This report is dedicated in memory of Thomas Colbert and in honor of his legacy.
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The Houston-Galveston area is the region of focus for hurricane surge reduction efforts conducted by the SSPEED Center. Since 2009, the SSPEED Center has been studying hurricane issues in the Houston-Galveston area ever since Hurricane Ike hit Galveston in September 2008.
Executive Summary

This report presents the status of the SSPEED Center’s research efforts to date for its first year of its current three-year study (2014-2017) for the Houston Endowment on hurricane surge reduction in the Galveston Bay region. This 2015 H-GAPS Annual Report will be followed by subsequent annual reports in 2016 and 2017.

The SSPEED Center has been studying hurricane issues in the Houston-Galveston area since 2009 on behalf of the Houston Endowment, ever since Hurricane Ike hit Galveston in September 2008. Through generous funding from the Houston Endowment, the SSPEED Center is currently engaged in a study to investigate and develop a potential regional surge protection system for the Houston-Galveston area, known as H-GAPS (Houston-Galveston Area Protection System). This regional system might then be implemented by someone else, such as the U.S. Army Corps of Engineers (USACE), with funding from a variety of sources, including the federal government, and then would have to be in compliance with various applicable federal laws and regulations.

Others are also working on hurricane surge reduction measures in the Galveston Bay area, such as Texas A&M University at Galveston (TAMU-Galveston), the six-county surge district (GCCPRD), the Texas General Land Office (GLO) and the U.S. Army Corps of Engineers (USACE). These groups have their own research/study teams that are involved in numerous aspects of hurricane storm surge reduction efforts. The SSPEED Center is collaborating with these other study groups so as not to duplicate research efforts, but rather to share the workload and compare study results with the goal of collectively developing a single storm surge protection system for the region.

During the first year of this study, the SSPEED Center’s storm surge modeling team has been performing extensive computer modeling of a variety of hurricanes that could potentially hit the Houston-Galveston area. The ADvanced CIRCulation and Simulating WAves Nearshore (SWAN+ADCIRC) models, utilized in our research, are the state-of-the-art storm surge models. The SWAN+ ADCIRC models have been used to evaluate various storm surge reduction scenarios to determine how effective they would be at reducing storm surge flooding in various parts of the Galveston Bay area. Such scenarios have included structural measures such as...

In 2008, Hurricane Ike highlighted the vulnerability of the Houston-Galveston region to hurricane storm surge.
as navigation gates, levee, dikes, and elevated roadways, which are depicted on Figure 3-1 of the main report. In addition, some nonstructural measures have also been investigated for reducing storm surge-related flood damages, such as preserving and enhancing existing marshlands and other ecologically valuable habitat areas (Section 7).

As a result of this initial evaluation of surge reduction scenarios, the SSPEED Center determined that a gate somewhere across the HSC was needed to produce meaningful reduction in storm surge damages in the Houston-Galveston area. Therefore, the SSPEED Center has initially identified three regional strategies for further evaluation. These three strategies are referred to as the Upper-, Middle- and Lower-Bay Gate Strategy (shown in Figure 5-1 to Figure 5-3) that include a navigation gate respectively across the upper, middle, and lower portion of the HSC. The purpose in evaluating these three strategies is to determine where one should place such a large gate, so as to provide the most benefits in terms of reduced flood damages for the least cost. The SSPEED Center had previously investigated placing a large surge protection gate across the HSC in the upper portion of the Bay, near the Hartman Bridge (previously known as the “Centennial Gate”) to protect the industrial facilities up into Houston along the HSC. At the same time, the TAMU-Galveston study group has been investigating placing a similar gated barrier in the lower portion of the Bay, across the opening between Galveston Island and the Bolivar Peninsula (known as “Bolivar Roads”) as a component of the “Ike Dike”, to protect more of the Galveston Bay area. Since both of these gate locations have advantages and disadvantages, it was decided that they both be incorporated into the initial regional gate strategies being investigated by the SSPEED Center. Recently, a third gate location across the HSC in the middle of the Bay has been identified for further investigation to better protect the west side of the Bay and the HSC industries from residual surge.

Preliminary results showing computed maximum water levels (i.e. storm surge plus wave height above NAVD88) for the three regional gate strategies are presented in Figure E-1 and Tables E-1 and E-2. The results reflect strategy performance for a storm representing Hurricane Ike shifted 30 miles southwest of its original landfall at Bolivar Roads (landfall p7), with winds increased by 15% (i.e. IKE15-P7). IKE15-P7 was selected to represent the approximate 100-year surge conditions along the coast at Galveston Island (19 to 20 feet).
Table E-1 shows the maximum water level by regional zones that would be expected to occur under existing or Baseline Conditions for IKE15-P7. This table also shows the reduced surge levels resulting from the incorporation of the three regional gate strategies.

Table E-2 provides a preliminary economic investigation by the SSPEED Center, in collaboration with TAMU-Galveston, on flood damages resulting from IKE15-P7, such as industrial and residential damages, in order to evaluate the associated benefits and costs.

These results show significant benefits for these three strategies; however, more work is needed to develop and evaluate these strategies, and to coordinate the components and results of these strategies with those being investigated by the other study teams, to allow for a better evaluation and comparison of their advantages and disadvantages, not only economically, but also socially and environmentally. This is the ongoing work that will be done in the second year of this study.
TABLE E-1 MAXIMUM WATER LEVELS BY ZONE USING IKE15-P7

<table>
<thead>
<tr>
<th>Approx. Max. Water Levels by Location (ft. above NAVD88)</th>
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<tbody>
<tr>
<td>IKE15-P7</td>
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<tr>
<td></td>
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<td></td>
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<tr>
<td>HSC Clear Lake Port of Galveston Galveston Seawall</td>
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<tr>
<td></td>
</tr>
<tr>
<td>Baseline Conditions</td>
</tr>
<tr>
<td>Upper-Bay Strategy</td>
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<tr>
<td>Mid-Bay Strategy</td>
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<tr>
<td>Lower-Bay Strategy</td>
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</table>

TABLE E-2 H-GAPS BENEFIT-COST SUMMARY USING IKE15-P7

<table>
<thead>
<tr>
<th>Industrial Damages</th>
<th>Baseline Conditions</th>
<th>Lower Bay</th>
<th>Mid Bay</th>
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<table>
<thead>
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<th>Lower Bay</th>
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<td>$4.8 B</td>
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<th>Total Damages</th>
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<table>
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<th>Upper Bay</th>
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<td>$41.1 B</td>
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</table>

<table>
<thead>
<tr>
<th>Cost</th>
<th>Lower Bay</th>
<th>Mid Bay</th>
<th>Upper Bay</th>
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<td>$7.6 B</td>
<td>$2.8 B</td>
<td>$2.8 B</td>
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</table>

1 For the Lower-Bay Gate Strategy, approximately $4 billion is for the environmental gate alone (cost estimate based on TU Delft 2015 report); however, this gate could cost as high as $10 billion based on recent storm surge barrier construction costs.

Note: Estimated construction costs include $300 million for Galveston Levee ("H").
Introduction

One of the most important issues facing the Houston-Galveston region today is its vulnerability from hurricane storm surge. The Houston-Galveston region is a heavily populated coastal region and remains a vital location for industries that provide economic value to the region and the United States. Although winds and rainfall associated with hurricanes can themselves generate significant damage, the Galveston Bay region is also particularly vulnerable to storm surge flooding due to the mild slope of the coastal shelf and the flat, low-lying areas onshore. Hurricane Ike hit the Texas coast at Galveston in 2008 and generated nearly $29.5 billion in damages for the region (Blake et al. 2011).

For the last six years the SSPEED (Severe Storm Prediction Education and Evacuation from Disasters) Center at Rice University has worked with generous funding from the Houston Endowment to evaluate the various aspects of storm surge and rainfall associated with severe hurricane events in the Houston-Galveston region.

This annual report describes research findings as part of a Phase 3, Year 1 (2014-2015) storm surge protection study on behalf of the Houston Endowment. This Phase 3 report builds on key aspects and modeling efforts from Phases 1 and 2, while extending those efforts towards addressing a more regional storm surge protection system for the Houston-Galveston area. One of the primary goals of this most recent work has been to develop and evaluate structural and nonstructural approaches for reducing storm surge flooding along the Houston Ship Channel (HSC) and greater Houston-Galveston region.

This report also outlines and proposes necessary future research for the SSPEED Center to continue in its efforts to develop a regional storm surge protection system, known as the Houston-Galveston Area Protection System (H-GAPS). Specific areas of research addressed in this annual report include:

1. Storm surge modeling being used;
2. Development of Baseline Conditions;
3. Initial evaluation of certain storm surge reduction scenarios, including the Ike Dike, and;
4. The development and evaluation of 3 regional storm surge reduction strategies, including corresponding reduction in damages (including residential and industrial) and the costs associated with these strategies.

1.1 MOTIVATION FROM HURRICANE IKE

In September 2008, Hurricane Ike made landfall with its center located just east of Galveston Island, TX. Ike was a strong category 2 hurricane with maximum wind speeds of 109 miles per hour at landfall on the Texas coast. Ike’s center passed over Bolivar Peninsula, covering most of the area with at least 10 feet of water (not including wave heights), then traveled through Galveston Bay and hit landfall a second time east of Houston.
Future hurricane surge impacts in the Houston-Galveston region have the potential to damage millions of livelihoods. Hurricane Ike was “only” a Category 2 storm, but due to its large wind field and relatively slow forward motion, it generated significant storm surge that flooded inland areas stretching from Galveston Bay to Grand Isle in Louisiana, causing over $29.5 billion in damages (Blake et al. 2011). Heavy industrial damage occurred further east of landfall on the “dirty” side of the storm in areas near Beaumont and Orange approaching the Louisiana border where the storm surge extended north into Sabine Lake and the Sabine-Neches Waterway. Figure 1-1 illustrates flooding that took place on Galveston Island. The highest storm surge level was recorded in Chambers County where the storm surge nearly reached Interstate Highway 10 (IH-10), about 20 miles inland; that storm surge was over 17 feet above sea level (Berg, 2009). Damage along the west side of Galveston Bay was primarily caused by counter-clockwise winds blowing from east to west, causing water to build up along the northwest shoreline near Shore Acres and La Porte, as well as in the Bacliff and San Leon areas. The storm surge level in
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West Galveston Bay and the HSC reached about 13 feet. Early results from the SSPEED Center indicate that if Hurricane Ike had made landfall at San Luis Pass, where it was originally predicted to hit, storm surge levels and damages would have been much worse across the more populated and industrialized areas on the west side of Galveston Bay. The realization that even greater flood damage from Ike’s storm surge was avoided has raised awareness to the fact that the region is gravely at risk from probable future events, especially if future storms impact the area more directly than Ike. With over 1.6 million people today, and over 2.4 million residents predicted to live in the Hurricane Evacuation Zones surrounding Galveston Bay in the next two decades, future hurricane storm surge impacts in the Houston-Galveston region have the potential to damage millions of livelihoods (Sebastian 2014). In addition, the Galveston Bay area is home to various ports and shipping channels. The Port of Houston is the second largest port of the U.S. and the HSC is home to the largest petrochemical complex in the U.S. (Port of Houston Authority, 2012). There are hundreds of industrial facilities along the HSC that are vulnerable to storm surge flooding. These facilities are to be protected from flooding, pursuant to Federal Emergency Management Agency (FEMA) regulatory requirements, up to the predicted 100-year flood level (currently estimated at about 13 to 14 feet). Surge levels along the HSC during Hurricane Ike never exceeded 13 feet, due primarily to Ike’s track and landfall location being further east. Had the storm taken a more southerly path to landfall, storm surge levels would have approached 20

Ike’s Potential Impacts

Had Hurricane Ike made landfall 30 miles southwest of its original landfall location (shown as Landfall Point 7 in Figure 1.2), it would have generated up to 18 feet of surge in the Houston Ship Channel and up to 15 feet of surge in the populated and industrialized areas on the west side of Galveston Bay.

FIGURE 1-2, SURGE GENERATED BY HURRICANE IKE MAKING LANDFALL AT POINT 7
Source: Rice University

The realization that even greater flood damage from Ike’s storm surge was avoided has raised awareness to the fact that the region is gravely at risk from probable future events, especially
feet and significant damage to industrial facilities and hazardous material storage tanks would have likely occurred, crippling the region. Equally alarming, preliminary FEMA flood maps now show the 100-year base flood elevations (BFEs) have significantly increased along the HSC with water levels as high as 19 to 20 feet. Stronger hurricanes than Ike would produce even higher storm surge levels.

In the earlier phases of this study, the SSPEED Center tested eight hypothetical landfall locations of Hurricane Ike along the upper Texas coast and found that landfall near San Luis Pass, with the same angle of approach, would have generated the greatest storm surge levels from that storm in the northwest portion of Galveston Bay and up into the HSC. For example, had Hurricane Ike made landfall 30 miles southwest of its original landfall location (shown as Landfall Point 7 in Figure 1-2), it would have generated up to 18 feet of storm surge in the HSC and up to 15 feet of storm surge in populated and industrialized areas on the west side of Galveston Bay. Simply increasing the wind speed of the storm would have also resulted in more significant storm surge levels at locations surrounding Galveston Bay and the HSC (Sebastian et al. 2014). The SSPEED Center’s earlier research (Phases 1 and 2) did not include any analysis of storms with varying angles of approach and forward motion regimes (Sebastian et al. 2014). This Phase 3 report introduces a unique approach of shifting historical hurricane tracks (with various angles of approach) to the Galveston region, allowing SSPEED Center researchers to investigate the influence of wind speed and track angle on storm surge.

Based on historical storm surge records along the coastline of the Gulf of Mexico, the upper Texas coast has the third highest magnitude in terms of 100-year storm surge levels, and the 100-year recurrence regional storm surge level has been calculated to be approximately 21 feet at the coastline (Needham et al. 2012). Similarly, FEMA recently released preliminary floodplain maps showing an expected 100-year storm surge level of 19 ft along the coast at Galveston. These storm surge levels are higher than what occurred during Hurricane Ike and point to the likelihood of the Houston-Galveston region experiencing a more significant storm surge.

Had Ike taken a more southerly path to landfall, storm surge levels would have approached 20 feet and significant damage to industrial facilities and hazardous material storage tanks would have likely occurred, crippling the region.
In addition to economic disaster, such a storm surge event would likely inflict massive environmental damage if the hazardous materials and oil stored in petrochemical tanks along the HSC were to spill into neighboring communities and Galveston Bay.
seawall along the Gulf side constructed after the 1900 Galveston Hurricane. The existing measures are shown in Figure 1-3.

Historically, these local protection systems have performed well, but are inadequate to protect against more severe hurricane events. For example anecdotal evidence indicates that the debris during Hurricane Ike reached the top of the Texas City Levee, demonstrating that it was nearly breached in certain low areas. Likewise, the Freeport Levee protected the Freeport and Lake Jackson area, but concern exists about the adequacy of its height to protect against more severe events. The City of Galveston suffered significant flooding during Hurricane Ike, but it was not due to a failure in the structural stability or height of the seawall. Instead, Galveston flooded from the backside, as the water level in the Bay rose and counter-clockwise hurricane winds pushed the water towards the south end of Galveston Bay. This Bay-side vulnerability is a significant risk for the City of Galveston and existing island development. The limited existing storm surge protection systems are one of the many issues that our current phase of research aims to address. In addition, as Ike showed us, there are many other areas in our region that are not protected from major storm surge flooding, such as the west side of Galveston Bay and in Houston along the HSC, where no existing storm surge protection systems exist. These areas are the focus of SSPEED’s current research efforts.
These levee systems have been adequate to date, but are inadequate to protect against a future disastrous surge.
2. Review of Findings from Previous SSPEED Efforts

In 2008, Hurricane Ike revealed the vulnerabilities of the Houston-Galveston region to storm surge. Since 2009, the SSPEED Center, with funding from the Houston Endowment, has focused on modeling, understanding, and evaluating ways to mitigate coastal flood risks from hurricane storm surge. During Phase 1 and Phase 2 of the Houston Endowment-funded SSPEED Center storm surge research efforts, two initially promising storm surge protection proposals were analyzed and are summarized in the 2014 SSPEED Center Report. The two proposals developed during Phase 1 (2009-2011) and Phase 2 (2011-2014) of research included (1) the HSC gate and levee structure protecting Houston along the HSC (known as the “Centennial Gate”), and (2) the Lone Star Coastal National Recreation Area (LSCNRA), which creates economic incentives for preserving existing natural areas along the coast via public and private partnerships (described in section 7).

