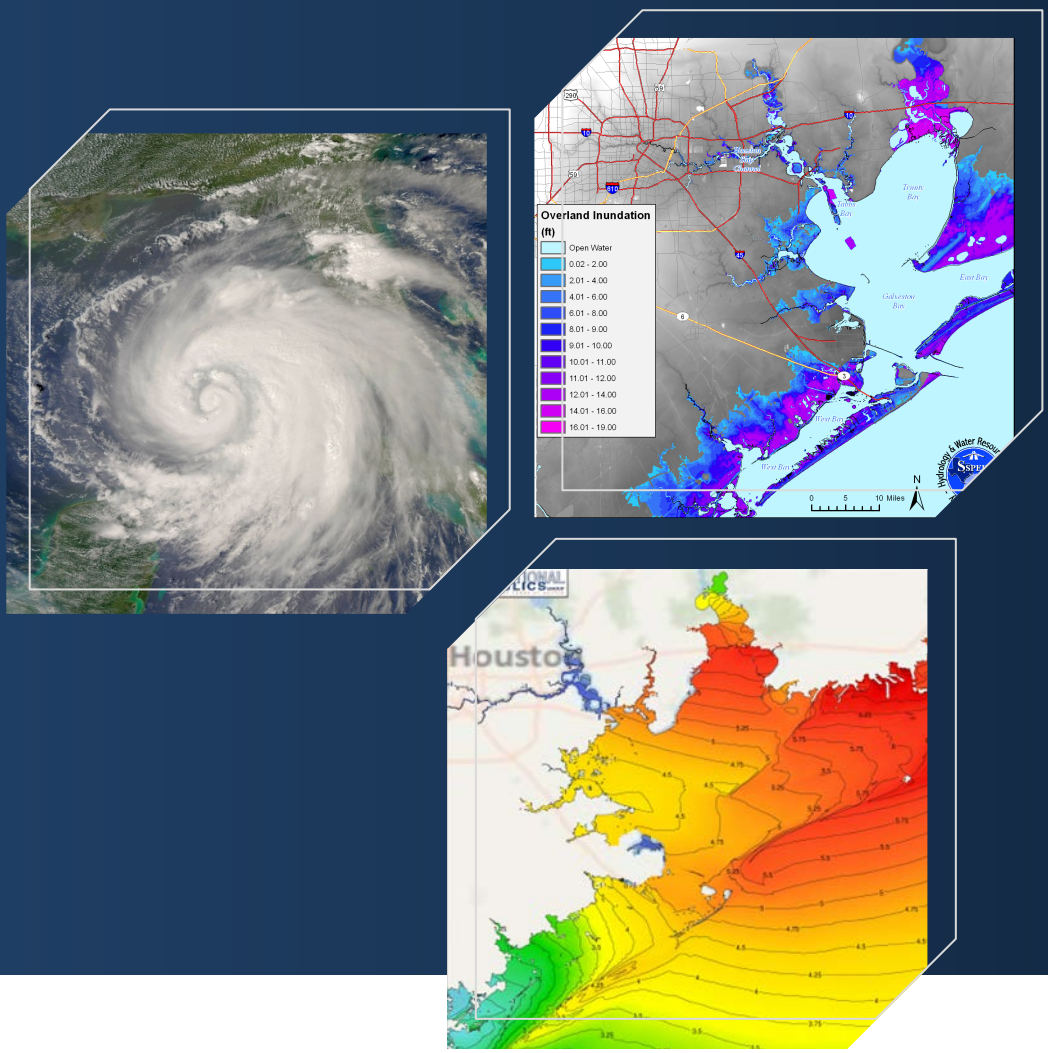

J.B. Blackburn
P.B. Bedient
L.G. Dunbar

SSPEED Center

2014 REPORT

Severe Storm Prediction, Education and Evacuation from Disasters Center

SSPEED Center | Rice University | 6100 Main Street/MS-317, Houston, Texas 77005
sspeed@rice.edu | phone: (713) 348-4977

EXECUTIVE SUMMARY

For the last five years the Severe Storm Prediction Education and Evacuation from Disasters (SSPEED) Center at Rice University has worked primarily with funding from the Houston Endowment to understand the potential impacts of storm surge and rainfall associated with severe hurricane events in the Houston-Galveston region. One of the primary goals of this work has been to develop structural and non-structural approaches to address storm surge flooding in vulnerable areas. This report outlines the key findings of the SSPEED Center's research to date and outlines future proposed work.

In 2008, Hurricane Ike made landfall just east of Boliver Roads, generating storm surge that flooded inland areas from Galveston Bay to Grand Isle in Louisiana. Although Ike was "only" a Category 2 storm, it caused over $25 billion in damages. However, research indicates that had Hurricane Ike made landfall 30 miles southwest of its original landfall location, it would have generated 18 feet of surge in the Houston Ship Channel and 15 feet in the populated and industrialized areas on the west side of Galveston Bay. Thousands of people who chose not to evacuate could have died and the environmental impact to Galveston Bay and economic devastation to the Houston-Galveston region and US would have been irreparable.

The 2014 SSPEED Center Report to the Houston Endowment included herein details the research into larger hurricanes and the destruction that they could case. A number of damage models have been developed to predict dollar losses from storm surge inundation of industrial facilities, residential structures, and infrastructure, such as bridges, roads, and industrial storage tanks to better assess the vulnerability of the region. This report also details the initial proposals for structural and non-structural protection developed during the first two phases of funding from the Houston Endowment. These surge mitigation strategies were primarily focused in four areas of the Houston-Galveston region: the Houston Ship Channel, the west side of Galveston Bay, Galveston Island, and the low-lying areas of Chambers, Galveston, Brazoria, and Matagorda Counties.

The most promising proposals developed during Phase I (2009-2011) and Phase II (2011-2014) of research are a gate and levee structure protecting the Houston Ship Channel, formally known as the Centennial Gate in honor of the 100th year anniversary of the Houston Ship Channel, and the Lone Star National Recreation Area (LSCNRA), which creates economic incentive for preserving the natural area along the coast. Analysis indicates that the Centennial Gate can offer significant storm surge protection for the industrial facilities and residential communities located along the Houston Ship Channel at a high benefit-cost ratio to the region. The Center estimates that the initial construction cost of the Centennial Gate would be approximately $2 billion, while damages to the Houston Ship Channel resulting from storm surge could easily exceed $100 billion. The SSPEED Center is continuing to investigate potential geometrical alignments and operational configurations of the Centennial Gate.

The LSCNRA is expected to receive 2 million visitors per year, generate more than $200 million in income, and create 5,000 new jobs under the purview of the National Park System

within a time frame of five to ten years. More than 20 local governmental and non-governmental organizations endorse the LSCNRA and state and federal agencies have informally agreed to participate in the LSCNRA upon congressional approval. Under the leadership of Chairman John Nau and Honorary Chairman, former Secretary of State James Baker III, and with the guidance of former Deputy Assistant Secretary of the Interior, Lynn Scarlett, the LSCNRA Partners Coalition and Steering Committee have developed a management framework and drafted legislative concepts that have become part of a congressional bill to create the LSCNRA in the next year.

As we enter Phase III (2014-2017) of funding, the Houston-Galveston region finds itself in a difficult situation. Five years after Ike, no comprehensive plan has been established for protecting the region from future hurricanes. Generally speaking, the landscape-scale green space solutions, like the LSCNRA, proposed by the SSPEED Center have been well received by governmental and business leaders, but they are also the "no-brainers" of hurricane surge mitigation.

The situation becomes much more difficult when considering structural alternatives within the currently developed portions of the region. The Centennial Gate is an excellent project that has a great price tag and has the ability to be constructed relatively quickly. However, it does not address the surge vulnerability of the communities along the west side of Galveston Bay and it does not help Galveston Island or the communities along the west side of Galveston Bay. Local businesses and governmental leaders are hesitant to support this alternative because they fear that to do so would result in a regional fight between southern Harris and Galveston County over the Centennial Gate and the Ike Dike, which has been proposed by Dr. Bill Merrill at Texas A&M Galveston. The SSPEED Center believes that the ultimate solution for the region will include multiple lines of defense built over a period time and financed through a variety of sources.

In the final sections of this report, we lay out the future direction of the SSPEED Center. This work includes the development of a storm surge mitigation proposal for the entire region, which will continue to include the LSCNRA and the Centennial Gate. The comprehensive regional plan, referred to as H-GAPS (shown in Figure 29), and its associated reduction in surge inundation will be evaluated using detailed storm surge and damage models in order to establish co-benefits and/or cost associated with each structural or non-structural option such as environmental impacts, construction feasibility, operations and management requirements, and long-term sustainability. As a part of this study the SSPEED Center will also evaluate the Ike Dike. The resulting information will provide stakeholders with a choice between various alternatives that can protect Galveston Bay in a more holistic manner.

Finally, as part of the SSPEED Center's educational and outreach efforts regarding its work for the Houston Endowment, there will continue to be numerous speaking engagements, conferences, media coverage and academic publications moving forward. Those associated with the work that the SSPEED Center has undertaken during the past 5 years are listed on the following page.

SSPEED CENTER PARTICPANTS (2011-2014)

FACULTY	
Dr. Philip B. Bedient, Director	Rice University
Mr. Jim B. Blackburn, Co-Director	Rice University
Dr. John B. Anderson	Rice University
Dr. Samuel P. Brody	Texas A&M University
Mr. Tom Colbert	University of Houston
Dr. Clint N. Dawson	University of Texas at Austin
Dr. Jamie E. Padgett	Rice University
Dr. Hanadi Rifai	University of Houston
Dr. John Pardue	Louisiana State University
POSTDOCTURAL RESEARCHERS	
Dr. Jennifer Proft	University of Texas at Austin
Dr. Zheng (Nick) Fang	Rice University
PHD STUDENTS	
Wei Du	University of Texas at Austin
Russell Blessing	Texas A&M University
Daniel Burleson	University of Houston
Jason A. Christian	Rice University
Sabarethinam Kameshwar	Rice University
Antonia Sebastian	Rice University
Jacob Torres	Rice University
CONSULTANTS	
Joe Cibor	Cibor Geoconsultants
Larry Dunbar	-
Elizabeth Winston-Jones	Resource Strategy Partners
Charles Penland	Walter P. Moore
Bob McIntosh	-
Jill Nesting	Willis Communications
Lynn Scarlett	Resources for the Future
Kevin Shanley	SWA Group
George Smalley	Bridge Builder Communications
Margaret Vaughn Robinson	MCV Consulting
Baxter Vieux	Vieux and Associates, Inc.
National Parks Conservation Association	

TABLE OF CONTENTS

I. Introduction

Since 2009, the SSPEED Center, with funding from the Houston-Endowment, has researched one of the most important issues facing the region today: vulnerability from hurricane storm surge. This report outlines the findings from the Phases I (2009-2011) and II (2011-2014) of research and the proposed work in Phase III (2014-2017). Ultimately, the SSPEED Center has proposed to develop a comprehensive Houston-Galveston Area Protection System (H-GAPS) which will consist of a combination of structural and non-structural solutions for the region which can be built at once or piece-meal through a variety of funding sources, thus providing multiple lines of defense to storm surge impacts.

Although the wind and rainfall associated with hurricanes can generate significant damage, the Galveston Bay region is extremely vulnerable to storm surge flooding. Based on historical storm surge records in the Gulf of Mexico, the Upper Texas coast has the third highest hurricane surge probability. Hal Needham at Louisiana State University calculated that the 100-year recurrence surge event for the Houston-Galveston Region is approximately 21 feet at the coast. Similarly, FEMA recently released preliminary surge maps show an expected 100-year storm surge of 19 feet at the coast. Given the size of Galveston Bay and the substantial set-up caused by counter-clockwise rotating hurricane winds, a 20-foot surge at the coast could result in 23 to 25 feet in Houston Ship Channel given a westerly-angled storm approach.

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 from Galveston Bay to Grand Isle in Louisiana. In fact, Hurricane Ike prompted the National Weather Service to decrease its reliance the Saffir Simpson hurricane categories for predicting surge height and migrate to a system that identifies surge as a function of a storm’s energy rather than wind speed. Unfortunately, much of emergency planning and evacuation infrastructure remains tied to storm categories.

As part of the Houston Endowment funded research (Phases I and II), extensive computer modeling work been completed by the research team led by Dr. Clint Dawson and Dr. Jennifer Proft at the University of Texas at Austin. This team has gained the ability, through the use of the ADCIRC model, to replicate storm surge from past events and to predict storm surge for hypothetical events occurring at various locations along the coast.

The team tested eight hypothetical landfall locations along the upper Texas coast and found that a hurricane making landfall near San Luis Pass \would likely generate a worst case surge for the vulnerable areas in the Houston-Galveston region, including the heavily populated and industrialized west side of Galveston Bay and the Houston Ship Channel. This landfall point has been identified as P7 and will show up in multiple maps and discussions in this document. If Ike had made landfall at P7, it would have generated a 18-foot surge in the Houston Ship Channel, compared to the 13-foot surge caused by the original Ike landfall location, and might have killed thousands of persons who did not evacuate the west side of Galveston Bay because

Ike was “only” a Category 2 storm. The findings from this research were published in Coastal Engineering.

Storms larger than Ike are both probable and likely. It is simply a matter of time until a storm with Category 3 or 4 winds makes landfall in the area of P7. If that storm occurs and if the Houston-Galveston Area has failed to protect critical infrastructure against a 25-foot to 30-foot surge, such a surge could literally destroy the economy of the Houston region, if not the United States. In addition to economic disaster, such a surge would likely inflict massive environmental damage if the hazardous materials and oil presently stored adjacent to the ship channel were to spill into adjacent neighborhoods as well as Galveston Bay. See Figures 1, 2 and 3 for a depiction of the various areas expected to be flooded by a surge associated with a Hurricane Ike, Ike plus 15% increase in winds and Ike plus 30% increase in winds. Table 1 lists storm surge heights and key locations in the region associated with the modeled hurricane events.

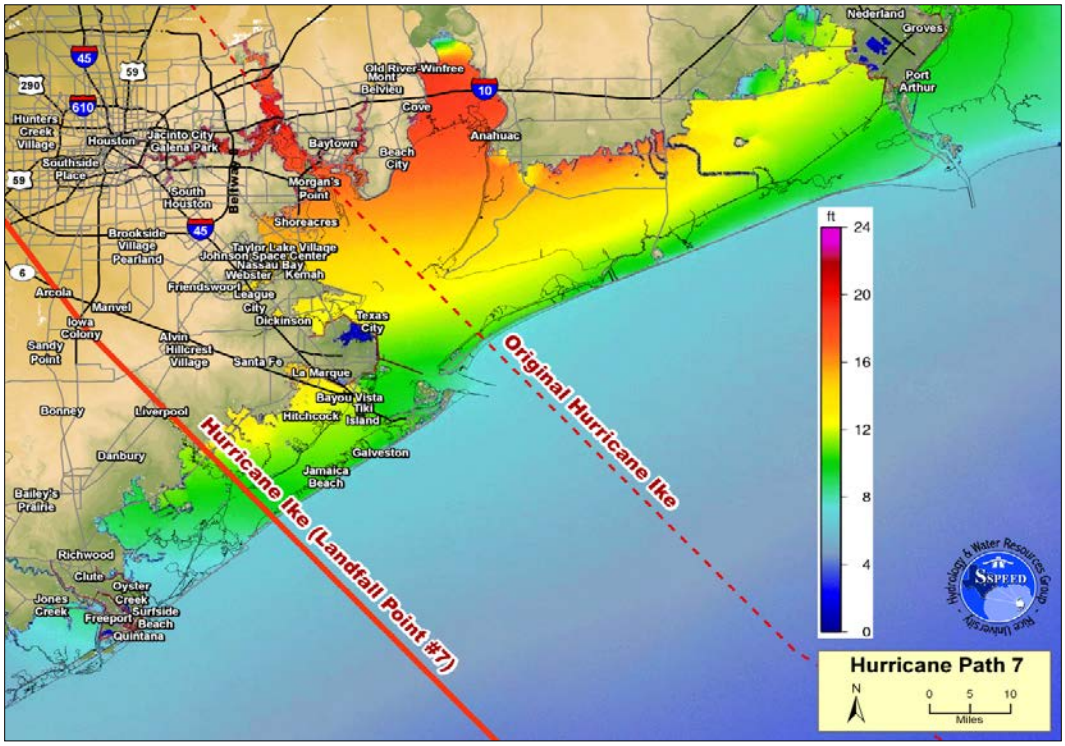

Figure 1. Surge generated by Hurricane Ike making landfall at Point 7 near San Luis Pass.

Modeled Event	Description	Storm Surge at Galveston (ft)	Storm Surge at West Side (ft)	Storm Surge at HSC (ft)
Ike, OL	Category 2 @ Boliver Roads	13.9	10.7	12.6
Ike +15%, OL	Category 3 @ Boliver Roads	16.9	13.1	15.6
Ike +30%, OL	Category 4 @ Boliver Roads	20.1	15.6	18.6
Ike, P7	Category 2 @ San Luis Pass	15.8	14.7	18.2
Ike +15%, P7	Category 3 @ San Luis Pass	19.3	18.7	22.9
Ike +30%, P7	Category 4 @ San Luis Pass	22.7	23.3	27.3

Table 1. Height of modeled storm surge at critical locations in the Houston-Galveston region.

