Coastal Texas Protection and Restoration Feasibility Study

Final Feasibility Report

Appendix D – Annex 15:

March 2019 Gate Design Workshop

August 2021

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DEPARTMENT OF THE ARMY
U.S. ARMY CORPS OF ENGINEERS
P.O. BOX 1229
GALVESTON, TEXAS 77553

MEMORANDUM

CESWG-EC 6/23/2019

MEMORANDUM FOR RECORD

SUBJECT: Recommendations from the Coastal Texas Gate Design Workshop

1. PURPOSE: To document the findings and discussions from the Coastal Texas Gate Design Workshop which will be used to recommend a path forward for the Galveston Entrance Channel Closure Structure component of the Tentatively Selected Plan (TSP) for the Coastal Texas Feasibility Study.

2. BACKGROUND AND METHOD:
   a. International experts from around the world were invited to Galveston, Texas for the first International Network for Storm Surge Barriers (I-STORM) gate design collaborative workshop held 17 to 19 March 2019. All discussions / views expressed at the workshop were those of I-STORM not of individual companies that individuals may represent.

   b. Encl 1 includes the attendee list.

   c. Background materials were provided electronically to attendees before the event to help focus in-person discussions on reaching consensus rather than spending valuable time on learning background information. Encl 2 includes key read-ahead materials and background presentations provided on 17 March.

   d. The event began with a site visit by boat to introduce all of the participants to the project site. During the boat tour, presentations were given which covered general background information and design work already completed by the Coastal Texas Project team. The site visit was followed by a crawfish boil networking and ice-breaker event to get to know the team and begin discussion.

   e. The meeting was professionally facilitated by USACE staff.

   f. The main event was held 18-19 March and consisted of the following major tasks (Encl 3 includes the event agenda):

      i. Introduction, debate and finalization of ranking criteria.

      ii. Breakout group brainstorming multiple options for closure structures. The structures were subdivided by draft and navigability requirements into 3 sections; shallow, intermediate, and deep.

iii. Presentation of closure structure options by the breakout groups to the larger team for debate.

iv. Re-assessment of ranking criteria to incorporate lessons learned during the brainstorming sessions.

v. Individual ranking of all provided options.

vi. Summarization and presentation of ranking results followed by debate and consensus around understanding.

vii. A short 20 minute breakout into the original groups to combine the highest ranked gate designs into comprehensive closure systems.

viii. Presentation and discussion of the recommended closure structures.

ix. Closing comments.

x. Group photo.

3. RESULTS: The teams identified 10 to 20 structure types for each section and screened those down to a total of 18 closure types for the larger team to rank. Encl 4 includes presentations from each group discussing pros and cons. The following tables show the raw data resulting from the ranking exercise averaged by all participants (Table 1), I-STORM invited members only (Table 2), and USACE, Texas A&M University at Galveston (TAMUG) faculty, and Gulf Coast Community Protection and Recovery District (GCCPRD) participants (Table 3). The ranked structure types, identified by numbers along the top of the second row in Tables 1-3, are listed following the Tables. A larger view of this data is included as Encl 5. Meeting notes (Encl 6) include a detailed discussion of all structure types considered. Encl 7 contains the group photo.

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MEMORANDUM

Table 1: Raw scores averaged across all participants.

		Shallow Draft								Intermediate Draft					Deep Draft				
	Criteria	1	2	3	4	5	6	7	8	11	12	13	14	15	21	22	23	24	25
a	Blockage Ratio	3.3	3.9	4.1	3.7	3.1	3.3	4.7	3.7	3.3	3.3	3.0	2.2	4.6	1.6	3.3	5.0	5.0	3.5
b	Time to open and close	4.3	4.0	3.7	4.5	4.2	2.0	2.6	3.0	4.5	4.3	4.2	3.8	3.9	3.5	4.2	4.2	4.0	4.0
c	Alignment	3.8	3.7	4.0	3.7	3.4	3.4	3.5	3.2	3.7	3.8	3.0	3.4	4.2	3.7	3.4	4.3	4.4	3.6
d	Cost	3.1	2.8	3.5	2.6	4.4	3.2	2.9	2.1	3.4	2.9	2.9	2.4	2.6	2.9	2.7	2.2	2.0	2.1
e	Operation and Maintenance Cost	3.7	2.4	3.1	2.4	4.2	2.5	2.4	2.2	3.9	2.9	3.4	3.1	1.9	4.2	3.0	1.4	1.5	2.1
f	Reliability and Redundancy	4.7	3.5	3.4	3.2	4.7	2.0	1.6	1.1	4.7	4.4	4.2	4.2	2.6	4.6	4.2	2.0	1.6	2.7
g	Adaptability	3.7	2.7	2.2	2.3	2.7	2.7	2.7	1.5	3.8	3.6	2.6	2.7	2.2	3.0	3.2	1.6	1.8	2.3
h	Constructability	4.0	3.5	3.4	3.1	4.2	3.3	2.8	2.1	3.8	3.5	3.1	3.3	2.9	3.4	3.2	2.5	1.7	2.0
i	Technology	4.7	3.7	3.6	3.5	4.5	3.2	1.8	1.1	4.6	4.2	4.0	4.0	2.9	4.5	3.3	2.7	1.3	2.5
j	Impact	3.1	3.3	3.3	3.9	2.5	3.1	3.3	2.7	3.1	3.3	2.9	2.6	3.8	2.2	3.1	3.6	3.6	2.9
k	Additional Benefits (Bonus)	2.5	2.0	1.6	2.0	2.8	1.2	1.6	1.3	2.6	2.0	1.9	1.8	1.8	1.6	1.8	2.0	1.9	1.8
	SUM	41.0	35.4	36.0	34.9	40.9	29.7	29.8	24.1	41.4	38.1	35.1	33.3	33.2	35.3	35.5	31.5	28.6	29.5

Table 2: Raw scores averaged across I-Storm member participants.

		Shallow Draft								Intermediate Draft					Deep Draft				
	Criteria	1	2	3	4	5	6	7	8	11	12	13	14	15	21	22	23	24	25
a	Blockage Ratio	3.5	3.6	4.2	3.5	3.2	3.6	4.2	3.7	3.5	3.2	2.9	2.4	4.3	1.4	3.2	5.0	4.9	3.6
b	Time to open and close	4.5	4.0	3.9	5.6	4.1	1.7	2.4	3.3	4.5	4.6	4.5	4.1	4.3	3.4	4.4	4.4	3.7	4.2
c	Alignment	4.2	4.1	4.4	4.3	3.4	3.8	3.9	3.8	3.9	4.3	3.0	3.6	4.5	3.8	3.5	4.4	4.4	3.8
d	Cost	3.2	3.0	3.4	2.7	4.6	3.1	3.0	2.5	3.6	2.9	3.0	2.2	2.6	2.9	2.9	2.4	1.6	1.9
e	Operation and Maintenance Cost	3.7	2.5	3.3	2.6	4.5	2.6	2.1	2.3	4.2	3.1	3.8	2.8	1.9	4.3	3.4	1.5	1.1	1.9
f	Reliability and Redundancy	4.9	3.4	3.6	3.1	4.9	1.8	1.1	1.4	4.6	4.5	4.3	3.9	3.1	4.6	4.2	2.2	0.8	2.5
g	Adaptability	3.7	2.8	2.4	2.4	2.6	2.5	2.3	1.6	3.7	3.8	2.8	3.1	2.4	3.0	3.5	1.4	1.6	2.0
h	Constructability	3.9	3.8	3.4	2.9	4.2	3.4	2.7	2.2	3.9	3.5	3.2	3.2	2.9	3.4	3.2	2.6	1.1	1.4
i	Technology	4.9	4.1	4.1	3.8	4.4	2.9	1.8	1.3	4.9	4.5	4.2	3.9	3.4	4.8	3.8	2.9	1.0	2.3
j	Impact	3.2	3.2	3.6	3.4	2.8	3.2	3.1	3.0	3.4	3.4	3.1	2.9	3.6	2.6	3.3	3.4	3.0	2.8
k	Additional Benefits (Bonus)	2.4	1.8	1.4	1.8	2.7	1.1	1.1	1.4	2.6	1.7	2.0	1.9	1.4	1.5	1.4	1.4	1.2	1.5
	SUM	42.3	36.3	37.8	36.1	41.6	29.7	27.7	26.6	42.9	39.5	36.8	33.9	34.4	35.6	36.7	31.5	24.3	28.0

Table 3. Raw scores averaged across USACE, TAMU faculty, and GCCPRD participants.

		Shallow Draft								Intermediate Draft					Deep Draft				
	Criteria	1	2	3	4	5	6	7	8	11	12	13	14	15	21	22	23	24	25
a	Blockage Ratio	3.3	4.3	4.1	3.9	3.0	3.1	4.9	3.7	3.4	3.4	2.9	2.0	5.0	2.1	3.5	5.0	5.0	3.6
b	Time to open and close	4.4	4.0	3.7	3.7	4.3	2.1	2.7	2.9	4.4	4.0	3.9	3.2	3.4	3.2	3.8	3.7	3.9	3.4
c	Alignment	3.4	3.1	3.4	3.1	3.1	3.0	2.8	2.5	3.5	3.3	2.8	3.0	3.8	3.5	3.1	3.8	4.1	3.3
d	Cost	3.2	2.9	3.3	2.6	4.2	2.9	2.7	1.6	3.4	2.9	2.7	2.8	2.8	2.9	2.7	2.3	2.4	2.5
e	Operation and Maintenance Cost	3.6	2.2	2.7	2.1	3.9	2.1	2.4	2.0	3.6	2.8	2.9	3.3	1.7	4.0	2.6	1.6	1.9	2.1
f	Reliability and Redundancy	4.6	3.6	3.4	2.9	4.6	2.2	2.1	0.8	4.8	4.4	3.8	4.5	2.5	4.6	4.1	1.6	2.2	2.3
g	Adaptability	3.6	2.9	2.2	2.3	2.8	2.9	2.9	1.5	3.8	3.3	2.3	2.5	1.9	3.1	2.9	1.7	1.9	2.3
h	Constructability	3.9	3.0	3.2	2.9	4.1	2.9	2.5	1.9	3.9	3.5	3.1	3.2	2.6	3.6	3.2	2.5	2.4	2.6
i	Technology	4.5	3.5	3.2	3.2	4.6	3.3	2.0	1.1	4.4	3.8	3.9	3.8	2.4	4.1	2.8	2.3	1.7	2.6
j	Impact	3.1	3.3	3.5	5.1	2.4	3.4	3.6	2.7	3.1	3.3	2.9	2.4	4.1	2.3	3.1	3.9	4.2	2.9
k	Additional Benefits (Bonus)	2.2	2.0	1.9	2.3	2.7	1.4	2.4	1.5	2.3	2.4	1.7	1.8	2.7	2.0	2.5	3.0	2.6	2.2
	SUM	39.8	34.7	34.7	34.0	39.7	29.3	30.9	22.3	40.5	36.8	32.9	32.4	32.9	35.4	34.3	31.3	32.2	29.9

The numbers shown across the second row in Tables 1-3 relate to the following closure types:

Shallow water closures:	Intermediate closures:	Deep water closures:
1. Vertical lift gate	11. Vertical lift gate	21. Floating sector gate
2. Crest gate	12. Rising sector gate	22. Rising sector gate
3. Bladder gate	13. Tainter gate	23. Flap gate
4. Vertical rising gate	14. Sector gate	24. Piston gate
5. Box culvert (precast)	15. Flap gate	25. Vertical drop gate
6. Swinging barge gate		
7. Railroad gate		
8. Texas armadillo		

4. RECOMMENDATION: The data in Tables 1-3 were presented to the entire group for discussion. From visual observation of the raw data, some structure types for each section clearly ranked higher which are listed below. Interestingly, these same structure types ranked highest regardless of the overall group considered.

- Shallow Draft Section
  - Vertical lift gate
  - Precast Box culvert

- Intermediate Draft Section
  - Vertical lift gate
  - Rising sector gate

- Deep Draft Section
  - Floating sector gate
  - Rising sector gate

The breakout groups reconvened to consider and recommend comprehensive closure systems using the highest ranked structure types, listed above. Figure 1 shows group one recommendations. All three were similar, recommending box culverts in the shallowest section with vertical lift gates in the intermediate sections, and either rising or floating sector gates for navigation access.

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MEMORANDUM

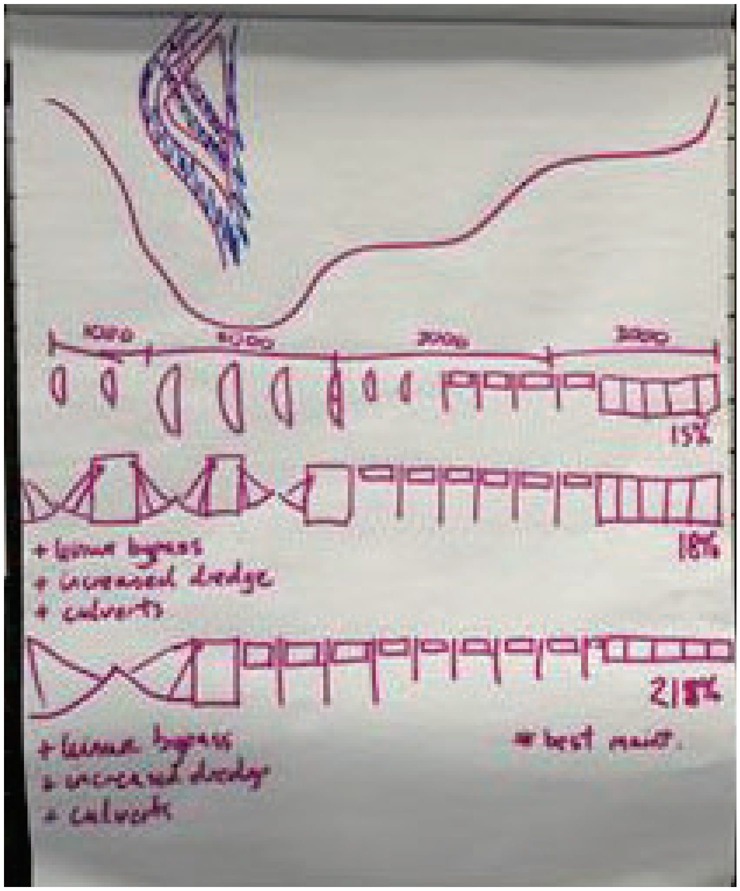

Figure 1. Recommended closure systems (Deep Draft Group)

5. <u>CONCLUSIONS</u>: The following general conclusions were reached by the team:

   a. Results of ranking structures to close the Galveston Entrance Channel:

      i. The I-STORM group rated many different closure structure types for application in closing the Galveston Entrance Channel during extreme events.
      ii. Of the ranked structure types, top two were recommended for consideration for each of the shallow, intermediate, and deep sections.
      iii. Ultimately, the group reached consensus around a combination of structures that could be used to close the entrance channel.

   b. General recommendations:
      i. Each of the I-STORM experts recommended structures that optimize the use of known systems with proven technologies to enhance reliability.

ii. There were many general recommendations to improve use of structures with higher closure percentages, including those listed below:
    1. One island onshore
    2. Needs diverted shipping channel
    3. Possibly a leisure craft canal landward of dry-dock
    4. Barrier located at wider channel (modelling needed to confirm benefit)
    5. Split navigation channel in two or three (overlapping islands)
    6. Barrier design with no islands (or small piers)
    7. Extend Deep Draft into intermediate (e.g. with three channels)
    8. Deeper Channel (includes ship increase adaptability)
    9. New shipping canal through peninsula

c. General concerns:

i. For both the rising sector gate and the floating sector gate there is a scale problem that has to be solved to make them feasible. The rising sector gate has a width of 2 to 3 times that of the Thames Barrier and might not be possible due to the necessary vertical dimensions. The required strength of the floating sector gate, when spanning the entire shipping lane, is approximately 50% higher than at the Maeslant Barrier and requires heavier ball joints. The construction of such a ball joint might not be possible given the fact that the only factory that has produced them does not exist anymore.

ii. Division of the shipping lane is necessary for the rising sector gate and maybe also for the floating sector gate which may not feasible from shipping perspective. Coordination with the Port Authority is needed.

iii. Not all risks are considered properly. The risk of ship collision is very important especially with the heavy ship traffic and multiple piles or islands in the shipping lane.

iv. Lack of detailed knowledge of some barrier characteristics may have biased the ranking procedure. For example the flap gate is much less expensive than the sector gates which has been confirmed by the bidding process for Maeslant Barrier and also more redundant (the failure of one segment is no problem for the water level in the bay). For both criteria the scores came much lower than for the sector gates.

v. Not all relevant requirements were available during the workshop (e.g. navigability, leakage, integral flood safety, lead times for closure). Adding these requirement at a later stage might influence the preferred barrier types.

vi. Relative weights of different ranking criteria may influence the final barrier selection.

d. Lessons learned related to the workshop process:

   i. Applying a quantitative process to evaluate closure structures helped to focus discussion on criteria of greatest concern for the Galveston Entrance Channel Closure.
   ii. The quantitative ranking process also enables rapid access to individual and group opinions as well as serving as a look up table for the meeting notes and presentations.
   iii. The process also provided a quantitative method to drive innovation by ranking many different structure types with respect to the criteria controlling design, construction, operation, and maintenance. As different criteria control the decision process, the ranking information gleaned from this workshop will identify where each structure type requires innovation to meet performance requirements.
   iv. Providing read ahead materials covering the background information early helped to focus available time on discussion related to a closure system for the Galveston Entrance Channel.
   v. The site visit coupled with a refresher of background information before starting the workshop was helpful for optimizing use of available time.
   vi. Additional time was needed to more deeply explore the integration of structures into a comprehensive system. An extra 4 hours would have helped better investigate pros and cons of a comprehensive system.

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ANDY BATCHELOR
Chair I-STORM Delivery Board

ROBERT C. THOMAS, P.E
CHIEF, E&C DIVISION
USACE, GALVESTON

7 Encls
1. Attendee List
2. Read-Ahead Materials and Background Presentations
3. Final Agenda
4. Power point summary of alternatives
5. Spreadsheet including ranking data
6. Meeting notes
7. Group Photo

CESWG- 1st End

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COASTAL TX PROTECTION AND RESTORATION FEASIBILITY STUDY

I-Storm Gate Design Workshop Briefing

Dr. Kelly A. Burks-Copes, Project Manager
US Army Corps of Engineers
Galveston District

17 March 2019

US Army Corps of Engineers

US Army Corps of Engineers

PROJECT GOALS & OBJECTIVES

Goals

Coastal Storm Risk Management (CSRM)

Develop and evaluate **coastal storm damage risk reduction** measures for coastal Texas residents, industries and businesses which are critical to the nation's economy.

Ecosystem Restoration (ER)

Increase the net quantity and quality of coastal ecosystem resources by maintaining, **protecting, and restoring coastal Texas ecosystems** and fish and wildlife habitat

Objectives

- **Reduce economic damage** from coastal storm surge flooding to business, residents and infrastructure through 2085
- **Reduce risk to critical infrastructure** (e.g. medical centers, government facilities, universities, and schools) from coastal storm surge flooding to the maximum extent practical and reduce emergency costs
- **Reduce risk to public health and safety** from storm surge
- **Increase the resilience** of communities, the economy, coastal ecosystems, and infrastructure, including existing coastal storm risk reduction systems, from sea level rise and coastal storm surge
- **Enhance and restore coastal landforms** along Galveston Island and Bolivar Peninsula that contribute to reducing the risks of coastal storm surge damages
- **Improve hydrologic connectivity** of area wetlands in the Texas-Louisiana coastal marshes, mid-coast barrier islands and coastal marshes
- **Improve and sustain coastal marshes and bay shorelines** on barrier island and estuarine systems

THE TENTATIVELY SELECTED PLAN (TSP)

US Army Corps of Engineers

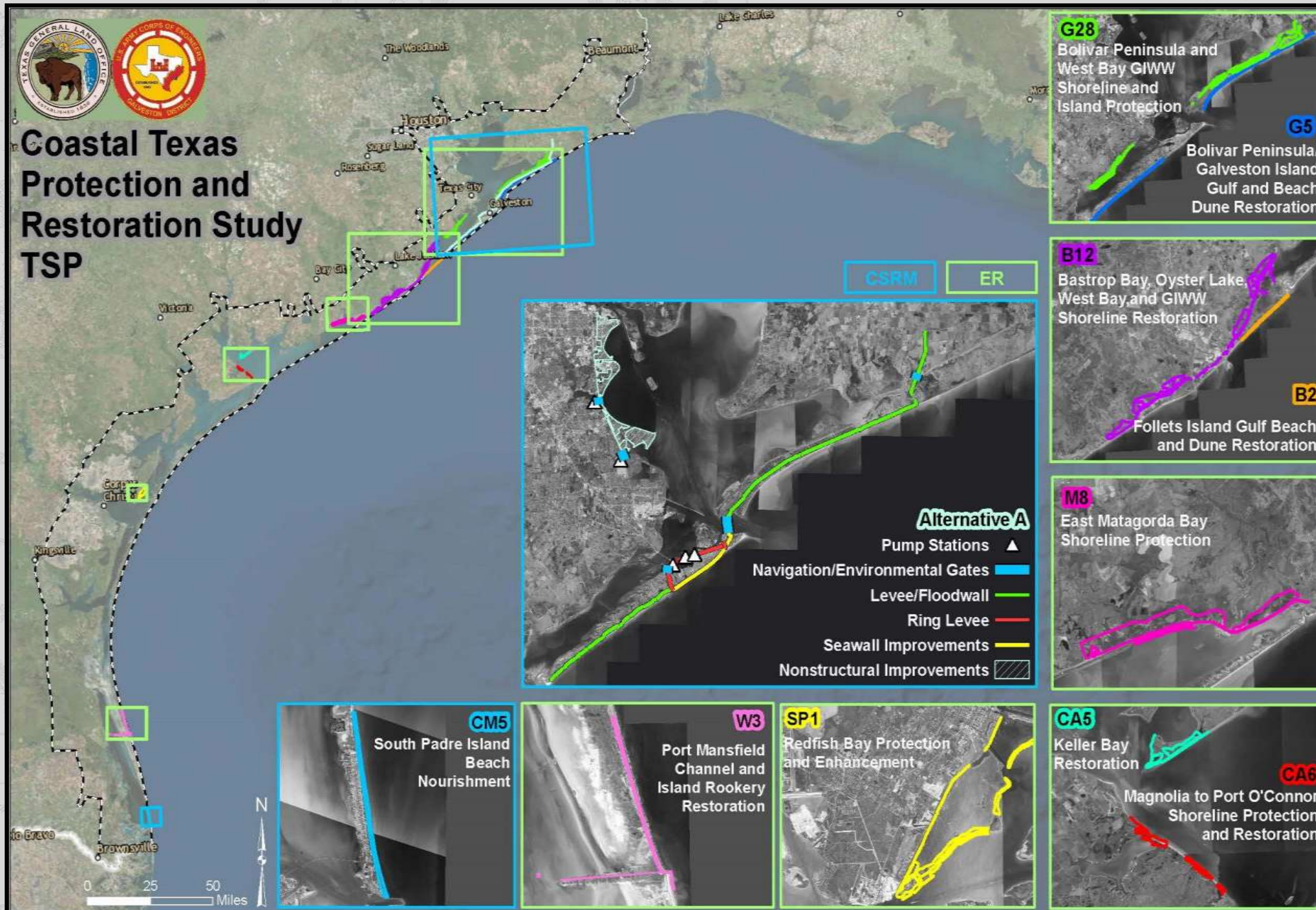
Coast-wide system of ecosystem restoration and storm-risk management features

TSP supports the resilience of coastal communities and natural habitats in Coastal Texas

Coastwide:
Large scale ER features which focus on critical landscape features and areas of threatened biologically diverse ecosystems

Lower Coast:
CSRM Dune and beach restoration project on South Padre Island

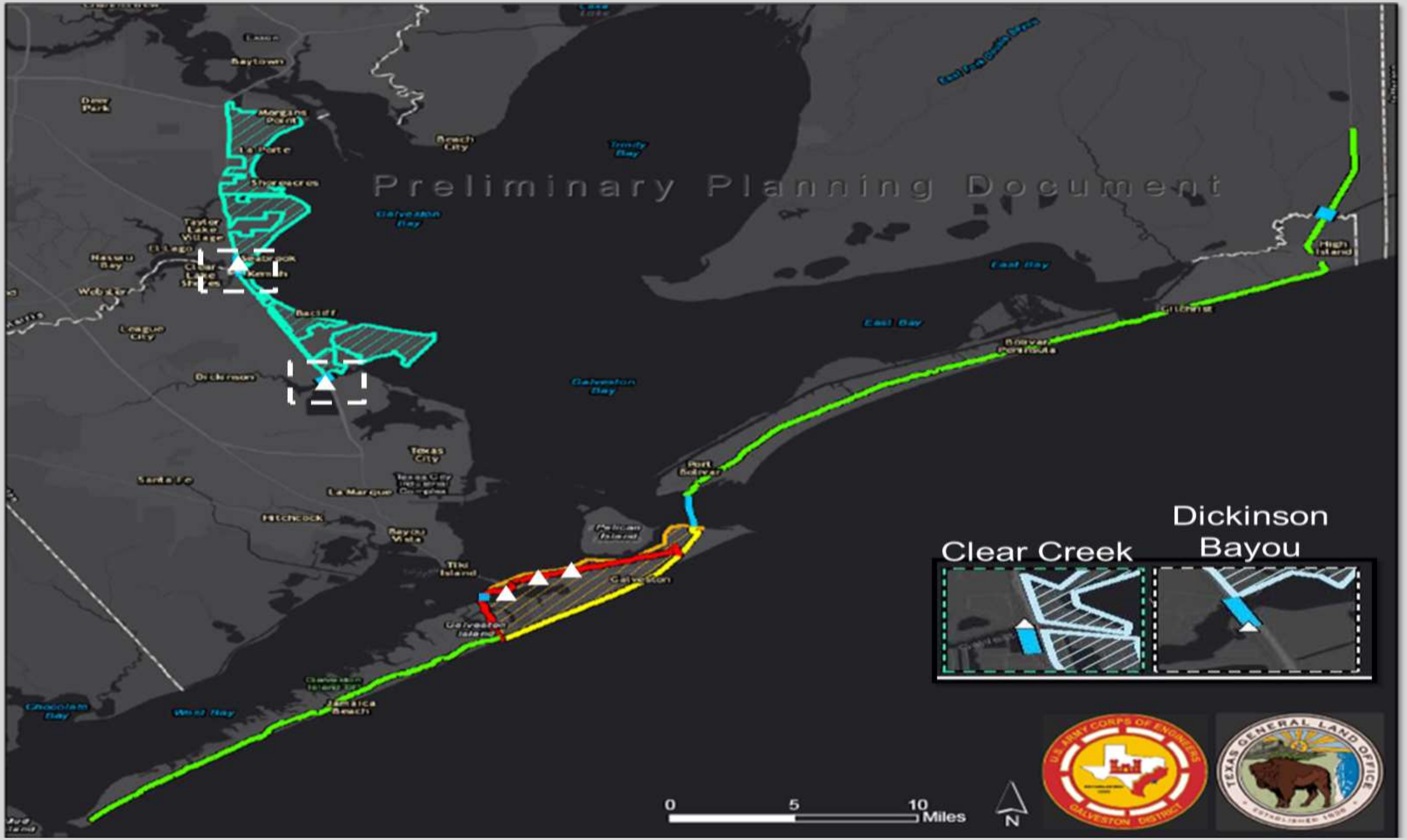
Upper Coast:
CSRM surge barrier system to protect the Houston-Galveston Region (Coastal Spine)



OPTIONAL ALIGNMENTS

US Army Corps of Engineers

ALT A: COASTAL BARRIER



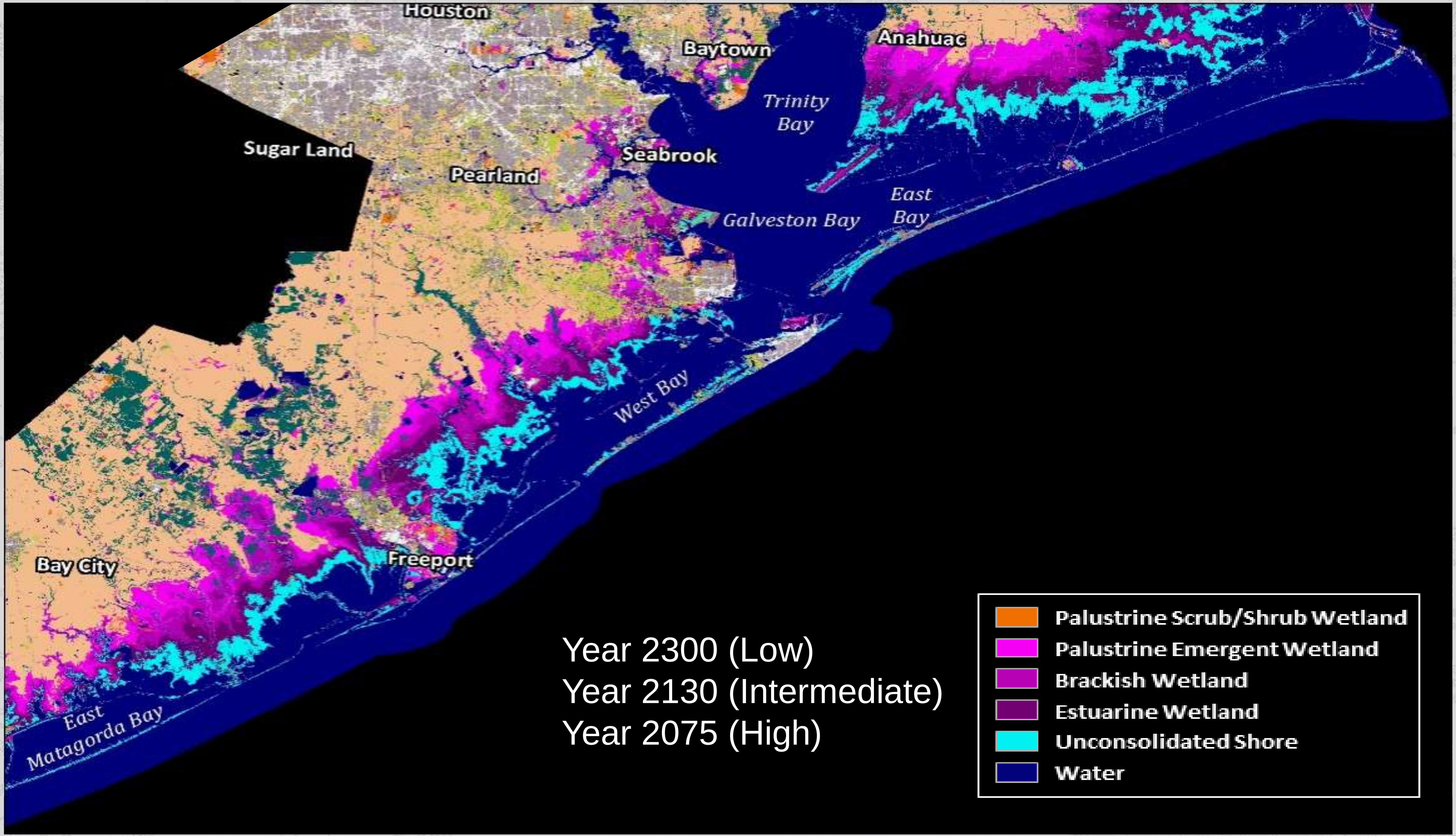
US Army Corps of Engineers

ECOSYSTEM RESTORATION MEASURES IN REGION 1

ANTICIPATED RELATIVE SEA LEVEL CHANGES

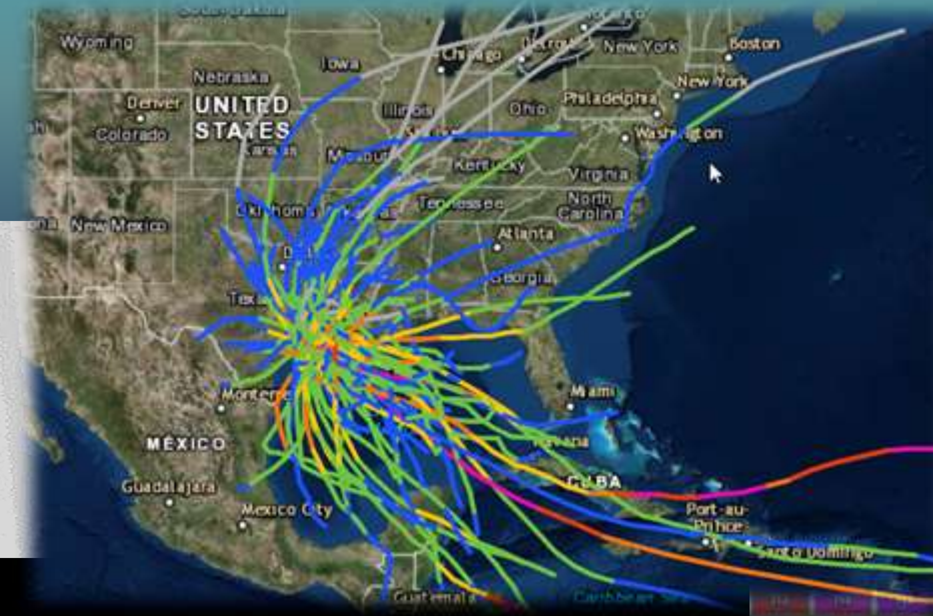
Upper Texas Coast

Break Point in Sea Level Change (about 3.5 feet)

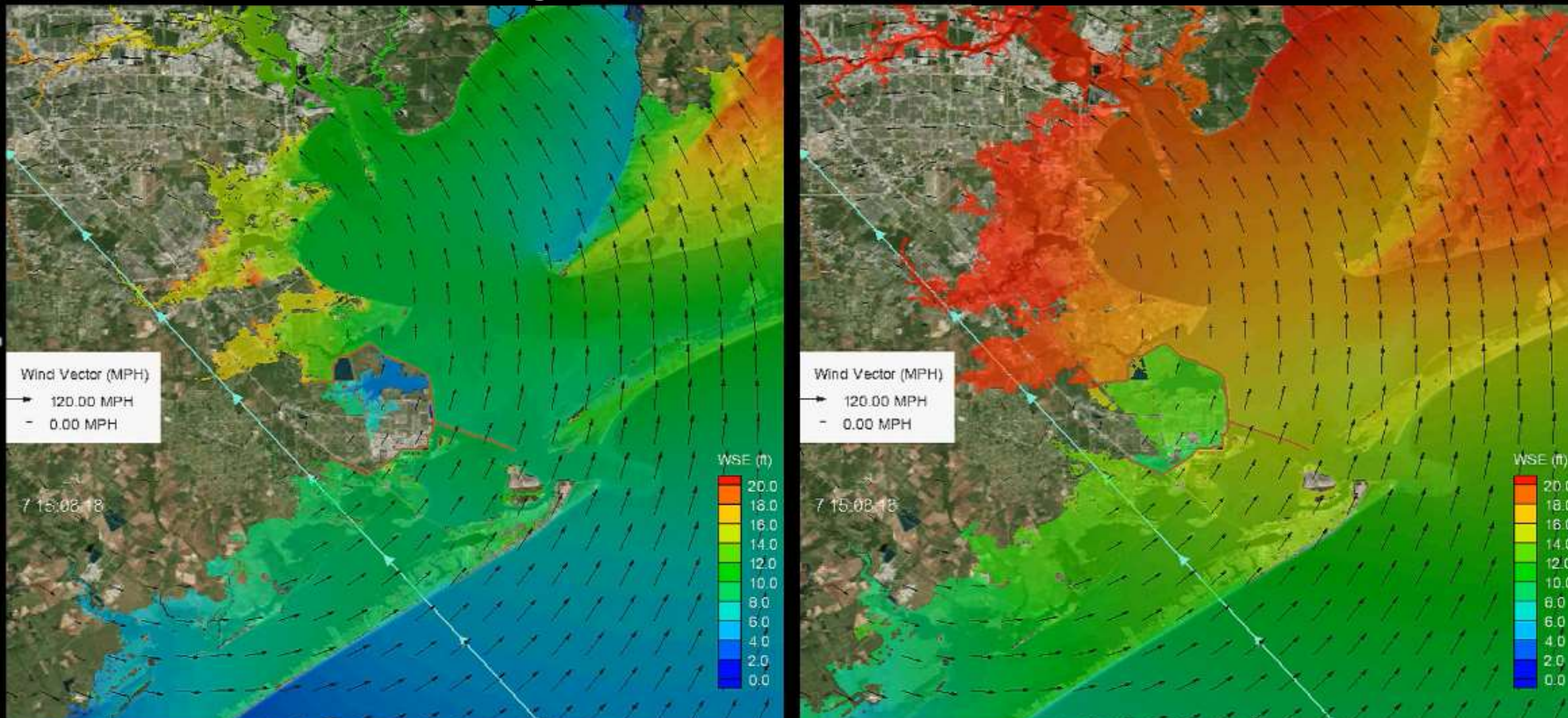


COASTAL STORM RISKS

US Army Corps of Engineers

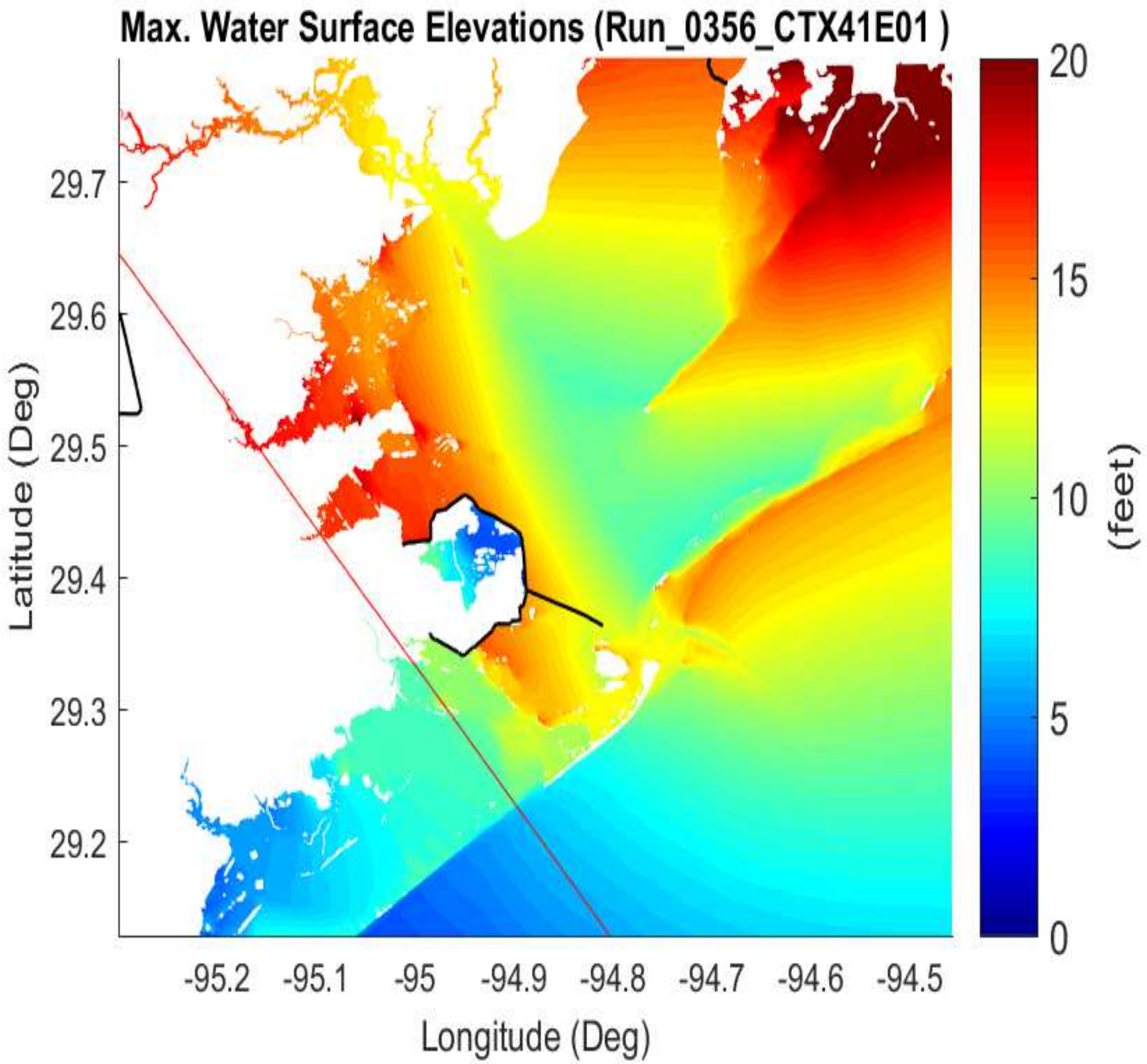


Present Day | **With Sea Level Rise**

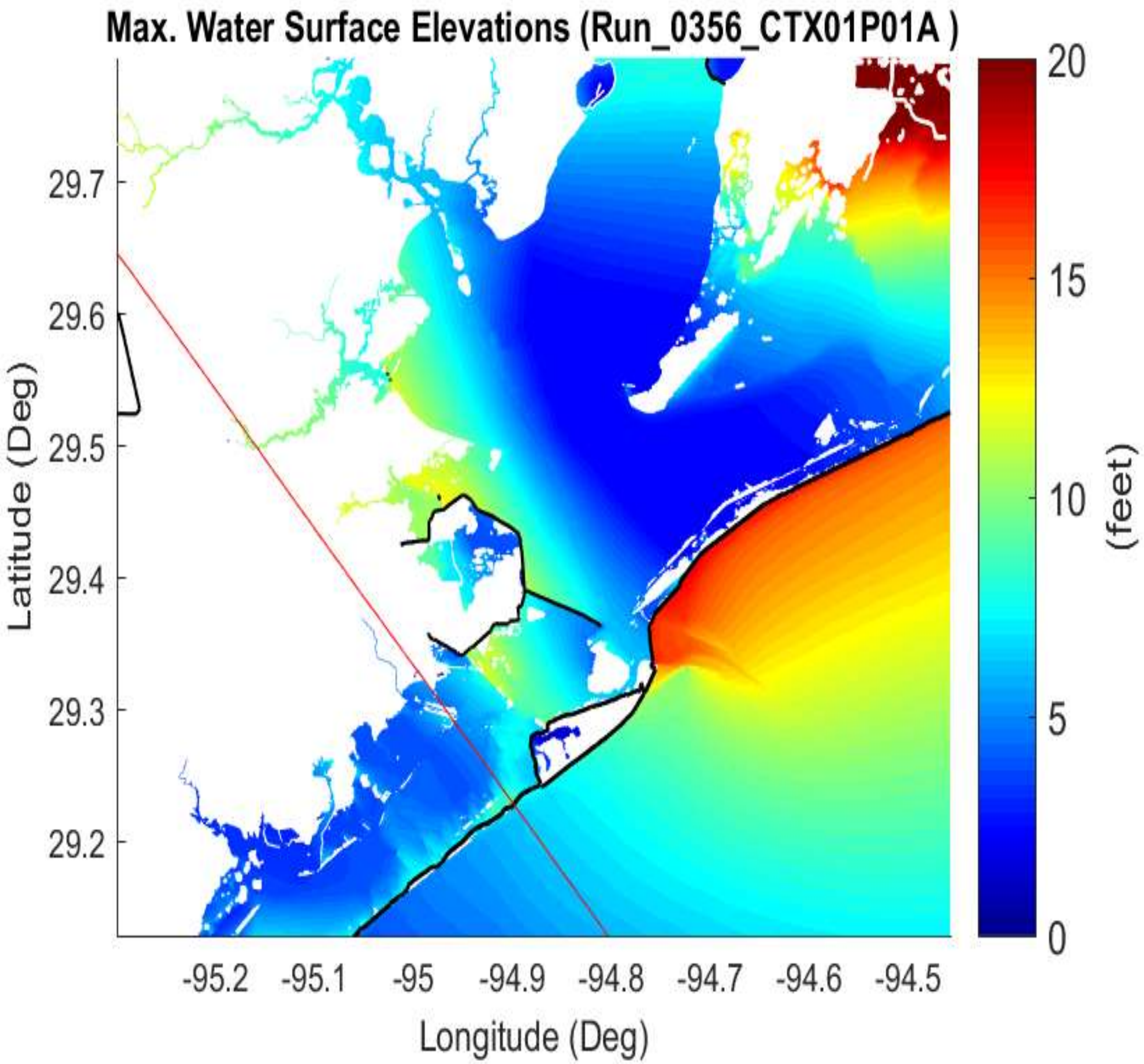


PLAN EVALUATION & COMPARISONS

Without Project



Plan A: Coastal Barrier



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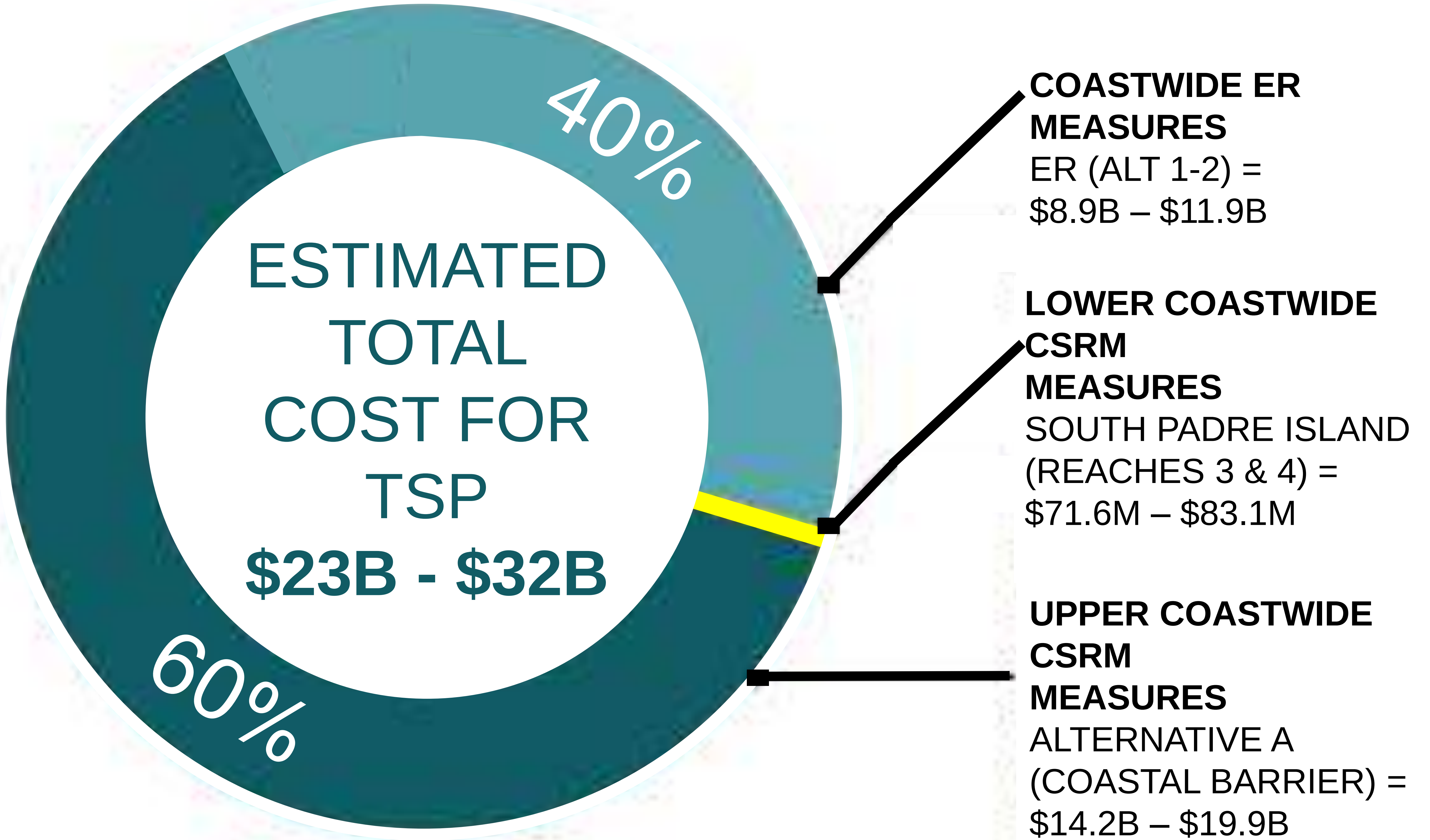
TSP TOTAL PROJECT COST



ENVIRONMENTAL IMPACTS & MITIGATION

- **Direct Impacts**

  Alt A (TSP): 4,525.3 acres

  South Padre: 365.8 acres

- **Indirect Impacts:**
  - Altered tidal exchange
  - Reduced velocities in Galveston Bay

- **Ecosystem Restoration Benefits**
  - 160,000 acres of marsh, islands, dunes, beaches & oyster reefs

<u>TOTAL MITIGATION COST RANGE:</u>

$676 M – $906 M

PATH FORWARD

- Based on public comments we are now:
  - Evaluating moving the barrier to the beach and re-aligning the Galveston ring barrier
  - Exploring the utility of gates Clear Creek and Dickinson
- In addition:
  - We have met with Rice University (SSPEED Center) & Texas A&M at Galveston to understand the differences between the proposals
  - GLO is establishing Community Working Groups
- Over the remaining study process we will:
  - Host an International Gate Design Workshop
  - Conduct additional storm modeling
  - Evaluate non-structural measures on the west side of upper Galveston Bay
  - Continue Natural Resource Agency coordination
  - Evaluate a second Public Review and comment period

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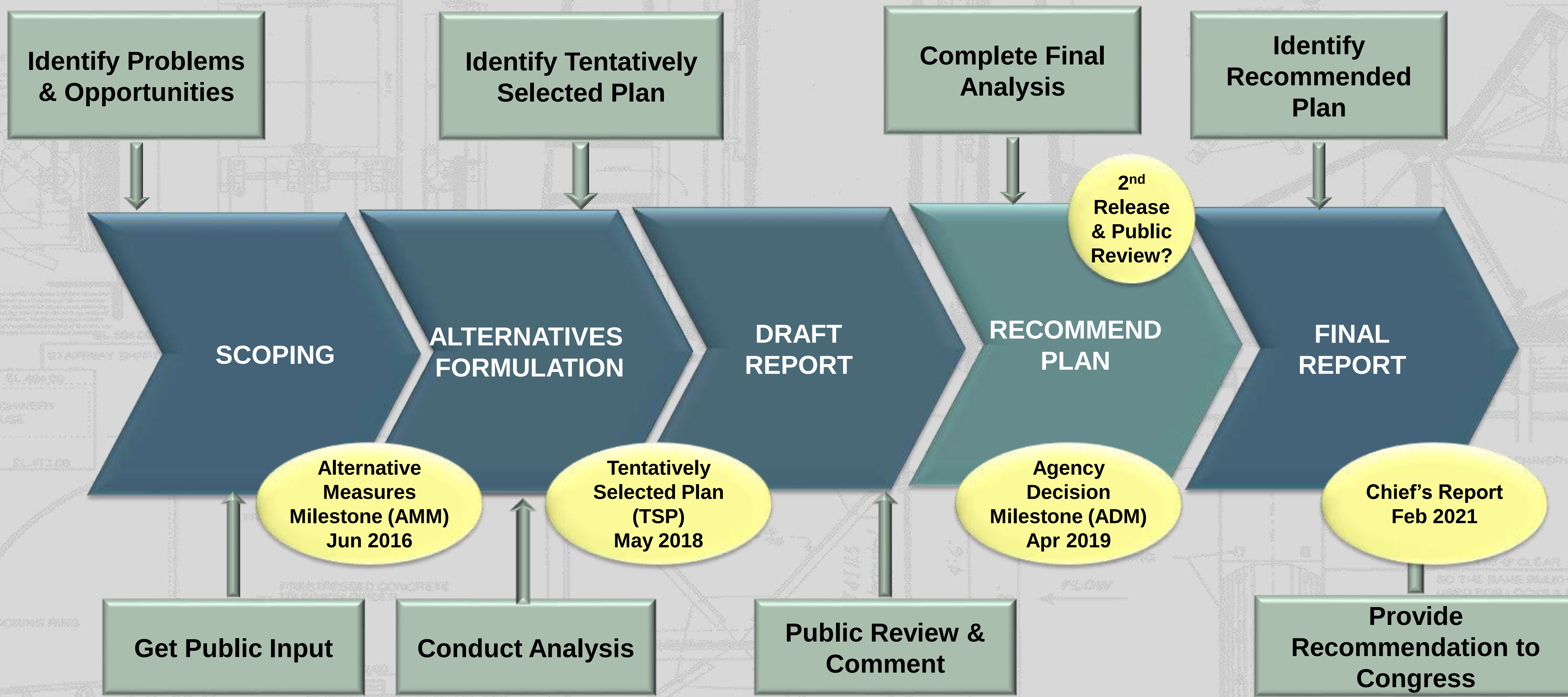
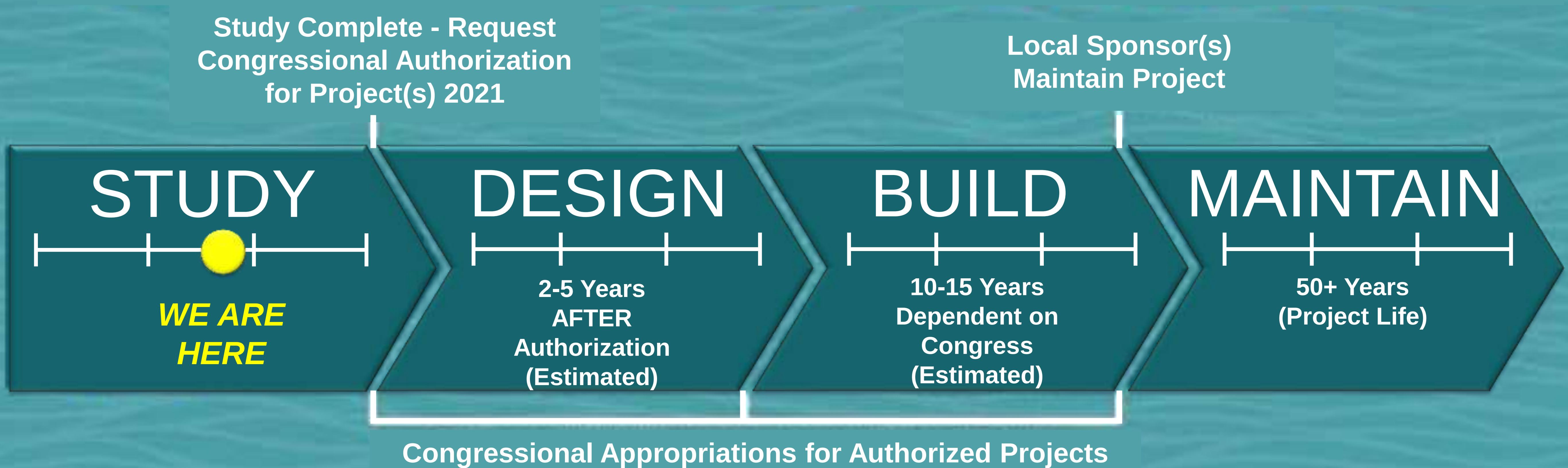
WHERE WE ARE IN THE STUDY PROCESS

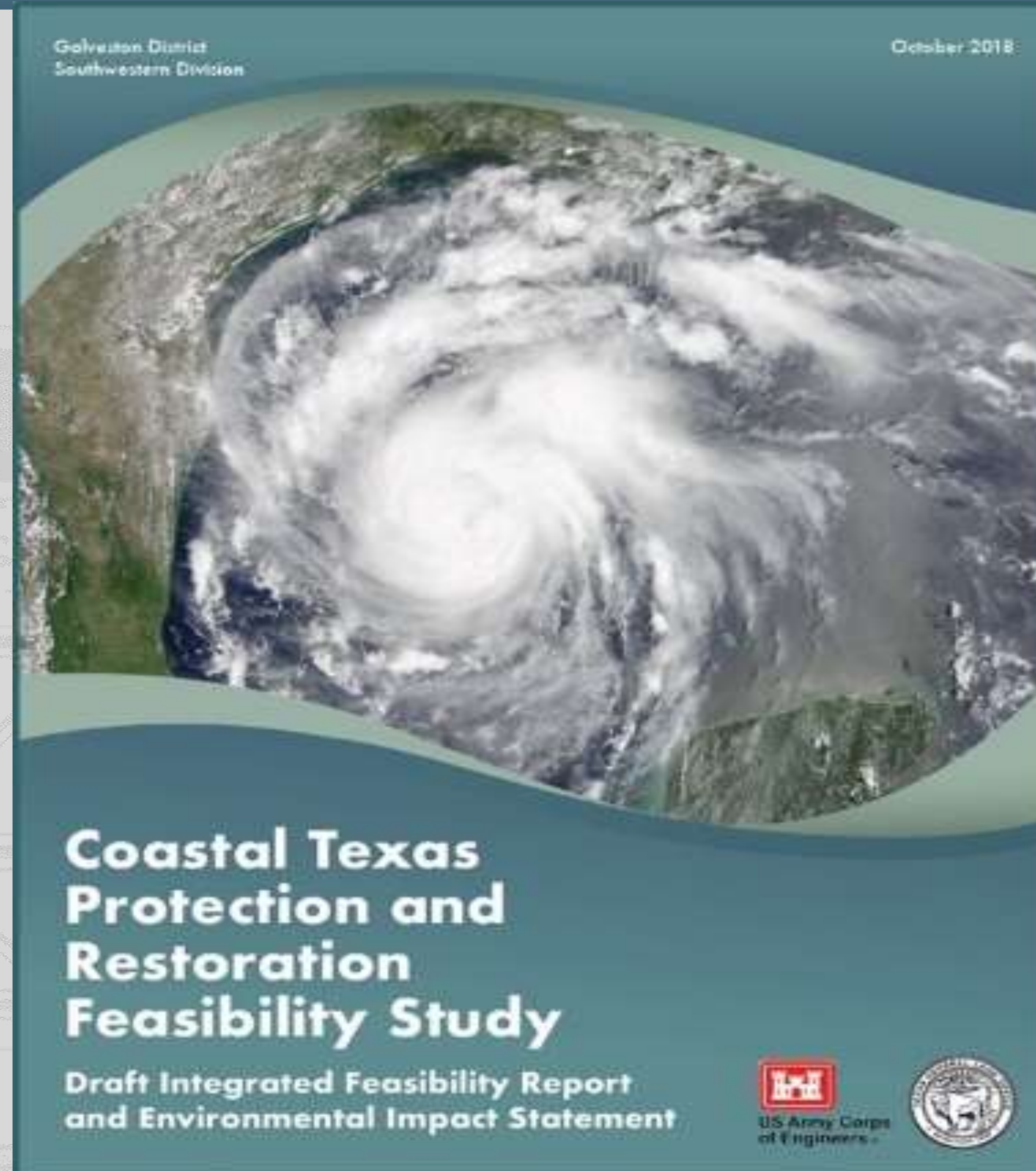


NEXT STEPS

ESTIMATED PROJECT SCHEDULE



COASTALSTUDY.TEXAS.GOV



Coastal Storm Risk Management and Ecosystem Restoration Projects along the Texas Coast

Background Information

Geometry, Climate and Environmental Stressors

Himangshu Das & Jennifer Morgan (SWG), Dianna Ramirez (GLO)

03/15/2019

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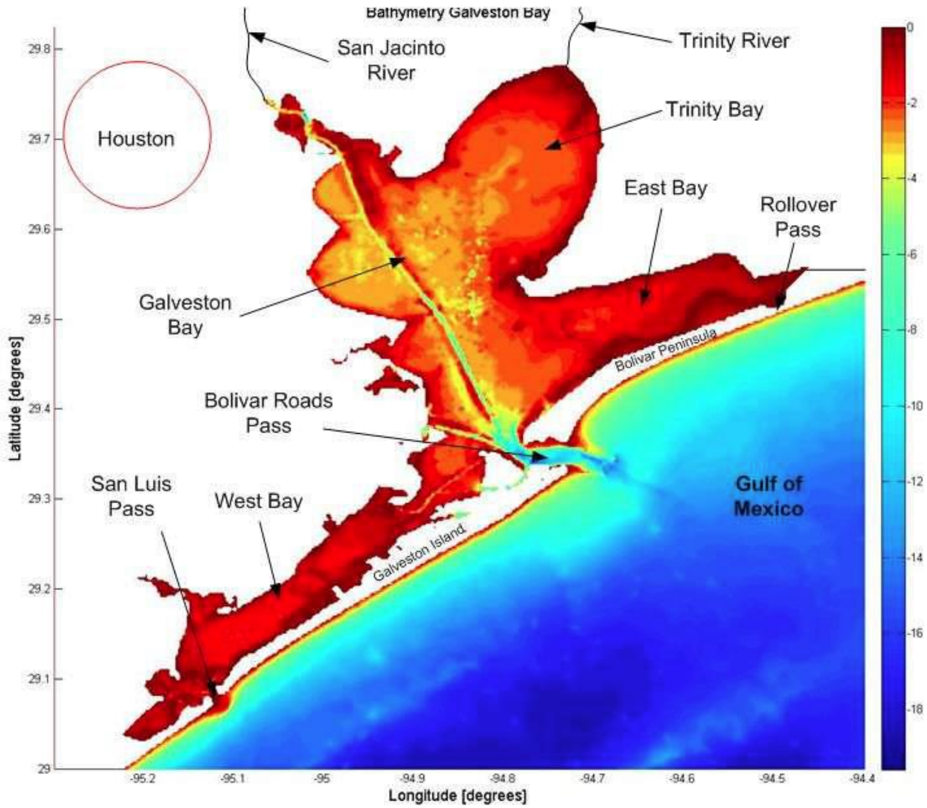
OVERVIEW



618 mile^2 (1600 Km ^2) Bay

Freshwater Flow: Includes Trinity River (66%) and San Jacinto River (19%)

Gage Name	Gage Number	Range [ft]
Rainbow Bridge	8770520	1.06
Texas Point, Sabine Pass	8770822	1.96
Eagle Point	8771013	1.10
Galveston Pleasure Pier	8771510	2.04
Galveston Pier 21	8771450	1.41
Matagorda Bay Entrance Channel	8773767	1.23
Aransas Pass	8775241	1.36
USS Lexington	8775296	0.59
South Padre Island, Brazos Santiago	8779749	1.43

Tide Range : 1 -2 ft
Tidal Range decays progressively into the bay system

Tide Period (Diurnal dominated) : 24 Hour
3 Inlets
Bolivar Inlet constitutes about 80% of tidal exchange (Flux)

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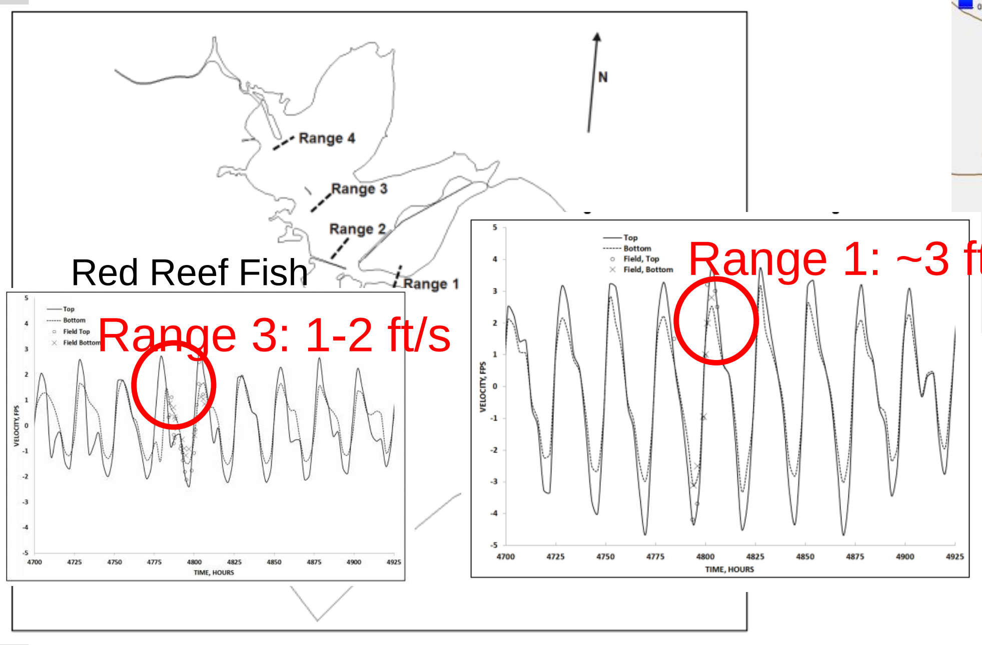
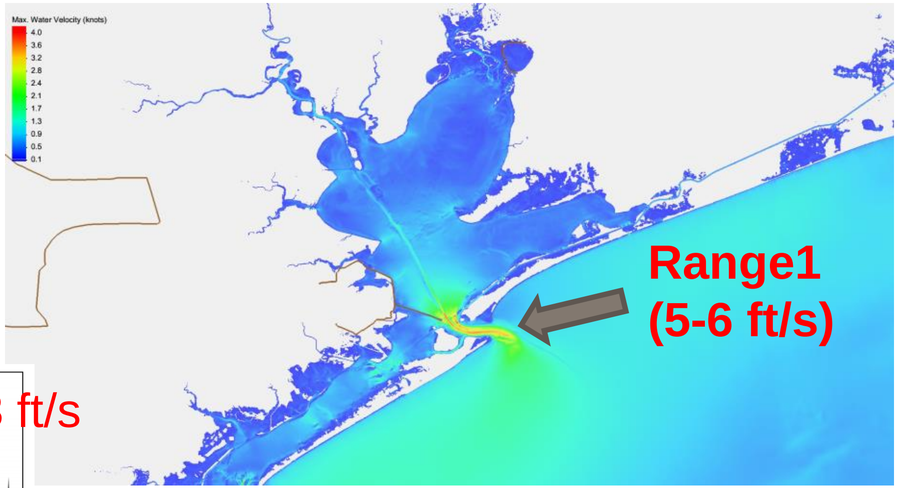
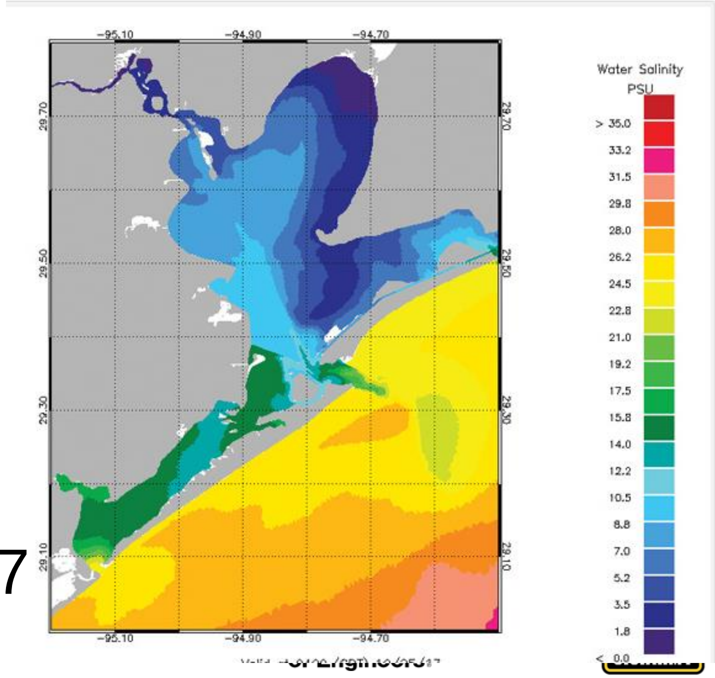
TIDE AND CURRENT (DATA)



Observed Velocity (May 2011)



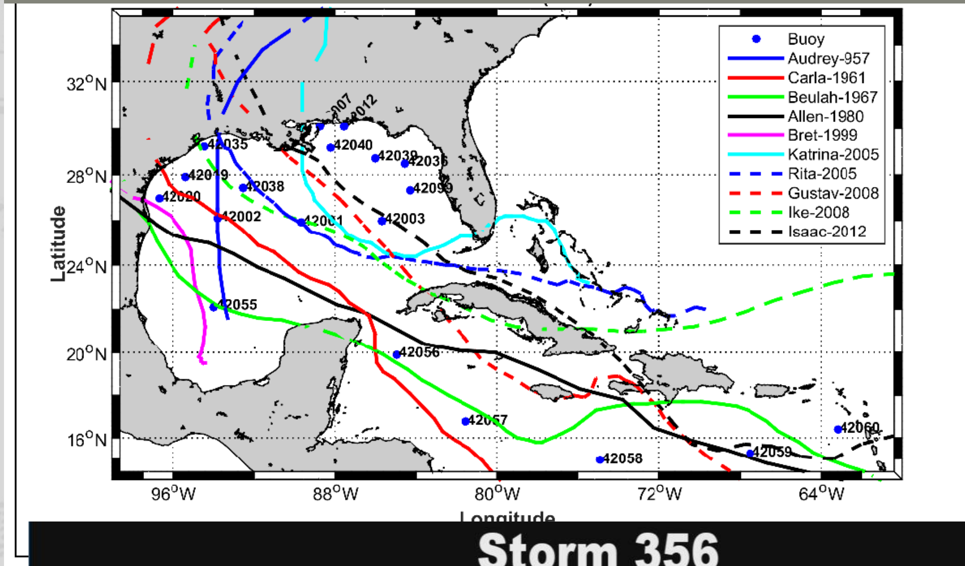
Simulated Velocity (Harvey, 2017)

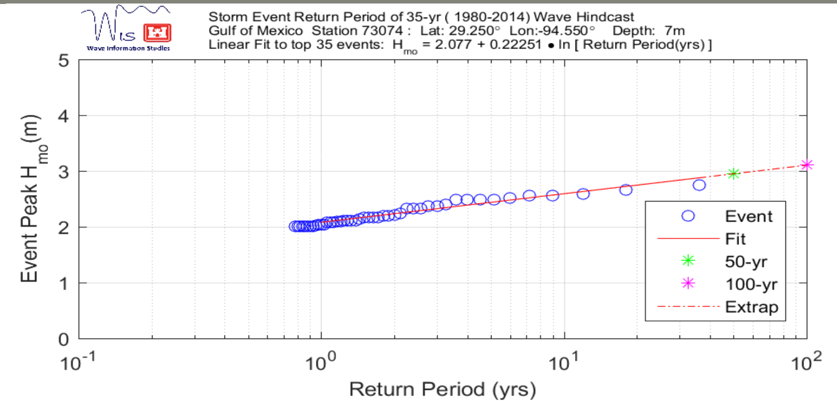


[Harvey decimated Galveston Bay's oyster population](#)
-Houston Chronicle, Sept 21, 2017

Harvey (Aug 29)
Bay Salinity
October 10, 2017

Storm Surge



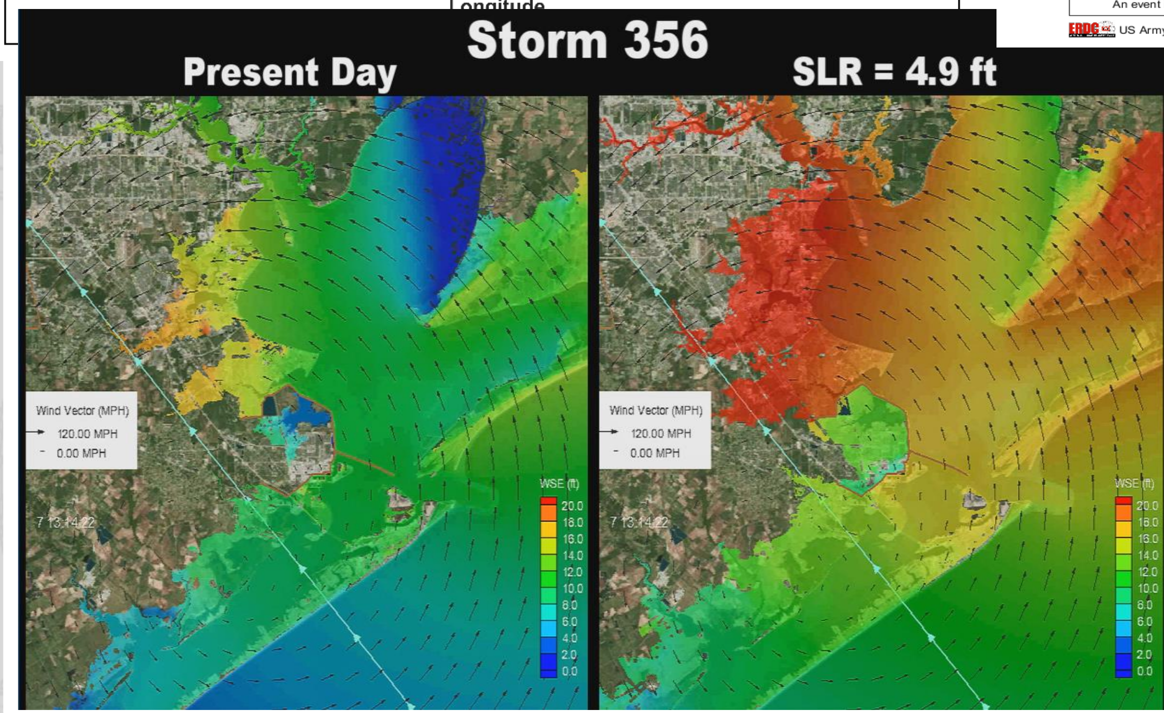


Top 10 events based on Peak H_{mo}

Event	Date/Time(UTC)	H_{mo}	T_p	θ_{mean}	Event	Date/Time(UTC)	H_{mo}	T_p	θ_{mean}
1	2008/09/13 09:00	2.74	7.51	200.0	6	2001/06/05 22:00	2.51	8.55	156.0
2	1985/10/28 18:00	2.66	5.74	343.0	7	2002/09/07 00:00	2.49	9.90	124.0
3	1983/08/18 06:00	2.58	10.48	137.0	8	1993/03/13 00:00	2.49	5.69	356.0
4	1989/10/16 00:00	2.56	11.31	145.0	9	1988/09/16 21:00	2.49	16.27	155.0
5	2005/09/24 07:00	2.55	5.75	7.0	10	1998/09/11 07:00	2.48	10.07	136.0

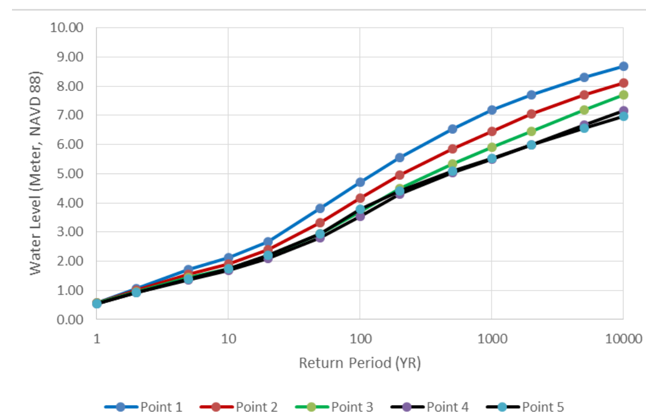
An event is defined as any period when H_{mo} > 2.00m θ_{mean} is direction that waves are arriving from

ERDC US Army Engineer Research & Development Center   ST73074_v02



100 year Wave > 3m

Above 6.5 Storm surge



HOUSTON SHIP CHANNEL

Fast Facts: The Port of Houston is…

- *1st* in U.S. in foreign waterborne tonnage
- *1st* in U.S. imports
- *1st* in U.S. export tonnage
- *2nd* in U.S. in total tonnage
- The nation's leading breakbulk port, handling *41%* of the project cargo at all Gulf Cargo ports

The Port of Houston is an integral part of the regional economy.

- The Greater Houston region one of the nation's largest concentrations of consumers, and the Port of Houston is a strategic gateway for cargo originating in or destined for the United States West or Midwest. Each year, more than 200 *million* tons of cargo move through the Port of Houston, carried by more than 8,000 vessels and 200,000 barges.

52 miles long

From mile 0 to mile 40 (Boggy Bayou), the authorized channel depth is 45 feet, with a bottom width of 530 feet. The remaining channel depth from mile 40 (Boggy Bayou) to 52 (turning basin) varies from 36 feet to 40 feet, with a bottom width of 300 feet.

Model	Name	LOA (ft)	Beam (ft)	Draft (ft)
CNTNR21L	KMSS Ultra	935.0	131.2	41.7
CNTNR44	Zim Piraeus	964.9	105.6	43.0
VLCC15B	MT Brittania	859.6	137.8	27.2

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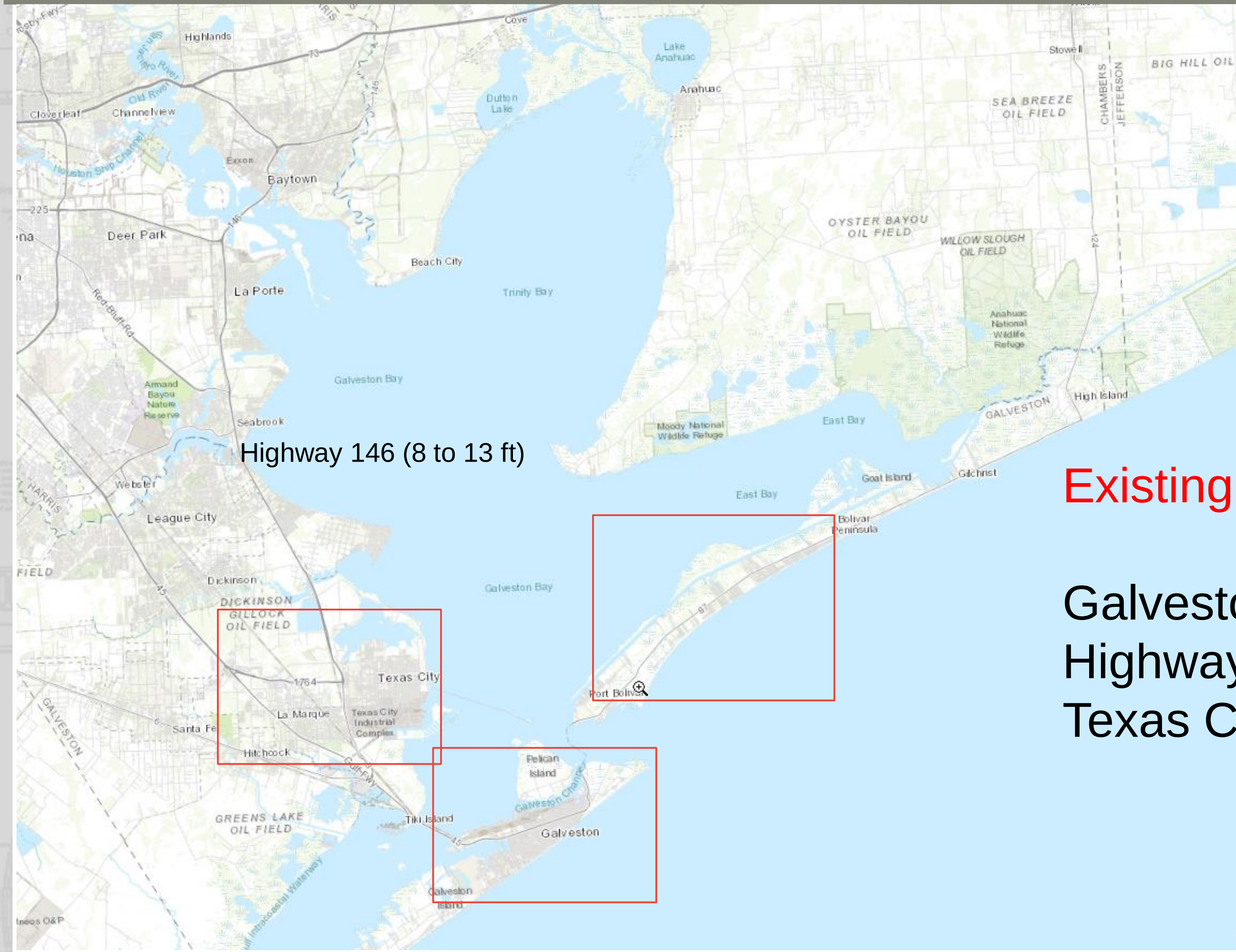
Background Data



Highway 146 (8 to 13 ft)

Existing Protection System

Galveston Sea Wall
Highway 87
Texas City Dike

US Army Corps of Engineers.

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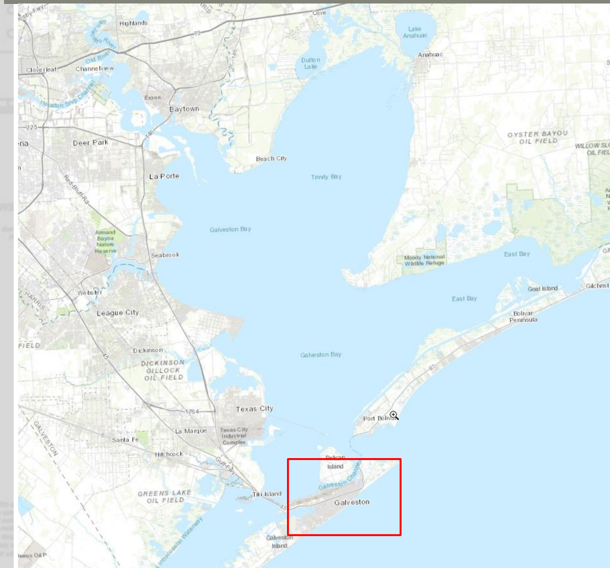
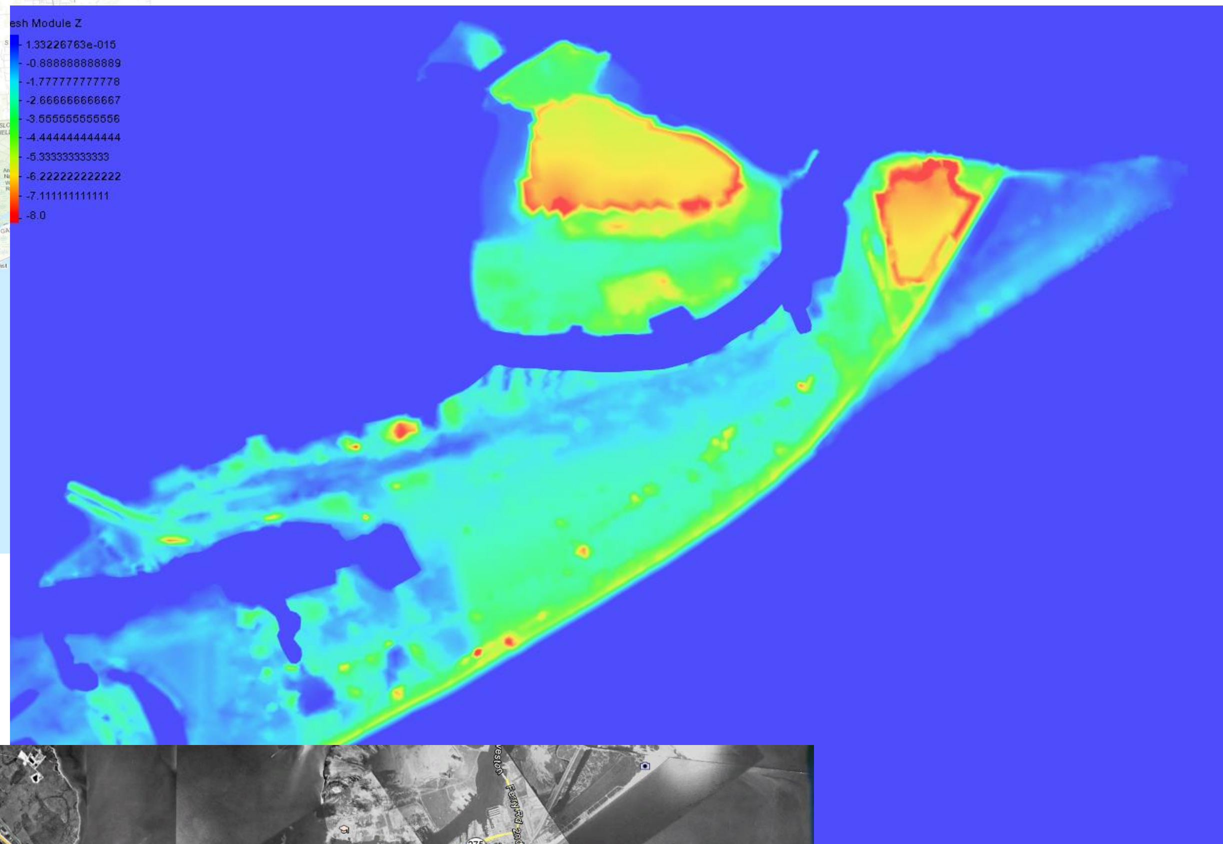
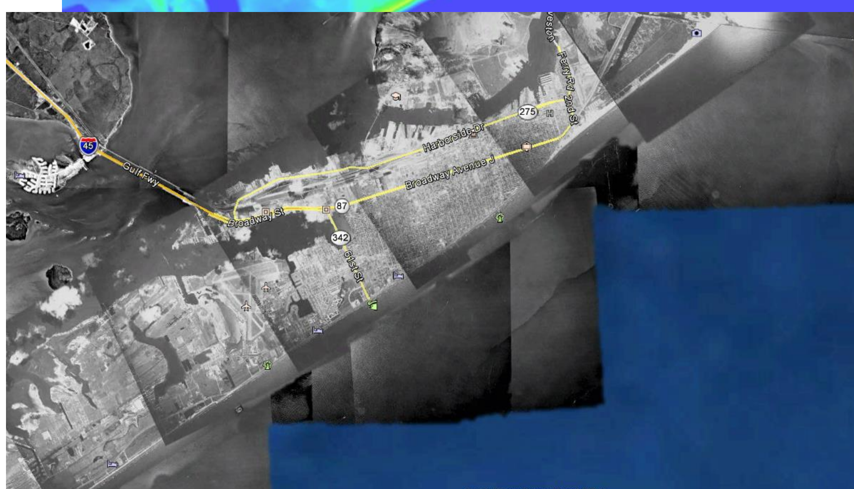
Background Data





Galveston Sea Wall
+17-20 ft NAVD
Developed area
behind (~>8 ft)



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Engineers

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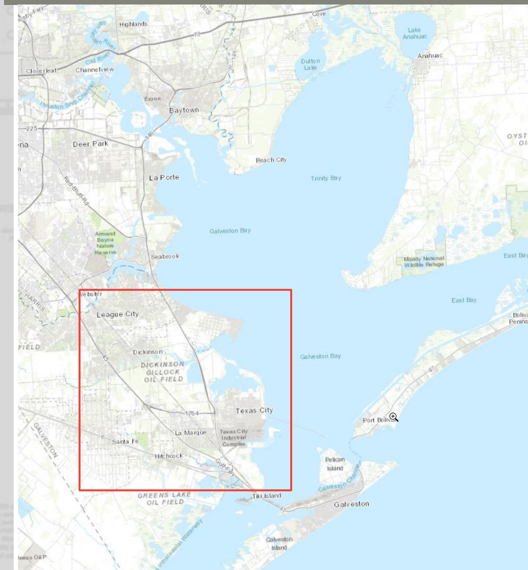
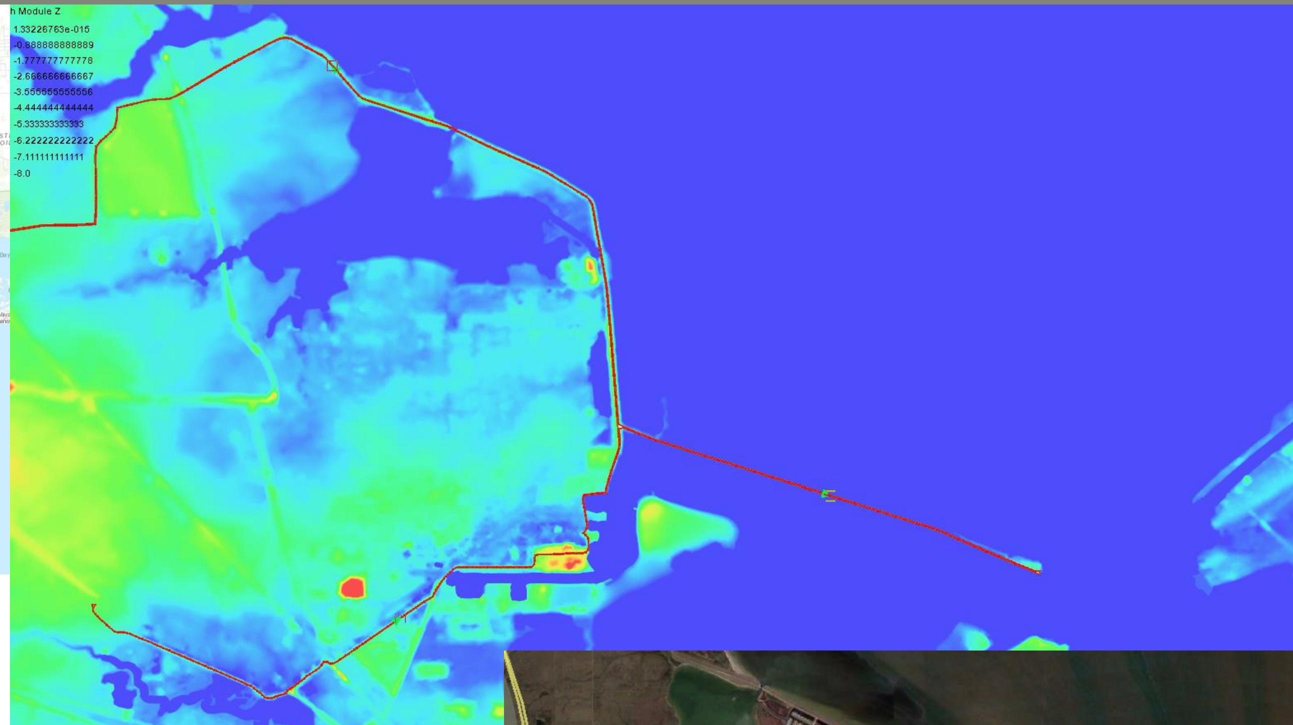
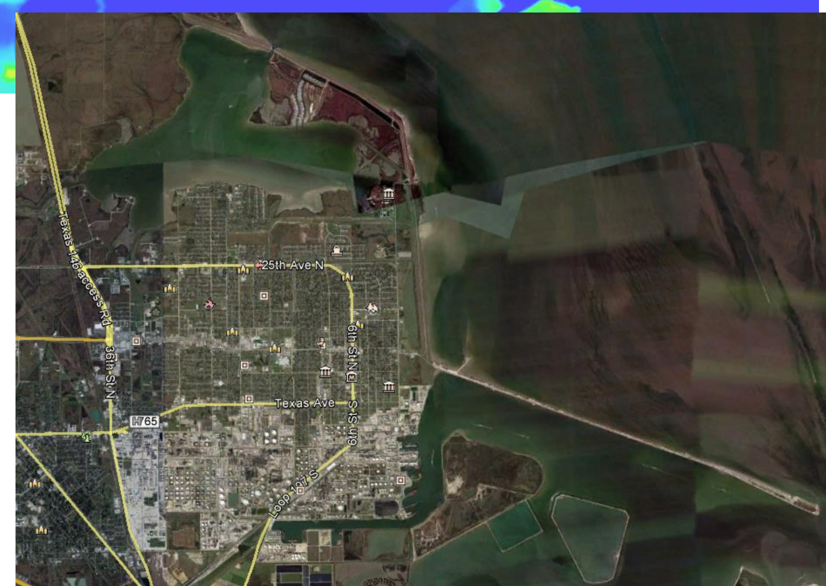
Background Data



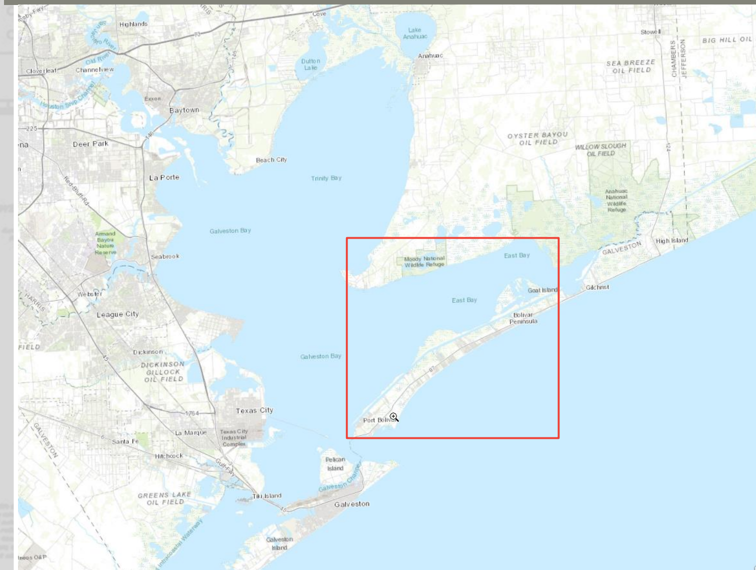




Texas City Protection System
Levee +15-22 ft NAVD

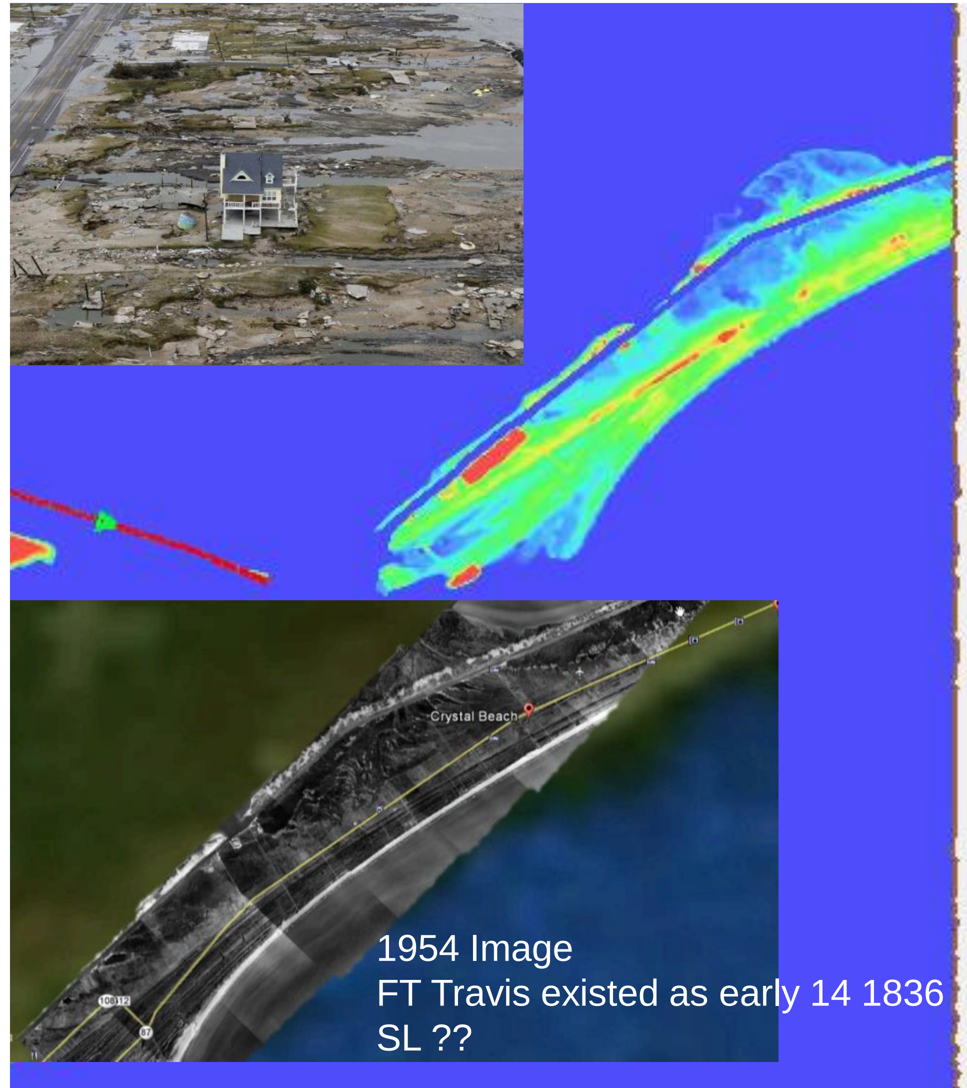
Protected up-to 100 Yr Flood

Background Data



Bolivar Peninsula
Avg. Elevation +3-f ft NAVD
Highway 87

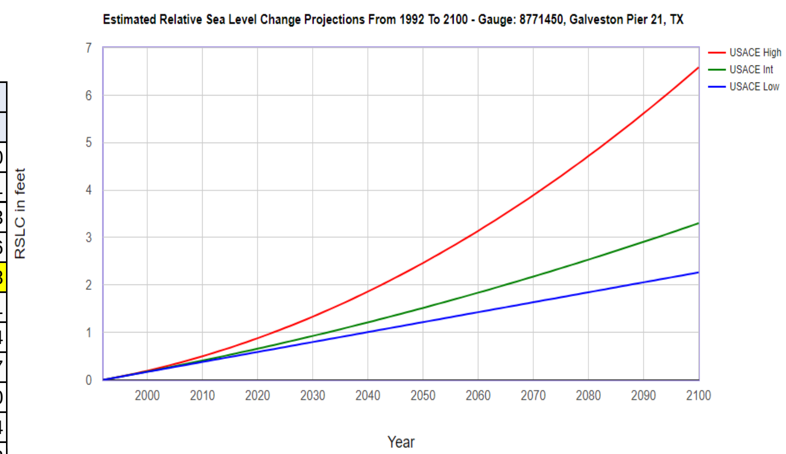
100 Yr Flood : 12-13 ft



RSLC CHANGE

Galveston Pier 21 RSLC

Year	USACE Low	USACE Int	USACE High
2017	0.0	0.0	0.0
2020	0.1	0.1	0.1
2025	0.2	0.2	0.3
2030	0.3	0.4	0.6
2035	0.4	0.5	0.8
2040	0.5	0.6	1.1
2045	0.6	0.8	1.4
2050	0.7	0.9	1.7
2055	0.8	1.1	2.0
2060	0.9	1.3	2.4
2065	1.0	1.4	2.8
2070	1.1	1.6	3.1
2075	1.2	1.8	3.5
2080	1.3	2.0	4.0
2085	1.4	2.1	4.4
2090	1.5	2.3	4.9
2095	1.6	2.5	5.3
2100	1.7	2.7	5.8
2105	1.9	2.9	6.4
2110	2.0	3.1	6.9
2115	2.1	3.3	7.4
2120	2.2	3.6	8.0
2125	2.3	3.8	8.6
2130	2.4	4.0	9.2
2135	2.5	4.2	9.8



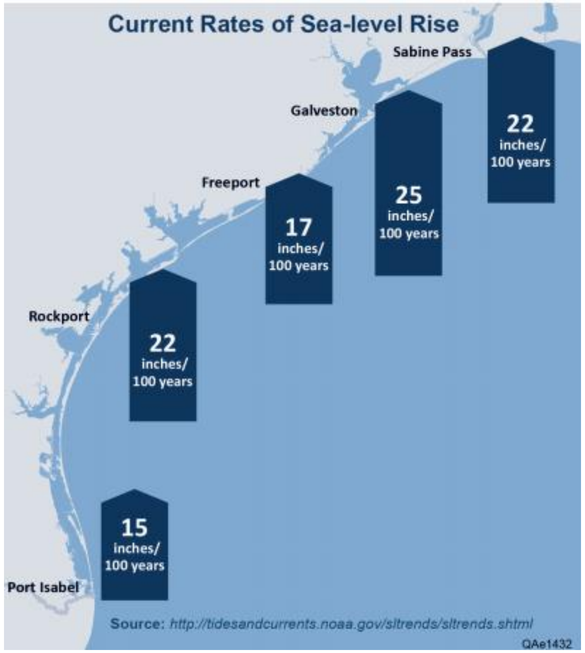
From 1992 to 2008, Historical RSLC = 0.34 ft

From 2008 to 2017, Historical RSLC = 0.18 ft

From 2017 to 2035, (L=0.38 ft, 0.49 ft, 0.83 ft)

From 2017 to 2085, (L=1.43 ft, 2.14 ft, 4.40 ft)

From 2017 to 2135, (L=2.48 ft, 4.24 ft, 9.82 ft)



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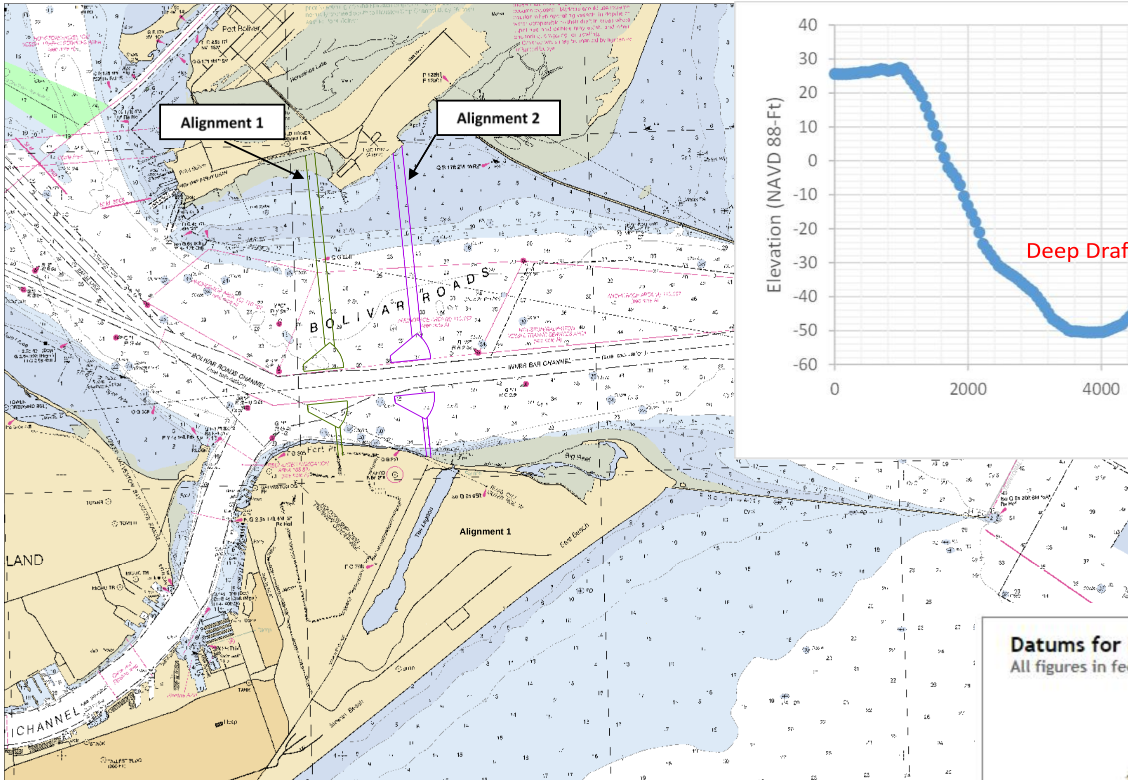
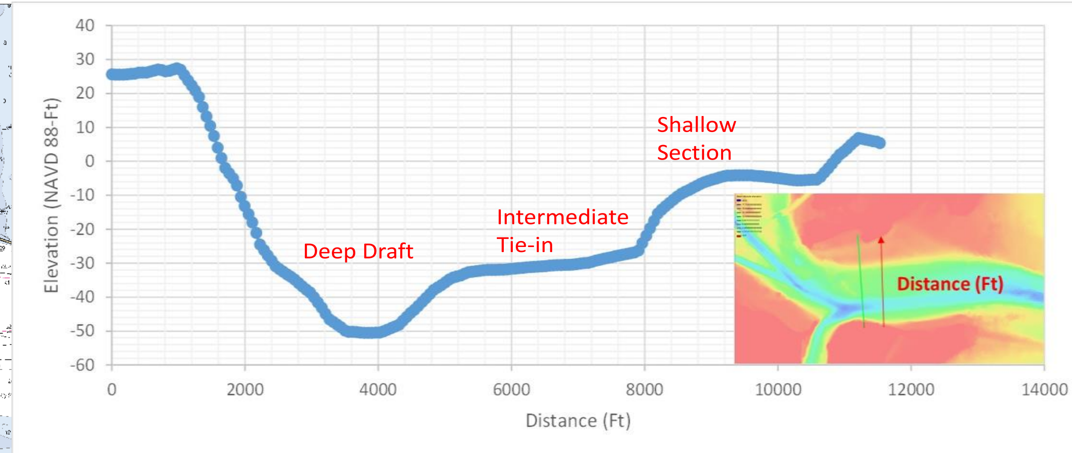
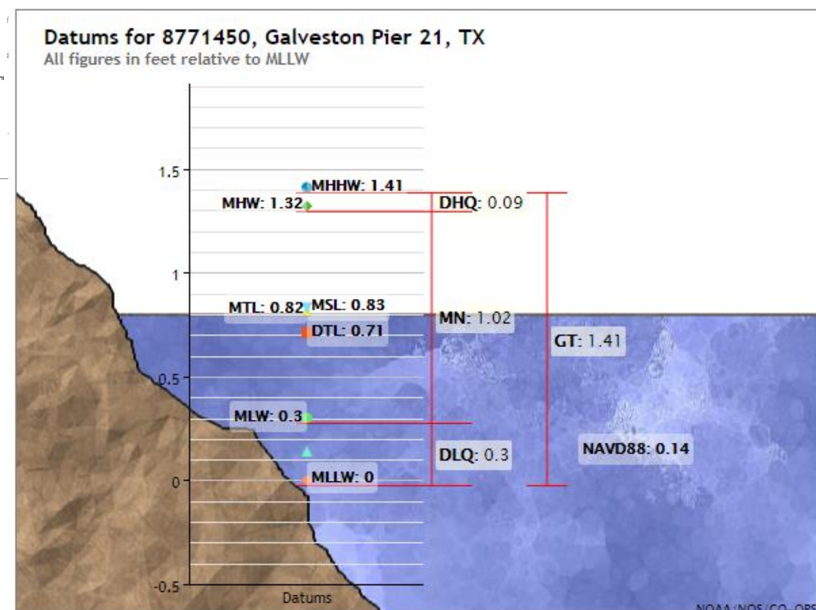
OVERVIEW





Inlet is about 2 mile (3.2 KM) long
Varying Depth (~50 ft in deeper section –HSC
Shallow section ~10 ft Depth

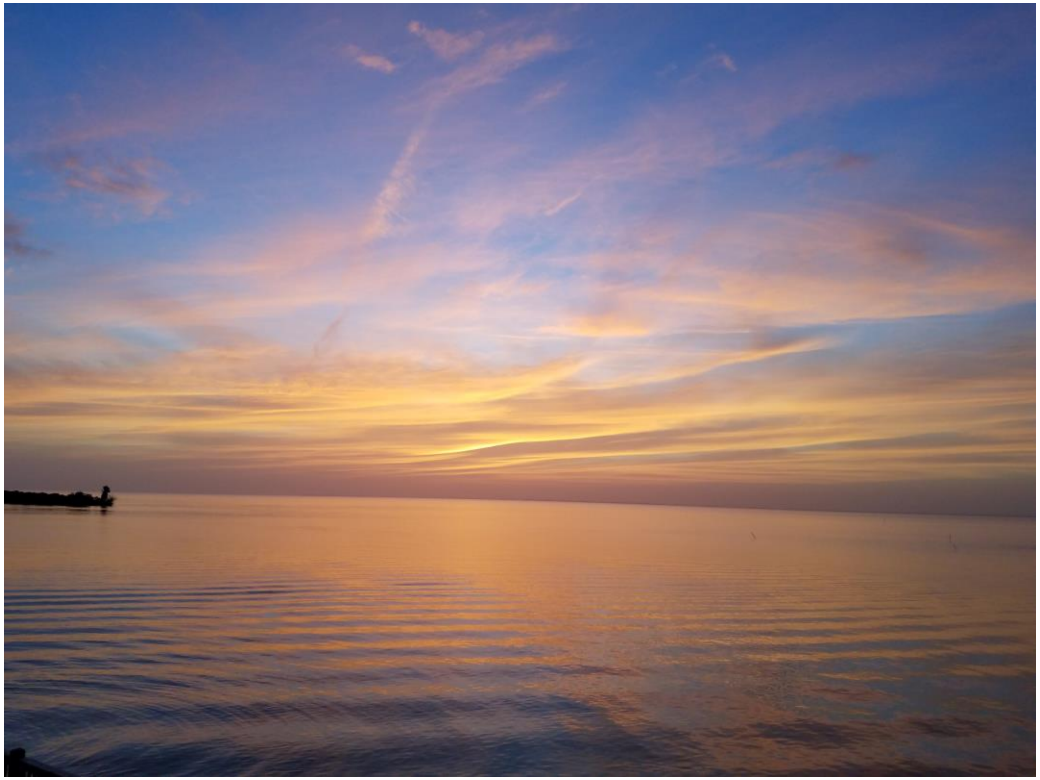
MSL(1992,ft) = 0.83–0.14 = 0.69ft (NAVD1988)
1 Ft = 0.305 ft



ENVIRONMENTAL CONCERNS

GATE DESIGN WORKSHOP
MARCH 17, 2019

Dianna Ramirez (GLO)
Jennifer Morgan (SWG)



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GALVESTON BAY CHARACTERISTICS

- **Surface Area of Galveston Bay: 600 sq. mile**
- **Avg Depth of Bay : 8 Ft**
- **Tide Period (Diurnal dominated) : 24 Hour**
- **Bolivar Inlet constitutes about 80% of tidal exchange (Flux)**
- **Tide Range : 1 -2 ft**
- **Tidal Range decays progressively into the bay system**
- **Bolivar Inlet constitutes about 80% of tidal exchange (Flux)**
- **Wind-driven currents have a large impact on water-surface elevations**
  - **Predominant south-southeast**

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ADH MODELING RESULTS

27% constriction at Bolivar Inlet analyzed

Overall Tidal Prisms reduction about 10-15%

Overall Tidal Amplitude reduction about 15%

No significant impact on salinity (avg change, 2-4 ppt)

In general freshwater tends to stay longer = fresher Bay

In General, slight reduction in velocity in the Bay (avg, change 2-10 cm/s)

In General, increase in velocity at the inlet (Max vel change from 1.2 to 1.8 m/s)

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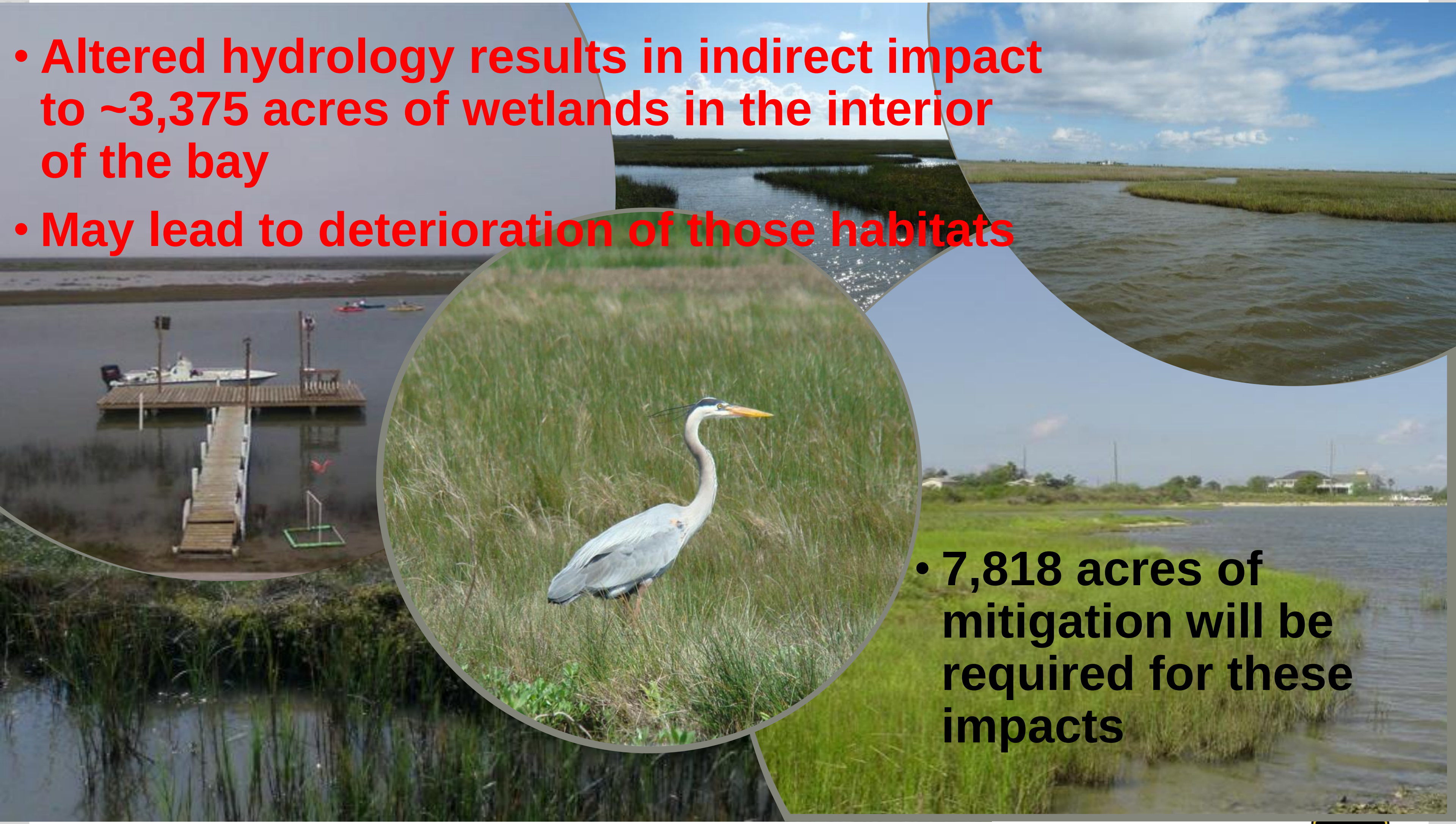
- Altered hydrology results in indirect impact to ~3,375 acres of wetlands in the interior of the bay
- May lead to deterioration of those habitats



- 7,818 acres of mitigation will be required for these impacts

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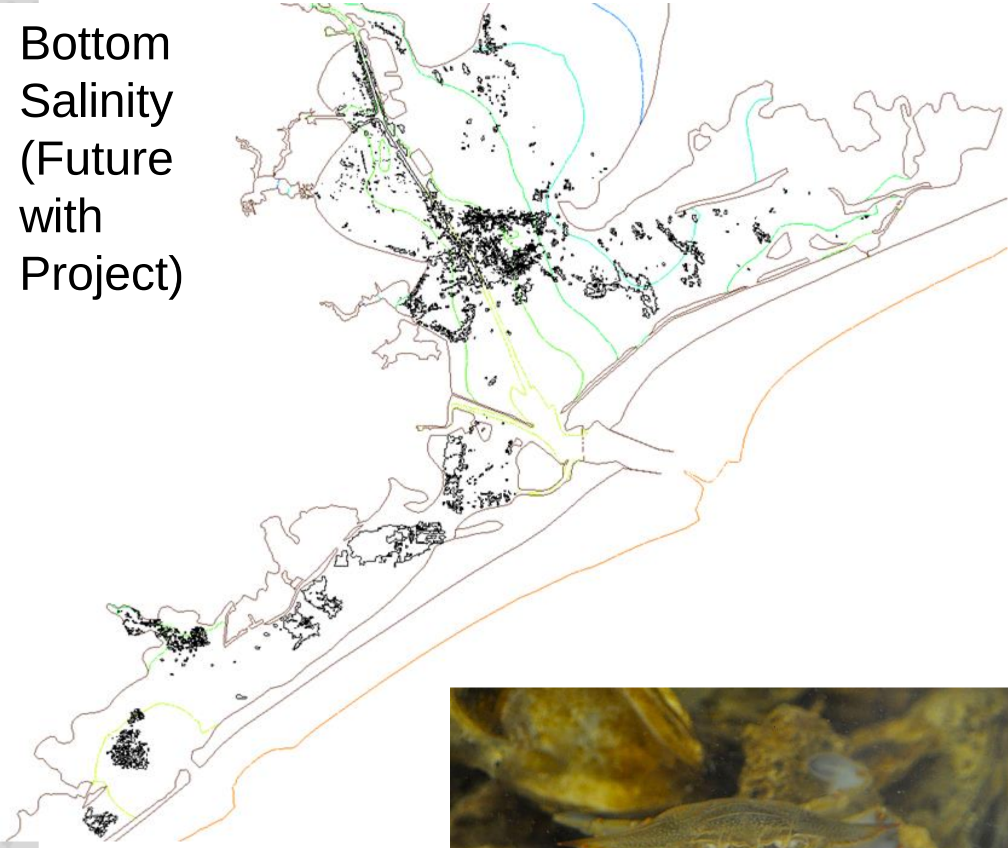
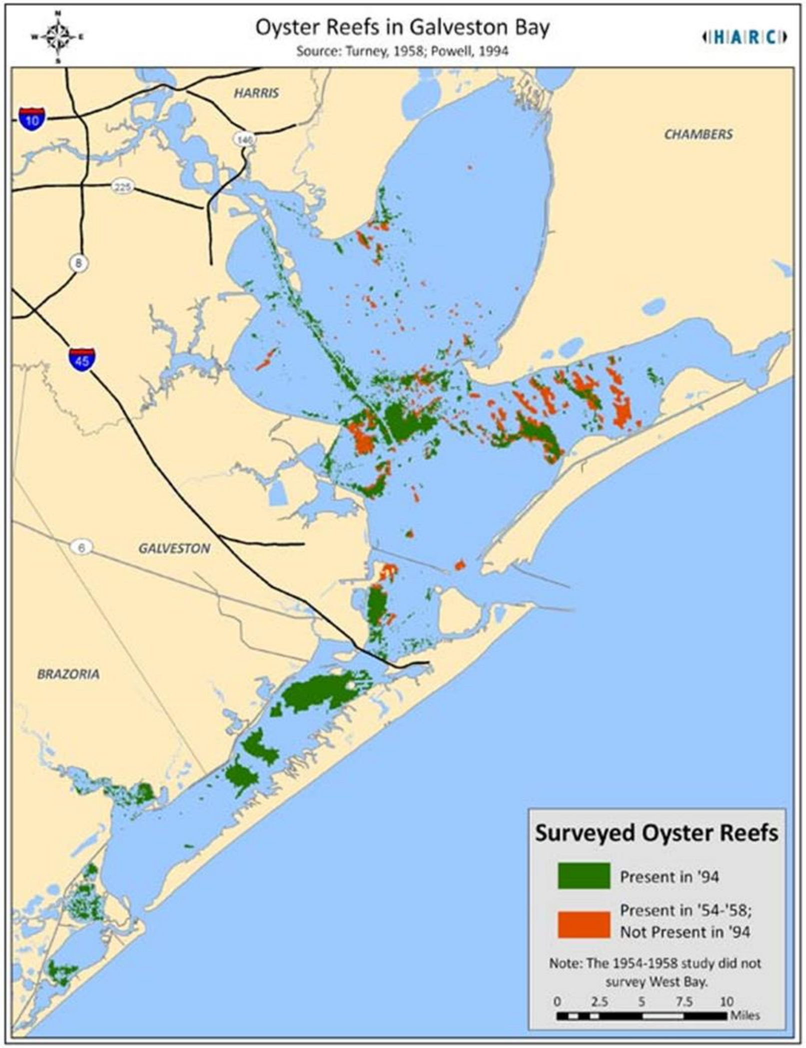
Bottom Salinity (Future with Project)





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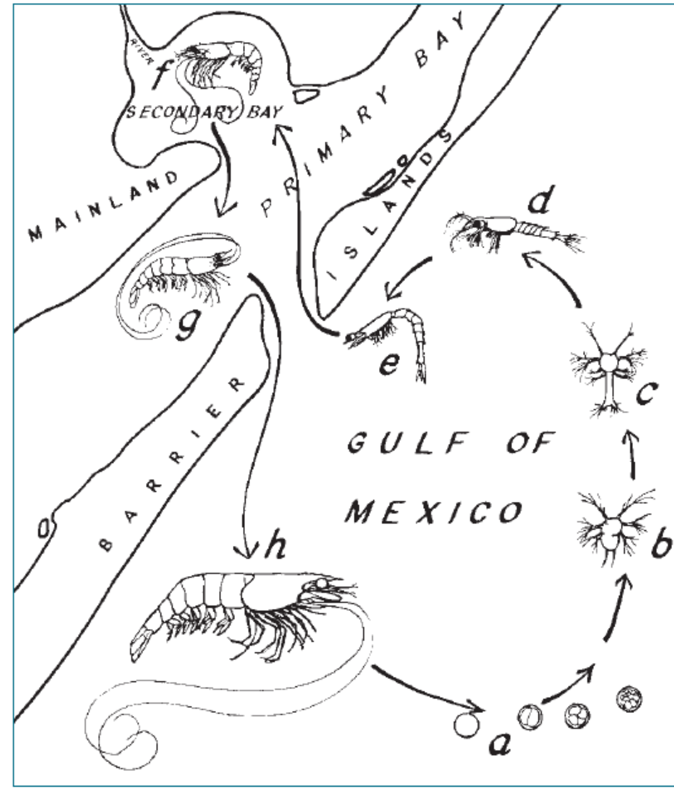
SPECIES NEED TO BE ABLE TO MOVE FROM GALVESTON BAY TO THE GULF OF MEXICO AND BACK DURING DIFFERENT



a) shrimp eggs
b) nauplius larva
c) protozoea
d) mysis
e) postmysis
f) juvenile shrimp
g) adolescent shrimp
h) mature adult shrimp

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Commercial Fishing

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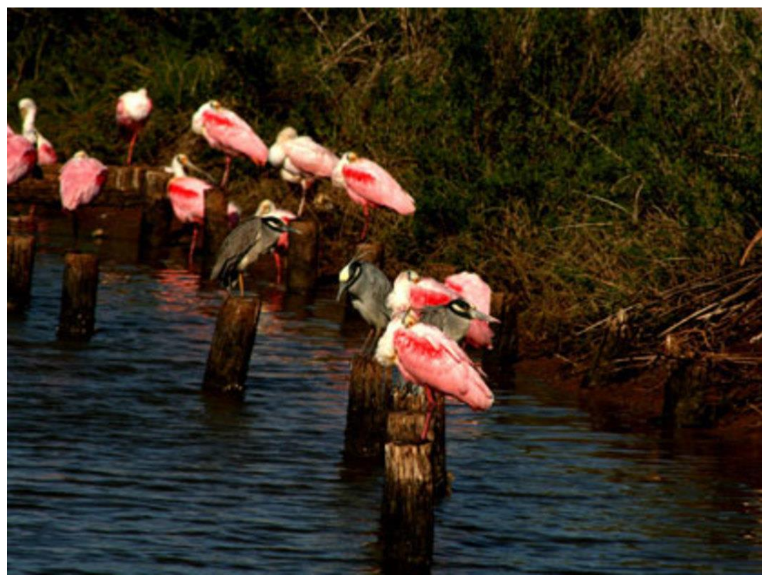
Recreational Fishing

Other Wildlife



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QUESTIONS?

