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Economic impacts of storm surge events: examining state and national ripple effects

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Abstract

Understanding socioeconomic consequences of natural disasters both locally and nationally is critical in assessing and informing mitigation strategies to combat future catastrophic threats. We develop a state-level computable general equilibrium model and assess the vulnerability of state and US national economies to surge events affecting coastal communities and strategic industrial assets including petroleum and chemical manufacturing in the south-eastern region of Texas. In addition to enumerating these impacts, our model also assesses loss avoidance associated with one kind of adaptation strategy, a storm surge suppression system, that has been proposed for the region to address growing concerns over storm surge inundation. Our results indicate persistent and adverse long-term impacts of storm surge events on the economies of Texas and the USA without the surge suppression system. Importantly, while neighboring states may temporarily benefit from substitution effects and reallocation of resources, the majority of states will suffer welfare losses as a result of surge-induced impacts in Texas. Adjusting impacts by storms' return probabilities, the average annualized decline in Texas Gross State Product is approximately 0.05% in 2066, corresponding to $5 billion, while welfare and personal income will decline by 0.05% and 0.04%, respectively. Model simulations with the storm suppression system indicate moderation in negative impacts. Our research provides a modeling framework for assessing economic impacts of disasters and further contributes to estimating ripple effects on national and regional economies.

Keywords Storm surge · CGE model · Economic impacts · Natural disasters · Mitigation · Coastal spine

1 Introduction

Tropical cyclones (TC) and associated hazards including damaging winds, excess rainfalls, and storm surges have been threats for coastal communities worldwide (Dasgupta et al. 2011),

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Extended author information available on the last page of the article and the USA is not an exception to this threat. TC-induced storm surges, while rare, unarguably represent the most devastating aspect of tropical cyclones and are a concern for many low-lying areas in the USA, with the East and Gulf coastal communities at particularly greater risk of impacts (Balaguru et al. 2016). Neumann et al. (2015) estimate asset losses due to storm surge and sea level rise (SLR) in the USA could reach $990 billion by 2100. It is further expected that impacts will exacerbate with the ongoing climate change. While there are significant uncertainties associated with modeling the relationship between global climate change and TC frequencies at the global and regional scales (Grossmann and Morgan 2011), studies that are more localized indicate surge heights will become higher with the warmer climate (Lin et al. 2010; Mousavi et al. 2011; Siverd et al. 2020). Furthermore, recent studies link elevated surge heights with SLR and indicate that the heights of storm surge currently associated with a 100-year recurrence interval could become as frequent as one in every 4 years, as a result of SLR creating a higher “launch point” for future storm surges (Frumhoff et al. 2007). These characteristics contribute to the growing societal concern about future damaging storms and heightened policy interests in mitigation projects.

Various coastal adaptations including building flood defense barriers, gradual retreat of population from vulnerable communities, and land-use and zoning restrictions have been considered as means of managing inundation risk (Kousky 2014). However, adoption of particular strategies has generally been slow and contentious primarily due to uncertainty associated with storm-surge impacts and differences in physical and institutional settings that make transferability of adaptation strategies across locations difficult (Harman et al. 2015).

Hard structures such as seawalls, dikes, surge barriers, and levees have been widely adopted in many European counties (e.g., the Netherlands, Germany, UK) and in the USA as a way to manage coastal flooding. Upgrading existing dikes and levees to accommodate rising sea levels has been an on-going concern among European counties (Garrelts and Lange 2011; Secretariaat Deltacommissie 2008) while in the USA, there has been mounting interest in building storm surge barriers, particularly following recent surge events associated with Hurricanes Ike (2008) and Sandy (2012) (Aerts et al. 2013; Davlasheridze et al. 2019; Dircke and Molenaar 2010; Van Ledden et al. 2012).

Estimating economic damages associated with coastal storms, and more specifically the long-term socioeconomic effects and spatial spill-overs of local impacts, are important in order to comprehensively assess the magnitude of economic consequences and inform future mitigation policies. In this paper, we estimate state and national impacts of surge events in the Galveston Bay region, located in the south-eastern part of Texas. The Galveston Bay is one of the most vulnerable regions to storm surge impacts in the USA (SURGEDAT 2017), largely driven by its population and residential and industrial asset exposure. The region contains the fifth most populous metro area (Houston) in the USA with population exceeding 7 million people according to the 2019 US Census (Greater Houston Partnership 2020). Furthermore, Galveston Bay is often referred to as the energy capital; it is the largest center for oil companies, refineries, and petro-chemical plants in the USA. Looming threats of environmental catastrophes due to storage tank failure containing a multitude of contaminants and toxic materials are considered one of the biggest threats to the region in the face of intensifying surge conditions under future climate change (Burleson et al. 2015; Holley 2020). A coastal storm surge suppression system (coastal spine) has long been proposed as a mitigation strategy following 2008’s Hurricane Ike, which brought historic surge levels and severe economic damages (TAMUG 2017). Interest in a barrier as a mitigation strategy for Galveston Bay has been increasingly sustained, especially in response to more recent hurricanes (USACE 2019).