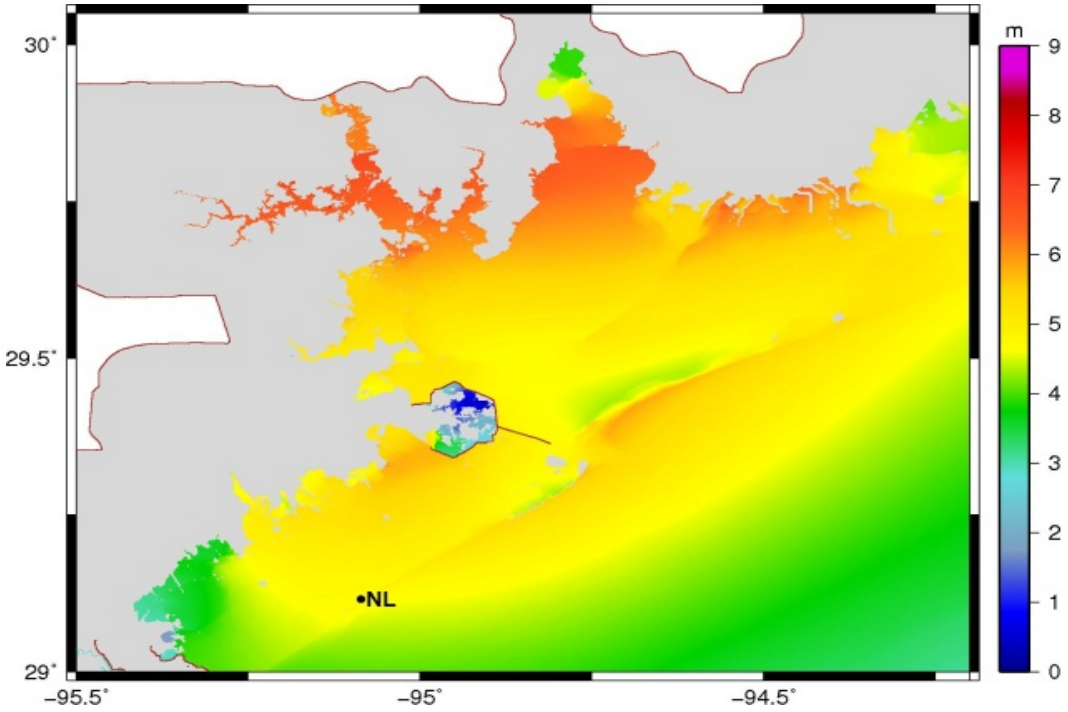

Figure 2. Surge generated by Hurricane Ike +15% wind speeds making landfall at Point 7.

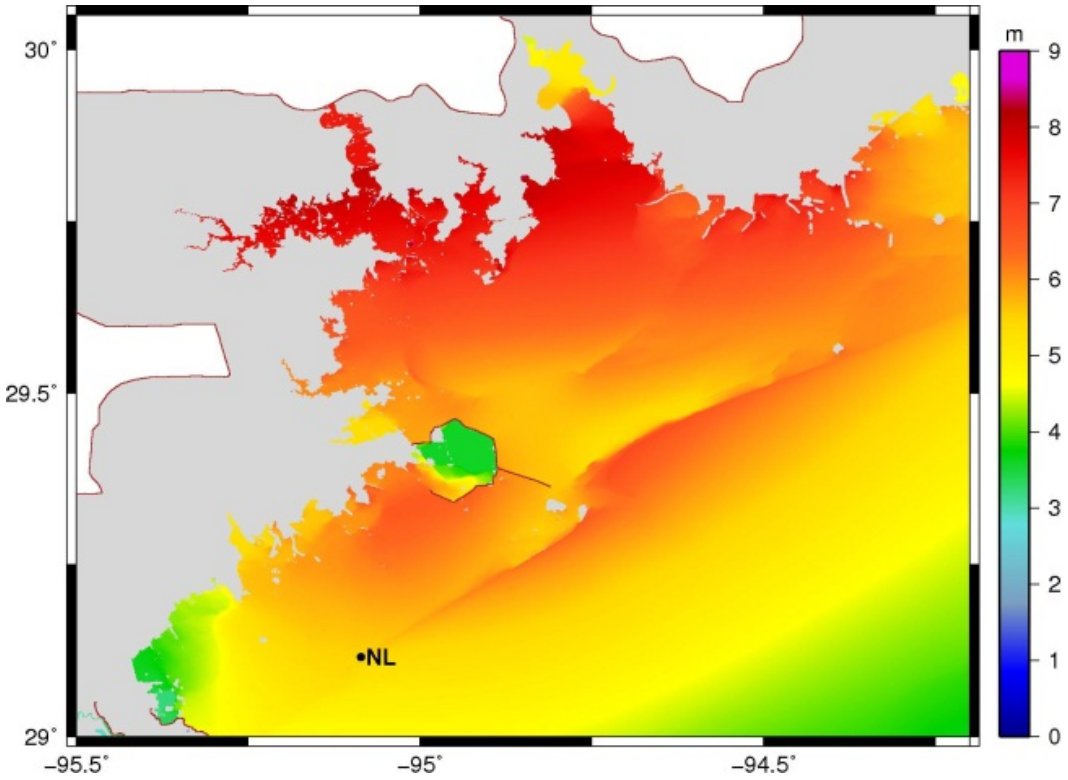

Figure 3. Surge generated by Hurricane Ike +30% wind speeds making landfall at Point 7.

II. Risk of Damage from Modeled Storm Surge Events

Hurricane Ike made landfall just east of Bolivar Roads, the major pass that connects Galveston Bay to the Gulf of Mexico. Although Ike caused over $25 billion in damages, it basically missed the heavily populated and industrialized areas along the west side of Galveston Bay and Houston Ship Channel. The surge from Hurricane Ike caused extensive inland flooding from Galveston Bay east to Grand Isle, Louisiana. The highest surge was recorded in Chambers County where the surge nearly reached Interstate Highway 10, about 20 miles inland.

Damage along the west side of Galveston Bay was primarily caused by counter-clockwise winds blowing from north to south on the “clean” side of the storm causing water to build up along the north shoreline of Red Bluff in Shoreacres and La Porte as well as in the Bacliff and San Leon areas. Heavy industrial damage occurred further east of landfall on the “dirty” side of the storm in Beaumont and Orange near the Louisiana border where surge extended north into Sabine Lake and the Sabine-Neches Waterway.

Along the Houston Ship Channel, where most facilities were protected to the 100-year FEMA floodplain of about 13 to 14 feet as required by various federal regulatory requirements, surge levels during Hurricane Ike never exceeded about 13 feet due primarily to Ike’s track and landfall location. Similarly, residential structures in the region are required to elevate the first floor at or above the FEMA floodplain, but those constructed prior to the introduction of these standards were subject to significant surge damage during Hurricane Ike. Had Ike made landfall

further southwest, as originally predicted, both industrial and residential damages from storm surge would have been much worse.

Ike was not a "worst case" storm. As previously discussed, the SSPEED team considers a 23-25 foot surge to be a reasonable 100-year surge event for the Houston Ship Channel. A "worst-case" surge could be 30 feet. Such a surge would far exceed existing FEMA base flood elevations and likely flood most homes, businesses and industry throughout the west side of Galveston Bay and Ship Channel, as well as Galveston Island. The coastline would likely see a "worst-case" surge of about 25 feet or higher from the same storm event.

The extent of the flood damages caused by a 20-foot storm surge is shown in Figure 4 for the west side of Galveston Bay, where about 8,200 acres of residential land, or about 29,000 homes, would be flooded by such a surge. Many homes would be inundated by ten or more feet of water. If evacuation did not occur, such a surge event could result in an extensive loss of life.

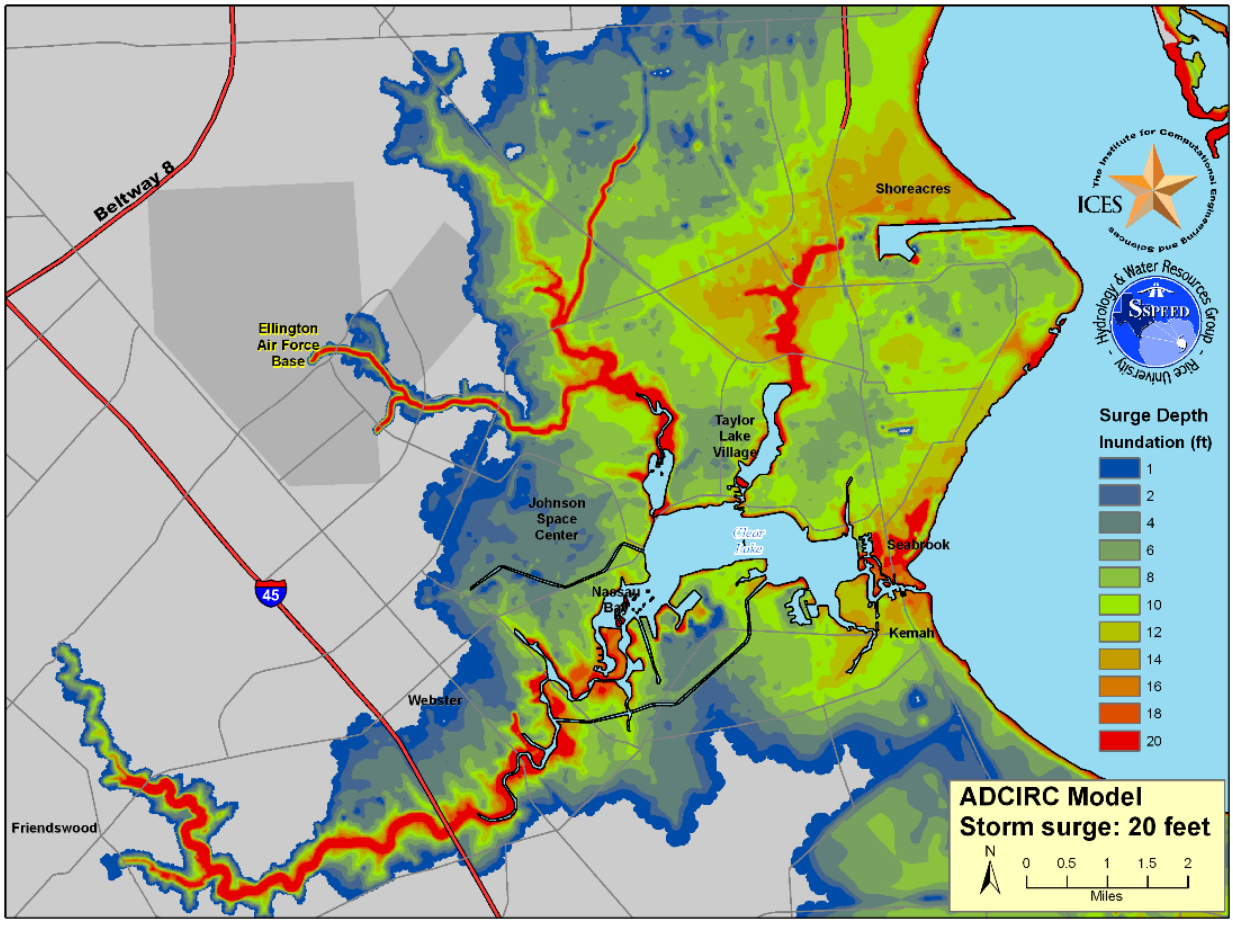

Figure 4. Map depicting depth and extent of flooding generated by a 20-foot surge on the west side of Galveston Bay.

The extent of damage in the Houston Ship Channel from such a surge event would also be enormous as is shown in Figure 5. Work completed by Dr. Hanadi Rifai and Dan Burleson at

the University of Houston as part of this project concluded that over 4,000 cylindrical tanks would be subject to some level of inundation from a 25-foot surge in the Houston Ship Channel, and most industrial facilities would experience greater than 60% inundation (see Figure 6). According to cost curves developed by Dr. Rifai and Mr. Burleson, the estimated damage along the Houston Ship Channel could range from a low of about $33 billion for a 13-15 foot surge to in excess of $140 billion for a 25 foot surge (see Figure 7). The resulting environmental damage to natural resources in Galveston Bay was not included in that estimate, although clean-up costs were included. Extensive physical damage would also occur to industry along Cedar Bayou and west of State Highway 146 in the Bayport Industrial Complex.

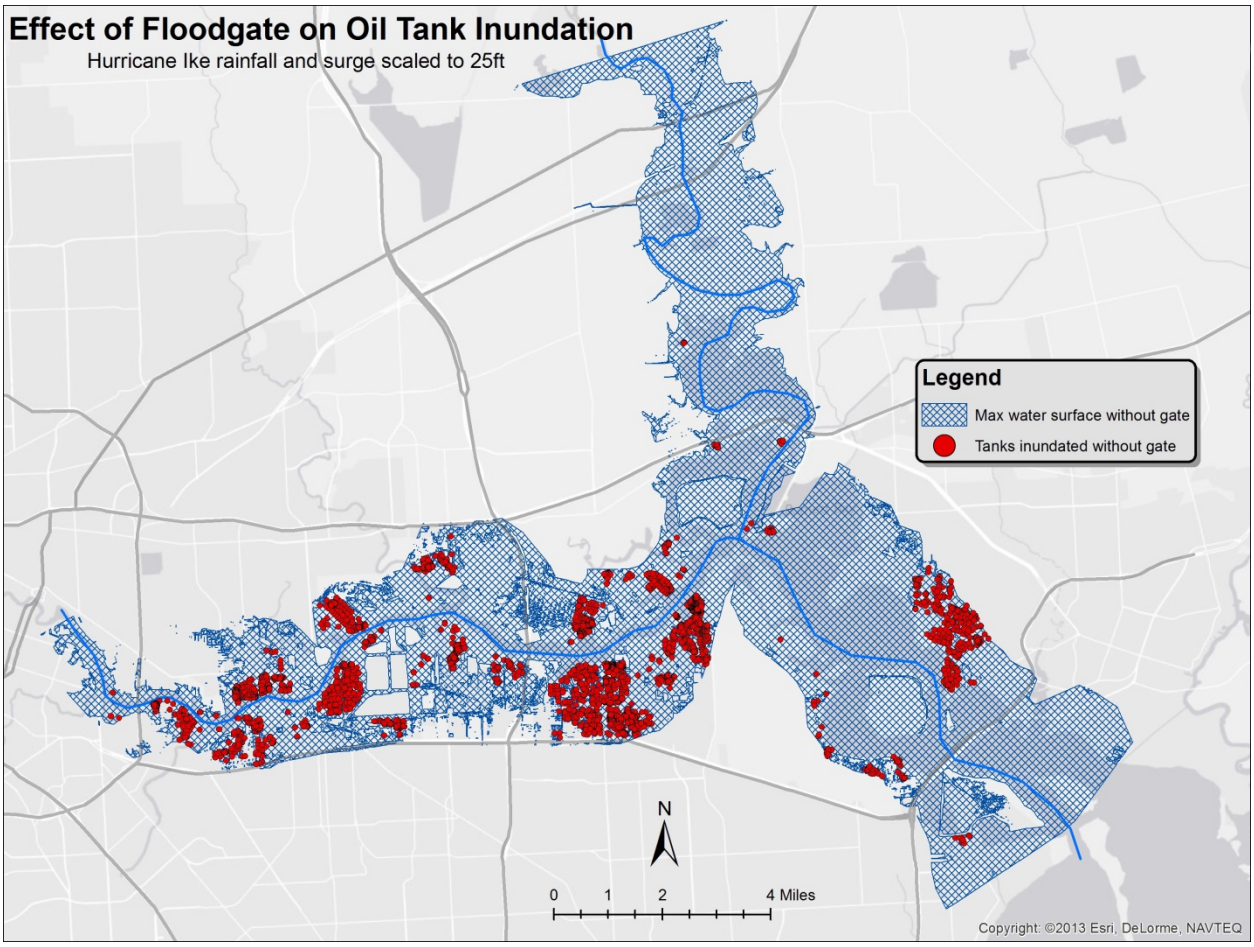

Figure 5. Approximately 4,000 cylindrical tanks would experience some level of inundation under a 25 foot storm surge scenario.

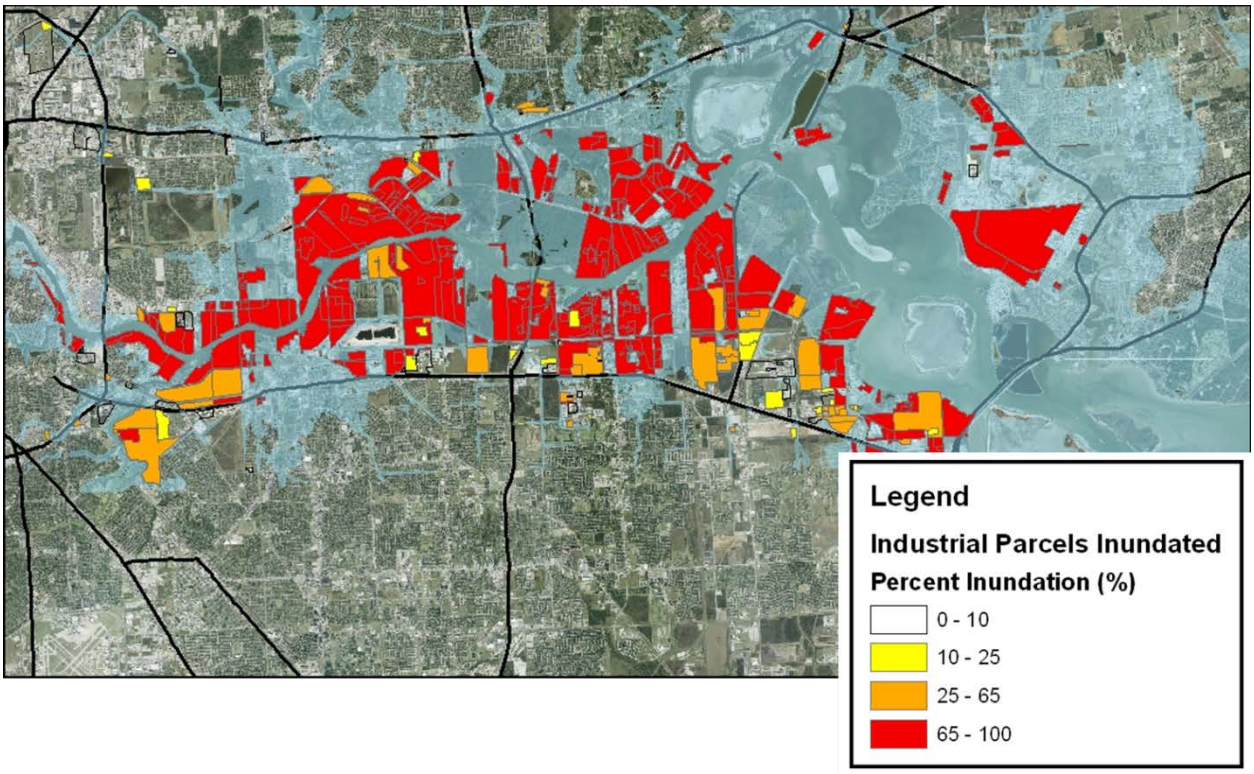

Figure 6. Percent Inundation of Industry along Houston Ship Channel.

