Identifying the Future Costs of Flooding in the Houston-Galveston Region

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Dedicated to the conservation and protection of the Texas shoreline
Texas A&M University at Galveston

Prepared for:

TEXAS GENERAL LAND OFFICE
ESTABLISHED 1836

Contract No. 17-358-000-A389

Final Report

Executive Summary

In the wake of recent disasters, and with an increased understanding of the impact of future events along the Texas coast, a coastal barrier system has been proposed and studied to protect the Houston-Galveston Region from the adverse impacts of storm surge. While preliminary results indicate that a coastal barrier system is effective in reducing storm-surge related damage, no study has assessed future damages as a result of predicted development and potential sea level rise. The purpose of this study was to estimate and compare flood losses resulting from storm surge in two time periods, over four synthetic storms in Harris, Galveston, and Chambers Counties. In addition, we also compare estimated flood damages in the presence/absence of a 17' coastal barrier and with the addition of 2.4 feet of sea level rise.

To accomplish this aim, we coupled two analyses. First, we forecasted change in developed land cover from 2015 to 2080. Land cover predictions were modeled through the use of neural networks and demonstrated approximately 82% accuracy when hind-casting previous development. Second, we parameterized a flood damage estimation model with updated residential housing characteristics and inundation depths derived from Advanced Circulation (ADCIRC) hurricane models. Damage was estimated for 24 storm scenarios including four sets of storms (10/100/500 year and hind-casted Hurricane Ike) with and without a coastal barrier under current conditions, under predicted 2080 development, and under predicted 2080 development with 2.4 feet of sea level rise.

A summary of results includes the following:

- Land cover predictions indicate a 48% increase in developed area from 2015 to 2080 across the three-county study area.
- The forecasted increase in developed land cover corresponds to an estimated 148% increase in the number of residential structures.
- The change in developed land and associated residential structures increases inundation exposure 125% from 2015-2080 for a 100-year event, and 143% for a 500-year event.
- The addition of 2.4 feet of sea level rise more than doubles residential inundation exposure from 2015-2080, with a 262% increase for a 100-year event and 271% for a 500-year event.
- Under current development and sea level rise conditions, the presence of a coastal barrier reduces estimated residential storm surge damage for a 100-year storm from $4.3 billion to $1.3 billion (69% reduction), and from $8 billion to $2.3 billion (71% reduction) for a 500-year storm.
- Under predicted 2080 development and current sea level rise conditions, damage is reduced from $8.3 billion to $2 billion (76% reduction) with the presence of a coastal barrier for a 100-year storm. Damage from a 500-year storm is reduced from $15.7 billion to $3.8 billion, a 76% reduction.
- With predicted 2080 development and 2.4 feet of sea level rise, the presence of a coastal barrier reduces residential damage 80%—from $18.8 billion to $3.7 billion—for a 100-year storm. Damages resulting from a 500-year storm are reduced from $31.8 billion to $6 billion, an 81% reduction.

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Introduction

The Houston-Galveston region is one of the most flood-impacted areas in the nation. Due to its vulnerability to tropical storm events, the metropolitan area is regularly subjected to billion-dollar losses when residential and industrial areas are inundated from storm surge. Based on expected sea level rise, more intense rainfall episodes, and a rapidly growing population, the flood loss problem is becoming worse. In recent years, scientists, policy makers, and elected officials have been calling for a comprehensive coastal storm surge protection system for the Galveston Bay region, yet little is understood on the future costs of flooding in the Houston-Galveston Region.

Project Goals and Objectives

The primary goal of the "Future Costs of Flooding" study is to further articulate the effectiveness of a coastal storm surge protection system, both spatially and temporally. We address this objective through the estimation and identification of the changes in residential damage from coastal surge based on forecasted residential development with and without a coastal spine surge protection system in place. More specifically, we compare the expected losses from storm surge for four storms of varying probabilities with existing and predicted development in 2080 based on development trends and changing environmental conditions. The Future Costs of Flooding study was approached through five separate objectives:

- The first objective, *Quantify residential flood losses*, was undertaken to establish a baseline of damages with current development, both with and without a coastal barrier in place.
- The second objective, *Development prediction,* was carried out to spatially predict land cover change and development patterns out to 2080.
- The third objective, *Development of ADCIRC wave models*, integrated ADCIRC storm surge outputs into HAZUS damage estimation software.
- The fourth objective, *Estimation of future losses with sea level rise,* re-estimates storm surge damage based upon the presence of predicted development and 2.4 feet of sea level rise, both with and without a coastal barrier in place.
- Finally, the fifth objective compares all damage estimates across scenarios to quantify the effects of a coastal spine system in current and future conditions.

The completion and integration of these five objectives allowed us to quantify and compare the benefits of a coastal spine across multiple scenarios. The remainder of the "Future Costs of Flooding" report will describe the methodologies, results, and overarching conclusions of the study. First, we detail our approach to forecasting future development across the three-county study area. Next, we describe the methods used to integrate ADCIRC into HAZUS-MH, modify and improve HAZUS-MH for the study area, and estimate damage for four storms across multiple scenarios. We then compare the results of the 24 damage estimations in 2015 and 2080 with and without a coastal spine.

Methods

The following sections describe the three major methodological approaches used in the Future Costs of Flooding study. First, we detail the approach to predicting land cover over the Houston-Galveston region. We then describe the methods used to make the link from developed area to counts of residential structures in each census block used for damage estimation by HAZUS-MH. Finally, we discuss our approach and improvements to damage estimation using a combination of HAZUS-MH and ADCIRC surge outputs.

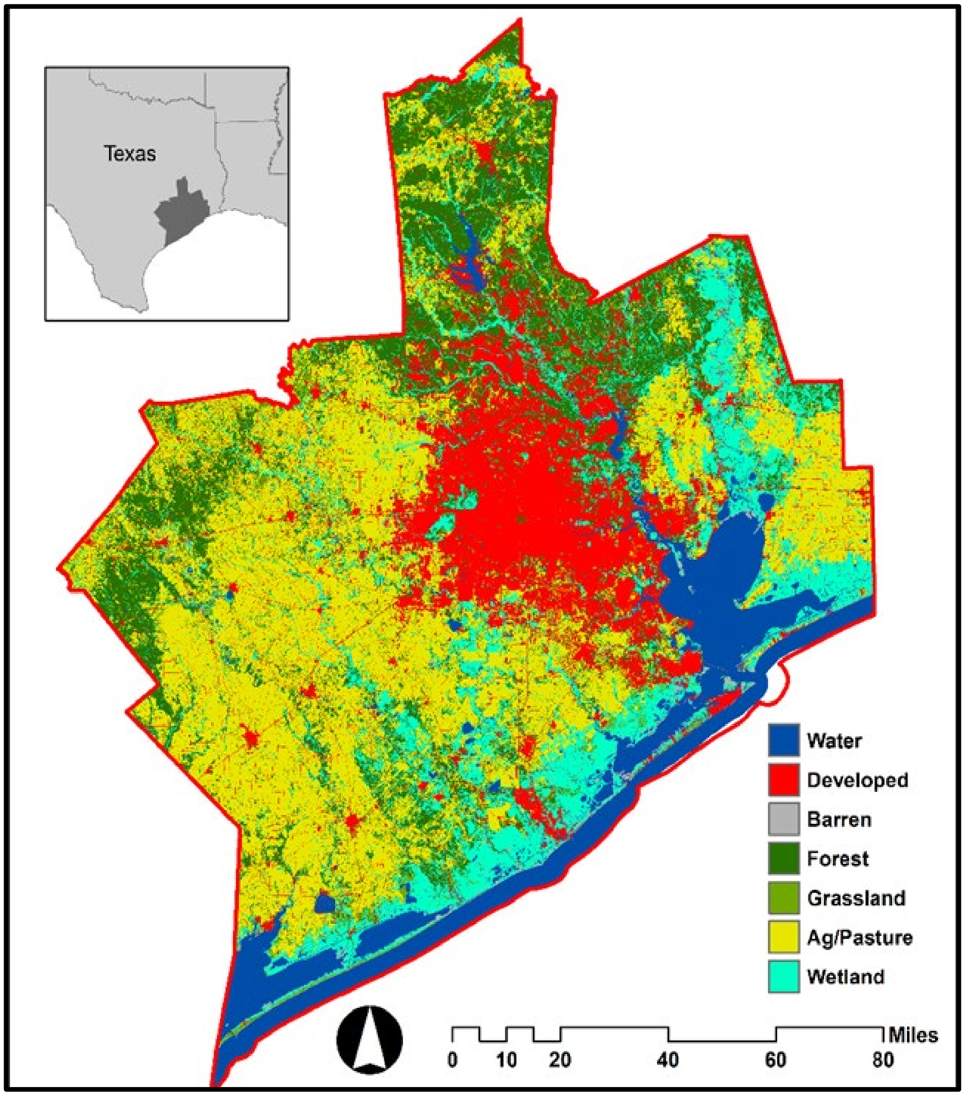

Figure 1. The 13-County HGAC Study Area accompanied by the 7-class land cover data.

