GCCPRD

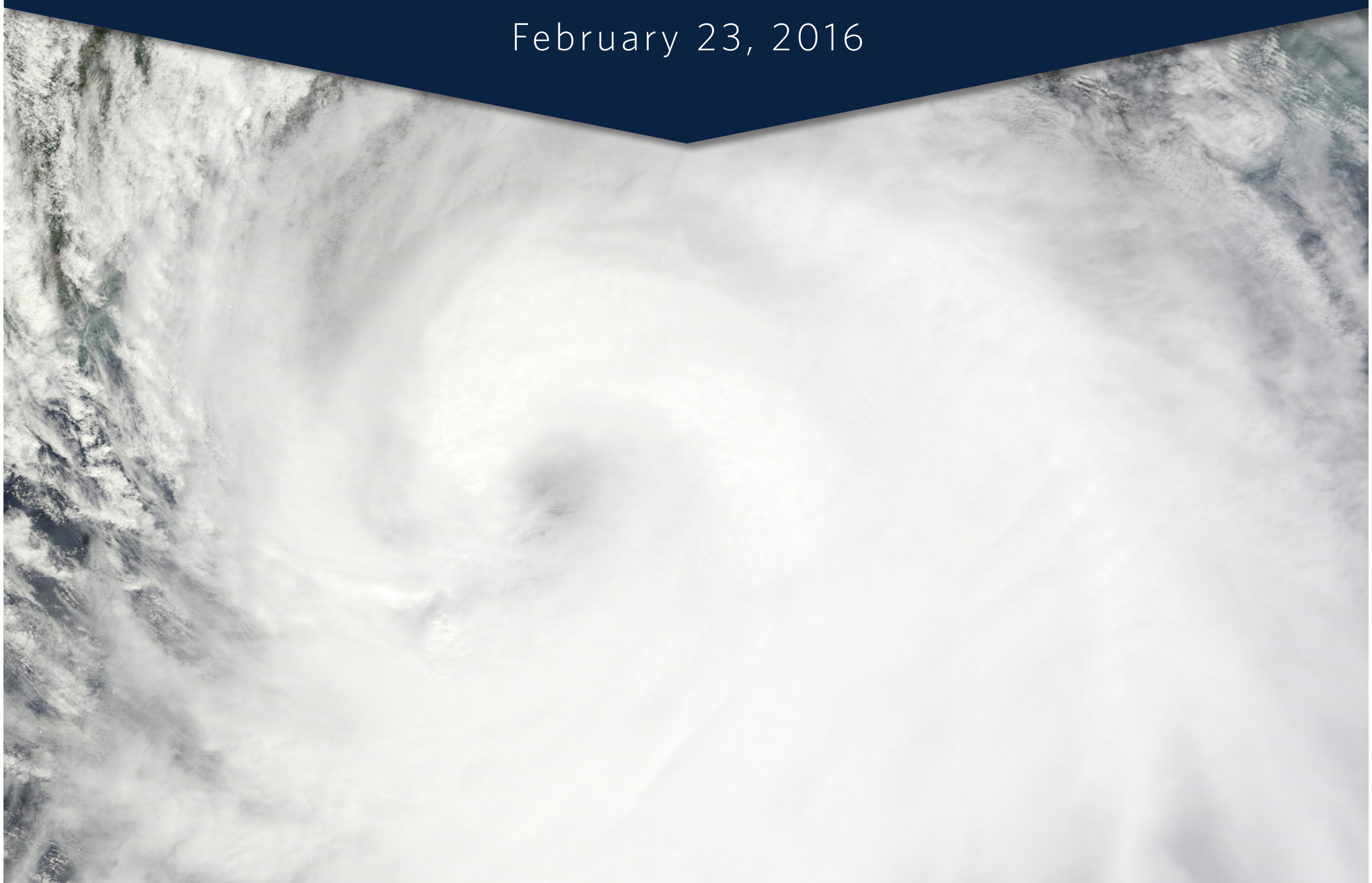
The Gulf Coast Community Protection and Recovery District

TEXAS GENERAL LAND OFFICE
ESTABLISHED 1836

STORM SURGE SUPPRESSION STUDY

PHASE 2 REPORT

February 23, 2016



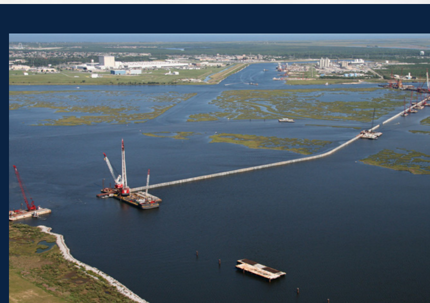


Table of Contents

List of Figures

Executive Summary

This report represents the Gulf Coast Community Protection and Recovery District's (GCCPRD) technical analysis for Phase 2: Technical Mitigation of the *Storm Surge Suppression Study*. During Phase 2: Technical Mitigation, potential alternatives were identified and screened, and two distinct systems of alternatives per region were fully developed and analyzed. The alternatives analysis considered the technical, environmental, social, and economic factors associated with each alternative. Social factors will be further evaluate during Phase 3 of the study and will be included in the final report scheduled for release in June of 2016.

The purpose of the Storm Surge Suppression Study is to investigate the feasibility of reducing the vulnerability of the upper Texas coast to storm surge and flood damages. The intent of this study is to develop a plan to protect the life, health, and safety of the community, and provide environmental and economic resilience within the study region. This will be achieved through the study and analysis of integrated flood damage reduction systems comprised of structural and nonstructural alternatives as well as natural or nature-based features.

As a part of evaluating the technical aspects for each alternative, the study team executed extensive storm surge modeling for the years 2035 and 2085 to evaluate future conditions. Present day conditions were establish using the latest FEMA data. The team made the assumption that if construction began in 2020, all alternatives could conceivably be in place by 2035. A fifty-year design life was assigned to each alternative, so the system would remain resilient through the year 2085.

The team calculated the expected intermediate rate for Relative Sea Level Rise (RSLR) within the study area from 2035 to 2085 and incorporated this data into the storm surge model. RSLR is estimated as 0.9 feet in 2035 and 2.4 feet in 2085.

The resulting storm surge data was used to develop a probabilistic approach to determine the 1 percent and 0.2 percent (100-year and 500-year events) annual chance storm surge elevations in the years 2035 and 2085. Wave data was also analyzed to determine run-up on levees and structures and to determine forces that proposed structures would need to withstand. The minimum level of protection considered by the team is the 1 percent storm. This corresponds with the minimum level for the Federal Emergency Management Agency (FEMA) to accredit a system with regard to the National Flood Insurance Program (NFIP).

The team used storm modeling and wave data to establish the structural top elevations for each alternative reach. Alternative alignments, structural configurations, and components of each reach were determined based on geography, existing infrastructure, and environmental and social concerns. Levees are proposed in reaches that are less congested, and T-walls are proposed in more developed and restricted areas.

A key consideration for each alternative is analysis of interior drainage. When gates are closed to protect inland areas from storm surge, pump stations are required to convey stormwater runoff from rainfall events within the protected area to avoid interior backflow and flooding. The team analyzed numerous rainfall events associated with hurricanes and tropical storms and measured the capacity required to convey interior flows through the protection system. Pump stations were not specifically sited during this study. This will be conducted during preliminary engineering and design in order to take advantage of economies of scale as well as capacity within the existing drainage system.

Environmental and cultural resource studies were executed using the existing National Wetlands Inventory maps, Resource Conservation and Recovery Act and Comprehensive Environmental Response, Compensation, and Liability Act databases, the National Register of Historic Places, the Coastal barrier Resources Act, and the US Fish and Wildlife Service's critical habitat mapper for threatened and endangered species. The team made every effort to avoid and minimize potential impacts to sensitive areas during the development of alternative alignments. Impacts that could not be avoided were determined based on habitat type, and estimated mitigation costs are included in overall project costs.

Given the nature of the study region, many of the proposed alternatives require navigation gates to effectively close the protection system during a tropical storm. For small navigation gates (barge and recreation traffic only), the team made use of design and cost data for structures similar to those built by the US Army Corps of Engineers in Louisiana during the past seven years. The data associated with those build structures enabled the team to determine the appropriate costs for proposed small navigation gates.

Two large navigation gates, proposed at Bolivar Roads and along the Neches River, were independently studied. Various types of deep draft gates in operation worldwide were modeled, and Table 1 outlines the two recommended types of gate and specifications identified for this region. Because these gates encompass large areas, the team considered the potential environmental impacts on bays and estuaries associated with a change in tidal conditions. After extensive hydrodynamic modeling, the team determined that Vertical Lift Gates in ancillary structures parallel to the navigation gates would reduce the change in tidal prism. To further identify potential impacts, the tidal prism would be further evaluated and modelled during the preliminary engineering and design phase. The evaluation would result in the final design configuration of these gates.

Table 1: Large Navigation Gate Details

Gate Location	Type	Opening	Sill Depth	Top Elevation	Number of Vertical lift Gates
Bolivar Roads	Floating Sector Gate	840 ft.	60 ft.	+18 ft.	25
Neches River	Sector Gate	240 ft.	52 ft.	+21 ft.	4

The team developed an Engineer Data Cost Library to estimate the probable cost of construction for each alternative. The Data Library was developed by analyzing representative projects executed by US Army Corps of Engineers (USACE) in Louisiana, the USACE Civil Works Construction Cost Index, and the commercial cost database, RSMeans, in order to define quantity and unit costs factors. For cost determination, structures were categorically separated into: levees, T-walls, highway gates, railroad gates, navigation gates, gravity drainage structures, utility crossings, roadway relocation and pumping stations. Non-construction costs such as right-of-way costs, mitigation costs, and relocations were also factored into the library. A 25 percent contingency was added to each cost contained within the library to mitigate cost fluctuation risks. A

40 percent contingency was added to the costs associated with the large navigation gates due to their extreme complexity and the lack of current and reliable cost data for comparable structures.

A benefit-cost analysis was used to evaluate, in monetary terms, the output achieved (the benefits) from a proposed action, and the expenditures required (the costs) to achieve the output. This analysis is used to verify that the value of the benefits exceeds the value of the costs and ensures that the resources are allocated in the most efficient manner possible. A benefit to cost ratio (BCR) for each alternative was calculated by dividing the Total Annual Benefits by the Total Annual Costs. A benefit-cost ratio of 1.0 indicates that the total benefits equal the total costs. In other words, for every dollar spent, a dollar of benefits is produced.

Alternative Analysis and Comparison:

North Region: Jefferson and Orange Counties

In Jefferson and Orange Counties, the team developed various potential alternatives for regional protection. The team developed two distinct systems of alternatives that would provide comprehensive protection to the entire region. One alternative would include a large navigation gate on the Neches River. The second alternative consists of a land-based system that does not include the Neches River navigation gate.

North Region Alternatives

Orange and Jefferson Counties

- ***North Region Alternative #1 (NR#1) -*** The Jefferson/Orange Protection System –with the Neches River Navigation Gate
- ***North Region Alternative #2 (NR#2) -*** The Jefferson/Orange Protection System –without the Neches River Navigation Gate

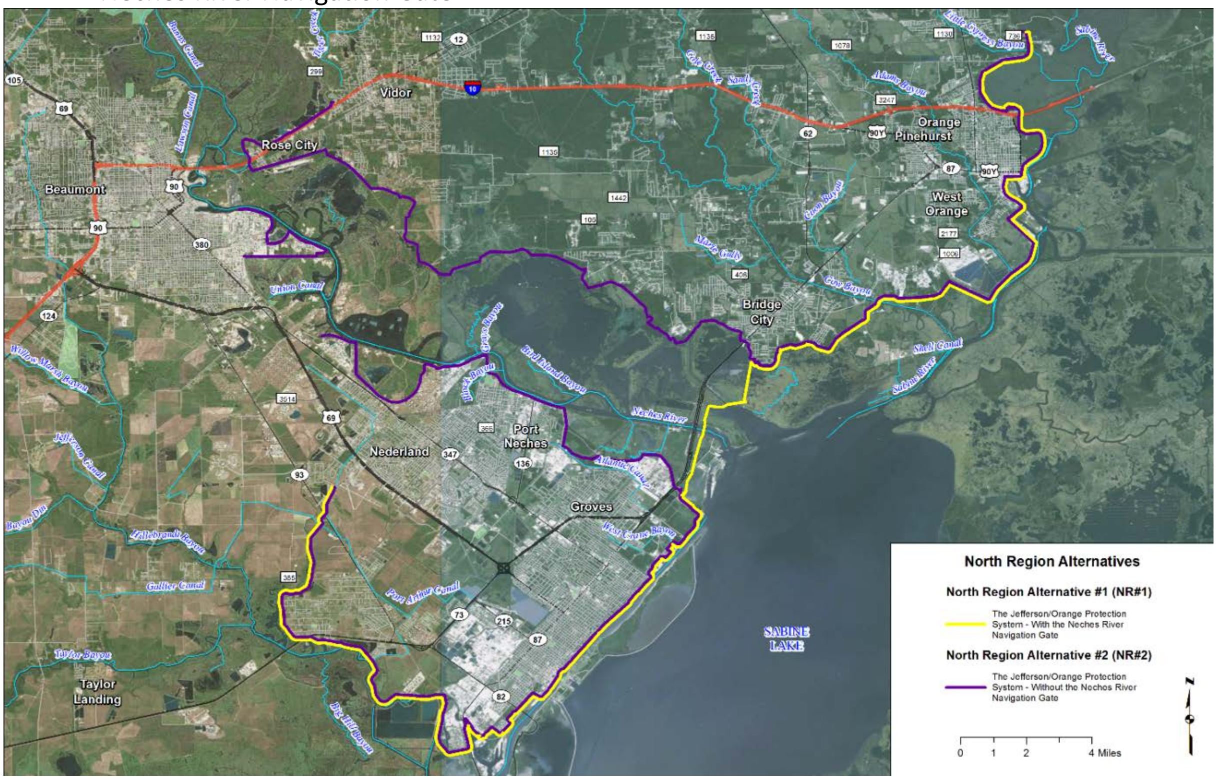


Figure 1: North Region Alternatives Selected for Development

Alternative NR#1 is a continuous protection system that would provide protection to the region by restricting storm surge from moving inland at the most reasonable forward point. The geography of the region does not permit a structure that would function as a coastal barrier, and the environmental impacts of such a structure would be extensive. Alternative NR#1 includes a 5,500 cfs pump station at the Neches River Gate to divert the flow of the river around the gate when the protection system is closed. Elevations within this alternative vary from 15 to 25.5 feet, depending on the existing topography with the region.

Alternative NR#2 is a fragmented system that protects Jefferson and Orange Counties individually through alignments along the Sabine and Neches River. This system does not include the Neches River Gate; resulting in a much longer line of protection. The longer line of protection increases the amount of right-of-way, mitigation, and pump stations required, which all affect the overall cost of construction. Elevations within this alternative vary from 15 to 25.5 feet, depending on the existing topography with the region.

Each alternative requires upgrades to the existing Port Arthur Federal Levee System to higher elevations in order to remain effective given the projected conditions in 2085.

Table 2 provides a summary and a side-by-side comparison for each alternative.

Table 2: Comparison of Alternatives NR#1 and NR#2

North Region Alternative Summary and Comparison	NR#1- *The Jefferson/Orange Protection System –with the Neches River Navigation Gate*	NR#2- *The Jefferson/Orange Protection System –without the Neches River Navigation Gate*
Total length of the system (miles)	55.2 miles	92.2 miles
Right of way required	612 acres	1,401 acres
Pump stations required / total capacity (cfs.)	7 / 25,711 cfs.	14 / 31,626 cfs.
Environmental mitigation required	232.89 acres	559.6 acres
Construction cost	$2,502,650,000	$3,228,580,000
Annual Operations and maintenance cost	$12,513,000	$16,143,000
Total Annual Costs (TAC)	137,132,000	1,76910,000
Total Annual Benefits (TAB)	$140,877,000	$140,877,000
Benefit - Cost Ratio (TAB/TAC) (3.125% Interest Rate)	**1.03**	**0.80**
Benefit - Cost Ratio (7.0% Interest Rate)	**0.40**	**0.31**

Alternatives NR#1 and NR#2 provide the same level of protection and the same average annual benefits to the North Region. The total length of Alternative NR#2 is 60 percent larger than that of Alternative NR#1, which increases the cost of construction, right-of-way, and mitigation without a corresponding increase in benefits. The increased cost of Alternative NR#2 without additional benefits decreases the benefit to cost ratio (BCR) for this alternative.

Central Region: Chambers, Harris, and Galveston Counties

In Chambers, Harris, and Galveston Counties, the team reviewed numerous alternatives, many of which considered different locations for a large navigation gate along the Houston Ship Channel. The team chose to develop Alternative CR#1, which proposes a large navigation gate located at Bolivar Roads. The team chose to study a gate at Bolivar Roads because placing a gate anywhere else in the overall protection system would require additional ancillary structures to protect the region. The second alternative to be developed is the without-gate alternative (Alternative CR#2). Alternative CR#2 was developed based upon an assumption of what would be required to protect the region if a gate could not be built. This assumption is not based on technical or constructability concerns, but is focused on potential environmental impacts to the bays and estuaries, and economic impacts associated with maritime activity.

Central Region Alternatives

Galveston, Chambers, and Harris Counties

- ***Central Region Alternative #1 (CR#1)*** - High Island to San Luis Pass Coastal Spine
- ***Central Region Alternative #2 (CR#2)*** - Texas City Levee Modifications and Extensions North (SH-146) and West--Galveston Ring Levee

Figure 2: Central Region Alternatives Selected for Development

Alternative CR#1 is a continuous system that would provide protection to the region by restricting storm surge from moving inland at the coast. This alternative requires an exceptionally large navigation gate across the Houston Ship Channel at Bolivar Roads. Twenty five vertical lift gates are proposed parallel to the navigational opening in order to maintain the environmental flow to the region's bay and estuary systems. Elevations within this alternative vary from 18.0 to 21.0 feet, depending on the existing topography with the region.

Alternative CR#2 is a series of separate systems that provide protection to the City of Galveston and the west side of Galveston Bay. This alternative would not provide direct protection to the upper reaches of the Houston Ship Channel. This alternative requires modifications and upgrades to the existing Texas City Hurricane Protection System in order for the overall protection system to remain effective given the projected conditions in 2085. Elevations within this alternative vary from 19.0 to 27.0 feet, depending on the existing topography with the region.

Table 3 provides a summary and a side-by-side comparison for each alternative.

Table 3: Comparison of Alternatives CR#1 and CR#2

Central Region Alternative Summary and Comparison	CR#1- *High Island to San Luis Pass Coastal Spine*	CR#2- *Texas City Levee Modifications and Extensions North (SH-146) and West--Galveston Ring Levee*
Total length of the system (miles)	55.6 miles	62.6 miles
Right of way required	1,220 acres	344.7 acres
Pump stations required / total capacity (cfs.)	0 / 0 CFS	13 / 61,611 CFS
Environmental mitigation required	303.35 acres	122.00 acres
Construction cost	$5,832,095,000	$3,534,442,000
Annual operations and maintenance cost	$29,160,000	$17,672,000
Total Annual Costs (TAC)	319,569,000	193,669,000
Total Annual Benefits (TAB)	$1,029,399,000	$1,230,928,000
Benefit - Cost Ratio (TAB/TAC) (3.125% Interest Rate)	**3.22**	**6.36**
Benefit - Cost Ratio (7.0 % Interest Rate)	**1.29**	**2.55**

Alternative CR#1 and CR#2 are two distinct alternatives and based on their alignments provide different levels of annual benefits. The annual benefits are greater for CR#2 and this can be attributed to the enhanced level of protection that is provided to the City of Galveston and the west side of Galveston Bay by a system that effectively seals these areas from tidal surge. CR#2 is much less expensive than CR#1. The cost taken with the higher benefits has resulted in an alternative with much higher BCR.

South Region: Brazoria County

In Brazoria County, development of Alternative SR#1 consisted of reviewing the existing Freeport Hurricane Flood Protection System and evaluating extensions of that system to protect areas that would be at risk in 2085. Development of Alternative SR#2 included evaluation of areas that have been developed since the existing Freeport Hurricane Flood Protection System was constructed and an assessment of their potential need for protection in 2085.

South Region Alternatives

Brazoria County and Galveston County (vicinity of San Luis Pass)

- ***South Region Alternative #1 (SR#1)*** - Freeport Hurricane Flood Protection System Modernization and Extension North toward Angleton
- ***South Region Alternative #2 (SR#2)*** - Freeport Hurricane Flood Protection System Modernization and Extension North toward Angleton- Jones Creek Levee, Jones Creek Terminal Ring Levee, and Chocolate Bayou Ring Levee

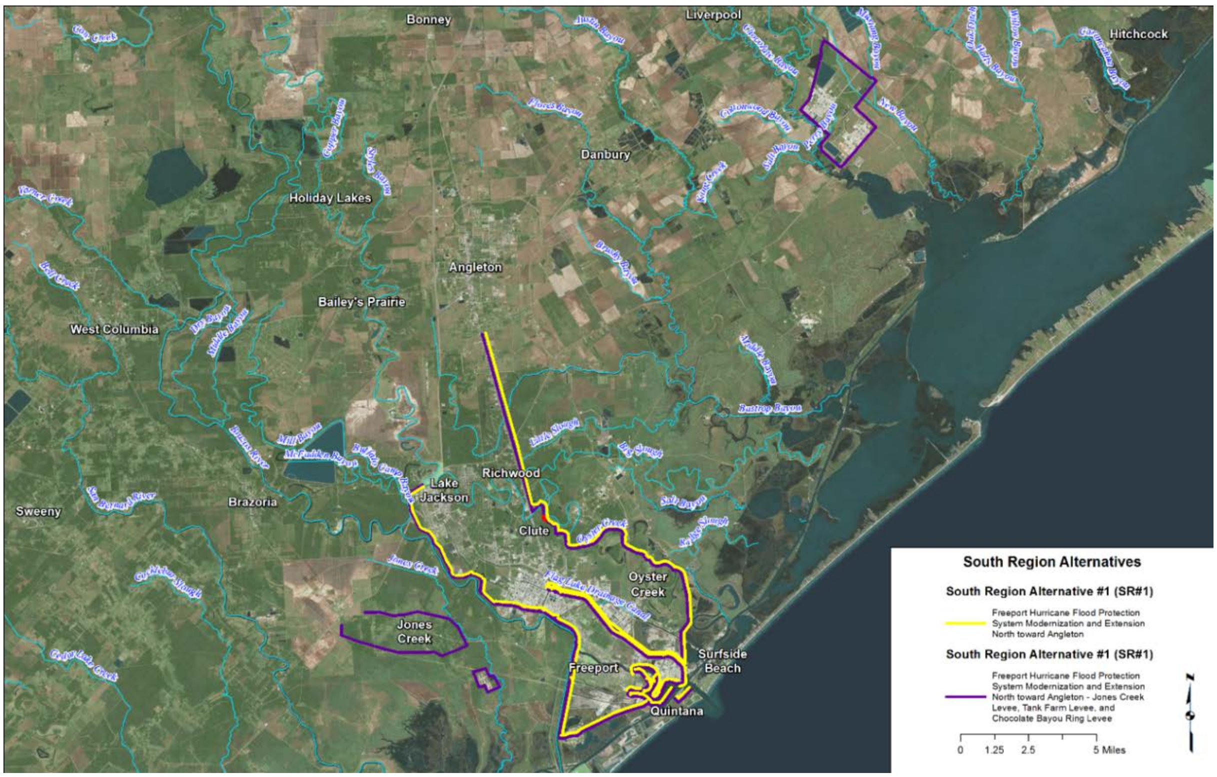


Figure 3: South Region Alternatives Selected for Development

Alternative SR#1 is a continuous system that would protect the Freeport-Angleton-Lake Jackson area from storm surge. This alternative consists mainly of the existing Freeport Hurricane Flood Protection System and outlines the requirements to enhance the system for conditions predicted in 2085. The system extends from Oyster Creek toward Angleton to avoid the risk associated with flooding overtopping and wrapping around the east side of the system in 2085. Elevations within this alternative vary from 17.0 to20.0 feet, depending on the existing topography with the region.

Alternative SR#2 includes all the components proposed in Alternative SR#1 in addition to three areas that are subject to storm surge flooding in 2085: Jones Creek, the Jones Creek Terminal, and the Chocolate Bayou petrochemical complex. These three new elements could each standalone but are considered in the context of a single alternative for the purposes of regional protection.