Damage Region	Inundated Parcel Count		
	Ike	Ike at Point 7	Ike at Point 7 with Increase Wind
Low Damage Region	38	47	30
Medium Damage Region	61	76	97
High Damage Region	105	235	562
Total Damage Estimate for HSC Industry	$33 Billion	$76 Billion	$148 Billion

Figure 7. Numbers and damage estimates for Houston Ship Channel facilities under various modeled storm surge events.

III. Existing Storm Surge Protection Systems

There is some existing infrastructure for surge protection in the Galveston Bay region, albeit limited. Texas City is protected by an existing levee system to a height of about 18 feet. Freeport and Lake Jackson are also protected by a similar structure. The City of Galveston is protected by a 17-foot seawall constructed after the 1900 Galveston Hurricane. The existing infrastructure in the Houston-Galveston region is shown in Figure 8.

Figure 8. Map showing the existing storm surge protection infrastructure, the Freeport Levee, Texas City Levee, and Galveston Seawall, along with 10- and 20-foot elevation contours.

These levee systems have been adequate to date, but are likely inadequate to protect against the “worst-case” surge, or even the 100-year surge, discussed previously. Anecdotal evidence indicates that the debris during Hurricane Ike reached the top of the Texas City Levee, indicating that it was nearly breached. Likewise, the Freeport Levee protected the Freeport and Lake Jackson area, but concern exists about its height and structural integrity. At a minimum, both of these levee systems should be increased in height and made structurally sound.

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 surge in the Bay rose and counter-clockwise hurricane winds pushed water towards the south end of Galveston Bay. This bay-side vulnerability is a significant risk for the City of Galveston and island development.

IV. Protection for the Houston Ship Channel

A. Risk

The Houston Ship Channel is the economic engine of the Galveston Bay region. The twenty or so miles of channel from the Loop 610 bridge east of downtown Houston to the Fred Hartman Bridge (SH 146) near the outlet to Galveston Bay is lined with chemical plants and several major refineries. Data from the Port of Houston indicate that over 1 million jobs and over $175 billion in economic activity are generated by the Port of Houston statewide and even more from a national perspective. There are at least 100,000 direct jobs associated with channel industries. A direct hit on the channel would be an economic catastrophe. Research being completed by Dr. Hanadi Rifai and Dan Burleson indicate that damages from a large surge event could exceed $140 billion in facility and infrastructure damage as well as lost production.

A direct hit on the channel would also be an environmental catastrophe. Research conducted by Dr. Padgett and Mr. Kameshwar indicates that approximately 4,000 cylindrical storage tanks could be flooded to some extent with a 25-foot surge up the Houston Ship Channel. As can be seen in Figure 5, these tanks dot the channel and would be subjected to both lifting forces and horizontal crushing forces. There is no doubt that a large storm surge coming up the channel would cause the release of a variety of hazardous products and oil, likely creating the worst environmental disaster in United States history.

This issue of the magnitude and destructive nature of such an event is hard to overstate. During Hurricane Katrina, one Murphy Oil tank lifted from its foundation, spilling its contents into an adjacent neighborhood. This resulted in the abandonment of 300 homes and a $300 million damage payment by Murphy Oil. In addition to the number of neighborhoods that lie adjacent to the refineries and petrochemical plants along the Houston Ship Channel, the potential environmental damage to ecological sustainability in Galveston Bay is a major concern.

It is doubtful that Galveston Bay could survive such a spill of hazardous chemicals and crude oil as would likely occur if a major hurricane made landfall just southwest of the Bay. Such an event would destroy recreational use of Galveston Bay and real estate values and utility around the bay. In short, Galveston Bay would cease to function from an ecological standpoint and would become a toxic mess for all users of Galveston Bay. Simply stated, this is a disaster that cannot be allowed to occur.

B. Centennial Gate Project

In order to protect and maintain the industrial complex along the Houston Ship Channel, the SSPEED Center has proposed building a gate and levee structure across the mouth of the San Jacinto River where it empties into Galveston Bay. This project was initiated by planners Tom Colbert of the University of Houston and Kevin Shanley of SWA Architects, who discovered that a 25-foot to 30-foot natural elevation existed on both sides of the Houston Ship Channel at

its entrance into upper Galveston Bay. This apparently had not been recognized in previous studies that led to the construction of industrial protection levees in Freeport and Texas City in the aftermath of Hurricane Carla in 1961. These two planners proposed consideration of a gate to connect these high land areas as a hurricane surge protection system for the Houston Ship Channel. Due to the fact that the Centennial of the Port of Houston will occur in 2014, this proposed structure at the mouth of the channel has been labeled as the Centennial Gate.

In Figures 9 and 10, two potential structural alignments to protect the Houston Ship Channel are shown. Both alternatives involve a combination of a gate across the Houston Ship Channel, which is 600 feet wide and 45 feet deep, and a levee across the remaining area with openings to allow for normal circulation and/or flood flow. In addition, a third variation has been proposed that would extend the levee across Cedar Bayou, thereby protecting the east side of Baytown as well as additional industries up Cedar Bayou near Interstate Highway 10.

Figure 9. Centennial Gate Option A downstream of Fred Hartman Bridge.

Figure 10. Centennial Gate Option B (with dashed option to Protect Cedar Bayou)

More detailed work on the Centennial Gate has been underway for some time under the leadership of engineering consultants Charlie Penland of Walter P. Moore and Associates and Joe Cibor of Cibor Geoconsultants. Preliminary work on the gate and levee concept indicates that a gate in this vicinity is feasible from an engineering standpoint. Several examples of existing gates have been studied, including the MOSE Project in Venice, Italy, which consists of a system of flood gates that float from the seafloor to form a surge barrier, the Thames River Barrier, in London, which consists of multiple rotating gates, and the Delta Works in the Netherlands, which is an integrated system of gate and levee structures. The engineering consultants have concluded that a structural solution similar to the Maeslant Barrier in the Netherlands and more recently the Lake Borgne Surge Barrier in New Orleans, Louisiana (as shown in Figure 11) would provide the best basis for design for the Centennial Gate. It is estimated that this structure alone would cost in the vicinity of $900 million with the total structure being currently estimated to cost less than $2 billion.

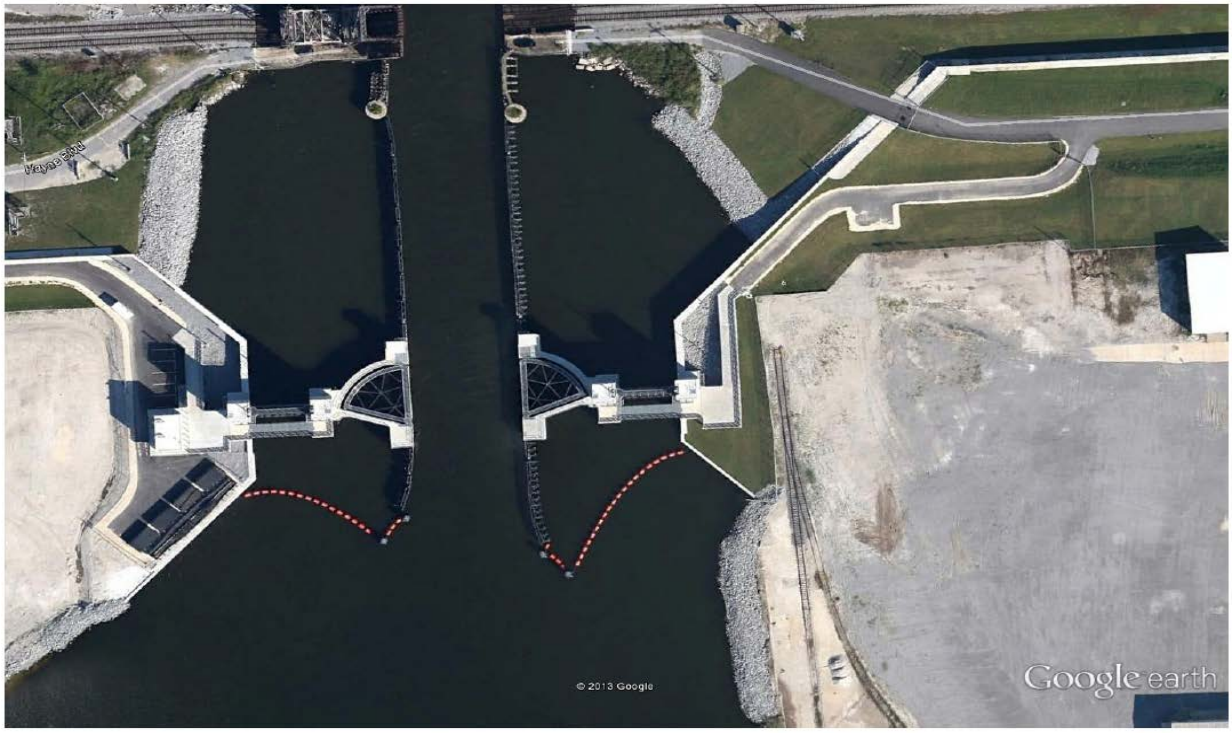

Figure 11. Lake Borgne Surge Barrier in New Orleans, Louisiana

As part of this work effort, we are currently investigating financing options for the Centennial Gate. Drew Masterson with First Southwest, a local bond expert, has evaluated various options for moving forward with construction of the gate as a local project. A bond issue in the $1.5 to $2 billion range is feasible both through a general bond election or through a special district comprised of ship channel industries. What remains to be seen is if either the voters or the industries, or some combination of the two, are willing to be taxed in order to create this project. Financing by the federal government is possible through the US Army Corps of Engineers and the United States Congress, but such action takes substantial time, and the willingness of Congress to allocate additional funds is unclear. At the current time, the Corps has embarked upon a three-year feasibility study and the results of the SSPEED Center work will be turned over to the U.S. Army Corps of Engineers for their use in performing their study of this region.

C. Analysis of the Centennial Gate

This gate structure and the accompanying levee system are currently proposed to protect the Houston Ship Channel from a 25 foot surge, which we have assessed to be a reasonable surge resulting from a 100-year return period hurricane. As part of our completed work, we have evaluated the various potential effects of alternative alignments “A” and “B” and their respective operational requirements. Of particular concern were the hydrologic issues associated with first stopping the surge and then opening the gates and passing rainfall/runoff through the gate

structure. Rainfall associated with historical hurricane storm events such as Rita, Katrina and Ike was evaluated, and the events were hydrologically and hydraulically modeled in the San Jacinto River watershed in an attempt to understand a reasonable worst-case combination of surge and rainfall. Computer simulations were used to determine what volume of water must pass through the gate and levee structure in order to eliminate upstream flooding due to impoundment of surge upstream of the gate. As a result of this work, the design team is confident that there is sufficient capacity behind the gate structure to avoid upstream flooding in the Ship Channel. Results show that the Centennial Gate would have had surge reduction benefits of approximately 4 feet during Hurricane Ike and could have up to 8 feet of surge reduction benefit under a scenario where Hurricane Ike wind speeds were increased by 30%.

Another concern has been expressed by residents living south of the levee proposed under Option B along Barbours Cut Boulevard. The residents of the City of LaPorte are concerned that the levee will increase flooding in LaPorte by intercepting and repelling storm surge waters. This issue has been examined in two ways. First, from an elevation perspective, the area adjacent to Barbours Cut Boulevard is at a higher elevation than most of LaPorte, meaning that much of LaPorte will be under several feet of surge before the surge reaches the base of the levee. Second, preliminary ADCIRC storm surge modeling completed by Drs. Dawson and Proft, at the University of Texas, indicates that the construction of Option A or B would only increase surge flooding a small amount (<1%) for a major event, thereby causing minor incremental impact in areas that would be subject to 10 to 12 feet of inundation from a 25-foot surge. However, additional modeling refinements are being investigated to verify if such an incremental impact really would occur and if so, what other alternatives might be considered to address this issue.

From a land use perspective, both Options A and B do not appear to raise any significant land use conflicts. Option A will require park land and may alter an existing water storage reservoir. Option B is currently shown as connecting to Atkinson Island, the feasibility of which will need to be further investigated with respect to potential use by nesting birds and the chance of predators being brought to the site by the structure. However, for the most part, there are no major land use conflicts. Residents of LaPorte have questioned why their area is not being protected by the Centennial Gate and this issue is addressed in the following section: Protection for the West Side of Galveston Bay.

It is also worth noting that there are residential benefits that result from the Centennial Gate. There are many low-lying areas within the City of Houston along Hunting, Brays and Sims Bayous as well as areas in other jurisdictions along Greens, Carpenters and Cedar Bayous. Under one or another variation of the Centennial Gate, several thousand homes will receive protection from surge damage. An example of this is shown in Figure 12, demonstrates the difference in inundated area along Hunting Bayou as a result of the Centennial Gate. With the gate in place, the flooded area was reduced by three square miles for a 25-foot surge in lower Hunting Bayou, thereby removing hundreds of residences as well as commercial properties from the area. The remaining flooded area shown on the left diagram.

.

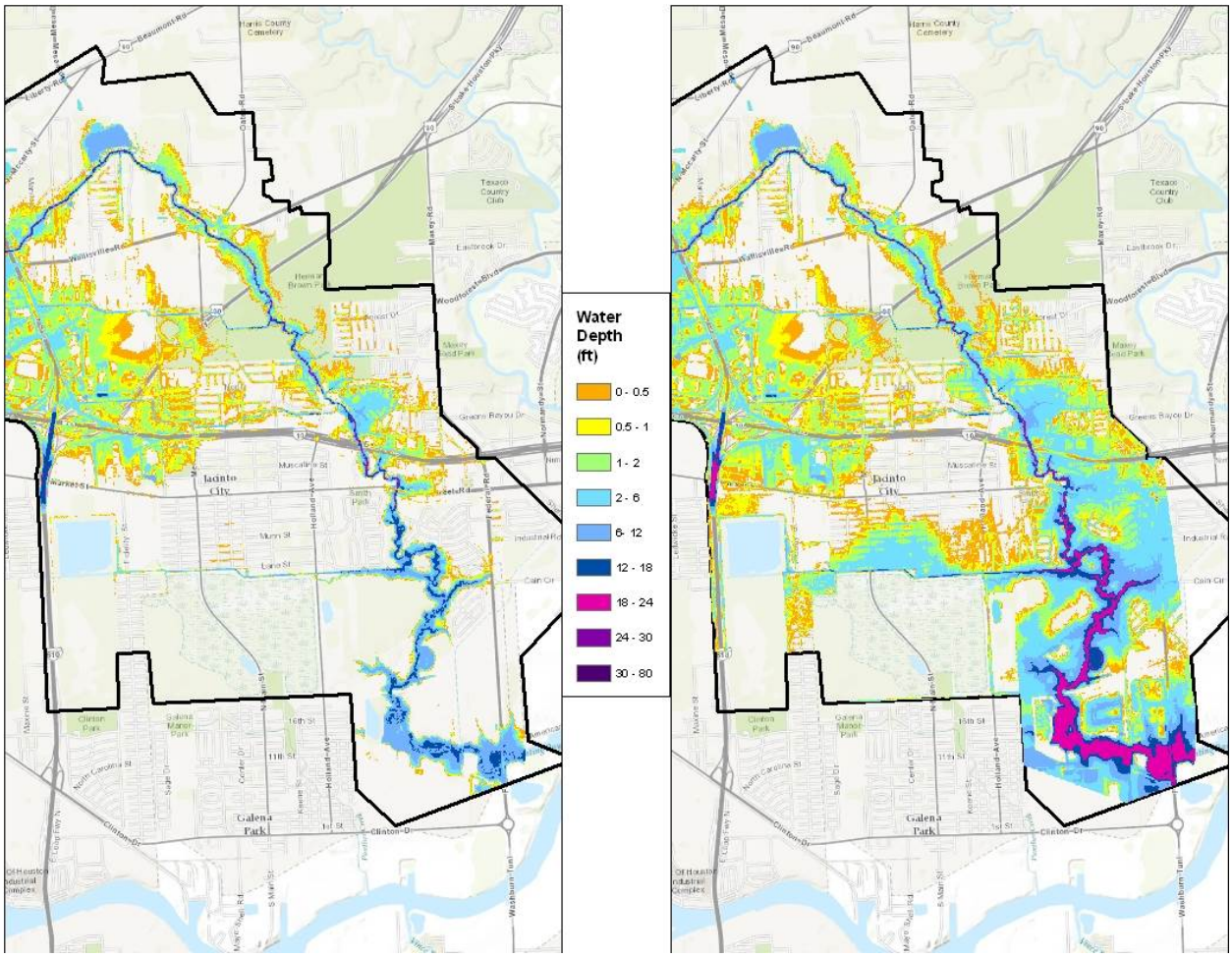

Figure 12. Flood reduction benefits in lower Hunting Bayou from Centennial Gate during the 100 year rainfall coupled with 25 feet of surge. The figure on the left shows depth of water with the gate in place, the figure on the right shows depth of water without the gate.