Previous research has offered a modeling framework for evaluating storm surge–induced economic impacts while incorporating various forms of coastal protection as a mitigation strategy. For example, Hallegatte et al. (2011) have used advanced Input-Output (IO) models to estimate impacts for the city of Copenhagen in Denmark, but did not account for spatial spillover effects. Neumann et al. (2015) estimated only direct impacts as measured by asset values due to storm surge and SLR for coastal communities in the USA. Similarly, other studies have focused on delineating the hazard exposure of structures and industries (Atoba et al. 2018; Burleson et al. 2015), as well as quantifying the benefits of a coastal spine realized in terms of avoided direct damages (Davlasheridze et al. 2019). 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 (Rose and Guha 2004; Hallegatte 2015). Disruption of important and strategic assets could reverberate throughout not only the local or regional economies, but also other states and the entire USA, with a persistent consequences in the long term (Cavallo and Noy 2011; Kousky 2014; Norio et al. 2011). In the context of the Galveston bay, assets would include oil refineries, petro-chemical manufacturing, and the Port of Houston.

This study builds on and further extends previous research on this topic by developing a nationwide economic model using the Computable General Equilibrium (CGE) model. The CGE model allows for modeling economic impacts at the sector level, and explores how direct impacts on a specific sector(s) propagate through state economies and the US economy while capturing general equilibrium effects. The CGE model has a rigorous theoretical foundation and has been widely used to model economic impacts associated with policy changes at the sector level (Bergman 1991; Böhringer et al. 2003; Shoven and Whalley 1992; Sue Wing 2009, 2007) as well as economy-wide implications of extreme events (Rose and Guha 2004; Rose and Liao 2005; Rose et al. 2007a, b; Sue Wing et al. 2016), sea level rise (Parrado et al. 2020), and climate change in general (Abler et al. 2009; Hsiang et al. 2017; Palatnik and Roson 2012; Zhou et al. 2018).

In our CGE model, the second-order effects are modeled through direct impacts on the two primary sectors that are the most surge-sensitive in the study area: (i) residential property and (ii) petroleum refinery and chemical manufacturing sectors. Furthermore, the direct impacts through property losses are estimated by coupling outputs from the ADvanced CIRCulation Model (ADCIRC) that generates surge inundations associated with storms of varying intensities with the Federal Emergency Management Agency's (FEMA) US Multi-Hazard (HAZUS-MH) model. The latter estimates losses to residential and commercial properties associated with different levels of inundations. The ADCIRC inundation outputs are also used to spatially delineate petroleum refinery and chemical manufacturing plants prone to surge and estimate output losses associated with their production cessation due to a storm surge. As such, the modeling framework presented in this manuscript integrates three models, ADCIRC, HAZUS-MH, and CGE models, with assumptions related to plant shut-down durations. The impact scenarios are built around the intensity of storms while also factoring in the mitigating effect of a coastal spine. The coastal spine serves as a coastal barrier and achieves its effectiveness by suppressing entry of the water into West and Galveston bays, subsequently reducing the extent of storm surge–induced flood inundation. These updated inundation outputs are fed in HAZUS-MH to estimate exposure of petro-chemical industrial plants and property damage with and without coastal spine protection. The benefits of the spine system are then estimated by comparing the impacts with and without the spine.

Following a 500-year storm surge event (0.2% annual probability of occurrence), the most destructive and lowest probability event evaluated, we estimated Texas' Gross State Product (GSP) in 2066 to decrease by 1.96% corresponding to $83 billion loss in present value GSP and exposed petroleum and chemical manufacturing firms cease operations for approximately 1 month. All macroeconomic indicators except for government expenditures and investments in the state will decline in 2066, with the value of net exports (exports – imports) suffering the most profound decline by approximately 4.8% compared to the business as usual scenario (BAU) in the same year. The BAU assumes undisrupted (no surge impact) growth trajectory of the economy. The welfare will be 1.87% lower and consumption will decline by 2.6%. Total government expenditures will increase in response to surge events and will be 0.5% higher in 2066 likely due to increases in output prices in the major industries (e.g., petro-chemical, electricity). We also estimated total investment to increase by 0.8% in 2016. One possible explanation is an increase in the prices of investment goods and assets (e.g., housing). Surge impacts are also estimated to have long-term adverse socioeconomic effects nationally; however, estimated effects are smaller in magnitude. The US GDP is estimated to be 0.3% lower, corresponding to an estimated present value of a $89 billion loss. US net exports will decline by 1.6%, household consumption will be 2.6% lower, and overall welfare will be reduced by 0.23%.

Our CGE model results further indicate that while neighboring states will experience positive GSP, as a result of income and welfare gains partially due to substitution of inputs of production and inflows of labor and skills, 30 states exclusive of Texas will have lower GSPs in response to a surge event in Texas. In terms of 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 Galveston bay. The coastal spine mitigates impacts on Texas' GSP by elevenfold, which still declines in 2066, however, by only 0.18%. Importantly, storm suppression system will induce positive growth in the value of net export in 2066 by an estimated 2.81%. Similarly, although major macroeconomic indicators on national accounts will still exhibit declines in 2066, the rates of decrease were estimated as relatively small. For example, with the coastal spine protection, the US GDP will be 0.04% lower and welfare will decline by only 0.05% relative to BAU scenario if the 500-year surge event disrupts housing and petroleum and chemical manufacturing sectors in the southeastern Gulf Coast of Texas.