Future Land Cover Prediction

Forecasting land cover change is a data-intensive, three-step process consisting of *land change analysis, transition potential modeling,* and *change prediction*. This approach integrates both spatial and statistical methods to quantify past land cover change, develop and validate statistical drivers of changes, and spatially forecast future land cover. The following describes our approach to predicting land cover change—with the focus on developed areas—and the resulting outcomes for the Houston-Galveston region.

We began by accessing land cover data sourced from the U.S. Geological Survey National Land Cover Dataset (NLCD) for the years 2001, 2006 and 2011. These data were extracted to a 13-county study area boundary[1] (see Figure 1). The NLCD is a 30-meter resolution land cover product that is classified at Anderson Level II. In order to improve land cover predictions, we aggregated land cover classes to a coarser level, similar to the Anderson I classifications. This reclassification resulted in the aggregation of the initial 17 land cover classes to seven land cover classes for all three years (see Figure 1).

Land Cover Change Analysis

Following data preparation, we conducted the initial land cover change analysis to determine the changes that have occurred from 2001 to 2006 in the 13-county study area. Land cover change during this time period provides a sense of what has occurred on the landscape and serves as the explanatory variables for the next analysis steps. Not surprisingly, the developed land cover category, which consists of impervious surfaces, experienced the largest increase of all seven land cover types with over 150 added square miles of development from 2001 to 2006 (see Figure 2). Gains in developed area arose primarily at the expense of forest and agriculture land cover types. Wetlands and grasslands also experienced appreciable losses to developed area.

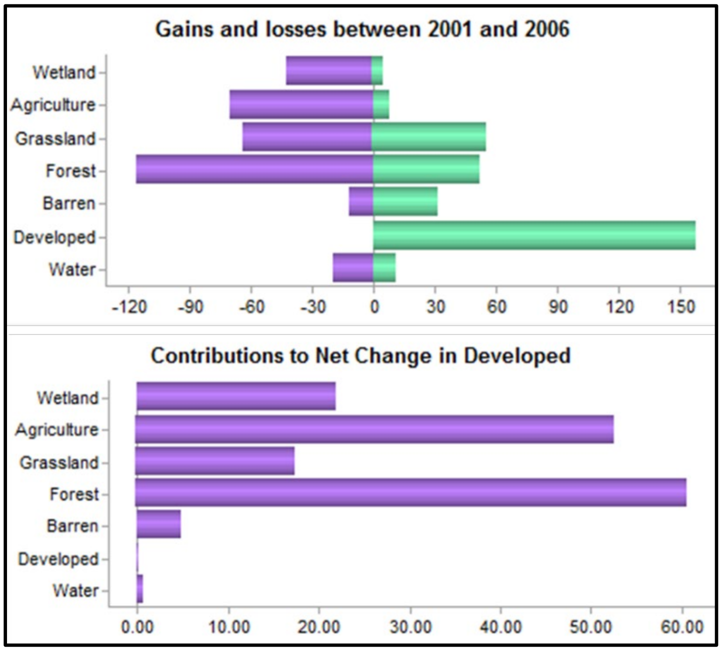

Figure 2. Categorical gains and losses of land cover change, 2001-2006.

Transition Potential Modeling

Perhaps the most data and analysis-intensive step in the process was modeling of land cover transition potential. In short, transition potential modeling seeks to determine what variables, or drivers, explain the change to developed land cover from 2001-2006. Thirteen drivers were measured and iteratively modeled to generate the best-fitting model (see Figure 3). Modeling

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[1] Although damage estimates are only performed across three counties, we use a 13-county study area to more accurately predict regional growth and reduce any edge-effects that may be introduced by administrative boundaries.

was performed using an Artificial Neural Network (ANN). A machine learning technique, ANN's are flexible modeling approaches that have the ability to model complex, non-linear relationships using a network of weights that are formed using an iterative learning process (i.e. training). We implemented an ANN to explain the relationship between our measured drivers and the change in developed land cover. Drivers were assessed in two ways: 1) by using Cramer's V, a measure of the strength of the drivers as an initial scan primary to full-modeling (see Figure 3); and 2) by a more comprehensive measure of accuracy following ANN modeling.

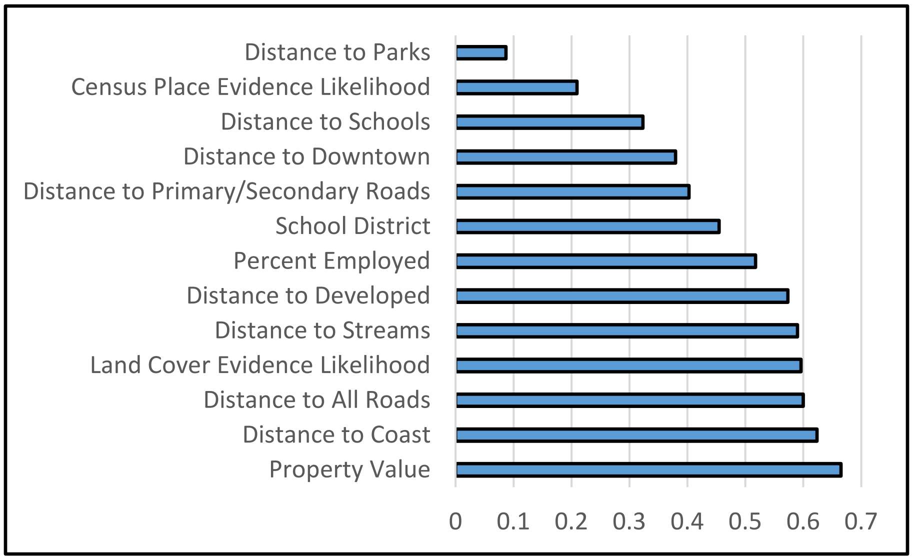

Figure 3. Measured drivers of developed land cover, 2001-2006, and associated measures of Cramer's V.

The Cramer's *V* values on our 13 drivers indicated that nearly all ($V > 0.15$) of the variables may be useful for modeling efforts, resulting in very little data reduction and the need to conduct modeling analyses on all drivers except for distance to parks. Following our initial attempt at data reduction, numerous ANN models were fit using all possible combinations of drivers to derive the most accurate and parsimonious model to predict change in developed area from 2001-2006. The final model used to explain the change in developed land cover consisted of the following four drivers: Existing Land Cover, Distance to Developed Land Cover, Distance to Downtown, and Distance to Schools with an accuracy of 82.27%.

Land Cover Change Validation and Prediction

The final step in land cover transition potential modeling is change prediction and model validation. The ANN model used to determine the drivers of change from 2001-2006 was used to "predict" change in developed land cover from 2006-2011. Because this change has already occurred, it presents an opportunity to subjectively measure how well the model performs in predicting developed land cover change. We used the Area Under the Curve (AUC) of the Relative Operating Characteristic (ROC) to determine the ability of the final model discussed above to correctly predict change in developed land cover from 2006-2011.

The results of our model validation were overwhelmingly positive. Our final model yielded an AUC value of 0.948. For reference, an AUC of 1 indicates perfect agreement between the transition potential layer, or the predicted land cover, and the actual land cover change; an AUC of 0.5 would be expected by chance alone. Using the final model ANN model with accurate predictors and a strongly validated model of change prediction, we predicted developed land cover change in seven time steps, up to the year 2080 (see Figure 4).