Coastal Texas Protection and Restoration Project

Bert Sweetman

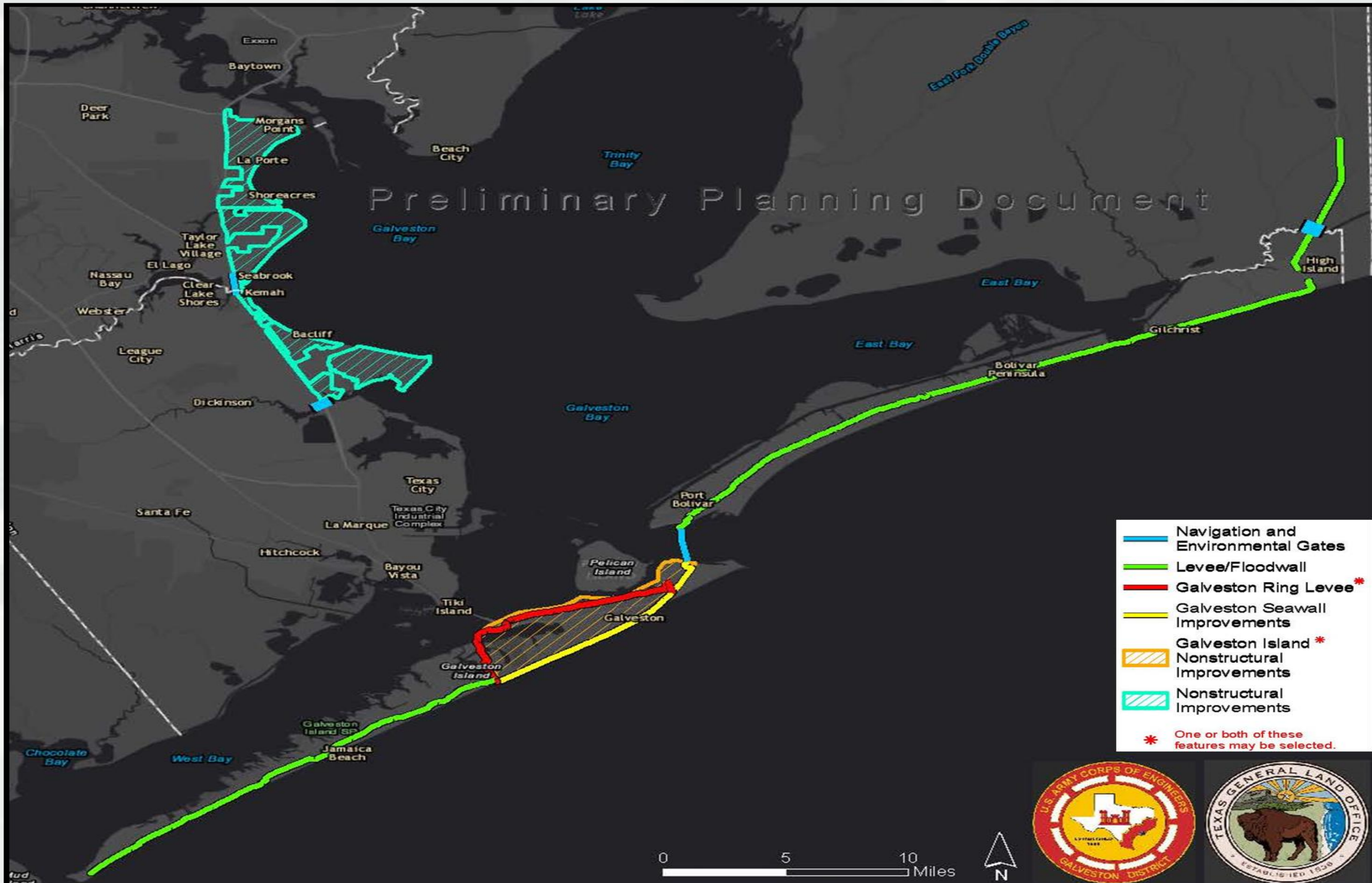
Charlie Brandsletter

Himangshu S. Das

®

Tentative Selected Plan (TSP)

Alternative A: Coastal Barrier Alignment

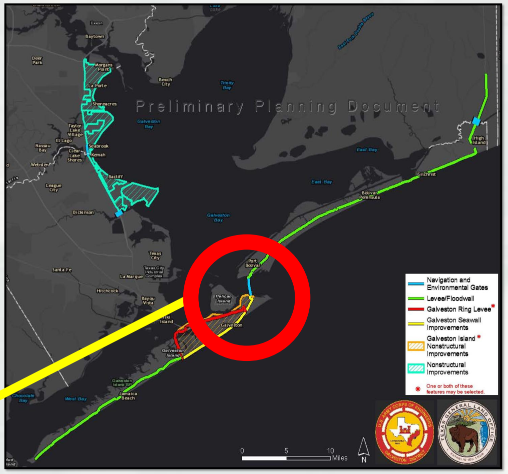


BUILDING STRONG®

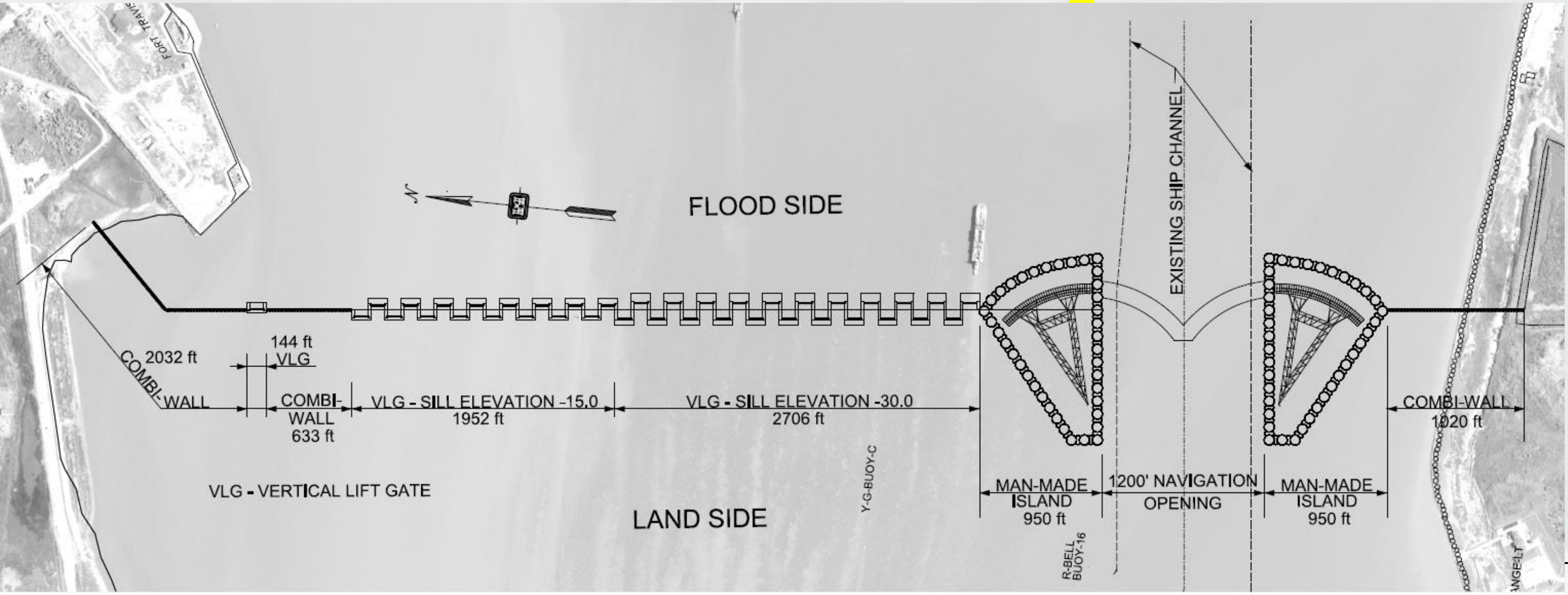
Bolivar Road Crossing

Bolivar Road Crossing

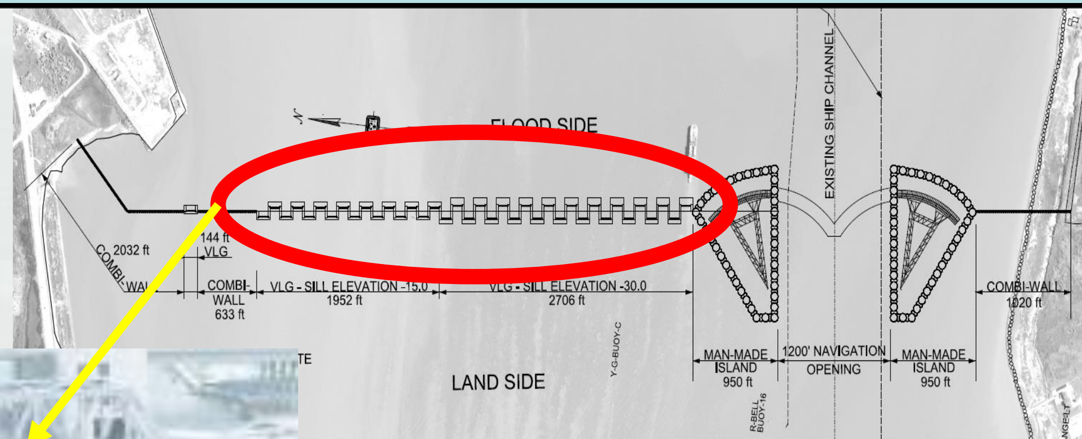
- Vertical Lift Gates
- Large Navigation Gate



39 environmental Gates (100 ft)



Bolivar Road Crossing - Vertical Lift Gates



BUILDING STRONG®

Bolivar Road Crossing – Large Navigation Gate

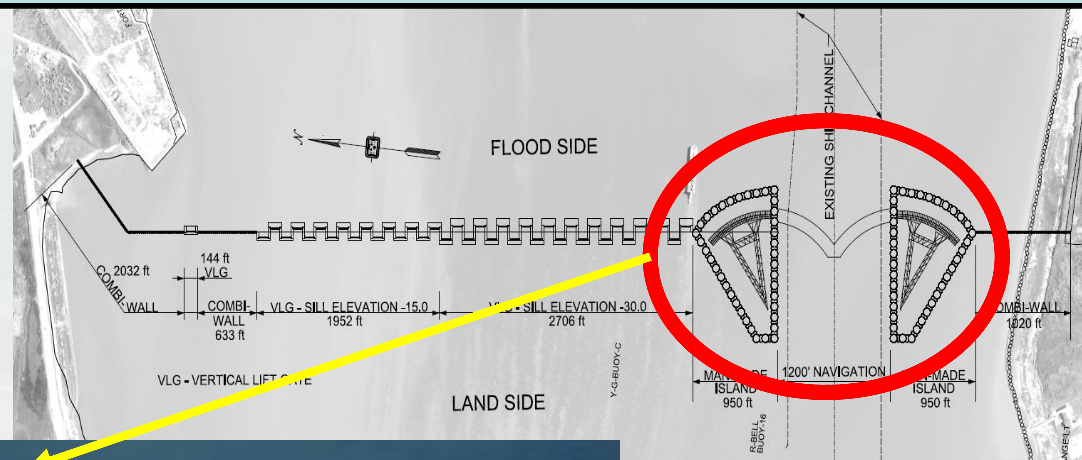


Image Courtesy:
Maeslant Barrier

Buoyance Piston Storm Surge Gate

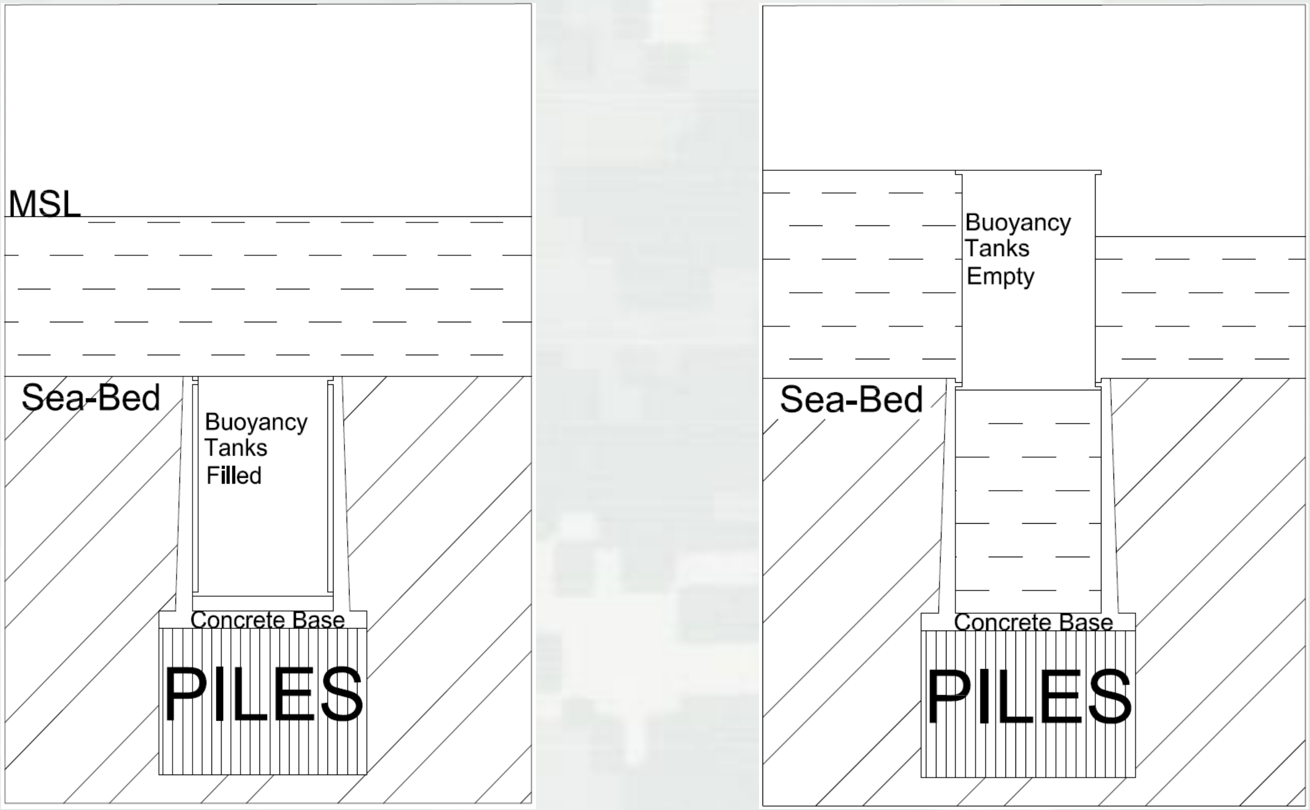
Galveston Inlet Ship Channel
Coastal Texas Protection Workshop
March 17, 2019

Backdrop: Fall 2017

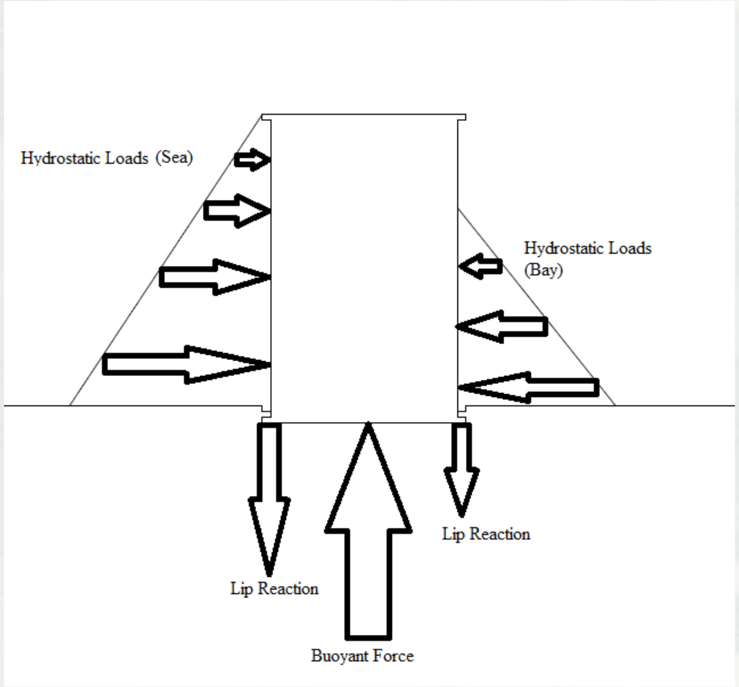
- USACE Coastal Texas Protection Project well underway
  - Costs and environmental assessment being based on sector gates
- GCCPRD Study finding major impact on tidal prism
  - Potential for very large mitigation costs
- Significant concerns about geotechnical conditions
- Silty waters with high sediment transport

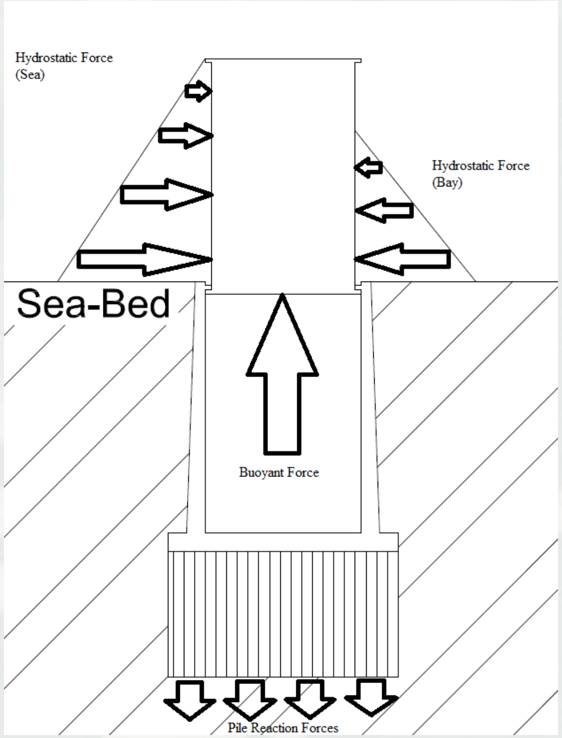
- Objective:
  - Develop a concept to minimize impact on tidal prism

Barrier Cross-Section: Open and Closed

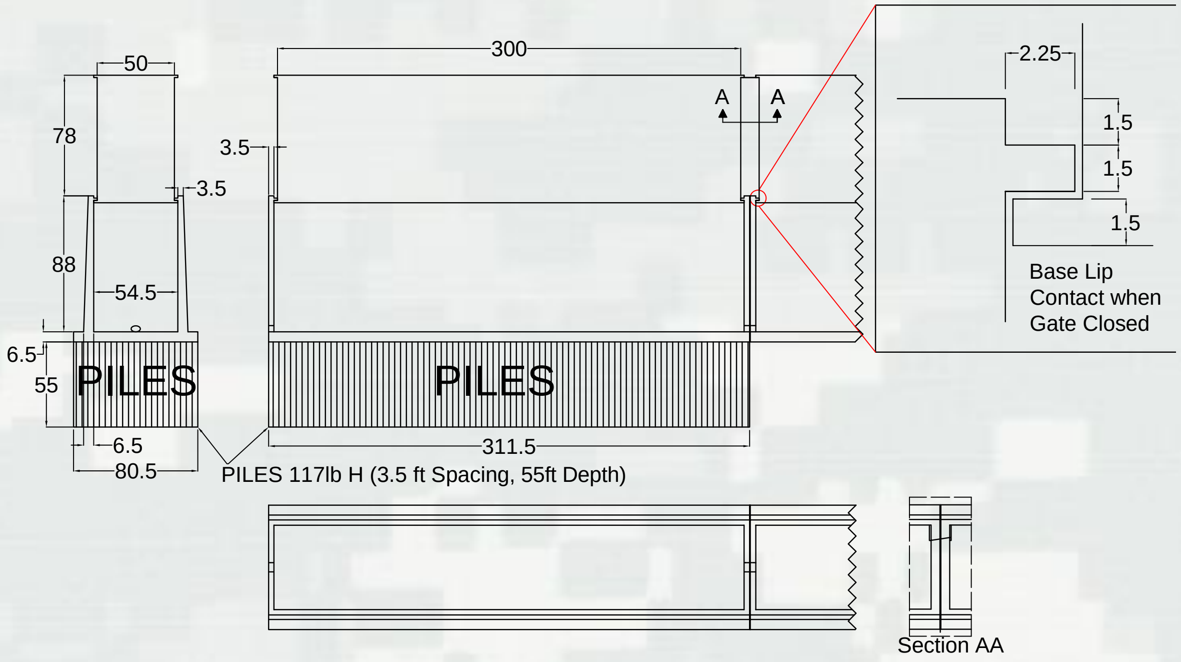


How it Works: Free Body Diagram

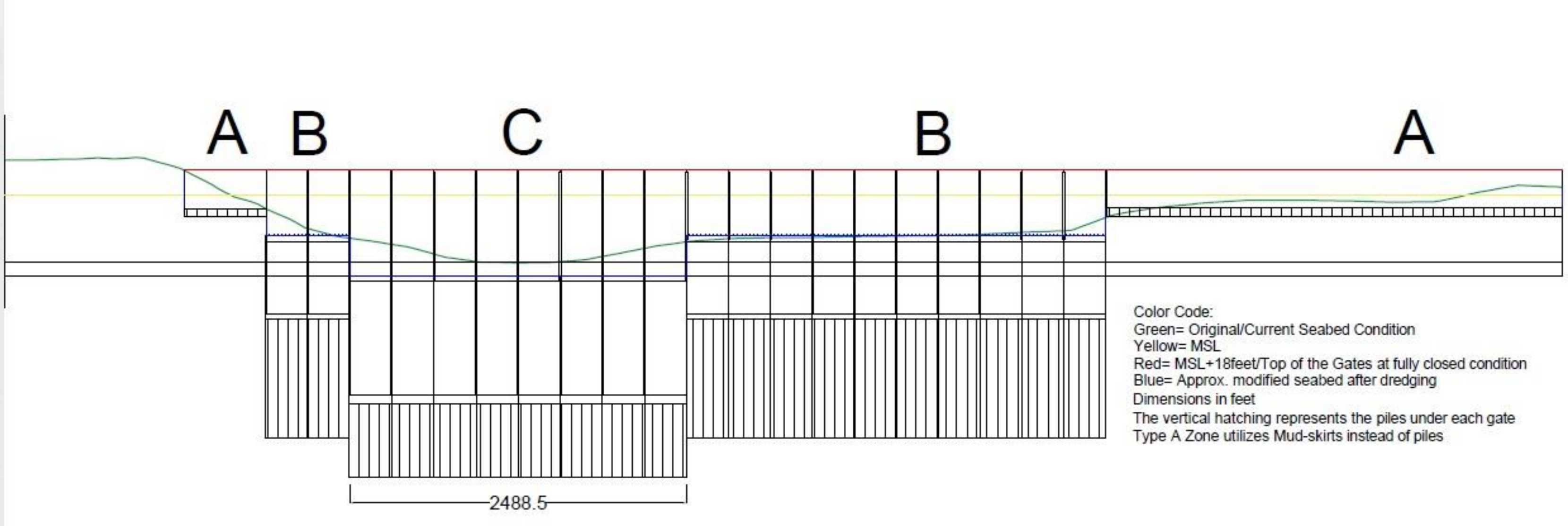




Solution: Piston gate concept



Eliminates all blockage in deep water column



Benefits

- Minimal environmental impact, especially on tidal prism
- Minimal impact on shipping
- Minimal visual impact
- Silt-tolerant design
- Geotechnical reaction spread over large area
- Piles begin well-below existing mud-line

Main Limitations

- New: Not a proven technology
- Not cost-effective for shallow water
- Configuration used for cost-estimate can not be opened against large hydrostatic head

Present Status

- Preliminary Design Complete
  - Structural steel scantling design of piston (ABS Code)
  - Concrete and rebar quantities but not reinforcement arrangement
  - Foundation piling
  - Major equipment (pumps, compressors)
  - Installation plan
  - Provisional patent application filed
- Cost estimates: Based on USACE rates
  - Material takeoffs
  - Individual components
  - Day-rates on installation equipment

Major Work yet to be undertaken

- Scaled operational model test to verify concept
- Accurate operational scenarios (opening against head difference)
- Details of mechanical equipment
- Detailed design and installation plans
- Identification of construction location options for concrete bases
- More accurate cost estimates
- Environmental Impact Assessment

GCCPRD

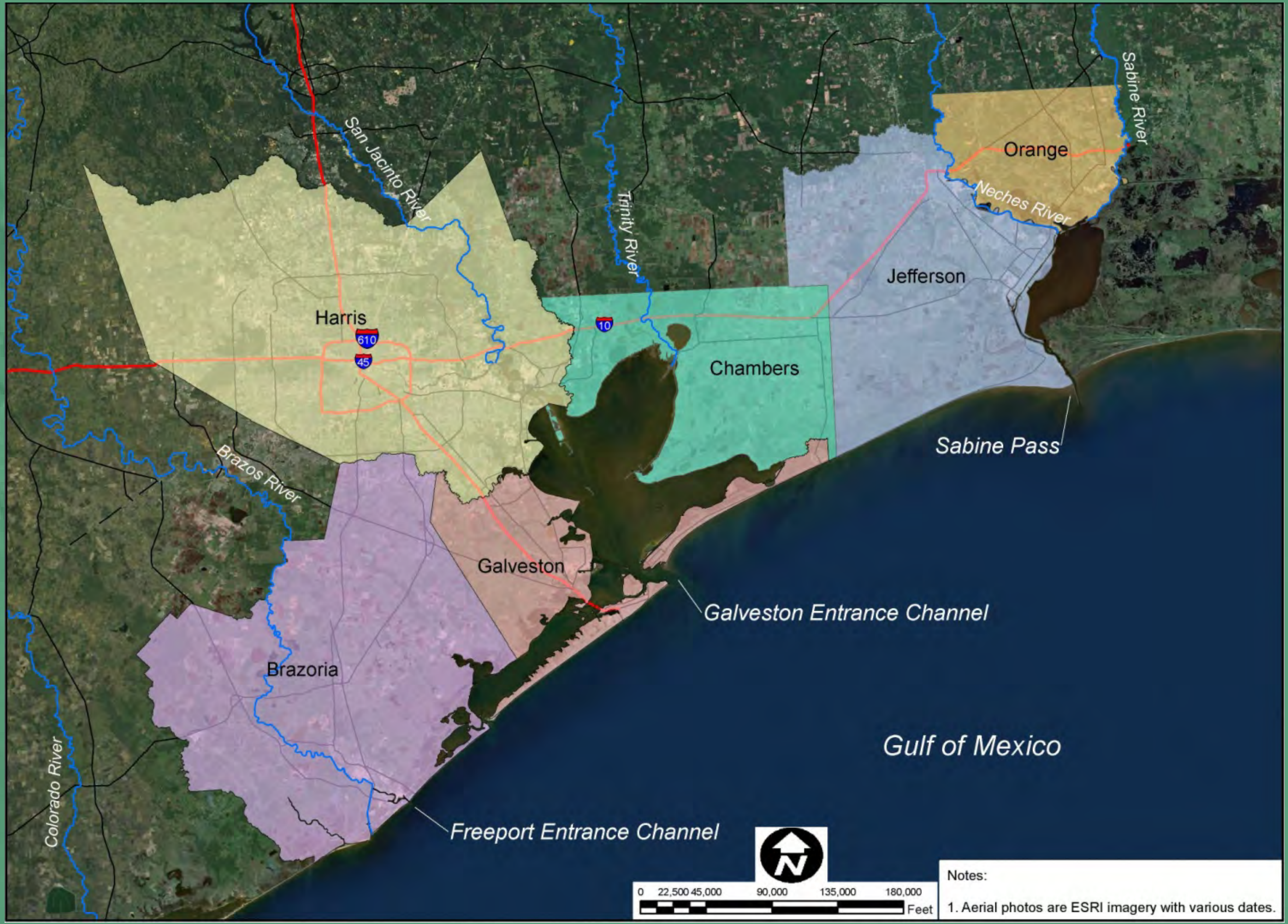
The Gulf Coast Community Protection and Recovery District

Storm Surge Suppression Study

March 15, 2019

www.gccprd.com

STUDY AREA



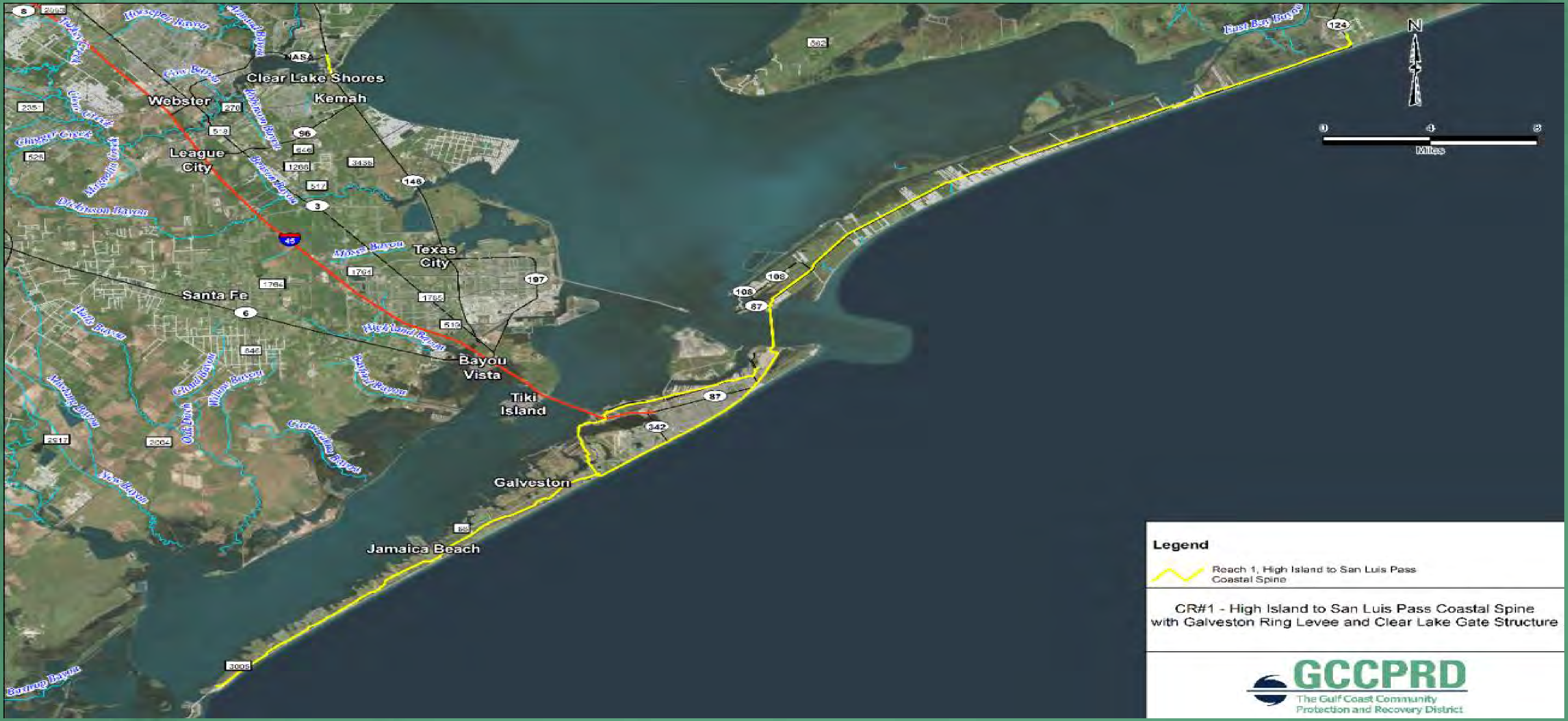
San Jacinto River
Trinity River
Sabine River
Orange
Neches River
Jefferson
Harris
610
45
10
Chambers
Brazos River
Galveston
Sabine Pass
Galveston Entrance Channel
Brazoria
Gulf of Mexico
Colorado River
Freeport Entrance Channel
N
0 22,500 45,000 90,000 135,000 180,000
Feet
Notes:
1. Aerial photos are ESRI imagery with various dates.

STUDY PURPOSE

To investigate the feasibility of reducing the vulnerability of the upper Texas coast to hurricane surge and flood damages through the study of an integrated flood protection system that relies on natural or nature based features, nonstructural and structural interventions.

GCCPRD Recommended Plan

CENTRAL REGION - *GALVESTON, CHAMBERS, AND HARRIS COUNTIES*

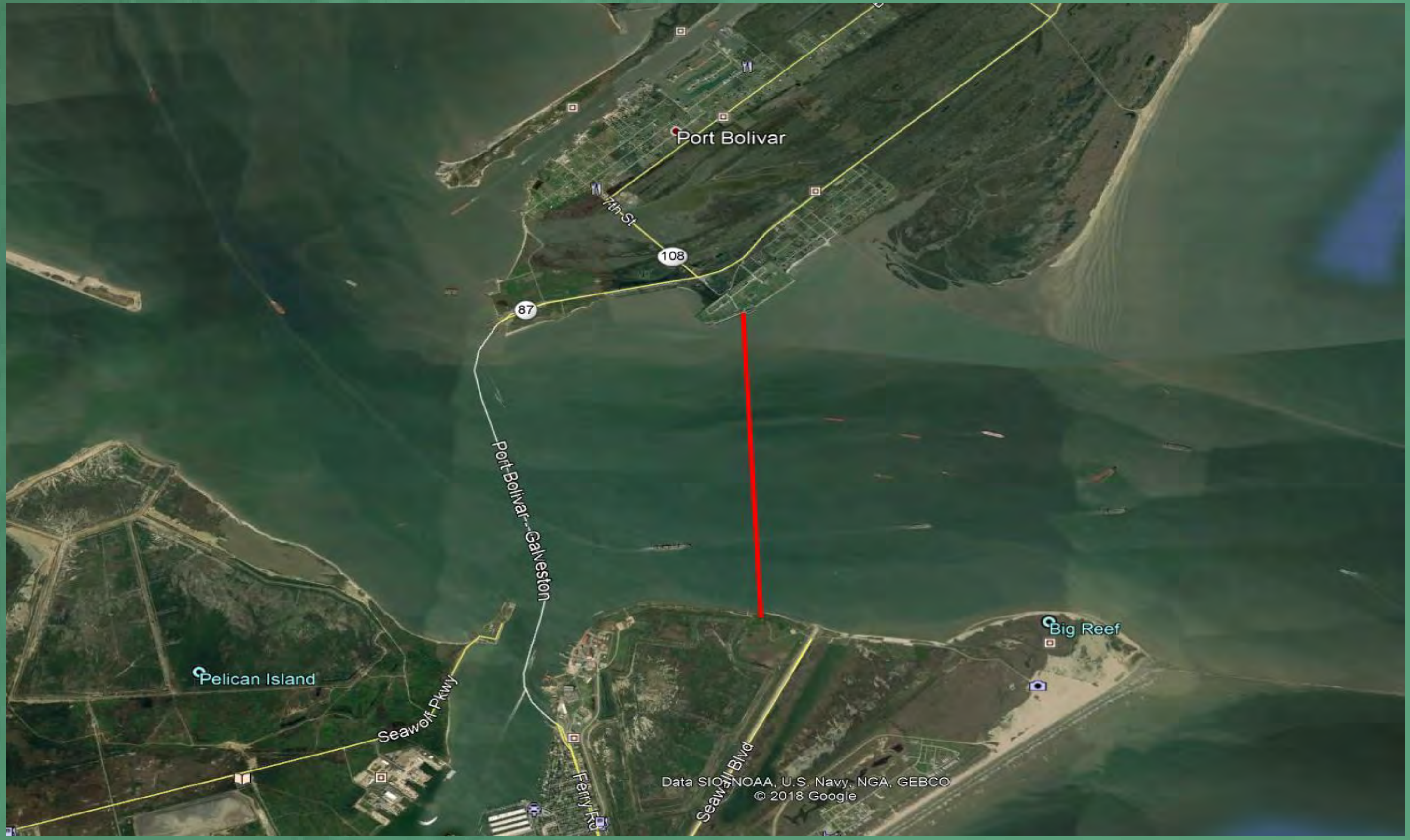


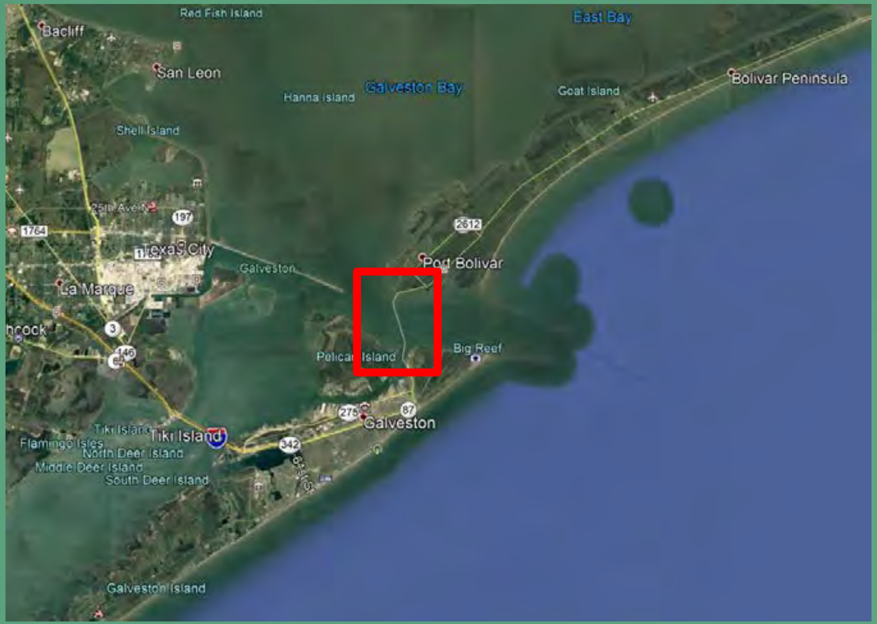

GCCPRD
Galveston Ring Levee
Clear Lake Structure
Closure Structure
Floodwall
Gate
Levee
Coastal Spine
0
1,500
3,000
6,000
Feet
1 in = 3,000 ft
GCCPRD


GCCPRD
Clear Lake Structure
BAYPORT BLVD
E NASA PKWY
BLUE DOLPHIN DR
TEXAS AVE
Clear Lake Structure
Closure Structure
Floodwall
Gate
Levee
0 300 600 1,200 Feet
1 in = 600 ft
GCCPRD

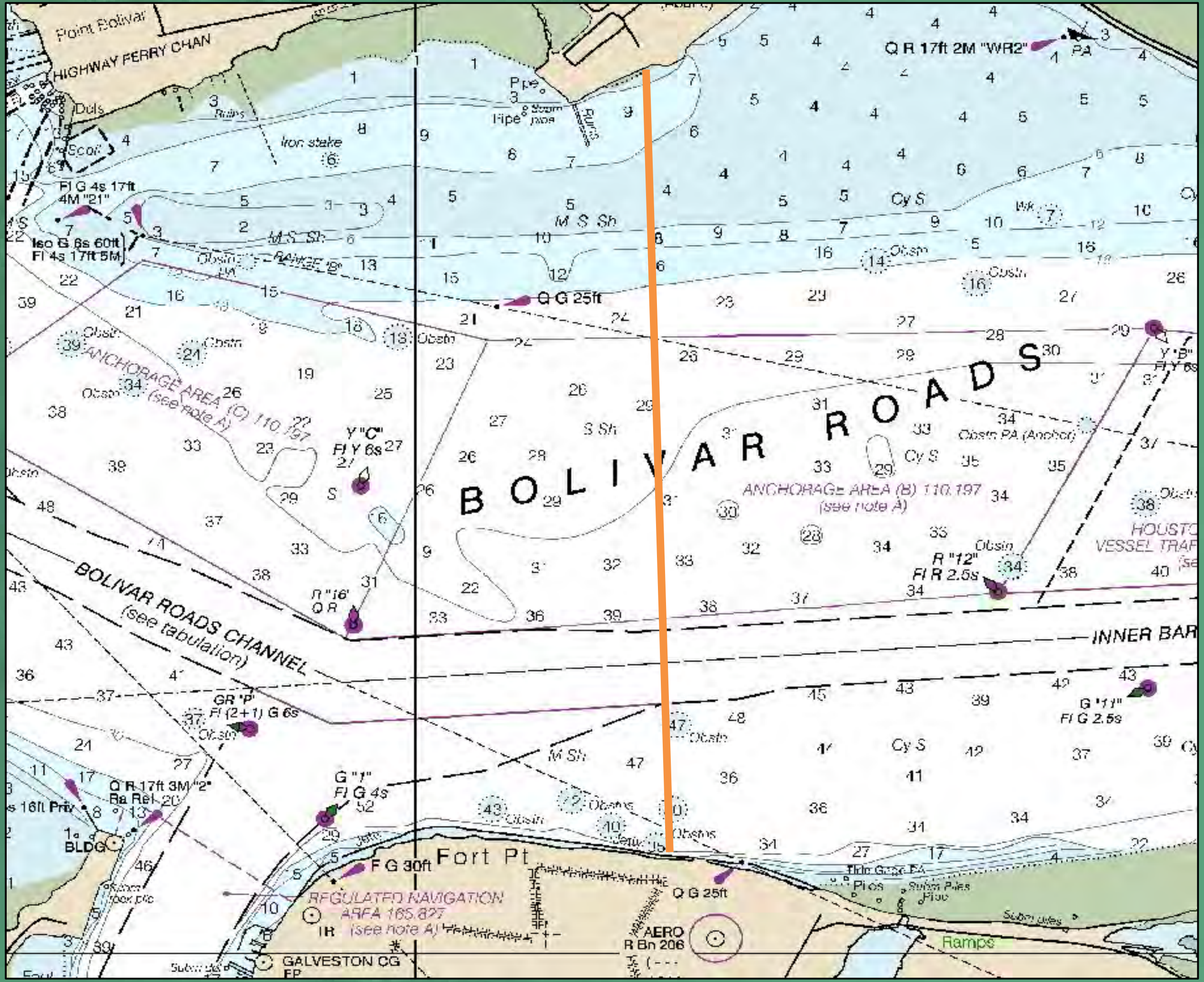
Bolivar Roads Alignment

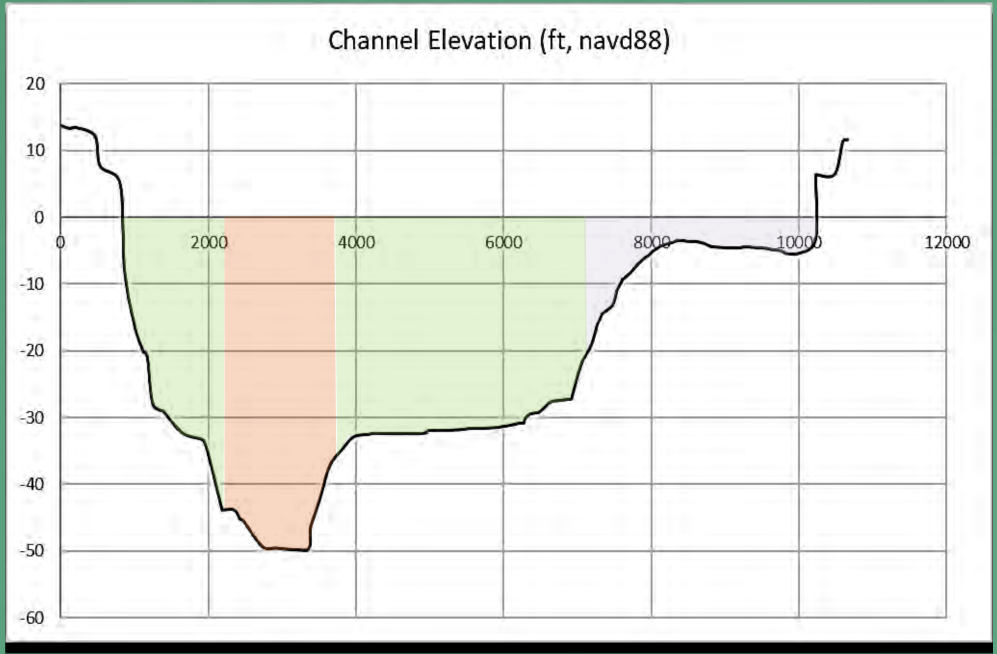
- Span – 10,000 ft.





Bathymetry





- Max. invert: EL -50.0
- Three distinct zones
  - EL -50.0
  - EL -30.0
  - EL -10.0

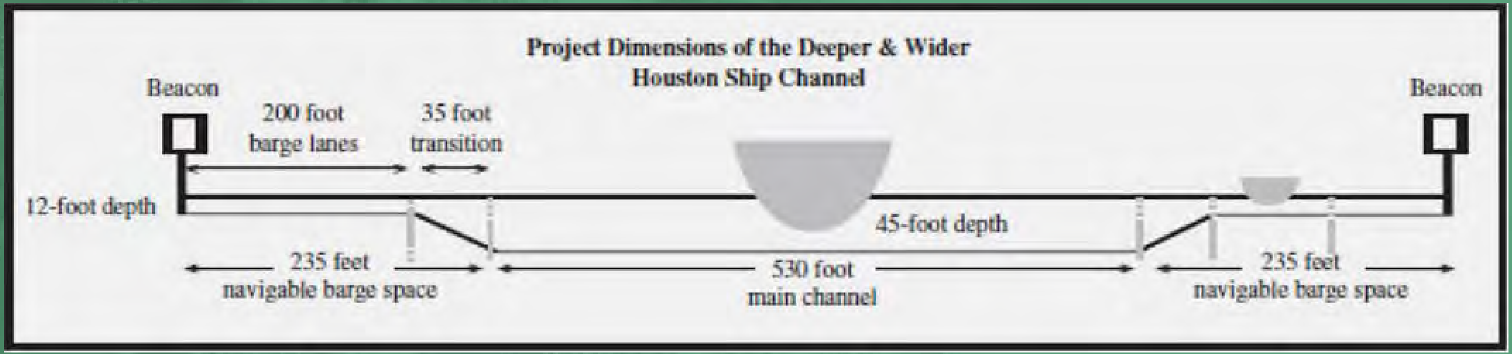
Bolivar Roads Barrier and Gate Design Process

- Analyzed three different gate configurations
  - GCCPRD840- 840 ft. floating sector gate w/ 24 VLGs
  - GCCPRD 1200- 1200 ft. floating sector gate w/ 24 VLGs
  - GCCPRD1200-Barge- 1200 ft. floating sector gate w/ 15 200 ft. barge gates and 8 VLGs
- Gate parameters factored into the environmental modeling conducted for Galveston Bay

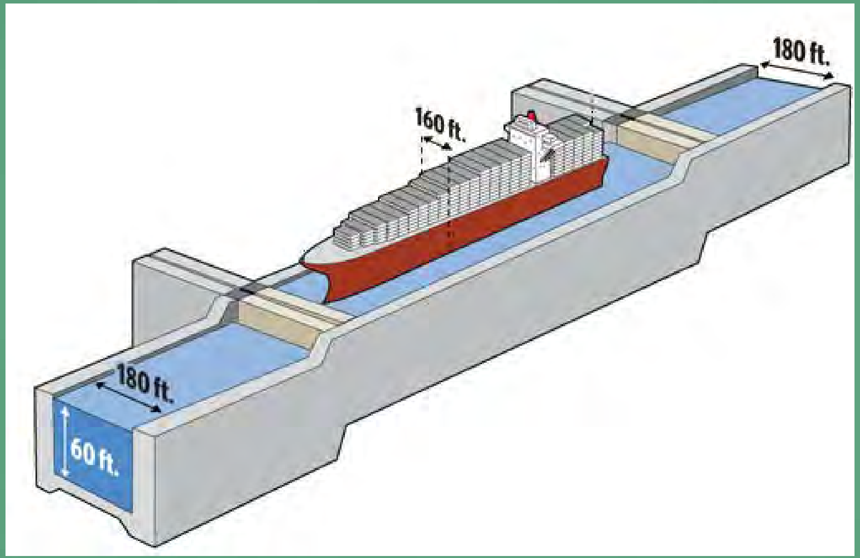
Barrier Design Criteria

- Design invert elevation for navigation – EL -60.0
  - Based on New Panamax
- Top of wall elevation +18.0 including freeboard
- Navigation channel width – at least 840 ft.
- Target porosity of barrier during regular condition – 70%
- Gates for navigation channel closure
- Environmental gates for tidal exchange
- Least amount of closure time
- Relatively easy and expedited construction
- Minimal operation and maintenance (O&M) effort.

Navigable Gate Width & Draft



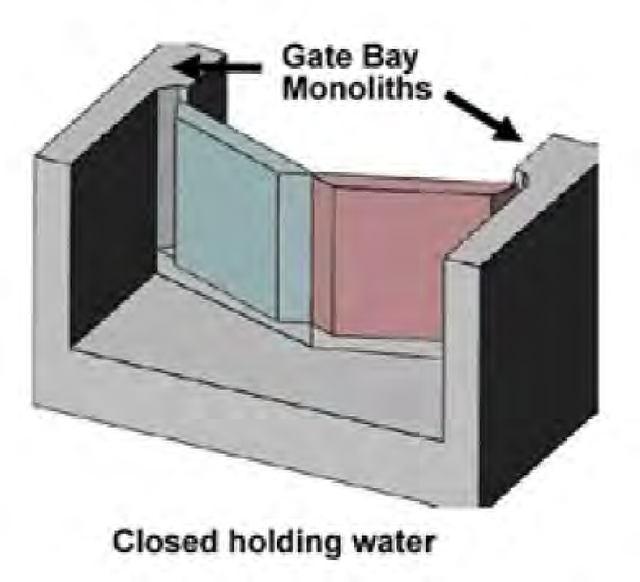
BANK CLEARANCE	MANUEVERING LANE	SHIP CLEARANCE	MANUEVERING LANE	BANK CLEARANCE
98'	258'	128'	258'	98'
(0.6)(161)	(1.6)(161)	(0.8)(161)	(1.6)(161)	(0.6)(161)

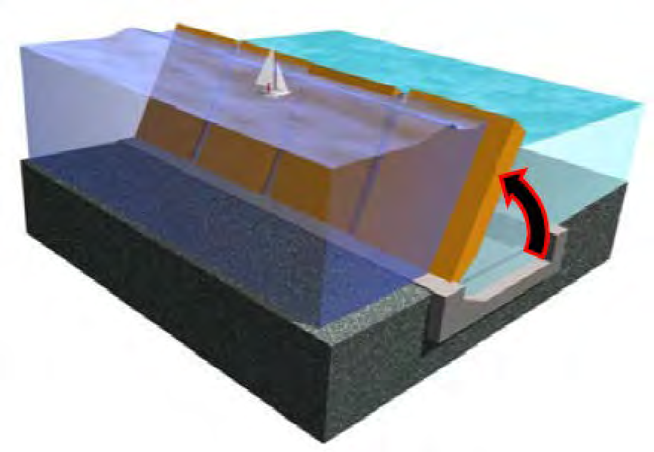


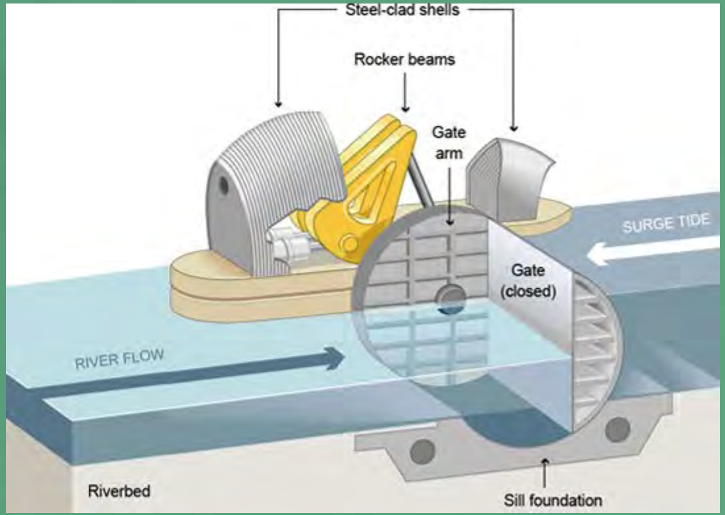
- **840 ft. total**

Gate Type Selection

- Gate evaluation included
  - Miter Gates
  - Vertical Lift Gates (VLG)
  - Flap Gates
  - Vertically Rotating Gates
  - Horizontally Rotating Gates
  - Barge Gates
  - Inflatable Rubber Dams.

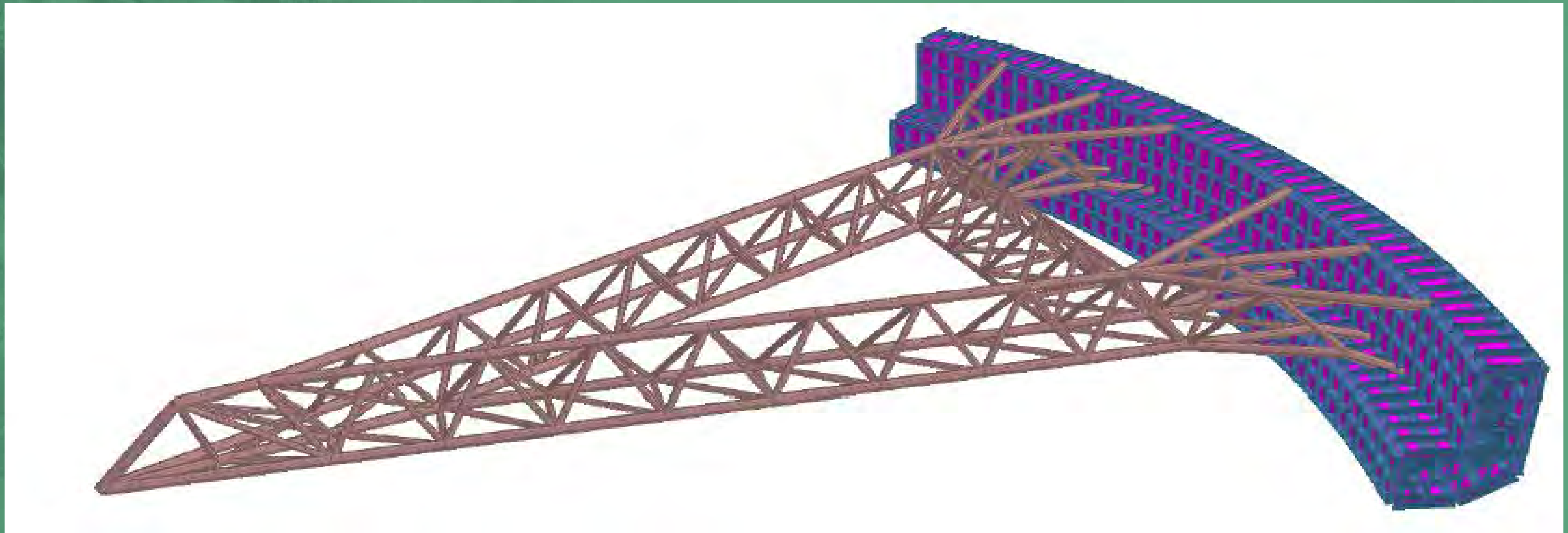






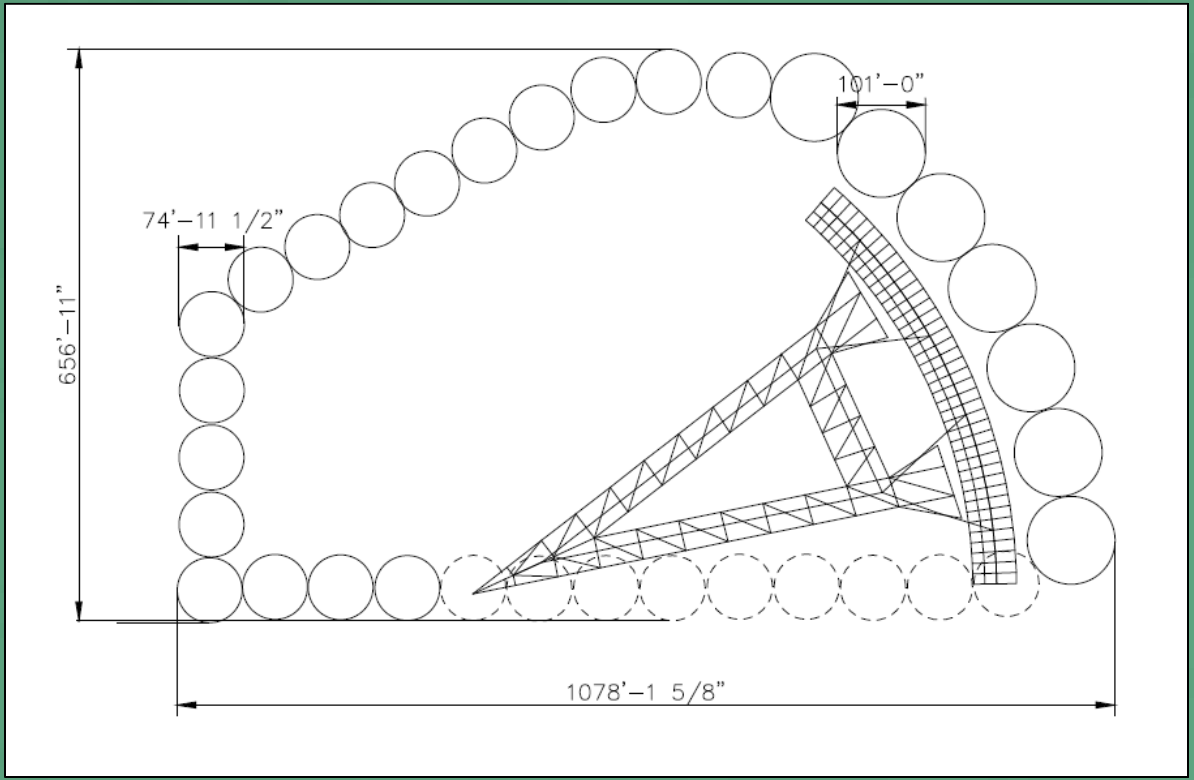
Navigation Gate

- Floating Sector Gate
- Span 1200 ft.
- Invert EL -60.0
- Top of wall EL +18.0



Gate Support Islands

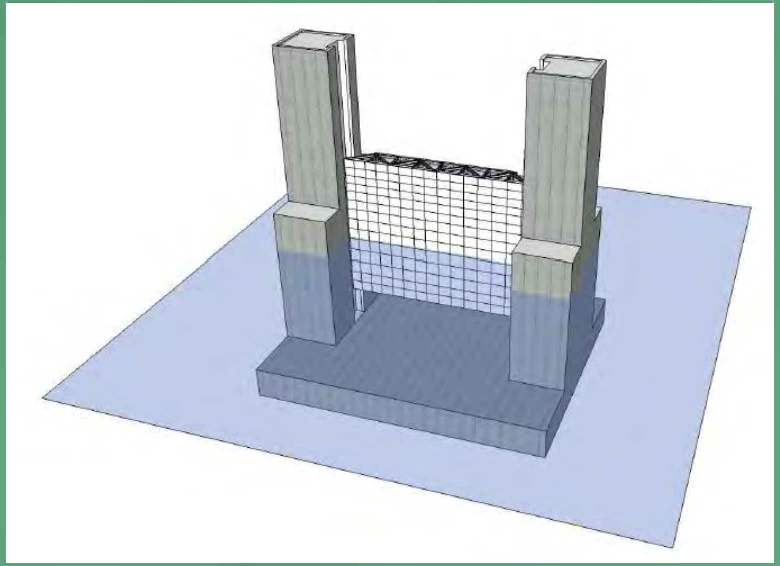
- 100 ft. dia. coffer cells in front (EL from -60.0 to +18.0
- 75 ft. dia. coffer cells (EL from -60.0 to +10.0

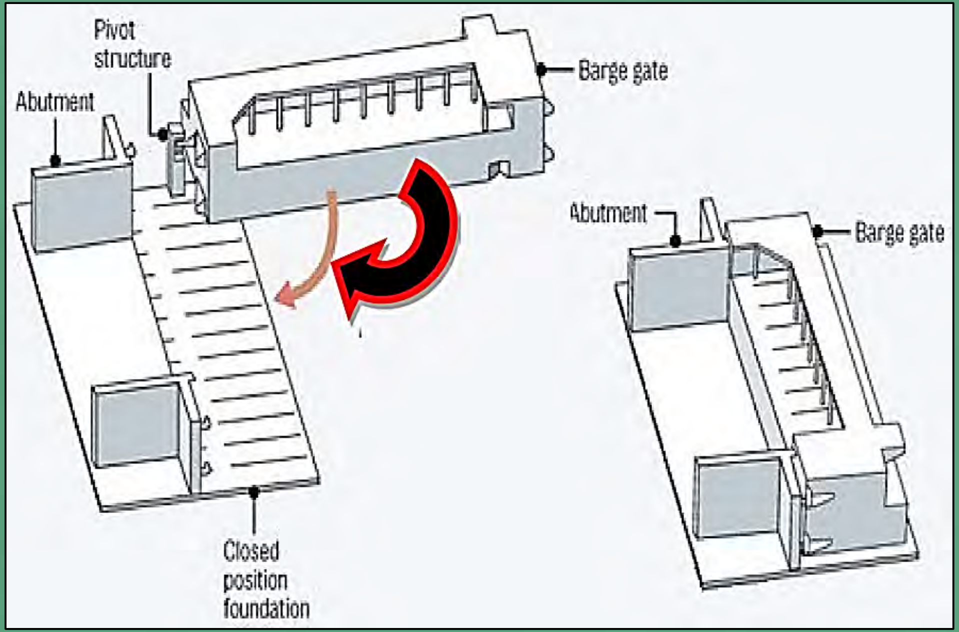


- Cells and islands to be jet grouted.
- Filled with sand afterwards

Environmental Gates

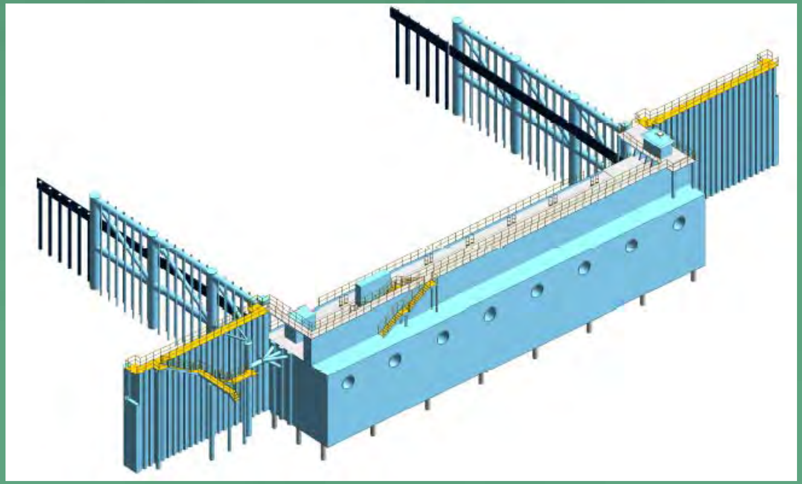
- Satisfies tidal exchange requirement
- Gates are kept open all the time.
- No navigation is allowed.
- Will be guarded using dolphins.
- Likely to be closed prior to the navigation gate.

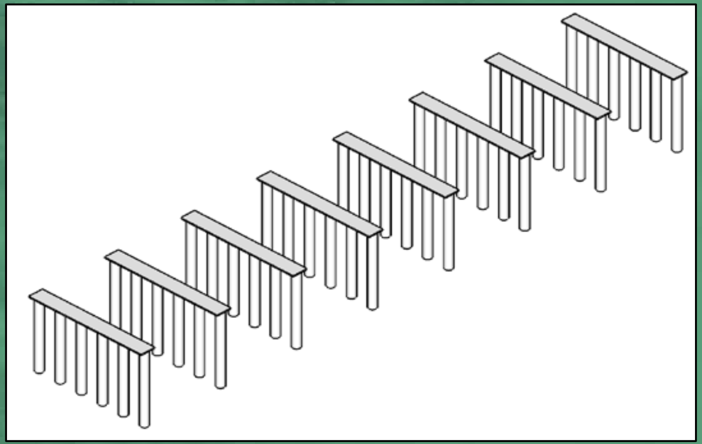


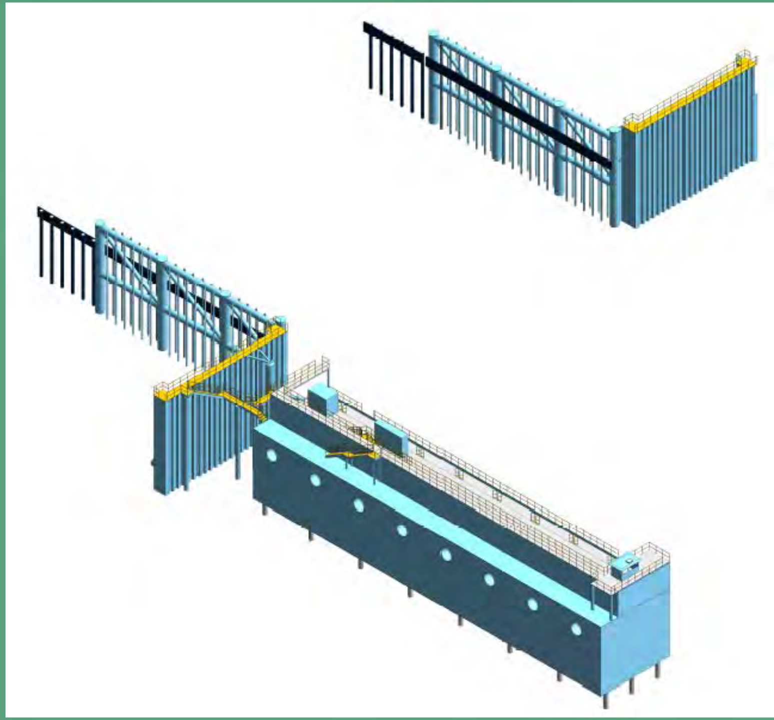


Barge Gate

- 200 ft. span
- Accommodates reverse head discharge.
- No cofferdam required for construction.

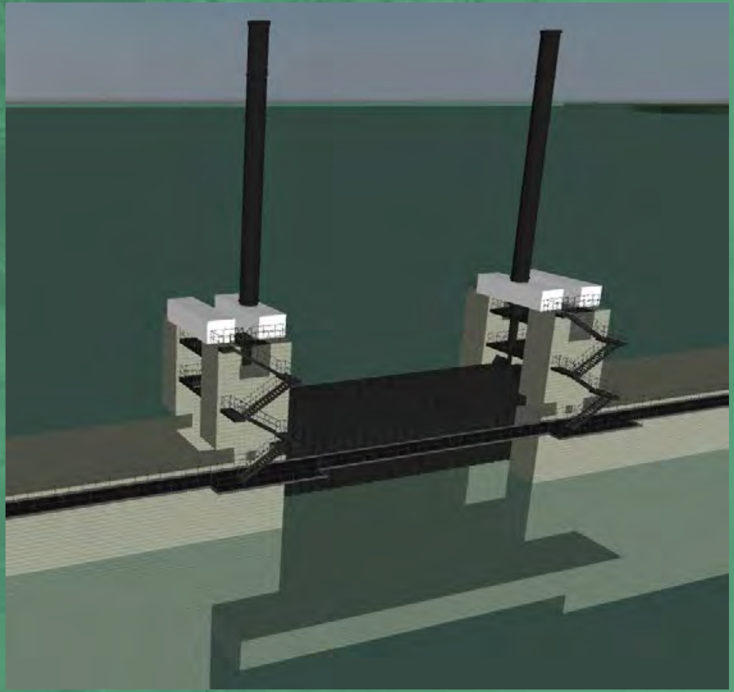






Vertical Lift Gate

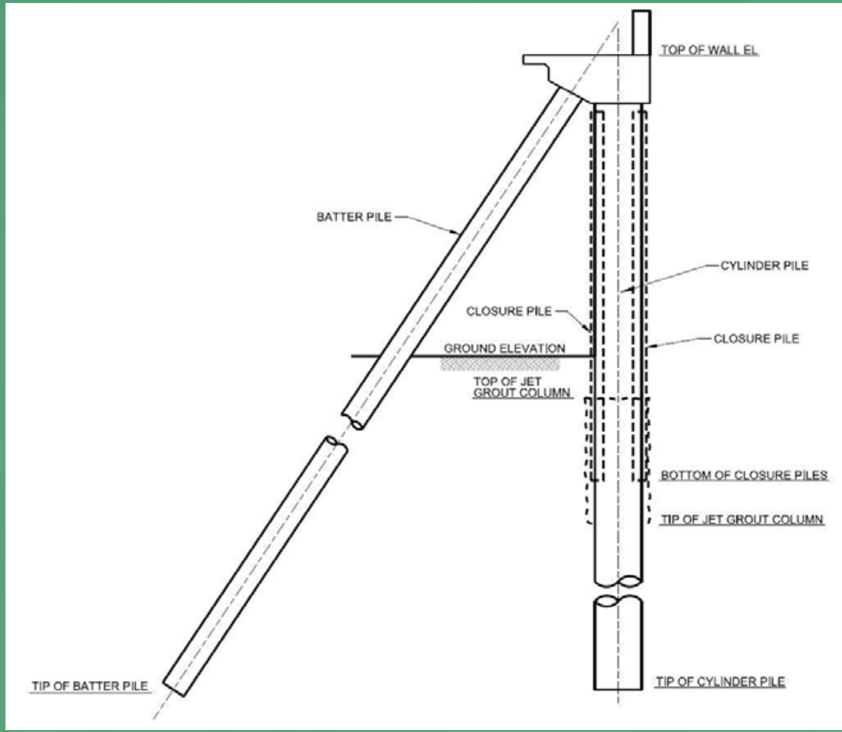
- Mechanically operated
- Will be opened just above regular water level



- Invert elevation EL -10.0
- TOW elevation EL +18.0
- Steel gate panel width 100 ft.

Intermediate & Tie-in Barriers

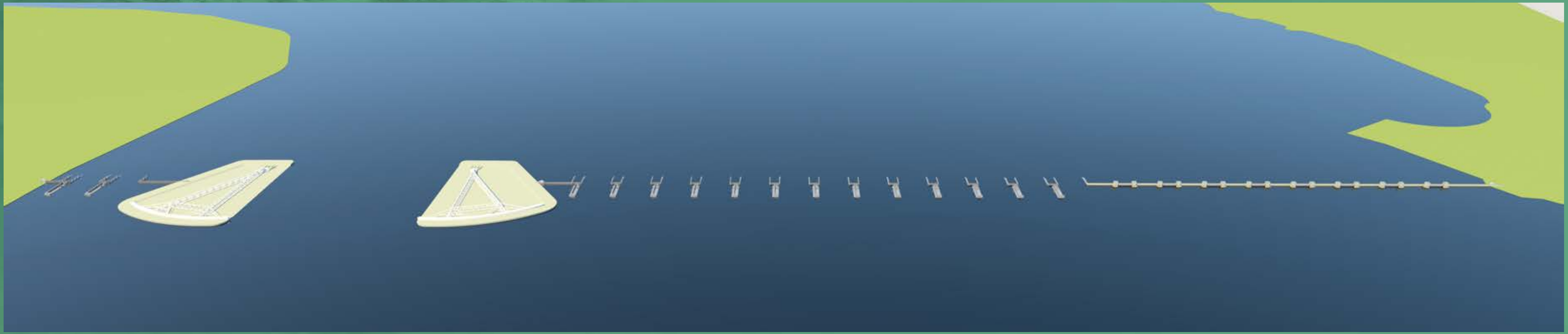
- Combi-wall system in the channel
  - In between VLGs and Barge gates
  - Also connects Barge Gate and island for Floating Sector Gate
  - Can accommodate a roadway for maintenance access
- T-walls closed to the bank



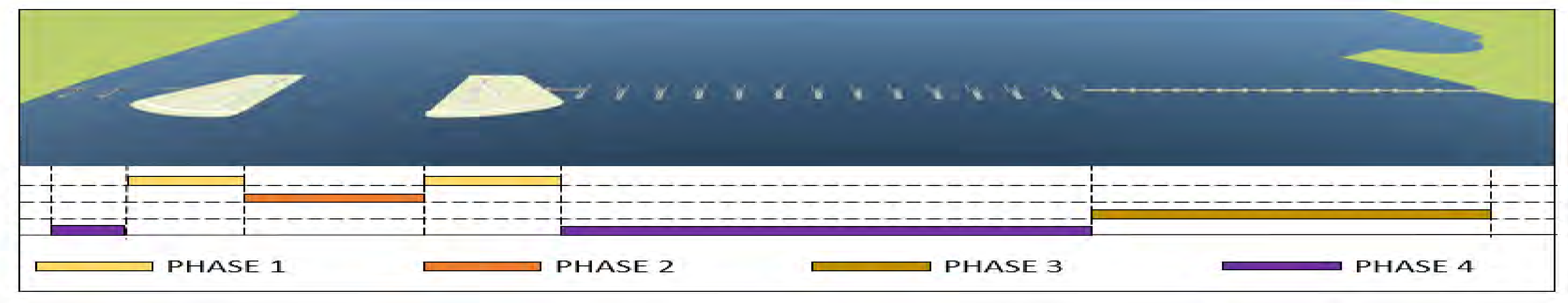
Combined Barrier Alignment

- 1200 ft. Floating Sector Gate
- 15 – 200 ft. Barge Gate
- 8 – 100 ft. Vertical Lift Gate

Channel Blockage – 38.5%



Constructability



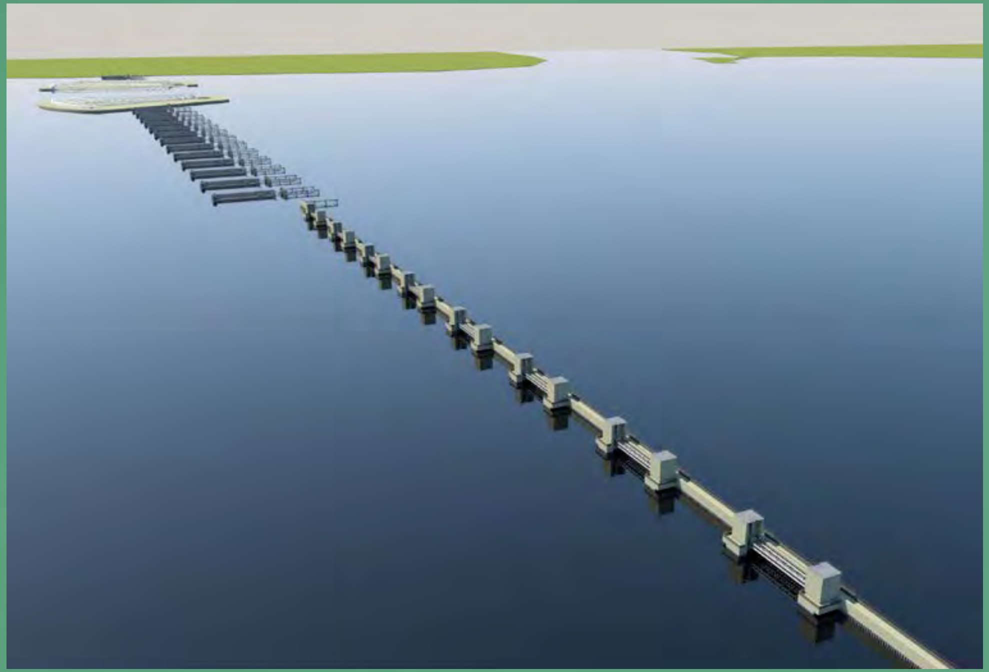
- Phased construction
- Minimal dredging required
- Navigation will be maintained at all time
- All gates fabricated off-site
- Cofferdam is required only for VLG
- Minimum amount of concrete work in the wet.

Operations

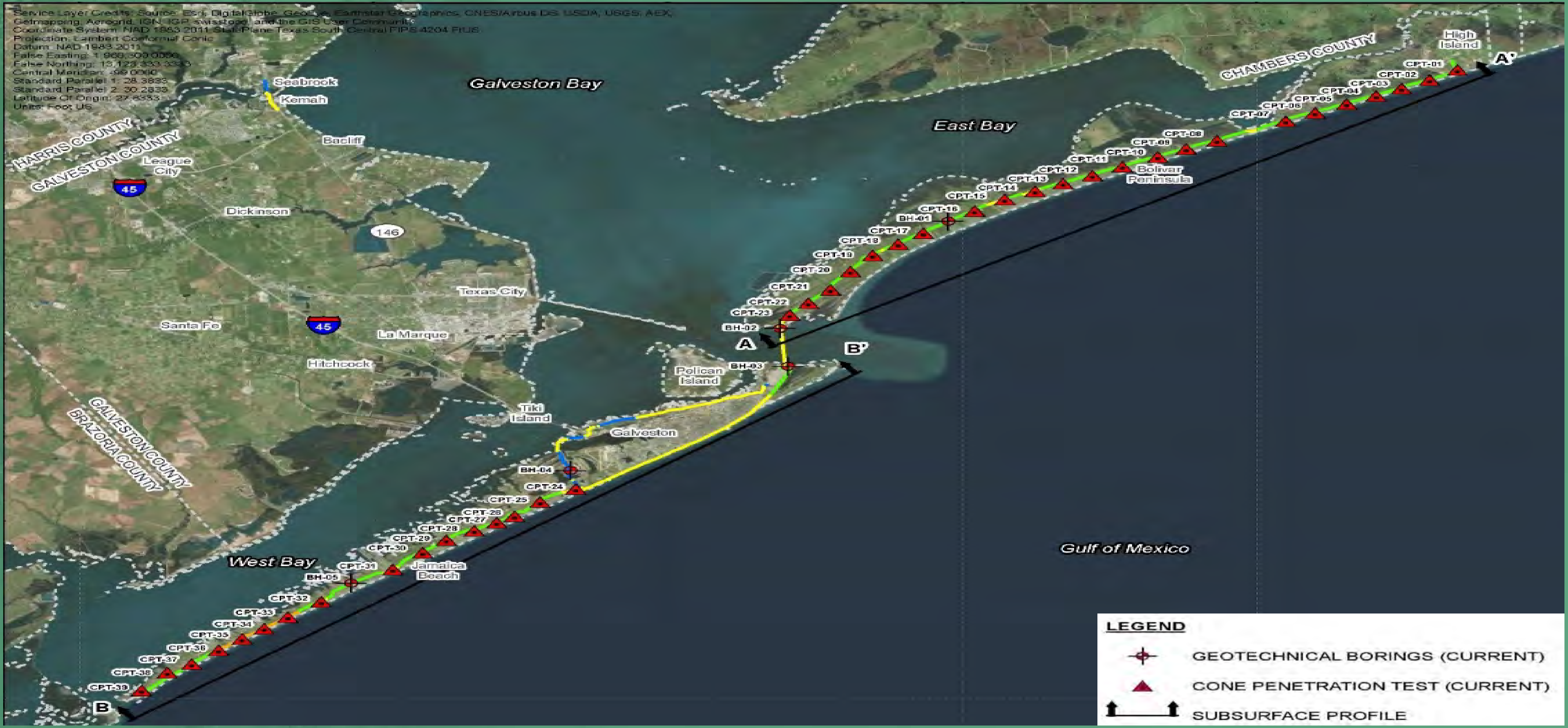
- Gate closing operation can continue concurrently.
- Multiple crews will be needed for barge gate closure
- Total time for closure 6-7 hours.
- Floating Sector Gate and VLG closure are based on electro-mechanical system.
- Redundancy will be available for manual closure.

Summary of Barrier Alternative Costs & Permanent Blockage

Configuration	Costs, in millions	Permanent Blockage
GCCPRD840	$3,540	54.8%
GCCPRD1200	$3,956	52.8%
GCCPRD1200-Barge	$3,674	38.5%



Geotechnical Investigations



Barrier Environmental Analysis

- Used Deltares D-Flow Flexible Mesh [D-Flow] and Advanced Circulation [ADCIRC]
- Analyzed changes in conditions associated with the various gate configurations:
  - Salinity
  - Circulation, tidal and sediment impacts
  - Discharge velocities
  - Benthic habitat
  - Marine and estuarine habitats
  - Invertebrate species
  - Fish and wildlife species

Summary of Barrier Gates Modelled

Alternative	Navigational Gate Opening (feet)	Number of Environmental Gates	Environmental Gate Total Opening (feet)
GCCPRD840	840	24 VLG	2,400
GCCPRD1200	1,200	24 VLG	2,400
GCCPRD1200-Barge	1,200	15 barge +8 VLG	3,800
USACE-TexasCity	1,200	36 VLG	3,600
USACE-MidBay	1,200	200 VLG	20,000
SSPEED Center Mid Bay Regional Strategy	850	5- VLG	750

Final Benefit to Cost Ratio for the Central Region

Central Region Summary	Coastal Spine	Galveston Ring Levee*	Clear Lake Gate	Total
Total length of the system (miles)	57.0	10.5	1.7	69.2
Right of way required (acres)	1,220	71	33	1524
Pump stations required / total capacity (CFS)	0 / 0	3/117,000	1/10,900	4/127,900
Environmental mitigation required (acres)	220.78	62.61	20.28	303.67
Construction cost ($000)	$6,206,250	$3,422,084	$492,502	$10,120,836
Annual operations and maintenance cost ($000)	31,031	17,110	2,463	50,604
Total Annual Costs (TAC)				522,479
Total Annual Benefits (TAB)				842,287
Benefit - Cost Ratio (TAB/TAC) (2.875 % Interest Rate)				1.61

Questions?

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Barrier Design Constrains and Ranking Methodology

A. Background Information

A1. Alignment:

The USACE Tentatively Selected Plan (TSP) includes a closure at Bolivar Roads. Figure 1 shows alignments considered for these crossings with a large navigation gate to accommodate the Houston Ship Channel (HSC). Alignment #2 is preferred after conducting ship simulation. However, current authorized width of Houston Ship Channel (HSC) along Alignment #2 is 800 foot channel toe to toe, compared to alignment #1 which is 1,490 foot which includes a 1000 foot channel toe to toe. Figure 2 shows the smoothed bathymetry along alignment #2 with the deep draft channel, shallow margin, and an intervening intermediate depth section broadly corresponding to the anchorage basin.

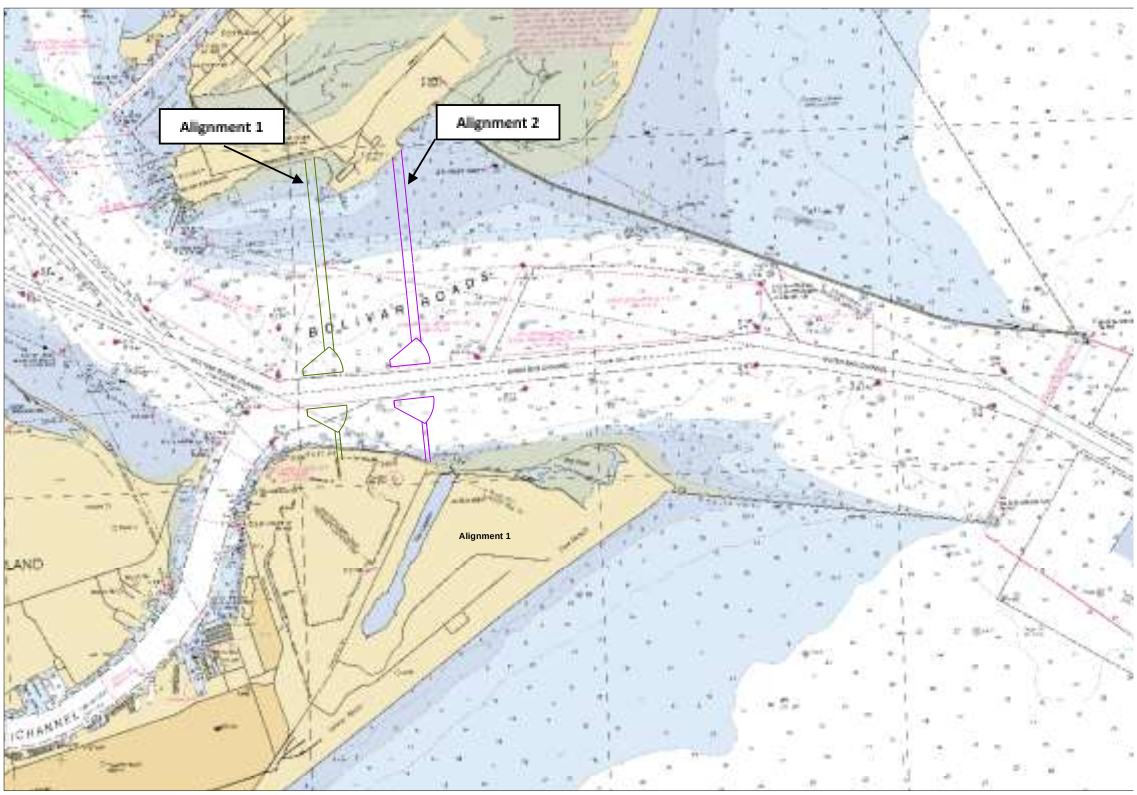


Figure 1. Navigation Chart featuring proposed structure locations

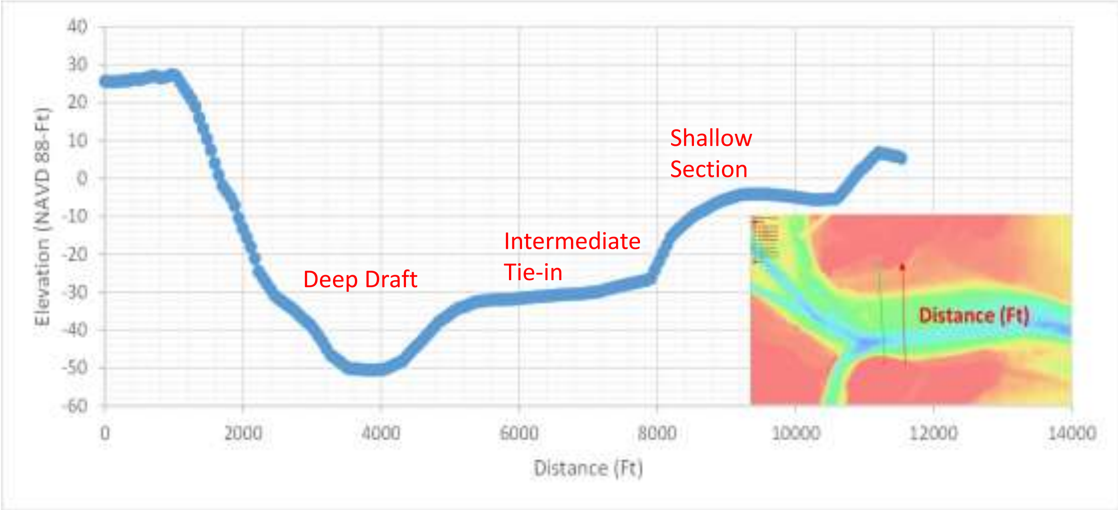


Figure 2(a). Bathymetry along the proposed structure location (Alignment 2)

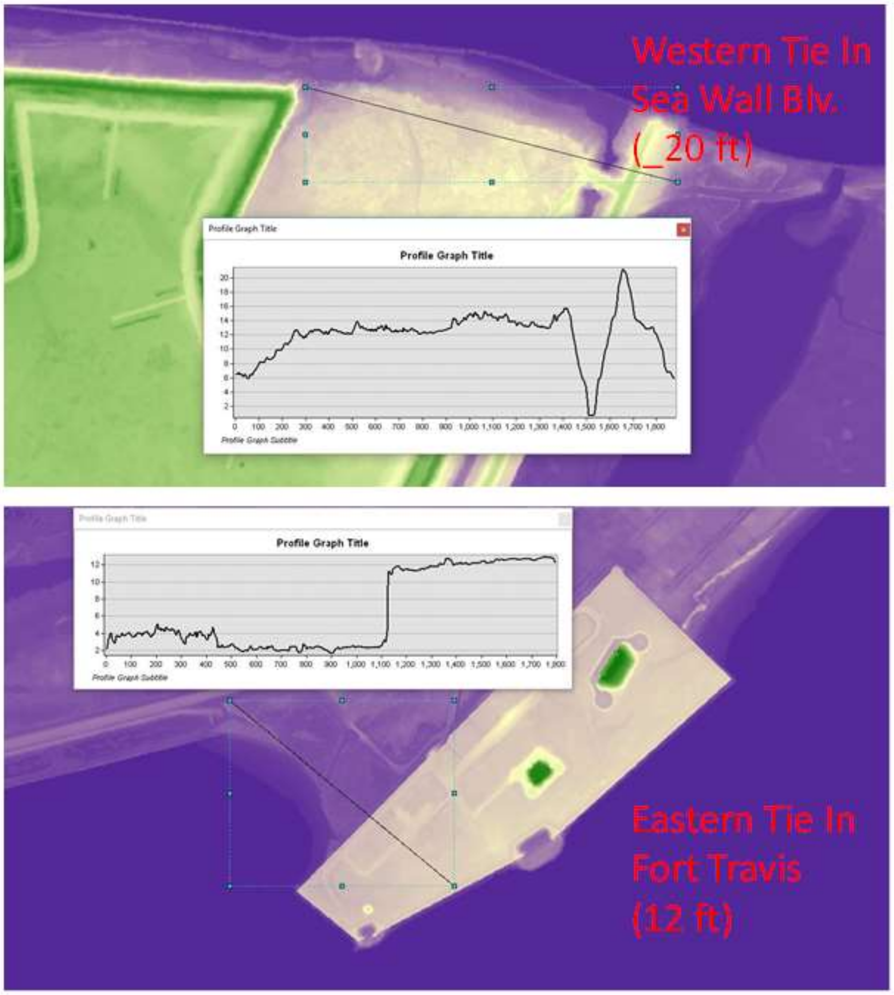


Figure 2(b). Topography along East and West Tie-in location

A2. Current and Projected Environmental Condition

(a) *Tide:* Tide Range at the Inlet: ~2 ft (Diurnal dominated, 24 hour); Bolivar Inlet constitutes about 80% of tidal exchange (Flux) between the Gulf of Mexico and Galveston Bay.

(b) *Velocity:* Figure 3(a) shows the observed velocity along different parts of the Houston Ship Channel (HSC) under typical tidal forcing. Although the inlet has typical velocity ~3 ft/sec, in windy conditions, velocity could be higher (Figure 3(b)).

(c) *Storm Surge and Wave Setup:* Figure 4 shows maximum water level from a synthetic Category 4 storm with water levels reflecting present day and a future conditions with 4.9 feet of sea-level rise. Figure 5 shows the hazard curve at 98% Confidence Limit at different points along the HSC. The water-surface elevation at point 5 (near the Bolivar inlet) is simulated at 5.5m (18ft) NAVD88 for the 500-year return period given present day water-level conditions. The maximum of the maximum (MOM) water surface elevation at the Bolivar inlet was 5.78m (19ft) NAVD88 from 660 storm simulations.

(d) *Sea Level Rise:* Figure 6 shows Relative Sea Level Rise Change (RSLC) scenarios specific to the project area. Using the intermediate curve for the 50 year performance period, the RSLC is 2.1 ft and for 100 year performance period, RSLC is 4.2 ft.

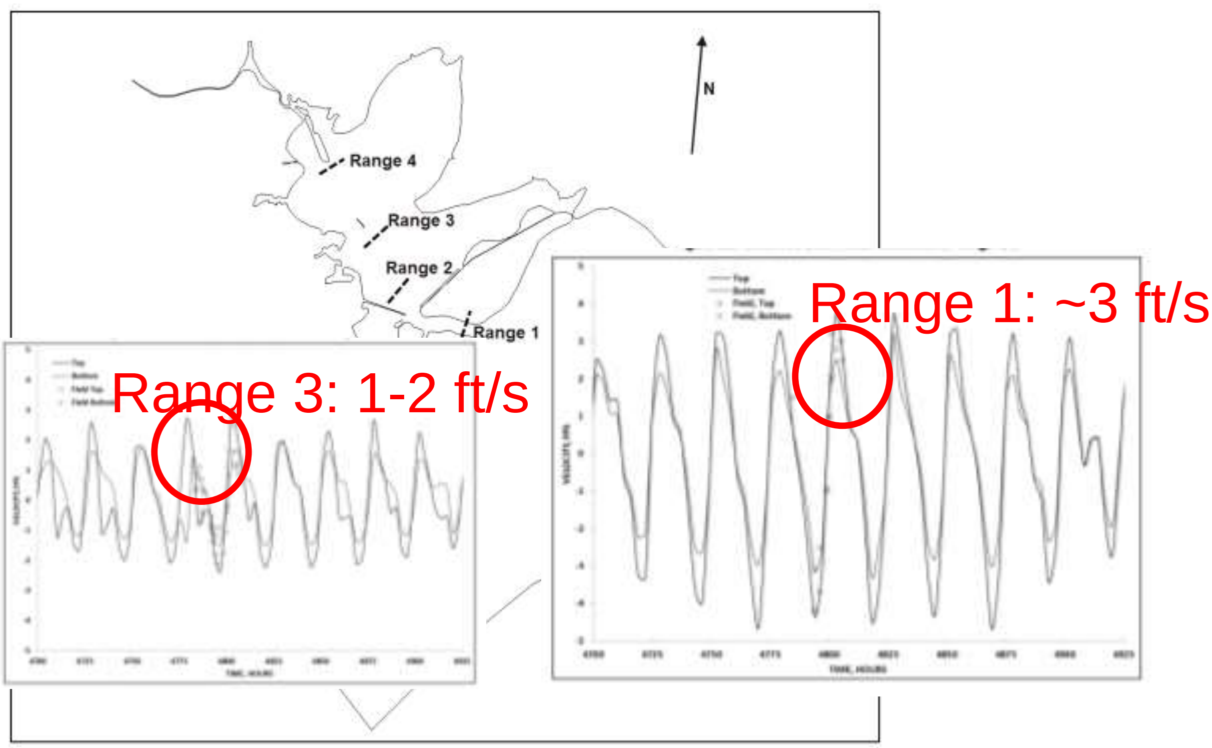


Figure 3(a). Observed Velocity along HSC (May 2011)

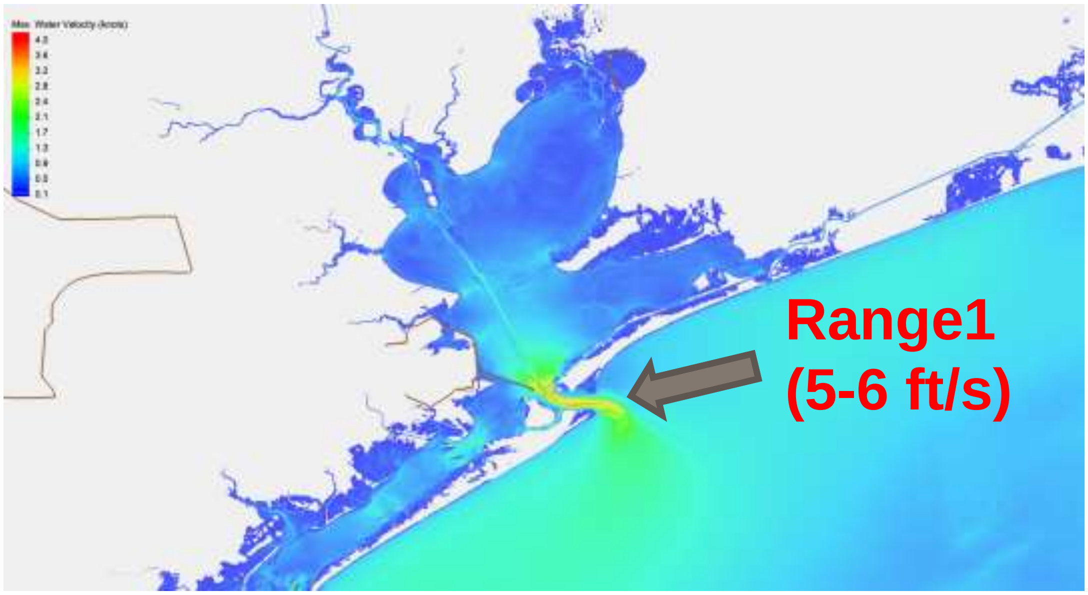


Figure 3(b). Simulated Velocity (Hurricane Harvey)

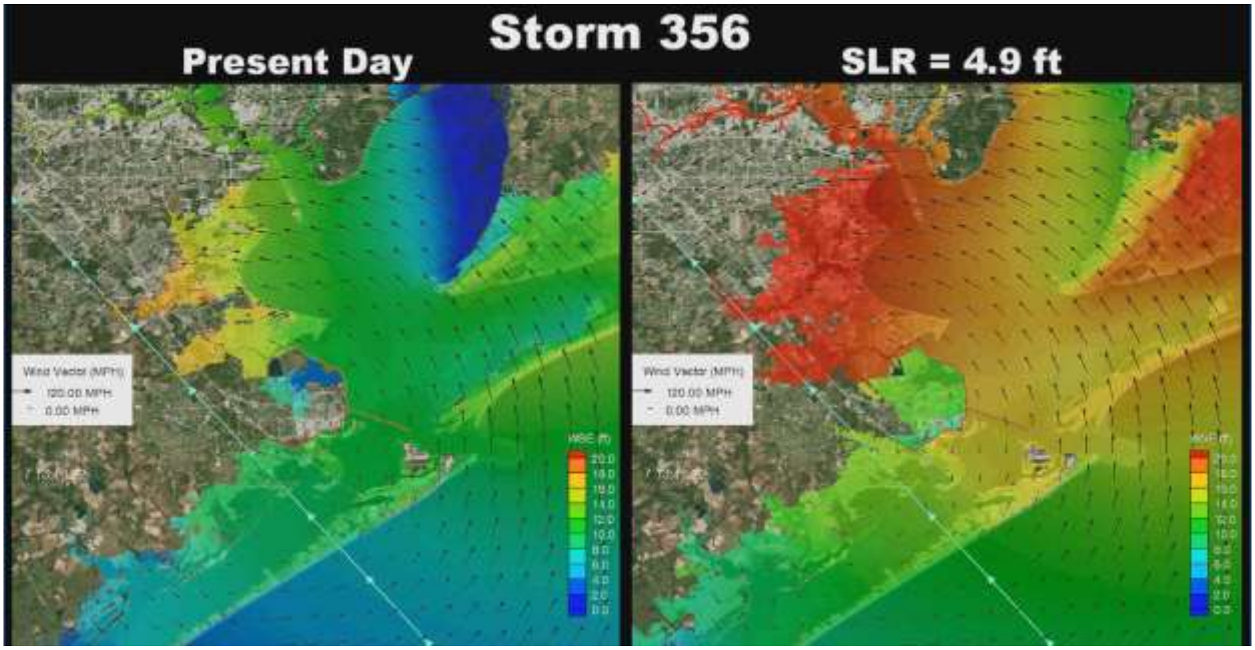


Figure 4. Maximum Water Level (Storm #356, With and Without RSLC) in ft NAVD 88

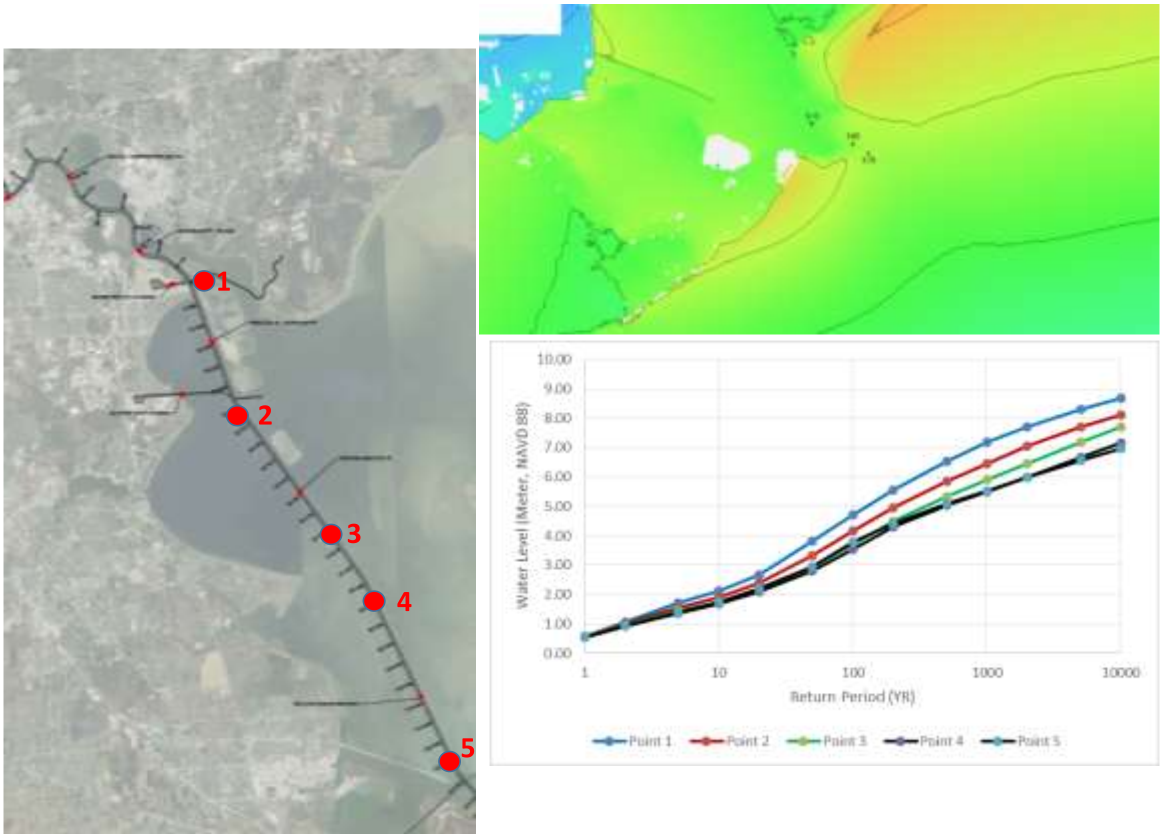


Figure 5. Hazard Curve (98% CL) at different points along the Houston Ship Channel. Inset figure shows the maximum of maximum (MOM) water surface elevation (5.78m, 19ft) from 660 storm simulations

(e) *Hydraulic Conveyance:* Figure 7 shows modelled barrier structure (1 sector gate-1200 ft wide and 39 lift gates -100ft wide with total reduction in hydraulic conveyance (cross sectional area) by ~27.5%

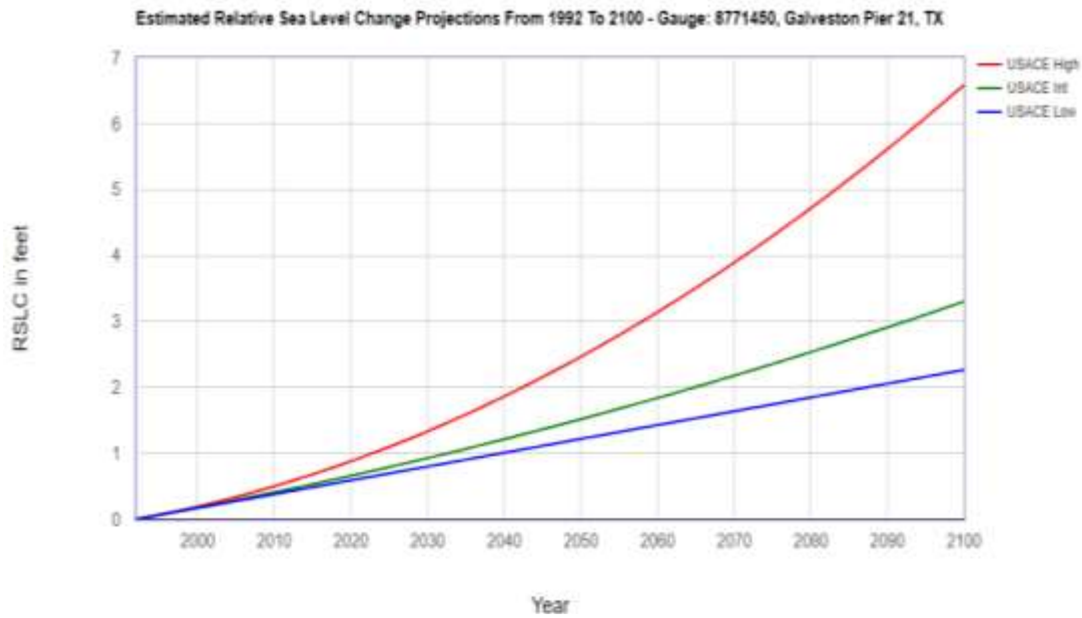


Figure 6. Relative Sea Level Rise (Galveston Pier 21)

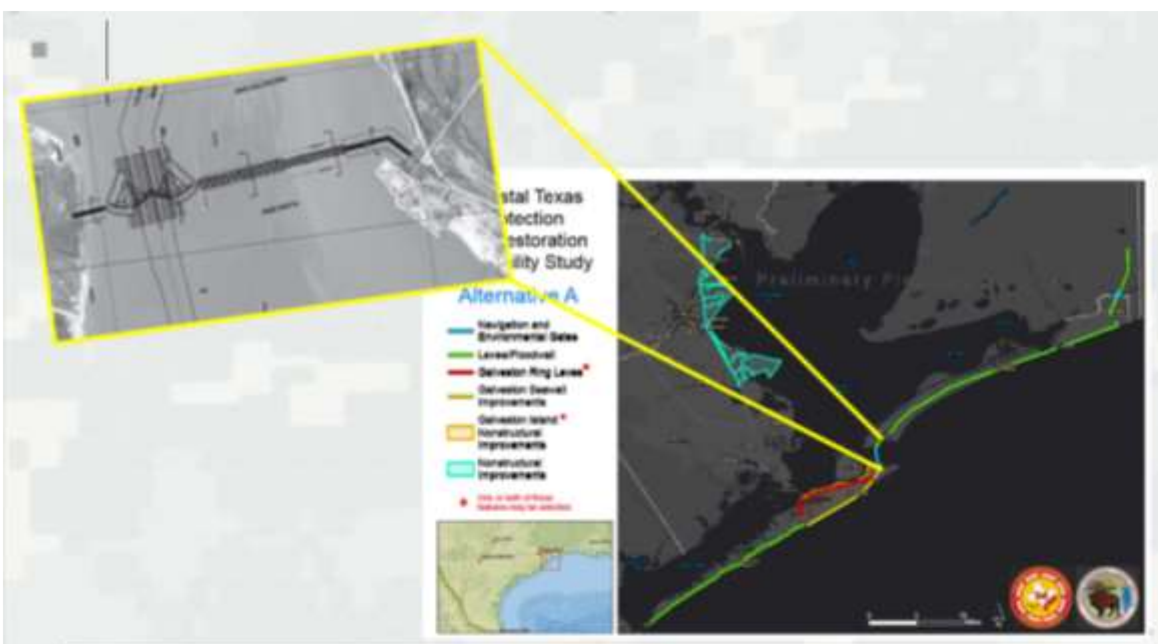


Figure 7. Modelled Barrier Configuration (27.5% reduction in hydraulic conveyance)

(f) *Impact on Tidal Amplitude:* Figure 8 shows the impact on tidal amplitude due to proposed structure and due to ~27.5% reduction in hydraulic conveyance along the alignment. On average, a 10 to 15% reduction in tidal amplitude was observed.