A recent SSPEED Center paper published by Christian et al. (2014) proposed the Centennial Gate protection system and modeled its hydraulic effectiveness at reducing inland storm surge flooding impacts in the HSC. The results showed that locating a moveable gate structure across the San Jacinto River near the State Highway 146 (SH-146) bridge, and a levee protection system extending west and east of the gate, effectively reduces surge inundation depths and the overall flood extent within Houston along the HSC and upstream in the San Jacinto River basin.

The gate would also be opened at the point when upland runoff flooding behind the gate reaches the surge elevation in front of the gate within the Bay to prevent the occurrence of propagated inland flooding due to the river collecting runoff during intense rainfall associated with the hurricane event. Under various storm scenarios, inundation levels and floodplain areas along the HSC were reduced significantly with the addition of the gate and levees. However, after much community discussion and evaluation, this upper gate proposal (Figure 2 1) proved to not be regional enough in its protection for the entire Houston-Galveston area, and has been expanded to include a series of mitigation measures described in Sections 3 and 4.

The second recommendation, the Lone Star Coastal National Recreation Area (LSCNRA), is predicted to provide both economic benefits to the region and incentives to preserve and protect the undeveloped areas that help to buffer the region from storm surge. The LSCNRA has been developed as a proposal by a coalition of local partners and a steering committee. This includes leadership by former Secretary of State James Baker and Houston businessman John Nau, and facilitated by the National Parks Conservation Association (NPCA). The LSCNRA is predicted to provide economic benefits to the region by developing ecotourism associated with our preserved lands and world-class birding as well as related efforts developed in this phase of the research to provide incentives to increase the economic benefits to private landowners developing ecosystem services for market transactions. Over the past two years, a series of meetings have occurred with potential partners in the formation of this national recreation area (NRA), which would be operated as a unit of...
FIGURE 2-1, CONCEPTUAL RENDERING OF THE CENTENNIAL GATE NEAR HIGHWAY 146 ACROSS THE SAN JACINTO RIVER

Source: Rice University

The perspective of the photo is looking upstream into the HSC.
the National Park System. An economic study commissioned by NPCA and SSPEED Center found that such an eco-tourism facility could generate upwards of 5,000 jobs and add about $200 million annually to the local economy. This park system would be a network of existing publicly and privately protected lands. The proposed LSCNRA concept is shown in Figure 2-2. On the map, the lands officially included as National Recreation Area are shown in pink, the lands of potential partners are shown in green and the proposed partnership interest area (the area where potential partners may be added) is outlined in green.

This first-of-its-kind management approach for a National Recreation Area was envisioned and developed by local landowners and business and community leaders as a flexible way to achieve the benefits and stature of National Park Service involvement while sustaining local participation in planning and governance. Other partnership approaches have been implemented successfully in the past by the National Park Service, as well in other similar applications by the United States Fish and Wildlife Service. The LSCNRA has garnered support from residents, government leaders, businesses and conservation organizations. The LSCNRA is an exciting idea that includes flood mitigation, land conservation, economic development and outdoor recreation. It has been designed with Texas values of respect for private property rights and limited federal government in mind. In many ways, it provides one approach that could emerge as a future model for the National Park Service as a provider of important outdoor opportunities and enjoyment adjacent to major urban areas. More information on the SSPEED Center’s previous research efforts and findings can be found in the 2014 SSPEED Center Annual report. See also Section 8.2 of this report.
An economic study commissioned by NPCA and SSPEED Center found that an ecosystem tourism facility could generate upwards of 5,000 jobs and add $200 million annually to the local economy.

Six years after Hurricane Ike, a lack of stakeholder leadership and public consensus hindered progress towards a unified solution for mitigating storm surge flooding along the HSC. Conversely, the LSCNRA proposed by the SSPEED Center has been well received by governmental and local businesses throughout the region. While the HSC Gate is an excellent project with a useful price tag and an ability to be constructed in a short time horizon, it does not address storm surge vulnerabilities for communities south of the gate, such as the west side of Galveston Bay and the City of Galveston. Local business and governmental leaders called for a more regional approach to storm surge risk management that addresses storm surge vulnerability in the greater region of Galveston Bay, not just protecting Houston along the HSC. The SSPEED Center has spent the past year addressing these regional concerns in detail.

In the meantime Texas A&M University at Galveston (TAMU-Galveston) has been working on the Ike Dike as their regional storm surge protection system. While some in the public saw these two different research efforts as being in competition with each other, others saw it as two different approaches that would eventually lead to a single solution. To avoid any misunderstanding, the two research groups issued the following joint statement in November 2014:

“The SSPEED Center at Rice University and TAMU-Galveston, with their respective research teams, has been studying strategies for surge suppression for the Galveston Bay Region. SSPEED has concentrated efforts on suppressing storm surge using barriers and non-structural approaches within Galveston Bay, while TAMU-Galveston has concentrated on methods for stopping storm surge at the coast using a continuous coastal barrier - the “Ike Dike” (also known as the “Coastal Spine”) concept. Both TAMU-Galveston and the SSPEED Center are now coordinating their research efforts with an eye towards ultimately unifying various strategies into a single storm surge reduction plan consisting of “Multiple Lines of Defense.”

This is to help achieve the best regional solution for the region from an economic, environmental and social perspective. The SSPEED Center and TAMU-Galveston will continue to coordinate their modeling efforts so that collective knowledge can be shared and utilized to more efficiently and effectively formulate a regional storm surge reduction plan for the Houston-Galveston area.”

With Phase 3 funding from the Houston Endowment starting in June 2014 and the collaborative efforts with TAMU-Galveston, the SSPEED Center has been developing and analyzing a comprehensive plan for the Houston-Galveston region, known as the Houston-Galveston Area Protection System (H-GAPS). The regional storm surge reduction strategy is focused initially on three primary potential flood damage areas of the Houston-Galveston region: the industrial complex along the HSC, the west side of Galveston Bay, and the City of Galveston. Galveston Island and Bolivar Penninsula are also experiencing severe beach erosion problems that are caused by storm surge and need to be addressed. Additionally, the SSPEED Center is looking at the low-lying areas of Chambers, Galveston, Brazoria, and Matagorda Counties for participation in a novel ecosystem services exchange program meant to help solidify and preserve the current storm surge risk reduction services and other ecosystem services provided by natural areas along the Texas coast (see Chapter 7).

Various H-GAPS storm surge reduction scenarios range in nature from structural to non-structural solutions, including the following:

- Building storm surge gates and levees
- Raising roadways for protection and evacuation
- Constructing enclosed dredge containment berms with associated constructed wetlands
- Restoring oyster reefs
- Developing the ecosystem services exchange platform mentioned above

The various structural scenarios are displayed in Figure 3-1 and will eventually evolve into what we generally refer to as the Houston-Galveston Area Protection System (H-GAPS). Details of the H-GAPS scenarios are discussed in Section 4.

The most promising structural scenarios have been analyzed using advanced storm surge and damage models customized for the region. Through these analyses, three comprehensive regional storm surge reduction strategies have been initially formulated for evaluation under various hurricane intensity and tract scenarios. This report summarizes the efforts conducted by the SSPEED Center over the past year and provides the region with a comparative analysis of these regional storm surge reduction strategies to date.
CONSIDERATIONS FOR A REGIONAL APPROACH

Figure 3-1, H-GAPS Proposed Regional Storm Surge Protection Alternatives

- 1 - GALVESTON SEAWALL
- 2 - TEXAS CITY LEVEE
- 3 - RAISING TEXAS CITY DIKE
- 4 - OYSTER REEFS
- 5 - HIGHWAY 146
- 6 - DREDGE SPOILS
- 7 - RAISED HIGHWAY 87
- 8 - RAISED FM 3005
- 9 - GALVESTON LEVEE
- 10 - RAISING JETTIES
- 11 - BOLIVAR ROADS GATE
- 12 - MID-BAY GATE
- 13 - HOUSTON SHIP CHANNEL GATE

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Figure 3-1, H-GAPS Initial Storm Surge Reduction Scenarios
4. The H-GAPS Initial Evaluation
Process of Storm Surge Reduction Strategies

With support from the Houston Endowment, the SSPEED Center has worked vigorously towards developing an appropriate methodology for analyzing the Houston-Galveston region’s risk from storm surge. There are many components involved in the Phase 3 analysis that are described in the following sections, such as (1) storm surge modeling, (2) establishing baseline condition of storm surge flooding, (3) evaluating initial storm surge reduction scenarios, and (4) initial evaluation for 3 regional storm surge reduction strategies.

4.1 STORM SURGE ANALYSIS

The following paragraphs describe the basis for the modeling of the different storm surge scenarios that are presented in this report. Storm surge modeling is a very complex issue, especially along the coastline of Texas and Louisiana due to the mildly sloping continental shelf, low-lying coastal areas and the presence of local bays. As such, the SSPEED Center employed the use of the sophisticated hydrodynamic ADvance CIRCulation (ADCIRC) and Simulating WAVes Nearshore (SWAN) models to conduct its storm surge modeling work, using a modeling team from the University of Texas in Austin. The modelers at University of Texas are some of the best experts for handling complex hydrodynamic modeling efforts, and Hurricane Ike was one of the best-monitored and subsequently one of the most validated hurricanes modeled in history. For a more in-depth and technical discussion of the SWAN+ADCIRC models and the methodology of our research, see Appendix 1.

4.1.1 UNDERSTANDING STORM SURGE

The rise in ocean water level generated by a hurricane as it approaches the shoreline and subsequently moves inland is sometimes referred to as “storm surge” (Figure 4-1). However, the maximum water level generated by a hurricane is actually the result of a combination of various water levels, such as that generated by (1) the drop in atmospheric pressure, (2) the forward movement of the storm, (3) the wind set-up, (4) the wave set-up, and (5) waves. Added to this is the daily fluctuation of tides.

The major characteristics of a hurricane that influence the overall storm surge response include (1) angle of approach, (2) wind speed, (3) radius to maximum winds, and (4) the forward speed of the storm. In addition, the local bathymetry, or underwater topography, is another major factor affecting the magnitude of storm surge. Since the majority of the storm surge hitting the coastline is wind-driven, the maximum water level occurs on the “dirty” side of the hurricane, which is the right side of the eye of the hurricane. As a hurricane’s maximum winds move past the coastline, they can continue to result in wind-stress across large
volumes of water within bay systems to generate storm surge. The long fetch of open water in Galveston Bay makes it particularly vulnerable to residual storm surge impacts, especially on the west side of Galveston Bay, up into the industrial complex along the HSC, and the backside of Galveston Island. In addition to storm surge, the rainfall occurring over a bay, as well as rainfall/runoff entering a bay, can contribute to creating a maximum water level within a bay that is typically higher than that occurring at the coast (Figure 4-2).

4.1.2 MODELING STORM SURGE

The SWAN+ADCIRC models have been selected by the SSPEED Center’s modeling team to be used to model the hurricane wind fields and resulting storm surge levels, including waves, in and around Galveston Bay. The SWAN model was developed by Delft University of Technology (TU-Delft) to simulate wind-generated waves during a hurricane. SWAN and ADCIRC can be coupled and run on the same system, simultaneously. The coupling of the ADCIRC and SWAN models, referred to collectively as SWAN+ADCIRC, utilizes a flexible computational mesh of triangular elements to compute and simulate the storm surge and waves caused by a hurricane with unique characteristics and landfall locations (Figure 4-3). The SWAN+ADCIRC coupled model was validated for Hurricane Ike, as well as other historical hurricane events such as Katrina, Rita, and Gustav. We generally refer to the SWAN+ADCIRC coupled model simply as ADCIRC, but it is important to note that the resulting modeled storm surge levels include wave heights. For these reasons, the UT-Austin research effort has centered on the application and continued development of the SWAN+ADCIRC coupled model for simulating hurricane storm surge and wave setup within the Gulf of Mexico, Galveston Bay, and the HSC.

As this is an active area of research, improvements and new features are constantly being included in the ADCIRC software, and the model must be...
continuously analyzed and verified. Recently, the high resolution finite element mesh in the ADCIRC model was refined for the Texas coast such that it drastically decreases the time to perform model runs. These modifications to the model had to undergo extensive testing before being put into “production” mode.

The bathymetry and coastline shape of Galveston Bay and the Gulf of Mexico heavily influence the resulting storm surge that occurs as a hurricane approaches the Galveston area. The ADCIRC model incorporates the bathymetry of the Bay using various sources of information. All of this data was obtained prior to Hurricane Ike. The SSPEED Center obtained updated bathymetry information from the US Army Corps of Engineers (USACE) for the HSC (dated 2010) and checked it against the existing data in the ADCIRC model to determine if there were any significant changes resulting from Hurricane Ike. The results showed fairly insignificant changes in the bathymetry between the two data sets for the HSC and in the Bolivar Roads Inlet area, confirming that the bathymetry within the ADCIRC model represents current conditions (see Appendix 1).

The various scenarios modeled in this study varied from altering the hurricane’s storm parameters (such as landfall location and wind speed) to altering the model’s mesh to include new features, such as gates, levees, or other barrier scenarios to evaluate their storm surge reduction effects. A storm surge reduction scenario is simulated in the ADCIRC model by altering the topographic mesh to include a solid barrier of a designated height at specific locations, such as a 15-foot high wall along Bolivar Peninsula that represents elevating State Highway 87 (SH-87) roadway. By running various scenarios, with modified meshes and storm parameters, the storm surge reduction capabilities of the proposed scenarios for a variety of storm events were investigated.

Moreover, the ADCIRC model is a sophisticated computational tool that relies on the use of state-of-the-art large scale high performance computing platforms (linux clusters) to achieve results within a useful timeframe. The computational resources at the University of Texas Advanced Computing Center (TACC) were utilized for all hurricane simulations.

4.1.3 STUDIED HURRICANE LANDFALL LOCATIONS & TRACKS

The landfall location of a hurricane determines where the maximum water level (i.e. storm surge plus waves measured above NAVD88) will most likely occur (i.e. on the dirty side or right side of the eye or center of the hurricane). SSPEED
researchers utilized the ADCIRC model and hurricane wind field inputs to simulate storm surge levels. We then moved the landfall location of those hurricanes to various spots along the coastline of Galveston to evaluate the differing storm surge levels that result in the area. Three landfall locations were eventually selected as good representatives for evaluating the different types of storm surge that can affect the Houston-Galveston region. These three landfall locations (Figure 4-4) include:

1. San Luis Pass – “p7”
2. Bolivar Roads – “p0” (original landfall location of Hurricane Ike)

The landfall location that tends to produce the greatest storm surge levels within the industrial complex along the HSC is the San Luis Pass (p7) landfall. This is because the p7 landfall tends to maximize the HSC’s placement within a hurricane’s “radius to maximum winds” as the storm traverses through Galveston Bay. The landfall location that tends to produce the greatest wind-induced storm surge along the backside of Galveston is the Rollover Pass (pR) landfall. These differing landfall locations will be used to evaluate the performance of any storm surge-reduction strategy or system that is to be considered for recommendation.

The track, or angle of approach, of a hurricane is very significant as it relates to the resulting storm...
surge levels that might occur within Galveston Bay. However, it is much less important in determining the resulting storm surge levels along the Gulf side of Galveston. Historically, hurricanes that have struck the Texas Coastline in the vicinity of Galveston Island have had tracks between a northerly track and a westerly track, with the majority of hurricanes following a northwesterly track, such as Ike and the 1900 Hurricane of Galveston, which strike perpendicular to the coast (Figure 4-5). When landfall is just west of the Bay, along the northwesterly track, the hurricane tends to produce the highest storm surge levels within the industrial complex along the HSC. This is because the strongest winds along the “dirty” or east sides of the hurricane’s eyewall align parallel to the HSC, as it crosses through Galveston Bay up to Houston.

The SSPEED Center has been able to move historic hurricane wind fields and their tracks, such as Hurricanes Katrina, Rita, and Isaac, so they can be modeled striking the Texas coast in the vicinity of Galveston, at various landfall locations, as previously discussed (Figure 4-5). As such, SSPEED researchers have been able to model different hurricanes, having different tracks and wind speeds, to evaluate how they might affect the Galveston Bay area, both under existing conditions as well as with certain storm surge-reduction scenarios. TAMU-Galveston has requested that the SSPEED Center perform storm surge modeling with its ADCIRC model of the area using some of these historic storms transported or moved to the Galveston area so as to help in evaluating various storm surge-reduction strategies, including the Ike Dike.

FEMA has developed its own set of hurricane tracks for synthetic hurricanes in developing their latest Digital Flood Insurance Rate Maps (DFIRMs) for the Texas Coast, including the Galveston Bay area. These FEMA tracks are based on the tracks of historic hurricanes that have hit the Texas Coast, generally falling between a northerly track and a westerly track. This confirms that our historical tracks provide a good representative sample of expected hurricanes to make landfall near Galveston Island.

