%
Other Mining	-2.93%	-0.57%	0.14%
Electricity	-3.49%	-0.70%	1.58%
Natural Gas, Oil, Coal	-2.86%	-0.19%	-0.24%
Water and Sewage	-2.17%	0.09%	0.34%
Construction	-1.65%	-0.04%	-0.35%
Food, Tobacco	-2.33%	-0.20%	0.07%
Wood Products	-0.88%	0.57%	-0.17%
Pulp Paper	-1.74%	0.18%	-0.03%
Petroleum Products	-2.78%	-0.92%	0.84%
Chemicals	-4.63%	-1.79%	0.35%
Rubber Plastics	-2.55%	-0.48%	0.10%
Non-metallic Metals	-2.09%	-0.04%	0.08%
Primary Metals	-1.11%	0.67%	-0.08%
Heating, Air-conditioning	-2.67%	-0.55%	0.07%
Other Manufacturing	-1.91%	0.05%	0.00%
Furniture	-0.39%	1.23%	-0.10%
Services	-1.69%	0.08%	-0.19%
Insurance	-2.01%	0.04%	0.10%
Dwelling	-2.00%	-0.08%	-0.08%

Notes: In red are highlighted the top ten most sensitive sectors in terms of the indirect impacts of the direct shock of surge on a dwelling sector. Source: Authors.

In Table 7 we report macroeconomic impacts associated with the Ike-like storm surge on Texas economy. There are noticeable differences in terms of the magnitude of effects associated with the 500-year and the Ike-like storms. It is notable that impacts from the no protection scenario of Ike-like storm resembles the impacts from the protection scenario when Texas is struck by the 500-year storm surge. Nonetheless, the Ike-like storm produces adverse impacts on overall state economy. Texas GSP will be 2.6% lower without a coastal spine and only 0.12% lower relative to the BAU scenario when the spine is accounted for in 2066. The immediate effect of the storm on net exports is again pronounced, indicating 20% decline relative to the BAU projected level of this indicator. Over decades these declines shrink and in the year 2066 net exports are estimated 3.8% lower. The coastal spine largely mitigates the impacts of Ike-like storm and while almost all economic indicators fall in 2066 relative to the BAU, the declines are negligible.

Table 7: CGE Results for Selected Decades for Texas Economy, Dwelling Sector Impacts Associated with Ike-like Storm Surge Event.

	2017	2026	2036	2046	2056	2066
Panel A: No Protection Relative to BAU						
Per Capita Income	0.25%	-0.03%	-0.31%	-0.52%	-0.67%	-0.76%
GDP	-1.58%	-1.83%	-2.10%	-2.32%	-2.48%	-2.60%
Real Total Consumption	-1.60%	-1.84%	-2.06%	-2.21%	-2.30%	-2.35%
Total Investment	-1.62%	-1.87%	-2.11%	-2.28%	-2.37%	-2.43%
Government Consumption	0.00%	0.04%	0.09%	0.14%	0.19%	0.23%
Net Export	-19.60%	-6.54%	-4.60%	-4.04%	-3.86%	-3.77%
Welfare	-1.58%	-1.84%	-2.09%	-2.28%	-2.41%	-2.50%
Panel B: Protection Relative to BAU						
Per Capita Income	0.01%	0.00%	-0.01%	-0.02%	-0.03%	-0.04%
GDP	-0.07%	-0.08%	-0.10%	-0.11%	-0.11%	-0.12%
Real Total Consumption	-0.07%	-0.08%	-0.09%	-0.10%	-0.10%	-0.11%
Total Investment	0.00%	0.00%	0.00%	0.01%	0.01%	0.01%
Government Consumption	-0.89%	-0.30%	-0.21%	-0.18%	-0.18%	-0.17%
Net Export	-0.07%	-0.08%	-0.09%	-0.10%	-0.11%	-0.11%
Welfare	0.01%	0.00%	-0.01%	-0.02%	-0.03%	-0.04%

Notes: Economic-wide impacts are presented associated with the Ike-like storm surge impact on dwelling sector with and without coastal spine protection. Source: Authors.

Sectoral impact associated with Ike-like storm impact on housing are presented in Table 8a and 8b without and with protection. Order of sensitive sectors is consistent with the order of the 500-year storm surge. The difference is in magnitude of impacts. Ike-like storm will result in a decline of chemical sector output by 5.9% without protection and only by 0.27% with coastal spine protection, relative to the BAU. The electricity sector output is the second most impacted, shrinking by 4.45% if no coastal protection is provided. Prices also increase in these storm sensitive sectors, but the rise is relatively small compared to the price responses to the 500-year storm. For example, electricity product prices will be 2% higher in 2066 without coastal protection, and petroleum product prices will increase by only 1%.

Table 8a: Sectoral Impact of Ike-like Storm Surge without Protection vs. BAU (year 2066).

Sectors	Output	Employment	Price
Fruits, Vegetables, Nuts	-1.90%	0.35%	-0.05%
Other Animal Production	-3.04%	-0.34%	0.00%
Forestry	-0.07%	1.41%	-0.53%
Other Agriculture	-1.69%	0.57%	-0.32%
Other Mining	-3.74%	-0.72%	0.18%
Electricity	-4.45%	-0.89%	2.03%
Natural Gas, Oil, Coal	-3.65%	-0.24%	-0.31%
Water and Sewage	-2.77%	0.12%	0.43%
Construction	-2.11%	-0.05%	-0.44%
Food, Tobacco	-2.98%	-0.25%	0.09%
Wood Products	-1.12%	0.72%	-0.22%
Pulp Paper	-2.23%	0.23%	-0.04%
Petroleum Products	-3.55%	-1.18%	1.08%
Chemicals	-5.90%	-2.30%	0.45%
Rubber Plastics	-3.26%	-0.61%	0.13%
Non-metallic Metals	-2.67%	-0.06%	0.10%
Primary Metals	-1.42%	0.86%	-0.10%
Heating, Air-conditioning	-3.40%	-0.71%	0.09%
Other Manufacturing	-2.44%	0.07%	-0.01%
Furniture	-0.50%	1.57%	-0.13%
Services	-2.17%	0.10%	-0.24%
Insurance	-2.57%	0.05%	0.13%
Dwelling	-2.56%	-0.10%	-0.10%

Notes: In red are highlighted the top ten most sensitive sectors in terms of the indirect impacts of the direct shock of surge on a dwelling sector. Source: Authors.

Table 8b: Sectoral Impact of Ike-like Storm Surge with Protection vs. BAU (year 2066).

Sector	Output	Employment	Price
Fruits, Vegetables, Nuts	-0.09%	0.02%	0.00%
Other Animal Production	-0.14%	-0.02%	0.00%
Forestry	0.00%	0.06%	-0.02%
Other Agriculture	-0.08%	0.03%	-0.01%
Other Mining	-0.17%	-0.03%	0.01%
Electricity	-0.20%	-0.04%	0.09%
Natural Gas, Oil, Coal	-0.17%	-0.01%	-0.01%
Water and Sewage	-0.13%	0.01%	0.02%
Construction	-0.10%	0.00%	-0.02%
Food, Tobacco	-0.14%	-0.01%	0.00%
Wood Products	-0.05%	0.03%	-0.01%
Pulp Paper	-0.10%	0.01%	0.00%
Petroleum Products	-0.16%	-0.05%	0.05%
Chemicals	-0.27%	-0.10%	0.02%
Rubber Plastics	-0.15%	-0.03%	0.01%
Non-metallic Metals	-0.12%	0.00%	0.00%
Primary Metals	-0.06%	0.04%	0.00%
Heating, Air-conditioning	-0.15%	-0.03%	0.00%
Other Manufacturing	-0.11%	0.00%	0.00%
Furniture	-0.02%	0.07%	-0.01%
Services	-0.10%	0.00%	-0.01%
Insurance	-0.12%	0.00%	0.01%
Dwelling	-0.12%	0.00%	0.00%

Notes: In red are highlighted the top ten most sensitive sectors in terms of the indirect impacts of the direct shock of surge on a dwelling sector. Source: Authors.

Economic Impacts to Petroleum Products and Chemical Manufacturing Sectors Only

We now turn to the estimated results when major industrial sectors (petro products and chemical manufacturing) are impacted in the region by the 500-year storm surge. In particular, we present results from the scenario when a storm forces 33-day shutdown of plants, translating these shut down days into output losses (i.e., proxying for direct losses to the sector). We should note that under this scenario total direct loss to these sectors is $7.9 billion, 7% lower than the damages sustained in the dwelling sector. This damage figure corresponds to approximately 8% of the total output value of these sectors in Texas in 2016. The impacts on petroleum and chemical manufacturing sectors are relatively smaller within the state as shown by major economic indicators in Texas than the macroeconomic impacts seen through the destruction of the dwelling sector. One explanation is that in the CGE model, damage to the dwelling sector is modeled as a decline in capital endowment to households. Reduced capital affects production output for those sectors that are capital-intensive (e.g. manufacturing sectors) in addition to affecting sectors directly servicing the dwelling (e.g., electricity, heating and gas). This is one of the primary reasons we observe the largest decline in production output in chemical manufacturing and petroleum products locally as a result of housing destruction, followed by the negative output growth in electricity as well as heat and air conditioning. We should also note that capital destruction translates into reduced wage earnings for households who are endowed with factors of production (e.g., capital). On the contrary, output losses to these major industrial sectors are modelled through the reduced total factor productivity parameter related to all factors of production (not only to capital), while assuming the effective capital stock is undamaged.

While indirect impacts are relatively smaller in the state, all major macroeconomic indicators still decline relative to the BAU in Texas. Specifically, GSP will be 1.20% lower in 2066 relative to projected GSP in the BAU; personal income also declines by 1%. Social welfare is 0.88% lower and net exports fall by approximately 3% (see panel A of Table 9). These are all without factoring in the mitigating effects of a coastal spine. Impacts are largely mitigated under the protection scenario; declines in major economic indicators are in the range of 0.01-0.03% (Panel B of Table 9).

Table 9: CGE Results for Selected Decades for the Texas Economy (500-year).

	2017	2066	2036	2046	2056	2066
Panel A: No Protection Relative to BAU						
Per Capita Income	-0.95%	-0.95%	-0.93%	-0.92%	-0.94%	-1.01%
GDP	-0.98%	-1.00%	-1.01%	-1.05%	-1.11%	-1.20%
Total Consumption	-0.61%	-0.64%	-0.64%	-0.60%	-0.57%	-0.56%
Government Consumption	0.32%	0.31%	0.31%	0.33%	0.38%	0.44%
Net Export	-13.07%	-4.28%	-3.06%	-2.86%	-2.93%	-2.98%
Welfare	-0.90%	-0.88%	-0.85%	-0.83%	-0.83%	-0.88%
Panel B: Protection Relative To BAU						
Per Capita Income	-0.02%	-0.02%	-0.02%	-0.02%	-0.02%	-0.03%
GDP	-0.02%	-0.02%	-0.03%	-0.03%	-0.03%	-0.03%
Total Consumption	-0.01%	-0.01%	-0.01%	-0.01%	-0.01%	-0.01%
Total Investment	-0.02%	-0.02%	-0.02%	-0.02%	-0.02%	-0.02%
Government Consumption	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%
Net Export	-0.31%	-0.11%	-0.08%	-0.08%	-0.08%	-0.08%
Welfare	-0.02%	-0.02%	-0.02%	-0.02%	-0.02%	-0.02%

Notes: Economy-wide impacts are presented associated with the 500-year storm surge impact on petro and chemical manufacturing sectors (resulting in 33-day shutdown of production operation) with and without coastal spine protection.
Source: Authors.

While impacts reflected on macroeconomic indicators are negligible, sector-specific impacts in the state of Texas indicate that outputs decline and remain low relative to BAU in chemical and petro products sector, along with natural gas, oil and coal mining. Employment also declines in these sectors. Prices are relatively more sensitive to storm surge impacts on these sectors as well (see Table 10a). Specifically, we observe 10% increase in composite prices of the petro products and chemicals relative to those in the BAU. This increase is three times larger than the price increase in the sector when these sectors are indirectly impacted from the shock on the dwelling sector. Prices in all other sectors fall due potentially to substitution effects and shifts in consumption patterns post-surge event. The impacts are largely mitigated with the coastal spine (Table 10b).

Table 10a: Sectoral Impact of 500-year Storm Surge without Protection vs. BAU (year 2066).

Sector	Output	Employment	Price
Fruits, Vegetables, Nuts	0.57%	0.90%	-0.03%
Other Animal Production	0.77%	1.08%	-0.01%
Forestry	0.64%	0.93%	-0.14%
Other Agriculture	0.74%	1.09%	-0.10%
Other Mining	-0.15%	0.33%	-0.17%
Electricity	0.49%	0.98%	-0.13%
Natural Gas, Oil, Coal	-5.97%	-0.92%	-2.86%
Water and Sewage	-0.32%	0.08%	-0.60%
Construction	-0.82%	-0.41%	-0.61%
Food, Tobacco	0.55%	1.09%	-0.14%
Wood Products	0.40%	0.75%	-0.17%
Pulp Paper	0.90%	1.35%	-0.09%
Petroleum Products	-10.36%	-13.92%	9.56%
Chemicals	-3.46%	-2.25%	0.37%
Rubber Plastics	0.24%	0.85%	-0.03%
Non-metallic Metals	-0.06%	0.46%	-0.38%
Primary Metals	1.06%	1.47%	-0.11%
Heating, Air-conditioning	0.37%	1.10%	-0.14%
Other Manufacturing	0.61%	1.27%	-0.11%
Furniture	0.61%	1.24%	-0.11%
Services	-0.05%	0.31%	-0.51%
Insurance	0.13%	0.37%	-0.41%
Dwelling	-0.79%	-0.40%	-0.52%

Notes: In red are highlighted the top ten most sensitive sectors in terms of the indirect impacts of the direct shock of surge on petro and chemical manufacturing sectors, when plants shut down for 33 days. Source: Authors.

Table 10b: Sectoral Impact of 500-year Storm Surge with Protection vs. BAU (year 2066).

Sector	Output	Employment	Price
Fruits, Vegetables, Nuts	0.02%	0.02%	0.00%
Other Animal Production	0.02%	0.03%	0.00%
Forestry	0.01%	0.02%	-0.01%
Other Agriculture	0.02%	0.03%	0.00%
Other Mining	-0.01%	0.01%	-0.01%
Electricity	0.01%	0.02%	-0.01%
Natural Gas, Oil, Coal	-0.12%	-0.01%	-0.06%
Water and Sewage	-0.01%	0.00%	-0.02%
Construction	-0.02%	-0.01%	-0.02%
Food, Tobacco	0.02%	0.03%	0.00%
Wood Products	0.01%	0.02%	0.00%
Pulp Paper	0.02%	0.03%	0.00%
Petroleum Products	-0.20%	-0.26%	0.16%
Chemicals	-0.16%	-0.12%	0.02%
Rubber Plastics	0.00%	0.02%	0.00%
Non-metallic Metals	0.00%	0.01%	-0.01%
Primary Metals	0.03%	0.04%	0.00%
Heating, Air-conditioning	0.01%	0.03%	0.00%
Other Manufacturing	0.02%	0.03%	0.00%
Furniture	0.02%	0.03%	0.00%
Services	0.00%	0.01%	-0.01%
Insurance	0.00%	0.01%	-0.01%
Dwelling	-0.02%	-0.01%	-0.02%

Notes: Table presents indirect sectoral impacts of the direct shock of surge on petro and chemical manufacturing sectors, when plants shut down for 33 days. Source: Authors.

As shown in Table 11, the Texas economy-wide impacts of Ike-like storm on petro and chemical manufacturing sectors are less pronounced. The state GSP will be 0.10% lower in the year 2066, per capita income will decline by 0.08%, and the net export value will fall by 0.24%, all relative to the BAU in 2066. In terms of sectoral impacts, reductions in output and employment are substantially reduced. For example, in terms of the output value, the most sensitive sectors are petroleum (-0.85%), natural gas, oil, and coal mining (-0.5%) and chemical manufacturing (-0.23%). Prices are subsequently less responsive to such insignificant changes in production output. The coastal spine fully mitigates the impacts of surge events on petroleum and chemical manufacturing sectors, assuming the dwelling sector is unaffected.

Table 11: CGE Results for Selected Decades for Texas Economy (Ike-like).

	2017	2026	2036	2046	2056	2066
Per Capita Income	-0.08%	-0.08%	-0.08%	-0.08%	-0.08%	-0.08%
GDP	-0.08%	-0.08%	-0.08%	-0.09%	-0.09%	-0.10%
Total Consumption	-0.05%	-0.05%	-0.05%	-0.05%	-0.05%	-0.05%
Total Investment	-0.07%	-0.07%	-0.06%	-0.06%	-0.05%	-0.05%
Government Consumption	0.03%	0.02%	0.02%	0.03%	0.03%	0.04%
Net Export	-1.08%	-0.35%	-0.25%	-0.23%	-0.24%	-0.24%
Welfare	-0.07%	-0.07%	-0.07%	-0.07%	-0.07%	-0.07%

Notes: Economy-wide impacts are presented associated with the Ike-like storm surge impact on petro and chemical manufacturing sectors (resulting in 33-day shutdown of production operation) with and without coastal spine protection. Source: Authors.

Table 12: Sectoral Impact of Ike-like Storm Surge without Protection vs. BAU (year 2066).

Sectors	Output	Employment	Price
Fruits, Vegetables, Nuts	0.05%	0.07%	0.00%
Other Animal Production	0.06%	0.09%	0.00%
Forestry	0.06%	0.08%	-0.01%
Other Agriculture	0.06%	0.09%	-0.01%
Other Mining	-0.01%	0.03%	-0.01%
Electricity	0.04%	0.08%	-0.01%
Natural Gas, Oil, Coal	-0.50%	-0.08%	-0.23%
Water and Sewage	-0.02%	0.01%	-0.05%
Construction	-0.07%	-0.03%	-0.05%
Food, Tobacco	0.05%	0.09%	-0.01%
Wood Products	0.03%	0.06%	-0.01%
Pulp Paper	0.08%	0.11%	-0.01%
Petroleum Products	-0.85%	-1.18%	0.74%
Chemicals	-0.23%	-0.14%	0.02%
Rubber Plastics	0.03%	0.07%	0.00%
Non-metallic Metals	0.00%	0.04%	-0.03%
Primary Metals	0.09%	0.12%	-0.01%
Heating, Air-conditioning	0.03%	0.09%	-0.01%
Other Manufacturing	0.05%	0.10%	-0.01%
Furniture	0.05%	0.10%	-0.01%
Services	0.00%	0.03%	-0.04%
Insurance	0.01%	0.03%	-0.03%
Dwelling	-0.06%	-0.03%	-0.04%

Notes: In red are highlighted the top ten most sensitive sectors in terms of the indirect impacts of the direct shock of surge on petro and chemical manufacturing sectors, when plants shut down for 33 days. Source: Authors.

Economic Impacts when the 500-Year Storm Surge Simultaneously Impacts Petroleum Products, Chemical Manufacturing, and Dwelling Sectors

The scenario where dwelling, petro products and chemical manufacturing sectors are all impacted by the storm surge event is the most realistic scenario and shows the full magnitude of changes in the Texas state economy as well as the economies of other states and the entire U.S.

Texas' GSP will be approximately 8% lower in 2066, relative to the BAU if no coastal spine protection is considered, and the impact is mitigated to a 2.06% decline with a coastal protection scenario. Furthermore, there is a substantial social welfare loss associated with storm surge, which also lingers over the long-term, indicating a decline of 7.6% without a coastal spine as opposed to a decline by 1.97% when the coastal spine is considered, relative to BAU in 2066. Among major macroeconomic indicators, the largest decline is observed in net export value (export-import). The decline in net export value is due to a rise in prices of goods that are heavily traded intranationally and internationally (e.g., petroleum, chemical products) and further underscores the dependence of the state on these major tradable goods (Table 13).

Table 13: CGE Results for Selected Decades for the Texas Economy.

	Per Capita Income	GDP	Total Consumption	Total Investment	Total Government Consumption	Net Export	Social Welfare
Panel A: No Protection Relative to BAU							
2017	-0.17%	-5.27%	-5.00%	-5.25%	0.31%	-66.22%	-5.21%
2026	-0.91%	-5.96%	-5.64%	-5.89%	0.40%	-21.90%	-5.87%
2036	-1.67%	-6.68%	-6.24%	-6.48%	0.52%	-15.35%	-6.52%
2046	-2.25%	-7.29%	-6.61%	-6.85%	0.68%	-13.55%	-6.99%
2056	-2.66%	-7.77%	-6.81%	-7.03%	0.86%	-13.11%	-7.32%
2066	-2.97%	-8.16%	-6.93%	-7.18%	1.05%	-12.90%	-7.58%
Panel B: Protection Relative to BAU							
2017	0.17%	-1.25%	-1.25%	-1.28%	0.01%	-15.56%	-1.25%
2026	-0.04%	-1.45%	-1.45%	-1.48%	0.04%	-5.20%	-1.45%
2036	-0.26%	-1.66%	-1.65%	-1.67%	0.07%	-3.66%	-1.65%
2046	-0.43%	-1.83%	-1.80%	-1.79%	0.11%	-3.22%	-1.80%
2056	-0.54%	-1.96%	-1.90%	-1.86%	0.15%	-3.09%	-1.90%
2066	-0.62%	-2.06%	-1.97%	-1.91%	0.19%	-3.02%	-1.97%

Notes: Economy-wide impacts are presented associated with the 500-year storm surge impact on dwelling, petro and chemical manufacturing sectors (resulting in 33-day shutdown of production operation) simultaneously with and without coastal spine protection. Source: Authors.

In terms of sectoral impacts in Texas, we should note that all aggregate sectors experience adverse shock due to the 500-year surge events as indicated by declines in output relative to the BAU scenario (Table 14a). The petroleum products and chemical manufacturing sectors are the most sensitive to storm surge events, which is not surprising given these sectors are the primary industries and net exporters of the state economy. Natural resources mining and energy sectors (e.g., electricity and heating) are another two sectors with the largest declines in output value. While the coastal spine does not fully mitigate negative impacts of storm surge events in the long-term, the magnitude of effects on other sectors are four times less than observed if no protection was placed, all relative to the BAU (Table 14b).

Table 14a: Sectoral Impact of 500-year Storm Surge without Protection vs. BAU (year 2066).

Sector	Output	Employment	Prices
Fruits, Vegetables, Nuts	-4.76%	1.80%	-0.16%
Other Animal Production	-7.68%	-0.01%	-0.01%
Forestry	0.41%	4.94%	-1.61%
Other Agriculture	-4.05%	2.63%	-0.99%
Other Mining	-10.26%	-1.72%	0.36%
Electricity	-11.52%	-1.51%	5.69%
Natural Gas, Oil, Coal	-15.28%	-1.57%	-3.70%
Water and Sewage	-7.83%	0.43%	0.69%
Construction	-6.50%	-0.50%	-1.77%
Food, Tobacco	-7.68%	0.26%	0.12%
Wood Products	-2.74%	2.76%	-0.77%
Pulp Paper	-5.34%	1.89%	-0.20%
Petroleum Products	-19.01%	-16.76%	12.81%
Chemicals	-18.69%	-8.63%	1.59%
Rubber Plastics	-8.67%	-0.97%	0.33%
Non-metallic Metals	-7.34%	0.25%	-0.06%
Primary Metals	-2.97%	3.81%	-0.39%
Heating, Air-conditioning	-8.95%	-1.00%	0.12%
Other Manufacturing	-6.18%	1.34%	-0.11%
Furniture	-0.83%	5.70%	-0.47%
Services	-5.99%	0.57%	-1.12%
Insurance	-6.92%	0.49%	0.01%
Dwelling	-7.69%	-0.66%	-0.74%

Notes: In red are highlighted the top ten most sensitive sectors in terms of the indirect impacts of the direct shock of surge on dwelling, petro and chemical manufacturing sectors, when plants shut down for 33 days. Source: Authors.

Table 14b: Sectoral Impact of 500-year Storm Surge with Protection vs. BAU (year 2066).

Sector	Output	Employment	Prices
Fruits, Vegetables, Nuts	-1.47%	0.29%	-0.04%
Other Animal Production	-2.36%	-0.24%	0.00%
Forestry	-0.05%	1.12%	-0.42%
Other Agriculture	-1.31%	0.47%	-0.25%
Other Mining	-2.94%	-0.56%	0.14%
Electricity	-3.48%	-0.68%	1.57%
Natural Gas, Oil, Coal	-2.97%	-0.20%	-0.30%
Water and Sewage	-2.18%	0.09%	0.32%
Construction	-1.67%	-0.05%	-0.36%
Food, Tobacco	-2.32%	-0.17%	0.06%
Wood Products	-0.87%	0.58%	-0.17%
Pulp Paper	-1.72%	0.21%	-0.04%
Petroleum Products	-2.97%	-1.18%	1.00%
Chemicals	-4.79%	-1.91%	0.37%
Rubber Plastics	-2.55%	-0.46%	0.10%
Non-metallic Metals	-2.09%	-0.03%	0.07%
Primary Metals	-1.08%	0.71%	-0.08%
Heating, Air-conditioning	-2.66%	-0.53%	0.06%
Other Manufacturing	-1.89%	0.09%	-0.01%
Furniture	-0.37%	1.26%	-0.11%
Services	-1.70%	0.09%	-0.20%
Insurance	-2.01%	0.05%	0.09%
Dwelling	-2.02%	-0.09%	-0.09%

Notes: In red are highlighted the top ten most sensitive sectors in terms of the indirect impacts of the direct shock of surge on dwelling, petro and chemical manufacturing sectors, when plants shut down for 33 days. Source: Authors.

The direct and rippling effect through interconnected sectors and intra-, inter-national trade result in about 1.1% loss in U.S. GDP without a coastal spine; the magnitude of impact is mitigated with protection and the GDP decreases by 0.28% in the spine protection scenario. Social welfare is also lowered by 0.92% relative to the BAU and 0.24% without and with protection, respectively. While Texas experiences a decline in net exports, for the entire nation there is an increase in net exports relative to BAU during the first decade (2017-2026) following a surge event both with and without a protection, which then start to decline in the following decades (Table 15).

Table 15: CGE Results for Selected Decades for the U.S. Economy.

	Per Capita Income	GDP	Total Consumption	Total Investment	Total Government Consumption	Net Export	Social Welfare
Panel A: No Protection Relative to BAU							
2017	0.00%	-0.45%	-0.42%	-0.57%	-0.02%	2.00%	-0.41%
2026	-0.07%	-0.54%	-0.51%	-0.70%	-0.02%	7.60%	-0.50%
2036	-0.16%	-0.67%	-0.63%	-0.84%	-0.01%	-8.58%	-0.62%
2046	-0.25%	-0.81%	-0.72%	-0.97%	0.02%	-4.38%	-0.73%
2056	-0.33%	-0.96%	-0.78%	-1.07%	0.05%	-3.93%	-0.83%
2066	-0.39%	-1.10%	-0.83%	-1.14%	0.09%	-3.96%	-0.92%
Panel B: Protection Relative to BAU							
2017	0.02%	-0.10%	-0.10%	-0.14%	-0.01%	0.45%	-0.10%
2026	0.00%	-0.13%	-0.12%	-0.18%	-0.01%	1.76%	-0.12%
2036	-0.03%	-0.17%	-0.16%	-0.22%	0.00%	-2.03%	-0.16%
2046	-0.05%	-0.20%	-0.19%	-0.25%	0.00%	-1.03%	-0.19%
2056	-0.07%	-0.24%	-0.21%	-0.28%	0.01%	-0.91%	-0.21%
20.66	-0.08%	-0.28%	-0.24%	-0.30%	0.02%	-0.90%	-0.24%

Notes: Nation-wide impacts are presented associated with the 500-year storm surge impact on dwelling, petro and chemical manufacturing sectors (resulting in 33-day shutdown of production operation) simultaneously with and without coastal spine protection. Source: Authors.

To translate these percentage changes into actual dollars, in Table 16 we report national and TX values for macroeconomic indicators in the year 2066 in level terms (e.g., GDP, consumption, per capita income, and net export, consumption, investment welfare (in 2016 prices) associated with the three scenarios (i.e. BAU, without coastal protection, and with protection), and corresponding losses relative to the BAU.

Table 16: Impacts in Levels for Texas and the U.S. Economy in 2066.

	No Protection	Protection	BAU	No Protection - BAU	Protection-BAU	Protection – No Protection
Texas						
Per capita Income	144,389.02	147,875.12	148,804.18	(4,415.16)	(929.06)	3,486.10
GDP	9,718.16	10,362.40	10,581.19	(863.03)	(218.79)	644.24
Total Consumption	7,265.28	7,661.52	7,806.32	(541.04)	(144.80)	396.23
Total Investment	2,107.25	2,226.72	2,270.22	(162.97)	(43.51)	119.47
Government Consumption	322.09	319.37	318.76	3.33	0.62	(2.71)
Net Exports	1,081.74	1,204.28	1,241.99	(160.25)	(37.71)	122.54
Welfare	6,340.30	6,724.64	6,860.45	(520.14)	(135.80)	384.34
USA						
Per Capita Income	144,189.94	144,634.18	144,753.54	(563.60)	(119.36)	444.24
GDP	79,445.00	80,106.18	80,328.39	(883.39)	(222.21)	661.18
Total Consumption	63,760.62	64,147.72	64,292.17	(531.54)	(144.44)	387.10
Total Investment	14,479.15	14,601.36	14,646.07	(166.92)	(44.71)	122.21
Government Consumption	4,215.74	4,212.69	4,211.88	3.86	0.82	(3.05)
Net Exports	4,021.58	4,149.61	4,187.55	(165.97)	(37.94)	128.03
Welfare	57,696.80	58,091.15	58,230.11	(533.31)	(138.95)	394.36

Notes: Macroeconomic impacts in levels are presented associated with the 500-year storm surge impact on dwelling, petro and chemical manufacturing sectors (resulting in 33-day shutdown of production operation) simultaneously with and without coastal spine protection; except for income, other economic indicators are given in billions of US Dollars; negative values are reported in parenthesis. Source: Authors

As for the immediate and the long-term impacts on other states, the model results indicate that while some states (primarily neighboring) experience positive GSP, income and welfare growth due to potential substitution of inputs of production and labor outmigration, 30 states, not including Texas itself, will have a lower GSP in response to a surge event in Texas. Immediate responses as reflected in GSP without the spine system are seen in Figure 5 and are less pronounced than the responses in the year 2066 (Figure 6). In terms of social welfare, except for handful of states, the majority of the states will experience welfare loss in 2066 if the coastal spine is not constructed (see Figure 7). The spine substantially attenuates effects spatially and in the long term. Figures C1 – C2 in Appendix C depict state-level GSP and welfare in 2066 with a coastal spine, and income responses without and with coastal spine are presented in Figures C3 & C4. Sectoral responses (output value and prices) can be viewed in the companion Atlas.

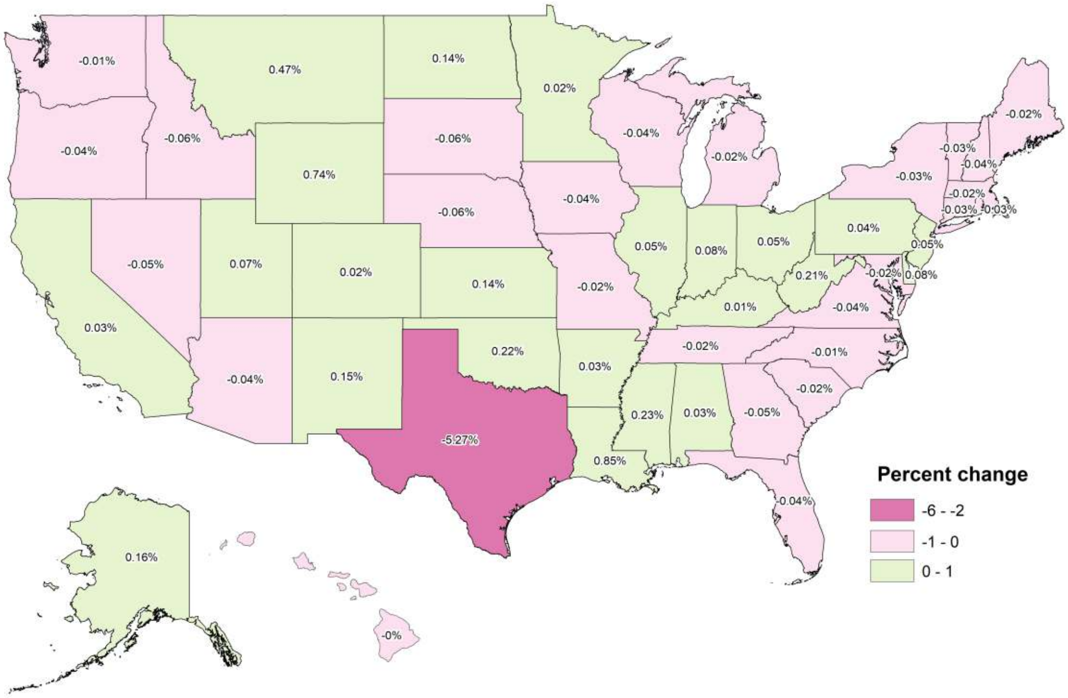

Figure 5: 500-yr Storm Surge without a Coastal Spine, Impacts in 2017 (GSP).

Notes: Percent change in GSP by states relative to the BAU GSP levels in 2017 without a coastal spine are shown. Source: Authors.

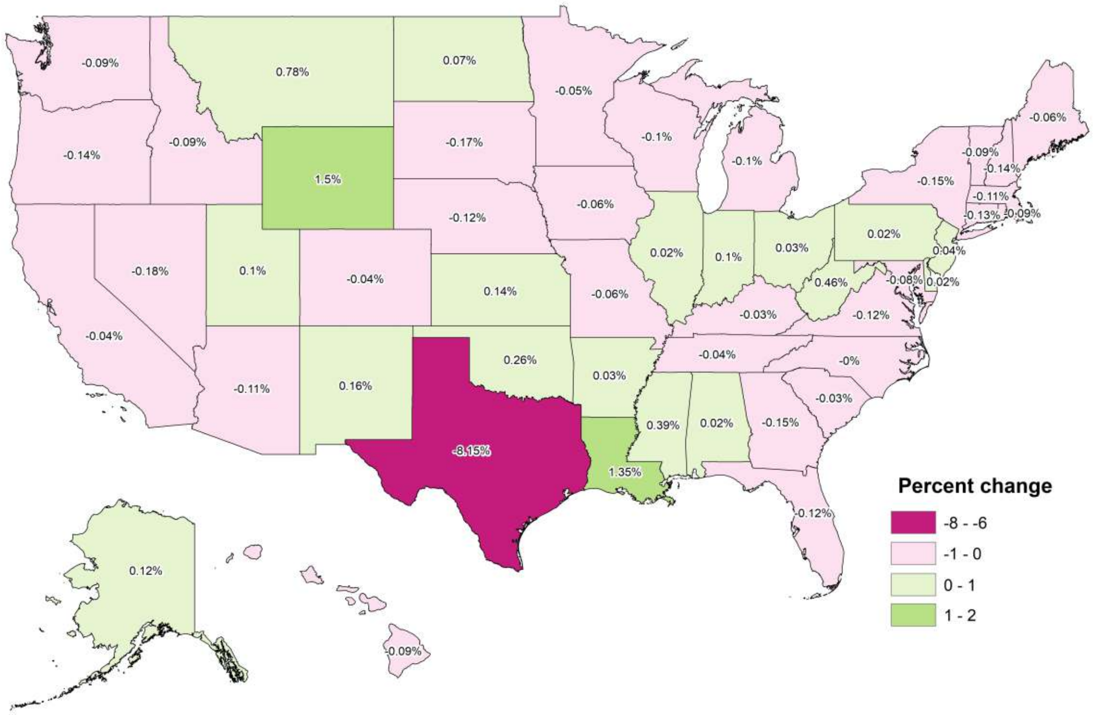

Figure 6: 500-year Storm Surge without a Coastal Spine, Impacts in 2066 (GSP).
Notes: Percent change in GSP by states relative to the BAU GSP levels in 2066 without a coastal spine are shown. Source: Authors.

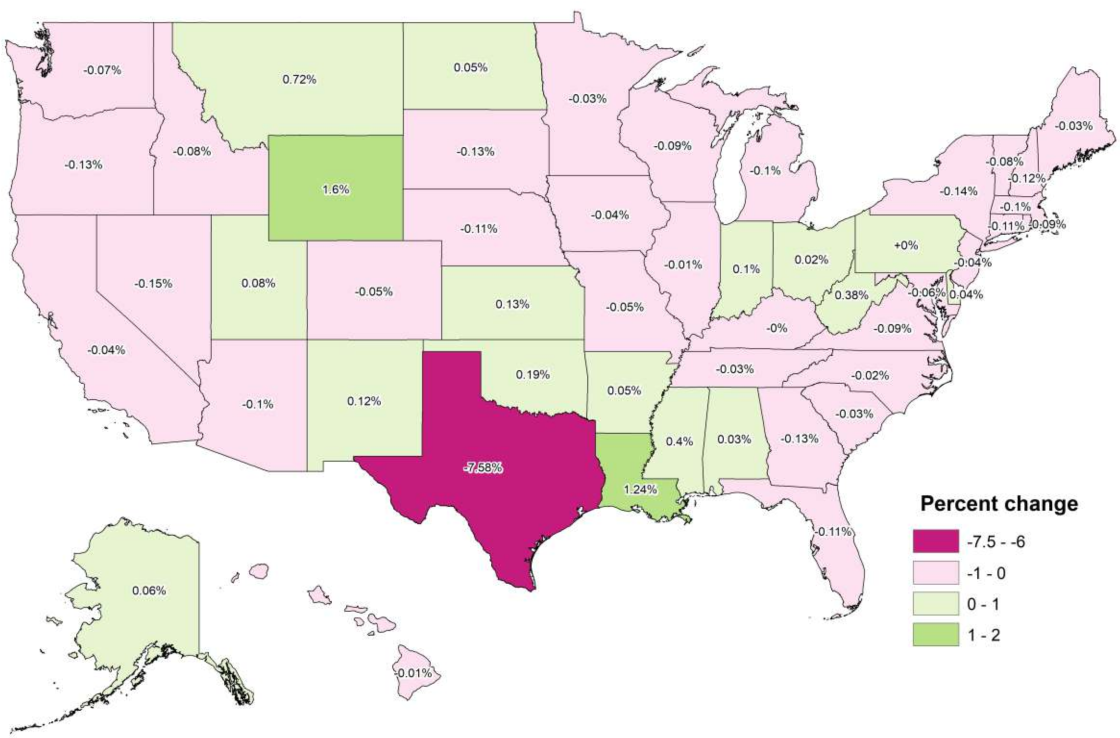

Figure 7: 500-yr Storm Surge without a Coastal Spine, Impacts in 2066 (Welfare).
Notes: Percent change in social welfare by states relative to the BAU social welfare levels in 2066 without a coastal spine are shown. Source: Authors.