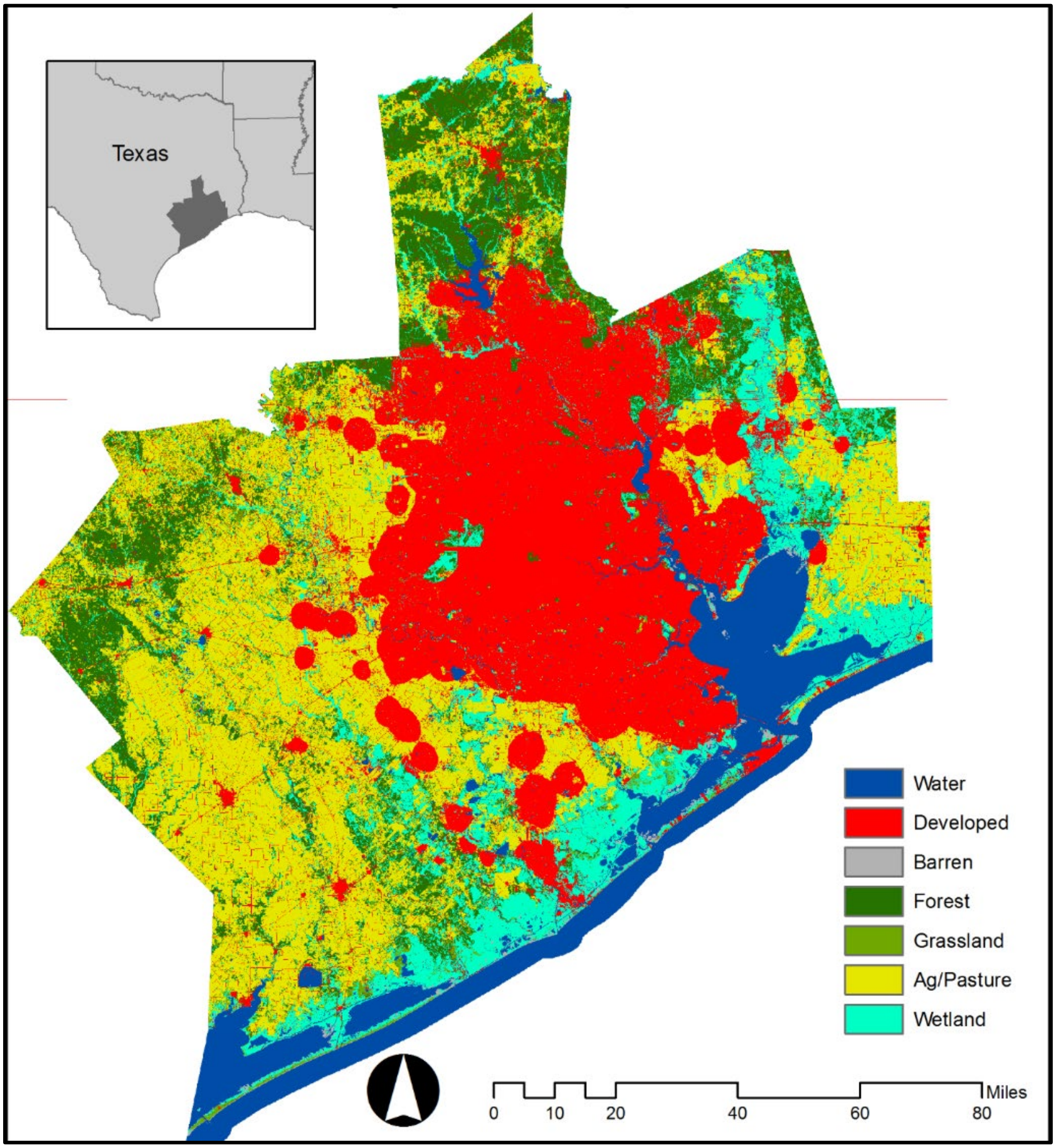

Figure 4. Predicted land cover in 2080 for the 13-county study area.

Developing a land cover-residential structure count relationship

The prediction of future developed area in 2080 provides only area as a measure, however an estimate of *residential counts* by type is required to estimate damage in later analyses. To generate the structure counts, we assessed the relationship of developed area to residential structures in 2015 using multivariate zero-inflated negative binomial regression models. Zero-inflated negative binomial regression models are suited to modeling count variables with excessive zeros (Ridout, 2001). In our application, the counts are residential structures, and zeros are undeveloped census blocks.

We estimated the zero-inflated negative binomial regression models by regressing the area of development in each census block in 2015 and a fixed-effects term for administrative boundaries (cities, unincorporated counties) on the number of residential structures. This estimate was calculated individually for five categories of residential structures, including: Single Family Dwellings (RES1), Mobile Homes (RES2), Multi Family Dwelling – Duplex (RES3A), Multi Family Dwelling – 3-4 Units (RES3B), and Multi Family Dwelling – 5-9 Units (RES3C). Six additional categories of residential structures did not have sufficient counts across the study area for the models to converge. For these categories, we took a conservative approach and did not add any additional units (see Appendix A for detailed counts by residential category). Figure 5 shows the predicted change in all residential units from 2015 to 2080.

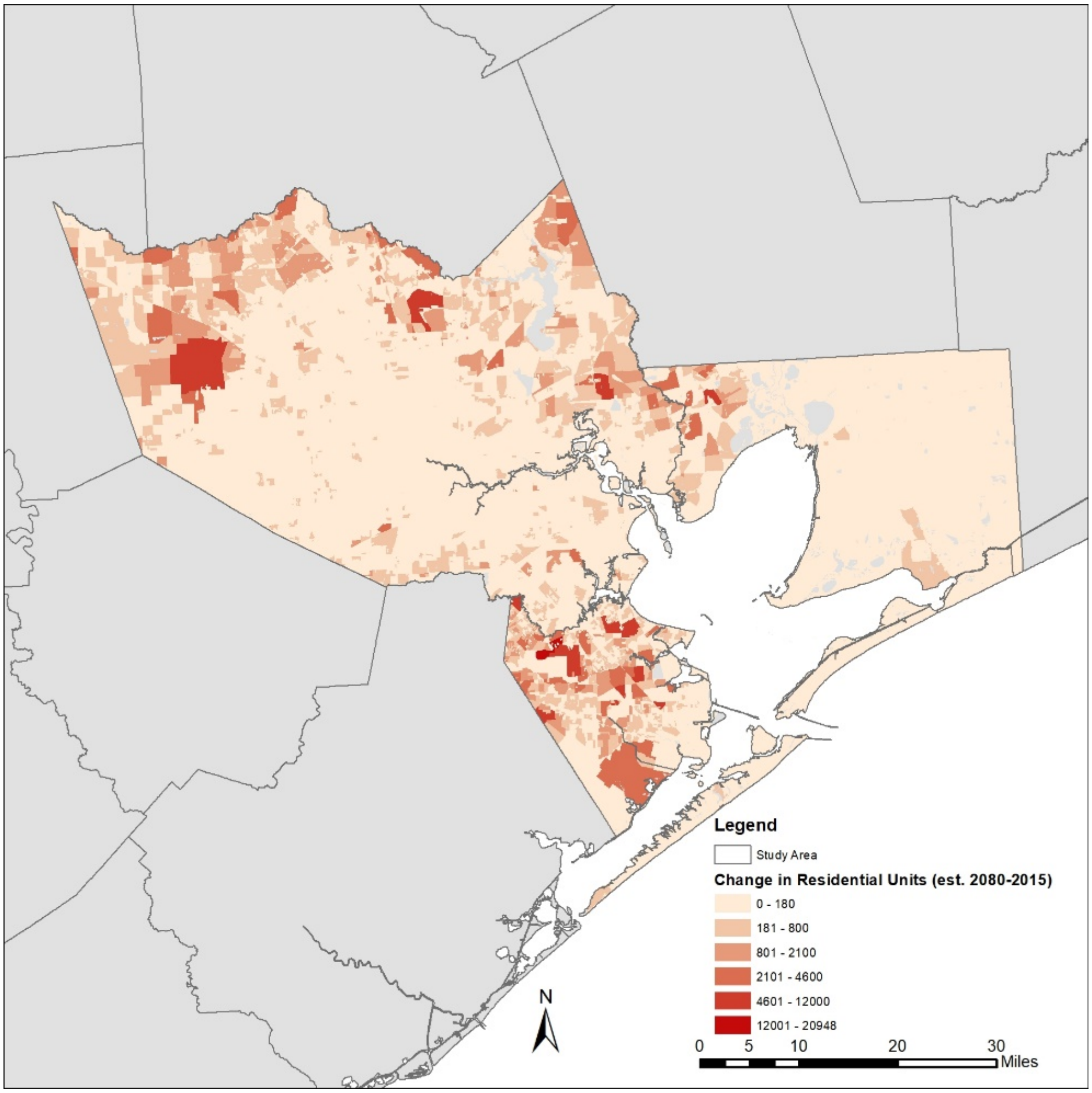

Figure 5. Raw change in predicted residential structures from 2015 to 2080.

Three generally distinct areas appear to have a high propensity for future development. First, the census blocks in northwest Harris County immediately stand out as an area with high predicted future development. While important for future studies, this area is out of range for storm-surge based flooding. Second is the southeast corner of Harris County and northern most portion of Chambers County. Despite the generally small size of these census blocks, development was predicted to be high and is in close proximity to the Houston ship channel and associated industrial and petro-chemical complexes. Finally, a large portion of Galveston County was predicted to have large amounts of predicted growth. These areas follow the I-45 corridor, the Texas State Highway 6 corridor, and areas in proximity to Clear Creek and associated tributaries. While anecdotal, all three of these areas parallel previous growth and population increases over the last 20 years.

Estimating Current and Future Residential Storm Surge Damage

We follow three major steps in estimating direct losses to residential properties: (1) modeling surge inundation from ADCIRC outputs, (2) modeling residential building stock for current and future conditions, and (3) estimating direct losses from surge inundation using Hazus-MH damage curves (see Figure 6). First, we estimate surge inundation from Advanced Circulation (ADCIRC) models generated by the U.S. Army Engineer Research and Development Center (ERDC) at Jackson State University. The dataset input from ERDC includes maximum water surface elevations (MWSE) points for three proxy storms (10-year/10% chance, 100-year/1% chance, and 500-year/0.2% chance), and a Hurricane Ike reconstruction. We further used Geographic Information System (GIS) to generate a hydrologic flood depth raster from the MWSE points and a 3-meter LIDAR Digital Elevation Model (DEM). Second, we develop an inventory of current residential building count (2014 appraised values) and a projection of future building count (year 2080) as detailed above. Finally, we calculated direct damages to these residential properties using damage curves generated by the U.S. Army Corp of Engineers (USACE).