Table 4 provides a summary and a side-by-side comparison for each alternative.

Table 4: Comparison of Alternatives SR#1 and SR#2

South Region Alternative Summary and Comparison	SR#1 - Freeport Hurricane Flood Protection System Modernization and Extension North toward Angleton	SR#2- Freeport Hurricane Flood Protection System Modernization and Extension North toward Angleton- Jones Creek Levee, Jones Creek Terminal Ring Levee, and Chocolate Bayou Ring Levee
Total length of the system (miles)	49.1 miles	74.2 miles
Right of way required	73 acres	383 acres
Pump stations required / total capacity (cfs.)	2 / 2,500 CFS	5 / 11,460 CFS
Environmental mitigation required	49 acres	129.89 acres
Construction cost	$1,897,635,000	$2,571,551,000
Annual operations and maintenance cost	$9,488,000	$12,858,000
Total Annual Costs (TAC)	103,981,000	140,907,000
Total Annual Benefits (TAB)	$186,583,000	$206,654,000
Benefit - Cost Ratio (TAB/TAC) (3.125% Interest Rate)	**1.79**	**1.47**
Benefit - Cost Ratio (7.0 % Interest Rate)	**0.73**	**0.59**

Alternative SR#2 is a variation of SR#1 and includes three additional reaches which provides flood risk reduction for three outlying areas (Jones Creek Levee, Jones Creek Terminal Ring Levee, and the Chocolate Bayou Ring Levee). The addition of these three reaches has increased the overall benefits in SR#2 but also reduced the BCR and the net benefits, when compared to SR#1. This indicates that the additional cost of constructing these reaches is greater than the additional benefits.

The Way Ahead-Phase 3: Final Report Development (Feb 2016-June 2016)

The Phase 2 results clearly indicate that there are economically feasible and environmentally acceptable alternatives which provide storm surge reduction in the six county area. During Phase 3, the team will continue to analyze the data to optimize the alternatives. Additionally, the team will continue to engage the public and critical stakeholders to solicit feedback on the technical results and the alternatives that were presented in this report.

1. Introduction

In September 2014, the Gulf Coast Community Protection and Recovery District received a $3.9 million grant funded by the Texas General Land Office (GLO) through the Federal Housing and Urban Development (HUD) Community Development Block Grant (CDBG) Program. The purpose of this grant is to study opportunities for storm surge and flooding-related disaster mitigation, hazard warning, and other projects or programs to assist and protect people, businesses, and properties along the upper Texas coast. The Storm Surge Suppression Study is a technical effort, based on science and economics, to investigate opportunities to mitigate the vulnerability of the upper Texas coast from storm surge and flooding. The study scope of work encompasses the following three phases:

- **Phase 1:** Data Collection
- **Phase 2:** Technical Mitigation
- **Phase 3:** Final Report Development

In February 2015, the team completed Phase 1: Data Collection and began working on Phase 2: Technical Mitigation. All data collected during Phase 1 was consolidated into a data library and provided to the GLO in order to support future study efforts. The Phase I report and the data library were also published through the GCCPRD's official website to the public.

1.1. The Gulf Coast Community Protection and Recovery District (GCCPRD)

The GCCPRD is a local government corporation that includes Brazoria, Chambers, Galveston, Harris, Jefferson, and Orange Counties, which are the six counties included in the study area. The GCCPRD is governed by a board of directors comprised of the county judge of each participating county and three additional appointed members, each serving three-year terms. Board members include:

- Judge Ed Emmett – Harris County
- Judge Mark Henry – Galveston County
- Judge Matt Sebesta – Brazoria County
- Judge Jimmy Silva – Chambers County
- Judge Jeff Branick – Jefferson County
- Judge Stephen Carlton – Orange County
- Robert Eckels – District President
- Lisa LaBean – At-large Member
- Jim Sutherlin – At- large Member
- Victor Pierson – At-large-Member

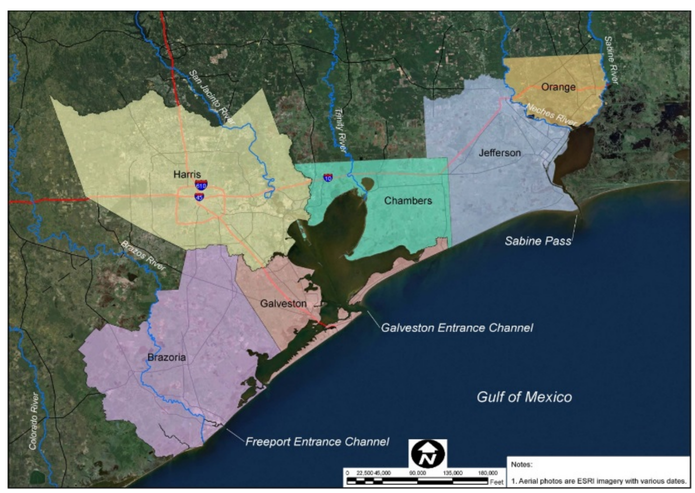


Figure 4: GCCPRD study area

1.2. Storm Surge Suppression Study Purpose

The purpose of the Storm Surge Suppression Study is to investigate the feasibility of reducing the vulnerability of the upper Texas coast to storm surge and flood damages. The intent of this study is to develop a plan to protect the life, health, and safety of the community, and provide environmental and economic resilience within the study region. This will be achieved through the study and analysis of integrated flood damage reduction systems comprised of natural or nature-based features, as well as structural and nonstructural alternatives. The study will examine the technical, environmental, social, and economic factors that will determine a cost-effective and efficient set of alternatives for flood damage reduction and surge suppression to help protect the six-county region. The study outcomes are critical to informing the general public and industry of the potential risks associated with living and operating within this region, and to solicit future support to procure the necessary resources to implement an integrated protection system.

The goals of the study are to:

- Determine appropriate actions that may be taken to protect the life, health, and safety of the community, and provide environmental and economic resilience within the study area.
- Develop a viable region-wide program that, once implemented, that would better protect the region from future natural disasters associated with storm surge flooding events.
- Identify potential funding mechanisms to implement a storm surge suppression system for the study region.

1.3. Phase 2 - Scope of Work

The Phase 2 scope of work included all the planning activities associated with identification and the development of proposed alternatives to protect the region from storm surge and flooding caused by devastating storm events.

Phase 2 considered the following planning factors:

- Hydrologic and hydraulic modeling and analysis
- Preliminary structural analysis and design
- Cost estimation
- Geotechnical analysis of available data
- Environmental analysis
- Economic modeling and analysis
- GIS and mapping
- Real estate considerations- Right of way acquisition, utilities and relocations
- Public engagement with stakeholders and industry

The objective of Phase 2 was to identify and develop two alternatives per study area region that provided region-wide protection from hurricane surge and flooding.

2. Phase 2 – Planning Methodology

2.1. Alternative Scoping

Phase 2 of the study initially focused on scoping and screening of various alternatives. The study area has been thoroughly examined by the US Army Corps of Engineers (USACE) and other researchers over the past 50 years, and the majority of the technical alternatives were already identified through these efforts. The team took advantage of this prior work in order to develop a viable list of alternatives to scope and screen, which were published in the Phase 1 report.

The preliminary analysis of the terrain, drainage patterns, and geomorphology of each region showed that the needs and types of protection for each region were unique. For simplicity, the team divided the study area into three distinct regions.

The regions were defined as follows:

- **North Region**: Orange and Jefferson Counties
- **Central Region**: Galveston, Chambers, and Harris Counties
- **South Region**: Brazoria County and Galveston County (vicinity of San Luis Pass)

Alternatives were scoped for each region with the understanding that the benefits and impacts of these alternatives would be confined within their respective regions.

2.2. Alternative Screening Criteria

The team used the following criteria to define the alternatives that would be selected for further development and analysis:

1. The proposed alternative must effectively reduce the risk associated with storm surge/coastal flooding, and reduce impacts to:
   - People
   - Infrastructure
   - Environment
   - Regional and National economy
2. The proposed alternative must be in compliance with local, state, and federal regulations.

These criteria enabled the team to quickly review numerous alternatives and define critical alternatives that were regionally comprehensive in their scope of protection. From this analysis, the following alternatives were defined for each respective region.

2.2.1. North Region Alternatives:

In the Jefferson and Orange County region of the study, the team reviewed various potential alternatives for protection. The team developed two distinct alternatives that provide comprehensive protection to the entire north region. One alternative would consist of a large navigation gate on the Neches River. The second alternative would consist of a comprehensive plan that did not include the Neches River navigation gate. These two alternatives would provide the same level of protection and benefits to the region.

2.2.1.1. North Region Alternative #1 (NR#1) - The Jefferson/Orange Protection System –with the Neches River Navigation Gate

Alternative NR#1 consists of three different reaches that the team developed to provide comprehensive protection to the region.

Reach 1 - Orange-Sabine River Levee – This reach consists of a line of protection which starts on the high ground along the Sabine River, north of I-10 and the City of Orange. The system follows the Sabine River, crossing Adams and Cow Bayous, protecting the southeast side of Bridge City, to the east bank of the Neches River downstream of the Veterans Memorial Bridge on SH-87. The reach is composed of 125,579 feet of new levee, 16,842 feet of T-wall construction, six pump stations, 22 drainage structures, a 56-foot navigation gate on Adams Bayou, and a 30-foot navigation gate on Cow Bayou. Highway and roadway crossings are modified by grade elevation and railroads will need to pass through gate structures. Elevations of this reach vary from 15.5 feet to 24.5 feet.

Reach 2 - Neches River Crossing – This reach connects to Reach 1 southwest of Bridge City and follows an alignment parallel to SH-87 downstream of the Veterans Memorial Bridge, crossing the Neches River and tying into the existing Port Arthur federal levee system along its alignment on the west bank of the Neches River. This reach is composed of 27,076 feet of new levee, 600 feet of T-wall, one new pump station, four 100-foot wide vertical lift gates and a 450-foot wide navigation gate across the Neches River. Elevations in this reach vary from 19.5 feet to 25.5 feet.

Reach 3 - Modernization of the Port Arthur Federal Levee System – This reach consists of upgrading the Port Arthur Federal Levee System for conditions reflected by the team's modeling in 2085. This reach is composed of 89,752 feet of levee to be raised, the replacement of 48,052 feet of I-wall with new T-wall, 10 railroad gates, 15 road gates, and 29 drainage structures. Elevations in this reach vary from 15 feet to 24.5 feet.

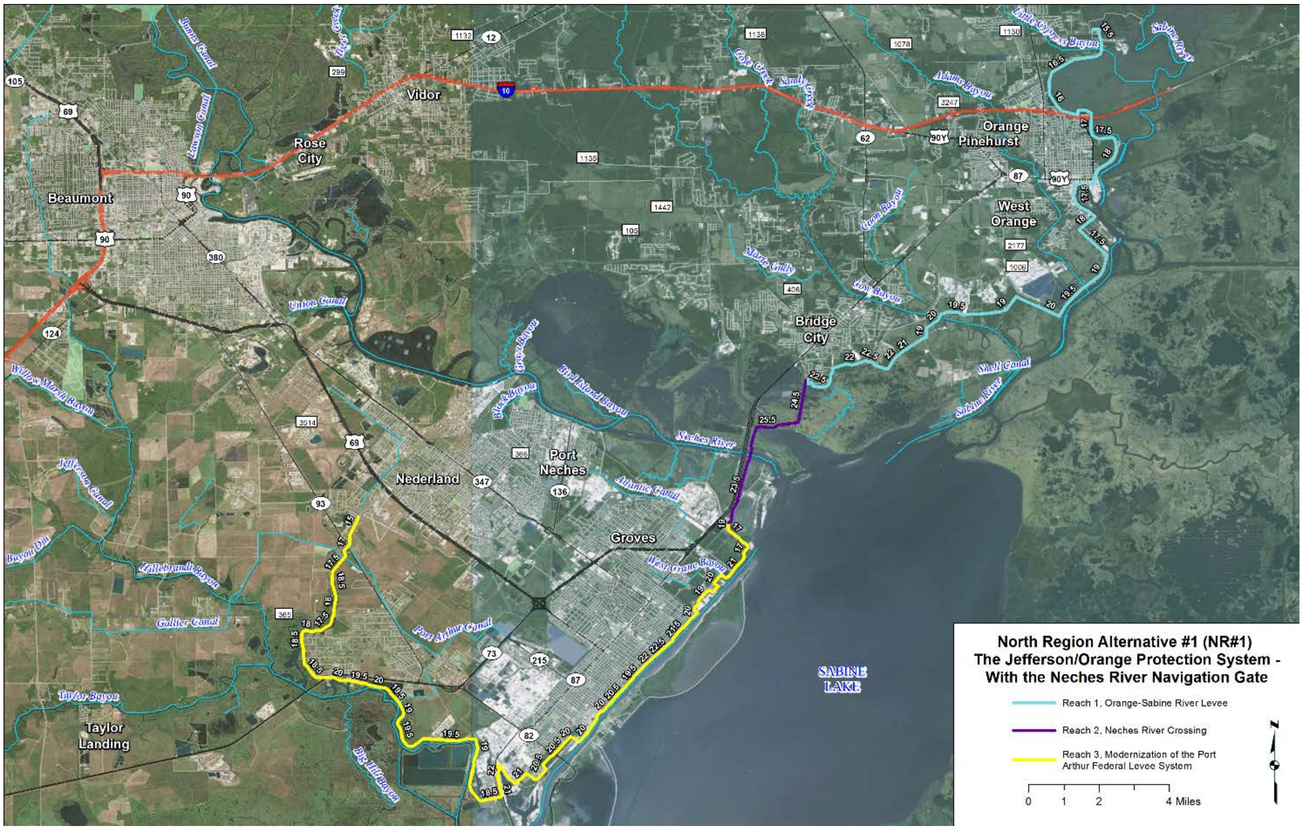


Figure 5: Diagram of North Region Alternative #1

2.2.1.2. North Region Alternative #2 (NR#2) - The Jefferson/Orange Protection System –without the Neches River Navigation Gate

Alternative NR#2 consists of four reaches, and is distinct from Alternative NR#1 in that it excludes the large navigation gate across the Neches River. Alternatives NR#2 and NR#1 provide the same level of protection to the region and differ based on alignment and associated structural configuration.

Reach 1 - Orange- Sabine River Levee – Same as defined for Alternative NR#1

Reach 2 - East Bank of the Neches River – Reach 2 ties into Reach 1 south of Bridge City and follows an alignment along the east side of the Neches River to I-10. This reach is composed of 125,278 feet of new levee, 10,433 feet of T-wall, 19 new drainage structures, three new pump stations, and 24 roadway gates. Elevations in this reach vary from 18.0 feet to 22.5 feet.

Reach 3 - Modernization of the Port Arthur Federal Levee System – Same as defined for NR#1

Reach 4 - West Bank of the Neches River – Reach 4 extends the existing Port Arthur federal levee system northwest along the west bank of the Neches River. This reach consists of 55,311 feet of new levee, 32,645 feet of T-wall, 21 railroad gates, five new pump stations, and 16 drainage structures. Elevations in this reach vary from 17.0 feet to 20.0 feet.

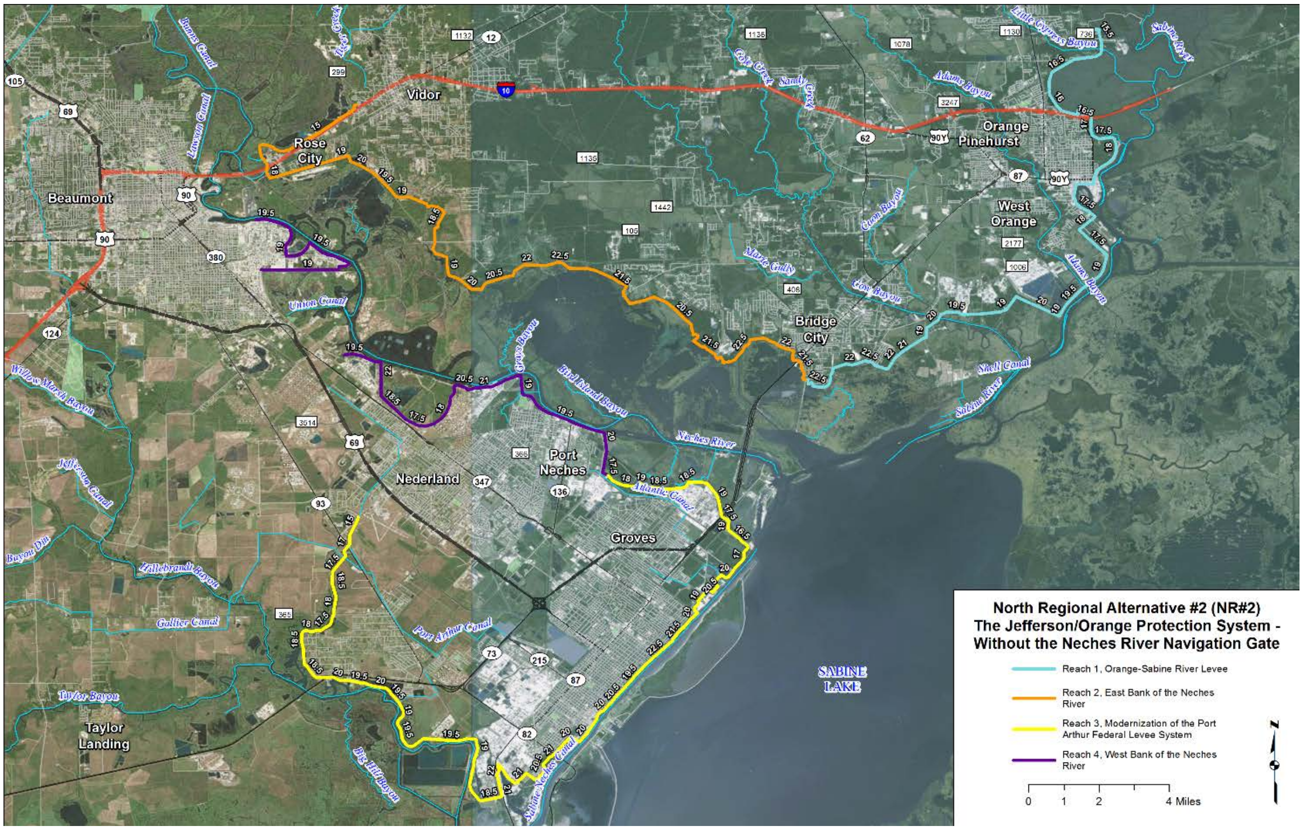


Figure 6: Diagram of North Region Alternative #2

2.2.2. Central Region: Chambers, Harris, and Galveston County

The team reviewed numerous alternatives for the central region. Many of the alternatives were variations of an alternative that proposed different positions for a large navigation gate along the Houston Ship Channel. After review, the team decided to develop one alternative with a large navigation gate located at Bolivar Roads. The team chose to study the gate at Bolivar Roads because placing the gate anywhere else in the system would require additional ancillary structures to protect the region. The second alternative was developed without the gate. This alternative was developed based upon an assumption of what would be required to protect the region if the gate could not be built within this region. This assumption was not based on technical or constructability concerns; rather, it was focused on potential environmental impacts to the bays and estuaries, economic impacts associated with maritime activity and social acceptance by the local community.

2.2.2.1. Central Region Alternative #1 (CR#1)- High Island to San Luis Pass Coastal Spine

Alternative CR#1 consists of a coastal protection system that starts at the high ground north of High Island running parallel to SH-87 along the Bolivar Peninsula, crossing Bolivar Roads and tying into the existing federal protection system at the Galveston Seawall. At the end of the seawall, the system continues along the length of the island, parallel to Hwy 3005, and terminates at San Luis Pass. The major elements of this alternative include: 221,105 feet of new levee, 18,916 feet of new T-wall, 41,651 feet of seawall enhancements, an 850-foot wide sector gate including twenty five 100-foot wide vertical lift gates at the Bolivar Roads crossing, seventy eight drainage structures, thirty five highway gates, and the reconstruction of 12 miles of two lane highway. Elevations in this reach vary from 18 feet to 21 feet.

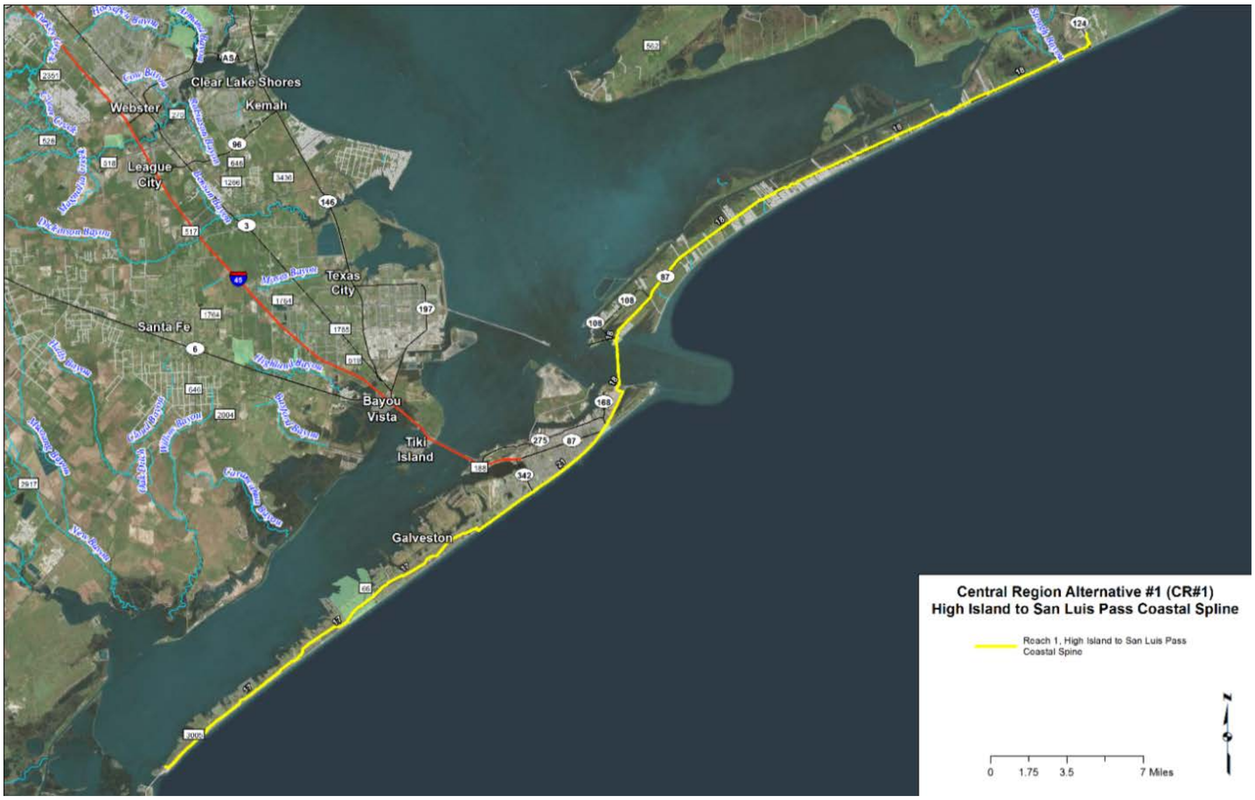


Figure 7: Diagram of Central Region Alternative #1

2.2.2.2. Central Region Alternative #2 (CR#2) - Texas City Levee Modifications and Extensions North (SH-146) and West-Galveston Ring Levee

Alternative CR#2 consists of four separate reaches that the team developed as a distinct alternative to Alternative CR#1.

Reach 1 - Galveston Ring Levee – The reach consists of a ring levee which runs the entire length of the existing seawall and includes a new levee extension that extends this line of protection west to Stewart Road. The levee then turns north, parallel to Stewart road and continues to Offatts Bayou. The system then crosses Offatts Bayou and turns east along Teichman Road, crossing I-45, and running parallel to the rear of the properties on the south side of Harborside Drive. The system then crosses Harborside Drive and follows an alignment parallel to the north side of Harborside Drive to Ferry Road. At Ferry Road, the system turns north parallel to Ferry road and then crosses Ferry Road at Fort Point Road to tie into the high ground at the San Jacinto federal dredge material placement area. Elevations for this reach vary between 17.5 feet and 26 feet. The major elements of this reach include: 26,303 feet of new levee, 70,488 feet of T-wall, forty six

2-lane highway gates, five 4-lane highway gates, four railway gates, three new pump stations, and one navigation gate (Offatts Bayou). Elevations in this reach vary from 21 feet to 26 feet.