V. Protection for the West Side of Galveston Bay

A. Risk

The developed west side of Galveston Bay has little topographic relief and is extremely vulnerable to hurricane surge flooding. Among the most vulnerable areas are the cities of LaPorte, Shoreacres, Seabrook, Kemah and San Leon as well as more inland communities such as Nassau Bay, Taylor Lake Village and several others. The vulnerability of communities located on the west side of Galveston Bay to a 20- foot storm surge is shown in Figure 13.

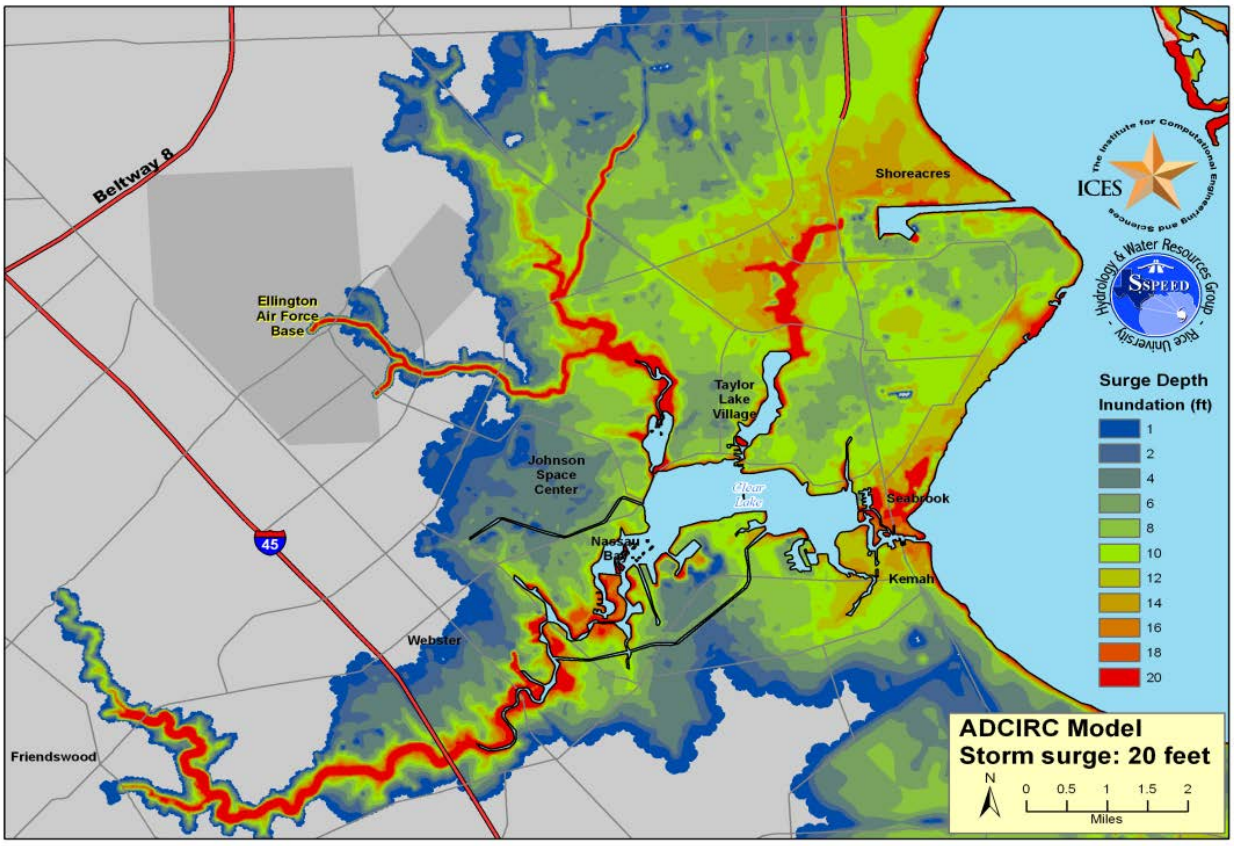

Figure 13. ADCIRC model results showing depth of inundation resulting from 20-foot storm surge in the communities along the west side of Galveston Bay.

In Figure 14, the hurricane evacuation zones are shown for Chambers, Galveston, Harris and Brazoria Counties. The areas in yellow are the most vulnerable and are intended to be the first evacuated, followed by the green and then the orange. According to the Houston-Galveston Area Council, about 1.6 million people currently live in this evacuation zone with another 800,000 projected to move into this area by 2035. Unfortunately, only about 1 million people can be evacuated from this area in 36 hours. Given this statistic, if a hurricane is moving into the region, evacuation needs to start well in advance of 36 hours prior to landfall in order to be

effective in removing the current residents to safe ground. This problem will only become more pronounced as the population continues to grow.

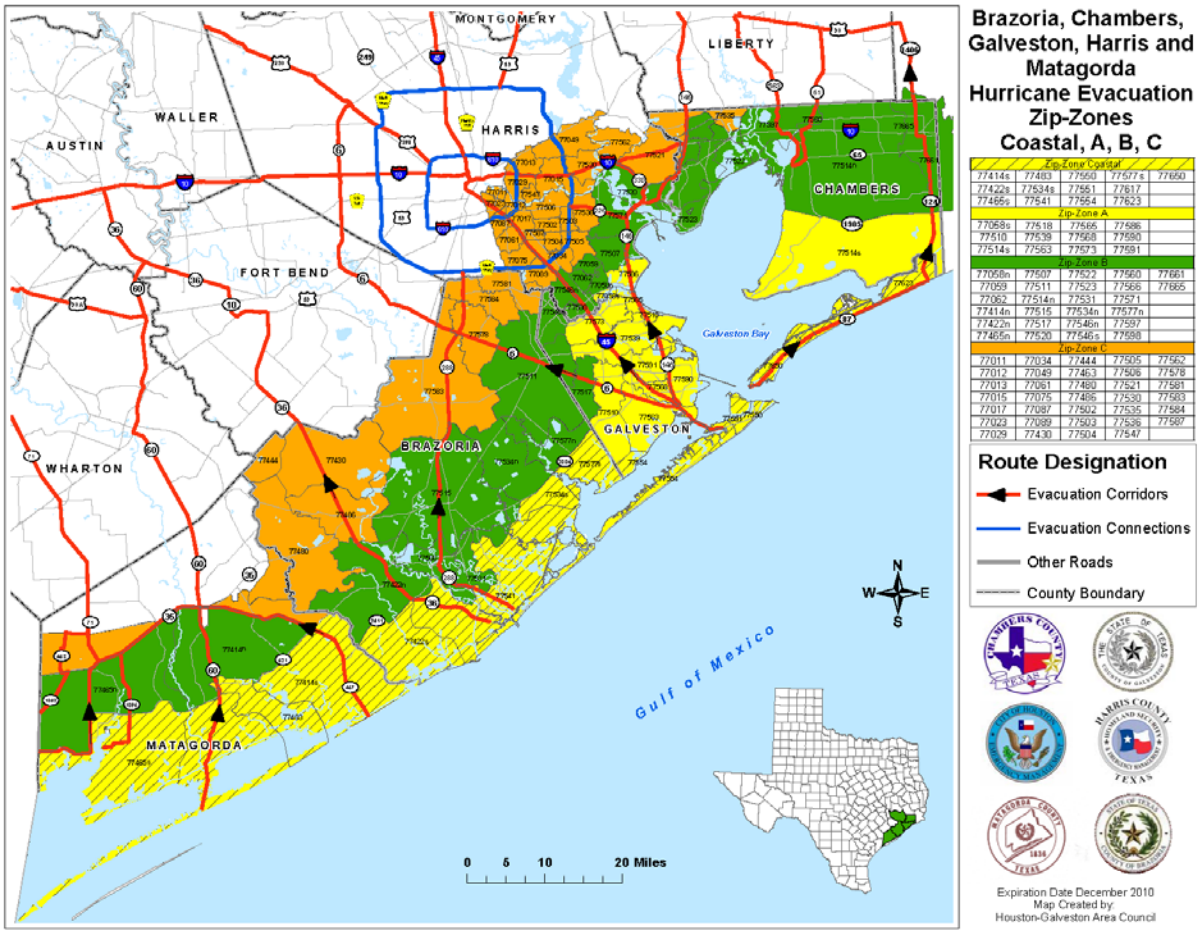

Figure 14. Coastal evacuation zones A (yellow), B (green) and C (orange). *Courtesy of Houston-Galveston Area Council*

Because Ike was "only" a Category 2 storm, many residents of the west side of Galveston Bay chose not to evacuate, based at least in part on the bad experiences many endured during evacuation before Hurricane Rita in 2005. During Hurricane Ike, the Houston-Galveston region was fortunate. If Ike had made landfall further down the coast near Freeport or San Luis Pass, the surge flooding on the west side of Galveston Bay would have been substantially higher and the likelihood is that hundreds, if not thousands, of residents of this area would have been killed. This is a very serious situation that deserves significant attention.

The SSPEED team has spent significant time attempting to identify solutions to address the threat posed by storm surge to the communities along the west side of Galveston Bay. In the following section, the structural and non-structural alternatives for this area will be presented.

B. Structural Mitigation Alternatives

Two major structural alternatives have been considered which would link the Centennial Gate with the Texas City Levee. One alternative is to elevate State Highway 146 to protect the communities west of the highway from a 25 foot surge. The second alternative is to construct a levee along the shoreline of Galveston Bay, which would protect all of the communities along the west side of Galveston Bay. These alternatives are shown in Figures 15 and 17, respectively. Also shown in Figure 16 is a profile view of the elevated SH 146 levee in which the land on the east side of SH 146 has been bought out, either before or after surge damage.

Figure 15. Plan view of the proposed SH 146 Levee connecting the proposed Centennial Gate with the existing Texas City Levee.

Figure 16. Profile view of the proposed SH 146 Levee after buy-out of east side of SH 146.

Figure 17. Plan view of the proposed Galveston Bay Shoreline Levee connecting the proposed Centennial Gate with the existing Texas City Levee.

There are obvious positives and negatives associated with each of these structural solutions. Raising SH146 is attractive because there is an existing right-of-way potentially bringing transportation funding forward in addition to reducing land acquisition costs. However, this alternative leaves developed lands east of SH 146 without protection and likely would mean that most, if not all, of these developed areas would be lost over time. This loss could be addressed by either implementing additional surge protection measures or a buy-out over time or after a major hurricane. Without this levee, a much larger area will likely be destroyed.

The Galveston Bay Shoreline Levee would be longer and more expensive than the SH 146 alternative. This levee would involve significant land acquisition, most likely through condemnation, and would remove large numbers of private houses along the shore. A similar structural concept was proposed by the U.S. Army Corps of Engineers in the 1970s and generated large-scale opposition from bay front communities and residents who did not want to lose their connection to Galveston Bay.

Neither of these two structural alternatives has generated any significant support in the west side communities that would be benefited by them. Instead, many support various forms of non-structural alternatives and those in the community that favor structural controls generally support the Ike Dike. Unfortunately, even if the Ike Dike is constructed, there could still be surge flooding that would threaten the communities on the west side of Galveston Bay. Although the overall extent of flooding in the region would be reduced, the vulnerable area west of the proposed elevated SH 146 would still be at risk with the Ike Dike in place. Additional surge protection strategies will be explored in future work to help reduce flooding in this west side Galveston Bay.

C. Non-Structural Mitigation Alternatives

There are a wide variety of non-structural damage mitigation alternatives that are available to communities along the west side of Galveston Bay. These alternatives are designed to address different issues. Educational alternatives that are intended to provide information to home-buyers and potential new residents and those that are intended to assist in evacuation and re-entry. Sustainable economic alternatives are intended to assist financially with coping with damages and permanent evacuation and that are intended to lead to better building practices. Each category is discussed in the following sections.

Risk Disclosure

The risk posed by hurricane surge is generally not found on typical real estate disclosure documents. The fact is that the 100-year floodplain maps do not identify high surges that historical data reveal. An international person, or even a person from another part of the United States, moving into southeastern Harris or northeastern Galveston County would likely find little information about this surge risk, yet it is very real. After Hurricane Ike, Harris County Precinct

2 placed markers on various street corners identifying the potential storm surge depths associated with Category 4 and Category 5 hurricanes (see Figure 18), but these markers were removed after strong protests by real estate and economic development interests. SSPEED team members believe that some type of disclosure should be required for buyers of homes in various evacuation zones. An example figure disclosing information about the risk of storm surge inundation is in Figure 19. The bottom line is that there is little discussion or graphic information about the risk of surge flooding in real estate related information which means that someone not familiar with hurricanes could buy into a surge evacuation zone without ever realizing the risk. This situation can and should be addressed by much greater information availability and disclosure.

Figure 18. Public service information displayed after Hurricane Ike. These markers were removed due to negative response from real estate and economic development proponents.

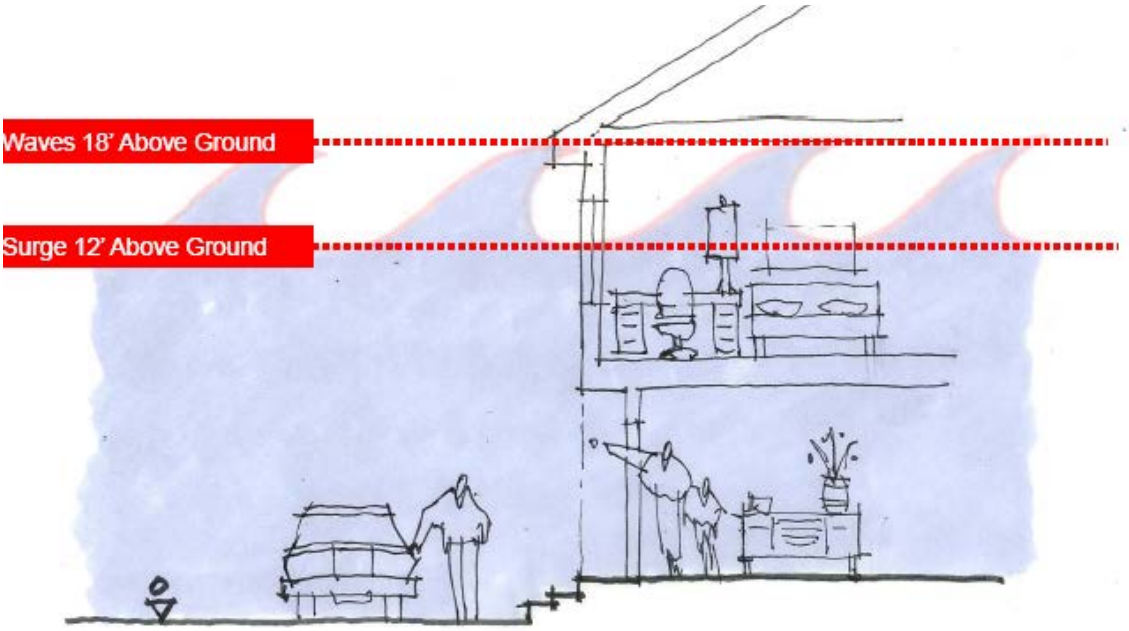

Figure 19. Suggested real estate disclosure information for homes located within hurricane surge inundation areas.

Real-time Flood Information Systems

Another non-structural surge damage mitigation option is to raise awareness of flooding in real-time to help with evacuation and post-storm re-entry. While there is generally good forecasting available regarding hurricane pathways, there is often vague information regarding the potential extent of surge flooding that is likely to occur with a particular storm on a particular pathway. Modeling today is sufficiently sophisticated that model results could be made available every several hours based upon the most recent coordinates of a hurricanes position, bay levels, and rainfall data could be recorded and distributed in real-time. This could then help refine evacuation warnings and decision making. Perhaps more importantly, these same data sources could help understand the extent of impact in various areas affected by the storm and with real-time aerial photography, up-to-date information could be made available to evacuees to help them understand the extent of damage and to provide information on the timing of re-entry. With better methods for understanding potential impacts and transmitting this information to evacuees, perhaps more people in these high risk zones would evacuate, lessening the risk of loss of life from a major surge event.

Real Estate: Building Codes and Buyouts

Early on, SSPEED team members were concerned about the role of flood insurance in worsening both the potential dollar damage from surge and also potentially the loss of life by incentivizing construction in vulnerable areas. The federal flood insurance floodplain maps set

base flood elevations for new housing and, until recently, have provided for subsidized insurance rates for homeowners within flood prone areas regardless of whether their homes were elevated above the 100-year flood elevation. This situation recently changed with the passage of the Biggert-Waters Flood Insurance Reform Act of 2012 which phases out subsidies over time for homes that lie below flood elevation levels. This change in the status quo has resulted in substantial political interest in revoking the Biggert-Waters Act because many homeowners find themselves unable to sell their homes to new buyers and/or pay for the new premiums which can exceed $20,000 for $200,000 coverage for structures and $100,000 for contents.

In the Houston region, land use controls are not favored, and we often have no zoning or no willingness to use regulations to prevent development of high risk areas. We hear a lot about the right of a private property owner to develop their land, but there are also costs that are imposed on all of us by certain land use decisions. While there are fairness issues with the phase-in of Biggert-Waters, there are also fairness issues about taxpayers outside of these flood prone areas being asked, if not expected, to provide subsidized flood insurance to landowners who choose to live in high risk areas. One fair resolution to this situation is to offer a one-time buyout to remove these homeowners from high risk areas. And we should not wait until the next hurricane surge event to make this decision, we should start to remove these high risk homes from high risk areas now. If this were done as part of a federal project, it would be considered federal flood disaster relief. We should simply do it because it makes sense, is fair, and avoids major long term loss of life, especially of responders asked to save those who insist on living in these high risk areas.