Moreover, in order to examine scenarios that are not covered by the historical record, we have developed a technique to generate a suite of synthetic storms that can be utilized to develop storm surge return period elevations. Thus, the development of synthetic hurricanes with properties that are consistent to this general region can allow for the simulation of thousands of storms whose characteristics match those of the historical record but do not rely solely on limited data. Probable combinations of central pressure, radius to maximum winds, forward speed and track can be generated to drive the synthetic data construction. The well-known Holland windfield model, incorporated in ADCIRC, generates hurricane data based on the suite of synthetic parameters to drive storm surge modeling techniques. The generation of these
synthetic storms will be conducted during the second year of this Phase 3 study.

4.1.4 WIND SPEED AND HURRICANE STRENGTH

Historically the most significant feature of a hurricane, as it relates to its resulting storm surge levels at landfall, is its maximum wind speed. Categorization of hurricane strength using the well-known Saffir Simpson Scale (Category 1-5) is based on the maximum wind speed of a hurricane. The wind speeds of a hurricane generally increase radially from the eye of a hurricane until they reach a peak or maximum wind speed, after which they begin to decrease towards the outer edges of the hurricane. Thus, there is a characteristic of a hurricane known as the “radius of maximum winds” that indicate the distance from a hurricane’s eye to its strongest winds. Table 4-1 provides a summary of key

---

**Radius of Maximum Winds**

The characteristic of a hurricane known as “radius of maximum winds” is the distance from a hurricane’s eye to its strongest winds.

---

**FIGURE 4-5, HISTORICAL GULF SYSTEM HURRICANES SHIFTED TO MAKE LANDFALL AT P7**

- **Shifted Hurricane Tracks (at p7)**
  - Ike
  - Rita
  - Carla
  - Katrina
  - Isaac
  - Hurricane_1915
  - Hurricane_1900_(Orig_Landfall)
TABLE 4-1 HISTORICAL GULF SYSTEM HURRICANE CHARACTERISTICS

<table>
<thead>
<tr>
<th>Hurricane</th>
<th>Year</th>
<th>Date of Landfall</th>
<th>U.S. Landfall Location</th>
<th>Saffir-Simpson Category</th>
<th>Minimum Central Pressure (mb)</th>
<th>Radius to Maximum Winds (mi)</th>
<th>Maximum Sustained Winds (mph)</th>
<th>Maximum Water Level (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Camille</td>
<td>1969</td>
<td>Aug. 18</td>
<td>MS</td>
<td>5</td>
<td>909</td>
<td>&lt; 15</td>
<td>200</td>
<td>24.6</td>
</tr>
<tr>
<td>Katrina</td>
<td>2005</td>
<td>Aug. 29</td>
<td>LA</td>
<td>3</td>
<td>920</td>
<td>29 to 35</td>
<td>127</td>
<td>28</td>
</tr>
<tr>
<td>Ivan</td>
<td>2004</td>
<td>Sept. 16</td>
<td>AL/FL</td>
<td>3</td>
<td>943</td>
<td>46 to 58</td>
<td>121</td>
<td>10 to 15</td>
</tr>
<tr>
<td>Carla</td>
<td>1961</td>
<td>Sept. 11</td>
<td>TX</td>
<td>3</td>
<td>931</td>
<td>40</td>
<td>115</td>
<td>18.5</td>
</tr>
<tr>
<td>Rita</td>
<td>2005</td>
<td>Sept. 24</td>
<td>TX</td>
<td>3</td>
<td>930</td>
<td>35 to 45</td>
<td>115</td>
<td>15</td>
</tr>
<tr>
<td>Ike</td>
<td>2008</td>
<td>Sept. 13</td>
<td>TX</td>
<td>2</td>
<td>951</td>
<td>46</td>
<td>109</td>
<td>13</td>
</tr>
<tr>
<td>Gustav</td>
<td>2008</td>
<td>Sept. 1</td>
<td>LA</td>
<td>2</td>
<td>953</td>
<td>-</td>
<td>104</td>
<td>12 to 13</td>
</tr>
<tr>
<td>Isaac</td>
<td>2012</td>
<td>Aug. 29</td>
<td>LA</td>
<td>1</td>
<td>965</td>
<td>46 to 52</td>
<td>81</td>
<td>11</td>
</tr>
</tbody>
</table>

hurricane characteristics for notable Gulf system hurricanes.

More recently, the extent of a hurricane’s wind field has been recognized as a significant feature in assessing the strength of a hurricane and its damage potential, in addition to its maximum wind speed. For example, Hurricane Ike had maximum sustained wind speeds of about 109 mph at landfall, with a radius of maximum winds of about 46 miles; whereas Hurricane Katrina had maximum wind speeds of about 127 mph at landfall, with a radius of maximum winds of roughly 29 to 35 miles. Each of these hurricanes produced about the same maximum water levels at Galveston Island when modeled with ADCIRC to make landfall at p7. Thus, it was determined that maximum wind speed by itself is not necessarily a good predictor of the resulting maximum water levels of a hurricane.

In 2007, Powell and Reinhold proposed a new methodology to characterize the strength of a hurricane based on the cumulative energy of its wind field, referred to as its Integrated Kinetic Energy (IKE). This methodology is intended to incorporate not only a hurricane’s maximum wind speed, like the Saffir Simpson Scale, but also the size of the hurricane’s wind field. For example, Hurricane Ike has a calculated IKE of 129, as compared to Katrina with an IKE of 122, while Sandy has the highest IKE of 302. This methodology not only allows for a comparison of the storm surge damage potential of a hurricane in terms of their IKE value, but also allows the SSPEED researchers to ensure any historic hurricanes modeled with increased wind speeds in ADCIRC fall within the range of historical Gulf Coast storms. Also, further research is being done by the SSPEED team to develop a more site-specific relationship between the IKE of a
hurricane and its resulting storm surge level. The SSPEED Center is also investigating the utility and benefits of including the IKE factor in a more dedicated and explicit analysis. For more information on IKE see Appendix 1.

Finally, the forward speed of a hurricane as it moves across the Gulf has previously not been considered a primary factor for influencing storm surge level as the hurricane reaches landfall. However, there is new information suggesting a hurricane’s forward speed may be more critical than previously understood, especially in coastal bay systems, warranting additional research into this factor.

### 4.1.5 FREQUENCY OF SURGE LEVELS

The frequency of a particular storm surge height is the probability, likelihood or chance that that height will be equaled or exceeded in any given year. For example, a storm surge height that has a 1 in 100, or 1%, chance of occurring in any given year is referred to as the 100-year surge level. Similarly, a surge level that has a 1 in 10, or 10%, chance of occurring in any given year is referred to as the 10-year surge level. Different statistical methods and historical data sets can be used to calculate the frequency of an event. The two primary methods that have been used to determine storm surge level frequencies are to (1) statistically analyze historically observed or recorded water surface elevations, and (2) simulate storm surge using synthetic hurricanes to probabilistically determine frequency surge. These can result in different frequency estimates. In Table 4-2 a list of recent studies and the calculated frequency surge levels are shown.

The NOAA Tide Gage at Galveston Pier 21 is the longest operating tide gage on the Upper Texas Coast and is located on the backside of Galveston Island in the Port of Galveston. The gage has a

<table>
<thead>
<tr>
<th>TABLE 4-2 100-YEAR FREQUENCY STORM SURGE LEVEL COMPARISON</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Method</strong></td>
</tr>
<tr>
<td>-----------------------------------</td>
</tr>
<tr>
<td>Statistically Derived Synthetic Storms</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Statistical Analysis of Observed Surge Level Data</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>
record spanning from 1908-2015. (Note: some significant historical events were missed by the tide gage, including the peak water levels during the 1915 and 1919 hurricanes.) Based on a statistical analysis of the historical gage data, NOAA calculated a 1% annual exceedance probability water level estimate of 10.16 feet relative to NAVD88.

A more recent analysis, conducted by the SSPEED Center, overcomes the limitations of the NOAA study after correcting for tidal fluctuations, accounting for missing data (including the 1900 hurricane), and applying a minimum threshold. Using the graphical method to establish a best-fit curve for the historic storm surge levels, the 100-year frequency storm surge level at the gage was calculated to be 14.37 feet as shown in Figure 4-6. This number does not include tidal fluctuations, which can be as high as 1.41 feet at the gage, resulting in a 100-year water level as high as 15.78 feet. This value is consistent with the preliminary FEMA floodplain maps which show 100-year Base Flood Elevations (BFEs) in the Port of Galveston between 15 and 16 feet.

In 2012, Needham published a statistical analysis of observed water levels collected on the Texas and Louisiana coastline. He calculated that for the upper Texas coast, the 100-year water level is approximately 20.7 feet. This is also consistent with the preliminary FEMA floodplain maps which show 100-year Base Flood Elevations (BFEs) at the Gulf-side of Galveston Island near Bolivar Roads. Two other studies have been published and have been cited by other authors, but these only look at a portion of the period of record so their results were not taken into consideration and are not included in Table 4-2.

Other probabilistic analyses have been conducted using synthetic storms to determine frequency water levels for the region. The first was by FEMA, as previously referenced, in which a suite of synthetic hurricanes were created for the Gulf of Mexico and modeled with ADCIRC. The second analysis was conducted by a master’s student at TU Delft, who developed a simple hydraulic bay model, and used it to simulate storm surge within Galveston Bay and at the coast using synthetic storms generated in a Monte Carlo analysis. The
resulting 100-year water levels were 12.8 feet on the Gulf-side of Galveston Island near Bolivar Roads and 9.5 feet in the southern portion of Galveston Bay near the Port of Galveston. These values are much lower than those published by most other studies. Recently, the model in this study has been updated to include a suite of synthetic storms based on the historical characteristics of hurricanes producing storm surge in the region. Preliminary results indicate that the water levels will be higher than previously reported in Stoeten (2013).

Based on the various studies that have been conducted to determine frequency water levels for the Galveston Bay area, SSPEED has concluded that the preliminary 100-year BFEs reported by FEMA for the coast (19 to 20 feet) and the Port of Galveston (15 to 16 feet) are consistent with the statistical analyses conducted by Needham and the SSPEED Center and should be considered reasonable for use in this H-GAPS study. However, additional work is needed to establish frequency water levels within Galveston Bay and the industrial complex along the HSC since there is little existing literature on this topic, other than the preliminary FEMA BFEs. The work by TU Delft and others has indicated that water levels tend to be higher in the upper portions of the Bay during severe hurricane events. This phenomenon is not currently reflected in the preliminary FEMA BFEs.

In addition, in the second year of Phase 3 of this study, research will be conducted to assess the impacts of (1) sea level rise and (2) climate change on frequency water levels.

4.1.6 HURRICANE RAINFALL AND ASSOCIATED RUNOFF

Hurricane rainfall can vary significantly along coastal watersheds. For example, during Hurricane Ike (2008), approximately 13.2 inches (33.6 cm) of rainfall was recorded in northwest Houston, Texas in 24 hours (HCFCD, 2014). This rainfall intensity equates to a 100-year storm for the Houston region. Hurricane Isaac (2012) was unique because of its significant rainfall, with its peak rainfall intensity having occurred at the time of maximum storm surge (Boyett, 2013a). In this regard, the coupled characterization of joint flood hazards (hurricane rainfall and storm surge) is critical to our understanding of coastal flood risks and risk management. Computational joint flood and hydraulic analyses involving the coupling of hurricane rainfall with storm surge for the Houston-Galveston region were conducted by Ray et al. (2011) and Christian et al. (2014). Torres et al (2015) expanded this understanding by analyzing an enhanced dataset through the shifting of historical hurricane rainfall and wind fields to p7, p0, and pR landfall locations. Given the insights provided through the past work, the next step is to introduce deeper concepts of probabilistic rainfall through the use of synthetic hurricane rainfall distributions.

Associated hurricane rainfall-runoff can also be a contributing factor to the extent of flooding within a bay or riverine system resulting from a hurricane as it approaches and moves inland. Past storm surge modeling efforts using ADCIRC have not incorporated such rainfall-runoff contribution into the computation of inland storm surge levels in the Galveston Bay area. The SSPEED team has been investigating ways to address this issue, as it could have a significant impact of flood levels in the area, and influence the performance of certain storm surge-mitigation strategies. The contributions from antecedent freshwater inflows and hurricane rainfall-runoff can become increasingly significant, particularly for semi-enclosed bays, where storage and residence time are finite. This issue will be further evaluated in the second year of this Phase 3 research study.

4.2 ESTABLISHING SURGE MODEL “BASELINE CONDITIONS”

Prior to detailed evaluation of hurricane storm surge reduction measures, baseline storm surge conditions were investigated using historical and shifted hurricanes for Ike, Katrina, and Isaac. “Baseline,” as defined in this report, refers to the modeling of existing levees and topographic features, without inclusion of proposed levee or gate reduction measures. This baseline served as an initial sensitivity analysis for identifying geographic regions that are persistently vulnerable to storm surge flooding under a variety of storm tracks, landfall locations, and hurricane properties.

Table 4-3 shows the suite of historic storms analyzed, along with their short-hand
### TABLE 4-3 MODELED "BASELINE CONDITION" FOR VARIOUS STORMS

<table>
<thead>
<tr>
<th>Storm No.</th>
<th>Storm</th>
<th>Landfall</th>
<th>Storm ID</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Ike</td>
<td>p0</td>
<td>IKE-P0</td>
</tr>
<tr>
<td>2</td>
<td>Ike</td>
<td>p7</td>
<td>IKE-P7</td>
</tr>
<tr>
<td>3</td>
<td>Ike</td>
<td>pR</td>
<td>IKE-PR</td>
</tr>
<tr>
<td>4</td>
<td>Ike+15%</td>
<td>p0</td>
<td>IKE15-P0</td>
</tr>
<tr>
<td>5</td>
<td>Ike+15%</td>
<td>p7</td>
<td>IKE15-P7</td>
</tr>
<tr>
<td>6</td>
<td>Ike+15%</td>
<td>pR</td>
<td>IKE15-PR</td>
</tr>
<tr>
<td>7</td>
<td>Katrina</td>
<td>p0</td>
<td>KAT-P0</td>
</tr>
<tr>
<td>8</td>
<td>Katrina</td>
<td>p7</td>
<td>KAT-P7</td>
</tr>
<tr>
<td>9</td>
<td>Katrina</td>
<td>pR</td>
<td>KAT-PR</td>
</tr>
<tr>
<td>10</td>
<td>Isaac</td>
<td>p0</td>
<td>ISA-P0</td>
</tr>
<tr>
<td>11</td>
<td>Isaac</td>
<td>p7</td>
<td>ISA-P7</td>
</tr>
<tr>
<td>12</td>
<td>Isaac</td>
<td>pR</td>
<td>ISA-PR</td>
</tr>
</tbody>
</table>

1 Detailed results of Baseline Conditions for Katrina and Isaac (p0, p7, and pR) are provided in Appendix 1.
identifications that will be used throughout the report. For example, IKE15-P0 is a storm using Hurricane Ike’s original landfall track and properties, but with a 15% increase in the wind speed, which produces a maximum wind speed of 125 mph at landfall, the same as Hurricane Katrina. Figure 4-7 through Figure 4-9 show images of the maximum water level produced from a subset of the modeled Baseline Conditions of different historical hurricanes and tracks for the Houston-Galveston region. All elevations are reported with respect to the NAVD88. Figure 4-7 shows the modeled maximum water level for the Baseline Condition of IKE-P0 and IKE15-P0, near the Bolivar Roads Inlet. Figure 4-7(a) represents the original Hurricane Ike track and landfall location. For Ike, water levels were particularly high near High Island and the eastern portions of Bolivar Peninsula, ranging from 15 to 16 feet. At these same locations, IKE15-P0 resulted in maximum water levels ranging between 19 to 20 feet as shown in Figure 4-7(b).

Figure 4-8 shows the modeled maximum water level for the baseline scenarios of IKE-P7 and IKE15-P7, located near the San Luis Pass inlet approximately 30 miles southwest of its original landfall at Bolivar Roads. The p7 landfall places much of the HSC and upper portions of Galveston Bay directly in the path of Ike’s stronger wind field (“dirty right” hurricane phenomena). When IKE-P0 is shifted to a p7 landfall, IKE-P7 produces maximum water levels near Bolivar Roads of approximately 16 feet. For IKE15-P7, the higher hurricane winds produce maximum water levels near Bolivar Roads of approximately 19 feet. This result for IKE15-P7 most closely resembles the 100-year maximum storm surge level near Bolivar Roads as reported by FEMA. Thus, IKE15-P7 was selected to be used as a proxy storm to represent the 100-year storm surge event at the coast of Galveston Island.