Accounting for the annual return probabilities of storms differing in intensity (i.e., 500-year, 100-year, and 10-year storms), we estimated the average annualized loss to be relatively small. Specifically, TX GSP in 2066 will be approximately 0.05% lower, while the welfare and income will decline by 0.05% and 0.04% respectively without the coastal spine. The expected annualized loss on US national GDP is 0.01%. We also estimate Texas government expenditure in 2066 to increase, however, negligibly.

The remainder of the paper is organized as follows. In Section 2, we provide background information about the study area. In Section 3, we review methodology and the integration of the three different models. Section 4 presents scenario development for impact analysis and in Section 5, we present CGE model results. Section 6 provides extension by incorporating storm return probabilities. Finally, Section 7 concludes with future directions.

2 Study area

The study area, the Galveston bay region covering Galveston, Harris, and Chambers counties, is located in the southeastern part of Texas Gulf coast, and is surrounded by the Galveston and Trinity bays (see Fig. 1). The region covers 2727 mile^2 and is one of the most populous in the USA; according to the 2010 US Census, the region's 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 USA and accounts for approximately 93% of total population of the study area. A recent report by the Houston-Galveston Area Council indicates that the population will surpass 6.3 million by 2040 (HGAC 2017).

The Galveston Bay, often referred to as petro-chemical capital of the USA, houses one-third of the petroleum refineries in the USA 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 the largest port in the USA in terms of import and export tonnage (Port of Houston 2017). The region contributes approximately a quarter of the Texas GSP with an estimated GSP value of $341 billion, and employs over 60% of the state's total population (MIG 2012). In terms of sectoral contributions, chemical manufacturing contribution to Texas GSP was the highest among manufacturing subsectors reaching $56.1 billion in 2015, followed by petroleum and coal products manufacturing at $43.4 billion (Texas Controller of Public Accounts 2020).

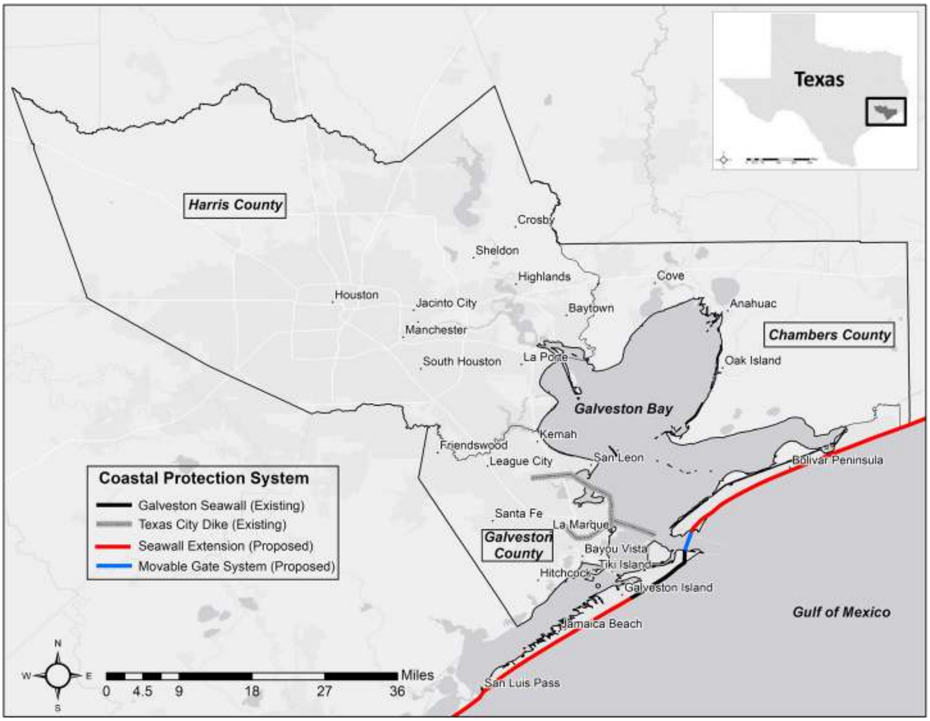

Fig. 1 Impacted area. Source: Davlasheridze et al. (2019). Notes: The figure shows the Galveston bay region covering Galveston, Harris, and Chambers counties and also indicates the location of the suggested coastal spine system, which will connect the existing Galveston seawall with the proposed extensions and a retractable gate system, covering approximately a 57-mile-long barrier along the Galveston bay

The Galveston Bay is also one of the most flood- and surge-prone areas in the USA (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 destructive storms. While destruction of valuable assets is expected to generate sizeable economic disruptions locally and regionally, the greater vulnerability also arises from the potential environmental catastrophe that could be triggered due to failure of storage tanks and containers that store deadly chemicals and toxins (Burleson et al. 2015).