Building codes are an accepted form of land use control in the Houston region and our building codes have improved since Hurricane Ike. Most communities on the west side of the bay have upgraded and improved their codes in the last five years. However, while stronger buildings may withstand surge and wind to a greater extent than older structures, the problem of people living in these high risk areas remains. Even with stronger buildings, it does not make sense to stay in these high risk areas during a major hurricane event. Electricity, water and sewer likely will not be maintained during and after a storm and will likely shut down or partially function for weeks if not months. Streets and bridges may not be passable. Gasoline and food supplies will be difficult if not impossible to find. The building may survive but the community may not.

VI. Protection for Galveston Island and Boliver Peninsula

A. Risk

Galveston Island can be divided into two parts: the City of Galveston, located primarily behind the Galveston Seawall, and the West End developments, which include the city of Jamaica Beach. These two areas are quite different. Galveston Island was hit very hard by Hurricane Ike, but not in the ways that many expected. The City itself was relatively well protected by the seawall, but was inundated from the back side as counter-clockwise hurricane winds pushed onto the island. The West End was flooded but escaped the devastation that occurred on Bolivar Peninsula because it was to the west of the eye of the storm. However, there is no doubt about the vulnerability of Galveston Island. It is a barrier island and relatively low. Even the area behind the seawall which is 17 feet high could be subject to flooding from a major storm event making landfall in the San Luis Pass region.

B. Structural Mitigation Alternatives

From the evaluations undertaken by the SSPEED Center team, the portion of the city behind the seawall can be protected with a structural solution whereas structural protection for the west end is much more difficult. Again, the problem is that the Island is subject to flooding from both the Gulf and the Bay. Protecting one side only – such as the protection offered by the seawall – will not be sufficient unless there are also structures crossing Bolivar Roads and San Luis, thereby closing off these areas to the surge moving inland with the hurricane.

The City of Galveston currently enjoys the protection of the seawall. Since its construction, the seawall has protected the area directly behind it although Hal Needham's historical evaluation of storm surge indicates that a 21-foot surge is a reasonable 100-year surge level at the coast. If that surge occurred, the seawall would be overtopped by two to three feet with added height due to wave action. So, the seawall could and should be raised.

Most of the work of the SSPEED Center team focused upon creating a back-side barrier to prevent the Bay from simply rising into the City. This problem is substantial as indicated by the Ike experience, and it likely will continue to exist, depending upon storm track, even if gates were built across Boliver Roads and San Luis Pass to shut off Galveston Bay from the Gulf of Mexico (as proposed in the Ike Dike concept). The SSPEED Center felt the primary goal of flood protection for the City of Galveston should be to protect the University of Texas' Medical Center and the historic East End and Strand communities and other residential areas roughly lying behind the seawall.

There are several variations of the basic concept of taking a levee south from both ends of the seawall and connecting these two prongs across the back-side of the City. One variation is shown in Figure 20, which shows the levee extending along Harborside and then crossing Offats Bayou and turning back toward the seawall on the east side of the airport. Other variations could include going further west to protect the airport and extending the protection over to Pelican

Island to protect Texas A&M Galveston. It is worth noting that this alternative has been rejected by several prominent Galvestonians because it does not protect the "tax base" of the City of Galveston, the majority of which is in the West End residential development. However, this alternative does protect many residences as well as key employers and institutions.

Figure 20. Proposed backside levee extending from the Seawall along Harborside, crossing Offats Bayou and connecting back to the seawall east of the airport.

Extending the Seawall protection further down the island or placing a levee in front of the first row of beach houses is essentially what is proposed with the Ike Dike. As a stand-alone project, the SSPEED team questions the economic and environmental viability of the project. Given the current ownership of the beach by private landowners down to the "wet line", there will likely be a substantial land acquisition and construction costs. On the other hand, the back side vulnerability will still exist. As most of the structures on the West End are elevated and insured by federal flood insurance, the pay back for this alternative is suspected to be lacking by the SSPEED team.

C. Non-Structural Mitigation Alternatives

The West End of Galveston Island is a historically important and unique area that can be protected against most reasonably sized hurricanes with strong building codes, elevated first floors and federal flood insurance. In this instance, it is reasonable to revisit Biggert-Waters and the increase in flood insurance costs that are anticipated under that Act. Without flood insurance, many of the homes would remain, but transactions may become harder and harder. However, the maximum coverage of the federal flood insurance program is limited to $250,000 for structural damage and $100,000 for contents and many of the west end homes are valued far above

structural coverage under federal insurance. Nonetheless, if available, most residents would willingly purchase maximum structural coverage at whatever cost.

Unlike the West End of Galveston Island, much of the Bolivar Peninsula was destroyed by Hurricane Ike. Despite this, beach homes have been and are being aggressively rebuilt in areas where federal flood insurance is available. The only major undeveloped beach tracts are those that were not identified as developed areas for flood insurance purposes. The new structures are, for the most part, elevated higher and built to more stringent standards than the homes that were destroyed. The new homes are better able to withstand surge flooding than were those destroyed in Ike, many of which were built decades ago and not designed or intended to survive the surge of Ike.

On the other hand, US 87, the major road providing reliable ingress and egress, is extremely vulnerable to surge flooding. Just west of High Island, the Gulf waters come to within several feet of the highway right-of-way. It is likely that entire sections of this roadway will be destroyed in the next major surge event. This is a significant vulnerability of the peninsula which is linked to the mainland only by ferry to Galveston and US 87 connecting to State Highway 124 heading north out of High Island to IH 10. This potential loss of access could be critical in the future.

After Ike, the residents of Bolivar came together and with the assistance of the Federal Emergency Management Agency developed a document titled the Bolivar Blueprint dated May 2009. This document outlined what could and should be done to restore the Bolivar Peninsula. Among other things, this document discussed development other than beachfront homes and lamented the lack of day recreational use of the Peninsula and the absence of “backside” development. This document became the inspiration of the non-structural alternatives that are discussed in the next section.

VII. Landscape-Scale, Non-structural Surge Mitigation Alternatives

Although Ike caused over $25 billion in damages, it also narrowly missed the majority of the developed area on the west side of Galveston Bay. Had Ike made landfall further southwest, the damages would have been much more severe. On the other hand, given the location of Ike's landfall, the majority of the storm surge from Ike was absorbed by and stored upon the low-lying lands of Chambers and Galveston Counties. Days after Ike, surge water could be observed flowing back over rangeland and marshland and emptying back into the Gulf or the Intracoastal Waterway (see Figure 21). And although there was some economic damage to ranching and to scattered settlements, the storm surge was largely absorbed by the natural system. Within six months to a year after Ike, the marsh and prairie systems that were inundated by Ike had recovered and were back to functional natural systems. That is the genius of nature – of the coastal ecosystem; it can accept surge flooding and recover.

Figure 21. Surge water flowing back across the coastal marsh into the Gulf four days after Ike. *Photo by Bryan Carlile*

Based upon this observation and the comment by the Bolivar Blueprint that a goal for Bolivar was to develop economic activity on the "backside" of the peninsula, the SSPEED team began working upon ideas for non-structural storm surge damage mitigation that involved creating a new type of "economic development" based upon leaving the natural system natural.

In this manner, storms could come and go without leaving a vast footprint of destruction of human economic activity. Therefore, one goal became rethinking the economic opportunities for the low-lying areas of the Upper and Middle Texas Coast.

To this end, two alternatives have been developed. One alternative involves creating a National Recreation Area within these low-lying lands and the second involves creation of a system for trading, i.e. buying and selling, the services of the natural system. Each of these two approaches will be discussed further in the following sections.

A. The Lone Star Coastal National Recreation Area

The first non-structural surge damage mitigation proposal that emerged from our work was to create a National Recreation Area in the low-lying coastal lands of Chambers, Galveston, Brazoria and Matagorda Counties. Spurred in part by the Bolivar Blueprint, the team began to research both assets and opportunities that exist for economic development based upon the natural abundance of these low-lying lands. And make no mistake about it, these low-lying lands are among some of the most ecologically important and significant lands within the United States.

In considering alternative use ideas, it became clear that birds and bird-watching provide a major opportunity within these coastal areas. A review of trade information indicates that nature watching is the number one outdoor recreational activity in the United States with about 66 million participants, followed closely by bicycling, hiking and camping. In short, there is a market for outdoor recreational activities of a high quality.

Secondly, the Upper and Middle Texas Coast have excellent ecological resources. The birds of the Texas coast are well known to bird-watchers across the world. The Texas coast is both a winter destination and a migratory path for millions of species of birds. Three of the top ten Christmas Bird Counts in the United States are found in Brazoria and Matagorda counties. These counts are noted for large numbers of species that can be explained by the diversity of habitat types found in these areas. Furthermore, both the fall and particularly the spring migrations come through these low-lying lands, with millions of migratory songbirds of every color in the rainbow moving through in April and May. Later in the year, in September, hundreds of thousands of hawks come through, followed by the wintering ducks and geese and other waterfowl later in the fall. These low-lying areas offer a world-class recreational opportunity that can be enhanced by the wider usage of recreational kayaks for exploring the bay and bayou shorelines where many of the water birds are found.

Once the SSPEED team understood the recreational opportunity, the task transitioned into identifying a mechanism for realizing this potential. Lynn Scarlett, a team member and former Deputy Assistant Secretary of the Interior under the George W. Bush administration, suggested that a mechanism called a National Recreation Area might be workable for this coastal natural area. National Recreation Areas are part of the National Park System, yet there is quite a

lot of flexibility regarding how to structure and implement the concept, which became known as the Lone Star Coastal National Recreation Area (LSCNRA).

From the outset, the SSPEED team was focused upon the fact that Texas is a private property-oriented state that is wary of the federal government. For this reason, the structure proposed for the LSCNRA focused upon a partnership of federal, state, local, non-governmental organizations, and private property owners to create a "network" of properties that would be managed together as a unit of the National Park System. The precedent for this "networked" NRA was established in the Boston Harbor Islands National Recreation Area and in the Santa Monica Mountains National Recreation Area, each of which enjoy a partnership arrangement by which responsibility and implementation of the recreational concepts are shared. It was also essential that this LSCNRA only involve willing landowners and create no additional regulations for adjacent landowners. As discussions progressed, it also became clear that local and state elected officials were very concerned about any action that increased demands on the federal budget, which they felt to be strained at this time.

Out of the focus on surge mitigation and a recreation partnership, a number of tracts emerged as candidates for inclusion in the LSCNRA. These tracts include lands within the Big Boggy, San Bernard, Brazoria, Moody and Anahuac National Wildlife Refuges, the Corps of Engineers' Wallisville project, wildlife management areas and state parks managed by Texas Parks and Wildlife Commission, lands managed by the General Land Office of the State of Texas, lands owned by the Lower Colorado River Authority, parks operated by Matagorda, Brazoria, Galveston and Chambers Counties, various tracts owned by non-governmental organizations such as the Houston Audubon Society, Galveston Bay Foundation, Scenic Galveston and the Texas Nature Conservancy as well as lands owned and managed by the Galveston Historical Society. A map depicting these lands and the 20-foot contour is shown in Figure 22.

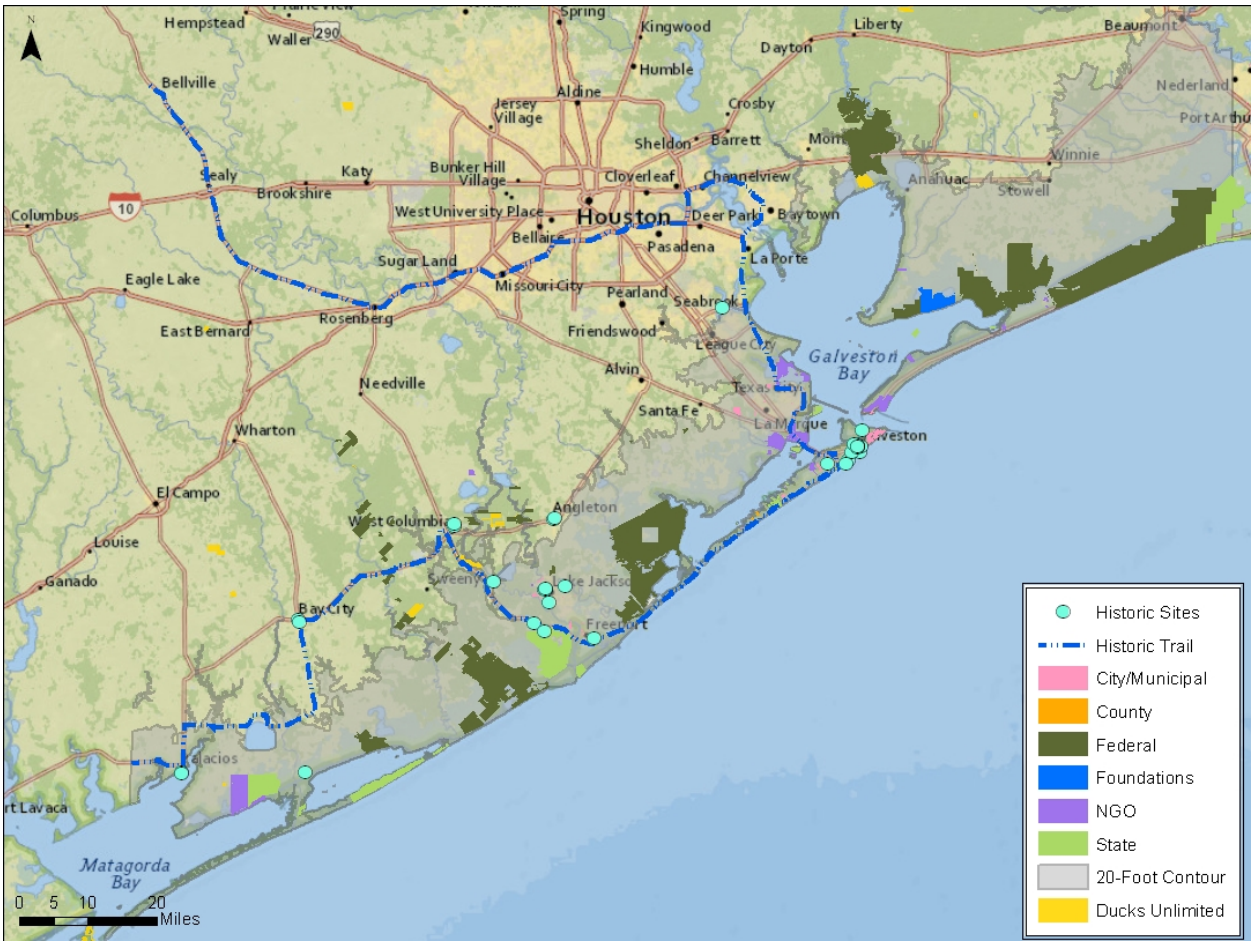

Figure 22. Map depicting the 20-foot contour and various federal, state, local and NGO tracts proposed for inclusion in the Lone Star Coastal National Recreation Area. The map also depicts an automobile trail based on historic sites that traverses the area.

Once the concept was generated by the SSPEED Center, the National Parks Conservation Association (NPCA), a non-governmental entity collaborating with the SSPEED Center, began to work on the establishment of the LSCNRA, working in concert with former Secretary of State James Baker III (Honorary Chair) and local businessman John Nau (Chair). Under their leadership, two advisory groups have been established: the Partners Coalition and Steering Committee. The Partners Coalition is comprised of land-owning entities and supportive non-governmental organizations that may become involved in the partnership to implement the LSCNRA. The Steering Committee is comprised of local business and political leaders who will assist Mr. Nau in attempting to obtain support necessary to create the LSCNRA by the passage of Legislation by the United States Congress.

Given that the basic purpose of the creation of the LSCNRA was to establish an economy based upon these natural resources, the NPCA, with assistance from the SSPEED Center and Mr. Nau, commissioned a study of the economic benefits that would result if the LSCNRA was created. This study found that after ten years, the LSCNRA would, at a minimum, generate 5,000

new jobs and increase tourism-related economy by almost $200 million. It is projected that actual tourist visits will increase to almost 2 million per year over that time. Among other things, being linked with the National Park System and its web site provides excellent branding and marketing for the Texas coast, which is one of the least known yet one of the most remarkable natural ecosystems in the country.

During 2013, the Partners Coalition and Steering Committee met several times to develop the framework of the partnership and to begin to draft legislative concepts that would become a part of the Congressional bill to create the LSCNRA. To date, there have been over twenty endorsements of the LSCNRA from various local governmental and non-governmental organizations. Various state and federal agencies have been briefed on the concept and have informally agreed to participate in the LSCNRA when it is created. At the time of this writing in early 2014, the legislative concepts are in the process of being discussed.

B. Ecosystem Services Trading

1. Valuing Ecosystem Resources

Ecosystem services trading is a concept that arises from the recognition that nature possesses an innate economic value to humans. Perhaps even more importantly, these values are being recognized from a transactional standpoint, meaning that humans are willing to spend money to obtain rights to these values.

Although ecologists have long understood the services and functions provided by the Earth's ecological systems, economists have been much slower to understand and appreciate these values. Robert Costanza and a team of economically-thinking ecologists published an article in *Nature* in 1998 that first attempted to establish a dollar value for these natural functions. In *The Book of Texas Bays*, Jim Blackburn took Costanza's per acre values and translated that into an annual value for Texas estuaries, marshes, sea grass beds and tidal flats. These calculations demonstrated huge dollar values for the Texas bays, ranging from a low of about $2 billion per year for San Antonio, Aransas and Corpus Christi Bay systems and a high of over $5 billion per year for Galveston Bay. Collectively, the bays along the Texas coast were valued at over $22 billion per year. While this may be an accurate reflection of the services that are provided, buyers for most of these services, such as wastewater treatment, do not currently exist.