Impacts of Ike-like storms as reflected on selected macroeconomic indicators for TX and US are presented in Tables 17 and 18, respectively. Both tables report results without and with coastal protection. Texas GSP declines by 2.7% in 2066, welfare is 2.6% lower, and net export falls by 4% short of that in the BAU if no coastal protection is provided. The nation is almost insulated from the rippling effects of the Ike-like storm on the communities in Galveston Bay in Texas. While in the no protection case the U.S. economy shrinks, the declines are substantially marginal. Notably, the coastal protection almost fully mitigates the impacts on the U.S. economy. This is partially because the petroleum and chemical manufacturing sectors do not sustain damages when coastal spine is factored into direct damage assessment. Responses in terms of GSP, income and welfare across other states in 2066 relative to the BAU are depicted in Appendix C Figures C5-7.

Table 17: CGE Results for Selected Decades for the Texas Economy (Ike-like Storm).

	2017	2066	2036	2046	2056	2066
Panel A: No Protection Relative to BAU						
Per Capita Income	0.17%	-0.10%	-0.38%	-0.60%	-0.74%	-0.84%
GDP	-1.65%	-1.91%	-2.18%	-2.40%	-2.57%	-2.70%
Total Consumption	-1.65%	-1.89%	-2.11%	-2.26%	-2.34%	-2.40%
Total Investment	-1.69%	-1.93%	-2.17%	-2.33%	-2.42%	-2.48%
Government Consumption	0.03%	0.06%	0.11%	0.16%	0.22%	0.27%
Net Export	-20.65%	-6.88%	-4.84%	-4.26%	-4.09%	-4.01%
Welfare	-1.65%	-1.91%	-2.16%	-2.35%	-2.47%	-2.57%
Panel B: Protection Relative to BAU						
Per Capita Income	0.01%	0.00%	-0.01%	-0.02%	-0.03%	-0.04%
Gdp	-0.07%	-0.08%	-0.10%	-0.11%	-0.11%	-0.12%
Total Consumption	-0.07%	-0.08%	-0.09%	-0.10%	-0.10%	-0.11%
Total Investment	-0.07%	-0.08%	-0.10%	-0.10%	-0.11%	-0.11%
Government Consumption	0.00%	0.00%	0.00%	0.01%	0.01%	0.01%
Net Export	-0.89%	-0.30%	-0.21%	-0.18%	-0.18%	-0.17%
Welfare	-0.07%	-0.08%	-0.09%	-0.10%	-0.11%	-0.11%

Notes: Economy-wide impacts are presented associated with the Ike-like storm surge impact on dwelling, petro and chemical manufacturing sectors (resulting in 33-day shutdown of production operation) simultaneously with and without coastal spine protection. Source: Authors.

Table 18: CGE Results for Selected Decades for the U.S. Economy (Ike-like Storm).

	2017	2066	2036	2046	2056	2066
Panel A: No Protection Relative to BAU						
Per Capita Income	0.02%	-0.01%	-0.04%	-0.07%	-0.09%	-0.11%
GDP	-0.14%	-0.17%	-0.22%	-0.27%	-0.32%	-0.36%
Total Consumption	-0.14%	-0.17%	-0.21%	-0.24%	-0.27%	-0.29%
Total Investment	-0.18%	-0.23%	-0.28%	-0.33%	-0.37%	-0.39%
Government Consumption	-0.01%	-0.01%	0.00%	0.00%	0.01%	0.03%
Net Export	0.60%	2.34%	-2.69%	-1.37%	-1.21%	-1.21%
Welfare	-0.13%	-0.16%	-0.20%	-0.24%	-0.28%	-0.31%
Panel B: Protection Relative to BAU						
Per Capita Income	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
GDP	-0.01%	-0.01%	-0.01%	-0.01%	-0.01%	-0.02%
Total Consumption	-0.01%	-0.01%	-0.01%	-0.01%	-0.01%	-0.01%
Total Investment	-0.01%	-0.01%	-0.01%	-0.01%	-0.01%	-0.01%
Government Consumption	-0.01%	-0.01%	-0.01%	-0.01%	-0.02%	-0.02%
Net Export	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Welfare	0.03%	0.10%	-0.12%	-0.06%	-0.05%	-0.05%

Notes: Economy-wide impacts are presented associated with the Ike-like storm surge impact on dwelling, petro and chemical manufacturing sectors (resulting in 33-day shutdown of production operation) simultaneously with and without coastal spine protection. Source: Authors.

The sectoral impacts of the Ike-like storm in Texas presented in Table 19 show that the chemical sector production value declines by 6% and the outputs of electricity, petroleum, natural gas, oil and coal mining sectors all fall by nearly 4%, without a coastal spine. Prices on petroleum products rise by 1.82% without a coastal protection and electricity sector prices go up by 2%. Impacts are largely mitigated with the coastal spine protection.

Table 19: Sectoral Impact of Ike-like Storm Surge Without and With Protection vs. BAU (year 2066).

	No Protection			Protection		
	Output	Employment	Price	Output	Employment	Price
Fruits, Vegetables, Nuts	-1.86%	0.42%	-0.05%	-0.09%	0.02%	0.00%
Other Animal Production	-2.98%	-0.26%	-0.01%	-0.14%	-0.02%	0.00%
Forestry	-0.02%	1.49%	-0.54%	0.00%	0.06%	-0.02%
Other Agriculture	-1.63%	0.66%	-0.33%	-0.08%	0.03%	-0.01%
Other Mining	-3.75%	-0.69%	0.17%	-0.17%	-0.03%	0.01%
Electricity	-4.41%	-0.82%	2.02%	-0.20%	-0.04%	0.09%
Natural Gas, Oil, Coal	-4.12%	-0.33%	-0.54%	-0.17%	-0.01%	-0.01%
Water and Sewage	-2.80%	0.13%	0.39%	-0.13%	0.01%	0.02%
Construction	-2.17%	-0.08%	-0.49%	-0.10%	0.00%	-0.02%
Food, Tobacco	-2.94%	-0.17%	0.08%	-0.14%	-0.01%	0.00%
Wood Products	-1.09%	0.79%	-0.23%	-0.05%	0.03%	-0.01%
Pulp Paper	-2.15%	0.34%	-0.05%	-0.10%	0.01%	0.00%
Petroleum Products	-4.37%	-2.35%	1.82%	-0.16%	-0.05%	0.05%
Chemicals	-6.12%	-2.44%	0.47%	-0.27%	-0.10%	0.02%
Rubber Plastics	-3.23%	-0.54%	0.13%	-0.15%	-0.03%	0.01%
Non-metallic Metals	-2.67%	-0.02%	0.07%	-0.12%	0.00%	0.00%
Primary Metals	-1.33%	0.98%	-0.11%	-0.06%	0.04%	0.00%
Heating, Air-conditioning	-3.37%	-0.62%	0.08%	-0.15%	-0.03%	0.00%
Other Manufacturing	-2.39%	0.17%	-0.01%	-0.11%	0.00%	0.00%
Furniture	-0.45%	1.68%	-0.14%	-0.02%	0.07%	-0.01%
Services	-2.17%	0.13%	-0.28%	-0.10%	0.00%	-0.01%
Insurance	-2.56%	0.08%	0.10%	-0.12%	0.00%	0.01%
Dwelling	-2.62%	-0.14%	-0.14%	-0.12%	0.00%	0.00%

Notes: In red are highlighted the top ten most sensitive sectors in terms of the indirect impacts of the direct shock of surge on dwelling, petro and chemical manufacturing sectors, when plants shut down for 33 days. Source: Authors.

Extension

Economic Impacts with the Sea Level Rise (SLR)

Surge impacts are expected to by exacerbate with the SLR (Frumhoff et al., 2007). To capture the magnifying effects of SLR on Texas and regional economies, as an extension we also simulated the CGE model incorporating the effects of SLR.

Specifically, surge inundation maps associated with the different proxy storms incorporating SLR for the year 2080 were generated with the ADCIRC model, which were overlaid with the plant locations to identify the firms that will potentially be inundated under future SLR. To assess damages to residential structures, the inundation maps with the SLR were inputted in the HAZUS-MH model. In the HAZUS-MH model, building counts for different types of dwelling category were updated using the predicted number of housing units in the year 2080. The average value by each dwelling type were then assigned to these projected number of new units to estimate respective losses to dwelling sector in 2080 (see Table 13).

Table 13: Housing Damages under Future SLR in 2080.

Scenario	Housing Damages ($millions)
No Protection 500-yr 2080 +SLR	31,883.92
Protection 500-yr 2080 +SLR	6,092.87
No Protection 100-yr 2080 +SLR	18,803.34
Protection 100-yr 2080 +SLR	3,699.55
No Protection 10-yr 2080 +SLR	2,616.50
No Protection Ike-like 2080 +SLR	234.72

In order to assess output losses for the 33-day shutdown of petro products and chemical manufacturing plants we followed the framework described in Section 2.1. Specifically, it was assumed that the number of actively operating plants will be unchanged (i.e., there will not be new entrants in the industry); however, the number of inundated plants increases because the spatial extent of inundation with SLR is much larger. While the effective number of plants were assumed to be unchanged, we assumed that the output produced by each plant will grow at the same annual growth rate as the overall industry growth rate as solved in the BAU scenario. It was also assumed that the output loss in 2080 associated with the SLR will grow at the same rate of the industry output growth rate.

In order to project the output losses for the year 2080 under SLR, we first ran the recursive dynamic CGE baseline scenario—the business as usual (BAU) scenario (assuming no SLR) from 2016 to 2080—to obtain the annual output growth rates for the major industries for Texas. Based on the annual outputs solved in the CGE baseline scenario, annual output growth rates were calculated. These annual growth rates were used to compute output losses for the year 2080 respectively for petro products and chemical manufacturing sectors if plants are shut down due to SLR-induced storm surge (output losses for the starting year 2016 and ending year 2080 are presented in Table 14).

Table 14: Major Industry Output Losses for the Year 2080 with SLR.

BAU scenario (billions of 2016 $)					
		2016		2080	
	Petro products	35.99			318.34
	Chemical manufacturing	62.48			1,506.31
Output losses (billions 2016 $)					
Scenario			18-day shutdown	26-day shutdown	33-day shutdown
Petro products					
Ike-like	No Protection	0.0483	7.690508	11.10851	14.09926
10-year	No Protection	0.002655	0.422717	0.610591	0.77498
100-year	No Protection	0.149	23.72434	34.26849	43.49463
500-year	No Protection	0.202	31.91548	46.10014	58.51171
100-year	Protection	0.002655	0.416144	0.601097	0.762931
500-year	Protection	0.0155	2.467968	3.564843	4.524609
Chemical manufacturing					
Ike-like	No Protection	0.008475	3.678033	5.312715	6.743061
10-year	No Protection	0.005098	2.21229	3.195531	4.055866
100-year	No Protection	0.0779	33.80643	48.83152	61.97846
500-year	No Protection	0.12	52.07666	75.22185	95.47388
100-year	Protection	0.0108	4.6869	6.769966	8.592649
500-year	Protection	0.005763	2.500982	3.612529	4.585133

Incorporating Industry Output Loses and Housing Damages to the CGE Model

Similar to the modeling approach discussed throughout, industrial output losses for petroleum products and chemical manufacturing sectors were incorporated into the CGE model by changing scaling parameter associated with total factor productivity. The appropriate scaling parameter was selected until the simulated output losses solved in the CGE model matched the expected losses (as shown in Table 14) for the same year 2080.

Similarly, it was assumed that property damages associated with SLR would reduce a household's capital endowment in Texas. The share of the property damage relative to the baseline dwelling value for the state was calculated using the property losses (see Table 13) divided by the dwelling value in the BAU scenario for the year 2080. This parameter was then incorporated into the CGE model as a coefficient to adjust capital endowment for households in Texas due to external shock.

We take the 500-year storm (33-day plant shutdown) scenarios under SLR as an example and report impacts for selected economic indicators and for all the states for the year 2080. It should be noted that unlike the model results presented without SLR, the economy-wide impacts under SLR reflect immediate effects only in the year 2080. Results in Table 15 and Table 16, respectively, show economic impacts from output losses in petroleum and chemical manufacturing sectors and impacts from property damages (with protection and without protection). Results from the model where all sectors are simultaneously impacted are shown in Table 17.

Compared to the BAU scenario in 2080, Texas GSP declines by approximately 2.3% in 2080 as a result of SLR-induced storm surge impacts without structural protection, for both the scenario when output losses are incorporated (500-year storm) and the scenario when property damages are considered. The impact on the national GDP is also similar between the scenario when output losses are incorporated (-0.384%) and the scenario that captures only property damages (-0.343%). When structural protection is not factored in, the impact on consumption is slightly larger from property damages, while impacts from output losses are larger on per capita income and net exports. Turning to Table 17 which presents results from the model incorporating both industry output losses and property damages under SLR in the year 2080, GSP decreases by 4.5% in Texas without structural protection. The impact is mitigated to -0.63% with protection. Similarly, results suggest that structural protection significantly mitigates negative impacts on consumption, per capita income, and net exports. Although the national impact is generally small, the impacts of SLR-induced storm surge on net exports without protection tend to be larger (-3%), compared to the BAU scenario without SLR in the year 2080.

Table 15: Regional Economic Impacts from SLR Scenario (33-Day Plant Shutdown, 500-year Storm, % Change Relative to BAU Scenario in 2080).

	Gsp		Consumption		Per Capita Income		Net Export (Export-Import)	
	Without Protection	With Protection	Without Protection	With Protection	Without Protection	With Protection	Without Protection	With Protection
AK	-0.056%	-0.006%	0.090%	0.008%	-0.007%	-0.001%	-0.324%	-0.034%
AL	-0.033%	-0.004%	0.123%	0.011%	0.040%	0.003%	0.598%	0.061%
AR	0.001%	-0.001%	0.153%	0.014%	0.080%	0.007%	0.469%	0.047%
AZ	-0.121%	-0.010%	0.054%	0.006%	-0.058%	-0.004%	0.523%	0.053%
CA	-0.066%	-0.006%	0.042%	0.004%	-0.031%	-0.003%	-0.182%	-0.019%
CO	-0.089%	-0.008%	0.069%	0.007%	-0.028%	-0.002%	1.751%	0.174%
CT	-0.137%	-0.012%	0.040%	0.004%	-0.085%	-0.007%	-0.497%	-0.047%
DC	0.072%	0.008%	0.548%	0.048%	0.411%	0.038%	0.331%	0.031%
DE	-0.005%	-0.001%	0.095%	0.008%	0.025%	0.001%	-0.020%	-0.004%
FL	-0.113%	-0.010%	0.037%	0.004%	-0.063%	-0.005%	0.472%	0.050%
GA	-0.160%	-0.014%	0.022%	0.003%	-0.115%	-0.009%	-0.959%	-0.091%
HI	-0.075%	-0.006%	0.151%	0.014%	0.046%	0.005%	-9.626%	-0.919%
IA	-0.099%	-0.010%	0.043%	0.003%	-0.061%	-0.007%	-0.826%	-0.082%
ID	-0.111%	-0.010%	0.069%	0.007%	-0.042%	-0.003%	0.328%	0.035%
IL	-0.038%	-0.005%	0.044%	0.004%	-0.020%	-0.002%	-0.176%	-0.022%
IN	0.043%	0.001%	0.118%	0.009%	0.080%	0.004%	-0.317%	-0.035%
KS	0.045%	0.003%	0.122%	0.011%	0.080%	0.006%	-0.288%	-0.036%
KY	-0.073%	-0.007%	0.115%	0.011%	0.005%	0.001%	0.957%	0.094%
LA	1.212%	0.095%	0.755%	0.061%	1.253%	0.098%	-10.020%	-0.627%
MA	-0.131%	-0.012%	0.032%	0.004%	-0.087%	-0.007%	-0.372%	-0.037%
MD	-0.075%	-0.007%	0.106%	0.011%	0.024%	0.004%	1.091%	0.115%
ME	-0.028%	-0.002%	0.127%	0.012%	0.059%	0.006%	0.310%	0.032%
MI	-0.119%	-0.011%	0.041%	0.005%	-0.073%	-0.006%	6.340%	0.653%
MN	-0.056%	-0.005%	0.070%	0.007%	-0.012%	-0.001%	-0.666%	-0.065%
MO	-0.098%	-0.010%	0.045%	0.004%	-0.055%	-0.006%	2.282%	0.240%
MS	0.345%	0.027%	0.406%	0.035%	0.451%	0.036%	0.358%	0.038%
MT	0.766%	0.062%	0.572%	0.049%	0.845%	0.069%	0.404%	0.040%
NC	-0.058%	-0.008%	0.044%	0.004%	-0.019%	-0.004%	-1.430%	-0.162%
ND	-0.040%	-0.003%	0.110%	0.010%	-0.006%	0.001%	-1.596%	-0.150%
NE	-0.160%	-0.015%	0.014%	0.001%	-0.126%	-0.011%	-0.443%	-0.042%
NH	-0.138%	-0.012%	0.053%	0.006%	-0.071%	-0.005%	1.510%	0.146%
NJ	-0.023%	-0.004%	0.042%	0.006%	-0.001%	0.000%	-0.269%	-0.056%
NM	0.046%	0.003%	0.168%	0.016%	0.116%	0.010%	0.443%	0.050%
NV	-0.176%	-0.015%	0.039%	0.004%	-0.116%	-0.009%	-1.461%	-0.137%
NY	-0.172%	-0.015%	0.011%	0.002%	-0.133%	-0.011%	-0.307%	-0.028%
OH	-0.021%	-0.003%	0.071%	0.007%	0.012%	0.000%	-0.699%	-0.080%
OK	0.066%	0.005%	0.165%	0.015%	0.133%	0.011%	0.630%	0.070%
OR	-0.146%	-0.013%	0.020%	0.002%	-0.108%	-0.009%	-0.772%	-0.073%
PA	-0.040%	-0.005%	0.063%	0.006%	-0.006%	-0.001%	-0.588%	-0.068%
RI	-0.102%	-0.009%	0.058%	0.007%	-0.040%	-0.003%	0.932%	0.102%
SC	-0.077%	-0.009%	0.071%	0.007%	-0.018%	-0.003%	0.454%	0.052%
SD	-0.166%	-0.014%	0.042%	0.005%	-0.110%	-0.009%	-2.499%	-0.230%
TN	-0.095%	-0.010%	0.058%	0.006%	-0.047%	-0.005%	-1.794%	-0.197%
TX	-2.294%	-0.190%	-0.988%	-0.085%	-1.962%	-0.166%	-5.197%	-0.423%
UT	0.036%	0.001%	0.080%	0.007%	0.063%	0.004%	-0.033%	-0.011%
VA	-0.128%	-0.011%	0.087%	0.009%	-0.034%	-0.002%	5.466%	0.545%
VT	-0.108%	-0.009%	0.101%	0.010%	-0.013%	0.000%	0.390%	0.039%
WA	-0.080%	-0.007%	0.062%	0.006%	-0.033%	-0.002%	-0.300%	-0.028%
WI	-0.114%	-0.010%	0.042%	0.004%	-0.071%	-0.006%	19.779%	1.966%
WV	0.129%	0.006%	0.212%	0.018%	0.201%	0.014%	0.309%	0.032%
WY	1.150%	0.092%	1.076%	0.088%	1.425%	0.113%	12.490%	0.950%
US	-0.384%	-0.033%	-0.067%	-0.005%	-0.276%	-0.023%	-2.105%	-0.185%

Table 16: Regional Economic Impacts from SLR-Induced Property Damages (500-year Storm, % Change Relative to BAU Scenario in 2080).

	Gsp		Consumption		Per Capita Income		Net Export (Export-Import)	
	Without protection	With Protection	Without Protection	With Protection	Without Protection	With Protection	Without Protection	With Protection
AK	0.025%	0.005%	0.010%	0.002%	0.011%	0.002%	0.151%	0.028%
AL	0.004%	0.001%	0.025%	0.005%	0.013%	0.002%	0.057%	0.011%
AR	0.005%	0.001%	0.027%	0.005%	0.015%	0.003%	0.055%	0.011%
AZ	-0.022%	-0.004%	0.004%	0.001%	-0.017%	-0.003%	0.036%	0.007%
CA	-0.013%	-0.003%	-0.002%	0.000%	-0.014%	-0.003%	-0.013%	-0.003%
CO	-0.009%	-0.002%	0.005%	0.001%	-0.007%	-0.001%	0.068%	0.015%
CT	-0.033%	-0.006%	0.001%	0.000%	-0.026%	-0.005%	-0.092%	-0.018%
DC	-0.143%	-0.027%	-0.016%	-0.003%	-0.291%	-0.055%	-0.235%	-0.045%
DE	-0.021%	-0.004%	0.006%	0.001%	-0.018%	-0.003%	-0.021%	-0.004%
FL	-0.024%	-0.005%	0.002%	0.000%	-0.018%	-0.003%	0.042%	0.008%
GA	-0.034%	-0.006%	0.002%	0.000%	-0.027%	-0.005%	-0.153%	-0.030%
HI	-0.028%	-0.005%	0.023%	0.004%	-0.008%	-0.002%	-1.744%	-0.338%
IA	0.003%	0.001%	0.020%	0.004%	0.011%	0.002%	-0.090%	-0.018%
ID	-0.015%	-0.003%	0.009%	0.002%	-0.008%	-0.001%	0.026%	0.005%
IL	-0.001%	0.000%	0.001%	0.000%	-0.003%	-0.001%	0.012%	0.002%
IN	0.029%	0.005%	0.029%	0.006%	0.036%	0.007%	-0.032%	-0.006%
KS	0.014%	0.003%	0.018%	0.003%	0.016%	0.003%	0.065%	0.012%
KY	-0.005%	-0.001%	0.022%	0.004%	0.006%	0.001%	0.098%	0.019%
LA	0.198%	0.038%	0.107%	0.020%	0.206%	0.039%	-2.670%	-0.506%
MA	-0.025%	-0.005%	0.000%	0.000%	-0.022%	-0.004%	-0.044%	-0.009%
MD	-0.015%	-0.003%	0.009%	0.002%	-0.005%	-0.001%	0.086%	0.017%
ME	-0.024%	-0.005%	0.017%	0.003%	-0.007%	-0.001%	0.058%	0.011%
MI	-0.025%	-0.005%	0.002%	0.000%	-0.020%	-0.004%	0.768%	0.151%
MN	-0.020%	-0.004%	0.007%	0.001%	-0.013%	-0.003%	-0.119%	-0.023%
MO	-0.003%	-0.001%	0.012%	0.002%	0.003%	0.001%	0.169%	0.034%
MS	0.044%	0.008%	0.054%	0.010%	0.058%	0.011%	0.037%	0.007%
MT	0.085%	0.016%	0.066%	0.013%	0.094%	0.018%	0.009%	0.002%
NC	0.020%	0.004%	0.011%	0.002%	0.021%	0.004%	0.054%	0.009%
ND	-0.003%	-0.001%	0.017%	0.003%	-0.011%	-0.002%	0.048%	0.006%
NE	-0.017%	-0.003%	0.007%	0.001%	-0.013%	-0.002%	-0.048%	-0.009%
NH	-0.035%	-0.007%	0.003%	0.001%	-0.025%	-0.005%	0.220%	0.043%
NJ	0.011%	0.002%	-0.016%	-0.003%	-0.006%	-0.001%	0.243%	0.046%
NM	0.022%	0.004%	0.020%	0.004%	0.021%	0.004%	-0.044%	-0.008%
NV	-0.044%	-0.008%	0.003%	0.001%	-0.033%	-0.006%	-0.285%	-0.055%
NY	-0.040%	-0.008%	-0.003%	0.000%	-0.035%	-0.007%	-0.061%	-0.012%
OH	0.006%	0.001%	0.011%	0.002%	0.008%	0.002%	0.002%	0.000%
OK	0.051%	0.010%	0.018%	0.004%	0.043%	0.008%	-0.106%	-0.019%
OR	-0.031%	-0.006%	0.002%	0.000%	-0.026%	-0.005%	-0.134%	-0.026%
PA	0.004%	0.001%	0.008%	0.002%	0.005%	0.001%	0.013%	0.002%
RI	-0.018%	-0.003%	0.001%	0.000%	-0.015%	-0.003%	0.038%	0.008%
SC	0.007%	0.001%	0.012%	0.002%	0.011%	0.002%	-0.003%	0.000%
SD	-0.041%	-0.008%	0.006%	0.001%	-0.032%	-0.006%	-0.510%	-0.099%
TN	-0.001%	0.000%	0.014%	0.003%	0.004%	0.001%	0.001%	-0.001%
TX	-2.303%	-0.438%	-2.041%	-0.388%	-0.719%	-0.138%	-3.111%	-0.593%
UT	0.012%	0.002%	0.005%	0.001%	0.009%	0.002%	0.049%	0.009%
VA	-0.024%	-0.005%	0.009%	0.002%	-0.013%	-0.003%	0.609%	0.120%
VT	-0.022%	-0.004%	0.013%	0.003%	-0.010%	-0.002%	0.053%	0.010%
WA	-0.033%	-0.006%	0.004%	0.001%	-0.026%	-0.005%	-0.069%	-0.013%
WI	-0.018%	-0.003%	0.006%	0.001%	-0.012%	-0.002%	2.437%	0.478%
WV	0.132%	0.025%	0.057%	0.011%	0.120%	0.023%	-0.011%	-0.002%
WY	0.209%	0.040%	0.141%	0.027%	0.224%	0.042%	3.381%	0.637%
US	-0.343%	-0.065%	-0.264%	-0.050%	-0.103%	-0.020%	-0.971%	-0.186%

Table 17: Regional Economic Impacts from Output Losses (33-Day Plant Shutdown) and Property Damages under SLR in 2080 (500-year storm, % change relative to BAU scenario in 2080).

	GSP		Consumption		Per Capita Income		Net Export (Export-Import)	
	Without Protection	With Protection	Without Protection	With Protection	Without Protection	With Protection	Without Protection	With Protection
AK	-0.024%	-0.001%	0.097%	0.010%	0.007%	0.001%	-0.138%	-0.006%
AL	-0.025%	-0.003%	0.143%	0.016%	0.053%	0.006%	0.615%	0.071%
AR	0.009%	0.000%	0.173%	0.019%	0.094%	0.009%	0.491%	0.057%
AZ	-0.137%	-0.014%	0.054%	0.007%	-0.074%	-0.007%	0.521%	0.060%
CA	-0.075%	-0.009%	0.037%	0.004%	-0.042%	-0.005%	-0.181%	-0.021%
CO	-0.093%	-0.009%	0.069%	0.008%	-0.035%	-0.003%	1.696%	0.186%
CT	-0.163%	-0.018%	0.038%	0.005%	-0.109%	-0.012%	-0.558%	-0.065%
DC	-0.072%	-0.020%	0.516%	0.044%	0.102%	-0.018%	0.082%	-0.015%
DE	-0.020%	-0.005%	0.099%	0.009%	0.012%	-0.002%	-0.033%	-0.008%
FL	-0.132%	-0.014%	0.035%	0.005%	-0.080%	-0.008%	0.477%	0.058%
GA	-0.186%	-0.020%	0.022%	0.003%	-0.138%	-0.015%	-1.053%	-0.120%
HI	-0.098%	-0.012%	0.165%	0.019%	0.036%	0.004%	-10.798%	-1.247%
IA	-0.092%	-0.010%	0.060%	0.007%	-0.048%	-0.005%	-0.865%	-0.098%
ID	-0.121%	-0.013%	0.073%	0.009%	-0.049%	-0.005%	0.328%	0.040%
IL	-0.034%	-0.005%	0.044%	0.005%	-0.021%	-0.003%	-0.146%	-0.019%
IN	0.074%	0.006%	0.144%	0.015%	0.116%	0.011%	-0.323%	-0.040%
KS	0.063%	0.005%	0.136%	0.014%	0.098%	0.009%	-0.181%	-0.024%
KY	-0.072%	-0.008%	0.132%	0.015%	0.012%	0.002%	0.991%	0.112%
LA	1.392%	0.132%	0.849%	0.082%	1.440%	0.137%	-12.722%	-1.136%
MA	-0.150%	-0.017%	0.028%	0.004%	-0.106%	-0.011%	-0.393%	-0.045%
MD	-0.087%	-0.009%	0.107%	0.013%	0.015%	0.003%	1.095%	0.131%
ME	-0.049%	-0.007%	0.137%	0.016%	0.049%	0.005%	0.345%	0.043%
MI	-0.138%	-0.016%	0.040%	0.005%	-0.090%	-0.010%	6.661%	0.796%
MN	-0.071%	-0.009%	0.074%	0.008%	-0.023%	-0.003%	-0.740%	-0.087%
MO	-0.096%	-0.010%	0.054%	0.006%	-0.049%	-0.005%	2.290%	0.271%
MS	0.387%	0.035%	0.450%	0.045%	0.502%	0.047%	0.369%	0.045%
MT	0.842%	0.078%	0.626%	0.061%	0.926%	0.087%	0.393%	0.042%
NC	-0.035%	-0.004%	0.052%	0.006%	0.002%	0.000%	-1.270%	-0.151%
ND	-0.036%	-0.003%	0.124%	0.013%	-0.012%	-0.001%	-1.390%	-0.141%
NE	-0.169%	-0.018%	0.020%	0.003%	-0.134%	-0.014%	-0.466%	-0.051%
NH	-0.167%	-0.018%	0.052%	0.006%	-0.094%	-0.010%	1.630%	0.187%
NJ	-0.009%	-0.002%	0.022%	0.003%	-0.007%	-0.001%	0.021%	-0.009%
NM	0.072%	0.007%	0.181%	0.019%	0.136%	0.014%	0.347%	0.042%
NV	-0.211%	-0.023%	0.038%	0.005%	-0.144%	-0.016%	-1.656%	-0.190%
NY	-0.203%	-0.023%	0.007%	0.001%	-0.162%	-0.018%	-0.350%	-0.040%
OH	-0.011%	-0.002%	0.079%	0.009%	0.022%	0.002%	-0.639%	-0.079%
OK	0.122%	0.014%	0.176%	0.019%	0.175%	0.019%	0.464%	0.050%
OR	-0.171%	-0.018%	0.020%	0.003%	-0.130%	-0.014%	-0.861%	-0.098%
PA	-0.032%	-0.004%	0.068%	0.008%	0.002%	0.000%	-0.523%	-0.065%
RI	-0.115%	-0.013%	0.053%	0.007%	-0.054%	-0.005%	0.898%	0.109%
SC	-0.066%	-0.007%	0.078%	0.009%	-0.007%	0.000%	0.415%	0.051%
SD	-0.199%	-0.022%	0.045%	0.006%	-0.137%	-0.015%	-2.860%	-0.326%
TN	-0.090%	-0.010%	0.068%	0.008%	-0.041%	-0.004%	-1.663%	-0.196%
TX	-4.503%	-0.627%	-2.982%	-0.472%	-2.644%	-0.304%	-8.131%	-1.013%
UT	0.050%	0.003%	0.083%	0.008%	0.074%	0.006%	0.031%	-0.002%
VA	-0.147%	-0.016%	0.089%	0.011%	-0.048%	-0.004%	5.706%	0.659%
VT	-0.125%	-0.013%	0.106%	0.013%	-0.024%	-0.002%	0.414%	0.049%
WA	-0.108%	-0.013%	0.063%	0.007%	-0.056%	-0.007%	-0.350%	-0.041%
WI	-0.126%	-0.014%	0.045%	0.005%	-0.080%	-0.008%	20.893%	2.420%
WV	0.263%	0.031%	0.261%	0.029%	0.319%	0.036%	0.277%	0.030%
WY	1.350%	0.131%	1.201%	0.114%	1.635%	0.156%	15.903%	1.589%
US	-0.710%	-0.098%	-0.328%	-0.055%	-0.373%	-0.043%	-2.980%	-0.369%

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Appendix A: Detailed CGE Model Description

The main features of the recursive dynamic inter-regional computable general equilibrium (CGE) model used in our analysis and data construction are described in this appendix. The model is based on the modeling framework of Rausch and Rutherford (2008)—which calibrates the model to the IMPLAN state-level accounts—and the static regional modeling applications of Sue Wing (2007).

Producers

Each of the 35 industries is assumed to be a profit maximizer where output is produced using a constant returns to scale technology. For each sector *j* in region *r* at time *t* this can be expressed as:

$$QO_{j,r,t} = f(K_{j,r,t}, L_{j,r,t}, A_{1,j,r,t}, \dots, A_{n,j,r,t}, g(t)) \qquad \text{(B.1)}$$

where $K_{j,r,t}$, $L_{j,r,t}$, and $A_{i,j,r,t}$ are capital, labor, and intermediate inputs, respectively and $g(t)$ represents autonomous technological change which improves total factor productivity. A nested Cobb-Douglas-constant elasticity of substitution (CD-CES) functional form was adopted in the model. By nesting production functions, the model can account for different elasticities of substitution within the same functional form. Figure A-1 below displays the nesting structure of the production sector.

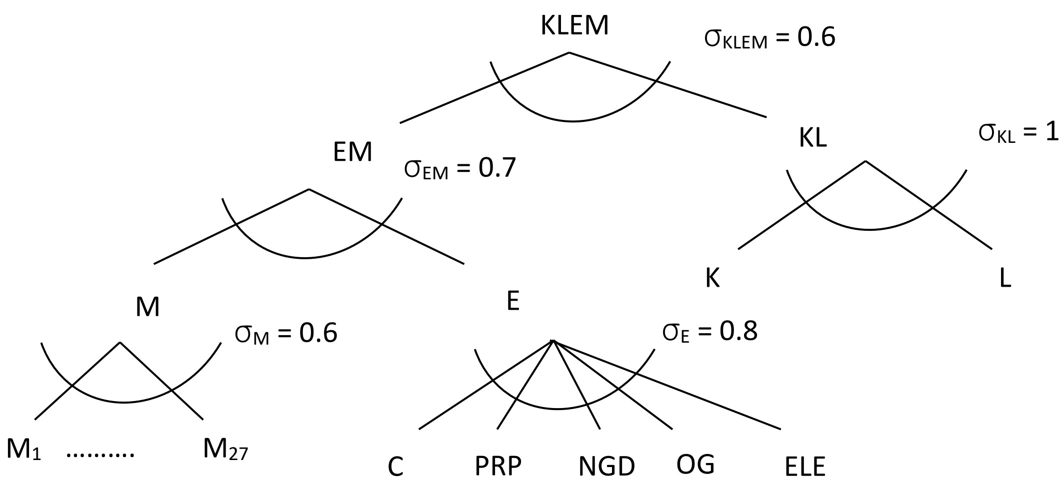


Figure A-1: Nesting Structure in the Production Sector.

As shown in Figure A-1, the top nest of the CD-CES production function consists of a Cobb-Douglas aggregate of value-added (i.e., capital (K) and labor (L)), and a CES aggregate of energy I and non-energy materials (M) inputs with an elasticity of substitution (σ_{KLEM}) of 0.6 between the KL and EM aggregates. The second tier separates the EM aggregate into an energy composite and a non-energy materials composite, both CES aggregates with elasticities of substitution (σ_M and σ_E) of 0.6 and 0.8, respectively. The non-energy materials composite includes the 27 non-energy materials listed in Table 1. The energy composite includes coal mining I, petroleum refining and products (PRP), natural gas distribution (NGD), oil and gas extraction (OG), and electricity (ELE).

Output in each producing sector is allocated to the domestic, intranational, and international markets assuming a constant elasticity of transformation (CET) functional form where the elasticity of transformation between products allocated to these three markets is assumed to be two. Prices paid by purchasers of industry output include a tax on production calibrated to benchmark data and the prices of capital and labor purchases by industry include taxes on capital and labor also calibrated to benchmark data.

Consumers

The consumer sector is modeled as a utility-maximizing representative consumer that derives utility from the consumption of commodities, is assumed to supply labor inelastically, and is the owner of capital stock. The household sector in each region receives income from the employment of labor and capital. Therefore, private income in region *r* at time *t* can be written as:

$$Y^p_{r,t} = YL_{r,t} + YK_{r,t} \tag{B.2}$$

where YL denotes labor income from supplying *LS* units of effective labor, and *YK* denotes capital income from supplying *KS* units of effective capital. *YL* is equal to:

$$YL_{r,t} = PL_{r,t}LS_{r,t} \tag{B.3}$$

where PL represents the wage rate received by households. The relationship between labor demand and supply is described below. *LS* is a function of the working age population (POP^W) and an index of labor quality (q^L); i.e.,

$$LS_{r,t} = POP^w_{r,t}q^L_t \tag{B.4}$$

In each region, household income is allocated between consumption ($VCC_{r,t}$) and savings (S^P). In this model we use a simple Solow growth model formulation with an exogenous savings rate ($s_{r,t}$) to determine private savings ($S^p_{r,t}$):

$$S^p_{r,t} = s_{r,t}Y^p_{r,t} = Y^p_{r,t} - VCC_{r,t} \tag{B.5}$$

The household savings rate is chosen to mirror the observed rates in the benchmark data set.

Household utility is a nested CES function of consumption goods financed by household income net savings. The nested structure adopted in the model is shown in Figure A.2

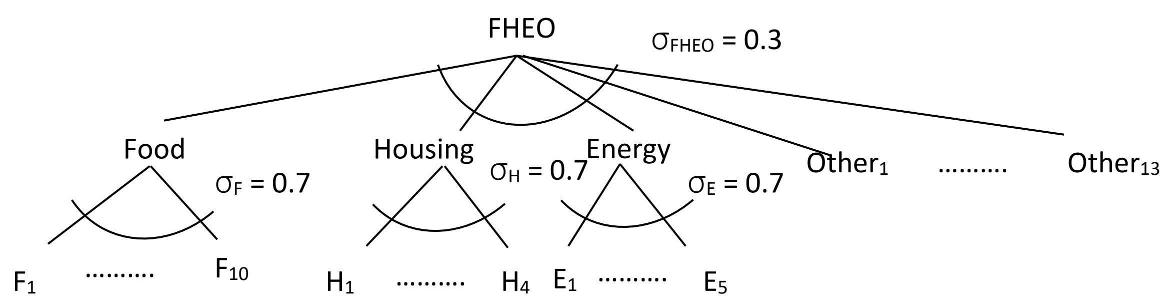


Figure A-2.