(a) *Impact on Tidal Prism:* Figure 9 shows impacts on tidal prism, approximately 13.5 to 16.5% reduction due to 27.5% reduction in channel conveyance. It is expected that further reduction of channel cross section would have significant adverse impact on tidal prism (Figure 10).

(b) *Impact on Salinity and Velocity:* Figures 11 and 12 show some changes in velocity and salinity due to proposed gate. It is expected that further reduction of channel cross section would have a significant adverse impact on Bay environmental conditions.

(c) *Hydrostatic Load, Wave Force, and Reverse Head:* Figures 13 and 14 show results from the simulation of storm #356. Figure 13 shows the maximum water-surface elevation during the simulations with surge piling up on the Gulf side of the closure structure. The difference in head could be in excess of 25 ft which needs to be further explored with advanced modeling. Figure 14 shows the hydrograph from Storm #356 on both the flood and lee side of the structure showing setup and set down with hydrostatic head difference around ~6.5 m or 21.5ft. There is also a reverse head condition toward the end of the simulation since the system closure was a binary condition throughout the simulation. Figure 15 shows the difference in maximum elevations between the front and back of the gate showing several simulations where hydrostatic head difference could be around ~6.5 m or 21.5ft and reverse head condition could be around 3m (~10ft) based on 170 storm simulations. Figure 16 (a) and 16(b) shows the significant wave height and period near the tentative location of the structure. For 100 year return period, H_S is 3 m (~10ft) and T_P is 15 sec. Figure 17 justifies the values with observed values.

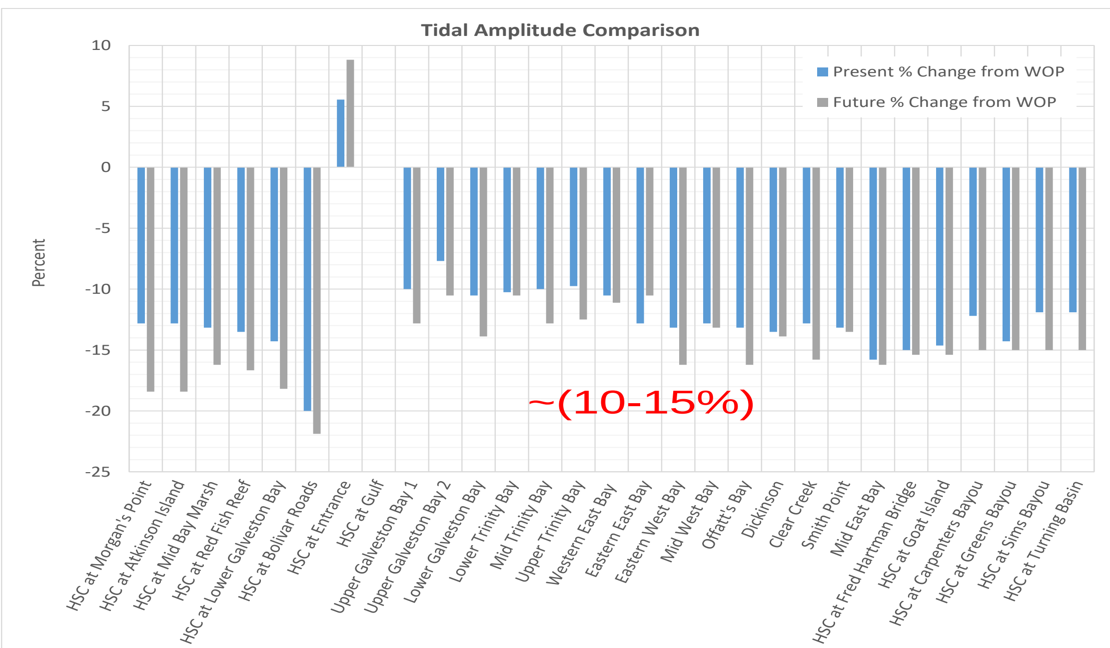


Figure 8. Reduction in Tidal Amplitude (average 10 to 15%). The future condition accounts for the projected RSLC scenario.

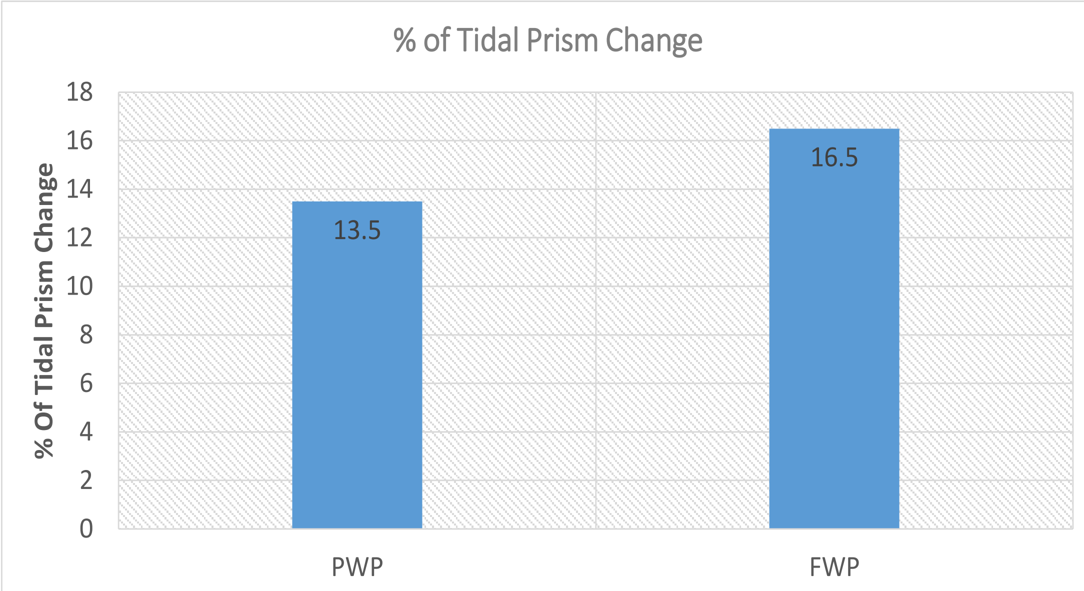


Figure 9. Reduction in Tidal Prism at Bolivar Inlet (13.5%, 16.5% with RSLC). Here PWP represents Present with Project Condition and FWP represents Future with Project Condition that includes RSLC

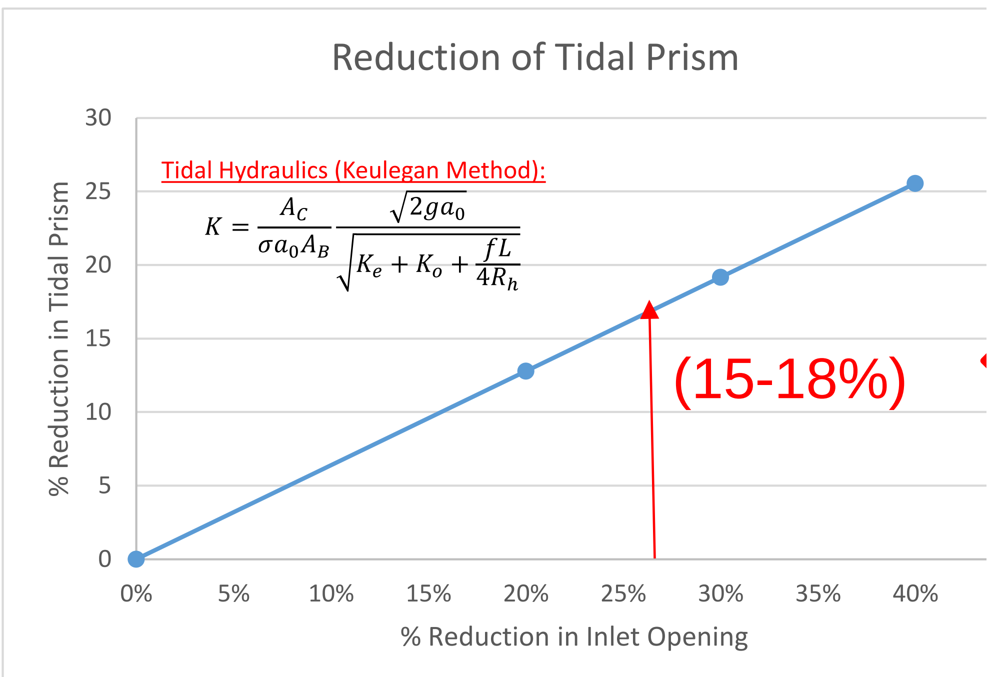


Figure 10. Impact on Tidal Prism with reduction in channel conveyance.

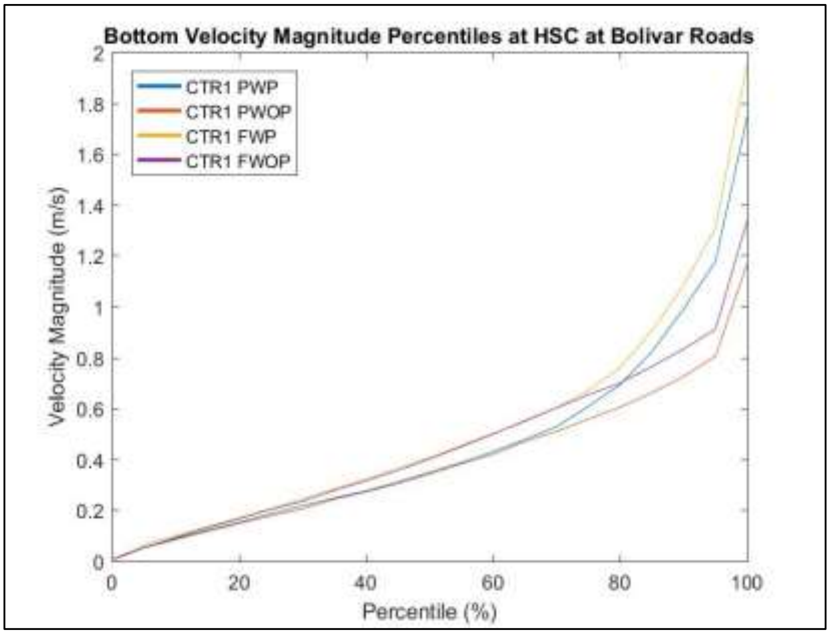


Figure 11. Impact on Velocity (the 50% exceedence speed is higher through the gate with project situation. Here bottom velocity has been extracted at the midpoint of bottom cell, ~0.5ft above bed).

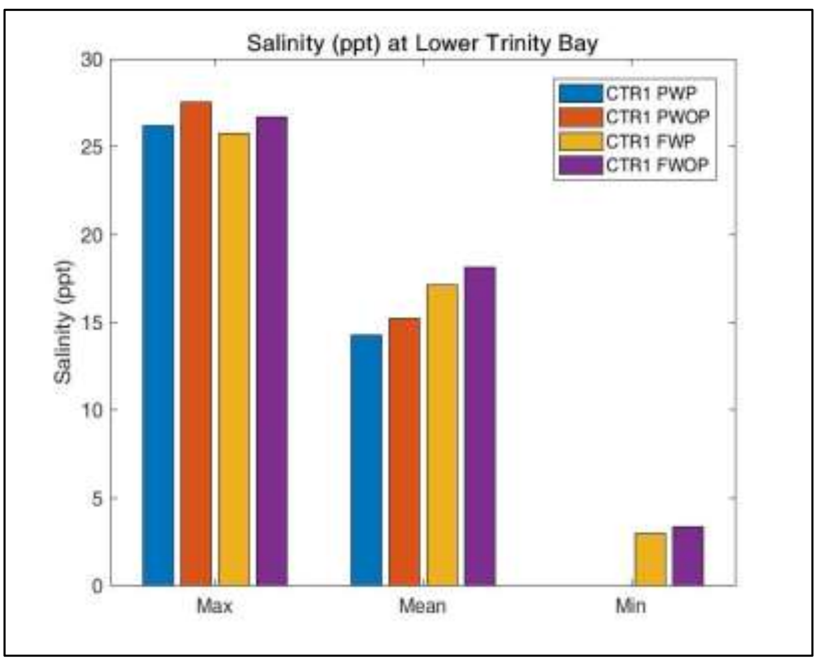


Figure 12. Impact on Salinity in lower Trinity Bay (Salinity in Bay drops slightly as water tends to stay longer into the Bay)

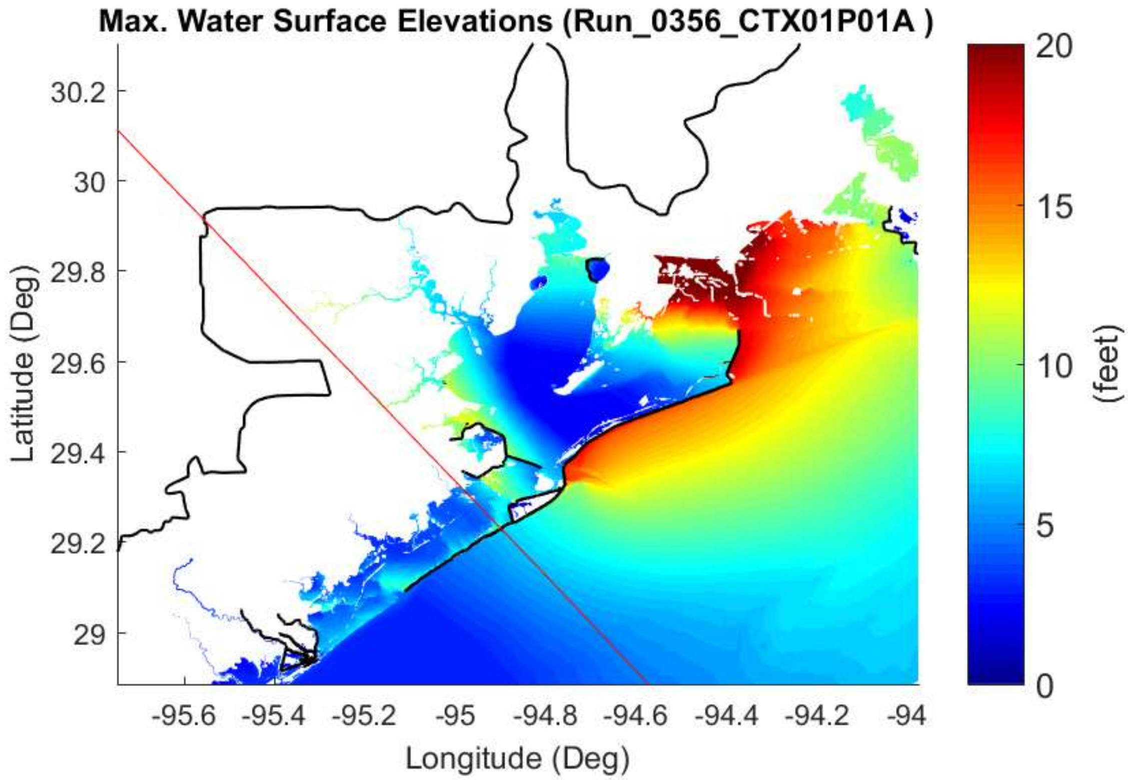


Figure 13. Storm surge piling against proposed structure (>20 ft)

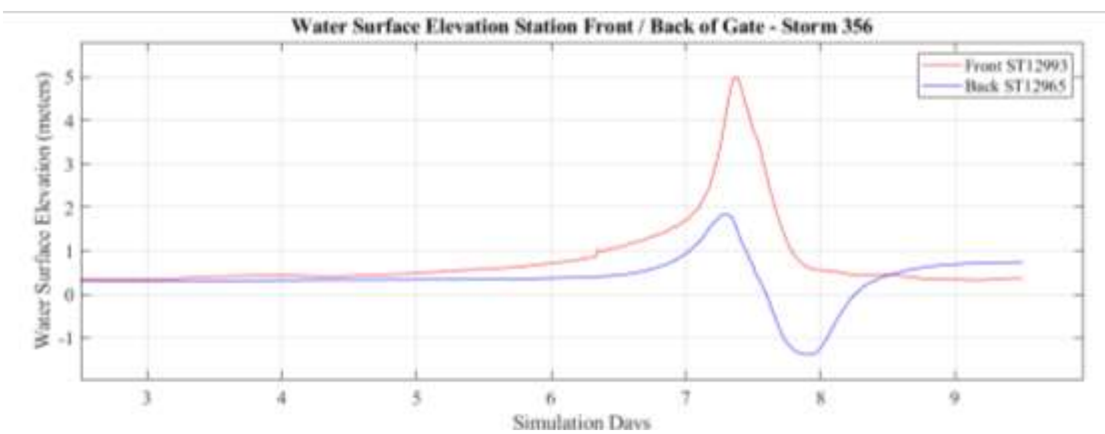


Figure 14. Hydrograph showing setup and set down (Hydrostatic head difference ~6.5 m or 21.5ft)

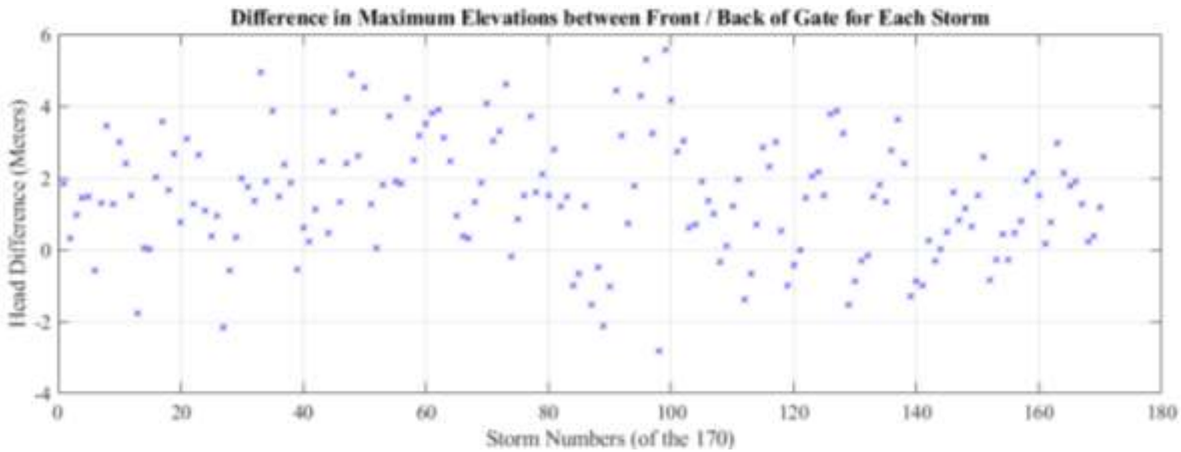


Figure 15. Difference in Maximum elevations between front and back of gate showing reverse head about 3m (~10ft)

Figure 16 (a). Significant Wave Height near the Tentative Location of the Structure

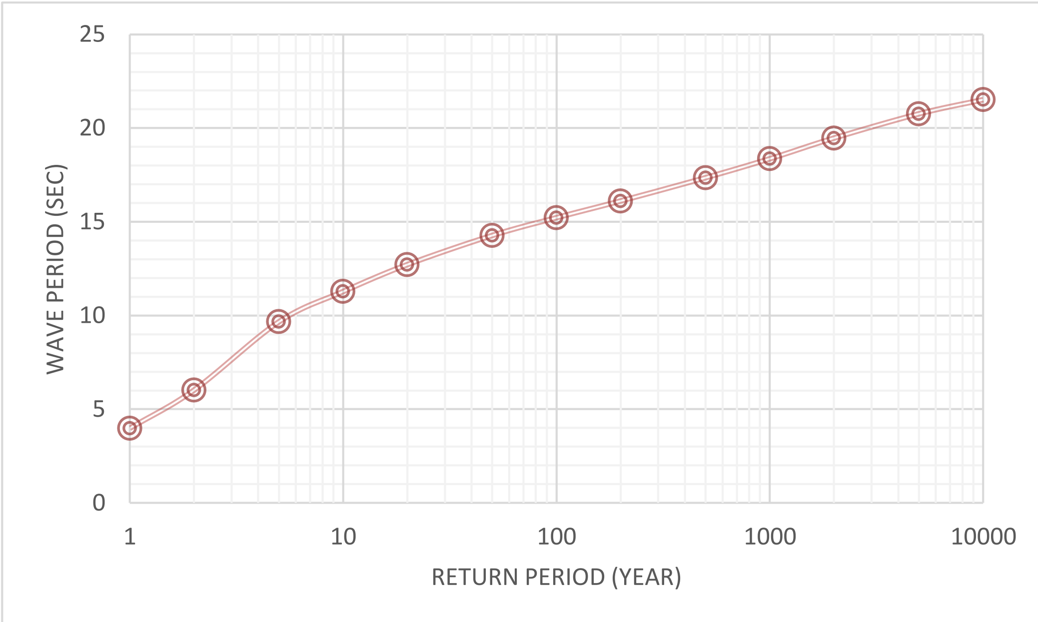


Figure 16(b). Wave Period near the Tentative Location of the Structure

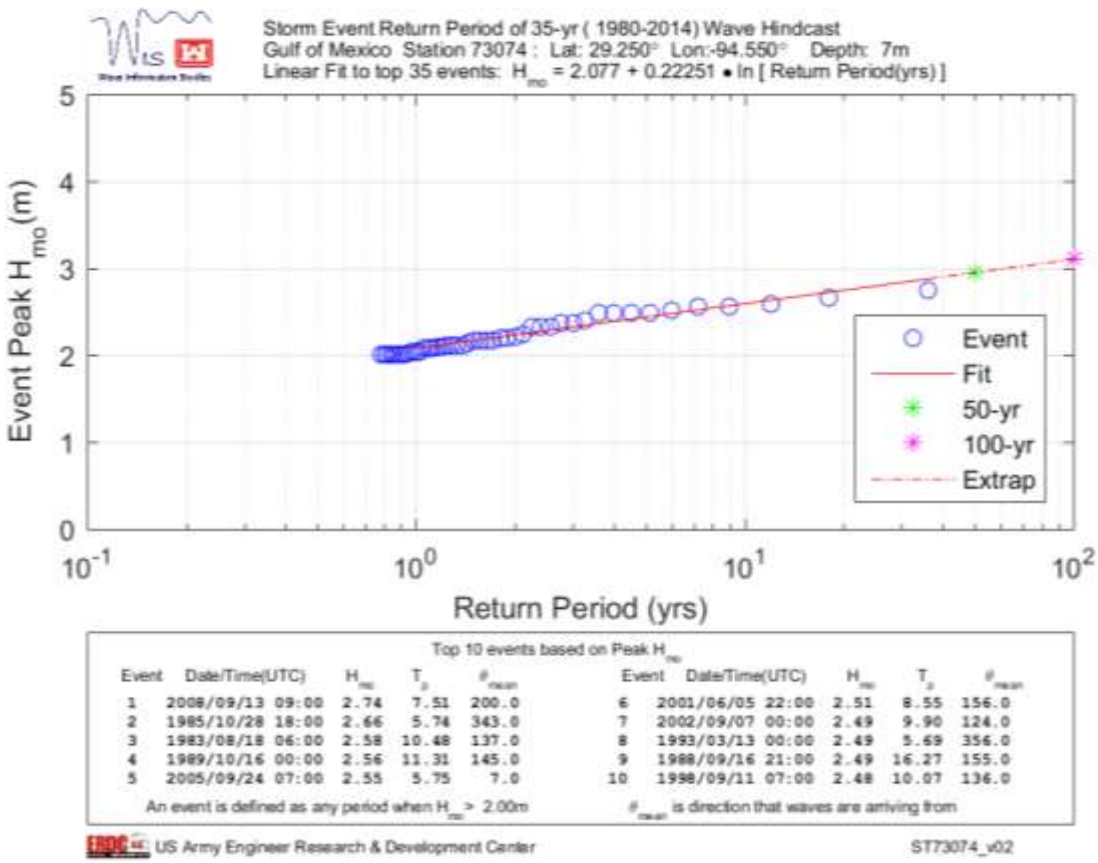


Figure 17. Wave Hindcast (Gulf of Mexico Station 73074)

A3: Subsurface Conditions - Galveston Harbor Entrance Channel Crossing and Bypass Channel

GCCPRD conducted a geotechnical investigation in 2017 along the levee alignment on Bolivar and on Galveston Island where the crossing ties back into land. Two deep borings (BH-02 and BH-03) drilled to a depth of 400 feet below existing grade at Bolivar Peninsula and Galveston Island as shown on Figure 18. The Approximate Subsurface Profile developed based on above mentioned geotechnical investigation is shown on Figure 19. See Attachment A for Logs of Soil Borings and Key to the Logs of Borings as presented in GCCPRD (2017) report.

Figure 18: Boring Plan on Gates- Navigation and Environmental (Source: GCCPRD, 2017)

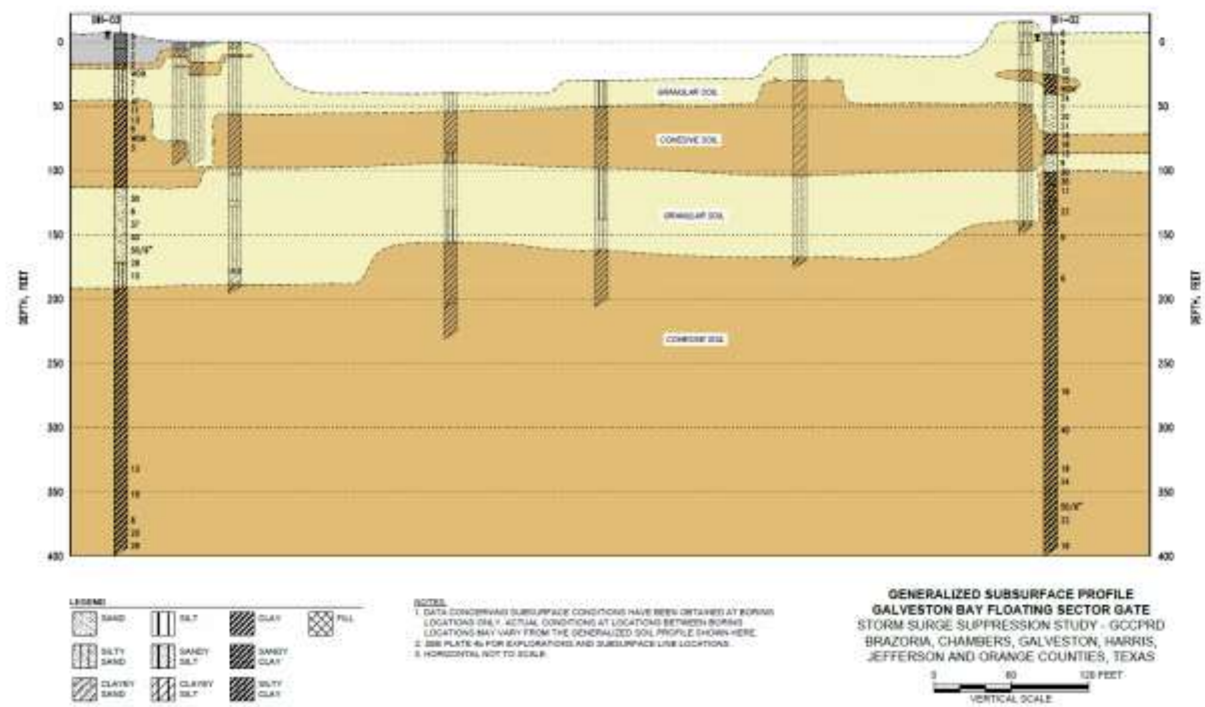


Figure 19: Subsurface Profile - Galveston Harbor Entrance Channel Crossing and Bypass Channel (Source: GCCPRD, 2017)

Subsurface conditions at the northern portion of the alignment: soil boring BH-02 was explored to a maximum depth of 400 feet below existing grade. Alternating layers of granular soils and cohesive soils were encountered below a depth of 47 feet. Granular soils were encountered at a depth of 47 feet and extends to 78 feet. The granular soils consisted of medium dense sands. The standard penetration test (SPT) N-values of the sands primarily ranged from 13 to 21 blows per foot at depths between 47 to 73.5 feet. However, a SPT N-value of 9 blows per foot was encountered at depths between 73.5 to 78 feet. Firm to very stiff cohesive soils were encountered at a depth of 78 feet and extends to about 93.5 feet. The undrained shear strength of clays, obtained from field and laboratory testing, generally ranged from 550 pounds per square foot (psf) (firm) to greater than 2,000 psf (very stiff). The Atterberg Limits testing indicated measured liquid limit of 57 percent and plastic limit of 14 percent, resulting in the calculated plasticity index of 43. The measured natural water content of the clays was approximately 21 percent. Granular soils were encountered at a depth of 93.5 feet and extends to a depth of about 108 feet. These granular soils consisted of medium dense to dense sands. The SPT N-values of these sands ranged from 30 to 35 blows per foot. Stiff to very stiff cohesive soils consisting of sandy clays and clays with sand and silt seams are encountered at a depth of 108 feet and extends to about 400 feet. These cohesive soils consisted of sandy clays and clays. The undrained shear strength of the sandy clays and clays ranged from about 1,000 psf (stiff) to greater than 2,000 psf (very stiff). The Atterberg Limits testing indicated measured liquid limits ranging from 24 to 88 percent and plastic limits ranging from 13 to 24 percent, resulting in the calculated plasticity indices ranging from 9 to 64 percent. The measured natural water contents of the sandy clays and clays ranged from 20 to 34 percent.

Subsurface conditions at the southern portion of the alignment: Soil boring BH-03 was explored to a maximum depth of 400 feet below existing grade. Cohesive soils with sand seams were encountered from a depth of 60 feet and extending to about 120 feet. The undrained shear strength of the clays ranged from about 500 psf (firm) to 1,900 psf (stiff). The Atterberg Limits testing indicated measured liquid limits ranging from 60 to 95 percent and plastic limits ranging from 16 to 21 percent, resulting in the calculated plasticity indices ranging from 44 to 74 percent. The measured natural water contents of the clays ranged from about 28 to 56 percent. Medium dense to very dense granular soils were encountered beneath the clays. The granular soils consisted of silty sands and sands and were encountered from a depth of 120 feet and extends to about 198 feet. The SPT N-values of the sands primarily ranged from 28 to greater than 50 blows per foot at depths between 120 to 178 feet. However, loose to medium dense silty sands with SPT N-values ranging from 10 to 28 blows per foot were encountered at between depths of 178 to 198 feet. Stiff to very stiff cohesive soils were encountered beneath the loose to medium dense silty sands from a depth of 198 feet and extending to about 400 feet. These cohesive soils cohesive primarily of clays. The undrained shear strength of the clays generally ranged from about 1,200 psf (stiff) to greater than 2,000 psf (very stiff). The Atterberg Limits testing indicated measured liquid limits ranging from 30 to 87 percent and plastic limits ranging from 12 to 21 percent, resulting in the calculated plasticity indices ranging from 17 to 68 percent. The measured natural water contents of the clays range from about 19 to 37 percent.

B. Design Considerations and Ranking Matrix

B1. Constraints

(i) Deep, Intermediate, and Shallow Draft Sill Depth: Structure must handle required depth and changing bathymetric condition. For deep draft, the depth is -60 ft MLLW. For shallow draft structures, the depth requirement is -5ft to -20 ft MLLW. For intermediate draft structures, the depth requirement is -20 to -40 ft MLLW. (Refer to Figure 2, 6).

(ii) Hydrostatic Load: Structure must handle significant hydrostatic head difference (>25 ft) and some reverse head condition (< 5 ft) (Refer to Figure 13, 14, and 15). The structures will be subject to substantial wave loads (Figure 16 and 17) and potentially impact loads from vessels.

(iii) Bay Environmental Health: To minimize the ecological impact, cross section of the inlet must be maintained at least 70% of the current configuration.

B2. Ranking Criteria 1 (Quantitative)

(a) Reduction in Cross Section: Maximum reduction of inlet cross section where ideal condition would be not to significantly alter the current configuration and minimize environmental impacts (Refer Figure 8, 9, 10)

Blockage Ratio (%)	Score
0 to 10	5
11 to 20	3
20 to 30	1

(b) Operation Time: Maximum time allowance to close the system fully and restore navigability where less time is more favorable. System needs to be reliable to open or close in that given time frame. Note that impotence should be given to closing and opening time for the navigation gates. The other gates (environmental gates) can be closed based on a pre-approved water control manual ahead of a storm.

Time to open and close (Hour)	Score
Fastest	5
Fast	1
> 24 hours	0

(c) Alignment: Preferred location of the alignment (Alignment 1 or 2 or somewhere else, Refer Figure 2)

Alignment	Score
Minimize total length, minimize ship collision, minimize impact to anchorage area, maximize ship turn over to Galveston channel, proper tie-in to reduce flanking	5
Minimize ship collision, maximize ship turn over to Galveston channel	3
Significant impact due to structure	1

(d) Lifecycle Cost: Minimize cost for the designed system

Cost	Score
Low cost compared to other barrier	5
Medium cost compared to other barrier	3
High cost compared to other barrier	1

(e) Lifecycle Operation and Maintenance Cost: Minimize cost for the designed system

O & M Cost	Score
Low cost compared to other barrier	5
Medium cost compared to other barrier	3
High cost compared to other barrier	1

B3. Ranking Criteria 2 (Qualitative)

(f) Reliability: System can be reliably closed within the required time limit, opening time can be reliably met to restore navigation through the inlet, and this system can be maintained to be reliable for the life of the project. For O&M, the ability (ease of) to inspect critical members of the structure is imperative. If we can't gain access to something that is critical to the performance of the feature, we can get ourselves in trouble. System has redundancy plan

Reliability	Score
Highly reliable, reliable O&M operation, redundant system	5
Not reliable, cant's get access to the system for O&M	0

(g) Degree of Adaptability: Ideal condition will be structures that can be adaptive to future changes in channel bathymetry, future sea level rise & subsidence, and expansion of HSC

Adaptability	Score
Adaptable to future	5
Adaptable to future but with major difficulty	3
Not adaptable to future	1

(h) Constructability: Plan that maximizes HSC operation during construction should be favorable. Consideration of the construction feasibility based on project conditions and requirements (e.g., subsurface, corrosive environment, risk of ship collision)

Constructability	Score
Maintains navigation service during construction, suitable for project condition	5
Constructible, contingency plan for navigation	3
Severe impact on navigation	1
Not constructible	0

(i) Technology: Design method, proven technical/innovative approach (proven by model tests, studies, case studies on previous construction& operation records, computer stimulations etc.). Note that non US made items needs exemption.

Technology	Score
Proven technology, examples around the globe with excellent performance record	5
Proven technology	3
New technology, never built	1

(j) Direct and Indirect Impacts (not related to change in cross section): Minimize impact both during construction and operational time period (refer figure 11, 12)

Impact	Score
Low impact compared to other barrier	5
Medium impact compared to other barrier	3
High impact compared to other barrier	1

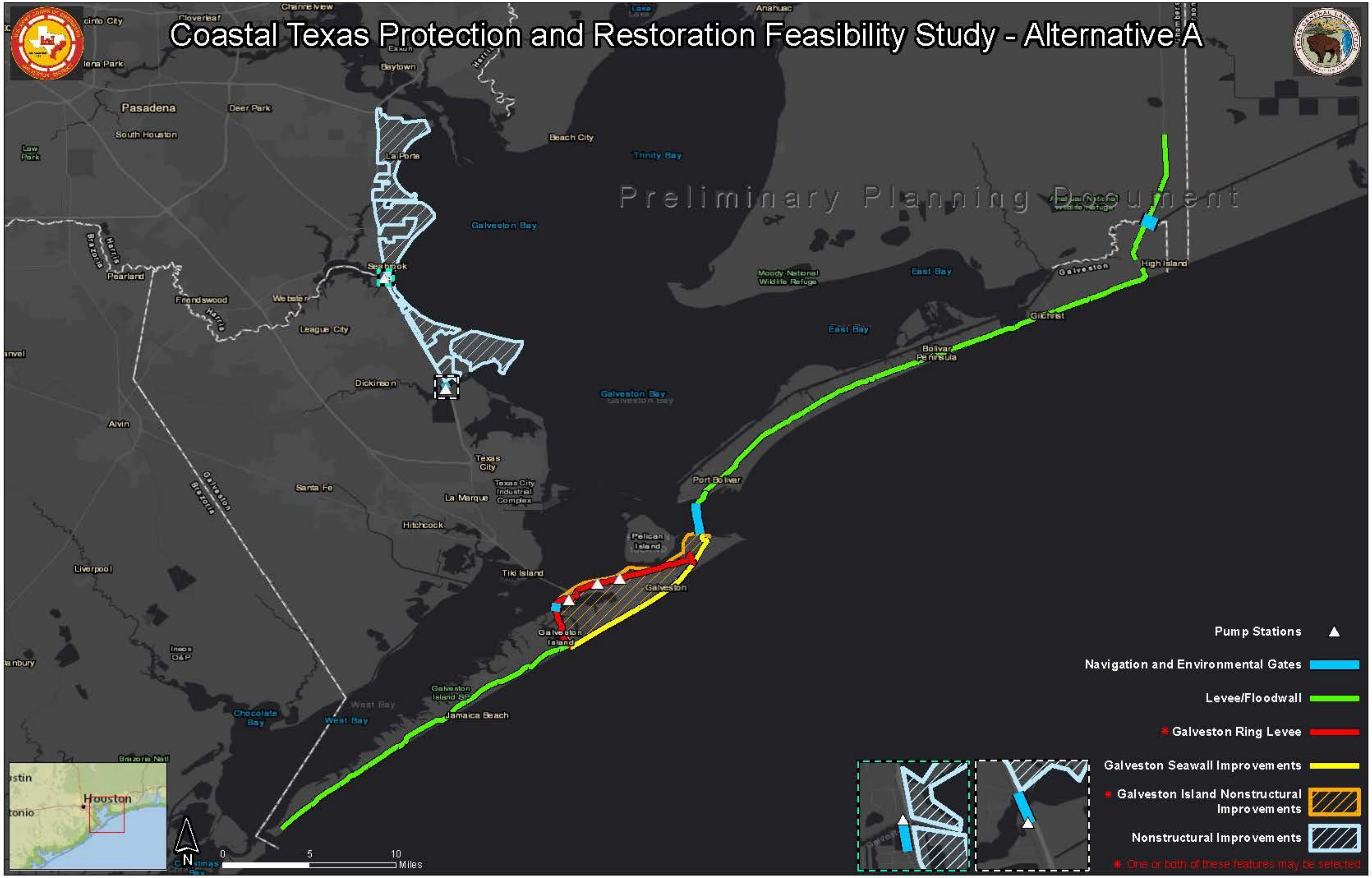
(k) Additional benefits (ie access for roadway, recreation, etc)

Additional Benefits	Score
High additional benefits	5
Medium additional benefits	3
Low additional benefits	1

B4. Grouping and Tentative Weights of Individual Criteria

1. Hydraulics [Constraints]
2. Environment [Criteria - a (0.15), Criteria – j (0.1)]
3. Construction [Criteria – c (0.1), Criteria - h (0.1), Criteria – i (0.1)]
4. Cost [Criteria - d (0.1), Criteria – e (0.1)]
5. Operation and Reliability [Criteria - b (0.1), Criteria – f (0.1), Criteria – g (0.05),]

ALTERNATIVE A (BOLIVAR CROSSING)



CURRENT ALIGNMENT

CHALLENGES


Not enough space & Time for turning
<0.4 mile
Current speed > 3 ft/s
Pelican Island
lican Island
Pelican Island Groceries
Shell Pelican Island Heliport
Seawolf Pkwy
Port Bolivar - Galveston
Ferry Rd
Seawall Blvd
7th St
108
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image © 2018 TerraMetrics
Google

CHALLENGES

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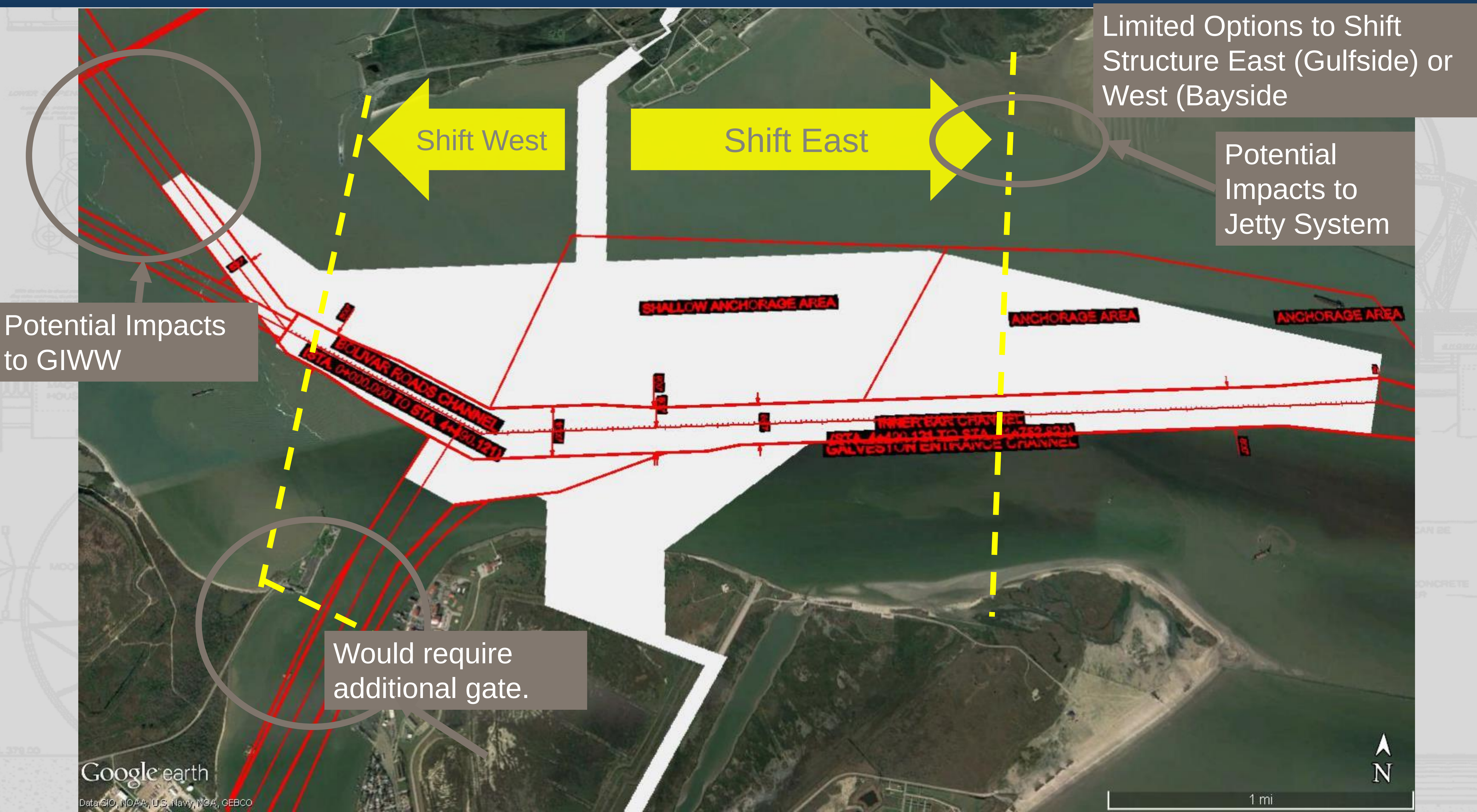
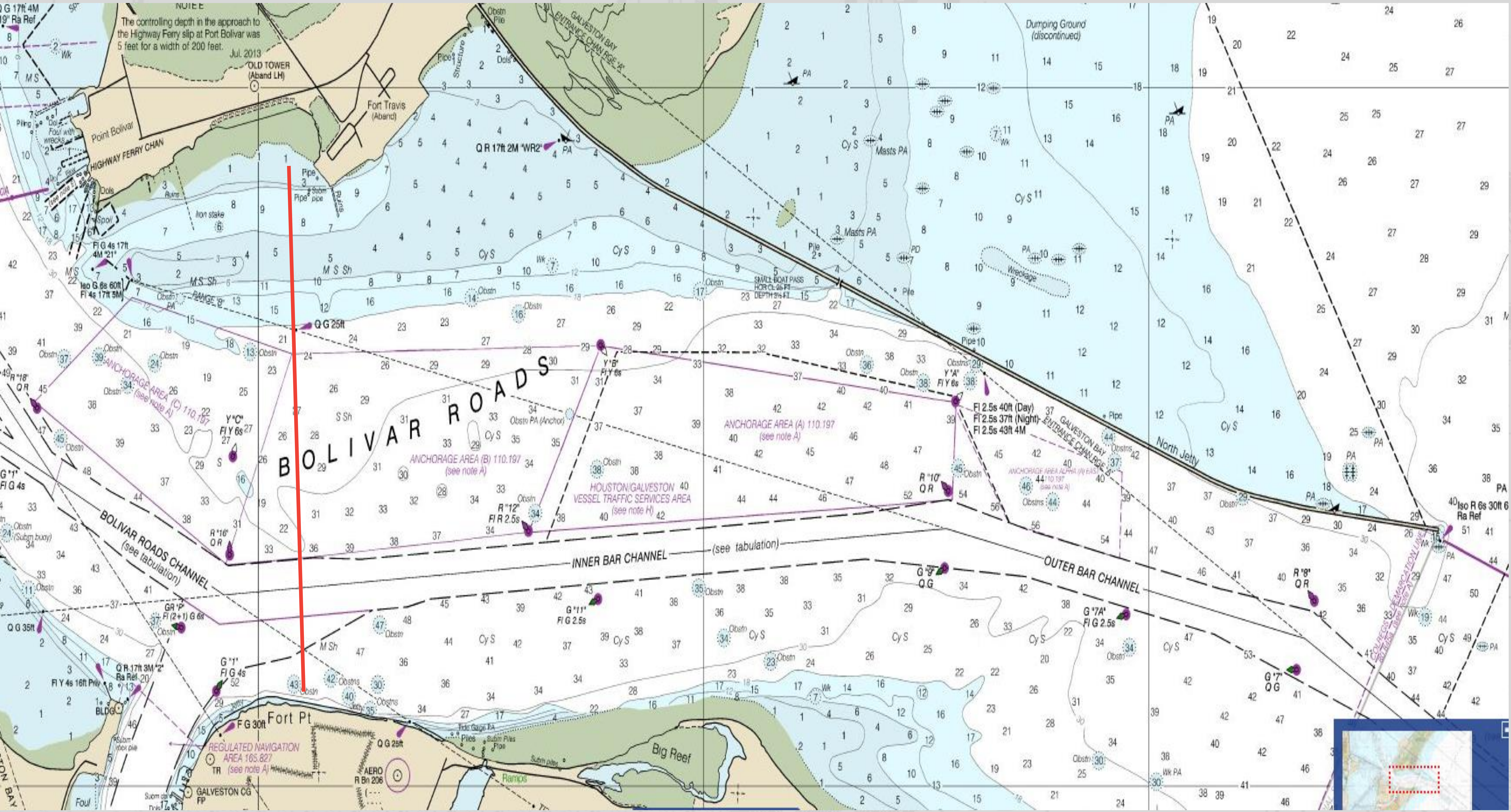


CHALLENGES (ANCHORAGE AREA ??)



CHALLENGES RELATED TO NAVIGATION

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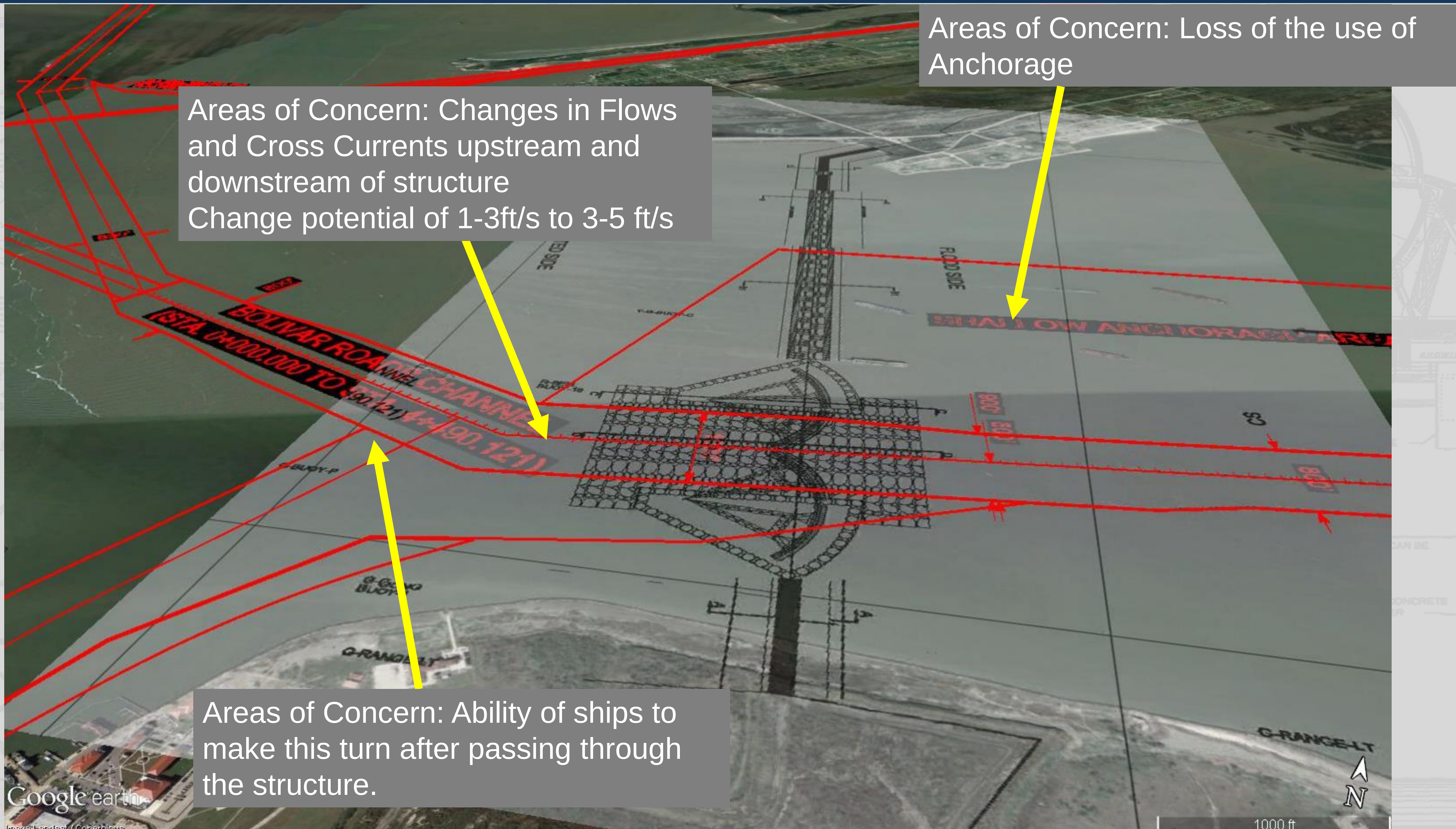


PROPOSED MODIFICATION

US Army Corps of Engineers

U.S. ARMY

Coastal Texas Protection and Restoration Project

Point of Contact

Charlie Brandstetter, IV P.E.

Mississippi Valley Division and New Orleans District

Galveston District Structural PDT member

Email: Charles.P.Brandstetter@usace.army.mil

®

Leveraging On-going Studies

- Texas A&M Galveston
- Severe Storm Prediction Education and Evacuation from Disasters (SSPEED Center) – Rice University
- Gulf Coast Community Protection and Recovery District (GCCPRD)

Leveraging On-going Studies

- Texas A&M Galveston: Coastal Spine/Ike Dike

- Developed by Texas A&M professor Bill Merrell after Hurricane Ike

Leveraging On-going Studies

- SSPEED Center

The SSPEED Center is a university-based research & education center led by Rice University.

Leveraging On-going Studies

- SSPEED Center

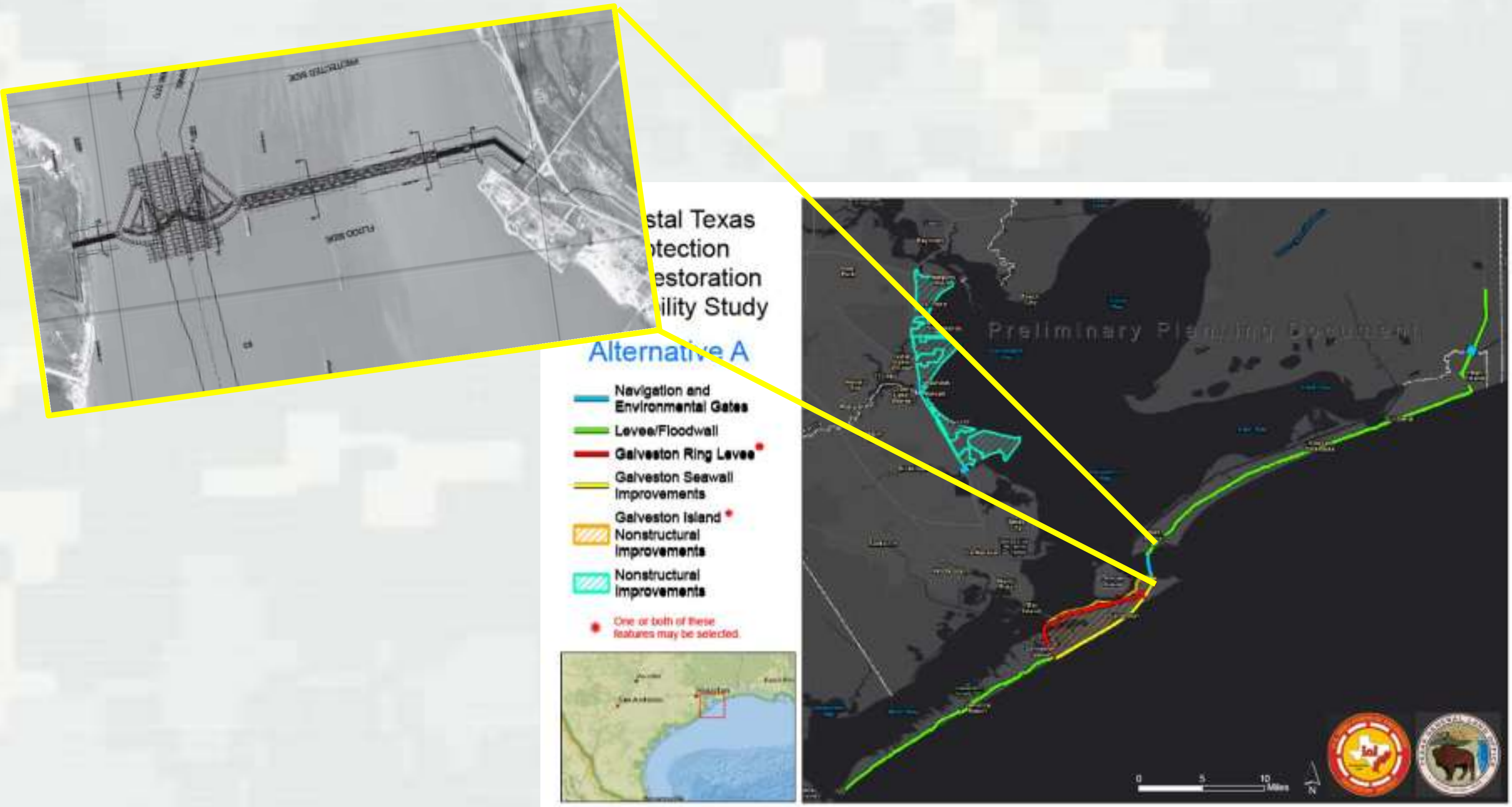
The Centennial Gate at the Fred Hartman Bridge

Leveraging On-going Studies

- The Gulf Coast Community Protection and Recovery District (GCCPRD)

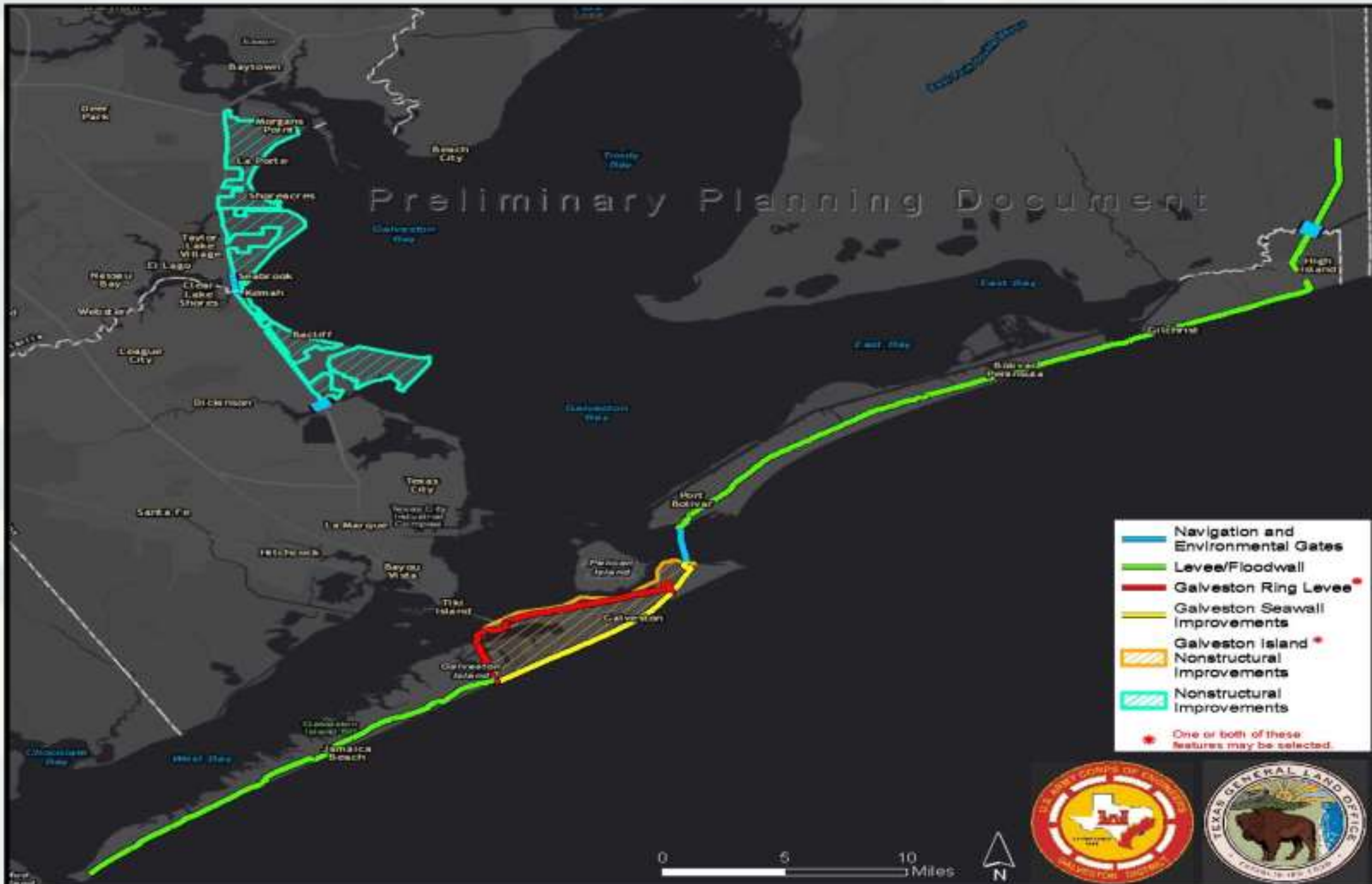
Pre-AMM Alternatives Investigated

Alternative A: Coastal Barrier Alignment (GCCPRD)



Tentative Selected Plan (TSP)

Alternative A: Coastal Barrier Alignment (GCCPRD)

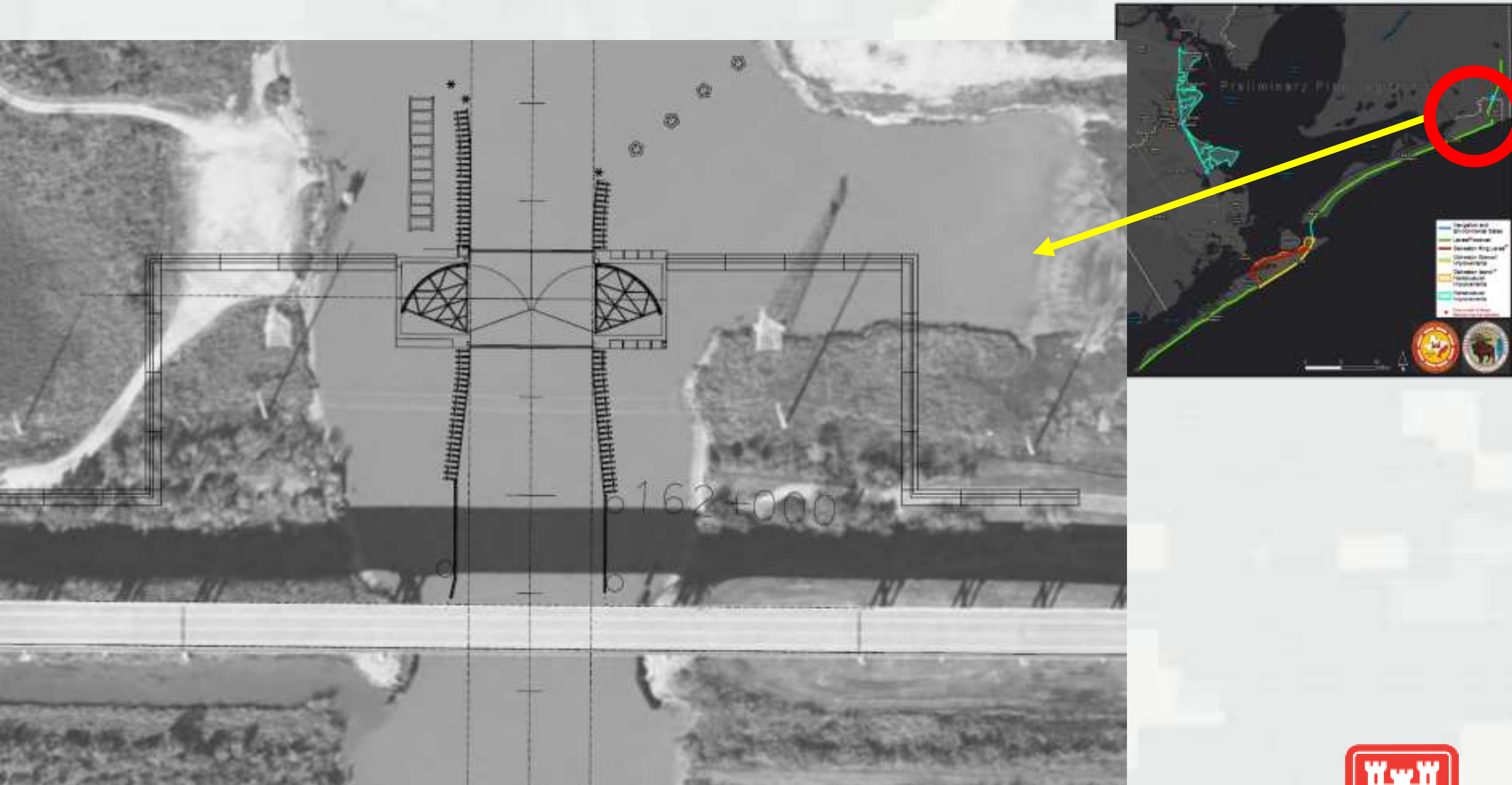


BUILDING STRONG®

TSP – Significant Features

- GIWW Sector gate – 125’ Wide
- Bolivar Road Crossing
  - Combi Wall
  - Vertical Lift Gates
  - Large Navigation Gate
- Galveston Island
  - Seawall
  - Offatts Bayou crossing
- Dickerson Bayou - Pump Station & Sector Gate
- Clear Creek - Pump Station & Sector Gate

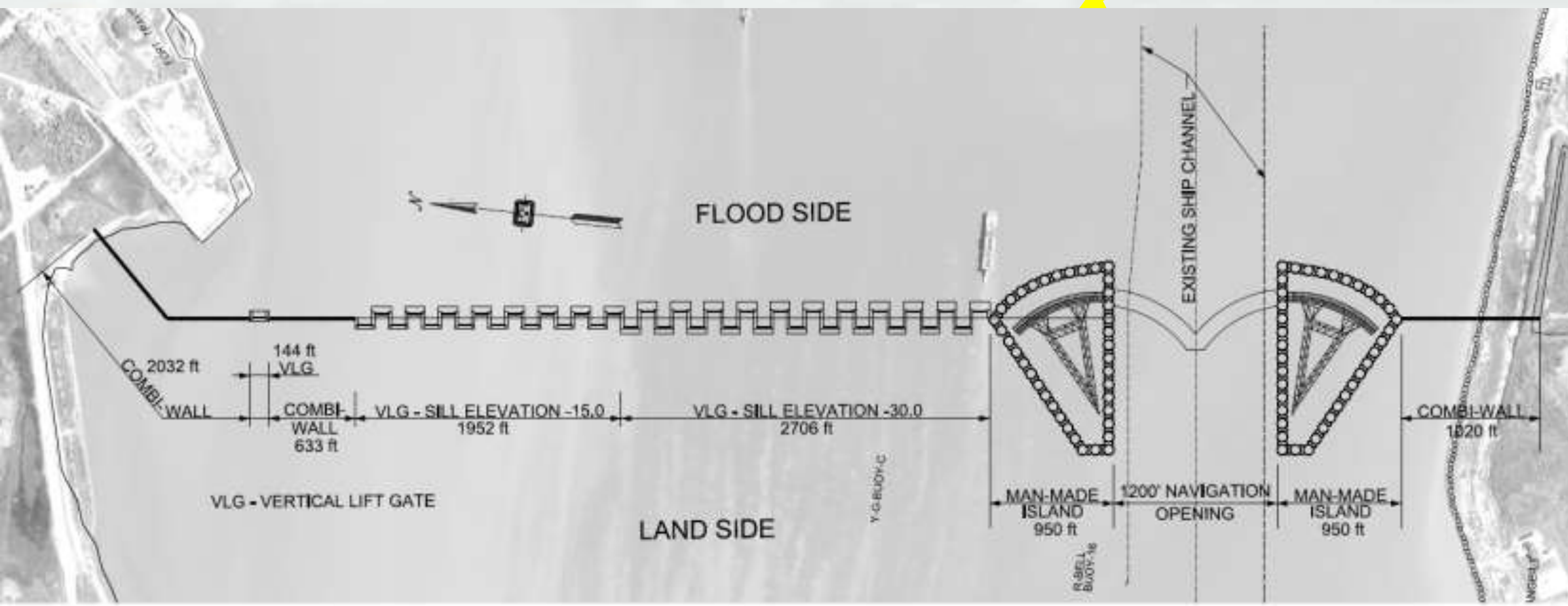
GIWW Sector gate – 125' Wide



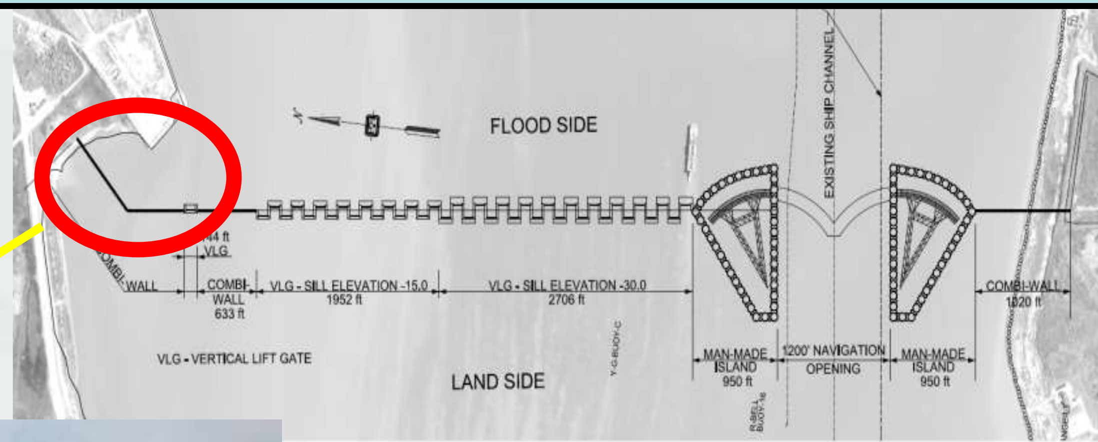
Bolivar Road Crossing

Bolivar Road Crossing

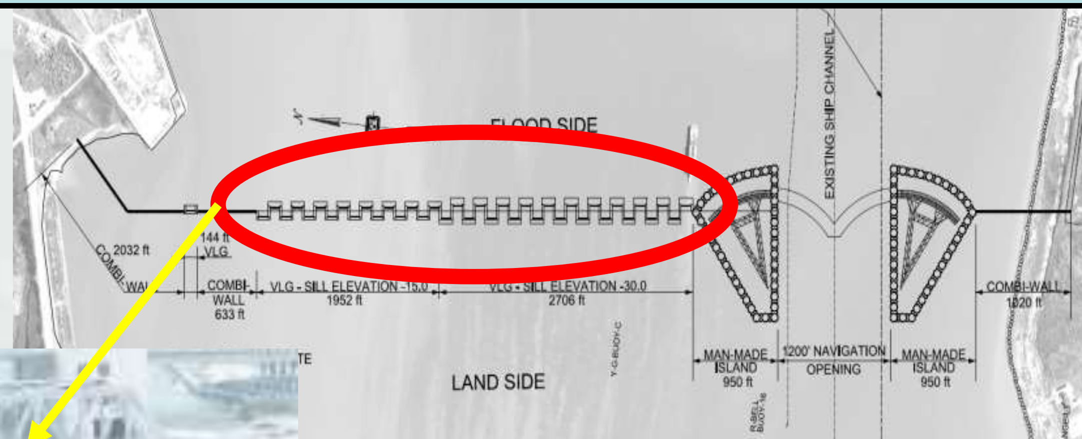
- Combi Wall
- Vertical Lift Gates
- Large Navigation Gate



Bolivar Road Crossing - Combi Wall

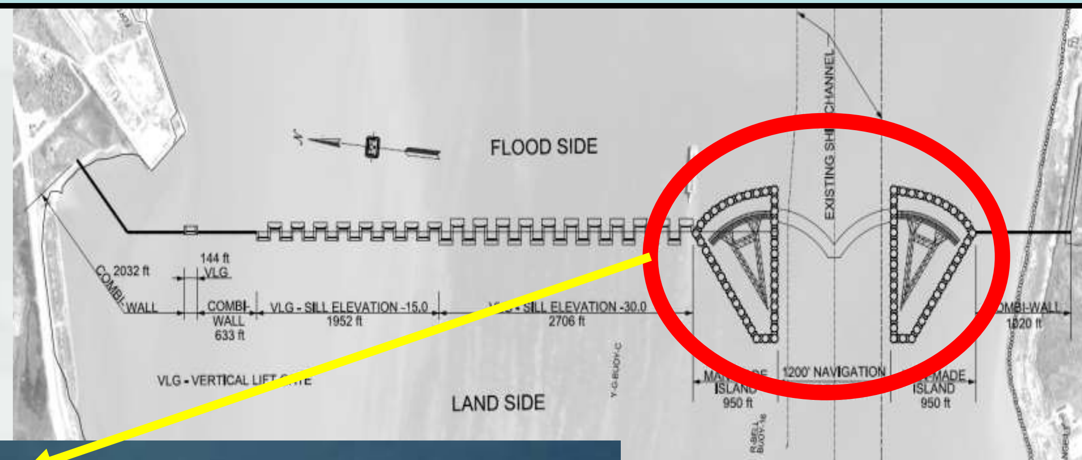


Bolivar Road Crossing - Vertical Lift Gates



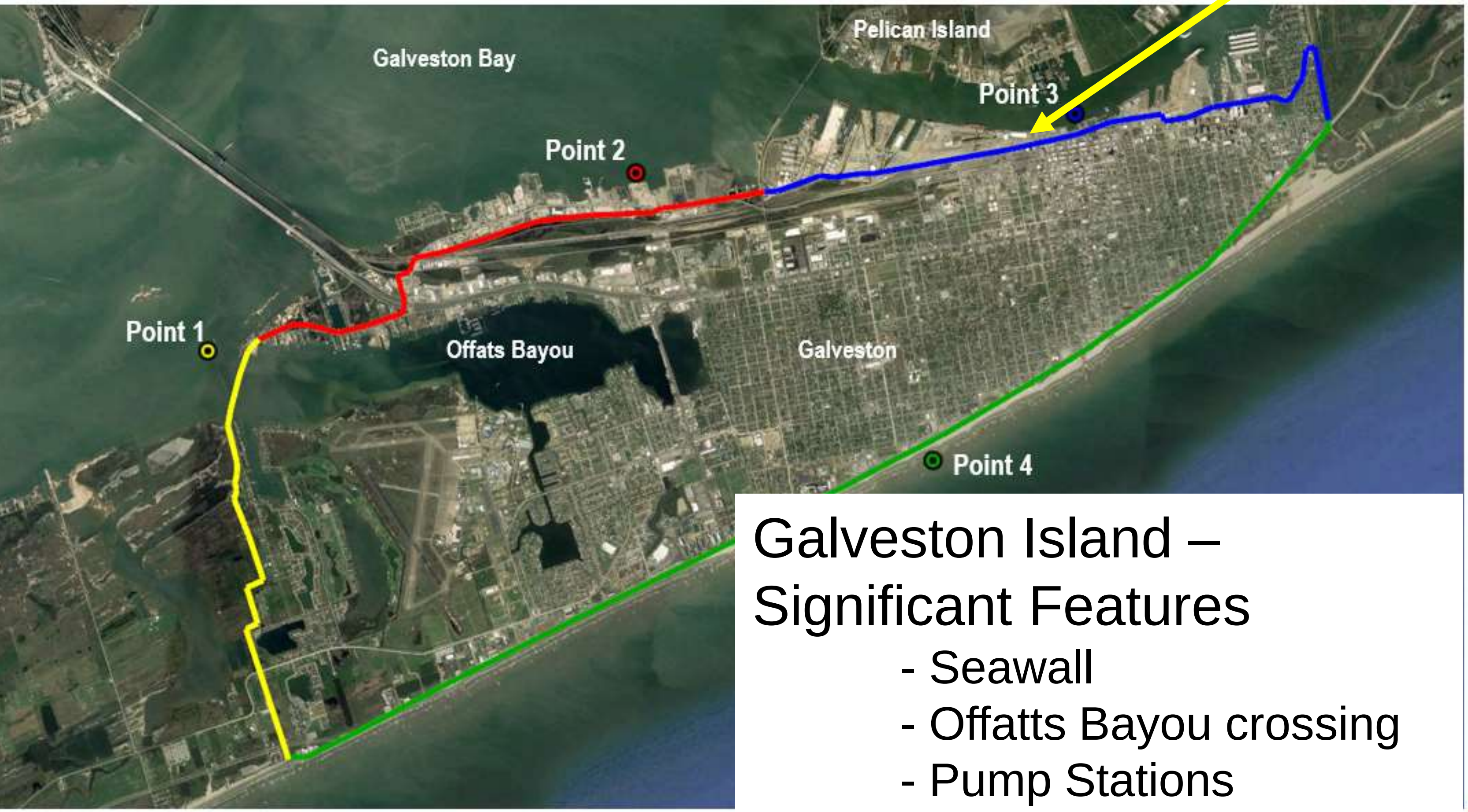
BUILDING STRONG®

Bolivar Road Crossing – Large Navigation Gate



BUILDING STRONG®

Galveston Island



Galveston Island – Significant Features

- Seawall
- Offatts Bayou crossing
- Pump Stations

STRONG®

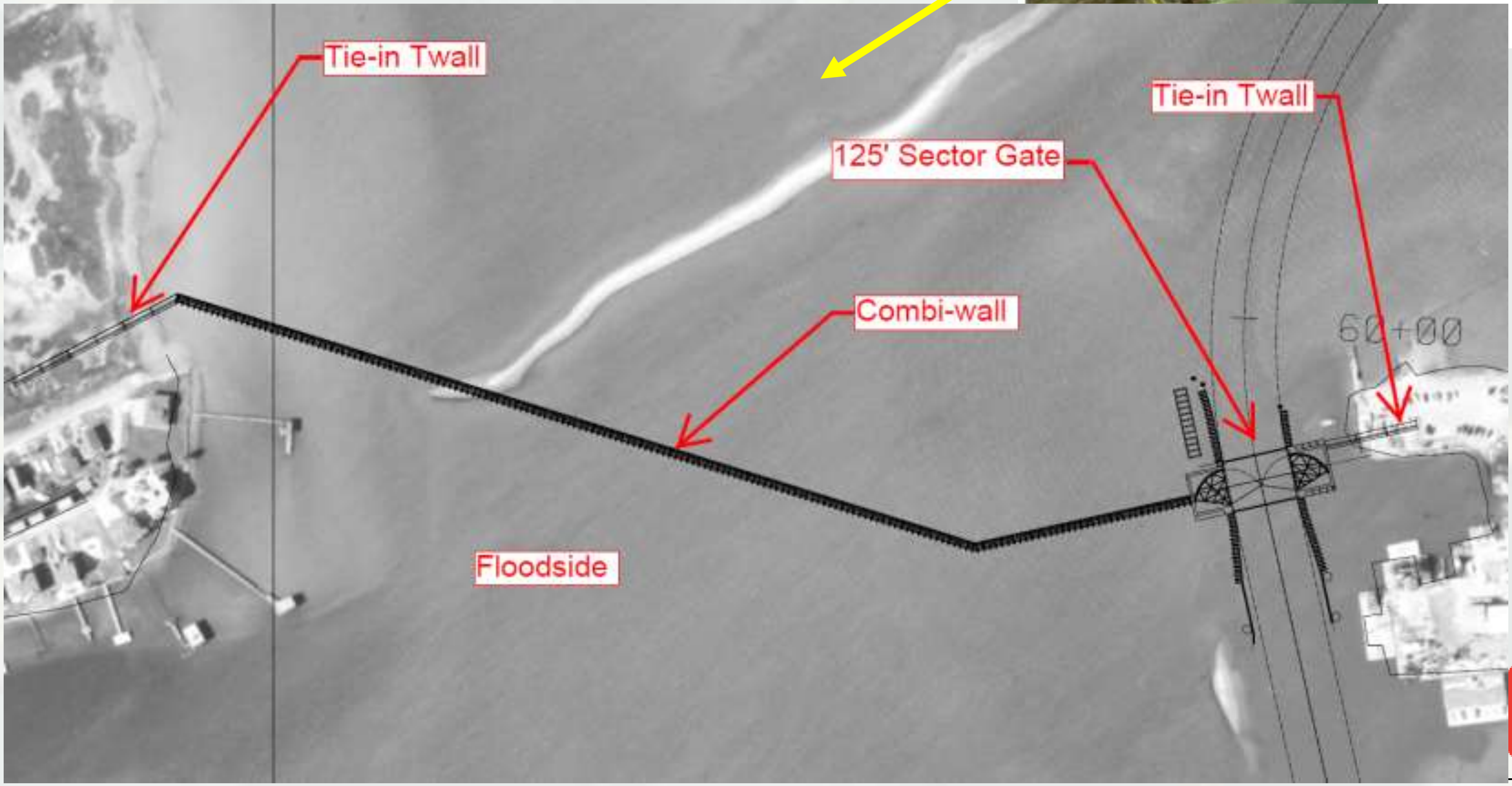
Galveston Island - Seawall

Galveston Seawall – needs to be raised

Galveston Island – Offatts Bayou

Offatts Bayou Crossing

- Combi Wall
- Large Navigation Gate



TSP – Significant Features Not Shown

- Dickerson Bayou - Pump Station & Sector Gate
  - ▷ 100’ wide Sector gate
  - ▷ 19,125 CFS Pump Station
- Clear Creek - Pump Station & Sector Gate
  - ▷ 80’ wide Sector gate
  - ▷ 44,660 CFS Pump Station
- 4 Galveston Island Pump Stations
  - ▷ 250 CFS Pump Station
  - ▷ 1500 CFS Pump Station
  - ▷ 4500 CFS Pump Station
  - ▷ 1500 CFS Pump Station
- T-walls, Drainage Structures & Hwy & Road Floodgates

Cost Drivers for Alternatives

- Pump station sizes and the number of them
- Pile foundation
- Dredging
- Complexity of the design and construction of such large Floodgates
- Uncertainty in the availability of borrow material on Bolivar or Galveston Island possible higher transportation costs
- Complexity of floodwall placement on the backside of Galveston due to Port facilities
- Mitigation for indirect impacts to fisheries access to entire Galveston Bay complex

Coastal Storm Risk Management and Ecosystem Restoration Projects along the Texas Coast

Hydraulics & Environmental Analyses

Point of Contact

Himangshu S. Das, Ph.D., PE
Technical Lead, Coastal TX Study
USACE Galveston
Himangshu.s.das@usace.army.mil

- Background, Methodology
- Data, Results

Topic concentrates only on Storm Surge !

US Army Corps of Engineers

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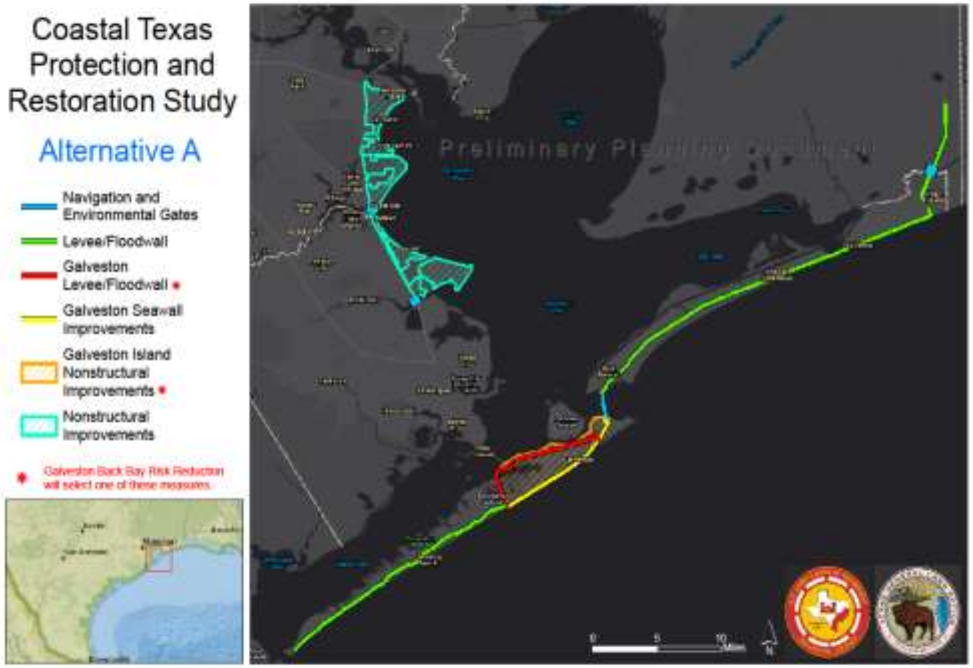
BACKGROUND



Develop a quantitative framework to screen alternatives (CSRM)

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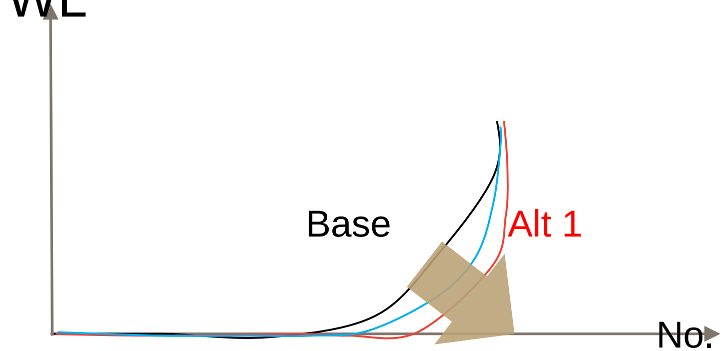
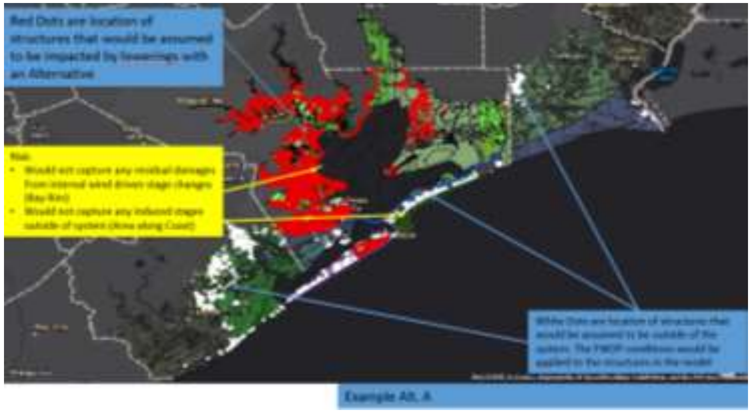
METHODOLOGY

- <u>Qualitative/Semi Quantitative Method</u>

  -Use existing FEMA data and use of 2-4 storms to evaluate alternatives. No statistical surface

  - Biasness in storm selection

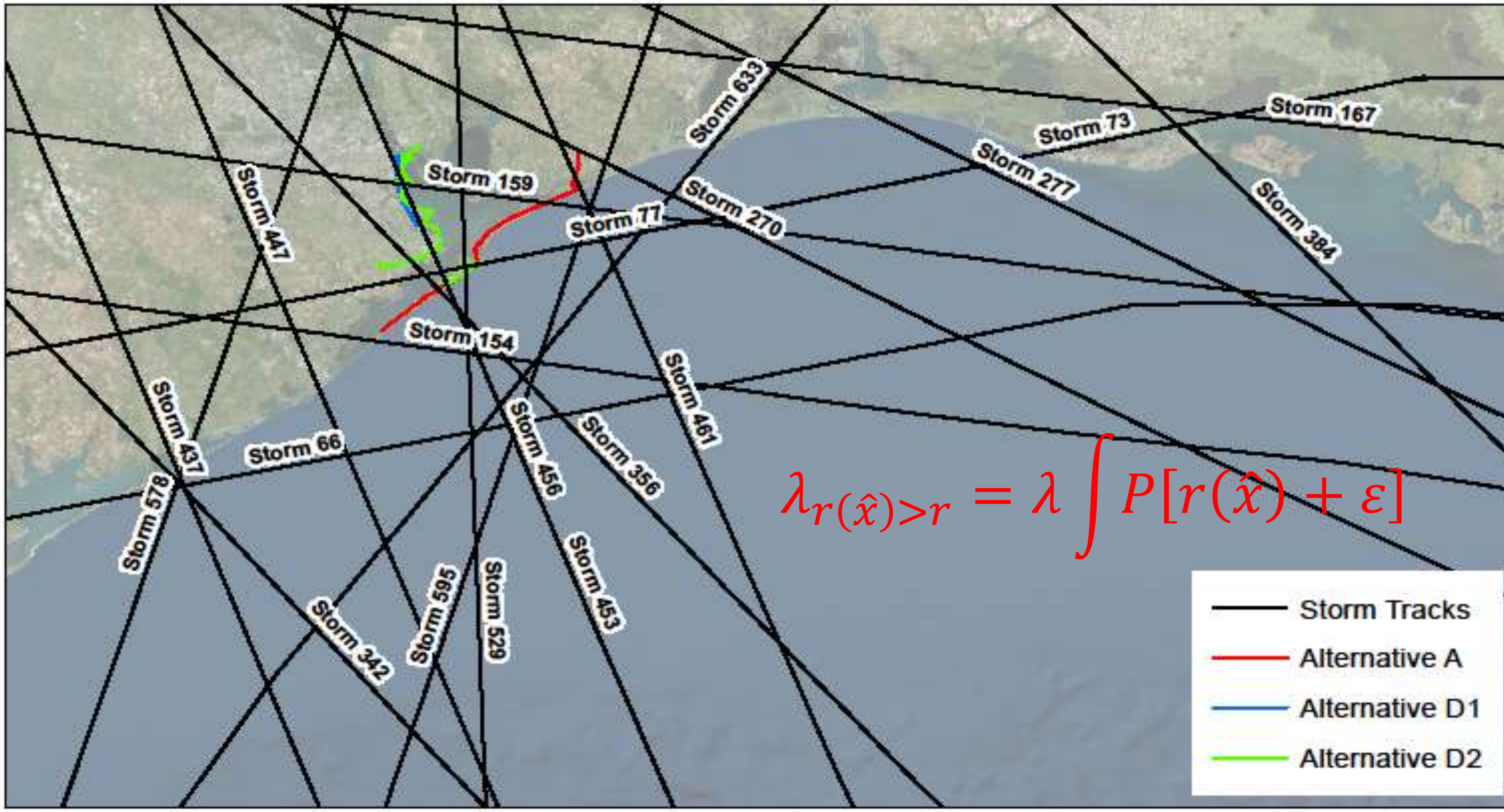




- <u>Quantitative Method (Use of a reduced storm sample)</u>

  - Statistical WL surface
  - Reduce bias in selection process
  - Established method

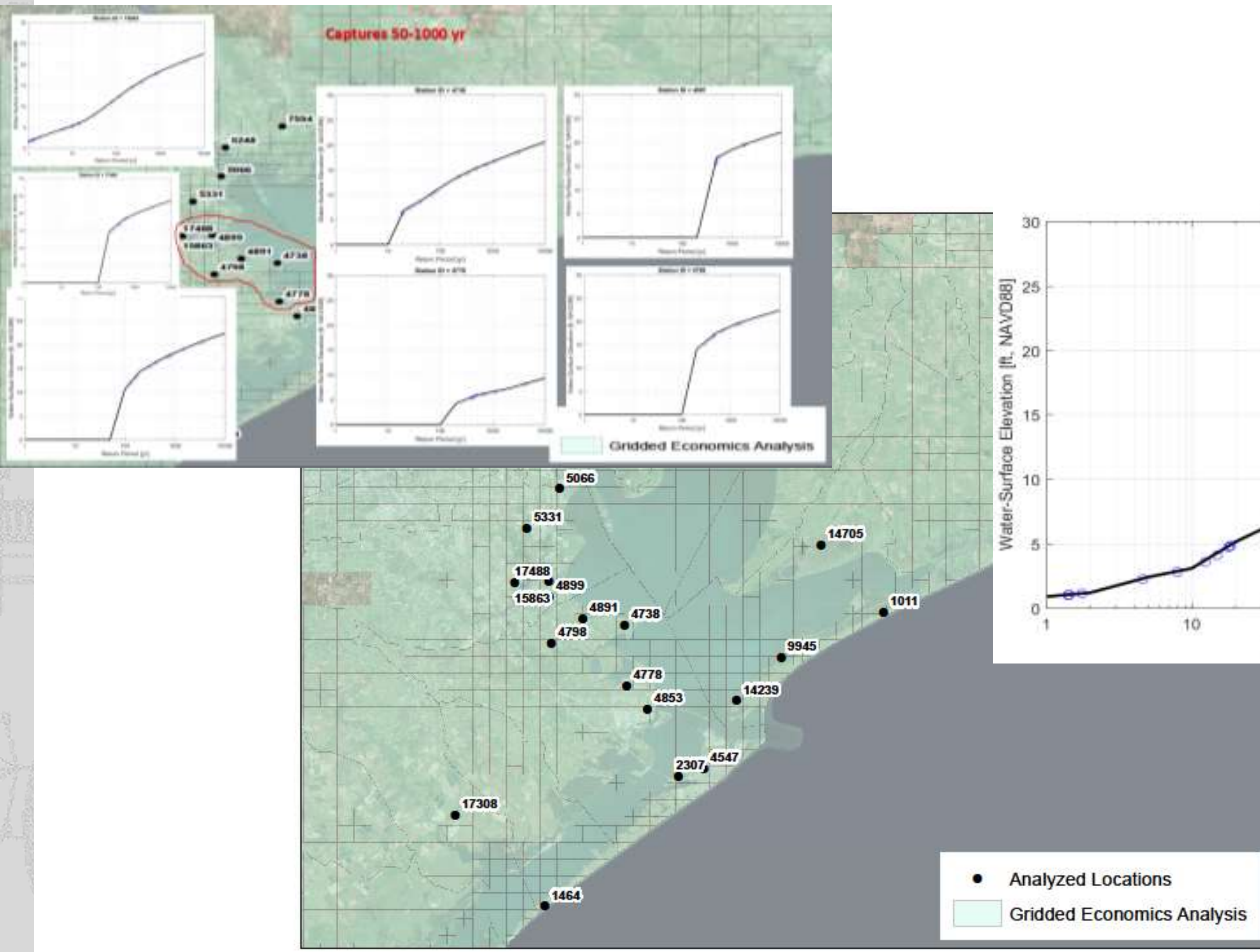
Selection of Storms (Sample of 20)

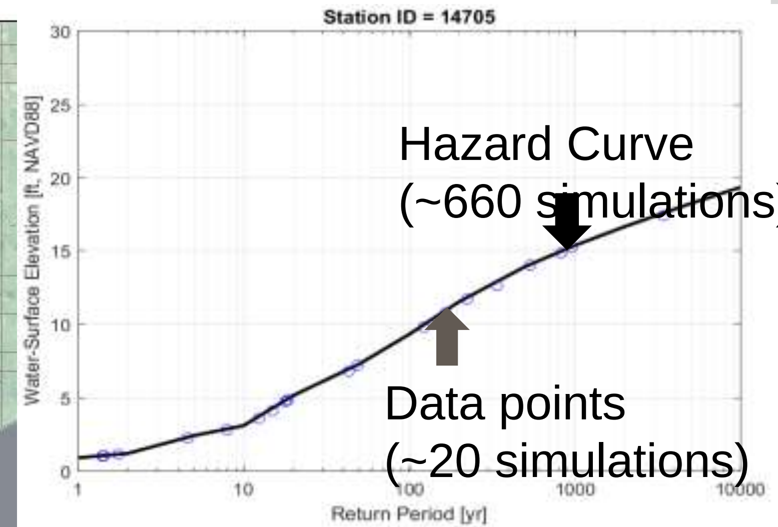


$$\lambda_{r(\hat{x})>r} = \lambda \int P[r(\hat{x}) + \varepsilon]$$

Storm No.	66	73	77	154	159	167	270	277	342	356	384	437	447	453	456	461	529	578	595	633
Max. Wind Speed [mph]	117	181	115	121	101	89	143	162	109	152	162	206	105	201	87	197	187	210	195	170
Saffir-Simpson Scale Cat. #	3	5	3	3	2	1	4	5	2	4	5	5	2	5	1	5	5	5	5	5
Min. Central Pressure [mb]	885	865	945	935	895	915	905	885	915	915	915	865	905	865	925	865	895	865	885	875
Radius to Max. Winds [nmi]	28.9	8.0	26.6	39.7	27.2	32.3	17.8	24.7	54.1	24.6	20.8	9.3	44.6	12.3	44.3	17.5	21.5	12.8	17.0	22.7
Forward Storm Speed [kts]	13.2	4.3	12.2	10.3	4.6	9.2	7.5	5.4	12.9	5.9	19.1	14.3	8.6	8.6	5.9	11.9	23.4	22.4	19.7	7.9

Validation of Hazard Curve (Sample of 20)





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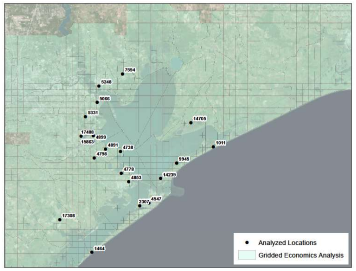
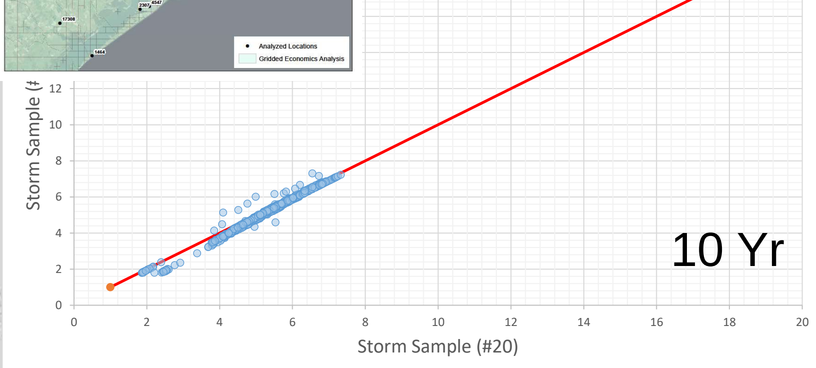
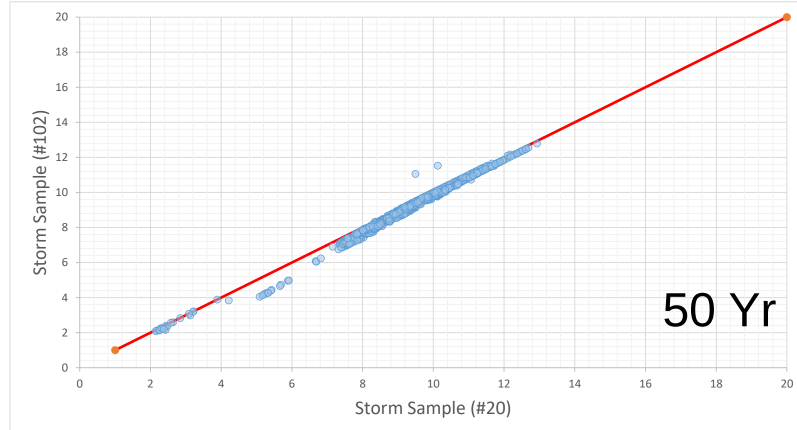
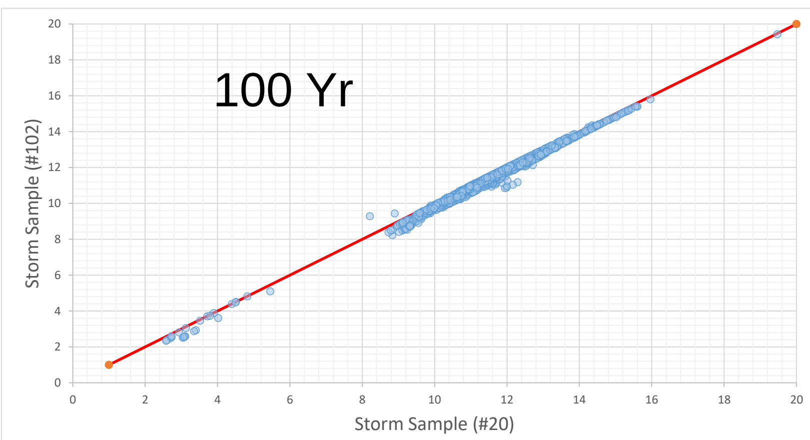
Validation of WOP Hazard Curve (Sample of 20 & 102 storms)

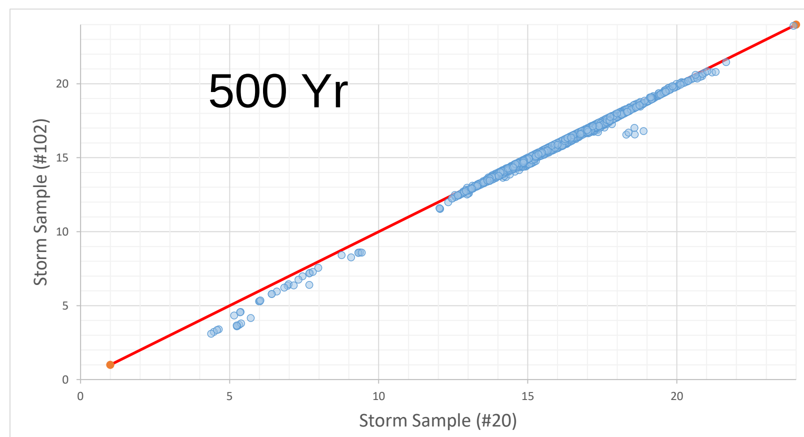


Correlation (R^2 > 0.9)









Justified use of a reduced storm sample (20) for screening alternatives

US Army Corps of Engineers

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Agenda

- Background, Methodology
- Data, Results
- Issues, Resolution
- Future Direction

Topic concentrates only on Storm Surge !

"The views, opinions and findings contained in this report are those of the authors(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other official documentation."

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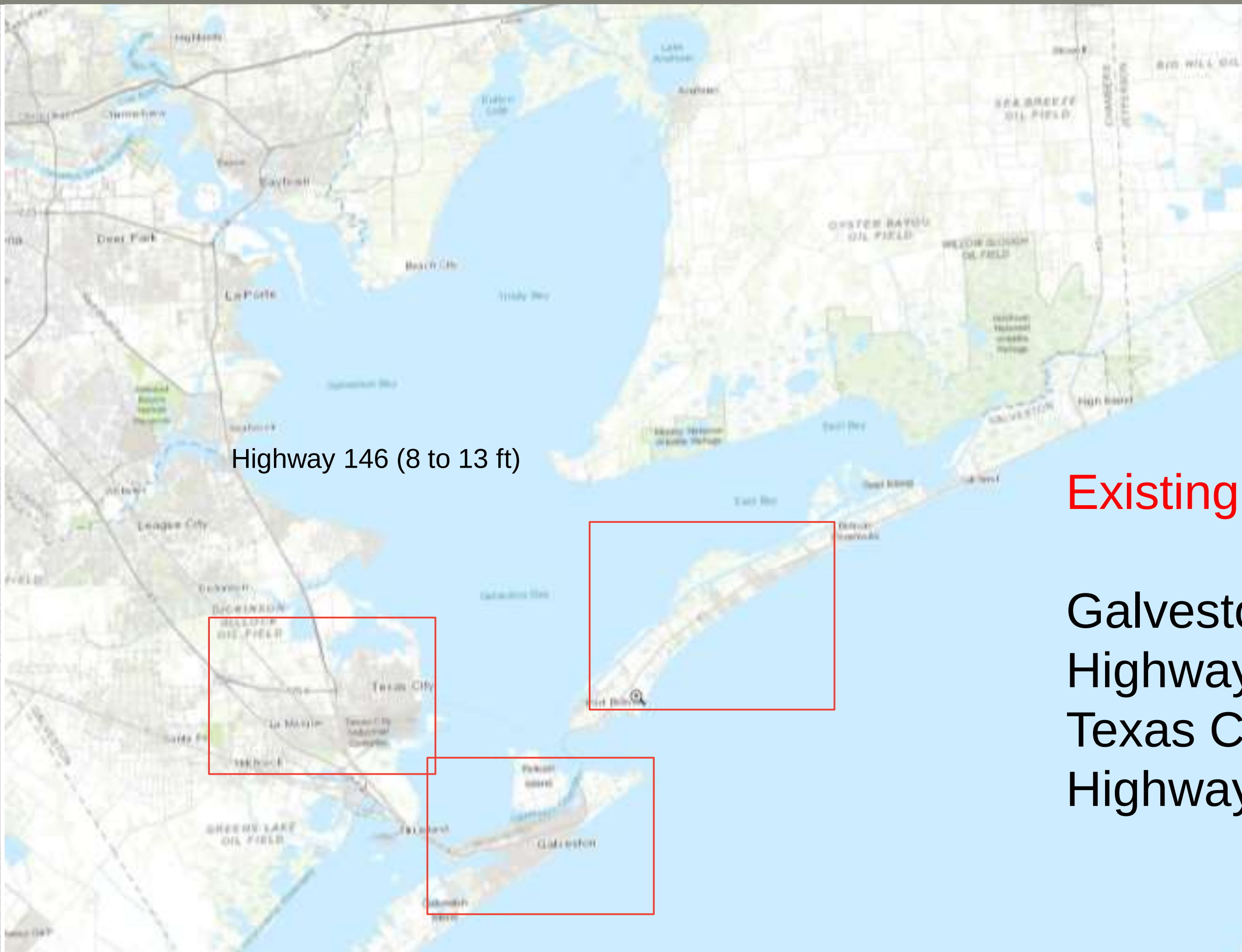
Background Data



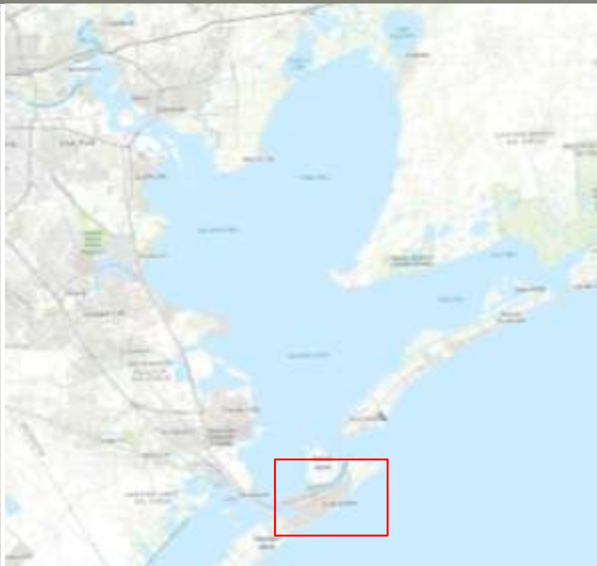
Existing Protection System

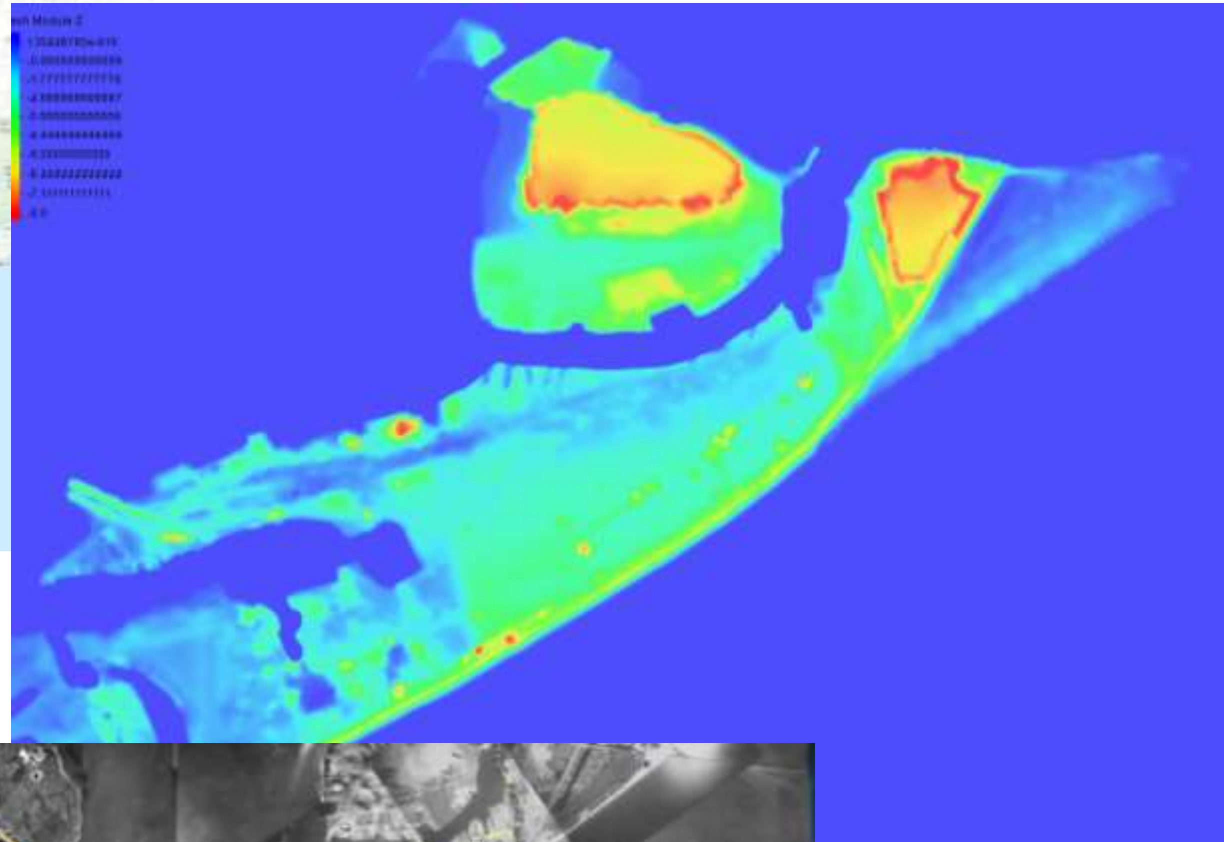
Galveston Sea Wall
Highway 87
Texas City Dike
Highway 146

US Army Corps of Engineers.