A second force leading to creation of ecological service value arises from the evolution of environmental law. In 1990, the Clean Air Act was altered to create a market for emission and assimilation rights to sulfur dioxide. Under the Section 404 permit program, a market has evolved for wetland credits while a similar habitat protection market has emerged under the Endangered Species Act. These markets are very real and they are substantial, as shown in the attached chart prepared by Adam Davis from Ecosystem Investment Partners (see Figure 23).

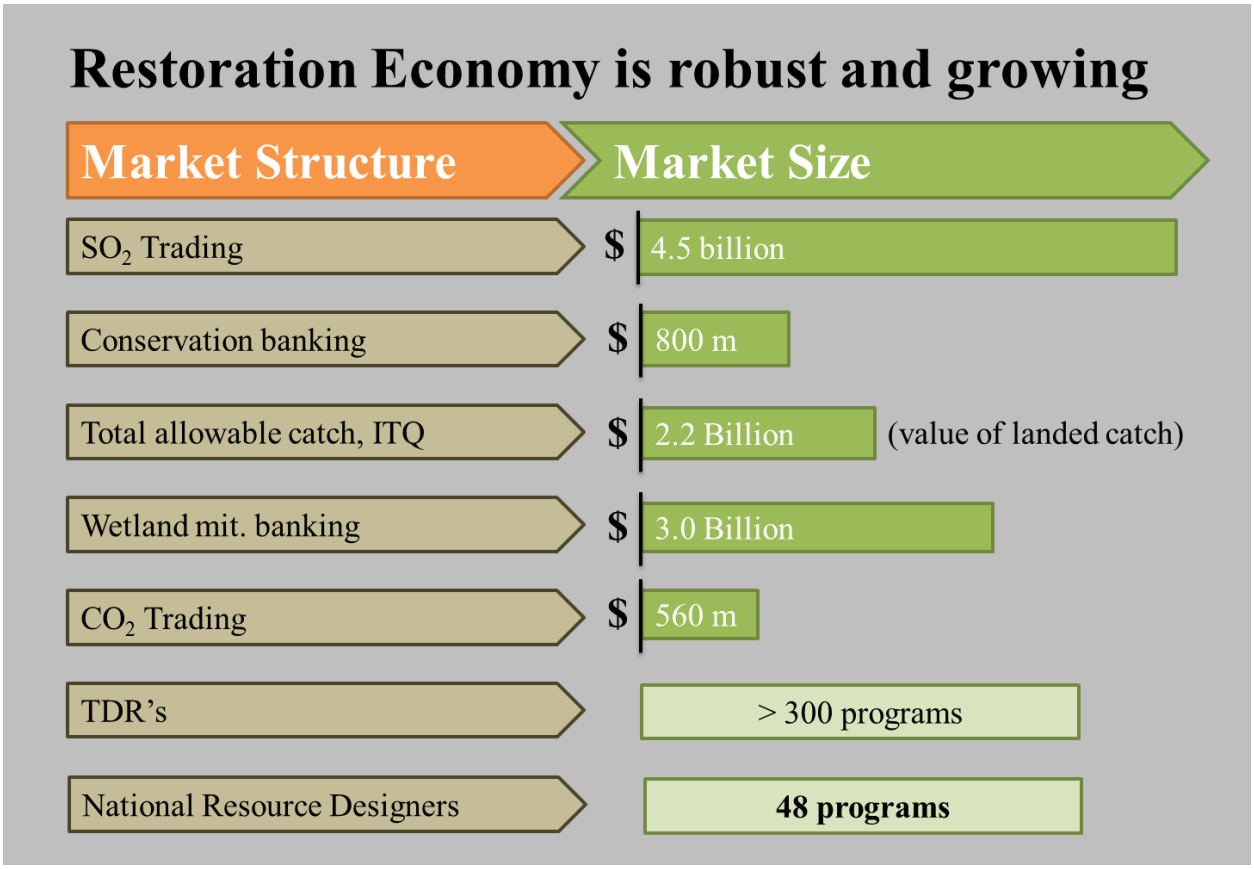

Figure 23. Ecosystem markets created by environmental laws

The bottom line is that there is value in the natural system, and some of that value is recognized by dollar transactions today. The SSPEED team has envisioned a second landscape-scale project out of the buying and selling of ecological values that either exist or can be restored within the Upper and Middle Texas Coast. We call this system the "Texas Coastal Exchange" or TCE.

2. Texas Coastal Exchange

The starting point for the Texas Coastal Exchange (TCE) is that we are trying to create an economic system that will reward private landowners for restoring and protecting the natural system that is resilient to hurricane surge damage. Our constraints are similar to those in the LSCNRA. We cannot create new regulations, we need to be respectful of private property rights and we cannot depend upon billions of dollars of federal or state support.

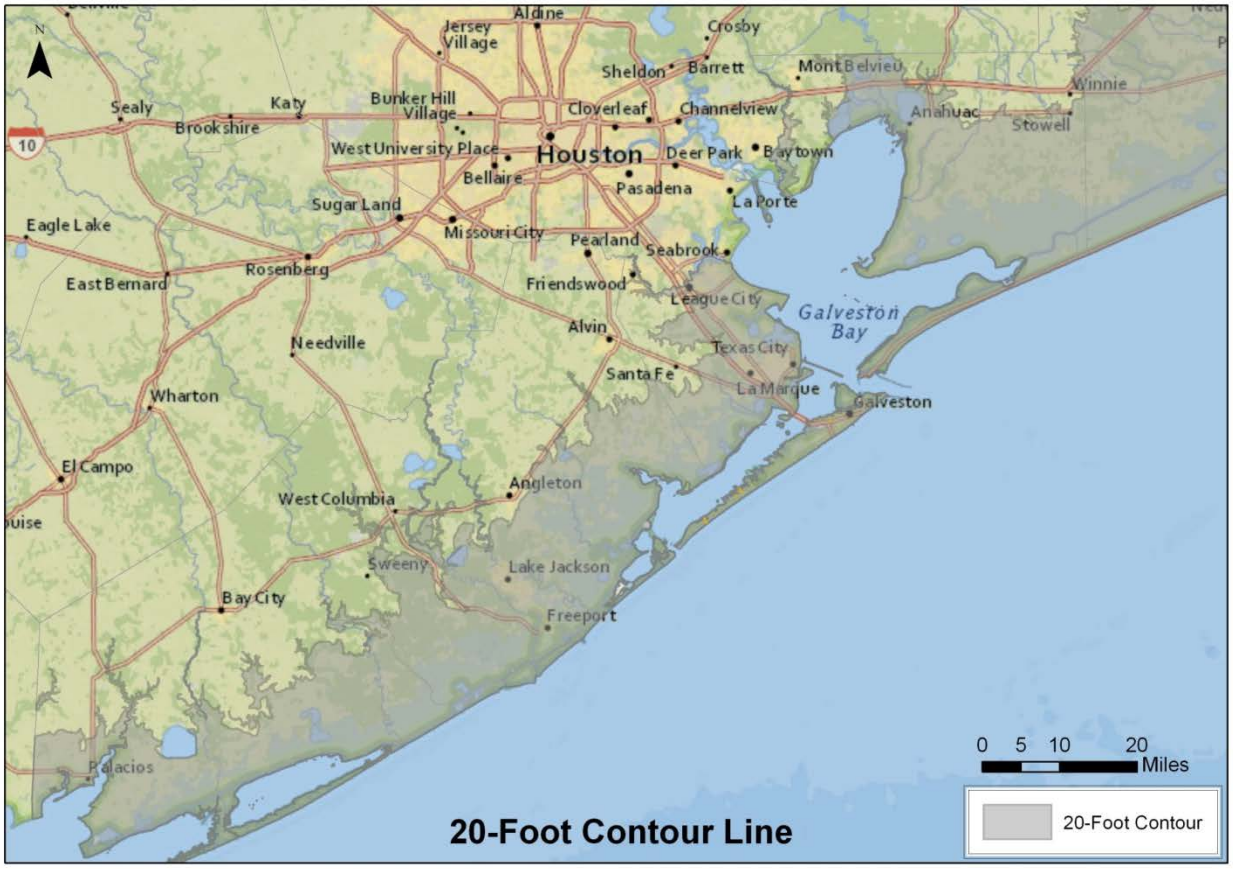

Figure 24. 20-foot contour line across Matagorda, Brazoria, Galveston and Chambers Counties.

As a starting point, we are interested in those lands that are at 20 feet of elevation and lower. This is the area that is most "at risk" from a major hurricane surge in our area of the coast, based upon reported historic surge events as compiled by Hal Needham of LSU. The area shown in Figure 24 covers roughly 2 million acres of which the majority is private property. This is the area for which we are proposing the creation of the TCE.

Within the TCE area, there are two major issues. First, are there buyers for ecological services that either currently exist or can be created/restored on these private lands? And second, would the landowners be willing to undertake land management programs necessary to generate these values and are the potential revenues from the sale of these services sufficiently high to justify the investment of time and effort on the part of these landowners? Those are the issues and the challenges of the TCE.

The "Demand Side": Funding Partners and Beneficiaries

The primary goal of the TCE is to provide an efficient and effective means for private, philanthropic, NGO and public entities to purchase and receive benefits from private landowner actions without having to buy or control land directly. By providing an online transaction

platform using consistent metrics that reflect verifiable performance on the ground, the barriers to participation in this non-structural flood abatement concept are minimized.

In order to realize our vision for the potential of the TCE, we recognize that buyers are absolutely essential. Without buyers, there is no new revenue stream for the participating landowners to tap. Therefore, substantial attention will be focused on identifying and soliciting the six major classes of buyers we believe will participate in the Exchange.

The six major classes are:

- Entities that desire to voluntarily purchase offsets for impacts related to their business activities, but which are not regulated by law. Examples include unregulated greenhouse gas emissions or certain land and water related impacts from development.
- Flood storage beneficiaries funded through public purchase of verifiable benefits
- Corporate sustainability initiatives (i.e. to support "Net Zero" accreditation).
- Traditional conservation finance (i.e. NGOs, philanthropy, conservation easements).
- The gift market.
- Entities in need of compensatory mitigation that is part of legal compliance requirements under the Clean Water Act, Endangered Species Act, Natural Resource Damage provisions, or California's cap and trade program for greenhouse gas offsets may be appropriate for inclusion but are not the primary focus at this time.

These will be discussed in greater detail in the following paragraphs.

3. Role of Ecological Services Exchange - Private Landowner Participation

One of the key reasons for developing the TCE concept was to find a way to include private landowners in the non-structural storm surge mitigation concept for the low-lying lands of Chambers, Galveston, Brazoria and Matagorda Counties. As part of the work undertaken by NPCA and the SSPEED Center, there has been substantial outreach to private landowners. In particular, there have been substantial discussions about what their needs are going into the future and what their interests and opportunities are.

There are several general observations that can be made relative to landowners. First, most of the large tract owners along the Upper Texas Coast have been approached numerous times over the years and the fee or easement sale of their property has not been appealing. Many of these landholdings have been in the family for generations, and the current owners would like to retain control over them. On the other hand, particularly for those landowners who have been farming rice, the economic challenges are mounting. Rice farmers in Matagorda County have been denied irrigation water from the Colorado River for the last two years and they are actively looking for options. Most of the land that is in rice farming was originally native prairie. Some of these landowners might be willing to plant and restore native prairie if there was a market to

support such actions. Others would likely be willing to restore bottomland forests and wetland areas. The key is whether or not sufficient cash flow can be realized to make the effort worthwhile.

There are a number of types of ecosystem services that can be marketed within the study area. There are existing tracts that would simply benefit from invasive species control. There are significant opportunities for restoring prairie grasslands and freshwater wetlands. This requires more extensive and intensive “farming” to create carbon sequestration and habitat values, but is certainly feasible. Those properties bordering tidal waters have significant opportunities to allow the inland expansion of Spartina marshes which provide both carbon and habitat values as well as brackish wetlands. And finally, there is significant opportunity for forest restoration and coastal woodlot creation throughout the Brazoria and Matagorda County lowlands.

A team will need to be developed to work with these farmers and ranchers to help them make the conversion to carbon and habitat farming. Invasive species control is better known to these landowners and freshwater wetland creation is relatively easy and straightforward in these flat and generally poorly drained lowlands. While this will take some effort, it is certainly doable.

A key to feasibility here is that the farm or ranch owner must have a clear understanding of what they need to do in order to make and receive income from these ecosystem service transactions. A regional procurement program, registry, and marketplace will all require sufficient standards and protocols to ensure credibility, accountability, and transparency. Stakeholders in the region will need to be assured, and be able to verify, that the environmental benefits being provided by the program are real and are achieving the performance required to support the Buyer’s and Seller’s goals.

To be credible, a procurement program or ecosystem marketplace must contribute to achieving real environmental improvements. To verify this, performance measures related to market functioning need to be in place. Performance measures should be related to the type, number, and quality of ecosystem service credits generated by the marketplace, and ultimately linked to the overall goals and targets for ecosystem recovery. Objective verification and certification of credits is necessary for credibility. This requires: (1) an agreed-upon method for measuring credits—an accounting system or currency; (2) performance standards or measures that credits must meet (e.g., conservation easements on land, quality of wetland area); (3) a system for certifying that credits are real; (4) a way to track credits through all steps in the process—production, certification, sale, and retirement; and (5) provisions for insurance to provide a buffer against unforeseen losses.

Market standards and frameworks for accountability and transparency can be provided by the key structures and functions that must be established in a registry and exchange system. Much like other systems commonly used to establish economic values, like rules for listing stocks and appraisal standards for real estate, a structure that allows a consistent basis for the exercise of discriminating judgment is required. First, an accounting system, with tools to measure debits and credits, must be established. All stakeholders must agree to systems that

standardize how the ecosystem service benefits provided are calculated and what units are traded. While scoring methods are available for a number of credit types, including carbon, impervious surface, nutrients for water quality trading, and some types of habitat (e.g., wetlands), others must be developed to meet the specific goals of TCE buyers. Accounting tools need to be relatively simple to implement, but robust enough to provide confidence that they capture the environmental benefit of interest.

Second, registries are required for tracking credits and providing transparency about what credits are available, of what quality, whether credits have been certified as meeting standards, what credits have been bought and sold, and at what prices. Registries allow exchanges more readily and can greatly lower transaction costs by making it easy for buyers and sellers to connect. Registries are also important for providing credibility for markets—by tracking and maintaining information on credits, they can ensure that credits cannot be sold multiple times. Associated with registries are processes for verifying credits, ensuring that the number and quality of the credits placed on the registry is accurate. Certification of credits by third parties is also a function associated with registries. And third, registries provide a process and framework for making transactions; they allow buying and selling to take place without the need for individual buyers and sellers to negotiate each transaction with separate rules. Exchanges also contribute to lowering transaction costs.

The specific conservation actions required for participation will depend on the physical location and characteristics of specific properties. The actions required of the private sector participant could include creation of specific ecological areas that are set aside for protection in various ways or might include mixed use of certain areas, such as prairie restoration along with cattle grazing. The TCE intends to make use of innovations in (1) GIS analysis, (2) standard setting, (3) a process for determining landowner eligibility, (4) project development, (5) verification and (6) a web-based platform for transactions that will enable private landowners to customize their participation in a way that works for them. Each of these elements is under development at the SSPEED Center at this time.

C. Conclusion of Landscape-Scale Green Alternatives

The bottom line is that both the LSCNRA and the TCE are viable options that would allow the creation of an economy based on the natural system – an economy that is resilient, a different economy than we have today. The LSCNRA could be created by Congress in 2014 and the transactional platform for the TCE should be ready for installation on the internet by late 2014 or early 2015. These alternatives are “keepers”; they will benefit the Texas coast in many ways beyond surge flood mitigation.

VIII. 2014 Status: Phase III

At the beginning of 2014, the Houston-Galveston region finds itself in a difficult situation. Five years after Ike, a lack of leadership and public consensus has slowed progress in determining how the region proposes to address hurricane surge flooding. Generally speaking, the landscape-scale green space solutions proposed by the SSPEED Center have been well accepted by governmental and business types throughout the region, but what's not to like about these alternatives. They pay for themselves, create economic activity and impose no new restrictions or regulations. They are the "no-brainers" of hurricane surge mitigation.

The situation becomes much more difficult when considering structural alternatives within the currently developed portions of the region. The Centennial Gate is an excellent project that has a great price tag and has the ability to be constructed relatively quickly. However, it does not address the surge vulnerability of the communities along the west side of Galveston Bay and it does not help the City of Galveston or the West End of Galveston Island. Local business and governmental leaders are hesitant to support this alternative because they fear that to do so would result in a major regional fight with southern Harris and Galveston counties over the Centennial Gate vs. the Ike Dike.

On the other hand, it is reasonable to ask what the situation is with regard to the Ike Dike. The Ike Dike was proposed by Dr. William Merrell of Texas A&M Galveston and has been championed by the leadership of the City of Galveston as well as the several communities along the west side of Galveston Bay. To date, no comprehensive plan for the Ike Dike has been produced, nor has a comprehensive assessment been completed. This is a significant problem that should be of great concern to the region, given that Congressional support is being organized for this proposal and, unlike the SSPEED Center proposals, it has never been transparently vetted in the community. Whether you like the SSPEED Center proposals or not, they have been fully vetted publicly and both positive and negative information has been disclosed about all SSPEED Center projects.

In the paragraphs that follow, the direction of the SSPEED Center for the next two years will be set forth. Initially, this discussion will focus upon moving forward with solutions for the entire region with the "bookends" of the green space alternatives and the Centennial Gate. The discussion will then focus upon the Ike Dike and the concerns that must be addressed and resolved before the region can have a reasoned discussion about one proposed alternative or another.