Reach 2 - Texas City Levee Extension North (SH-146) – This reach consists of extending the Texas City Hurricane protection system north along SH-146 to SH-225. The reach starts where the current levee crosses SH-146 at TC Reservoir Street and runs along the east side of the highway to Dickenson Bayou. The system crosses Dickenson Bayou and continues north parallel to the east side of SH-146, crossing Clear Lake and continuing north to Red Bluff Road. At Red Bluff Road, the system crosses SH-146 and continues north parallel to the west side of the highway to Old La Porte Road. At Old La Porte Road, the system turns west until it reaches its terminus at high ground. The major elements of this reach includes: 81,057 feet of new levee, 10,190 feet of T-wall, six drainage structures, thirty one 2-lane road gates, nine 4-lane road gates, five railroad gates, four new pump stations, and two navigation gates (Dickenson Bayou and Clear Creek). Elevations along this reach range from 21.5 feet to 27 feet.

Reach 3 - Texas City Levee Extension West (Highland Bayou) – This reach consists of extending the existing Texas City Hurricane protection system west from intersection of the Union Pacific Railroad and the levee in the vicinity of I-45 to Santa Fe. The reach starts at the existing railway gate vicinity I-45 and the current levee system and proceeds west across Highland Bayou and SH-6. Just east of SH-6 the system turns north, paralleling N Martin Luther King Ave, and then proceeds west across the Highland Bayou Diversion Channel to SH-2004 vicinity of Avenue C in Hitchcock. At Avenue C, the system then runs parallel to the south side of SH-2004 to the channel east of Tacquard Ranch Road and turns north following the channel to the terminus at high ground, in the vicinity of Winding Trail Street. The major elements of this reach include: 53,980 feet of new levee, 5,530 feet of new T-wall, three drainages structures, seven highway gates, two railroad gates, four new pump stations, and two small navigation gates for recreational traffic (Highland Bayou and Highland Bayou Diversion Channel). Elevations along this reach range from 19 feet – 26 feet.

Reach 4 - Modernization of the existing Texas City Hurricane Protection System – This reach consists of upgrading the Texas City Hurricane Protection System for conditions reflected by the team's modeling in 2085. The major elements of this reach include: 70,454 feet of levee to be raised, the replacement of 7,096 feet of T-wall, five railway gates, twenty two drainage structures, twenty 2-lane roadway gates, the expansion of the existing pump stations and retrofitting the Moses Lake vertical lift gate. Elevations in this reach vary from 21.5 feet – 27 feet.

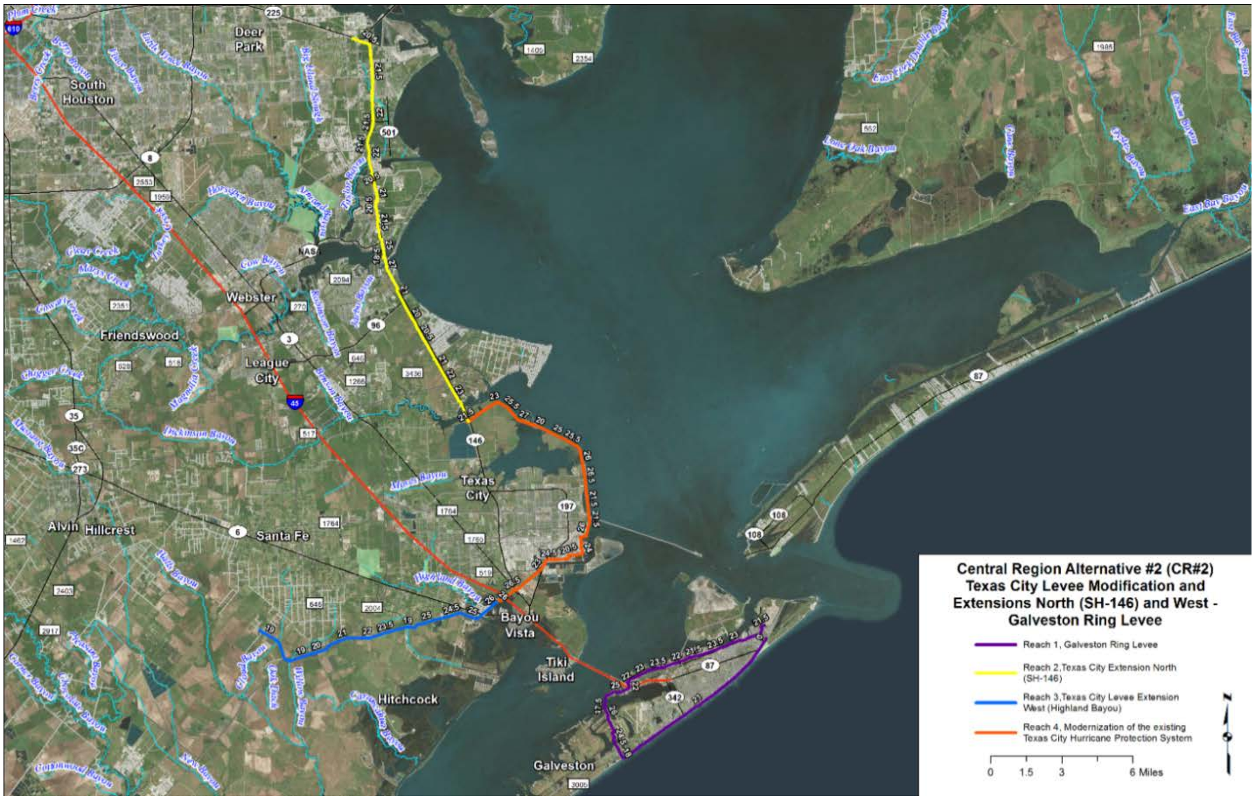


Figure 8: Diagram of Central Region Alternative #2

2.2.3. South Region - Brazoria County

In the Brazoria County region of the study area, the team reviewed numerous potential alternatives and selected two for further analysis and development. Alternative one consisted of reviewing the existing Freeport Hurricane protection system and evaluating extensions of the system to protect areas that will be at risk in 2085. The second alternative included evaluating areas that are outside of the existing system that have been developed since the system was constructed to assess their potential need for protection in 2085. All these new elements are separable, and will be considered based upon their individual benefit to cost ratios.

2.2.3.1. South Region Alternative #1 (SR#1) - Freeport Hurricane Flood Protection System Modernization and Extension North toward Angleton

Alternative SR#1 consists of two distinct reaches that provide protection for the cities of Freeport, Lake Jackson, Clute, and Angleton, Port Freeport, and the industry located behind the existing Freeport Hurricane Flood Protection System.

Reach 1 - Freeport Hurricane Flood Protection System modernization – This reach consists of upgrading the federally authorized Freeport Hurricane Flood Protection System and the locally owned and operated levee system along Buffalo Camp Bayou for conditions reflected by the team's modeling in 2085. Elevations in this reach vary from 17.0 feet to 20.0 feet.

Reach 2 - Richwood to Angleton Extension of the Freeport Hurricane Flood Protection System – This reach consists of an extension to the east side of the existing federally authorized Freeport Hurricane Flood Protection System that begins begin at the east side terminus. The extension would cross Oyster Creek and continue north parallel to the west side of Brazosport Boulevard North and continue north past Richwood, crossing SH-2004 and CR 220, and terminating at high ground south of Iden Road. The major elements of this reach include: 38,425 feet of new levee, twenty two drainage structures, nine roadway gates, and one new pump station. Elevations in this reach vary from 19.0 feet to 20.0 feet.

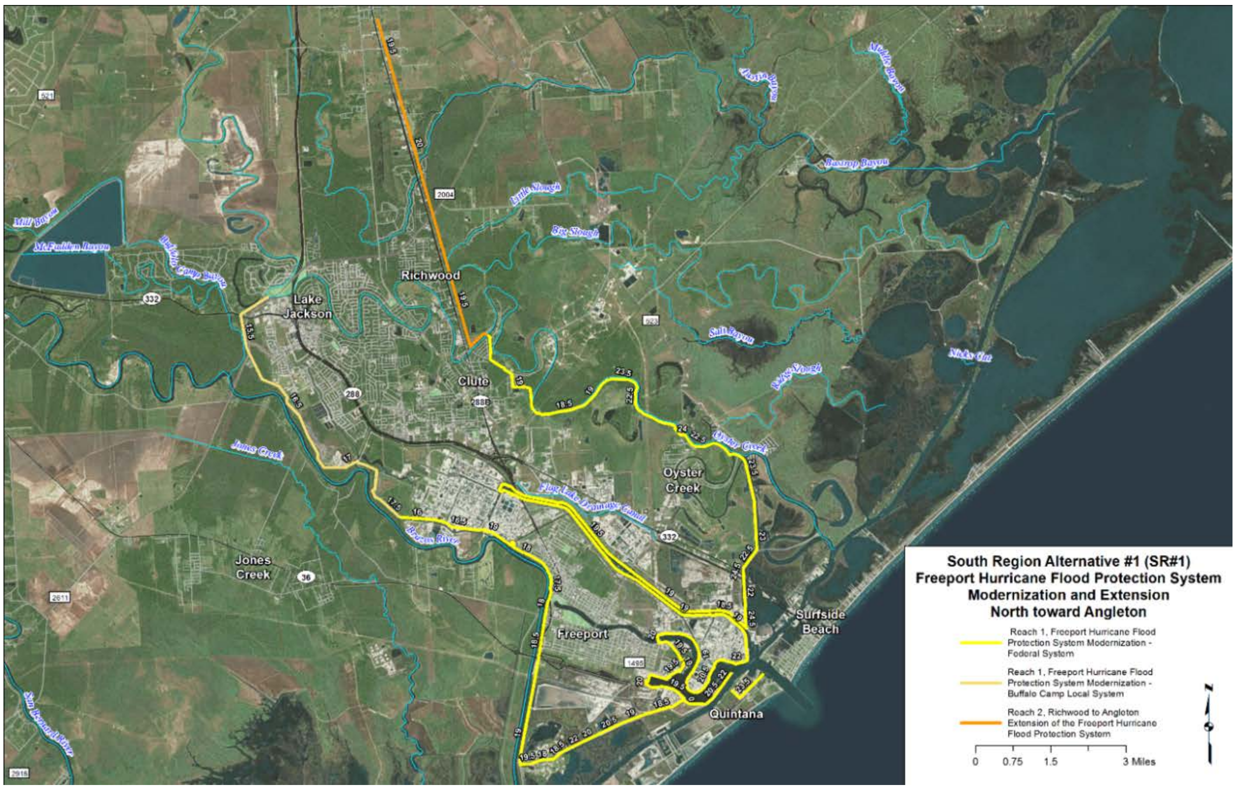


Figure 9: Diagram of South Region Alternative #1

2.2.3.2. South Region Alternative #2 (SR#2)- Freeport Hurricane Flood Protection System Modernization and Extension North toward Angleton- Jones Creek Levee, Jones Creek Terminal Ring Levee, and Chocolate Bayou Ring Levee

Alternative SR#2 consists of five distinct reaches that would provide protection to the cities of Freeport, Lake Jackson, Clute, and Angleton, Port Freeport, Jones Creek, the tank farm in the vicinity of Jones Creek, the industrial complex located along Chocolate Bayou and the industry located behind the existing Freeport Hurricane Flood Protection System.

Reach 1 - Freeport Hurricane Flood Protection System modernization – Same as defined for Alternative SR#1

Reach 2 - Richwood to Angleton Extension of the Freeport Hurricane Flood Protection System – Same as defined for Alternative SR#1

Reach 3 - Jones Creek Levee – This reach consists of a partial ring levee around the community of Jones Creek. The northern terminus of the proposed levee begins at high ground east of the intersection of SH-2004 and SH-2611 and continues east along the high ground and parallel to the north side on SH-36. The system then turns south crossing SH-36 and follows the southern perimeter of the Jones Creek community (SH-295). At Robin hood Lane, the system turns back to the west following the high ground back to SH-2611. The major elements of this reach include: 50,625 feet of new levee, eight drainages structures, one highway gate, and one new pump station. Elevations in this reach vary from 18.5 feet to 20.0 feet.

Reach 4 - Jones Creek Terminal Ring Levee – This reach consists of a ring levee around the existing Tank Farm boundary. The major elements of this reach include: 15,995 feet of new levee, three drainage structures, one roadway gate, and one new pump station. Elevations in this reach are 21 feet.

Reach 5 - Chocolate Bayou Ring Levee – This reach consists of a ring levee around the existing Chocolate Bayou petrochemical complex property boundary. The major elements of this reach include: 65,990 feet of new levee, thirteen drainage structures, six roadway gates, and one new pump station. Elevations in this reach vary from 20.5 – 24.5 feet.

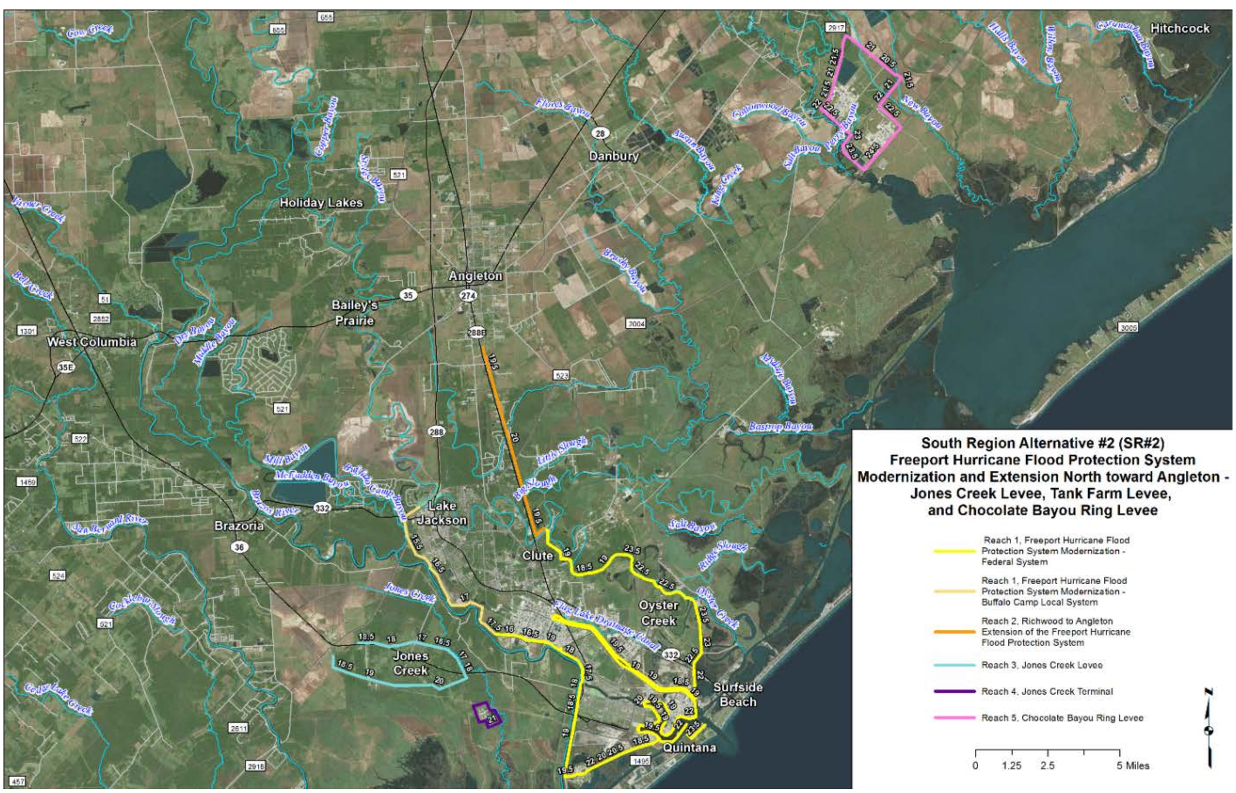


Figure 10: Diagram of South Region Alternative #2

Each of these alternatives were then fully developed to determine their technical, economic, environmental and social feasibility. Appendix F lists the alternatives that were reviewed as part of the screening process.

2.3. Alternative development

Once region alternatives were determined for further analysis, the team focused on determining the **technical, economic, environmental, and social feasibility** of the proposed alternatives. These factors became the basis of the team's alternative comparison.

The technical feasibility was determined through the analysis of storm surge heights and frequencies, storm intensity, storm impact location, wave run up data, rainfall amounts, engineering structural analysis, and determination of the cost associated with implementing the protection. ADCIRC modeling that incorporated future Relative Sea Level Rise and regional subsidence data was used to develop a probabilistic approach to determine the 1 percent and .05 percent (100-year and 500-year events) storm surge elevations, and wave heights for the years 2035 and 2085. The team made the assumption that if construction began in 2020 all the alternatives could conceivably be in place by the year 2035. A fifty year design life was assigned to each alternative, so in essence the system would remain resilient until the year 2085.

The engineering structural analysis involved the development of design concepts for each alternative that maximized life, safety, health, economic, and environmental benefits. The team carefully defined the various reaches that composed each alternative by the type of protection that best suited that reach. This took into consideration certain social and economic factors associated with the purchase of right of way, relocations, obstruction of scenic views, and regional transportation.

The economic feasibility for each alternative was derived using the HEC-FDA model. HEC-FDA is the US Army Corps of Engineers and Office of Management and Budget's approved model for determining economic impacts and benefits associated a federal flood risk management project. Inputs to HEC-FDA include all the structure types, first floor elevations, and appraisal values associated with each structure within the study area.

The environmental feasibility was assessed throughout the technical and engineering structural analysis phases. Once the alternatives were fully defined, the team then assessed the potential impacts that each alternative would have on the environment. Alternative alignments and structure types were continuously redefined in order to avoid and minimize environmental impacts. Impacts that could not be avoided were characterized by habitat type effected, and the costs associated with mitigation of the impacts were added to the overall project cost.

Social feasibility was assessed throughout the entire process. Comments from the public scoping meeting were factored into the development of alternatives in order to minimize impacts to the public. Impacts evaluated included the reduction in the quality of life, disruption of traffic flow/patterns, potential economic losses associated with tourism, and ensuring low income areas were not excluded from future protection. Phase 3 of the study involves additional public meetings to gather public comments on the alternatives developed during Phase 2.

The team's goal was to identify and fully develop two distinct alternatives, or series of alternatives within each region of the study area to provide a means of comparison for a recommended plan within each region.

3. Storm Surge Modeling

3.1. Modeling approach and Methodology

The coupled *ADvanced CIRCulation* (ADCIRC) and *Unstructured Simulating WAves in the Nearshore* (UnSWAN) model system were applied to simulate storm surge and waves for potential future sea level conditions. Several model scenarios, including without-action and two with-action configurations were implemented in the model. The without-action scheme was implemented for both future years 2035 and 2085, while the with-action schemes were implemented for the future year 2085.

The ADCIRC computational mesh and model setup used in this study were based on the Federal Emergency Management Agency (FEMA) Flood Insurance Study (FIS) analysis in coastal Texas (FEMA, 2011). However, the Texas FEMA FIS computational mesh was revised for this study to improve efficiency and stability, and the ADCIRC model versioning was updated to make use of the most recent version of the ADCIRC model and the associated advancements since the Texas FEMA FIS analysis. The updated computational mesh and ADCIRC model was validated by comparing simulation results to observation data from Hurricane Ike. Further details regarding mesh and model improvements can be found in Appendix A

Four scenarios were developed and analyzed using the updated ADCIRC and UnSWAN model system. The scenarios varied by storm risk management alignment and by the initial water level used to simulate future conditions. The four scenarios were Future Without Action (FWOA) 2035, FWOA 2085, Future With Action – Configuration 1 (FWA1) 2085, and Future With Action – Configuration 2 (FWA2) 2085. The FWOA configurations only implement existing storm risk management alignments, and thus are used as a control to compare the other scenarios against. FWA1 implements existing storm risk management alignments and adds the Central Region Alternative #1 (High Island to San Luis Pass Coastal Spine). FWA2 implements existing storm risk management alignments and adds three proposed alternatives across three regions: the North Region Alternative #2 (The Jefferson/Orange Protection System without the Neches River Navigation Gate), the Central Region Alternative #2 (Texas City Levee Upgrades and Extensions North and West, and Galveston Ring Levee), and the South Region Alternative #2 (Freeport Hurricane Flood Protection System Modernization and Extension North toward Angleton, Jones Creek Levee, Jones Creek Terminal Ring Levee, and Chocolate Bayou Ring Levee). The future year condition used in each scenario determines the initial water level used in the model to reflect potential future relative sea level changes. For 2035 and 2085 scenarios, the initial water levels were increased by 0.94 and 2.44 feet, respectively.

For each scenario, 254 synthetic storms were simulated to determine maximum water surface elevations, maximum significant wave heights, and maximum wave periods in the study area. Storms vary in several parameters, including forward speed, maximum radius, minimum central pressure, peak wind speeds, and storm track. The suite of 254 storms, selected for this study in coordination with the US Army Corps of Engineers (USACE), includes 152 high-intensity and 71 low-intensity storms from the Texas FEMA FIS storm suite, as well as 31 high-intensity storms from the Louisiana FEMA FIS storm suite (USACE 2008a, b) with landfall locations near the Louisiana-Texas border. Figure 11 shows the storm tracks from both Texas and

Louisiana FEMA FIS storm suites. Storm tracks are colored by region and FWOA existing storm risk management alignments are also shown.

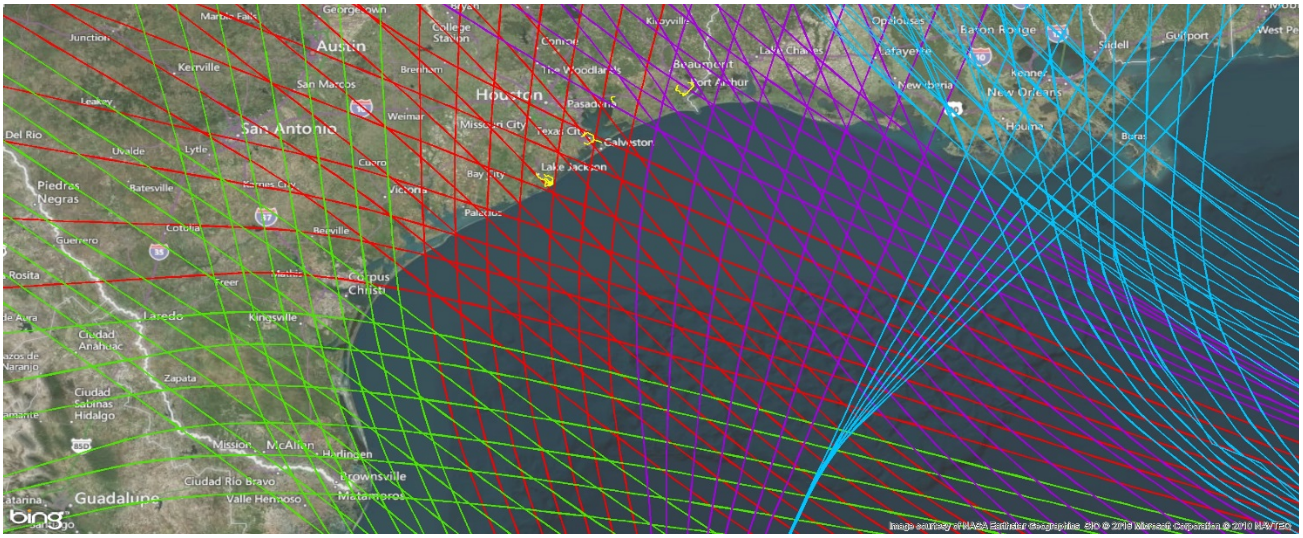


Figure 11: Synthetic storm tracks from Texas and Louisiana FEMA FIS studies. Blue lines are East Louisiana storm tracks. Purple lines are West Louisiana storm tracks. Red lines are North Texas storm tracks. Green lines are South Texas storm tracks. Yellow lines are existing storm risk management alignments in FWOA simulations.