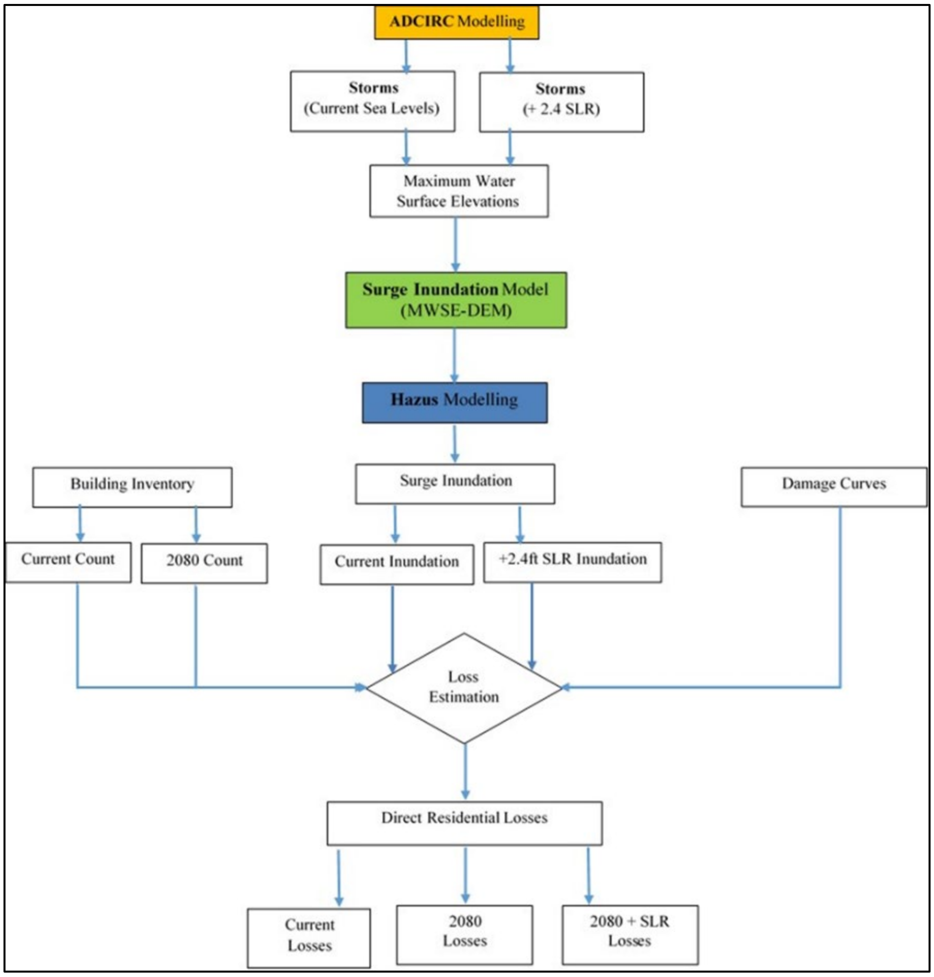

Figure 6. Conceptual flow-chart of damage estimation model approach.

Damage Estimation Software and Improvements

We modeled direct residential losses using Hazus-MH, a software created by the Federal Emergency Management Agency (FEMA). This program estimates losses to general building stock, indirect losses and other social impacts from flooding and earthquake hazards (FEMA, 2006; Scawthorn et al., 2006). We use the same methodology applied by Hazus-MH but with improved data quality to reduce bias in our loss estimates. This is important because previous studies on Hazus-MH models found that improving dataset resolution results in more reliable loss estimates (Brackins & Kalyanapu, 2016; Ding et al., 2008; Karamouz et. al., 2016). Our first improvement over the "native" HAZUS approach is the use of a 1/9 arc second (3-meter) DEMs for ground elevation, and improved hydraulic outputs provided by ADCIRC. We also improved the quality of our building-stock datasets by collecting current parcel-level data from Harris, Chambers and Galveston central appraisal districts rather than using default dataset in the Hazus-MH repository. Our models included improved first floor elevations for different foundation and building occupancy types derived from localized floodplain conditions and base-flood elevation (BFE) regulations. We incorporate more recent damage curves that are local to the Galveston Bay area to better improve the quality of our damage estimates. Overall, these customized and improved resolution of our data greatly increased the reliability of our flood loss estimates (see Tate, Muñoz, & Suchan, 2014).

ADCIRC and Inundation Modeling

Water surface elevations due to storm surge was modelled using a coupled wave and storm surge methodology. This method was applied to create three proxy storms with different intensities making landfall in San Luis Pass, and a Hurricane Ike reconstruction with landfall on Galveston Island. These storms were computed from Average Recurrence Interval (ARI) water surface elevations derived from specific locations in archived FEMA data. The recorded maximum surge elevations were eventually matched with the corresponding storm from the archived FEMA data, and the closest water surface elevations within a confidence level of 90% was estimated and selected as a proxy storm. (Ebersole et al., 2016). As shown in Table 1, these storms have different intensities with central pressure ranging from 900 to 975 millibars (mb).

Table 1. Storm Parameters

Storm Type	Landfall	Central Pressure (millibars)	Forward Speed (knots)	Radius of Maximum Winds (R_{max}) (nautical miles)
10-year Proxy	San Luis Pass	975	6	17.7 – 25.7
100-year Proxy	San Luis Pass	930	11	25.8 – 37.4
500-year Proxy	San Luis Pass	900	11	21.8 – 31.6
Hurricane Ike	Galveston	950	7.8	30 – 50

For current sea level conditions, we used the 2008 value (0.91 feet North American Vertical Datum of 1988 [NAVD88]), which is similar to the value used in a recent flood risk reduction mapping project for the Galveston region. For future conditions, we used a sea level of 3.31ft, which is an increase of +2.4 feet relative to present-day conditions. The sea level rise estimate is also similar to the value used (3.44 feet NAVD88) in a 2016 flood risk reduction project by the Gulf Coast Community Protection and Recovery in the northern Texas coast, by ERDC for a USACE Galveston District flood risk assessment project, and the U.S. Army Corps of Engineers (USACE) for the intermediate rate of sea level rise (see http://www.corpsclimate.us/ccaceslcurves.cfm).

The ADCIRC modeling resulted in generating MWSE points (NAVD88 feet). The second process in our modelling framework as shown in Figure 6 involves interpolating the water elevations using Topo to Raster conversion in GIS to generate a continuous hydrologic raster representing water surface elevations with drainage enforcement process. The final surge inundation is derived by calculating the difference between bare ground levels from a 3-meter resolution LIDAR DEM and the MWSE raster from ADCIRC for each scenario of flood infrastructure and storm intensity.

The modeling was computed for a "*Baseline*" scenario which represent current conditions with existing flood infrastructure within the study area. A second "*Protected*" scenario represents conditions under the proposed 17-foot coastal spine as well as existing flood infrastructure in the study area. A total of 16 flood depth raster layers were derived (i.e., eight raster files for current sea level conditions with and without a coastal spine and eight raster files under sea level rise conditions with and without a coastal spine). These datasets were used for subsequent inundation-induced flood damage analysis for residential structures in the three counties of the study area.

Residential Inventory Modeling

For general Hazus-MH modeling, default building information based on census data and estimates from past surveys are usually aggregated to the census block levels. However, in place of the aggregated census block-level building dataset in Hazus, we used 2014 parcel-level residential property data from the Chambers, Galveston, and Harris county appraisal districts. Unlike aggregate data from Hazus-MH, our data contain building value, square footage, foundation type, and other exterior and interior finish information, leading to improved data for current building conditions and subsequently improved loss damage estimation. We then linked each parcel to the corresponding geographical location of the parcel centroid and its associated building characteristics. The improved parcel-level data was then aggregated to the census block level for further analysis in Hazus-MH. Previous studies have shown that updating default Hazus-MH data with appraised property data significantly improves inventory building counts and leads to reduced bias in loss estimates (Ding et al., 2008; Scawthorn, Blais, et al., 2006; Scawthorn, Flores, et al., 2006).

As shown in Table 2, in some cases, residential properties exposed to storm surge inundation (baseline conditions only) nearly increase from current conditions to 2080 conditions by over 100%. These values are expected to reduce significantly with the presence of the proposed coastal spine as will be shown in future sections of this report.

Table 2: Residential exposure levels for current, 2080, and 2080+sea level rise conditions.

	Exposure Levels				
Storm	Current Exposure	2080 Exposure	2080 Increase	2080+ Sea Level Rise Exposure	2080+ Sea Level Rise Exposure Increase
500-year	$15,834.31 M	$38,461.89 M	142.9%	$58,758.41 M	271.1%
100-year	$12,042.75 M	$27,104.57 M	125.1%	$43,596.43 M	262.0%
10-year	$6,730.57 M	$14,642.50 M	117.6%	$18,420.70 M	173.7%
Hurricane Ike	$10,365.12 M	$21,836.22 M	110.7%	$26,063.10 M	151.5%

Foundation Heights and Damage Curves

After updating building information in Hazus-MH, we focused on identifying the appropriate first floor foundation heights, an important structural characteristic that must be addressed prior to applying spatial damage curves to estimate flood loss. We do this by calculating median foundation height for each foundation type across the 100-year floodplains and BFE requirements in the study area (see Appendix B for foundation height information and damage curves). For residential properties outside the 100-year floodplain where foundation type is unknown, we assign slab on grade foundation heights. For foundation height under the 2080 conditions, we assign the calculated post-FIRM first floor elevations for these properties.