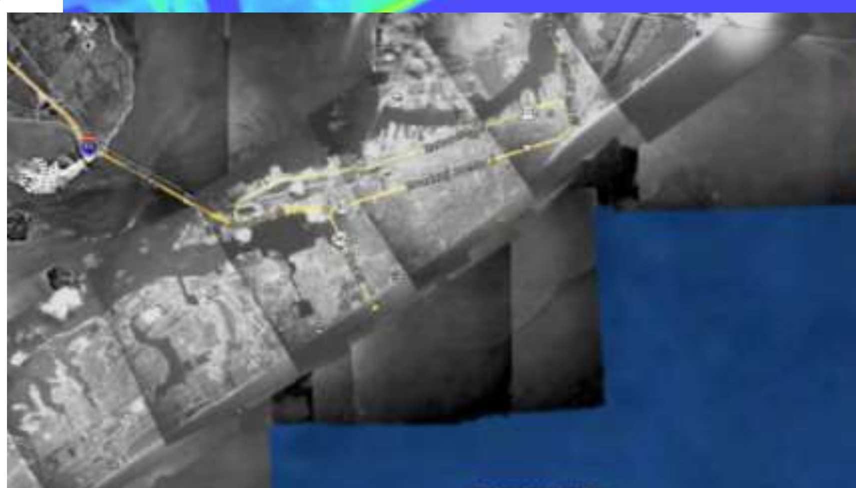
U.S.ARMY

Background Data

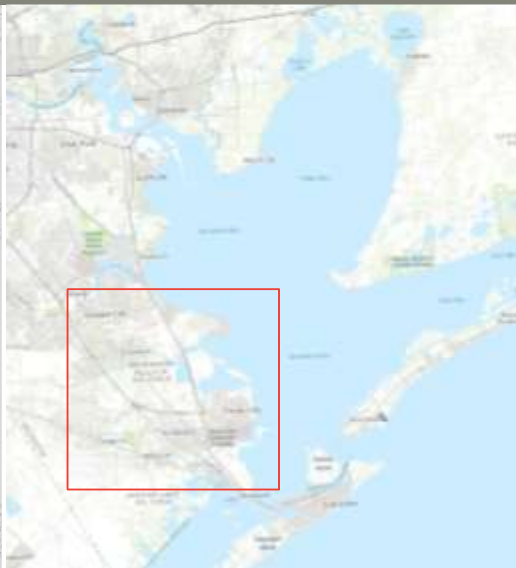


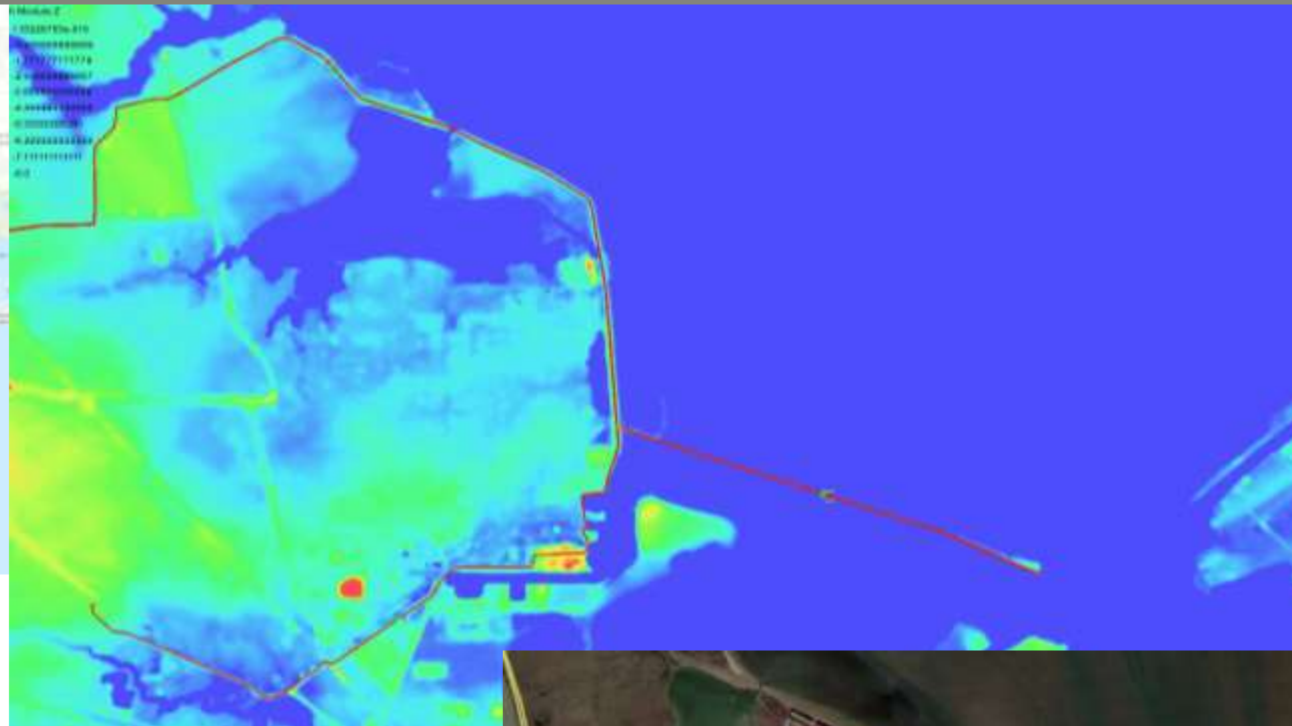


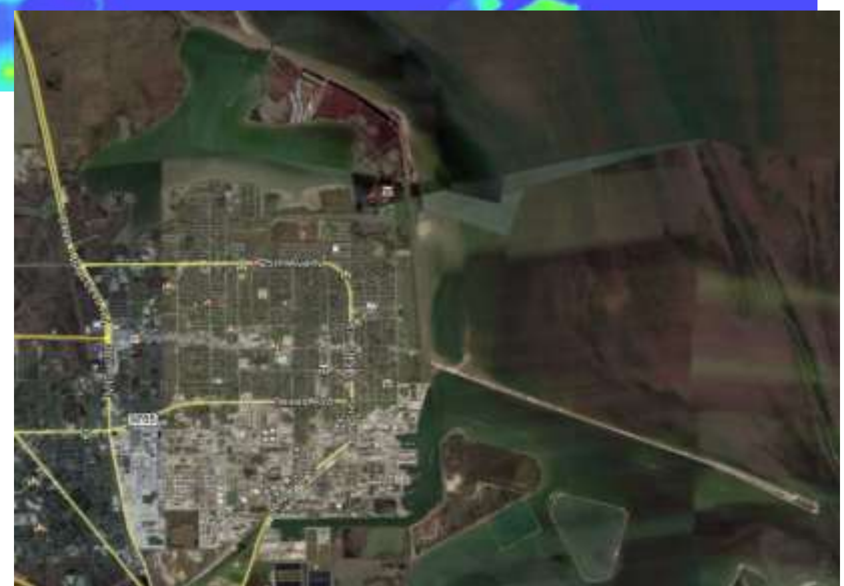
Galveston Sea Wall
+18-21 ft NAVD
Developed area
behind (~>8 ft)



Background Data



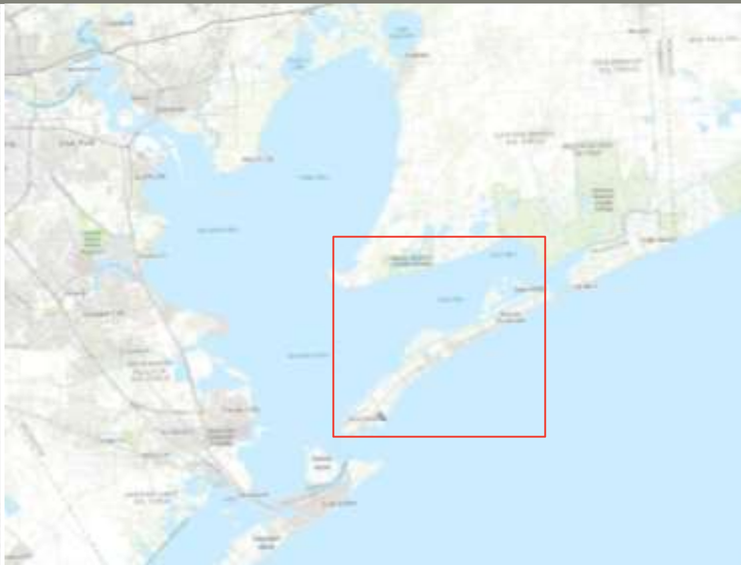


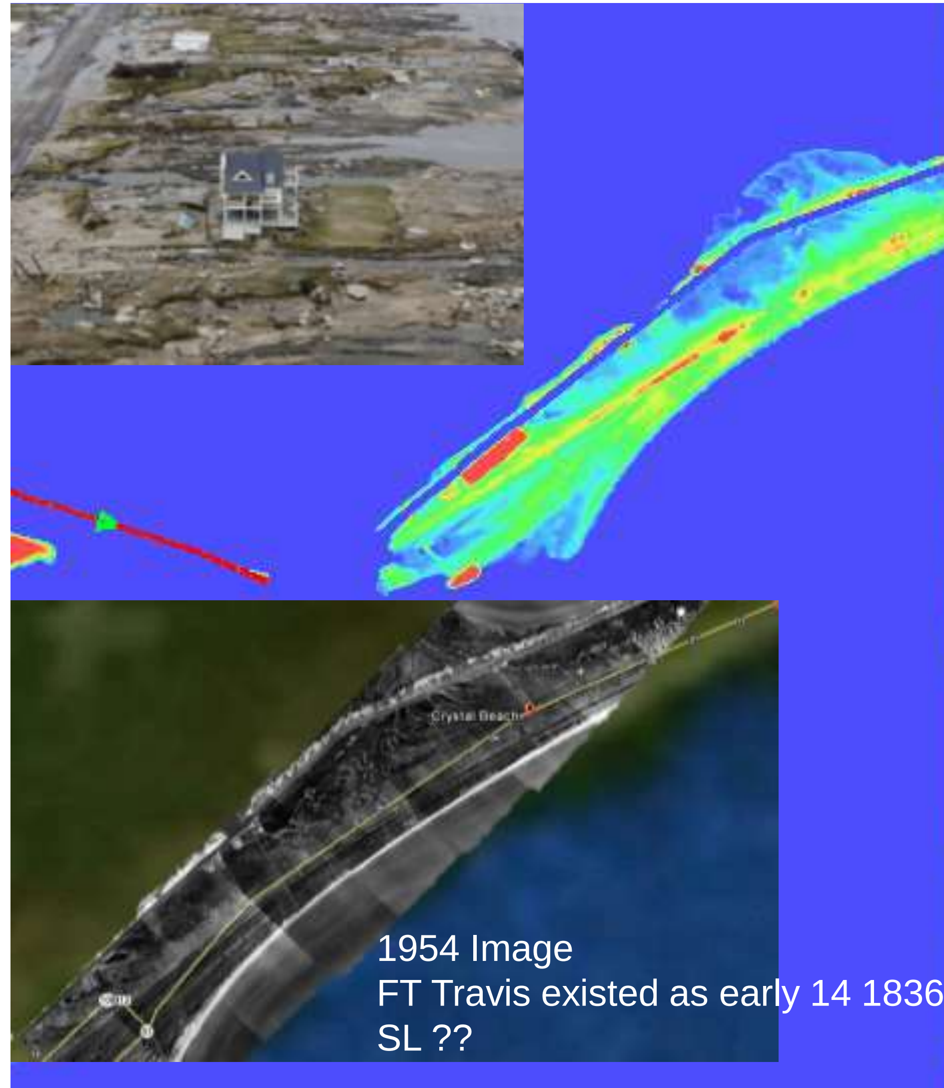


Texas City Protection System
Levee +15-22 ft NAVD

Protected up-to 100 Yr Flood

Background Data





1954 Image
FT Travis existed as early 14 1836
SL ??

Bolivar Peninsula
Avg. Elevation +3-f ft NAVD
Highway 87

100 Yr Flood : 12-13 ft

Tools: ADCIRC/STWAVE Computational Domain

The domain covers an approximately 38⁰ by 38⁰ square area in longitudinal (from 98⁰ W to 60⁰ W) and latitudinal (from 8⁰ N to 38⁰ N) directions. The mesh consists of approximately 4.5 million computational nodes and 9.0 million unstructured triangular elements with an open ocean boundary specified along the eastern edge (38⁰ W longitude).

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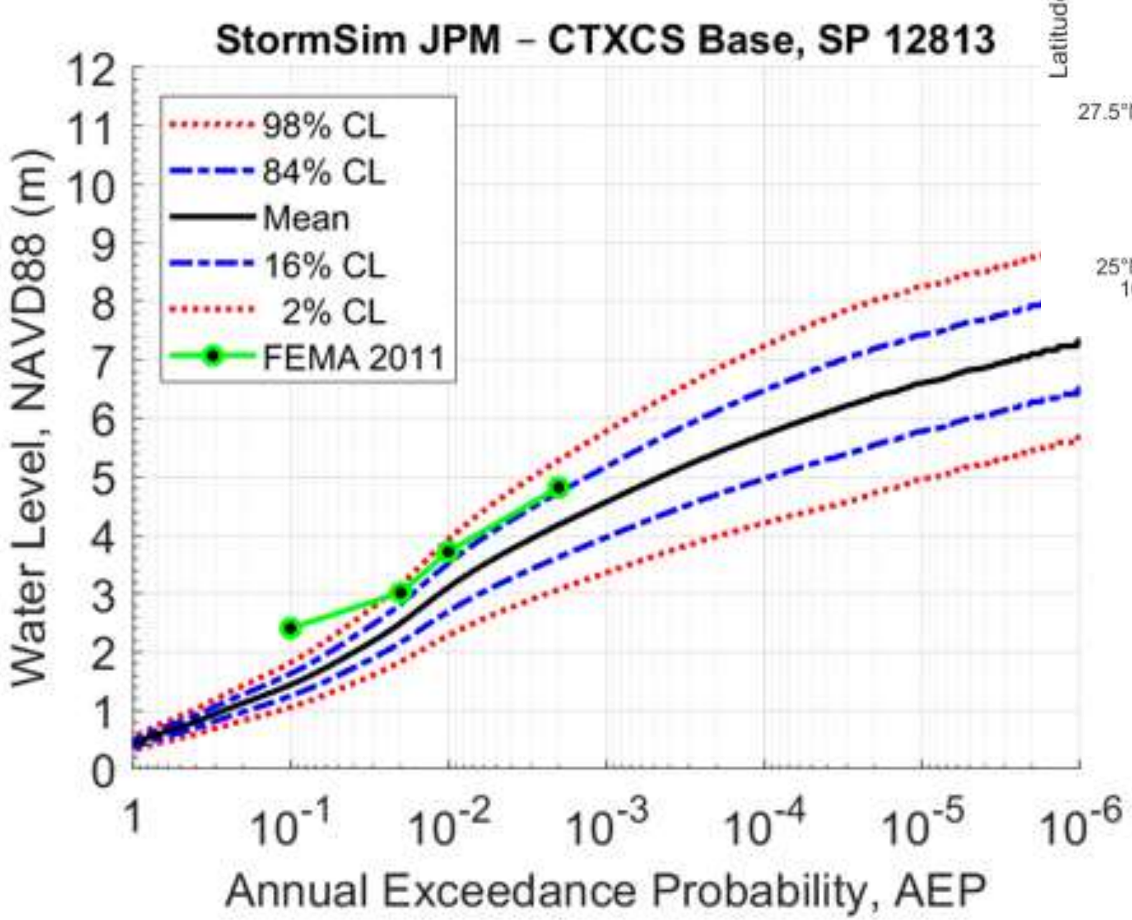
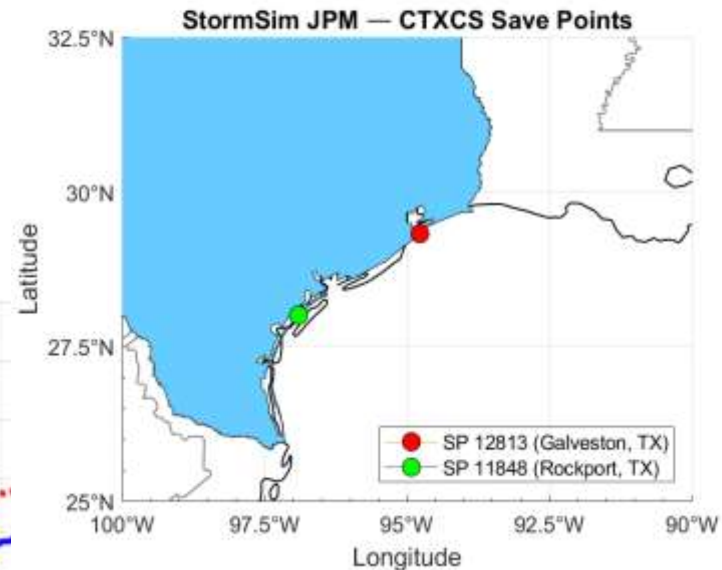
Comparison (FEMA 2011)





In general new statistics correlates with the FEMA values

While integrate all stations, generally new statistics values are lower

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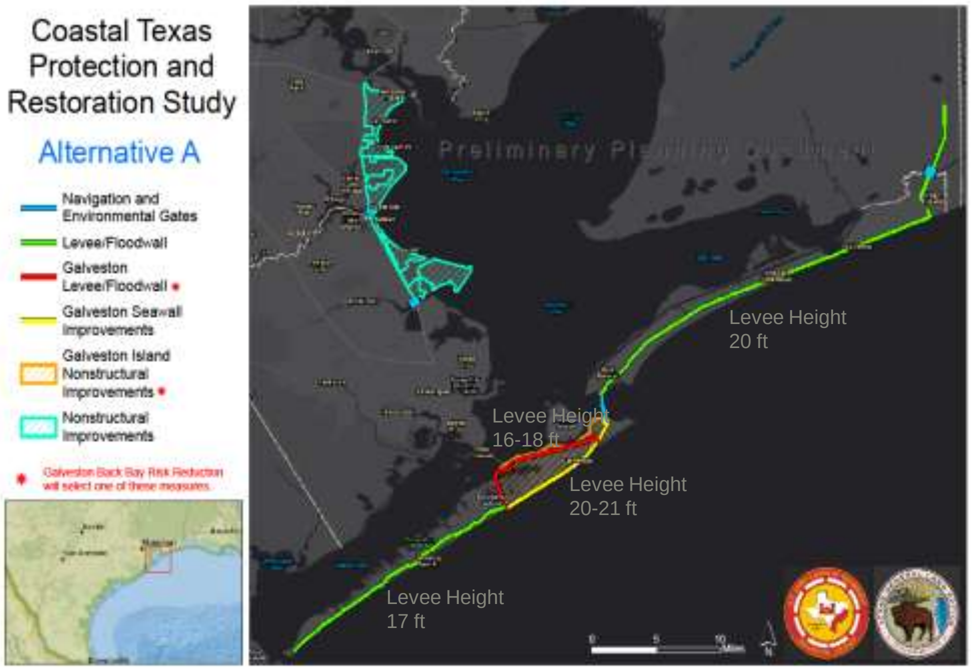
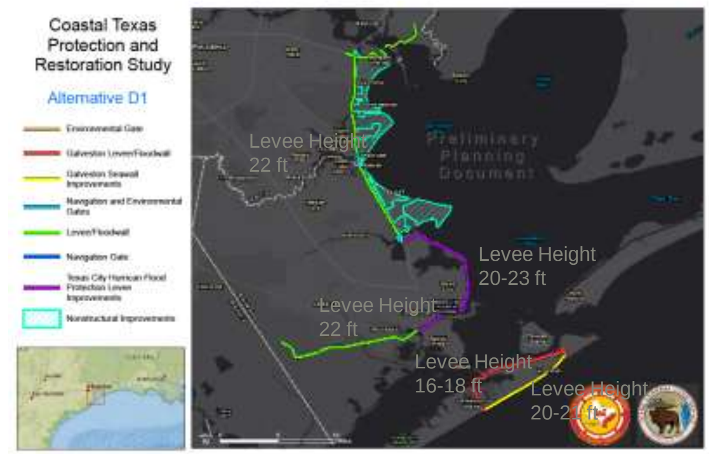
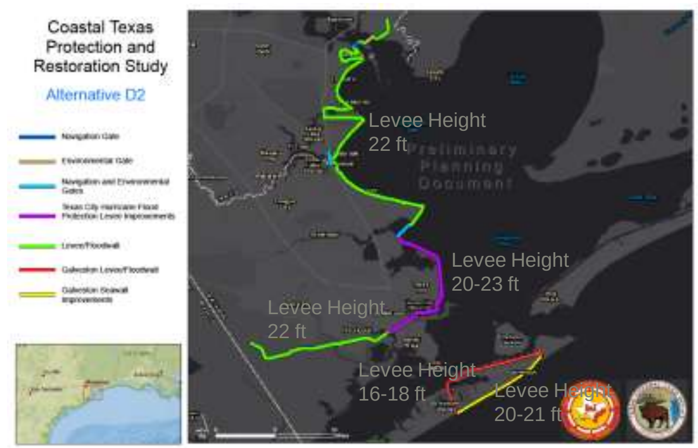
ADCIRC NEW GRIDS (WP CONDITION)







Levee heights are set in ADCIRC as overtopping weirs
Need to fine tune later

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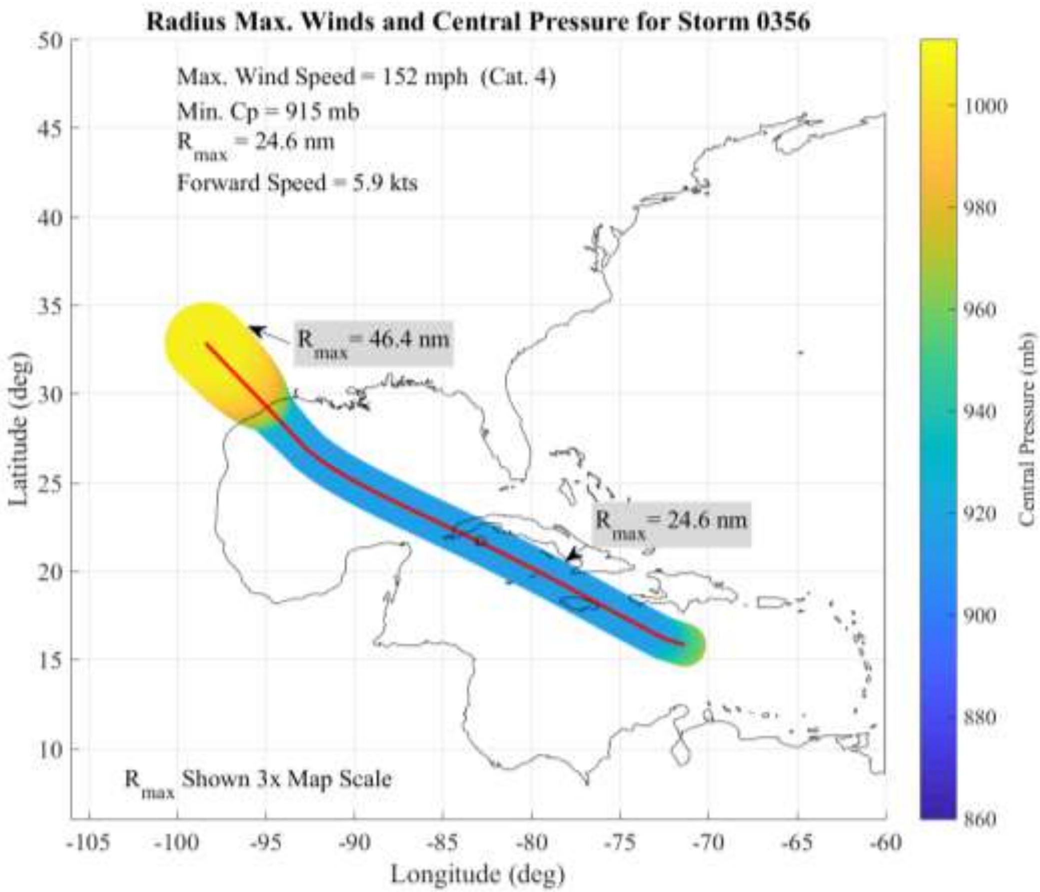
Example Simulation

STORM # 356



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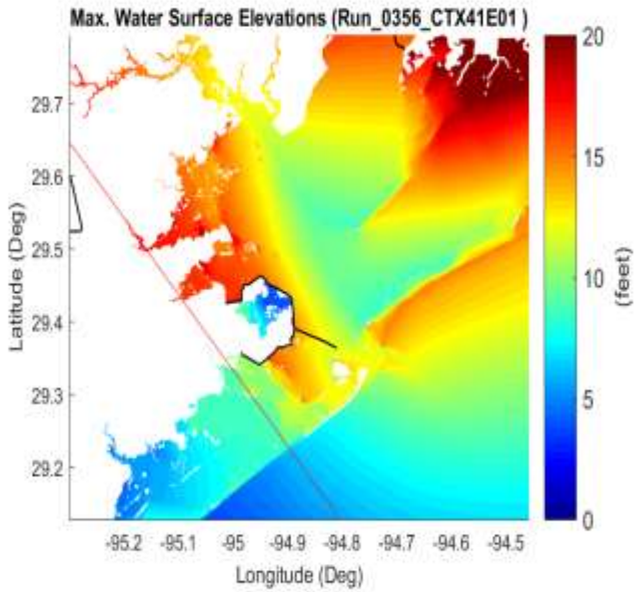
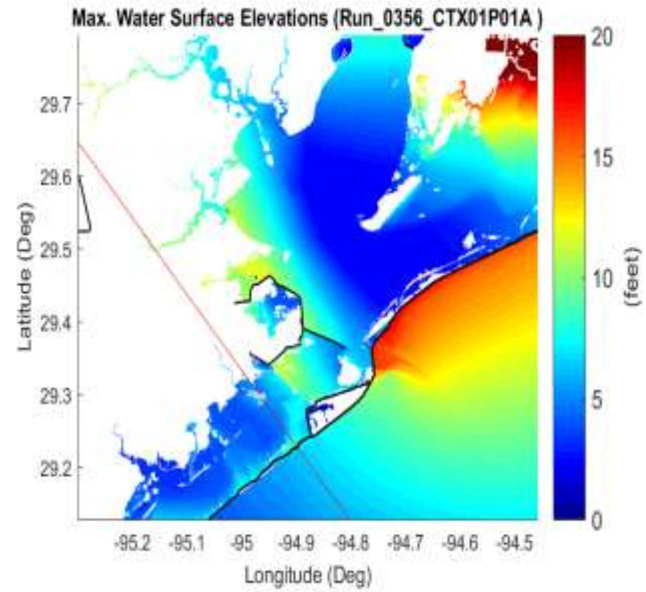
STORM # 356

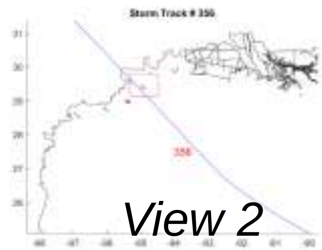


Base (Without Project)

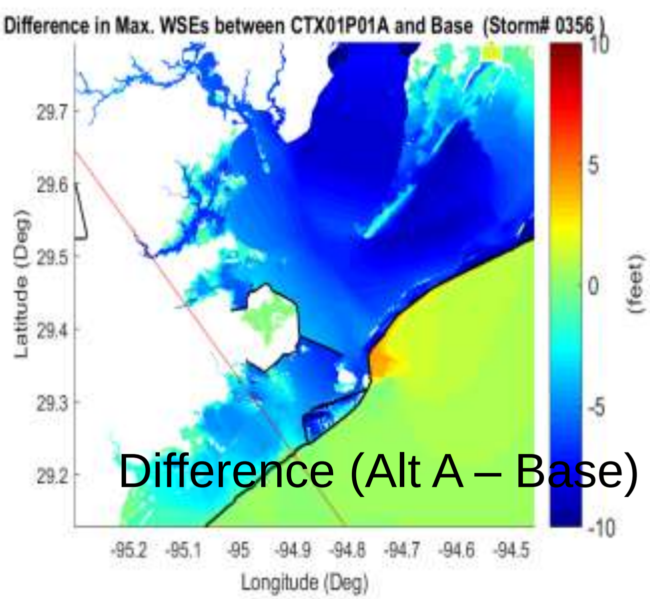
Max. Wind Speed: 152 mph (Cat. 4)
Min. Cp: 915 mb
Rmax: 24.6 nm
Forward Speed: 5.9 kts



Alt A

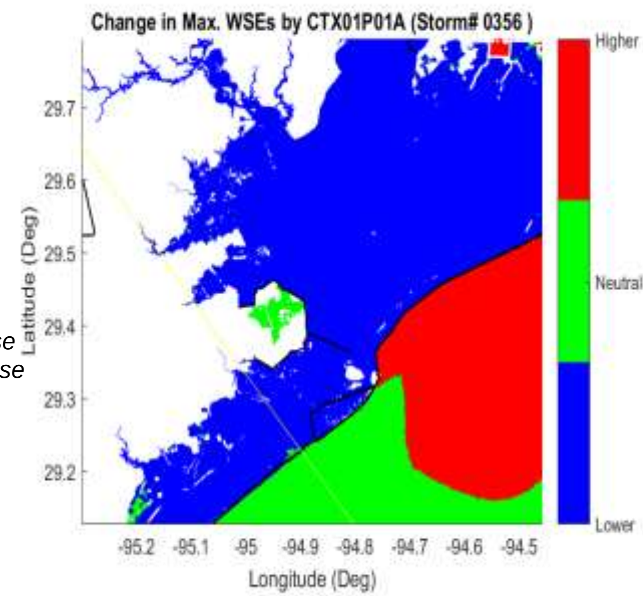


View 2



Difference (Alt A – Base)

Change in WSEs:
Higher: > 1/2 ft increase
Lower: > 1/2 ft decrease
Neutral: in between



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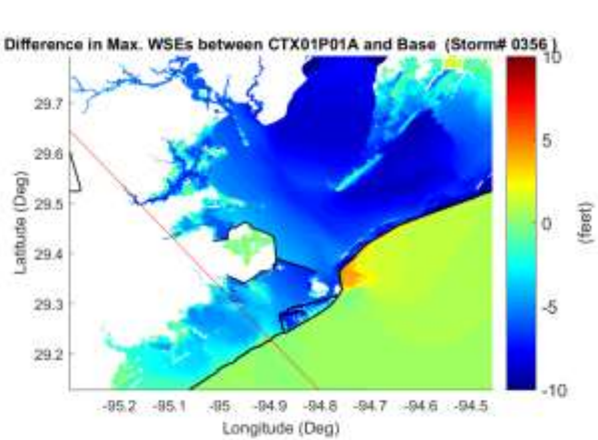
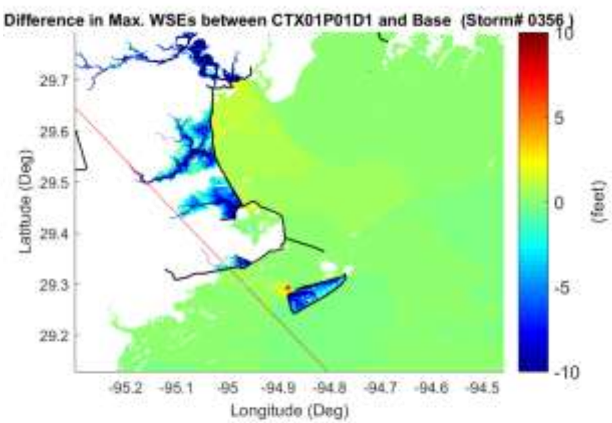
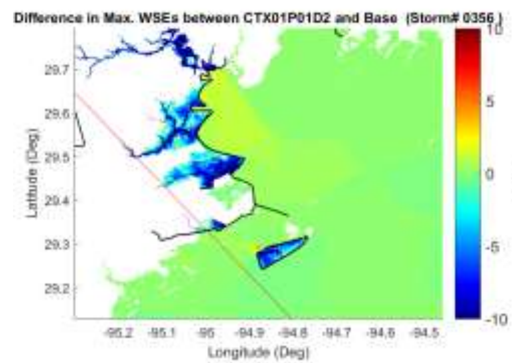


Difference (Alt A – Base)

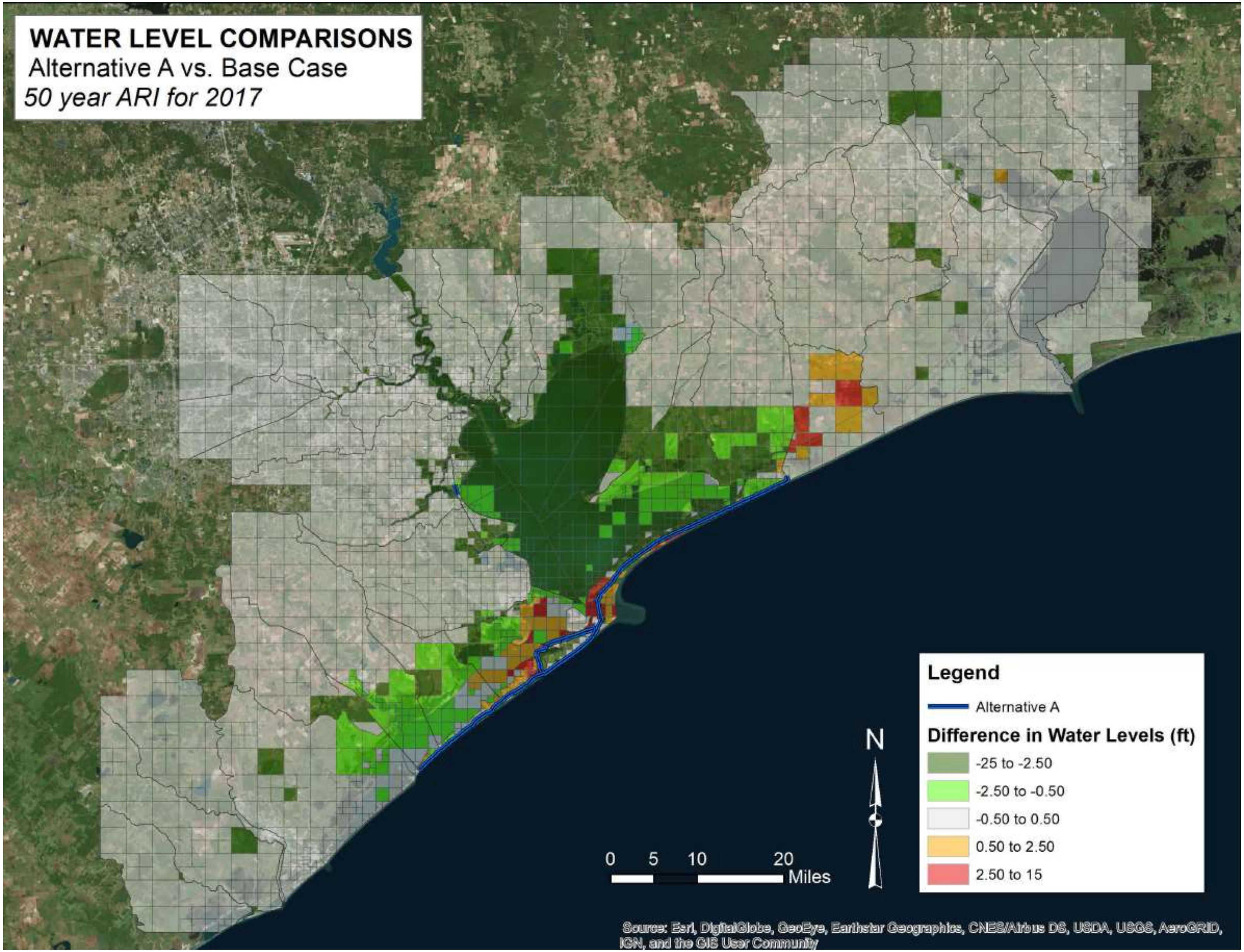


Difference (Alt D1 – Base)

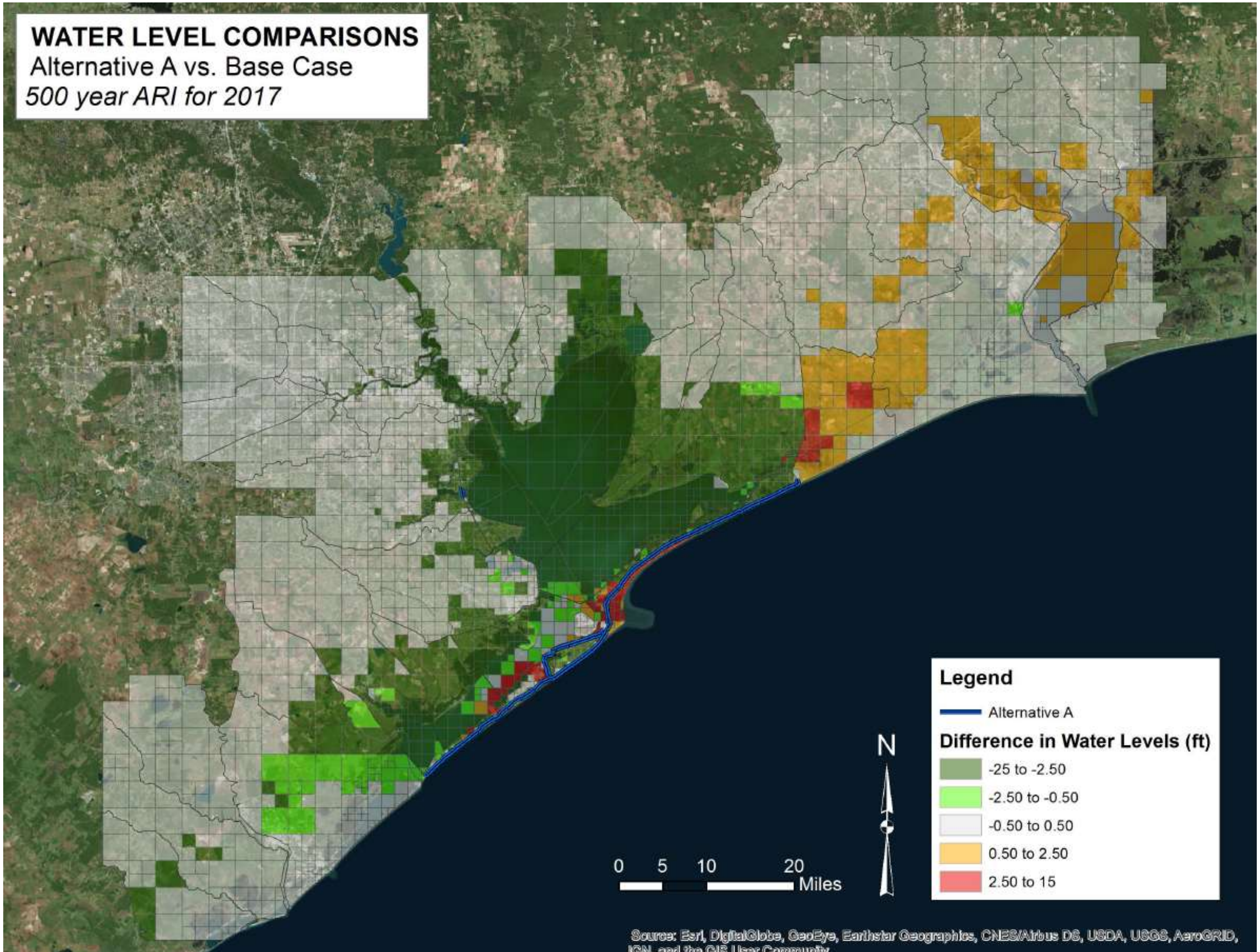


Difference (Alt D2 – Base

Statistical Water Surface



Statistical Water Surface



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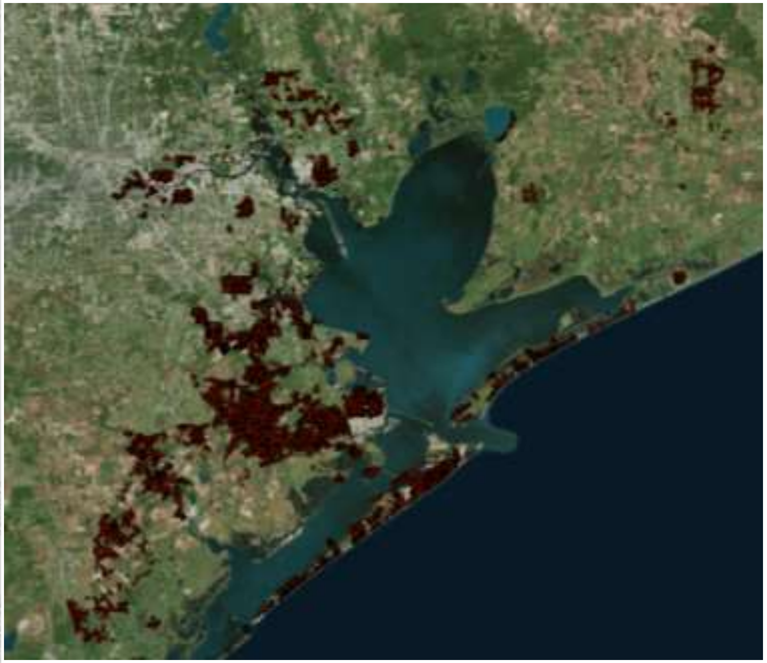
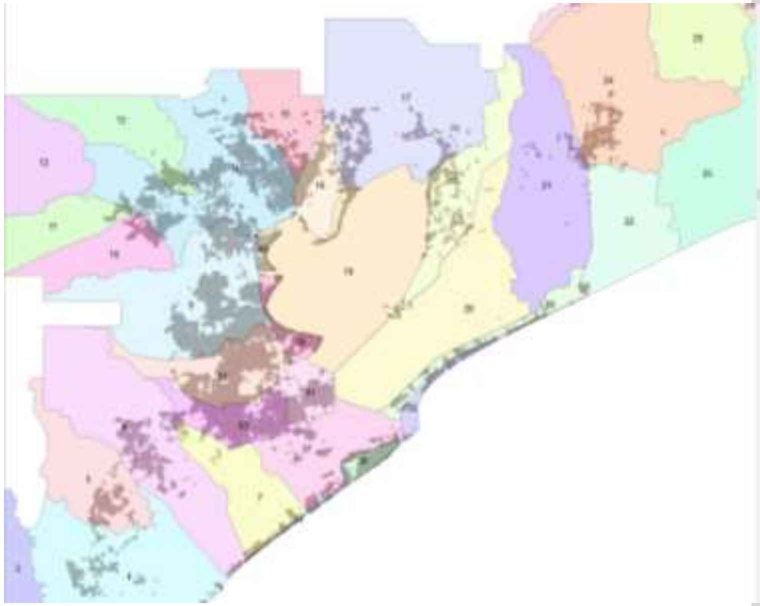
Impact on Water Surface



Row Labels	Count of SID_Rch
1	5
2	130
3	2
4	4520
5	2039
6	2849
7	3022
9	58141
10	4072
11	1416
13	3660
14	37013
15	2287
16	6129
17	4328
18	1178
19	1055
20	121
21	206
22	196
24	1195
25	1
30	10
34	1805
35	2208
36	14703
37	4264
38	1072
39	6867
40	2879
81	14831
82	19992
83	12387



Structure Inventory

Total 214,583

HEC-FDA Reaches

Significant Reaches:

Reach 9 : 58,141

Reach 14: 37,013

Reach 36: 14,703

Reach 39: 6,867

Reach 8 (81, 82, 83) : 47,000

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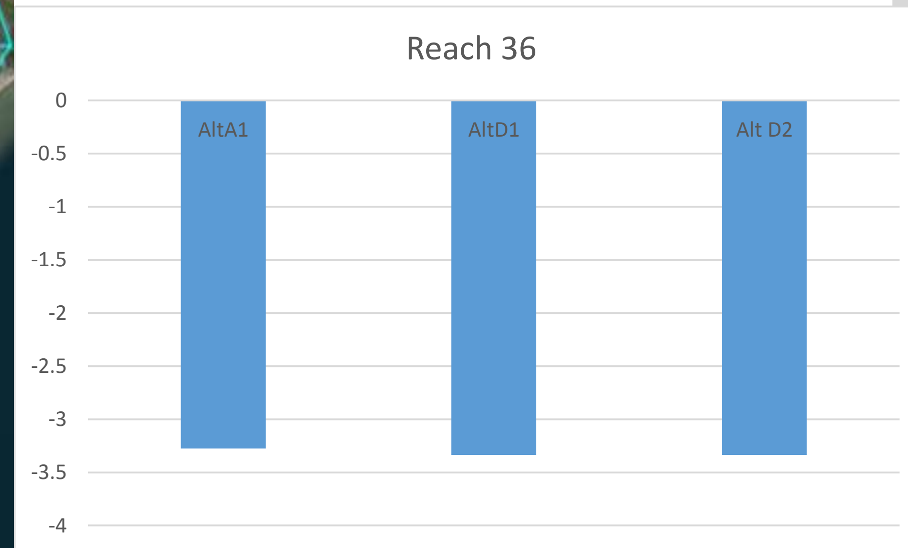
Impact on Water Surface

Reach 36 (Ring Levee)



Aggregate Reduction of surge in a reach

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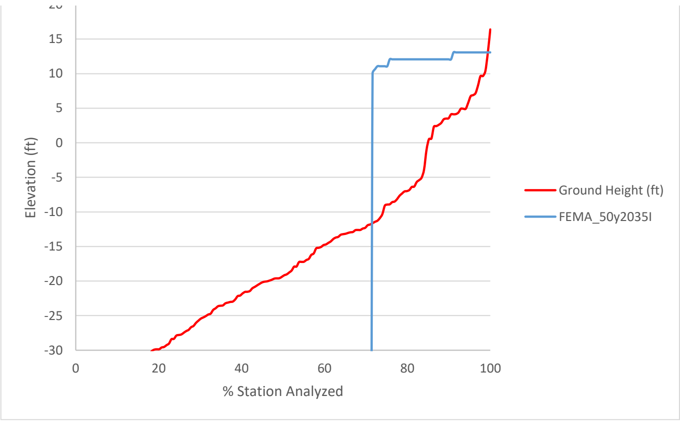
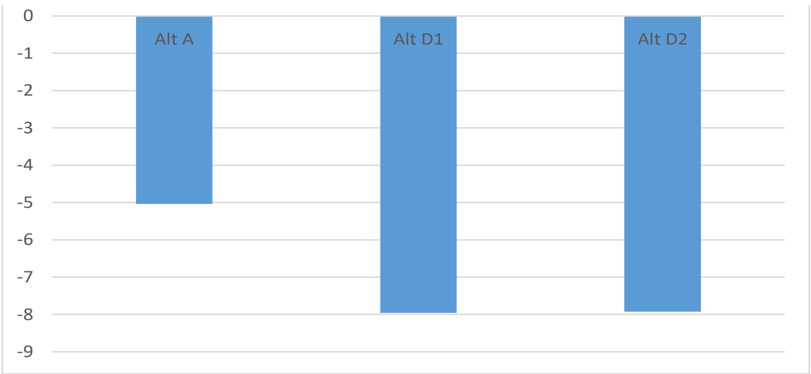
Impact on Water Surface

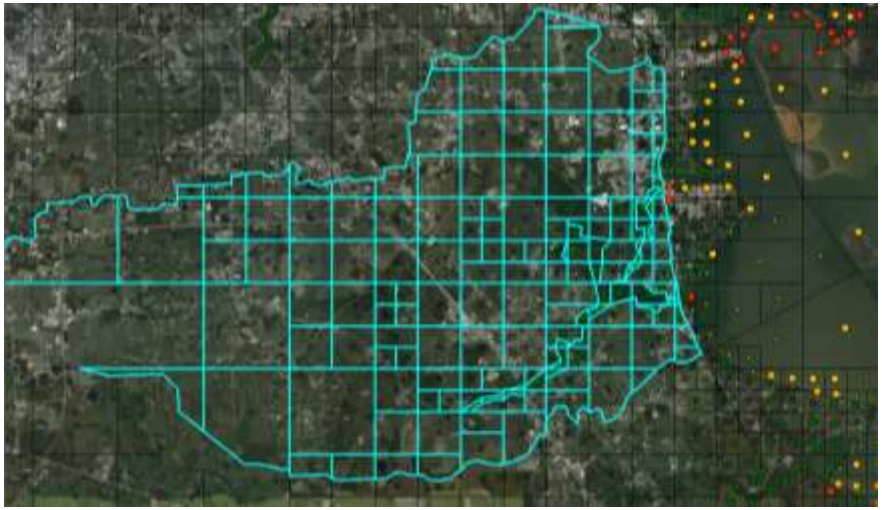
Reach 9 (Webster, Space Center)



Avg Reduction in WL (50 yr, 2035 I)



No of Structure
58,141



WL Difference (Alt D2)

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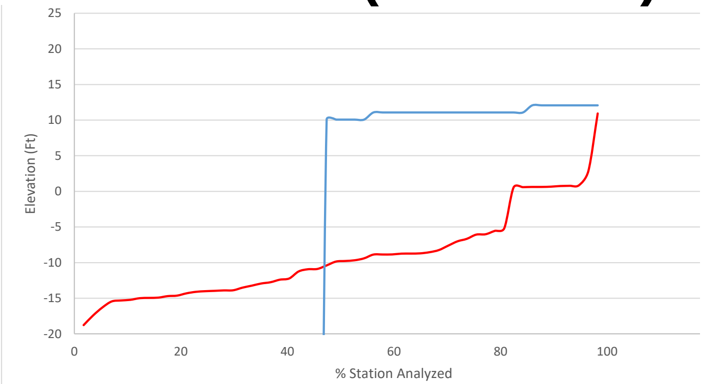
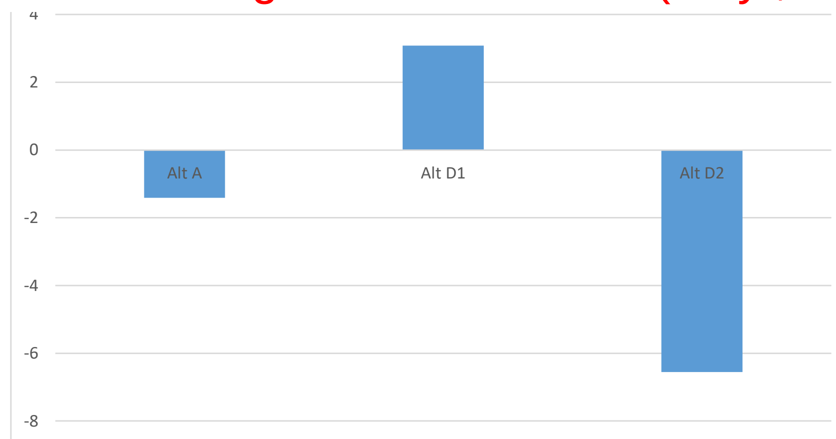
Impact on Water Surface

Reach 39 (SeaBrook)



Avg Reduction in WL (50 yr, 2035 I)



No of Structure: 6,867

Notice: Expected inducement due to D1)

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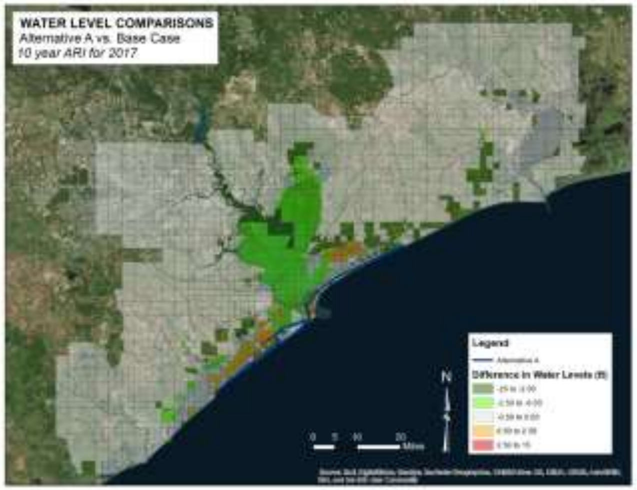
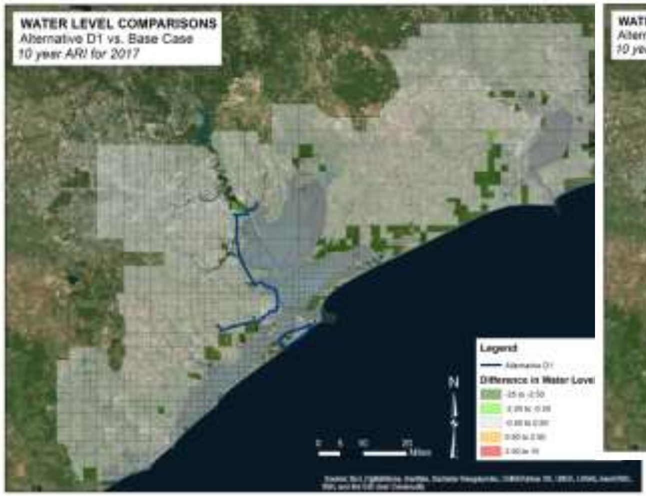
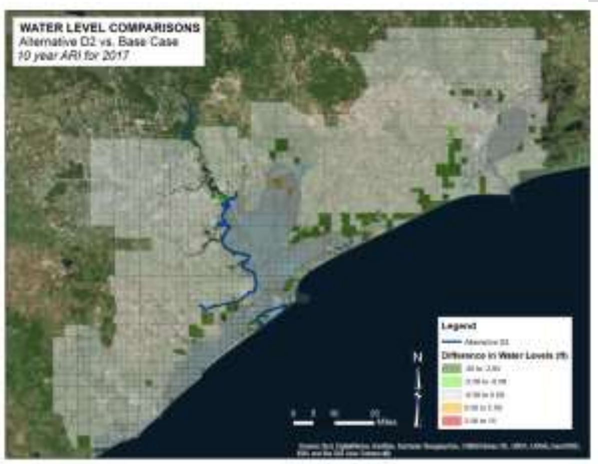
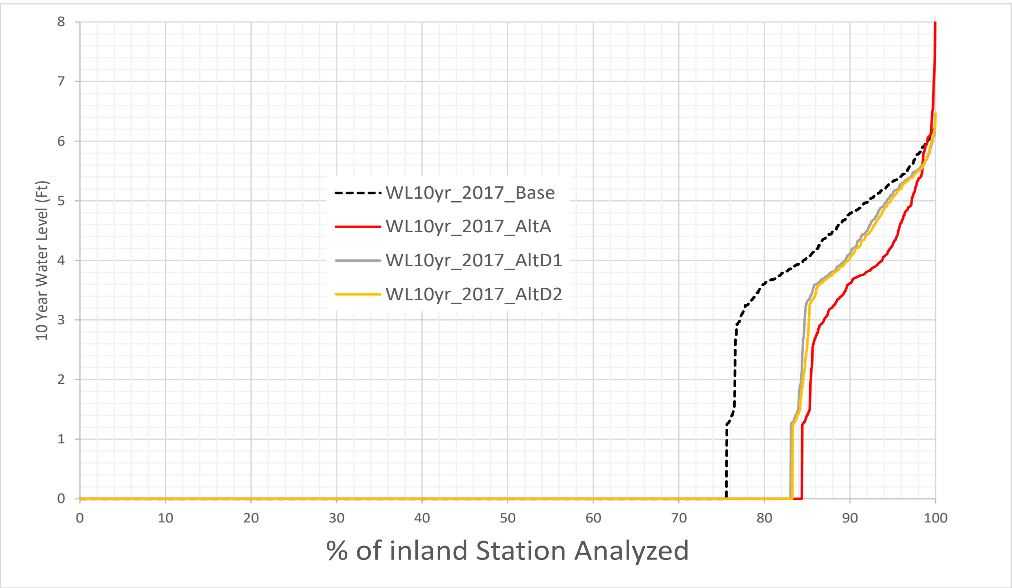
Impact on Water Surface (Area)









<u>Frequent Events</u>
<u>(10 to 50 years)</u>

No noticeable benefits

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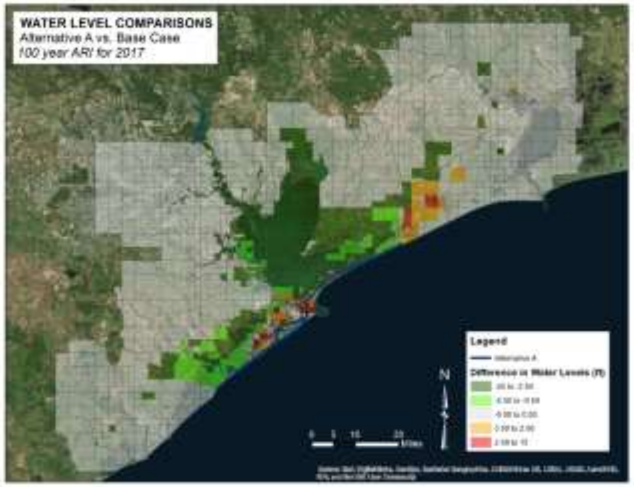
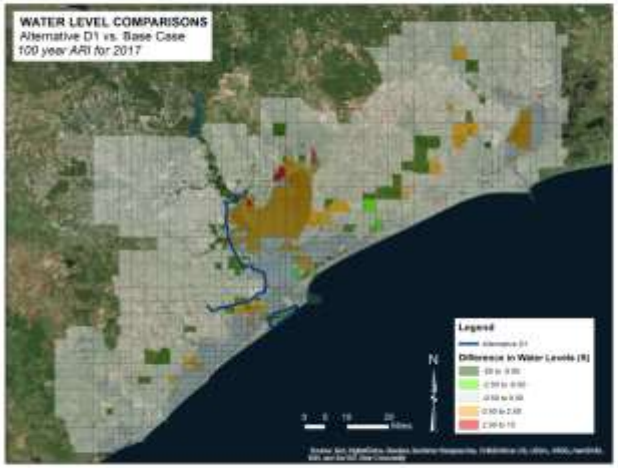
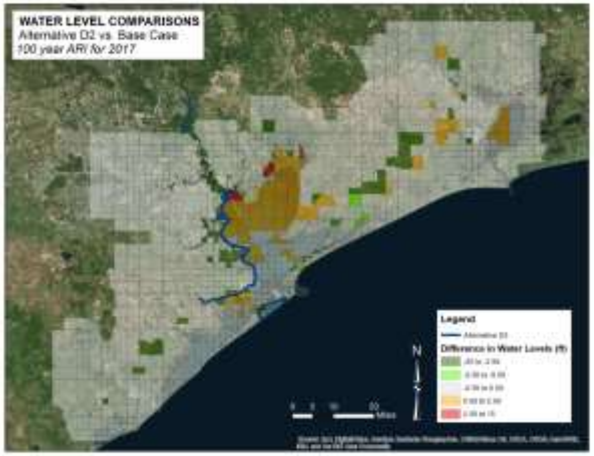
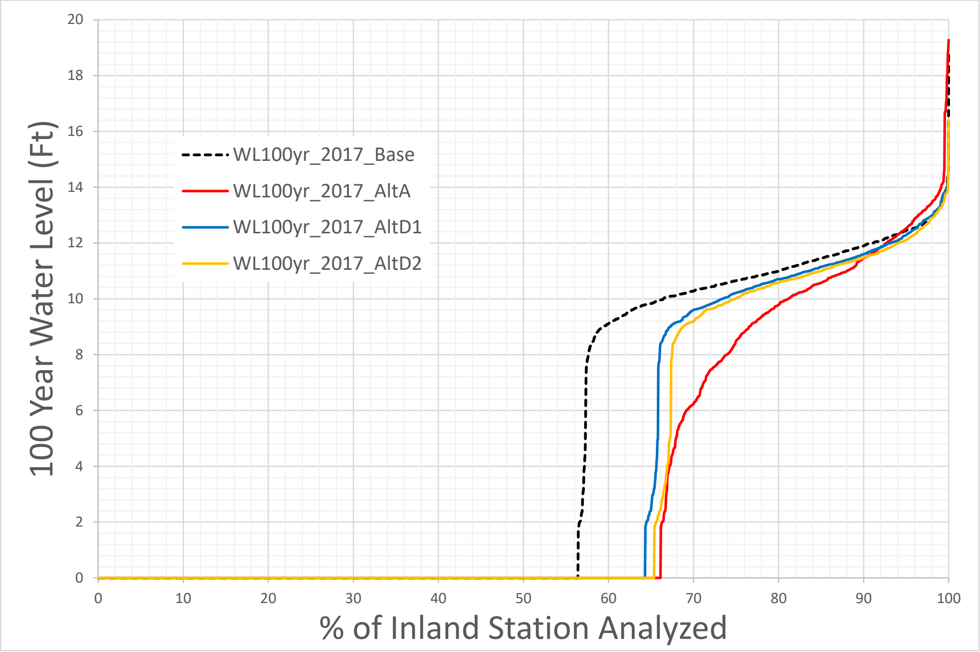
Impact on Water Surface (Area)









Return Period : 100 Year

Noticeable benefits
At 100 year level

~Additional stations are fully
protected by Both A, D1 and D2

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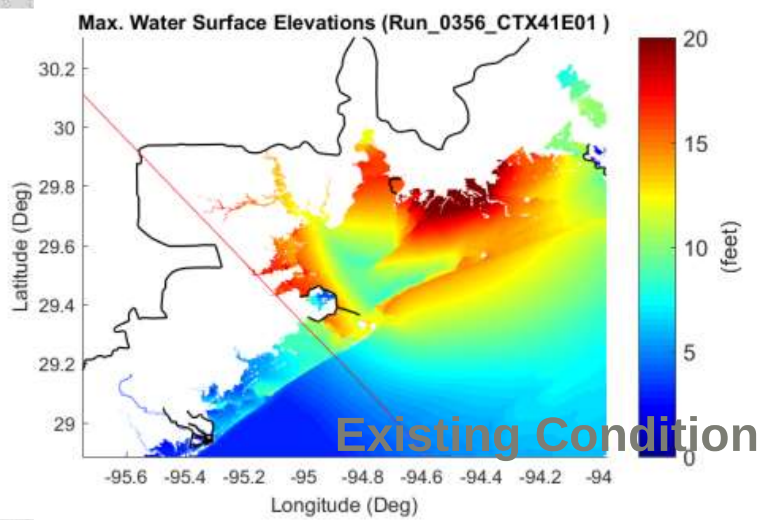
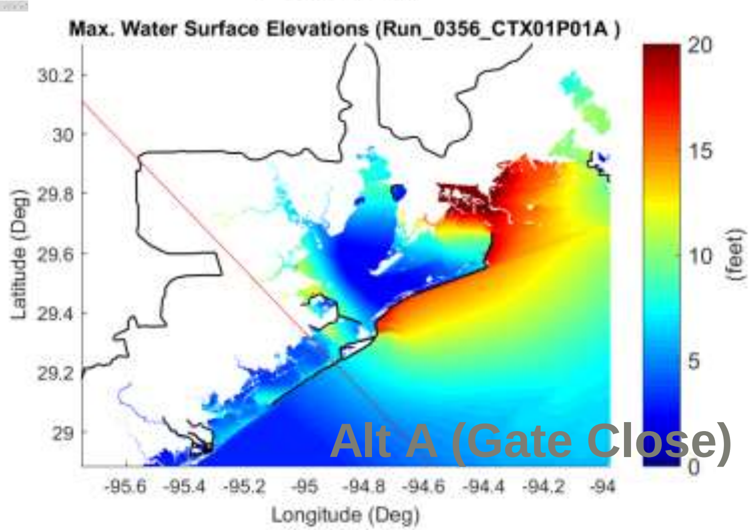
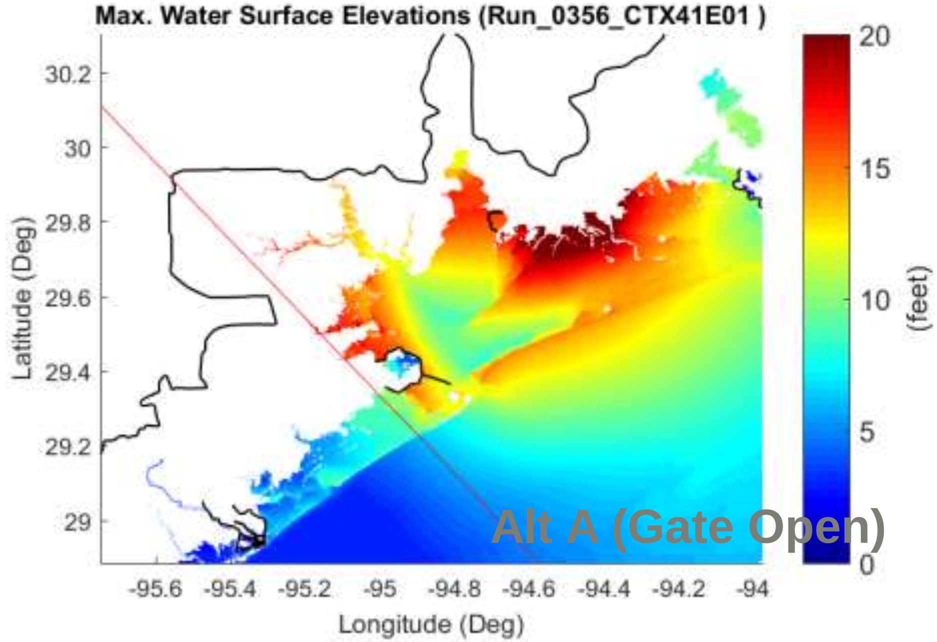
Discussion on Gate Operation





Storm 356 (Cat 4, Westward Track)



West Landfalling tracks have Positive impact on gate closure
As closing gate will leave surge out of the bay.

Closing gates in such scenario is beneficial relieving stress

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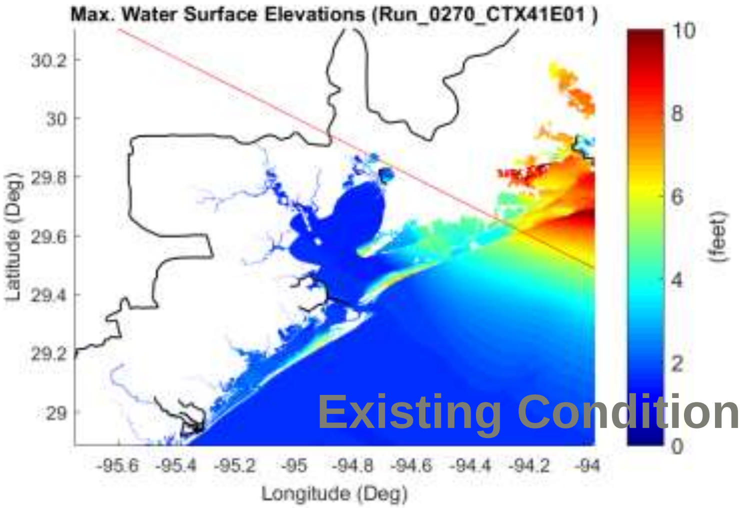
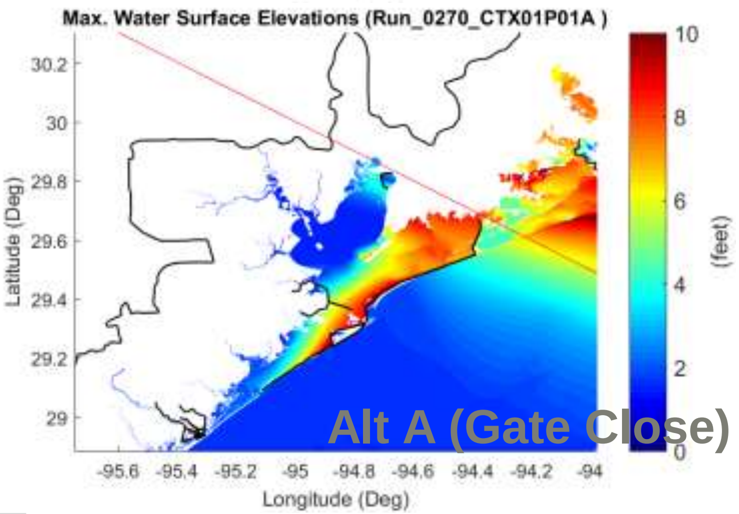
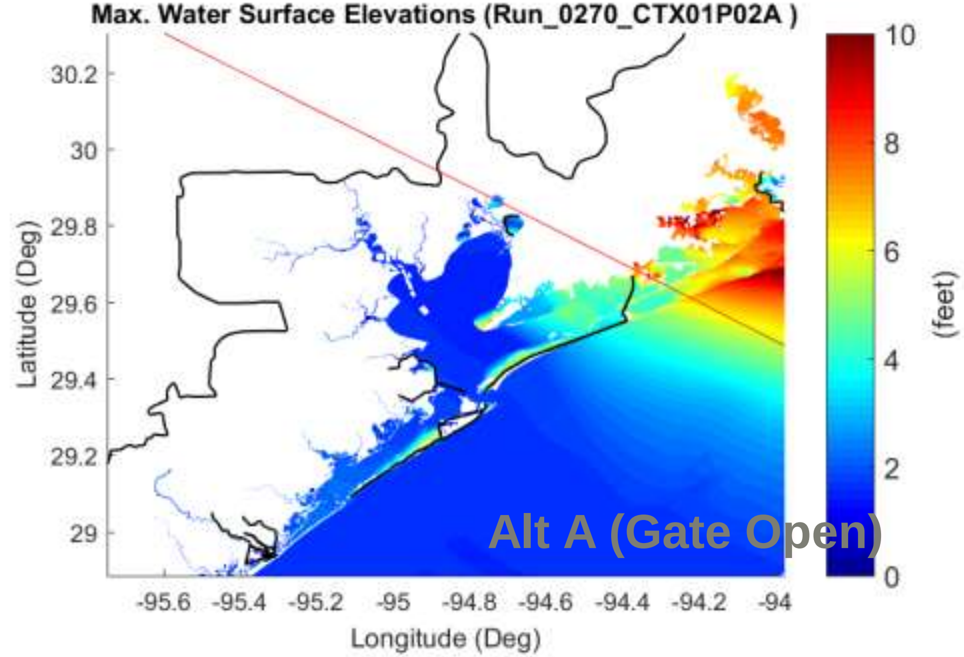
* Wind and hydrodynamic circulation is the key to determine gate closure/opening scenario

Discussion on Gate Operation

Storm 270 (Cat 4, Eastward Track)







East Landfalling tracks have adverse impact o
As internal/back bay surge have resonance cre
Stress on the back side of the levee.

Opening gates in such scenario is beneficial rel

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Coastal Storm Risk Management and Ecosystem Restoration Projects along the Texas Coast

Environmental Impact
(Tide, Salinity, & Velocity)

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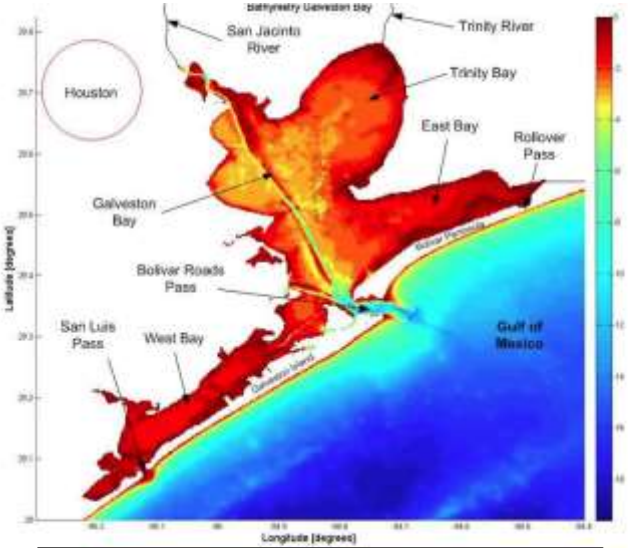
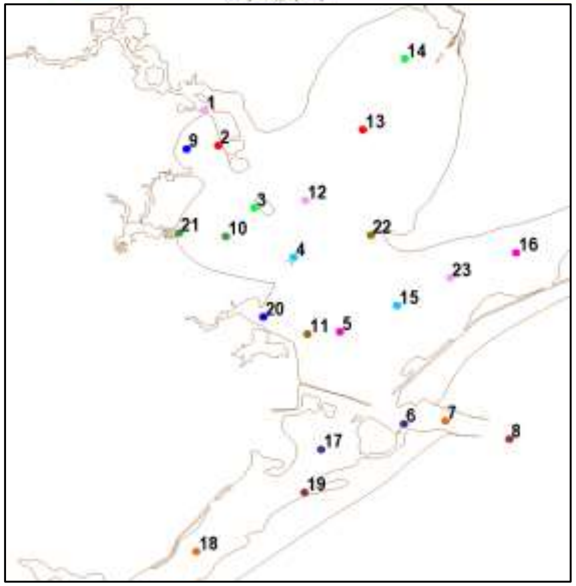
OVERVIEW



Broader picture of the hydrodynamics Within the bay system (Forcing, Response)



Closer look at different regions, points (Salinity, velocity, retention time)

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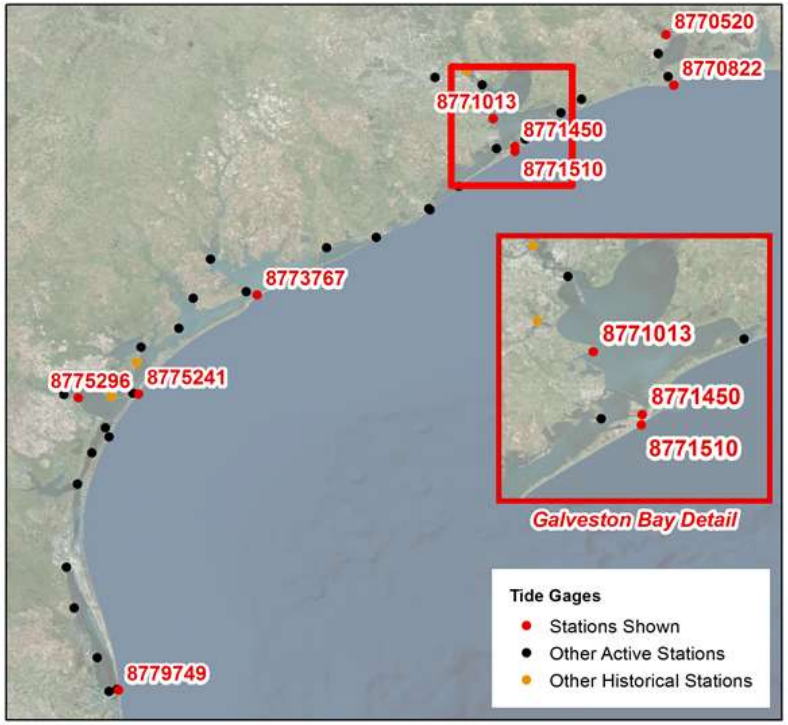
TIDE AND CURRENT (DATA)

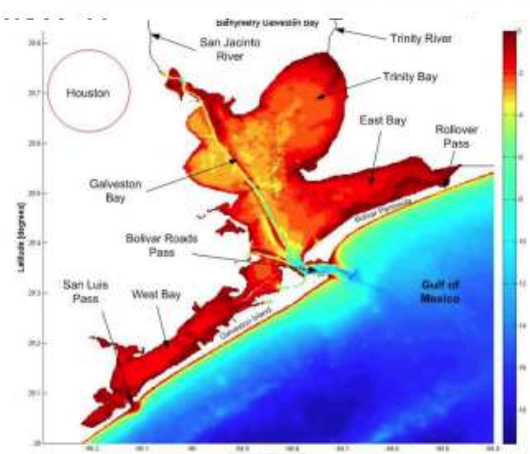


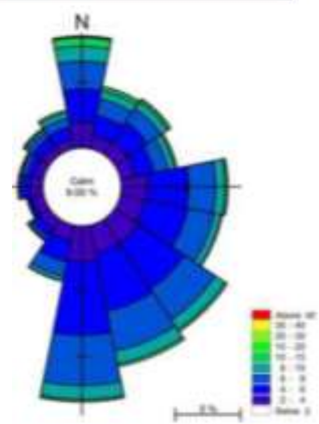
Gage Name	Gage Number	Range [ft]
Rainbow Bridge	8770520	1.06
Texas Point, Sabine Pass	8770822	1.96
Eagle Point	8771013	1.10
Galveston Pleasure Pier	8771510	2.04
Galveston Pier 21	8771450	1.41
Matagorda Bay Entrance Channel	8773767	1.23
Aransas Pass	8775241	1.36
USS Lexington	8775296	0.59
South Padre Island, Brazos Santiago	8779749	1.43

Tide Range : 1 -2 ft
Tidal Range decays progressively into the bay system

Tide Period (Diurnal dominated) : 24 Hour
Bolivar Inlet constitutes about 80% of tidal exchange (Flux)

Wind-driven currents have a large impact on water-surface elevations in the shallow Texas bays (Predominant south-southeast)





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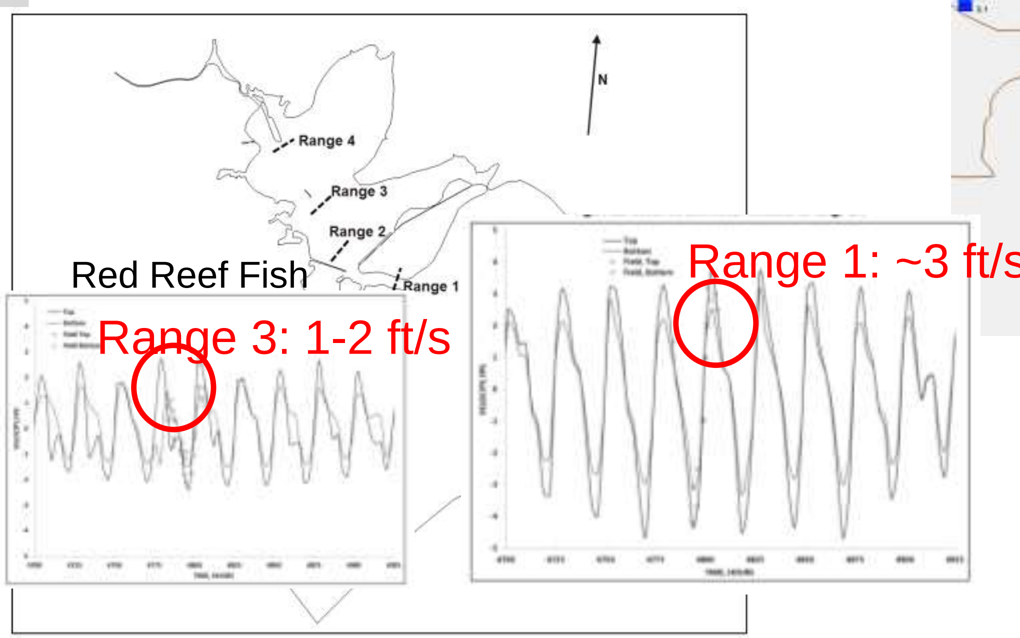
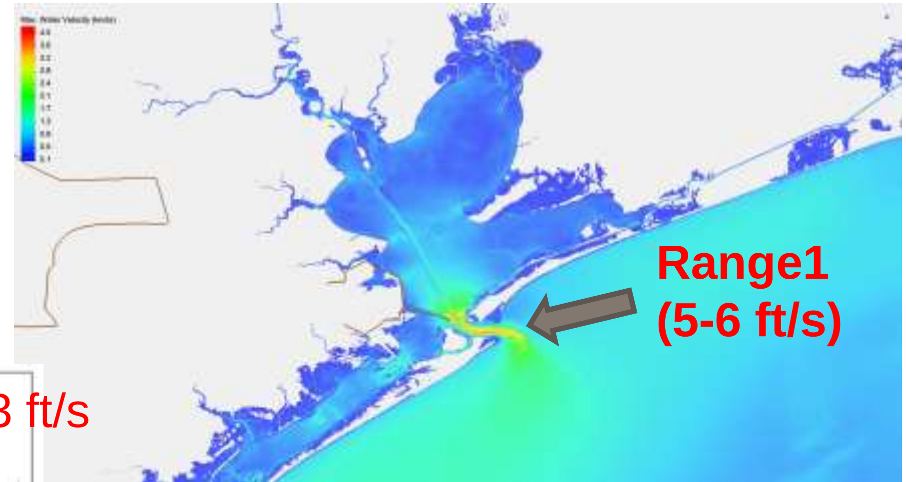
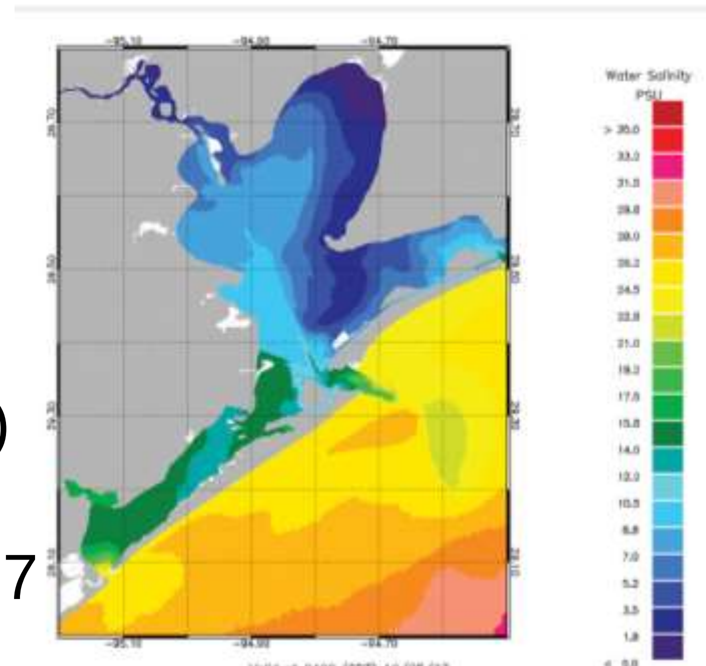
TIDE AND CURRENT (DATA)



Observed Velocity (May 2011)



Simulated Velocity (Harvey, 2017)



Harvey (Aug 29)
Bay Salinity
October 10, 2017

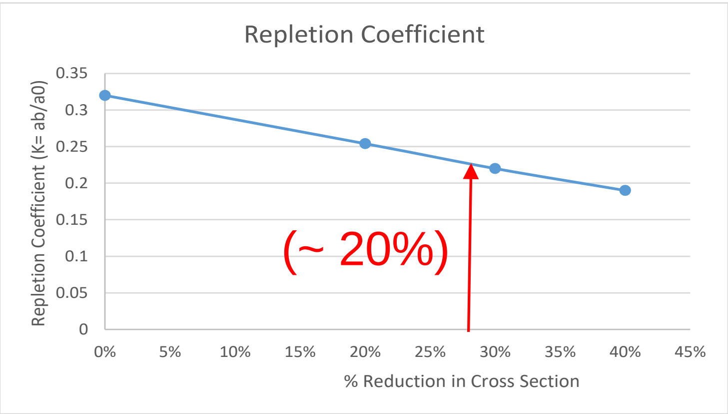
Harvey decimated Galveston Bay's oyster population
-Houston Chronicle, Sept 21, 2017

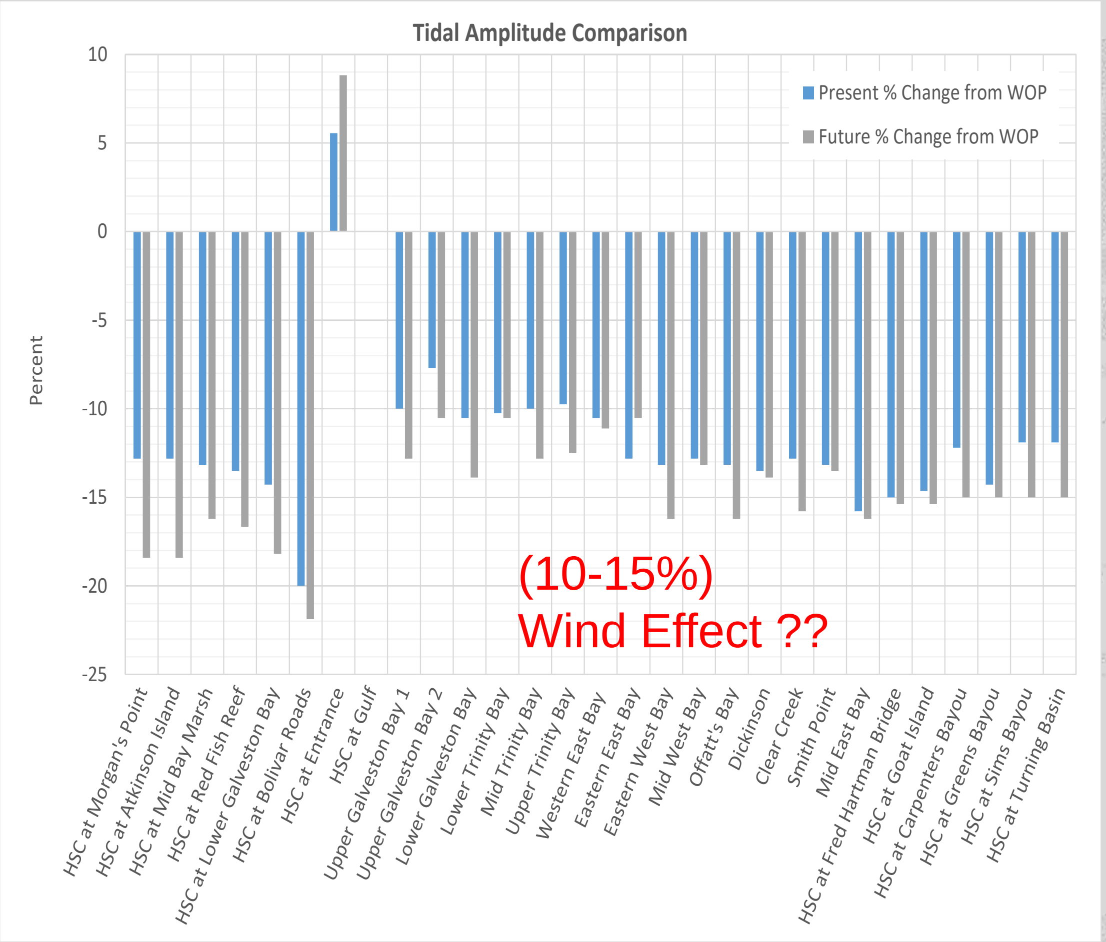
TIDAL AMPLITUDE REDUCTION (VISION/METHOD)

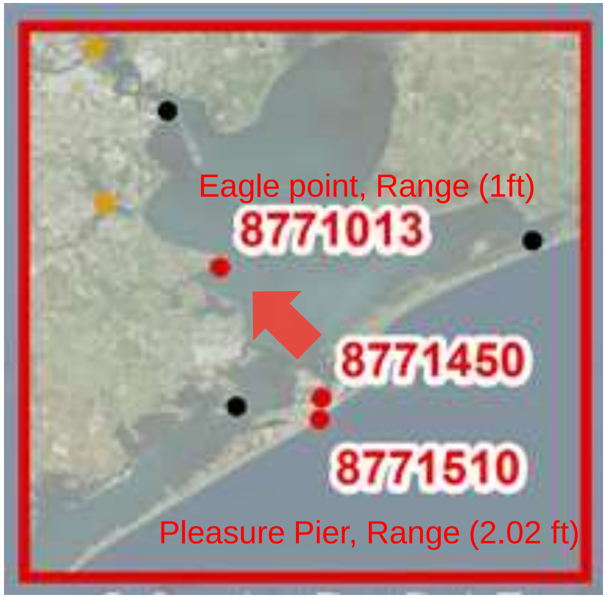
Repletion Coefficient = A_b/A_0)

Tidal Hydraulics (Keulegan Method):

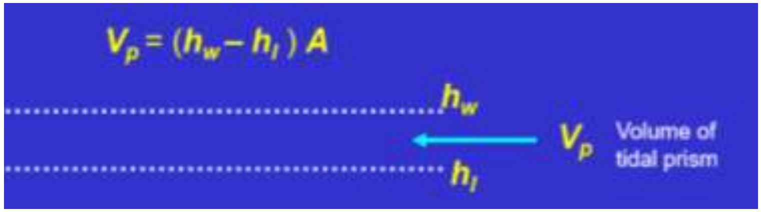
$$K = \frac{A_C}{\sigma a_0 A_B} \frac{\sqrt{2ga_0}}{\sqrt{K_e + K_o + \frac{fL}{4R_h}}}$$







Tidal Prism (Vision)



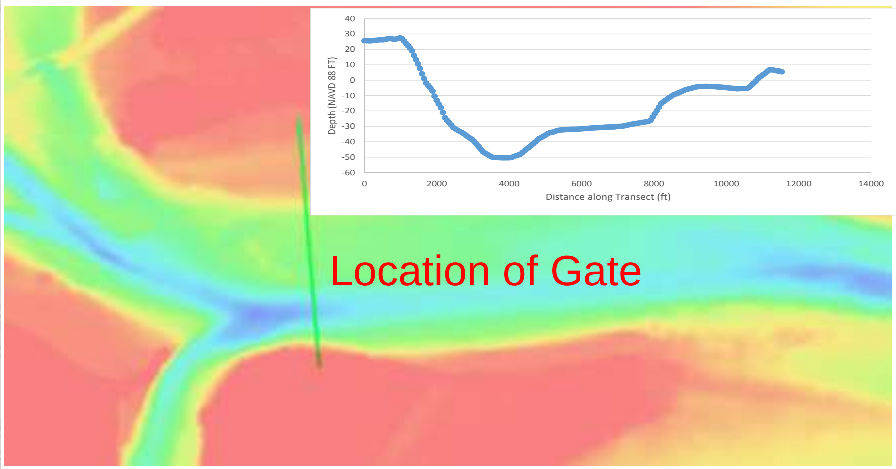
<u>Galveston Bay Characteristics:</u>

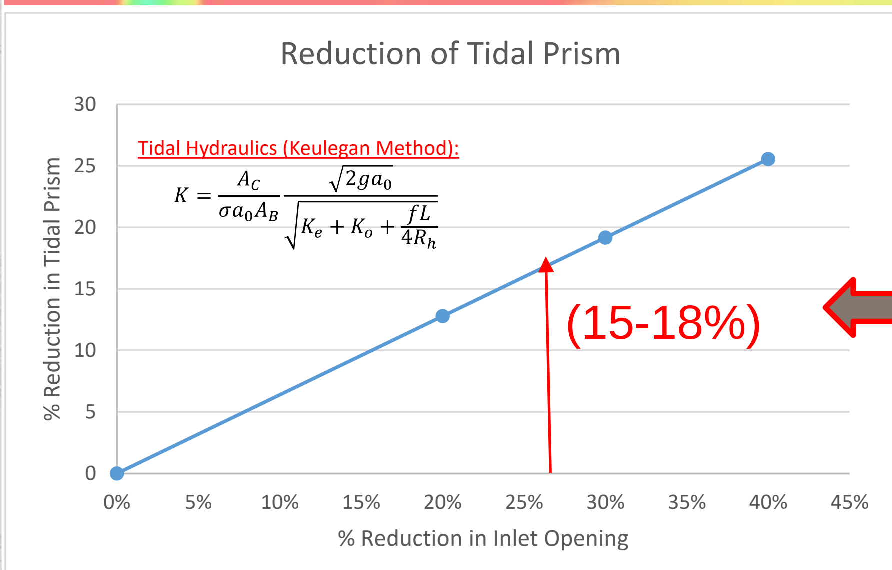
Surface Area of Galveston Bay: 600 sq. mile

Avg Depth of Bay : 8 Ft

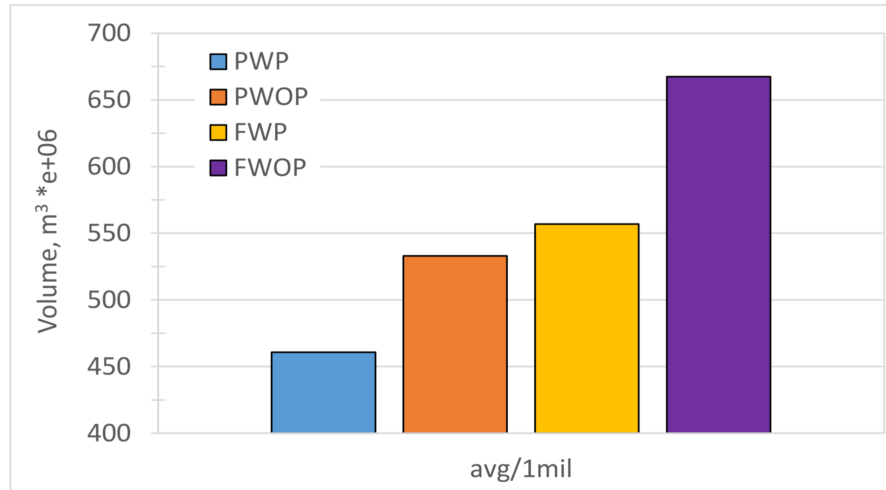
Tide Period (Diurnal dominated) : 24 Hour

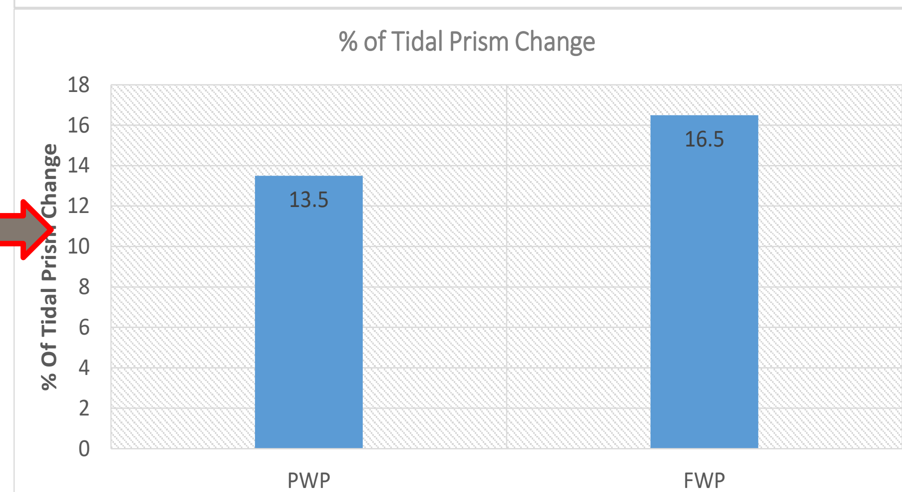
Bolivar Inlet constitutes about 80% of tidal exchange (Flux)





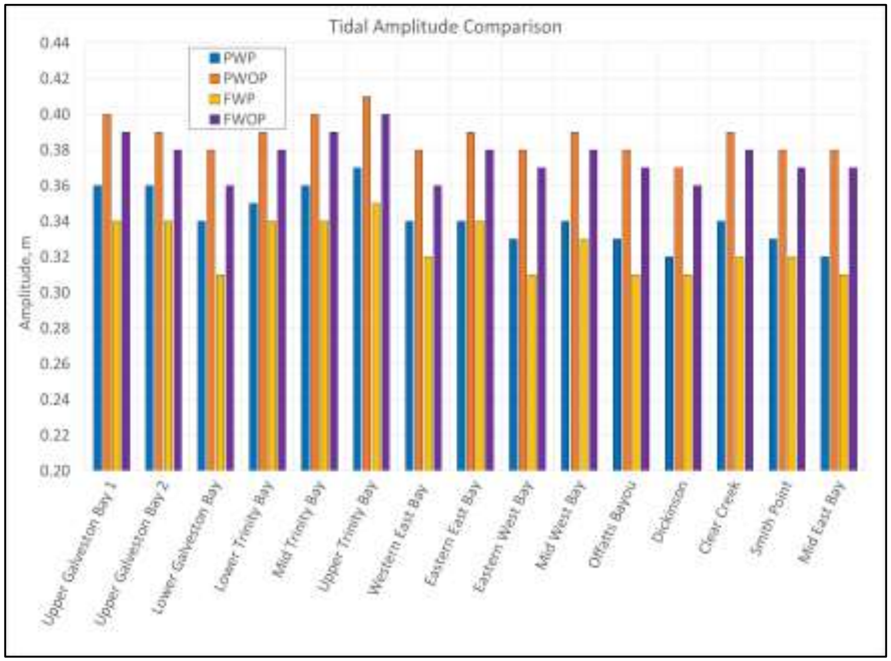
Tidal Prism (ADH Model)





Tidal Prism & Amplitude

Amplitude Reduction (10-15%)



Tidal Prism Reduction (~15%)

	PWP (m^3)	PWOP (m^3)	PWP % change from PWOP	FWP (m^3)	FWOP (m^3)	FWP % change from FWOP
Bolivar Roads	460,814,707	532,995,012	-13.5	556,945,721	667,353,415	-16.5
Offatts Bayou	1,067,941	1,265,050	-15.6	1,006,517	1,199,537	-16.1
Dickinson Bayou	490,992	571,414	-14.1	454,839	542,866	-16.2
Clear Creek	3,044,955	3,544,931	-14.1	2,792,991	3,326,102	-16.0

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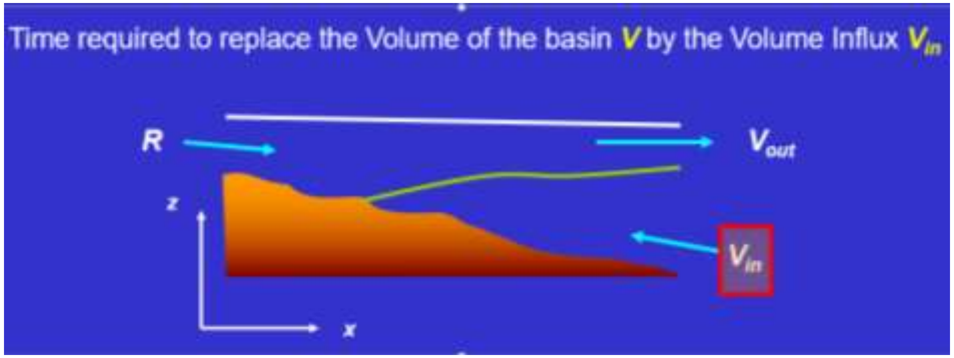
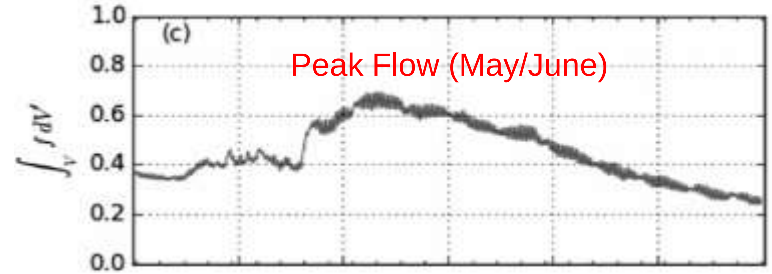
BAY FLUSHING TIME (VISION)

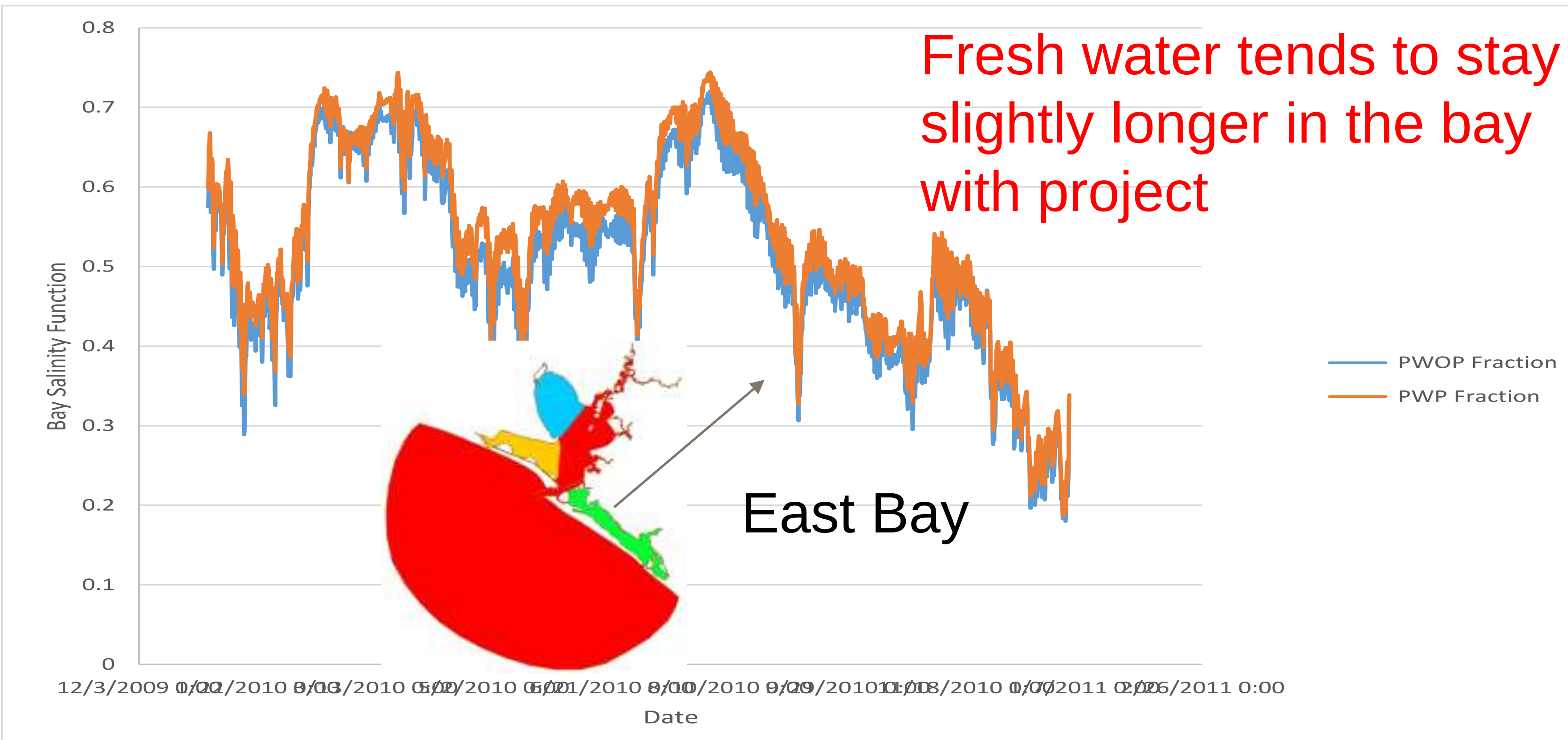
Bay Salinity Function f (f=1 fresh)

$$f = \frac{\sigma - S}{\sigma}$$

$$\tau_f = \frac{\int_V f dV}{Q_r}$$

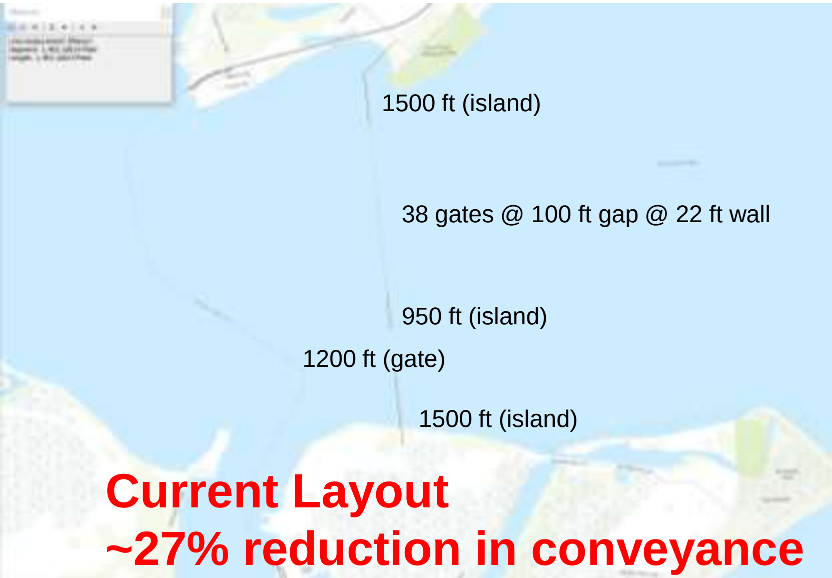


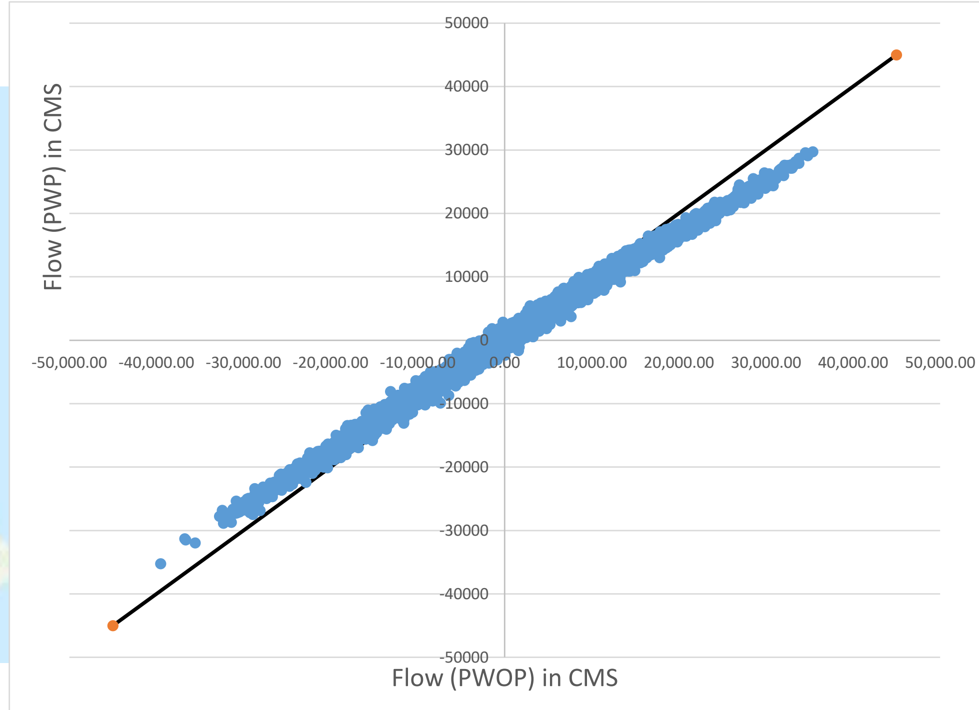


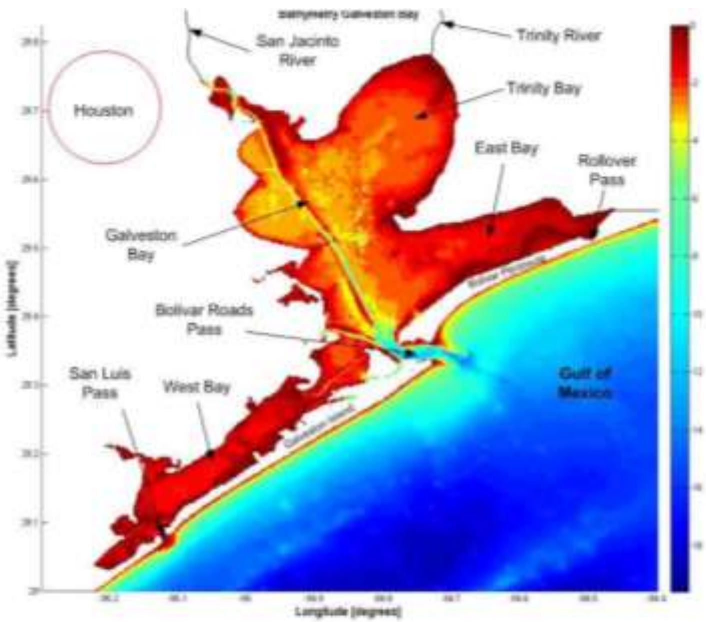


Fresh water tends to stay slightly longer in the bay with project

Overall Observation







Flood and Ebb Flow should be close to 45 degree line

Water tends to stay longer into the Bay system
With project (Fresher Bay)

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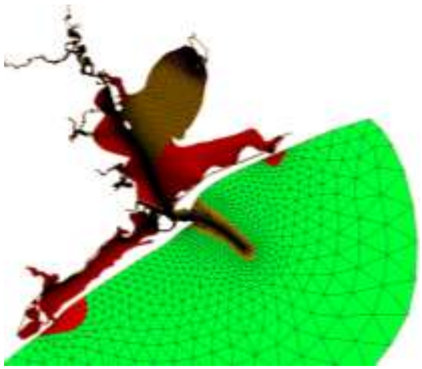
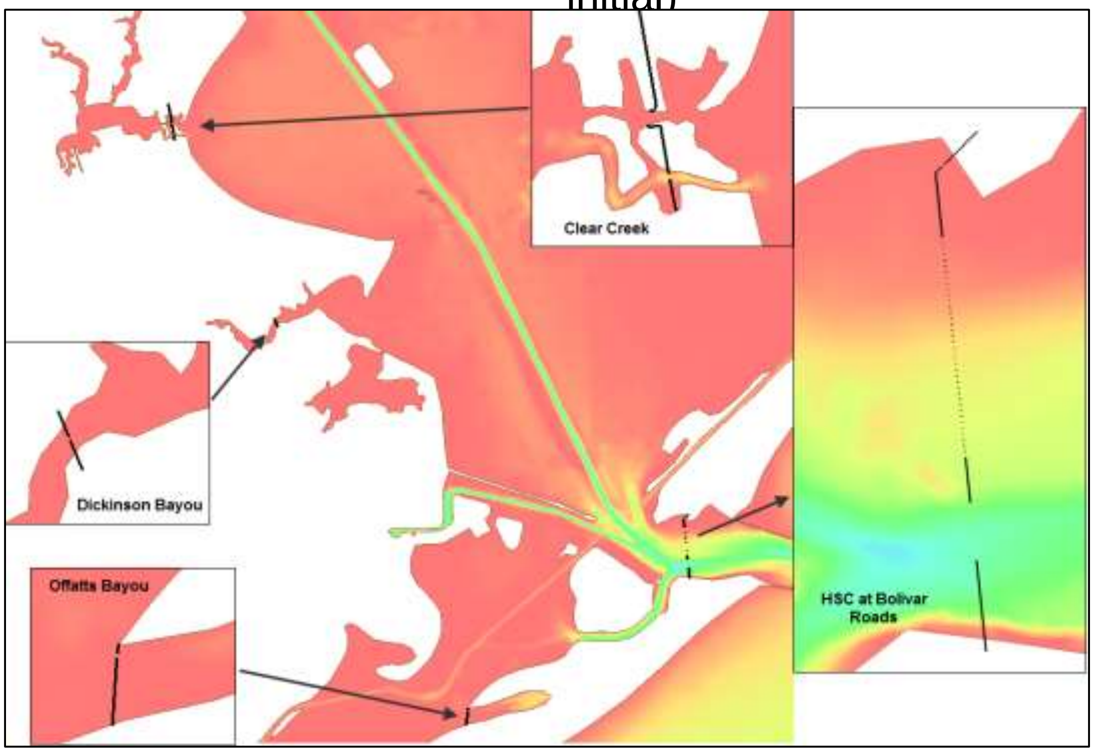
3D ADH MODEL



3D stats:
902,807 elements
197,473 nodes

Intermediate Sea Level Rise Condition
Present : 2035 (+0.5 ft)
Future : 2085 (+2.14 ft)
2 Year Simulation (1 yr initial)



The structures at Clear Creek, Dickinson Bayou, and Offatts Bayou consist of a single opening 112 feet wide with varying sill elevations: Clear Creek sill elevation -10 ft, Dickinson Bayou sill elevation -9 ft, and Offatts Bayou sill elevation -15 ft.

The structure for the HSC at Bolivar Roads includes a single 1200 ft wide, -60 ft sill elevation navigation gate at the ship channel with 39, 100 ft environmental gates (22 having a -30 ft sill elevation and 17 having a -15 ft sill elevation). All elevations are referenced to Mean Lower Low Water (MLLW).

Al Gates are OPEN !

Ref: Jennifer McAlpin, Cassandra Ross, and Jared McKnight
2018

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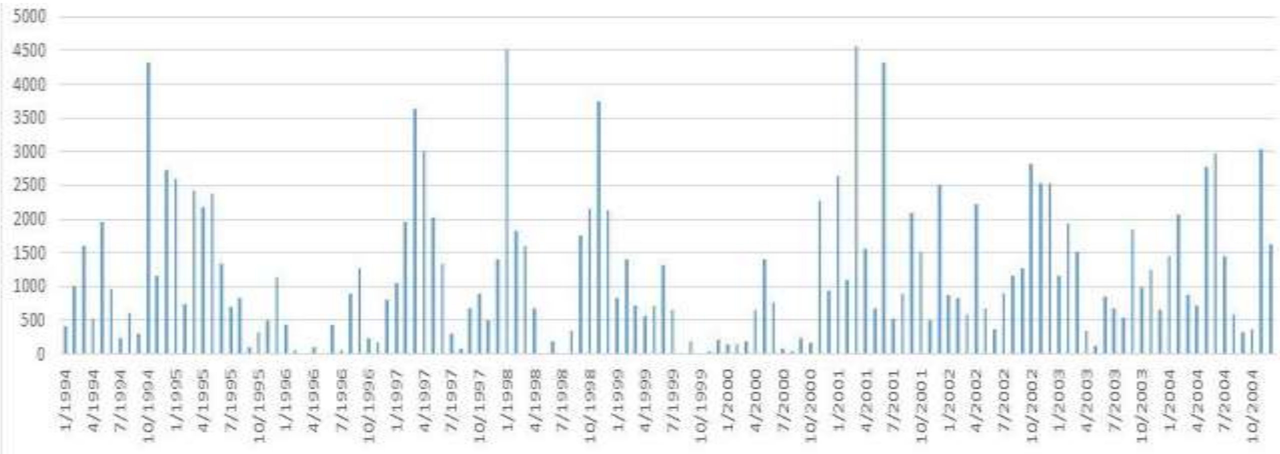
FRESHWATER FLOW (DATA)



#

<u>SOURCE TXWDB:</u>

BASIN 8010: TOTAL ANNUAL SURFACE INFLOW (ACRE-FEET) TO GALVESTON BAY FOR THE PERIOD 1941 –2005.
(MAINLY INCLUDES TRINITY RIVER (66%) AND SAN JACINTO RIVER (19%)

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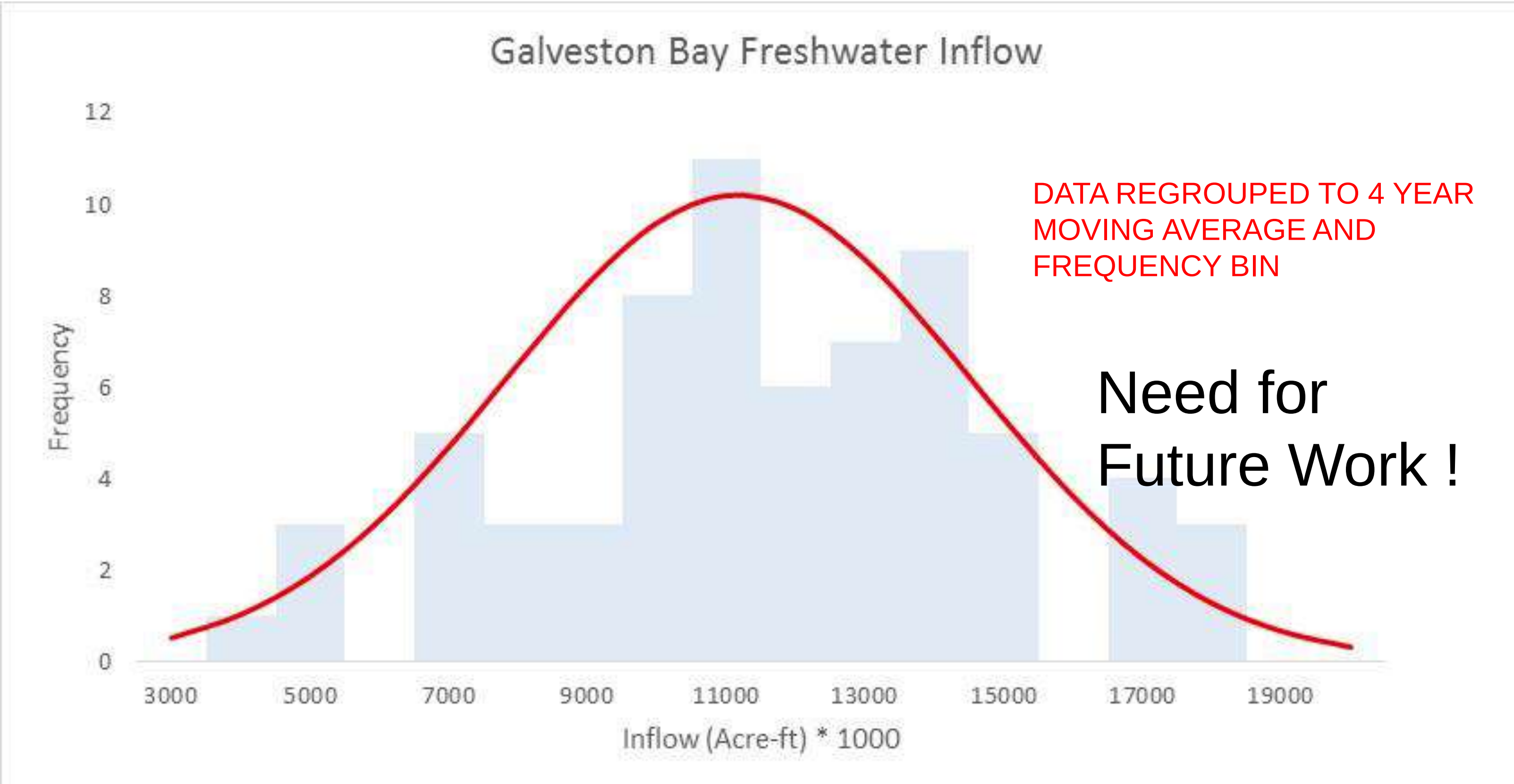
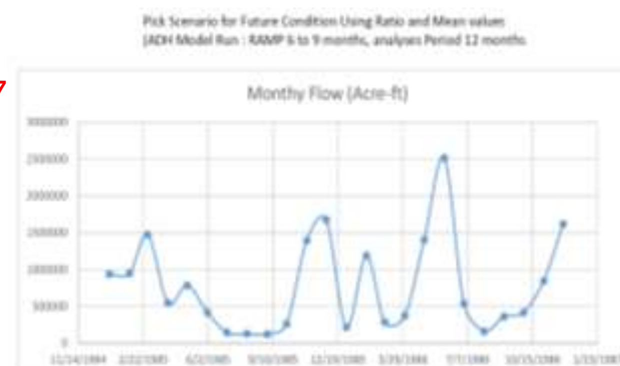
FUTURE FRESHWATER FLOW (VISION)

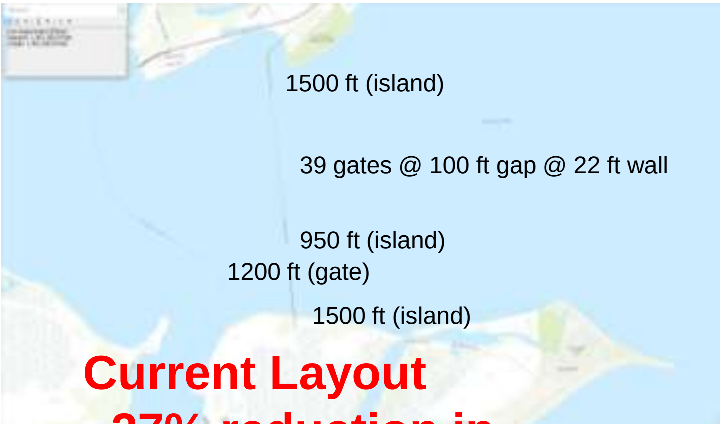


Mean: 9,832 (Avg. Flow Condition)
35% : 8,804 (Dry condition)
75% : 12,042 (Wet Condition)
90% : 14,554 (Max Flow condition)
* Use ratio between future to present Condition ~ 0.8 (Prev. study)

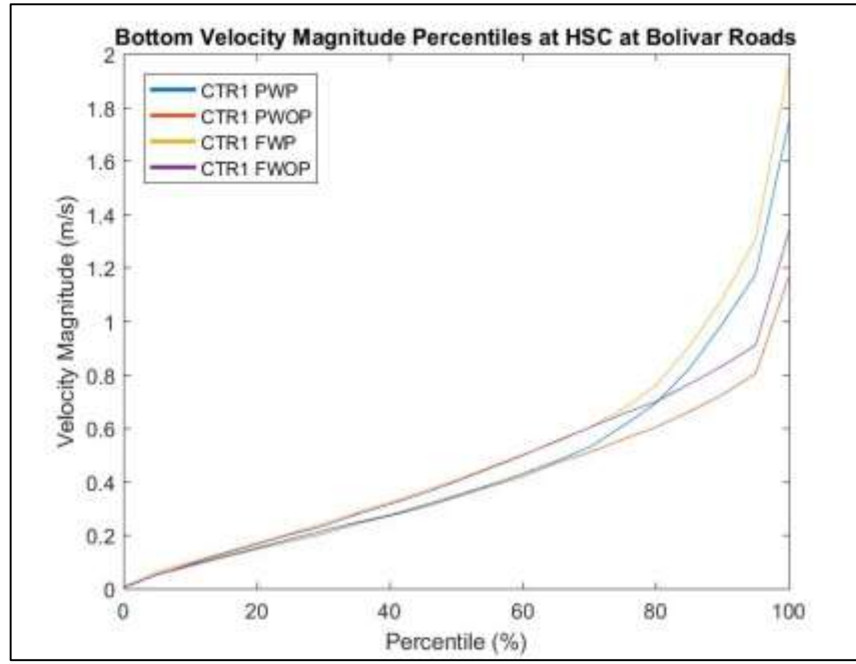
Future to present condition are analyzed and adopted a ratio of 0.7 to 0.9 from a previous study (Matsumuto 2012). The ratio considers long term urban growth and associated reduced flow while precipitation is held constant.