3.2. Relative Sea Level Rise

As part of establishing the 2035 and 2085 landscape conditions, the team reviewed the available information regarding Relative Sea Level Rise (RSLR) along the Texas coast. RSLR has two components: land subsidence and eustatic change to the offshore water level in the Gulf of Mexico. While the water level changes can be assumed to be uniform along the coastline between Freeport and Sabine, there have been substantial spatial variations of local land subsidence.

3.2.1. Regional Subsidence

Historically, the subsidence rates have been very large in Galveston and Harris Counties (see Figure 12) and lower in the adjacent counties. The large rates have been due primarily to water withdraw from aquifers resulting in compaction of the underlying sediments (Kazmarek et al, 2014). The Harris-Galveston Subsidence District (HGSD) was created to monitor and limit subsurface extractions in order to limit the degree of subsidence in the region. Typically, estimates of future conditions are drawn from historical data. However, the HGSD mission is to control future subsidence so that it does not match the historic trend (Turco, 2015). The HGSD subsidence targets are shown in Figure 13. County engineers for Jefferson, Chambers, and Orange counties have stated they do not have subsidence data and do not perceive subsidence to be a concern in their area.

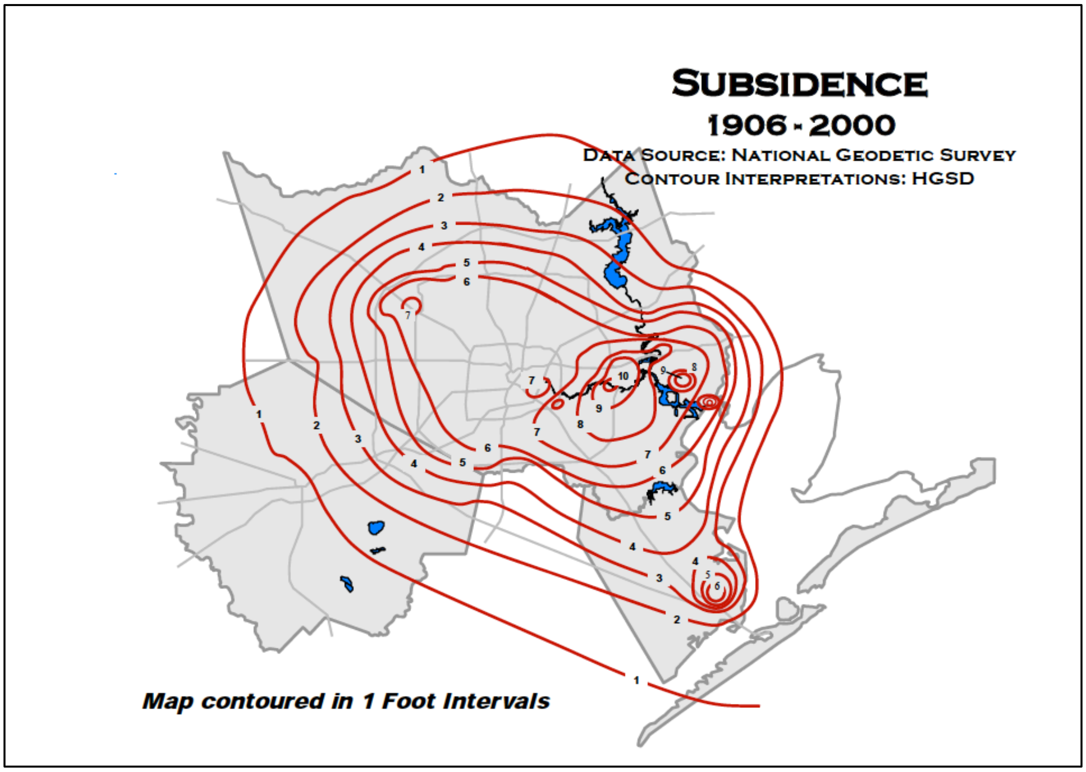


Figure 12: Historic Subsidence Rates

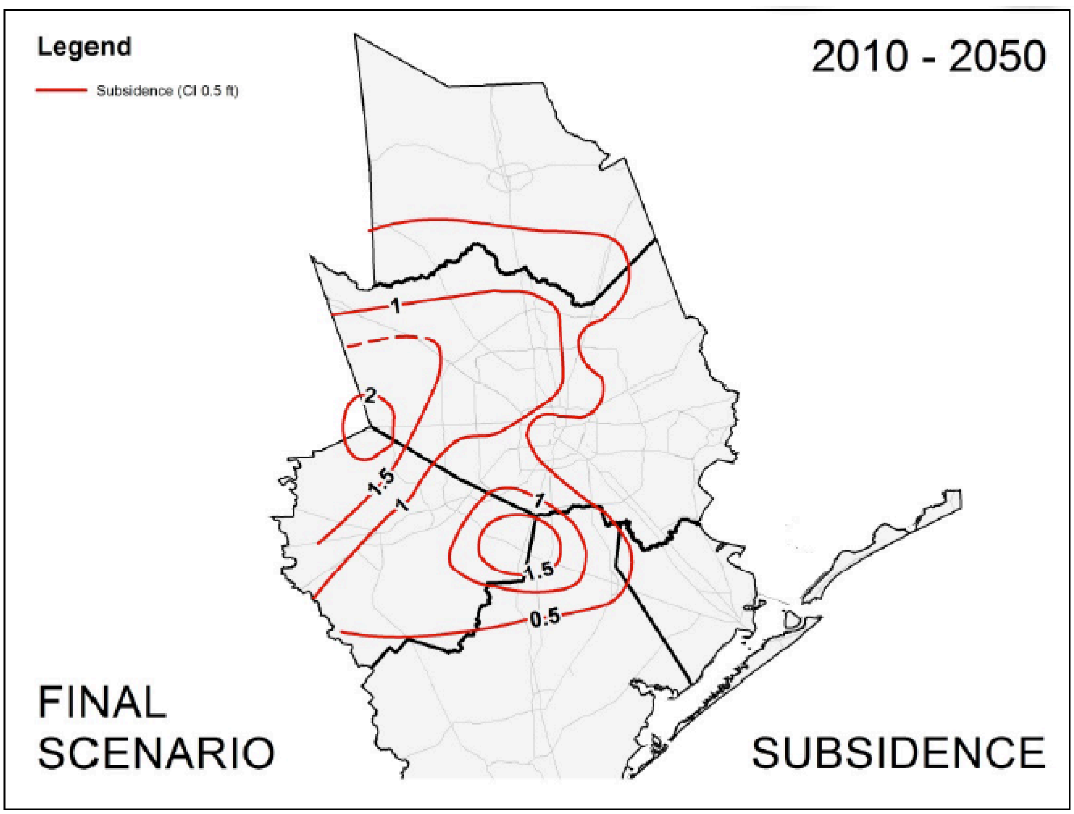


Figure 13: Future Subsidence Rates as per HGSD Strategic Plan.

3.2.2. Historic Subsidence

RSLR can be observed over time by examining long-term records of coastal tide gauges. Tide gauges measure “relative” sea level rise because they cannot distinguish between the contribution of subsidence or offshore water levels. Whether the gauge is sinking or the water is rising, the variation of gauge water levels is measured the same. Historically, the RSLR trend near Galveston is quite high. The data for the NOAA gauges at Pier 21 is shown in Figure 14. With what is known from independent subsidence data from HGSD, it is understood that a considerable portion of the RSLR trend at the Pier 21 gauge is due to subsidence. The long-term record for the Freeport gauge and the Sabine gauge are shown in Figure 15 and Figure 16. These gauges are located in regions that have not experienced significant subsidence and the long term RSLR trend is somewhat lower.

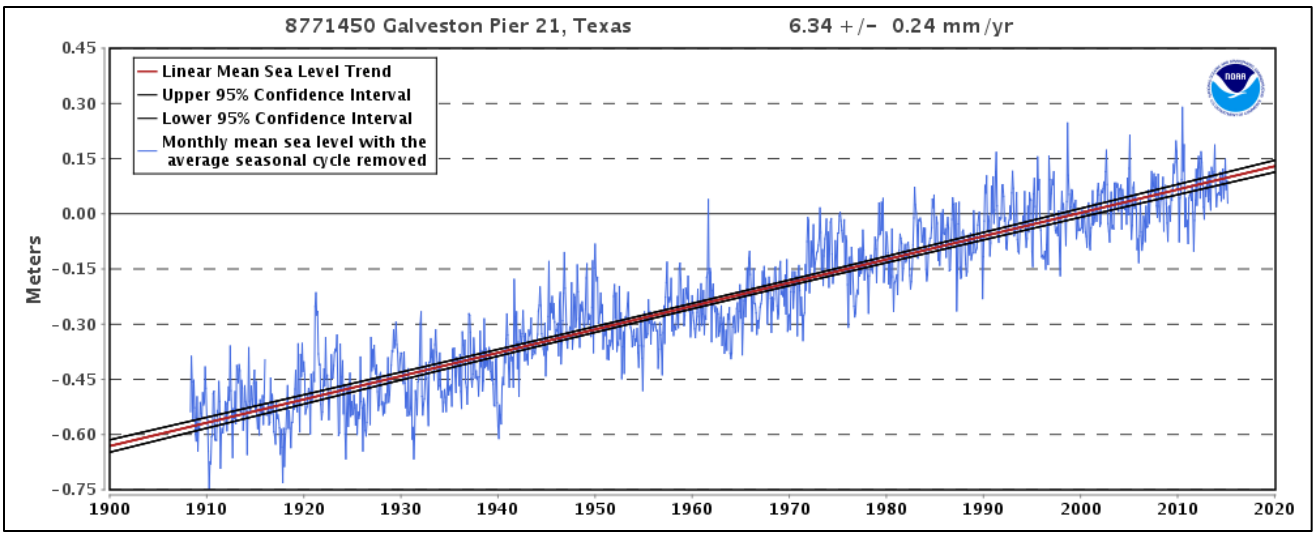


Figure 14: Long-term RSLR Trend at Galveston Island Pier 21.

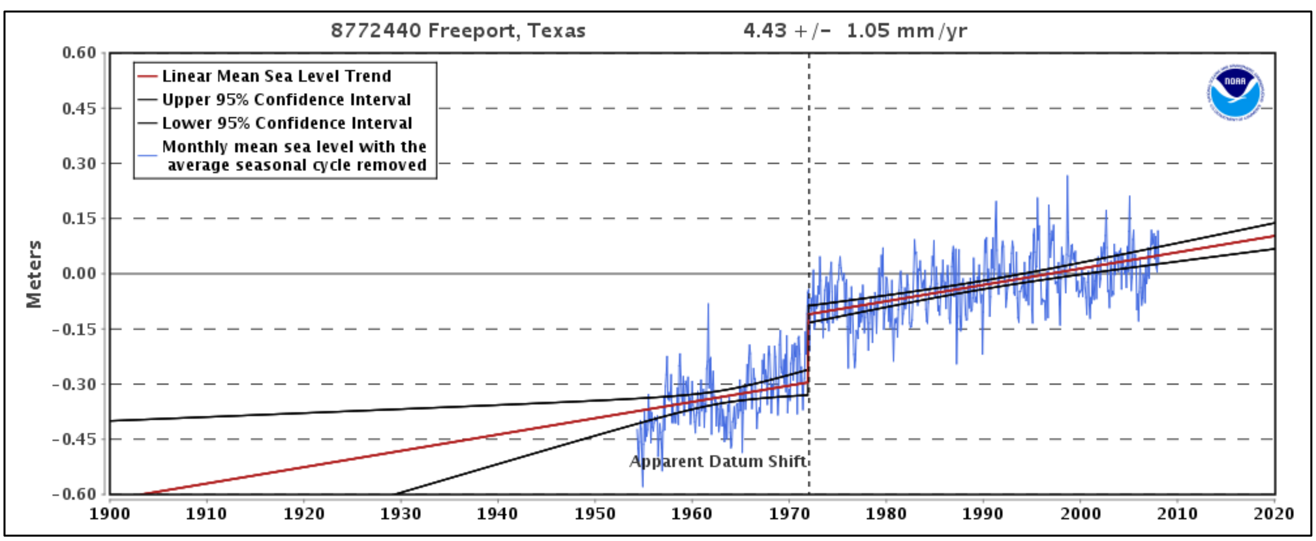


Figure 15: Long-term RSLR Trend at Freeport.

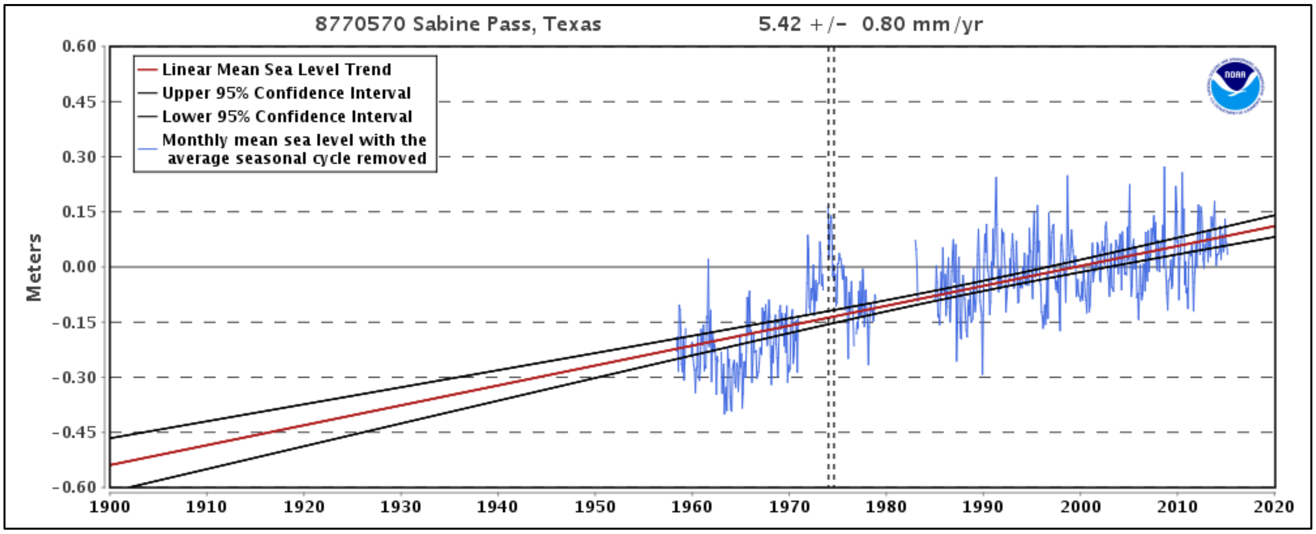


Figure 16: Long-term RSLR Trend at Sabine Pass.

In order to estimate a RSLR value for the future conditions modeling, a regional average can be derived by averaging the RSLR from the three gauges that cover the region. The values are shown in Table 1. The recommended values for use in the future conditions modeling are highlighted in yellow. Note that the median and the average are very close, indicating a central tendency with minimal skew. The averaging of the three gauges results in a value that is representative of the best available data in the northern counties (i.e. the Sabine gauge and average values are very similar). The magnitude of the projected RSLR in Galveston and Harris counties is lower than the gauge trend in the area which aligns with the HGSD forecast of lower rates of future subsidence. This projected RSLR is conservative by tenths of a foot near Freeport, though considerably lower than the high RSLR projection in the area as shown in Table 1.

Table 1: RSLR Data from NOAA Gauges.

	RSLR Scenario (feet)					
Gauge Location	2035 Low	2035 Int	2035 High	2085 Low	2085 Int	2085 High
Sabine	0.80	0.96	1.48	1.73	2.50	4.93
Galveston Pier 21	0.90	1.07	1.59	1.95	2.72	5.16
Freeport	0.61	0.78	1.30	1.33	2.10	4.53
Maximum	0.90	1.07	1.59	1.95	2.72	5.16
Minimum	0.61	0.78	1.30	1.33	2.10	4.53
Average	0.77	0.94	1.46	1.67	2.44	4.87
Median	0.80	0.96	1.48	1.73	2.50	4.93

Based upon the available data, the recommendation is to use a RSLR value of 0.94 feet for 2035 and 2.44 feet for 2085 for the entire six-county study area.

3.3. Return Water Level Analysis

To assess the flood risk for each future scenario, a return water level analysis was conducted using a statistical model. The statistical model was developed by the US Army Corps of Engineers (USACE) Engineering Research Development Center (ERDC) based on the Federal Emergency Management Agency (FEMA) Flood Insurance Study (FIS) for Texas and incorporates the most recent and advanced understanding of the Joint Probability Method (FEMA, 2011; Resio et al. 2009; Toro et al. 2010a; Nadal-Caraballo et al. 2015). The model takes maximum water surface elevations from the 254 synthetic storm simulations and outputs stillwater levels (SWL) at four specific return frequencies: 10-year (10 percent annual chance), 50-year (2 percent annual chance), 100-year (1 percent annual chance), and 500-year (0.2 percent annual chance).

The Joint Probability Method with Optimal Sampling (JPM-OS) scheme has been applied in storm surge elevation probability analysis for nearly three decades. Two optimal sampling approaches have been developed to reduce the efforts of storm surge numerical modeling (Resio et al. 2008; Resio et al. 2009; Toro et al. 2010a; Toro et al. 2010b). One approach is the interpolation of intermediate values from a storm surge response surface (Resio et al, 2007; Resio et al. 2008), and the other (called a Bayesian or Gaussian-process) is the weighting of storm parameters from a sampling set using a quadrature scheme for integration (Resio et al. 2008; Toro 2008; Toro et al. 2010a). The Texas FEMA FIS utilized exclusively JPM-OS response surface interpolation. The model used in this study developed by USACE ERDC is called the Joint Probability Analysis (JPA) model, and it employs a response surface interpolation method for central pressure deficit and heading, and a quadrature integral based weighting scheme for radius of maximum wind and storm forward speed (Nadal-Caraballo et al. 2015). The model calculates the annual exceedance probability (AEP) for a given water surface elevation, and outputs return SWLs at given frequencies.

The inputs for the JPA model are the maximum water surface elevations from each of the 254 storms extracted at specific points of interest from the ADCIRC and UnSWAN model outputs. At each location there are potentially 254 surge responses per future scenario. However, for locations of relatively high ground elevation, the number of surge responses may be less than that total because they are dry during some storms. The surge heights at these dry locations were approximated using water levels at nearby locations (Taflandis et al., 2012). The updated database of maximum surge heights was then used in the JPA model for flood stage frequency analysis.

Sensitivity tests were completed to compare the JPA model and the synthetic storm suite used in this study to the JPM-OS model and storm suite used in the Texas FEMA FIS. The updated JPA model increased the 1 percent return SWLs by 1 to 2 feet relative to the previous Texas FEMA FIS JPM-OS approach. Additionally, including the 31 Louisiana storms in the storm suite increased the 1 percent SWLs by 0.5 to 1 feet relative to a storm suite that does not include the Louisiana storms.

Following the sensitivity analysis, the JPA model was applied using the surge height datasets from the 254 storms for each of the four scenarios (FWOA 2035, FWOA 2085, FWA1 2085, FWA2 2085). A series of steps were completed to confirm the quality of the output statistics. Return SWL's from locations with fewer than 30 inundation events were replaced with those from a nearby point. Results were compared between scenarios to ensure return SWL's for FWOA 2035 conditions were not higher than those for FWOA 2085 and were not lower than those for present day conditions in the Texas FEMA FIS. Results were also compared between FWOA 2085, FWA1 2085, and FWA2 2085 to confirm that differences were negligible in areas away from the proposed alternatives.

The reviewed SWLs for 10-, 50-, 100-, and 500-year return frequencies were then extrapolated to higher frequencies, i.e. 1-, 2-, 5-, and 10-year return frequencies. Extrapolation was guided using data from the NOAA gauge at Galveston Pier 21. Further details regarding the return water level analysis can be found in Appendix B.

3.4. Preliminary Design Elevations

To estimate the effectiveness of the proposed alternatives, a set of preliminary design elevations were required. These preliminary design elevations were determined based on overtopping criteria recommended by the US Army Corps of Engineers (USACE) in Hurricane and Storm Damage Risk Reduction System Design Guidelines (USACE 2012). Hydraulic conditions obtained from the 254 synthetic storm simulations described in Appendix A and the JSA return analysis described in Appendix B were utilized in calculating overtopping rates to determine reach crest design elevations.

3.4.1. Hydraulic Conditions

A series of locations 600 feet offshore of the proposed alternatives and approximately every 1,500 feet along the alternatives were specified, and hydraulic conditions (maximum surface water level and maximum wave conditions) were extracted from the 254 synthetic storms modeled for this study under the FWOA 2085 scenario. From the extracted hydraulic conditions, the storms closest to the 100-year return stillwater level (SWL), calculated as described in Appendix B, at each location were identified. At each location, seven storms were selected: the storm with the closest maximum surface water level, the three storms with the next lower maximum surface water levels, and the three storms with the next higher maximum surface water levels. The significant wave heights and maximum wave periods of the seven storms were averaged, and these were used to represent the waves during a 100-year storm event, with a 100-year storm event defined as a storm that generates maximum surface water levels close to the 100-year return SWL at the target location. Because the present overtopping analysis was performed to determine crest elevation sufficient for a 100-year return SWL, it is reasonable to use the average condition of waves corresponding with the 100-year storm events instead of a return wave condition determined through an independent extreme value analysis.

The estimated wave conditions were then propagated to the toe of the alternatives and were used to calculate wave overtopping rates. This transformation was performed using shoaling, refraction, and depth-limited breaking based on equations from the USACE Coastal Engineering Manual (USACE, 2002).

3.4.2. Reach Types

The overtopping rate also depends on reach type used in the alternatives, as vertical reaches (e.g. floodwalls) and sloped reaches (e.g. levees) behave differently. Since the proposed alternatives are early enough in the planning process that reach types have not been defined along the entire alternative, five reach types were considered when calculating overtopping rates at each location:

- Vertical walls
- Levees with 3:1 grass-covered front slopes
- Levees with 4:1 grass-covered front slopes
- Levees with 3:1 armored front slopes
- Levees with 4:1 armored front slopes

The results from these five cases were then reviewed, and the most appropriate reach type was selected based on local factors to define a preliminary design elevation.

3.4.3. Overtopping Rate and Reach Elevations

Preliminary design elevations at each location along the reach were estimated using USACE-recommended criteria for probabilistic maximum overtopping rates for sloped and vertical structures (USACE 2002). According to these criteria, for sloped reaches (levees), overtopping may not exceed 0.01 cubic feet per second per linear foot (cfs/ft.) at the 50 percent level of assurance or 0.1 cfs/ft. at the 90 percent level of assurance. For vertical reaches, such as seawalls and floodwalls, overtopping may not exceed 0.03 cfs/ft. at the 50 percent level of assurance or 0.1 cfs/ft. at the 90 percent level of assurance. Elevations calculated based on this overtopping limit were then rounded up to the nearest half foot to determine preliminary reach elevations.

The criteria were applied directly to the vertical wall case and the grass-covered levee cases, but a modified approach was used for armored levees. Since the criteria were developed to protect levees from scour damage and resulting structural failure associated with high overtopping rates, the criteria are somewhat conservative for armored levees. Instead for armored levees, the overtopping rates were capped to 0.1 cfs/ft. at the 70 percent level of assurance, which is similar to the deterministic overtopping rate proposed by the EurOtop overtopping manual (Pullen et al. 2007). Preliminary design elevations calculated based on this overtopping limit were then rounded up to the nearest half foot to determine preliminary reach elevations.

3.4.4. Galveston and the Coastal Spine

Though the elevations based on overtopping rates were used for most locations, there were two major exceptions: the entire High Island to San Luis Pass Coastal Spine and the Galveston seawall portion of that same coastal spine. The coastal spine is being designed to slow storm surge as it crosses into Galveston and Trinity Bay, limiting the filling of the bay before and during a storm. Accordingly, the coastal spine does not necessarily need to be high enough to avoid overtopping for 100-year conditions. Therefore, the crest elevation was not determined using the overtopping criteria. Instead, the coastal spine elevations were set equal to the 100-year return SWL, rounded up to the nearest half foot, which permits overtopping but slows the advance of high water levels and dissipates large offshore waves.