Flood Loss Estimation

We modeled direct losses to residential properties using an area-weighted methodology, which involved distributing residential properties evenly across each census block based on the building count, structure cost, content cost, foundation type, and square footage. We applied the spatial damage curve corresponding to the building information for direct loss estimation. We then used the inundation data described above to determine the percentage of damage to the residential structure and then calculated the cost of the damage based on the building value. The loss for each building was aggregated to the census block level and summed for the entire study area to determine the overall direct residential damages. The direct residential damages represent the replacement value of the structure's damaged components and contents. Structures that experienced over 50% inundation are considered severely damaged, and the replacement value represents the full appraised value of the building and its contents.

Results

Loss estimation results are presented under three scenarios (see summary in Table 3). First, "*Current*" conditions represent residential losses under current building counts and current sea levels, (i.e., assuming the said storm were to occur now). Second, the "*2080*" conditions represent losses to residential property in year 2080 with current sea levels. Third, "*2080+sea level rise*" conditions represent losses to residential properties in year 2080 including the influence of sea level rise. All these conditions are modelled with "*Baseline*" and "*Protected*" infrastructure conditions.

Table 3: Description of Loss Estimation Scenarios

Scenario	**Description**
Current	Losses to current residential properties
2080	Losses to residential properties in 2080
2080+*sea level rise*	Losses to residential properties in 2080 with the influence of sea level rise

Current Conditions

As shown in Table 4, inundation exposure is reduced by 32%-52% depending on the intensity of the storm. Figure 7 shows the avoided inundation levels due to the proposed coastal protection system under current sea levels. The most significant reduction in inundation occurs for the 500-year storm, where inundation upwards of 12 feet are prevented on the west end of Galveston Island, on Bolivar Peninsula, and parts of the Houston Ship Channel. Hurricane Ike recorded reduction in flood inundation behind the existing Galveston Seawall where inundation is reduced by up to 5 feet, and up to 8 feet in the back-bay area of Galveston Island. Only the 10-year storm recorded limited reduction in inundation from coastal protection.

Table 4: Property value of inundated census block under current conditions and current sea levels

	Exposure			
	Baseline	Protected	Avoided Exposure	Reduction
500-year	$15,834.31 M	$9,556.88 M	$6,277.43 M	39.6%
100-year	$12,042.75 M	$8,147.69 M	$3,895.06 M	32.3%
10-year	$6,730.57 M	$4,123.69 M	$2,606.88 M	38.7%
Hurricane Ike	$10,365.12 M	$4,988.17 M	$5,376.95 M	51.9%

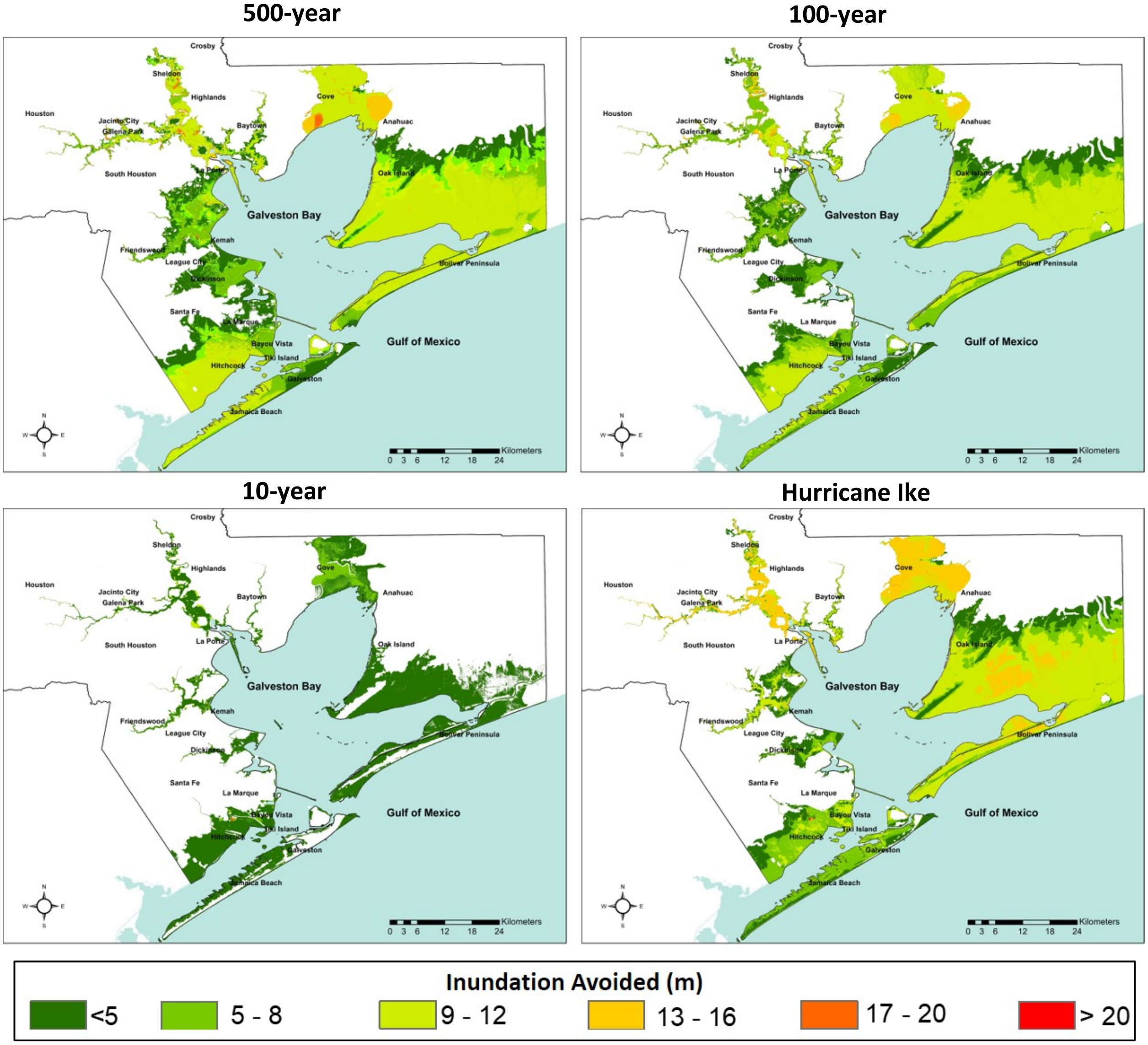

Figure 8: Inundation avoided due to coastal spine under current conditions.

The reduction in flood depth and inundation extent leads to significant reduction in flood losses. As shown in Table 5, residential losses are reduced by 69%-95% depending on storm intensity. For a 500-year storm, over $5 billion is avoided in residential losses alone. Over 95% of damages (about $2.8 billion) would be prevented if Hurricane Ike were to strike with a surge suppression system in place. Even low intensity storms record significant reduction in damaged properties when modeled with a coastal surge barrier.

Table 5: Residential losses under current conditions and current sea levels

	Losses			
	Baseline	Protected	Avoided loss	% Reduction
500-year	$8,022.13 M	$2,331.46 M	$5,690.67 M	70.9%
100-year	$4,351.74 M	$1,352.75 M	$2,998.99 M	68.9%
10-year	$527.71 M	$104.33 M	$423.38 M	80.2%
Hurricane Ike	$2,973.38 M	$135.88 M	$2,837.50 M	95.4%

Figure 9 shows the areas receiving the largest amount of damage reduction. For example, for 500-year and 100-year storms, multiple block groups in the west end of Galveston Island have over $125 million in avoided residential damages, while losses prevented in areas around Galveston Island are upwards of $60 million. Bolivar Peninsula also records significant avoided damages from the coastal spine especially in block groups situated directly on the coastline. Multiple areas further inland in Harris County in cities such as Friendswood, League City, and Dickinson also experience significant damage reduction in losses due to the coastal spine.