RESULTS (VELOCITY)



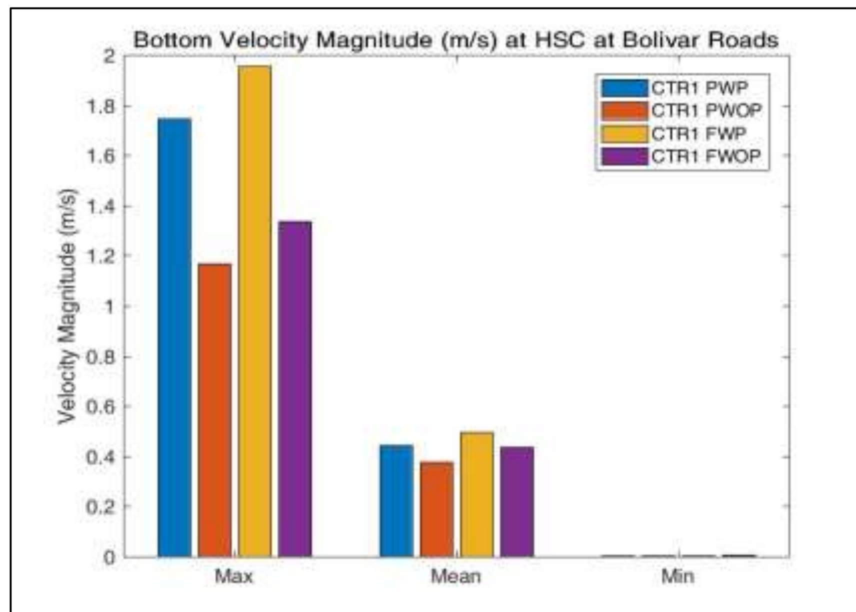
Current Layout
~27% reduction in conveyance



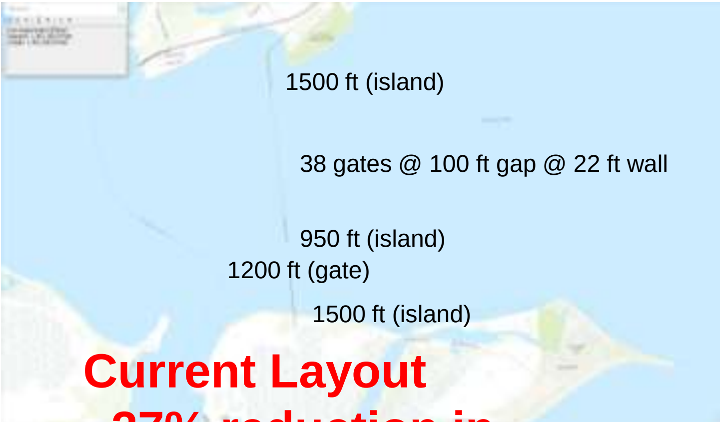
Mean Speed does not change

50% time speed is high with Gate

(Max Speed increase from 3 ft/s to 5 ft/s)



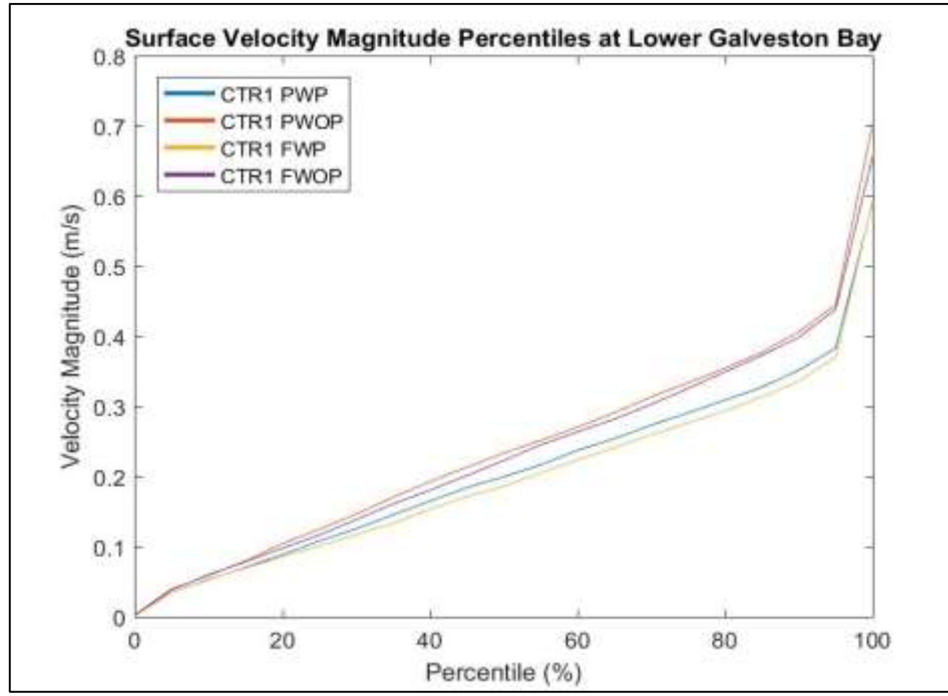
RESULTS (VELOCITY)

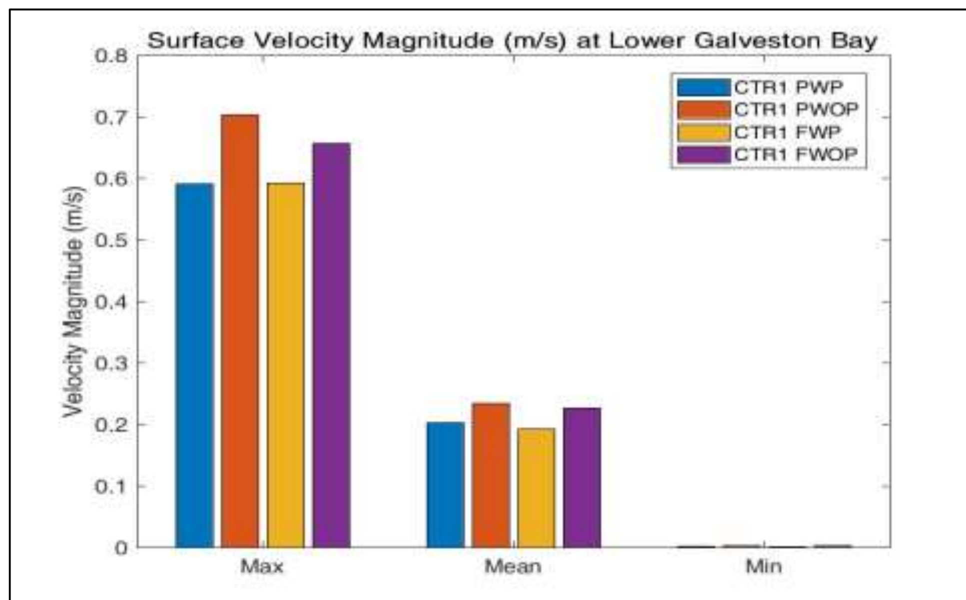


Current Layout
~27% reduction in conveyance

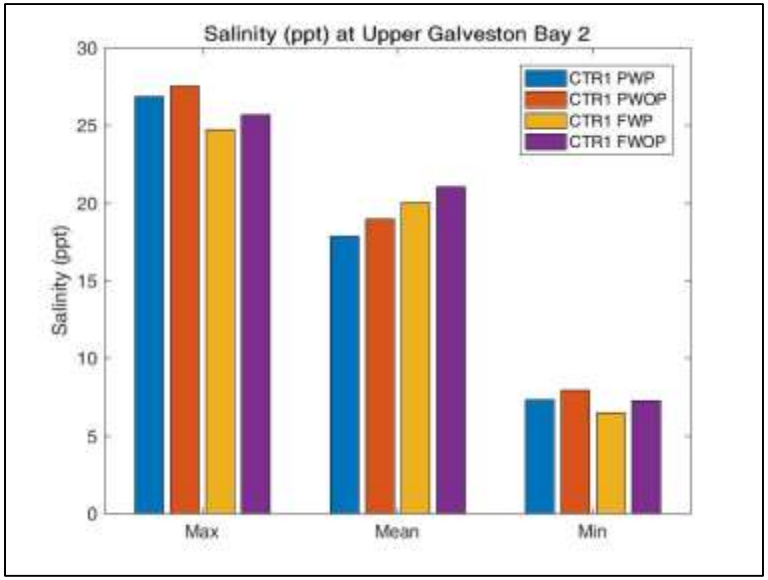
Mean Speed does not change

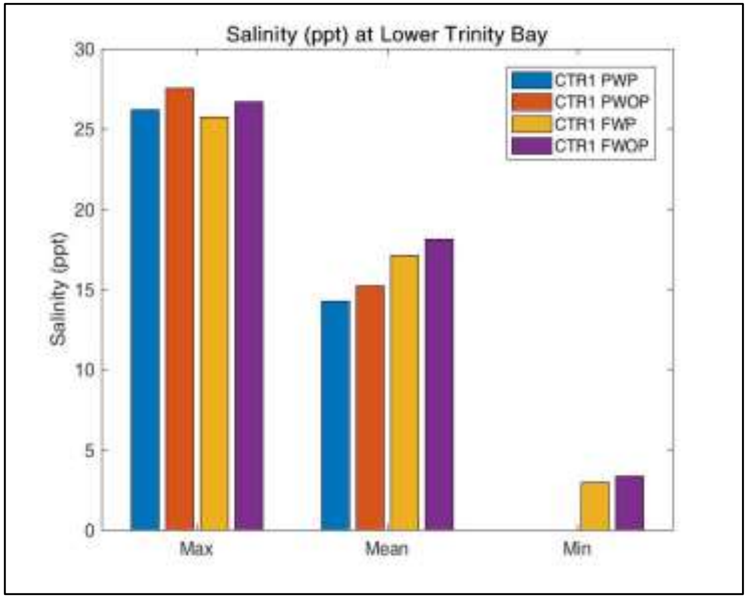
At Bay overall speed decreases with project (Repletion coeff.)

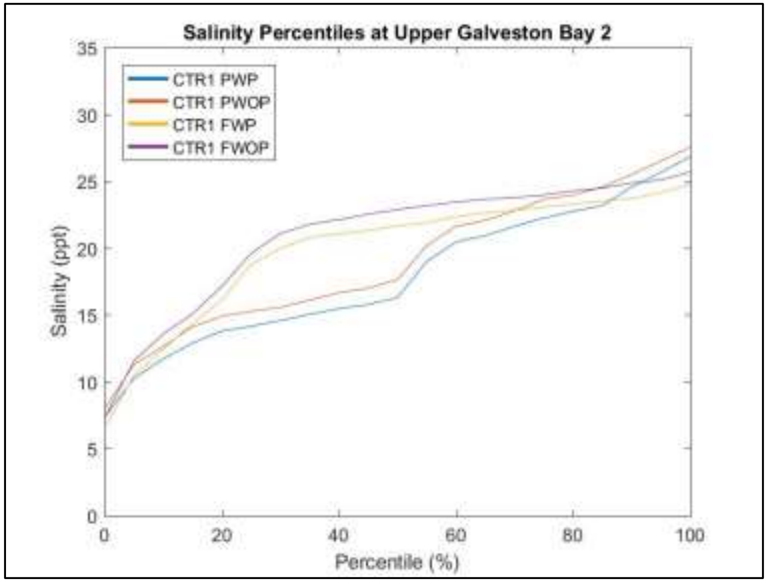




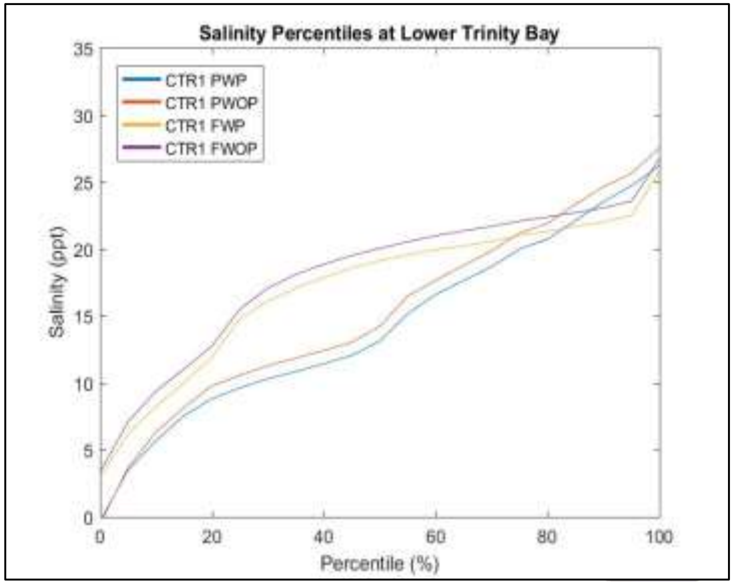
RESULTS (SALINITY)







Water tends to stay longer into the Bay system With project (Fresher Bay)



DETAILED RESULTS (SALINITY & VELOCITY)

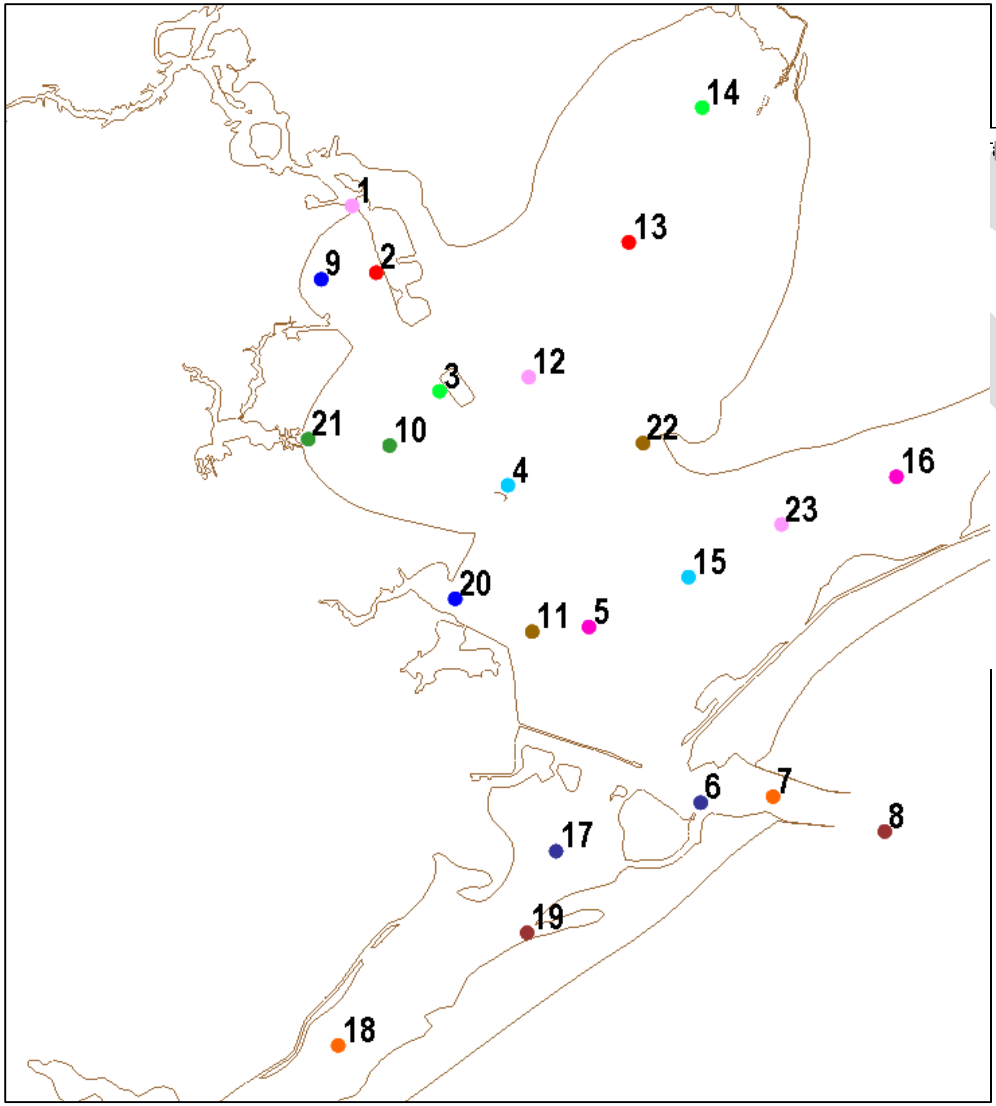


Table 2. Point analysis location names. Highlighted locations discussed in this section.

Point #	Name
1	HSC at Morgan's Point
2	HSC at Atkinson Island
3	HSC at Mid Bay Marsh
4	HSC at Red Fish Reef
5	HSC at Lower Galveston Bay
6	HSC at Bolivar Roads
7	HSC at Entrance
8	HSC at Gulf
9	Upper Galveston Bay 1
10	Upper Galveston Bay 2
11	Lower Galveston Bay
12	Lower Trinity Bay

Point #	Name
13	Mid Trinity Bay
14	Upper Trinity Bay
15	Western East Bay
16	Eastern East Bay
17	Eastern West Bay
18	Mid West Bay
19	Offatts Bayou
20	Dickinson
21	Clear Creek
22	Smith Point
23	Mid East Bay

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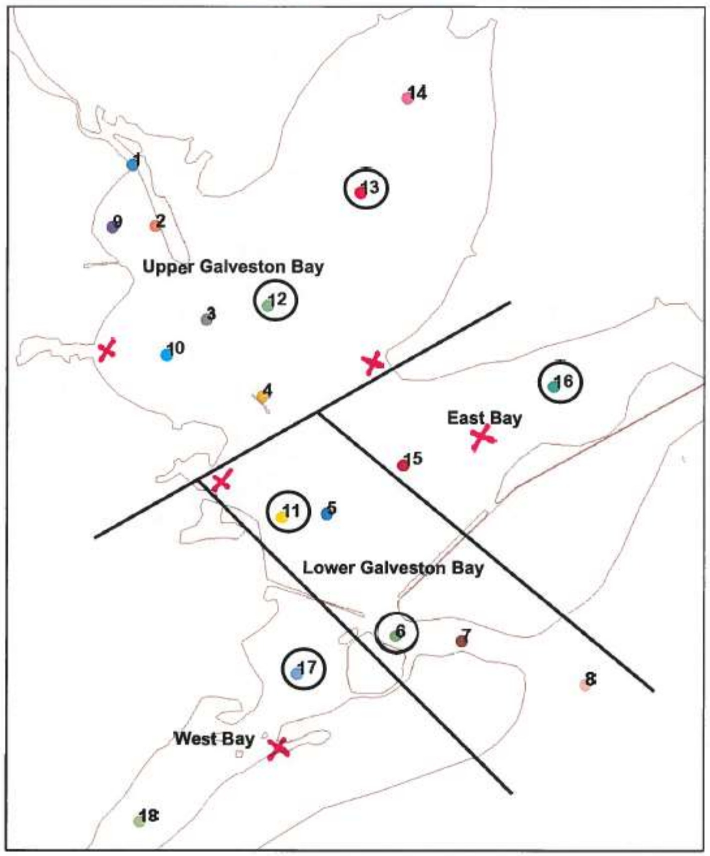
Salinity (Ouster Impact)

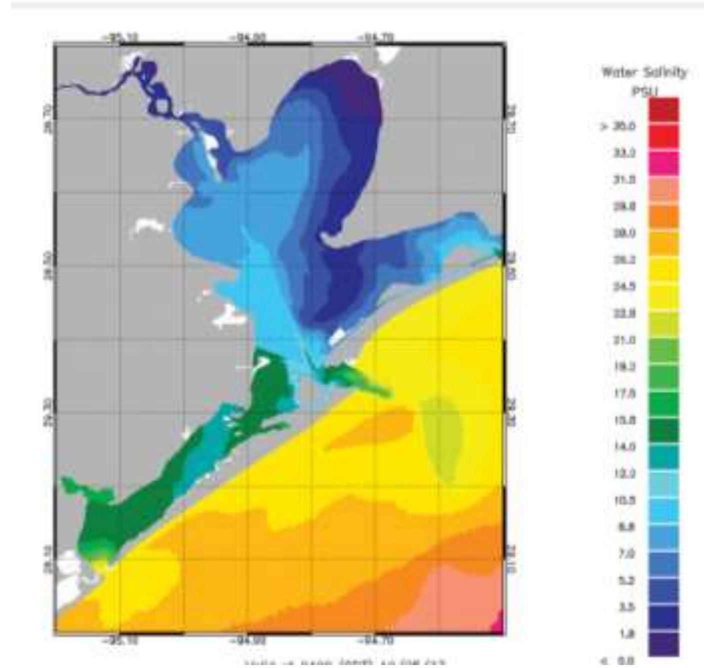
Data Points for Estuarine Modeling

Figure 1. Salinity and Velocity Analysis Points



*Black lines indicate how the bay was divided for presentation of data.

*Circles indicate specific data points that are being further discussed for the agency meeting.



*Time(s) when salinity would be below 5 ppt for 14 or more consecutive days, and time(s) above 30 ppt for 14 or more consecutive days .

* Time(s) when salinity is above 15 ppt (to identify periods when predators could be more abundant)

* Time(s) when salinity is above 101 ppt (to identify periods when Dermo could be activated)

* Summer low flow/high temperature period (July through September2)
*Spawning period (April-September3)

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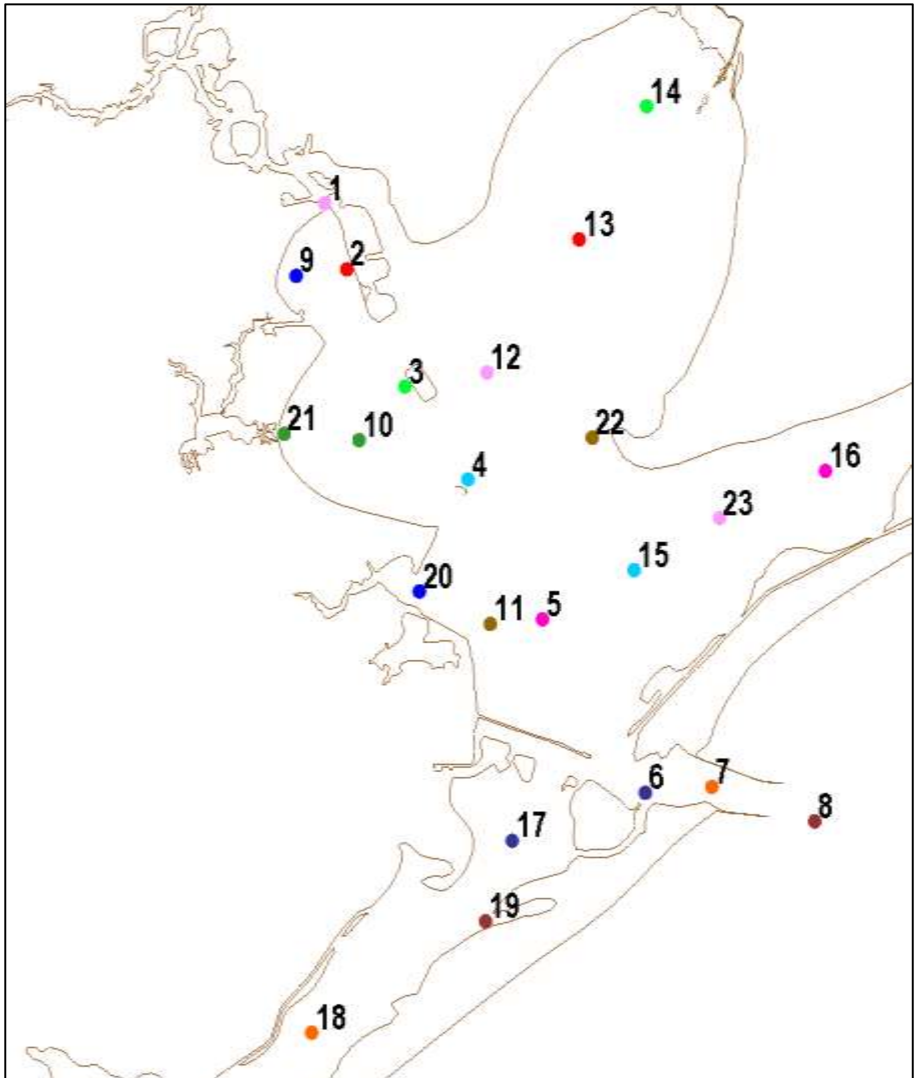
Salinity (Ouster Impact)

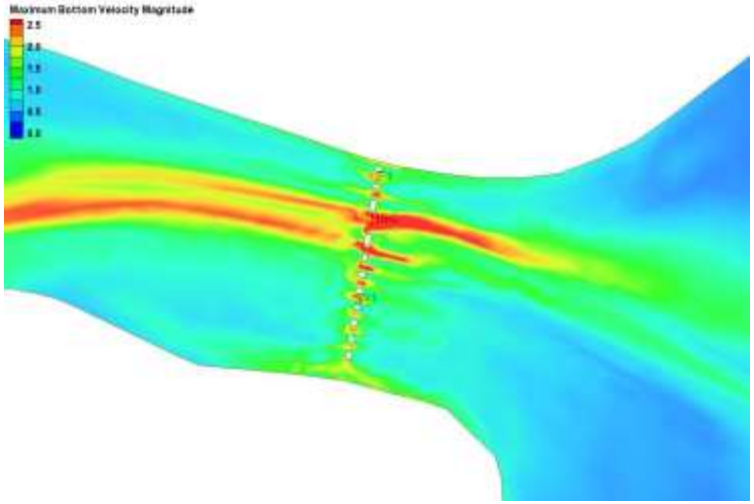


Greater Than 10 ppt for 14+ days - HSC at Red Fish Reef			
	Start	Stop	Duration(days)
PWP	1/1/2010 3:00	3/21/2010 18:00	79.6
	3/22/2010 21:00	12/30/2010 0:00	282.1
PWOP	1/1/2010 3:00	3/22/2010 6:00	80.1
	3/22/2010 21:00	12/30/2010 0:00	282.1
FWP	1/1/2010 3:00	7/3/2010 6:00	183.1
	7/4/2010 18:00	12/30/2010 0:00	178.3
FWOP	1/1/2010 3:00	7/4/2010 6:00	184.1
	7/4/2010 15:00	12/30/2010 0:00	178.4

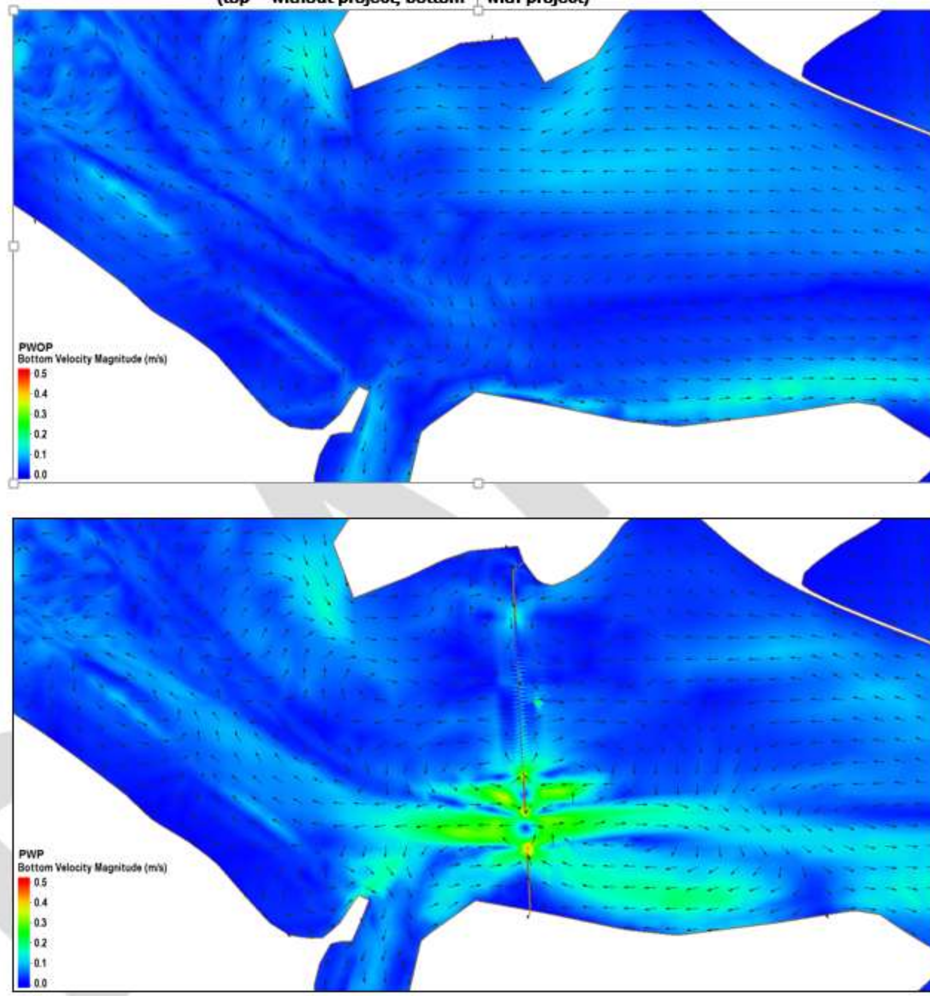
Greater Than 15 ppt for 14+ days - HSC at Red Fish Reef			
	Start	Stop	Duration(days)
PWP	1/1/2010 3:00	2/15/2010 21:00	45.8
	3/22/2010 21:00	7/2/2010 21:00	102.0
	7/11/2010 12:00	12/30/2010 0:00	171.5
PWOP	1/1/2010 3:00	2/15/2010 21:00	45.8
	3/22/2010 21:00	7/3/2010 21:00	103.0
	7/11/2010 12:00	12/30/2010 0:00	172.0
FWP	1/1/2010 3:00	7/2/2010 15:00	182.5
	7/11/2010 15:00	12/30/2010 0:00	171.4
FWOP	1/1/2010 3:00	7/2/2010 18:00	182.6
	7/11/2010 12:00	12/30/2010 0:00	171.5

Less Than 10 ppt for 14+ days - HSC at Red Fish Reef			
	Start	Stop	Duration(days)
PWP	NA	NA	NA
PWOP	NA	NA	NA
FWP	NA	NA	NA
FWOP	NA	NA	NA

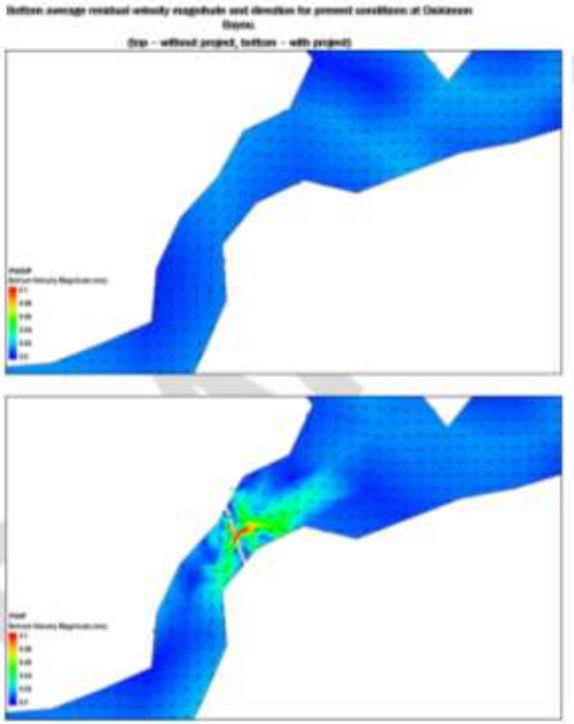
VELOCITY ANALYSES



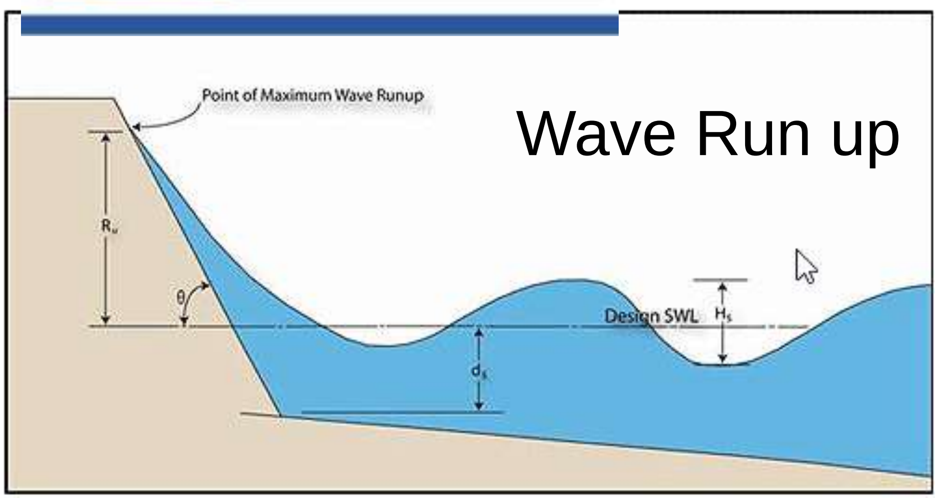
Bottom average residual velocity magnitude and direction for present conditions at Bolivar Roads.
(top – without project, bottom – with project)



VELOCITY ANALYSES (FUTURE WORK)



3D N-S Approach



Near Structure Velocity

GENERAL OBSERVATION

27% constriction at Bolivar Inlet analyzed
Overall Tidal Prisms reduction about 10-15%
Overall Tidal Amplitude reduction about 15%
No significant impact on salinity (avg change, 2-4ppt)
In general fresher Bay with freshwater tends to stay longer

In General, slight reduction in velocity in the Bay (avg, change 2-10 cm/s)

In General, increase in velocity at the inlet (Max vel change from 1.2 to 1.8m/s)

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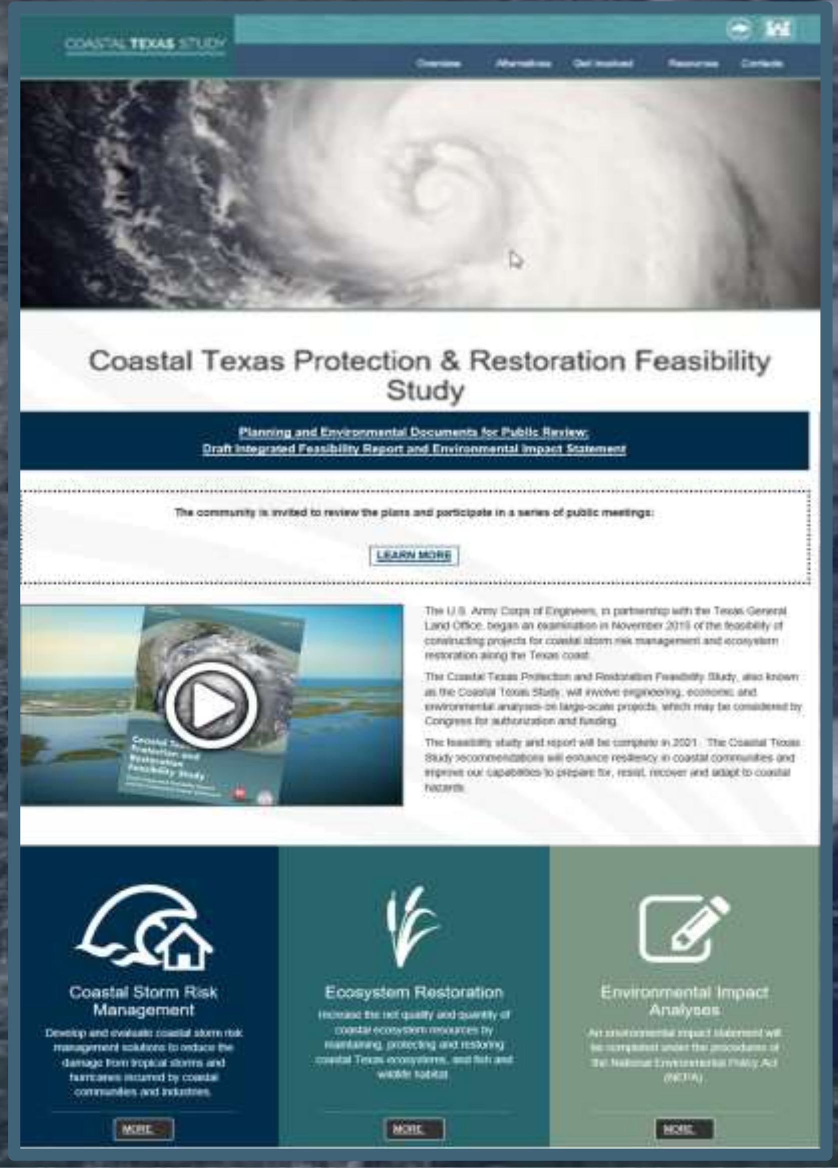
COASTAL TX PROTECTION AND RESTORATION FEASIBILITY STUDY

COASTALSTUDY.TEXAS.GOV



Point of Contact

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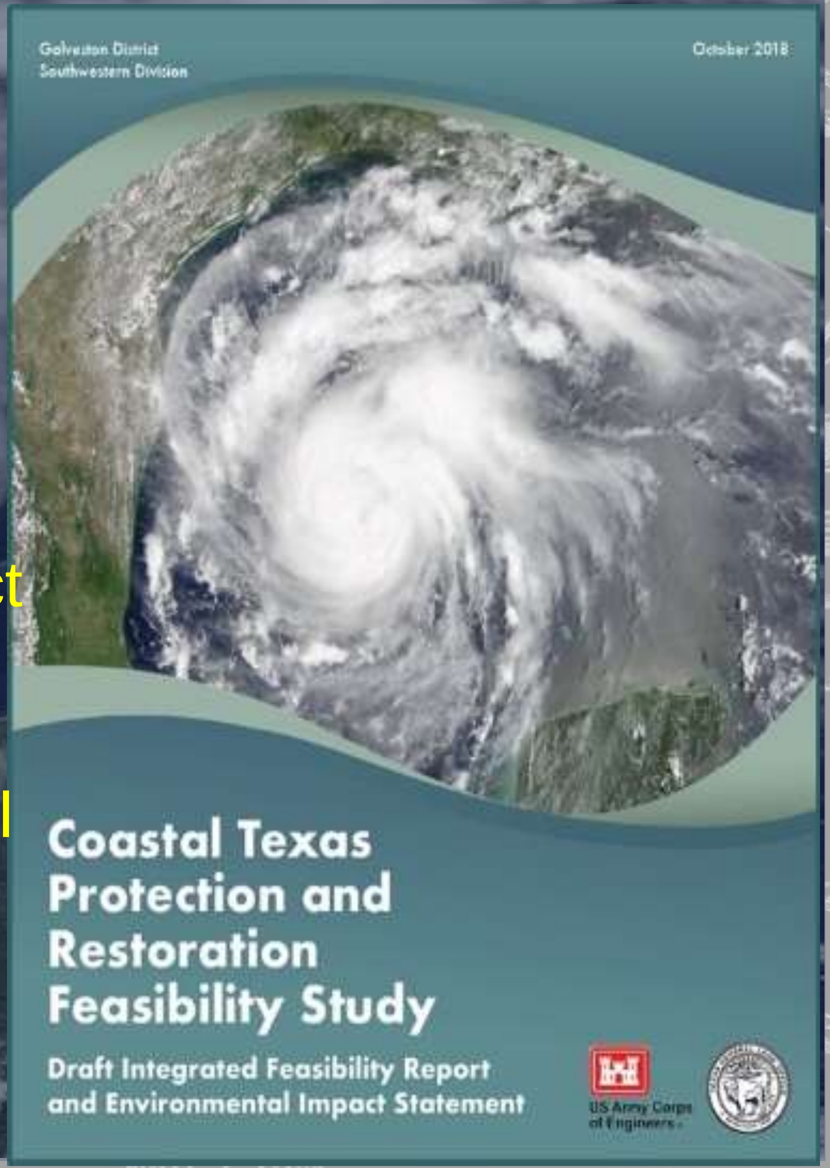
Project Manager, USACE – Galveston District
Office: (409) 766-3044
Mobile: (601) 618-5565
Email: Kelly.A.Burks-Copes@usace.army.mil



"The views, opinions and findings contained in this report are those of the authors(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other official documentation."

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PROBLEMS

Economic damage from coastal storm surge

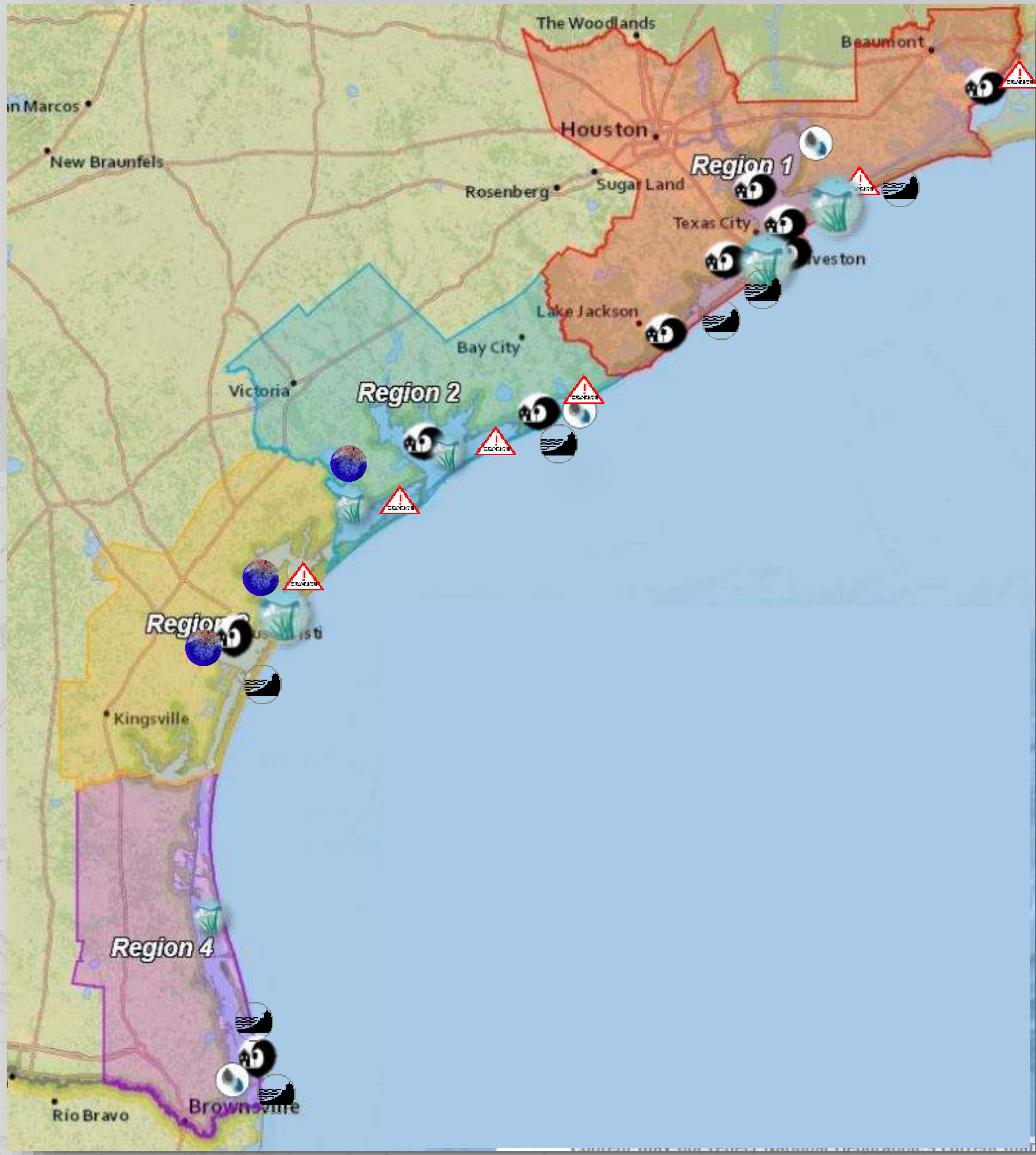
Inland shoreline erosion

Gulf shoreline erosion

Loss of T&E Critical Habitats

Loss of Natural Delta Processes

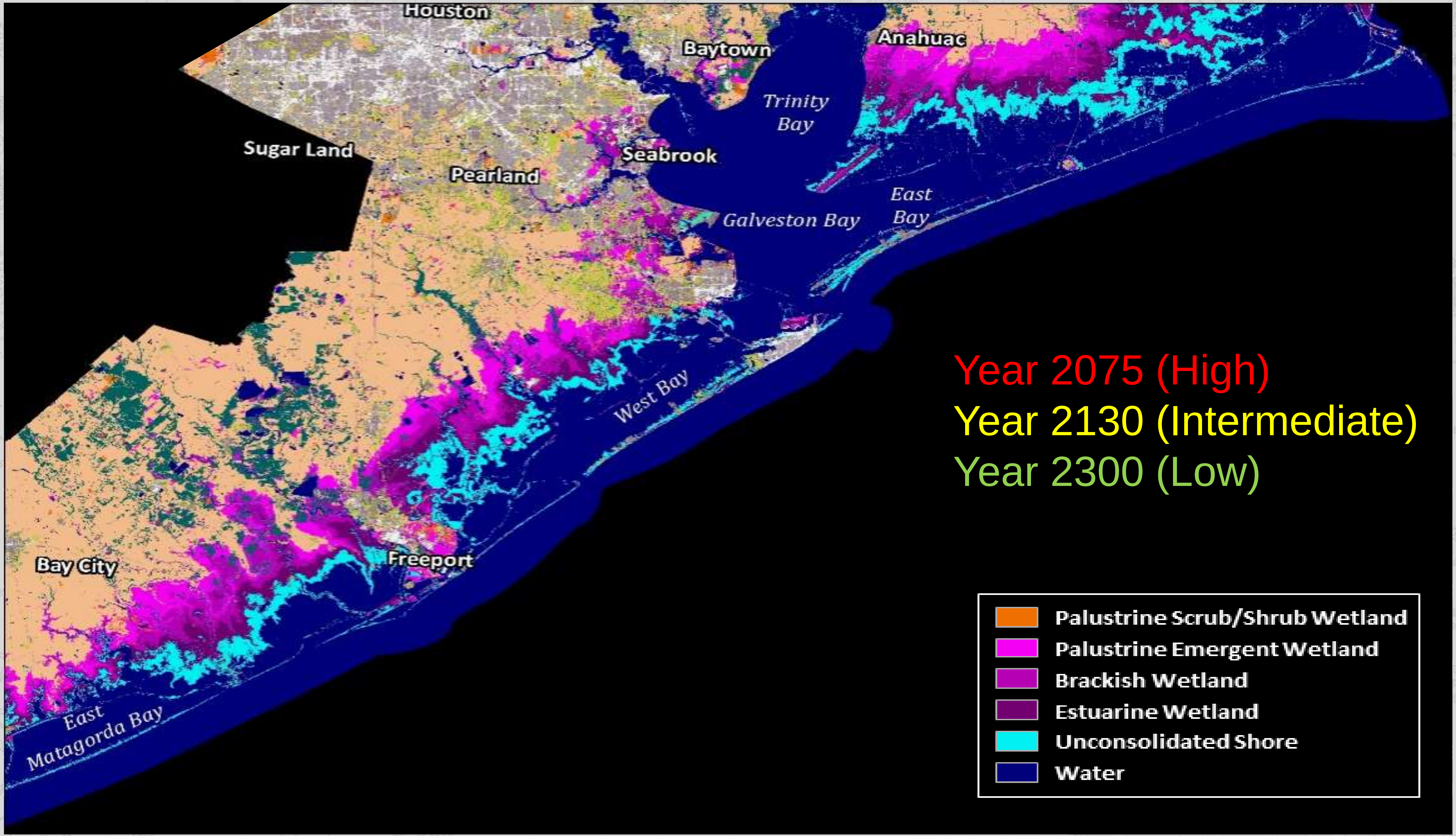
Disrupted Hydrology



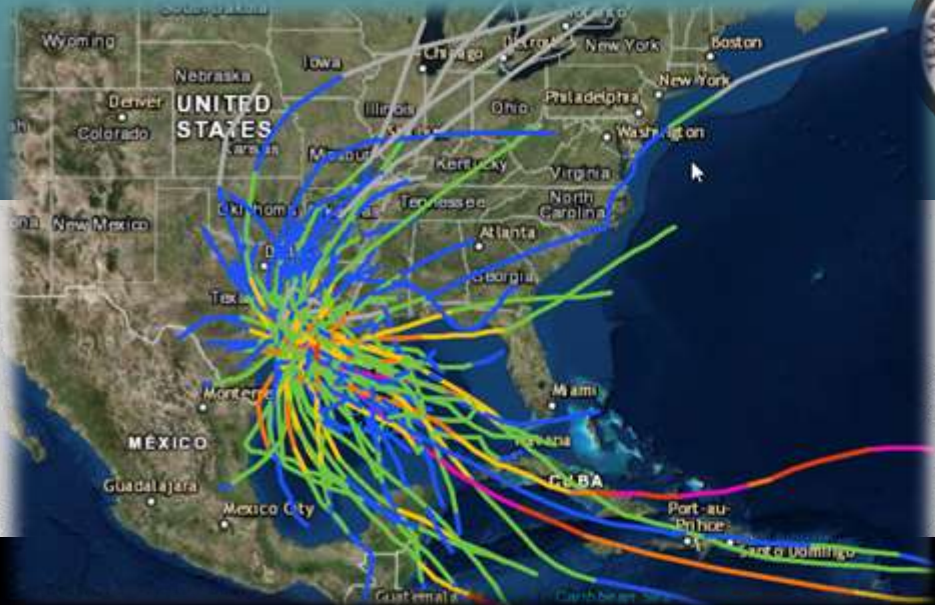
HOW BAD COULD IT GET?

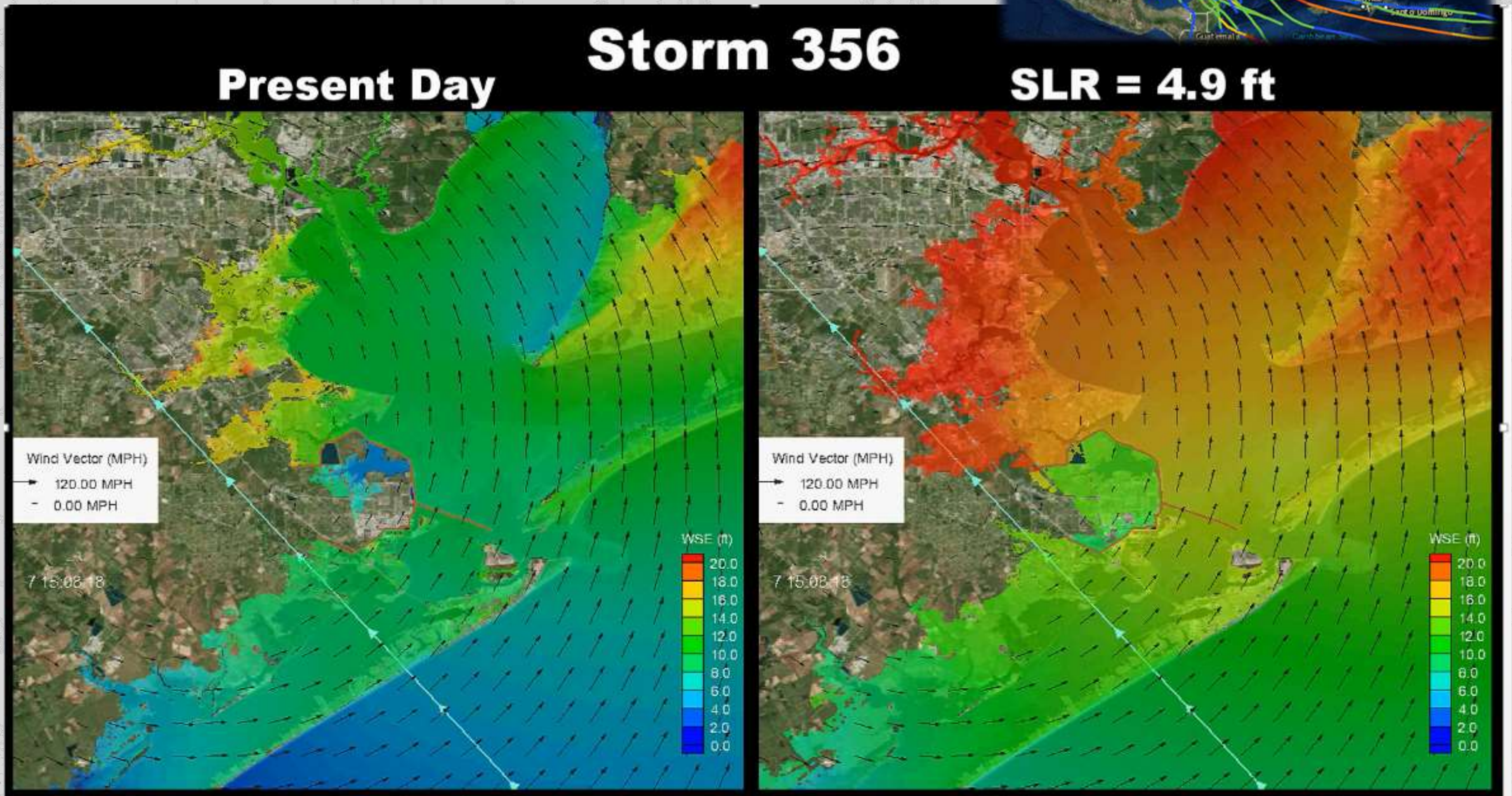
Upper Texas Coast

Break Point in Sea Level Change (about 3.5 feet)



AND THEN THE HURRICANES





PROJECT GOALS & OBJECTIVES

Goals

Coastal Storm Risk Management (CSRM)

Develop and evaluate **coastal storm damage risk reduction** measures for coastal Texas residents, industries and businesses which are critical to the nation's economy.

Ecosystem Restoration (ER)

Increase the net quantity and quality of coastal ecosystem resources by maintaining, **protecting, and restoring coastal Texas ecosystems** and fish and wildlife habitat

Objectives

- **Reduce economic damage** from coastal storm surge flooding to business, residents and infrastructure through 2085
- **Reduce risk to critical infrastructure** (e.g. medical centers, government facilities, universities, and schools) from coastal storm surge flooding to the maximum extent practical and reduce emergency costs
- **Reduce risk to public health and safety** from storm surge
- **Increase the resilience** of communities, the economy, coastal ecosystems, and infrastructure, including existing coastal storm risk reduction systems, from sea level rise and coastal storm surge
- **Enhance and restore coastal landforms** along Galveston Island and Bolivar Peninsula that contribute to reducing the risks of coastal storm surge damages
- **Improve hydrologic connectivity** of area wetlands in the Texas-Louisiana coastal marshes, mid-coast barrier islands and coastal marshes
- **Improve and sustain coastal marshes and bay shorelines** on barrier island and estuarine systems

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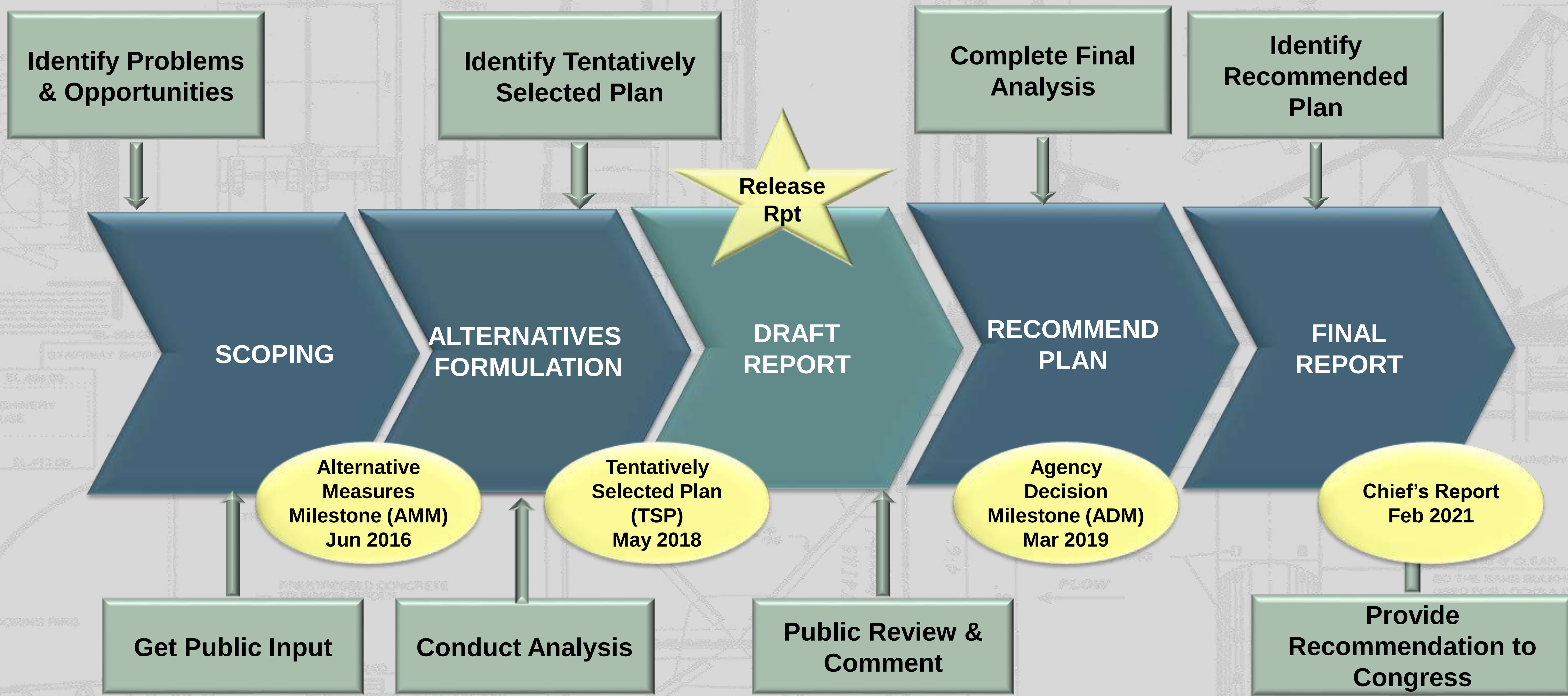
WHERE WE ARE TODAY



Upcoming Public Meetings:

Lower Coast: Nov 2018
Upper Coast: Dec 2018

NATIONAL SIGNIFICANCE

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Population Centers

- 18 coastal counties
- 6.1 million residents
- >24% of the TX population

Navigation

- Nationally ranked deep-draft ports
  - Houston
  - Beaumont
  - Corpus Christi
  - Texas City
- 450 miles of Gulf Intracoastal Waterway (GIWW)

Industry

- 40% of the Nation’s petrochemical industry
- 25% of national petroleum-refining capacity

Critical Infrastructure

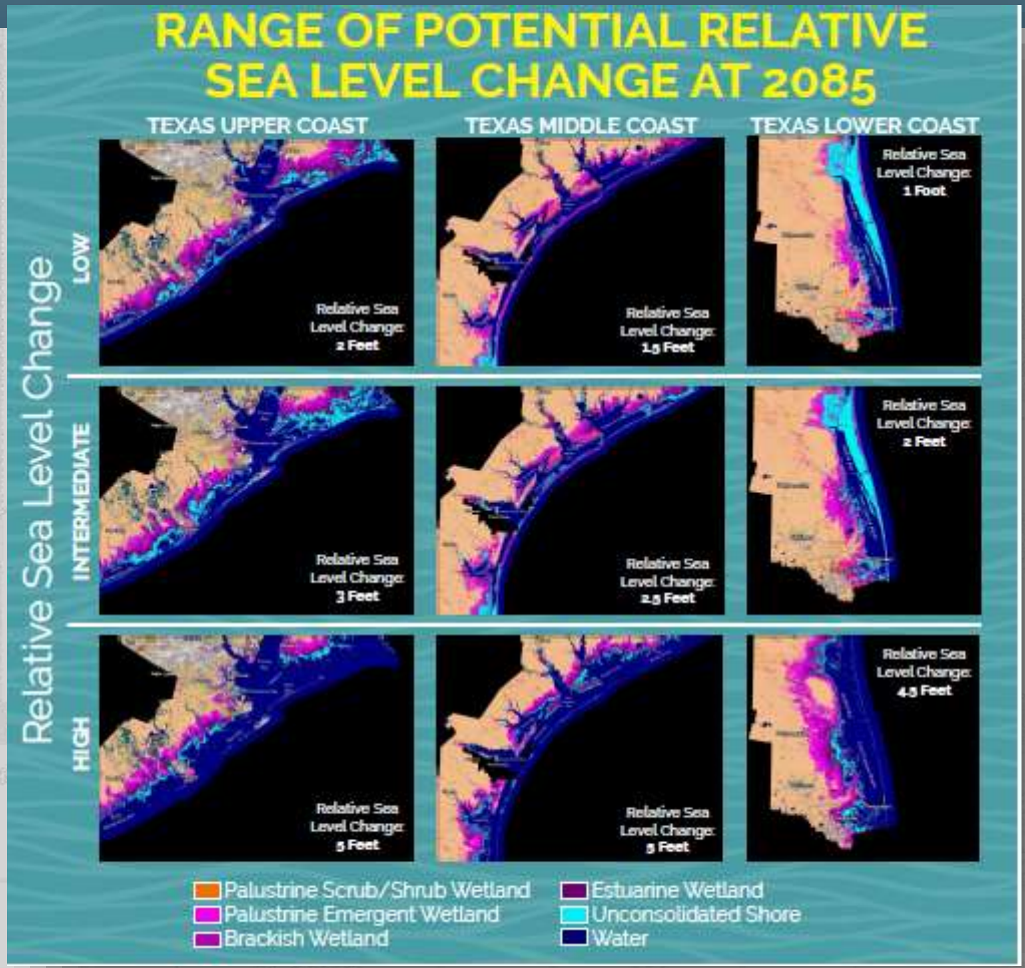
- NASA
- UTMB – Level 4 Viral Laboratory

SIGNIFICANT NATURAL RESOURCES

- **Critical coastal ecosystems** including wetlands, seagrass beds, oyster reefs, and sea turtle nesting habitat
- **Critical Habitat** threatened and endangered species
- 2 of 28 **National Estuary Program sites -** Galveston & Corpus Christi Bays
- **Central Flyway Migration Corridor**
- The **Laguna Madre -** a rare hypersaline lagoon
- **Nursery habitat** and **significant commercial fisheries** for oysters, shrimp, and finfish
- **Padre Island National Seashore**
- **12 National Wildlife Refuges**

USACE PLAN FORMULATION

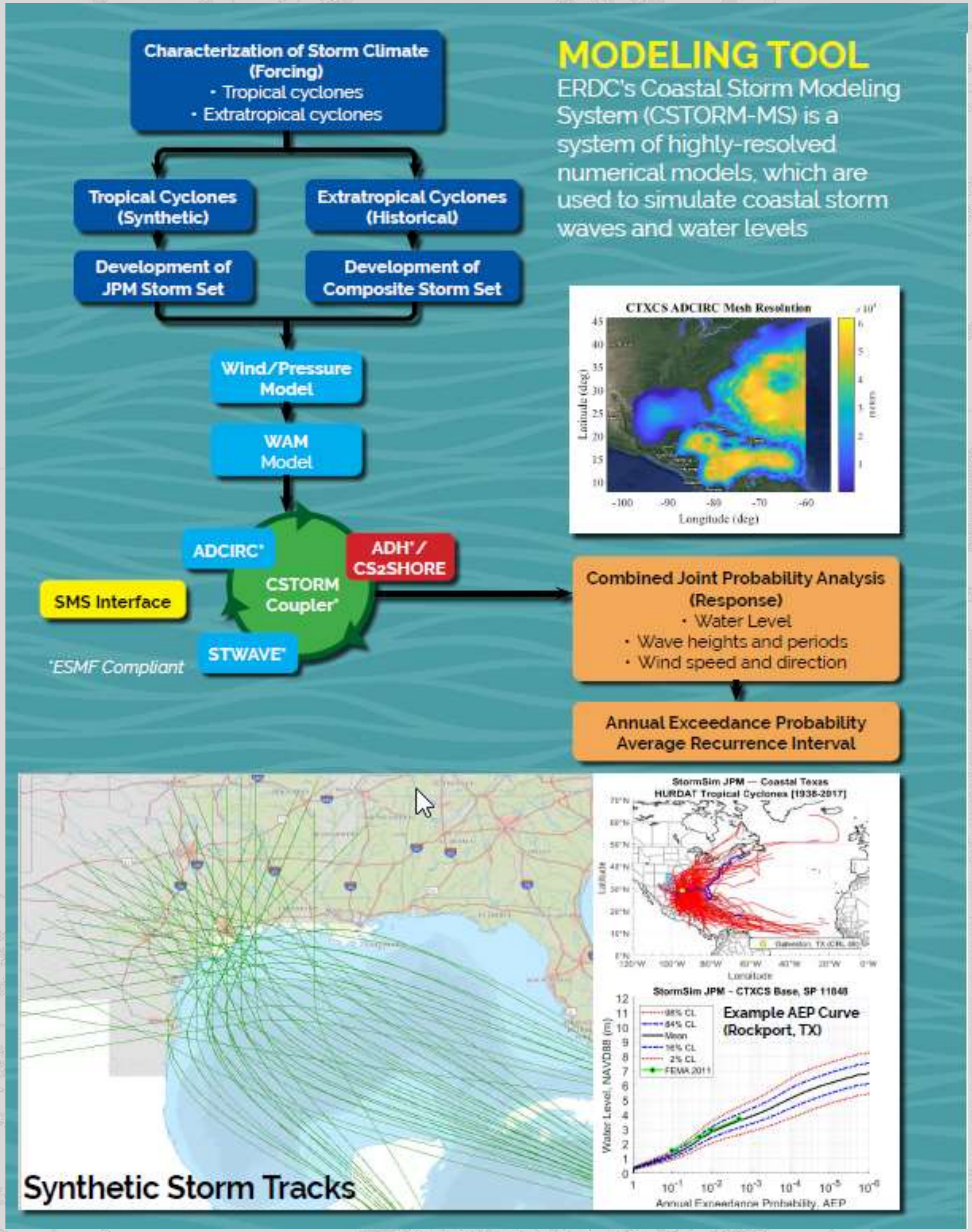
1. Data was produced by:
   - NOAA Sea Level Rise Viewer
   - Texas Shoreline Change Rates
   - National Structure Inventory Database
   - FEMA Inundation Mapping
   - NOAA's Sea Lake and Overland Surges from Hurricanes (SLOSH) Model
2. Features/actions/treatments were developed based on existing & past studies from:
   - GCCPRD
   - Texas A&M
   - SSPEED Center
   - USACE
   - GLO
3. AND from scoping meetings held in 2014.
4. Measures were then formulated meet the goals and objectives.

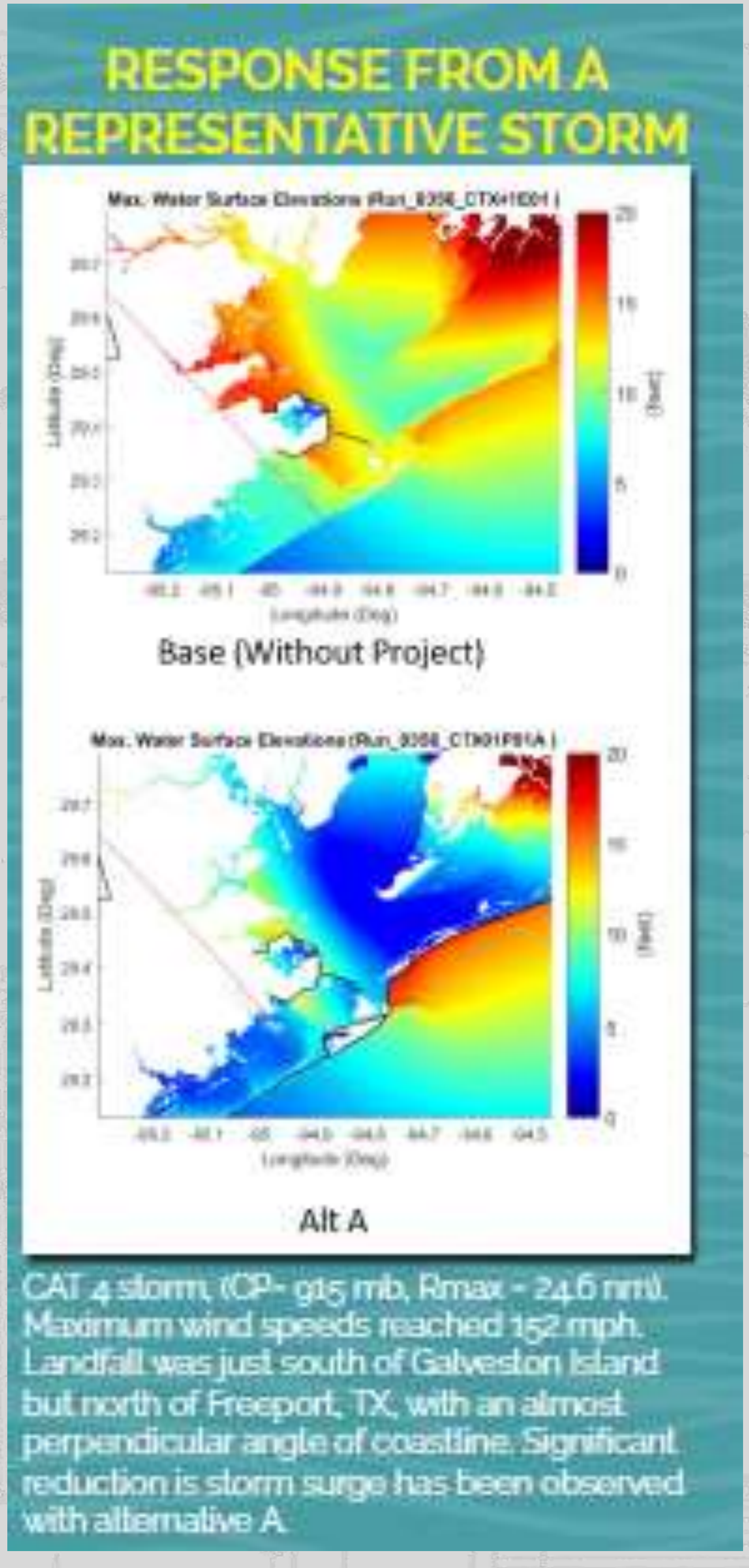


PLAN EVALUATION & COMPARISONS

Feasibility studies evaluate alternatives to identify a plans that are:

- ✓ Engineeringly sound
- ✓ Environmentally acceptable
- ✓ Economically justified





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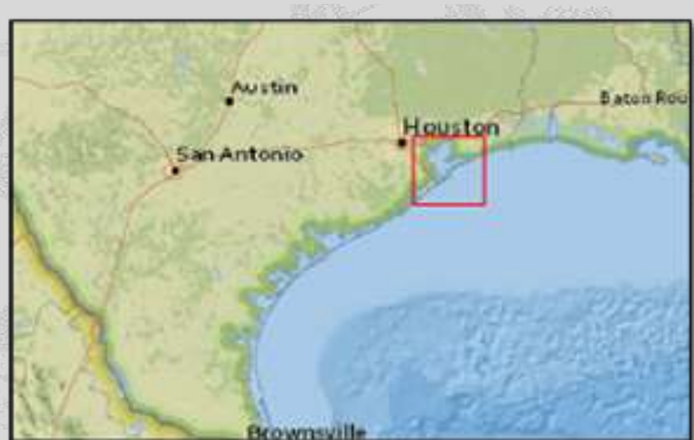
ALTERNATIVE A: COASTAL BARRIER

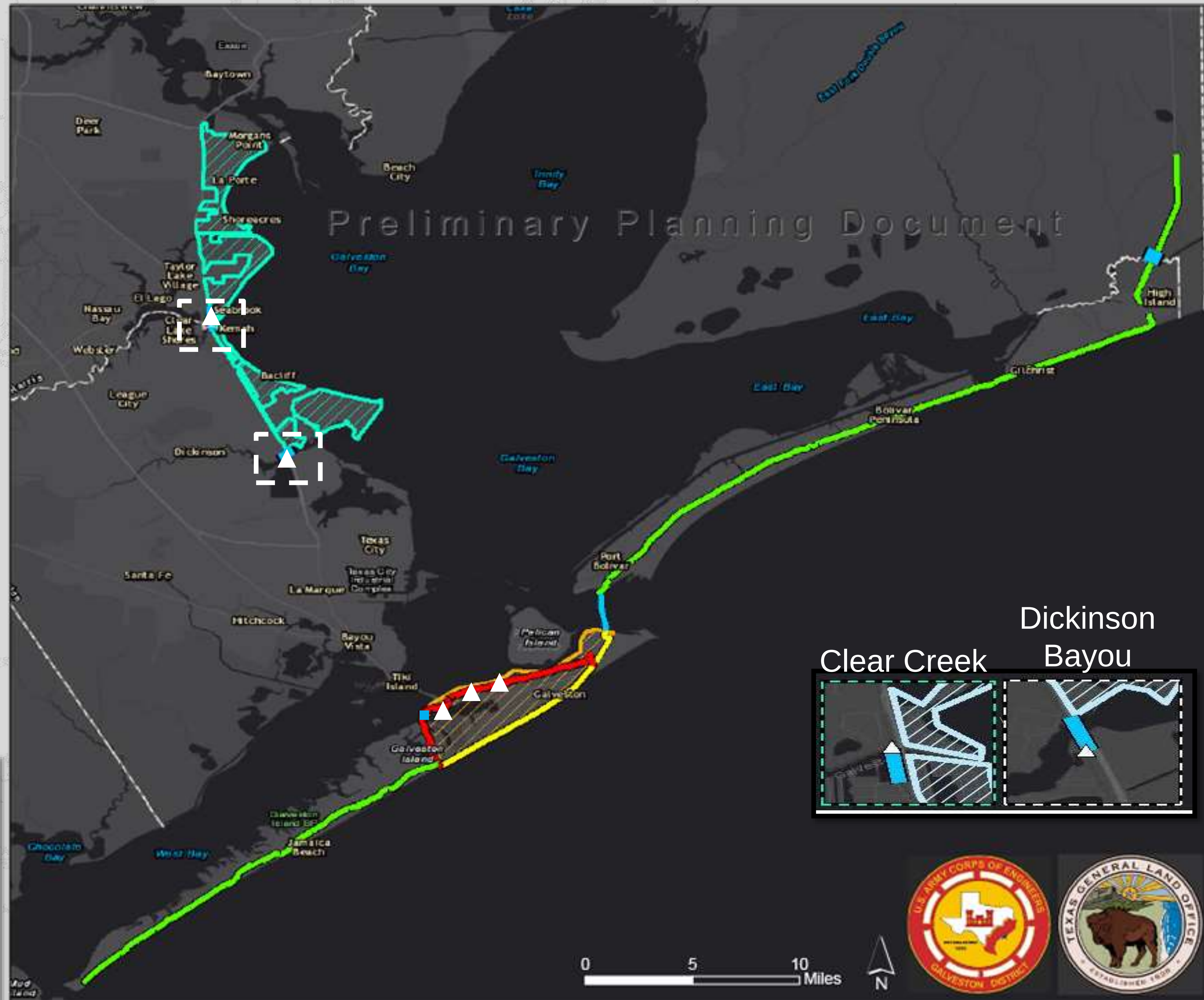
Coastal Texas Protection and Restoration Feasibility Study

Alternative A

- Navigation and Environmental Gates
- Levees/Floodwalls
- Galveston Ring Levee *
- Galveston Seawall Improvements
- Galveston Island * Nonstructural Improvements
- Nonstructural Improvements

* One or both of these features may be selected





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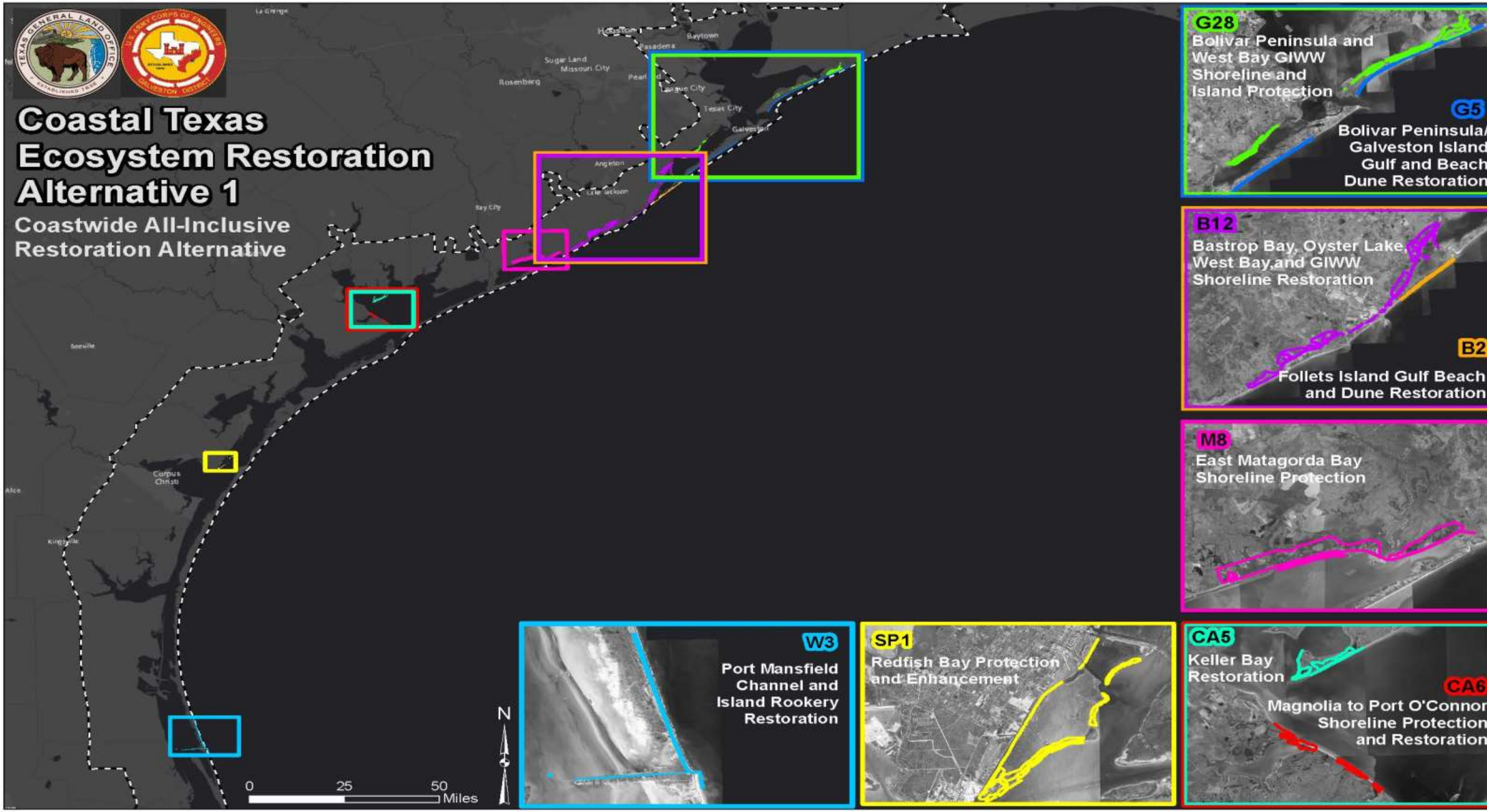
ECOSYSTEM RESTORATION MEASURES



THE TENTATIVELY SELECTED PLAN (TSP)

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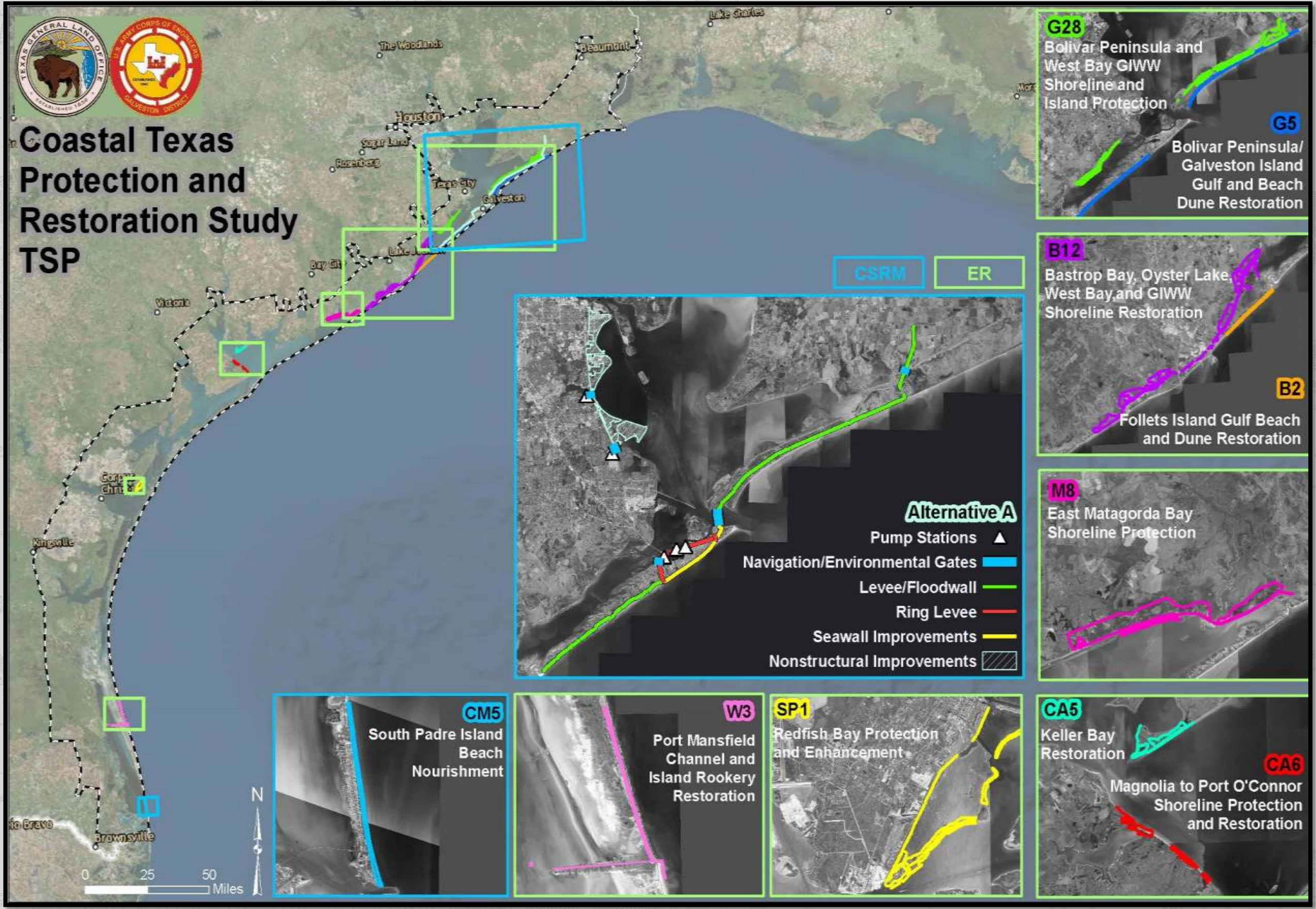
Coast-wide system of ecosystem restoration and storm-risk management features

TSP supports the resilience of coastal communities and natural habitats in Coastal Texas

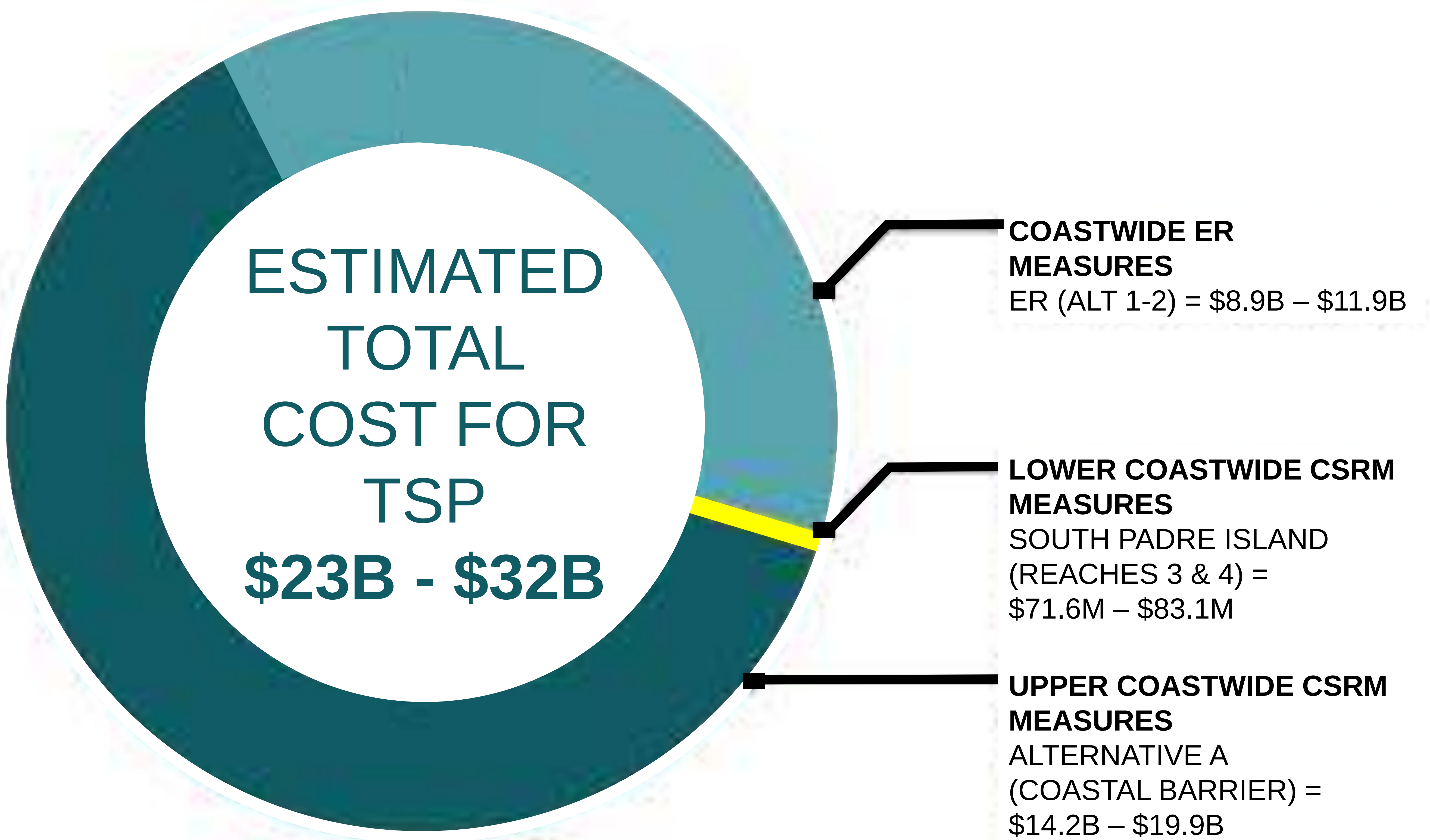
Coastwide:
Large scale ER features which focus on critical landscape features and areas of threatened biologically diverse ecosystems

Lower Coast:
CSRM Dune and beach restoration project on South Padre Island

Upper Coast:
CSRM surge barrier system to protect the Houston-Galveston Region (Coastal Spine)



TSP TOTAL PROJECT COST



ENVIRONMENTAL IMPACTS & MITIGATION

- **Direct Impacts**

  Alt A (TSP): 4,525.3 acres

  Alt D2: 2,334.3 acres

  South Padre: 365.8 acres

- **Indirect Impacts:**
  - Altered tidal exchange
  - Reduced velocities in Galveston Bay

- **Ecosystem Restoration Benefits**
  - 160,000 acres of marsh, islands, dunes, beaches & oyster reefs

TOTAL MITIGATION COST RANGE:

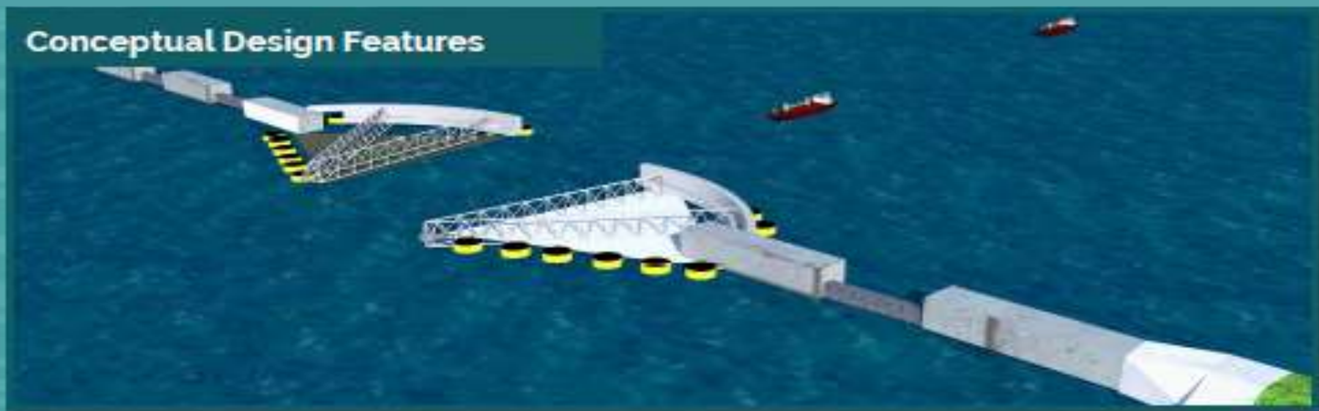
$676 M – $906 M

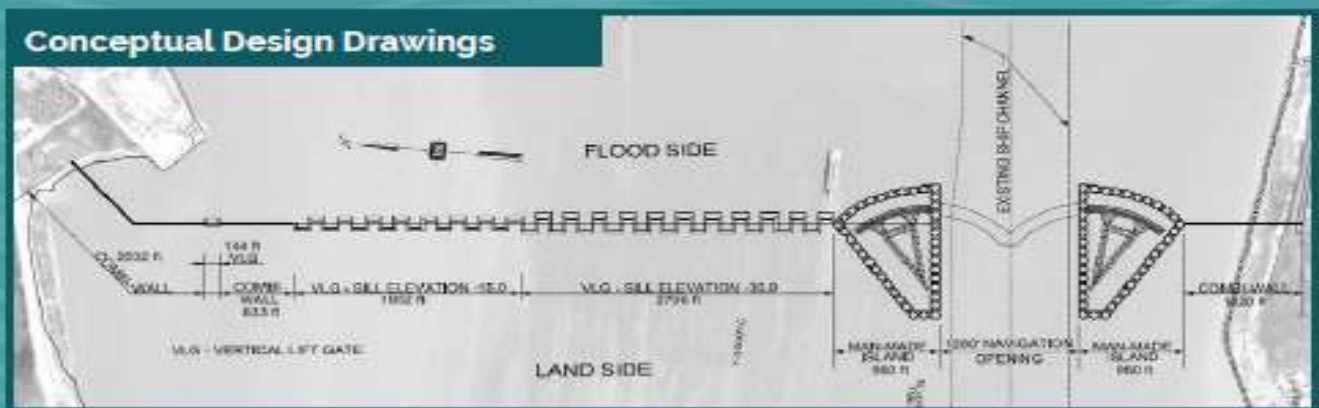
ALTERNATIVE A:COASTAL BARRIER
PHASED DESIGN & OPTIMIZATION

US Army Corps of Engineers

Coastal Texas Study DIFR-EIS

- Used for Baseline Design and Cost development for alternative identification and evaluation
- Used to inform baseline Environmental Impacts
- Based on known designs and risk, based on existing projects


Conceptual Design Features



Conceptual Design Drawings


Conceptual Construction Position Within Navigation Areas

Post Public/ Independent/ Policy Review & Contingent on Agency Decision Milestone Approval

Focus on Scaling Measures and Features

- Continue to focus on avoiding, minimizing and reducing environmental impacts
- Focus on Risk and Reliability
- Focus on Operation Concerns
- Focus on Construction Cost Concerns


Maeslant Storm Barrier Rotterdam

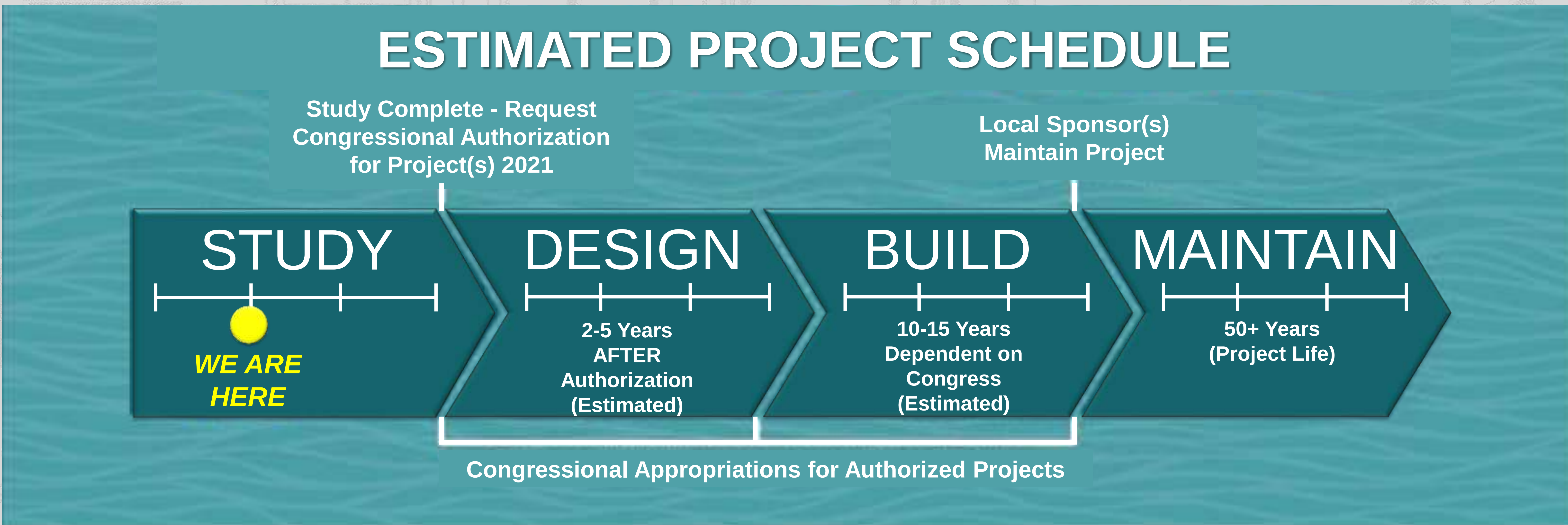

Eastern Scheldt Barrier


Venice Mose Barrier


Ramspol Barrier

US Army Corps of Engineers

NEXT STEPS



DEPARTMENT OF THE ARMY
ENGINEER RESEARCH AND DEVELOPMENT CENTER, CORPS OF ENGINEERS
COASTAL AND HYDRAULICS LABORATORY
WATERWAYS EXPERIMENT STATION, 3909 HALLS FERRY ROAD
VICKSBURG, MISSISSIPPI 39180-6199

REPLY TO
ATTENTION OF

CEERD-HNN-D

MEMORANDUM FOR Commander, U.S. Army Corps of Engineers, Galveston District (CESWGEC-HB /Dr. Himangshu Das), PO Box 1229, Galveston, TX 077550

SUBJECT: Coastal Texas Protection & Restoration Feasibility Study Report

1. Enclosed is a copy of the Coastal Texas Protection & Restoration Feasibility Study Report.

2. A Feasibility Level Screening Simulation Program (FLSSP) study for the proposed Coastal Storm Surge Reduction Measures (CSRM) alignment and gate structure across Bolivar Roads was conducted the week of 20-23 February 2019, at the U.S. Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory's Ship/Tow Simulator (STS). The purpose of the study was to obtain expert elicitation from the Galveston-Texas City Pilots resulting from the participation in ship simulation exercises at the ERDC. The results of the FLSSP are enclosed.

3. If you have any questions, please contact Mr. Keith Martin at (601) 634-3019 or Mr. Timothy W. Shelton, Chief, Navigation Branch at (601) 634-2304.

Encls

TY V. WAMSLEY, PhD, SES
Director

Coastal Texas Protection & Restoration Feasibility Study Report

1. INTRODUCTION

The U.S. Army Corps of Engineers (USACE), Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL) has completed a Feasibility Level Screening Simulation Program (FLSSP) to assist the USACE Galveston District (CESWG) analyzing the proposed Coastal Storm Surge Reduction Measures (CSRM) alignment and gate structure across Bolivar Roads which has been proposed as a Tentatively Selected Plan (TSP) for the ongoing Coastal Texas Protection & Restoration Feasibility project. The study was performed at CHL's Ship/Tow Simulator (STS) on 20-23 February 2019.

2. OVERVIEW

The TSP identified by the Coastal Texas Protection & Restoration Feasibility Study consists of a coastal barrier system aimed to protect the Galveston Bay region from storm surge. The proposed barrier system is a closure structure consisting of a 1200 foot (ft) sector gate and environmental lift gates. The proposed location is across Bolivar Roads, between Bolivar Peninsula and Galveston Island (Figure 1). Currently, there are three deep draft navigation channels that use the entrance channel at Bolivar Roads: Houston Ship Channel, Galveston Ship Channel, and Texas City Ship Channel. The effects the structure will have on ship traffic will depend on its alignment.

Two alternative alignments will be studied in this FLSSP. The first alignment is located immediately east of Galveston Channel (Figure 2). This location is a concern for inbound ship traffic heading towards Galveston as it reduces the amount of time and space for ships to complete the southward turn upon exiting the structure. The second alignment is shifted approximately 3,150 ft east of the first alignment (Figure 2). The immediate areas of concern include the loss of maneuvering area and potential increase in current velocity. The ship simulation study will evaluate whether the proposed alignments are feasible for maneuvering in and out of the Galveston Channel.

3. PURPOSE

The FLSSP provides a means of conducting expert elicitations. The use of real-time simulation provides an iterative framework within which to examine ideas and possible solutions within the confines of a laboratory experiment. At the conclusion of each simulation, results from the simulation can be discussed, modifications made, and then the simulation rerun. The FLSSP was conducted in order to provide essential information for the study process and to stay within the time and cost constraints of USACE's SMART Planning. To reduce time and cost, lower resolution databases are used for ship simulation and data processing is minimized. Lower resolution databases require less costly development and also allow database modification to be done quickly during the simulation week. A low resolution database can be modified (widened, realigned, tapered, etc.) within a few hours. This is critical so that ideas suggested by the pilots or others can actually be tested with the same pilots. Conclusions drawn from actual data should be limited and done very carefully due to the low resolution modeling and the assumptions used during modeling. In addition, once the meetings occur, the pilots often performed “what if” tests to check bank effects and other forces. Data processing is limited to presentation of track plots and run sheets, Appendix A, to document results. The most important analysis is the group discussion at the conclusion of the FLSSP.

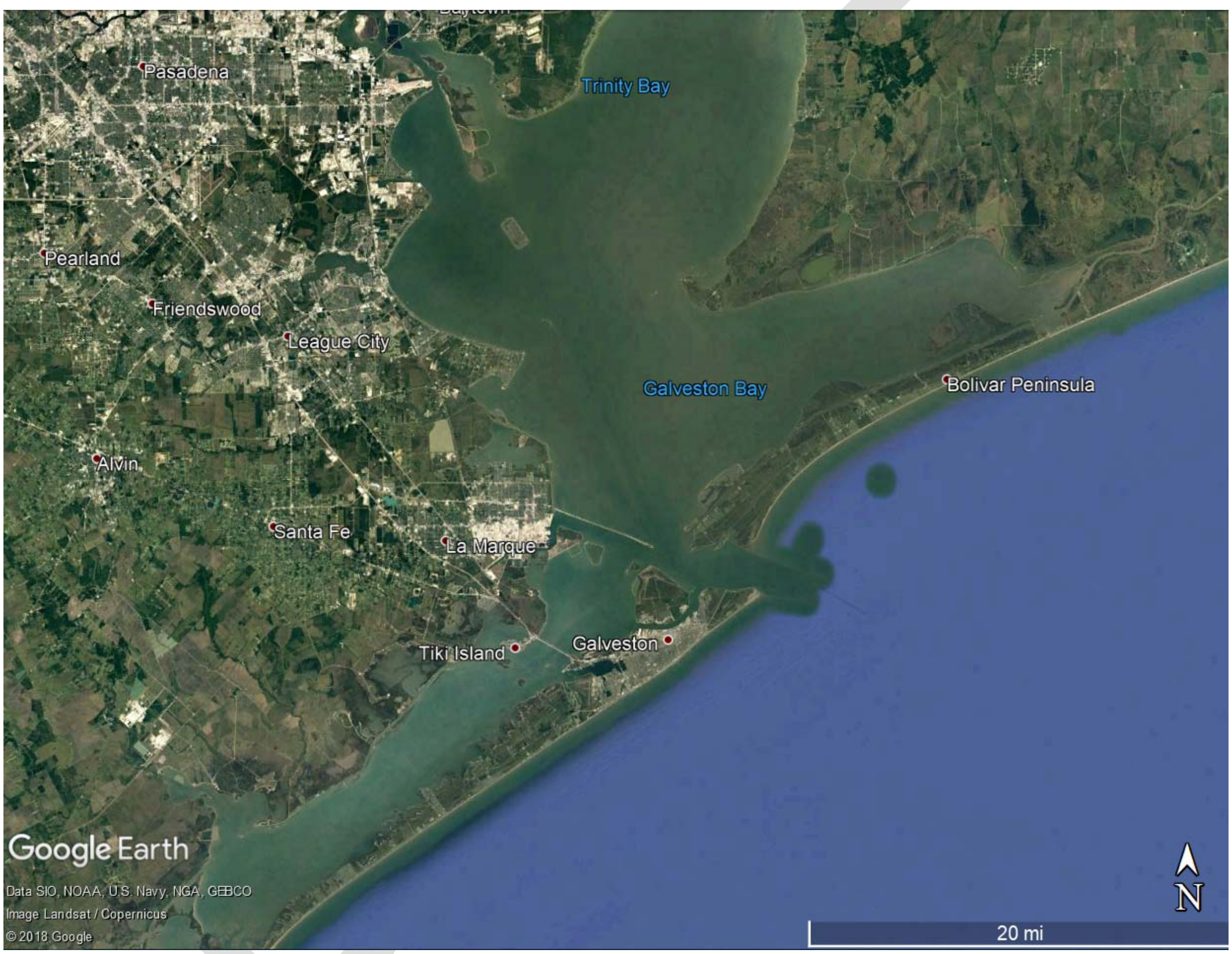
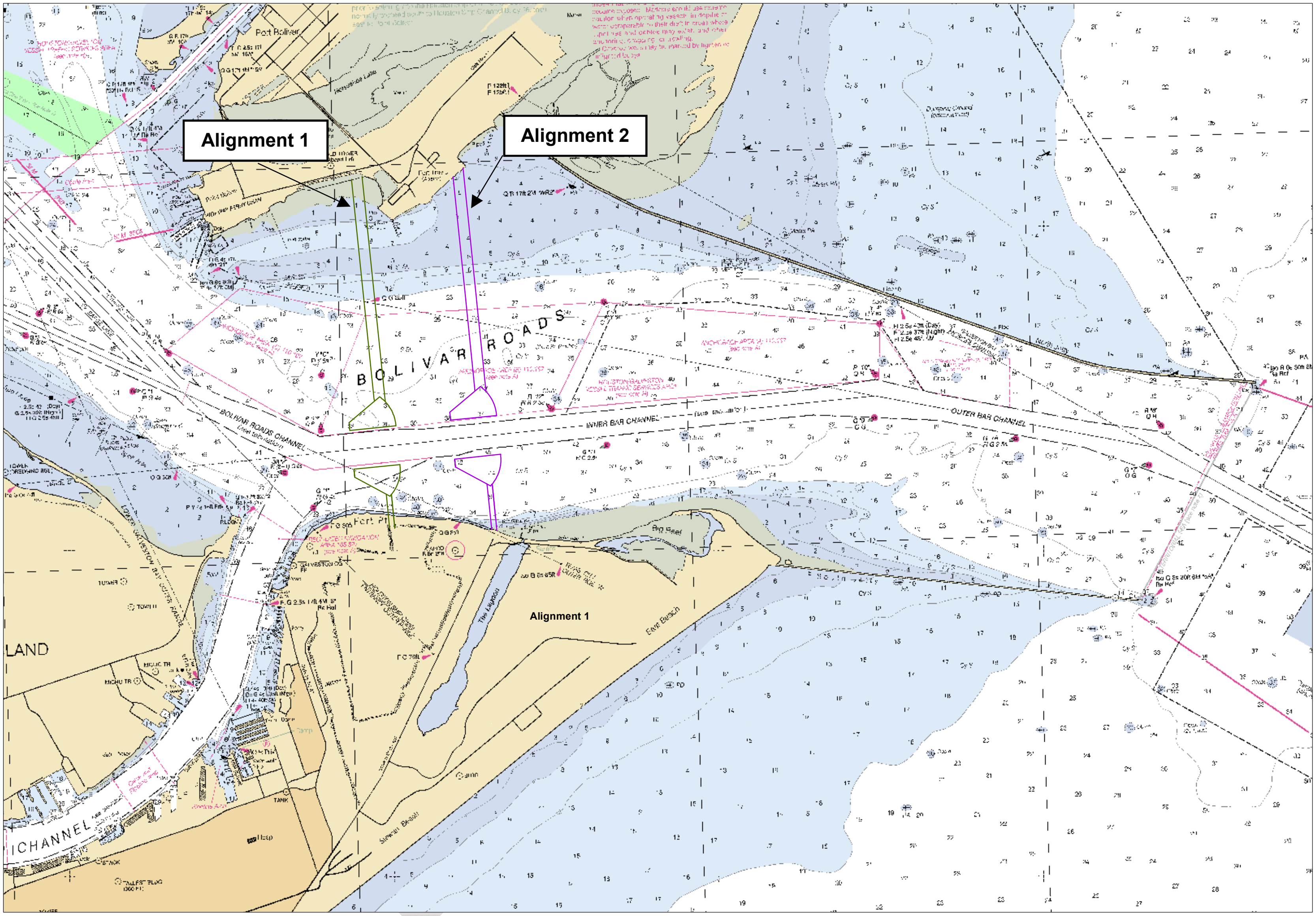


Figure 1. Location Map



`Figure 2. Navigation Chart featuring proposed structure locations

4. PARTICIPANTS

The FLSSP includes representatives from ERDC, CESWG, Texas General Land Office (GLO), Galveston-Texas City Pilots, and Houston Pilots. The individuals listed participated for the duration of the simulation testing unless otherwise noted.

- ERDC: Keith Martin, Kiara Pazan, Mary Claire Allison, Morgan Johnston, and Mario Sanchez
- CESWG: Himangshu Das and Mike Diaz
- GLO: Carla Kartman
- Galveston-Texas City Pilots: Captain Christos Sotirelis
- Houston Port Pilots: JJ Plunkett

5. CONSIDERATIONS

For reasons previously stated, model development is done in fairly low resolution. Below are the parameters and assumptions for testing

a. Currents for max ebb and flood are obtained from an Adaptive Hydraulics (AdH) model that is run for existing conditions and for the proposed alternatives. For the proposed alternatives, the gate structure was simplified to a wall.

b. The visual scenes consist of the background terrain and a few selected building/facility features.

c. Wind conditions were set at run time at 25 knots from the North.

d. Simulated ships are limited to ships already in ERDC's STS inventory. The tanker, VLCC05B, and the cruise ship, *Freedom of the Seas*, were used for the design ships for the FLSSP. The dimensions of the ships are listed in Table 1. Pilot cards are included in Appendix B. The dimensions of the VLCC05B are slightly smaller than typical vessels handled in Galveston, about 60 ft shorter and 42 ft narrower. Also, VLCCs are typically called into Texas City over Galveston. Since the study is in feasibility phase, the VLCC is adequate.

Table 1. Ship Models for Simulation Tests

Model	Name	LOA (ft)	Beam (ft)	Draft (ft)
VLCC05B	-	1033.5	154.9	36.1
CRUIS09L	*Freedom of the Seas*	1111.2	126.6	27.9

6. SIMULATED SCENARIOS

Two alternative locations of the gate structure provided by CESWG were simulated: the initially proposed alignment, closest to the entrance of the Galveston, and the second alignment shifted to the east. Additional runs using currents scaled by a 25 percent increase were included to simulate a strong storm condition. The channel lines for Alignment 2 had to be roughly adjusted in the simulator to accommodate the 1200 ft gate opening. At this alignment, the channel width is 800 ft.

Pre-programmed passing ships were included in several runs to simulate the heavy congestion in the meeting area. Vessel placement and speed was provided by the pilot. Because the routes are programmed, passing ship effects are not observed in the simulation. The ship to ship interaction can be only observed when both ships are being handled by pilots. The observations remain useful for spatial awareness. Combinations of the vessels in Table 2 were used.