The Galveston seawall lies along the coastal spine, but it provides protection to the City of Galveston and had to be addressed as such. However, the overtopping criteria yielded relatively high reach elevations, and the design team determined that these were infeasible for a coastal community, as they would infringe on beach access and line-of-sight from homes and businesses adjacent to the seawall. Instead, a higher overtopping rate (0.1 cfs/ft. at 70 percent level of assurance instead of 90 percent level of assurance) was permitted in conjunction with a more advanced interior drainage plan. This allowed the team to reduce the reach elevation while still providing reliable protection through sufficient drainage capacity removing water quickly enough to prevent severe structural damage to buildings and properties behind the seawall.

3.4.5. Rainfall and Interior Drainage Requirements

A key component of the each protection plan included an analysis of interior drainage. When the system is completely closed, pump stations are required to convey rainfall events within the protected area to avoid interior backflow and flooding. An H&H analysis was conducted to determine the pumping requirements associated with interior drainage associated with a 100-year event and a 200-year event. Pumping capacity was sized for each alternative to ensure the conveyance of interior flows through the system. Pump stations were not specifically sited during this study. This will be conducted during preliminary engineering and design in order to take advantage of economies of scale as well as capacity within the existing drainage system.

4. Environmental Analysis

This section describes the potential environmental impacts associated with the proposed alternatives for each of the three regions:

- The North Region consists of two distinct alternatives consisting of six components
- The Central Region which consists of two distinct alternatives with eleven components
- The South Region which consists of two distinct alternatives consisting of eight components

The proposed impact area for each alternative was defined by the length of the proposed alternative and a buffer area of 150 feet to account for future operations and maintenance activity. Environmental impacts in the following sections are defined as acreage amounts and sites that are within the proposed impact area. Each alternative and segment was reviewed for potential impacts and the results are summarized in the following sections (Section 4.1.1-4.1.8). If an alternative did not have an impact an environmental category, it was omitted from the summary tables. A more detailed environmental analysis discussion can be found in Appendix D.

This environment analysis was conducted using the most current and comprehensive data available to the team. Data sources are discussed in-depth in the Phase 1 Report, finalized February 27, 2015. The results included in this discussion are for planning purposes only and are fully expected to change once preliminary engineering and design (PED) begins. During the PED process, alternative alignments will be further defined enabling the team to conduct pedestrian field surveys to fully define proposed environmental impacts.

4.1. Proposed Environmental Impact Analyses

4.1.1. Hazardous Materials

Hazardous materials sites in Texas are defined and regulated primarily by laws administered by the US Environmental Protection Agency. The following sites were identified within the study area for this report: Hazardous Waste (RCRA); Water Discharges (NPDES/PCS/ICIS); Toxic Releases (TRI); and Superfund (CERCLIS).

Table 2 identifies the number of hazardous material sites impacted by each alternative:

Table 2: Hazardous Material Sites

Alternative	RCRA	ICIS	TRI	CERCLIS	TOTAL
North Region Alternative 1					
Sabine River Levee	3	2	1		6
North Region Alternative 2					
Sabine River Levee	3	2	1		6
West Bank Neches River	7	5	3		15
Central Region Alternative 1					
Coastal Spine	2	3	1		6
Central Region Alternative 2					
Galveston Ring Levee	10	2	1	2	15
Texas City Extension North	5	1			6
Texas Federal System	1	3	1		5
South Region Alternative 1					
Freeport Federal System	1		1		2
South Region Alternative 2					
Freeport Federal System	1		1		2

Source: EPA (21)

4.1.2. Historic Sites

The National Register of Historic Places is the official list of the Nation's historic places worthy of preservation. Authorized by the National Historic Preservation Act of 1966, the National Park Service's National Register of Historic Places (NRHP) is part of a national program to coordinate and support public and private efforts to identify, evaluate, and protect America's historic and archeological resources. Only one alternative would impact historic sites listed on the NRHP as shown in Table 3 (20):

Table 3: National Historic Sites

Alternative	Historic Sites
Central Region Alternative 1	
Coastal Spine	2

Source: NPS (20)

One of these sites is the Galveston Island Seawall. The Seawall is a federally authorized flood control project under the jurisdiction of the US Army Corps of Engineers (USACE). The suggested improvements to the seawall would require coordinated with USACE as well as with state and other federal regulatory agencies.

4.1.3. Coastal Barriers

Coastal barriers are landscape features that protect the mainland, lagoons, wetlands, and salt marshes from the full force of wind, wave, and tidal energy. “Undeveloped coastal barriers” are defined by the Coastal Barrier Resources Act (CRBA) to include barrier islands, bars, spits, and tombolos, along with associated aquatic habitats, such as adjacent estuaries and wetlands. Composed of sand and other loose sediments, these elongated, narrow landforms are dynamic ecosystems and are highly vulnerable to hurricane damage and shoreline recession. Coastal barriers also provide important habitat for a variety of wildlife and are an important recreational resource (16).

Table 4 identifies the acreage amounts of coastal barriers impacted by each alternative:

Table 4: Coastal Barriers

Alternative	Coastal Barriers in Acres
Central Region Alternative 1	
Coastal Spine	235.98
South Region Alternative 1	
Freeport Federal System	0.71
South Region Alternative 2	
Freeport Federal System	0.71

Source: USFWS (16)

4.1.4. Threatened or Endangered Species Critical Habitat

Critical habitat for a threatened and endangered species is a specific geographic area that contains features essential for the conservation of a threatened or endangered species and may require special habitat management and protection (17). According to the US Fish and Wildlife Service (USFWS) critical habitat mapper, one threatened species was identified to have critical habitat within the study area: the Piping Plover (*Charadrius melodus*).

Only one alternative would impact critical habitat for the Piping Plover as shown in Table 5:

Table 5: Critical Habitat for the Piping Plover

Alternative	Critical Habitat in Acres
Central Region Alternative 1	
Coastal Spine	47

Source: USFWS (17)

4.1.5. Essential Fish Habitat

Essential fish habitat (EFH) is defined as waters and substrate necessary to fish for spawning, breeding, feeding, or growth to maturity. For the purpose of interpreting the definition of essential fish habitat: "waters" include aquatic areas and their associated physical, chemical, and biological properties that are used by fish and may include aquatic areas historically used by fish where appropriate; "substrate" includes sediment, hard bottom, structures underlying the waters, and associated biological communities; "necessary" means the habitat required to support a sustainable fishery and the managed species' contribution to a healthy ecosystem; and "spawning, breeding, feeding, or growth to maturity" covers a species' full life cycle (NOAA, 2014).

Table 6 identifies the acreage amounts of EFH impacted by each alternative.

Table 6: Essential Fish Habitat

Alternative	EFH Sites in Acres
North Region Alternative 1	
Sabine River Levee	24.44
Neches River Crossing	3.16
Port Arthur Federal System	46.69
North Region Alternative 2	
Sabine River Levee	24.44
Port Arthur Federal System	46.69
West Bank Neches River	3.13
Central Region Alternative 1	
Coastal Spine	1.48
Central Region Alternative 2	
Galveston Ring Levee	1.60
Texas City Extension North	1.75
Texas City Extension West	0.71
Texas Federal System	25.21
South Region Alternative 1	
Freeport Federal System	45.08
South Region Alternative 2	
Freeport Federal System	45.08

Source: NOAA, 2014

4.1.6. National Wildlife Refuges and State Parks

National Wildlife Refuge (NWR) is a designation for certain protected areas of the United States managed by the USFWS. The National Wildlife Refuge System is the system of public lands and waters set aside to conserve America's fish, wildlife, and plants (USFWS, 2014).

Texas state parks are parks or other protected areas (such as state historic sites) managed by Texas Parks and Wildlife Department (TPWD). State parks are typically established by Texas to preserve a location on account of its natural beauty, historic interest, or recreational potential (TPWD, 2014).

Table 7 identifies the acreage amounts of NWR and Texas State Parks impacted by each alternative:

Table 7: NWR and State Parks

Alternative	Name	Acreage Impacted
Central Region Alternative 1		
Coastal Spine	Anahuac NWR	70.79
Coastal Spine	Galveston Island State Park	29.24

Source: USFWS and TPWD, 2014

The proposed alignment for the Alternative CR#1- Coastal Spine would parallel State Highway 87 on Bolivar Peninsula and State Highway 3005 on the west end of Galveston Island. Proposed levee alignments would be closely coordinate with TPWD and USFWS in order to integrate these structures into the park and refugee taking advantage of nature’s existing conditions.

4.1.7. *Existing Floodplains*

The 100-year floodplain is the land that is predicted to flood during a 100-year storm event, which has a 1 percent chance of occurring in any given year. Areas within the 100-year floodplain may flood in much smaller storms as well (15). The 100-year floodplain is used by FEMA to administer the Federal Flood Insurance Program.

From an environmental regulatory perspective, any improvements within the floodplain must be identified and significant changes to the floodplain (like those prosed by this study) will require a FEMA-approved Letter of Map Revision (LOMAR). A LOMAR enables FEMA to redraw the flood maps used for the Federal Flood Insurance Program.

Table 8 identifies the acreage amounts of existing 100-year floodplains impacted by each alternative:

Table 8: Existing Floodplains

Alternative	Acreage Impacted
North Region Alternative 1	
Sabine River Levee	360.76
Neches River Crossing	16.74
Port Arthur Federal System	470.86
North Region Alternative 2	
Sabine River Levee	360.76
East bank Neches River	372.30
Port Arthur Federal System	470.86
West Bank Neches River	512.41
Central Region Alternative 1	
Coastal Spine	998.99
Central Region Alternative 2	
Galveston Ring Levee	190.07
Texas City Extension North	326.55
Texas City Extension West	210.08
Texas Federal System	387.12
South Region Alternative 1	
Freeport Federal System	909.17
Freeport Extension to Angleton	132.22
South Region Alternative 2	
Freeport Federal System	909.17
Freeport Extension to Angleton	132.22
Jones Creek Levee	174.96
Jones Creek Terminal Levee	54.79
Chocolate Bayou Levee	227.57

Source: FEMA (15)

4.1.8. *National Wetland Inventory*

Wetlands of the United States are defined by the USACE and the EPA as "those areas that are inundated or saturated by surface or groundwater at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soils. Wetlands generally include swamps, marshes, bogs, and similar areas." Wetlands can be valued in terms of their contribution to ecological, economic, and social systems. Wetlands service these systems through multiple processes including water filtration, water storage, and biological productivity. They also contribute to the functions of flood control, providing a nutrient sink, groundwater recharge, and habitat (12).

In the United States, the National Wetland Inventory (NWI) is a USFWS program started in the 1970s to inventory and map all wetlands, primarily for scientific purposes. The data and maps it produces have been used to track gains and losses of wetlands for more than four decades.

Tables identifying the acreage amounts of NWI wetlands impacted by each alternative are included in Appendix D.

4.2. Tidal Flow Analysis

The construction of barriers at the inlets that connect the Gulf of Mexico to Galveston Bay are expected to influence the tidal flow within the bay. Altered tidal flow would change the hydrodynamics, morphology, and water quality of the bay. According to the Delft University of Technology study titled *The Effects of the "Ike Dike" Barriers on Galveston Bay* (June 2011), the tidal flow area would require an amplitude reduction of less than 20 percent to preserve a suitable tidal range that does not adversely affect the bay. Tidal analysis was performed on the Galveston Bay Alternative in the Central Region and the Neches River Gate Alternative in the North Region.

ADCIRC simulations were used to evaluate whether water quality impacts would be expected based on changes in tidal conditions related to the placement of various barrier alignments and gate configurations in the Houston Ship Channel and Neches River. These gate structures are intended to be closed only during tropical storms, remaining open otherwise. However, there is still potential for the open-gate configurations to inhibit tidal flow through a channel or river due to the structural elements necessary to house gate structures. To test the impact of the open-gate configuration, tides were simulated with and without these structural elements in an open configuration. Modeling outputs were used to determine the number of vertical lift gates (VLG) necessary to provide sufficient tidal exchange at the Houston Ship Channel and Neches River. These gates are discussed in detail in Section 5.

The preliminary conclusion of this effort is that water quality conditions will likely be minimally affected by the placement of proposed hurricane barriers. Observation of simulated hydrodynamics indicates that the hurricane barrier alternatives examined would result in a change in tidal amplitude of 5 and 10 percent for a range of tidal conditions when sufficient VLGs are implemented. This limited change indicates that it is possible to allow the natural environment driven by water circulation to remain undisturbed and water chemistry conditions to remain intact.

4.2.1. Results Summary

The Tidal Amplitude and Exchange analysis yields a relative comparison of the hydrodynamics in Galveston Bay and the Neches River with and without the proposed barriers. In Galveston Bay, the with-project scenarios result in the maximum tidal amplitude decreasing by 0.1 foot (12 percent) for G25 and 0.3 foot (25 percent) for G15, and tidal exchange decreasing by 5,000 m^3/s (10 percent) for G25 and 10,000 m^3/s

(25 percent) for G15. Similarly, in the Neches River, the with-project scenario results in maximum tidal amplitude decreasing by 0.03 foot (5 percent), and tidal exchange decreasing by 500m^3/s (5 percent). These results indicate that implementing sufficient VLGs would limit changes to the water column throughout the proposed project areas. Limited changes to the water column would allow the natural environment driven by water circulation to remain basically undisturbed and water chemistry, including that at the benthic layer, to be consistent with and without a hurricane barrier. A detailed water quality assessment is recommended in future phases of the study to further examine the ecological impacts of a barrier.

More detailed information can be found in Appendix C: Tidal Impact Analysis.

5. Gate Analysis

As a part of estimating the cost of coastal resiliency measures against hurricane induced storm surge, this section of the report discusses various aspects of preliminary structural design of two flood barrier alternatives proposed for the greater Houston and Port Arthur area. Following a brief discussion of the possible flood barrier alternatives, features of the chosen gate types, including protection heights, are explained. A summary of the preliminary structural design is presented with discussion of possible issues that influenced the design. Constructability issues for the various structures were investigated and possible solutions for providing access from and tying in these structures with high ground are discussed herein. Operation and maintenance requirements of these structures are briefly mentioned. Finally, the cost implications associated with the preliminary design are reflected at the end of this section.

5.1. Gate Modeling Parameters and Closure Requirements

5.1.1. History

The Phase I report for this study established three regions (North, Central, and South) as potential locations for structural and non-structural alternatives to mitigate storm surge induced flooding. A proposed structural alternative for the North region includes the construction of a gate structure on the navigable channel, forming a flood barrier across the Neches River and tying it to the existing levee at Port Arthur, Texas. The proposed central region gate structure alternatives include constructing a similar gate structure at Bolivar Roads, which is central to the Houston Ship Channel. Both gates would need to be wide enough to allow cargo ships to navigate through them, while forming complete barriers during tropical storms. It is imperative that these structures are equipped with ancillary features to allow ebb and flow tides through them during normal conditions (non-flooding events). Finally, the ensemble of structural measures, such as the proposed gates, needs to be tied to higher grounds and integrating into existing and/or proposed land-based flood damage protection systems.

5.1.2. Geometry

The proposed gates at Bolivar Roads and Neches River need to be appropriately sized to ensure that ships can navigate safely through them and do not impede the growth of the ports they serve. The following discussion addresses issues arose while preparing the estimates for the above-mentioned gates. This resulted in determination of the most appropriate gate dimensions associated with the preliminary design and cost estimates.

5.1.3. Bolivar Roads Gate

The area between the Bolivar Peninsula and Galveston Island serves as the entrance to the Houston Ship Channel. Figure 17 shows the area from a snapshot of the NOAA navigation maps for the area. It can be observed that the maintained channel for ship navigation is toward the south and marked by dashed lines surrounding the text “Inner Bar Channel” and “Bolivar Roads Channel”.

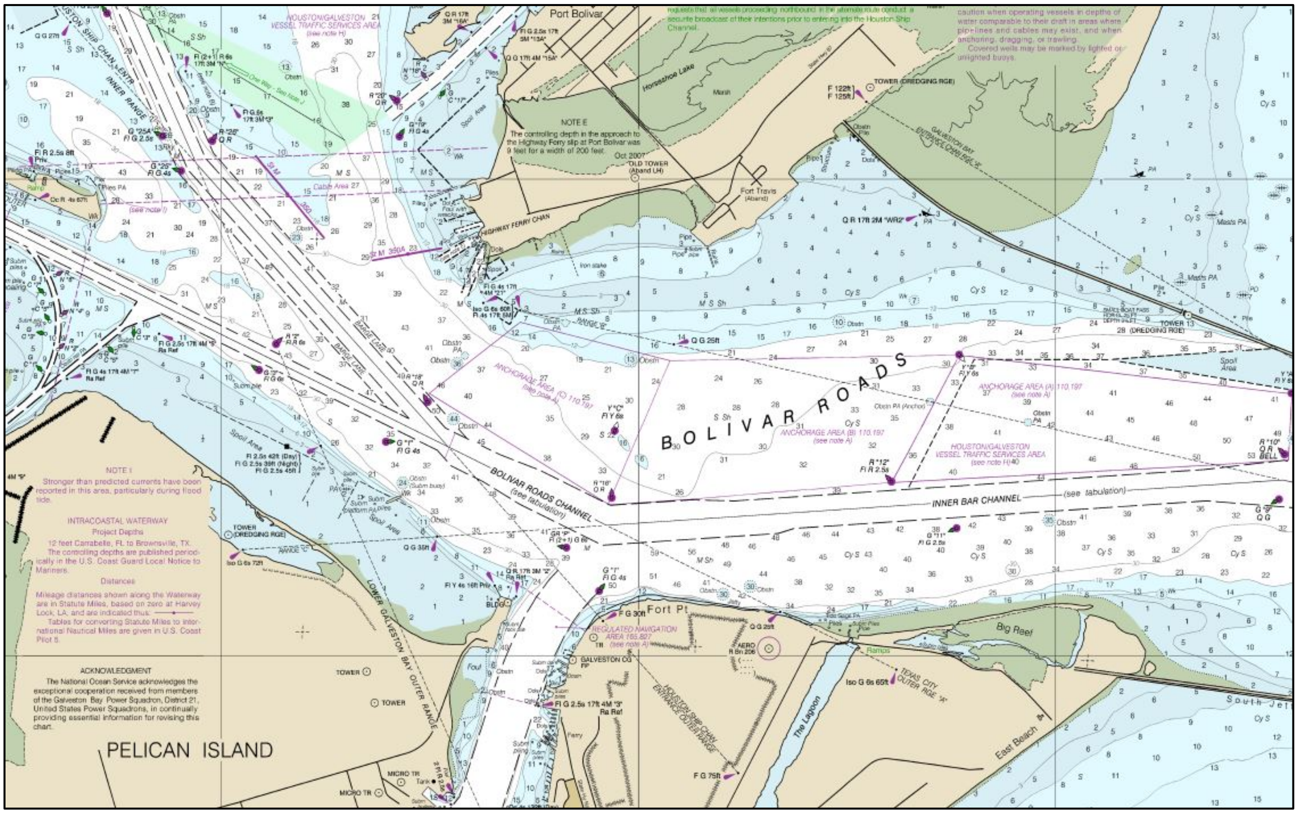


Figure 17: Ship Channel between Galveston and Bolivar Peninsula from NOAA chart 11324

In 2005, the channel was dredged to provide a main channel depth of 45 feet and width of 530 feet. The channel has 35-foot wide transition zones that lead to 200-foot-wide, 12-foot-deep barge lanes on both sides. The width of the entire channel is 1000 feet, as illustrated by Figure 18 and Figure 19.

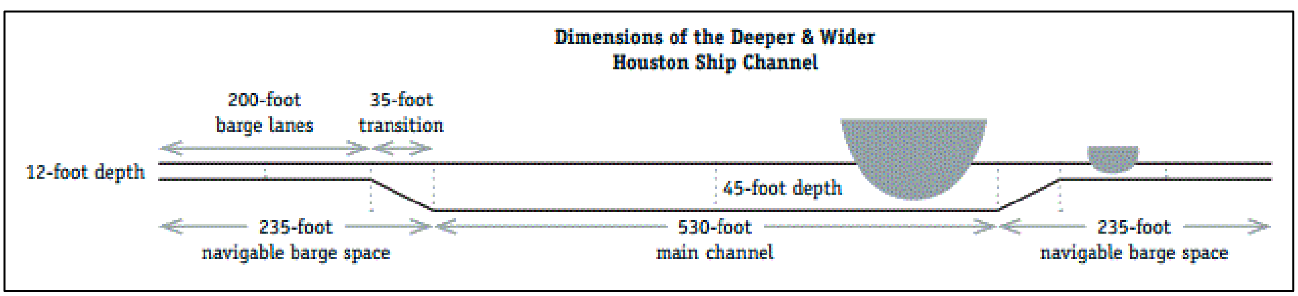


Figure 18: Houston Ship Channel Cross Section

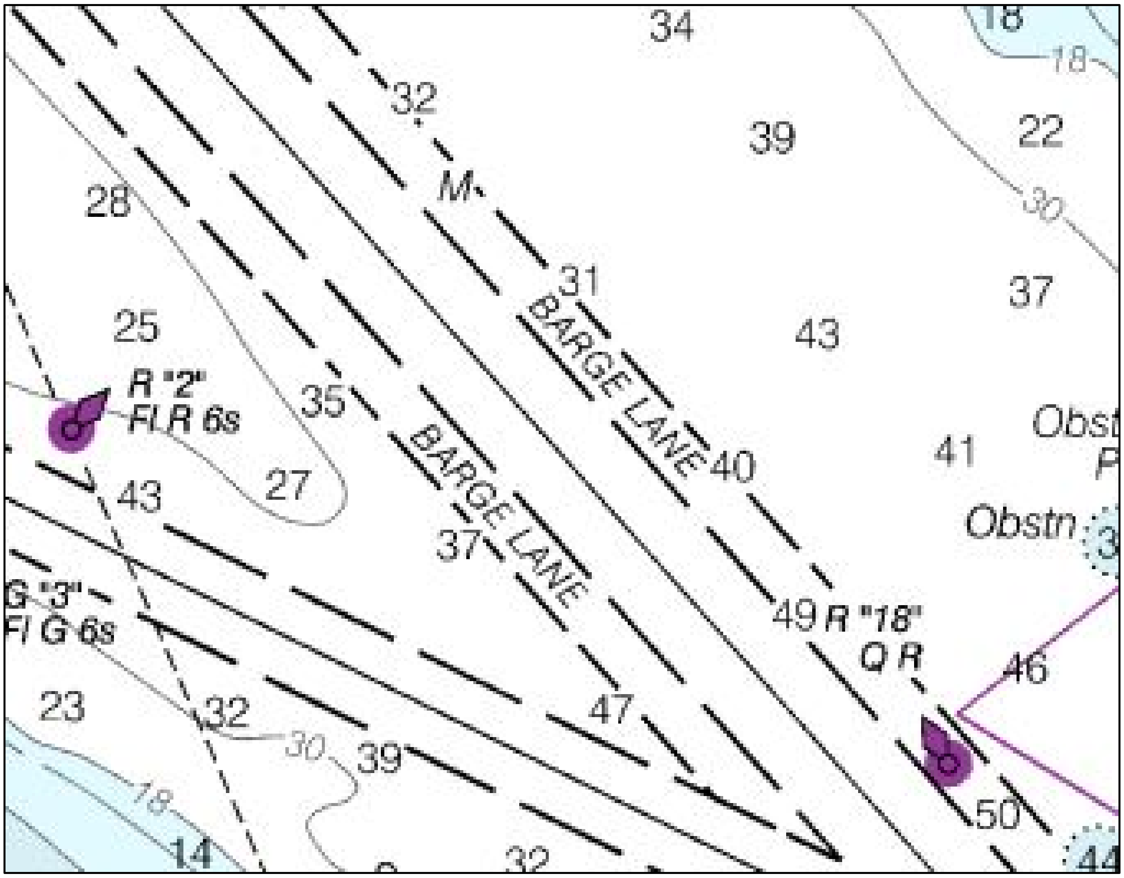


Figure 19: Houston Ship Channel Plan View

To protect the study area from a storm surge event, a floodgate complex is proposed for this region of the study area. The gate complex, referred to as the "Bolivar Roads Gate" would span the area between Galveston and the Bolivar Peninsula. The gate opening would be approximately 840 feet wide in accordance with USACE document EM 1110-2-1100, Coastal Engineering Manual – Part V, Figure V-5-24 (see Figure 20 below) for two-way traffic channels. In conjunction with Figure 20, Table 9 excerpted from the same USACE document describes the criteria for deep-draft channel design. Based on these two references and considering a maximum beam of 161 feet for largest navigating ship that may arrive at Port of Houston, the total channel width would be approximately 840 feet.