The most recent surge event was caused by the 2008's Hurricane Ike, which spurred the initial policy discussion around the coastal spine system 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 Fig. 1). The design standard of the barrier and subsequent cost estimates are based on a protection level of 1/10,000 years (Jonkman et al. 2015). This is commonly used protection level for storm surge barriers in the Netherlands for highly densely populated areas and is the highest in the world (Brouwer and Kind 2005; Kind 2014). Thus far, the US Army Corps of Engineers (USACE) has employed a design standard 1/100 years for flood control structures, and while for densely populated areas the exceedance standards of 1/500 years have been recommended, they have not been operationalized in practice (Galloway et al. 2006).

3 Methodology overview

The steps in this assessment of storm surge impacts include (1) assessing impacts on residential housing[1] and petroleum refinery and chemical manufacturing sectors, with and without coastal spine protection; (2) developing a multi-year, multi-sector CGE model; and (3) modeling surge impacts on the overall economy. The following subsections summarize key elements of these procedures.[2]

3.1 Synthetic proxy storms

Three proxy storms (500-year, 100-year, and 10-year) were generated using the ADCIRC model, assuming a present mean sea level (0.9 ft. NAVD88) (Ebersole et al. 2015). 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) (Hope et al. 2013; Westerink et al. 1992). ADCIRC outputs were used to assess and delineate hazard exposure of residential and petro-chemical plants for the Galveston Bay region. Of the three proxy storms, the 500-year is the strongest with a 0.2% chance of occurrence in any given year. Characteristics of the proxy storms are reported in supplementary material (Appendix A Table A1).

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[1] Throughout residential housing, housing and dwelling sectors are used interchainingly.

[2] More details pertinent to direct loss estimation in particular are provided in Davlasheridze et al. (2019) and Atoba et al. (2018).

3.2 Modeling property losses

The ADCIRC model outputs (e.g., peak surge-height) 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 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 (Ding et al. 2008; Scawthorn et al. 2006a, b). The HAZUS-MH default building inventory is based on US Census block group-level data containing information about population demographics, structural characteristics of buildings (e.g., square footage), and numbers and locations of critical infrastructure (e.g., bridges, hospitals, utility lifelines, schools). The HAZUS-MH Comprehensive Data Management System (CDMS) permits users to update and manage default datasets 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, such as year built, assessed value, building materials, number of storeys, and square footage. Relevant water depth-damage curves from the USACE Galveston District and the Federal Insurance Administration were then employed to estimate the direct loss to residential property. Impacts were estimated with and without a coastal spine system by factoring the spine system during ADCIRC model runs. Appendix B Figure B1 of supplementary material depicts the map of loss avoidance with coastal protection in a 500-year storm surge event.

3.3 Output losses for petroleum refinery and chemical manufacturing sectors

To estimate direct economic losses for petroleum refinery and chemical manufacturing sectors, several assumptions 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 the US Department of Energy estimates, these two causes have constituted over 80% of electrical problems in the US refineries during 2009–2013, of which 14% were caused by inclement weather incidents (i.e., hurricanes, winds, thunderstorms).

Hence, rather than modeling industrial property losses, we calculated total value of production output losses for each industrial plant and aggregated them at the sectoral level. In Appendix A Table A2 of supplementary material, we report the North American Industry Classification System (NAICS) codes and 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. (2019), we employed petro-chemical manufacturing plant-level data from Chemplants[4] and the 2012 Census of Manufacturers. The Chemplants 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 number of establishments, number of employees,annual payrolls, total cost of

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[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-day shutdown due to power outage (Hydrocarbon Publishing Company 2016).

[4] Available at www.chemplants.com

materials, total value of shipment and receipts for services, value added,total capital expenditure, and total output for NAICS classified (2–6 digit) industries at a zip code level.

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

As an illustration, in Appendix Figures B2 and B3, we depict plant exposure for the 500-year proxy storm without and with coastal protection along with their respective inundation levels.

3.4 Shut-down duration scenarios

To create plausible plant shut-down duration scenarios, we used the U.S. Department of Energy (2009) reported plant level shutdowns, restarting days, and the number of days during which refineries were operated at partial capacity in response to 2005 and 2008 hurricanes, respectively. The average number of shutdown and restarting days was approximately 18 in 2005 and 33 days in 2008, while the sample average for both years was 26 days. 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 shutdown.[5] Individual plant level output losses were then aggregated up to NAICS industry. Output losses for petro- and chemical-manufacturing sectors along with losses (structure and contents) to the dwelling sector associated with different storm surge and plant shut-down scenarios were converted to 2016 dollars using Urban Consumer Price Index (see Table A3 of Supplementary Material).

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 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 storm, while the residential housing sector still sustains damages, albeit substantially smaller relative to a scenario with no coastal protection.

3.5 CGE 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

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

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. A nested Cobb-Douglas-constant elasticity of substitution (CD-CES) functional form was adopted in the production functions for producers who maximize profits. Households maximize utility level, which is also a nested CES function of consumption goods constrained on budget constraint (total income minus savings). The details of the nesting structures are discussed in the appendix (see Figures C.1 and C.2). Government collects taxes and uses tax revenues to purchase goods and services. The model also covers both the domestic (i.e., intranational) and international trade.

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 solves for equilibrium prices and quantities using these three principles as guides. The model is described in detail in Appendix C of supplementary material.