Table 2. Pre-Programmed Passing Ships

Model	Name	LOA (ft)	Beam (ft)	Draft (ft)
CNTNR21L	KMSS Ultra	935.0	131.2	41.7
CNTNR44	Zim Piraeus	964.9	105.6	43.0
VLCC15B	MT Brittania	859.6	137.8	27.2

A summary of the runs simulated are shown in the test matrix in Table 3. Existing conditions are referred to as P0, and the proposed Alignment 1 and 2 are referred to as P1 and P2, respectively.

Table 3. Test Matrix					
Alt	**Vessel**	**Tide**	**Direction**	**Wind**	**Meeting**
P0	VLCC05B	Flood	Inbound	N25K	
	CRUIS09L	Flood	Inbound	0K	
	CRUIS09L	Flood	Outbound	N25K	
P1	VLCC05B	Ebb	Inbound	N25K	
	VLCC05B	Flood	Inbound	N25K	
	VLCC05B	Flood	Inbound	N25K	CNTNR21L and VLCC15B out from Houston
	VLCC05B	Flood-25%	Inbound	N25K	CNTNR21L and VLCC15B out from Houston
	VLCC05B	Ebb	Outbound	N25K	
	VLCC05B	Flood	Outbound	N25K	CNTNR21L inbound
	VLCC05B	Ebb	Outbound-Houston	N25K	
	VLCC05B	Ebb	Outbound-Houston	N25K	CNTNR21L inbound
	CRUIS09L	Ebb	Inbound	N25K	
	CRUIS09L	Flood	Inbound	N25K	
	CRUIS09L	Flood	Inbound	N25K	CNTNR44 out from Houston
	CRUIS09L	Ebb	Outbound	N25K	
	CRUIS09L	Ebb-25%	Outbound	N25K	CNTNR21L inbound, VLCC15B outbound
	CRUIS09L	Flood	Outbound	N25K	
P2	VLCC05B	Ebb	Inbound	N25K	
	VLCC05B	Flood	Inbound	N25K	CNTNR21L and VLCC15B out from Houston
	VLCC05B	Ebb	Outbound	N25K	CNTNR21L inbound
	VLCC05B	Flood	Outbound	N25K	
	CRUIS09L	Flood	Inbound	N25K	CNTNR21L and VLCC15B out from Houston
	CRUIS09L	Ebb	Outbound	N25K	CNTNR21L inbound, VLCC15B outbound
	CRUIS09L	Ebb-25%	Outbound	N25K	
	CRUIS09L	Flood	Outbound	N25K	CNTNR21L inbound, VLCC15B outbound

7. RESULTS

The initial validation effort was devoted to pilot familiarization and model adjustment. The environmental (wind and currents), and visual databases are deemed adequate for feasibility level testing. Data recorded during these exercises provide value in observing the current turning maneuver into Galveston Channel. This will vary with pilot preference, but can be used to generally compare with the vessel tracks in the alternatives.

Exercises were one-way transits, either inbound or outbound, passing through the structure. Two-way transits were also conducted using pre-programmed ships that not include ship-to-ship interaction. The initial and end vessel positions are outside the jetties, at buoys 5 and 6, and approximately 1 mile into Galveston Harbor.

A total of 25 test runs were completed. Track plots and run sheets for the FLSSP are included in Appendix A. Figure 3 is a photograph taken from the bridge of the design ship leaving the structure.

Figure 3. View from the *Freedom of the Seas*, heading inbound towards the structure.

8. DISCUSSION

The simulation program is a screening tool used to determine the feasibility of the storm surge control structure for the Coastal Texas TSP. The final FLSSP discussion was held on the Friday, 22 February 2019, while the majority of representatives were still present. The following conditions are agreed upon, discussed, and recommended for the feasibility level design.

Alignment 1:
The initial proposed location, Alignment 1, for the gate structure is in close proximity to the turn into Galveston Channel, approximately 2100 ft east of the entrance (Figure 1).

After simulation runs and discussions with the pilot, it was determined that this location is not favorable.

a. The pilot was able to make the turn into Galveston successfully, but was left with very little room for error. After leaving the structure, the pilot needed to put in significant effort to maintain control of the ship due to the increase of current velocities. The ship needed to be in full ahead (maximum RPM) and rudder placed in the “hard over” position, leaving no additional rudder control to respond to any unexpected change in environmental conditions.

b. Galveston has a speed restriction, limiting vessels to 10 knots when entering the channel. The pilot has to balance between ensuring vessel has enough velocity to make it through the turn and not exceeding the speed restriction.

c. Inbound runs where the vessel is meeting outbound ships presented potentially dangerous situations where the stern is caught in front the outbound ship when making the turn in Galveston.

d. The southern sector gate is placed in the channel’s bend ease in the meeting area, an area pilots currently use to assist with the turn in and out of Galveston, especially when needed to merge with outbound traffic from Houston. Pilot needed to use full ahead and hard over rudder heading outbound when ships were added to the scenario because of the loss of this area.

e. Pilots heading outbound from Houston also use this bend ease area in conditions where they need to make a wider turn. The outbound runs from Houston indicated no issues and the pilot was able to line up with the gate opening.

f. Currents at the jetties appeared to have been impacted by the structure, however pilot indicated currents behaved as expected.

g. Runs with scaled up currents increased difficulty in making the turn and required a wider turning area, again leaving no room for error.

h. Representatives from Galveston-Texas City Pilots and Houston Pilots strongly suggested against the Alignment 1 location. The merging of vessels through the meeting area is the primary concern.

Alignment 2:
The second proposed location of the gate structure is shifted approximately 0.5 mile east of Alignment 1. After simulation runs and discussions with the pilot, it was determined that this location provided increased maneuverability over Alignment 1.

a. The passing ships through the structure did not have a significant effect on transit. Vessels are usually lined up by the time they get to the location of the structure.

b. The turn outbound can require up to 30° of rudder to complete the maneuver and is typical in existing conditions.

c. Runs using scaled up currents presented the pilot with a stronger set east of the structure through the entrance of the jetties. An increase of rudder was required in this area.

d. Pilot felt more comfortable with this alignment because of the greater distance away from the congested meeting area. The placement on the straight leg of the channel was more adequate having no immediate turns.

No data analysis is included as part of the FLSSP as the purpose is to examine the feasibility of the gate structure alignments in the Coastal Texas Study in the CHL simulator, and to use pilot feedback as input for developing a range for feasible widening options. A more rigorous testing of the design is to be conducted during the PED. The visual databases are to be updated to include more detail.

9. FEASIBILITY PHASE RECOMMENDATIONS

For the feasibility phase, CESWG should consider the following recommendations. This can be refined further in the PED phase ship simulations.

a. Alignment 2 as the location for surge barrier
b. Additional feasibility testing with at least two pilots. This would provide a second pilot's input and would also allow testing of passing ships with the full hydrodynamic interactions.

For future PED phase ship simulations, the following is recommended:

a. Refined hydrodynamic modeling with the actual structure outline. An additional alternative using closed environmental gates to simulate flow only going through the main gate opening.

GCCPRD

The Gulf Coast Community Protection and Recovery District

STORM SURGE SUPPRESSION STUDY

PHASE 4 REPORT

November 30, 2018

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1. Executive Summary

In December 2013, The Gulf Coast Community Protection and Recovery District (GCCPRD) received a Community Development Block Grant (CDBG) from the Texas General Land Office (GLO) for the Upper Texas Coast Storm Surge Suppression Study. The purpose of the study is to investigate the feasibility of reducing the vulnerability of the upper Texas coast from storm surge and flood damages. The study evaluated numerous alternatives that could be implemented which would reduce the risk of storm surge flooding to life, health, and safety of the community and provide environmental and economic resilience within the study region. In June 2016, the GCCPRD published the Phase 3 report, which recommended a plan of action for the six-county area. The recommended plan identified the need to construct a new storm surge suppression system in Orange and Galveston Counties as well as the enhancement of existing systems in Jefferson, Galveston, and Brazoria Counties. The cost of the recommended plan was estimated at $13.6B with a regional benefit-cost-ratio (BCR) of 2.03.

In December 2016, the GCCPRD received funding to execute Phase 4 of the study. Phase 4 focused on optimizing the previously published recommended plan. Optimization measures included the following elements:

- Enhanced storm and wave modeling
- Optimization of the crest elevation for the Coastal Spine in the Central Region
- Economic impacts
- Environmental analysis
- Bolivar Roads barrier and gate design
- Wave overtopping and interior drainage analysis
- Cost review
- Geotechnical field investigations
- South Region alignment enhancements

1.1. Regional Summary

1.1.1. North Region Conclusions: Jefferson and Orange Counties

Phase 4 optimization did not change the recommended alignment or levee heights from the 2016 recommended plan. The construction costs were updated to reflect 2018 versus 2015 pricing, which increased the overall construction costs by 6 percent. The BCR in all of the elements within the North Region decreased. This can be attributed to the increase in construction cost and modifications that were made to the stage frequency and structure foundation height survey data that were provided to the study team by The U.S. Army Corps of Engineers (USACE).

1.1.2. Central Region: Chambers, Harris, and Galveston Counties

The crest elevation for the Coastal Spine did not change from the 17-foot elevation that was in the 2016 recommended plan. Lowering the elevation reduced the construction cost and increased net benefits, but only provided protection from the 50-year event. FEMA requires a 100-year level of protection for its Flood

Insurance Program, so this alternative was not feasible. Raising the elevation to 20 feet resulted in an increase in cost and a decrease in benefits. Seventeen feet was determined as the optimal height.

In the recommend plan, an 840-foot floating sector gate with 24, 100-foot vertical lift gates was recommended for the barrier crossing of the Houston Ship Channel at Bolivar Roads. Further environmental analysis and modeling determined that this structure should be 1,200 feet or larger in order to increase the tidal flow and reduce the potential environmental impacts to Galveston Bay. An alternate barrier design, the 1,200-foot floating sector with 15, 200-foot barge gates and 8 vertical lift gates was also analyzed. The barge gate increased the tidal flow and reduced the construction cost; however, it is much more complex to operate and maintain. The final configuration of the Bolivar Roads barrier will require further analysis and investigation to reduce the potential impacts to tidal flow to an acceptable level.

A more detailed analysis was also conducted to evaluate the effect of overtopping at the Galveston Seawall and its influence on the interior drainage and pumping requirements within the Galveston Ring Levee. The analysis showed that the pumping requirement within the ring levee increased from 7,400 cubic feet per second (cfs) to 117,000 cfs, which increased the cost of construction by $1.7B.

The overall cost of construction increased from $7.8B to $10.1B. This cost increase can be attributed to increasing the size of the floating sector gate from 840 feet to 1,200 feet, the increased pumping cost, and the 6 percent escalation that was used to update the construction cost to 2018 values. The increase cost combined with the updates to the stage frequency and structure foundation height survey data resulted in a final region BCR of 1.61.

1.1.3. South Region: Brazoria County

In the South Region, a new alignment for the Eastern Extension of the Freeport Hurricane-Flood Protection System (FHFPS) along FM 523 was adopted into the plan. In the 2016 plan, the alignment extended from the eastern terminus of the levee north toward the City of Angleton. The optimized plan extends the levee generally along FM 523 north to the City of Angleton. The new levee system will reduce the risk to 20,000 additional acres of land in the region where current and future residential and industrial development is expected to occur. The new alignment reduces the overall construction cost in the South Region by $100M; from $2.5B to $2.4B. The reduction in the construction cost is not enough to keep the overall BCR from dropping from 1.47 to 0.81. The decrease in the BCR is again attributed to the updates in the stage frequency and depth damage curves and the structure foundation height survey data.

Table 1 provides a consolidated summary of the economics analysis for each region. All benefits and costs are presented in thousands of dollars and reflect 2018 price levels.

Table 1: Consolidated Economic Analysis for the Six-County Region

	North Region	Central Region	South Region	Study Area Plan (North + Central + South)
Total length of the system (miles)	87	69	69	225
Pump stations required / total capacity (CFS)	22/29,650	4/127,900	5/10,925	31/168,475
Construction cost ($ thousands)	3,983,517	10,120,836	2,440,767	16,545,120
Annual Operations and Maintenance cost ($ thousands)	19,918	50,604	12,204	82,726
Total Annual Costs (TAC)	205,646	522,479	126,000	854,125
Total Annual Benefits (TAB)	126,431	842,287	102,097	1,070,815
Benefit - Cost Ratio (TAB/TAC) (2.875% Interest Rate)	0.61	1.61	0.81	1.25

Comparing the Phase 4 optimization to the 2016 recommend plan, construction costs for the entire region increased by $2.9B; from $13.6B to $16.5B. The increase is directly related to the increased cost for the 1,200-foot floating sector gate and the additional pumping capacity required for the Galveston Ring Levee. The overall BCR for the entire study region fell from 2.03 to 1.25.

2. Introduction

The upper Texas coast, stretching from Orange County to Brazoria County, has historically attracted people and industry to the region to take advantage of a multitude of economic opportunities and quality of life amenities. This six-county region is home to over 6 million people, the largest concentration of petrochemical complexes in North America, six of the top fifty ports in the United States, NASA's Johnson Space Center, and a highly productive coastal estuary system of national significance. The region is vitally important to the security of the national economy and the nation's energy sector. (Figure 1)

The study area is comprised of more than 4,300 square miles of land vulnerable to storm surge flooding associated with hurricanes and other tropical storm events. History has proven that Texas remains most vulnerable to large storms from June to October. The frequency of hurricanes along any 50-mile segment of the coast is about one storm event every nine years. Annual probabilities of a storm event range from 31 percent in the Sabine Pass Region to 41 percent in the Matagorda Region.

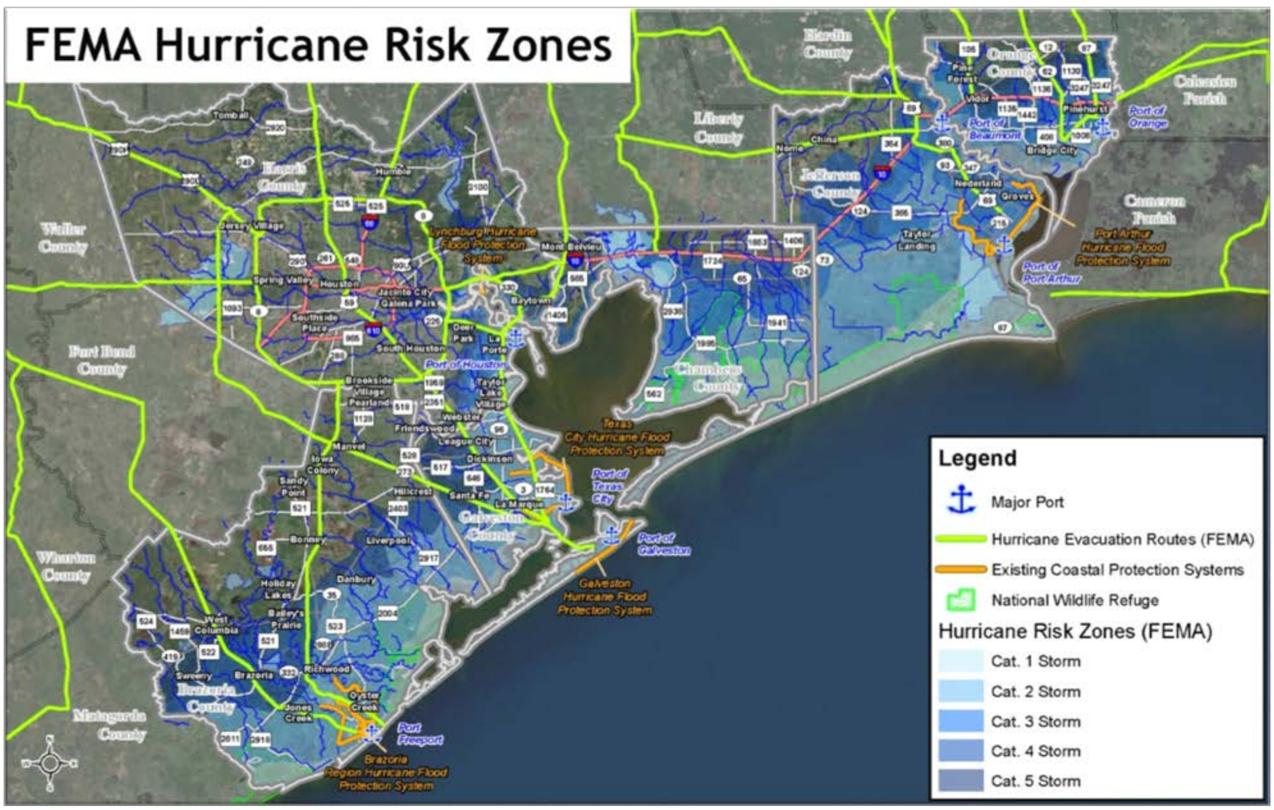


Figure 1: FEMA map illustrating coastal areas within the study area vulnerable to storm surge

In 2008, Hurricane Ike made landfall on the Texas coast in the vicinity of Galveston Island, causing 84 deaths and over $30 billion in damages. In 2017, Hurricane Harvey caused over $125 billion dollars in damages along the Texas Coast. These events clearly illustrate that additional flood risk mitigation measures are required throughout the region.

2.1. 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 this 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 Dean Crooks– Orange County
- Lisa LaBean – At-large Member
- Jim Sutherlin – At-large Member
- Victor Pierson – At-large Member

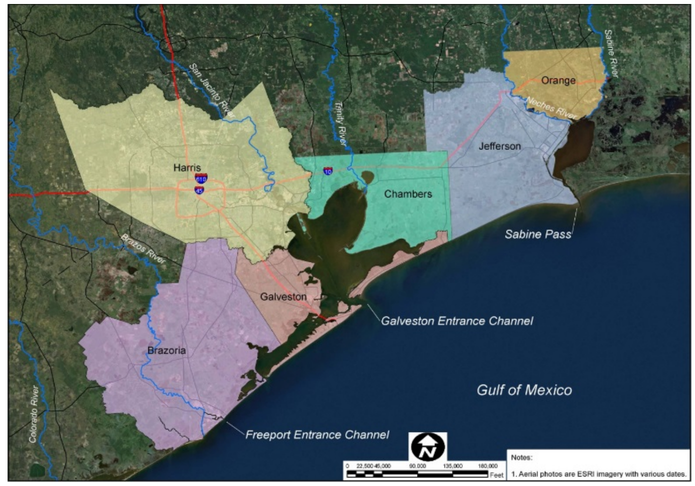


Figure 2: GCCPRD study area

Robert Eckels serves as President of the District and is appointed by the Board.

In September 2013, the GCCPRD received a $3.9 million grant funded by the Texas GLO through the Federal Housing and Urban Development (HUD) Community Development Block Grant (CDBG) Program to conduct the Storm Surge Suppression Study, which was completed in June 2016. In December 2016, an additional CDBG grant of $3.2 million was received to conduct additional analysis in order to optimize the recommended plan.

2.2. 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.

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, would better protect the region from future natural disasters associated with storm surge flooding events.

2.3. The Recommended Plan

In June 2016, the study team completed their initial study efforts and published the Storm Surge Suppression Study Phase 3 Report: Recommend Actions. The recommended actions identified specific structural solutions that should be implemented to reduce risk within the three geographic regions of the study area. The three regions are:

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

Figure 3 graphically illustrates the proposed alignments for the new structural features included in the recommended plan. ***The proposed alignments were studied to develop the concept for the recommended plan and should not be considered as final. It is expected that during the preliminary engineer and design phase of the project that the alignments will be adjusted to resolve potential technical, environmental and social conflicts.***

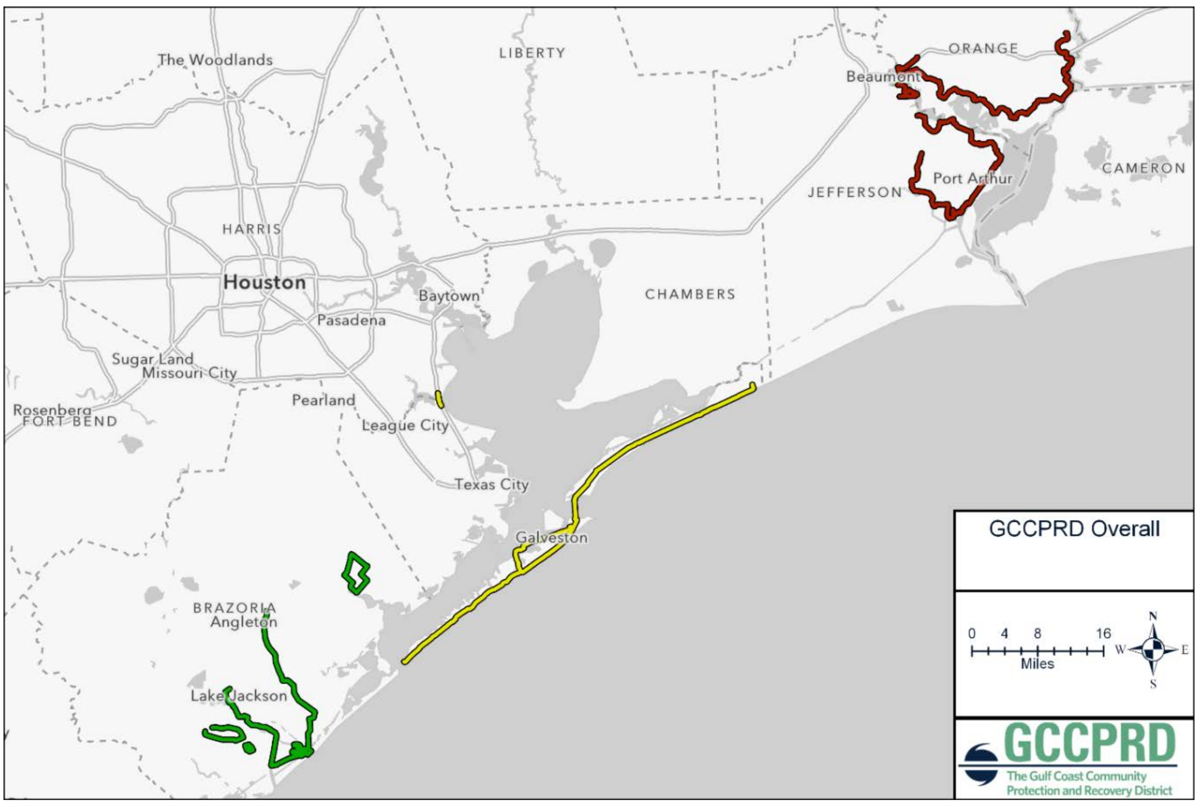


Figure 3: Alignments for Recommended Plan

The recommended plan includes the following elements:

- North Region – Enhancements to the existing Port Arthur Hurricane Protection System (PAHPS), Orange County Sabine River Levee, Orange County East bank of the Neches River Levee and Jefferson County West bank of the Neches River Levee
- Central Region – High Island to San Luis Pass Coastal Spine with a gate at Bolivar Roads (referred to as the "Coastal Spine"), the Galveston Ring Levee, and the Clear Lake Gate structure

- South Region – Enhancements to the existing Freeport Hurricane Protection System (FHFPS) and the Buffalo Camp Levee, Jones Creek Levee, Jones Creek Terminal Ring Levee, Chocolate Bayou Ring Levee, and the extension of the FHFPS along FM 523 to Angleton

The overall cost of the recommend plan was $13.6 billion and had a region-wide BCR of 2.03. The Phase 3 Report can be found at www.gccrd.com and is included as **Appendix A** to this report.

2.4. Phase 4 Optimization

The scope of work for Phase 4 focused on optimizing the recommended actions from the Phase 3 Report. Optimization included a more detailed environmental analysis, which enabled the study team to refine the recommended actions to reduce potential environmental impacts and cost and increase the project benefits. Optimization measures included:

- Enhanced storm and wave modeling
- Optimization of the structure's crest elevations
- Return frequency analysis
- Economic impacts
- Environmental analysis
- Bolivar Roads barrier and gate design
- Wave overtopping and interior drainage analysis
- Cost review
- Geotechnical field investigations
- South Region alignment enhancements

3. Phase 4 Optimization Measures

3.1. Storm Surge and Wave Modeling

During Phase 2 of the study, the study team executed extensive storm surge modeling for the years 2035 and 2085 to evaluate structural design elevations for each proposed alternative and to analyze storm surge related damages. The storm surge modeling provides the required data by evaluating flood hazards throughout the project region for hundreds of possible hurricanes and by accounting for potential future conditions including sea level rise in the model setup.

The coupled Advanced Circulation (ADCIRC) and Unstructured Simulating WAves in the Nearshore (UnSWAN) model system was improved and validated during these prior study phases. Model improvements included reduced friction dissipation in deep water and the Louisiana-Texas shelf, refined model resolution, and an integrated local instability smoother. The updated model was validated against high-water mark (HWM) data from Hurricane Ike, and the majority of differences between modeled and measured data were less than ±0.5 feet. Modeling scenarios were developed that analyzed the current conditions, the future without action (FWOA) in 2035 and 2085, and the future conditions with the alternatives (FWA) in place for 2035 and 2085.

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. The suite of 254 storms included 152 high-intensity and 71 low-intensity storms from the Texas Federal Emergency Management Agency (FEMA) Flood Insurance Study (FIS) storm suite (FEMA 2011), as well as 31 high-intensity storms from the Louisiana FEMA FIS storm suite (United States Army Corps of Engineers [USACE] 2008a and 2008b) with landfall locations near the Louisiana-Texas border. To simulate conditions for year 2035 and year 2085, the initial water level was increased by 0.94 feet and 2.44 feet, respectively, to reflect potential future relative sea level changes.

The FWOA configurations implemented existing storm risk management alignments and were used as a control to compare the effects of proposed alternatives during the FWA in place scenarios. This comparison process led to the selection of the recommended plan that was published in the GCCPRD Phase 3 Report in June 2016.

Appendix B provides a more detailed report for the storm surge modeling.

3.2. Optimization of Crest Elevations

In Phase 4, the validated ADCIRC and UnSWAN model was applied to two new FWA alternatives within the Central Region in order to optimize the crest elevations for the structures. Optimization of the crest elevations in the North and South Regions were not reevaluated based on a similar analysis conducted by USACE in their Sabine Pass to Galveston Study, which defined their optimal crest elevations.

The new FWA alternatives evaluated the costs and benefits associated with increasing and decreasing the levee height of the Coastal Spine elements and the Clear Lake Gate. The alignment for these systems based on the recommended plan was not changed.

The three FWA scenarios are referred to as FWA.a 2085, FWA.b 2085 and FWA.c 2085 and are described below:

- FWA.a 2085 – Crest elevation of the Coastal Spine and the Clear Lake system is maintained at 17 feet, based on the recommend plan.
- FWA.b 2085 – Crest elevation of the Coastal Spine is increased to 20 feet and Clear Lake system is reduced to 15 feet (new alternative)
- FWA.c 2085 – Crest elevation of the Coastal Spine is decreased to 15 feet and Clear Lake system is increased to 17 feet (new alternative)

Simulation results were reviewed and processed to create a dataset of individual storm surge peaks at all points of interest, which were used to estimate return interval stillwater levels.

3.3. Return Frequency Analysis

After completing the 254 storm simulations for each modeling scenario, the USACE Joint Probability Analysis (JPA) Model was used to combine the results of the storm simulations to calculate the 10-, 50-, 100-, and 500-year stillwater elevations for each of the modeling scenarios (FWOA 2035, FWOA 2085, and the three

FWA scenarios). Sensitivity tests, model optimization, and a thorough review of the results were completed to confirm the quality of the output statistics. The 10-, 50-, 100-, and 500-year stillwater elevations were also extrapolated to determine the 1-, 2-, 5-, and 10-year frequencies. By calculating the return stillwater elevations, the JPA Model allows the effects of each modeling scenario configuration to be compared and assessed. The following figures show the 100-year stillwater elevations throughout the region for multiple-model scenarios.

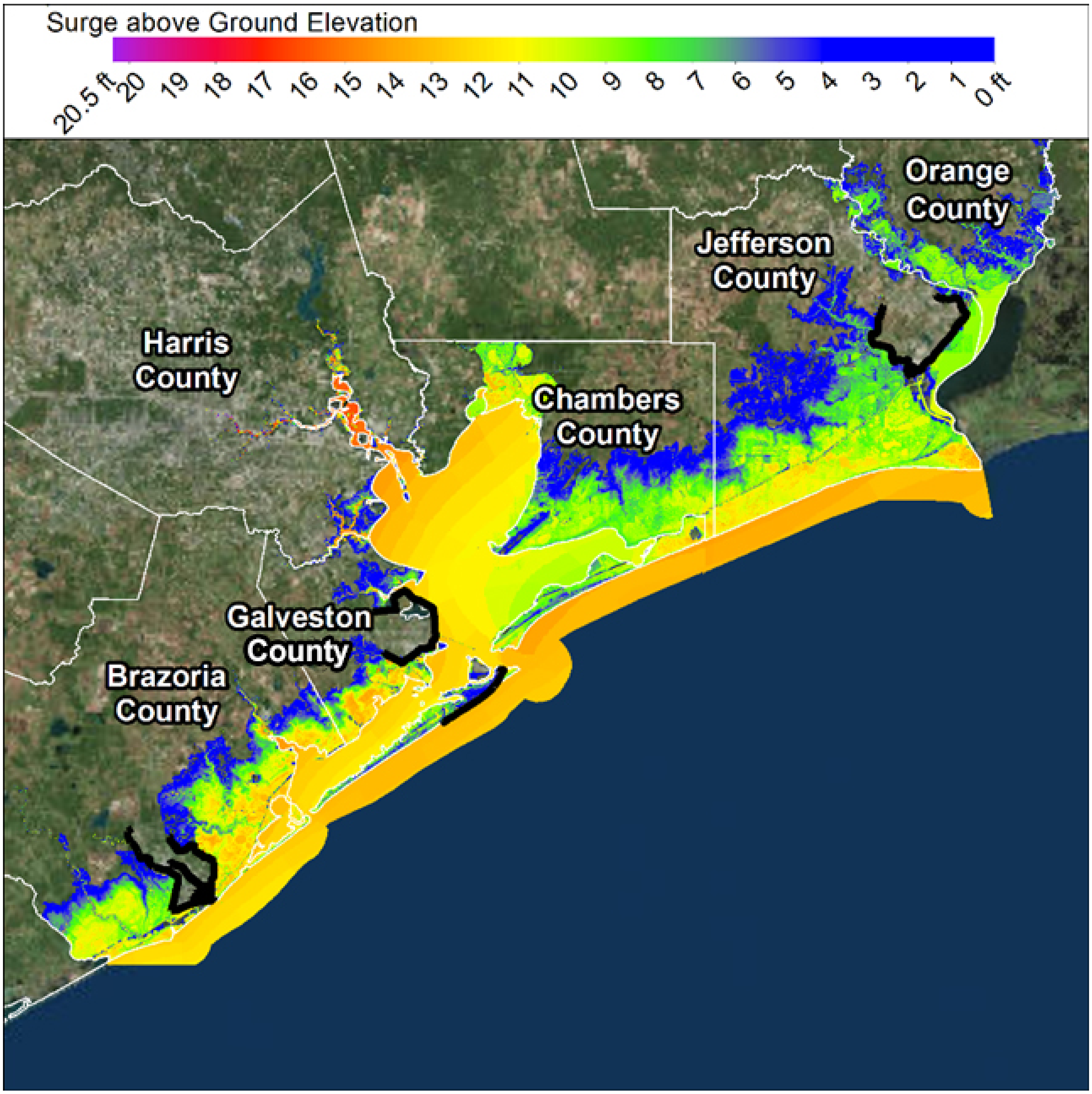


Figure 4: 100-year stillwater elevations for Current Conditions. Data referenced from FEMA 2008 FIS Map

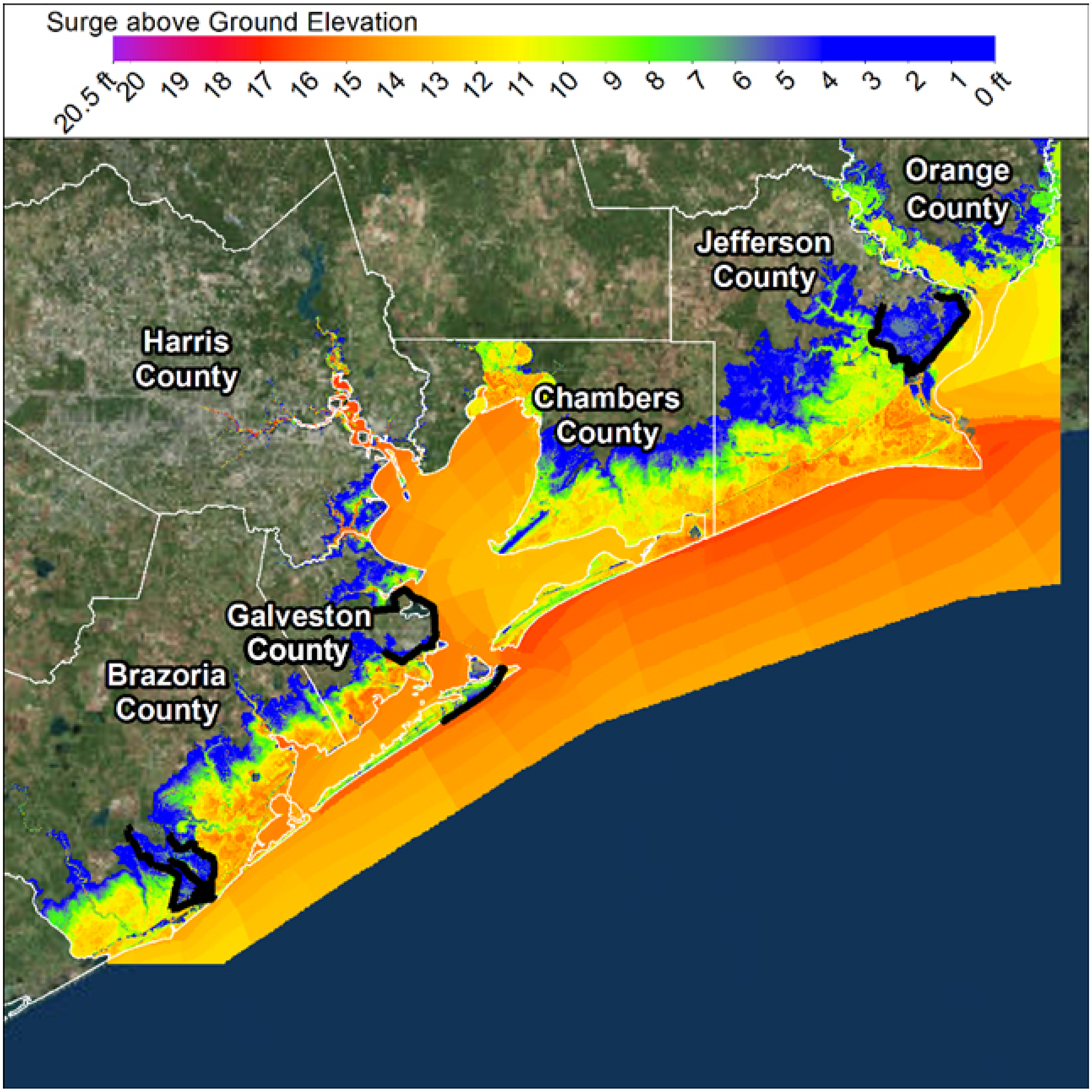


Figure 5: 100-year stillwater elevations for FWOA 2035 conditions. This model scenario includes 0.9 feet of Relative Sea level Rise

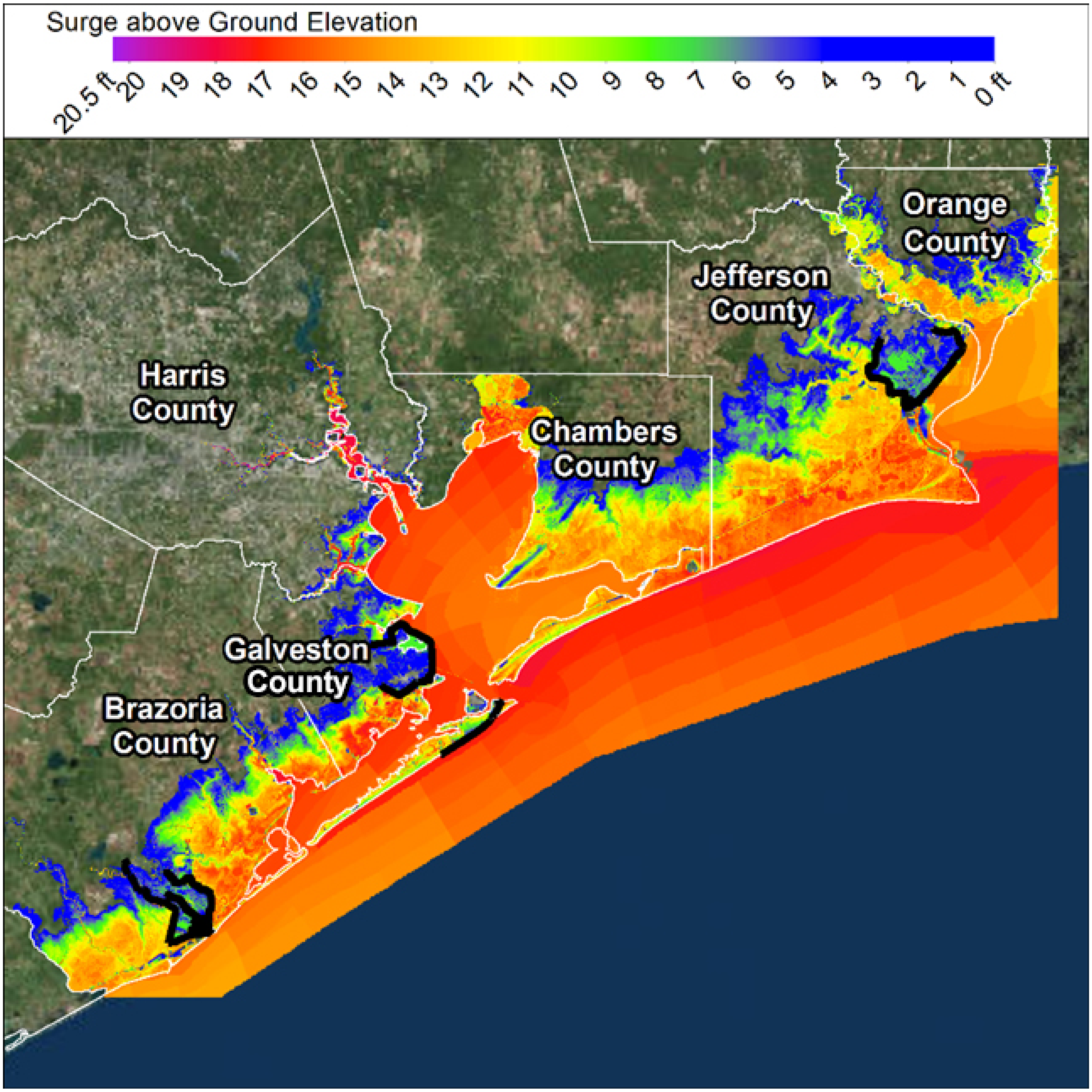


Figure 6: 100-year Stillwater elevations for FWOA 2085 conditions. This model scenario includes 2.4 feet of Relative Sea level Rise

The JPA model also allowed the study team to do additional analysis of interior flooding/ponding behind the levee systems. In order to understanding the flooding risk in an enclosed area, the overtopping rates for various return frequencies were estimated and input into the interior ponding analysis, which integrated the overtopping volume from the levee reaches and 25-year rainfall events. This analysis enabled the team to further refine and optimize interior drainage pumping requirements.

The estimated and stage frequency curves (including 1-, 2-, 5-, 10-, 20-, 50-, 100-, 200-, and 500-year frequency), after undergoing a quality assurance/quality control (QA/QC) check, were inputted into the USACE Hydrologic Engineering Center – Flood Damage Reduction Analysis (HEC-FDA) model for damage assessment and economics analysis.

3.4. Economics Optimization

The economic optimization measures incorporated during Phase 4 of the study build upon the work previously presented in the June 2016 GCCPRD Phase 3 Report and should be viewed as a supplement to that previous report. The additional analyses reported in this current phase focused on refinements and updates made to the previous analyses.

3.4.1. Damage Reach Designation

The review of the 2017 (HEC-FDA) model results revealed opportunities to streamline the modelling structure with minimal change to the required level of output detail. Streamlining took the form of damage reach consolidation. This consolidation reduced the original 41 damage reaches to 26. In addition to consolidation, the current analysis also added one damage reach to allow for incremental economic evaluation of a proposed project feature. The combined effect of these changes resulted in a total of 27 damage reaches for the current analysis, which is displayed in Figure 7.

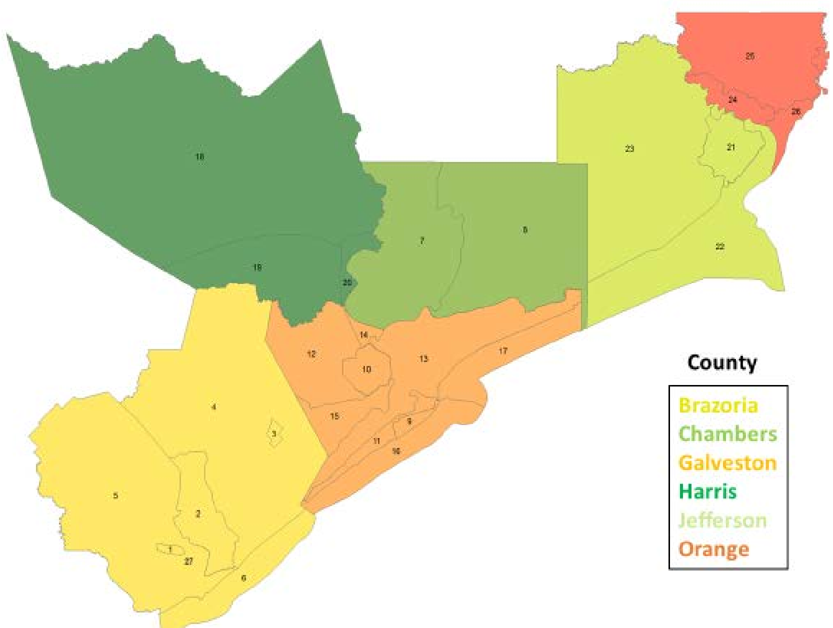


Figure 7: HEC-FDA Damage Reaches

The HEC-FDA model results were combined with project alternative cost information to perform benefit-cost analysis. Benefit-cost analysis was used to verify that the value of the benefits exceeded the value of the costs and ensured the resources would be allocated in the most efficient manner possible.

Benefit-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 preferred over 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-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 BCRs indicate which alternative produces the most benefits for every dollar of cost, it is useful for comparing or ranking alternatives when investment budgets are constrained.

Section 7 of the Phase 2: Technical Mitigation and **Appendix C** of this report provides additional details on the economic modeling approach and the methodology used.

3.5. Expanded Environmental Analysis

One of the key elements of Phase 4 of the study was to expand on the environmental analysis that was previously conducted to better quantify the potential environmental impacts that could occur with the implementation of the recommend plan. This analysis was conducted in two phases.

3.5.1. Phase 1: Enhanced Environmental Analysis of the Recommended Plan

Phase 1 was focused on the in-depth analysis of the potential environmental impacts that would occur with the construction of the recommended project alignments and structural features. A separate analysis was conducted for each region, and potential impacts were summarized on a regional basis. The analysis included the review and execution of the following National Environmental Protection Act (NEPA) elements:

- Clean Water Act Sections 303(d), 401, 402, and 404
- Rivers and Harbors Act 1899
- Floodplains, Wild and Scenic Rivers, and Coastal Barriers
- Socioeconomic impacts
- Cultural Resources
- Prime and Unique Farmlands
- Federal Water Project Recreation Act
- Biological resources- vegetation, marine and estuarine habitats
- Wildlife – invertebrate, migratory birds, fish, reptiles, terrestrial and marine mammal species
- Essential Fish Habitat
- Threatened and Endangered Species
- Air quality and greenhouse gas
- Hazardous waste
- Noise

This analysis included field inspections to verify habitat type and assess potential impacts. The study team used the Wetlands Value Assessment (WVA) model to determine mitigation requirements. Throughout this phase, the study team coordinated closely with USACE to ensure the latest models and baseline data were used for model setup. **Appendices D.1-D.3** contain the entire environmental report subdivided by region.

3.5.2. Phase 2: Environmental Modeling of Galveston Bay

Phase 4 also focused on defining the potential direct and indirect impacts of the proposed gate structure at Bolivar Roads on the Galveston Bay system. This modeling effort focused on the simulation of water levels, currents, and salinity due to astronomic tides, wind-driven water levels, and fresh water inflows throughout the bay. The selected models (Deltares D-Flow Flexible Mesh [D-Flow] and Advanced Circulation [ADCIRC]) demonstrate a high level of efficiency in simulating the physical dynamics of the bay while also being computationally efficient enough to simulate many different gate configurations.

This modeling effort was closely coordinated with USACE, Texas A&M University (TAMU)-Galveston, and the SSPEED Center at Rice University who were conducting similar modeling efforts. Each respective organization was using a different model for their analysis and by working together, the teams were able to gather and share the most up-to-date baseline data for the model setup. Using the same baseline data will allow all the teams to compare and a conduct a peer review of the results once all the efforts are complete. The outputs from this modeling effort defined and illustrated the following changes in conditions associated with the different gate configurations:

- Salinity
- Circulation, tidal and sediment impacts
- Discharge velocities
- Benthic habitat
- Marine and estuarine habitats
- Invertebrate species
- Fish and wildlife species

The data, the potential impacts, and the required mitigation costs were integrated into the cost of the overall plan. **Appendix E** contains the full report for the environmental modeling on Galveston Bay.

3.6. Bolivar Roads Barrier and Gate Optimization

Three alternative gate designs, which represent varying percentages of permanent cross-sectional blocking of the Houston Ship Channel, were evaluated for Bolivar Roads. The following sub-sections further discuss the details of structural gates within the barrier alternatives. Relative advantages and disadvantages of the barriers will be discussed along with constructability, operation and maintenance, and time required to close the gates. A discussion of the relative costs for all three alternatives will follow. The three alternatives for the Houston Ship Channel that will be discussed are:

1. GCCPRD840 – Features 54.8 percent permanent closure
2. GCCPRD1200 – Features 52.8 percent permanent closure
3. GCCPRD1200-Barge – Features 38.5 percent permanent closure

3.6.1. GCCPRD840

In the Phase 3 Report, an 840-foot floating sector gate was included in the recommended plan. This is the minimum width that is needed to span the ship channel in order to safely accommodate two-way traffic through the gate. This estimate was derived by reviewing the characteristics (draft, beam width, etc.) for the current and future fleet of vessels and assuming a potential future expansion of the Houston Ship Channel to a depth of 60 feet.

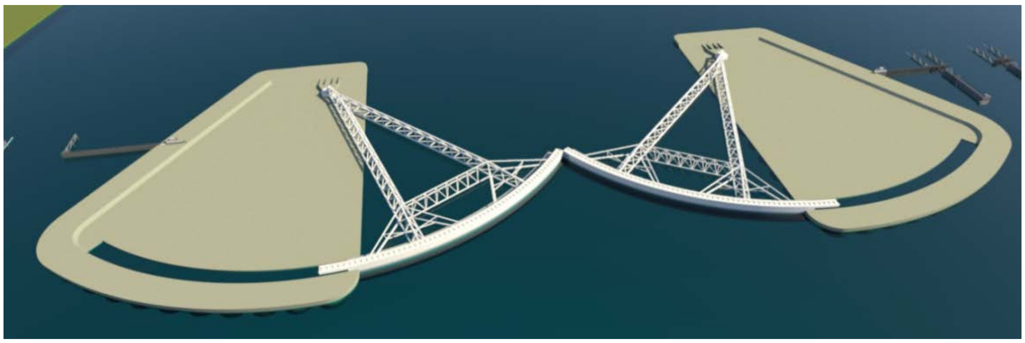


Figure 8: Floating Sector Gate and Artificial Island

As seen in Figure 8, the floating sector gate is comprised of two steel gate leaves and two artificial islands on either side. During regular channel operating conditions, the gate leaves rest on the island in their dry dock. During the time of closure, the dry docks are flooded and the gate leaves float up. These are then mechanically driven to position them in the middle of the 840-foot opening. Once in place, the gate chambers that act as flood barrier are filled with water and submerged to the bottom sill.

The flood barrier portions on either side of the artificial island of the floating sector gate consists of 24 vertical lift gates (VLG), Figure 9. The actual opening that is formed by a steel panel is 100 feet wide. This panel travels up and down mechanically as needed and is hosted on a concrete monolith and a tower on either side. The whole arrangement sits on a pile-supported concrete foundation slab. The concrete monoliths on both sides constitute 50 feet of permanent blockage of the waterway.

Figure 9: Bolivar Roads Floating Sector Gate with Vertical Lift Gates

Along the barrier, the space between adjacent VLG monoliths are permanently blocked using combi-wall sections. These are comprised of vertical and battered, concrete-filled steel pipe piles with a concrete cap on top that ties all of the piles.

The GCCPRD840 alternative blocked 54.8 percent of the channel cross-section permanently. This can have an extensive and long-lasting negative impact on growth and sustenance of aquatic life, vegetation, and geomorphology of the region.

3.6.2. GCCPRD1200

In order to further minimize the environmental impact a second alternative was developed: the GGCPRD1200 gate. This GCCPRD1200 widens the floating sector gate from 840 feet to 1,200 feet. The famous Maeslant Barrier in Rotterdam, Netherlands features a floating sector gate which is 1,200 feet wide. Because that gate has been in service for over 20 years, its width was considered as a natural choice for selecting a wider floating sector gate. The remainder of the closure structures for this alternative is comprised of 24 VLGs, similar to the GCCPRD840 alternative.

Since the sector gate leaves are larger and wider, there was a requirement to make the artificial islands broader to receive and fully protect the gate leaves. As such, even though the opening through the ship channel increased, longer lengths of the barrier were occupied by the islands on either side of the floating sector gate. Consequently, a minor increase in the amount of opening within the flood barrier was achieved, and a total of 52.8 percent of the waterway was still blocked.

3.6.3. GCCPRD1200-Barge

Analysis of the barrier alternatives previously discussed proved that the arrangement of the sector gate and combination of the VLGs was inadequate for lowering the permanent blockage of the tidal exchange through the ship channel to make it environmentally viable. One option to overcome this scenario could be to increase the number of VLGs throughout the barrier. However, that option would drive the cost of the entire barrier higher. It was imperative that a more economic closure structure be identified so that more openings through the barrier can be achieved at a lower cost. This resulted in the third option evaluated: the GCCPRD 1200-barge gate.

Information about the existing in-service barge gates in the United States was obtained and the feasibility of installing such gates within the barrier were investigated. The study team found that there are a number of these gates deployed in south Louisiana varying with a closure width of 100 feet to 270 feet. The largest barge gate installed is named Bubba Dove, located near Dulac, Louisiana, and boasts a total height of 43 feet. It should be noted that previous analysis confirmed that the VLGs need to span a vertical height from elevation (EL) -30.0 to EL +18.0; resulting in a total height of 48 feet. Thus, the Bubba Dove gate was considered a reasonable alternative for such application within Bolivar Roads.

The study team evaluated a barrier composed of the 1,200-foot wide floating sector gate, and fifteen (15) 200-foot-long barge gates and reduced the number of 100-foot VLGs to eight. Using the latest bathymetric profile of the channel cross-section through the proposed alignment, the deepest part of the channel (EL -60.0) will be blocked by the span of the 1,200-foot floating sector gate. The channel sill on either side of the artificial islands is located at an average elevation of EL -30.0, which is an ideal depth for the 48-foot-tall and 200-foot-long barge gates. On the north end of the barrier, the sill elevation depth is between EL -5.0 and EL -10.0, which is capability for the use of VLGs in these shallower depths. As before, the portions of the barrier between adjacent closure features will be blocked using combi-wall sections. Figure 10 below shows a three-dimensional (3-D) representation of this barrier option.

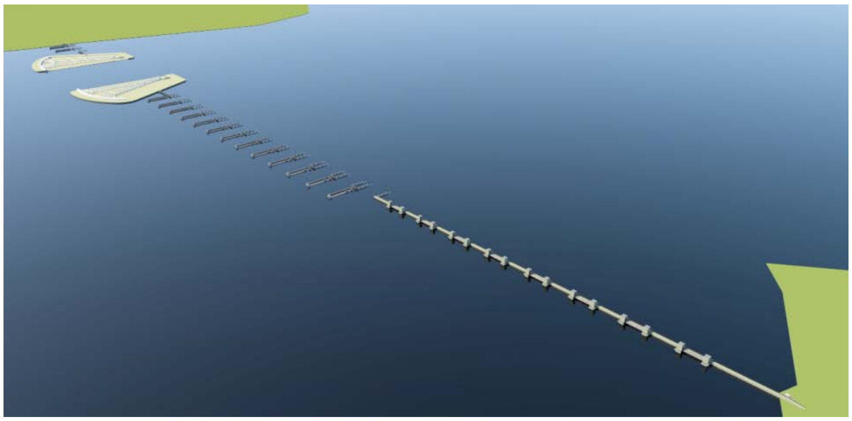


Figure 10: GCCPRD1200-Barge Alternative

The combination of the 1,200 ft. sector gate, barge gates and VLGs reduced the permanent blockage along the alignment to 38.5 percent.

3.6.4. Barge Gate Details

A series of barge gates are proposed in the GPPRD1200-Barge option. The reports from the previous phases described the structural details of floating sector gates, VLGs, and combi-wall segments. Since the barge gate is a newly introduced option, more details about this of type of closure structures are discussed below. Figure 11 illustrates the conceptual barge gate.

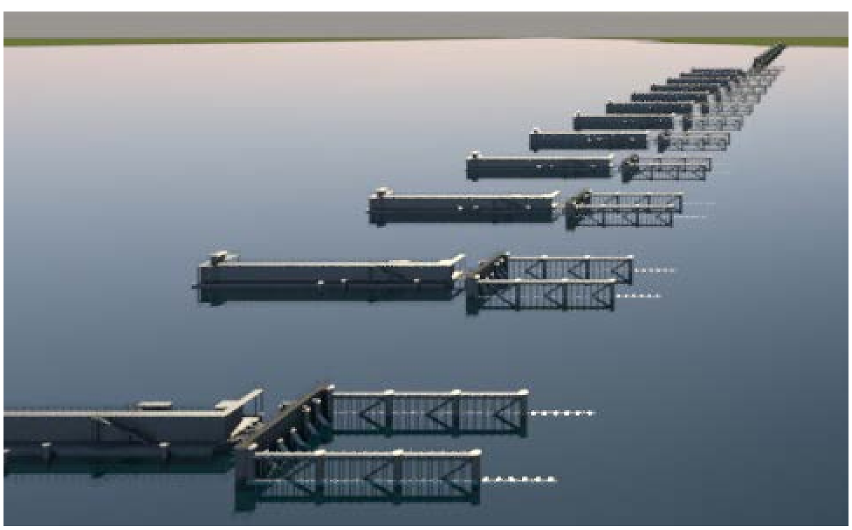


Figure 11: Series of Barge Gates

3.6.4.1. Structural Components

3.6.4.1.1. Chamber & Flood Wall

The barge gate is a steel structure which has two major components:

- A hollow steel rectangular chamber
- A 10- to 13-foot flood wall positioned on top of the chamber. The flood wall portion of the barge gate will constitute the top 10 to 13 feet of the barge gate height. The rest of the height is represented by the chamber itself.

The hollow chamber portion is equipped with an electro-mechanical pump system that can fill or drain the chamber within 1 to 2 hours. The chamber walls will be constructed with steel plates with additional bracing members in side. The chamber section is also equipped with a number of 6-foot diameter steel pipes that pass through the barge gate from the flood side to the protected side. These pipes will be fitted with mechanized sluice gates that will restrict flow of water through the gate.

The flood wall component on top of the barge gate chamber can be made from either concrete or steel. The walls may be fortified using stiffeners so that they can withstand the water pressure equal to their height. The flood wall portion provided space on the protected side of the barge gate on top of the chamber structure to house generators and other electro-mechanical controls. The flood walls are also somewhat offset from the flood side edge of the gate providing a platform on top of the chamber. This allows to have a platform on the flood side for personnel to perform periodic inspection and maintenance.

On top of the barge gate there will also be an operator's room which will house the winch mechanism that will close and open the gate. Figure 12 shows the details of a barge gate.

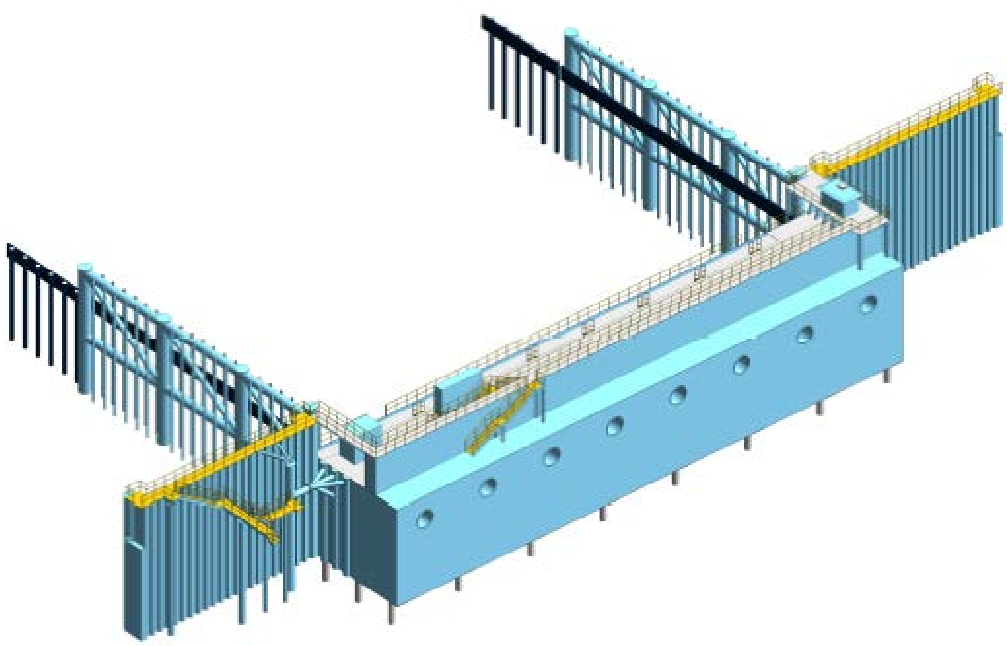


Figure 12: Barge Gate & its Components

3.6.4.1.2. Receiving Structure

In its deployed position, the barge gate needs to transfer the hydrostatic, hydrodynamic, and impact forces to a structure that can absorb the loads and safely transmit them to the ground. These structures are placed on either side of the barge gate and are referred to as "receiving structures." Each receiving structure comprises of a frame-like structure made from steel pipe piles, often filled with sand or grout and capped with concrete. For this current span of 200 feet, a four-pile frame was envisioned with the first pile close to the gate having a diameter of almost 8 feet. The other piles within the receiving structure will be smaller. To make the system efficient to resist lateral loads, the piles will have diagonal bracings which are also tubular. All the pile head tops will be connected with a top chord. A similar member parallel to the top chord will be provided at mid height of the pile length that will be sticking out of the ground. Based on further analysis, these connectors and diagonals can be repeated several times to make the receiving structures stiffer.

3.6.4.1.3. Gate Pivot

At one end of the barge gate, along the length of the span, it will always be connected with a pipe pile that will act as the pivot point when the gate moves from open to close position and vice versa. Since the gate will always open toward the flood side, the pivot pile will also be placed on the flood side. The pivot will not be designed to sustain any loads when the gate is deployed. The pivot to gate connection will be done in a manner so that the two can be disconnected if there is a requirement to float the barge gate to a dry dock for repair.

3.6.4.1.4. Barge Gate Foundation

Each barge gate will require two foundations. When the gate is open, the barge itself will rest on a foundation that is laid out perpendicular to the alignment. This foundation is placed on the flood side since the gate opens toward that direction. The second foundation is required to sustain the weight of the gate once it is closed. This foundation will be placed parallel to the barrier alignment and is adjacent to the receiving structures.

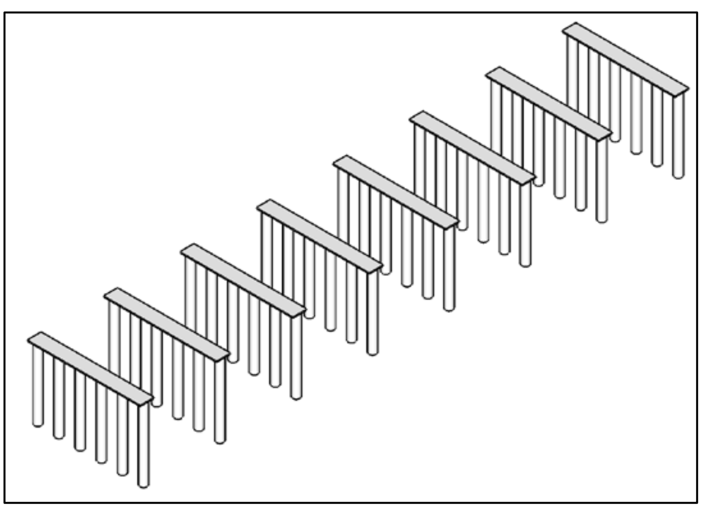


Figure 13: Barge Gate Foundation Pile Bents

As seen above in Figure 13, the foundation of the barge gate will be comprised of steel pipe piles. There is no need to install a concrete foundation slab. The gate sits on a series of pile bents that will be placed perpendicular to the span length of the barge. The number of pile bents is determined based on the total deployed weight of the gate. Each pile bent has a series of pipe piles that will be connected at the top using thick plates. The thickness of these plates is also determined from the distribution of weight of the barge gate. The top of the foundation will be placed near the existing sill elevation of the cross-section, so it is not necessary to perform a substantial amount of dredging. Riprap will be placed close to the pile bent tops for a distance before and after the bents. This will prevent scour at the pile bents. If needed, the minimal depth of riprap (2 to 3 feet) can be grout stabilized as well.

3.6.4.1.5. Tie-in Wall

A total of 15 barge gates is currently considered for the GCCPRD1200-Barge alternative. Adjacent barge gates will be placed 80 feet apart. The space between two barge gate structures will be closed using combi-wall segments. These will also be used to tie-in the barge gates at the periphery to the sector gate artificial island, VLGs, or adjacent land on higher grounds.

3.6.4.1.6. Barge Gate Operating Mechanism

When the flood barrier is not closed, each barge gate will rest on the foundation perpendicular to the alignment. This will allow tidal exchange through the 200-foot gate span. At this point the chamber within the barge gate will be full of water, producing enough ballast so that the gate will not be moved due to wave action. The gate will also be anchored to another a large pile that will be located on the flood side.

At the wake of a flood event an operator will start the pumps on the barge gate so that water will be drained out of the chamber and the gate will begin to lift due to buoyancy. At this point the barge will ride up along the vertical height of the pivot pile. Once the barge gate is buoyant enough, the winch rope will be tied to a pile close to the receiving structure. A boat will be required for this operation. Once the rope is fastened, the operator will start the mechanized winch, which will gradually pull the barge towards the receiving structure. Once in place, the pumps will be active again filling up the chamber with water. This will gradually ballast the gate and it will sit on top of the other foundation parallel to the alignment. Once the gate is sufficiently submerged, the pumps will stop and the gate will be fastened with the receiving structure. At this point the barge gate will be fully deployed and ready to take the loads from the storm surge. If required, the 6-foot diameter sluice gates within the gate can be opened remotely so that water can pass through from the protected side to the flood side.

Once the storm surge has subsided, the process will be repeated in reverse to stow the gates. The winch system is a critical system component to the operation of the gate, and in the event of a failure the gate can also be opened and closed using a tug boat.

3.7. Interior Drainage

Multiple areas within the region are protected by existing and proposed levee systems. Systems that are closed such as the FHFPS, the PAHPS, the proposed Galveston Ring Levee, and the Clear Lake Gate structure require pump stations to facilitate interior drainage and reduce the risk of interior flooding. During a tropical event, interior flooding is dominantly affected by the storm surge overtopping the levee system rather than the rainfall associated with the event.

Interior drainage for the existing and proposed levees included sizing pumps and mapping the floodplains for rainfall and storm surge scenarios of varying annual recurrence intervals for each proposed levee alignment established in Phase 3 of the study. The interior drainage pumping requirements associated with each levee alignment were sized to maintain internal flooding levels that result in minimal ponding and damage to properties and structures for a hurricane that simultaneously produces a 25-year internal rainfall event within the levee polder and a 100-year storm surge that overtops the designed levee. The pump sizing and requirement from this phase of the study are used to refine the cost and the overall BCR for the project through a comparison of the FWOA and the FWA 2085 scenarios.

3.8. Cost Analysis

During Phase 2 of the study, a data 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 study 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. Operations and Maintenance costs were estimated to be 0.5 percent of the total construction cost for each element.

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 gate complex crossing the Houston Ship Channel at Bolivar Roads, where a 40 percent contingency was used due to the extreme complexity and the varying dynamics associated with this structure.

During Phase 4 of the study, costs were escalated from the original 2015 United States Army Corps of Engineers Civil Works Construction Cost Index System to reflect 2018 values.

Section 6.0 of the Phase 2 Report discuss in more detail the cost methodology. **Appendix G** details the Phase 4 costs associated with each respective element and alternative by region.

3.9. Geotechnical Investigations

During Phase 4, the GCCPRD performed geotechnical investigations in the six-county region along the three regional alignments that were in the Phase 3 recommend plan. This work included the integration of existing subsurface soil data to create a GIS soil model and collection of new geotechnical data, culminating in preliminary geotechnical recommendations. These recommendations are in the form of a preliminary geotechnical report (Fugro Report No. 04.10160148 dated October 18, 2017), summarized in the following sections and located in **Appendix H:**

- Geological Site Assessment
- Field Investigation
- General Site Conditions
- Surge Protection Systems
- Additional Geotechnical Considerations

3.9.1. Geological Site Assessment

The geological site assessment of the preliminary geotechnical report contains a review of regional geology, stratigraphy, surface faulting, subsidence, salt domes, and expansive soils along the Texas Gulf Coast. The regional geology portion includes a review of tectonic activities that led to the formation of Texas, identifying major rivers and land features, and providing surface elevation data along the Gulf Coast. In the stratigraphy portion, the historical and prehistoric periods of the formation of Texas are examined to support the identification of soils and sediments which make up the Texas Gulf Coast. Surface faulting and salt domes were examined along the Texas Gulf Coast to determine whether the three regional alignments are in proximity to known growth faults. Based on the preliminary report, the alignments are not in proximity to known growth faults; however, the alignments are in proximity to several salt domes. The State of Texas has groundwater management entities which control the rate of subsidence caused by withdrawal of water from underground reservoirs. The Harris-Galveston Subsidence District (HGSD) is an agency located in Groundwater Management Area 14 which lies within the six-county region. The preliminary geotechnical report provided subsidence observations monitored by HGSD. In addition, expansive soils are commonly found in the near-surface stratigraphy throughout the Texas Gulf Coast. These soils have high potential for swelling and shrinking with seasonal fluctuations and could impact the performance of the proposed structural alternatives for the storm surge suppression systems.

3.9.2. Field Investigation

The purpose of the field investigation was to identify the subsurface conditions (e.g., encountered soil and groundwater conditions) along the Central Recommended Alignment (Coastal Spine), and South Recommended Alignment. USACE performed their own investigation in the North Region as a part of their Sabine Pass-Galveston study. The data from that study were incorporated into the report. Field exploration activities included performing geotechnical soil borings and piezocone penetration tests (CPT's). Figure 14 shows the geotechnical soil borings and CPTs performed along the Central Recommended Alignment (Coastal Spine).

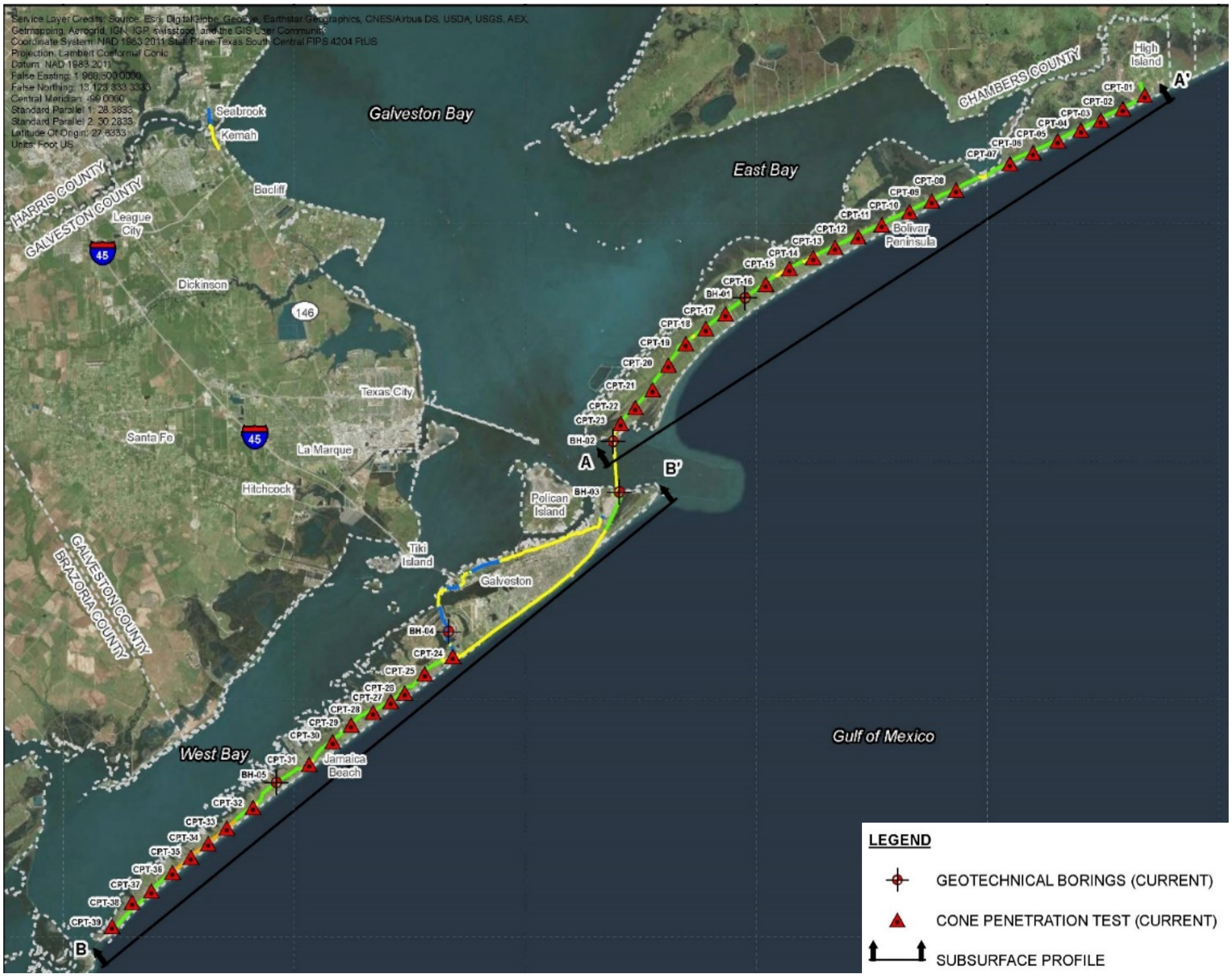


Figure 14: Plan of Explorations – Central Recommended Alignment (Coastal Spine)

3.9.3. Geotechnical Soil Borings.

The eight geotechnical soil boring operations were undertaken with a truck-mounted drilling equipment with a three-person crew. Six soil borings were explored below the ground surface to a depth of 50 feet, and two soil borings were explored below the ground surface to a depth of 400 feet. At each soil boring, the truck-mounted drilling equipment was used to drill soil borings and obtain soil samples at depth. The soil samples were transported to the laboratory for testing purposes.

<u>Piezocone Penetration Test (CPT's).</u> The 54 CPT's were conducted using our truck-mounted CPT equipment with a two-person crew. Each CPT was performed to a depth of about 60 feet below the ground surface. During CPT operation, no soil samples were collected. The CPT equipment utilizes a cone to advance into the ground to gather information on the soil stratigraphy.

3.9.4. Generalized Subsurface Conditions

The generalized subsurface conditions were developed based on reviewing geotechnical investigations performed by others and the current geotechnical data obtained by Fugro. Descriptions of the soil stratigraphy were provided for the Coastal Spine and the South Recommended Alignment only. No information was provided for the North Recommended Alignment because Fugro had limited access to obtain current geotechnical data along this alignment. In general, alternating layers of cohesive and granular soils were observed along areas of the Central Recommended Alignment (Coastal Spine) and the South Recommended Alignment. Figure 15 shows the Generalized Subsurface Profile Section A-A' along the Coastal Spine.

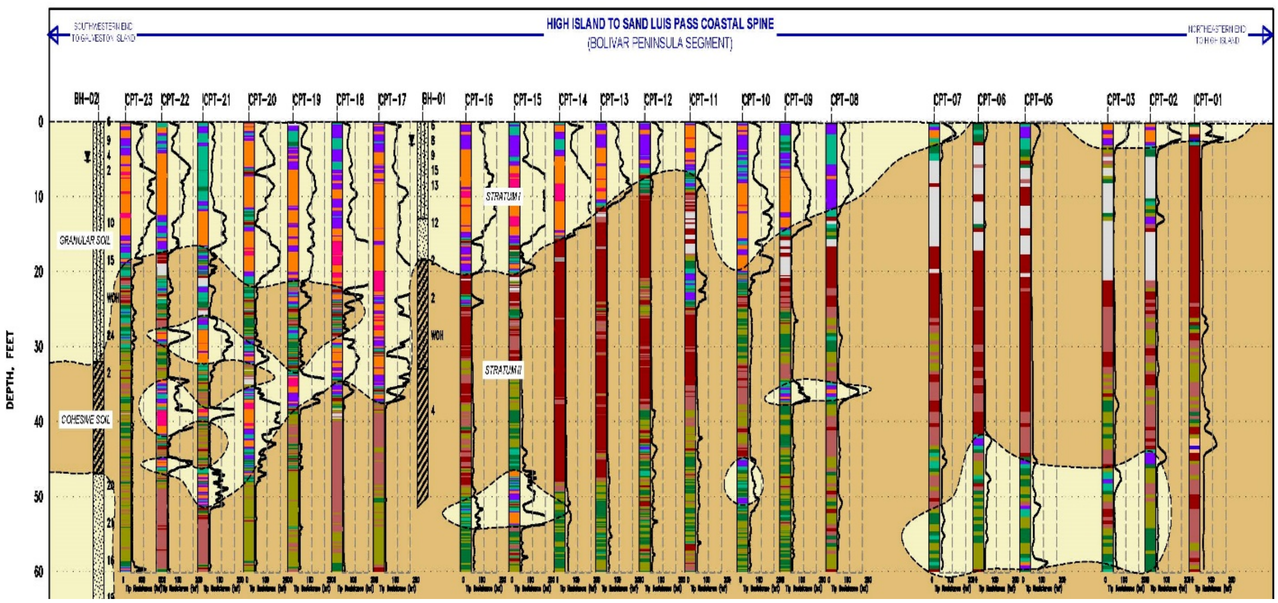


Figure 15: Subsurface Profile Section A-A': Central Recommended Alignment (Coastal Spine)

3.9.5. Additional Geotechnical Considerations

The geotechnical information collected during Phase 4 was used by the study team to identify areas along the alignment that may require additional structural stabilization. These factors were considered as we optimized the alignments and project costs.

The GCCPRD understands and recommends that a more detailed geotechnical study be performed prior to the design phase of the storm surge suppression system. The detailed geotechnical study should include performing additional land and marine borings/CPT's along all three alignments. The additional land and marine borings/CPT's should be performed where data gaps are present as well as at locations where the earth levees/T-walls and associated structures have a significant offset from the current soil borings/CPT's. These detailed geotechnical analyses should be performed for the earth levees, T-walls, the floating sector and barge gates, and the vertical lift gates once the updated information on these structures is available.

3.10. South Region Alignment Adjustments

During Phase 4, an alternate alignment for the extension of the FHFPS was evaluated. The modification involves realigning the recommended extension of the FHFPS east along SH 288 towards Angleton, to a new Freeport East Levee section along FM 523. The adjustment was made to provide additional protection to residential and commercial structures west of FM 523 by preventing storm surge from wrapping around the east side of the existing FHFPS alignment in 2085.

The new alignment along FM 523 protects approximately 20,000 additional acres over the previous alignment. Additional assets protected include south east Angleton, numerous residential neighborhoods, and the DOW Chemical Intermediates Plant.

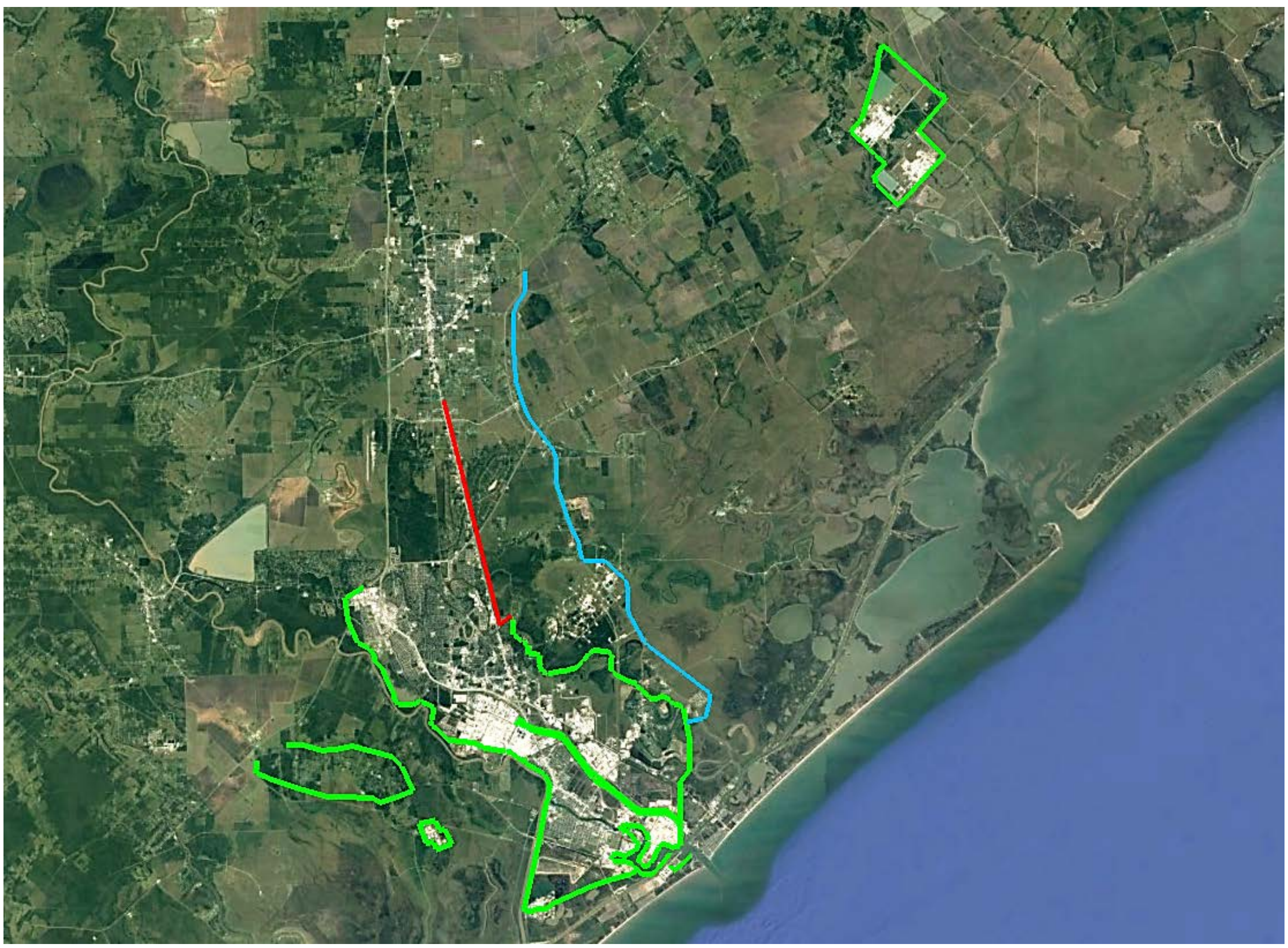


Figure 16: South Region Alignment (Green: Unchanged from the recommended plan, Red: Original alignment for the Freeport Levee Extension, Blue: New alignment for the extension evaluated in Phase 4 along FM 523)

4. North Region Optimization Results

4.1. General

The North Region of the GCCPRD jurisdiction consists of Orange and Jefferson Counties. The two counties are separated by the Neches River, which terminates into Sabine Lake, along with the Sabine River, which forms the eastern boundary of Orange County and the eastern boundary of the State of Texas. The southerly boundary of Orange County is Sabine Lake and the Sabine-Neches Canal. Jefferson County reaches to the Gulf of Mexico on the south and is bordered by Chambers and Liberty Counties on the West and Hardin County (Pine Island Bayou) to the north.

On September 13, 2008, the region was significantly affected by Hurricane Ike. In Orange County, the surge generated by Ike caused widespread flooding in industrial, commercial, and residential areas. The cities of Orange, Bridge City, West Orange, Pinehurst, Vidor, and Rose City, as well as unincorporated areas suffered extreme damages. Approximately one-third of the City of Orange was flooded, and primarily included the downtown and commercial districts of the city. Rose City also suffered major damages from the surge that traveled up the Neches River. Virtually 100 percent of Bridge City was flooded including most residential and commercial properties. It is estimated that only 15 of approximately 3,000 homes in the entire city were not flooded by Hurricane Ike's surge. The "chemical row" area of Orange County also received major damage. Total estimated damages including production losses exceeded $500 million.

In Jefferson County, Sabine Pass and rural areas south of the Cities of Beaumont and Port Arthur were similarly impacted by the surge generated by Ike. Except for low-lying areas along the Neches River, Beaumont was largely un-impacted, with the exception of the Exxon-Mobil plant facility situated on the western bank of the Neches River. Large parts of this facility were flooded with reported damage and production losses in the $1B range. The City of Port Arthur and the large petro-chemical complex in south Jefferson County were protected from surge impacts by the Port Arthur Hurricane Flood Protection System. This protection system, completed in the late 1970s, consists of earthen levees, floodwalls, gate structures and pump stations, and was largely constructed as a Federal Project by the USACE. The system performed as designed and prevented the damage seen in Orange County from occurring along the west bank of the Neches River in Jefferson County.

4.2. Phase 3: North Region Recommended Plan

The North Region recommended plan consists of four reaches that provide regional protection to Jefferson and Orange Counties.

Reach 1- Orange- Sabine River Levee – This reach consists of a line of protection that 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 and 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. The highway and roadway crossings are modified by grade elevations, and railroads will need to pass through gate structures. Elevations in this reach vary from 15.5 feet to 24.5 feet.

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 Interstate 10. This reach is composed of 125,278 feet of new levee, 10,433 feet of T-wall, 19 new drainage structures, 3 new pump stations, and 24 roadway gates. Elevations in this reach vary from 18 feet to 22.5 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 teams 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, and modification or reconstruction of 10 railroad gates, 15 roadway gates, and 29 drainage structures. Elevations in this reach vary from 15 feet to 24.5 feet.

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, 5 new pump stations, and 16 drainage structures. Elevations in this reach vary from 20 feet to 17 feet. Figure 17 illustrates the recommended plan for the North Region and the system crest elevations.

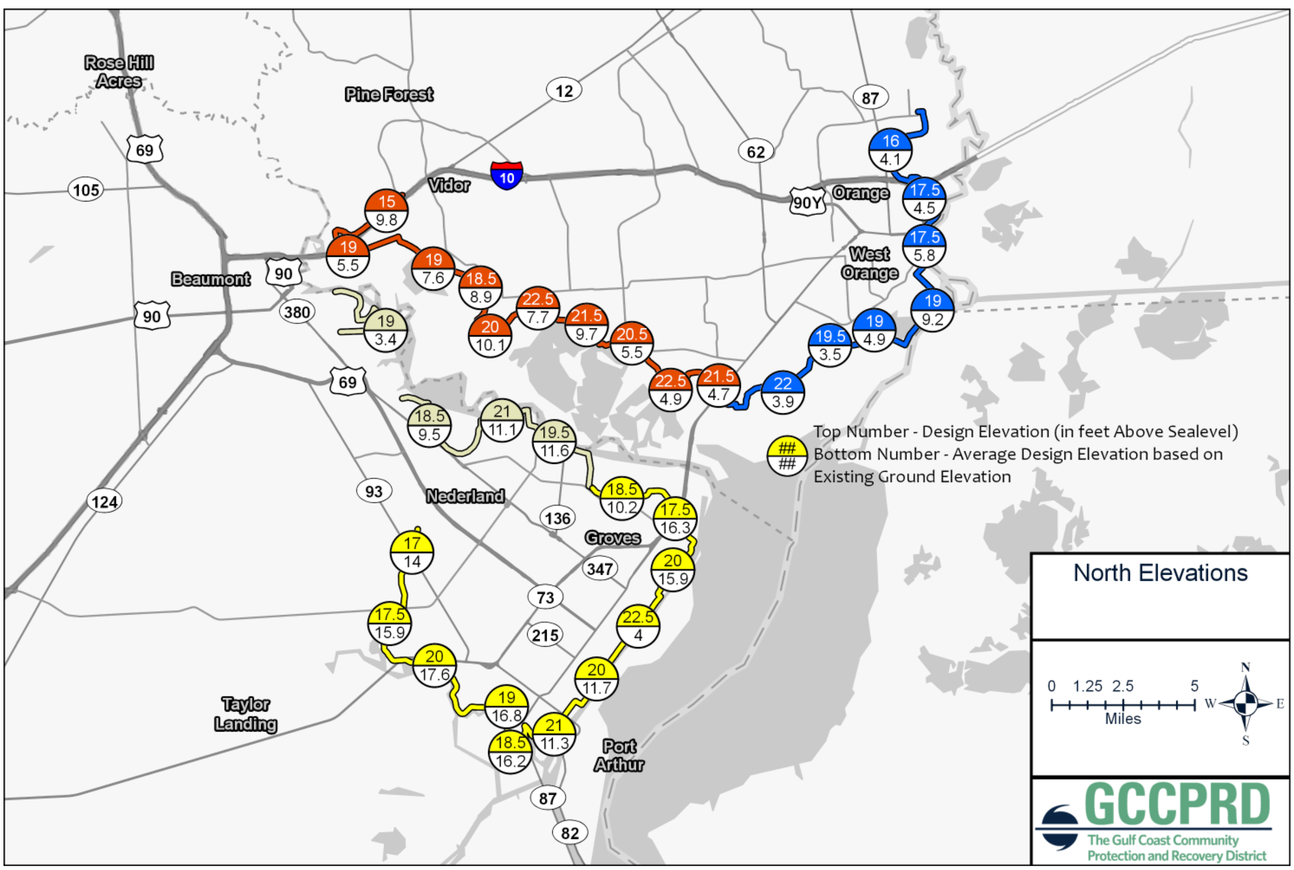


Figure 17: North Region Recommended Plan

4.3. Optimization Measures

The optimization process for the North Region consisted of the following steps:

- Comparison of alignments and lengths to USACE Sabine Pass to Galveston Study
- Separate examination and analysis of interior water levels for the Orange system and the Port Arthur system
- Enhanced Environmental analysis
- Revision of cost and economics based on the more detailed technical and environmental analysis

4.3.1. Comparison and Analysis of USACE Sabine Pass to Galveston Study

The USACE Sabine Pass to Galveston study (SP2G) recommended a protection system for Orange and Jefferson Counties that differs from the recommendation developed by the GCCPRD study team. In Orange County, the system along the east bank of the Neches River was truncated by the USACE due to economic factors. The GCCPRD study extends the system along the East bank of the Neches River to I-10 providing protection for the cities of Rose City and Vidor. Both cities experienced significant flooding during Hurricane Ike. Orange County officials requested this extension to ensure all citizens within the county received the same level of risk reduction. County officials also expressed concern that they would not be able to pass a future bond referendum for payment of their cost share if citizens within the county were excluded from the plan.

In Jefferson County, the USACE SP2G study includes a limited extension of the Port Arthur Hurricane Protection System along the west bank of the Neches River. The GCCPRD found that extending the system along the west bank of the Neches River would provide additional benefits and provide enhanced protection to the City of Beaumont and industry located along the river, especially the Exxon-Mobil facility. This facility sustained over $1B in damages and lost production associated with Hurricane Ike alone.

In February 2018, The Bipartisan Budget Act fully funded the recommendations in the USACE SP2G feasibility study. This is a positive step forward to providing and enhancing coastal storm surge protection for Jefferson and Orange Counties. The additional elements recommended by the GCCPRD study were not included in the overall budget. These elements remain viable and could be integrated into the system later by either local government authorities or the federal government.

4.3.2. Interior Water Levels and Drainage

4.3.2.1. Interior Drainage and Overtopping

The optimization process, as it relates to interior drainage and overtopping, consisted of development of overtopping models to predict flows and additional consideration of existing model information for interior drainage. This was necessary to account for a range of rainfall events as well as overtopping flows, which would occur in less frequent events.

Drainage system studies exist in Orange County and Jefferson County Drainage District No. 7 (DD7). For DD7, the existing studies consist of detailed hydrology and hydraulics models for every watershed and drainage facility within the district boundary. The modeling was developed for each separate watershed and utilized for identification and design of potential improvements within each of the watersheds, and they were utilized for Levee System Accreditation through FEMA.

In Orange County, broad, general models were developed as part of a study of a potential Hurricane Protection System in the aftermath of Hurricane Ike. Detailed models of Cow and Adams Bayous, which drain a majority of the east half of the county, were developed more recently and were utilized to develop a drainage improvement master plan for those two watersheds. The remainder of the county has not had detailed studies conducted.

To the extent possible, the existing studies were utilized to develop pumping requirements and gate and drainage structure sizes for the interior drainage of each system. For DD7, the levee and pump station systems already exist. For this study, it was determined that the older, less efficient pump stations would be replaced with new ones. The extensive system of gates and drainage structures were considered adequate in size, but each system is included for upgrade or replacement. Upgrades would include lengthening and/or the installation of positive closures.

For Orange County, no current storm surge protection system exists, and development of a levee system would necessitate a system of pump stations to drain the interior of the system during storm surge conditions. The previously mentioned studies in Orange County were utilized for development of pumping requirements and gate and drainage structure sizes in those watersheds. In un-modeled areas within the county, regional regression equations were used to develop runoff quantities for gate and structure sizing and pumping requirements.

For the purposes of optimization of the top elevation(s) and for consideration of additional pumping requirements of the systems in Orange and Jefferson Counties, the study team decided to utilize a broad, hydrologic modeling approach for each of the systems, which would not be as tedious as individual watershed models and would more efficiently deal with the analysis of potential overtopping of the proposed (and existing) protection systems. Overtopping of the levee systems would be expected when a storm event occurs in excess of the design event.

The following section describes the methodology used for the overtopping analysis.

4.3.2.2. Overtopping Methodology

The 2011 U.S. Geological Survey (USGS) National Elevation Dataset (NED) topographic information for the area was obtained from the Texas Natural Resources Information System (TNRIS) to develop drainage areas and stage volume relationships within the leveed areas. The study team determined that the best method to use for the determination of water surface elevations within the leveed areas during a storm surge event would be to model the areas using HEC-HMS.

The drainage area into each leveed area was determined based on the topographic information. For the Orange County area this was approximately 316 square miles with approximately 77 square miles draining into the Port Arthur area. The SCS Curve number loss method was used based on a curve number of 80 for both areas. The Clark Unit Hydrograph was used for the "transform method" for creation of the runoff hydrograph into the leveed areas.

Based on this methodology the precipitation excess for the Orange County basin was 9.49 inches for the 25-year, 96-hour event. For this event, the excess precipitation in the Port Arthur drainage area is 10.87 inches. This results in a total internal runoff of 160,069 acre-feet for the Orange County drainage area, and 44,496 acre-feet for the Port Arthur drainage area.

For the overflow rates for each frequency, the segment associated with each levee and the flows for each levee were determined by adding the flows for each segment associated with the levee. Because the overflows were based on cfs/ft for each segment, the flows for each segment were multiplied by the length of the segment in feet to obtain the total cfs for each segment at each time step. The flows for the segments were then summed at each time step to obtain the total inflow to the leveed area at each time step. The overflow rates for each levee for each frequency were input to the HEC-HMS model as discharge gage flows.

The HEC-HMS model had each basin connected to a reservoir. The storage-elevation data for each leveed area as determined from the topographic data was input for each of the reservoirs. A stage-discharge relationship for each leveed area reservoir was input based on the total pumping capacity of each leveed area. For the Port Arthur area, the existing total pumping capacity was used. For the Orange County area, it was assumed that nine pump stations with a total capacity of 16,000 cfs would be used.

The basins were connected to the reservoirs to simulate the inflow of the internal runoff. Sources were created using the overtopping discharge gage flows and connected to the reservoirs to simulate the inflow of the expected overtopping.

Based on the overtopping rates provided, there is essentially no overtopping for the 50- and 100-year events on either levee in the with-project condition. There are approximately 470 acre-feet (ac-ft) of overtopping volume for the 200-year event for the Orange County levee, and approximately 926 ac-ft for the Port Arthur levee. The 500-year overtopping volumes are approximately 17,175 ac-ft for the Orange County levee and 27,515 ac-ft for the Port Arthur levee.

Based on the HEC-HMS analysis, the Port Arthur system pumps approximately 28,240 ac-ft, and the Orange County system pumps approximately 157,667 ac-ft for the 200-year event. The peak storage for the Orange County system was 33,227 ac-ft, and the peak storage for the Port Arthur system was 33,281 ac-ft.

Table 2 illustrates the peak storage and the required pumping capacity for the overtopping associated with a 200-year surge event and a 25-year interior rainfall event.

Table 2: North Region Pumping Requirements

Location	Peak Storage Volume	Total Pumping Volume	Pump Stations Required
Jefferson County	926 Ac-Ft	6,100	16
Orange County	470 Ac-Ft	16,000	9

The peak storage values from the HEC-HMS model were used to determine the water surface elevation based on the stage-volume curves. These elevations were then mapped in GIS to determine the inundation areas.

4.3.3. Environmental Review

This section provides a summary of the potential environmental impacts associated the construction of the North Region system. The full North Region environmental report is located in **Appendices D.1-D1.2**.

During Phase 4, the study team conducted a more thorough review of the potential environmental impacts that would be associated with the construction of the four reaches in the North Region. In order to estimate potential impacts, the study team assumed that the proposed levee and T-wall system would have a 150-foot-wide footprint. This enhanced assessment included: field investigations conducted along publicly accessible rights-of-way, additional desktop analysis, coordination with USACE, and calculating future mitigation requirements using the WVA model. The costs associated with mitigation were incorporated into the overall project cost and considered in the BCR calculations.

Impacts to the following were minor and insubstantial:

- Prime and Unique Farmlands
- Socioeconomic Impacts
- Protection of Children from Environmental and Safety Risks
- Federal Water Project Recreation Act
- Executive Order 11990: Protection of Wetlands
- Section 303(d) of the Clean Water Act: Impaired Streams
- Section 402 of the Clean Water Act
- Wild and Scenic Rivers
- Coastal Barriers
- Vegetation
- Executive Order 13112 on Invasive Species
- Executive Memorandum on Environmentally and Economically Beneficial Landscaping
- Migratory Birds and the Migratory Bird Treaty Act
- Fish and Wildlife Coordination Act
- Bald Eagle Protection Act of 1940
- Air Quality
- Greenhouse Gas Impacts
- Noise

The primary potential impacts are described in the following sections.

4.3.3.1. Cultural Resources

A preliminary assessment of the cultural resources within the North Region Alternative was conducted using a combination of a desktop review of the Texas Historic Sites Atlas (THSA) and further confirmation of the mapped sites during a site visit. The Area of Potential Effect (APE) for the North Region Alternative would be the 150-foot buffer, 75-feet on either side of the proposed alternative for direct impacts on historic resources. There would be a 1,500-foot buffer for indirect impacts on standing structures or buildings.

A direct impact is determined if the site is within the 75-foot buffer that lies on either side of the proposed wall or levee. An indirect impact is determined if the site is within a 750-foot buffer that lies on either side of the proposed wall or levee.

There are three National Register Listings along the proposed North Region Alternative proposed vertical wall. The first is the Rose Hill National Register District, which was listed on October 31, 1979, and the official address is 100 Woodworth Boulevard, Port Arthur Texas. This is the address of the actual structure, though now it is part of Rose Hill Park. The property line for this parcel extends past the existing structure, according to the Jefferson County Appraisal District. The property itself could be indirectly impacted, depending on the level of ground disturbance. The structure on this property is called the Woodworth House.

The second National Register Listing is Eddingston Court and was listed on September 8, 2004. The official address is 3300 Procter Street. According to the Jefferson County Appraisal District, the parcel line for this historic site ends approximately 30 feet from the current existing seawall. The property could be directly impacted depending on modifications to the existing vertical wall and could be indirectly impacted depending on the level of ground disturbance.

The third National Register Listing is named Navy Park Historic District and was listed on November 18, 1999. This site would be considered an indirect impact because it is approximately 740 feet from the proposed alternative.

During the field visit, a potentially historic site was identified as the Arcadia House. This site was noted because the structure appeared to be eligible for the Historic Sites Atlas. If this site is deemed eligible, it would be considered an indirect impact since it is outside of the 150-foot direct impact APE, but is within the 1,500-foot indirect impact buffer.

Based on the current information for the proposed levee construction and improvements, 14 structures could be directly impacted, eight structures could be indirectly impacted, and one additional structure could be indirectly impacted if eligible for the Historic Site Atlas.

4.3.3.2. Texas Parks and Wildlife Code, Chapter 26

The proposed project would be located within the boundaries of Joe Hopkins Memorial Park, Ochiltree Inman Park, Oak Bluff Memorial Park, Port Neches Park, Rose Hill Park, and Lions Park as well as the Lower Neches Wildlife Management Area (WMA) Nelda Stark, Lower Neches WMA Old River, Adams Bayou WMA, and Tony Houseman WMA which are all Chapter 26 properties. A Public Hearing is required and would be held during the National Environmental Policy Act (NEPA) process in accordance with Chapter 26 requirements.

4.3.3.3. Section 404 of the Clean Water Act: Waters of the U.S.

Desktop surveys using U.S. Fish and Wildlife Services' (USFWS) National Wetland Inventory (NWI) maps, USGS 7.5-Minute Topographic Quadrangle maps, Federal Emergency Management Agency (FEMA) Flood Insurance Rate Maps (FIRM), aerial photographs and limited site surveys were conducted. There are 513 individual NWI signatures that occur within the 150-foot-wide footprint of the levees, which would be impacted by the proposed project.

The amount of NWI wetlands within the 150-foot-wide levee footprint is as follows:

- Orange Levee: 318.88 acres
- Beaumont Levee: 37.25 acres
- Port Arthur Levee: 48.26 acres

Although some of the other present NWI signatures that occur within the footprint may qualify for a Nationwide Permit, it is anticipated that an Individual Permit (IP) would be required for the project, and mitigation would be required.

Table 3 shows estimated costs for two types of wetland mitigation: mitigation banks, and preservation, restoration, and creation. The total cost of mitigation through mitigation banks would be $103,459,626, and the total costs of preservation, restoration, and creation mitigation would be $29,086,381. These wetland mitigation costs were estimated using the acreage amounts above.

Table 3: North Region Estimated Wetland Mitigation Types and Cost

Segment	Mitigation Bank Cost	Preservation, Restoration, Creation Mitigation Cost
Orange	$81,733,750	$22,934,806
Jefferson		
Beaumont	$9,079,688	$2,679,132
Port Arthur	$12,641,313	$3,471,004
Total North Region Mitigation Cost	$103,459,626	$29,086,381

4.3.3.4. Section 401 of the Clean Water Act: Water Quality Certification

The project would impact more than 1,500 linear feet of stream and/or 3 acres of waters of the U.S. A USACE IP is anticipated. The Texas Commission on Environmental Quality (TCEQ) Tier II 401 Certification requirements for the IP would be met by implementing approved erosion controls, sediment controls, and post-construction Total Suspended Solids (TSS) controls.

4.3.3.5. Rivers and Harbors Act of 1899

Section 9 of Rivers and Harbors Act of 1899 (33 U.S.C. 403; Chapter 425) regulates the construction of any bridge, dam, dike, or causeway over or in navigable waterways of the U.S. Section 10 of the Rivers and Harbors Act of 1899 regulates any structures or work in navigable waters. The proposed project would place a gate across Cow Bayou and Adams Bayou, which are navigable waters of the U.S. Therefore, this project would require a Section 9 permit from the U.S. Coast Guard (USCG) and a Section 10 permit from USACE.

4.3.3.6. Floodplains

The acreage amount in the FEMA 100-year floodplain is listed in Table 4:

Table 4: Floodplains

Levee	Acreage Amount in 100-year Floodplain
Beaumont	182 acres
Port Arthur	155 acres
Orange	617 acres

The North Region Alternative must be located in a floodplain in order to reduce flood risk behind the flood suppression system. The North Region Alternative would adhere to the 8-step process as outlined under Executive Order 11988, Floodplain Management, including consideration of sea level rise.

4.3.3.7. Texas Coastal Management Program

For the proposed project, the Texas GLO would have to prepare a Consistency Determination that evaluates the proposed project for consistency with the Texas Coastal Management Program.

4.3.3.8. Wetland Value Assessment

A Wetland Value Assessment (WVA) was conducted for the North Region. The environmental period of analysis is a total of 50 years based on the following assumptions: The construction period is assumed to end in 2035. The period for which mitigation benefits are analyzed is 2036-2085.

The direct impacts assume no change in wetlands between the baseline and the future target year without the project and total loss of all wetlands within the footprint due to construction impacts. Table 5 provides a summary of the results of the WVA modeling of direct impacts. Total direct impacts would affect 530.55 acres of wetlands and result in the net loss of 50.07 Average Annual Habitat Units (AAHU's) over the period of analysis.

Table 5: Direct Impacts to the North Region Alternative

Levee System	Marsh Model Type	Acreage	Future w/o project AAHU	Future w/project AAHU	Net Impact
Jefferson Beaumont Port Arthur	Freshwater	36.6	12.15	8.77	3.38
	Freshwater/Intermediate	39.12	11.06	8.09	2.97
	Brackish	20.83	3.34	2.58	0.77
	Bottomland Hardwoods	20.28	6.70	4.62	2.08
Orange	Freshwater	99	30.18	21.93	8.25
	Brackish	81.263	31.01	22.02	8.98
	Bottomland Hardwoods	151.425	49.12	33.77	15.35
	Swamp	82.03	27.07	18.77	8.30
Total		**530.55**	**170.62**	**120.55**	**50.07**

The WVA modeling evaluated and quantified direct impacts of the North Region Alternative. The Beaumont levee would negatively impact 36.6 acres; the Port Arthur levee would impact 80.23 acres; and the Orange levee would impact 413.72 acres. Total impacts of the North Region Alternative would be 530.55 acres.

Total direct impacts would affect 530.55 acres of wetlands and result in the net loss of 50.07 AAHUs over the period of analysis. Mitigation would be required to compensate for a loss of 50.07 AAHUs from marshes.

4.3.3.9. Essential Fish Habitat

Tidally influenced waters occur within the project area, and Essential Fish Habitat for Red Drum, shrimp, and reef fish occurs within the project area. Coordination with National Marine Fisheries Service (NMFS) would be required.

4.3.3.10. Marine Mammal Protection Act of 1972

The North Region Alternative is within two counties that both have the West Indian Manatee (*Trichechus manatus*) listed on the USFWS Threatened and Endangered Species List; however, there is no suitable habitat for the West Indian Manatee. The alternative would include gate structures for Cow Bayou and Adams Bayou. Coordination with NMFS would be required.

4.3.3.11. Threatened and Endangered Species

Review of the USFWS Endangered Species List and Critical Habitat for Jefferson and Orange Counties (October 2017), Texas Parks and Wildlife Department (TPWD) Annotated County List of Rare Species for Jefferson and Orange Counties (October 2017), and a search of the Natural Diversity Database, in conjunction with GIS, was conducted to determine the potential occurrence of State and Federally listed threatened and endangered species and their habitat.

The proposed project may impact the habitat of 22 state-listed species but no federally listed species. Prior to construction, coordination with the TPWD would be initiated, and best management practices (BMPs) would be implemented to minimize habitat loss and impact to any state-listed species.

4.3.3.12. Hazardous Materials

A hazardous materials regulatory database search was conducted. There are approximately 654 sites that could pose a risk to the proposed project. More complete hazardous materials site investigations would be done during the NEPA phase of the proposed project.

4.3.3.13. Summary of Direct Impacts

The proposed project would involve the following impacts:

- The project may impact three historic resources listed as National Register Historic Districts and would require coordination with Texas Historical Commission (THC), would directly impact an additional 11 Historic Places or historical markers, and would indirectly impact eight places or historical markers.

- Six pubic parks and four WMAs would be impacted, and a Public Hearing per Chapter 26 requirements is required.
- 404.39 acres of potential wetlands would be impacted across the four regional reaches. Mitigation would be required and the total estimated cost of mitigation for the North Region would be $103,459,626 for Mitigation Banking and $29,086,381 for Preservation, Restoration, and Creation.
- The project would impact more than 1,500 linear feet of stream and more than 3 acres of waters of the U.S. and would therefore require Tier II Water Quality Certification from TCEQ.
- The project would involve construction of gates across two navigable waters of the U.S. and would therefore need a Section 9 Permit from the USCG and a Section 10 Permit from USACE.
- The North Region Alternative must be located in a floodplain in order to reduce flood risk behind the flood protection system. The North Region Alternative would adhere to the 8-step process as outlined under Executive Order 11988, Floodplain Management, including the consideration of sea level rise.
- The GLO would have to prepare a Consistency Determination that evaluates the proposed project for consistency with the TCMP.
- A wetland value assessment was performed. Total direct impacts would affect 530.55 acres of wetlands and result in the net loss of 50.07 AAHUs over the period of analysis. Mitigation would be needed to compensate for a loss of 50.07 AAHUs from freshwater, brackish, and saline marshes.
- EFH has been designated in Sabine Lake and Neches River for Red Drum, shrimp and reef fish. Coordination with NMFS would be required.
- The proposed project may impact the habitat of twenty-two state listed species but no federally listed species.
- There are approximately 654 hazardous material sites that could pose a risk to the proposed project.

4.3.4. Cost and Economic Review

The cost estimates presented in the Phase 3 Report were reviewed to assure consistency between the regions and to assure correctness. For the North Region, adjustments were made in real estate values, mitigation costs, and some item quantities.

For real estate costs, escalation factors were introduced based on USACE cost estimating guidelines. Environmental mitigation costs were revised based on completion of detailed analyses and estimates. Several adjustments were made to pump station sizes based on the final interior drainage and overtopping analyses. Finally, levee and floodwall lengths were checked with some adjustments made based on a re-analysis of mapping and alignment drawings. Table 6 provides an updated cost and economics summary for the North Region. All benefits and costs are presented in thousands of dollars and reflect 2018 price levels.

Table 6: Cost and Economics Summary for the North Region (in $Thousands)

North Region Summary	Jefferson County	Orange County	Total
Total length of the system (miles)	46 miles	41 miles	87 miles
Right of way required	428 acres	973 acres	1,401 acres
Pump stations required / total capacity (CFS)	13 / 9,270 CFS	9/ 20,230 CFS	22/ 29,650
Environmental mitigation required	85.51 acres	318.88 acres	404.39 acres
Construction cost	1,544,132	2,439,385	$3,983,517
Annual Operations and maintenance cost	7,721	12,197	19,918
Total Annual Costs (TAC)	79,715	125,931	205,646
Total Annual Benefits (TAB)	46,963	79,468	126,431
Benefit - Cost Ratio (TAB/TAC) (2.875 % Interest Rate)	0.60	0.63	0.61

4.3.5. North Region Conclusions

Phase 4 optimization did not change the recommended alignment or levee heights from the 2016 plan. The BCR in all the regions decreased, which can be attributed to the modifications that were made to the economics model in order to align with USACE assumptions and data, and the increase in construction and mitigation costs. The construction costs were updated to reflect 2018 versus 2015 pricing, which increased the overall constructions costs, by 6 percent. The enhanced environmental review enabled the study team to more accurately determine potential impacts and the costs associated with mitigation.

5. Central Region Optimization Results

5.1. General

The Central Region of the GCCPRD consists of Chambers, Galveston, and Harris Counties. The three counties all border Galveston Bay, which has a direct nexus to the Gulf of Mexico making them highly vulnerable to tropical storm related surge flooding.

The region has two existing hurricane protection systems. The Texas City Hurricane Protection System is a levee system that that provides storm surge protection to 36 square miles of the greater Texas City-La Marque-Hitchcock area from a 15-foot hurricane storm surge with associated wave run-up. The system was completed in 1987 and is currently being reevaluated by USACE to determine if it is sufficient to adequately protect the area from storm inundation in the future.

The second system is the Galveston Seawall, which provides protection to the City of Galveston from surge and surge-related flooding. Construction of the seawall began in 1902 and the initial segment was completed in 1904. From 1904 to 1963, the seawall was extended from 3.3 miles to over 10 miles. The elevation of the seawall is 17 feet, and it consists of a recurved front face to limit wave overtopping and related flooding.

During Hurricane Ike, the seawall and the Texas City Hurricane Protection system performed well. Nevertheless, the City of Galveston still experienced extensive flooding due to surge that originated from the unprotected backside of the island. All homes on the Bolivar Peninsula and many on the west end of Galveston Island outside the protection of the seawall were severely damaged by the surge. The west and east side of Galveston Bay in Chambers, Galveston, and Harris counties experienced a storm surge of 15 to 21 feet. Along the Houston Ship Channel, the surge was in the 18- to 21-foot range. Overall, the losses in Texas associated the Hurricane Ike exceeded $30B.

5.2. Phase 3: Central Region Recommended Plan

The Central Region recommended plan consists of three reaches that provide regional protection to Chambers, Galveston, and Harris Counties.

Reach 1- Coastal Spine – Reach 1 is a coastal levee system that starts at the high ground north of High Island running parallel to Hwy 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 include: 221,105 feet of new levee, 18,916 feet of new T-wall, 41,651 feet of Seawall enhancements, and a 1,200-foot-wide floating sector gate including 24 100-foot-wide vertical lift gates at the Bolivar Roads crossing, 78 drainage structures, 35 highway gates, and the reconstruction of 12 miles of two-lane highway. Elevations for this reach vary between 17 feet and 18 feet.

Reach 2-Galveston Ring Levee – Reach 2 consists of a ring levee that 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, crosses Offatts Bayou and turns east along Teichman Road, crossing Interstate 45, and running parallel to the rear of the properties on the Southside of Harborside Drive. The system then crosses Harborside Drive and follows an alignment parallel to the Northside 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, 46 two-lane highway gates, five four-lane highway gates, four railway gates, three new pump stations, and one navigation gate at Offatts Bayou. Elevations for this reach vary between 18 feet and 21 feet.

Reach 3- Clear Lake Protection System – Reach 3 consists of a protection system that starts at the intersection of FM 518 and SH 146 extending northward to NASA Road 1. The major elements of the system include: 1,260 feet of levee systems, 7,575 feet of T-wall, a navigation gate at the Clear Lake channel, improvements to the existing Harris County Flood Control District second drainage outlet, two roadway crossings, and one new pump station. Elevations for this reach are at 17 feet.

Figure 18 illustrates the Central Region recommended plan.

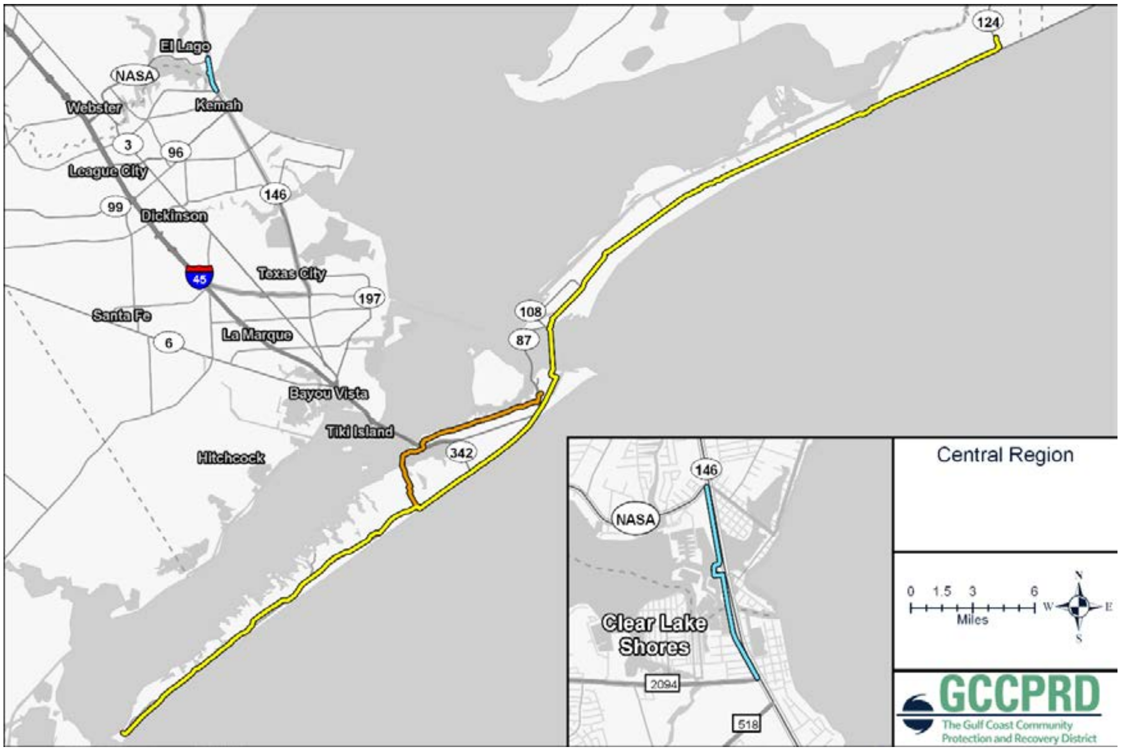


Figure 18: Central Region Recommended Plan

5.3. Optimization Measures

The optimization process for the Central Region consisted of the following steps:

- Analysis of final crest elevations for the Costal Spine to optimize the BCR
- Analysis of interior water levels and pumping requirements for the proposed Galveston Ring Levee and Clear Lake Gate system.
- Review of different alternatives for the Bolivar Gate structure
- Consideration of low economic impact areas (inclusion)
- Enhanced Environmental analysis for Galveston Bay
- Revision of cost estimates based on elevation and length revisions, and original cost estimate quality checking

5.3.1. Analysis of Crest Elevations

As mentioned in Section 3.2, three new scenarios were developed in order to optimize the crest elevations for the Coastal Spine within the Central Region. The goal of this analysis was to determine the ideal height of the Coastal Spine that would maximize the overall BCR for the region.