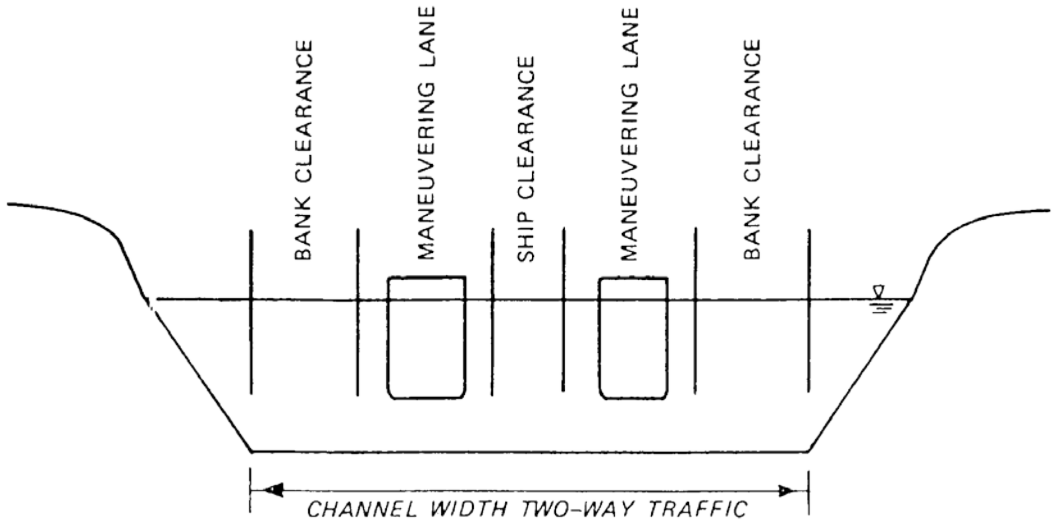


Figure 20: Recommended Channel WidthV-5-24 from - USACE EM 1110-2-1100

Table 9: Criteria for Deep Draft Channel Width Design

	Vessel Controllability			
Location	Very Good	Good	Poor	Channels with Yawing Forces
Maneuvering lane, straight channel	1.60	1.80	2.00	Judgment2
Bend, 26-deg turn	3.25	3.70	4.15	Judgment2
Bend, 40-deg turn	3.85	4.40	4.90	Judgment2
Ship clearance	0.80	0.80	0.80	1.00 but not less than 30 m (100 ft.)
Bank clearance	0.60	0.60+	0.60+	1.50

[1] Criteria expressed as multipliers of the design ship beam; i.e., W = (factor from table) × B

[2] Judgment is based on local conditions at each project.

Figure 21 below shows a breakup of the proposed 840-foot width of the anticipated navigable gate based on the design requirements stated in the USACE document.

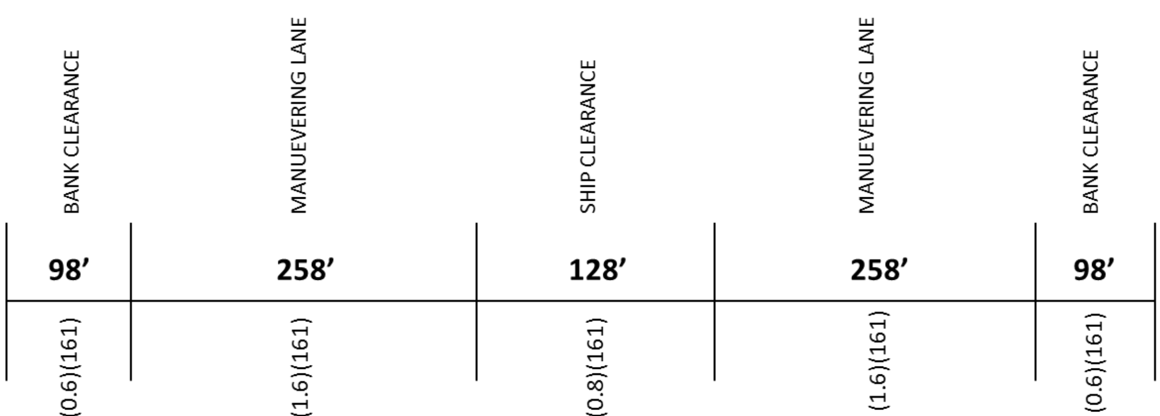


Figure 21: Channel Width Calculation

5.1.4. Neches River Gate

The mouth of the Neches River is the gateway to the Port of Beaumont. Three major rail carriers, five major roadways, the Gulf Intracoastal Waterway, and global steamship lines converge at this port. The ship channel (Figure 22) is 400 feet wide and 40 deep. The maximum height above sea level (air draft) allowed is 136 feet.

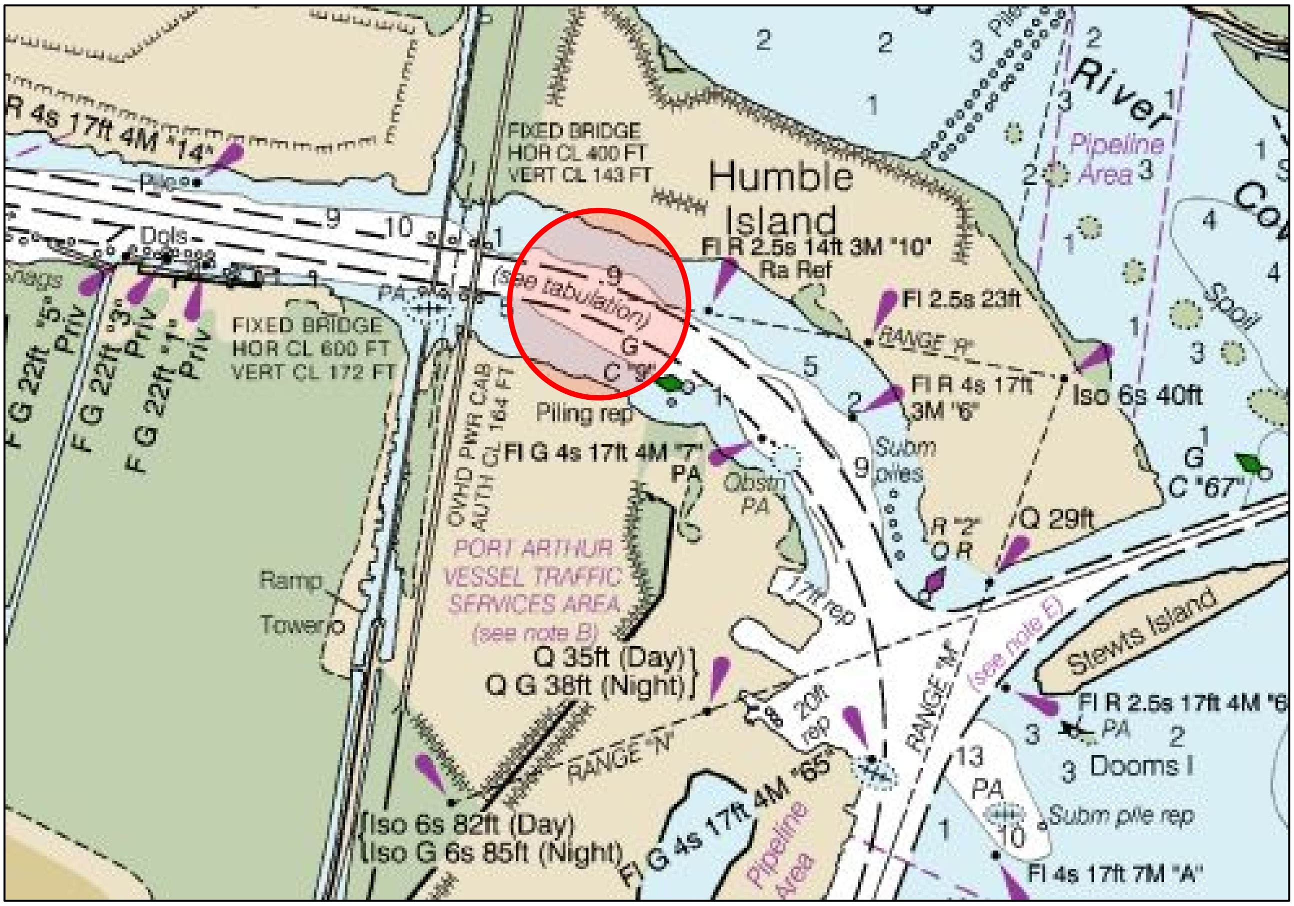


Figure 22: Mouth of the Neches River from NOAA Bathymetry Chart 11342

To protect the study area from storm surge, a floodgate complex is proposed to span the area at the mouth of the Neches River. The gate opening would be approximately 250 feet wide, considering a maximum beam of 145 feet, and a total of 105 feet clearance on both sides, assuming that, for large vessels, one-way traffic would apply.

5.2. Gate Selection

Proposed gate structures were selected through careful consideration of the respective channels, their structure, and the associated navigation. A horizontally rotating flood barrier was deemed suitable due to the constraint of restricting a large width of the Galveston Bay channel through Bolivar Roads. More precisely, a floating sector gate was selected due to its precedence (Maeslantkering in the Netherlands) to serve as a flood protection barrier for a wider channel (1200 feet) compared to Bolivar Roads. Traditional sector gates, rotating on a hinge-pintle connection placed on a king pin, were considered. However, these sector gates are not capable of providing flood protection for widths larger than 200 to 250 feet, due to cantilever-type construction that causes excessive dead load deflection towards the barrier face. Other sector gates are supported by wheels on the barrier side that traverse rail that arcs along the travel way. Wheeled gates present significant operations and maintenance concerns and are, therefore, similarly unsuitable for high traffic channels where reliability is critical. In addition, a portion of the regular sector gate is always submerged in water, while a floating sector gate can be rested in dry dock, inhibiting corrosion and debris accumulation and facilitates easy maintenance.

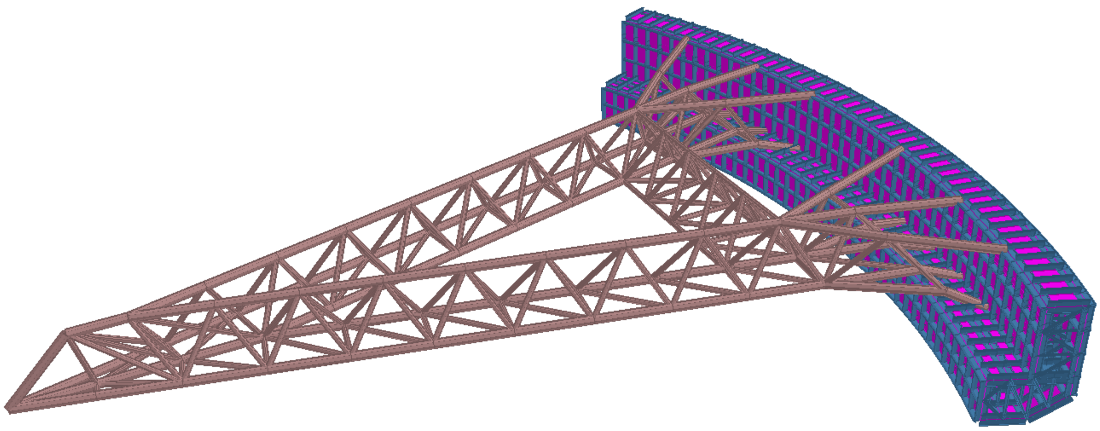


Figure 23: 3D Model of Floating Sector Gate

The Neches River barrier location is ideal for a traditional sector gate. A 250-foot-wide sector gate would provide sufficient clearance for safe passage of navigation traffic within the channel. The width of the channel is significantly smaller than Bolivar Roads and does not warrant installation of a floating sector gate.

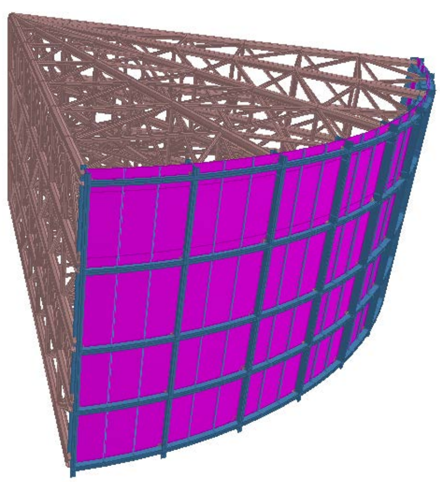


Figure 24: 3D Model of Regular Sector Gate

Vertical Lift Gates (VLGs) are not considered to be appropriate for the two barrier locations because these primary flood protection structures would not provide uninhibited vertical clearance for the safe passage of navigation traffic within the channel. Additionally, the widths and free height of the required vertical lift gate in these locations is structurally inefficient and costly. However, this type of gate has potential for serving as an environmental flow control structure to maintain the regular water velocity and tidal prism through the flood barrier. Installation of such flow control gates will ensure that the velocity through the main navigable gate is within the limits that would allow for safe navigation by vessel traffic. Additionally, these gates would ensure that marine and aquatic species have adequate space to pass through the barriers and thereby ensuring ecological balance between flood and protected side of the barrier. Within the current preliminary design, the Bolivar Roads Gate location will feature twenty–five VLGs with 100-foot-wide openings. The width of the flood control barrier for the Neches River Gate is much less compared to the Bolivar Roads Gate. The proposed sector gate in Neches River Area will accommodate four 50-foot–wide VLGs for flow control.

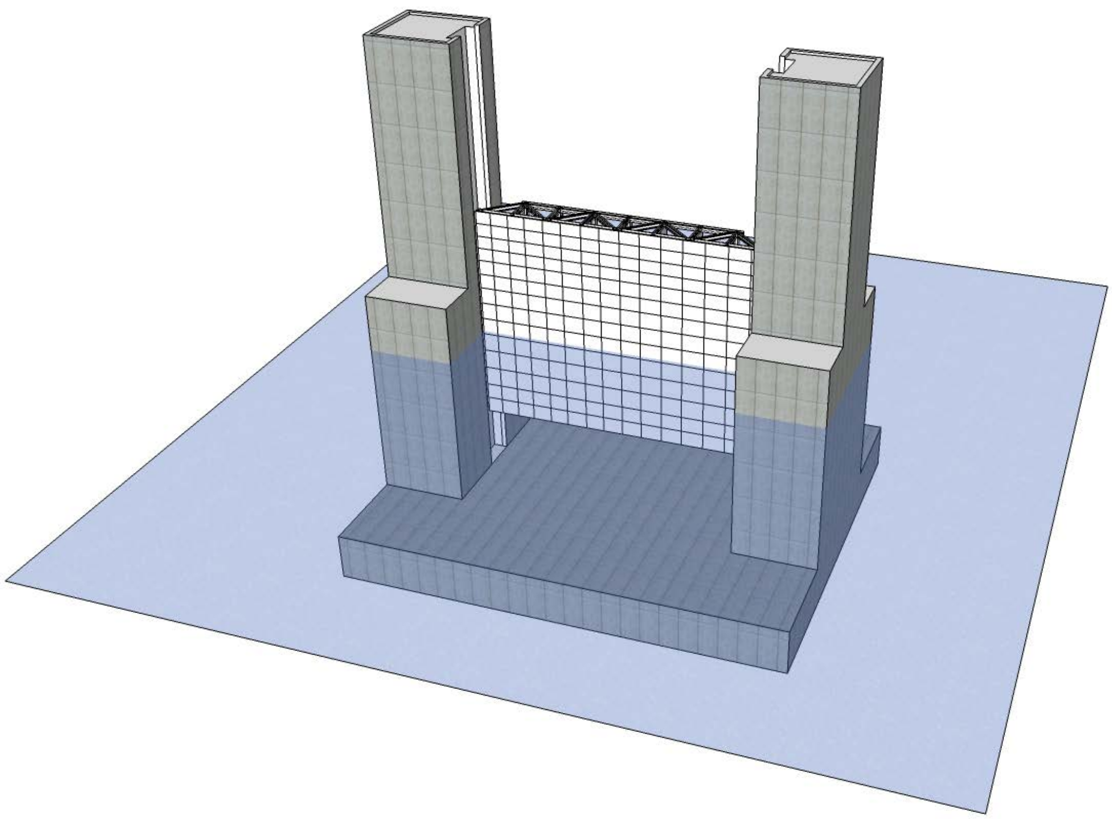


Figure 25: 3D Model of Vertical Lift Gate

5.3. Gate Cost Analysis

Unit cost for all proposed structures was determined for the purpose of the feasibility study to include the large sector gates. Since the large gates at the Bolivar Roads channel and Neches River location are unique relative to the vast majority of the levee reaches, separate more detailed cost values were calculated.

Typical reaches are comprised of relatively common structures with significant precedent in construction cost available through vast repetition in similar existing project areas like Louisiana and Texas. Large gates are much less common and therefore, "comparable" costs are generally less available. Additionally, the unique locations for these megastructures, in terms of adjacent existing infrastructure and resources like dry docks and dredge fill, must be considered. The relative location of steel mills and foundries that are able to manufacture unique and/or very large steel products can greatly affect constructed cost. The unique environmental conditions at these sites also require more detailed consideration as in the case of maintenance of the existing currents and tidal prism. Therefore, the more detailed effort for the large gates of this study is an effort to more reliably capture the unique costs for these particular large gate locations.

At the Bolivar Roads location, separate cost values were calculated for the following items:

1. Two leafs of the floating sector gates
2. Two artificial islands to be used for supporting the gates
3. A single 100-foot opening VLG
4. 100 feet of Combi-wall

The final cost of all VLGs within the location were calculated by multiplying the unit cost by total number of VLGs used, which is twenty-five. Similarly, the total cost of combi-wall can be found by extrapolating from the cost of 100 feet of the wall. Based on the opening width at Bolivar Roads, 5,500 feet of combi-wall is needed after placing the floating sector gate and the 25 VLGs. Similar unit costs for the following items were calculated for the Neches River location:

1. A sector gate with 250-foot opening
2. A VLG with 50-foot wide opening
3. 100-foot-long stretch of combi-wall

The total cost of VLG would be calculated by multiplying the unit cost by the total number of VLGs which is four. Similarly, the cost of combi-wall needed would be determined based on the 100-foot cost of such walls.

The details of these unit costs with break-down of the constituent material costs along with labor and installation can be found in the Appendix G.2. Based on these cost calculations, the project costs for deploying flood barriers at both Bolivar Roads and Neches River Gate location are shown below.

Table 10: Construction Costs for the Galveston and Neches River Gates

Location	Cost
Galveston Bay Gate	$3,874,220,262
Neches River Gate	$635,318,607

Appendix E provides more specific information associated with the gate modeling and analysis.

6. Cost Estimation

6.1. Cost Estimation Methodology

Due to the large study area and vast array of measures analyzed, cost estimates employed standardization and simplification techniques to ensure a like comparison of measures across the full array of alternatives. A large library of unit and lump sum costs was assembled from recently constructed hurricane protection projects from the Gulf Coast region. The library was standardized for all subgroups of the analysis team to employ, and then each subgroup applied the unit and lump sum cost library values to the alternatives under their charge. In some cases, such as calculating earthen levee fill costs, technology allowed for the quick calculation of actual quantities over a varying terrain surface and the application of a unit cost. In other cases of complex structures such as the medium and small navigation gates, a sufficient history of similar structure construction costs existed from which the team was able to aggregate and simplify costs for such structures into a single lump sum unit cost that encompasses all aspects of construction and installation. Appendix G.1 details the methodology associate with the development of cost estimates by particular structure. Appendix G.2 detail the costs associated with each respective alternative and gate structures.

6.2. Data Cost Library Description

The data cost library assembled was used across all elements of the analysis team in order to standardize assumptions of cost and reporting. The library is constructed in a manner that applicable unit costs for a given structure type or quantity may be accessed and manipulated to include contingency and the quantity of the cost item required. Structures were identified and sized for the proposed alignments to provide protection from the 2085 1 percent AEP storm surge event. Structures were categorically separated into highways crossings, railroad crossings, gravity drainage structures, navigable gates, and pumping stations, as discussed in the sections below. The cost library contains all the structural protection elements from which unit costs were derived.

6.2.1. Development of Cost Elements

Development of cost was based primarily on collection and evaluation of existing feasibility studies, design reports, and construction bid data for projects recently constructed or proposed along the Gulf Coast, primarily in neighboring Louisiana. A library of relevant structure and unit costs was compiled from the data sources listed below.

- Morganza to the Gulf-Local Projects (Lafourche and Terrebonne Parishes, LA);
- Larose to Golden Meadow Flood Protection Project (Lafourche Parish, LA);
- Southwest Coastal LA Feasibility Study (St. Mary and Iberia Parishes, LA);
- Calcasieu Lock Feasibility Study (Calcasieu Parish, LA);
- Donaldsonville to the Gulf Feasibility Study (Lafourche and St. Charles Parishes, LA);
- Hurricane Protection Master Plan-Lafourche Basin Levee District (Lafourche Parish, LA);
- New Orleans Federal Hurricane Storm Damage Risk Reduction System, HSDRRS (Orleans, Jefferson, St. Bernard, and Plaquemines Parishes, LA).

Costs were updated to 2015 prices using the United States Army Corps of Engineers' Civil Works Construction Cost Index System, Amendment No. 6 (March, 2015) into a cost menu from which the appropriate costs were used in this report. In the development of costs, more consideration was given to recently constructed projects than to engineer's estimates and costs used in other studies. All costs were also converted using the same USACE index to Texas-based coasts in instances that they originated from another region or state.

6.2.2. Contingency

For all costs in this report, a 25 percent contingency was added to account for the vast array of uncertainties and unforeseeable market changes which could occur in the near future and drive present-day costs up beyond the rate of inflation. Exceptions were made for the Houston Ship Channel and Neches River gates, where a 40 percent contingency was used due to the extreme complexity and rarity of such structures. The analysis team, after consultation with stakeholders and with technical experts, believed this conservative value was in order for civil works projects such as the proposed levee alignments in this report.

6.3. Development of Quantities for Levee and T-wall Sections

The team assumed a standard earthen levee cross sectional template for all alignments, with the exception of the Coastal Spine alignment. The team assumed the borrow areas with suitable material would be located within 10 miles of the alignment, except for the Coastal Spine alternative, which assumed suitable borrow was located within 30 miles of the alignment footprint. In many cases, adjacent material to the footprint may be suitable for levee construction. The design team accounted for sea-level rise and minor regional subsidence over the planning horizon to help determine an overbuild value.

6.3.1. Proposed Levee Profile

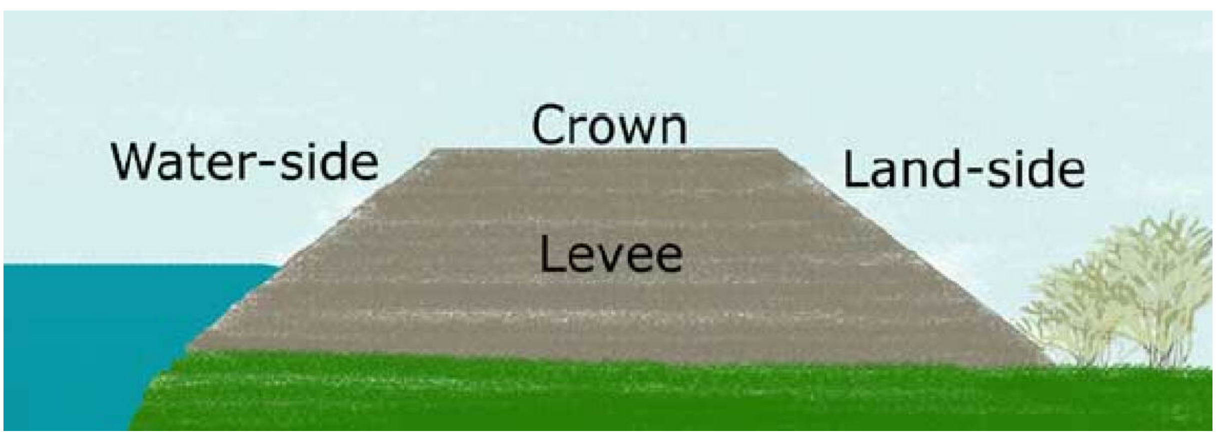


Figure 26: Typical Levee Section

All levees were analyzed with 4H:1V slopes on the flood side, with 3H:1V slopes on the protected side, and with a 12-foot crown width for vehicular access. Generally, slopes steeper than 3H:1V are difficult to maintain due to accessibility for mowing equipment and potential runoff erosion. On the flood side, 4H:1V slopes were chosen so that minimal armoring is required to mitigate the potential erosion due to wave action or water run up. The Coastal Spine alignment subscribes to this same geometry with the exception that a 20H:1V wave berm was assumed on the flood side due to the increased wave climate the levee would experience along the barrier shoreline of the Gulf of Mexico. All levee profiles were assumed to have 10-20 feet of ROW cleared parallel to the toes of the levee. Additional ROW could be needed for future levee lift events to address future conditions. In this case, additional land acquisition and mitigation costs could be incurred that are not quantified in this report. Existing ground surface elevations were taken from publically available LiDAR datasets and were used to create a three-dimensional point field of data, over which existing ground and future levee surface elevations could be assessed to calculate fill volumes.