A. Proposed Houston-Galveston Area Protection System

As stated previously, the SSPEED Center work to date has developed two bookends for Houston surge mitigation: the landscape-scale green space alternatives and the two potential alignments for the Centennial Gate. These major alternatives are shown in Figure 25 for the area immediately surrounding Galveston Bay along with the existing Texas City Levee and the Galveston Seawall.

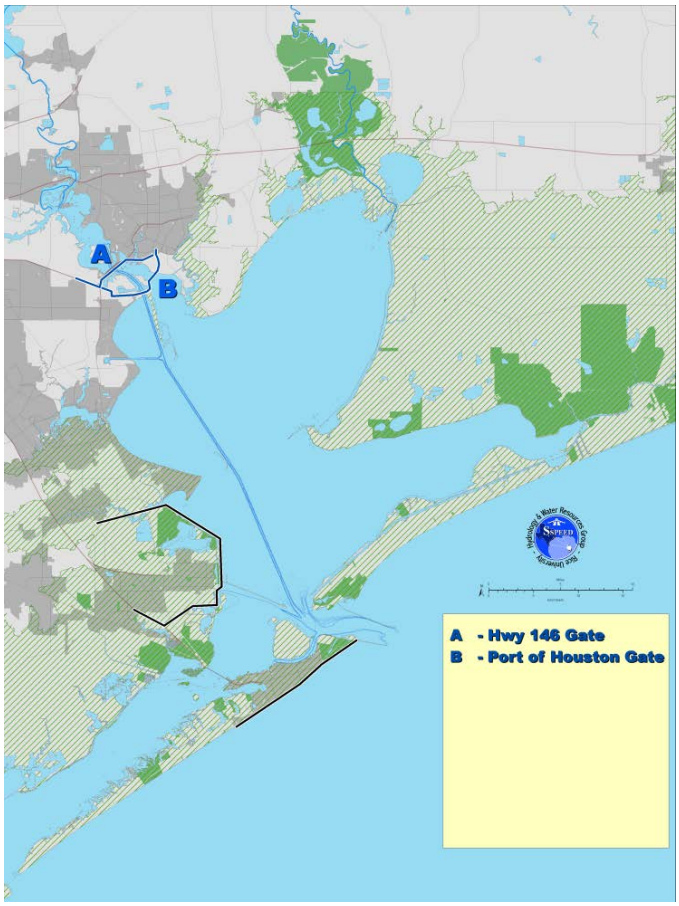

Figure 25. A map of Galveston Bay showing proposed green space alternatives, as well as the existing Texas City Levee and Galveston Seawall.

In 2014, Dr. Clint Dawson at the University of Texas at Austin is developing a surge model (ADCIRC) specific to Galveston Bay in order to more easily replicate the benefits and impacts of various structural alternatives relative to intercepting surge flooding and reducing levels in and around Galveston Bay. The goal of this tool is to evaluate multiple iterations of alternative features to determine those that produce the best results in combination with the Centennial Gate and the green-space alternatives.

Of the alternatives currently being explored by the SSPEED Center, one of the most promising alternatives is to elevate US 87 on the Bolivar Peninsula to provide structural

interference with the movement of surge over the Peninsula and into Galveston Bay. Hurricanes rotate in a counter-clockwise direction and a storm making landfall south of Bolivar Roads would bring water across the Peninsula and push it into both Chambers County and Galveston and Trinity Bays. The question that remains unanswered is what is the optimal height for both road construction and surge mitigation purposes? Similarly, some benefits could be obtained from elevating FM 3005 on Galveston Island. In both cases, evacuation could be enhanced and some surge mitigation would be provided that would benefit inland areas. This alternative is shown in Figure 26 along with the backside levee around the City of Galveston.

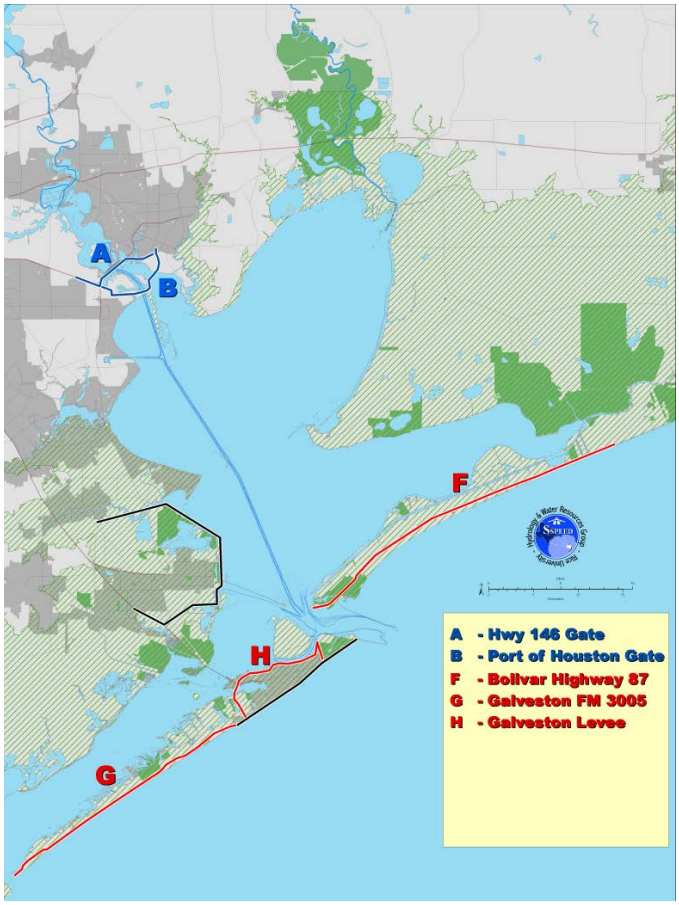

Figure 26. A map of Galveston Bay showing proposed elevated roadways on Galveston Island and Bolivar Peninsula and green space alternatives, as well as the existing Texas City Levee and Galveston Seawall.

Other structural alternatives will be evaluated in combination with elevated roadways. These include enhancement of oyster reefs and strategic placement of spoil disposal areas. One key concept is to restore the oyster reef that formerly connected Eagle Point to Smith Point across Galveston Bay. This reef could slow the movement of water into Upper Galveston Bay potentially reducing storm surge heights in both the Ship Channel and communities on the west side of Galveston Bay. There is also the potential to build an oyster reef off shore of the west

side of Galveston Bay. These alternatives will be modeled in ADCIRC to measure their potential benefit to the region. The oyster reef alternatives are depicted along with the elevated roadways and Galveston levee in Figure 27.

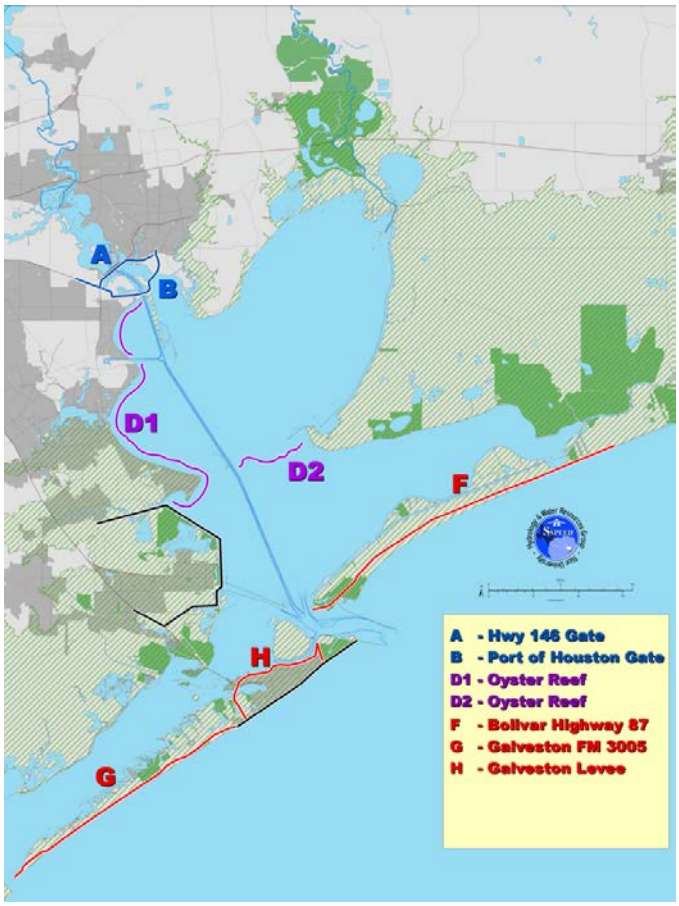

Figure 27. A map of Galveston Bay showing proposed oyster reefs, elevated roadways on Galveston Island and Bolivar Peninsula, and green space alternatives, as well as the existing Texas City Levee and Galveston Seawall.

There is yet a further refinement that may be offered by the strategic placement of dredged spoil material. At this time, dredged material is being beneficially used in the upper bay to create wetlands. This concept was innovated in the late 1980s and early 1990s to address criticism associated with open dumping of spoil material. Today, it is reasonable to ask if dredge disposal could be further utilized to provide surge interference along the Houston Ship Channel in order to reduce flooding on the western side of Galveston Bay. Again, this is a potential solution to be evaluated along with these other alternatives which are shown together on Figure 28.

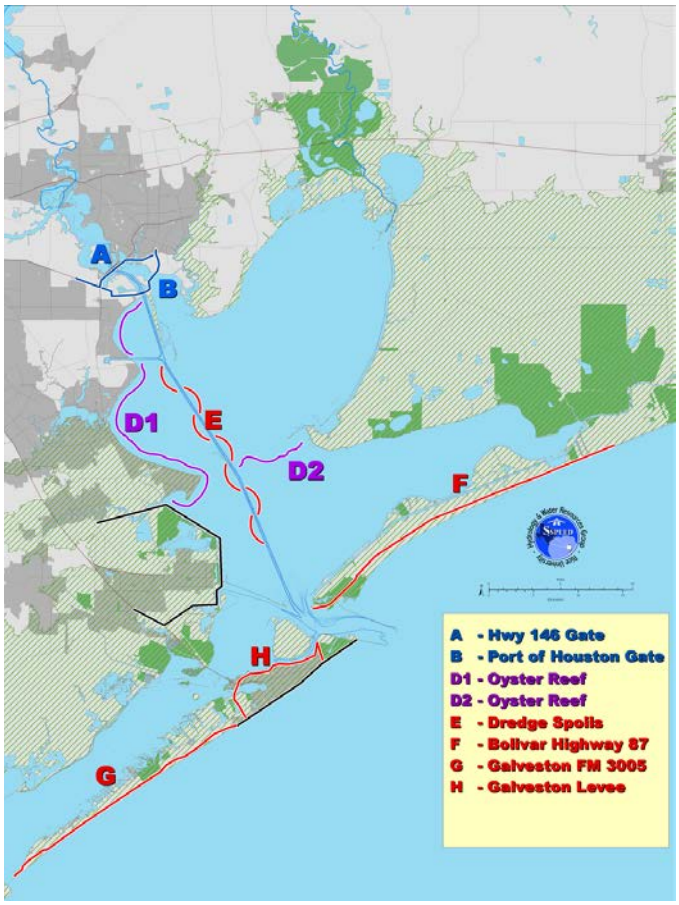

Figure 28. A map of Galveston Bay showing proposed dredge spoil islands, oyster reefs, elevated roadways on Galveston Island and Bolivar Peninsula, and green space alternatives, as well as the existing Texas City Levee and Galveston Seawall.

If all of these alternatives were constructed along with the elevation of SH 146, comprehensive surge mitigation and evacuation plan would exist that would offer significant improvement over the current situation. The potential comprehensive plan for Galveston Bay is shown in Figure 29.

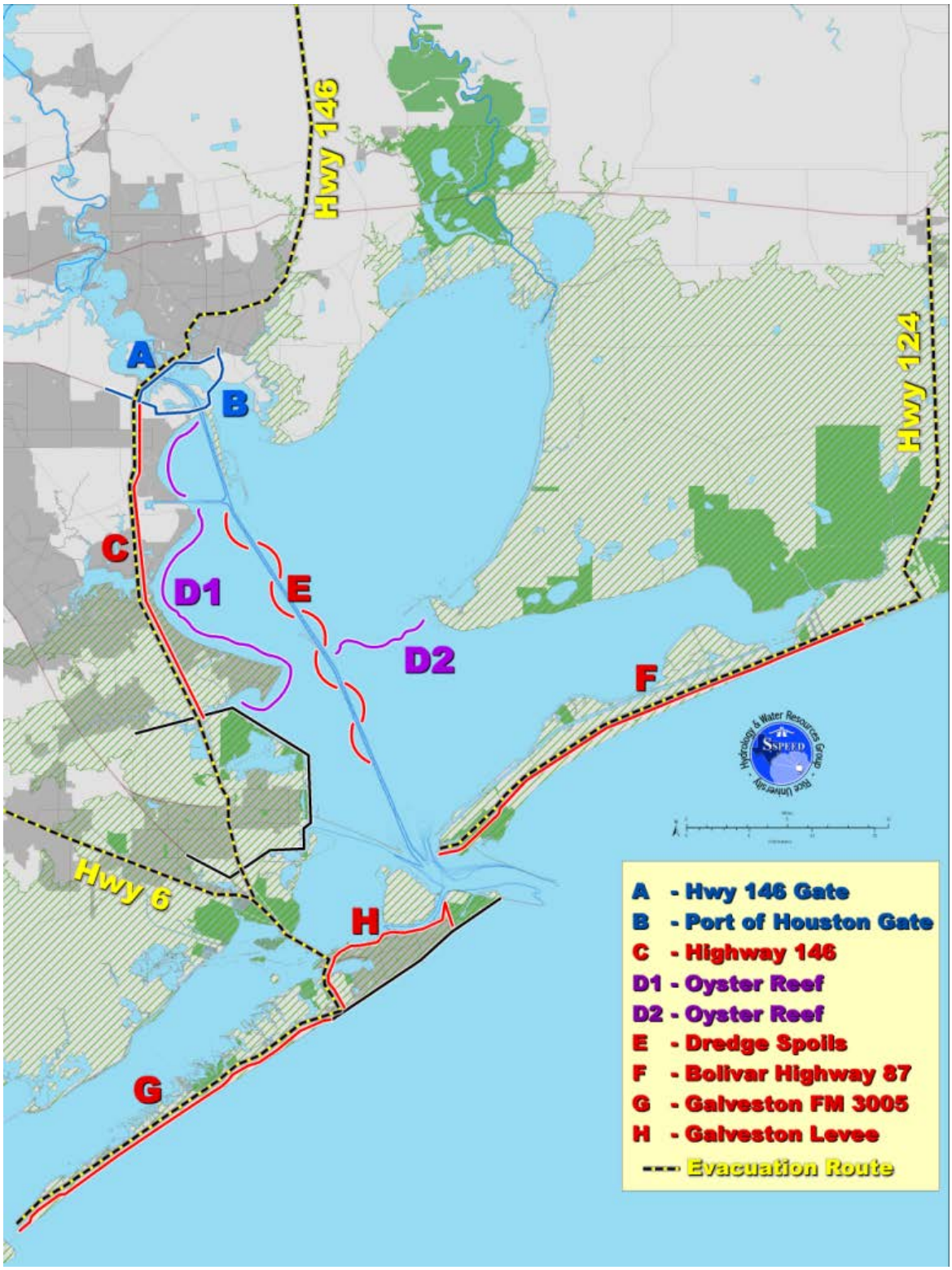

Figure 29. A map of Galveston Bay showing safe evacuation routes created by the proposed elevated SH 146, dredge spoil islands, oyster reefs, elevated roadways on Galveston Island and Bolivar Peninsula, and green space alternatives, as well as the existing Texas City Levee and Galveston Seawall.

There is much work to be completed before the optimal configuration of these elements is discovered. Modeling has to be run to determine which of these alternatives offer significant surge reduction. Cost estimates must be prepared to determine if certain alternatives would be feasible and whether the benefits justify the costs. We must determine if all portions of the community are benefitted. And we must be transparent about our calculations and assumptions. However, we are optimistic that out of this process will emerge an excellent alternative that optimizes the benefits throughout the Galveston Bay region.

B. Evaluation of the Ike Dike

At the same time that the SSPEED Center is continuing to work on bay-wide solutions, we will also be undertaking an evaluation of the proposed Ike Dike. The Ike Dike was originally proposed by Dr. Bill Merrell of Texas A&M Galveston and is proposed as an approximately seventy mile long dike that extends from High Island to beyond San Luis Pass. As originally proposed, it includes gate structures at both Bolivar Roads and San Luis Pass, at the southern tip of Galveston Island (see Figure 30).