It is worth noting that many of the petrochemical storage tanks within the industrial complex along the HSC begin to be inundated at a water level of approximately 15 feet. Based on previous statistical analyses of surge frequencies, water levels in the upper portion of Galveston Bay tend to be higher than those at the coast. This tendency is replicated by both IKE-P7 and IKE15-P7. Within the industrial complex along the HSC, maximum
FIGURE 4-8 BASELINE MAXIMUM WATER LEVELS FOR LANDFALL LOCATION P7

It is worth noting that many of the petrochemical storage tanks within the industrial complex along the HSC begin to be inundated at a water level of approximately 15 feet.

Water levels were computed to be 19 to 22 feet for IKE-P7, and from 23 to 26 feet for IKE15-P7. Thus, IKE15-P7 can also serve as a proxy storm to represent the 100-year storm surge event at the upper portion of Galveston Bay, including within the industrial complex along the HSC.

Figure 4-9 shows the modeled maximum water level for the Baseline Condition of Hurricane Ike, Isaac, and Katrina at a pR landfall, which is near the Rollover Pass inlet approximately 19 miles northeast of its original landfall at Bolivar Roads. The pR landfall location tends to place much of the backside of Galveston Island and Bolivar Peninsula at a higher risk of storm surge inundation. For IKE-PR, maximum water levels are shown to be particularly high near the backside of Galveston Island, ranging between 11 and 12 feet. For ISA-PR and KAT-PR, maximum water level ranged between 8 to 9 feet and 15 to 16 feet, respectively, on the backside of Galveston Island.
IKE15-P7 can also serve as a proxy storm to represent the 100-year storm surge event at the upper portion of Galveston Bay, including within the industrial complex along the HSC.

Table 4-4 summarizes the Baseline Condition results at selected sites for each storm and landfall location within the study region. It can be seen that the variation in storm surge is highly variable due to wind intensity and landfall location. Different landfall locations and their resulting surge levels may justify different elevations for certain scenarios for effective storm surge protection. This helped to select which scenarios warranted further consideration (Section 4.3).
### TABLE 4-4 SUMMARY OF BASELINE CONDITIONS
RESULTS AT SELECTED SITES

| Storm ID  | Storm     | Landfall | Maximum Computed Water Level for
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th>Select Locations within Study Region</th>
</tr>
</thead>
<tbody>
<tr>
<td>IKE-P0</td>
<td>Ike</td>
<td>p0</td>
<td>High Island: 15 to 16 ft</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Galveston Seawall: 12 to 14 ft</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Clear Lake: 11 to 12 ft</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>HSC: 13 to 14 ft</td>
</tr>
<tr>
<td>IKE-P7</td>
<td>Ike</td>
<td>p7</td>
<td>High Island: 14 to 15 ft</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Galveston Seawall: 15 to 16 ft</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Clear Lake: 16 to 17 ft</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>HSC: 19 to 22 ft</td>
</tr>
<tr>
<td>IKE-PR</td>
<td>Ike</td>
<td>pR</td>
<td>High Island: 14 to 15 ft</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Galveston Seawall: 11 to 12 ft</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Clear Lake: 7 to 8 ft</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>HSC: 9 to 10 ft</td>
</tr>
<tr>
<td>IKE15-P0</td>
<td>Ike+15%</td>
<td>p0</td>
<td>High Island: 20 to 22 ft</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Galveston Seawall: 14 to 17 ft</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Clear Lake: 14 to 15 ft</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>HSC: 16 to 17 ft</td>
</tr>
<tr>
<td>IKE15-P7</td>
<td>Ike+15%</td>
<td>p7</td>
<td>High Island: 17 to 19 ft</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Galveston Seawall: 19 to 20 ft</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Clear Lake: 21 to 22 ft</td>
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<td></td>
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<td>HSC: 23 to 26 ft</td>
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<tr>
<td>IKE15-PR</td>
<td>Ike+15%</td>
<td>pR</td>
<td>High Island: 16 to 18 ft</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Galveston Seawall: 14 to 15 ft</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Clear Lake: 7 to 8 ft</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>HSC: 10 to 11 ft</td>
</tr>
</tbody>
</table>
4.3 INITIAL EVALUATION OF H-GAPS SURGE REDUCTION SCENARIOS

4.3.1 DESCRIPTION OF SURGE REDUCTION SCENARIOS

In order to address the modeled storm surge vulnerabilities, the SSPEED Center has developed several structural scenarios to be evaluated. Three initial target areas were selected as primary flood damage areas in need of storm surge reduction, including the industrial complex along the HSC, the west side of Galveston Bay, and City of Galveston. The various structural scenarios that have been selected for evaluation are displayed in Figure 4-10 and were modeled with ADCIRC as independent storm surge reduction scenarios. Summarized descriptions are provided in Table 4-5 for each H-GAPS scenario. A summary of the evaluation of these various scenarios is provided in Section 4.3.2.

Another structural scenario that has been proposed is one by TAMU-Galveston that has been coined the “Ike Dike” (Berger, 2009; Merrell et al., 2010). The Ike Dike concept would extend the existing Galveston seawall structure into a continuous leveed feature along the barrier islands and contain gate structures at Bolivar Roads (both a navigation gate and an environmental gate). As a portion of this Phase 3 effort to develop a regional storm surge protection plan, the SSPEED Center has conducted an analysis of the “Ike Dike.” The SSPEED Center conducted its analysis of the Ike Dike by raising existing roadways (Scenarios “G” and “F”), using the existing Galveston Seawall (Scenario “1”), and tying in a proposed gate at the coast across Bolivar Roads (Scenario “L”), which combined to form a continuous coastal spine, similar to the Ike Dike as originally conceptualized by TAMU-Galveston. The results of the modeling provide the public with information regarding the effectiveness of such a structure in providing protection for Galveston Island, the industrial complex along the HSC, and the greater Galveston Bay communities. Preliminary results of the evaluation of the Ike Dike are included in Section 4.4.
FIGURE 4-10, H-GAPS INITIAL STORM SURGE REDUCTION SCENARIOS

- 1 - GALVESTON SEAWALL
- 2 - TEXAS CITY LEVEE
- 3 - TEXAS CITY DIKE
- 4 - OYSTER REEFS
- 5 - HIGHWAY 146
- 6 - DREDGE SPOILS
- 7 - RAISED HIGHWAY 87
- 8 - RAISED FM 3005
- 9 - GALVESTON LEVEE
- 10 - RAISING JETTIES
- 11 - BOLIVAR ROADS GATE
- 12 - MID-BAY GATE
- 13 - HOUSTON SHIP CHANNEL GATE
**TABLE 4-5 DESCRIPTION OF INITIAL H-GAPS STORM SURGE REDUCTION SCENARIOS**

<table>
<thead>
<tr>
<th>H-GAPS Scenario</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Galveston Seawall&lt;br&gt;The existing Galveston Island Seawall that was constructed after the Hurricane of 1900. The seawall is set at a height of 17 ft above sea level and designed to protect the eastern portion of Galveston Island from storm surge at the coastline.</td>
</tr>
<tr>
<td>2</td>
<td>Texas City Levee&lt;br&gt;The Texas City Levee is an existing levee system surrounding Texas City industries. It ranges in height from 17 to 25 ft.</td>
</tr>
<tr>
<td>D</td>
<td>Oyster Reef&lt;br&gt;Proposed oyster reefs located across Galveston Bay. The oyster reefs will be restored in an area of historical presence with a vertical retaining wall initially set to an elevation of 25 ft. The structures will provide for periodic passages through them to allow for boat traffic and to maintain tidal and environmental flows. The passages can be closed by a small gate system to completely close the interior of the bay.</td>
</tr>
<tr>
<td>E</td>
<td>Dredged Disposal Sites&lt;br&gt;Proposed containment berm sites located along the east and west sides of the HSC within Galveston Bay. These berms tie into high ground to the north at a location east of Cedar Bayou, and tie into the Texas City Levee to the south at Dollar Reef. This scenario utilizes the USACE’s existing berm-enclosed areas that are being filled with dredged material from the HSC. This scenario also presents opportunities for nonstructural improvements such as creating oyster reefs under the water surface of the berms or rookery habitat on the filled islands. This will also provide periodic openings for normal boat travel and environmental flows between the enclosed islands with a gate structure to block the flow of water through the system during a storm surge event.</td>
</tr>
<tr>
<td>F</td>
<td>Bolivar SH-87&lt;br&gt;Proposed levee that entails raising Bolivar SH-87 to a 10-17 ft. elevation, also serving as an evacuation route. This scenario could also be created with a sand dune/dike structure at the beach as currently being researched by TAMU-Galveston.</td>
</tr>
<tr>
<td>G</td>
<td>Galveston FM-3005&lt;br&gt;Galveston’s FM-3005 raised to a 10-17 ft. elevation, also serving as an evacuation route. This scenario could also be created with a sand dune/dike structure at the beach as currently being researched by TAMU-Galveston.</td>
</tr>
<tr>
<td>H-GAPS Scenario</td>
<td>Description</td>
</tr>
<tr>
<td>-----------------</td>
<td>-------------</td>
</tr>
<tr>
<td>H</td>
<td>Galveston Levee Proposed levee around the eastern portions of Galveston Island. The levee would likely be at a height corresponding to the new FEMA-released 100-year storm surge levels. This levee would be connected with the Galveston Seawall.</td>
</tr>
<tr>
<td>T</td>
<td>Raising Texas City Dike Proposed raising of the existing Texas City Dike to a higher elevation (currently approx. 5 ft).</td>
</tr>
<tr>
<td>J</td>
<td>Raising Jetty Proposed raising of existing jetties at the entrance of the HSC to the height of the Seawall and SH-87 (17ft or higher).</td>
</tr>
<tr>
<td>L</td>
<td>Lower-Bay Gate Proposed combination of environmental and navigable storm surge gates at the lower portion of Galveston Bay spanning across the 10,000 ft wide Bolivar Roads inlet, connecting the Galveston Seawall to Bolivar Peninsula's SH-87. This gate system is meant to isolate Galveston Bay during hurricanes, preventing much of the coastal storm surge from entering the bay. The gate system has been initially set at an elevation of 17 ft.</td>
</tr>
<tr>
<td>M</td>
<td>Mid-Bay Gate Proposed navigable storm surge gate across the HSC within Galveston Bay connecting dredged contaminant berms (&quot;E&quot;). The gate has been initially set at an elevation of 25 ft.</td>
</tr>
<tr>
<td>U</td>
<td>Upper-Bay Gate Proposed combination levee and navigable storm surge gate system in the upper portion of Galveston Bay, south of Barbours Cut, and connected to the northern portion of dredged contaminant berms (&quot;E&quot;) and extending west towards Barbours Cut Blvd. This gate system has been initially set at an elevation of 25 ft. to protect the industrial complex along the HSC.</td>
</tr>
</tbody>
</table>
4.3.2 QUALITATIVE INITIAL EVALUATION OF STORM SURGE REDUCTION SCENARIOS

The following results represent the ADCIRC modeling of IKE15-P7 for the above scenarios. This hurricane modeling was run for each of the H-GAPS reduction scenarios in order to better understand and evaluate effects of these scenarios on storm surge reduction in specific target areas. Using the proxy hurricane storm, the initial evaluations of various scenarios were conducted and summaries are provided in subsequent paragraphs. This led to the development of the three initial regional strategies for H-GAPS.

Galveston Seawall ("1")

The ADCIRC modeling showed that the surge overtops the Galveston Seawall since it is only at an elevation of 17 feet. This seawall may need to be raised if additional protection from the coastal storm surge is desired for the City of Galveston. This scenario has been evaluated for assessing the level of protection of the City of Galveston from coastal surge waters.

Texas City Levee ("2")

The ADCIRC modeling showed the surge overtops the Texas City Levee since it is at a varying elevation from 15 feet to over 25 feet. In addition, based on the new preliminary FEMA floodplain maps, this levee may need to be raised in certain locations to provide 100-year storm surge protection. This scenario has been evaluated for assessing the level of protection of the City of Galveston from coastal surge waters.

Raised Texas City Dike ("T")

The proposed raising of the existing Texas City Dike has not yet been evaluated. Future storm surge protection analyses will compare this scenario with the proposed Galveston Levee for measuring levels of backside flood protection during hurricane events.

Raising of SH-146 ("C")

The proposed raising of SH-146 to form a levee at an elevation of about 25 feet was evaluated with storm surge modeling in the earlier phases of the SSPEED Center’s work. As expected, this scenario was found to provide storm surge protection for areas to the west of the roadway, but none for the areas to the east. Thus, it was recognized that if this scenario were to be pursued further, it would have to be coupled with some other scenarios in order to provide regional storm surge protection. Since the GCCPRD is in the process of evaluating this scenario in more detail, the SSPEED Center chose to defer any further evaluation of this scenario until the surge district completed its evaluation of this scenario.

Oyster Reefs ("D")

The proposed construction of oyster reefs across the middle of Galveston Bay, along with vertical retaining walls, to provide storm surge protection for the upper portions of the bay was evaluated. From ADCIRC modeling, this scenario was found to not adequately reduce the storm surge generated by hurricane-force winds crossing over the upper portion of the bay, due to the large fetch that exists that exposes the western and northwestern portions of the bay to storm surge. In addition, such an east-west barrier across the middle of the bay may have significant environmental impacts by interfering with the bay circulation of freshwater and saltwater, as the majority of freshwater inflows into the bay come from the Trinity River. However, adding oyster reefs to other structural scenarios within the bay remains a viable option.

Dredged Disposals and Beneficial Use ("E")

The proposed dredge containment berms along the HSC within the bay were evaluated using ADCIRC modeling. There are existing berms along much of the HSC that have been constructed by the USACE to provide a disposal site for the material routinely dredged out of the HSC. Some of these berms are as high as 25 feet above sea level, such as the one that makes up an island called “Atkinson Island.” There are periodic openings between these berms to allow for small boat traffic and for bay circulation. This scenario was found to provide some significant storm surge reduction for storms that blew across the Bay from east to west and southeast to northwest, thereby protecting the west side and the upper portion of the Bay, including the...
industrial complex along the HSC. However, substantial amounts of water would still enter into these protected portions of the Bay if there were no gate across the large HSC channel cut in Galveston Bay.

Raising of SH-87 along Bolivar Peninsula ("F")
The proposed raising of SH-87 along Bolivar Peninsula was evaluated with ADCIRC modeling. It was found that this scenario provides significant reduction of storm surge within Galveston Bay, especially as the size of the storm surge along the coastline increases. This elevated roadway restricts the amount of storm surge waters that overflow the peninsula and enter into the bay. This scenario has been analyzed at heights ranging from 10 to 17 feet above sea level, as it was considered not viable to raise this existing roadway much higher than 17 feet.

Raising of FM-3005 along Galveston Island ("G")
The proposed raising of Farm-to-Market (FM) 3005 along the west end of Galveston Island was evaluated with ADCIRC modeling. It was found that this scenario provides some reduction of storm surge within Galveston Bay, especially as the size of the storm surge along the coastline increases. This elevated roadway restricts the amount of storm surge waters that overflow the island and enter into the Bay. This scenario has been analyzed at heights ranging from 10 to 17 feet above sea level, as it was considered not viable to raise this existing roadway much higher than 17 feet.

Galveston Levee ("H")
The ADCIRC modeling showed that the surge inundates significant parts of the eastern portion of Galveston Island, primarily from the Bay side. This protection scenario is provided in response to the backside storm surge flooding experienced during Ike, and is primarily intended to protect and preserve the historical nature of the area. This local scenario can also serve to supplement a larger regional storm surge protection strategy. Other variations of the Galveston Levee alignment will be analyzed, such as the formation of a unified ring levee system around the City that can tie into the Galveston Seawall. Further analysis will be done in future work to include a comprehensive storm surge and economic damage-cost analysis.

Raised Jetties ("J")
The proposed raising of the existing jetties at Bolivar Roads was evaluated using ADCIRC modeling. It was found that this scenario provided minimal storm surge reduction within the bay, as significant amounts of water still entered the bay through the Bolivar Roads opening.

Lower-Bay Gate ("L")
The ADCIRC modeling showed that the proposed Lower-Bay gate across Bolivar Roads was found to be very effective at reducing the amount of water that enters the Bay, and thus the height of storm surge within the Bay is significantly reduced. However, there is concern over the cost of a 10,000-foot long gate system across Bolivar Roads. Jonkman et al. (2015) released a preliminary cost estimate of approximately $4 billion to construct the environmental gate across Bolivar Roads (this estimate could be as high as over $10 billion based on recently constructed coastal barriers). Moreover, the potential environmental impacts from the reduction in flow capacity under normal tidal exchange between the Gulf of Mexico and Galveston Bay would also be interrupted to a level that is yet to be quantified.

Mid-Bay Gate ("M")
The ADCIRC modeling showed that the proposed Mid-Bay gate in combination with dredged containment berms ("E") provided substantial surge reduction in the western and upper portions of the Bay. This scenario provides a significant level of surge protection for the west side of Galveston Bay and the industrial complex along the HSC.