A recursive dynamic interstate 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) covering 536 industrial sectors for 50 states and Washington D.C. for the year 2016. These finer-scale sectors were aggregated to 23 industrial sectors (see Appendix A Table A4 of supplementary material) including the key sectors of interest such as petroleum refineries (i.e., petro products), chemical manufacturing (including petro-chemicals), and dwelling (residential housing) sectors.[6] The latter, as shown in Appendix A Table A2 of supplementary material, is defined by aggregating the following IMPLAN sectors: construction of new single-family residential structures (59); construction of new multifamily residential structures (60); construction of other new residential structures (61); and maintenance and repair of construction of residential structures (63).[7]

From SAMs, we derived labor and capital incomes, tax revenue by type of tax (production, capital, and labor taxes), 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 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 Appendix A Table A5 of supplementary material.

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[6] 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.

[7] These sectors are different from the IMPLAN 449 Owner occupied dwelling sector, which estimates "what owner/occupants would pay in rent if they rented rather than owned their families." This definition more closely aligns with flow variable as opposed to a stock.

The standard practice in our dynamic recursive CGE model is followed by assuming that economic growth is driven by exogenous variables including population growth, productivity growth (multifactor, labor, and energy productivity), and growth in the capital stock represented by a capital accumulation equation, which is a function of previous year capital stock, the depreciation rate (fixed), and a fixed savings rate that determines investment flows (see equation C.6 in the supplementary material).

4 Developing economic impacts of storm surge

4.1 Business as usual scenario

The economic impacts analysis presented in this paper involves comparing economic conditions without and with surge events. The economy without a storm surge incident 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 between 2016 and 2066 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 2016 US Census data. In the baseline scenario, a 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% per year initially, falling to a growth rate of 0.5% per year by the end of the modeling period. Similarly, capital quality changes in the model. We assumed that capital quality will rise by 2.5% per year initially, falling to a growth rate of 0.5% by the end of the modeling period.[8]

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% per year over the modeling period (Appendix A Table A5 of supplementary material), consistent with published forecasts. 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.

4.2 Impact scenarios

Economic indicators with storm surge events were derived by also simulating the model forward in time with changes in selected parameters (e.g., sector productivity growth rates) to

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[8] In our CGE model, labor and capital qualities are referenced in relation to productivity growth rates specifically related to labor and capital inputs of production, respectively.

reflect the impacts of surge events on underlying economic conditions. We note that in modeling surge impacts, we consider a one-time, temporary shock to a specific sector(s) in Texas at the beginning of the period (year 2016) and simulate its General Equilibrium (GE) effects over 50-year time span. Storm surge impacts affect how efficiently and intensively the inputs are utilized in production. Thus, we change the scaling parameter which affects TFP associated with all input factors (i.e., capital, labor, energy, and material) in a corresponding sector (i.e., petro, chemical manufacturing, and dwelling sectors) in the state of Texas only. The scaling parameter is adjusted to reflect the output losses (Table A3 of supplementary material). 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 relative to the BAU scenario for the petro product sector. Hence, the scaling parameter is adjusted until the output loss solved in the CGE model (the output difference between the counterfactual and BAU scenarios) matches the estimated losses as shown in Appendix Table A3. Similarly, we adjust the scaling parameter of TFP associated with all input factors for chemical manufacturing to match the estimated direct output loss in this sector.[9]

Losses to the housing sector directly affect a household's capital endowment. However, in the CGE model developed for this study, capital endowment is household- and state-specific, which limits our ability to apply the shock only to the "residential" part of the capital. Thereby, modeling losses as negative shock to all types of capital the household owns including a productive capital may overestimate the impacts. Instead, similar to the manner taken to shock outputs in chemical and petro sectors, we change the scaling parameter of TFP in TX's housing sector and adjust this parameter until the simulated output losses in the housing sector matches the estimated residential housing damages reported in Appendix Table A3. Appendix Table A6 shows TFP changes and corresponding sectoral output losses in the starting year in Texas.[10] We acknowledge that shocking the housing sector through TFP scaling parameter likely underestimates the impact yielding lower bound of impact estimates.[11]

To account for construction costs of a coastal spine when building the "with protection" scenarios, we draw upon the literature modeling funding schemes for various public infrastructure spending (Boccanfuso et al. 2014; Kim et al. 2011; Li 2015) as well as the CGE literature related to climate adaptation (Bachner 2017; Wang et al. 2009). Specifically, the latter studies regard adaptation spending as planned and anticipated investment (which likely is the case for the coastal spine (USACE 2019)) which is commonly carried out by the government and funded through taxes. In the CGE model, tax revenues come from three channels—taxes on production, taxes on capital, and taxes on labor. We chose to model investment cost through the increase in production taxes in Texas only, assuming that only its population will bear the full cost of investment, as Texas does not impose state income tax on its residents. More specifically, we added a scaling parameter associated with taxes on

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[9] We then use adjusted TFP values for actual CGE simulations. We acknowledge that using adjusted TFP may underestimate general equilibrium (GE) effects; however, since TFPs are sector- and state-specific, the bias is small. Please refer to GE effects estimated for the year 2017 for Texas and the USA in Tables 1 and 2, respectively.