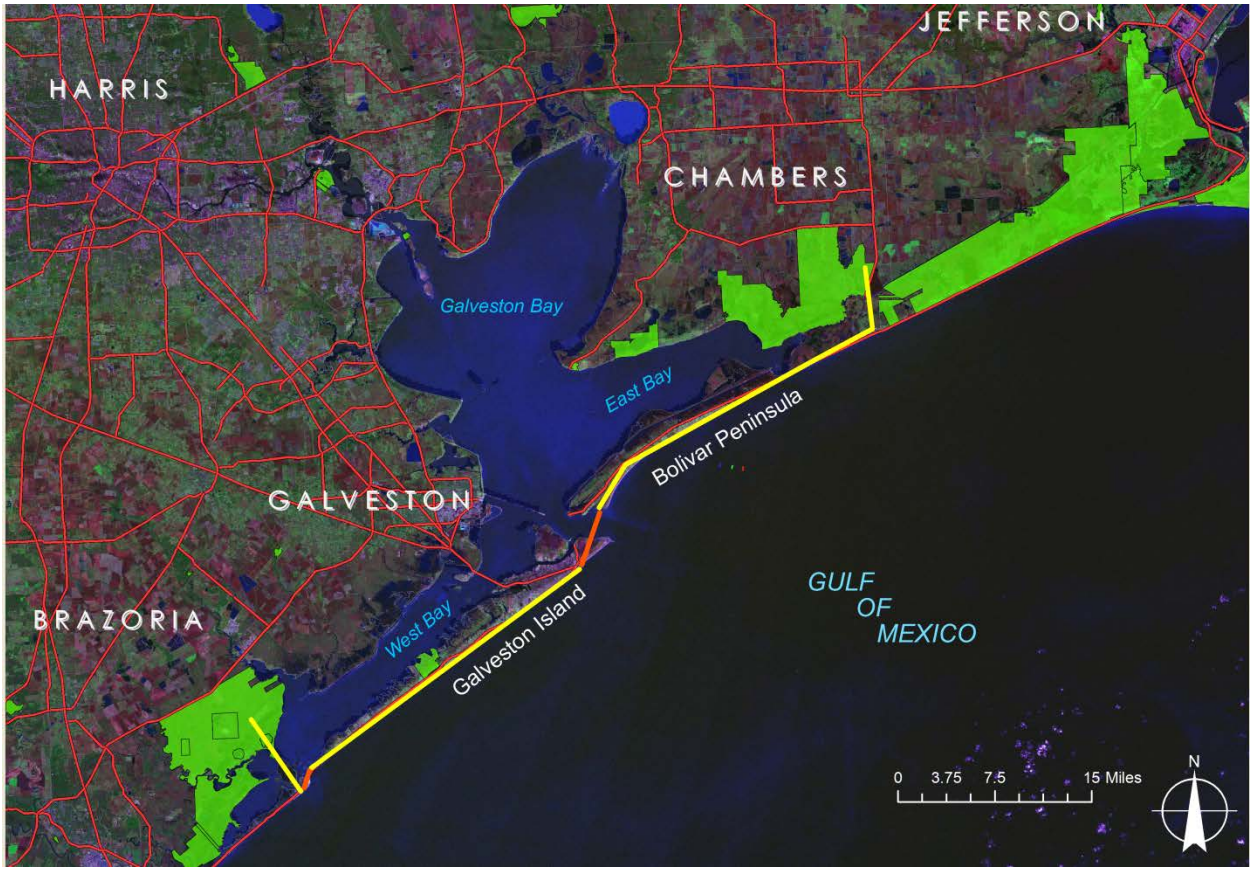

Figure 30. Schematic of the proposed Ike Dike, a coastal barrier concept that extends from High Island across Bolivar Roads and southward across San Luis Pass. *Courtesy of Rice University Archives*

Although the Ike Dike has been actively discussed since it was proposed in late 2008, there has been relatively little transparency about details of the Ike Dike and even less disclosure of the environmental and economic impacts of this huge coastal feature. As part of its upcoming work, the SSPEED Center will attempt to quantify the cost (economic and environmental) of the Ike Dike and the long-term operation and maintenance in order to compare it with other proposed alternatives in the Houston-Galveston region.

Some of the questions that must be answered are:

- Where on Bolivar Peninsula and Galveston Island can the Ike Dike be feasibly constructed? Will it be in front of beach houses or on existing roads?
    - What are its dimensions? e.g., if it is 17 feet high with a ten foot top width and 3:1 side slopes, the structure will be 110 feet wide at the bottom; if there is a road on top, the top width will need to be at least fifty feet. With a road on top, how is it accessed? Is there a parallel access road?

- What is the Ike Dike constructed of?
    - If it is to be covered by sand as has been suggested, where will the sand come from? At what cost?
    - If it is to be filled with clay, where will it come from? How many truckloads of clay will be required to construct the Ike Dike? At what cost?

- If it is in front of beach houses, will any sand remain on the beach? If not, will we be in a situation of perpetual sand augmentation?

- If it is behind the houses, what is the impact on the houses between the dike and Gulf?

- Under the federal cost-sharing for federal projects, can elevated beach houses qualify as being benefitted by such a levee proposal for calculation of federal benefits?

- What is the design of the Gate and Dike across Bolivar Roads and San Luis Pass?
    - Are there gates across the Gulf Intracoastal Waterway?
    - Are there subsurface foundation issues within Bolivar Roads that render the construction of a gate structure either structurally impossible or fiscally unreasonable?
    - Are there hydraulic restrictions at Bolivar Roads and San Luis Pass?
    - What is the impact of the levee on fish and shellfish movement through Bolivar Roads and San Luis Pass?
    - What is the impact of the levee on bay circulation?

- What is the residual flood risk for mainland areas surrounding Galveston Bay with the Ike Dike in place?
    - Residual risk along the west side of Galveston Bay?
    - Residual Risk in the Houston Ship channel?
    - Residual Risk in the City of Galveston?

- What is the realistic cost of the Ike Dike? How is it to be financed?

IX. Conclusion

In 2008, Hurricane Ike highlighted the vulnerability of the Houston-Galveston region to hurricane storm surge. This has become one of the most important issues facing the region today. Since 2009, the SSPEED Center, with funding from the Houston Endowment, has focused on modeling, understanding, and mitigating hurricane storm surge. Early research indicated that shifting the hurricane landfall further southwest or increasing wind speeds could easily produce devastating surge in the Houston-Galveston region. During Phases I and II (2009-2014), the SSPEED Center put forward two promising surge protection proposals: the Centennial Gate and the Lone Star National Recreation Area. We believe that the Centennial Gate is an obvious solution for protecting the Houston Ship Channel from devastating economic and environmental impacts. No other structural proposal put forward thus far can guarantee protection for the Houston Ship Channel. Similarly, the Lone Star National Recreation Area is a no-brainer. Packaging the natural resources and features of the upper Texas coast into a comprehensive ecotourism area would not only economically benefit the region, but provide incentive to preserve and protect the undeveloped areas that help to buffer the region from storm surge.

In Phase III, the SSPEED Center has proposed to put forth a comprehensive plan for the Houston-Galveston region, formally known as the Houston-Galveston Area Protection System (H-GAPS) (as shown in Figure 29). H-GAPS could consist of structural and non-structural alternatives ranging from raising roads to building levees to rehabilitating oyster reefs. Combinations of the most promising alternatives will be analyzed using advanced storm surge and damage models customized for the region. There are no easy answers for building storm surge protection in the Houston-Galveston region. Hurricane landfalls in this region are fairly infrequent, happening only every ten to twenty years. However, when the big hurricane does occur - and it's only a matter of when, not if - it could easily wipe out a century of economic development and create the worst ecological disaster ever seen on the Texas coast. A large hurricane could kill thousands of people who have moved into our coastal surge zones without adequate warning or information. And we will all ask why we didn't do something before it happened.

The time to act is now. We must create good plans and be transparent about impacts and costs. This is not one portion of the region versus another. This is about all of us being honest and realistic and open to ideas and information. This is about planning for the future in a manner that solves problems rather than creating them.

X. Appendices

Appendix 1: 2013-2014 Speaking Engagements

2013

05/01	BET Workshop, Austin
06/17	Brays Bayou Association
06/27	Democratic Club of Calhoun County, Port Lavaca
07/24	Emergency Management Commission
08/12	Gulf Coast Bird Observatory Annual Member Dinner
08/14	Breakfast Club of Houston
08/22	Silver Fox Advisors Group
09/12	Citizen Advisory Panel Presentation for DuPont employees
09/30	Baytown Citizens Advisory Panel
10/04	APA Meeting, Coastal Planning, Galveston
10/25	Mitchell Foundation Board Meeting guest speaker
10/30	USACE, presentation Col. Rich Pannell
11/08	Texas Environmental Grantmakers Group, Mad Island
12/04	SEACAP Dinner Meeting
12/12	Renewable Natural Resources Foundation Congress on Coastal Resilience, Maryland

2014

12/27	Galveston Bay Foundation
02/27	Houston Wilderness Collaborative Access Group
03/06	Woodlands Meeting
03/13	USACE Presentation, Galveston
03/19	Rice Discussion Group, Emily Todd
03/26	League of Women Voters
04/23	Galveston Bay Foundation Annual Meeting
05/06	Coastal Bend Bays Foundation
05/14	Houston Galveston Area Council Meeting
05/15	City of Houston Resilience Committee
05/16	En Cuentro Conference, Citizens Environmental Coalition

Appendix 2: 2013-2014 Media List

2013

06/03 Proposal to build gate to protect ship channel, ABC-KTRK, Channel 13
06/04 Look for ways to protect the Ship Channel against hurricanes, Village News
06/12 US expects active hurricane season, Gulf region vulnerable, Xinhua News
07/06 Bedient: Myriad projects can dampen storm surge, Houston Chronicle
09/13 Ike 5 years later: What lessons have we learned?, Local Channel 2
09/25 ABC-KTRK
09/25 Scientists tout big gate for storm protection, Houston Chronicle
09/25 Proposal introduced to build large floodgate for Houston Ship Channel, Local Channel 2
09/26 Researchers: Texas not ready for next hurricane, Texas Tribune
09/26 As county dithers on the Dome, it ignores a ticking time bomb across town, Houston Chronicle
10/06 A different idea for protecting ship channel from hurricanes, Houston Chronicle
10/07 How Hurricanes that Hit the Texas Coast Can Float Giant Tanks, State Impact, NPR
11/07 SSPEED Center Overview of Centennial Gate, Galveston News
11/11 One Wild Idea, Rice Magazine
11/29 On Storms, Leadership Needed, Houston Chronicle

2014

01/07 Hurricane Surge, Houston Chronicle
03/11 Rice University wins $3.1M to develop storm strategy for Houston-Galveston, Rice Media
03/11 Researchers get grant to study options to protect Houston area from next big storm. KTRK-ABC
04/22 Centennial Gate proposal gets closer to reality thanks to multi-million dollar grant, KPRC
04/29 Rice University helping to preserve natural environment, KPRC
05/31 “Eye on the Gulf”, KTRK-ABC
06/03 “Rice to study storm surge strategy”, The Baytown Sun

Appendix 3: 2010-2014 Journal Publications

Anderson, J., Milliken, K., Wallace, D., Rodriguez, A., Simms, A. (2010). Coastal Impact Underestimated from Rapid Sea Level Rise. *EOS Transactions, American Geophysical Union*, 91(23), 205-212.

Anderson, J.B., Wallace, D.J., Simms, A.R., Rodriguez, A.B., Milliken, K.T. (2013). Variable response of coastal environments of the northwestern Gulf of Mexico to sea-level rise and climate change: Implications for future change. *Marine Geology*, 1-19. http://dx.doi.org/10.1016/j.margeo.2013.12.008

Ataei, N., Padgett, J. E. (2013). Limit State Capacities for Global Performance Assessment of Bridges Exposed to Hurricane Surge and Wave. *Structural Safety*, 41, 73-81. http://dx.doi.org/10.1016/j.strusafe.2012.10.005

Ataei, N., Padgett, J. E. (2013). Probabilistic Modeling of Bridge Deck Unseating during Hurricane Events. *ASCE Journal of Bridge Engineering*, 18(4), 275-286. doi:10.1061/(ASCE)BE/1943-5592.0000371

Ataei, N., Padgett, J. E. (2014) Influential Fluid-Structure Interaction Modeling Parameters on the Response on Bridges Vulnerable to Coastal Storms. *Structure and Infrastructure Engineering*. doi: 10.1080/15732479.2013.879602

Ataei, N., Padgett, J. E. (in review). Reliability Surrogate Models for Coastal Bridges in Hurricane Prone Zones. *Engineering Structures*, submitted July 2013.

Atei, N., Stearns, M., Padgett, J.E. (2010). Response Sensitivity for Probabilistic Damage Assessment of Coastal Bridges Under Surge and Wave Loading. Transportation Research Record: Journal of the Transportation Research Board, 2022, 93-101. doi: 10.314/2022-12

Brody, S.D., Blessing, R., Sebastian, A., Bedient, P. (2013). Delineating the Reality of Flood Risk and Loss in Southeast, Texas. *ASCE Natural Hazards Review*, 14(2), 89-97. Doi: 10.1061/(ASCE)NH.1527-6996.0000091

Brody, S.D., Blessing, R., Sebastian, A., Bedient, P. (2013). Examining the impact of land use/land cover characteristics on flood losses. *Journal of Environmental Planning and Management*. doi:10.1080/09640568.2013.802228.

Brody, S.D., Sebastian, A., Blessing, R., Bedient, P. (in review). Where Will I flood? Identifying the impacts of residential location on flood risk and loss. *Journal of Flood Risk Management*.

Burleson, D., Rifai, H., Dawson, C., Proft, J., Bedient, P.B. (in review). Vulnerability of an Industrial Corridor in Texas to Storm Surge. *ASCE Natural Hazards Review*.

Christian, J.A., Fang, Z., Torres, J., Deitz, R., Bedient, P.B. (in review). Modeling the hydraulic effectiveness of a proposed storm surge barrier system for the Houston Ship Channel during hurricane events. *ASCE Natural Hazards Review*.

Christian, J.A., Osorio-Duenas, L., Teague, A., Fang, Z., Bedient, P.B. (2012). Uncertainty in floodplain delineation: expression of flood hazard and risk in a Gulf Coast watershed. *Journal of Hydrological Processes*, 27, 2774-2784. Doi:10.1002/hyp.9360

Dietrich, J.C., Dawson, C.N., Proft, J.M., Howard, M.T., Wells, G., Fleming, J.G., Luettich Jr., R.A., Westerink, J.J., Cobell, Z., Vitse, M., Lander, H., Blanton, B.O., Szpilka, C.M., Atkinson, J.H. (2013). Real-Time Forecasting and Visualization of Hurricane Waves and Storm Surge using SWAN+ADCIRC and FigureGen. *Computational Challenges in the Geosciences*, 156, 49-70. doi: 10.1007/978-1-4614-7434-0_3

Dietrich, J.C., Tanaka, S., Westerink, J.J., Dawson, C.N., Luettich Jr., R.A., Zijlema, M., Holthuijsen, L.H., Smith, J.M., Westerink, L.G., Westerink, H.J. (2012) Performance of the Unstructured-Mesh, SWAN+ADCIRC Model in Computing Hurricane Waves and Surge. (2012) *Journal of Scientific Computing*, 52(2), 468-497. doi: 10.1007/s10915-011-9555-6

Dolan, G., Wallace, D.J. (2012). Policy and management hazards along the Upper Texas coast. *Ocean & Coastal Management*, 59, 77-82. doi: 10.106/j.ocecoaman.2011.12.021

Fang, Z., Bedient, P.B., Buzcu-Guven, B. (2011). Long-term Performance of a Flood Alert System and Upgrade to FAS3: A Houston, Texas, Case Study. *Journal of Hydrologic Engineering*, 16(10), 818-828. Doi: 10.1061/(ASCE)HE.1943-5584.0000374.

Fang, Z., Dolan, G., Sebastian, A., Bedient, P.B. (2014). Case Study: Flood Mitigation and Hazard Management at the Texas Medical Center in the Wake of Tropical Storm Allison (2001). *ASCE Natural Hazards Review*, doi: 10.1061/(ASCE)NH.1527-6996.0000139

Hope, M.E., Westerink, J.J., Kennedy, A.B., Kerr, P.C., Dietrich, J.C., Dawson, C., Bender, C., Smith, J.M., Jensen, R.M., Zijlema, M., Holthuijsen, L.H., Luettich, Jr., R.A., Powell, M.D., Cardone, V.J., Cox, A.T., Pourtaheri, H., Roberts, H.J., Atkinson, J.H., Tanaka, S., Westerink, H.J., Westerink, L.G. (2013). Hindcast and validation of Hurricane Ike (2008) Waves, Forerunner, and Storm Surge, *Journal of Geophysical Research Oceans*, 118, 4424-4460, doi: 10.1002/jrgc.20314

Mattis, S., Dawson, C., Kees, C.E., Farthing, M.W. (2012). Numerical modeling of drag for flow through vegetated domains and porous structures. *Advances in Water Resources*, 39, 44-59. doi: 10.1016/j.advwatres.2012.01.002

Ray, T., Stepinski, E., Sebastian, A., Bedient, P.B. (2011). Dynamic Modeling of Storm Surge and Inland Flooding in a Texas Coastal Floodplain. *Journal of Hydraulic Engineering*, 137(10), 1103-1110. Doi: 10.1061/(ASCE)HY.1943-7900-0000398.

Sebastian, A., Proft, J., Dietrich, C., Du, W., Bedient, P.B., Dawson, C. (2014). Characterizing hurricane storm surge behavior in Galveston Bay using the SWAN+ADCIRC Model. *Coastal Engineering*, 88, 171-181. httpx://dx.doi.org/10.1016/j.coastaleng.2014.03.002

Stearns, M., Padgett, J.E. (2012). Impact of 2008 Hurricane Ike on Bridge Infrastructure in the Houston/Galveston Region. Journal of Performance of Constructed Facilities, 26(4), 441-452. doi: 10.1061/(ASCE)CF.1943-5509.0000213

Wallace, D.J., Anderson, J.B. (2010). Evidence of similar probability of intense hurricane strikes for the Gulf of Mexico over the late Holocene. *Geology*, 38, 511-514. doi: 10.1130/G30729.1

Wallace, D.J., Anderson, J.B. (2013). Unprecedented erosion of the upper Texas coast: Response to accelerated sea-level rise and hurricane impacts. *Geological Society of America Bulletin, May/June 2013* 125(5/6), 728-740. doi: 10.1130/B30725

Wallace, D.J., Anderson, J.B., Fernandez, R.A. (2010). Transgressive Ravinement versus Depth of Closure: A Geological Perspective from the Upper Texas Coast. *Journal of Coastal Research*, 26(6), 1057-1067. doi: 10.2112/JCOASTRES-D-10-00034