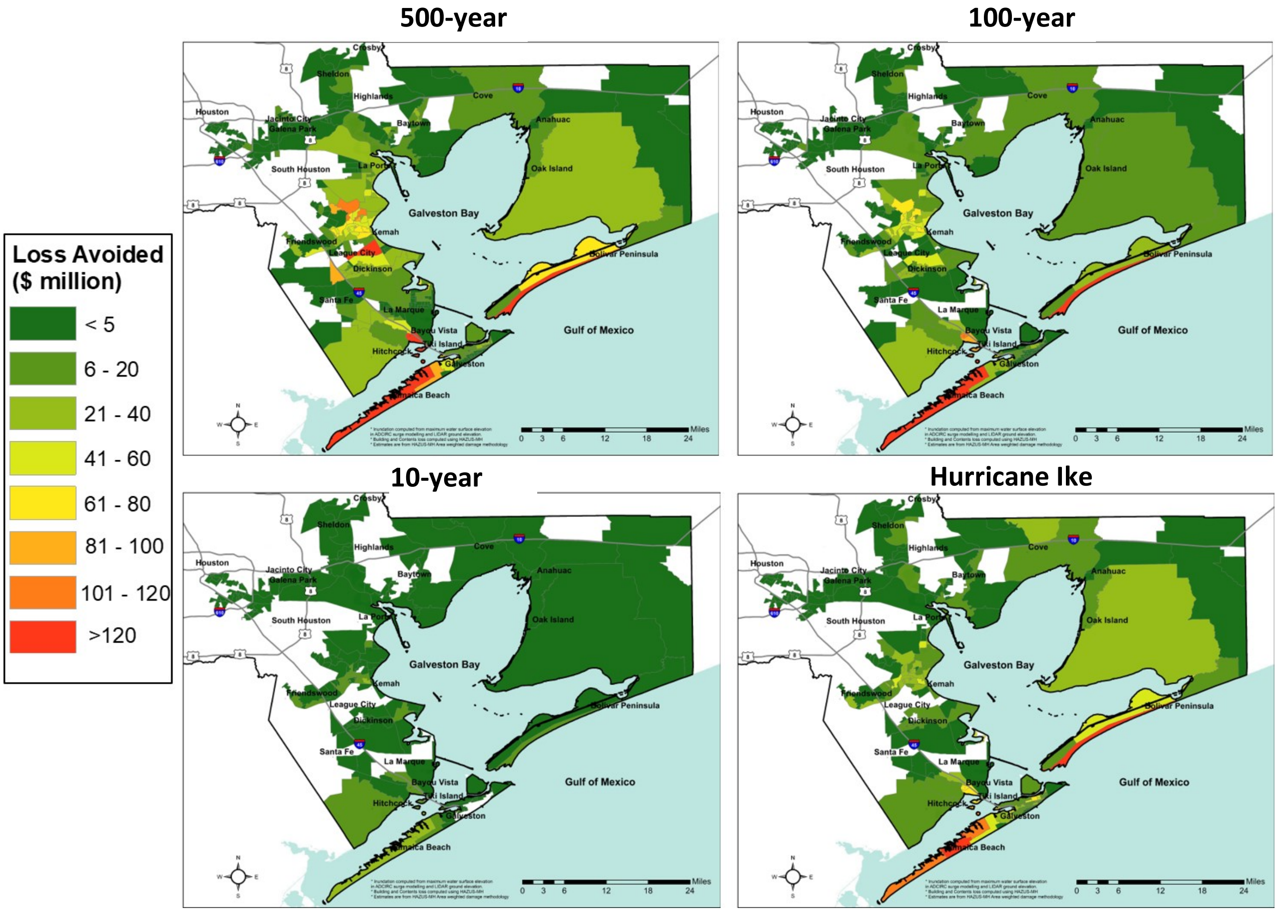

Figure 9: Residential losses avoided per census block group due to coastal spine under current conditions.

Current sea levels and 2080 development conditions

In this scenario, we use current sea levels, but with a projected increase in residential development under year 2080 conditions. Since current sea levels are used, flood inundation levels remain unchanged, however, exposure levels are increased because more residential properties are located in the hazard area (see Table 6). Residential exposure to storm surge are greatly reduced by the coastal spine and about 52% for hurricane Ike.

Table 6: Property value of inundated census block under 2080 conditions with current sea levels

	Exposure			
	Baseline	Protected	Avoided Exposure	Reduction
500-year	$38,461.89 M	$20,069.24 M	$18,392.65 M	47.8%
100-year	$27,104.57 M	$16,511.83 M	$10,592.74 M	39.1%
10-year	$14,642.50 M	$9,393.41 M	$5,249.09 M	35.8%
Hurricane Ike	$21,836.22 M	$10,347.61 M	$11,488.61 M	52.6%

Under 2080 conditions, the coastal spine prevents almost $12 billion in residential losses for a 500-year storm (see Table 7). Although more properties are damaged due to increased development, the coastal spine prevents a significant amount of losses. However, the loss reduction percentage is smaller than the loss reduction percentage for current residential development conditions. On the contrary, Hurricane Ike shows similarly avoided damage percentages under the year 2080 development scenario.

Table 7: Residential losses under 2080 conditions with current sea levels

	Losses			
	Baseline	Protected	Avoided losses	Reduction
500-year	$15,738.17 M	$3,848.06 M	$11,890.11 M	75.5%
100-year	$8,361.07 M	$2,005.82 M	$6,355.25 M	76.0%
10-year	$1,041.10 M	$241.96 M	$799.14 M	76.8%
Hurricane Ike	$4,924.56 M	$234.72 M	$4,689.84 M	95.2%

As shown in Figure 10, the 500-year storm shows an increase in avoided damages in areas further inland, such as near Friendswood, League City, and Dickinson, where sprawling development is expected. The coastal spine proved effective in mitigating losses in residential communities near the Houston Ship Channel, preventing upwards of $120 million in residential damages during the 500-year storm and significantly reducing losses during the 100-year storm and Hurricane Ike conditions.

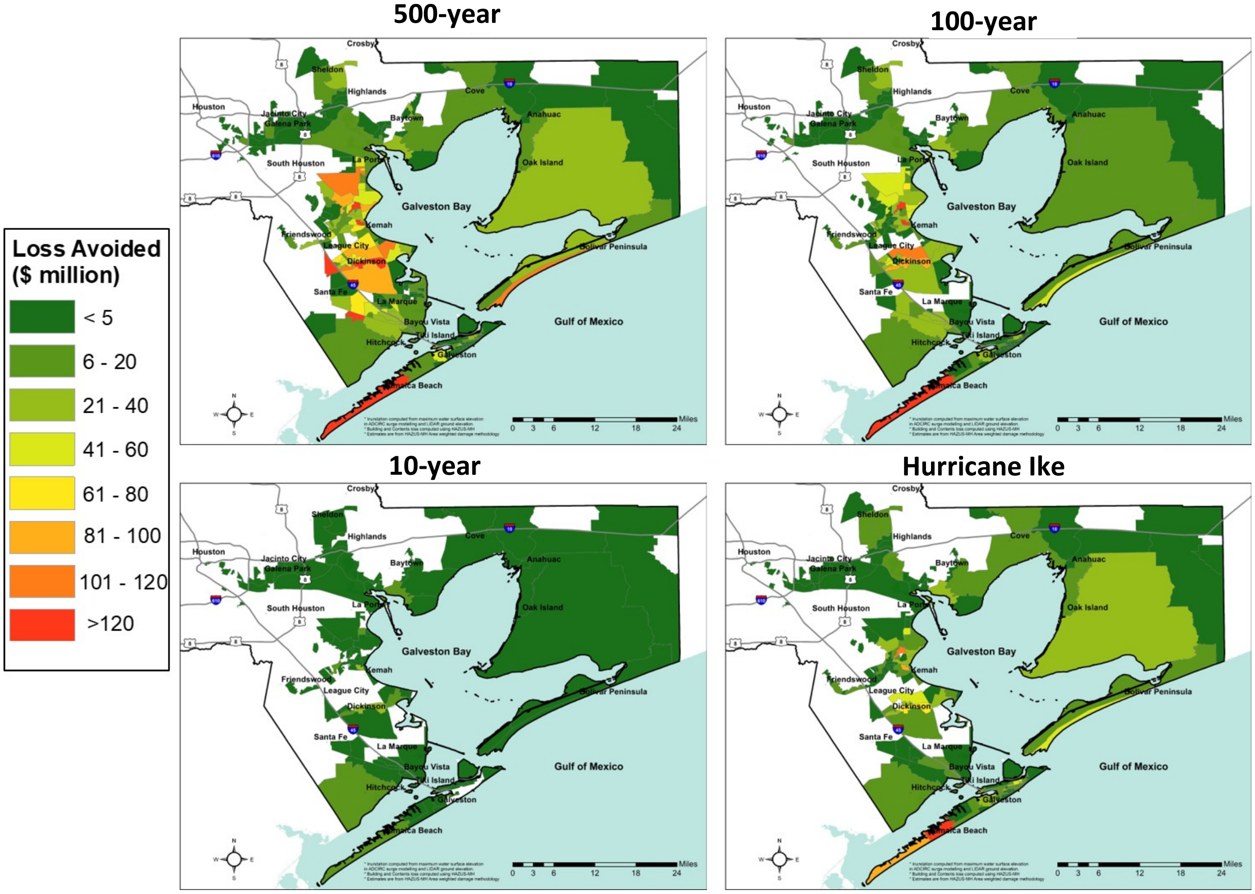

Figure 10: Residential losses avoided per census block group due to coastal spine under 2080 residential development and current sea levels.

Year 2080 and Sea Level Rise Conditions

This scenario shows an increase in residential exposure due to the growth of residential development and greater inundation rates from sea level rise. As shown in Table 8, inundation exposure for a 500-year storm totals approximately $58 billion (compared to $16 billion under current conditions).