[10] In the CGE model, the base year 2016 serves as the benchmark year, so that at the base year, all price indexes are equal to one. Prices are relative to the base year and to the numeraire. All the changes we report start in the following year 2017.

[11] Our model simulations indeed validated that shocking overall household capital endowment as opposed to shocking the specific "dwelling" sector for output losses yields upper bounds of impacts (refer to Appendix Tables A15 and A16).

production and adjusted the scaling parameter until the amount of increased tax revenues in Texas in 2016 equaled engineering cost of the dike. The latter is estimated at approximately 8.03 billion with a 40% margin (Jonkman et al. 2015). This increase accounted to approximately 6% of total revenues received in 2016.[12] Additional taxes raised to fund the coastal spine are expected to generate construction activities and further benefit the economy. In the model, we distribute these funds to boost output in the construction sector by adjusting the scaling parameter which affects TFP associated with all input factors in the aggregated construction sector (see Table A.2) until the output in the sector increases by $8.03 billion in the starting year.[13]

With the primary purpose to evaluate the impacts of storm surge events in a particular year, the CGE model is simulated forward given the changes of exogenous variables as discussed in the previous section, assuming the housing, petro-, and chemical-manufacturing sectors are impacted simultaneously by surge events in the starting year. Holding other factors constant, we are able to isolate the effects of changes in economic conditions arising from state-level housing damages and sectoral output losses as a result of storm surge events if happened in a particular year and location and further study their long-term ramifications over 50-year span.[14]

5 CGE model results

For brevity, the results reported in Table 1 correspond to 500-year storm surge events assuming industrial plants are down for 33 days. The impacts associated with 100-year and 10-year storm surges are reported in Appendix Tables A12 and A13 of supplementary material. As seen in Table 1, a 500-year storm surge event imposes a substantial economic toll for the Texas economy as indicated by declines in major economic indicators such as per capita income, total consumption, net export, GSP, and welfare in the starting year.[15] Specifically, Texas' GSP will be approximately 1.96% lower in 2066, relative to the BAU if no coastal spine protection is considered, and the impact is mitigated to a 0.18% decline with the protection. Furthermore, there is a welfare loss associated with storm surge impacts that lingers over the long term, indicating a decline of 1.87% without a coastal spine in contrast with a decline by 0.44% with a coastal spine in place, relative to BAU in 2066. Per capita income decreased partially due to the shutdown of major industries, which directly affect

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[12] Alternative funding structures would assume federal government to fully fund the coastal spine or to cover certain percentage of it. This would spread the cost share across all states and lesson the burden on Texas taxpayers. With adopted approach, however, we consider a scenario when construction is fully funded locally.

[13] Another way to model this link is to adjust government expenditure in construction sector, but government expenditures in our model are region-specific for six types of public sectors.

[14] We also consider scenarios when the surge impacts individual sectors such as (i) dwelling and (ii) petro and chemical manufacturing sectors. These results are available upon request.

[15] "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 our CGE model, we measure the change in a Hicksian money-metric welfare indices between the BAU (W_0) and counterfactual scenario (with storm surge) (W_1) as follows: $\mathrm{EV} = 100 \cdot \frac{W_1 - W_0}{W_0}$. These indices correspond to income-weighted sum of individual EVs and are measured as an aggregate expenditure of the representative agent on consumption (Fan et al. 2018; Markusen and Rutherford 2004; Rutherford and Paltsev 1999).

Table 1 CGE results for selected decades for Texas economy

	Per capita income	GSP	Total consumption	Total investment	Total government consumption	Net export	Welfare
Panel A: No protection relative to BAU							
2017	−0.94%	−1.05%	−2.02%	1.16%	0.28%	−19.22%	−1.25%
2026	−1.11%	−1.25%	−2.23%	1.02%	0.27%	−6.80%	−1.41%
2036	−1.28%	−1.45%	−2.42%	0.90%	0.28%	−5.07%	−1.56%
2046	−1.42%	−1.46%	−2.52%	0.85%	0.32%	−4.47%	−1.67%
2056	−1.54%	−1.81%	−2.57%	0.83%	0.38%	−4.77%	−1.77%
2066	−1.67%	−1.96%	−2.62%	0.77%	0.46%	−4.78%	−1.87%
Panel B: Protection relative to BAU							
2017	−0.63%	−0.11%	−0.50%	−1.16%	1.18%	29.32%	−0.50%
2026	−0.62%	−0.13%	−0.49%	−1.15%	1.19%	8.35%	−0.49%
2036	−0.61%	−0.15%	−0.48%	−1.12%	1.20%	5.00%	−0.48%
2046	−0.60%	−0.16%	−0.46%	−1.08%	1.20%	3.79%	−0.46%
2056	−0.58%	−0.17%	−0.44%	−1.06%	1.21%	3.18%	−0.44%
2066	−0.59%	−0.18%	−0.44%	−1.06%	1.21%	2.81%	−0.44%

Notes: The economy-wide impacts resulting from a 500-year storm surge impact on housing, petro-, and chemical-manufacturing sectors resulting in 33-day shutdown of production operations simultaneously with and without coastal spine protection

Source: Author

employment and labor wages in petro- and chemical-manufacturing sectors. Correspondingly, household consumption fell as income decreased and prices in selected sectors increased (e.g., petro products, chemical, electricity, and residential housing). Computing GSP in the CGE model uses the income approach and is defined as labor and capital earnings plus government transfers. Following a 500-year surge event, GSP decreased as labor and capital earnings in the affected industries were reduced. Consequently, welfare measurement that is based on aggregate expenditure of the representative agent on consumption decreased as consumption declined. Among macroeconomic indicators, the largest decline is observed in net export value (export – import), due to output losses in primary sectors and a rise in the prices of goods that are heavily traded intranationally and internationally (e.g., petroleum, chemical products).