Household utility, therefore, is a CES function of a food composite good, a housing composite good, an energy composite good, and 13 other (i.e., non-food, non-housing, and non-energy) goods.

Government and Taxes

In the model, the government has two major roles: to collect taxes and to purchase commodities using public revenue. Public revenue comes from direct taxes on capital and labor paid by industry and taxes on output paid by purchasers of goods and services. Total government expenditure is the sum of commodity purchases. Government purchases of specific commodities are determined through maximization of a Cobb-Douglas utility function of the 35 commodities where government consumption shares are derived from benchmark data.

Capital, Investment, and Labor

Capital stock in a given region *r* at time *t* in the model is the accumulation of region-specific investment net depreciation; i.e.,

$$K_{r,t} = (1-\delta)K_{r,t-1} + I_{r,t} \tag{B.6}$$

Total investment by region in a given year in the model is determined by household savings. As described above, following the Solow growth model formulation, household savings is an exogenously-determined share of household income. This share is set to follow the observed rates in the benchmark data set. The capital depreciation rate is set exogenously at 5% across all regions.

Imperfect mobility of capital across regions and industries in a given year is captured in the model through the use of a composite CET-CES function. Capital is allocated across industries in a given region based on differences in industries' returns to capital. The elasticity of transformation of capital across the different industries is assumed to be one so as to preserve the benchmark industry-specific capital shares. The CES aggregation of capital across regions is assumed to be Leontif, thus limiting the mobility of capital across regions in a given year. Investment final demand is distributed to the individual investment goods sectors through fixed shares, $\alpha^I_{i,r,t}$, derived from benchmark data:

$$PS_{i,r,t}I_{i,r,t} = \alpha^I_{i,r,t}VII_{r,t} \tag{B.7}$$

where $PS_{i,r,t}$ is the supply price of investment good *I* in region *r* and $VII_{r,t}$ is total value of investment. Total investment in region *r* at time *t*, $I_{r,t}$, therefore can be written as:

$$I_{r,t} = I_{1,r,t}^{\alpha^I_{i,r}} I_{2,r,t}^{\alpha^I_{2,r}} \dots I_{n,r,t}^{\alpha^I_{n,r}} \tag{B.8}$$

Similar to capital, labor is also assumed to be imperfectly mobile across industries and regions in a given year. As with capital, a CET-CES function is used to allocate labor to the 31 industries based on returns to labor and to aggregate labor across regions. The elasticity of transformation is assumed to be one; thus, labor is allocated to industries to preserve the benchmark values shares of labor. The elasticity of substitution is assumed to be zero, thus limiting the mobility of labor across regions in a given year.

Intra- and International Trade

Trade flows are modeled using the Armington approach where imported goods are considered to be imperfect substitutes for domestic goods. The total supply (*QS*) of commodity *I* in region *r* is represented as a nested CES function of the domestic (*D*) and traded good (*M*); i.e.,

$$QS_{i,r,t} = A_0\left[\alpha^d D^\rho_{i,r,t} + \alpha^m M^\rho_{i,r,t}\right]^{\frac{1}{\rho}} \tag{B.9}$$

where the traded good is a composite of the domestically traded good and internationally traded good. The elasticity of substitution between the domestic and traded good is assumed to be four while the elasticity of substitution between the domestically and internationally traded good is assumed to be eight.

There are two prices of imports to buyers in the model: an intra-national trade price of good *I* and the price of foreign exchange. The numeraire in the model is assumed to be the price of foreign exchange; thus, prices in the model are relative to the overall international goods price.

Markets

The economy is in equilibrium in period *t* when prices clear the market (i.e., supply equals demand) for the 31 commodities and two factors (i.e., capital and labor). The supply of commodity *I* must satisfy the total of intermediate and final demands:

$$QS_{i,r,t} = \sum_j A_{i,j,r,t} + C_{i,r,t} + I_{i,r,t} + G_{i,r,t} + X_{i,r,t}, \; I = 1, 2, \ldots, 31. \qquad \text{(B.10)}$$

where $QS_{i,r,t}$ equals the total supply of good *I* in region *r* at time *t*; $A_{i,j,r,t}$ is the inter-industry demand for good *I* by industry *j*; $C_{i,r,t}$ is the final demand for good *I* by the consumer sector; $I_{i,r,t}$ is the final demand for good *I* by the investment sector; $G_{i,r,t}$ is the final demand for good *I* by the government sector; and $X_{i,r,t}$ is net exports of good *i*.

In the labor and capital markets, we assume that labor and capital are fully employed. In this model without foresight, investment equals savings—i.e., there is no market where the supply of savings is equated to the demand for investment. As described in Section B.4, the sum of savings by households is equal to the total value of investment. Domestic prices relative to the price of foreign exchange adjust to hold the current account balance at its exogenously determined level.

Appendix B: Impact Sector Aggregation and Plant Shut-Down Days

Table B-1: Impact Sectors Aggregation.

CGE Sector Name	IMPLAN BEA Code	IMPLAN Description	NAICS 2012	NAICS 2012 6-digit
Petro Products	156	Refined petroleum products	32411	324110
	157	Asphalt paving mixtures and blocks	324121	324121
	158	Asphalt shingles and coating materials	324122	324122
	159	Petroleum lubricating oil and grease	324191	324191
	160	All other petroleum and coal products	324199	324199
Chemical	161	Petrochemical manufacturing	32511	325110
	163	Synthetic dye and pigment manufacturing	32513	325130
	164	Other basic inorganic chemical manufacturing	32518	325180
	165	Other basic organic chemical manufacturing	32519	325193, 325194, 325199
	166	Plastics material and resin manufacturing	325211	325211
	167	Synthetic rubber manufacturing	325212	325212
	168	Artificial and synthetic fibers and filaments manufacturing	32522	325220
	169	Nitrogenous fertilizer manufacturing	325311	325311
	170	Phosphatic fertilizer manufacturing	325312	325312
	171	Fertilizer mixing	325314	325314
	172	Pesticide and other agricultural chemical manufacturing	32532	325320
	173	Medicinal and botanical manufacturing	325411	325411
	174	Pharmaceutical preparation manufacturing	325412	325412
	175	In-vitro diagnostic substance manufacturing	325413	325413
	176	Biological product (except diagnostic) manufacturing	325414	325414
	177	Paint and coating manufacturing	32551	325510
	178	Adhesive manufacturing	32552	325520
	179	Soap and other detergent manufacturing	325611	325611
	180	Polish and other sanitation good manufacturing	325612	325612
	181	Surface active agent manufacturing	325613	325613
	182	Toilet preparation manufacturing	32562	325620
	183	Printing ink manufacturing	32591	325910
	184	Explosives manufacturing	32592	325920
	185	Custom compounding of purchased resins	325991	325991
	186	Photographic film and chemical manufacturing	325992	325992
	187	Other miscellaneous chemical product manufacturing	325998	325998

Dwelling	59	Construction of new single-family residential structures	23*	23*
	60	Construction of new multifamily residential structures	23*	23*
	61	Construction of other new residential structures	23*	23*
	63	Maintenance and repair construction of residential structures	23*	23*

Source: MIG (2016).

Table B-2: Shut-down Days by Texas Plants.

Company	Location	Year	# of shut-down days	# of days restarting	# of days at reduced capacity
Exxon Mobile	Beaumont, TX	2005	27	6	15
Shell (motiva)	Port Arthur, TX	2005	32	6	8
Total Petrochemicals	Port Arthur, TX	2005	19	20	8
Valoer (Premcor)	Port Arthur, TX	2005	19	8	6
BP	Texas City, TX	2005	77	0	0
Marathon	Texas City, TX	2005	4	7	0
Valero	Texas City, TX	2005	7	4	4
ConocoPhillips	Sweeny, TX	2005	5	7	1
Deer Park	Deer Park, TX	2005	8	6	11
ExxonMobil	Baytown, TX	2005	6	100	0
Lydonell Citgo	Houston, TX	2005	5	8	62
Astra Oil	Pasadena, TX	2005	5	8	0
Exon Mobile	Beaumont, TX	2008	28	0	7
Shell (motiva)	Port Arthur, TX	2008	13	0	15
Total Petrochemicals	Port Arthur, TX	2008	9	9	3
Valer0 (Premcor)	Port Arthur, TX	2008	14	6	15
BP	Texas City, TX	2008	12	6	10
Marathon	Texas City, TX	2008	18	2	15
Valero	Texas City, TX	2008	9	4	2
ConocoPhillips	Sweeny, TX	2008	4	10	6
Deer Park	Deer Park, TX	2008	4	9	2
ExxonMobil	Baytown, TX	2008	7	5	8
Houston Refining	Houston, TX	2008	9	6	20
Valero	Houston, TX	2008	8	20	0
Pasadena Refinery	Pasadena, TX	2008	9	9	17

Source: U.S. Department of Energy (2009).

Appendix C: Additional National Impact Figures

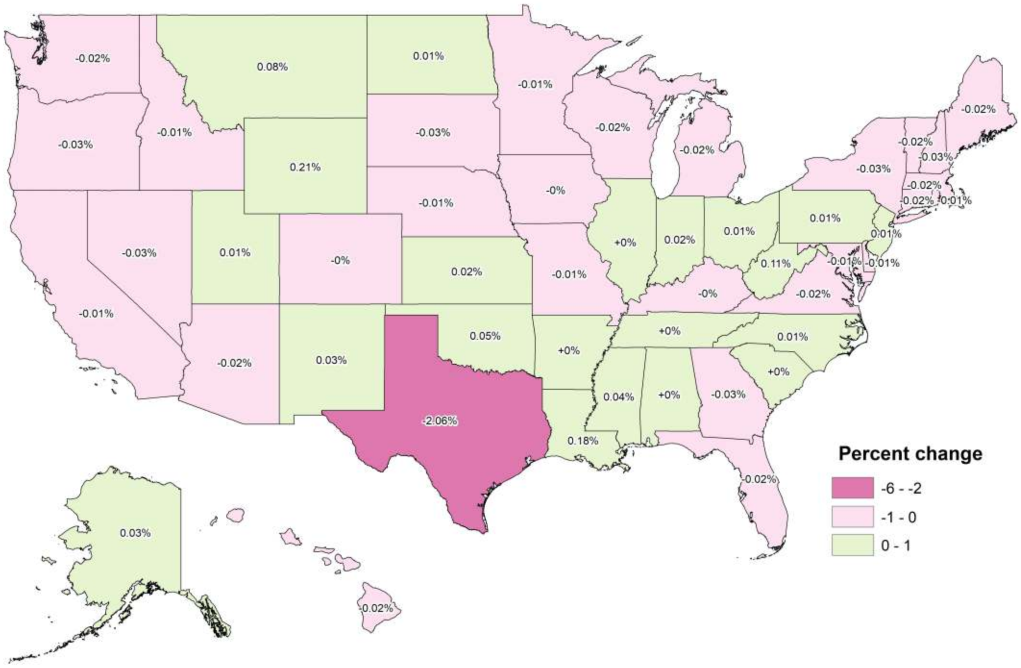


Figure C-1: 500-yr Storm Surge with Coastal Spine, Impacts in 2066 (GSP).
Notes: Percent change in GSP by states relative to the BAU GSP levels in 2066 with a coastal spine are shown. Source: Authors.

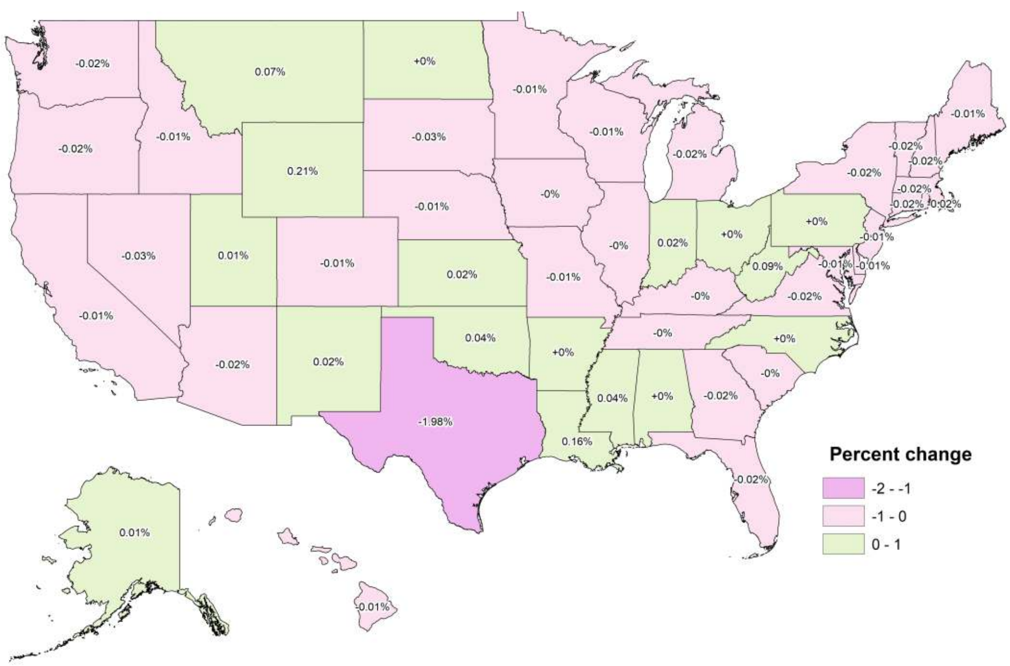


Figure C-2: 500-yr Storm Surge with Coastal Spine, Impacts in 2066 (Welfare).
Notes: Percent change in social welfare by states relative to the BAU social welfare levels in 2066 with a coastal spine are shown. Source: Authors

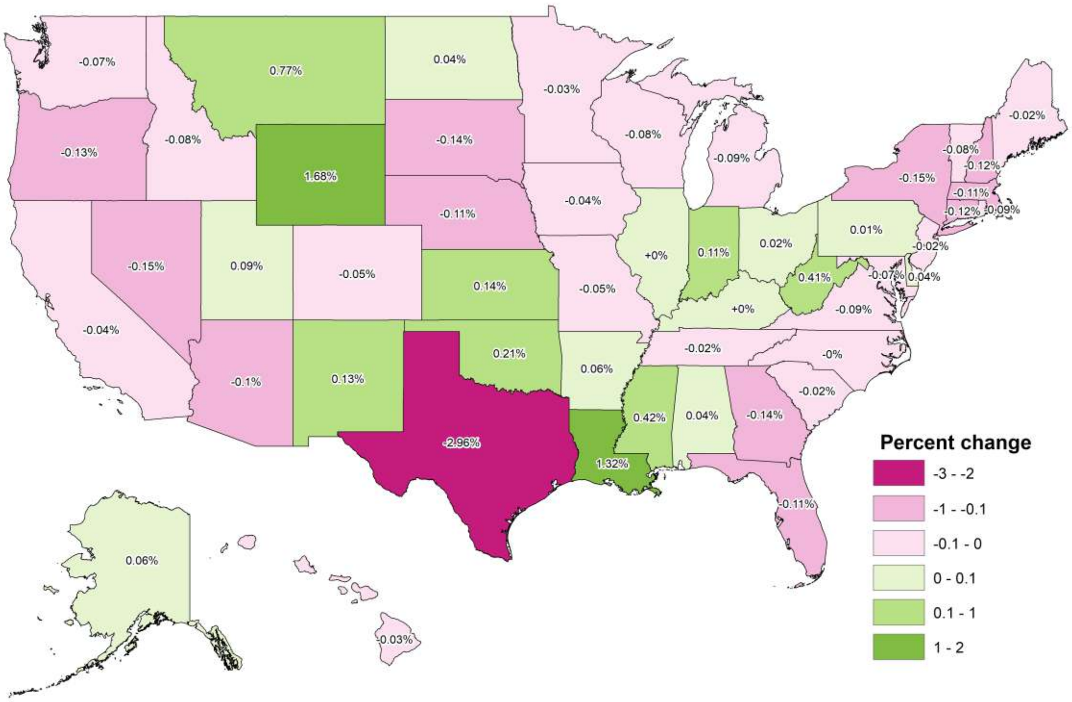


Figure C-3: 500-yr Storm Surge without Coastal Spine, Impacts in 2066 (Income).
Notes: Percent change in income by states relative to the BAU income levels in 2066 without a coastal spine are shown. Source: Authors

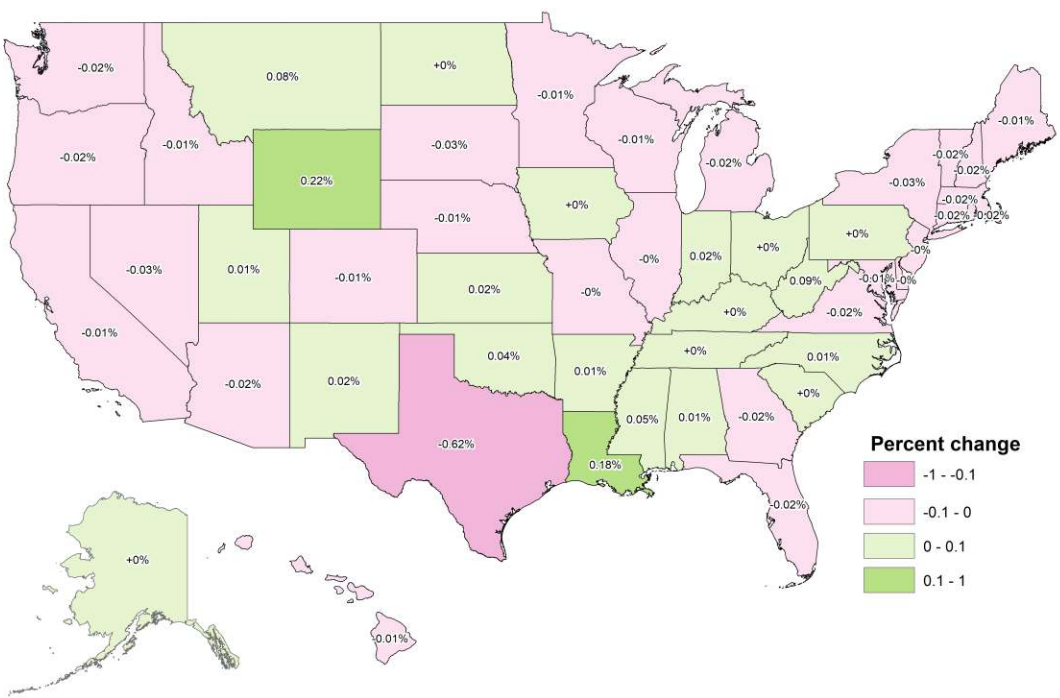


Figure C-4: 500-yr Storm Surge with Coastal Spine, Impacts in 2066 (Income).
Notes: Percent change in income by states relative to the BAU income levels in 2066 with a coastal spine are shown. Source: Authors

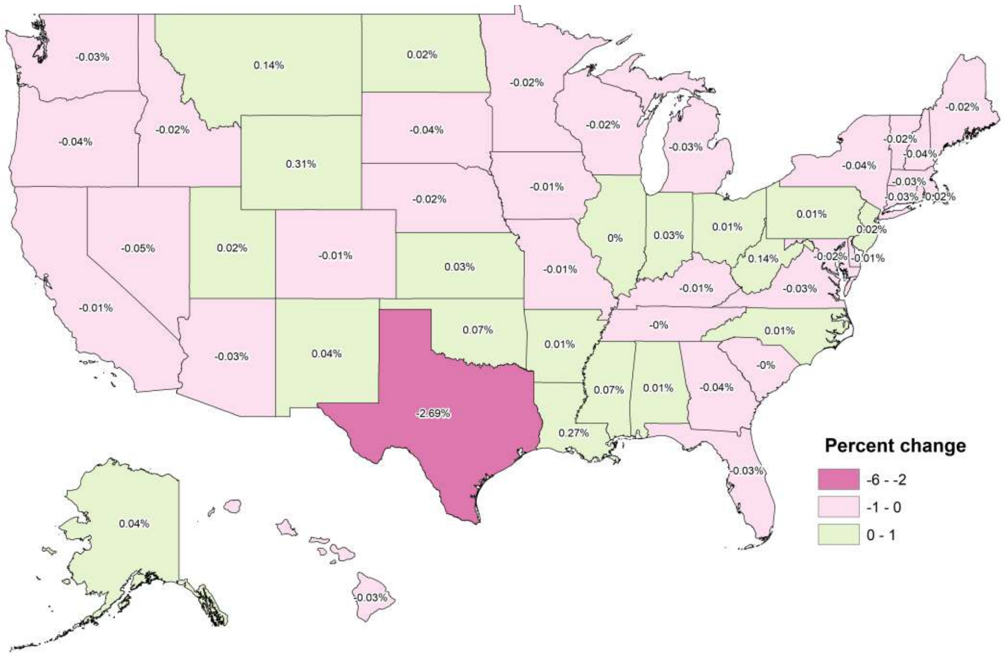


Figure C-5: Ike-like Storm Surge without Coastal Spine, Impacts in 2066 (GSP).

Notes: Percent change in GSP by states relative to the BAU GSP levels in 2066 without a coastal spine are shown. Source: Authors.

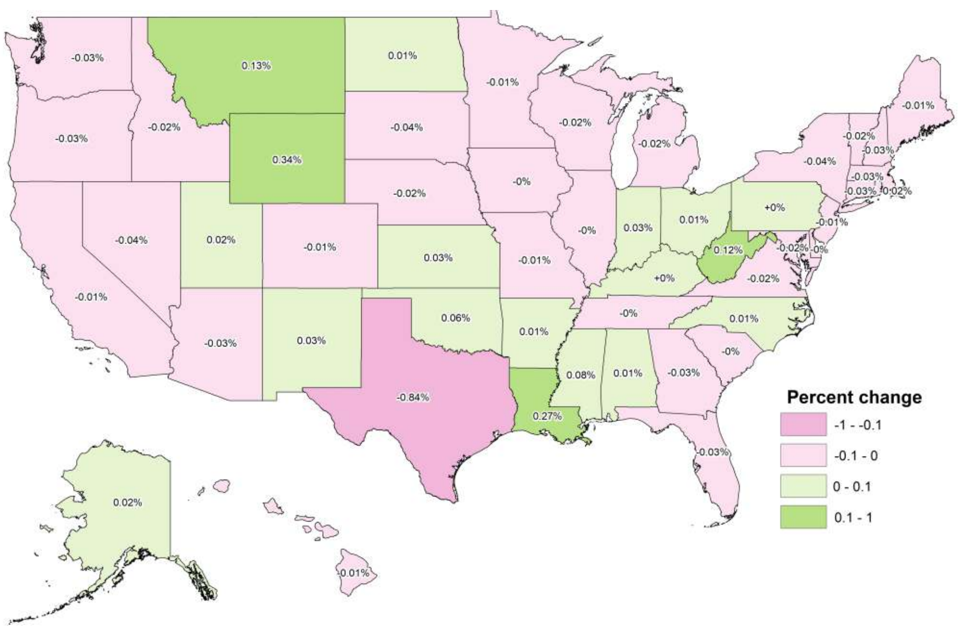


Figure C-6: Ike-like Storm Surge without Coastal Spine, Impacts in 2066 (Income).

Notes: Percent change in Income by states relative to the BAU Income levels in 2066 without a coastal spine are shown. Source: Authors.

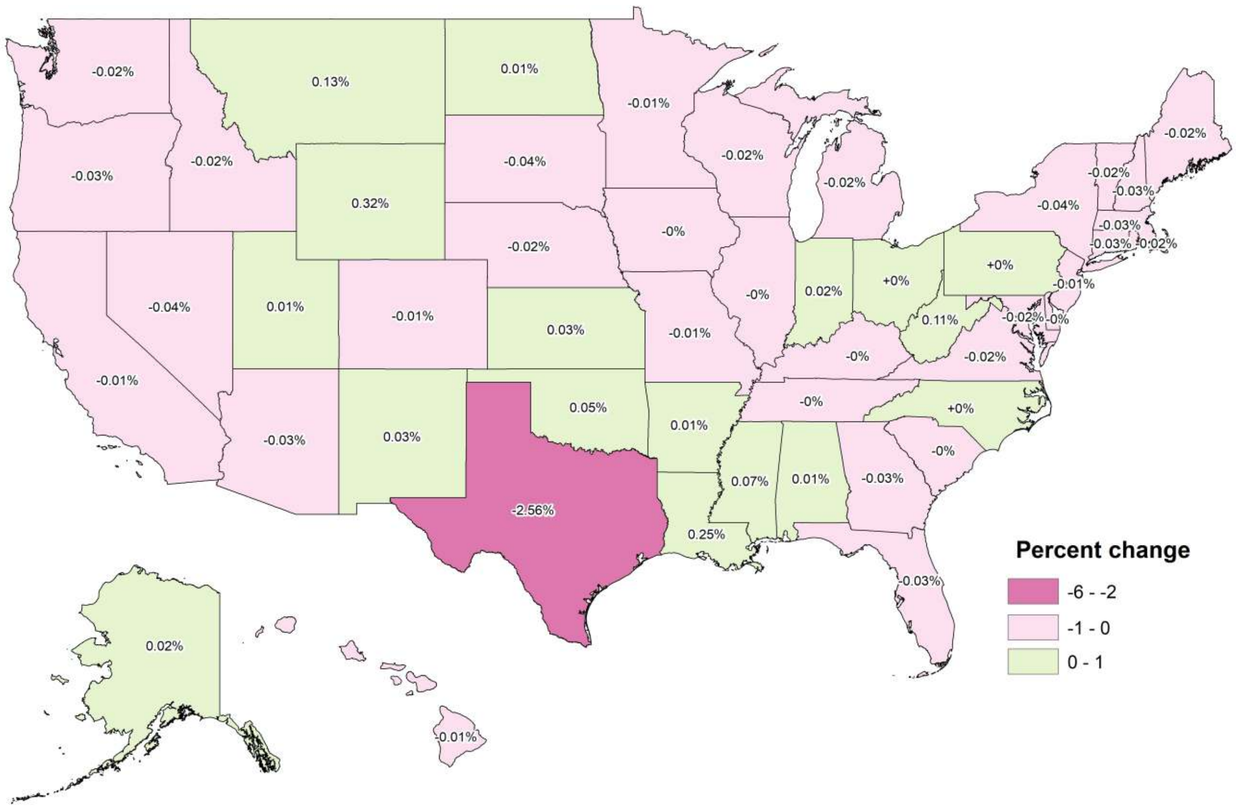
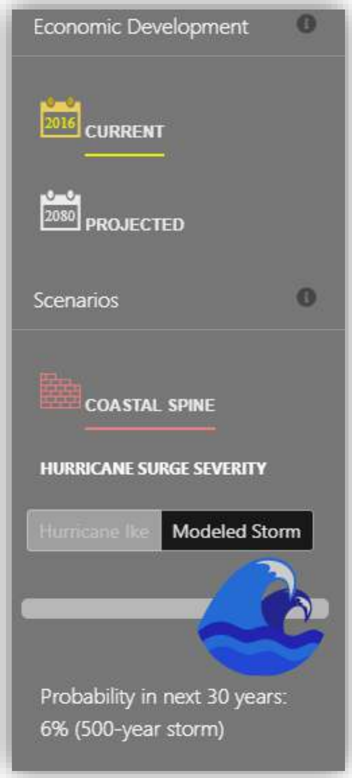


Figure C-7: Ike-like Storm Surge without Coastal Spine, Impacts in 2066 (Welfare).
Notes: Percent change in social welfare by states relative to the BAU social welfare levels in 2066 without a coastal spine are shown. Source: Authors.

Appendix D: Communicating Findings through Web-based Mapping and Visualization



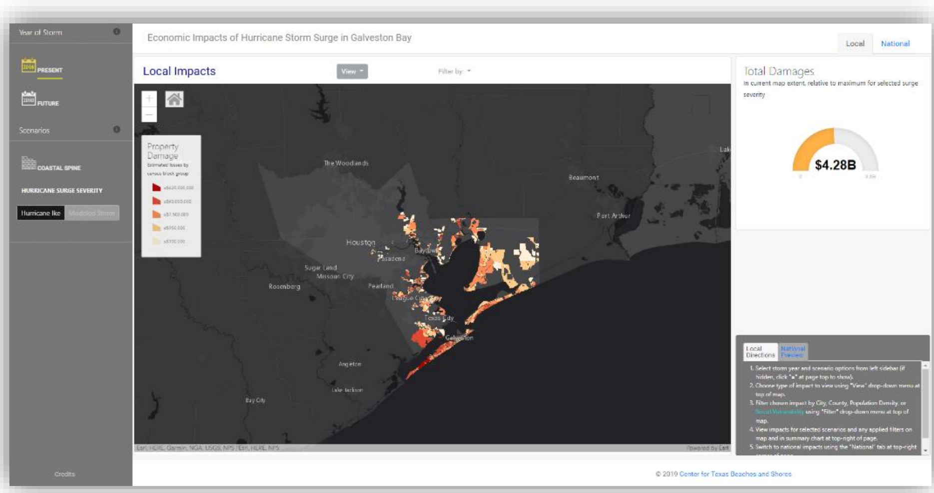
To extend our analysis efforts, we have developed of a purpose-built web interface that serves to communicate the economic results. Our web-based dashboard illustrates the impacts of storm surge for a variety of scenarios, linking them to a host of direct and indirect economic impacts at local, regional and national scales. Analysis results and contextual information can be visualized through a series of displays including two webmap cards and summary charts.

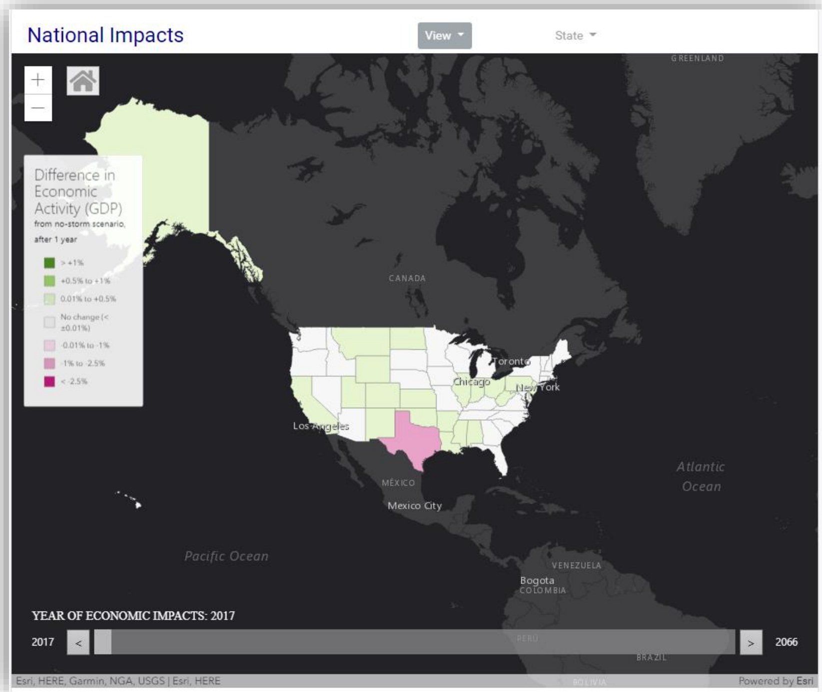
Scenarios included for the end user to view include:

- Storm size
- Landfall in 2016 or 2080, the latter of which includes projected land development
- The presence or absence of coastal spine
- Current or projected sea level rise

Web maps

Results of the scenarios above are displayed on two maps which can be viewed by changing tables. The center card is the map in focus, and is where charts (described below) draw information. One map displays information on local impacts of the selected storm surge scenario, including either residential damages or estimated storm surge. The second map displays national economic impacts at a state level. Clicking the tab in the top right allows the end user to alternate between local and national impacts. Within the local map, users can also filter areas by county or community impacted, population density and social vulnerability; the national map allows the users to query impacts by state.

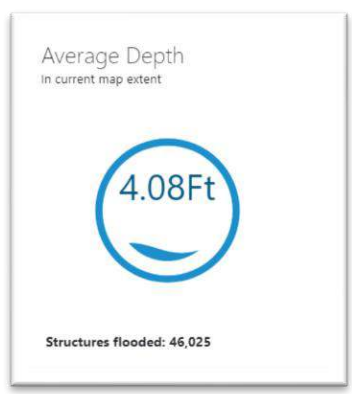


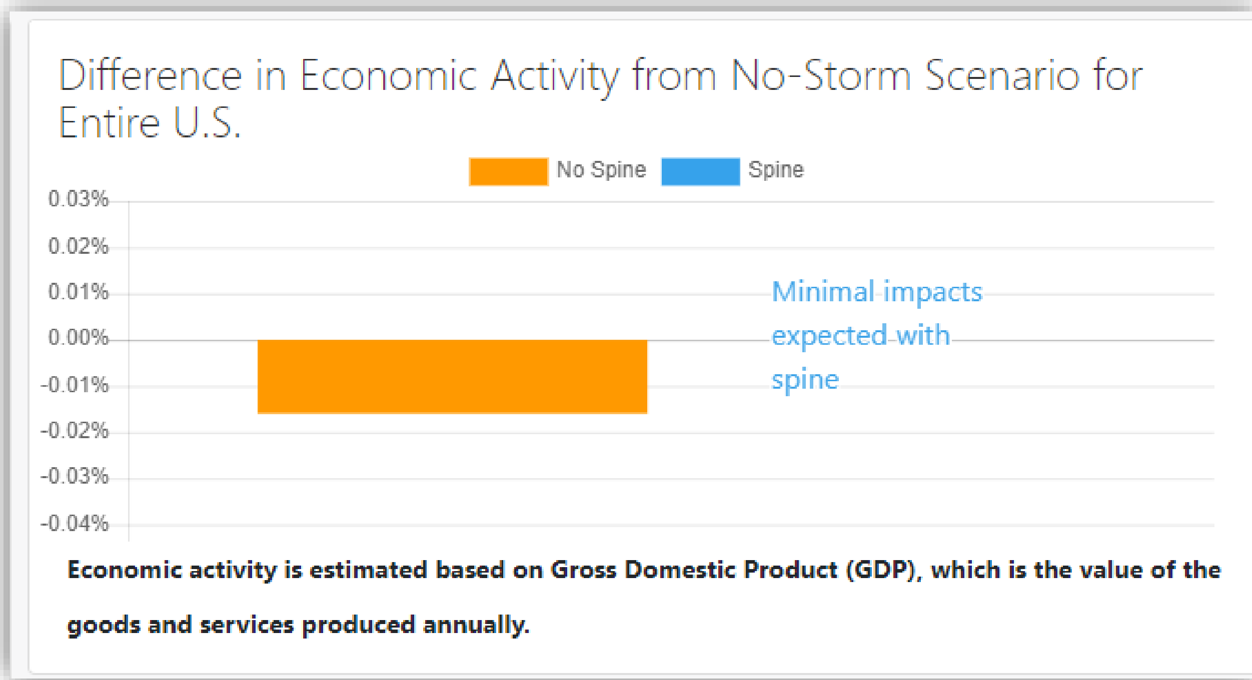


The U.S. map also has a slider at the bottom of the map which allows the user to change the year in which they are interested and demonstrating spatial variation over time. Users can also change which economic indicator they are displaying using the view drop down, and can also focus on a single state using the state drop down. Clicking on a state or polygon at the local level provides a popup with information of interest.

Charts

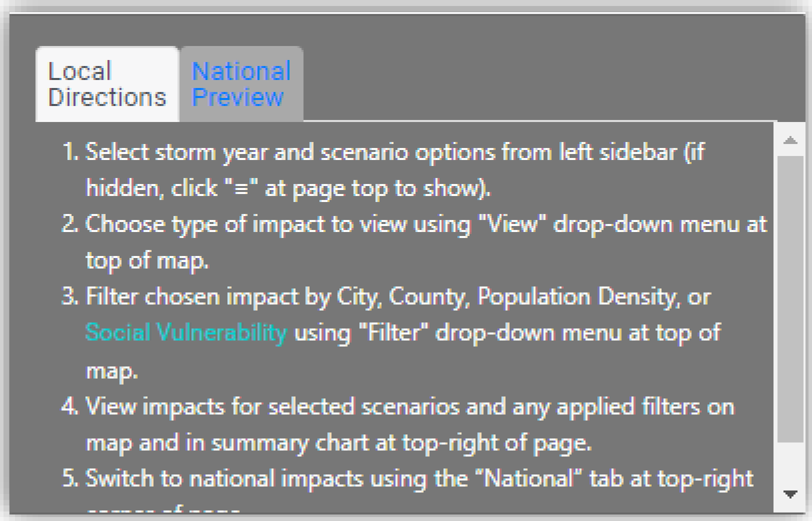
In addition to the web-maps, three types of charts are displayed based on the scenario, including local damages, average surge depth and U.S. impacts. The local damages chart provides an estimate of damages given storm size and future scenarios. This chart is dynamic and changes as the user zooms in or pans directionally, allowing the end user to gain additional understanding of how damages vary at an aggregate level across Galveston Bay. If the end user is more interested in surge depth, they can chose to view the average depth for structures that were flooded and the number of structures flooded in an area. Like the local damages chart, the graphic is dynamic and allows the end user to zoom and pan around Galveston Bay. Finally, the impacts chart uses the U.S. level dataset as the focus and leverages the economic analyses. This chart shows changes in economic indicators with and without a coastal spine. Multiple economic factors can be graphed including GDP, median income, changes in gas prices, insurance prices and housing prices.