Table 8: Property value of inundated census block under 2080 conditions with sea level rise

	2080 + Sea Level Rise Exposure			
	Baseline	Protected	Avoided Exposure	Reduction
500-year	$58,758.41 M	$23,606.21 M	$35,152.20 M	59.8%
100-year	$43,596.43 M	$20,016.83 M	$23,579.60 M	54.1%
10-year	$18,420.70 M	$12,376.12 M	$6,044.58 M	32.8%
Hurricane Ike	$26,063.10 M	$14,041.33 M	$12,021.77 M	46.1%

Figure 11 shows the avoided inundation levels due to the proposed coastal protection system under sea level rise conditions. The most significant reduction in inundation occurs from the 500-year proxy storm, where inundation upwards of 12 feet are prevented on the west end of Galveston Island, on Bolivar Peninsula, and areas adjacent to the Houston Ship Channel. Inundation depths of approximately 12 feet are also prevented from the coastal spine in Chambers County.

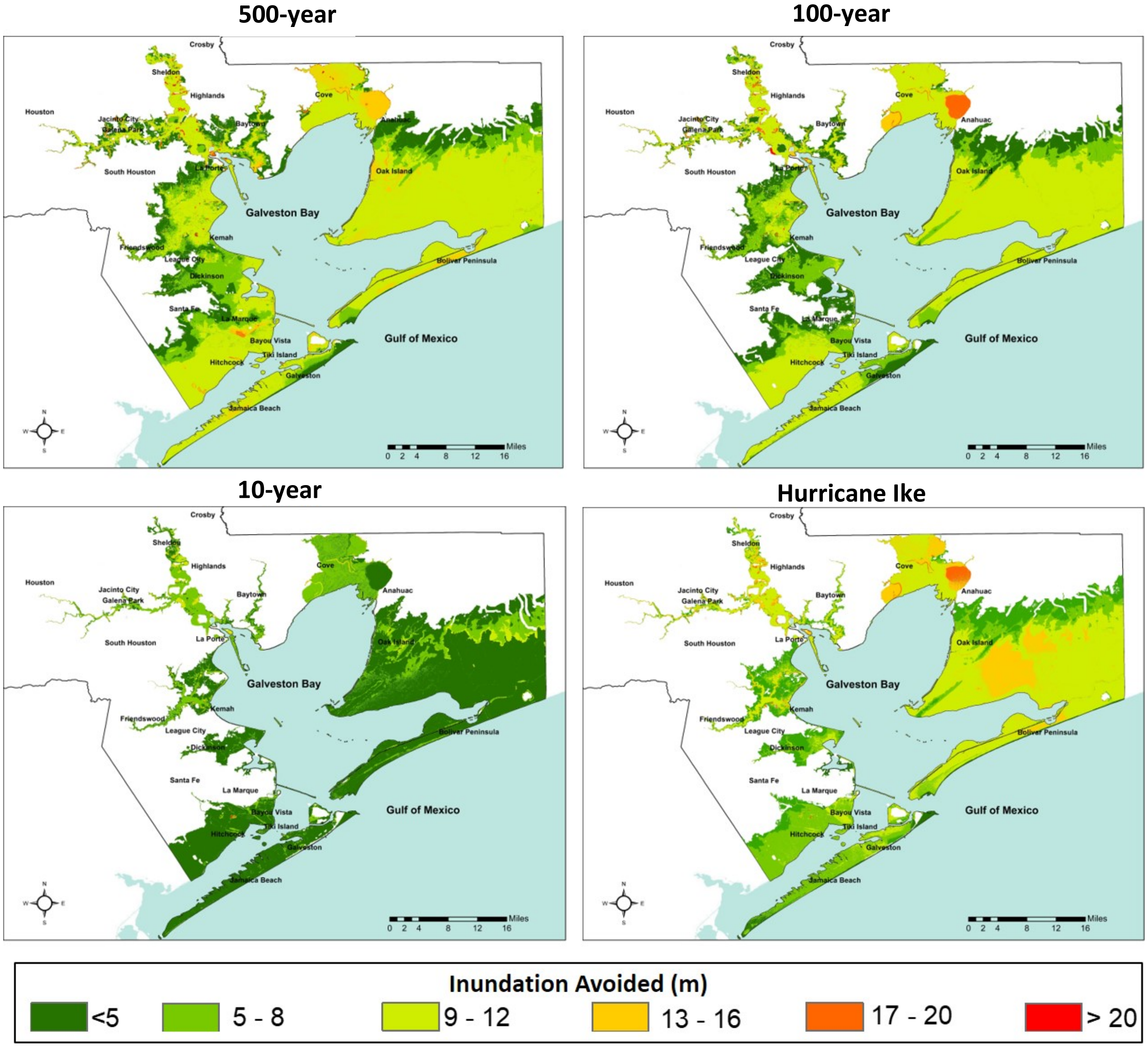

Figure 11: Inundation avoided due to coastal spine under 2080 residential development and 2.4 feet of sea level rise.

In general, the models show a significant increase in residential property loss with expected sea level rise in Galveston Bay. Consequently, the effectiveness of a coastal spine in reducing adverse economic impacts has increased importance when considering future environmental and built environment conditions. As shown in Table 9, the coastal spine prevents approximately $25 billion in residential losses for a 500-year storm and $15 billion for a 100-year storm. Prevented losses are more pronounced in areas further inland, while few changes can be noticed on Galveston Island and Bolivar Peninsula. As shown in Figure 12, locations further inland, such as areas near Friendswood, League City, and Dickinson, where increased development is expected with most census block groups, the 500-year storm shows avoided damages of $60-$120 million. The Baytown area also records a significant reduction in residential damage from the coastal spine.

Table 11: Residential losses under 2080 conditions with sea level rise

	Losses			
	Baseline	Protected	Avoided losses	Reduction
500-year	$31,883.92 M	$6,092.87 M	$25,791.05 M	80.9%
100-year	$18,803.34 M	$3,699.55 M	$15,103.79 M	80.3%
10-year	$2,616.50 M	$574.23 M	$2,042.27 M	78.1%
Hurricane Ike	$8,746.69 M	$881.65 M	$7,865.04 M	89.9%

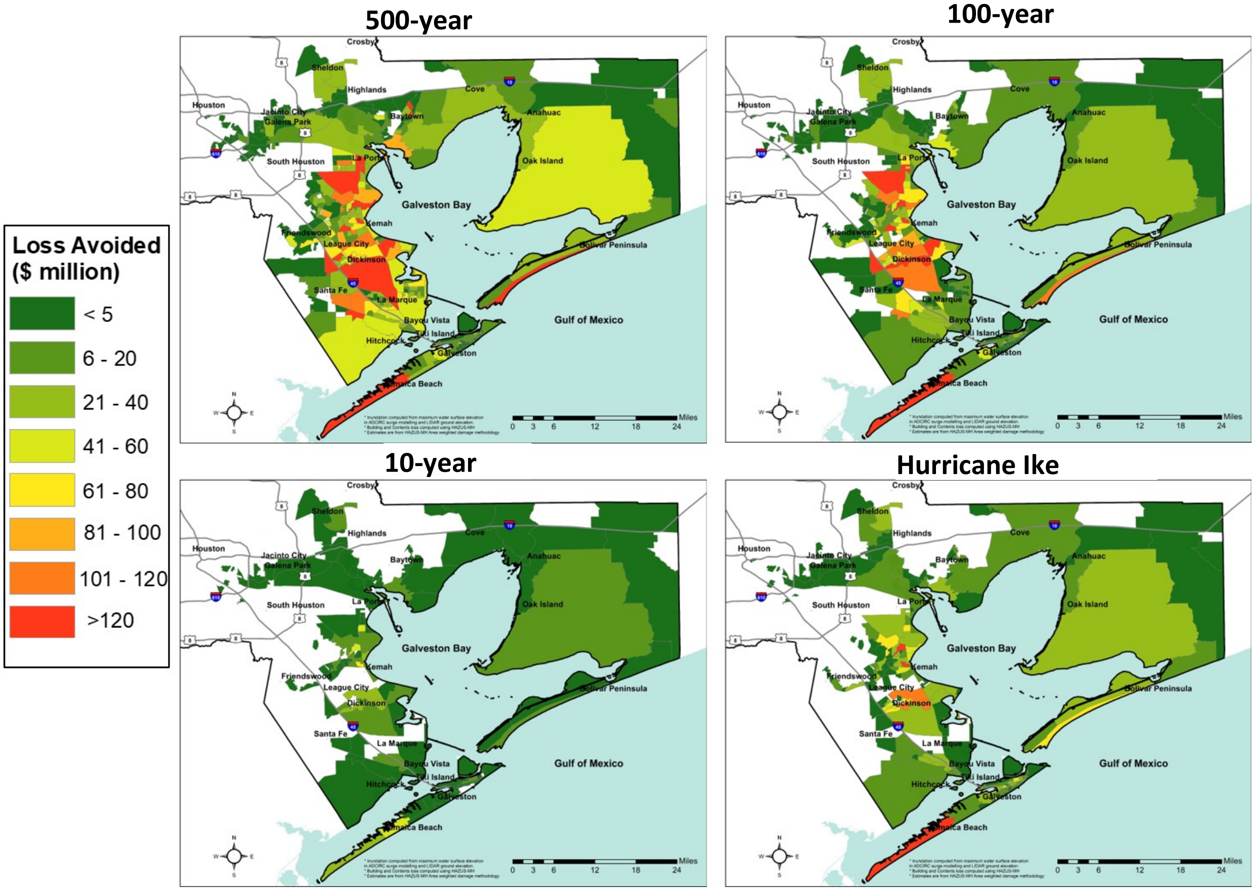

Figure 12: *Residential damages avoided due to coastal spine under 2080 residential development and 2.4’ of sea level rise.*

Summary of Residential Losses

Table 12 and Figure 13 shows a summary of all modeled losses. The lowest percentage of damage reduction occurs under the current conditions for a 100-year flood, while the highest percentage of loss reduction occurs under current conditions for Hurricane Ike. In general, the coastal spine reduced damages by 75%-95% for future development and sea level conditions in Galveston Bay.