Upper-Bay Gate ("U")
The ADCIRC modeling of the proposed Upper-Bay gate showed that this scenario is very effective in reducing the amount of water that enters the upper portion of the Bay, thus providing significant surge reduction within the industrial complex along the HSC. However, this gate location does not provide any surge reduction for areas throughout the remainder of Galveston Bay. As previously stated, the HSC gate concept was initially proposed in Phase 1 and 2 efforts and can be conceptualized as a combination radial swing gate with a levee system tie-in.
4.3.3 INITIAL EVALUATION OF THE IKE DIKE CONCEPT

The Ike Dike, as initially proposed by TAMU-Galveston, would provide a 17-foot high coastal barrier for inhibiting coastal storm surge waters from overtopping Galveston Island and Bolivar Peninsula and flowing into Galveston Bay. Based on ADCIRC modeling, hurricane-force winds moving across Galveston Bay may still lead to significant surge levels within the Bay. As reported in Sebastian et al (2014), the ADCIRC modeling showed that the “Ike Dike” blocked the majority of coastal surge water from entering Galveston Bay; however, significant storm surge (“residual surge”) is still created within Galveston Bay due to wind forces moving across the water in the Bay. Specifically for the proxy storm IKE15-P7, the residual surge produced with the presence of the Ike Dike is visually corroborated in Figure 4-11(c), with surge within the 13- to 15-foot range within the industrial complex along the HSC, and 10 to 11 feet for the westside of the Bay. Analyses by TAMU-Galveston and Jackson State University (Ebersole et al. 2015) also discovered similar levels of residual surge within the Bay with the presence of the Ike Dike at 17 feet for strong hurricanes. A similar analysis of the Ike Dike was modeled at 12 feet, but with the corresponding gate structures remaining at 17 feet, at the request of TAMU-Galveston. As shown in Figure 4-11(b), an even larger residual surge was produced within the Bay even with the presence of the Ike Dike at 12 feet.

In addition, ADCIRC modeling of severe hurricanes with landfall locations near Rollover Pass showed substantial residual surge-induced flooding on the backside of Galveston Island, due to the north-south wind fetch across Galveston Bay.

4.3.4 RESULTS AND CONCLUSIONS – INITIAL EVALUATION

In short, the HSC Gate and Ike Dike scenarios exhibited both strengths and weaknesses. The HSC Gate provides protection only at the local scale for the industrial complex along the HSC, while the Ike Dike provides reductions in regional storm surge throughout Galveston Bay; however, it fails to eliminate significant residual storm surge caused by wind fetch created across Galveston Bay. An ideal regional storm surge protection system...
Hurricane Ike’s Storm Surge Retreating at the McFaddin Wildlife Refuge
would work to eliminate storm surge flooding throughout the Bay, primarily for the sensitive and/or critical industrial, residential, commercial, and environmental areas. This served as the impetus for the H-GAPS formulation and development of the initial Upper-, Mid-, and Lower- Bay Gate strategies. This initial development process is described in the following sections.

5. Initial H-GAPS Regional Surge Reduction Strategies

Based on gained insight from the analyses of Baseline Conditions (Section 4.2) and the initial evaluation of storm surge scenarios (Section 4.3), three initial regional storm surge reduction strategies were developed to provide a more comprehensive approach for mitigating storm surge in the Houston-Galveston area. Each strategy was created with the focus being to provide regional protection, and includes a navigation gate either along the lower, middle, or upper portion of the HSC. As such, these initial regional protection strategies have been appropriately labeled, “Upper-Bay,” “Mid-Bay”, and “Lower-Bay” Gate Strategies, as shown in Figure 5-1 through Figure 5-3.

In addition, each of these strategies include both coastal as well as in-bay barrier scenarios. The coastal barriers for all three strategies include raising existing roadways along Galveston Island’s FM-3005 (“G”) and Bolivar Peninsula’s SH-87 (“F”) to a height of 15 feet. The in-bay barriers for all three strategies include the proposed extension and raising of existing dredged containment berms (“E”) to 25 feet, and the raising of the existing Texas City Levee (“2”) to a uniform height of 25 feet. The Upper- and Mid-Bay Strategies include navigation gates across the HSC at 25 feet, and the Lower-Bay Strategy includes both a navigation gate across the HSC and an environmental gate across the remainder of the opening at Bolivar Roads, each at 17 feet. The main difference between the strategies, as previously stated, is the location of the navigation gate across a upper, middle, or lower portion of the HSC, while the remaining components (“G, F, E, and 2”) are included and set at the same height for all of the strategies.

Three initial regional storm surge reduction strategies were developed to provide a more comprehensive approach for mitigating storm surge in the Houston-Galveston area.

In addition, all three gate strategies also incorporate the Galveston Levee (“H”) to 22 feet, including the Galveston Seawall (“1”) in order to provide complete protection across the eastern portion of Galveston Island for the initial strategy evaluations. Future work will look more closely at providing more economically and socially acceptable storm surge reduction scenarios for this portion of Galveston Island.

Preliminary ADCIRC modeling of these three initial gate strategies have recently been completed for IKE15-P7 and IKE-P0. These results are discussed in Section 5.1.
Initial H-GAPS Regional Surge Reduction Strategies

Three initial regional storm surge reduction strategies were developed to provide a more comprehensive approach for mitigating storm surge in the Houston-Galveston area. Each strategy was created with the focus being to provide regional protection.

Each of these strategies include both coastal as well as in-bay barrier scenarios.

The coastal barriers for all three strategies include raising existing roadways along Galveston Island’s FM-3005 (“G”) and Bolivar Peninsula’s SH-87 (“F”) to a height of 15 feet.

The in-bay barriers for all three strategies include the proposed extension and raising of existing dredged containment berms (“E”) to 25 feet, and the raising of the existing Texas City Levee (“2”) to a uniform height of 25 feet. The Upper and Mid-Bay Strategies include navigation gates across the HSC at 25 feet, and the Lower-Bay Strategy includes both a navigation gate across the HSC and an environmental gate across the remainder of the opening at Bolivar Roads, each at 17 feet.
FIGURE 5-1 UPPER-BAY GATE STRATEGY

RENDERING OF RADIAL GATE

RENDERING OF BARGE GATE
FIGURE 5-1 UPPER-BAY GATE STRATEGY (CONTINUED)

Upper-Bay Gate Strategy
- GALVESTON SEAWALL
- TEXAS CITY LEVEE
- TEXAS CITY DIKE
- DREDGE SPOILS
- RAISED HIGHWAY 87
- RAISED FM 3005
- GALVESTON LEVEE
- HOUSTON SHIP CHANNEL GATE
FIGURE 5-2 MID-BAY GATE STRATEGY

RENDERING OF SLIDE GATE

RENDERING OF DREDGED CONTAINMENT BERMS
FIGURE 5-2 MID-BAY GATE STRATEGY (CONTINUED)

Mid-Bay Gate Strategy

1. GALVESTON SEAWALL
2. TEXAS CITY LEVEE
3. TEXAS CITY DIKE
4. HIGHWAY 146
5. DREDGE SPOILS
6. RAISED HIGHWAY 87
7. RAISED FM 3005
8. GALVESTON LEVEE
9. RAISING JETTIES
10. MID-BAY GATE
FIGURE 5-3 LOWER-BAY GATE STRATEGY

RENDERING OF IKE DIKE GATE SYSTEM

Source: Jonkman et al. (2013)
FIGURE 5-3 LOWER-BAY GATE STRATEGY (CONTINUED)

Lower-Bay Gate Strategy

- **1**: GALVESTON SEAWALL
- **2**: TEXAS CITY LEVEE
- **3**: TEXAS CITY DIKE
- **4**: HIGHWAY 146
- **5**: DREDGE SPOILS
- **6**: RAISED HIGHWAY 87
- **7**: RAISED FM 3005
- **8**: GALVESTON LEVEE
- **9**: RAISING JETTIES
- **L**: BOLIVAR ROADS GATE

Map of Lower-Bay Gate Strategy with markers for various strategies.
5.1 EVALUATION OF STRATEGIES

Each of the three preliminary regional gate strategies have been initially analyzed with ADCIRC modeling using IKE-P0 and IKE15-P7 storms. Detailed results of these analyses are provided in Appendix 1, but summaries of results are briefly described in this section, and shown in Table 5-1 and Table 5-2 for key locations within the Galveston Bay area, as shown in Figure 5-7.

Currently, components for each regional strategy have been analyzed at consistent levee and gate heights. Future work will evaluate storm surge reductions provided by different levee heights to determine hydraulically optimal and cost-effective levee and gate heights for each component of the respective strategies. At the current time, the dredged containment berms ("E") and regional gates ("U" and "M") have been modeled at a constant elevation of 25 feet and "L" at 17 feet. FM-3005 ("G") and SH-87 ("F") are modeled as raised roadways at a constant elevation of 15 feet. The Galveston Seawall ("1") and the backside Galveston Levee ("H") are modeled at 22 feet, and the Texas City Levee ("2") was set to a uniform height of 25 feet.

5.1.1 UPPER-BAY GATE STRATEGY

The Upper-Bay Gate Strategy was initially evaluated using ADCIRC modeling. Figure 5-4 illustrates the maximum water surface elevations for IKE15-P7 under (a) Baseline Conditions, and (b) with the Upper-Bay Gate Strategy in place. As shown, this strategy reduces extreme storm surge quite significantly in the upper portions of the study area, most notably within the industrial complex along the HSC, Barbours Cut, Cedar Bayou, and Baytown.

Nearly absolute protection is provided in the northern portion of Galveston Bay due to the placement of the gate (Scenario "U") south of Barbours Cut and Cedar Bayou. Within Galveston Bay, the dredged containment berms ("E") are able to somewhat mitigate wind-induced storm surge from the east-to-west fetch, since the navigable portion of the HSC near mid-Galveston Bay was left open in this strategy. This opening allowed coastal storm surge to enter the west portion of Galveston Bay, and subsequently impact the Clear Lake and Upper Bay areas. With a lack of complete isolation of Galveston Bay at
The Mid-Bay Gate Strategy was initially evaluated using ADCIRC modeling. Figure 5-5 illustrates the maximum water levels for the IKE15-P7 storm under (a) Baseline Conditions, and (b) with the Mid-Bay Gate Strategy in place. The Mid-Bay Gate Strategy reduces storm surge significantly in the upper and middle portions of Galveston Bay, most notably within the industrial complex along the HSC, Barbours Cut, Cedar Bayou, and Baytown, as well as along the west of the Bay, such as in Clear Lake, Kemah, behind the Texas City Levee, and Dickinson.

Significant storm surge reductions for the entirety of the west and northwest portions of Galveston Bay are provided by the Mid-Bay Strategy as shown in Figure 5-5. Such reductions are primarily due to the inclusion of the navigation gate (Scenario “M”) across the HSC connecting the dredged containment berms (“E”). With this gate across the HSC, the dredged containment berms are able to form a complete barrier so as to significantly mitigate wind-induced storm surge from impacting the west and northwest portions of the Bay, as well as prevent any coastal storm surge entering through Bolivar Roads inlet to enter into these protected areas. Full protection is provided to the eastern portion of Galveston Island by the combination of Galveston Seawall (“1”) and the backside Galveston Levee (“H”). However, minimal storm surge reductions (~2.5 feet) are provided to the remainder of the Galveston Bay area. In addition, future analyses of this strategy...
will entail optimizing various components or scenarios associated with this strategy, as well as more refined economic analyses, and evaluations of social and environmental impacts.

**5.1.3 LOWER-BAY GATE STRATEGY**

Figure 5-6 shows the storm surge response for ADCIRC modeling for IKE15-P7 under (a) Baseline Conditions and (b) with the Lower-Bay Gate Strategy in place. For the modeled hurricane, it can be seen that the Lower-Bay Gate Strategy reduces storm surge throughout Galveston Bay, including the areas within the industrial complex along the HSC, Barbours Cut, Cedar Bayou, Baytown, Clear Lake, Kemah, Dickinson, behind the Texas City Levee, and along Galveston Island and Bolivar Peninsula.

Figure 5-6 supports the strategy of a continuous storm surge protection at the lower portion of Galveston Bay with the placement of the gate system across Bolivar Roads ("L"). The gate does well to prevent coastal storm surge from entering the bay, while the dredged containment berms ("E") do well to mitigate residual wind-induced storm surge within the western and northern portions of the Bay. Similar to Upper and Mid-Bay strategies, future analyses of the Lower-Bay Strategy will include further evaluation of the Galveston Levee ("H") for protecting the eastern portion of Galveston Island. In addition, future analyses of this strategy will entail optimizing various components or scenarios associated with this strategy, as well as more refined economic analyses, and evaluations of social and environmental impacts.

**5.2 SUMMARY OF INITIAL ADCIRC MODEL RESULTS FOR THE THREE GATE STRATEGIES**

As previously referenced, Figure 5-7 illustrates four key locations where maximum storm surge elevations were identified and are included within Table 5-1 and Table 5-2. As shown in these tables, the maximum surge elevations are significantly reduced for the areas being protected by a gate system; however, less significant reduction occurs for the areas not protected by a gate system.
Storm Surge Elevation Reporting Locations

Figure 5-7 illustrates four key locations where maximum storm surge elevations were identified.
### TABLE 5-1 H-GAPS REGIONAL STRATEGY STORM SURGE PERFORMANCE FOR IKE-P0

<table>
<thead>
<tr>
<th></th>
<th>HSC</th>
<th>Clear Lake</th>
<th>Port of Galveston</th>
<th>Galveston Seawall</th>
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<td>13</td>
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<td>13</td>
<td>13</td>
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<tr>
<td>Upper-Bay Strategy</td>
<td>3</td>
<td>11</td>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td>Mid-Bay Strategy</td>
<td>4</td>
<td>2</td>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td>Lower-Bay</td>
<td>4</td>
<td>4</td>
<td>5</td>
<td>13</td>
</tr>
</tbody>
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### TABLE 5-2 H-GAPS REGIONAL STRATEGY STORM SURGE PERFORMANCE FOR IKE15-P7

<table>
<thead>
<tr>
<th></th>
<th>HSC</th>
<th>Clear Lake</th>
<th>Port of Galveston</th>
<th>Galveston Seawall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline Conditions</td>
<td>24</td>
<td>19</td>
<td>18</td>
<td>19</td>
</tr>
<tr>
<td>Upper-Bay Strategy</td>
<td>6</td>
<td>18</td>
<td>17</td>
<td>19</td>
</tr>
<tr>
<td>Mid-Bay Strategy</td>
<td>7</td>
<td>2</td>
<td>18</td>
<td>19</td>
</tr>
<tr>
<td>Lower-Bay</td>
<td>8</td>
<td>7</td>
<td>9</td>
<td>19</td>
</tr>
</tbody>
</table>
Coastal Marsh in Galveston Bay

Source: Jim Olive
6. Flood Damage Risk Assessments

6.1 Residential Flood Damages

The SSPEED team, in conjunction with TAMU-Galveston, has developed a damage model for estimating the residential portion of the damages that might occur as a result of storm surges in the Galveston Bay area. This model will be used to estimate residential flood damages for both baseline conditions and the reduction of such damages (or benefit) from various storm surge-reduction strategies. While this damage model is still being refined, the SSPEED Center has utilized it to conduct a preliminary analysis of the storm surge reduction strategies evaluated in this report.

The residential damage model is based on tax appraisal district data that was available from Galveston, Harris and Chambers counties. This data set includes information at the parcel level, such as date of construction, type of structure (such as single family, mobile home, etc.), and appraised value of the residential property. In order to estimate the slab elevation of each residential property, the most recent LIDAR topographic data and FEMA floodplain information was utilized for each county. If the residential structure was located outside of the FEMA floodplain, the slab elevation of the structure was estimated based on the LIDAR data. If the residential structure was located inside of the FEMA floodplain, then the date of construction, the FEMA floodplain information, and the local government regulations were used to estimate the slab elevation. No commercial or public property damage information has been evaluated yet, although it is expected that the amount of damages attributable to most of these properties would be a small percentage of the residential damages. However, some high valued properties will need to be evaluated on a case-by-case basis as part of future work.

This preliminary residential database was then analyzed to estimate the amount of structural and personal property damages that would occur at various water levels on each parcel of residential property located within the three counties. The damage curves that were used for this analysis were obtained from the USACE-New Orleans District, who had recently developed such curves following Hurricane Katrina, specifically for use in coastal communities. Separate curves were used to estimate the damages to the structure and its contents based upon a percentage of their value, as shown below.

By using the preliminary damage model and the above methodology, estimates of the residential flood damages by county for both baseline conditions and the three gate strategies have been developed and are shown below. As seen in Table 6-1, the residential flood damages for Baseline Conditions are highest in Galveston County and lowest in Chambers County. The relative magnitudes of residential damages between these counties most likely reflect differences in both the number of inundated structures as well as their value.