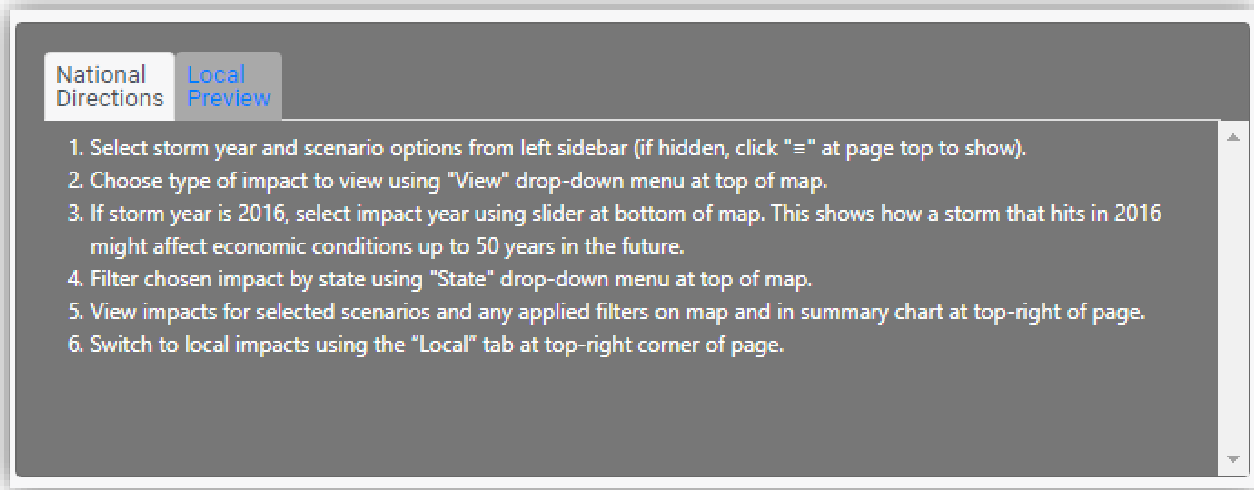




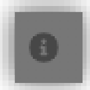
Directions

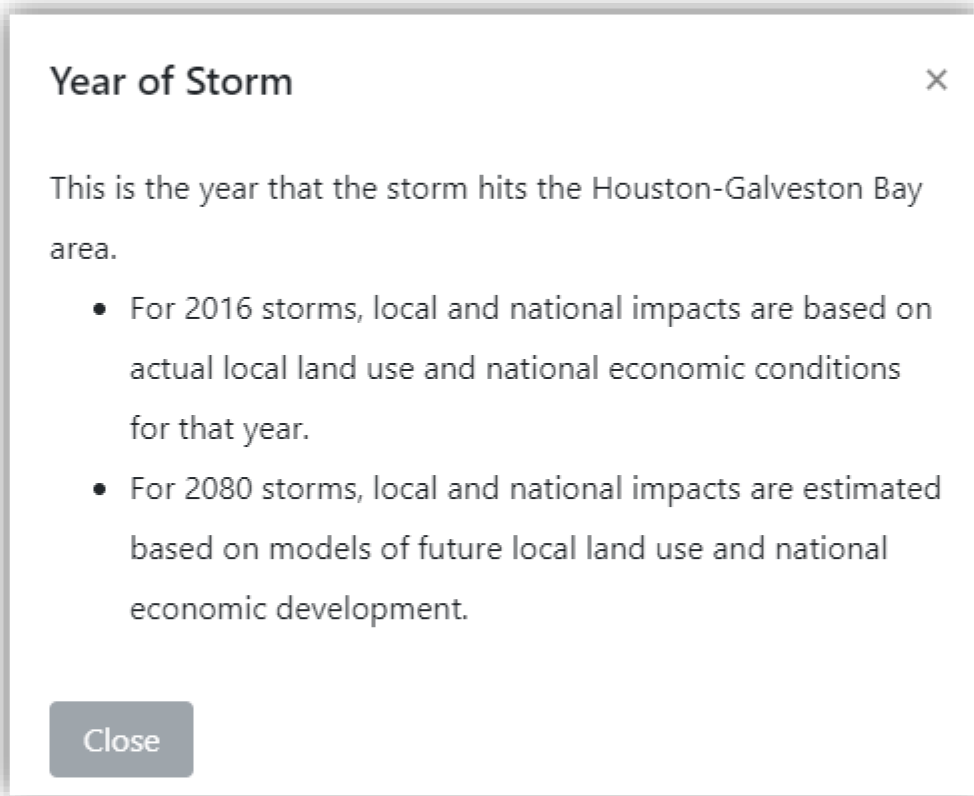
The local and US maps have different directions to help the user navigate the website. These can be found in the lower righthand corner. A second tab is available to show either the national or local webmap as well.





Additional information is available by clicking the info buttons which provide modals.





Chapter 2. Evaluating the Effects of a Coastal Spine on Flood Insurance Premiums

Chapter 2. Evaluating the Effects of a Coastal Spine on Flood Insurance Premiums

Wesley E. Highfield and Jaimlyn Sypniewski

Executive Summary

A coastal barrier system has been proposed to protect the Houston-Galveston Region from the adverse impacts of storm surge, due to both the recent disasters and an increased understanding of the impact of future events along the Texas coast. Previous evaluations have examined many direct and indirect economic impacts related to the establishment of a coastal barrier system, however the impacts on flood insurance have yet to be explored. To address this gap, we spatially and statistically analyzed the effects of a coastal barrier on flood insurance policies and premiums that would be protected from storm surge within Harris and Galveston county.

Highlights of our analysis include:

- Over 31,000, or 10% of all National Flood Insurance Program policies in Harris and Galveston Counties, would experience a reduction in 100-year storm surge as a result of a coastal spine.
- Areas that would have reduced storm surge with a coastal spine remit over $41 million dollars in annual NFIP premiums and have total flood insurance coverage of over $8 billion dollars.
- Under a 100-year storm surge scenario, over 3,000 coastal 100-year flood insurance policies would be protected to less than 1 foot of inundation.
- An additional 14,149 high-risk flood insurance policies would be protected completely protected from a 100-year storm surge.
- In the most conservative insurance scenario, nearly $5 million dollars in premiums could be saved annually by residents while still maintaining the same flood insurance coverage with the presence of a coastal spine.
- Additional scenarios suggest that total annual premiums in the coastal Houston-Galveston area could be reduced by 21-28% while still maintaining the same flood insurance coverage.

Introduction

Communities surrounding Galveston Bay have some of the highest flood insurance rates in the nation. Under the 2015 Homeowner Insurance Flood Affordability Act (HIFAA), National Flood Insurance Program (NFIP) premiums are being increased up to 18% a year until reaching actuarially-sound rates (FEMA, 2014). On the aggregate, this may be a sound approach to solvency for the NFIP, yet rising flood insurance rates are increasingly felt at the local level, especially in coastal communities with aging populations and infrastructures. Flood defenses, like the proposed coastal spine, may reduce structures' flood risk, effectively removing it from the regulatory floodplain or reducing its flood risk, which may in turn substantially reduce flood insurance costs. With this in mind, our overarching goal is to is to estimate the financial burden of NFIP policies with coastal, surge-based flooding risk in the Houston-Galveston region and determine the range of flood insurance premium savings to homeowners at the local level if a coastal spine was constructed. This study evaluates the potential effects of National Flood Insurance Program (NFIP) premiums, including the reduction of flood insurance rates for residents in the Galveston Bay region under 1) existing, baseline conditions and 2) with a coastal spine. We leverage existing Advanced Circulation (ADCIRC) storm surge model outputs to establish flood insurance policy exposure and the corresponding reduction in exposure given a coastal spine. We further demonstrate likely changes in flood insurance rates through two separate approaches under four different scenarios in Harris and Galveston Counties.

Background

Coastal Texas and Hurricane Ike

Texas has over 400 miles of coastline that has historically attracted people and industry to take advantage of a multitude of economic opportunities and quality of life amenities (Merrell, Reynolds, Cardenas, Gunn, & Hufton, 2011). In May of each year, coastal Texas residents, communities and businesses prepare for the annual hurricane season, which lasts from June to December. The Texas coastal region has over 4,300 square miles of land vulnerable to flooding induced by hurricane rains and storm surge. The frequency of hurricanes along any 50-mile segment of the coast averages about one storm event every nine years. Annual probabilities of a storm event range from 31% in the Sabine Pass Region to 41% in the Matagorda Region (Roth, 2010). The warm waters of the Gulf enable storms to rapidly grow in size and intensity, substantially increasing their ability to inundate areas with storm surges of 20 feet or higher while causing severe direct flood-related damages and indirect economic effects that linger for years. Texas' most recent large-scale storm surge event occurred in 2008 when Hurricane Ike, the primary catalyst for the proposed "Ike Dike," made landfall on the Texas coast near Galveston Island, causing over $28 billion in damages and 84 deaths (Stoeten, 2013). Ike was followed by Hurricane Harvey in 2017 and preceded by Hurricanes Gustav, Dolly, and Rita, as well as Tropical Storm Eduardo. Each of these storms struck the upper Texas coast within a three-year span. Devastating storms such as Hurricane Ike and Hurricane Harvey have plagued the Texas coast for centuries, claiming thousands of lives and placing overwhelming strains on communities, families, and individuals (Roth, 2010).

Hurricane Ike made landfall on the east end of Galveston Island as a category 2 storm in the early morning of September 13, 2008 (see Figure 1). Having decreased in intensity from a category 4 to a category 2 storm along its path over Cuba, many U.S. Gulf Coast residents would not have guessed that, at the time, Ike would be the third-costliest hurricane in U.S. history. Twelve fatalities in Galveston and Chambers Counties are directly attributable to Ike (Berg, 2009). The total financial damage from Ike in Texas, Louisiana, and Arkansas is estimated at $24.9 billion, at the time the third costliest storm behind Hurricanes Katrina and Andrew, respectively (Berg, 2009).

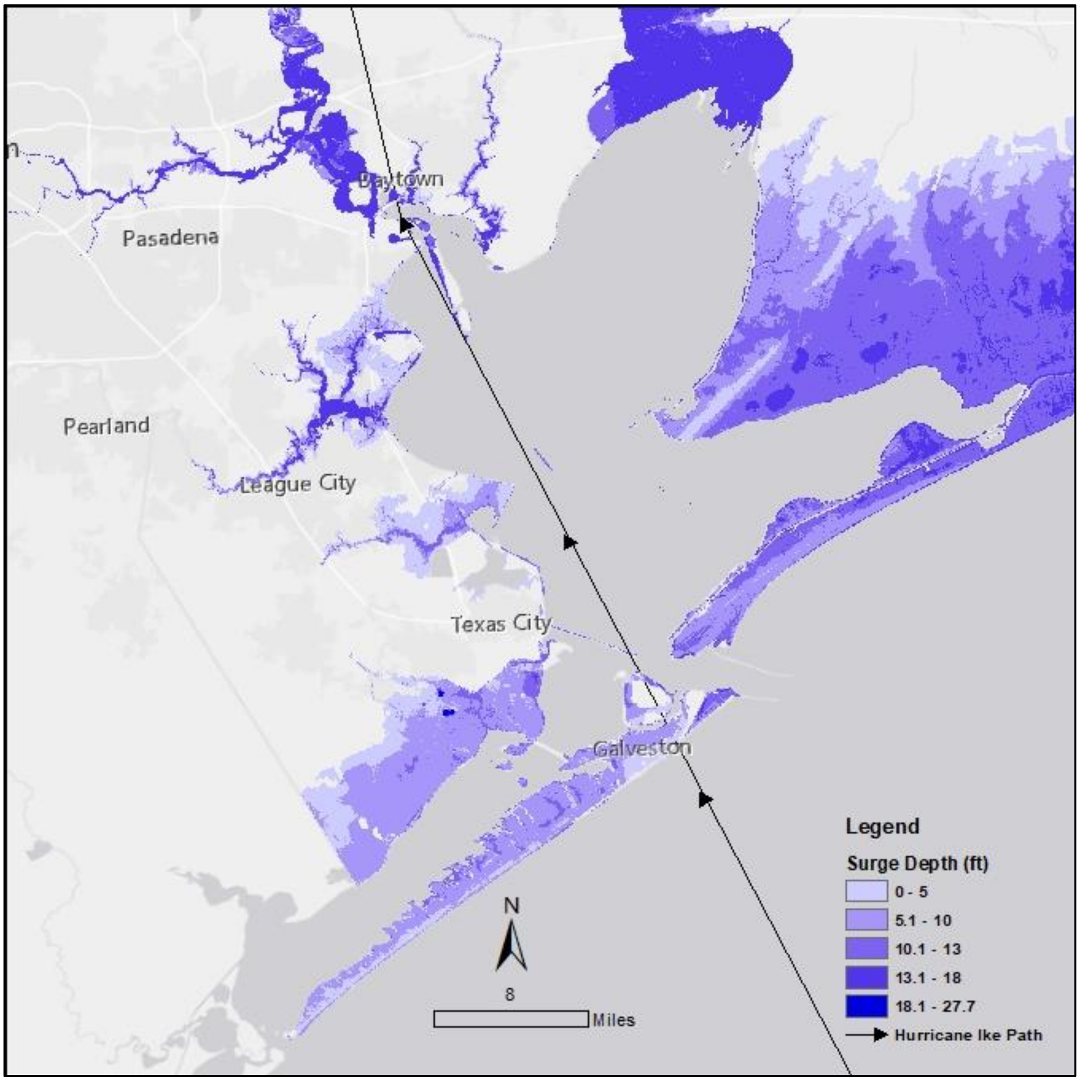


Figure 1. Path of Hurricane Ike and Resulting Estimated Storm Surge.
Source: Authors.

Despite its maximum sustained winds of 110 mph in the Galveston area, Ike is known more for its immense storm surge. The maximum high-water mark recorded by FEMA was 17.5′, located on Bolivar Peninsula. This surge event caused severe damage to structures and communities on Bolivar Peninsula. Galveston Island did not receive the equivalent surge on the Gulf side, yet its high-water mark values still ranged from 10′ to 13′, the result of a surge that pushed into Galveston and West Bay, forcing water back over the island from the north (bay) side. Hurricane Ike was also unique in the duration of its surge. A forerunner surge arrived late on September 11, marking an early start to rising water in the region (Kraus and Lin, 2009). Storm surge duration for a typical hurricane is less than a day, however Ike's surge lasted 2½ days (Kraus and Lin, 2009). Notably, the elevated area of Galveston Island located behind the seawall incurred less damage, especially compared to areas adjacent to the City of Galveston that were without dune or seawall protection (Kraus and Lin, 2009; Highfield et. al., 2014).

A Brief History of the Coastal Spine

The "Ike Dike" (see Figure 2) is a proposed barrier concept providing coastal protection against damage from hurricane storm surge to the Galveston Bay Area. In 2008, the waves and storm surge produced from Hurricane Ike alone destroyed 60% of homes in affected coastal communities with an estimated property damage cost of $5 billion ($25 billion total) (Davlasheridze, et al., 2016). The most prominent contributing factor to the damage caused by Ike was a storm surge that was able to enter Galveston Bay, where hurricane winds continued to amplify its damaging effect. Twenty lives were lost and Hurricane Ike was still far from the worst-case scenario: had Ike tracked 20-40 miles farther to the southwest, the resulting storm surge in the bay and Houston Ship Channel would have had far greater direct impacts and dramatic implications for local, state, and national economies.

The protective barrier being proposed is envisioned as an approximately 100-km long coastal spine along Galveston Island and the Bolivar Peninsula. The spine would connect a series of seawalls and fortified dunes/levees along the coastline to retractable navigation gates located at both the mouth of Galveston Bay and San Luis Pass. The intent is to limit the damaging effects caused by storm surge entering Galveston Bay by blocking a portion of the surge at the coast (Ruijs, 2011). The proposed coastal spine would not only suppress the storm surge, but is also argued to considerably reduce uncertainty in hurricane surge forecasts for the area protected by the spine (Stoeten, 2013), in addition to reducing property losses, decrease precautionary shutdowns, and reduce output losses for industrial plants (Davlasheridze et. al., 2019). The idea is certainly not unique, as comprehensive storm surge protection infrastructure systems have proven effective in protecting coastal communities prone to hurricane storm surge and resultant flooding both in the U.S. and internationally.

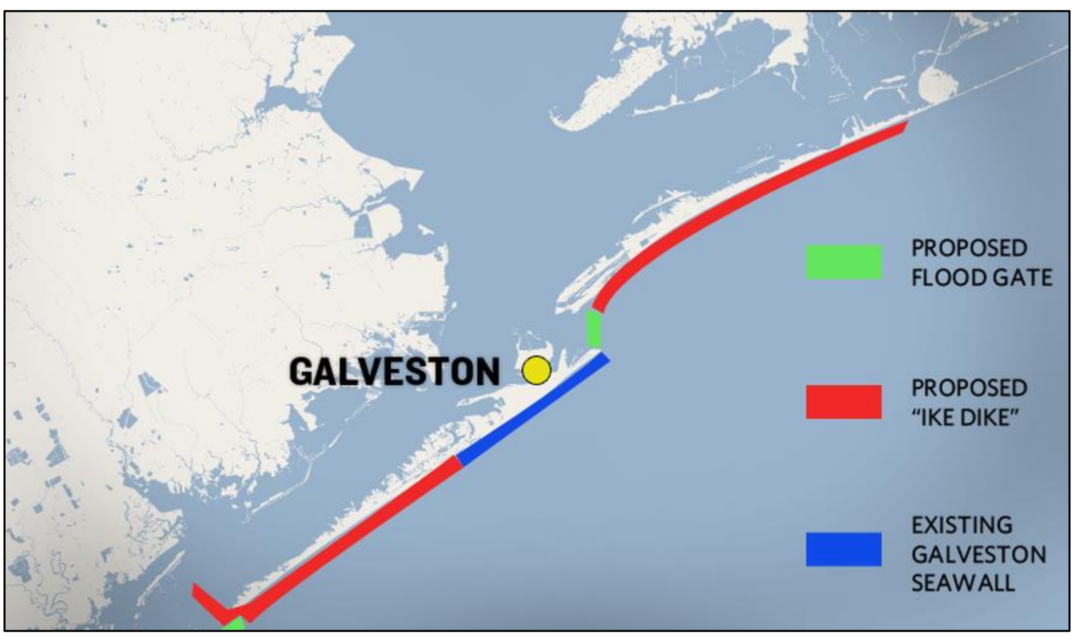


Figure 2. Conceptual Design of a Coastal Barrier System, Consisting of the Existing Seawall, Proposed Dikes and Floodgate.
Source: Authors.

From a benefit-cost ratio perspective, a coastal spine is economically feasible. The most recent research indicates a 70% reduction for the 500-year surge event, leading to an avoided loss of over $5 billion for residential structures and a total savings of about $12 billion for all occupancy categories. Significant loss reductions are also seen for the 100-year surge event, where damage among all occupancy classes is reduced by over 56%, avoiding almost $6 billion to property damages (Davlasheridze et. al., 2019).

The National Flood Insurance Program

By far the most comprehensive and widely implemented form of flood mitigation in the United States at the household level takes place through the National Flood Insurance Program (NFIP) (Highfield, Norman and Brody, 2013). The NFIP was established in 1968 to provide flood insurance to floodplain residents and businesses. Although private sector flood insurance is increasingly available to some, the NFIP is still the primary vehicle for providing flood insurance to residents and businesses. At the time of writing, the NFIP has over 29,000 participating communities and over 5.6 million flood insurance policies in force.

Risk identification identifies areas that are vulnerable to floods and is used to define levels of risk and determine actuarial rates. The result of this analysis is the Flood Insurance Rate Map (FIRM), which contains, among other delineations, the boundaries of the regulatory 1% flood (often referred to as the "100-year flood" or base flood). The riverine flood risk is estimated regarding the magnitude of a "design" flood or rainfall event (FEMA, 2005). Areas within the 100-year flood boundary have a 1% chance of being reached or exceeded by flood waters in any given year. A combination of hydrologic and hydraulic models are used to estimate the depth and extent of the resulting flood.

In comparison to riverine floodplains, floodplain delineation in coastal areas subject to storm surge is a far more complex and uncertain process that relies on simulation models, namely the the hydrodynamic Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model and, more recently, the Advanced Circulation (ADCIRC) model. The dynamic nature of lands influenced by coastal factors requires frequency based on historical storm surges, still water elevation levels, and models of wave generation, setup, overland propagation, run-up, and overtopping. Also, factors such as tides, erosion, and existing structures (e.g., seawalls and other barriers) must also be considered (FEMA, 2017).

These outputs, both riverine and coastal, are portrayed on FEMA's FIRMs as the elevation to which floodwater is anticipated to rise during the base flood (i.e., 100-year flood or base flood elevation), (FEMA, 2017). While frequently misconstrued as *the* measure of flood risk, FIRMs are created for the purpose represented by their namesake: to set flood insurance rates. FIRMs are divided into zones which broadly determine the probabilistic flood risk for the area delineated. Moderate- and low-risk areas are denoted by B-, C- or X-zone designations (see Table 1). Areas designated as X-zones are judged to be low flood risk and carry flood insurance premiums (usually preferred risk policies) of approximately $450 dollars per year, assuming there is no previous history of flood damage. Shaded X-zones are areas that are considered low to moderate risk due to protection by levees or other structural features. Shaded X-zones premiums are typically near the preferred risk policy cost.

Flood zones AE and VE are considered high-risk, and correspond to what is commonly referred to as the 100-year flood, or areas which have a 1% chance in any year of encountering a flood. Zone AE is the traditional 100-year or 1% flood zone, while zone VE carries the same flood probability but with the addition of wave action resulting from storm surge. Insurance costs in AE and VE flood zones carry higher annual premiums with much more variability, depending on the age, foundation type and elevation of the structure. For example, in Harris and Galveston counties, the average flood insurance premium for structures located in the AE-zone is $905 per year. This value is, however, highly variable (standard deviation $1013); structures built prior to the establishment of FIRMs (pre-FIRM) have premiums of nearly $1000, while structures built after the establishment of the FIRM (post-FIRM, and assumed to a higher standard) have an average annual premium of $795. Structures built in VE-zones, and thus subject to storm surge carry even higher premiums. The average flood insurance premium of VE rated structures is $1083, with average pre-FIRM VE rates of $1440 and average post-FIRM VE rates of $900.

Table 1: Definitions of FEMA Flood Zones (adapted from FEMA, 2017).

Moderate to Low-Risk Areas	
B and X (shaded)	Area of moderate flood hazard, usually the area between the limits of the 100-year and 500-year floods. B Zones are also used to designate base floodplains of lesser hazards, such as areas protected by levees from a 100-year flood, or shallow flooding areas with average depths of less than one foot or drainage areas less than 1 square mile.
C and X (unshaded)	Area of minimal flood hazard usually depicted on FIRMs as above the 500-year flood level. Zone C may have ponding and local drainage problems that don't warrant a detailed study or designation as a base floodplain. Zone X is the area determined to be outside the 500-year flood and protected by a levee from 100-year flood.
High-Risk Areas	
AE	Areas with a 1% annual chance of flooding where base flood elevations are provided.
High-Risk Coastal Areas	
VE	Coastal areas with a 1% or higher chance of flooding and an additional hazard associated with storm waves. These areas have a 26% chance of flooding over the life of a 30-year mortgage. Base flood elevations derived from detailed analyses are shown at selected intervals within these zones.

Study Area and Methods

Study Area

The focus area for this study are the portions of Harris and Galveston Counties that will experience a reduction in storm surge as a result of a coastal spine. The study areas in these two counties represent the primary impact of the proposed coastal spine as they will be directly affected by its construction and potential flood mitigation effects, while containing nearly all impacted NFIP policies. In order to determine our study area, we relied upon two datasets: NFIP policies from 2014 (the most recent available) and ADCIRC flood inundation outputs. We first calculated the difference in flood inundation from two ADCIRC runs that simulate a 100-year surge event: one modeled run that allows surge to impact the study area unimpeded from any barrier, and one that takes into account a 17' storm surge barrier as shown in Figure 2 above. The 100-year event was selected since current regulatory flood insurance policy uses this recurrence interval as the regulatory trigger for insurance purchase. NFIP policies were then spatially joined to the two ADCIRC runs, creating measures that provided estimated surge inundation with and without the presence of a coastal spine. Any NFIP policy located in an area that demonstrated a decrease in surge height was included for further analysis, effectively isolating only policies impacted by a coastal spine. Figure 3 (below) outlines our study area; areas in green indicate decreases in surge inundation as a result of a coastal spine in Harris and Galveston Counties.

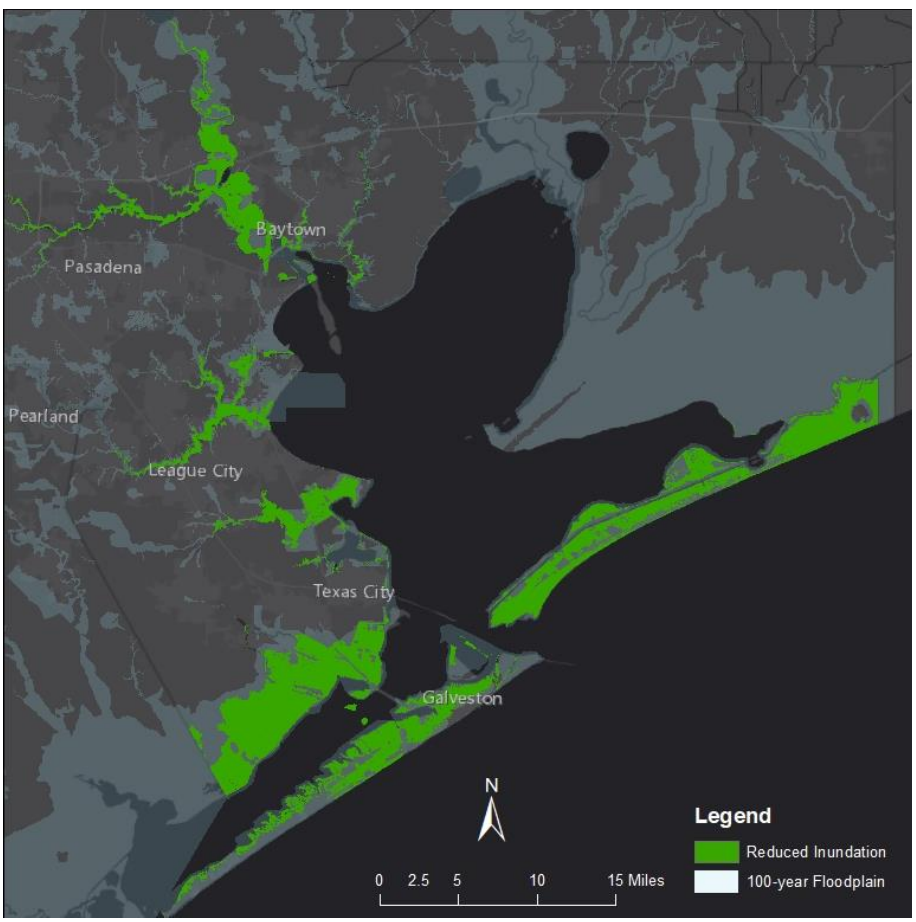


Figure 3. Study Area for Harris and Galveston County Insurance Analysis.
Note: Areas in green are those that will experience some level of surge reduction. Source: Authors.

Methods

Rating Change Scenarios

Following the establishment of our study area, we then developed a set of four scenarios to shift NFIP policies into new rating zones. These four scenarios represent the most likely changes in NFIP policy ratings should a coastal spine be constructed and certified to protect against a 100-year surge event. To determine changes in flood insurance costs with a coastal spine in place, we used these four scenarios of potential NFIP ratings changes to compare against the "baseline" rates—those rates that are observed in the dataset without any modification.

The first scenario is the most conservative and risk-averse. In this scenario, we assume that V-zone rated policies that experience a decrease in the 100-year surge to 1' or less as a result of the coastal spine shift from V-zones to A-zones. This scenario keeps existing policies in the high-risk flood category, but removes the threat of coastal wave action if surge water levels are less than 1'. All other zones remain unchanged (see Table 2).

The second scenario takes a slightly more lenient but still quite conservative approach to NFIP zone changes. In this scenario, V-zone rated NFIP policies in locations that have had 100-year surge levels reduced to zero inundation are shifted into shaded X zones—flood zones which are considered moderate risk due to structural mitigation features. No other policy rate changes are made.

Table 2. Scenarios Used to Analyze Changes in Flood Insurance Rating Based on Flood Zones.

Scenario	Description	V-Zone	A-Zone	Shaded X Zone	X-500 Zone	X-Zone
Baseline	"Baseline" Predicts current insurance rates	No Change				
1	100 yr surge reduction in V-Zones goes to less than 1'.	Shifts to A Zone	Receives increase from V-Zone	No Change	No Change	No Change
2	100 yr surge reduction in V-Zones goes to 0',	Shifts to Shaded X	No Change	No Change	No Change	No Change
3	100 yr surge reduction in V-Zone < 1', all A Zones =0'	Shifts to A-Zone	Shaded X	Receives increases from A-Zone	No Change	No Change
4	100 yr surge reduction in V-Zone < 1', all A-Zones = 0	Shifts to A-Zone	X-Zone	No Change	No Change	Receives increase from A-Zone

In our third scenario, we begin to shift two zones. First, and similar to the first scenario, V-zone rated policies that have 1' or less as of surge with the spine in place are shifted from the V-zone to the A-zone. Second, we now also shift A-zone policies into the shaded X-zone if the A-zone policy location has a surge reduction to zero feet. This scenario is an expansion of Scenario 1, with the assumption that the A- to shaded X-zone shift also represents a reduction in coastal flooding in areas that were previously not expected to have wave action.

The fourth and final scenario is perhaps the most liberal of the four. First, we shift V-zone rated policies to the A-zone if the policy location experienced a reduction in surge depth of less than one foot—the same approach taken in scenarios 1 and 3. Next, we shift A-zone rated policies that show complete protection (surge reduction to zero feet) from 100-year surge events with a coastal spine into low-risk, or X-zone ratings. This second shift is conceptually different from movement of policies into the shaded X-zone. However, our dataset has far more X-zone rated policies than shaded X rated policies, providing more variability in cost estimates.

Data Analysis

Building on the four flood insurance rate change scenarios outlined above, we then analyzed data through two approaches. The first approach simply uses the mean policy premium for each flood zone to substitute changes in flood insurance premiums as a result of a coastal spine reducing storm surge policy ratings. For example, a pre-coastal spine V-zone rated policy that exhibits a surge reduction of less than one foot may after the coastal spine may have its rating shifted to the A-zone. In this case, we subtract the mean V-zone policy premium from the total of all V-zone rated policies, and add an A-zone rated policy at its mean value, increasing the total of all A-zone rated policy premiums. The advantage of this spatial analysis-driven mean-substitution method is that it retains all of the raw flood insurance premium values—no modeling errors are introduced. The disadvantage, however, is that the mean-substitution approach only takes into account the flood zone location of the policy, it does not consider many of the characteristics used to assess or that drive flood insurance rates.

To address this shortcoming, we also took a second, statistical regression-based approach to estimate changes in flood insurance premiums. For this second approach, we measured a suite of variables to predict annual flood insurance premiums by estimating Ordinary Least-Squares regression models. First, we started with the dependent variable, flood insurance premiums, which was measured to the whole dollar and represents the total amount paid per year for flood insurance. This variable was further log-transformed to approximate a Gaussian distribution. Second, we measured a host of independent variables under the categories of cost factors, discounts, elevation and flood zones (see Table 3).

The cost factors examined consisted of the total replacement cost and total insurance coverage. The total replacement cost is a whole dollar estimate of the value of the insured building as provided by the insurance policy. The total coverage is the total of building and content coverage, and varies from the replacement coverage due to the maximum coverage amounts allowed by the NFIP. For a residential policy, the NFIP caps building coverage at $250,000 and contents coverage at $100,000, non-residential building and contents coverage is capped at $500,000 for each coverage type. Both total coverage and total replacement values were calculated and log-transformed before entering the model.

There are also several elements that can reduce insurance premiums. The variables examined in this category included the policies' CRS participation level, the elevation status of the building, and the policy's pre-FIRM status. The CRS level refers to the Community Rating System (CRS), which is a voluntary incentive program that recognizes and encourages community floodplain management activities that exceed the minimum NFIP requirements. The greater the CRS class, the greater the insurance premium discount will be, up to a maximum of 45%. We included the CRS scores of each policy as a series of indicator variables, ranging from no discount (non-participating) to a 25% discount, the maximum in the study area. Elevated buildings are also rated at a discount relative to slab-on-grade construction. An elevated building is defined by FEMA as, "a building that has no basement and that has its lowest elevated floor raised above ground level by foundation walls, shear walls, posts, piers, pilings, or columns." The elevation status of each policy (yes/no) was entered into the model as an indicator variable. The pre-FIRM status also drives individual flood insurance rates. A pre-FIRM is structure is defined by FEMA as "a building for which construction or substantial improvement occurred on or before December 31, 1974, or before the effective date of an initial Flood Insurance Rate Map (FIRM)." In other words, structures that were built prior to the development or implementation of the flood insurance mapping and rating system. Policies rated as pre-FIRM were entered into the model as an indicator variable.

Table 3. Variables, Summary Statistics and Sources Used to Predict Flood Insurance Premiums.

Variable	Mean	Std. Dev.	Source
Total Premium	1327.13	2360.72	NFIP
Total Premium (natural log)	6.65	0.94	Calculated
Replacement Value	323425	2834443	NFIP
Replacement Value (natural log)	12.16	0.63	Calculated
Total Coverage	2604.66	2078.09	NFIP
Total Coverage (natural log)	7.69	0.65	Calculated
A-Zone	0.72	0.45	FEMA FIRM
V-Zone	0.16	0.36	FEMA FIRM
500-year Zone	0.06	0.23	FEMA FIRM
Shaded X Zone	0.0007	0.03	FEMA FIRM
X Zone	0.0600	0.24	FEMA FIRM
post-FIRM status	0.63	0.48	NFIP
Elevated status	0.41	0.49	NFIP
Height Above Nearest Drainage	2.27	1.30	NCIE
CRS Class	2.40	5.54	NFIP
n=31,410			

The elevation of a structure is also an important determinant of a flood insurance rate. Typically, this form of elevation is measured as the first-floor elevation (FFE). The FFE in relation to the base flood elevation on a FIRM is critical to understanding how much, if any, water will be taken on by a structure in the event of a flood of a given height. Unfortunately, values of FFE are difficult if not impossible to obtain as FFEs are determined by a surveyor and recorded on an elevation certificate; many structures have not been surveyed, and no database of elevation certificates exists. As a proxy, we incorporated the Height Above Nearest Drainage (HAND) into the model (Liu et. al., 2018). While not a true FFE, the HAND does provide an elevation more accurate for flood impacts than traditional ground elevation and is roughly equivalent to FFE for most slab-on-grade structures. HAND values were previously calculated by and downloaded from the National Flood Interoperability Experiment (https://web.corral.tacc.utexas.edu/nfiedata/). Each NFIP policy was spatially joined to its HAND elevation, and each policy's HAND elevation value was entered into the model.

The primary variables of interest, flood zones, were allocated to each flood insurance policy. The most recent effective flood insurance rate maps for our study area were downloaded and spatially merged from the FEMA Map Service Center. Each flood insurance policy was then spatially joined to the merged FIRMs to determine its floodplain zone designation. The zones included in our analysis are described above in Table 1. Finally, we also included fixed-effects for community membership based on the FEMA community definition, to control for any additional mitigation activities that may occur at the community level and other unobserved heterogeneity. The regression-based analysis was performed on the same sub-set of policies that demonstrated a decrease in storm surge reduction. An initial regression model was estimated using the variables described above, and baseline flood insurance rates were predicted from this model. Following the baseline prediction, we then substituted observations into different flood zones using the factors described in the four scenarios, and predicted flood insurance premiums for each scenario.

Results

Descriptive

The results of our initial spatial analysis of NFIP policies indicated that 31,411, or 10% of all NFIP policies in Harris and Galveston Counties, would experience a reduction in 100-year storm surge as a result of a coastal spine (see Figure 4).

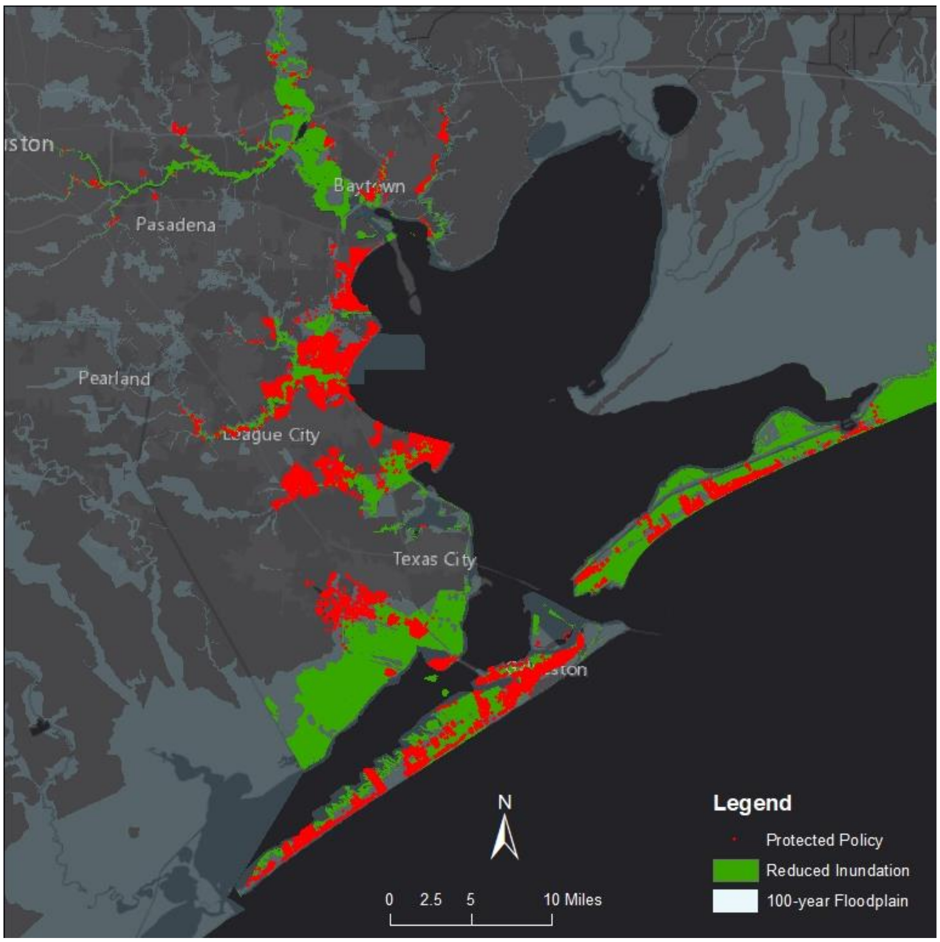


Figure 4. General Location of NFIP Policies that Would Experience a Reduction in Storm Surge From a 100-Year Event.
Source: Authors.