Table 12: Summary of residential losses across all scenarios

	Baseline	Protected	Avoided loss	Reduction
Current				
500-year	$8,022.13 M	$2,331.46 M	$5,690.67 M	70.9%
100-year	$4,351.74 M	$1,352.75 M	$2,998.99 M	68.9%
10-year	$527.71 M	$104.33 M	$423.38 M	80.2%
Hurricane Ike	$2,973.38 M	$135.88 M	$2,837.50 M	95.4%
2080				
500-year	$15,738.17 M	$3,848.06 M	$11,890.11 M	75.5%
100-year	$8,361.07 M	$2,005.82 M	$6,355.25 M	76.0%
10-year	$1,041.10 M	$241.96 M	$799.14 M	76.8%
Hurricane Ike	$4,924.56 M	$234.72 M	$4,689.84 M	95.2%
2080+Sea Level Rise				
500-year	$31,883.92 M	$6,092.87 M	$25,791.05 M	80.9%
100-year	$18,803.34 M	$3,699.55 M	$15,103.79 M	80.3%
10-year	$2,616.50 M	$574.23 M	$2,042.27 M	78.1%
Hurricane Ike	$8,746.69 M	$881.65 M	$7,865.04 M	89.9%

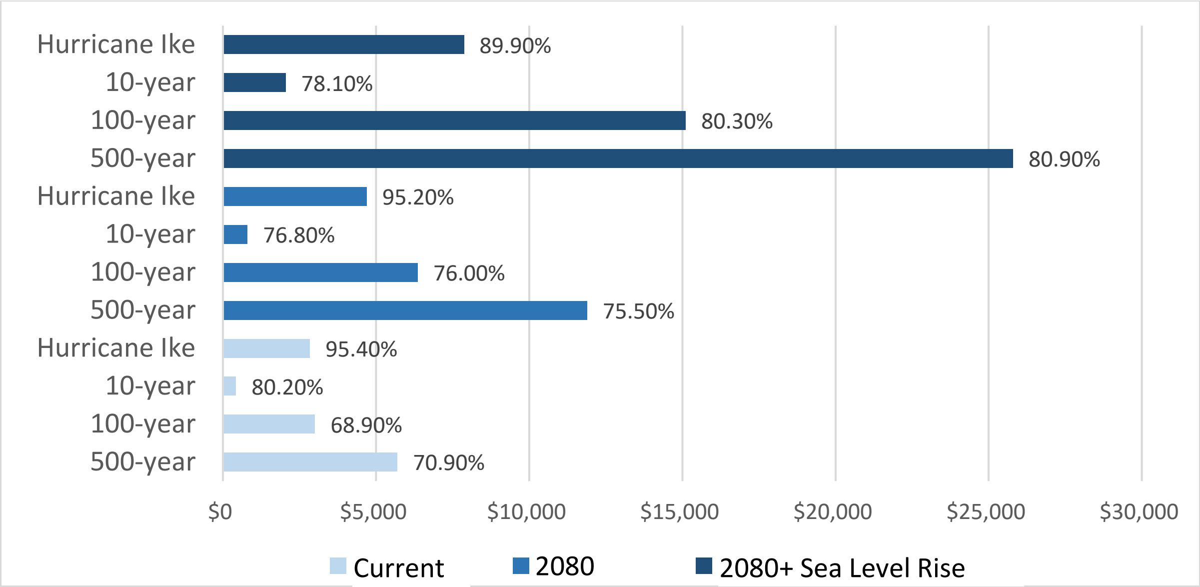

Figure 13. Summary of all modeled losses in current time, 2080, and 2080 with the addition of sea level rise in millions of U.S. dollars. Labels represent percent reduction in damage with the presence of a coastal barrier.

Temporal and Rising Sea Level Impact on Residential Losses

Table 13 shows the increase in costs and losses with current conditions as the base layer. Assuming sea levels remain unchanged and residential development continues to grow, residential losses are expected to increase between 66%-97% depending on storm intensity under baseline conditions. A further rise in sea level increases losses to residential structures by 194%-396% depending on storm intensity.

Table 13: Cost and loss increases due to temporal and sea level changes

	Change between Current Conditions and 2080			
	Baseline		Protected	
	Cost Increase	Loss Increase	Cost Increase	Loss Increase
500-year	$7,716.04 M	96%	$1,516.60 M	65%
100-year	$4,009.33 M	92%	$653.07 M	48%
10-year	$513.39 M	97%	$137.63 M	132%
Hurricane Ike	$1,951.18 M	66%	$98.84 M	73%
	Change between Current Conditions and 2080+Sea Level Rise Conditions			
	Baseline		Protected	
	Cost Increase	Loss Increase	Cost Increase	Loss Increase
500-year	$23,861.79 M	297%	$3,761.41 M	161%
100-year	$14,451.60 M	332%	$2,346.80 M	173%
10-year	$2,088.79 M	396%	$469.90 M	450%
Hurricane Ike	$5,773.31 M	194%	$745.77 M	549%

Conclusion

This study modeled residential property losses based on current and future conditions resulting from a 17-foot coastal storm surge barrier system (also known as “the Ike Dike”) across the mouth of Galveston Bay. All models show a significant reduction in expected flood losses for various storm intensities and for scenarios predicting future development both with and without 2.4 feet of sea level rise. Findings indicate a surge suppression system would have a more profound impact under conditions in year 2080, particularly for communities located further inland. Overall, this study finds that maintaining current storm surge mitigation measures will result in significantly greater adverse economic impacts if the strength and intensity of recent storm events continue in the future.

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Appendix A: Residential categories and structure counts

Table A1: Number of 2015 and predicted 2080 residential structures used in damage estimations.

	2015	2080
Single-Family Dwelling	893,960	2,331,361
Mobile Home	43,096	106,476
Multi-Family, Duplex	32,771	75,871
Multi-Family, 3-4 Units	26,987	54,732
Multi-Family, 5-9 Units	21,855	41,928
Multi-Family, 10-19 Units	19,654	19,654
Multi-Family, 20 to 49 units	14,924	14,924
Multi-Family, 50+ units	16,331	16,331
Temporary Lodging	721	721
Institutional Dormitory	1,469	1,469
Nursing Home	330	330
Total	**1,072,098**	**2,663,797**

Appendix B: Foundation height information and damage curves

Table B1: Foundation height modeling

	Hazus Pre-FIRM (meters)	Median post-FIRM (meters)	
Foundation Type		**A Zone**	**V Zone**
Pile (or column)	2.13	3.66	4.57
Pier (or post and beam)	1.52	3.35	4.54
Solid Wall	2.13	2.44	2.44
Fill	0.61	0.61	-
Slab	0.30	0.30	0.30

Table B2: Structure damage curves for residential occupancy categories

			Flood Depth (feet)																						
Occupancy	**Source**	**Stories**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
			Damage (%)																							
RES1	USACE - Galveston	1	21	27	32	37	43	46	50	54	58	60	63	67	70	74	79	82	83	84	85	86	87	88	89	90
RES1	USACE - Galveston	2	21	27	31	34	37	39	40	40	42	44	47	49	52	55	58	60	62	65	67	69	71	73	75	77
RES1	FIA	3	8	12	17	19	22	24	25	30	35	38	39	40	42	43	44	45	47	48	49	50	52	53	54	56
RES2	FIA	1	44	63	73	78	79	81	82	83	84	85	86	88	89	90	91	92	94	95	96	97	98	99	100	100
RES 3	USACE - Galveston	1-2	18	25	30	34	38	41	43	46	48	50	52	54	55	57	59	59	60	63	65	66	67	68	69	70
RES 3	USACE - Galveston	3-4	28	29	31	36	37	39	40	41	42	44	46	48	52	55	58	61	64	68	69	70	71	72	73	74
RES 3	USACE - Galveston	5+	28	29	31	36	37	39	40	41	42	44	46	48	52	55	58	61	64	68	69	70	71	72	73	74
RES4	USACE - Galveston	All	3	5	6	7	9	12	14	18	21	26	31	36	41	46	50	54	58	62	66	70	74	78	82	86
RES5	USACE - Galveston	All	7	10	14	15	15	16	18	20	23	26	30	34	38	42	47	52	57	62	67	72	77	82	87	92
RES6	USACE - Galveston	All	7	10	14	15	15	16	18	20	23	26	30	34	38	42	47	52	57	62	67	72	77	82	87	92

FIA (Federal Insurance Administration); USACE (United States Army Corps of Engineers).