Scenario 1, FWA.a, maintained the height of the spine at 17 feet in accordance with the recommended plan. Scenario 2, FWA.b, raised the height of the spine to 20 feet. Scenario 3, FWA.c, reduced the height of the spine to 15 feet. The height of the Galveston Ring Levee and the Bolivar Roads gate structure remained constant as the height of the spine along Galveston Island and the Bolivar peninsula were adjusted. Figure 19 through Figure 21 illustrate the changes in the top elevations for the three scenarios.

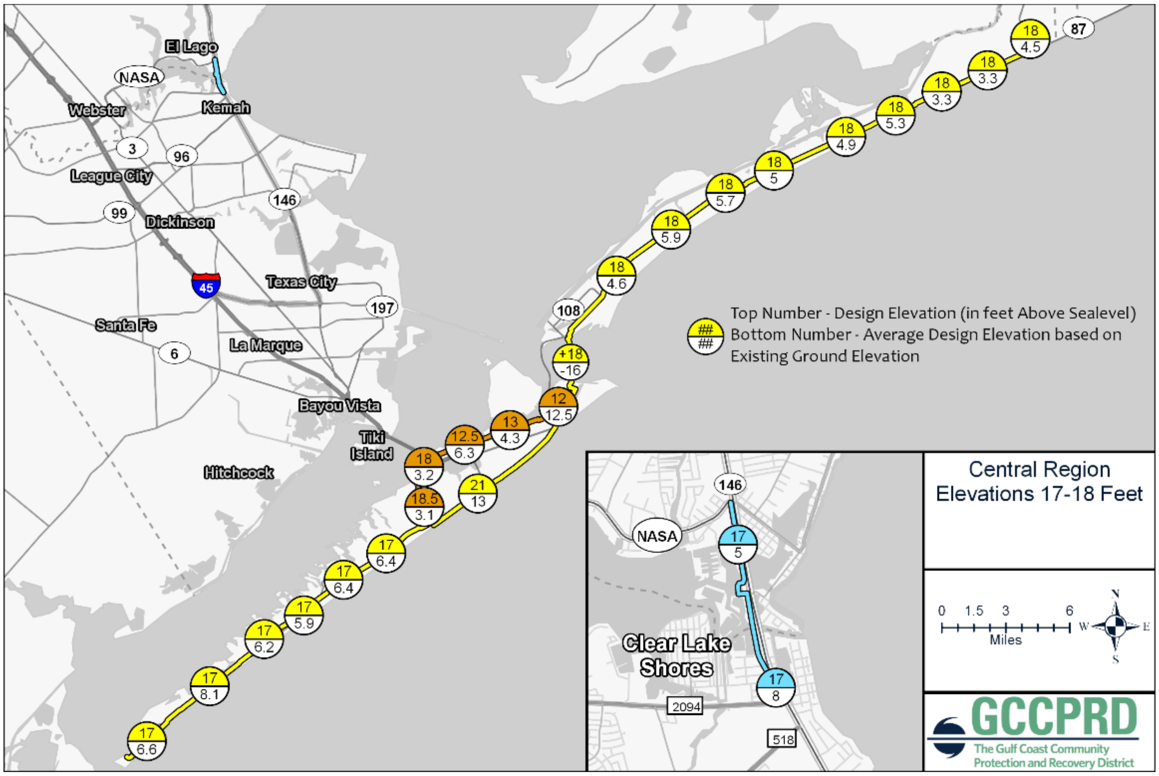


Figure 19: FWA.a – The Recommend Plan at Elevation 17 feet.

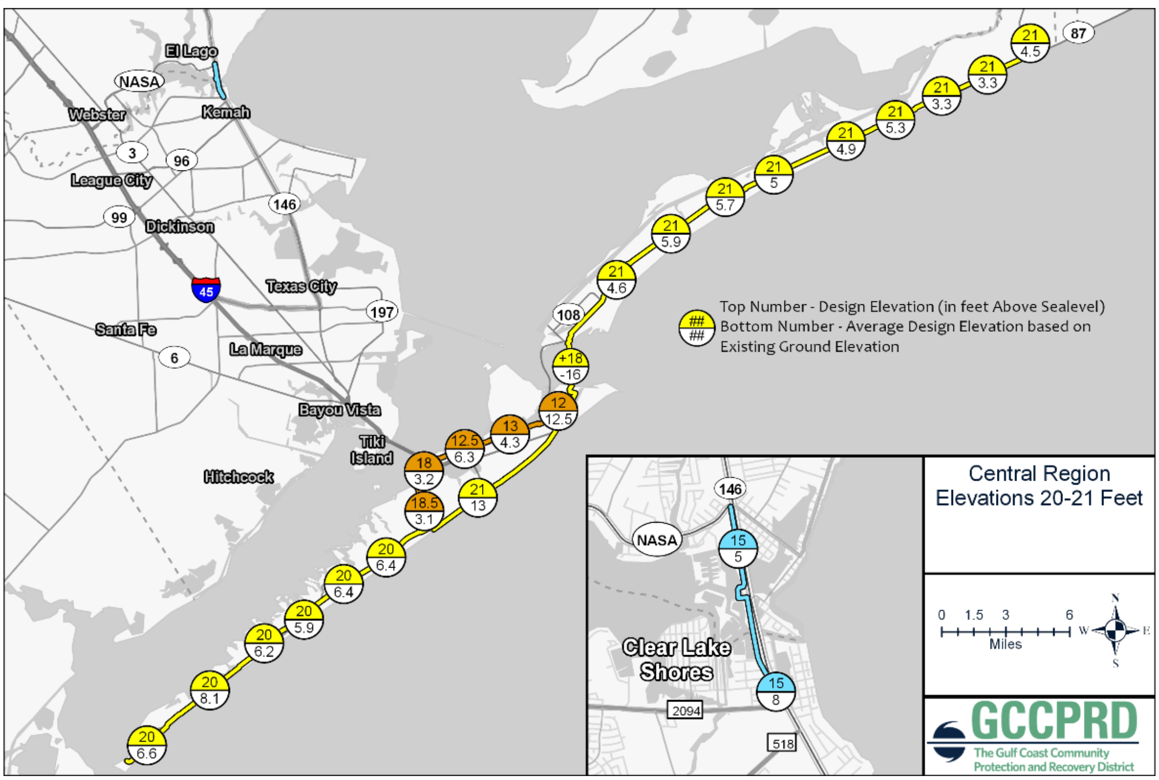


Figure 20: FWA.b - Raising the Height of the Coastal Spine to 20 feet.

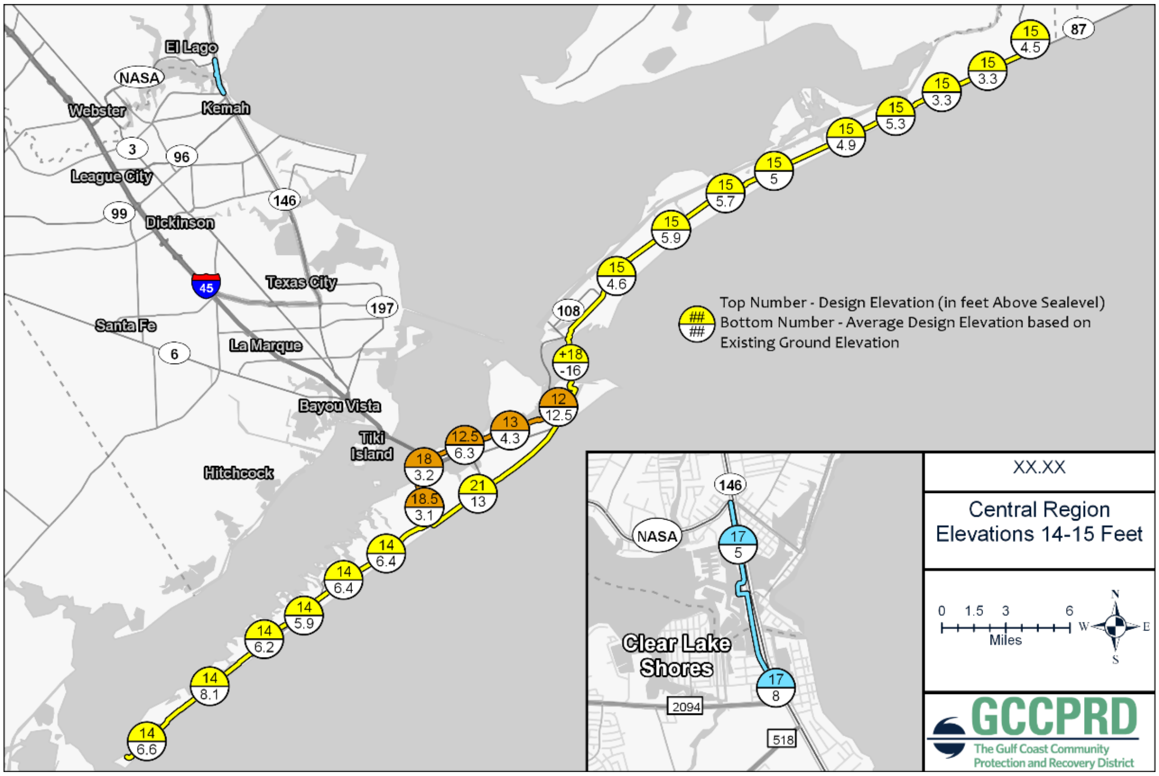


Figure 21: FWA.c – Reducing the Coastal Spine Elevation to 15 feet.

Figure 22 illustrates the changes in water surface elevations at various points within the region associated with each of the three alternatives for the 500-year event. The 500-year event was used to clearly illustrate the minimal difference in stillwater elevations associated with a Coastal Spine elevation between 15 feet and 20 feet. In all the scenarios, the Coastal Spine reduces the surge by 7 to 8 throughout the Central Region when compared to the future without action scenario.

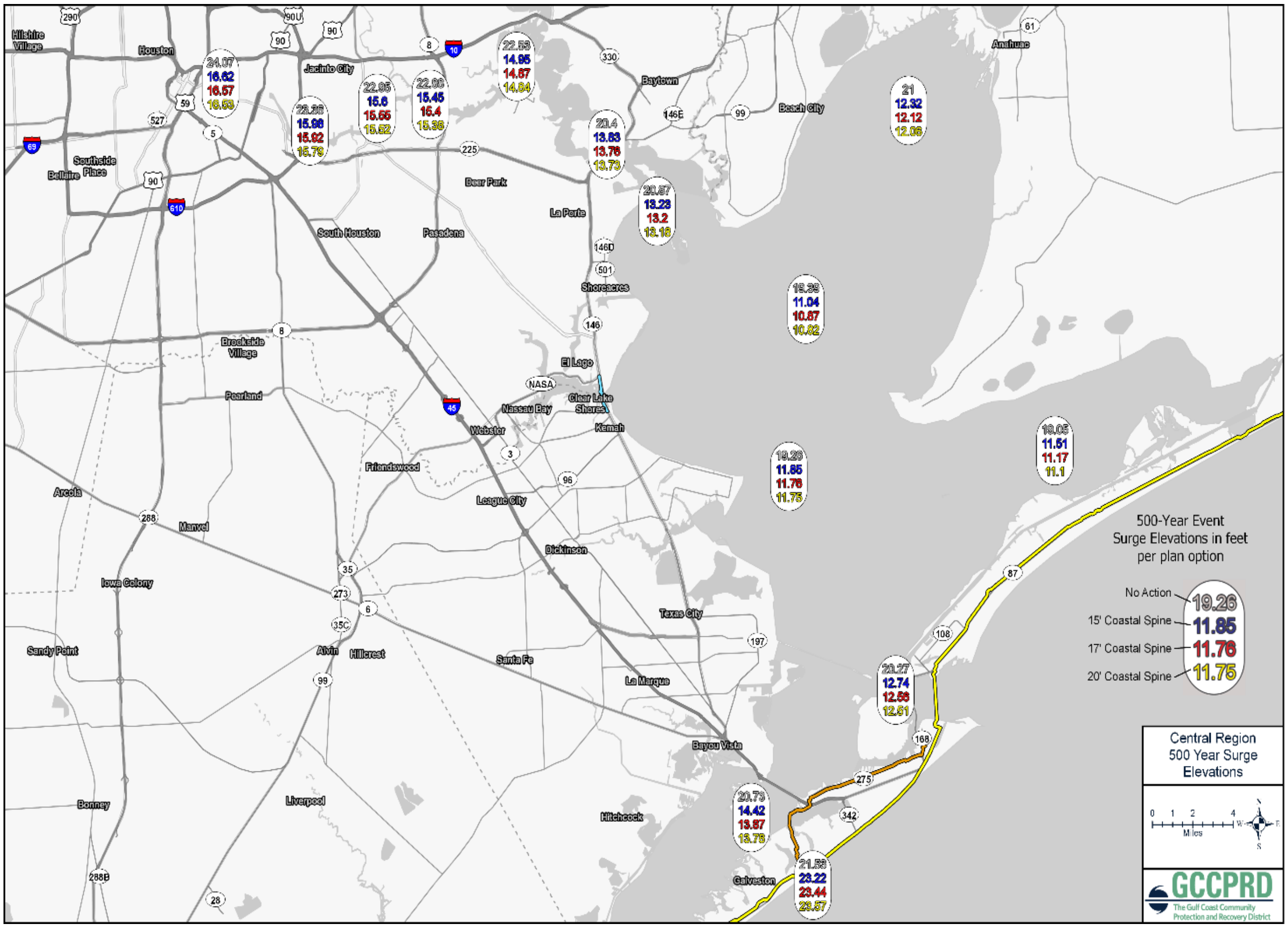


Figure 22: Stillwater Elevations in 2085 for the Various Coastal Spine Elevations

Further analysis identified the following levels of protection provided:

Table 7: Comparison of Coastal Spine Elevations

Alternative	Coastal Spine Elevation	Level of Protection	Construction Cost ($000)	Benefit-Cost Ratio
FWA.a	17 feet	100-yr	$10,120,836	1.61
FWA.b	20 feet	200-yr	$10,313,788	1.59
FWA.c	15 feet	50-year	$9,818,156	1.66

Alternative FWA.b, raising the spine to an elevation of 20 feet from 17 feet, increases the construction cost by $200 million and results in a slight decrease in the BCR. Similarly, alternative FWA.c, decreasing the spine to an elevation of 15 feet, reduces construction cost by $302 million and slightly increases the BCR. However, with only a 50-year level of protection, the project would not meet FEMA Flood Insurance requirements of providing protection from the 100-year event. Flood insurance rates within the region would not necessarily be reduced.

FWA.a, the elevation of 17 feet as define in the recommend plan, is the optimal elevation for the Coastal Spine.

5.3.2. Interior Water Levels and Drainage

The interior drainage analysis for the Central Region included floodplain mapping and pump sizing for the 25-year internal rainfall event and the overtopping associated with 100-year storm surge event for the proposed Galveston Ring Levee and the Clear Lake Gate system. Since the Coastal Spine along Bolivar Peninsula and West Galveston Island is not a closed system, the study team did not conduct an interior drainage analysis for this segment.

5.3.2.1. Methodology

The pumping rate analysis was performed using the USACE HEC-HMS modeling software. Within the model, the 25-year internal storm event flows were combined with the 100-year storm surge overtopping flows. The natural terrain being protected by the levee was modeled as a reservoir with the elevation-storage data obtained based on the LiDAR DEM of the natural ground. The peak pumping rate was determined based on maintaining a certain level of ponding within the protected area/reservoir that had minimal effects on existing structures.

5.3.2.2. Inland Drainage Area and Peak Flow

Inland drainage areas and peak flows for Clear Creek were obtained from the Flood Insurance Study for Clear Creek. The inland drainage areas for the Galveston Ring Levee were determined using aerial photography, LiDAR DEM, and ArcHydro tools in GIS. The 25-year peak flows were computed in HEC-HMS. The Green and Ampt Method was utilized for calculating runoff losses and the Clark Unit Hydrograph Method was used for calculating runoff hydrograph. The inland drainage area and peak flow are summarized in Table 8.

Table 8: Inland Drainage Area and 25-year Peak Flow

Alignment	Drainage Area (ac)	25-year Inland Flow (cfs)
Clear Lake	166,396	29,627
Galveston Ring Levee	8,824	7,153

5.3.2.3. Overtopping Analysis

The 100-year storm surge overtopping hydrographs for the study were derived from the ADCIRC storm surge models. The proposed levee segments were divided into several reaches and surge overtopping hydrographs were calculated for each reach. The surge hydrographs were summarized for each levee segment and utilized in the current analysis.

The 100-year storm surge peak flows for the 17 feet and 15 feet Coastal Spine levee height alternatives were analyzed to see if adjusting the levee height would influence overtopping especially within the Galveston Ring Levee. The internal pumping rates are summarized in Table 9.

Table 9: 100-year Storm Surge (Overtopping) Peak Flows

	100- Storm Surge Overtopping (cfs)	
Alignment	**Coastal Spine at 17.0 feet**	**Coastal Spine at 15.0 feet**
Clear Creek	552	556
Galveston Ring Levee	210,009	209,209

The storm surge analysis shows that in both the alternatives, the 100-year storm surge peak overtopping flows are relatively similar. This indicates that the height of the Coastal Spine does not have a significant impact on the overtopping rates for the Clear Creek and Galveston Ring Levee systems.

5.3.2.4. Pumping Rate

For Clear Creek, it was determined that an inland ponding elevation of 8 feet would result in little structural flooding while providing a reasonable amount of flood storage which is distributed over Clear Lake.

For the Galveston Ring Levee, the area protected by the ring levee was divided into three different regions based on geography and internal drainage conditions. In the western region (the vicinity of the airport) the ponding elevation was calibrated to 5.5 feet, and for the downtown and east end regions the ponding elevation was 8 feet. Ponding elevations were set in order to keep the majority of the area and structures above the flood level. The pumping rates were determined based on not exceeding the flood level.

5.3.2.5. Results

The peak pumping rate for Clear Creek was determined to be 10,900 cfs, which is 4.9 million gallons per minute. The peak pumping rate for the Galveston Ring Levee was determined to be 117,000 cfs, which is 55.2 million gallons per minute. The significantly higher pumping rate for the Galveston Ring Levee is directly related to the extremely high overtopping rate along the seawall. Additionally, the area protected by the Galveston Ring Levee is small and does not provide much storage capacity for ponding as the in the case of the Clear Lake Gate, so the water must be pumped out at a higher rate to avoid interior flooding.

The analysis shows that the peak pumping for the Clear Lake Gate is not dependent on the elevation of the Coastal Spine. The pumping rate for the Galveston Ring Levee is driven by the amount of water overtopping the seawall. To reduce this overtopping, the seawall would need to be raised higher than the proposed 21 feet. This would have a significant economic and social impacts on the City of Galveston.

The peak pumping rates are presented in Table 10.

Table 10: 100-year Storm Surge Peak Flows

Alignment	25-yr Inland Flow (cfs)	100-yr Storm Surge (cfs)	Inland Flooding	Peak Pumping (cfs)	Peak Pumping Rate (mgpm)
Coastal Spine Elevation 17 feet (Recommended)					
Clear Creek	29,627	552	8.0	10,900	4.9
Galveston Ring Levee	7,153	210,009	5.0-8.0	117,000	52.5
Coastal Spine Elevation 15 feet					
Clear Creek	29,627	556	8.0	10,900	4.9
Galveston Ring Levee	7,153	210,009	5.0-8.0	117,000	52.5

5.3.3. Bolivar Roads Gate Analysis

The study team evaluated the cost of construction and performance for the three potential gate alternatives for the Bolivar Roads crossing discussed in Section 3.6. The following table summarizes the cost of each option and the amount of permanent blockage in terms of percentage of the entire alignment length.

Table 11: Summary of Barrier Alternative Costs & Permanent Blockage

Configuration	Costs, in millions	Permanent Blockage
GCCPRD840	$3,540	54.8%
GCCPRD1200	$3,956	52.8%
GCCPRD1200-Barge	$3,674	38.5%

The GCCORD1200-Barge alternative has the lowest cost and creates the least impact associate with a loss of tidal flow. The reduction in cost for the GCCRPD1200-Barge can be attributed to the following advantages of the barge gate construction:

- No significant under-water construction
- No need for a cofferdam or temporary water retaining structures
- Major fabrication (steel barge gate) can be completed off-site
- No requirement for cast-in-place concrete monoliths

The selection of the final gate concept for construction should not be based on cost alone. Relative advantages and disadvantages of the alternatives should be weighed in in terms of environmental concerns, relative ease of construction, convenience in gate operations, and sustained cost of maintenance over the life of the design life of the structure. Each of these concerns will need to be further analyzed before the final design of the structure is begins.

After careful consideration, the study team elected to use the cost of the GCCPRD1200 alternative for the enhanced environmental and economic analysis. The GCCPRD1200-Barge would be a largest barge gate in the world. The detailed analysis required to evaluate the feasibility of constructing and operating this structure is not within the scope of the GCCPRD study and exceeds the financial resources available to the study team.

5.3.4. Environmental Review

5.3.4.1. Upland Features

This section provides a summary of the potential environmental impacts associated the construction of the Central Region system. The full Central Region environmental report is located in **Appendices D.2 and D.2.1**.

During Phase 4, the study team conducted a more thorough review of the potential environmental impacts that would be associated with the construction of the three reaches in the Central Region. In order to estimate potential impacts, the study team assumed that the proposed levee and T-wall system would have a 150-foot-wide footprint. This enhanced assessment included: field investigations conducted along publicly assessable rights-of-way, additional desktop analysis, coordination with USACE, and calculating future mitigation requirements using the WVA model. The costs associated with mitigation were incorporated into the overall project cost and considered in the BCR calculations.

Impacts to the following were very minor and insubstantial:

- Prime and Unique Farmlands
- Socioeconomic Impacts
- Protection of Children from Environmental and Safety Risks
- Federal Water Project Recreation Act
- Executive Order 11990: Protection of Wetlands
- Section 303(d) of the Clean Water Act: Impaired Streams
- Section 402 of the Clean Water Act
- Wild and Scenic Rivers
- Vegetation
- Executive Order 13112 on Invasive Species
- Executive Memorandum on Environmentally and Economically Beneficial Landscaping
- Air Quality
- Greenhouse Gas Impacts
- Noise

The primary potential impacts are described in the following sections.

5.3.4.1.1. Cultural Resources

Old Fort Travis, which is listed in the National Register of Historic Places, is located in Fort Travis Seashore Park, a Galveston County Park. This location contains remains of Fort Travis, and the proposed Bolivar Levee would run directly through the property with the current alignment. Coordination with the Texas Historical Commission (THC) would be required.

The Galvez Hotel, The Mosquito Fleet Berth Pier 19, and The Strand are listed in the National Register of Historic Places. At this time, direct impacts are not anticipated to these three historic resources. The Galveston Seawall is also listed in the National Register of Historic Places and was listed in March of 1977.

The Coastal Spine would raise the height of the Galveston Seawall; therefore, coordination with the THC is required in order to reduce any impacts to the historic significance of the seawall.

5.3.4.1.2. Texas Parks and Wildlife Code, Chapter 26

The proposed project would be located within the boundaries of Rollover Island Park, Fort Travis Seashore Park, Stewart Beach Park, Sandhill Crane Soccer Complex, and Galveston Island State Park, which are all Chapter 26 properties. A Public Hearing is required and would be held during the National Environmental Policy Act (NEPA) process in accordance with Chapter 26 requirements.

In addition, the proposed project would be located within the boundaries of the Audubon's Boy Scout Woods Bird Sanctuary and Horseshoe Marsh Bird Sanctuary and the Galveston Bay Foundation Sweetwater Preserve. While these properties have been set aside as wildlife sanctuaries and preserves, they are private properties and do not qualify as Chapter 26 properties.

5.3.4.1.3. Section 404 of the Clean Water Act: Waters of the U.S.

Desktop surveys using U.S. Fish and Wildlife Services' (USFWS) National Wetland Inventory (NWI) maps, USGS 7.5-Minute Topographic Quadrangle maps, Federal Emergency Management Agency (FEMA) Flood Insurance Rate Maps (FIRM), aerial photographs, and limited site surveys were conducted.

There are 289 individual NWI signatures that exist within the levee footprint and would be impacted by the proposed project.

The amount of NWI wetlands within the 150-foot wide levee footprint is as follows:

- Coastal Spine: 90.58 acres
- Bolivar Levee: 55.05 acres
- Galveston Ring Levee: 41.93 acres
- Clear Lake Levee: 12.2 acres

As a result, an Individual Permit (IP) and mitigation would be required.

Table 12 shows estimated costs for two types of wetland mitigation: mitigation banks and preservation, restoration and creation. The total cost of mitigation through mitigation banks would be $54,270,229 and the total cost of preservation, restoration, and creation mitigation would be $14,366,628. These wetland mitigation costs were estimated using the acreage amounts above.

Table 12: Estimated Wetland Mitigation Types and Cost

Segment	Mitigation Bank Cost	Preservation, Restoration, Creation Mitigation Cost
Coastal Spine	$26,044,000	$6,514,066
Bolivar Levee	$13,527,791	$3,959,370
Galveston Ring Levee	$10,885,938	$3,015,731
Clear Lake Levee	$3,812,500	$877,461
Total Central Region Mitigation Cost	$54,270,229	$14,366,628

5.3.4.1.4. Section 401 of the Clean Water Act: Water Quality Certification

The project would impact more than 1,500 linear feet of stream and more than 3 acres of waters of the U.S. The Tier II 401 Certification requirements for the IP would be met by implementing approved erosion controls, sediment controls, and post-construction Total Suspended Solids (TSS) controls.

The design and construction of the proposed project would include construction and post-construction TCEQ 401 Water Quality Best Management Practices (BMPs) to manage storm water runoff and control sediments.

5.3.4.1.5. Rivers and Harbors Act of 1899

Section 9 of Rivers and Harbors Act of 1899 (33 U.S.C. 403; Chapter 425) regulates the construction of any bridge, dam, dike, or causeway over or in navigable waterways of the U.S. Section 10 of the Rivers and Harbors Act of 1899 regulates any structures or work in navigable waters. The proposed project would place gate structures in Galveston Bay across the Houston Ship Channel at Bolivar Roads, Clear Lake, Rollover Pass, and Offatts Bayou, all of which are navigable waters of the U.S. Therefore, this project would require a Section 9 permit from the USCG and a Section 10 permit from USACE.

5.3.4.1.6. Floodplains

The acreage amount in the FEMA 100-year floodplain can be found below:

Table 13: Floodplains

Segment	Acreage Amount in 100-year Floodplain
Coastal Spine	453 acres
Bolivar Levee	486 acres
Clear Lake Levee	28 acres
Galveston Ring Levee	177 acres

The Central Region Alternative must be located in a floodplain in order to reduce flood risk behind the flood protection system. The Central Region Alternative would adhere to the 8-step process as outlined under Executive Order 11988, Floodplain Management, including consideration of sea level rise.

5.3.4.1.7. Coastal Barriers

The proposed Coastal Spine would construct levees through three Coastal Barrier Resource System (CBRS) units; one on Galveston Island and two on Bolivar Peninsula. In order for the proposed Coastal Spine that would go through a CBRS unit to receive federal funds, this project would need to meet at least one exception defined in the U.S. Code (USC) Title 16 Chapter 55 Section 3505 and be consistent with the purpose of the CBRA. The proposed Coastal Spine would meet the exception criteria under 16 USC 3505(a)(6)(E): assistance for emergency actions essential to the saving of lives and the protection of property and the public health and safety and that are necessary to alleviate the emergency. The proposed Coastal Spine would also be consistent with the purpose of the CBRA, which is to minimize the loss of human life; wasteful expenditure of federal revenues; and, in the event of a storm, reduce damage to fish, wildlife, and other natural resources (16 USC 3501(b). Therefore, the proposed project would be eligible for federal funds. The proposed Coastal Spine would traverse through three CBRS units; coordination with USFWS would be required.

5.3.4.1.8. Texas Coastal Management Program

For the proposed project, the Texas GLO would have to prepare a Consistency Determination that evaluates the proposed project for consistency with the Texas Coastal Management Program.

5.3.4.1.9. Wetland Value Assessment

A Wetland Value Assessment (WVA) was conducted for the Central Region. The environmental period of analysis is a total of 50 years based on the following assumptions: The construction period is assumed to end in 2035. The period for which mitigation benefits are analyzed is 2036-2085.

The direct impacts assume no change in wetlands between the baseline and the future target year without the project and total loss of all wetlands within the footprint due to construction impacts. Table 14 provides of summary of the results of the WVA modeling of direct impacts.

Table 14: Direct Impacts to the Central Region Alternative

Levee System	Marsh Model Type	Acreage	Future w/o project AAHU	Future w/project AAHU	Net Impact
Clear Lake Gate	Brackish	20.28	2.04	1.70	0.34
Bolivar Peninsula	Freshwater	93.47	26.36	19.28	7.08
	Freshwater Near Brackish	7.75	2.40	1.74	0.66
	Brackish	8.17	2.62	1.88	0.74
Bolivar Roads Gate System	Saline	33.8	4.51	3.63	0.88
Galveston Spine	Freshwater	47.46	12.69	9.33	3.36
	Brackish	30.13	4.04	3.25	0.79
Galveston Ring Levee	Freshwater	45.02	10.58	7.88	2.70
	Brackish	17.59	5.12	3.71	1.41
Total		**303.67**	**70.36**	**52.40**	**17.96**

Total direct impacts would affect 303.67 acres of wetlands and result in the net loss of 17.96 Average Annual Habitat Units (AAHU's) over the period of analysis. Mitigation would be needed to compensate for a loss of 17.96 AAHUs from freshwater, brackish, and saline marshes.

5.3.4.1.10. Galveston Bay Impacts

Biological impacts to Galveston Bay from the proposed gate at Bolivar Roads were analyzed and are documented in a separate report titled GCCPRD Bolivar Road Gates Biological Effects Analysis in The Bay, Texas.

It is inarguable that storm surge protection is important to the health of coastal ecosystems and communities, particularly for busy ports like Houston. This is especially true considering climate change causing strong storms to occur more frequently. It is likely that installing a barrier at Bolivar Roads will prove necessary and beneficial overall, even though there may also be adverse effects throughout the system from diminishing water flow and sediment exchange between the Bay and the Gulf of Mexico. However, there have been best practices put forward by National Marine Fisheries Service (NMFS) to reduce impacts to fish passage and population dynamics that are outlined here (NMFS, 2008).

The guiding principles for barrier design include the following:

- It should not be assumed that structures that allow for sufficient drainage also optimize fish passage, as these needs may be different
- Larger and more numerous openings in the barrier are better for fish migration
- The cross-section width and depth of the barrier location should be maintained as much as possible to minimize habitat changes, or there should be openings on either side of the barrier nearshore as well as in the center that extend to the bottom
- All gates should remain completely open except during storm events
- Barriers should include shoreline baffles or ramps to aid fish passage
- Average flow velocities during peak flood or ebb tides should not exceed 2.6 ft/s (0.80 m/s) to reduce impediment to fish passage
- Design should allow for rapid opening after the storm passes even if the power source is down
- Plans comprised of several structures (e.g., levees plus gates) should be designed to reduce the number of times fish need to pass through an obstacle (NMFS, 2008)

It became clear during the environmental review that there is a knowledge gap regarding the impacts of storm surge barriers on the ecology of estuarine systems, so assumptions were made based on impingement/entrainment or other related research for both these NMFS guidelines and the analysis conclusions. With the increasing prevalence of strong coastal storms and repeated flooding events, more site-specific research into potential effects will be needed for decision-making and barrier design. This involves biological surveys to determine baseline conditions; a thorough understanding of the life history strategies and migration patterns of representative species of concern; additional knowledge of the effects of the barrier on localized current speeds, and water flow velocity thresholds for different species and life stages.

There are various adverse impacts that could occur to the ecology of Galveston Bay due to the permanent presence of a storm surge barrier gate at Bolivar Roads. These impacts could include reduced tidal amplitude, loss of intertidal mudflat and marsh habitat, reduced discharge, increased current velocities, and impeded migration. In all cases, the 1,200-foot floating sector gate scenario would have less of an adverse impact on the environment than the smaller 840-foot floating sector gate scenario. However, these impacts are of much lower magnitude than the ecological effects caused by hurricanes and storm surge. Therefore, it will be necessary for regulators and stakeholders to weigh the risks and benefits of a short-term but high-impact hurricane storm surge occurring infrequently with the chronic but lower impact effects of a permanent barrier in the Houston Ship Channel between Galveston Bay and the Gulf of Mexico.

In the future, as sea levels continue to rise, the impacts on tidal amplitude associated with the presence of the gate structure may have a positive impact on environmental sensitive areas that would be subject to inundation and continued salt-water migration. This analysis exceeds the scope the study, and should be further evaluated to fully understand these potential benefits.

5.3.4.1.11. Marine Mammal Protection Act of 1972

The proposed alternative would include the installation of gate structures in Galveston Bay across the Houston Ship Channel at Bolivar Roads, Clear Lake, Rollover Pass, and Offatts Bayou. These gate structures would be built within the four waters, therefore the potential for marine mammal impacts needs to be addressed. At these four locations, the proposed alternative could have potential habitat for marine mammals such as the Bottlenose Dolphin (*Tusiops truncatus*) and the West Indian Manatee (*Trichechus manatus*), since these structures are within the Gulf and Bay system. Coordination with the National Oceanic and Atmospheric Administration (NOAA) Fisheries would be required and Marine Mammal Permit would need to be obtained prior to construction.

5.3.4.1.12. Essential Fish Habitat

Essential Fish Habitat (EFH) has been designated in Galveston Bay for Red Drum, shrimp, and reef fish to minimize fisheries-related impacts to these commercially important species (GMFMC, 2005). Coordination with NMFS would be required.

5.3.4.1.13. Threatened and Endangered Species

Review of the USFWS Endangered Species List and Critical Habitat for Galveston and Harris Counties (October 2017), TPWD Annotated County List of Rare Species for Galveston and Harris Counties (October 2017), and a search of the Natural Diversity Database, in conjunction with GIS, was conducted to determine the potential occurrence of State and Federally listed threatened and endangered species and their habitat.

The proposed project may impact the habitat of 18 state-listed species. Prior to construction, coordination with the TPWD would be initiated and BMPs would be implemented to minimize habitat loss and impact to any state-listed species.

The proposed project would impact 47 acres of critical habitat of the threatened Piping Plover (*Charadrius melodus*) along the Coastal Spine levee on Galveston Island. Mitigation cost for the Piping Plover critical habitat impacts was estimated at $20,000 per acre for a total mitigation cost of $940,000.

The proposed project could affect seven other federally listed species or their habitat. Formal coordination with USFWS would be required.

5.3.4.1.14. Hazardous Materials

A hazardous materials regulatory database search was conducted, and there are approximately 231 sites that could pose a risk to the proposed project. More complete hazardous materials site investigations would be done during the NEPA phase of the proposed project.

5.3.4.1.15. Conclusions

The proposed project would involve the following impacts:

- The project would impact two historic resources listed in the National Register of Historic Places and would require coordination with THC.
- Four pubic parks would be impacted, and a Public Hearing per Chapter 26 requirements is required.
- 199.76 acres of potential wetlands would be impacted across the four regional levees. Mitigation would be required and the total estimated cost of mitigation for the Central Region would be $54,270,229 for Mitigation Banking and $14,366,628 for Preservation, Restoration, and Creation.
- The project would impact more than 1,500 linear feet of stream and more than 3 acres of waters of the U.S. and would therefore require Tier II Water Quality Certification from TCEQ.
- The project would involve construction of gates across four navigable waters of the U.S. and would therefore need a Section 9 Permit from the USCG and a Section 10 Permit from USACE.
- The Central Region Alternative must be located in a floodplain in order to reduce flood risk behind the flood protection system. The Central Region Alternative would adhere to the 8-step process as outlined under Executive Order 11988, Floodplain Management, including consideration of sea level rise.
- The project would construct levees within CBRS units. The project would meet the exception criteria under 16 U.S. Code (USC) Title 16 Chapter 55 Section 3505 and would be consistent with the purpose of the CBRA which is to minimize the loss of human life; wasteful expenditure of federal revenues; and, in the event of a storm, reduce damage to fish, wildlife, and other natural resources and would therefore be eligible for federal funds. Additionally, coordination with the USFWS would be required.
- The GLO would have to prepare a Consistency Determination that evaluates the proposed project for consistency with the TCMP.
- A wetland value assessment was performed. Total direct impacts would affect 303.67 acres of wetlands and result in the net loss of 17.96 AAHUs over the period of analysis. Mitigation would be needed to compensate for a loss of 17.96 AAHUs from freshwater, brackish, and saline marshes.
- There are various adverse impacts that could occur to the ecology of Galveston Bay due to the permanent presence of a storm surge barrier gate at Bolivar Roads. These impacts could include reduced tidal amplitude, loss of intertidal mudflat and marsh habitat, reduced discharge, increased current velocities, and impeded migration. Additionally, the project would impact marine and estuarine habitats such as open bay waters, freshwater inlets, freshwater and marine wetlands, seagrass beds, and oyster reefs. The variety of habitat in the Bay supports diverse assemblages of freshwater, estuarine, and marine organisms. Wetlands, seagrass beds, and oyster reef habitats are some of the most important and sensitive habitats within the Bay.
- The proposed project may impact marine mammals. Coordination with NOAA NMFS would be required and Marine Mammal Permit would need to be obtained prior to construction.
- EFH has been designated in Galveston Bay for Red Drum, shrimp, and reef fish. Coordination with NOAA NMFS would be required.
- The proposed project would impact 47 acres of critical habitat of the threatened Piping Plover (*Charadrius melodus*) along the Coastal Spine levee on Galveston Island. The proposed project could affect seven other federally listed species or their habitat. Formal consultation with USFWS would

be required. Mitigation cost for the Piping Plover critical habitat impacts is estimated at $20,000 per acre for a total mitigation cost of $940,000.

- There are approximately 231 hazardous material sites that could pose a risk to the proposed project.
- Several species of invertebrates, fish, birds, reptiles, and terrestrial and marine mammals are supported by the Galveston Bay ecosystems. Commercial fisheries in the Bay include the white and brown shrimp and oysters. The proposed alternative would include the installation of gate structures in Galveston Bay across the Houston Ship Channel at Bolivar Roads, Clear Lake, Rollover Pass, and Offatts Bayou. Therefore, the potential for marine mammal impacts needs to be addressed. At these four locations, the proposed alternative could have potential habitat for marine mammals such as the Bottlenose Dolphin (*Tusiops truncatus*) and the West Indian Manatee (*Trichechus manatus*) since these structures are within the Gulf and Bay system.

5.3.4.2. Galveston Bay Environmental Analysis

To understand the impact of several proposed flood protection barrier gate designs and their potential impact on daily flows, tidal prism, velocities, and salinity within Galveston Bay (the bay) during non-storm conditions, hydrodynamic modeling was conducted using the D-Flow Flexible Mesh model.

Three types of gates were combined to generate a series of gate alternatives:

- Sector gates, which will be used for navigation access into the bay
- Barge gates, which provide a large opening width relative to the size of the abutments on either side and will be used to allow additional flow for environmental considerations
- Vertical lift gates, which provide an effective and low maintenance way to maintain natural tidal flushing of the bay

The gate alternatives analyzed in this study are described in Table 15 and their placement are shown in Figure 23.

Table 15: Summary of Barrier Gate Design Alternatives

Alternative	Navigational Gate Opening (feet)	Number of Environmental Gates	Environmental Gate Total Opening (feet)
GCCPRD840	840	24 VLG	2,400
GCCPRD1200	1,200	24 VLG	2,400
GCCPRD1200-Barge	1,200	15 barge +8 VLG	3,800
USACE-TexasCity	1,200	36 VLG	3,600
USACE-MidBay	1,200	200 VLG	20,000
SSPEED Center Mid Bay Regional Strategy	850	5- VLG	750

Figure 23: Locations Where Barrier Gates Would be Constructed

Note: All GCCPRD alternatives are in the same location, with variations to the number and type of gates only.

5.3.4.2.1. Model Development

The modeling conducted for this study focuses on the simulation of water levels, currents, and salinity due to astronomic tides, wind-driven water levels, and fresh water inflows throughout the bay. A two-phased approach was selected for modeling Galveston Bay. First, the well-exercised ADCIRC model developed and validated for the FEMA FIS (FEMA 2011) and later modified by the GCCPRD storm surge study to represent northern coastal Texas was used to simulate water levels along the Texas Coast, Gulf of Mexico, and Atlantic Ocean. The ADCIRC model results were used to provide offshore boundary conditions to the D-Flow model in the form of water levels at its open boundary. The model domains and their overlap are shown on Figure 24.

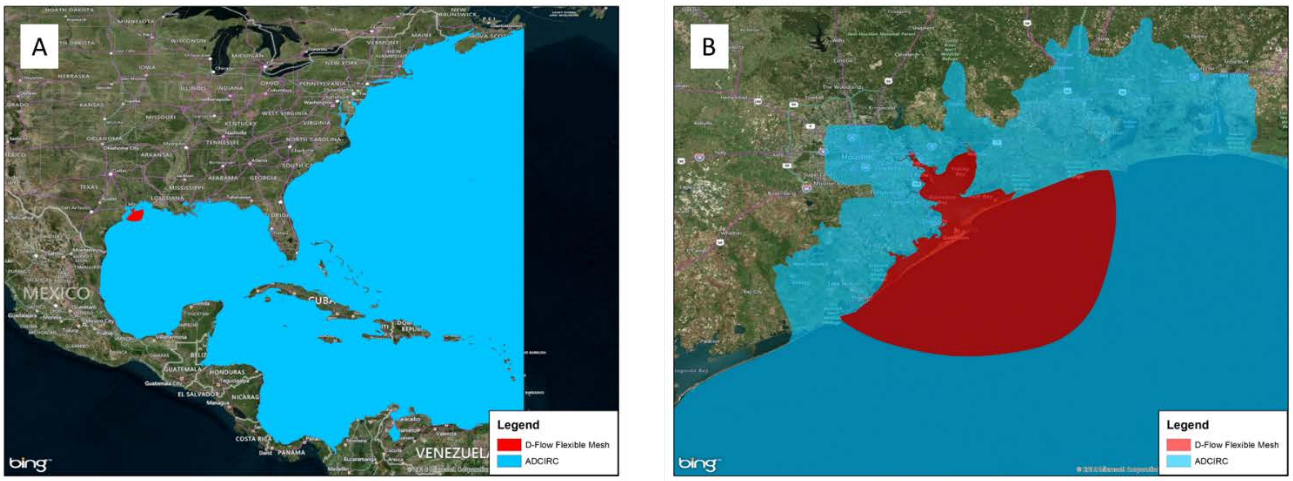


Figure 24: D-Flow and ADCIRC Flexible Mesh Domains

A three-year simulation period between January 1, 2009 through January 1, 2012 was used throughout the modeling for simulations of existing conditions and with the gates in place. The selected period was chosen to represent a range of flow conditions to evaluate the impact of the gates during an average flow year, a wet flow year, and a dry flow year. Selection of the modeling period also considered when adequate data exists to both set up and validate the model. All three flow conditions were conducted as a single simulation to ensure the model could replicate a variety of conditions as well as the transition between conditions without need for recalibration.

5.3.4.2.2. Model Validation

Models were validated using a variety of data sources to ensure that the model made accurate predictions about the water levels and salinities throughout the Bay. NOAA gage data was used to compare tidal harmonics as well as observed water levels at locations throughout the bay, and TWDB was able to provide continuous sampling salinity measurements as well as individual jar samples at many locations.

Figure 25 and Figure 26 show sample comparisons of water level and salinity observations to model predictions. Additional comparisons are available in **Appendix E**.

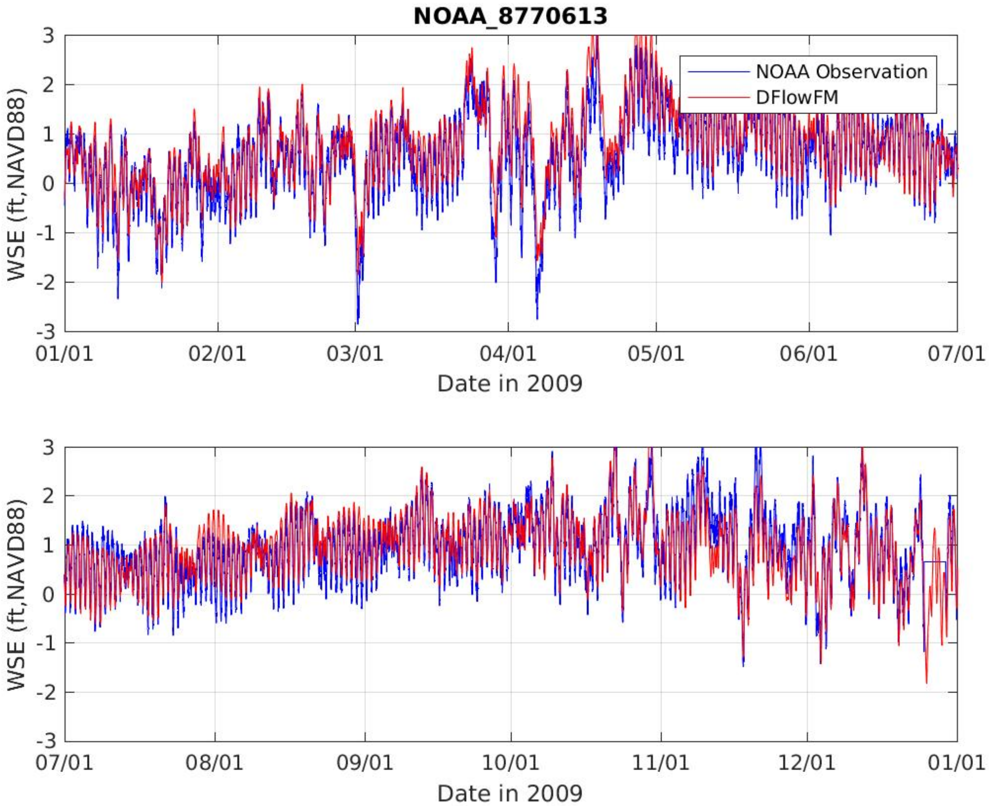


Figure 25: 2009 Water Level Comparisons at NOAA 8770613, Morgan's Point

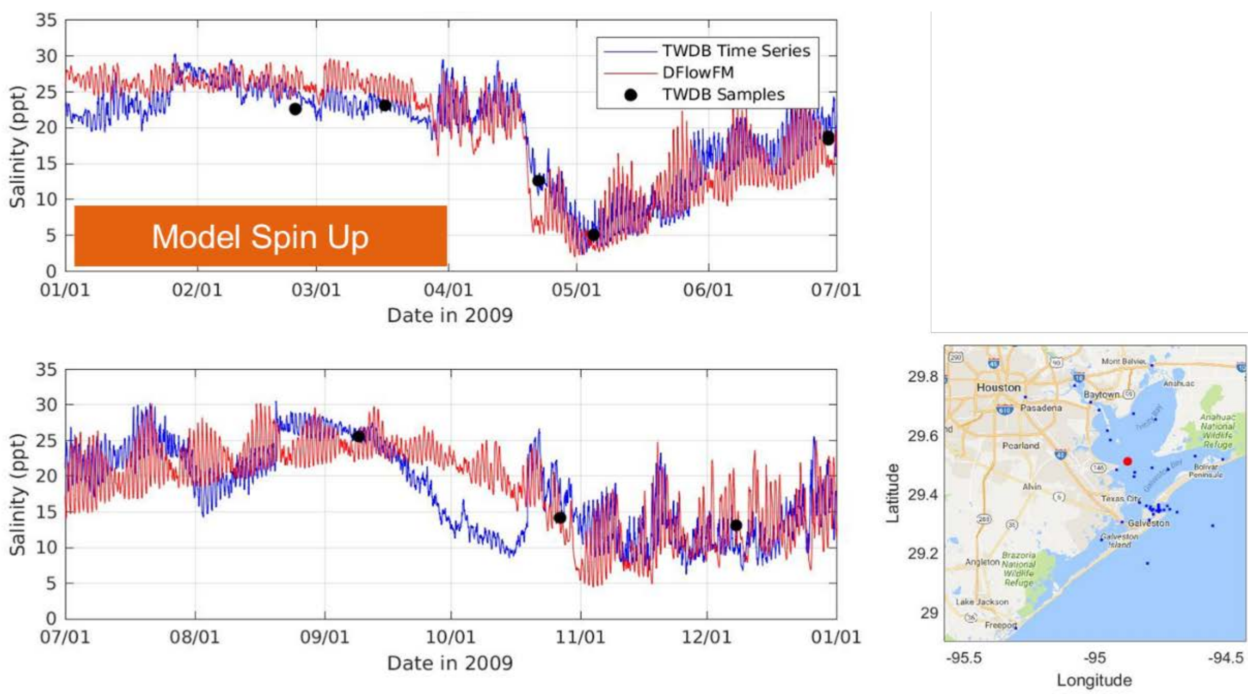


Figure 26: 2009 Salinity Comparisons at Mid Galveston Bay

5.3.4.2.3. Alternatives Evaluation

Gate alternatives for three GCCPRD alignments, two USACE alignments, and the SSPEED center alignment were modeled separately and the results were compared to the flow conditions without gates. Discharge, impact to tide levels, and salinity were compared for each of the scenarios.

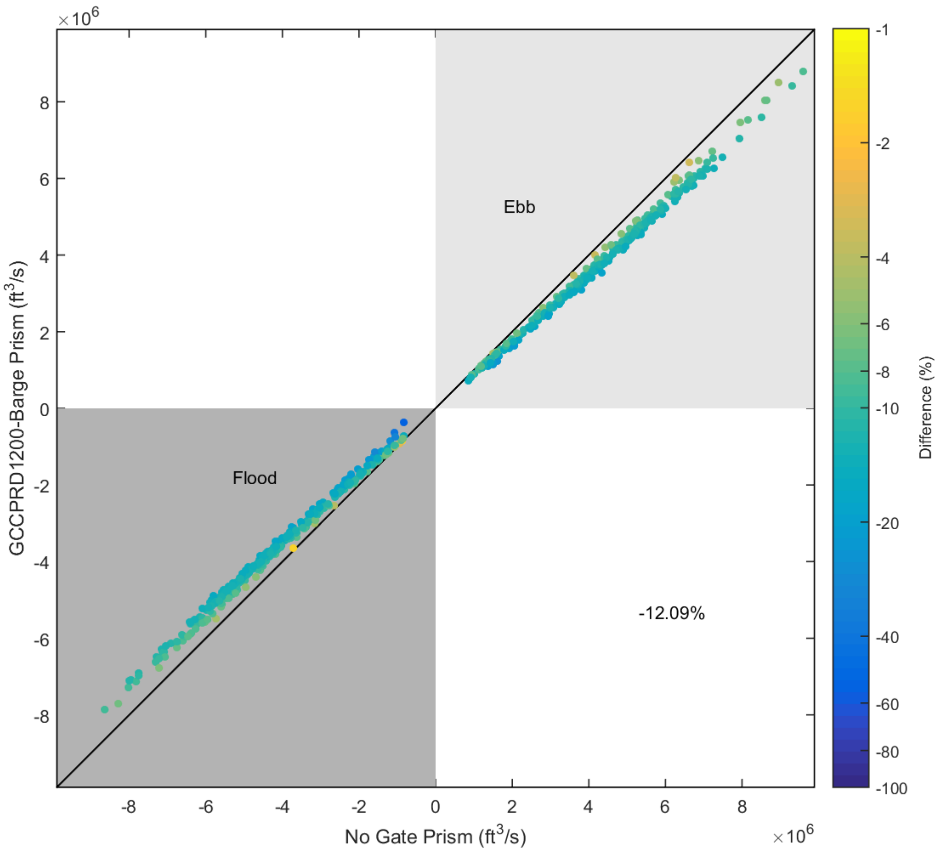


Figure 27: GCCPRD1200-Barge Tidal Prism Comparison at Bolivar Roads

Discharge in and out of the bay increases as the open portion of the gate cross-section increases. The change from the 840-foot opening to the 1,200-foot opening provides an approximately 4.5 percent increase in total discharge at Bolivar Roads. The greatest increase in discharge occurs when using barge gates along the deep portions of Bolivar Roads, which adds a 13 percent increase in discharge from the 840-foot gate.

Water levels in the bay are also impacted. The decreased discharge can result in lower high tides and higher low tides, which is particularly important when determining the impacts to marsh species and habitats. Using a series of tide-only simulations, mean lower low water (MLLW), mean low water (MLW), mean high water (MHW), and mean higher high water (MHHW) datums were computed with and without the barrier gates in place to provide insight into how water levels would be expected to change. Table 16 shows how MLLW, MLW, MHW, and MHHW are affected when each barrier gate configuration is constructed.

Table 16: Impact to Tidal Datums due to Gate Implementation compared to Without Gates (in feet)

	East Bay				Trinity Bay				San Jacinto River				West Bay				Texas City Dike				Dollar Point			
Gate Configuration	MLLW	MLW	MHW	MHHW	MLLW	MLW	MHW	MHHW	MLLW	MLW	MHW	MHHW	MLLW	MLW	MHW	MHHW	MLLW	MLW	MHW	MHHW	MLLW	MLW	MHW	MHHW
GCCPRD840	0.20	0.17	-0.09	-0.10	0.17	0.12	-0.11	-0.13	0.16	0.16	-0.11	-0.14	0.40	0.30	-0.19	-0.26	0.20	0.17	-0.09	-0.10	0.18	0.14	-0.09	-0.10
GCCPRD1200	0.17	0.14	-0.08	-0.08	0.14	0.10	-0.09	-0.11	0.12	0.12	-0.09	-0.12	0.30	0.27	-0.16	-0.22	0.17	0.14	-0.08	-0.08	0.14	0.12	-0.07	-0.08
GCCPRD1200-Barge	0.09	0.07	-0.04	-0.04	0.07	0.05	-0.05	-0.06	0.07	0.07	-0.06	-0.07	0.17	0.18	-0.10	-0.13	0.09	0.07	-0.04	-0.04	0.10	0.08	-0.04	-0.05
USACE-TxCity	0.12	0.10	-0.06	-0.06	0.12	0.10	-0.07	-0.09	0.10	0.09	-0.07	-0.09	-0.10	-0.07	0.06	0.10	0.12	0.10	-0.06	-0.06	0.12	0.11	-0.06	-0.07
USACE-MidBay	0.03	0.02	-0.02	-0.01	0.02	0.00	-0.02	-0.02	0.02	0.02	-0.01	-0.02	-0.05	-0.02	0.01	0.02	0.03	0.02	-0.02	-0.01	0.04	0.03	0.01	0.02
SSPEED	0.03	0.04	-0.03	-0.03	0.06	0.02	0.01	0.01	0.07	0.05	-0.04	-0.04	-0.09	-0.07	0.03	0.05	0.03	0.04	-0.03	-0.03	0.08	0.06	0.00	0.00

Additionally, placing a constriction at the entrance to the bay results in both increases and decreases in depth averaged velocity near the barrier gates. Understanding how and where the velocity increases is important for both ship navigation and environmental concerns such as fish migration. Like other parameters, the changes in velocity correlate well with the change in open area for the various proposed gate designs as shown in Figure 28. Near the navigational channel, the restriction of the opening increases the velocity of water. Away from the gate, the Houston Ship Channel shows decreases in velocity.

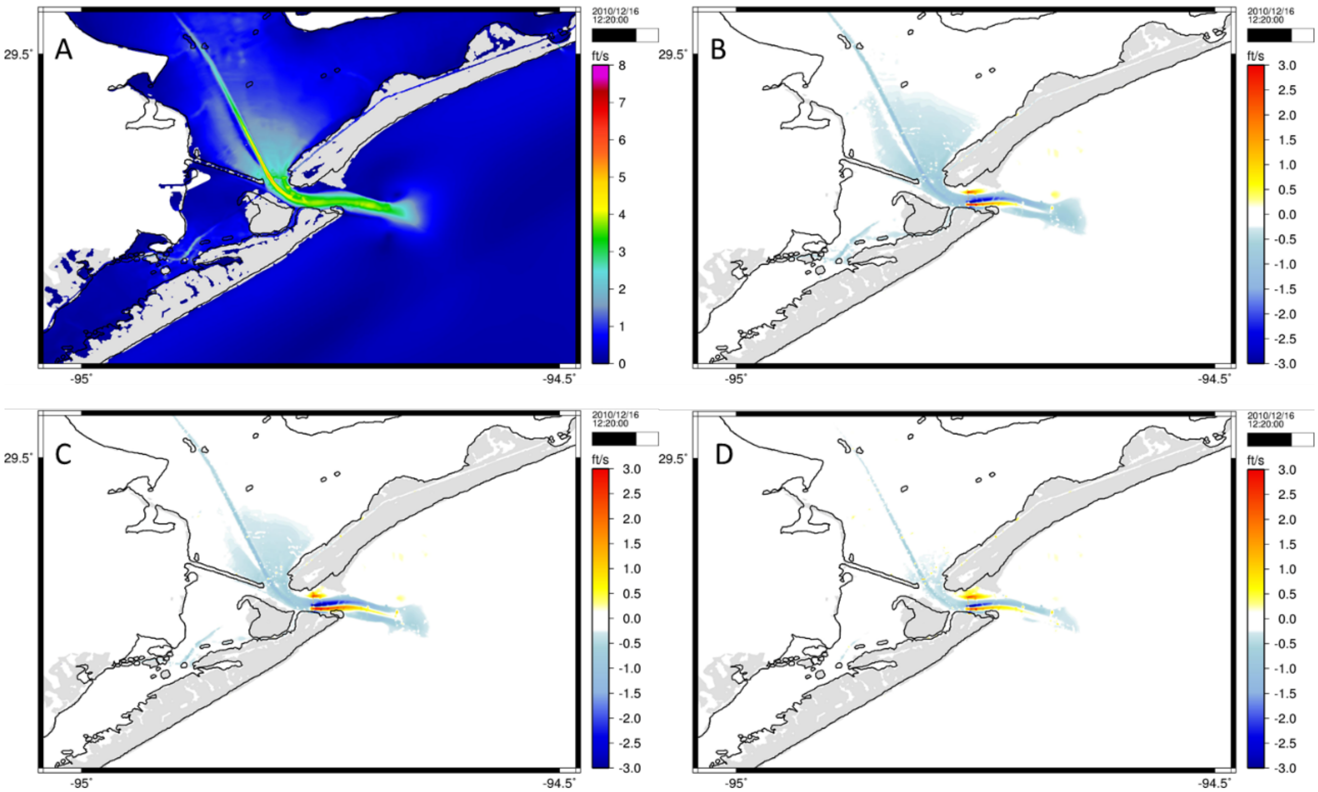


Figure 28: Regional Comparison of Velocities during Ebb Tide (Model A shows the velocity magnitude without gates. Model B shows the change in velocity with GCCPRD840. Model C shows the change in velocity with GCCPRD1200. Model D shows the change in velocity with GCCPRD1200-Barge.)

Salinity comparisons were made by computing the difference between the no-action scenario versus barrier gate installation. Figure 29 shows the salinity changes over a year of simulation at the same locations that the tidal datum calculations were processed. Additional salinity data for other locations in the bay is available in Appendix E.

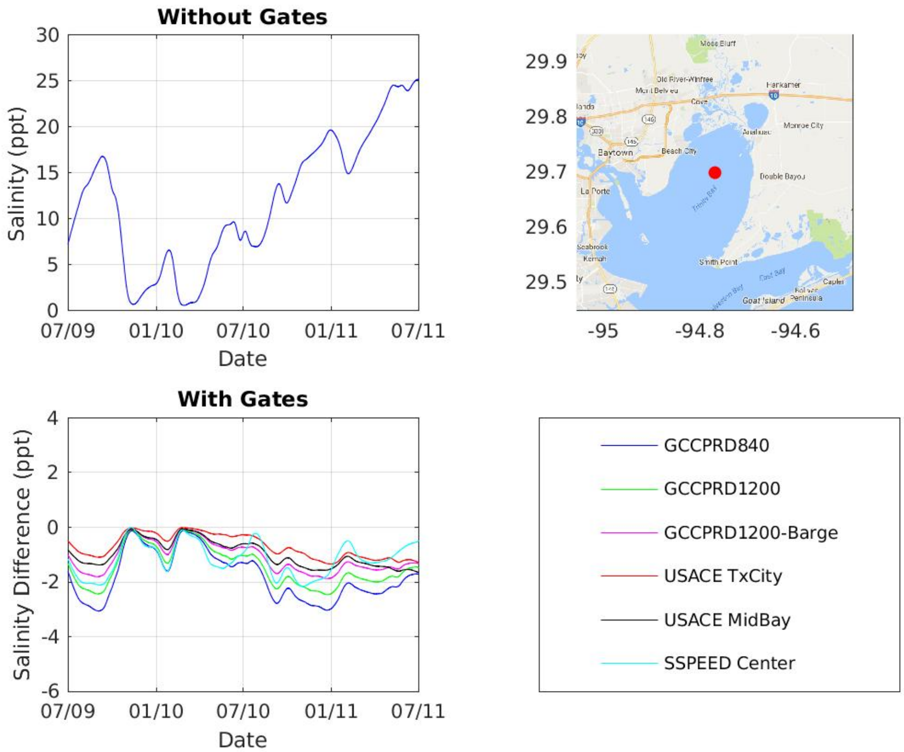


Figure 29: Time Series of Salinity Change in Trinity Bay

The Delft3D-WAQ (Water Quality) model was used to calculate the age of water parcels using a decaying tracer method. This was used as a proxy for impacts to overall water quality since it can quickly describe areas of either stagnation or increased tidal flushing. By injecting both a conservative tracer and a decaying tracer into the bay in identical quantities and comparing their concentrations, the length of time that a parcel of water has existed within the simulation is computed. Figure 30 shows the computed water levels at a single point in the without gates simulation.

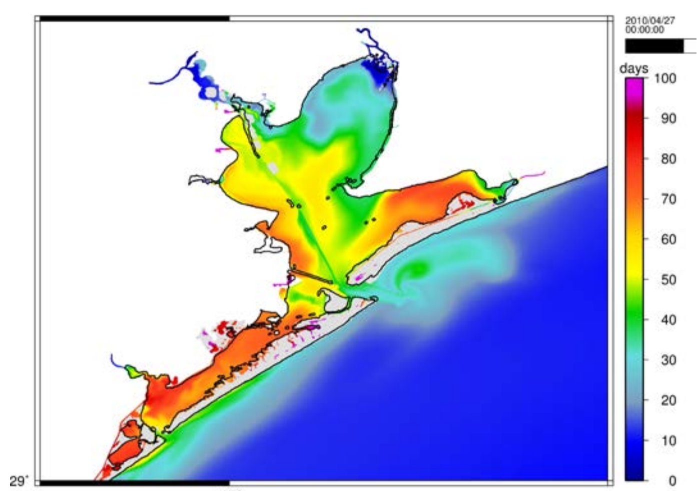


Figure 30: Delft3D-WAQ Water Age Simulation Without Barrier Gates

Figure 31 shows the change to bottom shear stress during ebb tide. Increases and decreases in bottom shear stress correspond to similar changes in velocity. The main navigational gate shows an increase in bottom shear stress in the direction of flow as well as in the areas directly between each of the environmental gates. These increases are present with all barrier gate configurations, though the magnitude is related to the degree of constriction. Decreases in bottom shear stress are present over a much larger area and extend inside into the bay along the Houston Ship Channel.

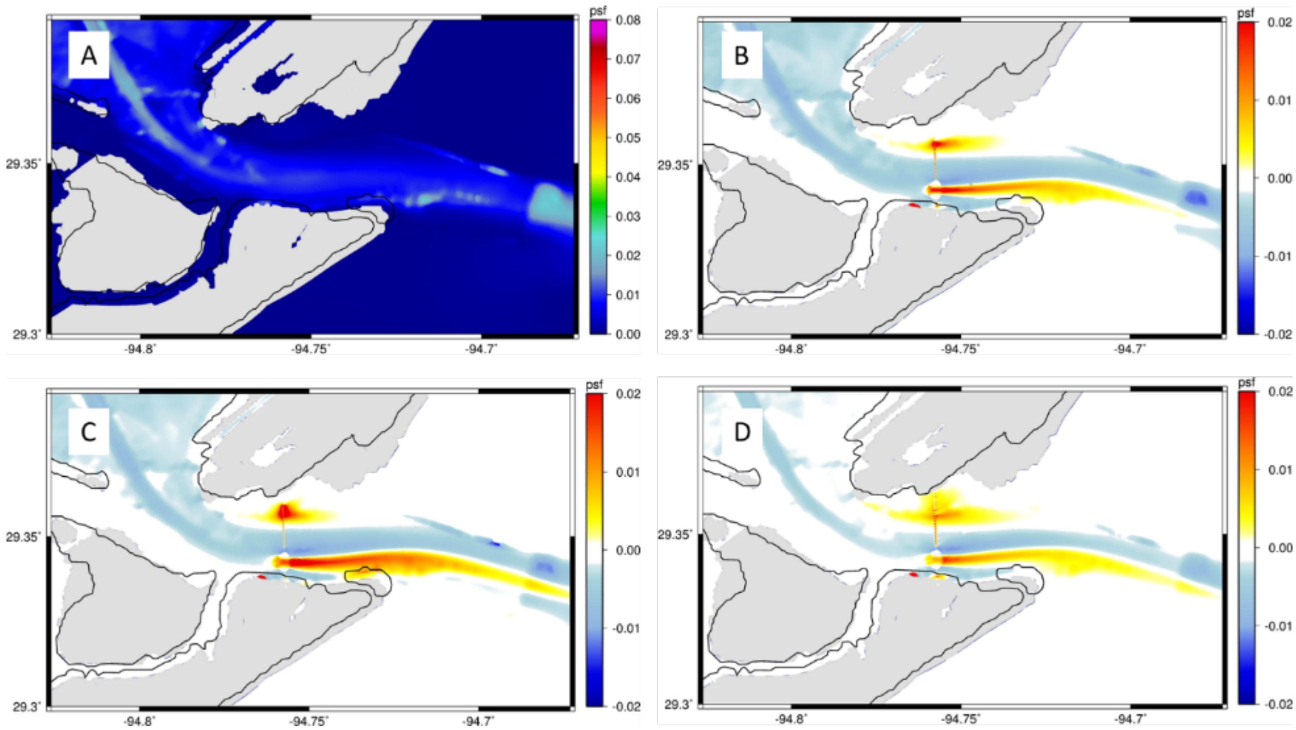


Figure 31: Bottom Shear Stress (psf) during Ebb Tide for (A) No Gates and the Change in Bottom Shear Stress for (B) GCCPRD840, (C) GCCPRD1200, and (D) GCCPRD1200-Barge

5.3.4.2.4. Conclusions

The D-Flow model developed for this study is designed to investigate the impacts to water levels, discharge, salinity, and potential changes in sediment transport and morphology in Galveston Bay. The model was successfully calibrated to match both water levels and salinity based upon available observation data.

Using the model to evaluate the different proposed gate configurations draws the following conclusions:

- The model shows that the reduction in tidal prism is proportional to the reduction in flow area.
- The salinity of the bay is controlled largely by the freshwater inflows to the bay, however the reduction in flow area at Bolivar Roads due to implementing the gates tends to result in a reduction of salinity throughout the system.
- The GCCPRD gate configurations with the largest open cross section, the GCCPRD1200-Barge configuration, result in the least impacts to hydrodynamics, salinity, and water age compared to other proposed gate configurations at Bolivar Roads.

- The model shows that there will be increased potential for sediment deposition in the Houston Ship Channel due to the reduction in shear stresses. Since dredging operations are already required, a morphology study should be conducted to understand this in greater detail.
- The USACE Texas City gate performs similarly to the GCCPRD1200-Barge. Though the USACE Texas City gate is constructed only vertical lift gates, it has the advantage that it does not close off flow from Bolivar Roads to the West Bay
- The results from the modeling conducted in this study can be used to inform environmental studies for marsh, shellfish, fish migration, and larval transport as part of a larger environmental impact assessment.

5.3.5. Cost and Economics Review

As discussed in section 5.3.1, the optimal crest elevation for the Coastal Spine which manages risk associated with a 100-year event is 17 feet and remains unchanged from the 2016 recommended plan. Based on the additional environmental and interior drainage analysis conducted during Phase 4, the overall cost of the project increased which was a factor that caused the BCR for the Central Region to decrease.

Environmental mitigation costs were revised based on the detailed analysis that was conducted to better assess impacts related to upland features as well as within Galveston Bay. Mitigation costs within the region varied between $54,270,229 and $14,366,628, depending on the method of mitigation selected. The Central Region offers the best opportunities for on-site mitigation and this method should be used exclusively to ensure mitigation of impacted nature resources remain within close proximity to where the impact occurred.

The detailed analysis for the interior drainage resulted in an increase in pumping requirements and overall cost especially for the Galveston Ring Levee. Storm surge overtopping the seawall was the main driver resulting in the increased pumping requirements. Raising the seawall to between 24 and 25 feet would reduce the overtopping however, this would create other negative economic and social impacts for the City of Galveston.

Table 17 provides the updated cost and economics summary for the Central Region. The components of the Central Region plan were modeled as a completed system and not individually. Therefore, the Total Annual Cost, Total Annual Benefits, and the BCR are reflected for the region. All benefits and costs are presented in thousands of dollars and reflect 2018 price levels.

Table 17: Revised Economics for the Recommended Plan (17 feet) for the Central Region

Central Region Summary	Coastal Spine	Galveston Ring Levee*	Clear Lake Gate	Total
Total length of the system (miles)	57.0	10.5	1.7	69.2
Right of way required (acres)	1,220	71	33	1524
Pump stations required / total capacity (CFS)	0 / 0	3/117,000	1/10,900	4/127,900
Environmental mitigation required (acres)	220.78	62.61	20.28	303.67
Construction cost ($000)	$6,206,250	$3,422,084	$492,502	$10,120,836
Annual operations and maintenance cost ($000)	31,031	17,110	2,463	50,604
Total Annual Costs (TAC)				522,479
Total Annual Benefits (TAB)				842,287
Benefit - Cost Ratio (TAB/TAC) (2.875 % Interest Rate)				1.61

** Length of the Galveston Seawall is included in the Coastal Spine Length*

5.3.6. *Central Region Conclusions*

The analysis of the optimal elevation of the Coastal Spine for the 100-year event in 2085 is 17 feet. Raising the spine elevation to 20 feet results in a slight loss of net benefits due to the increase in cost being greater than the increase in benefits. Lowering the spine elevation to 15 feet increases benefits, reduces cost, and results in an increase in net benefits but does not meet the FEMA goal of providing protection from the 100-year event. Property owners would not see the desired relief in the annual flood insurance rates.

The study reviewed various options for the gate complex at Bolivar Roads. Analysis clearly showed that the width of the floating sector gate crossing the Houston ship Channel should be 1,200 feet or larger and the structure should have a minimum of 24 vertical lift gates to enhance environmental flow conditions. The GCCPRD1200-Barge analysis greatly enhanced environmental flow however, the operation aspects of the system are cumbersome and complex. The final gate configuration will require further technical and environmental analysis to determine the best solution to reduce flood risk while limiting environmental impacts.

The interior drainage and pumping requirements for the Galveston Ring Levee are substantial due to the extreme overtopping along the seawall. More detailed modelling on the configuration of the wall should also be evaluated to see if a recurved face or other innovative solution could help reduce the overtopping.

6. South Region Optimization Results

6.1. General

The South Region of the GCCPRD study area consists of Brazoria County, which borders Galveston Bay and the Gulf of Mexico on the south-eastern boundary. The portion of the county from the Gulf of Mexico to north of SH 35 is highly vulnerable to tropical storm surge flooding.

The county is partially protected by the existing federally authorized Freeport Hurricane-Flood Protection Levee System (FHFPS). The FHFPS consists of over 45 miles of levees, 14 pump stations, a navigation gate structure and numerous other drainage structures. The system protects the cities of Freeport and Angleton, Port Freeport, and the strategically important petrochemical industry in the Freeport Vicinity, including the Strategic Petroleum Reserve. The system has performed very well through numerous storms especially during Hurricane Ike when the storm surge came within 2 feet of overtopping the levee.

6.2. Phase 3: South Region Recommended Plan

The South Region recommended plan consists of five distinct reaches that would provide enhanced protection to the cities of Freeport, Lake Jackson, Clute and Angleton, Port Freeport, Jones Creek, the tank farm south of Jones Creek, the industrial complexes located along Chocolate Bayou and behind the existing FHFPS.

The plan consists of:

- **Reach 1 – Freeport Hurricane Flood Protection Levee System modernization –** This reach consists of upgrading the federally authorized FHFPS and the locally owned and operated levee system along Buffalo Camp Bayou by raising the levees for the 100-year event in 2085 and installing a new vertical lift gate at the entrance to the Dow Barge Canal.
- **Reach 2** consists of extending the eastside of the existing FHFPS north through Richwood toward Angleton. The proposed extension would cross Oyster Creek and continue north parallel to the west side of Brazosport Boulevard North, through 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, 22 drainage structures, nine roadway gates, and one new pump station. Elevations in this reach vary from 19 feet to 20 feet.
- **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 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 gates, 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. The major elements of this reach include: 65,990 feet of new levee, 13 drainage structures, six roadway gates, and one new pump station. Elevations in this reach vary from 20.5 feet to 24.5 feet.

Figure 32 illustrates the South Region Recommended Plan and the optimization alignments.

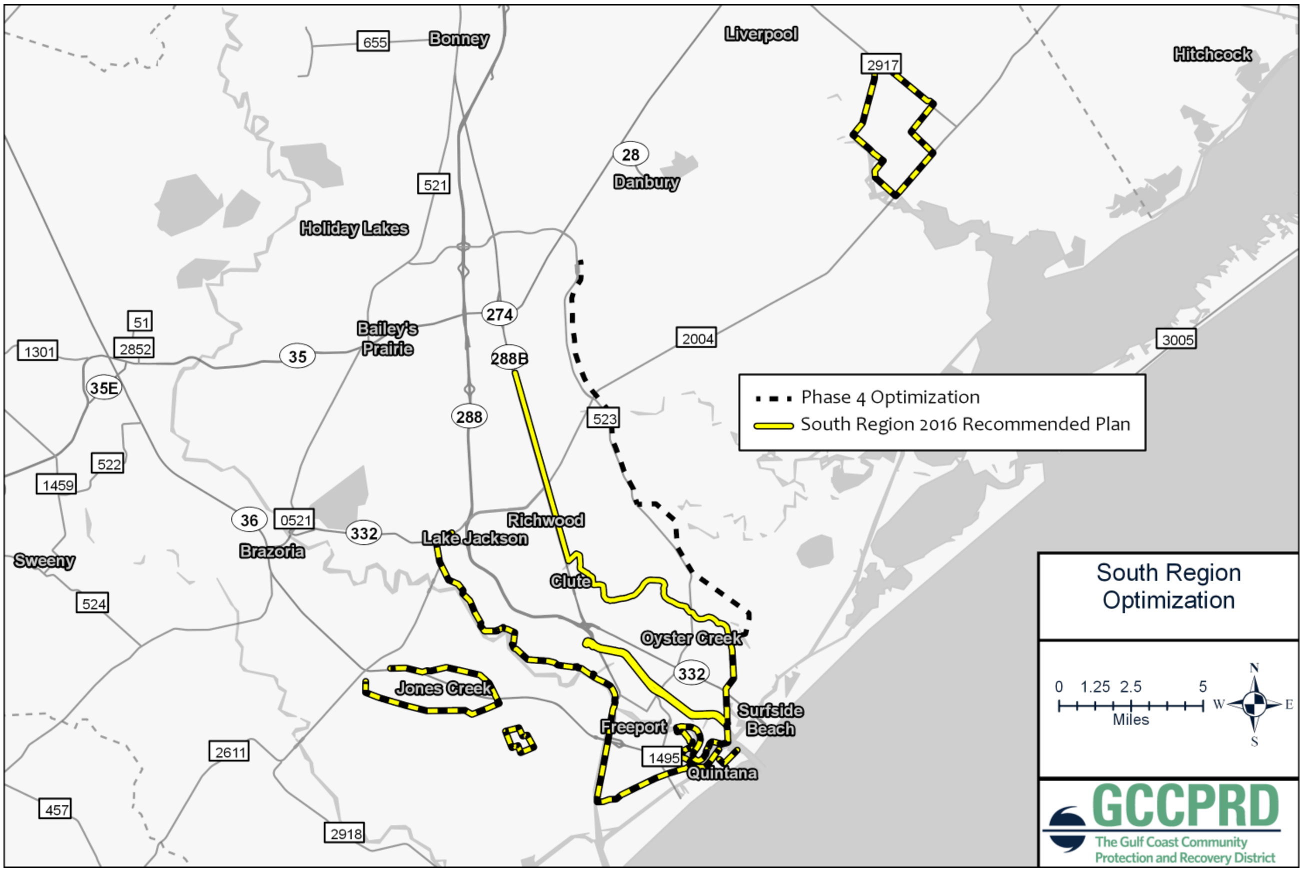


Figure 32: South Region Recommended Plan

The 2016 recommended plan had a construction cost of $2.5B and a Regional BCR of 1.47.

6.3. Optimization Measures

The optimization process for the South Region consisted of the following steps:

- Comparison of alignments and lengths to USACE Sabine to Galveston Study (SP2G study)
- Modification of Reach 2 along FM 523 to provide additional regional protection
- Separate examination and analysis of interior water levels for each Reach of the proposed system
- Enhanced Environmental analysis
- Revision of cost and economics based on the more detailed technical and environmental analysis

6.3.1. Comparison to USACE SP2G study

The USACE SP2G study generally aligns with the recommendations made by the GCCPRD for improvements to the FHFPS. The USACE study focused on the required improvements for the existing FHFPS. Prior to the start of the study, the local sponsor, Velasco Drainage District, was working closely with USACE on the implementation of a system-wide improvement framework plan in order to correct deficiencies and comply with USACE policies and FEMA levee certification requirements.

The GCCPRD study team evaluated additional areas outside of the existing FHFPS that would become vulnerable to storm surge flooding by 2085. This evaluation indicated that the existing FHFPS would need to be elevated and extended to reduce the risk of overtopping and wrap around flooding. Additionally, the GCCPRD evaluated and recommended a plan to reduce the risk to the community of Jones Creek, a tank farm complex south of Jones Creek and the petrochemical complex located along Chocolate Bayou. USACE will be evaluating the requirements for Chocolate Bayou as a part of their ongoing Texas Coastal Study.

6.3.2. Optimization of FHFPS Extension along FM 523

During Phase 4, a different alternative for the extension of the eastside of the FHFPS was evaluated. This new alignment generally parallels FM 523. The new extension reduces flood risk for an additional 20,000 acres of vulnerable land which coincides with the area where current and future residential and industrial economic development is occurring. Figure 33 illustrates the alignment and the associated levee elevations.

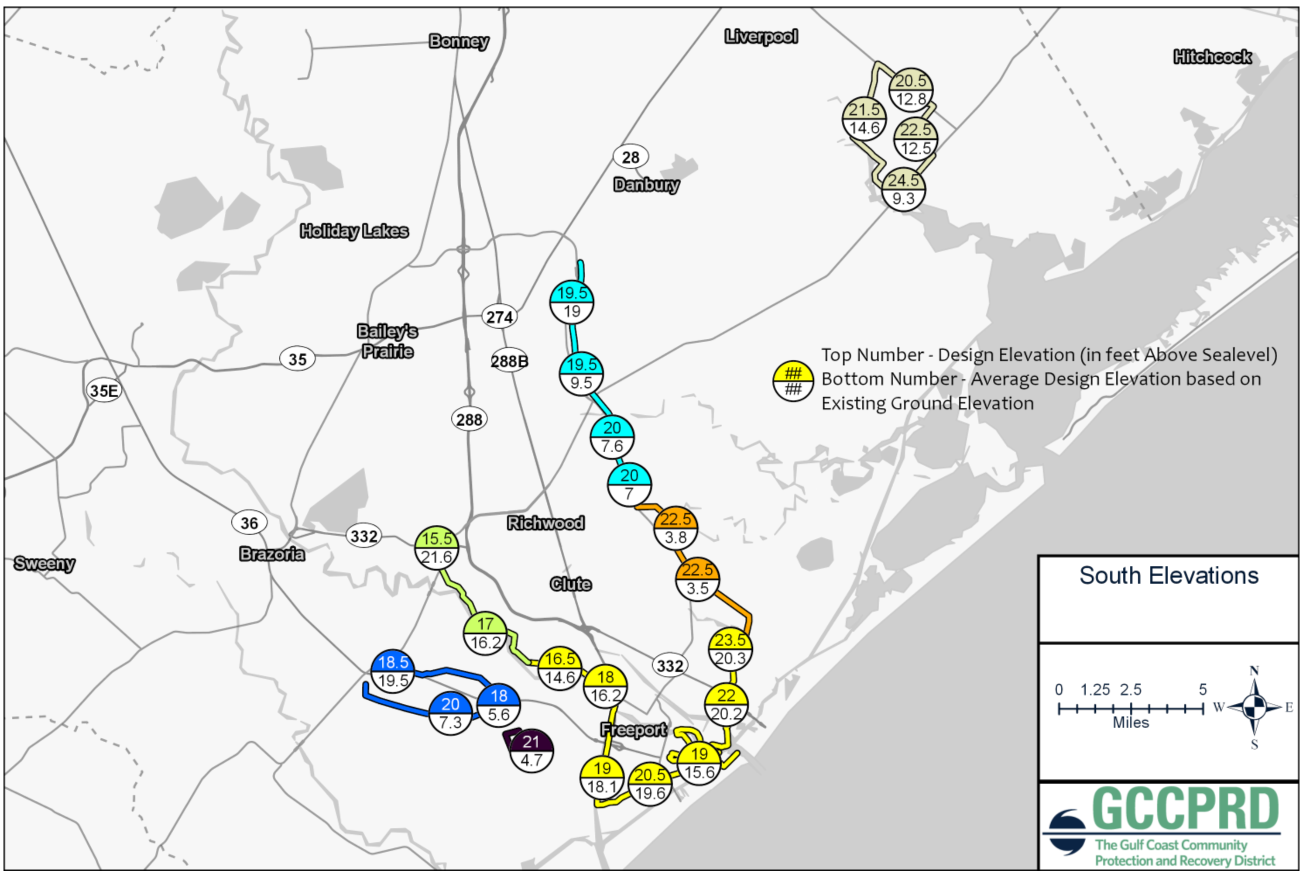


Figure 33: FHFPS Extension along FM 523

6.4. Interior Water Level and Drainage Interior Drainage

Interior drainage for the existing and proposed levees of the Southern Region GGCPRD included sizing pumps and mapping the floodplains for various rainfall and storm surge scenarios of varying annual recurrence intervals for each proposed levee alignments. The pumps associated with each levee alignment were sized to maintain internal flooding levels that result in minimal damage to properties and structures for a hurricane that simultaneously produces a 25-year internal rainfall event inside the levee and a 100-year storm surge that overtops the designed levee. The pump sizing from this phase of the study were used to refine the construction cost and the BCR for the FWA 2085 scenario.

6.4.1. Methodology

Five scenarios were run for each watershed; the 25-year Internal Rainfall (IN) with the 50-year, 100-year, 200-year, and 500-year Overtopping Storm Surge (OT) and the 100-year internal with the 25-year over topping. The same scenarios were run for the FHFPS for both the Future with Action and the Future Without Action to establish a baseline for comparison.

Existing HEC-1 models for Brushy Bayou, Bastrop Bayou, and Oyster Creek were sourced from the 2002 Brazoria County Master Drainage Plan (MDP), converted to HEC-HMS Ver 4.2, verified against original model output, updated with current meteorological models, and modified accordingly with the reservoirs and time series data.

HEC-HMS models for the Chocolate Bayou Levee, Freeport West Levee, Jones Creek Terminal Levee, and Jones Creek Levee were created for this project, as existing models were either unavailable. These models were created with one basin for each pump station. One runoff hydrograph was sufficient to define the hydraulic response of each leveed watershed. The new models utilize Green Ampt Loss parameters representative of Soil Type D and Clarks Unit Hydrograph Transform method congruent with models sourced from 2002 Brazoria County MDP.

The meteorological model input was derived from the Atlas of Depth-Duration Frequency of Precipitation Annual Maxima for Texas SIR 2004-5041 for a 24-hour event. A 67 percent rainfall hyetograph peak distribution was used to align the peak of the rainfall to the peak storm surge. In the models, rainfall peak is generally at hour 16 and runoff peak is at hour 20.

6.4.1.1. Overtopping methodology

Output from Advanced Circulation (ADCIRC) models of the storm surge for 50-year, 100-year, 200-year, and 500-year were used to derive overtopping hydrographs for each levee alignment. Separate hydrographs were derived to the three watersheds, Oyster Creek, Bastrop Bayou, and Brushy Bayou, protected by the Freeport East Levee along FM 523. Overtopping hydrographs peaked around hour 40 of the analysis at the peak flows.

Table 18 illustrates that the storm surge either does not overtop or negligibly overtops some levee segments in multiple storm surge events. With the rainfall event remaining constant, the model yields identical results for different combinations of events in the same watershed, such as Brushy Bayou, where the 25-IN/50-OT, 25-IN/100-OT, and 25-IN/200-OT remain constant.

Table 18: Overtopping Data

Event	Jones Tanks (cfs)	Mustang Lake (cfs)	Oyster Creek (cfs)	Bastrop Bayou (cfs)	Brushy Bayou (cfs)	Jones Creek (cfs)	DOW FWA (cfs)	DOW FWOA (cfs)
50-yr	-	-	1	-	-	-	20	2,800
100-yr	-	-	480	1	-	5	547	75,400
200-yr	74	2	8,400	1,570	-	2,120	13,900	584,000
500-yr	3,700	274	82,600	172,000	38,500	130,000	327,000	2,570,000

The time to peak of the rainfall runoff hydrograph and storm surge overtopping hydrograph were offset approximately 20 hours. Because of the offset of peaks, overtopping events with low volume have little impact to the flooding within the levee. The best example of this is the comparison between the 25-IN/100-OT and the 25-IN/200-OT for the Jones Creek Levee. The 100-OT peak is 5 cfs and the 200-OT is 2,120 cfs. Despite the significant difference in peak OT rate, the ponding within the levee never exceeds the runoff ponding from rainfall runoff.

The calculated ponding elevation for each scenario with the Design Pump Rate applied as the only means of discharge is in the table below.

Table 19: Results Summary

Alignment Reach		Pump Capacity Required (cfs)	Pump Capacity Currently Available (cfs)	Interior Ponding Elevation (ft)	25-IN 100-OT
Freeport East Levee (along FM 523)	Brushy Bayou	0	0	19.9	19.9
	Bastrop Bayou	5,100	0	7.0	7.0
	Oyster Creek	4,850	0	6.0	6.0
Freeport West Levee (FHFPS)	DOW FWA	10,627	10,627	5.5	5.5
	DOW FWOA	10,627	10,627	5.5	5.5
Jones Creek Levee		600	0	8.2	8.2
Jones Creek Terminal Levee		54	0	4.2	4.2
Chocolate Bayou Levee		325	0	11.0	11.0

Since the Freeport East Levee, the Jones Creek Levee, and the Jones Creek Terminal Levee segments are new features, the recommended pumping capacity will need to be added to the system by constructing new facilities. The Freeport West Levee consists of the existing FHFPS and the pumping capacity currently within the system is sufficient, so no new pumping facilities are required.

6.4.2. Environmental Review

This section provides a summary of the potential environmental impacts associated the construction of the South Region system. The full South Region environmental report is located in **Appendices D3-D3.1**.

During Phase 4, the study team conducted a more thorough review of the potential environmental impacts that would be associated with the construction of the five reaches in the South Region. In order to estimate potential impacts, the study team assumed that the proposed levee and T-wall system would have a 150-foot-wide footprint. This enhanced assessment included: field investigations conducted along publicly assessable rights-of-way, additional desktop analysis, coordination with USACE, and calculating future mitigation requirements using the WVA model. The cost associated with mitigation were incorporated into the overall project cost and considered in the BCR calculations.

Impacts to the following were very minor and insubstantial:

- Prime and Unique Farmlands
- Socioeconomic Impacts
- Protection of Children from Environmental and Safety Risks
- Federal Water Project Recreation Act
- Executive Order 11990: Protection of Wetlands
- Section 303(d) of the Clean Water Act: Impaired Streams
- Section 402 of the Clean Water Act
- Wild and Scenic Rivers
- Coastal Barriers
- Vegetation
- Executive Order 13112 on Invasive Species
- Executive Memorandum on Environmentally and Economically Beneficial Landscaping
- Migratory Birds and the Migratory Bird Treaty Act
- Fish and Wildlife Coordination Act
- Bald Eagle Protection Act of 1940
- Marine Mammal Protection Act of 1972
- Air Quality
- Greenhouse Gas Impacts
- Noise

The primary potential impacts are described in the following sections.

6.4.2.1. Cultural Resources

A preliminary assessment of the cultural resources within the South Region Alternative was conducted using a combination of a desktop review of the Texas Historic Sites Atlas and further confirmation of the mapped sites during a site visit. The Area of Potential Effect (APE) for historic resources is 150-feet, 75-feet on either side of the alternative for direct impacts and 1,500-feet, 750-feet on either side, for indirect impacts.

Part of the Velasco Cemetery is within the 150-foot APE of the Freeport Levee. Therefore, the alignment of the Freeport Levee will need to be shifted to avoid this cemetery during the design phase to avoid direct impacts.

According to the Texas Historic Sites Atlas, Futch Cemetery appears to be within the 1,500-foot APE of the Jones Creek Levee. However, Futch Cemetery was not observed during the field visit, so the exact location is unknown and unconfirmed. Based on current information for the proposed project, any impacts to the Futch Cemetery would be indirect. Two additional historical markers would be impacted. The Bryan Mound marker is within the 1,500-foot APE for indirect impacts. The marker for the Velasco Ghost Town is approximately 95-feet from the existing Freeport Levee and could be directly impacted by levee modification.

6.4.2.2. Texas Parks and Wildlife Code, Chapter 26

The proposed project would be located within the boundaries of Brazoria National Wildlife Refuge, Justin Hurst Wildlife Management Area, Riverside Park and MacLean Park, which are all Chapter 26 properties. Brazoria National Wildlife Refuge is northeast of Freeport along the Freeport Levee. Justin Hurst Wildlife Management Area is west of Freeport and south of Jones Creek along the Jones Creek Levee and Tank Farm Levee. Riverside Park is a City of Freeport park along the Freeport Levee. MacLean Park is a City of Lake Jackson park along the Freeport Levee. A Public Hearing is required and would be held during the National Environmental Policy Act (NEPA) process and in accordance with Chapter 26 requirements.

6.4.2.3. Section 404 of the Clean Water Act: Waters of the U.S.

Desktop surveys using U.S. Fish and Wildlife Services' (USFWS) National Wetland Inventory (NWI) maps, USGS 7.5-Minute Topographic Quadrangle maps, Federal Emergency Management Agency (FEMA) Flood Insurance Rate Maps (FIRM), aerial photographs and limited site surveys were conducted.

There are 262 individual NWI signatures that exist within the levee footprint and would be impacted by the proposed project.

The amount of NWI wetlands within the 150-foot wide levee footprint is as follows:

- Jones Creek Levee: 17.62
- Tank Farm Levee: 25.2
- Freeport Levee: 70.77 acres
- Chocolate Bayou Ring Levee: 28.86 acres

As a result, an Individual Permit (IP) and mitigation would be required.

Table 20 shows estimated costs for two types of wetland mitigation: mitigation banks and preservation, restoration and creation. The total cost of mitigation through mitigation banks would be $36,171,210, the total cost of for preservation, restoration, and creation mitigation would be $10,350,445. These wetland mitigation costs were estimated using the acreage amounts above.

Table 20: Estimated Wetland Mitigation Types and Cost

Segment	Mitigation Bank Cost	Preservation, Restoration, Creation Mitigation Cost
Jones Creek Levee	$4,294,875	$1,267,283
Tank Farm Levee	$6,142,500	$1,812,460
Freeport Levee	$17,920,897	$5,090,716
Chocolate Bayou Ring Levee	$7,812,938	$2,179,986
Total South Region Mitigation Cost	$36,171,210	$10,350,445

6.4.2.4. Section 401 of the Clean Water Act: Water Quality Certification

The project would impact more than 1,500 linear feet of stream and more than 3 acres of waters of the U.S. The Tier II 401 Certification requirements for the IP would be met by implementing approved erosion controls, sediment controls, and post-construction Total Suspended Solids (TSS) controls.

The design and construction of the proposed project would include construction and post-construction TCEQ 401 Water Quality Best Management Practices (BMPs) to manage storm water runoff and control sediments.

6.4.2.5. Rivers and Harbors Act of 1899

Section 9 of Rivers and Harbors Act of 1899 (33 U.S.C. 403; Chapter 425) regulates the construction of any bridge, dam, dike or causeway over or in navigable waterways of the U.S. Section 10 of the Rivers and Harbors Act of 1899 regulates any structures or work in navigable waters. The proposed project would modify a gate across the Brazosport Turning Basin and add a new gate across the Dow Barge Canal, both of which are navigable waters of the U.S. Therefore, this project would require a Section 9 permit from the USCG and a Section 10 permit from USACE.

6.4.2.6. Floodplains

The acreage amount in the FEMA 100-year floodplain can be found below:

Table 21: Floodplains

Levee	Acreage Amount in 100-year Floodplain
Chocolate Bayou Ring Levee	161 acres
Freeport Levee	268 acres
Jones Creek Levee	111 acres
Tank Farm Levee	41 acres

The South Region Alternative must be located in a floodplain in order to reduce flood risk behind the flood suppression system. The South Region Alternative would adhere to the 8-step process as outlined under Executive Order 11988, Floodplain Management, including consideration of sea level rise.

6.4.2.7. Texas Coastal Management Program

For the proposed project, the Texas GLO would have to prepare a Consistency Determination that evaluates the proposed project for consistency with the Texas Coastal Management Program.

6.4.2.8. Wetland Value Assessment

A Wetland Value Assessment (WVA) was conducted for the South Region. The environmental period of analysis is a total of 50 years based on the following assumptions: The construction period is assumed to end in 2035. The period for which mitigation benefits are analyzed is 2036-2085.

The direct impacts assume no change in wetlands between the baseline and the future target year without the project and total loss of all wetlands within the levee footprint due to construction impacts. Table 22 provides a summary of the results of the WVA modeling of direct impacts.

Table 22: Direct Impacts to the South Region Alternative

Levee System	Marsh Model Type	Acreage	Future w/o project AAHU	Future w/project AAHU	Net Impact
Tank Farm Levee	Freshwater	30.39	6.85	5.12	1.73
Jones Creek Levee	Freshwater	31.69	8.49	6.24	2.25
Chocolate Bayou Ring Levee	Freshwater	10.03	2.68	1.97	0.71
	Freshwater Near Brackish	8.82	3.37	2.41	0.96
	Brackish	9.20	2.64	1.91	0.73
Freeport Levee	Freshwater	41.02	10.50	7.75	2.75
	Freshwater Near Brackish	53.19	14.87	10.89	3.98
	Brackish	10.13	3.30	2.37	0.93
Total		**194.47**	**52.69**	**38.65**	**14.04**

Total direct impacts would affect 194.47 acres of wetlands and result in the net loss of 14.04 Average Annual Habitat Units (AAHU's) over the period of analysis. Mitigation would be needed to compensate for a loss of 14.04 AAHUs from freshwater and brackish marshes.

6.4.2.9. Essential Fish Habitat

Essential Fish Habitat (EFH) has been designated in the project area for Red Drum, shrimp, and reef fish to minimize fisheries-related impacts to these commercially important species (GMFMC, 2005). Coordination with National Marine Fisheries Service (NMFS) would be required.

6.4.2.10. Threatened and Endangered Species

Review of the USFWS Endangered Species List and Critical Habitat for Brazoria County (October 2017), TPWD Annotated County List of Rare Species for Brazoria County (October 2017), and a search of the Natural Diversity Database, in conjunction with GIS, was conducted to determine the potential occurrence of State and Federally listed threatened and endangered species and their habitat.

The proposed project may impact the habitat of seventeen state-listed species. Prior to construction, coordination with TPWD would be initiated and BMPs would be implemented to minimize habitat loss and impact to any state-listed species.

The proposed project would not impact or effect any federally listed species or its habitat

6.4.2.11. Hazardous Materials

A hazardous materials regulatory database search was conducted for the region. There are approximately 337 sites that could pose a risk to the proposed project. More complete hazardous materials site investigations will need to be done in the future as a part of the preliminary design in order to finalize NEPA documents.

6.4.2.12. Conclusions

The proposed project would involve the following impacts:

- The project may directly impact two historic resources and indirectly impact an additional two historic resources.
- Two public parks and 2 WMAs would be impacted, and a Public Hearing per Chapter 26 requirements is required.
- 142.45 acres of potential wetlands would be impacted across the four regional levee systems. Mitigation would be required and the total estimated cost of mitigation for the South Region would be $36,171,210 for mitigation banking and $10,350,445 for preservation, restoration, and creation mitigation.
- The project would impact more than 1,500 linear feet of stream and more than 3 acres of waters of the U.S. and would therefore require Tier II Water Quality Certification from TCEQ.
- The project would involve construction of gates across two navigable waters of the U.S. and would therefore need a Section 9 Permit from the USCG and a Section 10 Permit from USACE.
- The South Region Alternative must be located in a floodplain in order to reduce flood risk behind the flood protection system. The South Region Alternative would adhere to the 8-step process as outlined under Executive Order 11988, Floodplain Management, including consideration of sea level rise.
- The GLO would have to prepare a Consistency Determination that evaluates the proposed project for consistency with the TCMP.
- A wetland value assessment was performed. Total direct impacts would affect 194.47 acres of wetlands and result in the next loss of 14.04 AAHUs over the period of analysis. Mitigation would be needed to compensate for a loss of 14.04 AAHUs from freshwater and brackish marshes.
- EFH has been designated in the project area for Red Drum, shrimp and reef fish. Coordination with NMFS would be required.
- The proposed project may impact the habitat of seventeen state listed species but no federally listed species.
- There are approximately 337 hazardous material sites that could pose a risk to the proposed project.

6.4.3. Cost and Economics Review

Table 23 provides the updated cost and economics summary for each segment in the South Region plan. All benefits and costs are presented in thousands of dollars and reflect 2018 price levels. The segments within the FHFPS including the proposed extension along FM 523 were modelled together as a complete system. The other segments are stand-alone and provide risk reduction to specific areas; therefore, they were modelled individually.

Regionally, the overall BCR for the Phase 4 plan is 0.81, which was a reduction from the Phase 3 BCR of 1.47. This can be attributed to modifications that were made to the stage frequency and structure foundation height survey data, which lead to a reduction in the Total Annual Benefits. Revaluating the Phase 3 data with the new elevation data would result in the same degree of benefit losses.

The reevaluation of the construction cost for the optimized plan resulted in a $100M reduction. Unfortunately, the cost reduction was not enough to overcome the loss in benefits, which drove the BCR down.

Removing the low-performing Jones Creek Levee and Jones Creek Tank Farm segments would result in the BCR increasing to 0.87. The modest gain in BCR does not justify the removal of these two segments from the plan at this time.

Table 23: Cost and Economics Summary for the South Region (in $Thousands)

South Region Summary	FPHFPS and FM 523 Extension	Jones Creek Levee	Jones Creek Tank Farm	Chocolate Bayou	Total
Total length of the system (miles)	45.0	9.6	3.0	11.0	68.6
Right of way required (acres)	263	93	56	161	573
New Pump stations required / total capacity (CFS)	2/9,950	1/600	1/54	1/325	5/10,929
Environmental mitigation required	104.3	31.7	30.4	28.1	194.5
Construction cost $(000)	1,846,621	163,034	122,117	308,955	2,440,767
Annual operations and maintenance cost	9,233	815	611	1,545	12,204
Total Annual Costs (TAC)	95,330	8,416	6,305	15,952	126,000
Total Annual Benefits (TAB)	82,285	3,452	1,182	15,178	102,097
Benefit - Cost Ratio (TAB/TAC) (3.125% Interest Rate)	0.86	0.41	0.19	0.95	0.81

6.5. South Region Conclusions

In the South Region, a new alignment for the Eastern Extension of the FHFPS along FM 523 was adopted into the plan. In the 2016 plan, the alignment extended from the eastern terminus of the levee north toward the City of Angleton. The optimized plan extends the levee generally along FM 523 north to the City of Angleton. The new levee system will reduce the risk to 20,000 additional acres of land in the region where current and future residential and industrial development is expected to occur. The new alignment reduces the overall construction cost in the South Region by $100M for $2.5B to $2.4B. The reduction in the construction cost is not enough to keep the overall BCR from dropping from 1.47 to 0.81. The decrease in the BCR is again attributed to modifications that were made to the stage frequency and structure foundation height survey data.

7. The Way Ahead

7.1. Natural & Nature-Based Features

Natural and nature-based features (NNBF) provide coastal protection, ecosystem support, and socio-economic benefits. While beyond the scope of the GCCPRD's grant and funding, NNBF elements will be an important part of any coastal protection plan. The protection systems envisioned in this report provide an opportunity to look beyond traditional civil engineering and construction projects to provide better storm risk management, ecosystem restoration, and protection and community and recreational amenities. Aligning NNBF plans with the mitigation planning also ensures that the critical environmental resources impacted by the project are constructed at or near the site of impact and not moved to mitigation banks located elsewhere. Figure 35 outlines potential opportunities for NNBF benefits within the Central Region of the GCCPRD recommended plan. The GCCPRD encourages additional study and inclusion of natural and nature-based features in any final project design. **Appendix J** provides additional detail on the proposed NNBF opportunities and was provided to the GCCPRD through a collaborative effort with Ecology & Environment, Inc. It is included in this report with their permission.

Figure 34: Miami Beach Boardwalk

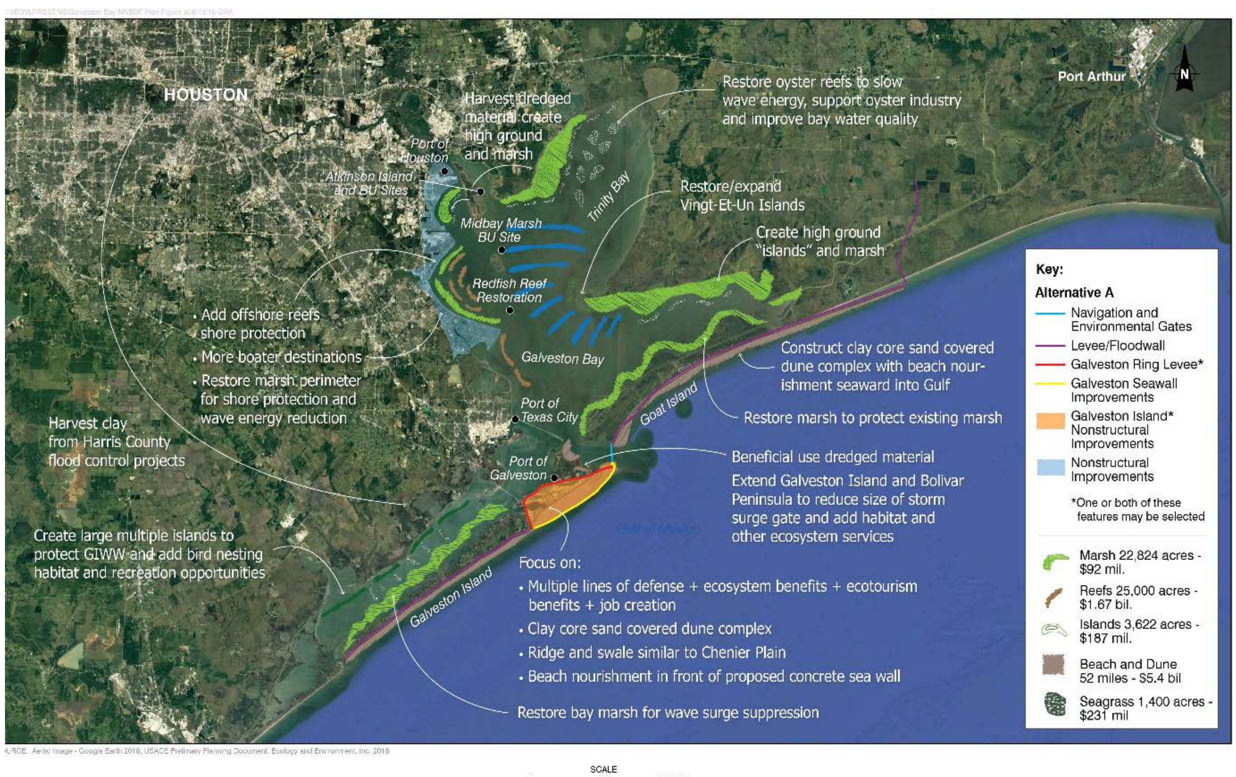


Figure 35: USACE & Texas GLO Coastal Texas Protection & Restoration Study with NNBF

7.2. Develop Innovative Finance Solutions

In February 2018, the Bipartisan Budget Act provided USACE $3.9B for the construction of the recommend plan outlined in the SP2G study. The legislation enables USACE to fully fund the construction Orange, Jefferson, and Brazoria Counties with federal dollars. The local sponsors for each project will have 30 years from the date of construction completion to repay their 35 percent cost share.

While this is good news for the region, many of the local sponsors are concerned with how they will repay their share in addition to paying the costs of operating and maintaining these new structures. For example, the Orange County cost share for their project is roughly $650M with an additional $6M to $7M for annual operations and maintenance. The entire Orange County currently operates on a budget of $45M per year.

This scenario clearly illustrates the need to re-evaluate how local entities pay for projects of this magnitude. There needs to be a be a discussion between federal, state, local officials and potentially private equity groups to look at innovative financial solutions and to develop a long-term strategy.

7.3. USACE Coastal Texas Protection and Restoration Study

In October 2018, USACE published their Tentatively Sleeted Plan (TSP) for the Coastal Texas Protection and Restoration Feasibility Study (the Coastal Texas Study). This study is evaluating the coastal protection needs for the remainder of the Texas Coast including the highly vulnerable and valuable portion that reduce risk in Galveston, Harris, and Chambers County. The USACE TSP resembles the 2016 recommended plan published in the GCCPRD Phase 3 Report. The GCCPRD will continue to collaborate with USACE until the Coastal Texas Study is completed in March 2021.

1. Introduction

The environmental impact assessment section of this report has already described the importance of minimally obstructing the tidal exchange through any flood barrier during regular operating conditions. It also mentions that a total of three alternatives has been evaluated for the Bolivar Roads that represents varying percentage of permanent blocking of the Houston Ship Channel cross-section. The following sub-sections further discuss the details of structural gates within the barrier alternatives. Relative advantages and disadvantages of the barriers will be discussed along with constructability, operation & maintenance and time required to close the gates. A discussion of the relative costs for all three alternatives will follow. Finally, a proposed phasing of construction will be proposed. The three alternatives for the Houston Ship Channel that will be discussed are,

1. GCCPRD840 – Features 54.8% permanent closure
2. GCCPRD1200 – Features 52.8% permanent closure
3. GCCPRD1200-Barge – Features 38.5% permanent closure

2. General Overview of Alternatives

The following sub sections describe the general features of each alternative.

2.1. GCCPRD840

This the first option that was developed for the Bolivar Roads. A prior study has determined that the maximum width that is needed at the ship channel to accommodate two ships passing side by side is 840 ft. This estimate was derived considering the ships with the largest draft possible and the future expansion of traffic at the Port of Houston. To block the deepest part of Bolivar Roads, which is expected to be used by the largest ships, an 840 ft. wide floating sector gate was proposed.

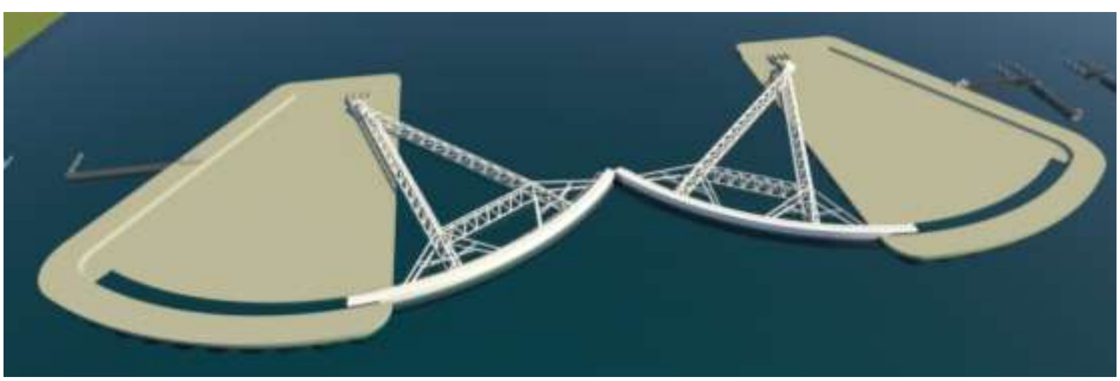


Figure 1: Floating Sector Gate and Artificial Island

As seen in Figure 1. The floating sector gate comprises of two steel gate leafs and two artificial islands on either side. During regular channel operating conditions, the gate leafs rest on the island in their dry dock. During the time of closure, the dry docks are flooded and the gate leafs float up. These are then mechanically driven to position them in the middle of the 840 ft. opening. Once in place the gate chambers which acts as flood barrier are filled with water and submerged to the bottom sill.

The flood barrier portions on either side of the artificial island of the floating sector gate constitutes of twenty-four Vertical Lift Gates (VLG). The actual opening that is formed by a steel panel is 100 ft. wide. This panel travels up and down mechanically as needed and is hosted on a concrete monolith and a tower on either side. The whole arrangement sits on a pile supported concrete foundation slab. The concrete monoliths on both side constitute around 50 ft. of permanent blockage of the waterway.

Along the barrier, the space between adjacent VLG monoliths are permanently blocked using combi-wall sections. These are comprised of vertical and battered, concrete filled steel pipe piles with a concrete cap on top that ties all of the piles.

2.2. GCCPRD1200

This second alternative was considered because of the fact that the previously mentioned GCCPRD800 alternative blocked 54.8% of the channel cross-section permanently. This can have an extensive and long lasting negative impact on growth and sustenance of aquatic life, vegetation and geomorphology of the region. As a remedy of this situation, a decision was made to widen the floating sector gate. The famous Maeslant Barrier in Rotterdam, Netherlands features a floating sector gate which is 1200 ft. wide. Since this gate has already been in service for a long time now, the width of this gate was considered as a natural choice for selecting a wider floating sector gate compared to the initially selected gate of 840 ft. width. The rest of the closure structures for this alternative still comprised of twenty four VLGs, similar to the GCCPRD800 alternative.

It should be mentioned that as the sector gate leafs grew wider, there was a requirement to make the artificial islands broader to receive and fully protect the gate leafs. As such, even though the opening through the ship channel increased, longer lengths of the barrier were occupied by the islands on either side of the floating sector gate. Consequently, a minor increase in the amount of opening within the flood barrier was achieved and a total of 52.8% of the waterway was still blocked.

2.3. GCCPRD1200-Barge

The barrier alternatives already discussed proved that the arrangement of the sector gate and combination of VLGs are inadequate for achieving lesser amount of permanent blockage of the tidal exchange through the ship channel to make it environmentally viable. One option to overcome this scenario could be to increase the number of VLGs throughout the barrier. However, that option would drive the cost of the entire barrier higher. It was imperative that a more economic closure structure be identified so that more openings through the barrier can be achieved at a lower cost. The Arcadis team evaluated a barge gate option towards that goal. Information about the existing in-service barge gates in the United States was obtained and feasibility of installing such gates within the barrier were investigated. The team found that there are a number of these gates deployed in South Louisiana varying with a closure width of 100 ft. to 270 ft. The largest barge gate that was installed is named Bubba Dove, located near Dulac, LA and boasts a total height of 43 ft. It should be noted that previous analysis confirmed that the VLGs need to span a vertical height from EL -30.0 to EL +18.0; resulting in a total height of 48 ft. Thus, the Bubba Dove gate was considered a reasonable alternative for such application within Bolivar Roads. The team decided to include fifteen 200 ft. span barge gates and reduce the number of 100 ft. VLGs to eight. In addition, this alignment also features the 1200 ft. wide floating sector gate. The figure below shows a bathymetric profile of the channel cross-section through the proposed alignment. Existing sill elevation of the deepest part of the channel is EL -50.0, which will be blocked by the 1200 ft. span floating sector gate. Bottom sill on either side of the artificial islands seem to be located at an average elevation of EL -30.0. The team decided that these locations are ideal for 48 ft. tall, 200 ft. span barge gates. Towards the north, along the proposed alignment, the sill elevation averages in between EL -5.0 and EL -10.0. The team chose to put VLGs in such shallower depths. As before, the portions of the barrier in between adjacent closure features will be blocked using combi-wall sections. Figure 2 below shows a three-dimensional representation of this barrier option.