These policies are all located in areas that are directly adjacent to the Gulf of Mexico, Galveston Bay, or along Clear Lake/Creek and the Houston Ship Channel. The 31,411 NFIP policies that will experience some level of storm surge reduction represent over $41 million dollars in annual premiums borne by residents, with total coverage of over $8 billion dollars without protection. Over 72% of affected policies occur in the A-zone, which has an annual policy premium of $1,167, accumulates over $26 million dollars per year in premiums and has total flood insurance coverage of $5.7 billion dollars. The other high-risk flood zone, the V-zone, has 4,919 policies that will experience some level of surge protection, with a mean annual policy premium of $2,719, over $13 million in annual flood insurance premiums and nearly $1.3 billion dollars of flood insurance coverage. The remaining moderate- and low-risk zones, including the 500-year, shaded X and X-zones, account for the remaining 3,799 NFIP policies that would experience a reduction in storm surge. Even these low-risk flood zones account for $1.8 million in annual flood insurance premiums and have $1.1 billion in covered assets. Mean annual policy premiums for these zones range from a high of $526 in the 500-year flood zone to $326 in the shaded X zone (see Table 4).

Table 4. Summary Statistics for NFIP Policies that Would Experience Storm-Surge Reduction with the Establishment of a Coastal Spine.

Flood Zone	Flood Insurance Premiums				Total Coverage	Policy Counts
	Total	Mean	Median	Std. Dev.		
A	$26,490,806	$1,167	$588	$2,048	$5,776,615,000	22,693
V	$13,377,044	$2,719	$1,918	$3,663	$1,299,704,200	4,919
X	$867,909	$442	$392	$384	$589,712,600	1,963
X500	$952,925	$526	$392	$703	$510,817,000	1,813
Shaded X	$7,507	$326	$312	$48	$4,626,000	23
Total	$41,696,191	$1,327	570	$2,361	$8,181,474,800	31,411

The reduction inundation from a coastal-spine protected 100-year surge for NFIP policies is variable, both overall and across zones (see Table 5), but follows the risk structure of existing flood zones. The largest average change in mean inundation is for policies located in V-zones, with a mean decrease of nearly 7' which affects nearly 5,000 policies. This result is not surprising, as these policies are located in areas most at risk from storm surge.

Policies in the A-zone sees the second-most decrease in mean storm surge at 4.45' and again reflect areas which would have experienced rising water in the event of a storm surge, but without (or with reduced) wave action. The largest impact in affected policies comes from this zone, with 22,693 NFIP policies benefitting from a reduction in storm surge. The third flood zone in order of flood risk is the 500-year flood zone, which is also ranked third in mean storm surge reduction at 2.2' and affects over 1,800 polices. The final two zones of low flood risk, the shaded X zone (23 policies) and the X-zone (1,813 policies), show minimal decreases in mean storm surge reduction at 0.66' and 2.2', respectively.

Table 5. Mean Change in Inundation from Base Levels (Without Protection) to Coastal Spine Levels (With Protection) for a 100-Year Surge Event by Flood Zone.

	Difference in Inundation, Feet				
Flood Zone	Mean	Min	Max	Std. Dev.	Policy Counts
A	4.45	0.01	17.48	2.55	22,693
V	6.98	0.25	16.3	1.67	4,919
X	1.48	0.01	15.8	1.03	1,963
X500	2.22	0.01	13.25	1.72	1,813
Shaded X	0.66	0.05	3.77	0.87	23

Scenario Results

Although the above sheds some light on the level of NFIP policy premiums and asset exposure that may be changed with a coastal spine in place, more spatially-explicit results were calculated based on the four scenarios outlined in Table 2 using two approaches: mean-substitution and regression-based. The mean-substitution approach retains the raw annual policy premiums, shifting policies from one flood zone to another based on the reduction in storm surge. When a policy changes flood zones, the mean premium for the original flood zone is subtracted from the total premium for that zone, and the mean premium for the new, or "protected," flood zone is added to the total premium for that zone. The results of the four scenarios are then compared to the baseline, or unprotected, flood insurance figures.

As previously noted, the mean substitution approach has a disadvantage in that it only takes into account the flood zone location of the policy, and does not consider any of the other characteristics used to assess flood insurance rates. This limitation was addressed through the use of a statistical regression-based approach to estimate changes in flood insurance premiums. The estimated regression model described above achieved an adjusted R^2 of 0.49. All independent variables described above in Table 3 behaved as expected and were significant at $p < 0.001$ (see Appendix A). Regression diagnostics did not yield any significant violations. It should be noted, however, that the model's baseline prediction underpredicted the raw premium values by approximately 50%. This was not wholly unexpected, as model fits of this type of data are notoriously difficult and do not yield high R^2 values. While this is not ideal for comparing the aggregate policy premiums predicted from the regression model to the raw, mean-substitution premiums, the percent-changes from the scenarios analyzed with the regression-based approach are still informative when compared to the predicted regression baseline and percent-changes calculated in the mean-substitution approach.

Scenario 1

In this conservative scenario, V-zone rated policies that experience a decrease in the 100-year surge to 1' or less were shifted from V-zones to A-zones. Notably, this scenario keeps all policies, regardless of their change in flood zone, in a high-risk flood category. Under this scenario with mean-substitution, 3,184 (65%) of NFIP policies in the V-zone are protected to less than 1' of storm surge and shifted into the traditional 100-year flood zone (A-zone) without wave action. This scenario results in nearly $5 million dollars in annual flood insurance savings to homeowners, a 13.45% reduction (see Table 6) from the baseline. Comparatively, the regression-based approach resulted in a comparatively similar reduction of 12.35% compared to baseline (see Table 7).

Scenario 2

Scenario 2 shifts V-zone rated NFIP policies in locations that have had 100-year surge levels reduced to zero feet of inundation into shaded X-zone rated policies, or ratings intended for moderate-risk areas due to structural mitigation features such as levees and dams. The calculated changes using mean-substitution under this second scenario show that 2,619 (53%) V-zone polices are fully protected from storm surge as a result of the coastal spine, which shifted the same amount into shaded X-zone policies with an average annual policy premium of $326. In the aggregate, this resulted in $6.2 million dollars per year in savings for annual premiums, a 17.7% reduction compared to the baseline (see Table 6). The regression-based estimates for Scenario 2 yielded a 12.42% reduction (see Table 7).

Scenario 3

The third scenario shifts policies into two zones: V-zone policies that had 1' or less of surge with a coastal spine were shifted to the A-zone, while A-zone policies that had a surge reduction to 0' were moved into the shaded X-zone. In this scenario, mean-substitution again resulted in 3,184 V-zone policies removed from the high-risk coastal zone, while 14,189 A-zone policies were shifted into the shaded X-zone. The overall effect of these policy re-ratings decreases the total annual policy premium by nearly $14 million dollars, or a 49% decrease in total annual premiums (see Table 6). This was the highest reduction of all scenarios across both methods. The regression-based estimated reduction was 28.81%, still over double that of the previous two scenarios, but not nearly as ambitious as the mean-substituted reduction (see Table 7).

Scenario 4

The fourth scenario follows the same decision logic as Scenario 3, except A-zone rated policies that show complete protection from 100-year surge events are moved into the X-zone (as opposed to the shaded X-zone). Results from the fourth scenario pick up on the relatively higher-cost of X-zone policies compared to shaded X-zone policies, which may be artificially low. This scenario yields the same 3,184 policy reduction in the V-zone, decreases A-zone policies by 51%, and adds 14,189 policies to the X-zone. In total, Scenario 4 decreases annual total flood insurance premiums by $7.4 million dollars, a 21.8% reduction (see Table 6). The regression-based figure also converged on a similar estimate of a 23% reduction (see Table 7).

Table 6. Changes in NFIP Policy Counts and Total Premiums across Four Scenarios of Flood Zone Changes Using the Mean-Substitution Approach. Policy Rating Shifts are the Result of a Coastal Spine Causing Decreases in 100-Year Surge Inundation Levels.

	Baseline		Scenario1		Scenario2		Scenario3		Scenario4	
Flood Zone	Policies	Premiums	Policies	Premiums	Policies	Premiums	Policies	Premiums	Policies	Premiums
A	22,693	$26,490,806	25,877	$30,206,534	22,693	$26,490,806	11,688	$12,842,835	11,688	12,842,835
V	4,919	$13,377,044	1,735	$4,717,465	2,300	$6,253,700	1,735	$8,657,296	1,735	8,657,296
X	1,963	$867,909	1,963	$867,909	1,963	$867,909	1,963	$867,909	16,152	7,139,184
X-500	1,813	$952,925	1,813	$952,925	1,813	$952,925	1,813	$952,925	1,813	952,925
Shaded X	23	$7,507	23	$7,507	2,642	$861,292	14,212	$4,633,112	23	4,633,112
Total	31,411	$41,696,191	31,411	$36,752,340	31,411	$35,426,632	31,411	$27,954,077	31,411	34,225,352
Percent Decrease				13.45%		17.70%		49.16%		21.83%

Table 7. Changes in NFIP Policy Counts and Total Premiums across Four Scenarios of Flood Zone Changes Using the Regression-Based Approach. Policy Rating Shifts are the Result of a Coastal Spine Causing Decreases in 100-Year Surge Inundation Levels.

	Baseline		Scenario1		Scenario2		Scenario3		Scenario4	
Flood Zone	Policies	Premiums	Policies	Premiums	Policies	Premiums	Policies	Premiums	Policies	Premiums
A	22,692	$17,029,228	25,876	$19,404,765	22,692	$17,029,228	11,688	$9,699,580	11,688	$9,699,580
V	4,919	$8,656,317	1,735	$3,286,515	2,300	$4,349,806	1,735	$3,286,515	1,735	$3,286,515
X	1,963	$765,983	1,963	$765,983	1,963	$765,983	1,963	$765,983	16,151	$8,305,689
X-500	1,813	$770,685	1,813	$770,685	1,813	$770,685	1,813	$770,685	1,813	$770,685
Shaded X	23	$8,316	23	$8,316	2,642	$1,305,775	14,211	$6,617,815	23	$8,316
Total	31,410	$27,230,530	31,410	$24,236,264	31,410	$24,221,478	31,410	$21,140,577	31,410	$22,070,785
Percent Decrease				12.35%		12.42%		28.81%		23.38%

Discussion

Using the 100-year storm surge event as a marker for flood insurance exposure reveals significant benefits to a coastal barrier system. Currently, policyholders that would be affected by a coastal spine spend over $40 million dollars on flood insurance annually. Results of our initial spatial analysis show that over 31,000 NFIP policy holders would experience a reduction in storm surge from a coastal spine, a number that has likely increased following Hurricane Harvey with its renewed sense of flood risk driving flood insurance policy purchases. Based on their proximity to the coast, V-zone policies show the largest decrease in inundation, yet over 22,000 A-zone polices also have reduced storm surge levels. All told, our analysis indicates that $8 billion dollars of NFIP insurance coverage would have reduced surge risk with a coastal spine.

Additional scenario-based analysis extended the specificity of these estimates and provided probable ranges of flood insurance reductions. Based on our analysis, even the most conservative estimates provide substantial insurance savings to coastal residents on annual basis. Scenarios 1 and 2, which only affect high-risk flood zones with wave action, still decrease annual insurance costs by 12-17%, a consistent figure across both estimation approaches. Scenarios 3 and 4, which provide the same level of protection for high-risk flood zones with wave action, but also extend to more traditional flood zones, showed higher reductions, realistically ranging from 21-28% per year.

The probability of each of these scenarios coming to fruition should a coastal spine be constructed is difficult to judge. Scenarios 1 and 2 are likely the most feasible, as they do not affect any existing high-risk flood zones, but remove the threat of wave action. Scenarios 3 and 4 are not unrealistic, but they are naïve with respect to riverine and pluvial flooding that may still occur in A-zones. Given the proximity of the A-zones analyzed to coastal waters, storm surge threats are likely the most probable cause of flooding, but other freshwater sources may still be present. On the whole, the most likely scenario is a mix of the four provided in our analysis.

One important aspect that needs to be considered is that each of the four scenarios will still allow residents to retain flood insurance at the same coverage level. In fact, our analysis assumes that each current policy holder renews their policies, with some benefitting from lower annual premiums as a result of decreased storm surge. Although the purchase flood insurance is one important characteristic of flood mitigation and resilience, there will undoubtedly be a decrease in flood insurance take-up rates should high-risk 100-year flood zones get re-zoned to moderate and lower risk flood zones. In this case, the mandatory flood insurance purchase requirements for residents in A- and V-zones with federally-backed mortgages would no longer apply, some proportion of policies would lapse, and the flood insurance premium savings would be 100%.

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Appendix: Regression model predicting flood insurance premiums

					95% Confidence Interval	
	Coef.	Std. Err.	t	*p*>t	Lower	Upper
Replacement Value	0.2200	0.0078	28.22	0.0000	0.2048	0.2353
Coverage	0.4514	0.0075	60.10	0.0000	0.4367	0.4662
A-Zone	0.1152	0.0192	6.01	0.0000	0.0776	0.1528
V-Zone	0.6696	0.0235	28.53	0.0000	0.6236	0.7156
X500-Zone	-0.1967	0.0262	-7.51	0.0000	-0.2480	-0.1454
Shaded X-Zone	-0.5135	0.1449	-3.54	0.0000	-0.7975	-0.2296
Post-FIRM	-0.4606	0.0090	-51.05	0.0000	-0.4783	-0.4429
Elevated Building	-0.0954	0.0108	-8.87	0.0000	-0.1164	-0.0743
Height above Drainage	-0.1305	0.0043	-30.22	0.0000	-0.1390	-0.1220
CRS Discount						
5	0.9741	0.0253	38.51	0.0000	0.9245	1.0237
10	0.3883	0.0235	16.54	0.0000	0.3423	0.4343
15	0.2968	0.0203	14.65	0.0000	0.2571	0.3366
20	0.1669	0.0332	5.02	0.0000	0.1018	0.2321
25	-0.0238	0.0457	-0.52	0.6030	-0.1134	0.0658
Constant	0.0492	0.6769	0.07	0.9420	-1.2776	1.3760
n=31,410						Adj. R^2 =0.491

Coefficients for community fixed effects not shown.

Chapter 3. Public Perceptions of Coastal Protection in Texas

Chapter 3: Public Perceptions of Coastal Protection in Texas: Findings from a Survey of Harris, Galveston, & Chambers Counties

Ashley Ross

Contributors: Sandra Lee and Ted Driscoll

Executive Summary

In recent years, scientists, policymakers, and elected officials have been calling for a comprehensive coastal storm surge protection system for the Galveston Bay region. However, the public's perception of this mitigation strategy has not been assessed. This chapter summarizes the findings of the first survey to systematically evaluate public perceptions in Chambers, Galveston, and Harris Counties of the coastal spine. A total of 2,300 phone and online surveys were completed. The construction of the survey sampling frame and estimates of the survey weight ensure, within a reasonable amount of statistical uncertainty, that the results are representative of the larger tri-county population.

The key findings of the survey include:

- ***Widespread public support for structural and non-structural mitigation to address the risk Texas coastal communities face from natural hazards.*** Multiple mitigation strategies were evaluated, ranging from levees and elevation to land use regulations, and all of them were supported by over 70% of the respondents in each county.
- ***Overwhelming public support for the coastal spine or Ike Dike.*** Approximately 73% of the respondents surveyed said they support the construction of the coastal spine.
- ***Public preference for shared responsibility for financing the coastal spine.*** The majority of respondents – 55% - believed that both government and port industries should be responsible for financing the coastal barrier system. Two-thirds of respondents also supported some type of public tax, including sales and hotel tax, to raise revenue to construct the coastal spine.
- ***A coastal spine will reduce risk to homes and provide job security for some.*** Over 50% of Chambers and Galveston County respondents said they feel their home would be at less at risk if the coastal spine were constructed; 47% of Harris County respondents said the same. Additionally, about 40% of Chambers and Galveston County respondents said their job would be more secure; 33% of Harris County respondents said the same.
- ***Environmental concerns related to the Ike Dike remain.*** Over 65% of Chambers County respondents expressed concern about the consequences of the Ike Dike on the environment. About 58% of Galveston County and 50% of Harris County respondents are equally concerned.

Introduction

On September 13, 2008, Hurricane Ike made landfall on Galveston, Texas. The storm caused 74 deaths and placed overwhelming strains on communities, public services, and households (FEMA, 2008). Property damages associated with the storm are estimated at $30 billion, making Ike the 6th costliest U.S. tropical cyclone on record (NOAA, 2018). The broader economic impact of Ike, in the eight county region of Texas most affected by the storm, is estimated to be $142 billion in losses (TEEX, 2009).

The severe destruction caused by Hurricane Harvey in 2017 is a reminder that coastal communities in Texas remain at risk. Harvey was largely a rainfall event, but it is a stark reminder that storm surge could devastate communities and cripple the state and national economies. More than 500,000 Texas homes are at risk of storm surge damage in the event of a Category 5 hurricane (CoreLogic, 2018). Approximately 25% of the nation's petroleum and more than half of its jet fuel is processed by refineries around the Galveston Bay (Scranton, 2016), and an environmental disaster in the form of millions of gallons of spilled oil and chemicals is possible (Graham, 2017).

The risk coastal Texas faces, however, can be mitigated. The proposed coastal barrier system would protect coastal communities and restore essential ecosystem functioning to reduce risk. *What do Texans think of these plans? What are their policy preferences and attitudes?* This chapter summarizes the methodology and findings of a survey, conducted May through July 2017, of residents in the three county area most invested in the coastal barrier system: Chambers, Galveston, and Harris Counties.

Survey Sample and Methods

To assess the public's perceptions of coastal protection and mitigation strategies, a survey was designed by the Center for Texas Beaches and Shores researchers and administered by the Public Policy Research Institute at Texas A&M University.[1] The survey was administered by phone May 11 through July 16, 2018 and online August 24 through September 27, 2018 to residents in Chambers, Galveston, and Harris Counties. This area was chosen as it is the region most affected by the proposed coastal spine (see Figure 1). According to the U.S. Census Bureau, 4.76 million people live in these three counties.

[1] See Appendix A for the survey questions presented in this chapter. Additional questions were included in the survey. For the full questionnaire, contact the principal investigator.

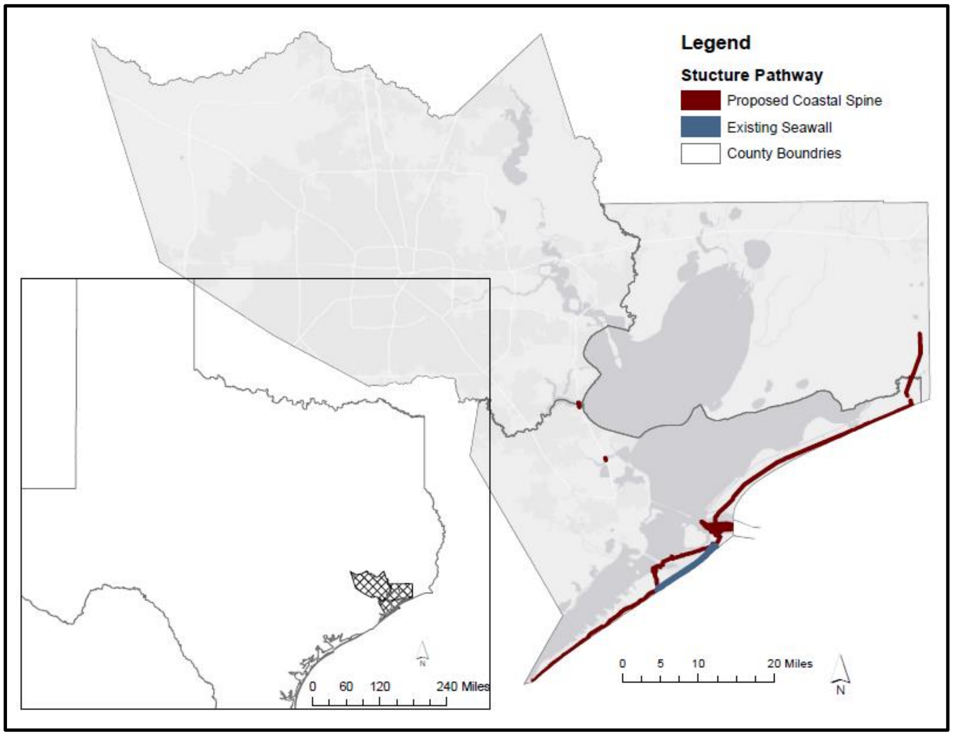

Figure 1. Map of the Tri-County Sample Area.
Source: Authors.

A total of 2,300 surveys were completed, including 805 phone interviews and 1,495 online surveys.[2] The phone interviews included 142 responses from Chambers County, 251 from Galveston County, and 412 from Harris County. A total of 90.7% of the respondents (N=730) took the survey via cell phone while 9.3% (N=75) took the survey on a landline phone. Of the 805 interviews completed, 32 were conducted in Spanish. Due to availability of respondents, the online survey was conducted only in Harris and Galveston Counties. A total of 365 online surveys were completed by Galveston County residents, and 1,130 surveys were completed by Harris County residents.

Methodology

The phone survey sample was probabilistic, using random digital dialing, and the online survey sample was quota-based, drawn from a panel of respondents provided by Qualtrics.[3] The phone survey sample was selected using dual frame sampling, which includes landline random digital dialing telephone and cell phone samples. According to the most recent estimates available from the National Health Interview Survey, 52% of adults are now wireless only (2017), meaning that they do not have a landline phone. An additional 15% of the population is wireless-mostly, meaning they accept most or all of their calls on their

[2] The number of observations for the analyses presented in this chapter may be less then 2,300 due to missing data for specific survey items.

[3] Qualtrics partners with numerous providers that have proprietary panels across the nation, incorporating participants from online communities, social networks, and websites of all types. Participants are offered a variety of incentives to increase the diversity of sample frames, including but not limited to cash, points, and donations to charity. Participants go through rigorous quality controls before being included in any sample.

cell phones. This sampling strategy takes into account these broader technological shifts and assures a representative sample of the local population.

The phone survey response and cooperation rates, calculated using Formula 4 from American Association of Public Opinion research, were 5.3% and 22.8%, respectively. The response rate of the survey was 5.3%, meaning 5.3% of all calls to eligible respondents resulted in a completed survey. The cooperation rate was 22.8%, meaning that 22.8% of the calls made actually made contact with an eligible respondent and resulted in a completed interview. Low response rates on cell phone samples are largely expected as it is increasing difficult to contact potential respondents. The cooperation rate is in the range of what might be expected on this type of survey.

The online survey sample matched available Qualtrics panel participants with U.S. Census Bureau data for age, race/ethnicity, and education.[4] Quota-based surveys are increasingly being used to reach participants online. While participation is improved, the reliance on quota sampling, rather than random sampling, means it is not possible to calculate margins of error for the data that provide a measure of precision. However, nonprobability, quota-based surveys offer valid measurements if sample selection and weighting make adjustments that create a representative sample (Kennedy et al., 2016). Steps have been taken in this study, pre and post survey administration, to adjust the online sample to make it representative of the population of Harris and Galveston Counties.

The phone survey data were weighted to approximate the most recently available population estimates from the U.S. Census Bureau. For these data, estimates from the 2016 American Community Survey for the adult population (18 years and over) in Harris, Galveston, and Chambers Counties were used. The sample weight is calculated by taking the inverse of the probability that an individual respondent would have been selected in the final sample. This weight is based on the population of the county divided by observed sample within the county. In addition, the weight is "raked" iteratively to adjust sample estimates to population estimates on education, race, and age. The phone survey weight results are provided in Appendix B.

Additionally, a weight to apply to the merged phone and online survey data was created using accepted techniques for combining probability and nonprobability samples (Mercer et al., 2017). First, the probability (phone) and non-probability (online) samples were merged into the same data file. Second, a logistic regression predicting membership in the non-probability sample was conducted. Third, the inverse of the probability was used to create initial weights for the non-probability sample. Fourth, the data was weighted, or "raked," to match population estimates for each county.

The combined weight results are provided in Appendix C. All analyses of these data, as presented in this chapter, include the combined weight so that the sample statistics are generalizable and representative of the tri-county area surveyed.

[4] Data included estimates from the 2016 American Community Survey for the adult population (18 and over) in Harris and Galveston Counties.

Disaster Experience Across Survey Sample

The coastal communities selected for this study have experienced multiple natural disasters in the past decade. Survey respondents were asked to indicate if they experienced negative impacts to their property, finances, and health due to Hurricane Ike. Respondents were also asked to indicate damages suffered from Hurricane Harvey to personal property. As shown in Figure 2, the majority of the survey sample responded that they had experienced damages from either or both Hurricanes Ike and Harvey.

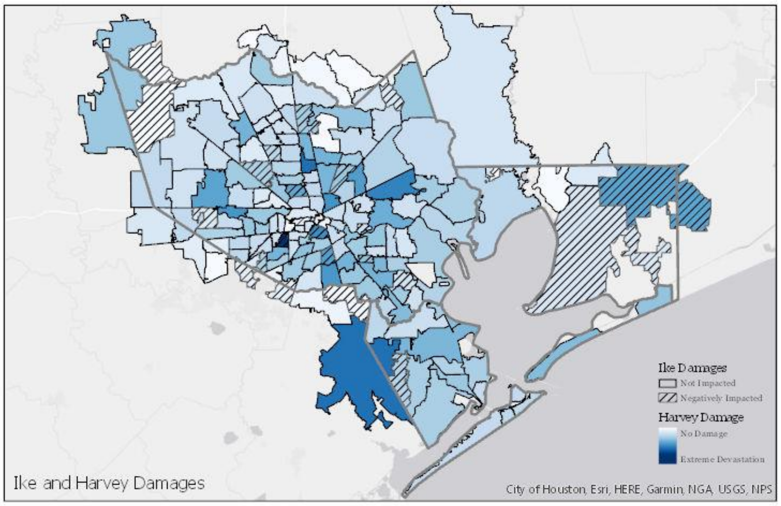

Figure 2. Map of Hurricanes Ike & Harvey Damages across Sample Area.
Source: Authors.

Coastal Mitigation in Texas

Coastal communities face multiple natural hazards that put people and property at risk. Hurricane force winds, storm surge, and flooding present sudden onset hazards. Coastal flooding, in particular, is the most costly, disruptive, and life-threatening hazard, whose negative impacts are only increasing. A recent study estimates that more than 500,000 Texas homes are at risk of storm surge damage in the event of a Category 5 hurricane (CoreLogic, 2018). Sea level rise and beach erosion, particularly of the upper Texas Coast in the area of Galveston Bay and Galveston Island, also threaten commercial and residential areas as they alter the ecosystem services provided by the environment and pose flooding threats (Yoskowitz et al., 2017; Ravens and Khairil, 2007).

To mitigate the risk coastal communities in Texas face, both structural and non-structural strategies have been pursued. Structural mitigation can be found across the tri-county area in the form of jetties, groins, and levees. The most recognizable is the seawall constructed in Galveston Island after the 1900 Hurricane that protects approximately nine miles of the east end of the island (Hansen, 2007). Non-structural mitigation features environmental alterations or policies that reduce risk. These include dune and beach restoration projects across Galveston and Bolivar Peninsula as well as marsh restorations around the Galveston Bay. This also entails policies to regulate land use.

As shown in Figure 3, the survey assessed public support for a range of protective features and strategies intended to reduce natural hazard risk to coastal communities. These represent both structural and nonstructural strategies, including some of the features being studied by the U.S. Army Corps of Engineers, in partnership with the Texas General Land Office, as part of a comprehensive plan to protect and sustain the coast.[5] Of the eight strategies assessed, the most support was observed for property elevation (85.44%), elevated infrastructure (81.70%), seawalls and levees (81.16%), and conservation of wetlands (80.50%). Another 77.23% expressed support for rehabilitation of sand dunes.[6] Nearly 30% of respondents opposed zoning ordinances, and 28.62% did not support home buy-outs.[7] An additional 24.5% also opposed the use of retention basins.

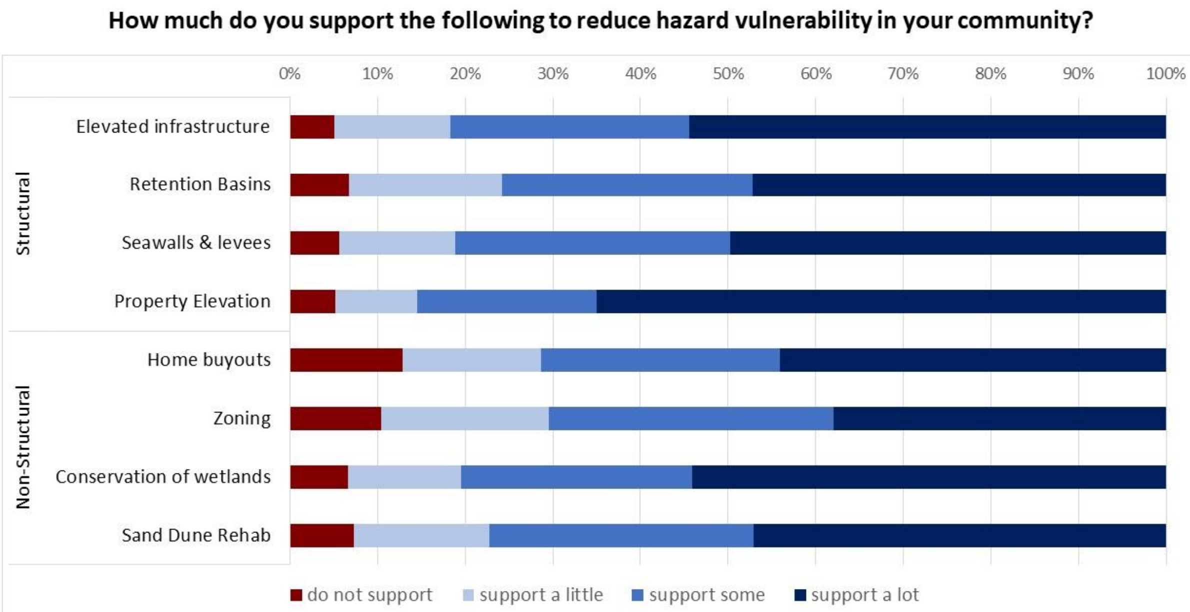

Figure 3. Public Support For Structural and Non-Structural Mitigation Strategies.
Source: Authors.

Support for mitigation strategies varied among the three counties sampled, as shown in Table 1. The environmental strategies, including sand dune rehabilitation and conservation of wetlands, were most supported in Chambers and Galveston Counties with about 8-in-10 respondents saying they "support some" or "support a lot" these measures. Slightly less – about 7-in-10 – respondents from Harris County support sand dune rehabilitation. There was also variance in seawall support with nearly 85% of Galveston County respondents supporting this protective strategy, compared to 81% of Chambers and Harris County respondents.

[5] See: "Coastal Texas Study," The Texas General Land Office, http://coastalstudy.texas.gov/index.html.
[6] These figures are the sum of responses that indicated "support some" or "support a lot".
[7] These figures are the sum of responses that indicated only "support a little" or "do not support".

Table 1. Variation in Support for Mitigation Strategies across Counties Sampled.

		Chambers Co.	Galveston Co.	Harris Co.	*Range*
Structural	Property Elevation	74.87%	85.33%	85.54%	*10.67%*
	Seawalls & levees	81.06%	84.97%	81.16%	*3.91%*
	Elevated infrastructure	83.72%	83.09%	81.59%	*2.13%*
	Retention basins	64.51%	75.15%	75.99%	*11.48%*
Non-structural	Sand dune rehab	88.93%	84.93%	76.57%	*12.36%*
	Conservation of wetlands	86.11%	83.53%	80.24%	*5.87%*
	Zoning ordinances	71.80%	71.15%	70.44%	*1.36%*
	Home buyouts	74.35%	71.33%	71.36%	*3.02%*

Note: Percentage of respondents that answers "support some" and "support a lot" is reported for each county sampled; the values for "range" represent the difference between the highest and lowest support. Source: Authors.

It is notable that the majority – over 70% of respondents – in Chambers, Galveston, and Harris Counties supported all of the strategies posed. This demonstrates widespread buy-in to take initiatives, across the public and private sectors, aimed at protecting communities and restoring coastal ecosystems.

Support for the Coastal Spine

Since the "Ike Dike" was proposed, it has drawn both support and criticism from experts, elected representatives, policymakers, and the general public. No polls, to our knowledge, have systematically assessed public awareness or support for the coastal barrier system. The survey asked respondents questions to evaluate both awareness and support.

Survey respondents were asked: "Before today, have you heard of the Texas coastal spine or Ike Dike?" Overall, 71.82% replied "no", 22.78% said "yes", and 5.4% replied "don't know". Lack of awareness was highest in Chambers County with 74.17% saying they had not heard of the Ike Dike. Knowledge of the coastal spine was highest among Galveston County respondents with 35.25% saying they have heard of the coastal spine. In Harris County, only 21.84% of respondents said they were aware of the Ike Dike. Given this widespread lack of awareness, all respondents were read the following description of the coastal spine:

> *Texas leaders are considering the construction of a coastal spine. Also known as the "Ike Dike," the coastal spine would connect a series of sea walls and sand dune barriers along Galveston Island's coastline to a retractable gate located on Galveston Bay. Geographically, Galveston Bay connects the Houston-Galveston area to the Gulf of Mexico. In the event of a major hurricane, the coastal spine will protect the Houston-Galveston region from a potentially devastating storm surge.*

Following the description of the Ike Dike, support for it was assessed by the question: "How much do you support or oppose the construction of a coastal spine in Texas?" As shown in Figure 4, the overwhelming majority expressed support for the Ike Dike. Respondents from Galveston and Harris County were most supportive with 73.52% and 73.05%, respectively, saying they "somewhat support",

"support", or "strongly support" the coastal barrier system. In comparison, 69.17% of respondents support the Ike Dike in Chambers County.

Chambers County residents demonstrated the biggest divides on the issue. Respondents in Chambers County expressed the strongest support and strongest opposition: 11.63% of Chambers County respondents were "strongly opposed" to the Ike Dike while 38.44% were "strongly supportive". Only 3.60% and 5.96% of Harris and Galveston County respondents, respectively, were "strongly opposed". Notably, Harris County respondents were the most ambivalent about the issue: 17.61% said they "neither oppose or support" the construction of the coastal spine. Only 12.96% and 13.4% of Galveston and Chambers County respondents, respectively, said the same.

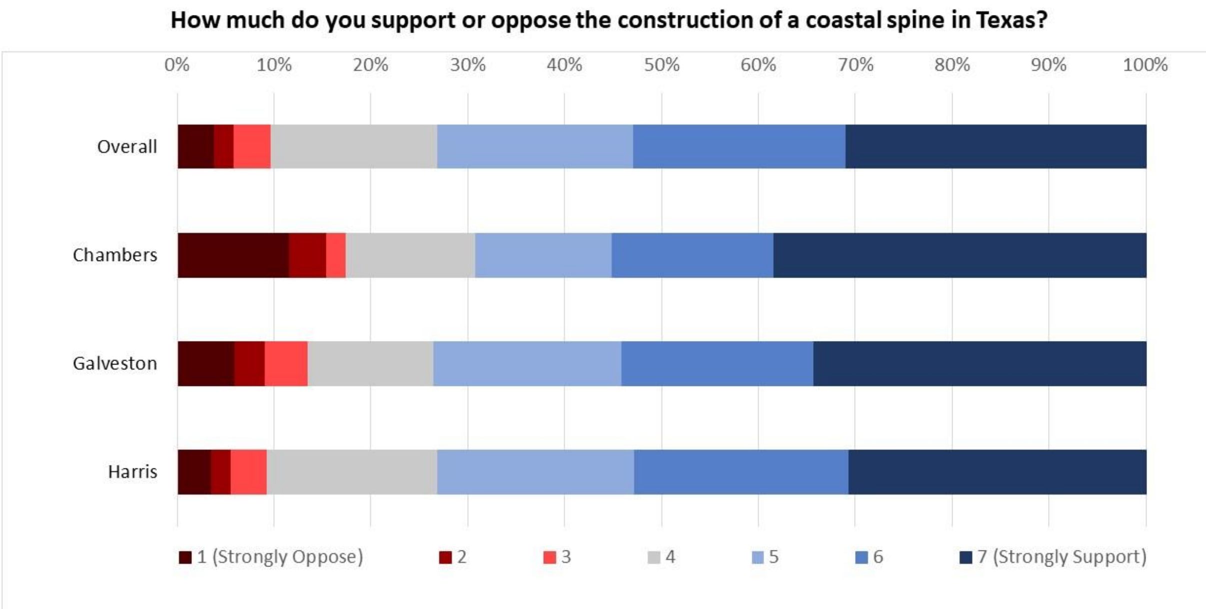

Figure 4. Public support of the coastal spine or "Ike Dike".
Source: Authors.

Support for Specific Features of the Coastal Spine

In addition to generalized support for the Ike Dike, specific features that have been proposed to comprise a larger coastal barrier system were also evaluated among a subset of the phone survey respondents (n=400). These features included the extension of the seawall, proposed to expand the current wall east along Bolivar Peninsula and west to the San Luis Pass. Also evaluated was support for a large retractable gate at Galveston Bay, a small navigation gate at Clear Lake, and a ring levee to surround the East End of Galveston Island. Support for raised coastal highways and sand dunes, proposed along Galveston Island and Bolivar Peninsula, was also assessed.

Support for specific coastal barrier system features is reported in Figure 5. Raised coastal highways and sand dunes garnered "a lot" of support from 50.79% and 43.27% of respondents, respectively. Over 35% of respondents expressed "a lot" of support for the large retractable gate at Galveston Bay (35.06%) and the small navigation gate at Clear Lake (37.32%). Less than one-in-three respondents said they support "a lot" the ring levee around Galveston Island (29.70%) or extending the Galveston seawall from High Island to San Luis Pass (27.00%). Notably, a sizable proportion of respondents said they "don't know" about the ring levee (30.35%) and seawall extension (40.34%), indicating lack of awareness of these strategies.