6.3.2. Proposed Floodwall Profile

Where existing right of ways were optimum for barrier alignment but restrictive in terms of available land, reinforced concrete T-walls were employed. Generally, T-walls are most usefully employed in urban landscapes where extensive land acquisition, as in the case of earthen levees, may be prohibitive.

The relative profile of the study T-walls was derived from Army Corps of Engineers Engineering Manual standard designs along with anecdotal designs from coastal Louisiana. Typical floodwalls are comprised of a reinforced concrete footing typically supported by steel H-piles or pre-stressed concrete piles. A steel sheet pile cut off wall is also installed under the footing to prevent seepage of surge side water under the footing to the protected side. A reinforced concrete stem wall extends, usually from the approximate center of the concrete footing, to the necessary flood design height. For the purposes of this study typical T-wall profiles are assumed to have a 20 foot wide footing, or base, with a 10 foot inspection right of way to either side for a total of 40 feet.

Floodwalls built within existing waterways were assumed to have a different profile since T-walls are not conducive to in water construction. Waterway floodwall profiles consist of a "combi-wall" system made up of vertically driven steel or concrete sheet piles. The vertical sheets are capped with reinforced concrete which also serves to connect the wall to lateral bracing piles.

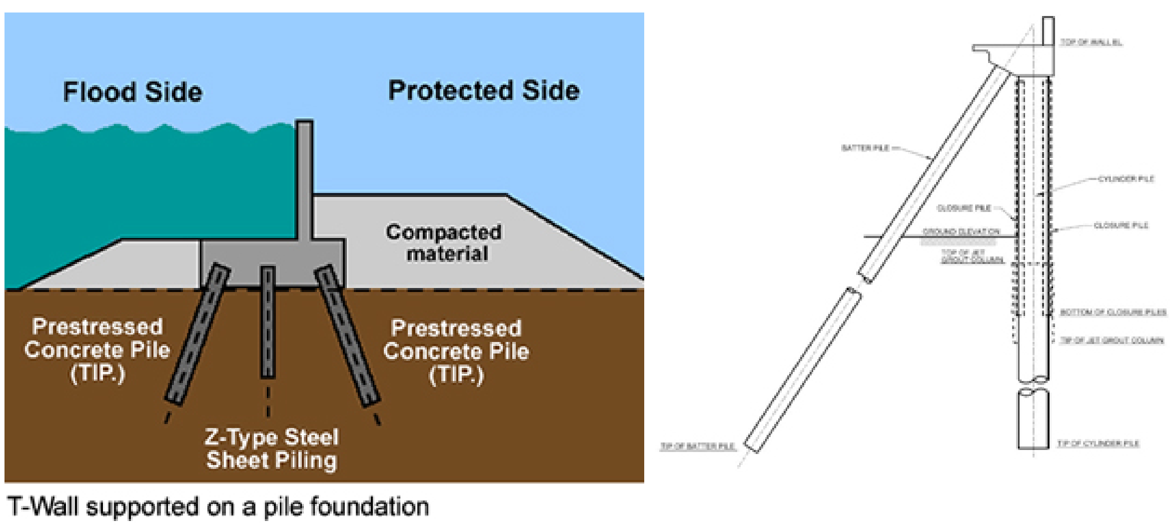


Figure 27: T-Wall and Combi-wall Sections

6.3.3. Highway and Railroad Crossings

All highway crossings identified would be served by swinging roller gates or raised earthen ramps over the protection system, depending on space requirements. Gates would remain open year-round and be closed only upon impending landfall of tropical events. Unit costs were calculated to include the accompanying tie-in and receiving structures and range from $3.5M for two-lane closures up to $17.0M for multi-lane Interstate Highway closures.

All railroad crossings identified would be served by swinging roller gates, which are widely used as part of the USACE's HSDRRS. Gates would remain open year-round and be closed only upon impending landfall of tropical events. Unit costs were calculated to include the accompanying tie-in and receiving structures and range from $3.6M for a single track closure to $6.0M for multi-track closures.

6.3.4. Drainage Structures

A uniform thru-levee vertical lift/sluice gate structure was assigned to preserve sufficient channel cross section for gravity drainage. As stated previously, many areas to be protected are served by a gravity drainage system. Multiple thru-levee drainage structures would be required to maintain gravity flow during non-tropical rain events, while allowing the levee system to be closed during storm surge events. This is necessary to protect the interior areas from surge backflow in gravity drainage canals. This gate type was broken out into three categories: less than 500 cfs capacity, 500 to 1,000 cfs capacity, and greater than 1,000 cfs capacity, with costs ranging from $2.5M to $11.7M respectively. Unit costs were calculated to include the accompanying tie-in and receiving structures.

6.3.5. Navigable Gates

Navigation gates are intended to remain open year-round to maintain continuous navigation and gravity stormwater runoff drainage. It is anticipated that they would only be closed during impending tropical events. Unit costs were calculated to include the accompanying tie-in and receiving structures.

6.3.5.1. Large Navigation Gate

Large channel navigation gates would be required on the Houston Ship Channel, and Neches River, within the Coastal Spine and the Neches River Crossing Alignments. The Houston Ship Channel gate is assumed to have a sill depth of -60 feet and a channel opening width of 840 feet. It is proposed as a floating sector gate across the navigation channel which would be flanked by a combi-wall and twenty-five 100-foot wide vertical lift gates to maintain the tidal prism. The Neches River gate is assumed to have a sill depth of -52 feet and a channel opening of 250 feet. It is proposed as a traditional sector gate across the navigation channel which would be flanked by a combi-wall and four 100-foot wide vertical lift gates to maintain the tidal prism. Both gates would provide sufficient cross section to maintain present navigation requirements as well as to cope with proposed future channel deepening projects. Gates would only be closed during impending tropical events.

6.3.5.2. Small Navigation Gate

Smaller channel navigation gates would be required on multiple smaller canal crossings within the proposed Galveston Ring/ SH 146, Coastal Spine, South, and North Alternative Alignments. Similar to the large navigation gate methodology, locations were refined based on identification of navigation infrastructure and evidence of recreational boating activity through satellite aerial analysis. Because most of the channels requiring small navigation gates were of similar geometry, uniform opening widths of 30 feet and 56 feet. Swing barge and sector gates were chosen with an 8-14-foot sill depth. These sizes were assigned to provide for adequate navigation and to maintain channel cross section for gravity drainage. A unit cost of $18.3M was assumed for all 30-foot barge gate locations. A unit cost of $40.0M was assumed for all 56-foot sector gate locations.

6.3.6. Pumping Stations

The addition of levees, T-walls and gate structures would interrupt the existing drainage patterns and in some cases pump stations would need to be added to the system to ensure flooding does not occur on the backsides of the levee's when the system is closed for tropical events.

Recommendations for development of costs associated with pump stations were taken from the Calcasieu Lock Replacement Feasibility Study – Value Engineering Study Report, August 2012, and the actual costs for similar projects recently constructed in South Louisiana. This study recommends using a $16,000 per cfs cost for pump station construction cost estimates based on average cost data from the data library.

6.3.7. Levee Sections

Borrow material unit costs were developed by evaluating bid tabs from numerous recently constructed levee projects and recently conducted planning studies in nearby Coastal Louisiana. An average unit cost for borrow of $33 per cubic yard was determined to be the most probable unit cost for the fill of the new levees. An exception was made for the Coastal Spine alternative, which assumed a unit cost of $40 per cubic yard due to increased haul distances to the project area from the mainland. In future levels of geotechnical investigation, adjacent areas and materials may be deemed suitable for levee construction. In these cases, the unit cost of material would be greatly decreased.

6.3.8. Floodwall Sections

T-wall costs per unit foot were developed by evaluating other coastal barrier studies and bid tabs for similar constructed projects in nearby Coastal Louisiana. T-walls were a necessary component of some of the optimum alternative alignments where real estate is at a premium like the Galveston Ring Levee. When compared to earthen levees, T-walls are significantly more expensive and have a significant impact on the overall benefit to cost ratio. The team leveraged GIS technology to accurately capture the variance in cost for walls of varying heights. T-wall cost varied between $5,500 a linear foot for a height of 10 feet to $20,000 a linear foot for a height of 25 feet or greater.

6.3.9. *Real Estate, Right-of-Way, and Structures*

The RE group adhered to Federal rules and regulations as it pertains to "relocation costs" as required under the Uniform Relocation Assistance and Real Property Acquisition Policies Act that Congress passed in 1970, and amended in 1987. The Code of Federal Regulations (CFR), Title 49, Part 24 is applicable to all Federal, State and local government agencies, as well as others receiving Federal financial assistance for public programs and projects, that require the acquisition of real property, must comply with the policies and provisions set forth in the Uniform Act and the regulation.

The RE group utilized several sources of information to arrive at their fair market valuation cost per acre of properties that are in the general categories noted immediately below.

Rural		
Agricultural and Undeveloped	Ac	$4,792
Urban		
Commercial	Ac	$730,501
Governmental	Ac	$732,679
Utility Company	Ac	$9,583
Industrial	Ac	$285,754
Residential		
Mobile Home	Ac	$60,113
Multi-family	Ac	$524,898
Single Family	Ac	$1,405,681
Vacant Property	Ac	$569,329
Railroad Property	Ac	$9,600,000
Relocation Costs	Parcel	$6,000

6.3.10. *Pipelines and Utilities Crossings*

The entire project area is traversed by a great number of oil and gas transmission pipelines as well as public utilities such as water and sewer lines. For the reaches of sufficient geometry, no further actions or costs were assumed. For reaches that are currently insufficient to defend against the 2085 1 percent AEP storm event, crossings were identified through an examination of data available from the Texas Railroad Commission Pipeline Database, the Texas General Land Office Pipeline Database, and the Texas General Land Office Electric Reliability Council of Texas Transmission Line Database. A unit cost of $250,000 was assigned to each crossing based on research of similar constructed or studied projects.

6.3.11. *Environmental Mitigation Elements*

This section describes the cost of environmental mitigation elements for the proposed alternatives. Mitigation cost estimates were determined for all NWI waters and threatened and endangered species critical habitat impacts identified under Sections 4.1.8 and 4.1.4 respectively. The impacted NWI acreage was separated into the following categories:

1. Freshwater Forested and Shrub Wetland
2. Freshwater Emergent Wetland
3. Freshwater Pond

4. Estuarine and Marine Wetland
5. Riverine
6. Lakes
7. Estuarine and Marine Deepwater
8. Other Freshwater Wetlands

Appendix F provides a breakdown for each alternative and individual reach for each of the categories. Table 11 is a summary of the all the environmental impacts and their total mitigation costs associated with each alternative and individual reach.

Table 11: Environmental Impacts and Mitigation Costs by Alternative and Reach

Alternative	NWI Wetland Acres	NWI Riverine Linear feet	Piping Plover Critical Habitat Acres	Total Mitigation Cost Estimate
		North Region Alternative 1		
Sabine River Levee	212.32	1,036		$56,317,125
Neches River Crossing	15.99			$4,292,188
Port Arthur Federal System	4.58	328		$5,854,750
North Region Alternative 1 Totals	**232.89**	**1,364**	**0**	**$66,464,063**
		North Region Alternative 2		
Sabine River Levee	212.32	1,036		$56,317,125
East bank Neches River	231.64	165		$63,589,563
Port Arthur Federal System	4.58	328		$5,854,750
West Bank Neches River	111.06	5,433		$32,384,313
North Region Alternative 2 Totals	**559.6**	**6,962**	**0**	**$158,145,751**
		Central Region Alternative 1		
Coastal Spine Totals	**303.35**	**0**	**47**	**$69,074,378**
		Central Region Alternative 2		
Galveston Ring Levee	48.59			$12,967,188
Texas City Extension North	33.79			$9,613,375
Texas City Extension West	15.50	798		$4,913,313
Texas Federal System	24.12	4,358		$10,102,375
Central Region Alternative 2 Totals	**122.00**	**5,156**	**0**	**$37,596,251**
		South Region Alternative 1		
Freeport Federal System	37.03	5,405		$15,378,876
Freeport Extension to Angleton	11.97	882		$3,744,563
South Region Alternative 1 Totals	**49**	**6,287**		**$19,123,439**
		South Region Alternative 2		
Freeport Federal System	37.03	5,405		$15,378,876
Freeport Extension to Angleton	11.97	882		$3,744,563
Jones Creek Levee	22.45			$5,472,188
Jones Creek Terminal Levee	29.39			$7,163,813
Chocolate Bayou Levee	29.05	209		$7,906,625
South Region Alternative 2 Totals	**129.89**	**6,496**	**0**	**$39,666,065**

7. Economic Modeling

7.1. Economic Modeling Approach and Methodology

This economic analysis was prepared in general accordance with policies and practices of the US Army Corps of Engineers (USACE.) As such, Engineering Regulation (ER) 1105-2-100, Planning Guidance Notebook, and ER 1105-2-101, Planning Guidance, Risk Analysis for Flood Damage Reduction Studies provide the framework for the analysis. The National Economic Development Procedures Manual for Flood Risk Management and Coastal Storm Risk Management, prepared by the USACE Water Resources Support Center, Institute for Water Resources, was also used as a reference.

The analysis estimates the National Economic Development (NED) damages and benefits for existing and future conditions, and all cost required for implementation of project alternatives. The NED benefits included in the analysis represent the reduction of potential damages caused by inundation. Inundation damage categories included are the physical damages to structures (residential, commercial, and industrial), the associated structure contents, and the privately owned vehicles associated with residential structures. In addition to the reduction in physical damages, the analysis also includes as a benefit the avoided cost of debris removal associated with physical damages to residential and commercial structures. As indicated above, damages included in the analysis consider both existing and future conditions. Consequently, projections of future development are incorporated as part of the future condition analysis, as are projections of relative sea level rise.

The analysis reports damages and costs at 2015 price levels. Damages were converted to equivalent annual values using the Federal Fiscal Year 2016 discount rate of 3.125 percent and a period of analysis of 50 years. The year 2035 was identified as the base year, year 1 of the period of analysis, with a subsequent end year of 2085.

As this analysis only addresses NED damages, the treatment of regional economic impacts, both with and without implementation of project alternatives, would be addressed in the next phase of reporting.

7.2. Description of the Hydrologic Engineering Center-Flood Damage Analysis Model

The USACE Hydrologic Engineering Center-Flood Damage Analysis Model (HEC-FDA) version 1.2.5a was the tool used to compute damages. HEC-FDA is an interdisciplinary program used to formulate and evaluate flood damage reduction plans. HEC-FDA addresses the USACE requirement for incorporation of risk analysis procedures in the formulation and evaluation of flood damage reduction measures. To address risk analysis HEC-FDA makes use of Monte Carlo simulation with probability distributions, as opposed to point estimates, to define the major variables of the damage analysis. Monte Carlo simulation is a numerical-analysis procedure that facilitates the computation of expected value of damage while explicitly accounting for the uncertainty in the basic parameters used to determine flood damage.

HEC-FDA performs economic (flood inundation damage analysis) and hydrologic engineering performance calculations for plan evaluations. The basic inputs to HEC-FDA contain information on: analysis years (points in time over the 50-year period of analysis to be evaluated); damage categories; damage reaches (the geographic boundaries of reported model output); an inventory of structures which includes depreciated structure replacement value and structure elevation; the relationship of content value to structure value by structure type; damage functions describing the susceptibility of structures and contents to varying depths of inundation; and stage-probability relationships which describe the annual probabilities associated with water surface elevations for a defined geographic area. The highest level of HEC-FDA economic outputs are expected value damage and equivalent annual damage. Expected annual damage is the probability-weighted expectation of damage in a given analysis year. Equivalent annual damage is the probability-weighted annual expectation of damage over the entire study period of analysis reflected as a single value by means of conventional present-value techniques.

7.3. Development of Benefit-to-Cost Ratios

7.3.1. Economic Inputs to the HEC-FDA Model

7.3.1.1. Analysis Years

Three analysis years were evaluated, 2015, 2035, and 2085. Year 2015 represents existing conditions, while years 2035 and 2085 represent the analysis base year and ending period of analysis year, respectively. As the base year, year 2035 represents year one of the 50-year period of analysis, and the common reference point for present value computations for all alternatives.

7.3.1.2. Damage Categories

Model output was generated for the following damage categories: residential, commercial, industrial, and debris removal. The residential category includes damages to the structure, damages to contents and damages to the associated vehicles for residential properties. The commercial and industrial damage categories include structure and contents damages. The debris removal damage category includes the debris removal costs associated with all residential and commercial properties.

7.3.1.3. Damage Reaches

A damage reach represents an aggregation of areas for which stage-probability relationships have been generated. County boundaries, physical landscape features, and clusters of development were considerations in defining the damage reaches.

7.3.1.4. Structure Inventory

County assessor data for 2014 was obtained for Brazoria, Chambers, Galveston, Harris, Jefferson and Orange Counties. These data provided an inventory of structures for each county. The county data included the following specific values of interest: structure location, property occupancy classification, and property square footage. To develop the structure inventory with the required HEC-FDA structure characteristics, the general steps described below were taken.

Step 1 - Overlay the study boundary on to the six counties. The study area was defined as the FEMA 500-year surge limits plus sea level rise over the period 2015 to 2085. Consequently any of the six-county properties located outside of the study area were removed from the HEC-FDA inventory.

Step 2 - Standardize county assessor occupancy codes. While the higher level classification of county assessor occupancy type is consistent across counties, the sub-classifications are not. It was therefore necessary to develop a consistent classification scheme for the sub-classifications.

Step 3 - Map county assessor occupancy codes to FEMA occupancy codes. The standardized county occupancy codes resulting from Step 2 were mapped to the 33 standard FEMA occupancy codes. This mapping was performed to facilitate computation of structure depreciated replacement values.

Step 4 - Compute depreciated replacement structure value. The commercial software RS Means was used to compute typical dollar per square foot depreciated replacement structure values (exclusive of land value) for each of the 33 FEMA occupancy codes.

Step 5 - Map FEMA occupancy codes to damage function categories. Each of the 33 FEMA occupancy codes was mapped to one of the five residential damage function categories or one of the eight commercial damage function categories.

Step 6 - Assign structure foundation heights and vehicle elevations. Foundation heights were assigned using FEMA standard values for foundation type (e.g. slab or pier) heights and Census block data on foundation type distribution. Vehicles elevations were assigned a value equal to the ground elevation of the adjacent residential structure.

Step 7 - Assign structures to a stage-probability area. Each structure was assigned to a geographic area represented by a stage-probability relationship.

Step 8 - Forecast future development inventory. Projections were made of the future residential and commercial development to take place in the study area under without-project conditions. County-specific population forecasts were used as a surrogate for growth in the number of both residential and commercial structures. (No growth in the size or number of industrial facilities was assumed.) The One-Half 2000-2010 Migration (0.5) Scenario population forecast taken from, *Projections of the Population of Texas and Counties in Texas by Age, Sex and Race/Ethnicity for 2010-2050* was used to forecast future development. This work was produced by The Office of the State Demographer, The Texas State Data Center in collaboration with The Hobby Center for Public Policy.

7.3.1.5. Content-to-Structure Value Ratios

Content-to-structure value ratios (CSVR) represent the ratio of total contents value to structure depreciated replacement value and provide the basis for computing the total contents value directly from the structure depreciated replacement value. CSVRs, which are damage function category specific, were taken from existing USACE investigations. Those investigations represented a series of on-site interviews with property owners conducted over the course of three separate storm risk management feasibility studies in coastal Louisiana.

7.3.1.6. Vehicle Inventory

The National Automobile Dealers Association (NADA) estimates for the U.S. average used vehicle price, along with US Census and Federal Highway Administration data to estimate the Texas average vehicles per household were used to compute total vehicle value per household. Total vehicle value per household was adjusted, according to the *Southeast Louisiana Evacuation Behavioral Report* published in 2006 following Hurricanes Katrina and Rita, to reflect the percentage of vehicles that would remain at the residence location as a household evacuates in the face of a storm threat.

7.3.1.7. Damage Functions

Saltwater, short duration (approximately one day) depth-damage relationships, developed by a panel of building and construction experts for structures and contents in support of the USACE's Lower Atchafalaya and Morganza to the Gulf, Louisiana Feasibility Study were used in the economic analysis. These relationships indicate the percentage of the total structure value that would be damaged at various depths of flooding

The depth-damage relationships for vehicles were taken from investigations performed for the USACE's Donaldsonville to the Gulf, Louisiana Feasibility Study. The damage relationships were developed based on interviews with the owners of automobile dealerships that had experienced flood damages.

7.3.1.8. Debris

Flood events typically generate large amounts of debris, the removal and cleanup of which generates economic losses. Debris removal and cleanup includes the collection, processing, and disposal of debris material. Thru the process of expert elicitation, the USACE report *Development of Depth-Emergency Cost and Infrastructure Damage Relationships for Selected South Louisiana Parishes, 2012,* estimated a damage function to relate debris removal cost to the depth of flooding in residential and commercial structures. The referenced report addressed the removal and cleanup costs associated with the following debris categories: vegetative; nonstructural, nontoxic building contents; sediment; hazardous waste; white goods (e.g. refrigerators and washing machines); vehicles, vessels, and tires; and electronic goods.

7.3.2. Engineering Inputs to the HEC-FDA Model

7.3.2.1. Ground Elevations

Light Detection and Ranging (LIDAR) topographical data was used to create a digital elevation model (DEM) to assign ground elevations for structures within the study area. The sum of ground elevation and foundation height represents the first-floor elevation for each structure.

7.3.2.2. Stage-Probability Relationships.

Stage-probability relationships for storm surge were generated for existing conditions (2015), and future-year without-project conditions (2035 and 2085), with future-year conditions reflective of the USACE

Intermediate Sea-Level Rise Scenario. Stage-probability relationships were also generated for with-project conditions for each alternative.

7.4. Benefit-to-Cost Ratios

Benefit-cost analysis is a technique used to evaluate, in monetary terms, the output achieved (the benefits) from a proposed action, and the expenditures required (the costs) to achieve the output. This analysis is used to verify that the value of the benefits exceeds the value of the costs and ensures that the resources are allocated in the most efficient manner possible.

Benefit to cost analysis involves two mathematical comparisons:

- Net benefits are calculated by subtracting the total economic costs from the total economic benefits. Alternatives with positive net benefits contribute to economic efficiency. In an unconstrained budget situation, an alternative with higher net benefits is superior to an alternative with lesser net benefits. This analysis can be used to help select and scale a recommended alternative from an array of alternatives.
- A benefit to cost ratio (BCR) is calculated by dividing the total economic benefits by the total economic cost. A BCR of 1.0 indicates that the total benefits equal the total costs. In other words, for every dollar spent, a dollar of benefits is produced. Because BCR analysis indicates which alternative produces the most benefits for every dollar of cost, it is useful for comparing or ranking alternatives.

Total Annual Benefits (TAB) – Total annual benefits represent the reduction in physical damages and/or the reduction in storm-induced debris removal expenditures expected over the period of project performance (2035 to 2085). TAB represents the economic benefits used in the calculation of the BCR for alternatives in this study.

Total Annual Costs (TAC) – Total annual cost are composed of annual construction costs plus annual operations and maintenance costs. Annual construction costs represent the amortized present value of construction expenditures, and as such include interest costs on all construction expenditures occurring prior to alternative implementation. Annual operations and maintenance costs represent the annual expenditures required for an alternative to perform as designed over the period of project performance (2035 to 2085). TAC represents the economic costs used in the calculation of the BCRs for alternatives in this study.