The residential flood damage reductions for the three gate strategies analyzed are similar to the reduction in maximum surge levels that were discussed above. As noted previously, all three gate strategies incorporate the Galveston Levee ("H") which contributes to a significant portion of the residential flood reductions for Galveston County. Future work will focus on making further improvements to the residential damage model as well as evaluating additional metrics to better understand the spatial distribution of residential damage estimates. This future work will be used to further refine the three gate strategies.

<table>
<thead>
<tr>
<th>County</th>
<th>Baseline Conditions</th>
<th>Lower-Bay</th>
<th>Mid-Bay</th>
<th>Upper-Bay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Galveston</td>
<td>$7,157 M</td>
<td>$1,469 M</td>
<td>$2,316 M</td>
<td>$3,848 M</td>
</tr>
<tr>
<td>Harris</td>
<td>$1,510 M</td>
<td>$3 M</td>
<td>$1 M</td>
<td>$864 M</td>
</tr>
<tr>
<td>Chambers</td>
<td>$229 M</td>
<td>$2 M</td>
<td>$153 M</td>
<td>$98 M</td>
</tr>
<tr>
<td>TOTAL</td>
<td>$8,896 M</td>
<td>$1,474 M</td>
<td>$2,470 M</td>
<td>$4,810 M</td>
</tr>
</tbody>
</table>
FIGURE 6-1 RESIDENTIAL DAMAGE CURVES - STRUCTURE

USACE DEPTH DAMAGE CURVES: SALTWATER, RESIDENTIAL STRUCTURES

FIGURE 6-2 RESIDENTIAL DAMAGE CURVE - CONTENTS

USACE DEPTH DAMAGE CURVES: RESIDENTIAL CONTENTS
6.2 INDUSTRIAL FLOOD DAMAGES

The SSPEED Center has focused their research of industrial damages on the numerous industrial facilities within the Galveston Bay area, and especially within the industrial complex along the HSC. These industrial damages include not only the flood damages for these industrial facilities but also the probability and risk associated with the thousands of petro-chemical industrial above-ground storage tanks (ASTs) that exist along the HSC. These ASTs pose a serious risk to the Galveston Bay area and the nation if they were to fail as a result of storm surge inundation. As such, the potential for such tank failure, and the resulting damages such as clean-up costs, are being investigated so as to be included in the industrial damages model for this study.

6.2.1 HSC TANK SPILL RELEASE MODEL

The failure of ASTs leading to spillage of hazardous material can be catastrophic to the surrounding environment and lead to enormous economic losses. The SSPEED Center is identifying the failure modes of ASTs under storm surge. Based on failure of ASTs during Hurricane Katrina, the major cause of tank failure was identified from the dislocation of tanks due to flotation and buckling of the tank shell. In order to facilitate flotation and buckling analysis of tanks, a comprehensive inventory of HSC tanks (over 4,000 tanks) was developed in geospatial formats consisting of tank heights, diameters, anchoring methods, and liquid contents. In addition, the height of berms surrounding any of these tanks was determined using LIDAR data in order to identify any additional protection from flotation for each tank. A probabilistic flotation relationship was then assigned for each AST and Monte Carlo simulation was performed to quantify uncertainties of tank levels in tanks. In short, an initial preliminary estimate of the total expected volume of spill from all the ASTs associated with different maximum water levels is provided in Figure 6-3 (Padgett and Kameshwar, 2015). In calculating the estimated spill volumes, it has been assumed that upon flotation, all the contents of the tank will be spilled. This preliminary spill information was used to then determine the estimated cost of clean-up associated with AST failure and is included as a component of the industrial damages discussed in Section 6.2.2. Future work will focus on refining the spill volume estimates and assessing the buckling fragility of the tanks which would help understand the risk to these ASTs during storm surge events.

These ASTs pose a serious risk to the Galveston Bay area and the nation if they were to fail as a result of storm surge inundation.
6.2.2 TOTAL INDUSTRIAL FACILITY ECONOMIC LOSS MODEL

In addition, an industrial Facility Economic Damage and Environmental Release Assessment Planning (FEDERAP) model was developed by the SSPEED Center at the University of Houston (Burleson et al. 2015a; Burleson et al. 2015b). This damage estimation model was applied to several industrial facilities along the HSC to estimate the total industrial damages from hurricane surge inundation, including tank spill release clean-up costs. These estimated facility damages have then been used to extrapolate to more than 200 facilities along the HSC to arrive at the total facility damage estimate. The framework for FEDERAP is shown in Figure 6-4.

Of all the industrial damages expected from storm surge flooding in the Galveston Bay area, the majority of them are associated with the inundation of facilities located within the industrial complex along the HSC. In addition, there are numerous storage tanks at these facilities that contain a variety of products (such as oil, gasoline, petrochemical products) that are subject to flotation as water inundates and rises adjacent to these tanks. Samples of 12 industrial facilities were selected for which cost information was available to derive a damage estimate due to the inundation of the facilities, including their tanks. These damage estimates were developed for each of these facilities, and then extrapolated to the more than 200 facilities along the HSC and San Jacinto River, based on acres of inundation. The total facility loss curves are shown in Figure 6-5. It should be noted that these curves only include those facilities located within the industrial complex along the HSC. As shown below, the difference between the high and low industrial damage estimates is associated with the ASTs spillage and clean-up costs. The high damage estimate includes the clean-up costs for each of the 12 industrial facilities evaluated in detail with the resulting total industrial damages extrapolated to the more than 200 facilities. The low damage estimate does not include the ASTs spillage clean-up costs for the 12 industrial facilities and the extrapolated results; however, the actual ASTs spillage clean-up cost associated with each of the over 4,000 storage tanks was calculated from the spill volume curves, as seen in Figure 6-3, and then added to the overall industrial facility damages. The clean-up costs for the ASTs spillage is based on $30.60 cost of clean-up per liter (Etkin, 2000).

FILE FIGURE 6-4 SCHEMATIC OF FEDERAP INDUSTRIAL LOSS MODEL
Based upon the above damage curves, preliminary industrial facility flood damage estimates associated with the IKE15-P7 storm, for the Baseline Conditions and the three gate strategies, are shown in Table 6-2 below. Table 6-2 shows that the Upper-, Mid- and Lower-Bay Gate Strategies eliminate all industrial damages since they all provide adequate surge protection for those facilities within the industrial complex along the HSC. Future work will include all the industrial facilities throughout the Galveston Bay area (e.g. behind the Texas City Levee).

The two curves represent an initial estimate of the range of potential industrial damages along the HSC for various maximum water levels. These damage curves do not include the additional indirect, economic damages resulting from the shut-down of any of these industrial facilities, or of the HSC itself, on the local, regional, state or national economies. This component of the total industrial damages is being investigated by the TAMU-Galveston team and will be added when completed by them.

6.3 INFRASTRUCTURE DAMAGES

During Hurricane Ike, the regional infrastructure was extensively damaged. Several bridges were rendered unusable due to unseating of the

These damage curves do not include the additional indirect, economic damages resulting from the shut-down of any of these industrial facilities, or of the HSC itself, on the local, regional, state or national economies.
### TABLE 6-2 INDUSTRIAL FACILITY FLOOD DAMAGE ESTIMATES FOR IKE15-P7

<table>
<thead>
<tr>
<th>Max. Water Level</th>
<th>Baseline Conditions</th>
<th>Lower-Bay</th>
<th>Mid-Bay</th>
<th>Upper-Bay</th>
</tr>
</thead>
<tbody>
<tr>
<td>FEDERAP (High Estimate)</td>
<td>$73 B</td>
<td>$0</td>
<td>$0</td>
<td>$0</td>
</tr>
<tr>
<td>FEDERAP (Low Estimate)</td>
<td>$37 B</td>
<td>$0</td>
<td>$0</td>
<td>$0</td>
</tr>
</tbody>
</table>
bridge deck (road surface), scouring of the bridge approaches and other bridge components such as foundations and abutments. Functionality of the transportation infrastructure after a hurricane is essential for rescue and relief operations. Furthermore, global phenomenon such as climate change brings further uncertainty in the frequency and intensity of future storm events. Under such circumstances, vulnerability assessment of regional infrastructure becomes essential to inform hazard mitigation decisions.

In this light, previous work has already identified unseating of the bridge deck, i.e. the roadway, and scouring of bridge components are identified as the major causes of failure due to hurricane storm surge and wave loads (Kameshwar and Padgett, 2014). Furthermore, an inventory of the bridges susceptible to hurricane wave and storm surge loads has also been created. The inventory has details about bridge length, bridge width, construction material and year of construction and other details such as type of connection between the bridge deck and its supporting structure, foundation design and soil type. These bridge details have been used to derive the deck unseating probability for all the bridges in the inventory for different hurricane scenarios. Figure 6-6 shows the probability of deck unseating of all the bridges in the region for a Hurricane “Super Ike” scenario, which would have 30% stronger winds and a more southerly landfall with respect to those associated with Hurricane Ike. Ongoing work is aimed at assessing the fragility of these bridges to scouring of foundations due to hurricane storm surge. For this purpose, a simplified methodology is being developed to assess the load carrying capacity of bridge foundation at different scour levels. Once completed, the scour fragility curves will enable safety assessment of bridges for passage of trucks and other heavy vehicles. Furthermore, scour fragility maps similar to Figure 6-6 will also be developed for several hurricane storm events. Future work will focus on scour fragility estimations and estimation of damages due to bridge failure. Furthermore, the fragility maps will be used to assist in evaluating the effectiveness of the H-GAPS strategies.

**FIGURE 6-6 BRIDGE FAILURE PROBABILITIES FOR IKE30-P7**

The fragility maps will be used to assist in evaluating the effectiveness of the H-GAPS strategies.
Traffic During Evacuation for Hurricane Ike
7. H-GAPS Initial Regional Gate Strategy Cost Estimates

A preliminary study of cost estimate was prepared for each of the three regional gate strategies, based on a rough conceptual design of the various scenarios or components of each strategy. Table 7-1 summarizes each of the three regional gate strategies and their corresponding preliminary cost estimates, while subsequent paragraphs provide expanded unit cost estimates and descriptions for each strategy.

7.1 UPPER-BAY GATE STRATEGY

The Upper-Bay Gate Strategy entails levee protection extending from SH-225 at Sens Road via SH-225, FM-146, NL Street, E. Barbours Cut Blvd and Ballester Street to the HSC and over to Atkinson Island to form the west portion of the Upper Bay protection, along with a navigation gate across this portion of the HSC. This gate spans 740 feet and protects to a depth of approximately 60 feet and a height of 25 feet. The eastern portion of this levee protection extends from Atkinson Island over to Mosquito Knoll (with a small craft gate included), southeast of Atlantic Pipeline to FM-1405, and then around the south and east side of Lone Star Energy Fabrication. The in-Bay portion of the strategy consists of dredge disposal containment berms stretching from Atkinson Island running south along the east side of the HSC to the Trinity River Cut. An HSC opening remains over the navigable portion of the HSC near the middle of the bay, but the dredged containment berms continue west of this opening and run south to Dollar Reef, until final tie-in with the Texas City Levee. These containment berms include small craft gates for both navigation and bay circulation. Elevating roadways include FM-3005 (from The Galveston Seawall to San Luis Pass) and SH-87 (from Galveston Seawall to High Island). Itemized cost estimates for these components of the Upper-Bay Gate Strategy are provided in Table 7-2.

---

TABLE 7-1 SUMMARY OF PRELIMINARY H-GAPS GATE STRATEGY COST ESTIMATES

<table>
<thead>
<tr>
<th>H-GAPS Strategy</th>
<th>Description</th>
<th>Cost Estimate (in billions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper-Bay Gate</td>
<td>Navigation gate across the HSC with levees connecting the gate into high ground (“U”), dredged containment berms along the HSC within the Bay (“E”), Galveston Levee (“H”), and raising the roadways of Hwy 87 (“F”) and FM-3005 (“G”)</td>
<td>$2.84</td>
</tr>
<tr>
<td>Mid-Bay Gate</td>
<td>Navigation gate across the HSC (“M”), with levees and dredged containment berms along the HSC within the Bay connecting it to high ground (“E”), Galveston Levee (“H”), and raising the roadways of Hwy 87 (“F”) and FM-3005 (“G”)</td>
<td>$2.76</td>
</tr>
<tr>
<td>Lower-Bay Gate¹</td>
<td>Navigation gate across the HSC, along with an environmental gate across the rest of Bolivar Roads, with levees connecting the gates into high ground (“L”), dredged containment berms along the HSC within the Bay (“E”), Galveston Levee (“H”), and raising the roadways of Hwy 87 (“F”) and FM-3005 (“G”)</td>
<td>$7.62</td>
</tr>
</tbody>
</table>

¹ For the Lower-Bay Gate Strategy, approximately $4 billion is for the environmental gate alone (cost estimate based on TU Delft 2015 report); however, this gate could cost as high as $10 billion based on recent storm surge barrier construction costs.

Note: Estimated construction costs include $300 million for Galveston Levee (“H”).
### TABLE 7-2 PRELIMINARY UPPER-BAY GATE STRATEGY COST ESTIMATES

<table>
<thead>
<tr>
<th>ID</th>
<th>Description</th>
<th>Quantity</th>
<th>Units</th>
<th>Unit Cost ($)</th>
<th>Total Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>U</td>
<td>HSC Gate</td>
<td>1</td>
<td>EA</td>
<td>400M</td>
<td>400.00M</td>
</tr>
<tr>
<td></td>
<td>Levee</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>West Section on Land - Sens to Atkinson Island</td>
<td>2,346,999</td>
<td>CY</td>
<td>12.00</td>
<td>28.16M</td>
</tr>
<tr>
<td></td>
<td>West Section on Water - Sens to Atkinson Island</td>
<td>225,487</td>
<td>CY</td>
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<td>3.38M</td>
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<tr>
<td></td>
<td>Roadway replacement</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>West Roadway Replacement</td>
<td>3,469,000</td>
<td>SF</td>
<td>5.00</td>
<td>17.35M</td>
</tr>
<tr>
<td></td>
<td>Railway Crossing Gate</td>
<td>3</td>
<td>EA</td>
<td>500,000.00</td>
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<td></td>
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<td>19.21M</td>
</tr>
<tr>
<td></td>
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<td>1</td>
<td>EA</td>
<td>100M</td>
<td>100.00M</td>
</tr>
<tr>
<td>E</td>
<td>Levee</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>East Section on Land - Atkinson Island to SH 99</td>
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<td>CY</td>
<td>12.00</td>
<td>3.29M</td>
</tr>
<tr>
<td></td>
<td>East Section on Water - Atkinson Island to SH 99</td>
<td>815,434</td>
<td>CY</td>
<td>15.00</td>
<td>12.23M</td>
</tr>
<tr>
<td></td>
<td>Sea Barrier / Dredge Containment Land Levee</td>
<td>3,034,000</td>
<td>CY</td>
<td>12.00</td>
<td>36.41M</td>
</tr>
<tr>
<td></td>
<td>Sea Barrier / Dredge Containment Water Levee</td>
<td>23,424,000</td>
<td>CY</td>
<td>15.00</td>
<td>351.35M</td>
</tr>
<tr>
<td></td>
<td>Roadway replacement</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>East Roadway Replacement</td>
<td>1,142,000</td>
<td>SF</td>
<td>5.00</td>
<td>5.71M</td>
</tr>
<tr>
<td></td>
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<td>100.00</td>
<td>4.05M</td>
</tr>
<tr>
<td></td>
<td>Small Craft Channel Barrier</td>
<td>5</td>
<td>EA</td>
<td>200.00M</td>
<td>1,000.00M</td>
</tr>
<tr>
<td>G</td>
<td>West Galveston Island Roadway replacement (FM 3005)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Road work</td>
<td>1,035,000</td>
<td>SY</td>
<td>50.00</td>
<td>51.75M</td>
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<tr>
<td></td>
<td>Earth work</td>
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<td>SY</td>
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<td>10.67M</td>
</tr>
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<td>13.00M</td>
</tr>
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<td>F</td>
<td>Bolivar Peninsula Roadway replacement (Hwy 87)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Road work</td>
<td>710,000</td>
<td>SY</td>
<td>50.00</td>
<td>35.50M</td>
</tr>
<tr>
<td></td>
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<tr>
<td></td>
<td>Drainage</td>
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<td>ALLOW</td>
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<tr>
<td></td>
<td><strong>Subtotal</strong></td>
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<td>2,119.76M</td>
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<td></td>
<td><strong>20% contingency</strong></td>
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<td></td>
<td><strong>Total Est. Cost</strong></td>
<td></td>
<td></td>
<td>2,543.71M</td>
<td></td>
</tr>
</tbody>
</table>

**Note:** The addition of the Galveston Levee (“H”) would cost approximately $300 million.
7.2 MID-BAY GATE STRATEGY

The Mid-Bay Gate Strategy entails a navigation gate across the HSC in the middle of Galveston Bay, connecting the east and west sides of the dredged containment berms. This gate spans 740 feet and protects to a depth of approximately 60 feet and a height of 25 feet. The remaining elements for cost estimates are similar to the Upper-Bay Gate Strategy, excluding the western portion of the levee protection system extending over to Atkinson Island. Itemized cost estimates are provided in Table 7-3.