Opposition was most prevalent for the gates: 12.45% and 12.49% of respondents said they "do not support" the large retractable gate at Galveston Bay and the navigation gate at Clearlake. Chambers County respondents were particularly opposed – 26.21% of Chambers County respondents, compared to 13.09% of Galveston County respondents and 12.02% of Harris County respondents, said they "do not support" the large retractable gate at Galveston Bay. Respondents from Galveston County were the most opposed to the navigation gate at Clearlake with 14.82% saying they "do not support" the strategy.

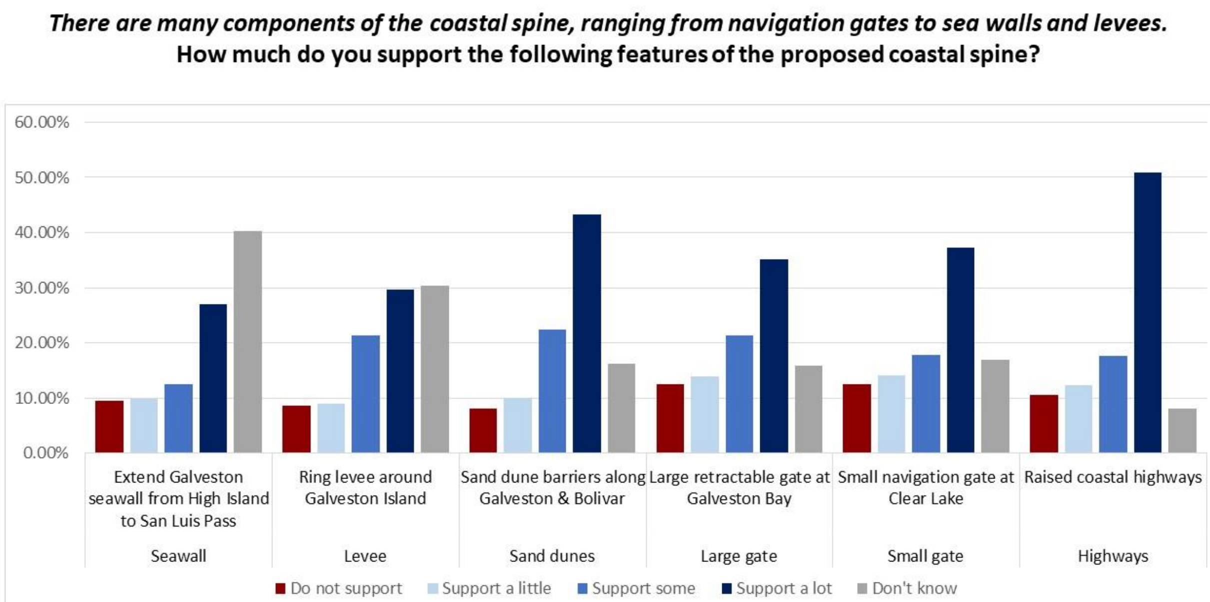

Figure 5. Public Support for Features of the Coastal Barrier System.
Source: Authors.

In sum, survey responses indicate widespread support, but also lack of awareness of, the Ike Dike. Specific features of the coastal barrier system did not garner as much support, suggesting that there may be knowledge gaps, perceived competing interests (i.e., gate at Galveston Bay versus Clear Lake), and divisions among subgroups of the community that oppose and support specific features. The map shown in Figure 6 demonstrates that support for the coastal spine, while generally high, is variant across the counties surveyed. More research is needed to assess this variance.

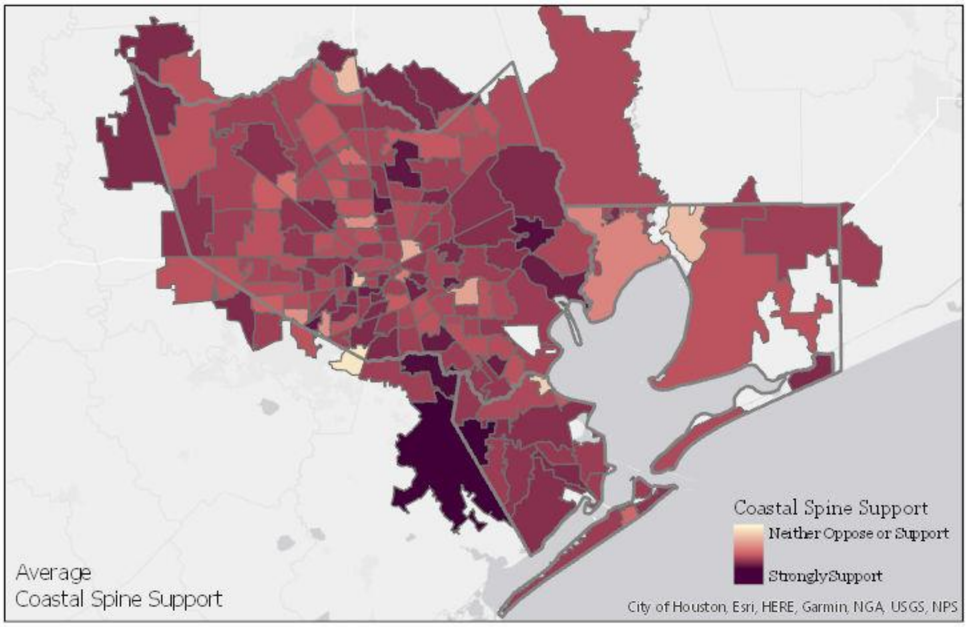

Figure 6. Map of Average Coastal Spine Support across Zip Codes in Sample Area.
Source: Authors.

Risk Perceptions Linked to Support for Coastal Spine

A preliminary analysis was conducted to explore the connection between support for the construction of a coastal spine and natural hazard risk perceptions. A number of research studies have found that risk perception is a major predictor of adoption of various types of hazard adjustments.[8] Risk perception, defined as "people's expectations about the probability of the occurrence of an extreme environmental event of a specific intensity at a particular place within a given period of time" (Lindell, 2013), indicates perceived danger of personal consequences due to natural hazards.

Consistent with past research (Brody et al., 2017), the survey measured risk as perceived personal damages from a severe flood in the next ten years. A risk perception factor score was created from a set of five survey questions that asked respondents to indicate the likelihood a flood in the next ten years will cause: 1) major damage to property in your city; 2) deaths and injuries to people in your community; 3) major damage to your home; 4) disruption to your job that prevents you from working; and 5) disruption of electrical, telephone, and other basic services.[9] As shown in Figure 7, risk perceptions (averaged by zip code) varied considerably across the Chambers, Galveston, and Harris Counties.

[9] The Cronbach's alpha for the factor score is 0.796, indicating an acceptable level of internal consistency.

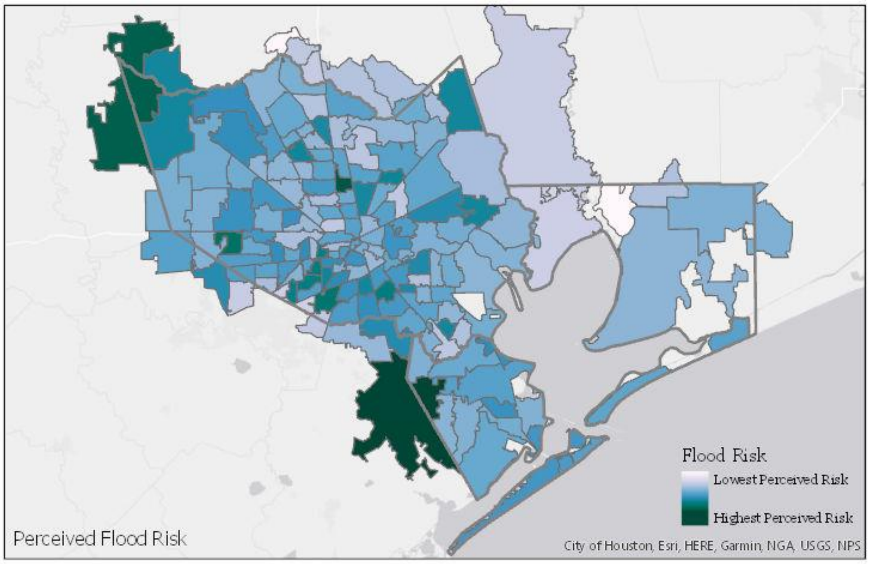

Figure 7. Map of Average Risk Perception across Zip Codes in Sample Area.
Source: Authors.

A bivariate ordered logistic regression was estimated to assess the effect of risk perceptions on support for construction of the coastal spine.[10] Risk perception was a significant predictor of support (p=0.000). Based on the regression estimates, the predicted probability of support and opposition is shown in Figure 8 (predicted probabilities are shown as dots and 95% confidence intervals as bars). The predicted probabilities indicate that an individual with the lowest perceived risk has a 12.58% likelihood of expressing strong support for the Ike Dike; in contrast, an individual with the highest perceived risk has a 44.37% of the same. The results show that as flood risk perceptions increase, strong support for construction of the coastal spine increases.

[10] The results of the bivariate ordered logistic regression were as follows: total number of observations = 2,145; coefficient for risk perception variable = 0.407; and standard error for risk perception variable = 0.055.

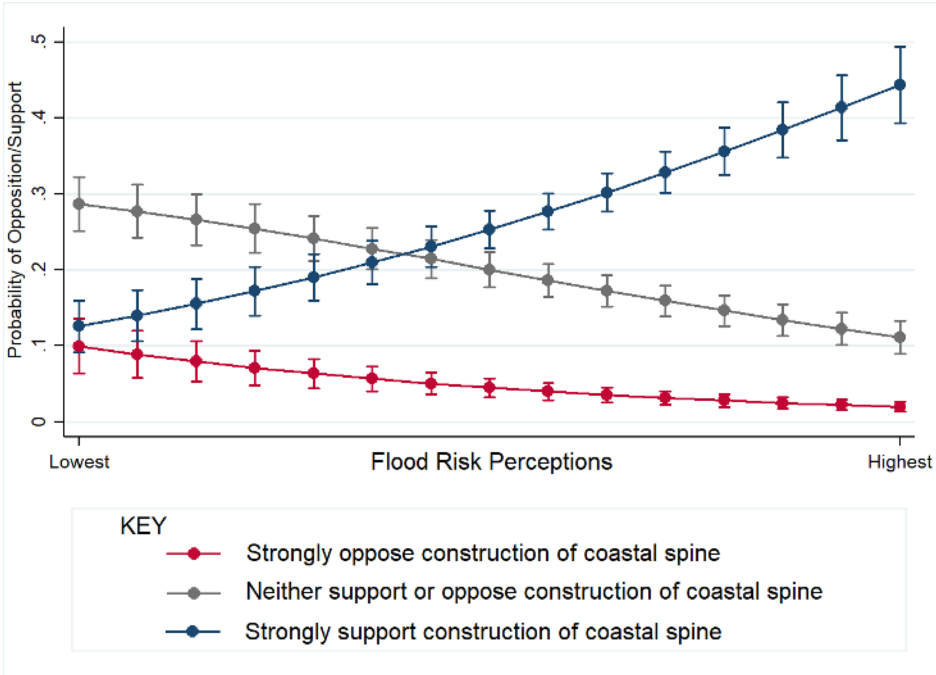

Figure 8. Predicted Probability of Support of Coastal Spine across Risk Perception Values.
Source: Authors.

This preliminary analysis demonstrates that flood risk perceptions are driver of support for the construction of the coastal spine. It is limited, however, in that it does not measure other risk perceptions relevant to coastal communities (i.e., storm surge) or control for the various factors that may influence opinions on the issue. Future research should more comprehensively analyze the individual correlates of support for the Ike Dike, including disaster experience, political ideology, homeownership, distance to the coast, and socioeconomic status.

Perceptions of Financng the Coastal Spine

Financing large scale infrastructure projects requires public buy-in. To assess the perceptions residents of Chambers, Galveston, and Harris Counties hold about financing the proposed coastal spine, respondents were asked if government on various levels or industry should be responsible for paying for the coastal spine. As shown in Figure 9, 55.48% of respondents expressed that both government and port industries should finance the proposed structure, while 19.42% and 17.68% held federal and state government, respectively, responsible. Responses across the three counties sample demonstrated little variance, with the exception that more respondents in Chambers and Galveston Counties indicated government and industry should be jointly responsible: 64.33% and 62.08%, respectively, said both parties should finance the construction of the coastal spine.

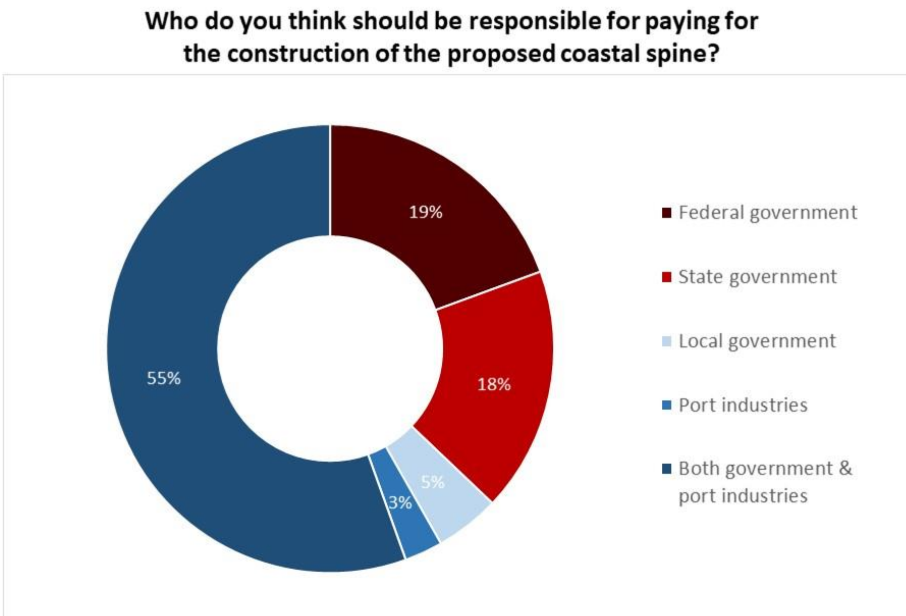

Figure 9. Public Perceptions of Financing the Coastal Spine.
Source: Authors.

Since taxes are often used to pay for public infrastructure projects like the coastal spine, respondents were asked to express preference for taxes to raise revenue for the construction of the coastal spine. Specifically, respondents were asked what type of tax they would support. Response options included: “property taxes”, “sales tax”, “hotel tax”, “a new tax for this purpose”, “a mix of these”, and “I don't support any taxes for this purpose”. Responses are shown in Table 2.

Table 2. Public Support for Taxes to Finance the Coastal Spine.

	Chambers Co.	Galveston Co.	Harris Co.	*Overall*
Property Tax	6.55%	4.74%	9.36%	9.03%
Sales Tax	9.08%	7.77%	9.67%	9.54%
Hotel Tax	6.34%	8.71%	7.44%	7.52%
A New Tax	12.35%	9.03%	8.90%	8.93%
A Mix Of These	34.36%	35.44%	31.58%	31.86%
No Taxes	31.31%	34.30%	33.05%	33.12%

Note: The survey asked respondents – “What type of tax would you support to raise revenue for the construction of the coastal spine?”

A third of respondents indicated they do not support taxes to raise revenue for the coastal spine. Nearly an additional third expressed that they support a mix of property, sales, hotel, and/or new tax to support the coastal spine. Preferences for property, sales, and hotel taxes to raise revenue for the coastal spine were mixed across the three counties. Sales tax was most preferred by Harris County respondents (9.67%) while hotel tax was preferred the most by Galveston County respondents (8.71%). Property taxes were supported by 9.36% of Harris County respondents; only 4.74% and 6.55% of Galveston and Chambers County respondents, respectively, supported property taxes to finance the coastal spine.

Perception of Consequences of the Coastal Spine

The primary reason for building the coastal spine is to protect the three counties that lie behind it from a storm surge event. Over 575,000 people live in low-lying areas adjacent to Galveston Bay (U.S. Census Bureau, 2017). The Bay area has a robust economy based on aerospace, petrochemical, and maritime industries. It is home to the largest petrochemical complex in the U.S. and the second largest in the world. The refineries along the coast are responsible for approximately half of the nation’s petrochemical manufacturing and approximately one-third of the nation’s petroleum refining and processing capacity. This sector employs over 15,000 people and contributes approximately $6 billion to the local economy through taxes, payrolls, purchases and capital expenditures. In addition, there are three thriving ports in the Bay Area: the Port of Houston, the Port of Texas City, and the Port of Galveston. These ports contribute a total of $277.6 billion in economic activity to the state of Texas, and ship channel-related businesses generate over one million jobs throughout Texas. The region also has the nation’s third largest marina, comprised of over 7,000 recreational boat slips, and there is a robust fishing and shellfish industry in the area.

The survey assessed public perceptions of the benefits of the coastal spine. Specifically, respondents were asked if building the coastal spine would make them feel that their home is at less risk to disaster impacts and that their job is more secure. Figure 10 displays the responses by county. The majority of Galveston (56.10%) and Chambers (52.78%) County respondents believed their home is at less risk; 46.63% of Harris County respondents said the same. Fewer respondents felt that their job is more secure as result of the coastal spine. Nearly 45% of Chambers County respondents said they feel their job is more secure, compared to 39.10% and 32.94% of Galveston and Harris County respondents, respectively.

In addition, the survey evaluated perceptions of failure of the coastal spine. Specifically the survey asked: “How concerned are you that a physical structure like the coastal spine has the potential to fail, meaning it might not work in a disaster or may break down?” Concern was highest among Chambers County respondents – 65.65% said they were “concerned a lot” or “somewhat concerned.” Only 58.55% and 59.33% of Galveston and Harris County respondents, respectively, expressed the same.

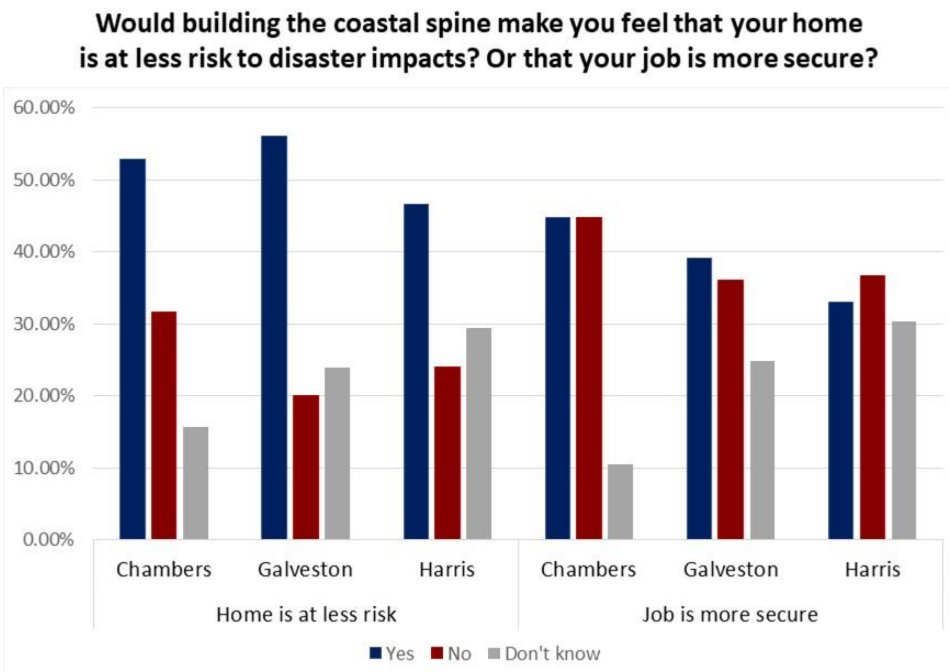

Figure 10. Public Perceptions of the Benefits of the Coastal Spine.
Source: Authors.

Concern for the negative environmental consequences of the coastal spine were also assessed. Several environmental groups in the area have raised concerns that the construction of the coastal spine and operation of its gate structures will have unintended environmental consequences.[11] These include changes in water flow, salinity, sediment transport, and restricted movement for larval and adult wildlife species. In line with the issues raised by environmental groups, the survey asked respondents: "How concerned are you that the construction of the coastal spine may damage the surrounding marine and coastal environment?" Overall, 50.59% of respondents said they were "concerned a lot" or "somewhat concerned" about the impacts of the coastal spine on the marine and coastal environment. The highest levels of concern were observed among Chambers and Galveston County respondents – 65.64% and 58.07%, respectively, compared to 49.91% of Harris County respondents.

Galveston County residents have expressed concern about the coastal barrier system that extends beyond environmental threats. The research team attended two public forums to assess the scope of citizen concerns in the county focused on the Ike Dike. Four major issues emerged in these community forums: 1) uncertainty regarding financing to support long-term maintenance of the structure; 2) the footprint of the extended seawall would cover many businesses and large parts of the channel; 3) uncertainty regarding communities on the outer edge of the storm barrier; and 4) construction of the coastal spine on Bolivar Peninsula will create accessibility issues for some neighborhoods.

[11] See, for example: The Galveston Bay Foundation. "Issues Facing the Bay." https://galvbay.org/about/about-the-bay/issues-facing-the-bay/

The survey results indicate that respondents in the tri-county area are both cognizant of the benefits of the coastal barrier system as well as unintended consequences on the natural system. The public forums showed that residents are also concerned about the implementation of the infrastructure project and how it may disrupt social and economic activities, particularly on Galveston Island and Bolivar Peninsula.

Conclusion

This chapter summarizes the findings of the first survey to systematically evaluate public perceptions in Chambers, Galveston, and Harris Counties of the coastal spine. The survey reveals that there is widespread lack of awareness of the coastal spine – approximately 72% of respondents have not heard of the Ike Dike before the survey. Yet, when survey respondents were read the description of the coastal spine, their responses were overwhelmingly positive. The results point to widespread support not only for general coastal mitigation strategies but specifically for a coastal barrier system. Approximately 73% of the respondents supported, to some degree, the construction of the coastal spine.

Despite widespread support for coastal protection, the survey reveals that there are challenges in the implementation of the coastal barrier system. First, such a regional project must balance varying community interests and concerns. The survey results indicate the highest levels of support for the Ike Dike was found among Galveston and Harris County respondents while Chambers County respondents were more divided in opposition and support. About 17% of Chambers County respondents expressed opposition to the coastal spine, compared to approximately 14% and 9% of Galveston and Harris County respondents, respectively. This underscores the variance of community interests and concerns as well as individual experiences, values, and perceptions. Preliminary analysis presented in this chapter demonstrated flood risk perceptions are connected to support for the coastal spine with higher risk linked to greater support. Future research should further unpack the drivers of support, likely based on proximity to the coast as well as other socioeconomic factors.

Second, financing the coastal barrier system will require public and private buy-in. The majority of respondents – 56% – believed that both government and port industries should be responsible for financing the coastal barrier system. Approximately two-thirds of respondents supported some type of tax (i.e., sales, hotel, property, new) to support the coastal spine. Although, support for tax type varied across county with Galveston County expressing the highest preference, among the three counties, for hotel tax while Harris and Chambers Counties were more supportive of sales taxes.

Third, the environmental consequences of the coastal spine remain a concern among coastal community residents. While over 50% of Chambers and Galveston County respondents said they feel their home would be at less risk as a result of the coastal spine, over 50% of respondents also expressed concern about the unintended consequences of the Ike Dike on the environment. Addressing these concerns, alongside the widespread lack of awareness among the public about the coastal spine, could increase community engagement in meaningful ways that not only reduce the risk faced by coastal communities in Texas but also increase their collective community resilience.

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Appendix A: Survey Questions

Q1 *I'm going to list ways that coastal communities can manage the risk posed by natural hazards. For each one, please tell me - how much do you support it?* Construction of seawalls and levees; rehabilitation of natural sand dunes; conservation of wetlands; elevation of infrastructure, such as roads; creation of retention basins. [Response options: do not support, support a little, support some, support a lot.]

Q2 *How much do you support the following government actions to reduce hazard vulnerability in your community?* Zoning ordinances to guide development; buy-outs of homes flooded multiple times; higher elevation requirements for homes in flood-prone areas. [Response options: do not support, support a little, support some, support a lot.]

Q3 *Before today, have you heard of the Texas coastal spine or Ike Dike?* [Response options: yes, no, I don't know.]

Here is a brief description of it. Texas leaders are considering the construction of a coastal spine. Also known as the "Ike Dike", the coastal spine would connect a series of sea walls and sand dune barriers along Galveston Island's coastline to a retractable gate located on Galveston Bay. Geographically, Galveston Bay connects the Houston-Galveston area to the Gulf of Mexico. In the event of a major hurricane, the coastal spine will protect the Houston-Galveston region from a potentially devastating storm surge.

Q4 *How much do you support or oppose the construction of a coastal spine in Texas?* [Response options: strongly oppose, oppose, somewhat oppose, neither oppose or support, somewhat support, support, strongly support.]

Q5 *Who do you think should be responsible for paying for the construction of the proposed coastal spine?* [Response options: federal government, state government, local government, port industries, both government and industry.]

Q6 *Taxes are often used to pay for public infrastructure projects like the coastal spine. What type of tax would you support to raise revenue for the construction of the coastal spine?* [Response options: property taxes, sales tax, hotel tax, a new tax for this purpose, a mix of these, I don't support any taxes for this purpose.]

Q7 *There are many components of the coastal spine, ranging from navigation gates to sea walls and levees. How much do you support the following features of the proposed coastal spine?* Extended seawall from the east at Bolivar Peninsula/High Island to the west at San Luis Pass; ring levee that surrounds the central part of Galveston Island; sand dune barriers along Galveston Island and Bolivar Peninsula; large, retractable navigation gate at Galveston Bay; small navigation gate at Clear Lake; raised coastal highways. [Response options: do not support, support a little, support some, support a lot, I don't know enough to say.]

Q8 *The proposed coastal spine could create public green spaces around Galveston Bay. These would offer the public ways to access and enjoy the water and surrounding coastal environment. Which of the* *following activities would you take part in if they were available as a result of the coastal spine project?* [Response options: Biking and hiking trails; bird watching; fishing camps; camping spaces; marina.]

Q9 *Now let's discuss the potential effects of the coastal spine. Would building the coastal spine make you feel that your home is at less risk to disaster impacts?* [Response options: yes, no, I don't know enough to say.]

Q10 *Would the construction of the coastal spine make you feel that your job is more secure?* [Response options: yes, no, I don't know enough to say.]

Q11 *How concerned are you that the construction of the coastal spine may damage the surrounding marine and coastal environment?* [Response options: not concerned, a little concerned, somewhat concerned, concerned a lot.]

Q12 *How concerned are you that a physical structure like the coastal spine has the potential to fail, meaning it might not work in a disaster or may break down?* [Response options: not concerned, a little concerned, somewhat concerned, concerned a lot.]

Q13 *How likely do you think it is that in the next 10 years there will be a flood that causes... Major damage to your city? Deaths and injuries to people in your community? Major damage to your home? Disruption to your job that prevents you from working? Disruption of electrical, telephone, and other basic services?* [Response options: not at all, small extent, moderate extent, great extent, very great extent.]

Q14 *Thinking back to 2008, what impact did Hurricane Ike have on your... Home and personal property? Job? Household finances? Physical health? Mental and emotional health?* [Response options: negative, some negative and some positive, positive, no impact, no applicable because I did not live in the area then.]

Q15 *On a scale of 0 (none at all) to 100 (extreme devastation), how much did Hurricane Harvey damage your home and personal property? Slide the indicator to that point.*

Appendix B: Phone Survey Weight

Comparison of Population, Unweighted and Weighted Sample Estimates for Chambers, Galveston, and Harris Counties

	Population Estimate (2016 ACS)	Unweighted Sample Estimate	Weighted Sample Estimate
Age			
18 to 24 years	13.3%	9.9%	13.3%
25 to 34 years	21.9%	15.2%	21.9%
35 to 44 years	19.5%	14.9%	19.5%
45 to 54 years	17.6%	17.4%	17.6%
55-65	14.7%	20.9%	14.7%
65 and older	13.0%	21.7%	13.0%
Race			
White, Non-Hispanic	33.3%	64.4%	33.3%
Hispanic	40.4%	16.8%	40.4%
African American	18.0%	12.8%	18.0%
Other	8.2%	6.1%	8.2%
Education			
High School or Less	43.7%	21.3%	43.7%
Some College	29.2%	33.2%	29.2%
College Degree	27.2%	45.5%	27.2%

Note: Figures may not sum to 100% because of rounding error.

Appendix C: Combined Phone and Online Survey Weight

Comparison of Population, Unweighted and Weighted Sample Estimates for Galveston and Harris Counties

	Unweighted Random Sample Estimate	Weighted Random Sample Estimate	Unweighted Qualtrics Sample	Weighted Qualtrics Sample	Unweighted Combined Sample	Weighted Combined Sample
Age						
18 to 24 years	9.9	13.3	15.0	13.3	13.7	13.3
25 to 34 years	15.2	21.9	29.2	21.9	26.2	21.9
35 to 44 years	14.9	19.5	18.8	19.5	17.8	19.5
45 to 54 years	17.4	17.6	13.7	17.6	14.3	17.6
55-65	20.9	14.7	12.1	14.7	14.3	14.7
65 and older	21.7	13.0	11.2	13.0	13.7	13.0
Race						
White, Non-Hispanic	66.7	33.1	48.3	33.1	52.5	33.1
Hispanic	15.2	40.1	26.2	40.6	23.6	40.1
African American	11.4	18.1	17.5	18.1	16.1	18.1
Other	6.1	8.3	8.0	8.3	7.7	8.3
Education						
High School or Less	21.3	43.7	25.1	43.6	23.4	43.6
Some College	33.2	29.2	37.6	29.1	36.3	29.1
College Degree	45.5	27.2	37.4	27.2	40.3	27.2

Note: Figures may not sum to 100% because of rounding error.

Chapter 4. Surge Models

Chapter 4: Omission of a Western Dike Section in the Likely USACE Tentatively Selected Plan Leads to an Increase in Storm Surge, Inundation, and Flood Risk throughout the Houston-Galveston Region

Bruce Ebersole

Background

The Ike Dike coastal spine concept was first proposed by Dr. William Merrell, Texas A&M Galveston (TAMUG), following Hurricane Ike in 2008. The Ike Dike concept significantly suppresses the hurricane storm surge that can impact the Houston-Galveston region. TAMUG researchers and collaborators have been examining performance of the Ike Dike concept for a number of years. As presently envisioned, the TAMUG Ike Dike concept is comprised of three sections (see Figure 1). A middle section extends from the western end of Galveston Island, across Bolivar Roads pass, to High Island at the northeastern end of Bolivar Peninsula; it includes a large storm surge gate system that spans Bolivar Roads. A western section extends from San Luis Pass to Freeport; it has a smaller storm surge gate system at San Luis Pass. An eastern section extends from High Island north to Winnie; it includes a very small surge gate on the Gulf Intercoastal Waterway.

Figure 1. Current Alignment of the Ike Dike Coastal Spine Concept Proposed by TAMUG and its Research Collaborators.

Source: Authors.

The middle section in Figure 1 is quite similar to the coastal spine that was recommended by the Gulf Coast Community Protection and Recovery District (GCCPRD, 2016). The combination of middle and eastern sections is quite similar to the coastal spine alignment that is included in Alternative A for the Houston-Galveston region, as proposed in the U.S. Army Corps of Engineers (USACE) Galveston District's Coastal Texas Study. Alternative A appears to be the likely USACE Tentatively Selected Plan (TSP). Note, that both the GCCPRD and USACE coastal spine alignments omit the western section shown in Figure 1. Omission of the western section of a coastal spine is the basis for the concerns expressed here.

The Ike Dike coastal spine concept achieves its effectiveness by suppressing entry of the open-coast storm surge into West and Galveston Bays. Once storm surge enters the very shallow bays, hurricane-force winds are extremely effective in pushing water from one side of the bay to the other, leading to even higher surge levels on the down-wind side. The specific areas around the bay's periphery which are impacted by the enhanced surge can change rapidly as a hurricane transits the region. The middle section of the coastal spine concept (see Figure 1) significantly reduces storm surge entry into the bays; the eastern section to a far lesser degree. Omission of a western section is akin to leaving a "back door" open; it significantly compromises the performance and effectiveness of the Ike Dike concept by allowing a substantial amount of water to flow into the bays prior to hurricane landfall.

Omission of the western section increases flood risk to most, if not all, areas of the Houston-Galveston region that are fronted by the coastal spine. It does so through the following two mechanisms: 1) allowing the hurricane surge forerunner to propagate through San Luis Pass into the bays, in the days leading up to hurricane landfall, and 2) allowing the peak storm surge to flank the western end of the coastal barrier, initially via San Luis Pass and then via an inundated Follet's Island, as the hurricane approaches and makes landfall. Adverse impacts due to forerunner propagation and storm surge flanking can be substantial for communities and industries in Brazoria and Galveston Counties that ring West Bay, including all of Galveston Island. Impacts can extend into Galveston Bay. Rising sea level will exacerbate adverse impacts associated with leaving the "back door" open, throughout the Houston-Galveston region. Analyses, and results derived from them, which led to conclusions regarding the adverse impacts associated with omission of a western section, are described in more detail below.

Leaving a "back door" open to West and Galveston Bays compromises performance of the coastal spine proposed by the USACE as part of the Coastal Texas Study's Alternative A for the Houston-Galveston region. We recommend that the USACE closely examine the adverse flooding that arises due to omission of a western dike section and re-evaluate the decision to not include a western dike/gate section in the likely TSP.

Investigative Approach

To examine the impacts of omitting the western section, storm surge simulations were made for two different alignments of a coastal spine. Each alignment had a different combination of the dike sections shown in Figure 1. The TAMUG Ike Dike concept was comprised of all three dike sections (middle+eastern+western sections). An alignment similar to that included as part of USACE Alternative A was comprised of two of the sections (middle+eastern sections), but with no western section. The crest elevation of all dike sections considered in the surge simulations, for both alignments, was 17 ft, NAVD88.

A set of eight hurricanes were simulated for each alignment using the USACE Coastal Modeling System (which includes the ADCIRC storm surge model). Simulations were made by staff at the U.S. Army Engineer Research and Development Center's Coastal & Hydraulics Laboratory, with analysis done by research staff at Jackson State University. Simulated hurricanes were selected from among historic and hypothetical, idealized storms that were considered in the FEMA RiskMap study which was most recently performed for the Texas coast. A summary of the characteristics for all eight simulated hurricanes is provided in Table 1.

Table 1. Characteristics of Simulated Hurricanes.

Storm Identifier	Central Pressure (mb)	Maximum Wind Speed (kt)	Forward Speed (kt)	Radius-to-Maximum-Winds (nm)	Target Average Recurrence Interval Water Level, Location
Hurricane Track 1					
Storm 019	960	88	11	11	10-yr, San Luis Pass
Storm 023	930	102	11	18	100-yr, San Luis Pass
Storm 027	900	113	11	22	500-yr, San Luis Pass
Hurricane Track 2					
Storm 3001	930	102	12	18	100-yr, San Luis Pass
Hurricane Track 3					
Storm 535	975	68	6	18	10-yr, Galveston Bay
Storm 033	930	100	11	26	100-yr, Galveston Bay
Storm 036	900	112	11	22	500-yr, Galveston Bay
Hurricane Ike Track					
Ike	950	80	10	45	

Hurricanes were selected using the following rationale. Hypothetical hurricanes were selected to best replicate peak surge levels associated with different average recurrence intervals at one of two desired locations, as indicated in Table 1, for the without-project condition. One set of hypothetical storms was selected to replicate 10-yr, 100-yr and 500-yr water levels along the western shoreline of Galveston Bay and into the upper reaches of the Houston Ship Channel. These are the areas with the highest potential for economic damage and losses. A second set was identified that replicates the 10-yr, 100-yr and 500-yr water levels at the entrance to San Luis Pass. Storm surge elevation at the entrance to San Luis Pass strongly influences the amount of water that enters through the open "back door" created by omission of the western dike section. The most intense hurricanes (having 900 mb minimum central pressure) are those that closely replicate the 500-yr water levels; the less intense hurricanes (having a 960 or 975 mb minimum central pressure) are those which closely replicate the 10-yr water levels. Hurricane Ike was selected because of the high surge forerunner and peak surge it created in the Houston-Galveston Region, and its relatively recent occurrence.

Simulated hurricanes followed one of the four tracks shown in Figure 2. Severe, land falling hurricanes that have impacted the Texas coast, historically, have generally approached from the southeast, like Hurricane Tracks 1 and 3 and the track for Hurricane Ike. Occasionally they have approached from the south, like Track 2. Hurricane Harvey approached from the south.

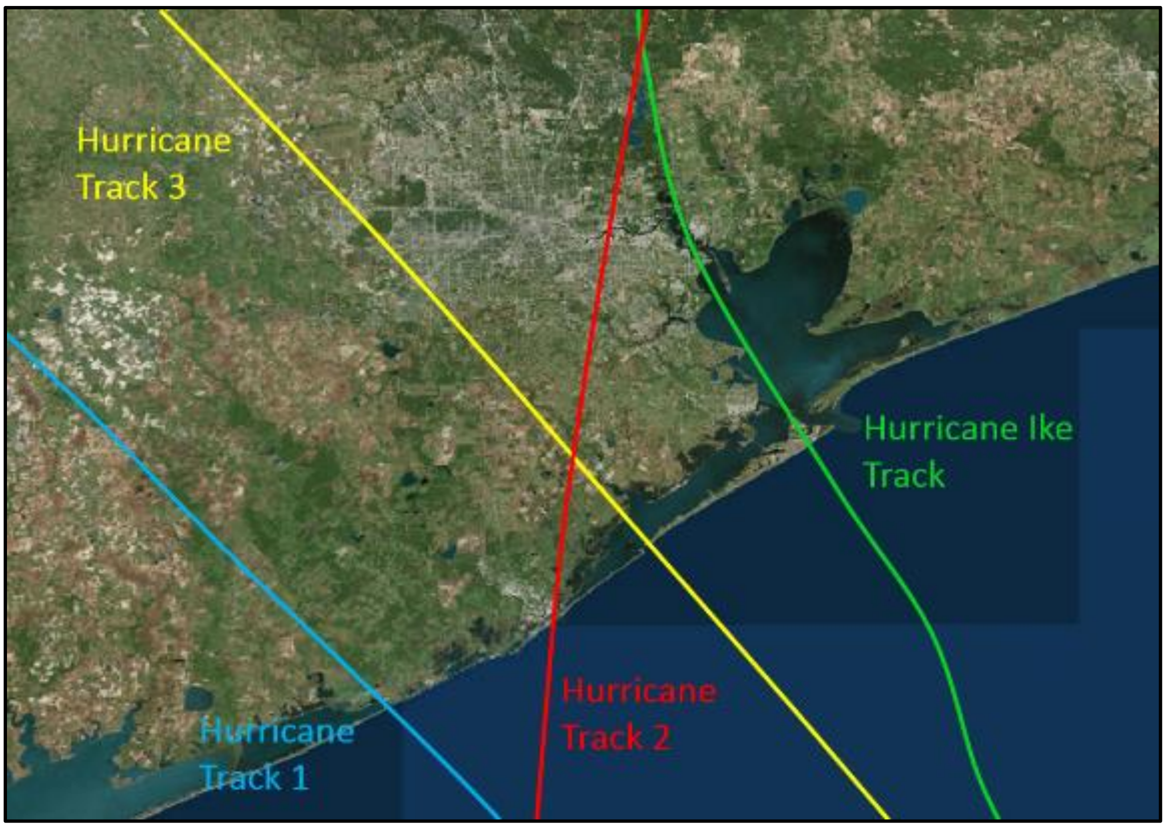

Figure 2. Different Tracks Considered in the Hurricane Simulations.
Source: Authors.