The following tables summarize the benefits, costs, net benefits (annual benefits minus annual costs) and benefit-to-cost ratios for each evaluated alternative. Table 12 factors in FY16 Federal Discount Rate for Civil Works Projects at 3.125% and Table 13 uses an extended rate at 7.0%

Table 12: Benefit-to-Cost Ratios ($ in Thousands; 3.125% Interest Rate)

Alternative	**NR#1** - *Neches River Navigation Gate*	**NR#2** - *Without the Neches River Navigation Gate*	**CR#1** - *High Island to San Luis Pass Coastal Spine*	**CR#2** - *Texas City Levee Modifications and Extensions North (SH-146) and West--Galveston Ring Levee*	**SR#1** - *Freeport Hurricane Flood Protection System Modernization and Extension North toward Angleton*	**SR#2** - *Freeport Hurricane Flood Protection System Modernization and Extension North toward Angleton- Jones Creek Levee, Jones Creek Terminal Ring Levee, and Chocolate Bayou Ring Levee*
Benefits						
Residential & Commercial	129,283	129,283	629,190	710,369	165,354	171,373
Industrial	6,176	6,176	381,861	502,266	18,437	32,231
Debris	5,418	5,412	18,348	18,293	2,792	3,049
Total Annual Benefits	140,877	140,872	1,029,399	1,230,928	186,583	206,654
Costs						
Construction	2,502,650	3,228,579	5,832,095	3,534,442	1,879,635	2,571,551
Annual Construction	124,619	160,767	290,409	175,442	94,493	128,050
Annual O&M	12,513	16,143	29,160	17,672	9,488	12,857
Total Annual Costs	137,132	176,910	319,569	193,669	103,981	140,907
Net Benefits	3,745	(36,038)	709,830	1,037,259	82,602	65,746
Benefit-to-Cost Ratio	**1.03**	**0.80**	**3.22**	**6.36**	**1.79**	**1.47**

Table 13: Benefit-to-Cost Ratios ($ in Thousands; 7.0 % Interest Rate)

Alternative	**NR#1 -** *Neches River Navigation Gate*	**NR#2 -** *Without the Neches River Navigation Gate*	**CR#1 -** *High Island to San Luis Pass Coastal Spine*	**CR#2 -** *Texas City Levee Modifications and Extensions North (SH-146) and West--Galveston Ring Levee*	**SR#1 -** *Freeport Hurricane Flood Protection System Modernization and Extension North toward Angleton*	**SR#2 -** *Freeport Hurricane Flood Protection System Modernization and Extension North toward Angleton- Jones Creek Levee, Jones Creek Terminal Ring Levee, and Chocolate Bayou Ring Levee*
Benefits						
Residential & Commercial	115,611	115,611	574,811	652,964	153,963	159,374
Industrial	5,547	5,547	358,414	470,795	17,775	30,675
Debris	4,879	4,872	16,781	16,800	2,542	2,773
Total Annual Benefits	126,307	126,030	950,005	1,140,559	174,279	192,822
Costs						
Construction	2,502,650	3,228,579	5,832,095	3,534,442	1,897,653	2,571,551
Annual Construction	303,796	391,916	707,956	429,045	230,353	312,160
Annual O&M	12,513	16,143	29,160	17,672	9,488	12,857
Total Annual Costs	316,309	408,059	737,116	446,717	239,841	325,017
Net Benefits	(190,272)	(282,029)	212,889	693,842	(65,562)	(132,195)
Benefit-to-Cost Ratio	**0.40**	**0.31**	**1.29**	**2.55**	**0.73**	**0.59**

Given the difficulty of predicting property owner response to predicted increases in future flood risk, the analysis makes no adjustments to the structure inventory.

7.4.1. Further Considerations - Refinement of Future Conditions Structure Inventory.

Flood risk as evaluated by HEC-FDA makes use of annual probabilities. As such, the expected value of future flood damages is estimated on the basis of damages for a range of specific events weighted by the probability of occurrence. The timing and severity of specific events is not incorporated into damage estimates, and certainly is not knowable.

For structures that reside in particularly high-risk areas, such as the 0 to 10-year floodplain, it is reasonable to expect the inventory of structures in that area to change over time under the future without-project condition. The incidence of flood events occurring closely together or by single-event severe flooding, while not predictable, has a higher chance of occurring in the 0 to 10-year floodplain. For this reason, some indefinite number of structures would be expected to change their location within the study area over time. This means that the owners of structures would undertake some mitigation of their own under without-project conditions. Mitigation options could include structure elevation, relocation, and floodproofing.

While it is reasonable to expect that that not all structures in the relatively high-risk floodplains would be subject to effective mitigation measures, to the extent that a significant number of property owners act to implement such measures, the estimate of future without-project damages is likely overestimated to some degree, as are estimates of project benefits.

8. Alternative Comparison

8.1 North Region Alternative Comparison

North Region Alternatives

Orange and Jefferson Counties

- ***North Region Alternative #1 (NR#1) -*** The Jefferson/Orange Protection System –with the Neches River Navigation Gate
- ***North Region Alternative #2 (NR#2) -*** The Jefferson/Orange Protection System –without the Neches River Navigation Gate

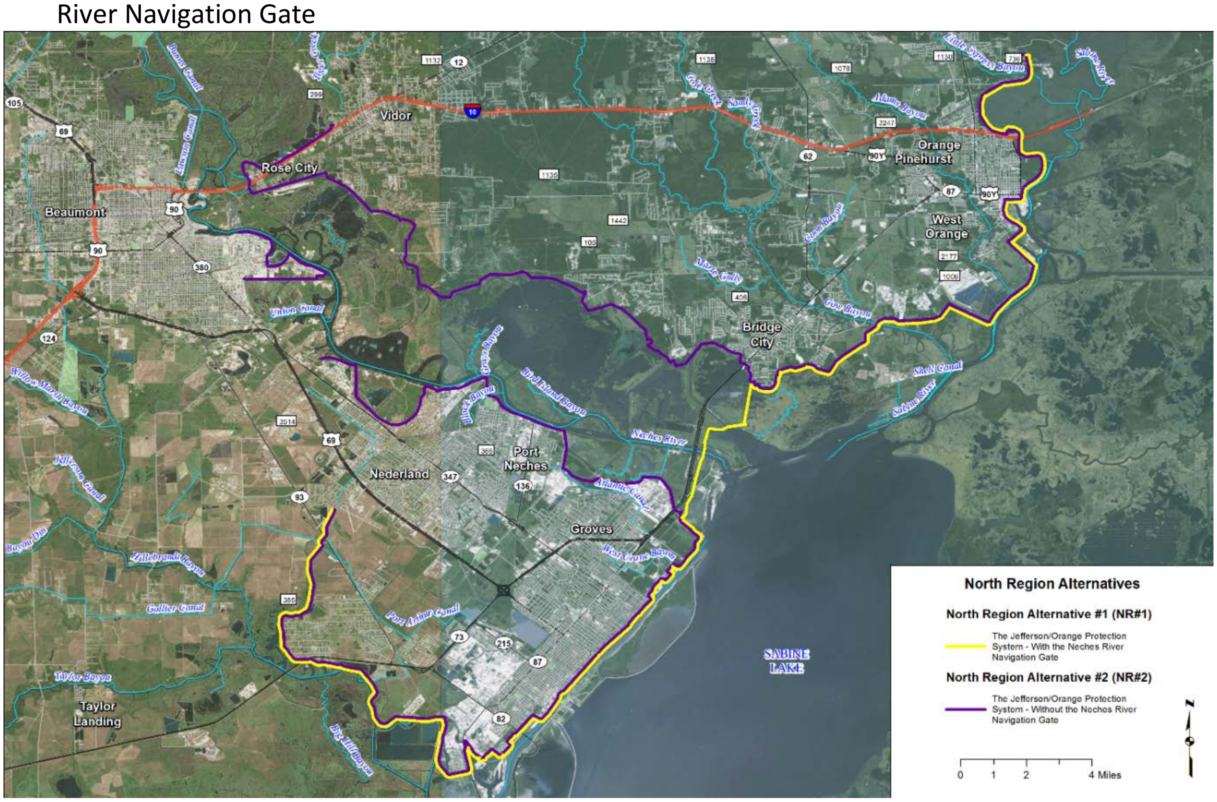


Figure 28: North Region Alternatives Selected for Development

Alternative NR#1 is a continuous protection system that would provide protection to the region by restricting storm surge from moving inland at the most reasonable forward point. The geography of the region does not permit a structure that would function as a coastal barrier, and the environmental impacts of such a structure would be extensive. Alternative NR#1 includes a 5,000 to 10,000-cfs pump station at the Neches River Gate to divert the flow of the river around the gate when the protection system is closed. Elevations within this alternative vary from 15 to 25.5 feet, depending on the existing geography with the region.

Alternative NR#2 is a fragmented system that protects Jefferson and Orange Counties individually through alignments along the Sabine and Neches River. This system does not include the Neches River Gate; resulting in a much longer line of protection. The longer line of protection increases the amount of right-of-way, mitigation, and pump stations required, which all affect the overall cost of construction. Elevations within this alternative vary from 15 to 25.5 feet, depending on the existing geography with the region.

Each alternative requires an upgrade of the existing Port Arthur Federal Levee System to higher elevations in order to remain effective given the projected conditions in 2085.

North Region Alternative Summary and Comparison	NR#1- *The Jefferson/Orange Protection System –with the Neches River Navigation Gate*	NR#2- *The Jefferson/Orange Protection System –without the Neches River Navigation Gate*
Total length of the system (miles)	55.2 miles	92.2 miles
Right of way required	612 acres	1,401 acres
Pump stations required / total capacity (cfs.)	7 / 25,711 cfs.	14 / 31,626 cfs.
Environmental mitigation required	232.89 acres	559.6 acres
Construction cost	$2,502,650,000	$3,228,580,000
Annual Operations and maintenance cost	$12,513,000	$16,143,000
Total Annual Costs (TAC)	137,132,000	1,76910,000
Total Annual Benefits (TAB)	$140,877,000	$140,877,000
Benefit - Cost Ratio (TAB/TAC) (3.125% Interest Rate)	**1.03**	**0.80**
Benefit - Cost Ratio (7.0% Interest Rate)	**0.40**	**0.31**

Alternatives NR#1 and NR#2 provide the same level of flood risk reduction and the same average annual benefits to the North Region. The total length of Alternative NR#2 is 60% larger than Alternative NR#1 which is driving up construction, right of way and mitigation cost without a corresponding increase in benefits. These increased costs without additional benefits are pushing the BCR for Alternative NR#2 below Alternative NR#1.

Alternative NR#2 has the advantage of being much easier to construct since it does not cross the Sabine Neches Waterway and would not have any impacts during construction on maritime activity. Additionally, Alternative NR#1 would require the US Army Corps of Engineers to closely manage river flow in the Neches River prior to and during a tropical event while the gates are close. Unmanaged flow could potentially create a flooding situation in the region behind the gates.

From a federal authorization and funding perspective, alternatives that have a BCR of 1.0 or greater are considered viable projects. In Phase 3, the team will look at Alternative NR#2 to see if there is a means to shorten the line of protection, reduce construction costs and preserve the existing benefits in order to increase the BCR.

8.2 Central Region Alternative Comparison

Central Region Alternatives

Galveston, Chambers, and Harris Counties

- ***Central Region Alternative #1 (CR#1)*** - High Island to San Luis Pass Coastal Spine
- ***Central Region Alternative #2 (CR#2)*** - Texas City Levee Modifications and Extensions North (SH-146) and West--Galveston Ring Levee

Figure 29: Central Region Alternatives Selected for Development

Alternative CR#1 is a continuous system that would provide protection to the region by restricting storm surge from moving inland at the coast. This alternative requires an exceptionally large navigation gate across the Houston Ship Channel at Bolivar Roads. Twenty-five vertical lift gates are proposed parallel to the navigational opening in order to maintain the environmental flow to the region's bay and estuary systems. Elevations within this alternative vary from 18.0 to 21.0 feet, depending on the existing geography with the region.

Alternative CR#2 is a series of separate systems that provide protection to the City of Galveston and the west side of Galveston Bay. This alternative would not provide direct protection to the upper reaches of the Houston Ship Channel. This alternative requires modifications and upgrades to the existing Texas City

Hurricane Protection System in order for the overall protection system to remain effective given the projected conditions in 2085. Elevations within this alternative vary from 19.0 to 27.0 feet, depending on the existing geography with the region.

Central Region Alternative Summary and Comparison	CR#1- *High Island to San Luis Pass Coastal Spine*	CR#2- *Texas City Levee Modifications and Extensions North (SH-146) and West--Galveston Ring Levee*
Total length of the system (miles)	55.6 miles	62.6 miles
Right of way required	1,220 acres	344.7 acres
Pump stations required / total capacity (cfs.)	0 / 0 CFS	13 / 61,611 CFS
Environmental mitigation required	303.35 acres	122.00 acres
Construction cost	$5,832,095,000	$3,534,442,000
Annual operations and maintenance cost	$29,160,000	$17,672,000
Total Annual Costs (TAC)	319,569,000	193,669,000
Total Annual Benefits (TAB)	$1,029,399,000	$1,230,928,000
Benefit - Cost Ratio (TAB/TAC) (3.125% Interest Rate)	**3.22**	**6.36**
Benefit - Cost Ratio (7.0 % Interest Rate)	**1.29**	**2.55**

Alternative CR#1 and CR#2 are two distinct alternatives and based on their alignments provide different levels of annual benefits. The annual benefits are greater for CR#2 and this can be attributed to the enhance level of protection that is provided to the City of Galveston and the west side of Galveston Bay by a system that effectively seals these areas from tidal surge. CR#2 is much less expensive than CR#1 and this combine with the higher benefits has resulted in an alternative with much higher BCR.

For CR#1, the modeling results shows a reduction in benefits for the City of Galveston and the Clear Lake Region. This indicates that flooding from the bay side of the city and flooding from the bay into Clear Lake is not totally attenuated. Adding additional structures to CR#1 to protect these regions will drive up the cost and generate a higher level of benefits while having and unknown impact to the BCR at this time.

From a federal authorization and funding perspective, both of these alternatives have BCRs that greatly exceed than 1.0 and are considered viable projects. In Phase 3, the team will engage the region stakeholders and reexamine NR#1 in order see if costs can be reduced further increase the BCR. One method of reducing cost would be to look at a different type of gate structure.

8.3 South Region Alternatives Comparison

South Region Alternatives

Brazoria County and Galveston County (vicinity of San Luis Pass)

- ***South Region Alternative #1 (SR#1)*** - Freeport Hurricane Flood Protection System Modernization and Extension North toward Angleton
- ***South Region Alternative #2 (SR#2)*** - Freeport Hurricane Flood Protection System Modernization and Extension North toward Angleton- Jones Creek Levee, Jones Creek Terminal Ring Levee, and Chocolate Bayou Ring Levee

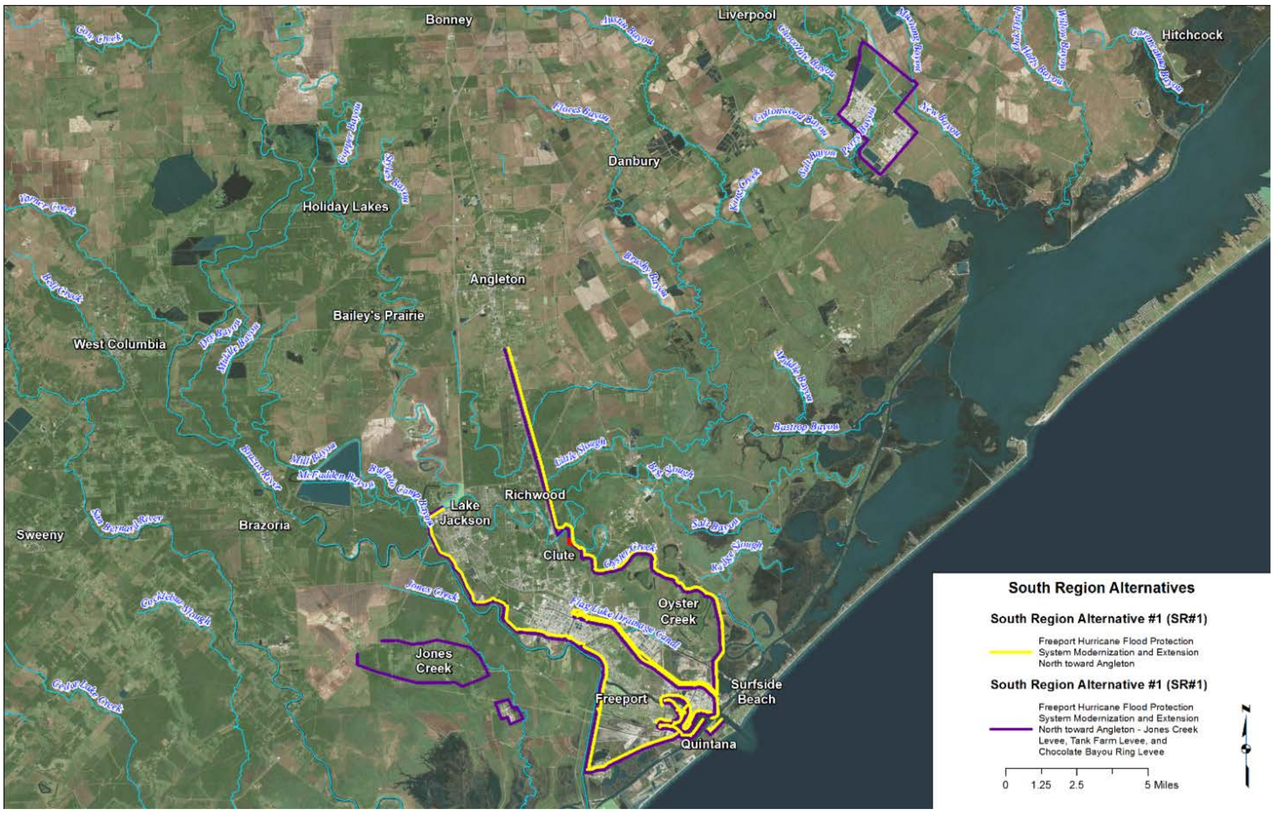


Figure 30: South Region Alternatives Selected for Development

Alternative SR#1 is a continuous system that would protect the Freeport-Angleton-Lake Jackson area from storm surge. This alternative consists mainly of the existing Freeport Hurricane Flood Protection System and outlines the requirements to enhance the system for conditions predicted in 2085. The system extends from Oyster Creek toward Angleton to avoid the risk associated with flooding overtopping and wrapping around the east side of the system in 2085. Elevations within this alternative vary from 17.0 to20.0 feet, depending on the existing topography with the region.

Alternative SR#2 includes all the components proposed in Alternative SR#1 in addition to three areas that are subject to storm surge flooding in 2085: Jones Creek, the Jones Creek Terminal, and the Chocolate Bayou petrochemical complex. These three new elements are separable and could stand alone but must be considered in the context of a regional protection plan.

Each alternative requires an upgrade of the existing Freeport Hurricane Protection System to higher elevations in order to be effective given the conditions in 2085.

South Region Alternative Summary and Comparison	SR#1 - Freeport Hurricane Flood Protection System Modernization and Extension North toward Angleton	SR#2- Freeport Hurricane Flood Protection System Modernization and Extension North toward Angleton- Jones Creek Levee, Jones Creek Terminal Ring Levee, and Chocolate Bayou Ring Levee
Total length of the system (miles)	49.1 miles	74.2 miles
Right of way required	73 acres	383 acres
Pump stations required / total capacity (cfs.)	2 / 2,500 CFS	5 / 11,460 CFS
Environmental mitigation required	49 acres	129.89 acres
Construction cost	$1,897,635,000	$2,571,551,000
Annual operations and maintenance cost	$9,488,000	$12,858,000
Total Annual Costs (TAC)	103,981,000	140,907,000
Total Annual Benefits (TAB)	$186,583,000	$206,654,000
Benefit - Cost Ratio (TAB/TAC) (3.125% Interest Rate)	**1.79**	**1.47**
Benefit - Cost Ratio (7.0 % Interest Rate)	**0.73**	**0.59**

Alternative SR#2 is a variation of SR#1 and includes three additional reaches which provides flood risk reduction for three outlying areas (Jones Creek Levee, Jones Creek Terminal Ring Levee, and the Chocolate Bayou Ring Levee). The additional of these three reaches has increased the overall benefits in SR#2 but also reduced the BCR and the net benefits, when compared to SR#1. This indicates that the additional cost of constructing these reaches is greater than the additional benefits.

From a federal authorization and funding perspective, SR#1 has a BCR greater than 1.0 which makes it a viable both viable alternative; however, the additional reaches are not currently viable. In Phase 3, the team will further examine the BCRs associated with the three additional reaches and look for a ways to further optimize the cost and benefits.

9. The Way Ahead to the Final Report

During Phase 3, the team will be conducting another series of public meetings to present the technical results and the alternatives that were developed in Phase 2. The team will be also be providing briefings to critical stakeholders and soliciting their feedback.

Additionally, the team will also be conducting an analysis of other economic impacts that affect the regional outside of the direct damages calculated in Phase 2. Lastly, the team will continue to review the data gathered in Phase 2 in more detail to optimize the developed alternatives looking for ways to reduce cost and gather additional benefits. This effort may require the team to access additional ancillary structures to support the existing alternatives and to increase regional protection and benefits.

9.1. Public Engagement

Three additional public meetings will be held in March on 2016 to solicited public feedback on the technical results of the study and the proposed alternatives. Public input is critical to the team's effort to making a decision on the final recommended alternatives to the GCCPRD Board in the final report. Subject to the approval of the Board, public meets are currently scheduled on the following dates and locations.

March 22, 2016
League City Civic Center
400 West Walker Street
League City, TX 77573
5 p.m. to 8 p.m.

March 24, 2016
Lake Jackson Civic Center
333 Highway 332 East
Lake Jackson, TX 77566
5 p.m. to 8 p.m.

March 29, 2016
Orange County Convention & Expo Center
11475 Highway 1442
Orange, TX 77630
5 p.m. to 8 p.m.

The team will also continue to collaborate with the US Army Corps of Engineers, Texas A&M University and the SSPEED Center at Rice University to review and share technical data and implement best practices into our final report.

9.2. Extended Economics Benefit Calculations

The economic model used in the Phase 2 report, HEC-FDA, is the model approved by the US Army Corps of Engineers (USACE) for calculating benefit-to-cost ratios (BCRs) for Civil Works Flood Risk Management Studies. HEC-FDA only calculates benefits associated with the reduction in direct damages associated with an alternative. Many other impacts such as the reduction in output by industry, the reduction in income, and jobs lost that are related to the storm events are not included. These second and third order losses have an impact on the regional, state and national economy, which are not factored into the conventional BCRs for the project.

The team will utilize a Regional Economic Models, INC (REMI) multi-region input-output model to analyze these second and third order impacts to tell the "full story" of the losses to the economy associated with hurricane events. Understanding the full range of benefits would help inform and improve the future public policy discussions and decisions that would determine what form of storm risk reduction would actually get constructed.

9.3. Final Report Development

The final report is due to the GCCPRD Board and the GLO by June 20, 2016. The study remains on schedule and would be complete on time.

Sources Cited

Kasmarek, M.C., Johnson, M.R., and Ramage, J.K., 2014, Water-level altitudes 2014 and water-level changes in the Chicot, Evangeline, and Jasper aquifers and compaction 1973–2013 in the Chicot and Evangeline aquifers, Houston-Galveston region, Texas: USGS Scientific Investigations Pamphlet 3308, *http://dx.doi.org/10.3133/sim3308*.

Mike Turco, pers comm, 2015.

Pullen, T., N.W.H. Allsop, T. Bruce, A. Kortenhaus, H. Schuttrumpf, J.W. van der Meer. 2007. EurOtop Wave Overtopping of Sea Defenses and Related Structures: Assessment Manual.

United States Army Corps of Engineers (USACE). 2002. Coastal Engineering Manual. Engineering Manual 1110-2-1100.

USACE. 2012. Hurricane and Storm Damage Risk Reduction System Design Guidelines. USACE New Orleans District Engineering Division, New Orleans, LA. 606 pages. Accessible at http://www.mvn.usace.army.mil/Portals/56/docs/engineering/HurrGuide/EntireDocument.pdf