### TABLE 7-3 PRELIMINARY MID-BAY GATE STRATEGY COST ESTIMATES

<table>
<thead>
<tr>
<th>ID</th>
<th>Description</th>
<th>Quantity</th>
<th>Units</th>
<th>Unit Cost</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>M</td>
<td>HSC Gate</td>
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<td>EA</td>
<td>$500.00M</td>
<td>$500.00</td>
</tr>
<tr>
<td>E</td>
<td>Levee</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>East Section on Land - Atkinson Island to SH 99</td>
<td>273894</td>
<td>CY</td>
<td>12 $</td>
<td>3.29M</td>
</tr>
<tr>
<td></td>
<td>East Section on Water - Atkinson Island to SH 99</td>
<td>815434</td>
<td>CY</td>
<td>15 $</td>
<td>12.23M</td>
</tr>
<tr>
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<td>Sea Barrier / Dredge Containment Land Levee</td>
<td>3034000</td>
<td>CY</td>
<td>12 $</td>
<td>36.41M</td>
</tr>
<tr>
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<td>Sea Barrier / Dredge Containment Water Levee</td>
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</tr>
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<td>Small Craft Channel Barrier</td>
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<td>EA</td>
<td>200.00M</td>
<td>1,000.00M</td>
</tr>
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<td>G</td>
<td>West Galveston Island Roadway replacement (FM 3005)</td>
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<tr>
<td></td>
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<td>SY</td>
<td>50 $</td>
<td>51.75M</td>
</tr>
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<td></td>
<td>Earth work</td>
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<td>SY</td>
<td>10 $</td>
<td>10.67M</td>
</tr>
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<td></td>
<td>Utility Adjustments</td>
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<td>LF</td>
<td>100 $</td>
<td>13.00M</td>
</tr>
<tr>
<td>F</td>
<td>Bolivar Peninsula Roadway replacement (Hwy 87)</td>
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<td></td>
<td></td>
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<tr>
<td></td>
<td>Road work</td>
<td>710000</td>
<td>SY</td>
<td>50 $</td>
<td>35.50M</td>
</tr>
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<td>Earth work</td>
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<td>10 $</td>
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<td>90000</td>
<td>LF</td>
<td>100 $</td>
<td>9.00M</td>
</tr>
<tr>
<td></td>
<td>Drainage</td>
<td>1</td>
<td>ALLOW</td>
<td>3.00M</td>
<td>3.00M</td>
</tr>
</tbody>
</table>

**Note:** The addition of the Galveston Levee (“H”) would cost approximately $300 million.
### 7.3 LOWER-BAY GATE STRATEGY

The Lower-Bay Gate Strategy entails a navigation gate across the navigable channel within Bolivar Roads that spans 740 feet and protects to a depth of approximately 60 feet and a height of 17 feet. In addition, this strategy entails an environmental gate that spans about 9,200 feet to connect the navigation gate across the HSC to high ground both on Galveston Island and Bolivar Peninsula at a height of 17 feet. The remaining components of this strategy are similar to the Upper and Mid-Bay Gate Strategies. Itemized cost estimates are provided in Table 7-4.

#### TABLE 7-4 PRELIMINARY LOWER-BAY GATE STRATEGY COST ESTIMATES

<table>
<thead>
<tr>
<th>ID</th>
<th>Description</th>
<th>Quantity</th>
<th>Units</th>
<th>Unit Cost</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>HSC Gate</td>
<td>1</td>
<td>EA</td>
<td>$550.00M</td>
<td>$550.00M</td>
</tr>
<tr>
<td></td>
<td>Environmental Gate</td>
<td>1</td>
<td>EA</td>
<td>$4000.00M</td>
<td>$4,000.00M</td>
</tr>
<tr>
<td>E</td>
<td>Levee</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>East Section on Land - Atkinson Island to SH 99</td>
<td>273894</td>
<td>CY</td>
<td>$12</td>
<td>$3.29M</td>
</tr>
<tr>
<td></td>
<td>East Section on Water - Atkinson Island to SH 99</td>
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<td>CY</td>
<td>$15</td>
<td>$12.23M</td>
</tr>
<tr>
<td></td>
<td>Sea Barrier / Dredge Containment Land Levee</td>
<td>3034000</td>
<td>CY</td>
<td>$12</td>
<td>$36.41M</td>
</tr>
<tr>
<td></td>
<td>Sea Barrier / Dredge Containment Water Levee</td>
<td>23424000</td>
<td>CY</td>
<td>$15</td>
<td>$351.36M</td>
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<td></td>
<td>Roadway replacement</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>East Roadway Replacement</td>
<td>1142000</td>
<td>SF</td>
<td>5</td>
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<tr>
<td></td>
<td>Utility Adjustments</td>
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<tr>
<td></td>
<td>Small Craft Channel Barrier</td>
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<td>EA</td>
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<td>$1,000.00M</td>
</tr>
<tr>
<td>G</td>
<td>West Galveston Island Roadway replacement (FM 3005)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Road work</td>
<td>1035000</td>
<td>SY</td>
<td>50</td>
<td>$51.75M</td>
</tr>
<tr>
<td></td>
<td>Earth work</td>
<td>1067000</td>
<td>SY</td>
<td>10</td>
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<tr>
<td></td>
<td>Utility Adjustments</td>
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<td>LF</td>
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<td>$13.00M</td>
</tr>
<tr>
<td>F</td>
<td>Bolivar Peninsula Roadway replacement (Hwy 87)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>Road work</td>
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<td>ALLOW</td>
<td>$3.00M</td>
<td>$3.00M</td>
</tr>
<tr>
<td></td>
<td>Subtotal</td>
<td></td>
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<td>$6,100.16M</td>
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<td>Total Est. Cost</td>
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<td></td>
<td>$7,320.48M</td>
<td></td>
</tr>
</tbody>
</table>

1 For the Lower-Bay Gate Strategy, approximately $4 billion is for the environmental gate alone (cost estimate based on TU Delft 2015 report); however, this gate could cost as high as $10 billion based on recent storm surge barrier construction costs.

**Note:** Estimated construction costs include $300 million for Galveston Levee ("H").
7.4 SUMMARY OF ECONOMIC DAMAGES AND COSTS

Taken collectively, the preliminary flood damage analyses and cost estimate analyses were combined to provide a preliminary sense of economic performance for each regional gate strategy. The results are shown in Table 7-5 using IKE15-P7. Referring to Table 7-5, it is apparent that all three strategies provide adequate storm surge protection to the HSC region. However, the major difference is the costs of the three gate strategies. The Lower-Bay Strategy is almost three times the implementation costs for the Upper- and Mid-Bay Strategies.

TABLE 7-5 H-GAPS BENEFIT-COST SUMMARY USING IKE15-P7

<table>
<thead>
<tr>
<th></th>
<th>Baseline Conditions</th>
<th>Lower Bay</th>
<th>Mid Bay</th>
<th>Upper Bay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Industrial Damages</td>
<td>$37.0 B</td>
<td>$0</td>
<td>$0</td>
<td>$0</td>
</tr>
<tr>
<td>Residential Damages</td>
<td>$8.9 B</td>
<td>$1.5 B</td>
<td>$2.5 B</td>
<td>$4.8 B</td>
</tr>
<tr>
<td>Total Damages</td>
<td>$45.9 B</td>
<td>$1.5 B</td>
<td>$2.5 B</td>
<td>$4.8 B</td>
</tr>
<tr>
<td>Reduced Damages (Benefit)</td>
<td>-</td>
<td>$44.4 B</td>
<td>$43.4 B</td>
<td>$41.1 B</td>
</tr>
<tr>
<td>Cost</td>
<td>-</td>
<td>$7.6 B</td>
<td>$2.8 B</td>
<td>$2.8 B</td>
</tr>
</tbody>
</table>

1 For the Lower-Bay Gate Strategy, approximately $4 billion is for the environmental gate alone (cost estimate based on TU Delft 2015 report); however, this gate could cost as high as $10 billion based on recent storm surge barrier construction costs.

Note: Estimated construction costs include $300 million for Galveston Levee (“H”).
8. Nonstructural Mitigation Strategies and Federal Policies

Recent changes to the Principles and Guidelines for water resource projects, including flood control projects, have been promulgated by the President’s Council on Environmental Quality (CEQ) as per the Water Resources Development Act of 2007. These changes require full consideration of nonstructural strategies, as well as the incorporation of ecological services into the content and valuation assessment of various structural scenarios. These recent revisions incorporate concepts that have been present in Corps of Engineers’ thinking about projects subsequent to Katrina along the Mississippi coast as well as subsequent to Sandy in New York and New Jersey. Consequently, as part of the work of the SSPEED Center, several nonstructural scenarios have been developed for use in tandem with structural scenarios. Two landscape-scale scenarios have been developed that are compatible with any structural alternative, as well as being individual projects, and other nonstructural scenarios may be used in tandem with some if not all of the proposed structural scenarios.

The SSPEED Center’s work on nonstructural scenarios has concentrated on two landscape-scale concepts that are proposed for low-lying, generally undeveloped areas of Chambers, Galveston, Brazoria and Matagorda Counties. These two strategies are the Texas Coastal Exchange (TCX) and the Lone Star Coastal National Recreation Area (LSCNRA). Both concepts are focused on the development and enhancement of economic activities that are based on the natural ecological systems of the region. Because the economy created is based on natural systems, it follows that it is compatible with occasional inundation by hurricane flooding. These nonstructural strategies will generate jobs within the four counties and income for landowners (TCX).

8.1 Texas Coastal Exchange

The Texas Coastal Exchange (TCX) is a concept for understanding and developing a market for commercial transactions involving the buying and selling of ecological services. Ecological services are natural systems and processes that produce “goods” that are used by humans.

The basic concept of the TCX as a nonstructural storm surge damage abatement option is to make land in its natural state economically competitive with land that has been developed. The native ecosystems of the Texas Coast are adapted to occasional inundation by hurricane storm surge tides and recover relatively quickly at little or no cost to the taxpayer. If an economic sector could be developed based upon these natural systems, then it would provide both damage risk reduction when storms occur as well as long-term economic resilience to the region. In other words, it would create an economic sector designed to survive inundation.

Along the Texas coast, several ecological systems exist that lend themselves to commercial transactions involving the buying and selling of ecological services. These are oyster reefs, coastal marshes, coastal prairies and bottomland forest systems. Some of these systems offer the
ability to support ongoing commercial activities, such as the collection of oyster meat from the reef, the harvesting of trees within the bottomland and cattle grazing within the prairie systems. However, each of these systems also offer additional “goods”, such as the sequestration of carbon, the removal of nitrogen and phosphorus, enhancement of water resources and support of fish and wildlife resources. These elements can be quantified to varying degrees based on existing literature. Similarly, there are different classes of users that may have an interest in purchasing these various services.

The idea behind the TCX is to develop an online trading system platform that will link sellers and buyers of ecological services. To this end, a robust GIS data base has been developed, and an interactive interface is being developed that will allow landowners within the four county area to determine which ecological systems exist or could exist on their property. Further, this system will allow landowners to express their interest in developing or enhancing the ecological service functions of their property and will connect them with potential buyers of those services. The transactions themselves would be negotiated between willing buyers and sellers within a general framework developed by researchers at the SSPEED Center. This system should be completed by the end of calendar year 2015.

**8.2 LONE STAR COASTAL NATIONAL RECREATION AREA**

The Lone Star Coastal National Recreation Area (LSCNRA) is the second of the two landscape-scale, nonstructural storm surge damage abatement strategies proposed by SSPEED...
Center. The LSCNRA is conceived as a method for organizing and assisting in the realization of the eco-tourism potential of the low-lying areas of the Upper Texas Coast. At the current time, over 200,000 acres of low-lying lands are preserved through ownership by federal, state and local agencies as well as non-governmental organizations. These low-lying, protected lands are shown in Figure 8-1.

8.3 SUBSIDIZED FEDERAL FLOOD INSURANCE AND BUYOUTS

The two landscape-scale strategies discussed above are primarily seen as being applicable to areas that are largely without urban development. Within developed areas, nonstructural strategies are generally integrated within or supplemental to, rather than totally independent from, structural scenarios. As such, this type of nonstructural strategies may be specific to one or more structural solutions. Many of these strategies are only now being considered as we better understand the relative effectiveness of various structural scenarios and particularly as we identify areas that are not fully protected.

The following nonstructural strategies are being considered for their applicability within the Houston-Galveston region. The presence of subsidized flood insurance as a nonstructural alternative could play a role in aiding those who might otherwise not be protected by a structural solution. Of course, those receiving protection would have their actuarial rates reduced due to their protection provided by the structure. Another nonstructural alternative is the buy-out of extremely high risk areas in a manner that proposes the creation of wetlands and the return of shorelines to natural conditions. Along the barrier islands, the integration of sand dunes and beach nourishment is another nonstructural alternative that could aid in the overall concept of protection. Lastly, the integration of oyster reefs could serve as another alternative by offering significant protection from less severe storm events.

8.4 ENVIRONMENTAL LEGAL ISSUES IN FLOOD DAMAGE REDUCTION

Often overlooked in planning for various types of damage reduction projects is the fact that a fabric of environmental laws usually plays a major role in determining which alternative is ultimately selected. At the least, such laws pose procedural hurdles that usually must be navigated. However, these laws have substantive requirements that might eliminate certain strategies. They certainly should not be overlooked. The key environmental laws include the National Environmental Policy Act (NEPA), the River and Harbor Act, the Clean Water Act, the Endangered Species Act (ESA), the Water Resources Development Act (WRDA), the Magnuson Stevens Fishery Management Conservation Act, Executive Order 11988 and Executive Order 12898. They are discussed in sequence.

8.5 NATIONAL ENVIRONMENTAL POLICY ACT (NEPA)

NEPA is a procedural act that applies to federal actions including Corps of Engineers permit requests from non-federal applicants. For federal actions having a significant environmental impact, an environmental impact statement (EIS) is required to be prepared, and little doubt exists that a storm surge damage reduction project as discussed in this document will generate significant environmental effects of varying types. NEPA does not prohibit projects that generate significant environmental impacts, but rather requires that the decision-makers and the public be fully informed about these impacts before the project is approved. As the U.S. Supreme Court has stated, NEPA “merely prohibits uninformed – rather than unwise – agency action”.

As part of NEPA compliance, a full and complete suite of alternatives must be developed and evaluated, including nonstructural strategies. For each of these strategies, full disclosure of environmental effects must occur. These strategies and their effects are set out in a Draft EIS that is circulated to the federal state and local agencies and to the public for their comments. These comments are then evaluated by the lead federal agency and a Final EIS is then prepared. No decision on a project may be made until after the completion of the FEIS and the preparation of a Record Of Decision (ROD).

8.6 RIVER AND HARBOR ACT AND CLEAN WATER ACT

Two Corps of Engineers’ permits will most likely apply to this storm surge damage reduction
project if undertaken by a non-federal applicant; and even if the Corps is the project sponsor, certain of the permit rules would still apply. Congress gave the Corps of Engineers authority over navigation in federal waters under Section 10 of the River and Harbor Act of 1899 which requires that a permit be obtained to undertake any work or erect any structure in navigable waters of the United States. In 1972, Congress gave the Corps authority over the discharge of dredge or fill material into waters of the United States under Section 404 of the Clean Water Act. All of the regional strategies discussed in this report would be expected to require both permits.

The regulatory requirements that control the issuance of Section 404 permits were issued by the U.S. Environmental Protection Agency and are substantive. These so-called 404(b)(1) guidelines contain several prohibitions that are binding upon the Corps and very protective of the aquatic environment. Here, a discharge of dredge or fill material is prohibited if there is a practicable alternative to the proposed discharge which would have less adverse impact on the aquatic ecosystem. This provision (found at 40 CFR 230.10(a)) is designed to protect aquatic environments such as Galveston Bay. This provision not only applies to permit applicants but also applies to internal actions of the Corps of Engineers. These same regulations also require discharges to be prohibited if they violate the Endangered Species Act, result in significant degradation of the nation’s waters or do not include adequate mitigation. These are serious regulations that should be considered in project design and selection of proposed alternative courses of action by interested parties and designers.