Simulations were made for each storm identified in Table 1, for each of the two coastal spine alignments (with and without a western section), and for both a present mean sea level (0.9 ft NAVD88) and a future sea level scenario that is 2.4 ft above present sea level (3.3 ft NAVD88). This future sea level is the level projected for the year 2085 using the USACE methodology and assuming an intermediate rate of sea level rise.

The modeling approach that was employed reflects the current state of engineering practice, which does not include the effects of hurricane rainfall in the storm surge simulations.

Results

Results are presented for four different aspects of the increased flood risk which results from omission of a western section of the coastal spine: 1) surge forerunner propagation through an un-gated San Luis Pass, 2) increase in peak surge elevation and inundation in both West and Galveston Bays caused by storm surge outflanking the western end of the coastal spine in the USACE Alternative A, 3) influence of sea level rise on increased peak surge and inundation associated with flanking, and 4) relative merits of the eastern and western dike sections in suppressing propagation of the coastal storm surge into the bays.

Each of these four aspects are briefly discussed in separate sections below. A number of figures are utilized to illustrate the adverse impacts on flood risk throughout the Houston-Galveston region that arise from omission of the western section.

Hurricane Surge Forerunner Propagation through San Luis Pass

Major hurricanes that traverse the Gulf of Mexico, and eventually approach the north Texas coast, can generate a significant hurricane surge forerunner. The combination of the curved shape of the Louisiana/Texas continental shelf in the northwest corner of the Gulf and the circular wind field about the eye of an approaching hurricane is conducive to formation of a wind-driven forerunner. The forerunner is forced by far-field winds that circulate in a counterclockwise direction about the hurricane eye while it is still far offshore in the deep Gulf. Such far field winds blow from east to west to southwest over the Louisiana and north Texas continental shelves. These winds tend to force an east-to-west movement of water along the shelf which is turned to the “right” in the northern hemisphere by the Coriolis force, and stacked against the Louisiana and north Texas coastlines. The Coriolis force is associated with the earth’s rotation. This stacking of water across the shelf and against the shoreline is called Ekman set-up, and this is the physical process behind formation of the wind-driven hurricane surge forerunner. The surge forerunner begins as a forced wave that advances along the northern Gulf shelf from east to west with the advancing storm; but then, after landfall on the north Texas coast, the forerunner propagates as a free wave southward along the south Texas continental shelf. This along-shelf propagation of the surge forerunner was first shown for Hurricane Ike by other researchers.

Hurricane Ike produced a sizable forerunner. The surge forerunner is experienced at the coast as a slow steady rise in the water surface elevation which begins while the hurricane eye is well offshore, days before landfall. The rate of water level rise begins to accelerate as the eye moves across the continental shelf. During Ike, the water level increase began several days before landfall and reached a measured amplitude in excess of 6 ft above the seasonal mean sea level at the Galveston Pleasure Pier, twelve hours before landfall. Water level data acquired by NOAA also show that the forerunner propagated into Galveston Bay through the tidal passes and into the upper reaches of the Houston Ship Channel with little attenuation.

As observed during Ike, the forerunner can propagate into the bays via the tidal passes. Once, closed, a storm surge gate system at the much deeper and more hydraulically efficient Bolivar Roads pass will eliminate subsequent forerunner propagation into the Bays through this particular pass. However, leaving the “back door” open at San Luis Pass, albeit a shallower, less hydraulically efficient pass, will still allow some propagation of the forerunner into West and Galveston Bays. This issue was examined using the simulation of Hurricane Ike, for both present and future sea levels.

Figure 3 shows the simulated surge forerunner elevation for Hurricane Ike, at a snap shot in time, twelve hours before landfall, when the eye (yellow dot) is still situated well offshore. At the open coast near San Luis Pass, the amplitude of the forerunner surge reached an elevation of 5.3 ft above the seasonal mean sea level approximately twelve hours prior to landfall.

Figure 4 shows the change in simulated water surface elevation with time for Hurricane Ike at two locations: the first inside West Bay (upper panel), midway between San Luis Pass and the City of Galveston; and the second roughly in the center of Galveston Bay (bottom panel).

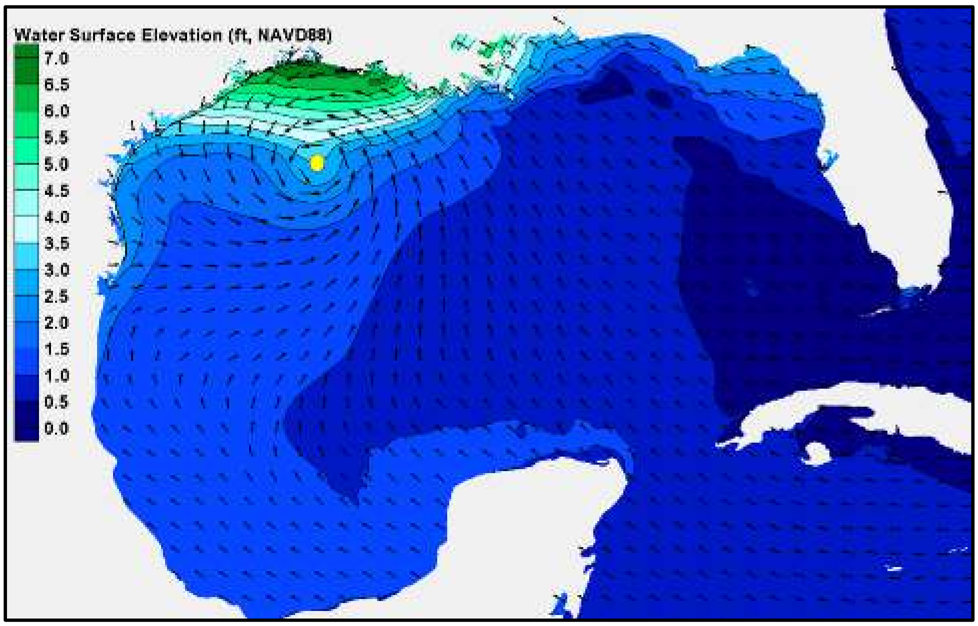

Figure 3. Snap-Shot of the Water Surface Elevation Field Associated with the Hurricane Ike Surge Forerunner, Twelve Hours Prior to Landfall. The Position of the Hurricane Eye is Shown as the Yellow Dot. Wind Speed and Direction are Shown as Black Vectors.
Source: Authors.

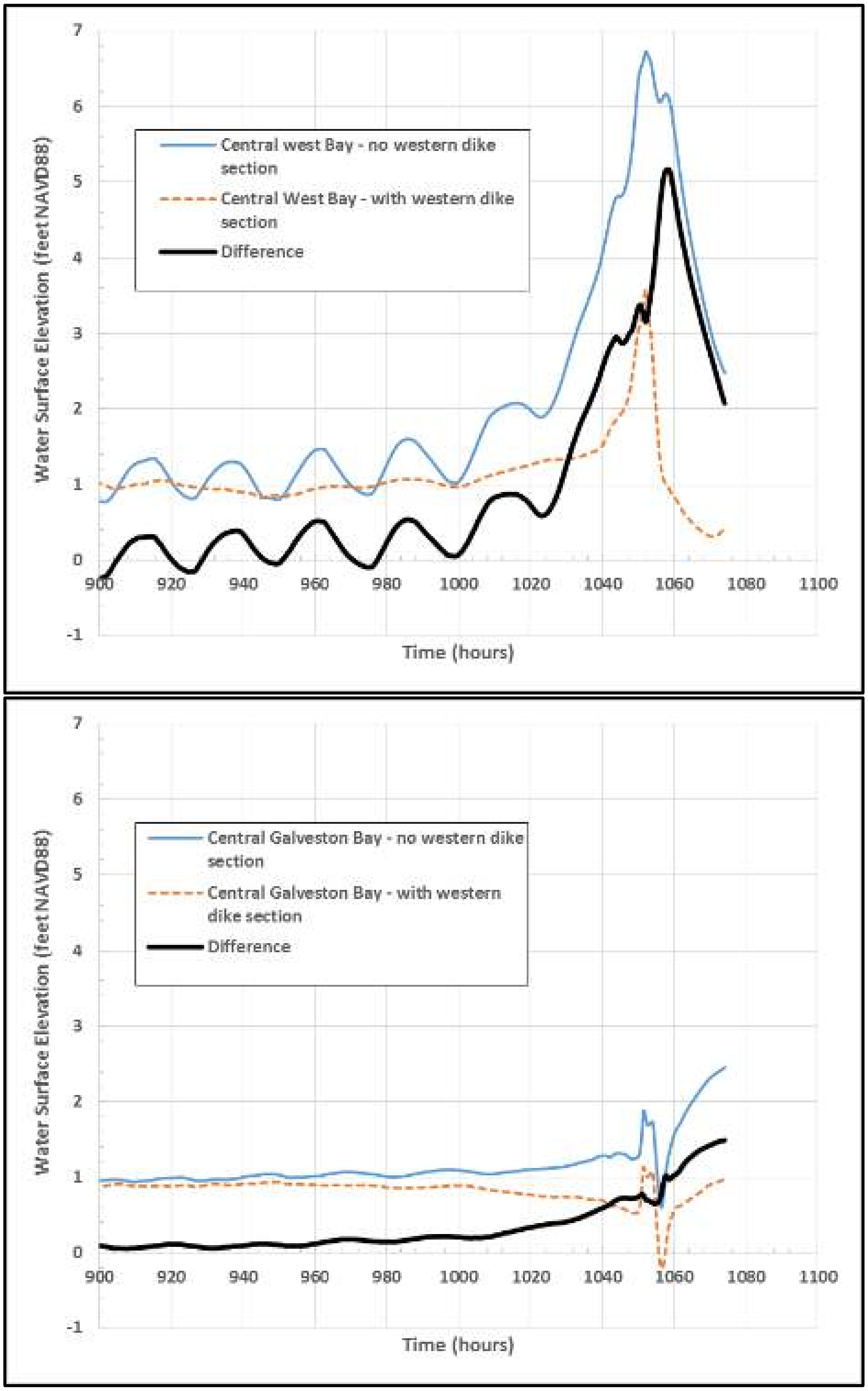

Figure 4. Water Surface Elevation in the Center of West Bay (Upper Panel) and Center Of Galveston Bay (Bottom Panel), With and Without a Western Section, for Hurricane Ike, Present Sea Level.
Source: Authors.

The thin orange dashed curves in both the upper and lower panels of Figure 4 show the water surface elevation time series for the TAMUG Ike Dike concept, which has a western closure section. The thin blue solid curves show the water surface elevation for the coastal spine alignment like the USACE Alternative A that has no western section. The thick black curve shows the difference between the orange and blue curves; it quantifies the change in water surface elevation due to leaving the "back door" open, i.e., the impact of having no western section.

Prior to hour 1044 of the simulation, the black "difference" curves reflect the influence of forerunner propagation through San Luis Pass. Without the western section, in West Bay, the forerunner surge elevation steadily rises to maximum amplitude of 2.9 ft, 12 hours before landfall. Results indicate some attenuation through the shallow San Luis Pass, from an amplitude of 5.3 ft on the open coast to an amplitude of 2.9 ft inside West Bay. In Galveston Bay, the forerunner also grows steadily in the days prior to landfall and its amplitude reaches 0.7 ft, evidence of forerunner propagation from West Bay into Galveston Bay; although additional attenuation occurs as the forerunner propagates from West Bay into Galveston Bay. Results for the Upper Houston Ship Channel, not shown here, are nearly identical to those shown for the center of Galveston Bay. Once inside Galveston Bay, there is little attenuation of the forerunner amplitude, as was observed during the actual Hurricane Ike. For the simulated Hurricane Ike, as a consequence of forerunner propagation through an open San Luis Pass, the entire West Bay water level is raised by 2.9 ft, and the entire Galveston Bay water level is raised by 0.7 ft, everywhere, 12 hours before landfall.

As also seen in Figure 4, around hour 1060 of the simulation, the effect of omitting a western section on peak surge is an increase of approximately 5.2 ft at the central West Bay location and an increase of 1.5 ft at the central Galveston Bay location. The adverse effects of an open "back door" on peak surge and inundation inside the bays are discussed at greater length in the next section.

The Hurricane Ike simulation for future sea level shows that omission of the western section leads to similar results for surge forerunner propagation into West Bay as obtained for the present sea level; a slightly higher hurricane forerunner surge of 3.1 ft twelve hours prior to landfall, and an increase in peak surge of about 5.2 ft. However, in Galveston Bay, the forerunner surge amplitude is 1.2 ft (0.5 ft higher than for present sea level case) and the increase in peak surge is 2 ft (also an increase of 0.5 ft). With the "back door" open, rising sea level apparently reduces the attenuation of, and increases the propagation efficiency of, the surge forerunner from West Bay into Galveston Bay. This leads to higher forerunner surge and peak surge values in Galveston Bay. The effects of higher future sea level on peak surge and inundation inside the bays are discussed at greater length in a subsequent section.

Influence of Flanking of the USACE TSP Coastal Spine by the Storm Surge

Without a western section of the coastal spine, as the hurricane eye approaches landfall and as the forerunner development period transitions into development of the peak surge, the storm surge continues to propagate into West Bay via San Luis Pass and then over Follet's Island as well once the island becomes inundated. Even for relatively frequent hurricane events, omission of the western section leads to inundation within communities on western and central Galveston Island, inundation that would be avoided with a western dike section in place. The adverse effects of flanking are much more widespread for more severe hurricanes.

The effect of surge flanking is illustrated below using both peak surge maps and inundation maps. Colored shaded contour maps of peak surge depict the peak storm surge elevation calculated at every location in the storm surge model's (ADCIRC's) computational domain, without regard to when the peak surge elevation occurred during the simulation. These peak surge maps do not represent snap shots in time. To illustrate the spatial extent of inundation, both with and without a western section, a "transparent" peak surge map is superimposed over a background satellite image to create an inundation map.

Pairs of maps are presented in figures below. The map in the top panel of each figure shows the peak surge map, or inundation map, for the Ike Dike coastal spine concept which has a western section; and, the map in the bottom panel shows results for the alignment that is similar to the USACE Alternative 1 alignment, which omits the western section. Peak surge and inundation maps are shown for three of the storms listed in Table 1: Hurricane Ike, Storm 023, and Storm 019. The simulation of Hurricane Ike produced a peak surge of approximately 10 ft NAVD88 at San Luis Pass and about 14 ft NAVD88 at the City of Galveston. Storm 023 is a hypothetical hurricane that produced the 100-yr water level at San Luis Pass of 14 ft NAVD88; and Storm 019 is a hypothetical hurricane that replicated the 10-yr water level at San Luis Pass of 7 ft NAVD88, a much more frequent event.

Figure 5 shows peak storm surge maps for Hurricane Ike, for present sea level, with (top panel) and without (bottom panel) a western section. Results clearly show that the peak surge is much higher in West Bay with the "back door" open. The increases in peak surge are greatest near San Luis Pass and they decrease from west to east within West Bay. Without the western section, peak surge at the west end of Galveston Island is 5 to 5.5 ft higher than the peak surge with the western section. The effect of leaving the "back door" open on peak surge extends to the City of Galveston, where the peak surge is 1.5 to 2 ft higher without the western section. The increase in peak surge with the "back door" open is not limited to West Bay. Increases also are evident in Galveston Bay; however, the magnitude of the increase in peak surge is less in Galveston Bay than it is in West Bay. Peak surge differences in Galveston Bay, approximately 1 to 1.5 ft in most places, are slightly smaller than differences at the City of Galveston.

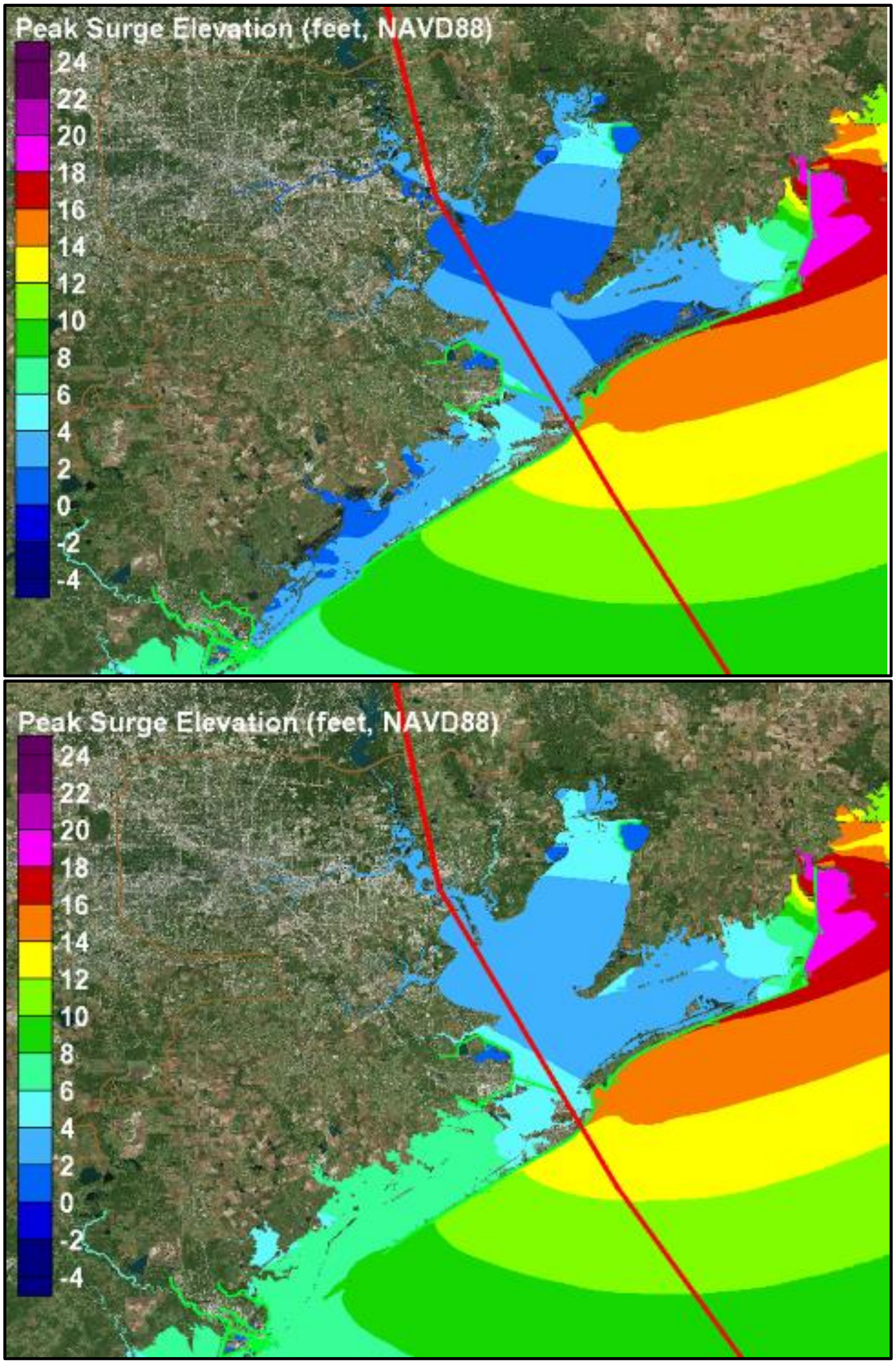

Figure 5. Peak Surge Maps for Hurricane Ike, Present Sea Level, for the Ike Dike Coastal Spine Concept Having a Western Section (top panel) and an Alignment Similar to the Likely USACE TSP that Does Not have a Western Section (bottom panel).
Source: Authors.

For Hurricane Ike, present sea level, some of lowest-lying areas on western Galveston Island closest to West Bay are inundated even with the western section in place (top panel in Figure 6). However, without the western section, inundation of terrain surrounding West Bay is much more widespread; and, western Galveston Island is nearly completely inundated (circled region in the bottom panel of Figure 6).

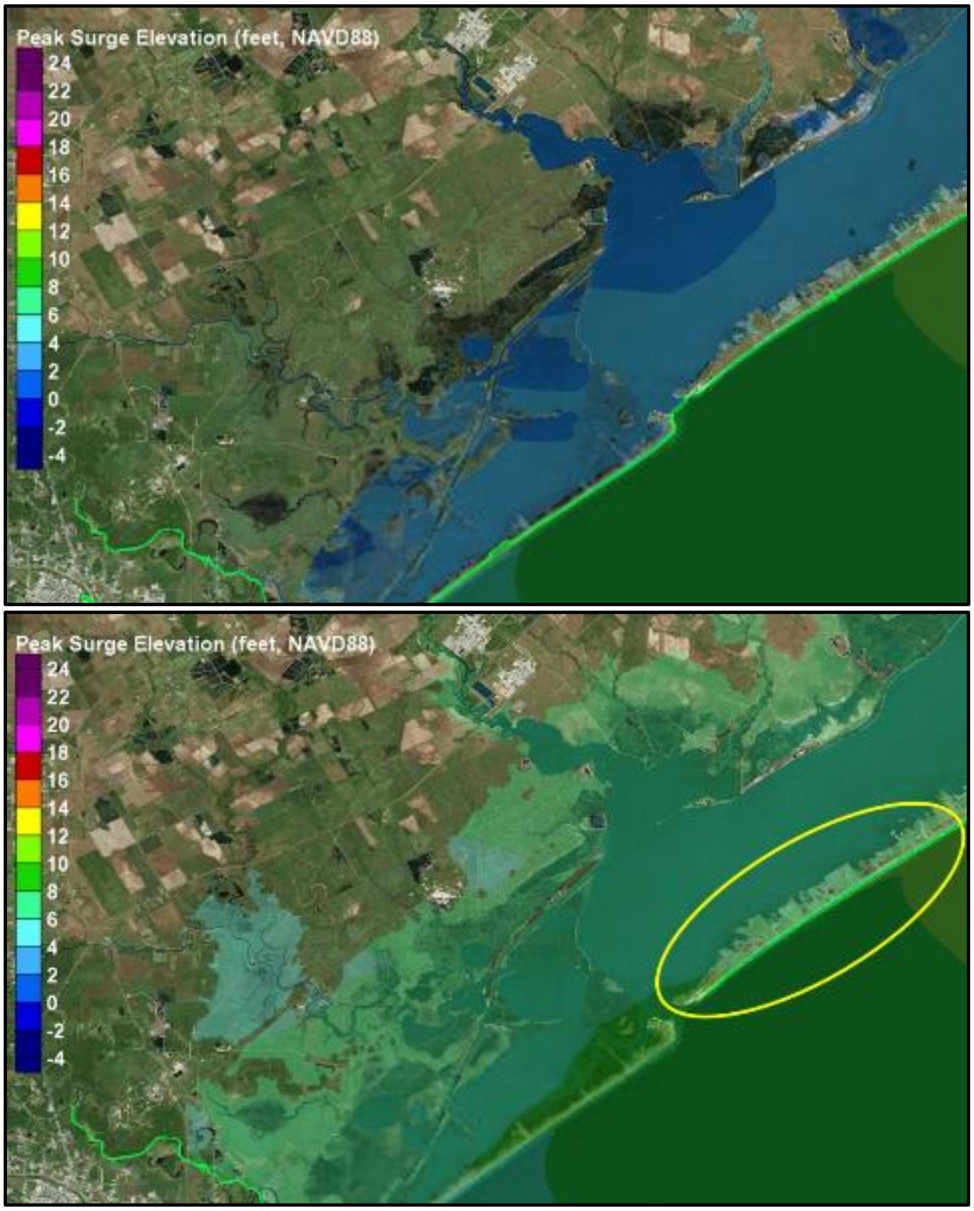

Figure 6. Inundation Maps in Near San Luis Pass, for Hurricane Ike and Present Sea Level, for the Ike Dike Coastal Spine Concept having a Western Section (top panel) and an Alignment Similar to the Likely USACE TSP that Does Not have a Western Section (bottom panel).
Source: Authors.

Figure 7 shows inundation maps for Hurricane Ike, present sea level, for eastern Galveston Island. Some of lowest-lying areas on eastern Galveston Island and a community on the north side of West Bay are inundated even with the western section in place. However, without the western section, inundation of the circled eastern Galveston Island communities is complete, multiple communities on the north side of

West Bay are inundated, as are parts of the City of Galveston, including the airport (see the circled areas in the bottom panel of Figure 7).

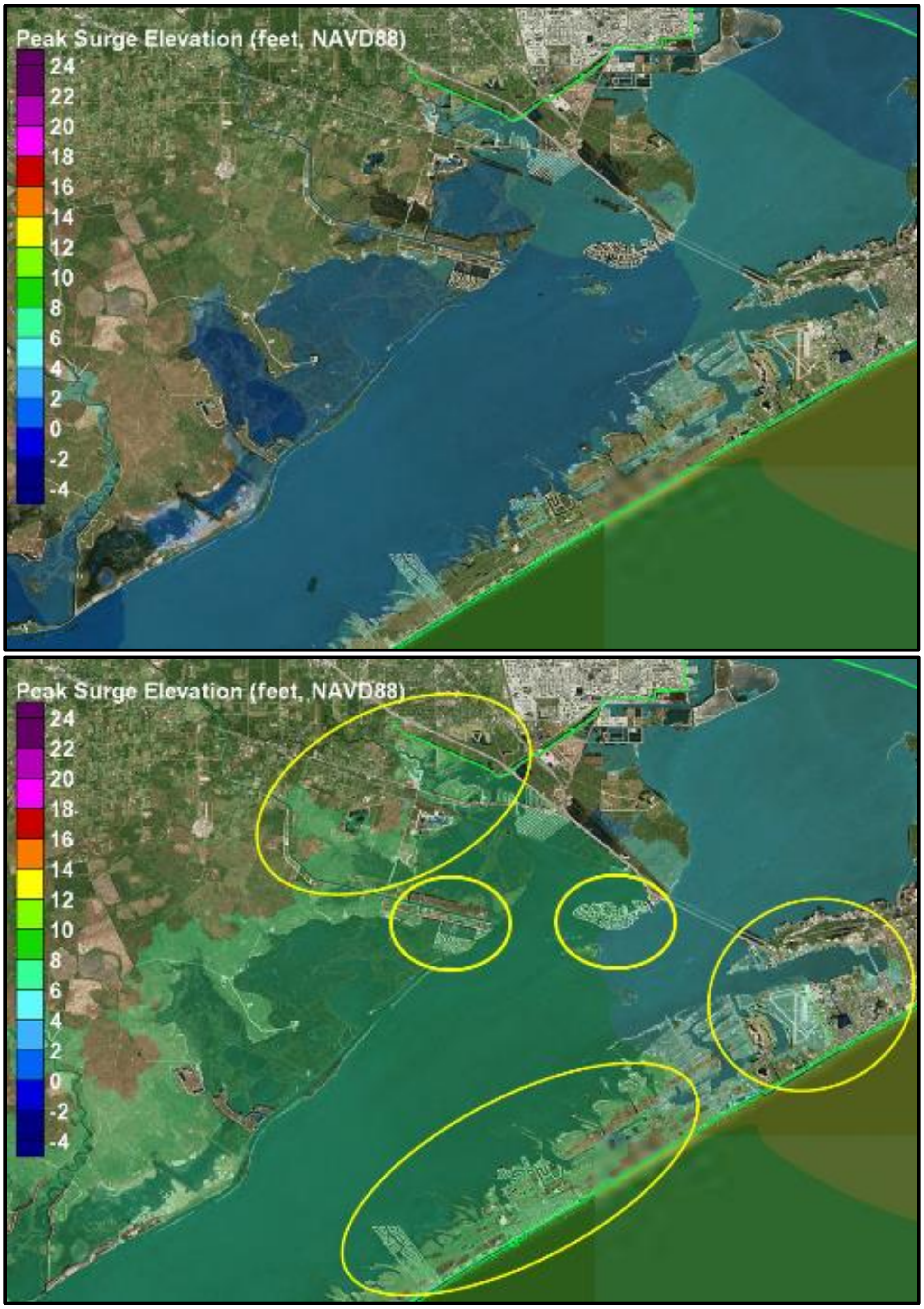

Figure 7. Inundation Maps in Eastern West Bay, for Hurricane Ike and Present Sea Level, for the Ike Dike Coastal Spine Concept having a Western Section (top panel) and an Alignment Similar to the Likely USACE TSP that Does Not have a Western Section (bottom panel).
Source: Authors.

Figure 8 shows peak surge maps for Storm 023, present sea level, with a western section (top panel) and without a western section (bottom panel). Results show that the peak surge is, again, much higher in West Bay with the "back door" open. Again, as is seen for this and all the storms that were simulated, the increases in peak surge are greatest nearer San Luis Pass and they decrease from west to east in West Bay. Without the western section, peak surge at the west end of Galveston Island is 7 ft higher than the peak surge with the western section in place. At the City of Galveston, the peak surge is 1 ft higher without the western section. Increases in peak surge also are evident in Galveston Bay; however, the magnitude of the increase in peak surge is less in Galveston Bay than it is in West Bay. Peak surge differences in Galveston Bay are comparable to the differences at the City of Galveston, approximately 1 ft in many places, less along the western side of the Bay.

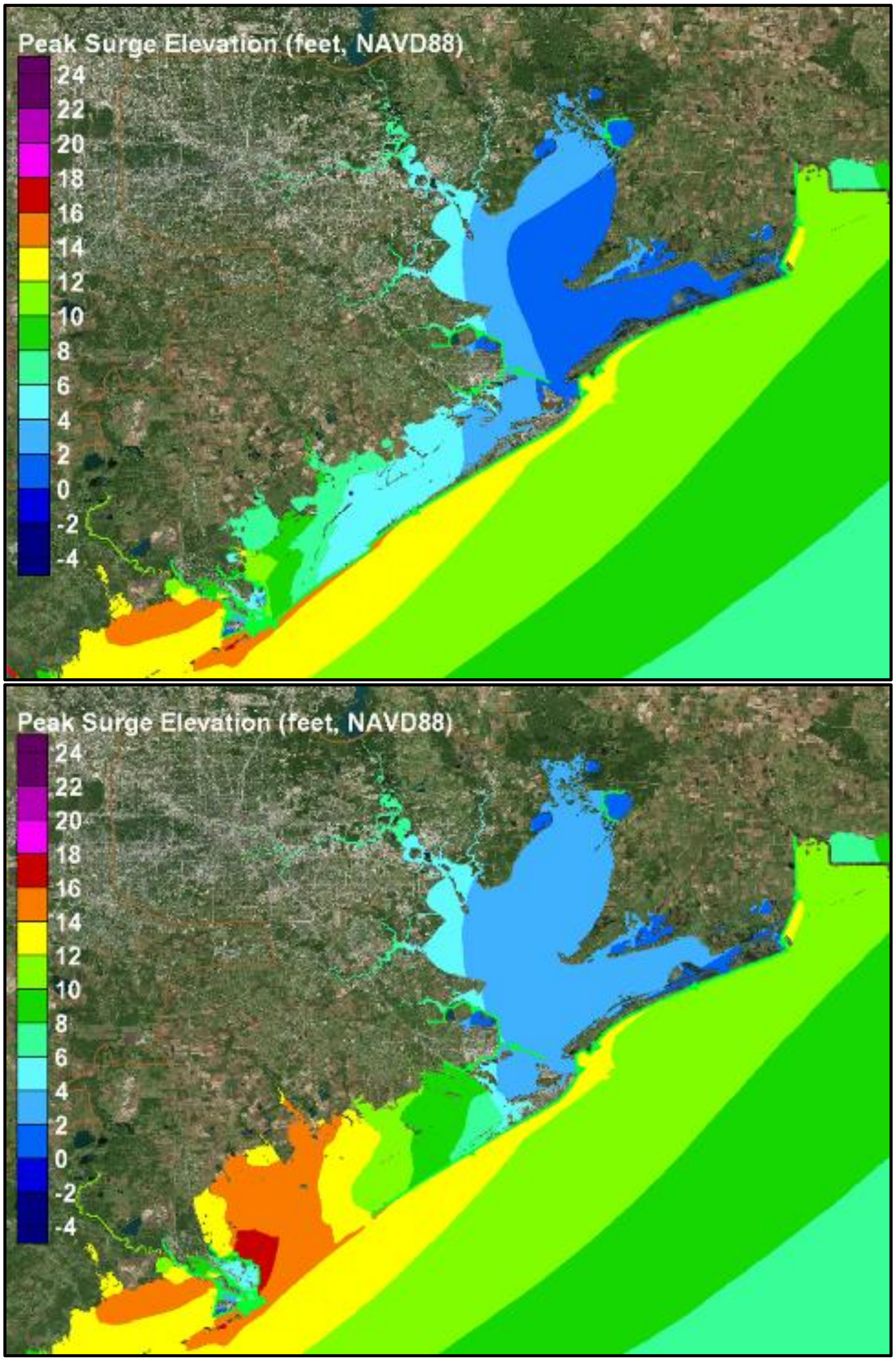

Figure 8. Peak Surge Maps for Storm 023, Present Sea Level, for the Ike Dike Coastal Spine Concept having a Western Section (top panel) and an Alignment Similar to the Likely USACE TSP that does not have a Western Section (bottom panel).
Source: Authors.

For Storm 023, present sea level, some of lowest-lying areas on western Galveston Island closest to West Bay are inundated with the western section in place (upper panel of Figure 9). However, without the western section, inundation of terrain surrounding West Bay is much more widespread and western Galveston Island is completely inundated (see the circled area in the bottom panel of Figure 9). Inundation is more severe for Storm 023 than for Hurricane Ike. Without the western section, a LNG complex near Freeport is significantly inundated as are the petro-chemical complexes along Chocolate Bayou; both facilities are circled in the bottom panel of Figure 9.

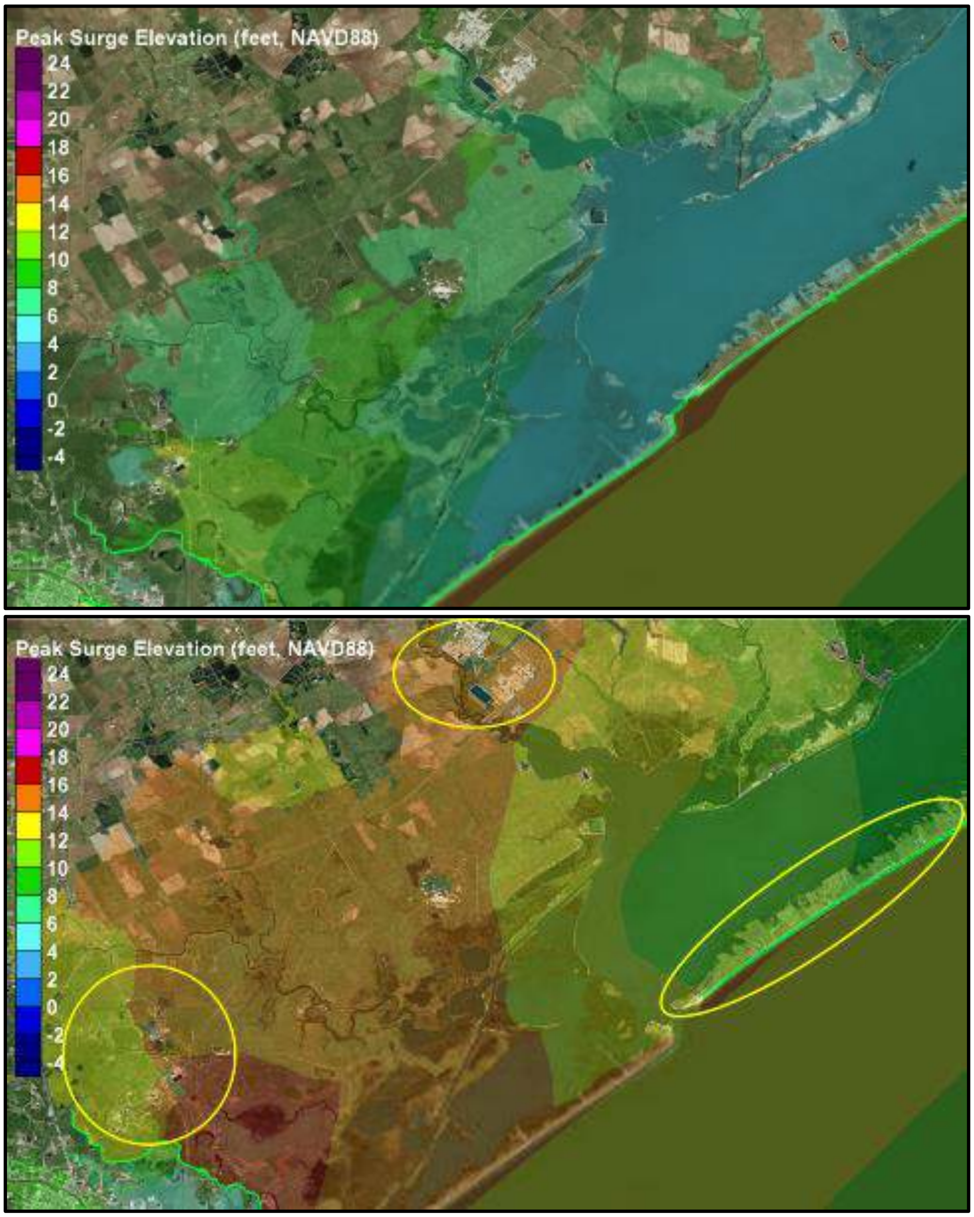

Figure 9. Inundation Maps Near San Luis Pass, for Storm 023 and Present Sea Level, for the Ike Dike Coastal Spine Concept having a Western Section (top panel) and an Alignment Similar to the Likely USACE TSP that does not have a Western Section (bottom panel).
Source: Authors.