As discussed above, economic growth in the CGE model is driven by population, productivity (multifactor, labor, and energy productivity), and growth in the capital stock. Although these annual growth rates are exogenous, the values in the starting year will affect values solved for future years. Our results indicate adverse impacts linger over the long term, which is consistent with previous empirical studies suggesting persistent declines in various macroeconomic indicators in response to disasters (Hsiang and Jina 2014). We also note that short-term impacts of a 500-year storm surge incident are relatively smaller in magnitude compared to its long-term effects (Appendix Figures B4 and B5). These patterns are consistent with previous findings suggesting that impacts could be multiples of immediate damages (Noy 2016).

In terms of sectoral impacts in Texas, we should note that all aggregate sectors experience adverse shock due to the 500-year surge event as indicated by declines in output relative to the BAU scenario (Appendix Table A7).[16] The petroleum products and chemical manufacturing sectors are the most sensitive to storm surge events, which is not surprising given that 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 two other sectors that experience 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 is markedly lower than the effects estimated for the scenario with no coastal, all relative to the BAU (Appendix Table A8).

The direct and rippling effect through interconnected sectors and intranational, international trade results in about 0.3% loss in US GDP without a coastal spine; the magnitude of impact is mitigated with coastal protection with GDP decreases of 0.04% in the spine protection scenario in 2066, relative to the BAU scenario in the same year. Welfare is also lowered by 0.23% and 0.05% without and with protection, respectively, relative to the BAU. 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 without a protection, which then starts to decline in the following decades (Table 2).[17] This trajectory reverses with the coastal spine.

As for the immediate and the long-term impacts on other states, the model results indicate that neighboring states of Arkansas, Louisiana, New Mexico, and Oklahoma show slight gains in GSP, possibly due to resource substitution and labor inflows from the adverse shock of storm surge in Texas. However, other states not including Texas will have a lower GSP (see Appendix Tables A10 and A11). The coastal spine attenuates the effects of storm surge spatially and economically in the long term.[18] As with any man-made protection structure, it is possible the coastal spine to fail to provide designed protection. As an extension, we also simulated models assuming the coastal spine achieves only 50% of direct loss avoidance capacity. The estimated impacts for all macroeconomic variables as expected are bounded between “no protection” and the “protection” scenario presented as main results in the manuscript (see Appendix Panel C of Table A14 in supplementary material).

6 Expected annualized impacts

Storms vary in annual return probabilities, and subsequent impacts and loss avoidance benefits of mitigation should be probability adjusted. To calculate expected impacts, we employ the strategy developed in Kousky et al. (2013) and estimate average annualized impacts on various economic indicators as the weighted sum of the impacts associated with different storms. The weights correspond to individual storm return probabilities (i.e., 500-year storm has estimated 0.2% probability of occurrence in a given year, whereas 100-year and 10-year storms have associated annual probabilities of one and 10%, respectively). A further assumption is that the

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[16] Sectoral results for 100-year and 10-year surge events are available upon request.

[17] Corresponding dollar values are reported in Appendix Table A9 of Supplementary Material.

[18] Full sets of state-by-state results are available upon request

Table 2 CGE results for selected decades for US economy

	Per capita income	GDP	Total consumption	Total investment	Total government consumption	Net export	Welfare
Panel A: No protection relative to BAU							
2017	−0.10%	−0.08%	−0.09%	−2.02%	0.14%	0.003%	0.68%
2026	−0.12%	−0.10%	−0.11%	−2.23%	0.13%	−0.005%	2.54%
2036	−0.15%	−0.13%	−0.15%	−2.42%	0.11%	−0.006%	−2.93%
2046	−0.18%	−0.16%	−0.19%	−2.52%	0.11%	0.003%	−1.59%
2056	−0.21%	−0.19%	−0.23%	−2.57%	0.11%	0.016%	−1.50%
2066	−0.23%	−0.22%	−0.28%	−2.62%	0.12%	0.033%	−1.56%
Panel B: Protection relative to BAU							
2017	−0.06%	−0.072%	−0.03%	−0.06%	−0.14%	0.12%	−0.80%
2026	−0.06%	−0.072%	−0.03%	−0.06%	−0.14%	0.12%	−2.58%
2036	−0.05%	−0.072%	−0.04%	−0.05%	−0.14%	0.12%	2.34%
2046	−0.05%	−0.070%	−0.04%	−0.05%	−0.14%	0.12%	0.92%
2056	−0.05%	−0.069%	−0.04%	−0.05%	−0.14%	0.12%	0.63%
2066	−0.05%	−0.071%	−0.04%	−0.05%	−0.15%	0.12%	0.51%