8.7 ENDANGERED SPECIES ACT

The federal Endangered Species Act is substantive and will most likely apply due to the presence of two endangered species in the Galveston Bay system. Both the Kemp’s ridley sea turtle and the piping plover are found here. The Kemp’s ridley feeds in the bay and nests on Galveston Island and Bolivar. The piping plover uses the beaches and sand flats as well of Galveston and Bolivar. Various provisions of ESA apply to both federal and non-federal actions. The most important requirement relative to the structural scenarios is Section 7 of the ESA that requires that all federal actions be evaluated to ensure that they do not “jeopardize” the continued existence of the species. Additionally, Section 9 prohibits the “take” of an endangered species.

With regard to Sections 7 and 9, the greatest risk will be associated with any construction activities involving beaches due to nesting usage by the Kemp’s ridley and feeding usage by the piping plover. Additionally, any construction of gates or other obstruction of flows at or near passes to and from the Gulf into Galveston Bay may be of concern due to potential impacts to sea turtles moving from the Gulf into the bay to feed on blue crabs.

8.8 WATER RESOURCES DEVELOPMENT ACT (WRDA) OF 2007

WRDA is a key statute with regard to rules associated with federal expenditures for water-related infrastructure projects such as many of the structures discussed earlier in this report. WRDA 2007 required the development of new Principles and Guidelines (P&G) for federal water projects and those guidelines have been developed by the President’s Council on Environmental Quality (CEQ). These CEQ-issued P&Gs are intended to replace the P&Gs developed by the Corps under WRDA 1986. These new regulations do not apply to state or local funding of projects or to private projects but only apply to federal ones.

The new CEQ P&Gs differ substantially from the 1986 P&Gs, primarily by adding ecological and socio-economic concerns to the traditional economic requirements. These new P&Gs are quite clear that ecological services are to be considered as part of the new project evaluation and that nonstructural solutions are to be considered alongside structural considerations.

8.9 EXECUTIVE ORDER 11988 AS AMENDED BY EO 13690

Executive Order 11988 was first issued in 1997 and addresses federal policy on flood plains and flood plain development. EO 11988 was amended on January 30, 2015 by Executive Order 13690 in order to implement the national policy on resilience and risk reduction consistent with the federal Climate Action Plan. As such,
this amendment implements a new flood risk reduction standard for federally funded projects. The primary change brought by EO 13690 is to redefine the floodplain from being a 1% per cent risk storm to being defined in one of three ways. These three ways are (1) using best climate and hydrologic science, (2) adding two feet to the base flood elevation for non-critical actions and three feet for critical ones and (3) using the 500-year flood event. While it is not clear exactly how these criteria will be implemented, one approach would be to add three ft to mapped FEMA flood levels. This would set the flood protection limits for various federal projects. EO 13690 also contains a provision requiring the agency to use natural systems, ecosystem processes and nature-based approaches when developing strategies for consideration.

The major policy change here is the direct integration of climate change considerations into project design. In addition to the fact that sea level has risen, is rising and will rise higher in the future, research conducted by Dr. Ron Sass for SSPEED Center indicates that hurricane intensity and frequency will also rise with a hotter climate in the future. EO 13690 addresses these resiliency-related aspects of climate change by altering project design parameters.

8.10 EXECUTIVE ORDER 12898

EO 12898 was issued by the Clinton Administration to address human health and environmental impacts upon minority populations and low income populations by federal actions. For federal projects, including permit actions, it has added the consideration of environmental justice issues to project evaluation. As such, the goal of such review is to determine if there are differential impacts to low income or minority communities from federal actions affecting human health and the environment. Until more is known about the impacts of the various strategies, the applicability of EO 12898 is unclear. However, each alternative will be evaluated vis a vis the distribution and relative protection of minority and lower income populations relative to the region as a whole.

8.11 IMPACT OF ENVIRONMENTAL LAW

In summary, these and possibly other federal environmental laws will most likely have a substantial impact on final project selection. By considering these laws early on in project development, the review process should be much more rapid and potential federal litigation potentially may be avoided. If these laws are not fully and openly considered, then they could significantly disrupt federal funding and/or permit approval.
Oyster Reefs
Source: Jim Olive
9. Overall Findings, Conclusions, and Future Work

The SSPEED Center has completed its work for the first year of a three-year study for the Houston Endowment on the evaluation and development of a regional surge protection system for the Houston-Galveston area (H-GAPS). To date, the work has involved the evaluation of Baseline Conditions and a variety of scenarios for reducing surge flooding in the Galveston Bay area. The SSPEED Center has just begun evaluating three gate option strategies for the bay, with very preliminary results, including rough costs and benefits for each strategy.

The results of this initial work on H-GAPS have shown the need for some type of surge barrier across the Houston Ship Channel (HSC) to block a large portion of the storm’s surge waters from entering into and affecting critical damage areas. This led the SSPEED Center to develop its three gate strategies for evaluation. These three gate strategies are referred to as the Upper-, Mid-, and Lower-Bay Gate Strategy (shown in Figure 5.1 to Figure 5.3) that include a gate system across the upper, middle, and lower portion of the HSC within the Bay. The purpose in evaluating these three strategies is to determine where one should place such a large gate, so as to provide the most benefits in terms of reduced flood damages for the least cost.

The results reflect strategy performance for a storm representing Hurricane Ike shifted 25 miles southwest of its original landfall at Bolivar Roads (landfall p7), with winds increased by 15% (i.e. IKE15-P7). IKE15-P7 was selected to represent the approximate 100-year surge conditions along the coast at the Galveston Seawall (19 to 20 feet).

Preliminary results showing computed maximum water levels (i.e. storm surge plus wave height above NAVD88) for the three regional gate strategies are presented in Figure E-1 and Table E-1. Table E-2 provides a preliminary economic investigation by the SSPEED Center, in collaboration with TAMU-Galveston, on flood damages resulting from IKE15-P7, such as industrial and residential damages, in order to evaluate the associated benefits and costs.

In its second and third year of the study, the SSPEED Center will continue to evaluate the above three gate option strategies, along with refining and optimizing their individual components, to better develop a set of regional plans for reducing surge flooding in the area. More work is needed to refine the residential and industrial damage models as well as costs.

In addition, the potential environmental impacts of any regional strategy need to be carefully evaluated, as Galveston Bay is a major productive estuary, and any strategy must minimize any impacts to either circulation, fisheries, or water quality. Circulation and spill modeling will be performed for Galveston Bay under various strategies and for various combinations of industrial spills in the HSC during and after storm surge conditions. In addition, socio-economic studies need to be performed for public acceptance of any of the strategies that might emerge.
Coastal Marsh
Source: Jim Olive
10. Public Outreach

The SSPEED Center’s mission is to educate the Gulf Coast region by increasing public awareness of the risks associated with severe storms and hurricanes, as well as inform the public about structural and nonstructural mitigation strategies at all scales for the region. In an effort to accomplish this goal, the Center has implemented several public outreach tactics to help us inform, educate and engage with the community. These strategies include hosting or attending conferences, workshops and one-on-one meetings, as well as using our online, electronic database and media outreach strategies to engage with our community at large.

10.1 CONFERENCES & EVENTS

Over the past year, the SSPEED Center has had representatives attend and present at various conferences. Additionally, we have hosted several meetings with various stakeholders and experts, including the Gulf Coast Community Protection and Recovery District (GCCPRD or Six County Surge District), the U.S. Army Corps of Engineers, top flood experts from Delft University of Technology (TU-Delft), as well as community, academic and industry groups ranging from local chapters to an international scale. Figure 10 1 shows one of many instances of this interactive collaborative exchange of ideas.

10.1.1 YEAR-END HIGHLIGHTS

EWRI-ASCE Conference: This May (2015) the SSPEED Center gave 12 presentations on coastal flooding and storm surge protection strategies at the Environmental and Water Resources Institute (EWRI)-American Society of Civil Engineers’ (ASCE) conference.

Texas Legislative Committee on Coastal Protection: SSPEED was invited to present in August 2014 its approach to coastal surge protection at a meeting in Austin, Texas. The status of H-GAPS was laid out in detail for the committee, and questions were answered.

TU-Delft/The Netherlands Collaboration: Representatives from the SSPEED Center have established a formal, long-term relationship with engineering and storm surge protection experts at TU-Delft in the Netherlands. This consisted of meetings, open forum discussions, and formal presentations from researchers, including SSPEED Center Director Philip Bedient, Charlie Penland of Water P. Moore, TU-Delft’s Bas Jonkman and Rice Alumna and current Fulbright Fellowship Recipient Antonia Sebastian.

SSPEED researchers presented and discussed on-going work on the Texas Case/H-GAPS initiative. Particular topics of discussion included storm surge modeling, optimization of gates and their design, and flood risk and damage.
assessments. From these presentations, ideas and opportunities for long-term collaboration between TU-Delft and the SSPEED Center were identified. SSPEED was also invited to participate in the Delta Infrastructure & Mobility Initiatives (DIMI) Colloquium, a formal program sponsored by TU-Delft and the Royal Dutch Society of Engineers (Figure 10-2). SSPEED presented new results from the H-GAPS regional storm surge protection strategy, and the audience consisted of students, researchers, and Dutch engineers with interests in flood risk reduction and planning in urbanized deltas. The talk was well received by the audience.

The visit also opened opportunities for storm surge barrier site visits. Students from the SSPEED Center took advantage of the visit by exploring well-known Dutch storm surge barriers in greater detail (i.e. the Maeslant and Oosterschelde) whose designs have inspired several of the preliminary scenarios for barrier design and research modeling adopted by the H-GAPS Study (Figure 10-3).

International Colloquium on Riverine and Coastal Flood Risk Management: This April (2015), researchers from TU Delft, the United Kingdom’s Met Office, Louisiana State University, the University of Texas at Austin, Rice University, and Deltares assembled in Amsterdam to plan and solicit discussion topics for a proposed international colloquium on “Riverine and Coastal Flood Risk Management.” It was agreed that the underlying theme for proposed colloquium be two-fold, to clearly (1) compare and contrast various flood risk management strategies from the three participating countries (the Netherlands, United Kingdom [U.K.], and United States [U.S.]), and (2) identify gaps and needs for achieving more resilient flood risk governance and practices.

It was proposed that the colloquium consist
of a two-day workshop with “Day 1” targeted towards public officials and relevant stakeholders. This first day would focus on broader flood risk management issues and “lessons learned,” using historical and notable cyclones/storm events from the respective countries. Invited speakers from the Netherlands would discuss societal and institutional responses to the North Sea Flood of 1953. The U.K. would discuss flooding events from summer of 2007 and winter 2014. The U.S. would disseminate detailed knowledge leading to, during, and recovering from Hurricanes Katrina (2005), Ike (2008), and Sandy (2012). Topics of how each country utilize flood warning and prediction to inform emergency response would also be discussed.

Day 2 would build from Day 1, but would emphasize technical elements as discussion topics, with the target audience consisting of experienced modelers, researchers, and scientists. Specifically, modeling methods for quantifying coastal flood risk; including cyclone storm surge, cyclone rainfall, inland riverine, and hydrometeorology would be disseminated. Methods for treating and handling parameter uncertainty would be openly shared among modelers, particularly for long-term model prediction scenarios when accounting for sea level rise and climate change. Modeling methods for representing flood risk reduction strategies would include “best modeling practices” for evaluating and representing structural storm surge barriers (e.g. levees, gates, and floodwalls) and nonstructural storm surge protection (wetlands, marshes, oyster reefs). Methods for how we place flood risk reduction into a probabilistic context for flood risk management and the means for translating modeling science into public policy and risk communication for the general public will be topics of particular interest to attendees.
In general, each day would consist of brief presentations from invited speakers to facilitate discussion topics, but the main benefit would come from the interchange of dialogue and ideas through open forum discussions and break-out sessions. A major “product” of the proposed colloquium will be a well packaged report consisting of each day’s objectives, discussion topics, and clearly marked gaps and needs for improving institutional and the overall management of flood risks in a changing climate.

Office of British Meteorology: The SSPEED Center is in process of formalizing our relationship with top British officials in storm surge protection. We have had meetings with the British Consulate to continue these discussions.

Commitment with Texas A&M Galveston: Joint Statement on Surge Suppression Research Strategies: The SSPEED Center has committed to working alongside the researchers at Texas A&M Galveston on our proposals for storm surge protection along the Gulf Coast. We will be coordinating our efforts with them when we meet with community decision makers on the issue of how to best protect the infrastructure of neighborhoods, industry and ecology in the Greater Houston Area.

Rice Continuing Studies- Houston of Tomorrow: Building a Resilient Coastal City: SSPEED Center representatives taught a seven-week class through Rice Glasscock School of Continuing Studies, which was open to the public. Courses introduced the SSPEED Center and included topics such as “Living with hurricanes and floods,” “Development, Sprawl and Resilient Coastal Communities,” “Sustainability in the City” and “Hazard Resilience of Structures and Infrastructure.”

Young Owls Leadership Program: Each year, the SSPEED Center partners with the Young Owls Leadership Program (YOLA). Its mission is to prepare high school students as both leaders in their communities and competitive applicants to top-tier colleges and universities. Our goal through this partnership is to instill an understanding and excitement around a major in Engineering. We also showcase what students in engineering study through activities and brief lectures in order to continue to attract bright and motivated students into our field.

10.2 ONGOING MEETINGS AND WORKSHOPS

In addition to the highlighted meetings and conferences above, we have included a list of groups that we are in meetings with on an ongoing basis in order to continue our efforts to protect the Gulf Coast from severe storms.

- **Academia**: including researchers from universities, such as Rice University, University of Texas, University of Houston, Texas A&M, TAMU-Galveston and Louisiana State University, well as experts who have studied Hurricane Katrina and Hurricane Sandy.
- **Political**: including representatives from the Texas General Land Office, local representatives in the Houston-Galveston region, as well as political representatives from coastal communities across the nation. This includes our contacts at the USACE, GCCPRD, and the Houston-Galveston Area Council.
- **Industry**: including senior officials from industry along coastal communities, including the Port of Houston Authority and oil and gas businesses. We work with businesses inside the HSC to include insights on how to best protect their oil tanks during severe storms and flooding events.
- **Community Organizations**: The SSPEED Center also has connections with grassroots community organizations across the region, including the Brays Bayou organization, the Emergency Management Commission and the Baytown Citizens Advisory Panel.
- **Environmental**: Through our nonstructural proposals, such as the Lone Star Coastal National Recreation Area (LSCNRA) and the Texas Coastal Exchange Project, we meet with groups, such as the Galveston Bay Foundation, Coastal Bend Bays Foundation, Texas Environmental Grant Makers Group, Renewable Natural Resources Foundation Congress on Coastal Resilience, and the Houston Wilderness Collaborative.
- **International**: The SSPEED Center has strong connections with its counterparts at the Delft University of Technology (TU-Delft) in the Netherlands, as well as representatives at the British Meteorology Office.
10.3 METHODS OF OUTREACH

The SSPEED Center employs various tactics for us to engage with the general community and inform them of our progress in storm surge protection for the Gulf Coast. These strategies include:

- **Email Database** - The SSPEED Center has an electronic database of more than 2,000 contacts, including academics and industry representatives to environmental and civic groups. We utilize this database when we have updates that would be valuable for our community or when we want to promote one of our conferences or workshops. The open-rate on our distributions is significantly higher than others in our industry. This shows us that our audience finds our distributions informative and valuable.

- **SSPEED Website** - The SSPEED Website, sspeed.rice.edu, hosts hundreds of visitors each month. We utilize this site to share the most up-to-date findings on our models, as well as our current activities, media coverage and conferences.

- **Media Coverage** - We have strong relationships with media in print, television, radio and online coverage. Not only do we engage with local media, but we also make an ongoing effort to share our expertise and strategies with technical publications and academic groups. Some of our media from the past year include Rice at Large, the American Water Resources Association (AWRA)- Integrated Water Resources Management Award (IWRM) association and the local media, such as broadcasting stations KPRC (NBC Affiliate) and KTRK (ABC Affiliate).
11. References


REFERENCES


Appendix 1 – Storm Surge Analysis

Appendix 1 will include technical details on the following topics not already covered in the Main Report:

- Data collection (bathymetry comparisons)
- ADCIRC (mesh development, validation, Ike forerunner)
- Basis for proxy storms
- I.K.E. Factor
- HGAPS formulation process
- ADCIRC max plots for all runs
- A few surge time series plots
- Hydrographs at key locations
- ADCIRC difference plots for all runs

Appendix 2 – Flood Damage Analysis

Appendix 2 will cover methodology and analysis details on the following topics not already covered in the Main Report:

- Damage assessment methodology
  - residential
  - commercial
  - industrial

Appendix 3 – Cost Estimates

Appendix 3 will cover details on the following topics not already covered in the Main Report:

- Cost estimates for various strategies
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