For Storm 023, present sea level, some of lowest-lying areas on eastern Galveston Island are inundated with the western section in place (see top panel in Figure 10). However, without the western section, inundation of the indicated eastern Galveston Island communities is complete, multiple communities on the north side of West Bay are inundated, as are parts of the City of Galveston, including the airport (see the circled areas in the bottom panel of Figure 10).

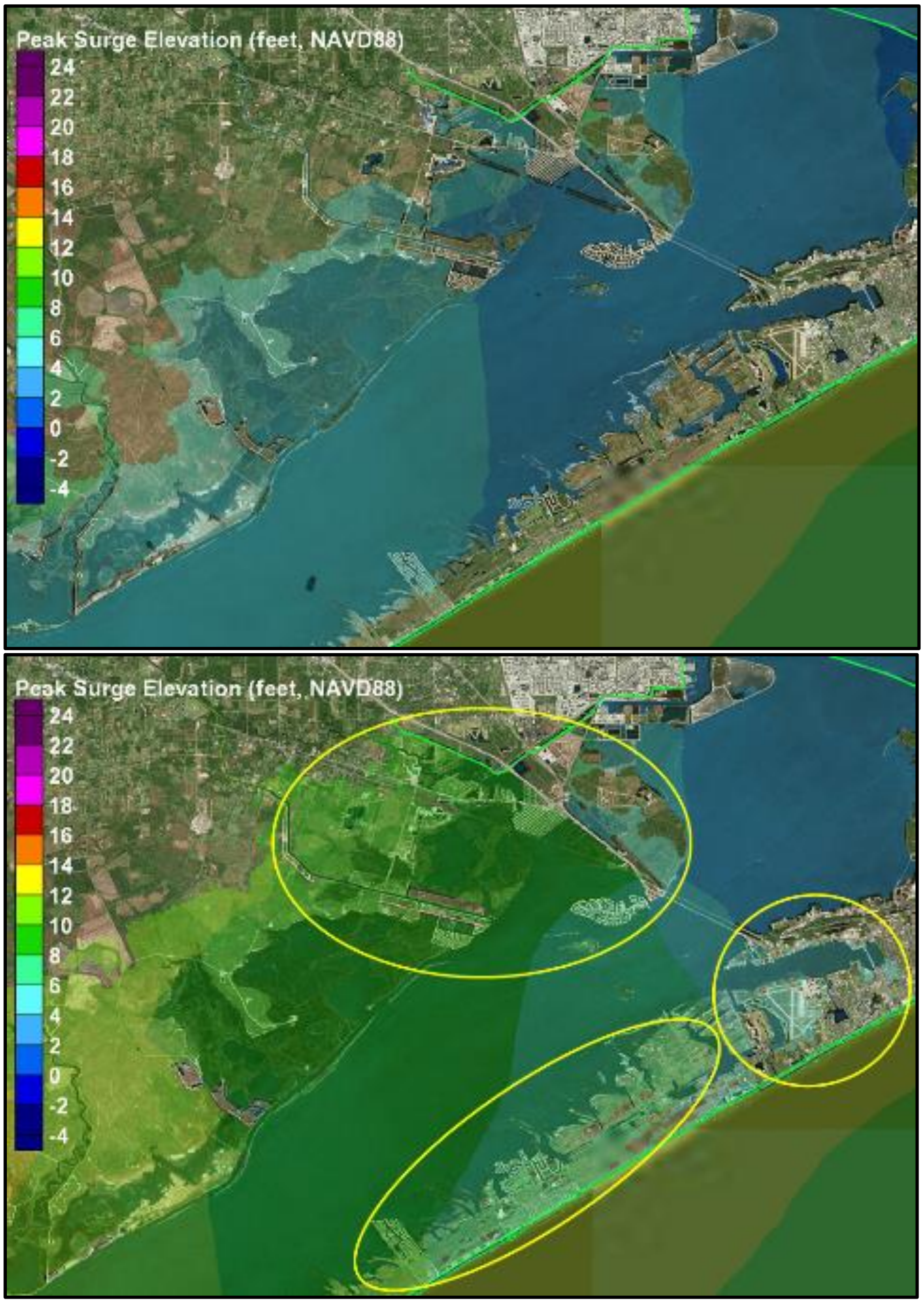

Figure 10. Inundation Maps in Eastern West Bay, for Storm 023 and Present Sea Level, for the Ike Dike Coastal Spine Concept having a Western Section (top panel) and an Alignment Similar to the Likely USACE TSP that does not have a Western Section (bottom panel).
Source: Authors.

Leaving the “back door” open leads to increased flooding and inundation on Galveston Island even for relatively frequent, weaker hurricane events, like Storm 019. Storm 019 was selected to replicate the 10-yr average recurrence interval water level at the entrance to San Luis Pass, a water level of 7 ft NAVD88. Figures 11 and 12, show the increase in inundation that occurs for Storm 019, present sea level, with the “back door” open (top panels) and the “back door” closed (bottom panels). Figures 11 and 12 show the differences in inundation for western and central Galveston Island, respectively.

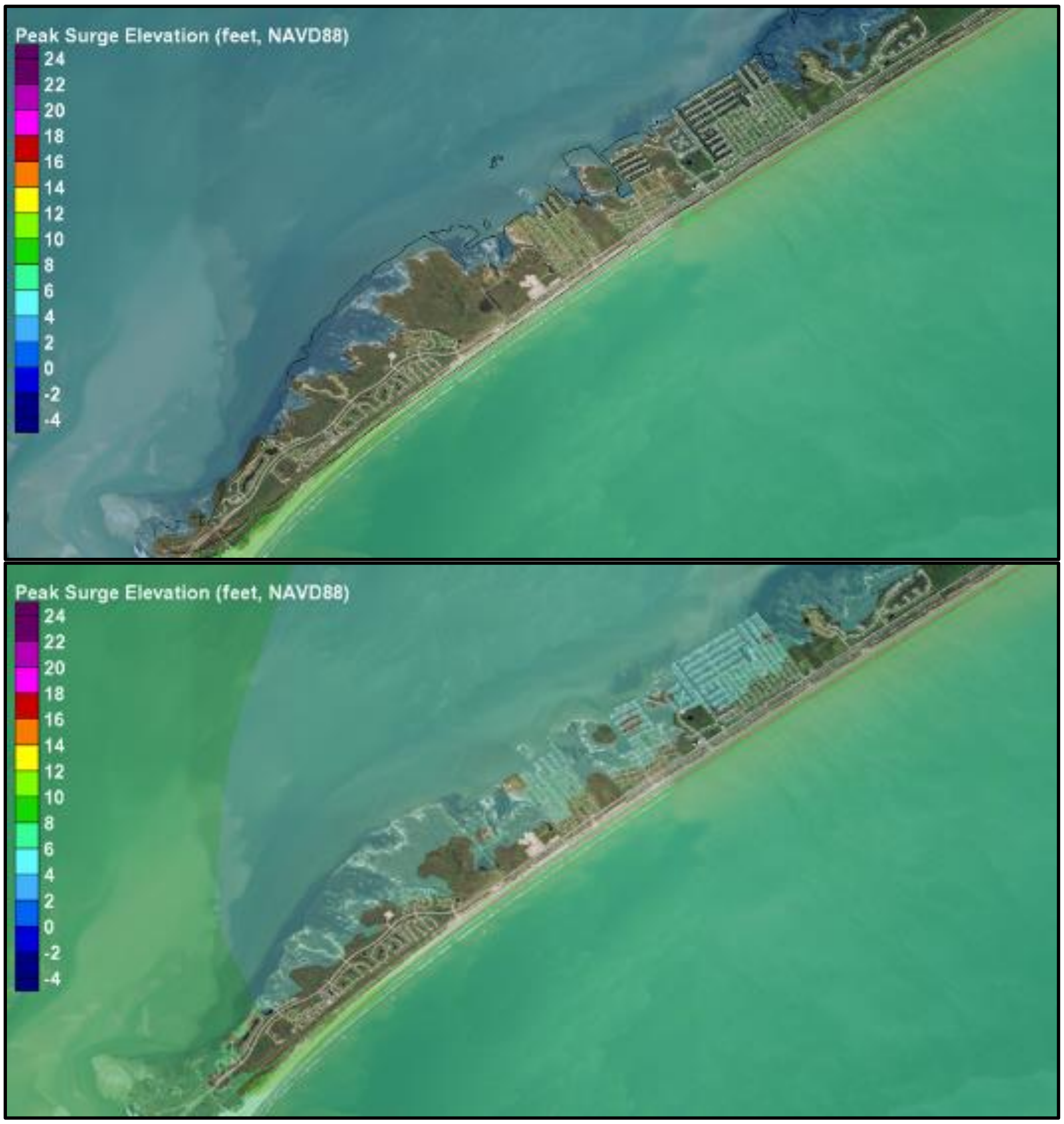

Figure 11. Inundation Maps for Western Galveston Island, for Storm 019 and Present Sea Level, for the Ike Dike Coastal Spine Concept having a Western Section (top panel) and an Alignment Similar to the Likely USACE TSP that does not have a Western Section (bottom panel).
Source: Authors.

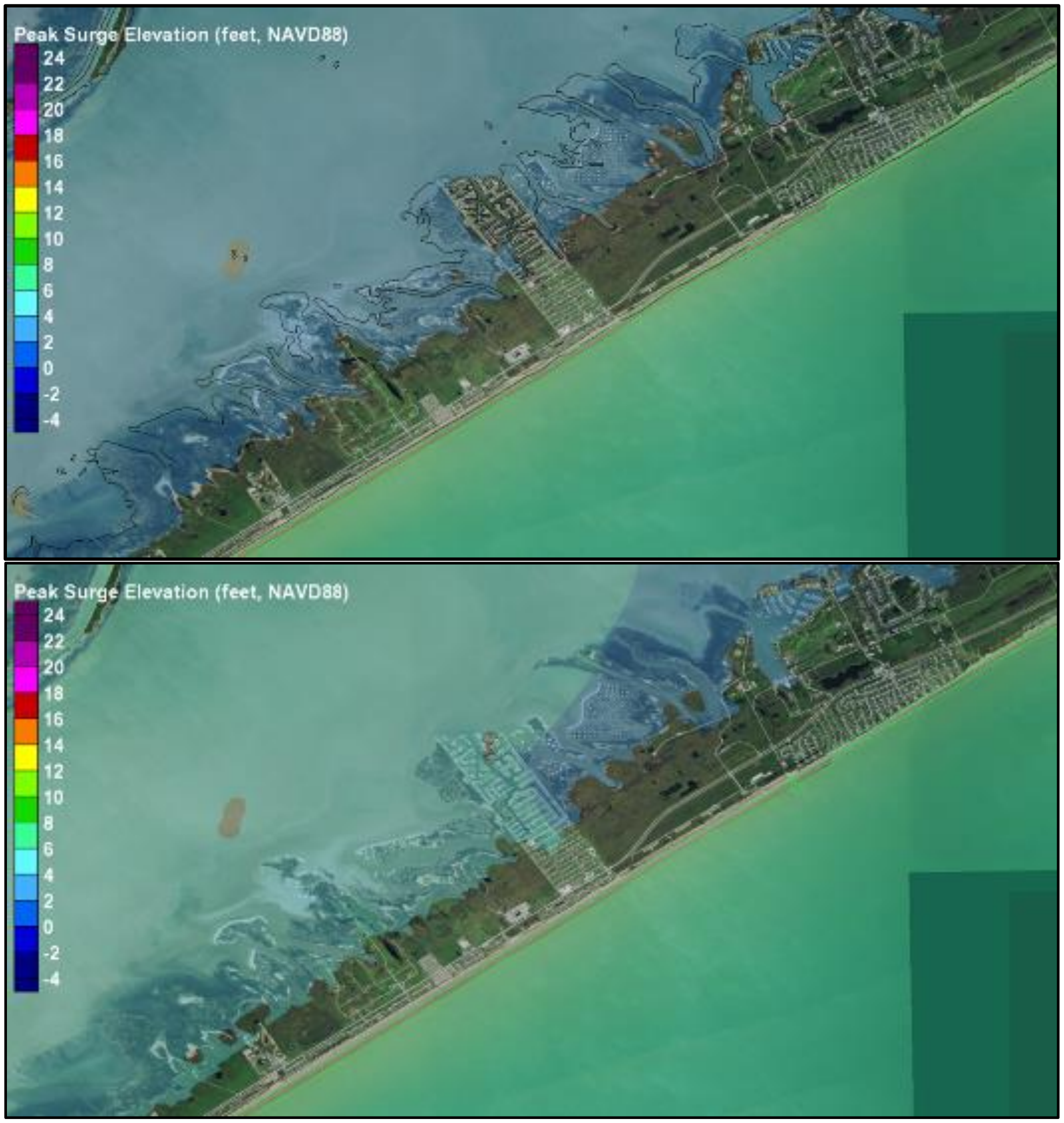

Figure 12. Inundation Maps for Central Galveston Island, for Storm 019 and Present Sea Level, for the Ike Dike Coastal Spine Concept having a Western Section (top panel) and an Alignment Similar to the Likely USACE TSP that does not have a Western Section (bottom panel).
Source: Authors.

Influence of Sea Level Rise on Increased Peak Surge and Inundation Associated with Flanking

In general, rising sea level will increase flood risk throughout the Houston-Galveston region, both with and without a western section. Low-lying areas and areas with low topography gradients are most susceptible to increases in sea level. However, leaving the "back door" open increases the susceptibility of the most vulnerable areas to flooding as sea level rises. Aside from those areas around West Bay where flooding and inundation is exacerbated by sea level rise, there also are areas around the periphery of Galveston Bay which experience exacerbated inundation for the future sea level scenario as a consequence of leaving the "back door" open.

For example, for Hurricane Ike and the future sea level scenario, a number of areas in the City of Galveston are exposed to inundation, which otherwise, would not be inundated with the western section in place (see the circled area in Figure 13).

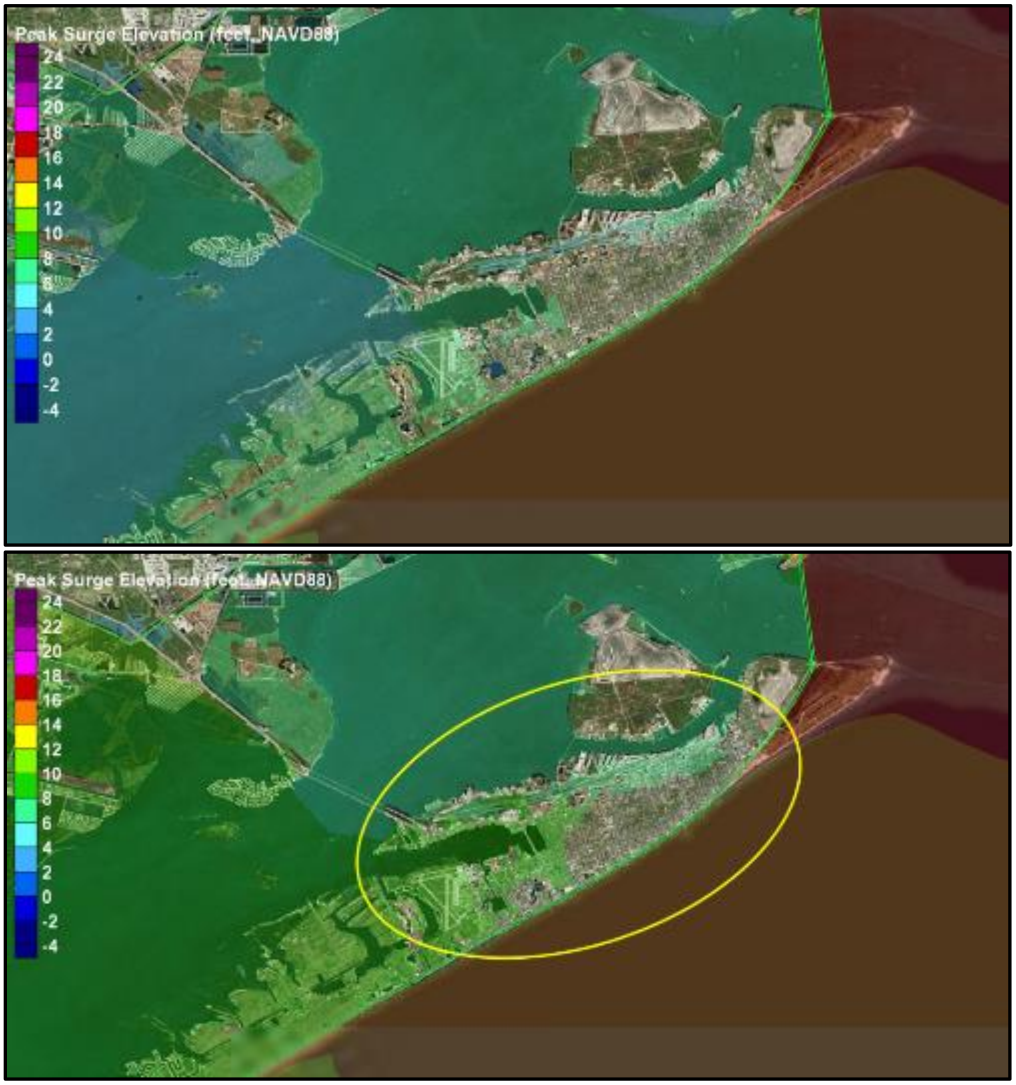

Figure 13. Inundation Maps for the City of Galveston, for Hurricane Ike and Future Sea Level, for the Ike Dike Coastal Spine Concept having a Western Section (top panel) and an Alignment Similar to the Likely USACE TSP that does not have a Western Section (bottom panel).
Source: Authors.

There also are similarly affected areas along the western shoreline of Galveston Bay. For Hurricane Ike, and the future sea level scenario, parts of the town of San Leon, adjacent to Dickinson Bay, are inundated (circled area in the bottom panel of Figure 14) which would not occur with the western section in place (top panel of Figure 14).

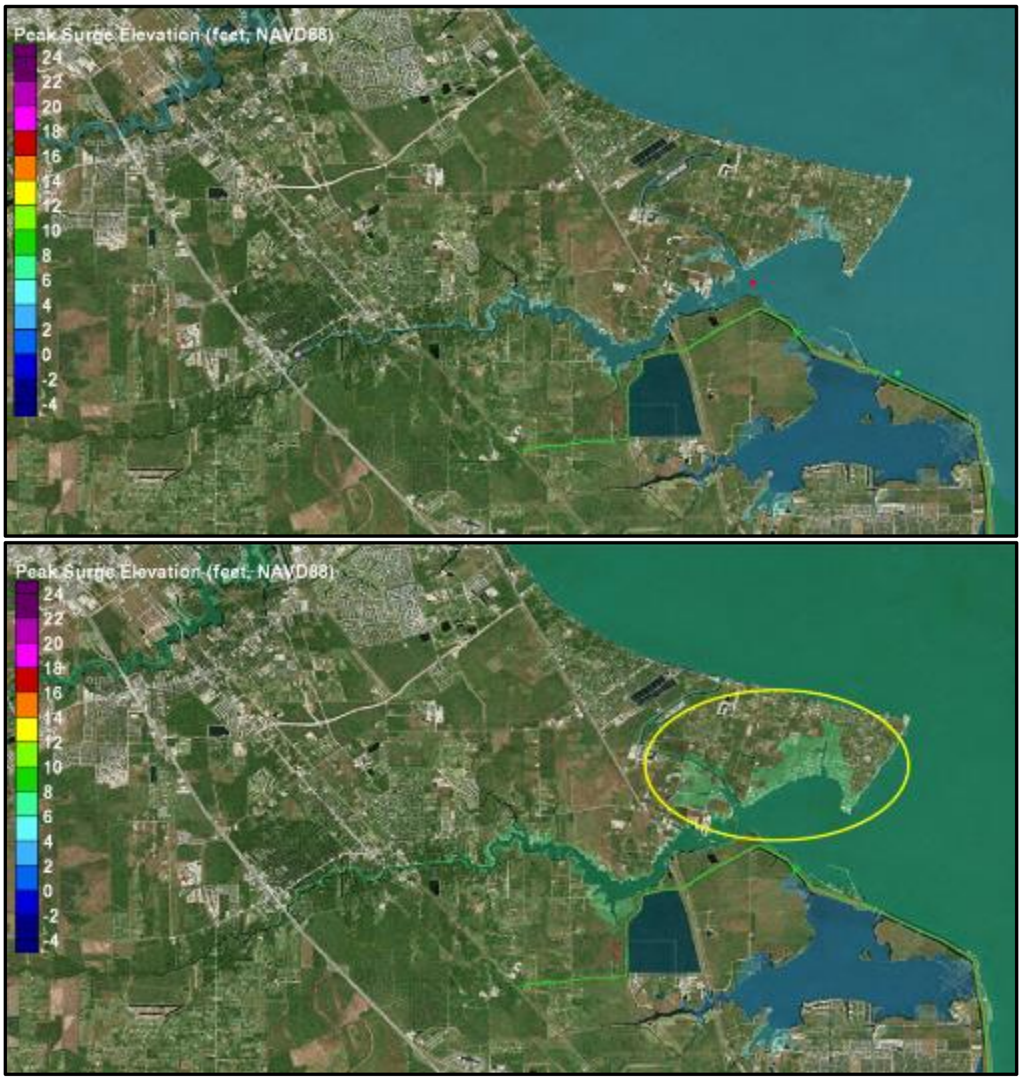

Figure 14. Inundation Maps for the Town of San Leon, for Hurricane Ike and Future Sea Level, for the Ike Dike Coastal Spine Concept having a Western Section (top panel) and an Alignment Similar to the Likely USACE TSP that does not have a Western Section (bottom panel).
Source: Authors.

A similar influence is seen along the east shore of Galveston Bay. For Hurricane Ike, and the future sea level scenario, the town of Oak Island is inundated (circled area in the bottom panel of Figure 15), which would not occur with the western section in place (top panel of Figure 15). With rising sea level, the adverse effects of leaving the “back door” open are clearly not restricted to West Bay.

Figure 15. Inundation Maps for the Town of Oak Island, for Hurricane Ike and Future Sea Level, for the Ike Dike Coastal Spine Concept having a Western Section (top panel) and an Alignment Similar to the Likely USACE TSP that does not have a Western Section (bottom panel).
Source: Authors.

Relative Merits of the Eastern and Western Dike Section in Suppressing Propagation of Storm Surge into the Bays

To examine the relative merits of both the western and eastern dike sections in suppressing storm surge propagation into the bays, all the storms in Table 1 were simulated for a third coastal spine alignment that is shown in Figure 16. This alignment is quite similar to the alignment recommended by the GCCPRD in their final report. This alignment has neither the western nor eastern dike sections; it has only the middle section, which extends from the west end of Galveston Island to High Island.

Figure 16. Alignment of the Coastal Spine Similar to that Recommended by the GCCPRD.
Source: Authors.

To quantify the additional storm surge that enters the Houston-Galveston region by not having an eastern section, the peak surge field for the alignment that is similar to the coastal spine included in the likely USACE TSP (comprised of middle+eastern sections), which was discussed previously and is shown in Figure 17, is subtracted from the peak surge field for the alignment shown in Figure 16 (middle section only).

Figure 17. Alignment of the Coastal Spine Similar to that Recommended by the USACE in the Coastal Texas Study as Part of Alternative A, the Likely TSP, for the Houston Galveston region.
Source: Authors.

Results are shown in a series of figures below, Figures 18, 19 and 20. There is one figure for each of three storms, Hurricane Ike (Figure 18) and the two hypothetical storms which best replicated the 100-yr and 500-yr water levels within Galveston Bay, Storms 033 (Figure 19) and 036 (Figure 20) in Table 1, respectively. Of all the storms simulated, these three produced the highest peak surges in the vicinity of the eastern dike section. Therefore, of all the storms simulated, these three would be those in which having an eastern section would be most beneficial. All results shown are from simulations made using the future sea level scenario.

For each storm, the upper panel in each figure shows the increase in peak surge that occurs without a western section of the coastal spine concept; and the bottom panel shows the increase in peak surge that occurs without an eastern section.

Results for all three storms show that the western dike section provides much greater flood risk reduction benefits throughout both West and Galveston Bays than does the eastern dike section. The eastern section primarily provides peak surge reduction benefits in the vicinity of the eastern dike section; whereas, the western section provides peak surge reduction benefits throughout the Houston-Galveston region that lies behind the coastal spine, even communities located along the eastern shoreline of Galveston Bay. Results are quite similar to those for the simulations made for present sea level.

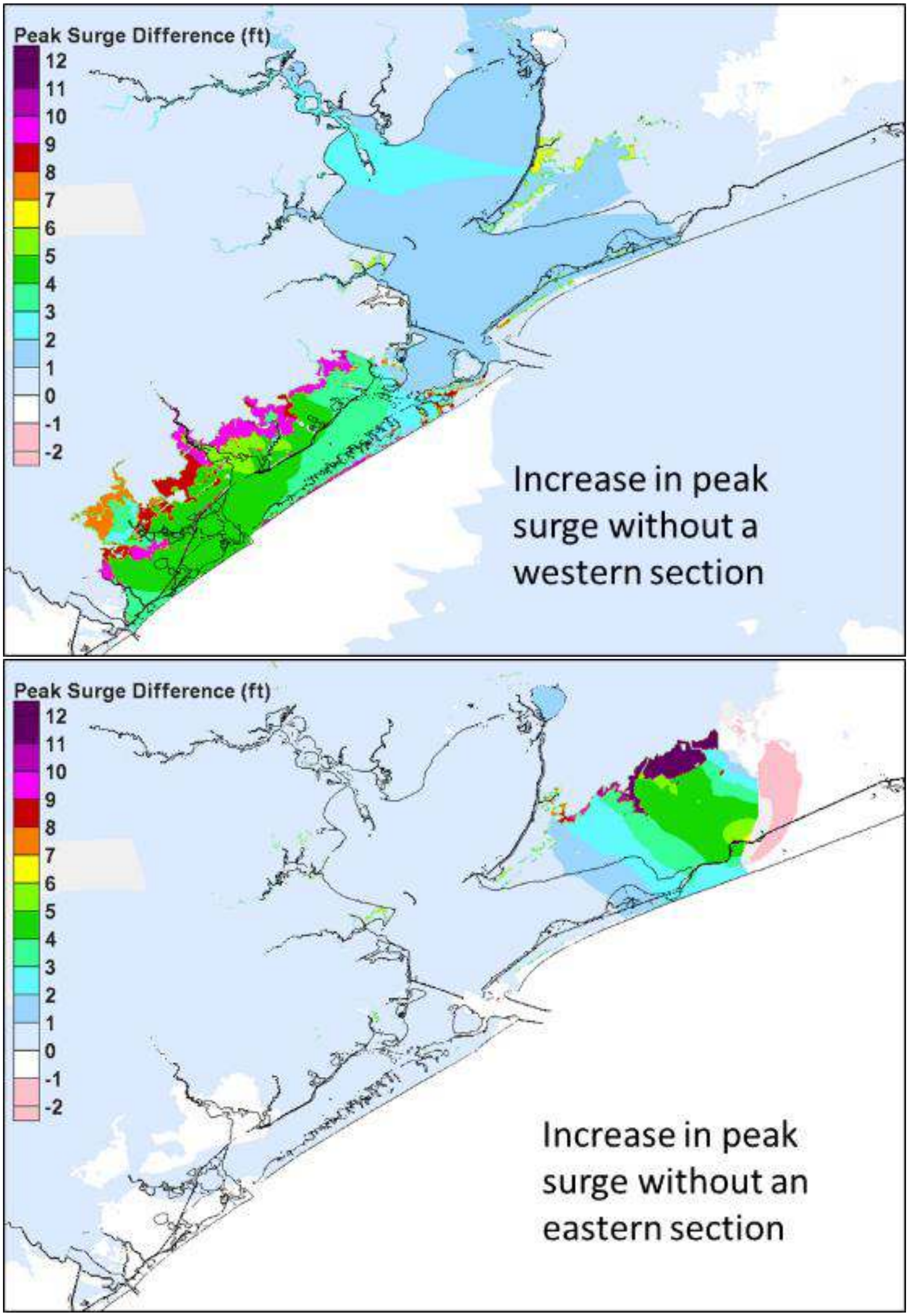

Figure 18. Increase in Peak Storm Surge Arising from Omission of the Western Dike Section (top panel), and Omission of the Eastern Dike Section, for Hurricane Ike, Future Sea Level (bottom panel).
Source: Authors.

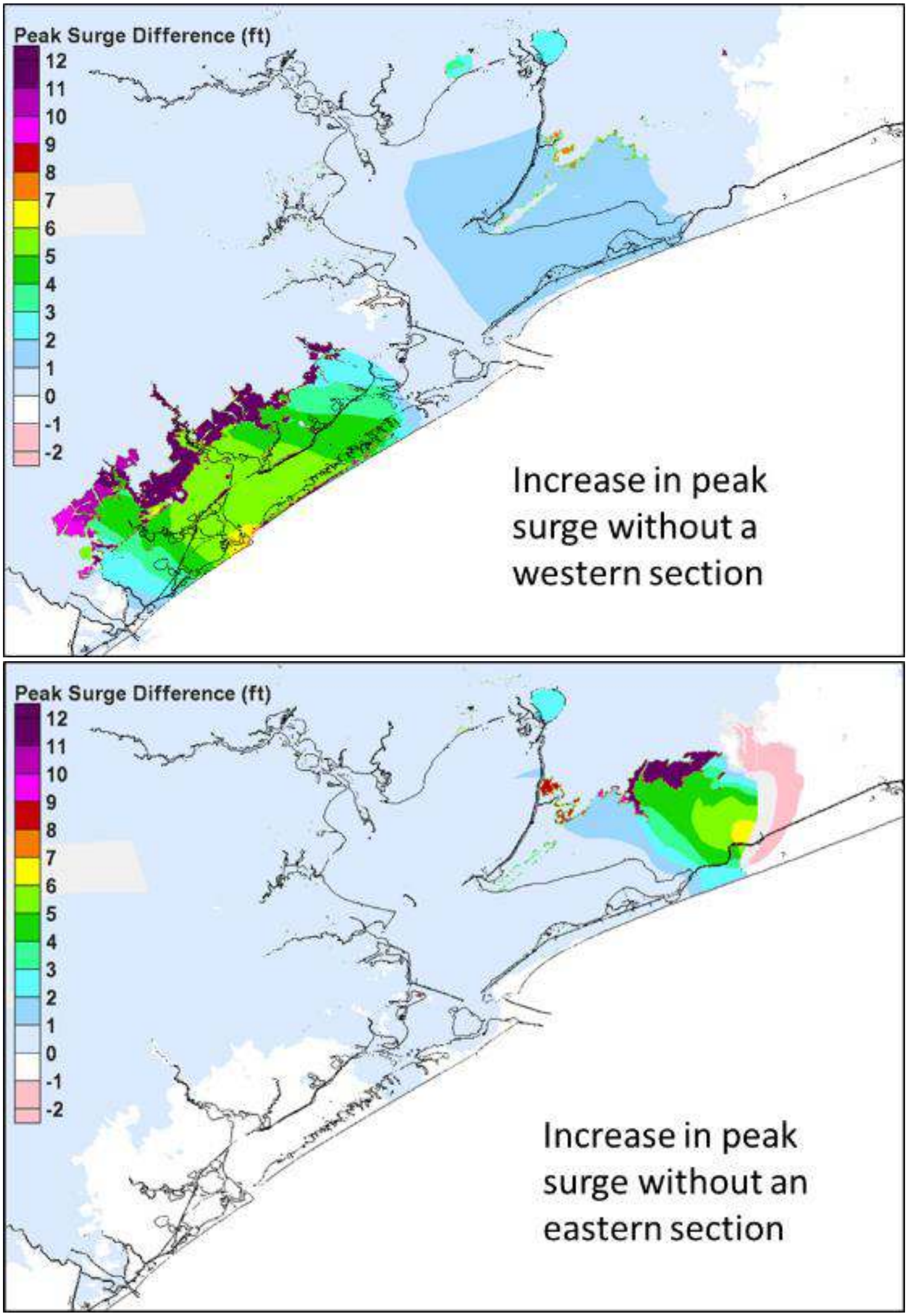

Figure 19. Increase in Peak Storm Surge Arising from Omission of the Western Dike Section (top panel), and Omission of the Eastern Dike Section, for Storm 033, Future Sea Level (bottom panel).
Source: Authors.

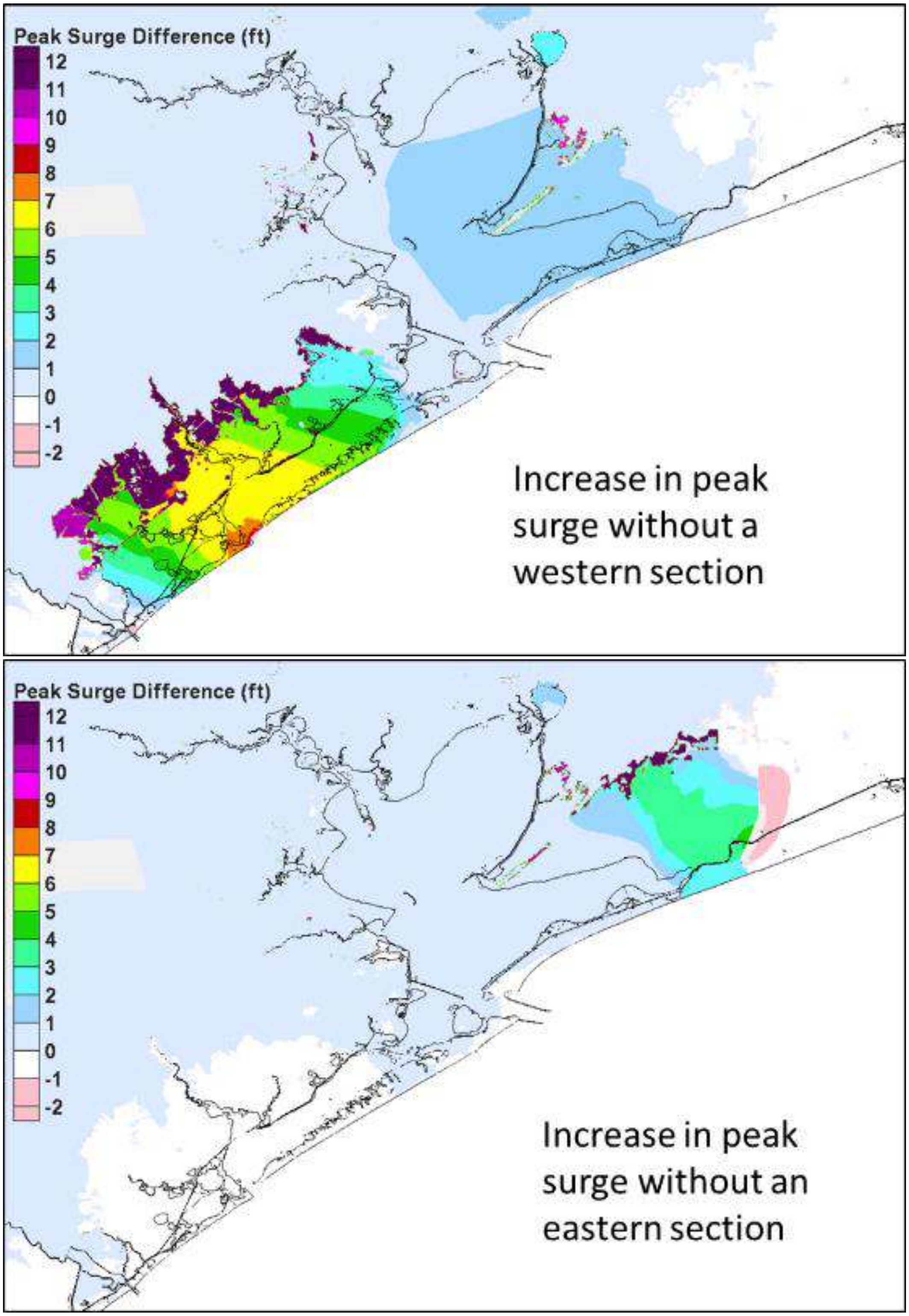

Figure 20. Increase in Peak Storm Surge arising from Omission of the Western Dike Section (top panel) and Omission of the Eastern Dike Section, for Storm 036, Future Sea Level (bottom panel).
Source: Authors.

These observations are primarily due to the fact that high storm surge conditions develop at the location of the eastern dike section much later during the storm, just before landfall. Flanking flow around the eastern end of the coastal spine at High Island, in the absence of an eastern section, commences at this time, relatively late in the storm. And, when flanking of the eastern side occurs, the eastern side of the bay is severely set down by hurricane force winds that blow from east to west within Galveston Bay. Water that flows around the eastern end of the barrier and into the eastern portion of the Bay, flows into an area where water levels are already significantly depressed, creating minimal influence on peak surge levels at locations in the bays away from the eastern section. Whereas, in the absence of a western section, storm surge steadily propagates through the open “back door” beginning with the surge forerunner several days before landfall. Flow into the bays continues while the storm transits the continental shelf, and approaches and makes landfall, as storm surge builds at the entrance to San Luis Pass. Flanking flow around the western end of the barrier in the likely USACE TSP occurs for a much longer duration and it influences peak surge levels throughout both bays.

References

Gulf Coast Community Protection and Recovery District (GCCPRD). (2016). *Storm Surge Suppression Study Phase 3 Report, Reccomended Actions*. http://www.gccprd.com/wp-content/uploads/2019/02/GCCPRD-Phase-3-Report-Recommended-Actions.pdf