Notes: The nation-wide impacts during the first decade (2017–2066) resulting from a 500-year storm surge impact on housing, petro-, and chemical-manufacturing sectors resulting in 33-day shutdown of production operation simultaneously with and without coastal spine protection

Source: Authors

impacts are constant in between return periods and correspond to the average of impact indicators at each end point. Correspondingly, the probabilities between return periods are estimated as the difference between the return probabilities at each end point. Using this approach, in Table 3, we present annualized impacts using estimates in 2066 for Texas and the USA. The average annualized impacts are estimated relatively small. We estimate Texas GSP to be 0.05% lower relative to the BAU scenario, while the net export declines by 0.11%. Meanwhile, government expenditure is expected to increase annually by 0.008%. The US GDP is estimated to decline by 0.01% and changes in national government expenditure are negligible in the long term.

Table 3 Annualized impacts without a spine for the selected economic indicators in 2066 (% change relative to BAU in 2066)

	Income	GDP	Welfare	Investment	Total consumption	Government consumption	Net export
TX	−0.040	−0.047	−0.049	0.036	−0.080	0.008	−0.111
USA	−0.005	−0.007	−0.006	0.006	−0.010	0.000	−0.036

Notes: The table presents annualized (i.e., expected) impacts without a coastal spine on selected macroeconomic variables measured in percentages, using the variable values relative to the BAU in 2066

Source: Authors

7 Conclusion

Storm surge poses threats of inundation for many coastal communities in the USA. While the impacts of flooding can be thought of as local, locations such as our study area of the Galveston Bay in Texas that house strategic national assets, local impacts can have profound national and regional socioeconomic ramifications. Hence, any local adaptation strategy will have important positive spillover effects on the economy and welfare of other states and the nation as a whole. Understanding the impacts of surge events locally and across other states further informs the feasibility of adaptation strategies proposed to combat future threats of storm surge inundation.

In this paper, we specifically focus on a surge barrier as the mitigation strategy proposed for Galveston Bay communities in Texas. We built a state-level CGE model and estimated storm surge impacts by integrating a storm surge model and a hazard loss estimation model with the recursive dynamic CGE model, with assumptions made related to plant shut-down durations. Our results indicate broad economic disruptions associated with storm events when the petroleum and chemical manufacturing plants shut down for approximately 1 month and Galveston Bay communities suffer substantial residential property losses. Specifically, a 500-year storm event will cause the Texas economy to shrink by an estimated 2% in 2066 and the US GDP to decline by 0.3%. All economic indicators in Texas will decline except for governmental expenditures and total investments, with net exports (exports minus import) suffering the most profound decline by 4.8%. The bulk of these adverse shocks are mitigated when the coastal spine is factored in as the mitigation strategy. Estimated annualized average impacts however were relatively small. Specifically, in the long term, Texas GSP is estimated to decline by $5 billion annually and the US economy to shrink by 0.01% without a coastal spine. The average expected loss in net exports will be approximately 0.11% without the coastal spine, while the Texas government expenditures will increase by 0.008%.

Our results shed light on the magnitude of both the spatial and temporal effects of surge-induced impacts on coastal communities that house assets that are strategic to the national economy. While it was beyond the scope of this research, it should be noted that the surge events also adversely impact human lives and will likely induce temporal or permanent migration of labor from impacted areas. These shifts in labor supply will have socioeconomic implications not only in coastal regions of Texas but for other regions gaining population. Understanding labor market dynamics of surge impacts is an important extension of the current study. We note that for long-term scenarios considered in this study, it is plausible to assume that there will be an evolution of major economic sectors in the region of interest (e.g., fossil fuel) with one potential possibility of stranded assets in the energy industry as clean energy gains more prominence. Such a shift will clearly diminish the role of petroleum sector and likely also decrease the ripple effect of surge events through this major sector. Exploring these alternative scenarios of energy mix in the future is a research extension that should be pursued.

Flooding conditions are expected to intensify in response to both climate change–induced SLR and changing climatology of TCs (Bender et al. 2010; Emanuel 2013; Vousdoukas et al. 2018). The former is expected to also increase storm surge heights and the probability of intense surge events (Frumhoff et al. 2007). Modeling TC flood variation under future climate, however, remains challenging as the global circulation models (GCMs) cannot resolve TCs well due to their lower resolutions. Several recently developed high-resolution GCMs have successfully downscaled climate models to study TCs under climate change, but due to their computational expense, their practical use for flood hazard assessments have remained challenging. The recent study by Marsooli et al. (2019) evaluates the compounding effects of SLR and TC climatology change along the US Atlantic coast and the Gulf of Mexico region, and suggests that for the Gulf of Mexico coastal counties, TC climatology change in the late twenty-first century will be 40% larger than the effects induced by the SLR. Incorporating the effects of the changing climatology of TC and the SLR is yet another research extension that should be pursued. Finally, our study does not account for the loss of ecosystem services associated with the storm suppression system. Accounting for this loss will inform both the design as well as the costs and benefits of the specific barrier type most suited for this specific ecological and human system.

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