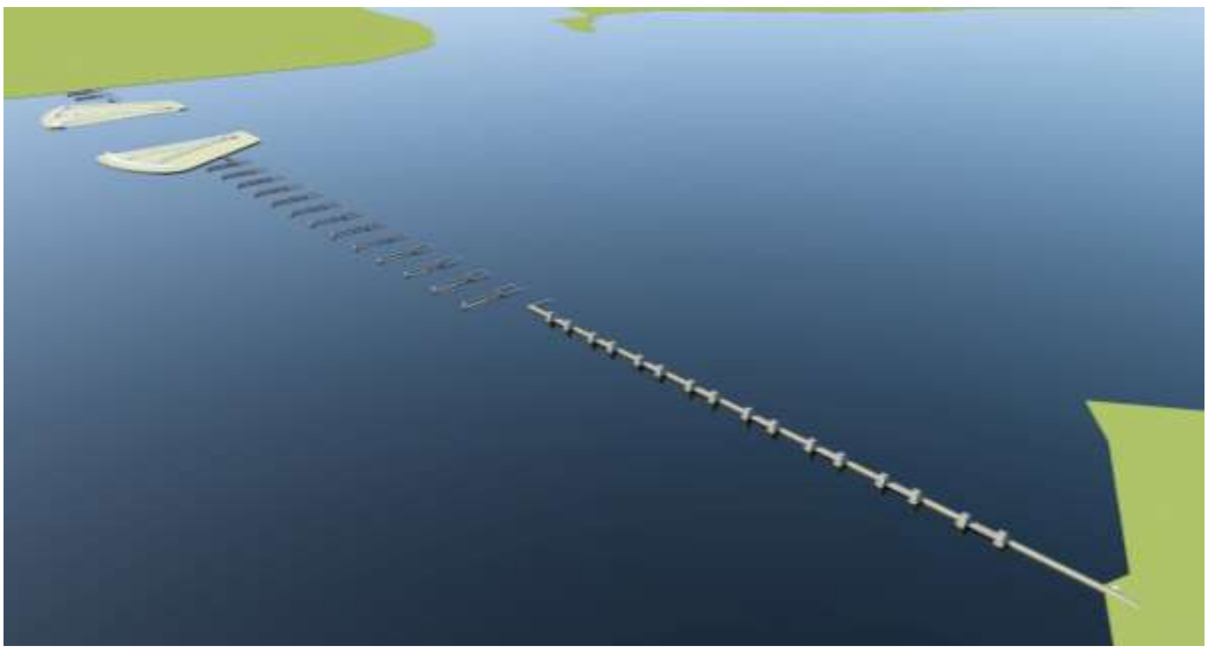


Figure 2: GCCPRD1200-Barge Alternative

The inclusion of the barge gate within the barrier alignment allowed for more openings. Further discussion on how this was achieved will be explained in the following sub-section where the structural details of the barge gate are laid out. It should be noted that the combination of the 1200 ft. sector gate, barge gates and VLGs reduced the permanent blockage along the alignment to 38.5%.

3. Barge Gate Details

A series of barge gates are proposed in the GPPRD1200-Barge option (Figure 3). Previous appendices of this report had described the structural details of floating sector gates, VLGs and combi-wall segments. Since the barge gate is a newly introduced option, more detailed about this of type of closure structures is discussed below.

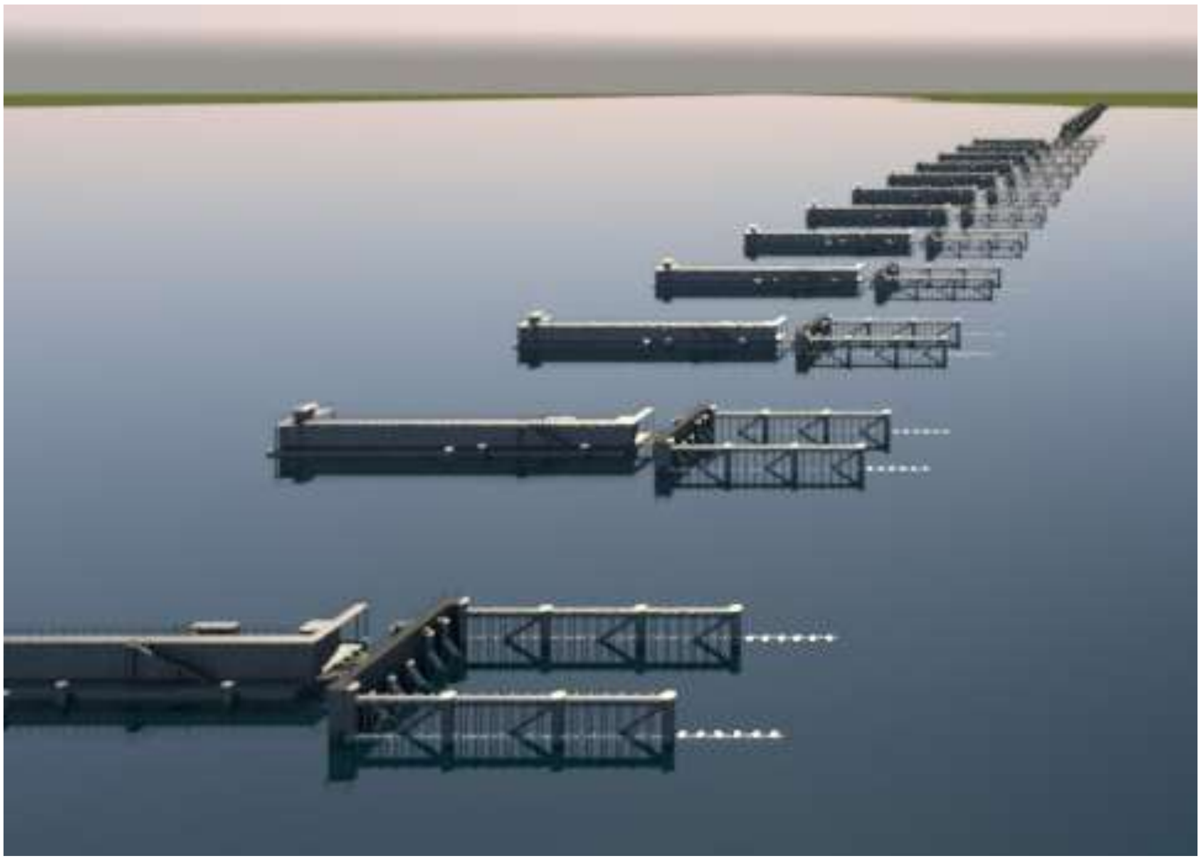


Figure 3: Series of Barge Gates

3.1. Structural Components

3.1.1. Chamber & Flood Wall

The barge gate itself is a steel structure which has two major components. The major portion of it's body is constructed as a rectangular chamber which is hollow inside. The other component is a smaller height flood wall which sits on top of the chamber. The flood wall portion of the barge gate will constitute the top 10-13 ft. of the barge gate height. The rest of the height is represented by the chamber itself.

The hollow chamber part of the barge gate is equipped with electro-mechanical pump system which can fill in the chamber within 1 to 2 hours. The pumps will have the capacity to drain out the water from the chamber within the same amount of time. The chamber walls will be constructed with steel plates with additional bracing members in side. The chamber section is also equipped with a number of 6 ft. diameter steel pipes that pass through the barge gate from the flood side to the protected side. These pipes will be fitted with mechanized sluice gates which will restrict flow of water through the gate.

The flood wall component on top of the barge gate chamber can be made out of either concrete or steel. The walls are thick enough or fortified using stiffeners so that they can withstand the water pressure equal to their height. The flood wall portion provided space on the protected side of the barge gate on top of the chamber structure to house generators and other electro-mechanical controls. The flood walls are also somewhat offset from the flood side edge of the gate providing a plat form on top of the chamber. This allows to have a platform on the flood side for personnel to perform periodic inspection and maintenance.

On top of the barge gate there will also be a operators room which will also house the winch mechanism that will close and open the gate. Figure 4 shows the details of a barge gate.

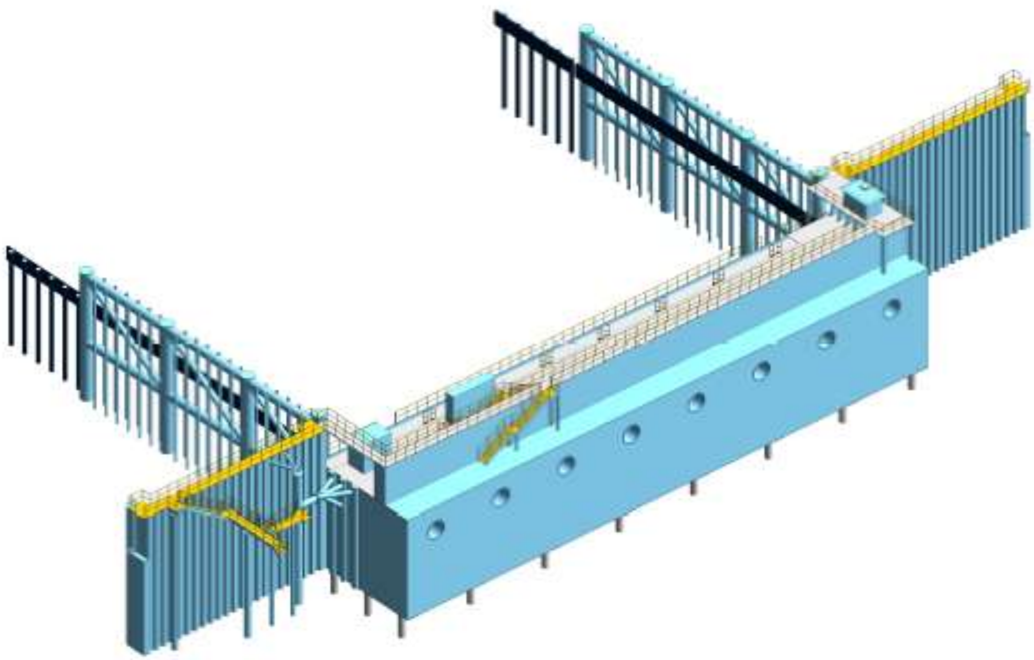


Figure 4: Barge Gate & it's Components

3.1.2. Receiving Structure

In its deployed position, the barge gate needs to transfer the hydrostatic, hydrodynamic and impact forces to a structure that can absorb the loads and safely transmit them to the ground. These structures are placed on either side of the barge gate are referred as "receiving structures". Each receiving structure comprises of a frame type structure made out of steel pipe piles, often filled with sand or grout and capped with concrete. For this current span of 200 ft., a four-pile frame was envisioned with the first pile close to the gate having a diameter of almost 8 ft. The other piles within the receiving structure will be smaller. To make the system efficient to resist lateral loads, the piles will have diagonal bracings which are also tubular. All the pile head tops will be connected with a top chord. A similar member, parallel to the top chord will be provided at mid height of the pile length which will be sticking out of the ground. Based on further analysis, these connectors and diagonals can be repeated several times to make the receiving structures stiffer.

3.1.3. Gate Pivot

At one end of the barge gate, along the length of the span, it will always be connected with a pipe pile which will act as the pivot point when the gate moves from open to close position and vice versa. Since the gate will always open toward the flood side, the pivot pile will also be placed on the flood side. The pivot will not be designed to sustain any loads when the gate is deployed. The pivot to gate connection will be done in a manner so that the two can be disconnected if there is a requirement to float the barge gate to a dry dock for repair.

3.1.4. Barge Gate Foundation

It should be noted that each barge gate will require two foundations. When the gate is open, the barge itself will rest on a foundation which is laid out perpendicular to the alignment. This foundation is placed on the flood side since the gate opens toward that direction. The second foundation is required to sustain the weight of the gate once it is closed. This foundation will be placed parallel to the barrier alignment and is adjacent to the receiving structures.

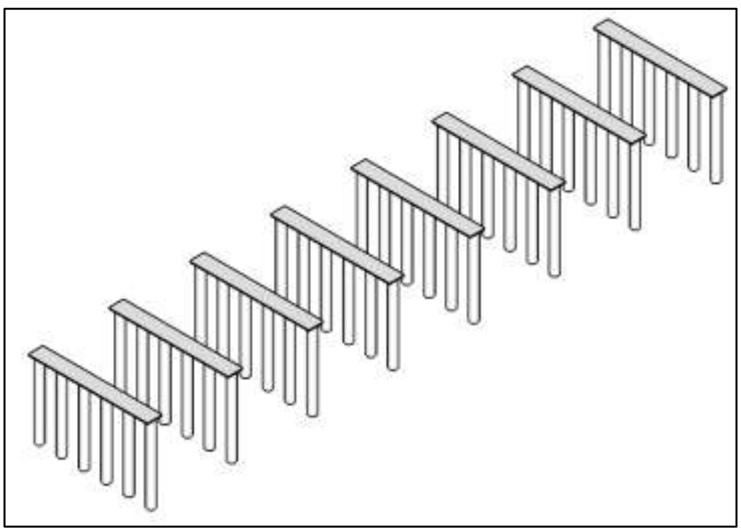


Figure 5: Barge Gate Foundation Pile Bents

As seen above in Figure 5, foundation of the barge gate will comprise of steel pipe piles. There is no need to install a concrete foundation slab. The gate sits on a series of pile bents which will be placed perpendicular to the span length of the barge. The number of pile bents is determined based on the total deployed weight of the gate. Each pile bent has a series of pipe piles which will be connected at the top using thick plates. The thickness of these plates is also determined from the distribution of weight of the barge gate. The top of the foundation will be placed near the existing sill elevation of the cross-section. This way there is no requirement to perform substantial amount of dredging. Riprap will be provided closed to the pile bent tops for a distance before and after the bents. This will prevent scour at the pile bents. If needed, the minimal depth of riprap (2-3 ft.) can be grout stabilized as well.

3.1.5. Tie-in Wall

A total of fifteen barge gates is currently considered for the GCCPRD1200-Barge alternative. adjacent barge gates will be placed 80 ft. away from each other. The space between two barge gate structures will be closed using combi-wall segments. These will also be used to tie-in the barge gates at the periphery to sector gate artificial island, VLGs or adjacent land on higher grounds.

3.2. Barge Gate Operating Mechanism

When the flood barrier is not closed, each barge gate will rest on the foundation perpendicular to the alignment. This will allow tidal exchange through the 200 ft. span. At this point the chamber within the barge gate is full of water producing enough ballast so that the gate is not moved due to wave action. The gate is also anchored to another big pile that is located on the flood side.

At the wake a of a flood event an operator will start the pumps on the barge gate so that water is drained out of the chamber and the gate starts to lift up due to buoyancy. At this point the barge will ride up along the vertical height of the pivot pile. Once the barge gate is buoyant enough, the winch rope will be tied to a pile close to the receiving structure. A boat will be required for this operation. Once the rope is fastened, the operator will start the mechanized winch, which will gradually pull the barge towards the receiving structure. Once in place, the pumps will be active again filling up the chamber with waters. This will gradually ballast the gate and it will sit on top of the other foundation parallel to the alignment. Once gate is sufficiently submerged the pumps will stop and the gate will be fastened with the receiving structure. The barge gate, at this time, is fully deployed and ready to take the loads from the storm surge.

Once the water due to hurricane has subsided, the gate will be floated up again and will be moved towards it's resting foundation using the winch system. Finally, the pumps will fill in the chamber again so that the gate stays fixed on the foundation. It should be noted that it is possible that before the gate is opened a reverse head condition may arise where the bay might have more water on the protected side compared to the flood side. If such a situation occurs, the sluice gates at the 6 ft. dimeter through pipes within the gate can be opened up remotely so that water can pass through from the protected side to the flood side. This will alleviate the lateral loading on the barge gate which will try to push the gate open during a reverse head condition.

It should also be mentioned that, although the winch system is very crucial to the operation of the gate, there is a possibility that it might fail when needed due to its electro-mechanical nature. If the winch system is rendered ineffective, the gate can also be opened and closed by pulling them using a tug boat. As the gate becomes buoyant, the force requirement to pull the gate should become less and the tasks can be performed using a smaller vessel.

3.3. Constructability Analysis of Barge Gate

The flood barrier portion of the barge gate, constituting the chamber and the flood wall, can be monolithically fabricated off-site. Once the gate is painted and subjected to final inspection, the gate can be floated on water and pulled to the deployment site like a regular barge using tug boats. Prior to this all the foundation work and installation of the receiving structure needs to be finished. Piles for receiving structures can be driven from barge and then filled with sand and capped with concrete. The chord members and the diagonals can be pre-painted and welded to the vertical piles on site. If the chord members are designed to be above EL 0.0 thru EL +4.0, no under water welding may be required.

The piles for the two perpendicular foundations can also be driven from barge. The top plate on each pile bent can be fitted with steel pile caps or jackets having a diameter slightly larger than the foundation piles. Once all the piles in a certain bent is driven, the plate with the jackets can be lowered using a barge mounted crane and put on top of the piles. Since the bent cap will always remain under water and is substantially heavy there is no need to weld it to the piles. If needed, however, the jackets can be bolted to the piles by utilizing divers.

Once the barge gate is floated in place, it can be emptied and lifted up to attach to the pivot pile. The generators, control system, pumps, winch systems and sluice gate mechanisms should already be there before it is floated in to the job site. It should be noted that the installation of barge gate does not require any substantial underwater work. Since there is no concrete construction is involved, there is no need to dewater the job site. Hence the barge gates do not need any cofferdam for construction which leads to significant cost savings.

4. Construction Sequence

Sequencing of construction of the entire alignment should also be aware of the fact that the blocking of the channel needs to be kept at a minimum at all time. During the construction certain structural features may require temporary blockage of the tidal exchange as cofferdam or temporary water retaining structures are expected to be erected. Since the construction of these features are expected to span a number of months, the team tried to devise a phasing of construction work where the ultimate goal was to keep the channel open as much as possible. It should also be noted that ship traffic to and away from Port of Houston cannot be impeded due to construction. Thus, an opening must be maintained during construction which has sufficient depth to allow the maximum draft required for navigation.

Since the GCCPRD1200-Barge option allows the maximum passage of water through the barrier alignment, a detailed construction sequencing was identified for this option. The figure below identifies the different stretches of the barrier and identifies construction phasing sequence of each stretch. A brief description of each phase is provided below.

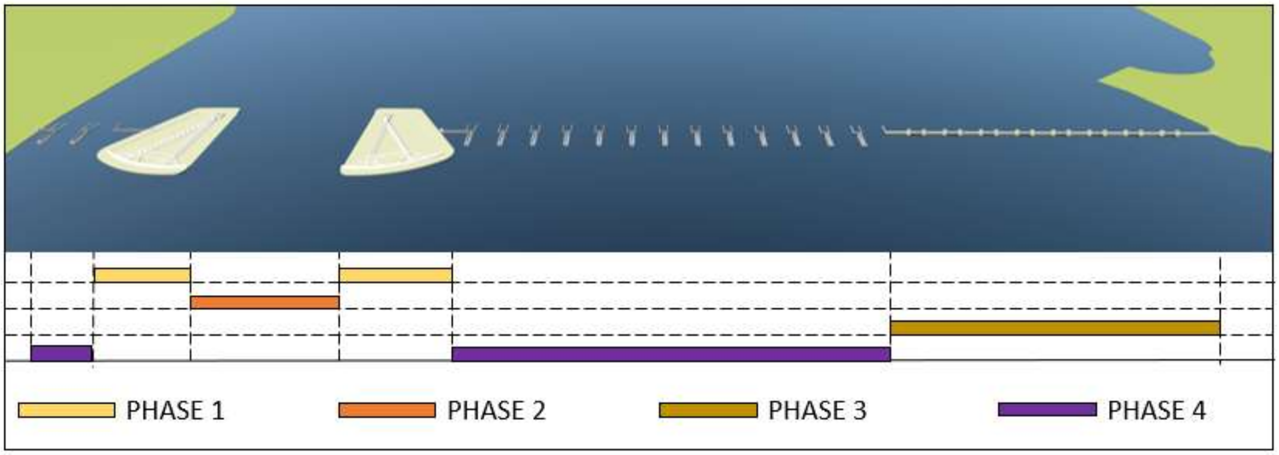


Figure 6: GCCPRD1200-Barge Alternative Construction Phasing

4.1. Phase 1

In this first phase, the two artificial islands will be constructed. The coffer-cells for the islands will be installed on either side or on both side simultaneously. Previous appendix has shown that a width of 840 ft. is required for two ships to pass side by side. The construction of the islands shall be spaced by at least 1000 ft. and is not expected to impede any navigation traffic to the port.

4.2. Phase 2

This phase assumes that all the construction on the artificial island has concluded. The dry docks for the gate leafs and the boll socket joint hinge connection of the gate are in place on top of the island. At this point the sill of the gate will be prepared. The sill will be made with cement stabilized graded stone or riprap. This work will not need any cofferdam construction and will not block the channel. However, this will restrict navigation through Bolivar Roads. Hence, at this time the ship traffic needs to be diverted toward the middle of the channel where barge gates will be constructed at a later phase. The diversion of traffic may require some dredging to increase the sill depth to allow maximum required vessel draft.

Once the sill of the floating sector gate has been prepared, the actual gate leafs can be floated in from off-site fabrication facility and connected to the hinge on the island. This construction phase would then continue and incorporate testing of the gate opening and closing to ensure that the gate is functioning properly.

4.3. Phase 3

In phase 3 of the construction sequence, the VLGs on the shallow depths can be constructed. At this point, the ship traffic will be diverted back to the channel section thru the floating sector gate. There is no other construction going on which significantly blocking the tidal exchange. The only obstruction related to the construction will be the cofferdams needed for the VLG construction. However, since these are built in shallow waters, environmental impact due to channel closure should be minimal during this time. The construction at this phase will include, installing the cofferdams, dewatering the cofferdams, construction of the sill foundation, monoliths and towers and finally the installation of the VLG steel panels. This construction period will also produce the combi-wall segments spanning between adjacent VLGs and the tie-ins of the last VLG to the higher ground. Once the construction within this phase is over, all the cofferdams will be removed allowing water through the VLGs.

4.4. Phase 4

This is the final phase of the construction which builds the barge gates on either side of the floating sector gate and the combi-walls in between. No significant construction closure is required for the barge gates. Most of the work is pile driving from barge and some minor underwater construction tasks. The barges will be floated in from the off-site fabrication utility and installed to the pivot.

The above subsections summarizes the major parts of the construction phasing for the barrier incorporating the 1200 ft. floating sector gate, barges and VLGs. It should be noted that within each phase, repetitive tasks can be run simultaneously. For example, construction may continue to build two or three barge gates or VLGs at the same time. This will save construction time and money as well as minimize the impact to the environment.

5. Time Requirement for Gate Operation

The floating sector gate and VLGs are fully mechanized and can be closed by operating the control systems of individual gates. The barge gate closing operation is more involved. At the beginning of the closing operation, all fifteen barge gates can be de-ballasted using the pumps at the same time. This operation may take up to 2 hours for all fifteen gates. All gates will then be closed using the mechanically operated winch system. It is possible that some of the winches may not work or malfunction during this time. The design team thus proposes to have five tug boats handy so that each of them can close three gates. Assuming that each gate may need one hour to move the gate in deployed position, the total time required to move all fifteen barge gates might require three hours. Once all the gates are in their respective closing alignments, the pumps can be started to fill in the chambers and the gates can be ballasted into their deployed position. This operation for all fifteen gates may require up to two hours. In total, all fifteen gates can be closed in seven hours starting from their open position. An equal amount of time may be required to open the gate from their deployed position. The estimated time frames for such operations are based on the experience of the 270 ft. span in-service barge gate in Louisiana, added with a factor safety considering the larger stretch of water and higher wave conditions.

The closing of floating sector gate requires flooding of the dry dock, moving the gate leafs mechanically in the middle of the channel and then fill up the gate wall tanks to sink the gate. The Maeslant Barrier in Netherlands require two and a half hour time for this operation. Considering the location of the current gate in Bolivar Roads and the wave action at the Bay, the team conservatively chose a closing time of six hours for this gate, which is about twice than what is required for the barrier in the Netherlands. It should be noted that the proposed floating sector gate should require same amount of time to open the gate once the flood water has receded.

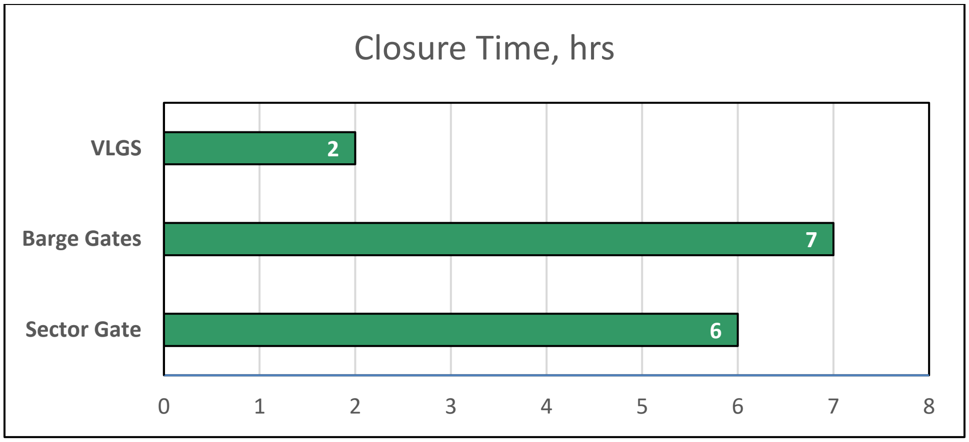


Figure 7: Comparison of Gate Closure Times

6. GCCPRD1200-Barge Cost Analysis

The Arcadis team evaluated the cost of construction for all three barrier alternatives and made a comparative analysis. The following table summarizes the cost of each options and the amount of permanent blockage in terms of percentage of the entire alignment length.

Table 1: Summary of Barrier Alternative Costs & Permanent Blockage

Configuration	Costs, in millions	Permanent Blockage
GCCPRD840	$3,540	54.8%
GCCPRD1200	$3,956	52.8%
GCCPRD1200-Barge	$3,674	38.5%

GCCPRD1200 option costs highest with a 1200 ft. wide sector gate and all VLG configuration. Compared to this option, the 1200 ft. floating sector gate option (GCCRPD1200-Barge) coupled with mostly barge gate and some VLGs turns out to be cheaper and provides significant improvement of the environmental openings. Replacing many of the VLGs using 200 ft. barge gate results in cost saving. The reduction in cost can be attributed to the following advantages of the barge gate construction.

- No significant under-water construction.
- No need for a cofferdam or temporary water retaining structure.
- Major fabrication (steel barge gate) done off-site
- No requirement for cast-in-place concrete.

It should also be noted however, that the challenges in operating the barge gate are more involved compared to VLGs. The closing and opening of VLGs is completely mechanized using electro-mechanical and hydraulic systems and such operations can be performed within a short period of time. The closing operation of barge gate involves de-ballasting the gate using pumps, moving the gate in place using a winch and finally filling in the chamber with water. The whole operation thus takes more time and in case of a failure of any of the operational component will require more manpower to close the gate compared to VLGs. In addition, the overall closing time for the barge requires more time and resources which leads to additional operation and maintenance cost throughout the life of the gates. From an eco-friendly perspective, the barge gates dominate the all VLG alternative as they allow more water to pass through them at lesser capital cost.

It is evident from the discussion above that a decision to choose the final alternative should not be based on cost alone. Relative advantages and disadvantages of the alternatives should be weighed in in terms of environmental concerns, relative ease of construction, convenience in gate operations, and sustained cost of maintenance over a long period.

The Piston Surge Gate

An alternative barrier concept has been developed in response to concerns over environmental impact associated with the reduction in tidal prism associated with tentatively selected navigation sector gate and environmental lift gates, and to address specific geotechnical concerns associated with application of a sector gate in Galveston Bay. The piston gate concept enables significant reduction in environmental remediation cost because it enables surge barrier designs with virtually no effect on the existing tidal prism. A side-benefit of the piston gate option is that the full navigable width of the Bolivar Roads remains available in non-storm conditions. The existing level of engineering design is comparable between the piston gate vs the sector and environmental lift gates, but at present virtually no detailed environmental assessment has been performed for the piston gate concept. The cost estimate for the piston gate is meaningfully lower than the sector gate.

The minimal-blockage designs are possible because the gate foundation is directly below the gate, such that gates can be placed nearly side-by-side across the bay entrance without need for the large artificial islands required for sector gates and environmental lift gates. The piston gate reacts horizontal forces due to hydrostatic pressure primarily as a moment transferred to the foundation soil through the pile cap at the bottom of large concrete bases. Moments and shear forces are transferred to the earth directly below the hydrostatic pressures generating these forces. Shear forces are not dominant because these forces are distributed over the entire length of the gate, which eliminates the potential for large force concentrations on the foundation. The piston concept offers another foundation advantage: the pile tops are at the bottom of the concrete bases, so most of the piling is below the very soft surface soils. The design and analysis of the piston gate presented here is for the Option A location (Bolivar Roads), but the concept is equally applicable to other bay locations, most notably to Option B (Texas City Dike).

Relation to other Barrier Gate Concepts

A flap gate, comparable to the Mose gates in Italy, was briefly considered. A key benefit of the flap gate is that hydrostatic loads due to differential head are reacted by hydrostatic forces induced by the leaning of the rotating flaps towards the low-water side of the barrier. The benefit is that hydrostatic moments are not transmitted to the foundation, the end result of which is a meaningfully lower foundation and installation costs than designs that react those loads through the soil. There are two main concerns with the flap type gate for this application: The first concern is the large difference between the upstream and downstream sides of the gate at the height of the design storm event: the flap relies on buoyancy on the low side of the gate to provide the restoring moment such that for very large storm surge events the buoyant base of the flap would need to be quite large. The second concern is the extremely silty water conditions in Galveston Bay, which would be difficult to manage with any gate concept that hinges down to the seafloor. A detailed silt control strategy complete with equipment and operational cost estimates would need to be developed before potential cost savings of a flap gate could be realistically assessed.

A barge gate system was investigated for use in place of the environmental lift gates in the shallow areas of Bolivar Roads. The barge gates appear to be less costly than the lift gates mainly because of reduced foundation costs, and has the added benefit of imposing virtually zero effect on the tidal prism. The primary challenge that has been identified with the barge gates is prompt opening of the gates shortly after a storm event at a time when there is a significant differential head between the gulf and the bay. Neither the piston gate nor the barge gate design is amenable to be opened in the presence of a significant differential head such that the water elevations can equalize.

Prior to recognizing the challenge of opening the barge gates in the presence of an environmental head, preliminary designs for the submersible barges had also been developed in accordance with the ABS rules. Each barge is fitted with a 6 foot mud skirt that will be pressed into the soil by the weight of the barge to prevent water from passing below the barge. Barges for the Type A location require 2,033 tons of structural steel per barge, and a total of 10 barges are required to span Bolivar Roads. Flexible membranes could be used to connect the barges, such that angular alignment between barges is not critical. A single line of freestanding piles could be installed to help align the barges during installation

Wicket gates, as used in riverine lock systems, may provide a much simpler and less costly alternative to the shallowest environmental lift gates presently being considered as part of the sector and piston gate systems. Application of wicket gates in place of the environmental lift gates in the shallow areas of the crossing could also reduce the percentage closure for the piston-gate crossing design from 1% to 0%. Application of wicket gates is probably relevant only to shallow waters because of challenges presented by the potential for extreme siltation around the gates in the open position, and challenges associated with rapid closure of large wicket gates.

The 1% Closure Design: Minimal tidal flow blockage

1.0 Overview

Piston gates span the Bolivar Roads crossing in all water depths greater than 10 feet MSL. Each piston is approximately 300 feet long. In the open-gate position, all of the piston gates are fully retracted into concrete bases below the soil; closure is by sequential buoyant raising of each piston

The piston gate option includes deployment of 20 piston gates, each of which is represented by one of two design types. The deepest part of the Bolivar crossing will be spanned by eight of the Type C gates with a 60 foot sill depth. Type C gates will span a total of 8 times 312 feet, for a total of 2,496 feet, which is across the full ship channel plus some nearby deep water. There are an additional 12 Type B gates with a 30 foot sill depth. Type B gates will span 12 times 310 feet, for a total of 3,720 feet. The unobstructed clear opening with sill depth of 30 feet or greater will be almost 1.2 miles, which represents virtually all of the existing profile with water depth greater than 10 feet.

Piston gates may not be technically viable for sill depths less than 10 feet because the concept relies on buoyant support during the entire hurricane event; a negative surge event after the eye of the storm passes the bay could make the water depth inadequate to support the gate. Environmental lift gates are proposed for the sections of the bay shallower than 10 feet; the design and cost of these gates has been taken directly from the baseline sector gate estimates, which slightly overestimate the cost because a 15 foot sill depth is assumed, rather than the 10 foot depth that is typical of existing conditions.

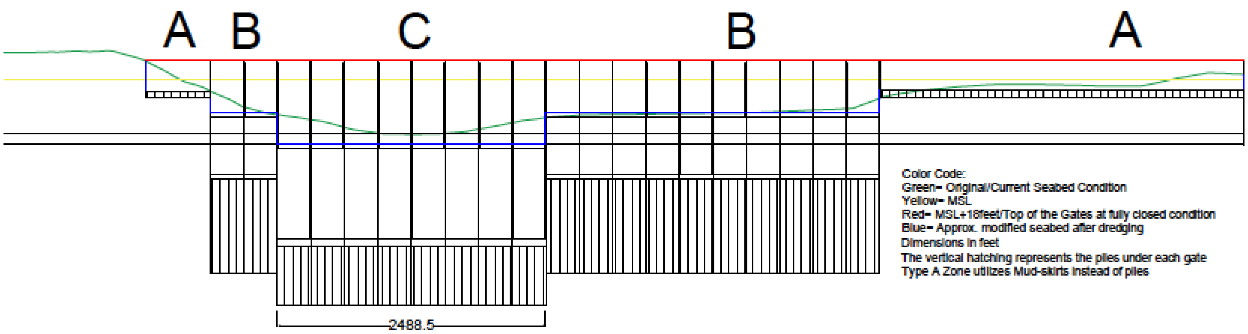


Figure 1. Cross section of Galveston Bay Inlet with surge gates fully closed. Vertical dimension X10.

2.0 Concept Details

The overall piston gate system is formed as a series of 20 rectangular steel pistons, each of which is housed within a vertical concrete base sleeve. The pistons will normally be hanging from a structural lip at the top of the piston, which is in turn supported by sitting on a matching structural lip at the top of the sleeve (Figure 3, inset). The structural lip provides a reasonable seal against silt, water transfer and light, such that the retracted gates are subject to only very minimal bio fouling and corrosion. In preparation for a surge event, the pistons are de-ballasted by pumping water out of the pistons such that they float vertically within the cylinder until they are mechanically blocked from further vertical motion by interference between the top of another structural lip, located at the bottom of the cylinder and the underside of the lip at the top of the concrete base sleeve (Figure 4, inset). De-ballasting of the individual gates is accomplished using a compressed air system to inject air at the same time as hydraulic ballast pumps remove water from the submerged pistons. Water is expelled from the steel gates into the space within the concrete base to minimize silt intake during deployment. The air injected into the gates is supplied by onshore compressors and distributed via a system of pipes passing through the concrete bases. The hydraulic ballast pumps will be powered via onshore hydraulic piping in the bases below the cylinders running to onshore hydraulic pumps. The gates could be raised by air injection alone in the event of total failure of the hydraulic pumps or by hydraulic pumping alone in the event of failure of the air compression system.

Preliminary designs for two different water depths have been developed, with larger piston units in deeper water and smaller in shallower. Three types of closure are applied for the span: Type A closure is applicable to 0 to 10 feet of water depths. The present cost estimate assumes use of environmental lift gates in the 0 to 10 foot water depths, though wicket gates may provide a meaningfully simpler and lower-cost option while eliminating the need for artificial islands. Type B closure is applicable for water depths from 10 to 30 feet, and Type C from 30 to 60 feet. Type B and C units are conceptually similar and differ primarily by scale. A total of 12 Type B bases plus 8 Type C bases will span the entire deepwater span.

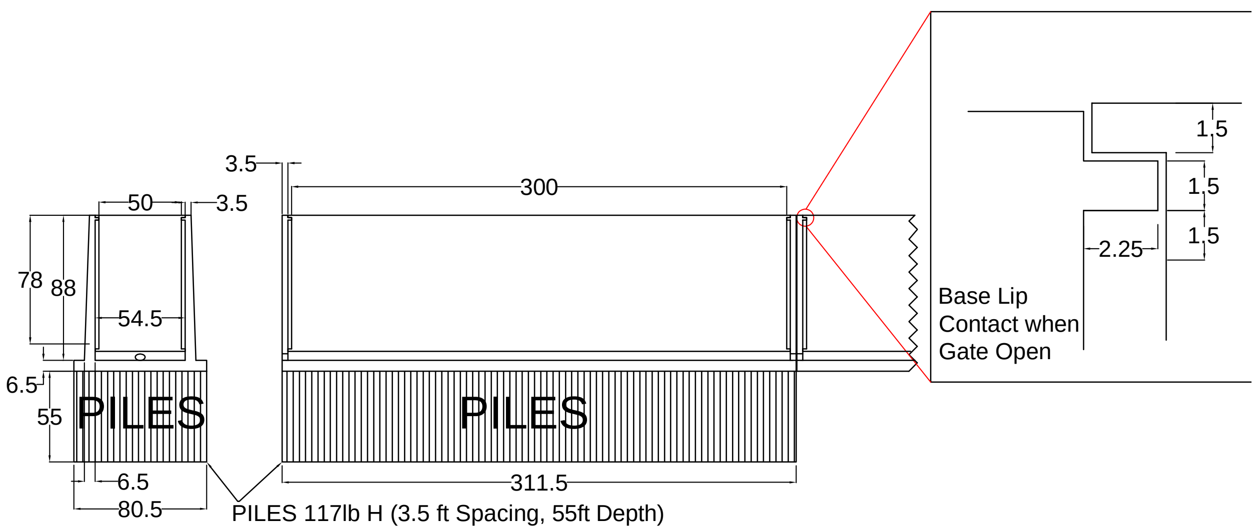


Figure 2. Type C (deep) Piston Gate in retracted (open) configuration. Dimensions in feet.

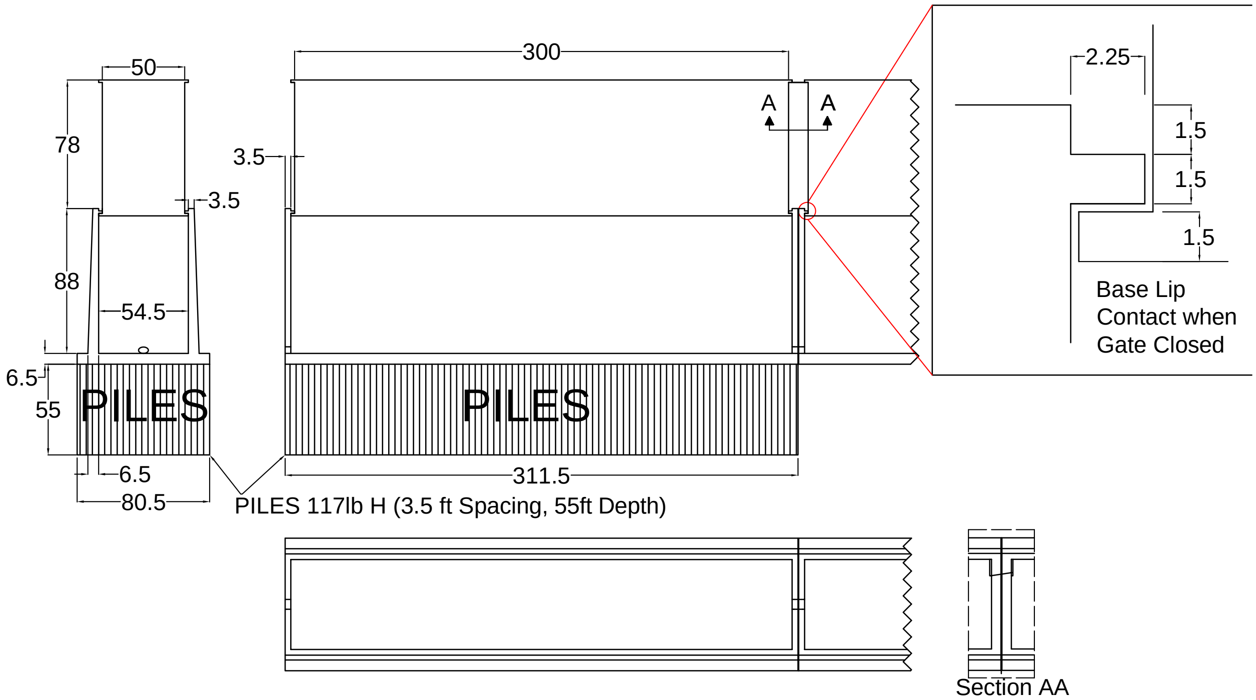


Figure 3. Type C (deep) Piston Gate in extended (closed) configuration. Dimensions in feet.

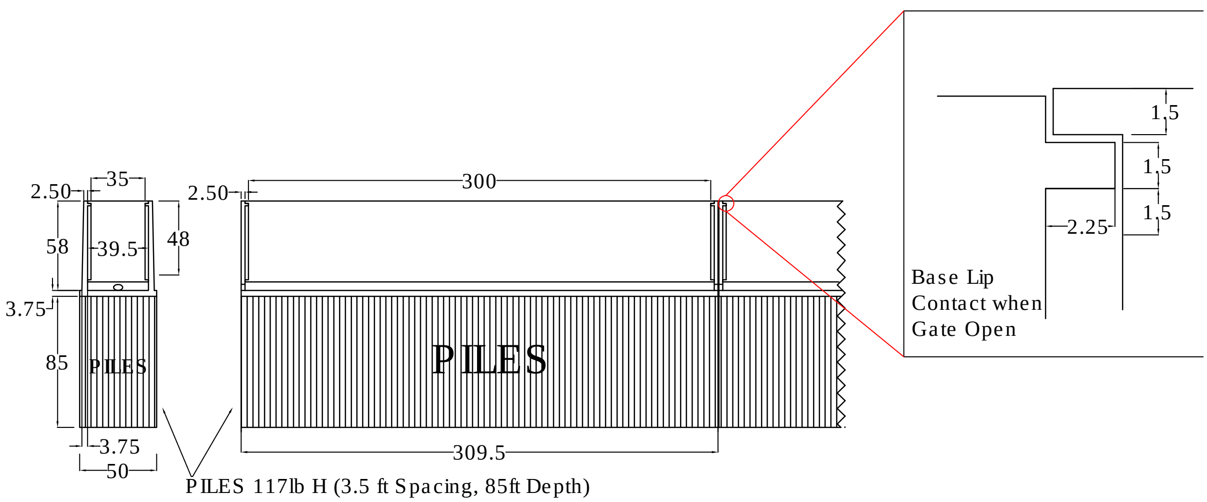


Figure 4. Type B (shallow) Piston Gate in retracted (open) configuration. Dimensions in feet.

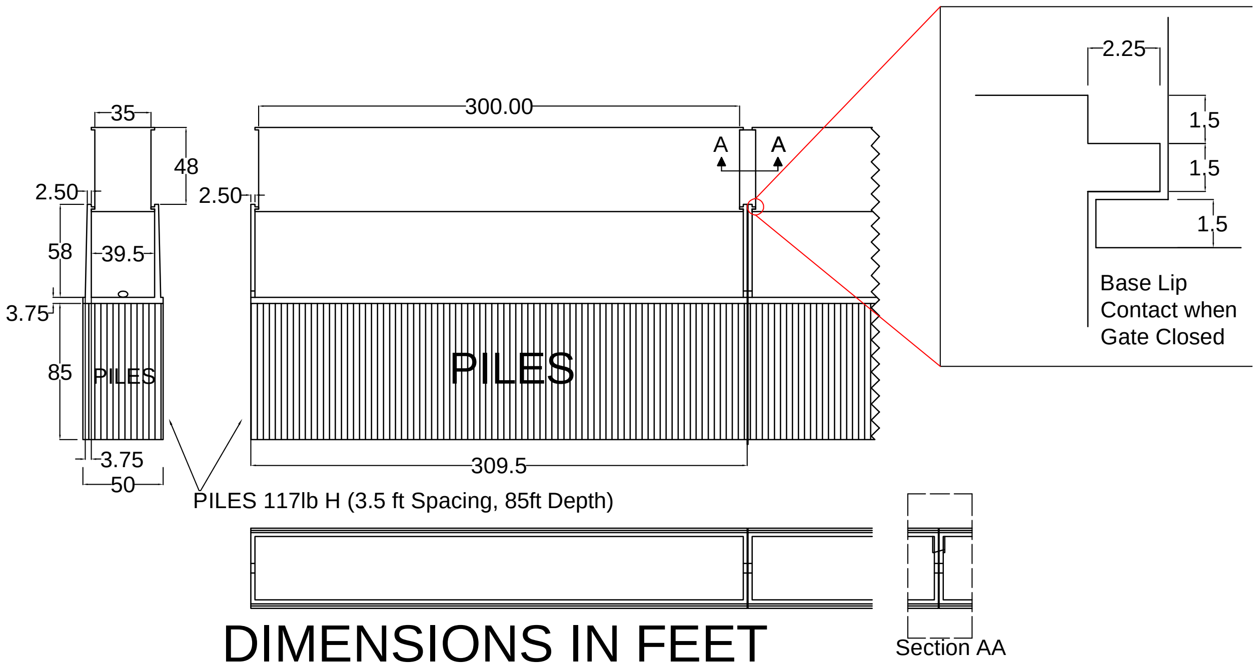


Figure 5. Type B (shallow) Piston Gate in extended (closed) configuration.

3.0 Component Design Concepts and Assumptions

The level of engineering design and detail of cost estimating for the piston gates are advanced to the point that engineering is believed adequate to be confident in technical viability of the concept and for a +/- 20% scoping-quality cost estimate. The main cost drivers are expected to be the fabrication of the steel piston gates, fabrication of the concrete bases that support those pistons, piling of the gates, plus installation which includes significant dredge operations and purpose-built installation aids. The design basis is an assumed storm surge on the gulf side of the gate of 18 feet above MSL coincident with a storm-induced set-down on the bay side of the gate of 7 feet below MSL, for a total differential head of 25 feet. Soil conditions are taken from the very limited number of deep soil borings available (four). Geotechnical uncertainty is believed to be a significant risk to existing cost estimates for all alternatives.

3.1 Steel Piston Structures

The steel pistons are designed as large barges; structural arrangements are in conformance with American Bureau of Shipping (ABS) standards. The primary loading on the pistons is hydrostatic; the pistons are conservatively designed for the full hydrostatic pressure associated with having the inside of the piston at atmospheric pressure while the piston somehow remains fully submerged in the base. The interior of each piston is segmented into 10 separate buoyant compartments by watertight bulkheads, which provide protection against piston sinking in the event of mechanical damage during a storm, and also structurally reduce the span of the longitudinal stiffeners along the 300 foot length of the piston. Steel weights could be reduced after a careful assessment of operational scenarios and structural design optimization. The design is amenable to fabrication outside of a major shipyard, such that many could be constructed in parallel. Specifically, the design avoids use of curved plates and avoids welding steel plate thicker than 5/8 of an inch. Arrangements are developed to the point of being realistic for the purpose of material takeoffs for cost estimating. Each Type B piston will be composed of about 3,740 tons of structural steel; each Type C piston will be composed of about 8,540 tons of structural steel.

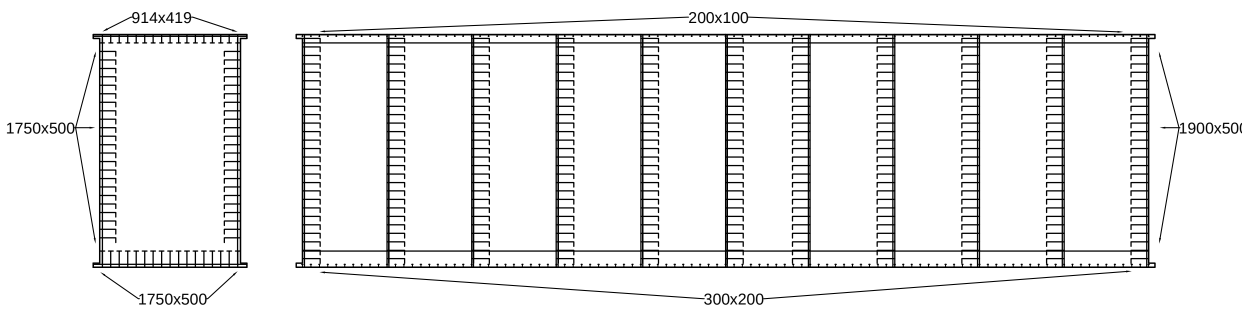


Figure 6. Type C Scantlings. Dimensions in millimeters

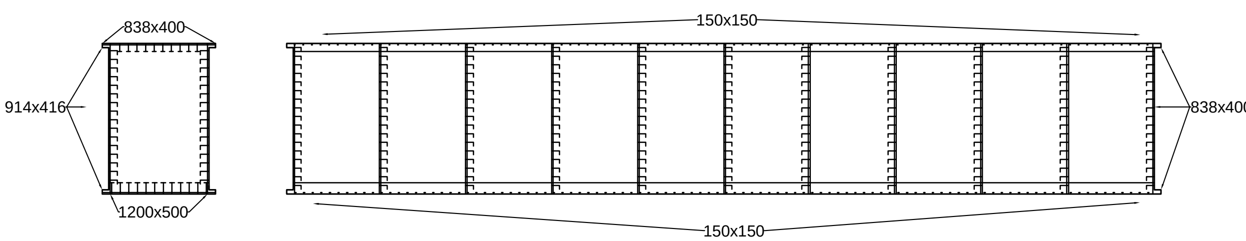


Figure 7. Type B Scantlings. Dimensions in millimeters.

3.2 Concrete Base Structures

Each side of the concrete bases is designed as a static pile cap supporting two large static retaining walls. The pile foundation is designed to resist all environmental loading such that there is no requirement that the soil surrounding the concrete base be reconsolidated after base installation. The primary loading on the concrete base is gravity-induced soil pressure. The concrete sides also transmit tension, sheer and overturning moments from the pistons to the pile foundation. The concrete bases have been sized in accordance with the American Concrete Institute requirements including consideration of maximum allowable steel reinforcing. The main driver of the concrete design is the moment where the horizontal pile cap meets the vertical wall; the primary loading at that location is static soil pressure (K_0). The design uses ordinary high-strength concrete and conventional steel reinforcement. Specific re-bar arrangements have not been developed; only the sectional steel area has been computed. Advanced fabrication techniques such as pre- and/or post-tensioning have not been considered at this stage of the design. The Type B bases require 5,900 cubic yards of concrete per base, and the Type C require 17,300 cubic yards per base. The Type B and Type C bases float upright and could be towed as barges; the larger Type C bases freely float in seawater with a 46 foot draft.

3.3 Foundation and Piling

The foundation piling design is extremely robust to the point that all applied loads can be reacted by the foundation piles. The extremely robust foundation enables substantially lower concrete cost in the concrete bases because the walls resist only static soil pressure, and also simplifies installation because full strength if achieved without consolidation of the backfill surrounding the bases.

The piles selected for the foundation are HP14x117 piles on 3.5 foot centers (each direction). Type B gates require 85 foot piles; Type C require 55 foot piles. The shallower gates require longer piles because the pile caps are shallower, which subjects the upper part of the piles to weak soils. These are non-displacement piles and no hard driving conditions are anticipated based on foundation soil conditions.

3.4 Installation Supplemental Buoyancy

Supplemental buoyancy is included as an installation aid. Two large buoyancy chambers will be fabricated to fit on the outside shelf of the pile cap. The chambers are sized such that the when attached to the concrete bases the assembly can be made neutrally buoyant. The buoyancy aids enable use of much smaller cranes that can work in smaller water depths and that are less expensive and more generally available. The buoyancy chambers are 16 feet by 60 feet by 300 feet. A steel weight estimate has been made by assuming these chambers have the same volumetric weight as the Type C steel pistons, on the basis that these structures are exposed to the same hydrostatic pressure. The total steel weight for two chambers is 4,300 tons.

3.5 Dredging Requirements

The seafloor is to be dredged to a depth slightly below the level of the base of the pile cap, plus some additional dredging to allow for sidewall sluffing. The width of the horizontal base of the dredged hole will be the width of the pile cap plus an additional horizontal distance on each side of the pile cap equal to 1/3 of the distance from the mudline to the bottom of the hole. The sidewall slope is to be 2.5:1. The soils to be removed are generally layered and consist of layers of silty sand (SP-SM), which is regarded as a waste material that will require disposal, and clay and clayey sand, (primarily SH with a small quantity of SL), which is regarded as a potentially valuable resource for building of levies needed as part of the spine. Cost estimates presently assume all material is to be disposed of offshore. The soil types and layers are estimated from a total of four borings made in 1972. This existing boring data shows a clay layer varying in thickness between 25 and 45 feet across the deepwater section of the crossing.

Use of the large volumes of clay and sandy clay likely to be valuable in construction of the coastal levee on Bolivar peninsula would require use of a bucket dredge would leave the clays in a more useful consolidated form, though the depth and speed of dredging necessary is a concern. A combination of bucket dredging and a modified cutter head dredge may enable preservation of valuable soils along with maintenance of a reasonable excavation schedule. The dredging technology to use a cutter-head dredge at this water depth is believed to exist in Europe. It is presumed that a US dredge could be modified to reach the required depths, or the European dredging equipment could be fitted in a US vessel for the duration of the project. Preliminary calculations based on limited soil boring data predict removal of about 2,895,000 cubic yards of silty sand plus about 2,210,000 cubic yards of clay and sandy clay (CH-CL); some of the excavated sediments can be used immediately as backfill.

3.6 Onshore Facilities

Significant support facilities are needed on land adjacent to the surge gates for operation and control. The major equipment required consists of hydraulic pumps, air compressors with compressed air storage, and backup power generation. The size of the onshore equipment depends on the speed at which the gates are required to be closed. In this estimate it is assumed that four 60-foot sill gates must be closed within a 2-hour span, which conforms to the closure rate of the Maeslant barrier; onshore costs will scale approximately linearly with required closure rates. It is further assumed that all 15-foot sill gates and all but the last four 60-foot sill gates are closed in advance, and do not contribute to the sizing requirements for the design.

Reliability of the system is critical. The main ballast system is based on electro-hydraulic power of submerged hydraulic ballast pumps. Electricity is provided by onshore connection to the public utility grid, plus full back-up Diesel-electric generators. Backup and improved function of the submerged pumps is provided by an independent compressed air system that is capable of closing the gates using compressed air alone in the event of total failure or required routine maintenance of the electro-hydraulic ballast system. Shore-based pumps and power systems with a maximum discharge rate of 650 cubic feet per second and air compressors with a maximum discharge rate of 9,750 SCFM have been preliminary specified for cost estimating.

4.0 Construction Equipment Required

The pistons are to be fabricated in shipyards using well-known steel shipbuilding standards and techniques; the base sleeves will be fabricated offsite at a coastal onshore fabrication location using well-known concrete fabrication standards and techniques. Tugs will be used to transport the sealed cylinders and sleeves to the site as barges.

The soil around each gate must be sequentially excavated and backfilled as base installation progresses to minimize siltation between dredging and base placement. As each section is being dredged, the temporary buoyancy aids are fitted to a concrete base, after dredging each section the base is lowered and positioned using two 1,000 ton cranes on shallow-draft barges. A pile driving spread with multiple underwater pile driving operations progressing in parallel will be used to meet the very substantial piling requirements.

5.0 Duration and Sequence of Construction

The duration of construction is a minimum of 3 years. Major construction activities progress in parallel: The concrete foundations and steel pistons will be fabricated in parallel, with unit fabrication nearing completion prior to commencement of dredging at the site for base installation. Dredging operations are likely to control the installation schedule if the excavated materials are to be used in the levy construction.

The concrete foundations will be fabricated offsite in a shipyard or temporary drydock. These 312 or 310 foot long concrete bases will be sealed against water passage through the pile guides and free-floated in a level configuration with a draft of 46 feet and towed to the installation site as free-floating barges. It will take about one year from contract initiation to fabricate the first concrete foundation unit, with subsequent units being produced more quickly; all units can be produced with 2 years depending on contracting strategy. Construction of the steel piston gates will progress in parallel with the concrete base units and on a similar schedule.

Installation of the base units will progress with dredging and unit placement progressing together to prevent the dredged area from filling with sediment before the concrete bases can be placed and piled. A low movable structural wall will be installed subsea on each side of the trench to reduce sediment deposit during construction; these temporary walls will be relocated by crane as dredging and base placement progresses. A segment of the seafloor long enough for placement of a single unit will be dredged to installation depth, including clear space around the pile cap and sloped sidewall to provide slope stability. After dredging, a steel guide frame will be placed on the seafloor and held with a limited number of piles to provide temporary support for placement of the concrete base and for the remainder of piling operations. As piling progresses, the dredging operations continue for the next unit, with much of the soils used directly as backfill for the prior unit most recently to have been placed. The parallel dredging and placement operations are believed to be necessary because the open trench may fill with sediment relatively quickly. The piles are to be driven using underwater hammers. After pile installation, the top of each pile will be structurally connected to the concrete bases. The structural steel pistons will be fabricated and coated offsite and brought to the site for installation. The pistons need to be placed in the bases and the piston retaining lip bolted in place at the bottom of the piston after the piston has been placed, but before it has been fully lowered. Placement of the piston into the base soon after base installation will reduce sedimentation inside the concrete base, but some sediment will have accumulated in each base; any significant quantity will need to be removed prior to lowering of the piston gate.

Cost estimates included here assume one base can be set every two weeks; installation is a significant cost area for which detailed planning and scheduling will be required as part of the next phase of development.

6.0 Operation and Maintenance

The primary concern for operation and maintenance is silt accumulation within the base sleeve due to very slow silt intrusion over time. The tops of the cylinders are nearly sealed to the concrete bases in the fully retracted positions to minimize silt intrusion. Despite these measures, an automated submersible, self-propelled dredging apparatus will be applied to travel within the concrete bases below the fully retracted pistons to remove accumulated silt. There will be water circulated through a pipe system running the full length of the piston gate assembly as a path to extract the silt collected by the robotic dredge to the outside of the piston base assembly.

Extensive siltation is also expected to accumulate over time on the outside and on top of the fully retracted cylinders, especially for those areas below the surrounding mud-line. The piston gates will have more than adequate excess buoyancy to self-raise without first removing the external silt, but de-silting operations before such self-elevation should be considered. Silt can be jetted away from this area into the passing current in preparation for a major storm and subsequent raising of the piston.

Maintenance and inspection of the pumps within the deeper pistons will also be necessary. Hydraulic pumps will be employed to minimize required maintenance. A passage for dry access to these pumps when the piston is fully extended will be provided. The pistons can be fully de-ballasted by air injection only, which serves as a backup system in case of total failure of the pumps within the submerged piston.

Corrosion and marine grown within the sleeves is expected to be minimal because the area will be dark and will generally become hypoxic after the pistons have been retracted.

7.0 Cost Estimate

A cost estimate has been prepared based on computed quantities and/or equipment costs for steel, concrete, dredging, piling and heavy-lift installation; other material costs are built from cost estimating factors. Installation costs are based on a single vendor quote for crane, barge, and tug time. Unit rates for other cost items are the same as applied in the sector gate cost estimate. A 45% contingency is applied to on all cost items. Engineering, Design, and Construction Management are not explicitly included. The total estimated installed cost for the 8 type C Piston Gates, the 12 Type B piston Gates plus the 16 environmental lift gates is $3,090,000,000 ($3.09 Billion), of which the 16 vertical lift gates cost-estimated for a -15ft sill depth are $862 Million. All costs are presented at 2018 price levels.

The total cost estimate for just four of the Type C piston gates, which provide a combined free opening in the navigation channel equivalent to the sector gate (1,200 feet) is $566,000,000 ($566 Million), including installation and on-shore support and a 45% contingency. Engineering, Design and Construction Management have not been explicitly included.

Buoyance Piston Storm Surge Gate

Galveston Inlet Ship Channel

Coastal Texas Protection Workshop

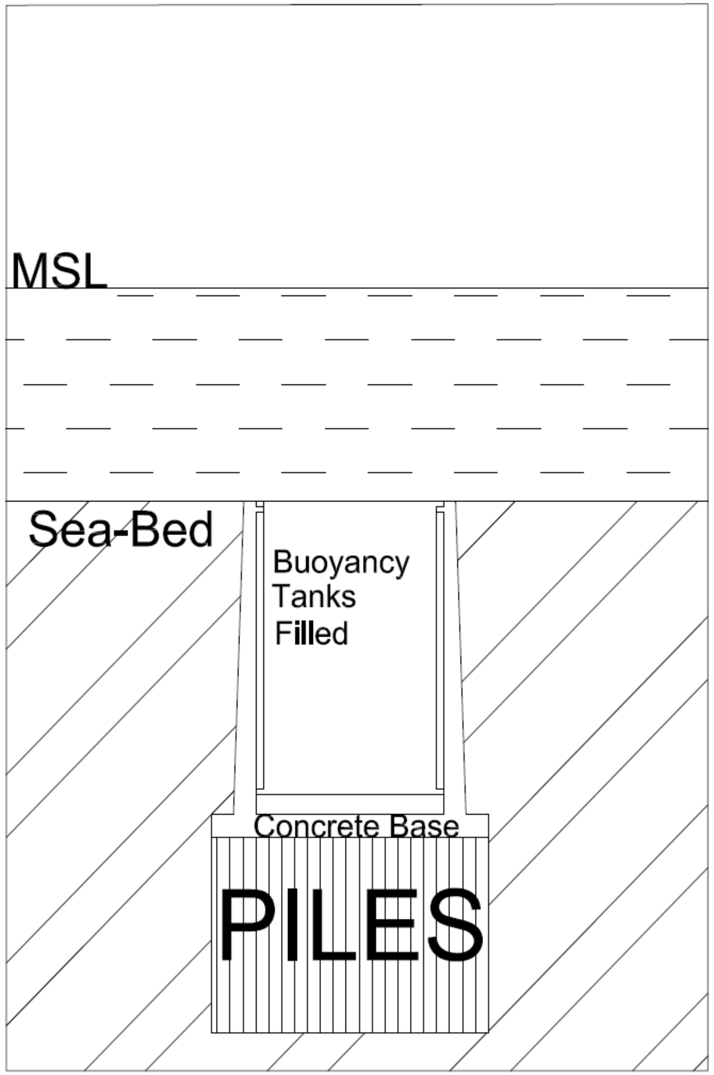
March 17, 2019

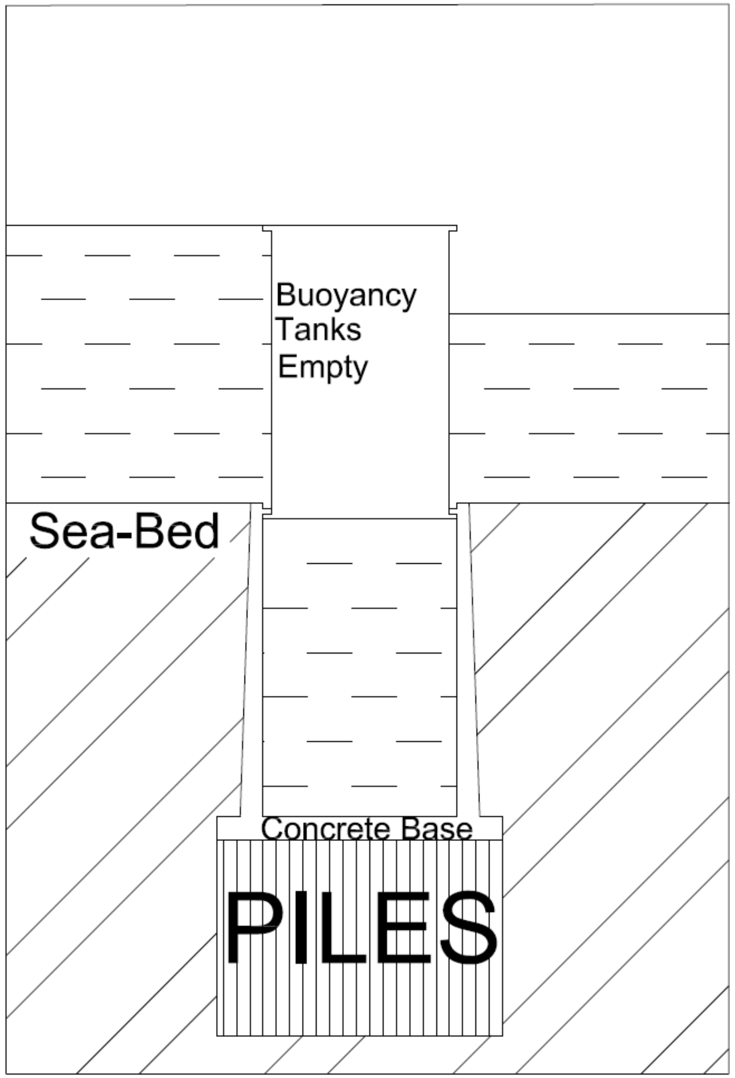
Backdrop: Fall 2017

- USACE Coastal Texas Protection Project well underway
  - Costs and environmental assessment being based on sector gates
- GCCPRD Study predicts major impact on tidal prism
  - Potential for very large mitigation costs
- Significant concerns about geotechnical conditions
- Silty waters with high sediment transport

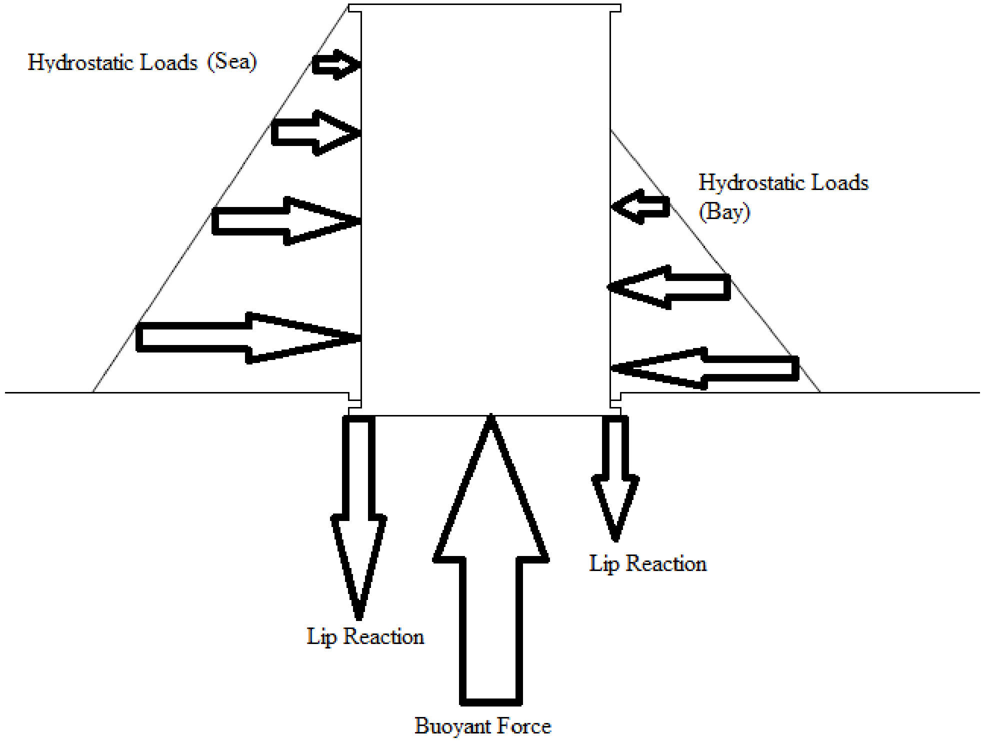
- Objective:
  - Develop a concept to minimize impact on tidal prism

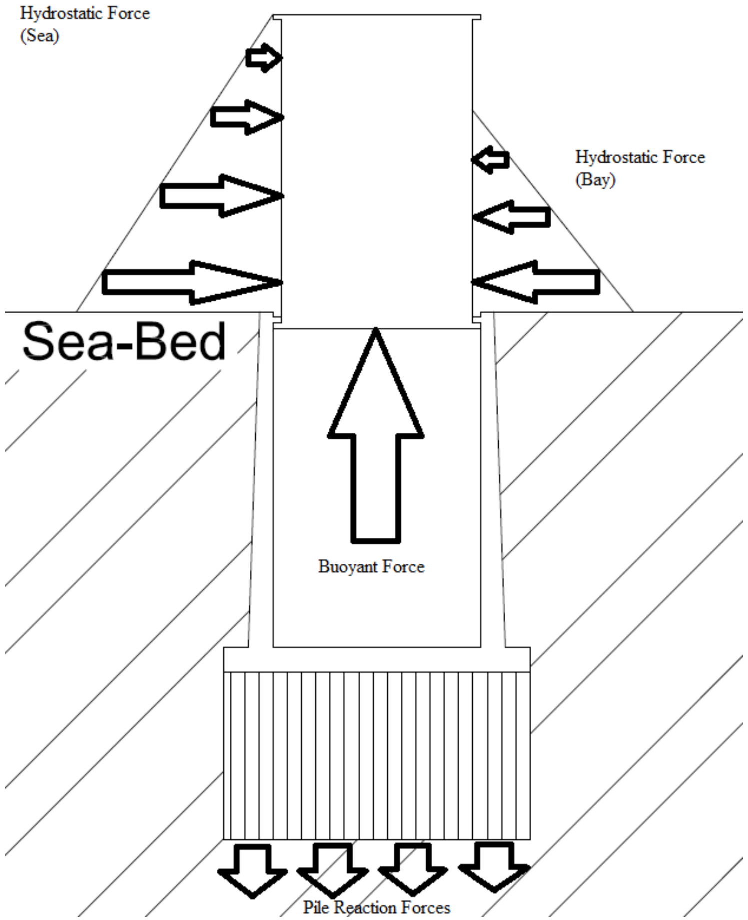
Barrier Cross-Section: Open and Closed



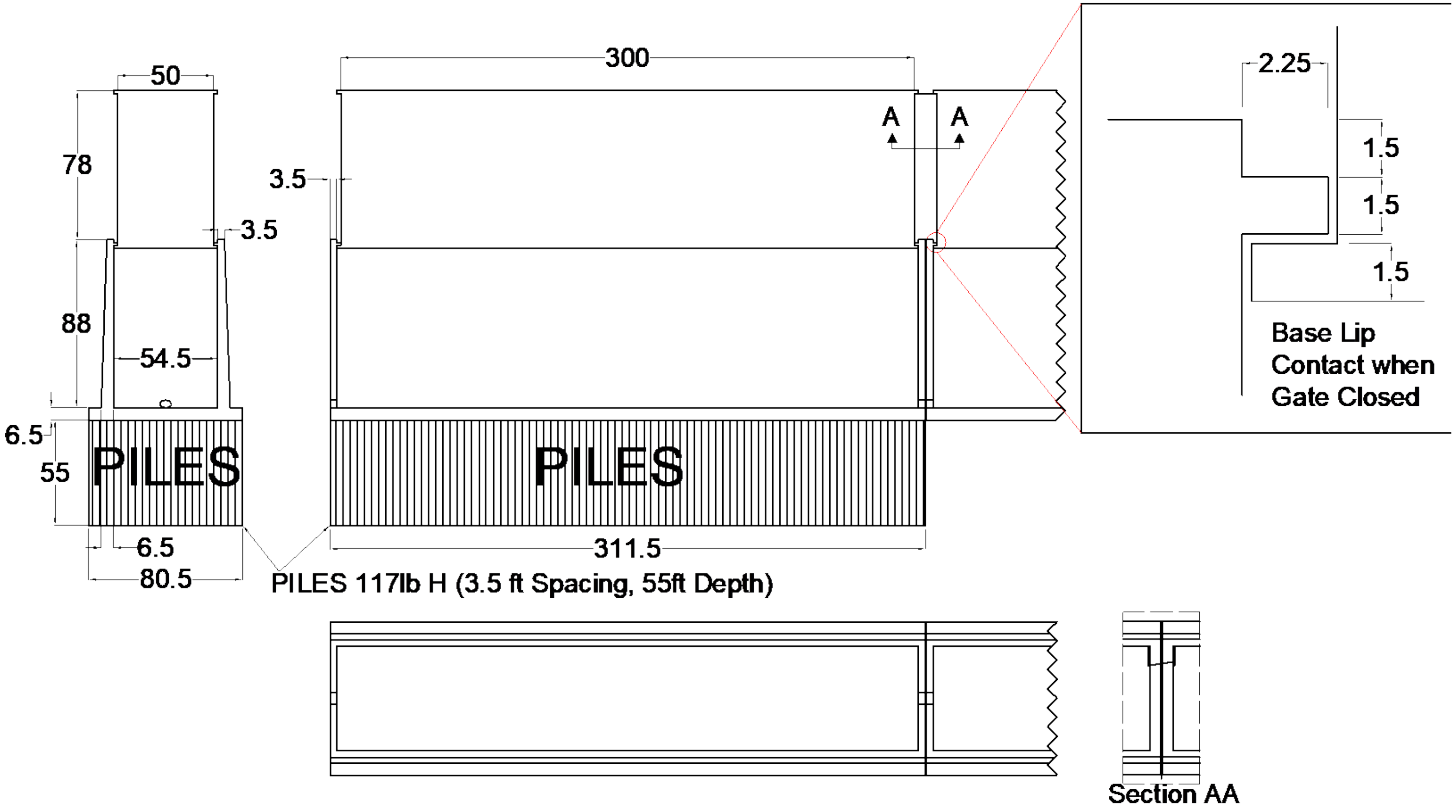


How it Works: Free Body Diagram

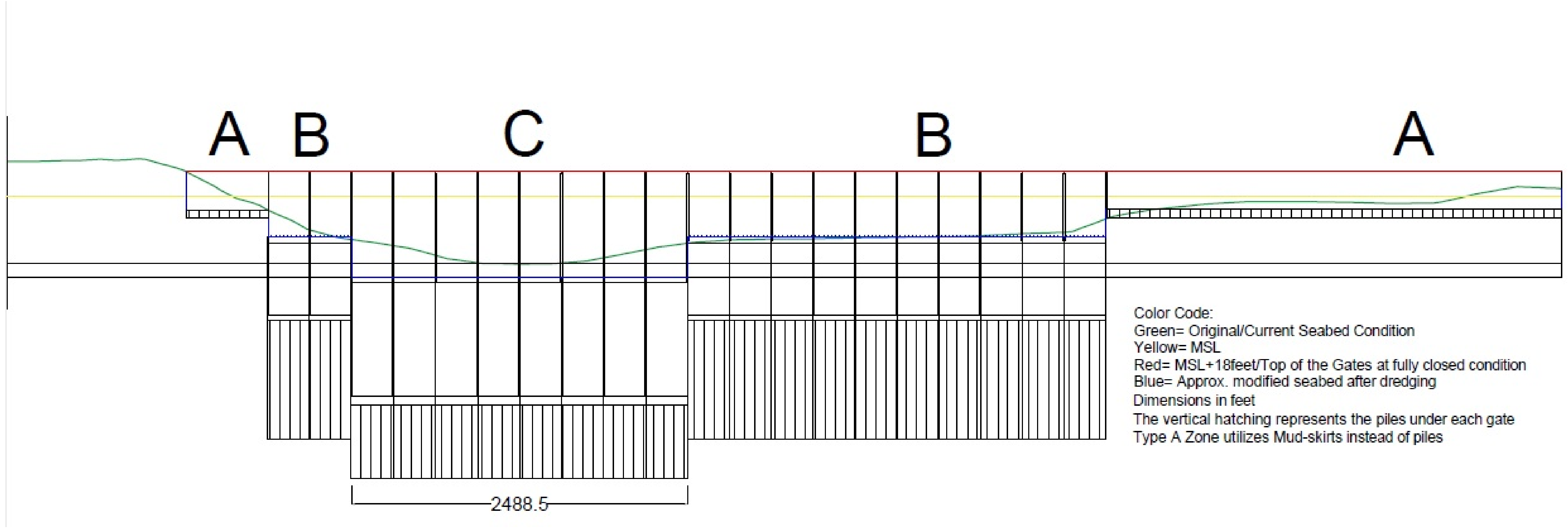




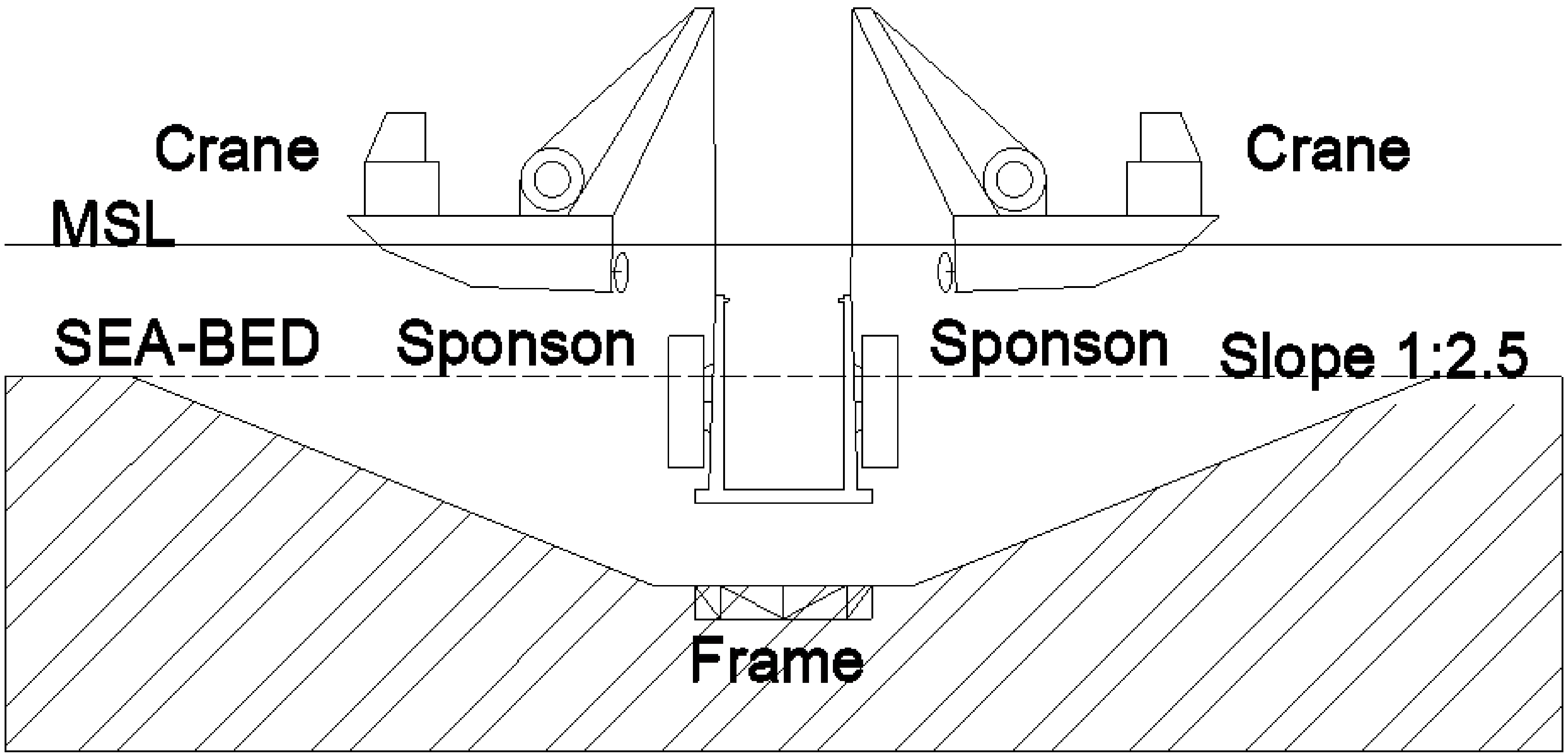
Solution: Piston gate concept



Eliminates all blockage in deep water column



Installation Plan



Benefits

- Minimal environmental impact, especially on tidal prism
- Minimal impact on shipping
- Minimal visual impact
- Silt-tolerant design
- Geotechnical reaction spread over large area
- Piles begin well-below existing mud-line

Main Limitations

- New: Not a proven technology
- Not cost-effective for shallow water
- Configuration used for cost-estimate can not be opened against large hydrostatic head

Present Status

- Preliminary Design Complete
  - Structural steel scantling design of piston (ABS Code)
  - Concrete and rebar quantities but not reinforcement arrangement
  - Foundation piling
  - Major equipment (pumps, compressors)
  - Installation plan
  - Provisional patent application filed
- Cost estimates: Based on USACE rates
  - Material takeoffs
  - Individual components
  - Day-rates on installation equipment

Major Work yet to be undertaken

- Scaled operational model test to verify concept
- Accurate operational scenarios (opening against head difference)
- Details of mechanical equipment
- Detailed design and installation plans
- Identification of construction location options for concrete bases
- More accurate cost estimates
- Environmental Impact Assessment

Gate Selection Workshop

Coastal Texas Protection and Restoration Study (Coastal TX Study- CTS)
in Association with I-STORM

Date: March 17-19, 2019
Location: US Army Corps of Engineers District Office, 2000 Fort Point Rd. Galveston, TX 77550, Conference Room 175

Purpose of the Workshop:

The aim of the workshop is to:

- Brainstorm many possible moveable barrier concepts for the Galveston Entrance Channel with national and international experts from International Network of Storm Surge Barriers (I-STORM)
- Select a concept (or concepts) on which final feasibility analysis will be conducted.

Tentative Agenda

Day 1 (Sunday, March 17, 2019)

TIME	ITEM
14:00-14:30	*Arrival at Jadwin Building*
14:30-18:30	**Field Trip, Background Information & Social** • Charter boat/Ferry Ride through the Inlet to Bolivar Peninsula • Icebreaker (Get to know each other) • Coastal Texas Study Overview *(Kelly Burks-Copes, USACE Galveston District (SWG))* • Geometry, Climate and Environmental Stressors relevant to CTS *(Himangshu Das & Jennifer Morgan (SWG), Dianna Ramierz (GLO)* • CTS Preliminary Barrier Design (*Charles Brandstetter, Chris Sallese, Gulf Coast Community Protection and Recovery District, Bert Sweetman*) • Dinner* (Crawfish Boil).
20:00	*Adjourn*

Day 2 (Monday, March 18, 2019)

TIME	ITEM
8:00-8:05	**Welcome and Introductions** *(LT. COL Jay Luckritz)*
8:05-8:20	**Introduction, Meeting Purpose** *(Robert Thomas & Tony Williams)* **Meeting Facilitation and Ground Rules** (*Brian Harper*)
8:20-8:40	**CTS Barrier Design Questions & Criteria** *(Himangshu Das, Rob Thomas, Coraggio Maglio, (SWG), Bert Sweetman (Texas A&M University at Galveston)*
8:40-9:50	**Discussion on CTS Barrier Design Criteria** *(All)* • Hydraulics • Engineering
9:50-10:00	*Break*
10:00-12:15	**Discussion on CTS Barrier Design Criteria** *(All)* • Hydraulics • Engineering • Environmental • Climate and Adaptability (Potential offline discussion) • Cost • Operation and Maintenance • Any other factors need to consider
12:15-13:00	*Lunch* Break (On Site)*
13:00-1400	**Finalize and Document CTS Barrier Design (Ranking) Matrix** *(All)*
14:00-17:00	**Expert Team work on Design Concept, Individual or Group** *(Assigned Leads)* • Deep Draft (Navigation Gate) • Intermediate Depth (Environmental Gates) • Interface and Tie-in
17:00-17:30	**Wrap Up & Next Steps** *(Rob Thomas, Brian Harper, Sharon Tirpak)*
18:30-20:00	**Dinner and Social** *(*Olympia Grill)*

Day 3 (Tuesday, March 19, 2019)

TIME	ITEM
8:00-8:30	*Arrival*
8:30-9:00	Team or group discuss about the design concept, wrapping up
9:00-12:00	**Expert Team Presentation, Discussion on Design Concept** • Summarize plans for ranking • Finalize Spreadsheet for ranking
12:00-13:00	*Working Lunch** • Discussion anything left out of evaluation matrix
13:00-14:00	**Expert Team work on ranking and voting of design concepts** • Deep Draft (Navigation Gate) • Intermediate Depth (Environmental Gates) • Interface and Tie-in
14:00-14:15	*Break to consolidate results*
14:15-15:15	**Summarize and discuss results** • Present raw data • Discuss to develop understanding • Summarize
15:15-16:30	**Way Forward Discussion** *(Facilitator: Brian Harper/Rob Thomas/*) • Signed Memo • What's critical for the PDT team to design the preferred concept • Physical/CFD modeling needs • Risk and uncertainties • What is needed to get a good cost estimate
16:30-17:00	**Wrap Up & Next Steps** *(Brian Harper, Rob Thomas, Sharon Tirpak)*
17:00	*Adjourn*

Additional information to be provided: TBD

*All lunches/dinners will be at own expense. Funds will be collected for lunches at the beginning of the workshop.
** Snacks and coffee will be available with the option of contributing to the cost of purchase

Deep Draft Gate Design

Presenter: Philip Welton

Introduction – Deep Draft Gate Types

1) Floating Sector Gate
2) Rising Sector Gate
3) Floating Mechanical Flap Gate
4) Rising Piston Gate
5) Floating Barge Gate
6) Special Barge Gate
7) Rolling Door Gate
8) Vertical Drop Gate
9) Inflatable Gate

Narrowed to

- Floating Sector Gate
- Rising Sector Gate
- Floating Mechanical Flap Gate
- Rising Piston Gate
- Rolling Door Gate
- Vertical Drop Gate

Introduction – Reducing Closure

Channel closure was identified as the biggest impact of the Deep Draft Barrier:

Mitigation options:

- One island onshore
  - Needs diverted shipping channel
  - Possibly a leisure craft canal landward of dry-dock
- Barrier located at wider channel (modelling needed to confirm benefit)
- Split navigation channel in two or three (overlapping islands)
- Barrier design with no islands (or small piers)
- Extend Deep Draft into intermediate (eg with three channels)
- Deeper Channel (includes ship increase adaptability)
- New shipping canal through peninsular

Concept 1: Floating Sector Gate

Ranking Criteria	Score
Blockage Ratio	1
Time to open and close	4
Alignment	4
Cost	1
O&M Cost	5
Reliability	5
Adaptability	3
Constructability	3
Technology	5
Impact	1
Additional Benefits	1

Concept 1: Floating Sector Gate

Pros

- Time to Open <2hrs
- Alignment – Can be very wide (reduced collisions)
- Reliability – proven at Maeslant
- Proven Technology at the scale needed
- O&M in dry – easy access/low deterioration
- Construction – Up to design, could block ship traffic

Cons

- Reduced CSA
    - One barrier – 54% loss
    - Two barriers – 47% loss
    - Three Barriers – 44% loss
- There needs mitigation or other parts of structure to be very low constriction
- Largest Footprint

Concept 2: Rising Sector Gate

Ranking Criteria	Score
Blockage Ratio	3
Time to open and close	5
Alignment	4
Cost	1
O&M Cost	3
Reliability	5
Adaptability	3
Constructability	3
Technology	3
Impact	3
Additional Benefits	1

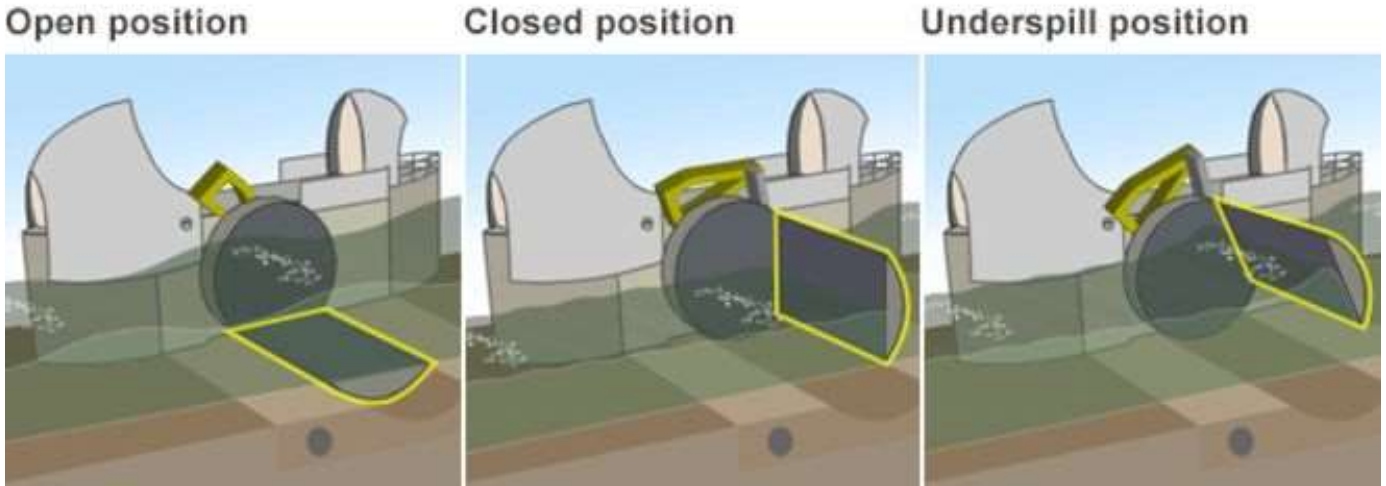
Concept 2: Rising Sector Gate

<u>Pros</u>

- Blockage Ratio low (15%)
- Time to Open <1hr
- Can work with any alignment
- Reliability – proven design
- Impact
- O&M Cost – has to be taken out of water

<u>Cons</u>

- Main negative is that is has not been tried at this scale
    - About 3 time scale of Thames Barrier
- Not available as one single opening (although group consensus was 2 or 3 is better anyway)



Concept 3: Floating Mechanical Flap Gate

Ranking Criteria	Score
Blockage Ratio	5
Time to open and close	5
Alignment	5
Cost	1-3
O&M Cost	1-3
Reliability	3
Adaptability	1
Constructability	3
Technology	1-3
Impact	5
Additional Benefits	1-3

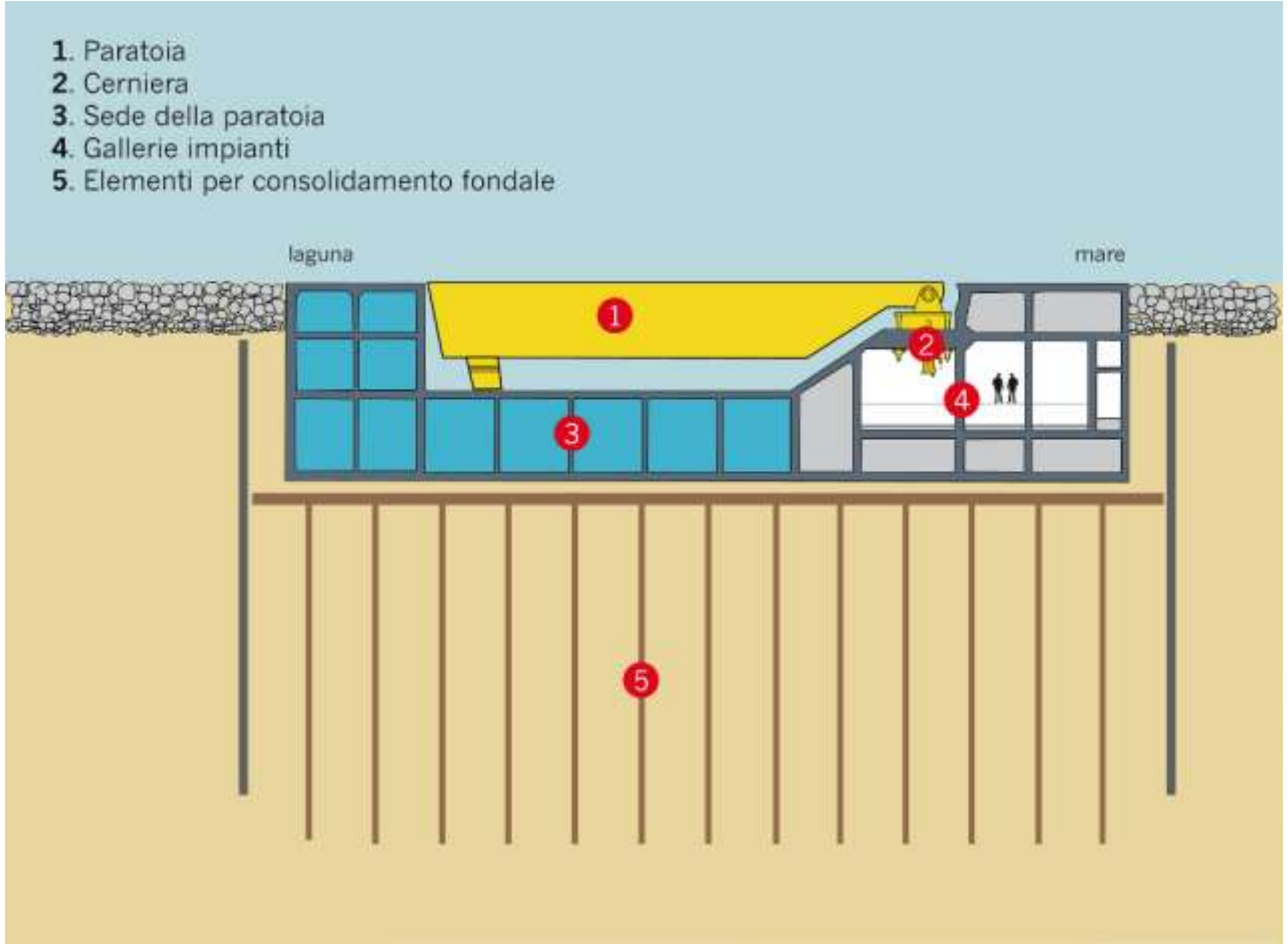
Concept 3: Floating Mechanical Flap Gate

Pros

- Blockage Ratio can be zero
- Time to Open
- Any alignment

Cons

- Inspection and Maintenance – whole structure underwater



Concept 4: Rising Piston Gate

Ranking Criteria	Score
Blockage Ratio	5
Time to open and close	5
Alignment	5
Cost	5
O&M Cost	1-3
Reliability	3
Adaptability	3
Constructability	3-5
Technology	1-3
Impact	5
Additional Benefits	1-3

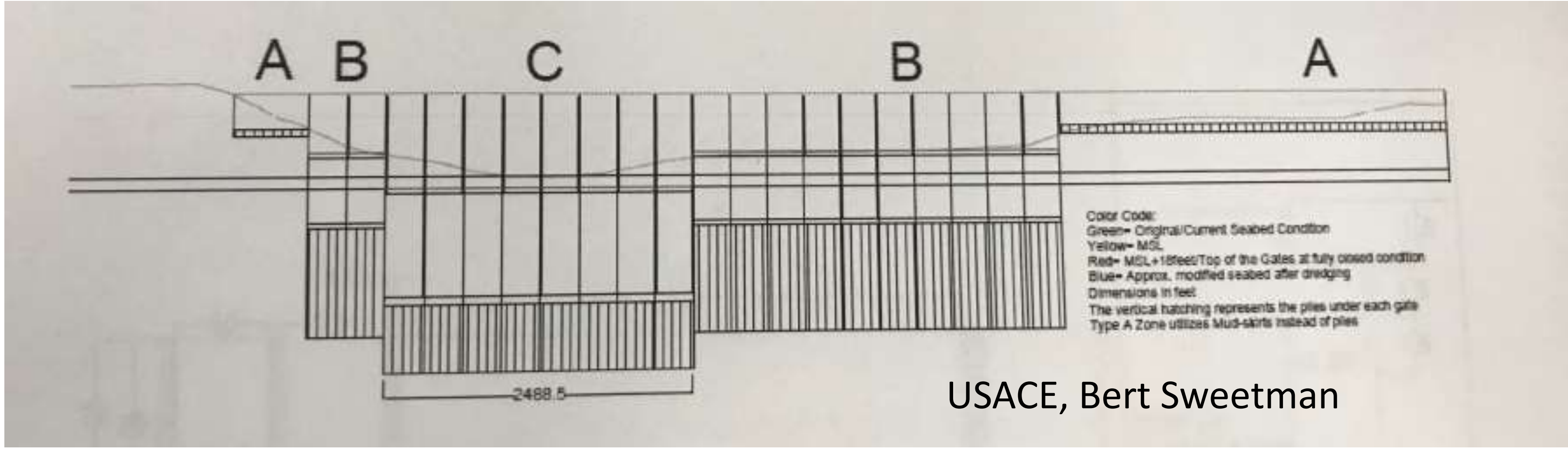
Concept 4: Rising Piston Gate

Pros

- Blockage Ratio can be zero
- Time to Open
- Any Alignment

Cons

- Inspection and Maintenance – whole structure underwater
- Unproven technology
- Very deep construction
- Potentially hidden components



USACE, Bert Sweetman

Concept 5: Vertical Drop Gate

Ranking Criteria	Score
Blockage Ratio	3
Time to open and close	5
Alignment	4
Cost	1
O&M Cost	1-3
Reliability	3
Adaptability	3
Constructability	0
Technology	1-3
Impact	3
Additional Benefits	1

Concept 5: Vertical Drop Gate

<u>Pros</u>

- Low Blockage Ratio (~15%)
- Time to Open
- Any Alignment

<u>Cons</u>

- Inspection and Maintenance – most of structure underwater
- Very deep construction
- Potentially hidden components

Key Comparisons

- Comparison of Structures depends on what is most important

Cross Sectional Area:

- Best: Flap Gate, Piston Gate
- Mid: Rising Sector Gate, Vertical Lift Gate
- Worst: Floating Sector Gate (can be mitigated)

Key Comparisons

- Comparison of Structures depends on what is most important

Proven Technology:

- Best: Floating Sector Gate
- Mid: Rising Sector Gate, Flap Gate
- Worst: Piston Gate, Vertical Drop Gate

Key Comparisons

- Comparison of Structures depends on what is most important

Navigation Channel Width:

- Best: Flap Gate, Piston Gate
- Mid: Floating Sector Gate
- Worst: Rising Sector Gate, Vertical Drop Gate

Key Comparisons

- Comparison of Structures depends on what is most important

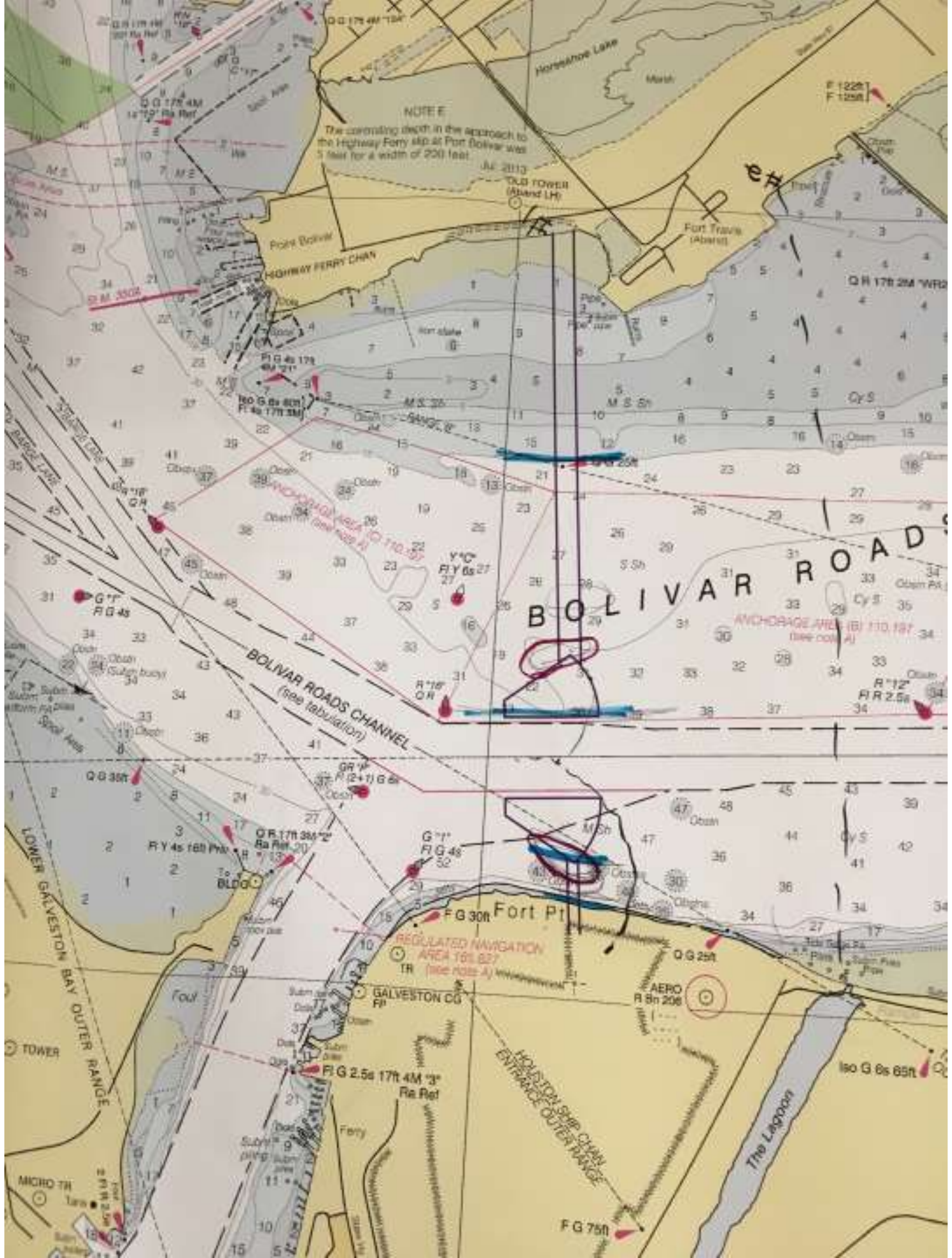
Deterioration, Inspection and Maintenance:

- Best: Floating Sector Gate
- Mid: Rising Sector Gate, Vertical Drop Gate
- Worst: Flap Gate, Piston Gate

Questions / Discussion

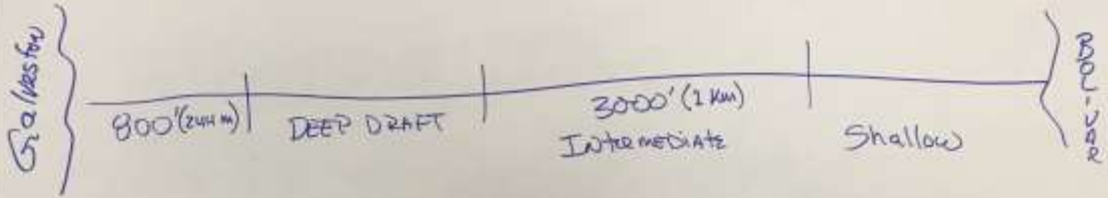
“The Best Ideas are started in the Pub!”

Intermediate Water Depth


NOTE E
The controlling depth in the approach to the Highway Ferry slip at Port Bolivar was 5 feet for a width of 200 feet.
Jul 2013
Horseshoe Lake
Marsh
OLD TOWER (Aband LH)
Point Bolivar
HIGHWAY FERRY CHAN
Fort Travis (Aband)
BOLIVAR ROADS
BOLIVAR ROADS CHANNEL (see tabulation)
ANCHORAGE AREA (B) 110.197 (see note A)
Fort Pt
F G 30ft
Q G 25ft
REGULATED NAVIGATION AREA 165.807 (see note A)
GALVESTON CG
AERO R Bn 206
HOUSTON SHIP CHAN ENTRANCE OUTER RANGE
LOWER GALVESTON BAY OUTER RANGE
TOWER
MICRO TR
F G 75ft
Iso G 6s 65ft
Fl G 2.5s 17ft 4M "3" Ra Ref
The Lagoon
Y "C" Fl Y 6s
G "1" Fl G 4s
Q R 17ft 2M "WR2"
Q G 30ft
Ferry

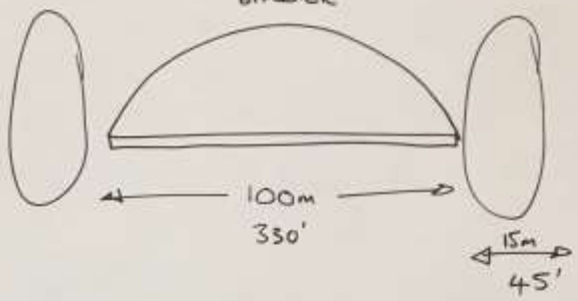
CRITERIA - INTERMEDIATE

- Size 3000' (1 km) [Bolivar side] / 800' (244 m) [Galveston side]
- DEPTH 20-40' (6-12m)
- Top of Gate at LEAST 17' (5m) (able to adjust)

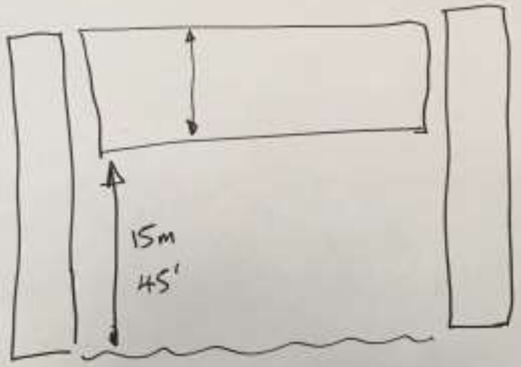


I 1 A

VERTICAL LIFT GATE



15/115 = 13% BLOCKAGE



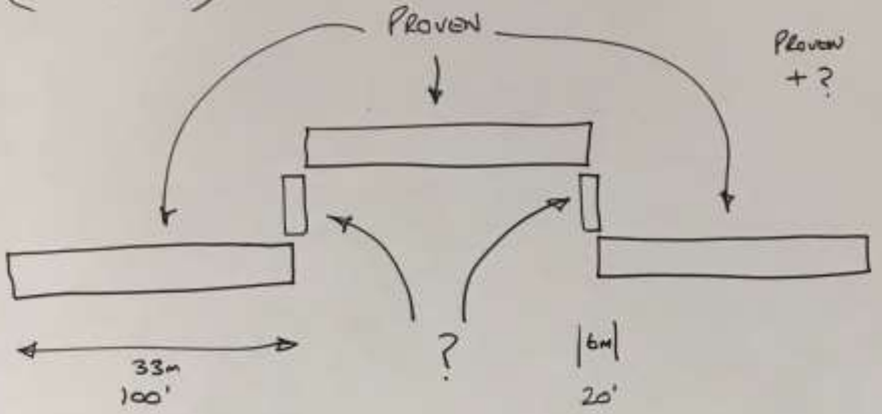
1000m ÷ 115 = 9 GAT

- RELIABILITY GOOD — PROVEN
- MAINTAINABILITY — ALL ABOVE WATER
- OK FOR REVERSE HEAD - IF DESIGNED
- NEED CHECK OF ESTUARINE TO COAST — WIND / WAVES / HEAD DIFF
- ROAD COULD BE ADDED
- NAVIGATION OK FOR SMALL RECREATIONAL.
  OR MAKE LOWER TO REDUCE STEEL
- VISIBILITY OK FOR SHIPPING

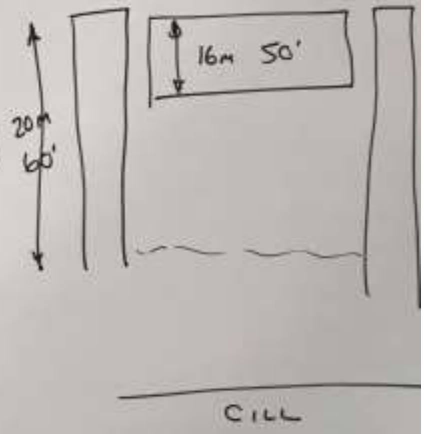
VERTICAL LIFT GATE

(IN STUDY)

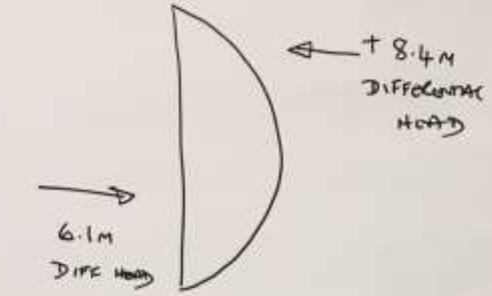
PROVEN 6/39 = 15.4%

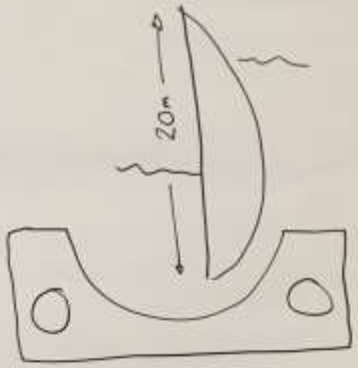


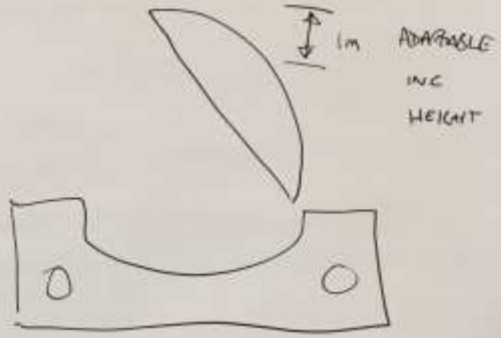
- SOLID STRUCTURE LOSS OF VISIBILITY
- ISSUES WITH MARINE LIFE (CRITTERS)
- NON NAVIGABLE
- GRAVITY WORKS
- PROVEN
- CONSTRUCTION - COFFERDAM.



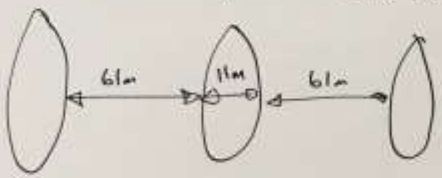
RISING SECTOR GATE







11/72 = 15% BLOCKAGE



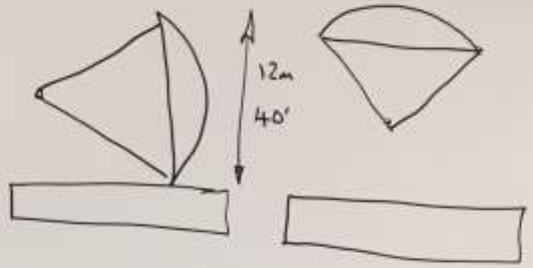
1000m → 13 GATES REQ

- PROVEN GOOD RELIABILITY
- OK FOR REVERSE HEAD
- OK FOR DEPTH

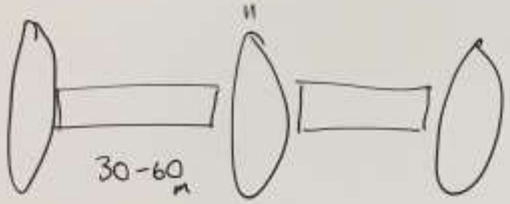
I 3

TAINTER GATE

FALLING RADIAL GATE



11 / 72 = 15%



RELIABILITY GOOD – WELL PROVEN

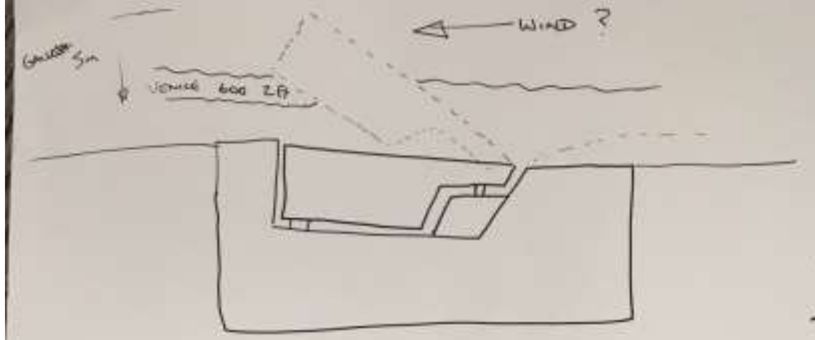
ENVIRONMENT OK SAME AS LIFT

VISIBILITY OK AS GATE HORIZONTAL

LESS WIND LOADING

COMMON IN UK & USAGE

NON NAVIGABLE



I4

0% BLOCKAGE

FLAP GATE

-VE WIND SHEAR CAN IT BE DESIGNED TO COPE ?

-VE CONCERN IF DEBRIS IN OPENING IN CILL WHEN GATE OPEN

+VE AT MAESLANT DESIGN STAGE – DESIGN PROVED 5m 15' DIFFERENTIAL OK

? DESIGN NEED CHECKING IF WIND LOAD TOO MUCH

-VE SILT ~~COULD~~ WILL BE A CONCERN – AS EXCEEDS VENICE WHERE ALREADY A CONCERN THERE & MAY REQUIRE MORE FREQUENT TESTING TO KEEP CLEAR.

+VE NO BLOCKAGE

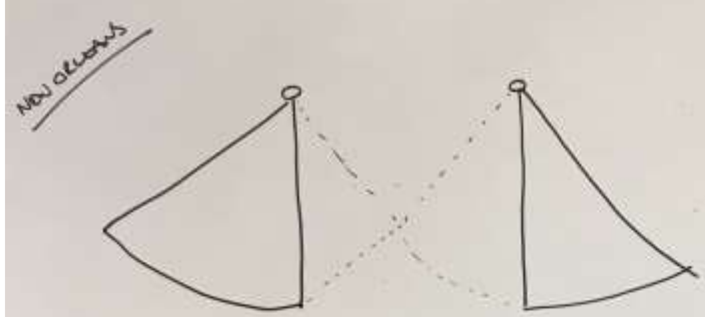
? RELIABILITY – NOT PROVEN @ PRESENT

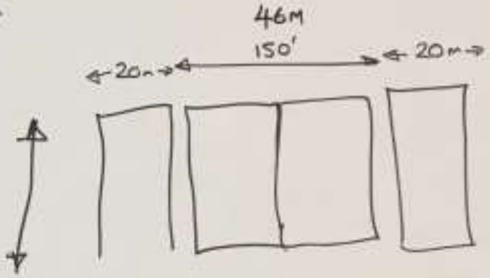
– NAVIGATION NOT AN ISSUE

IS

HINGED SECTOR GATE

$46/86$ = 53% BLOCKAGE



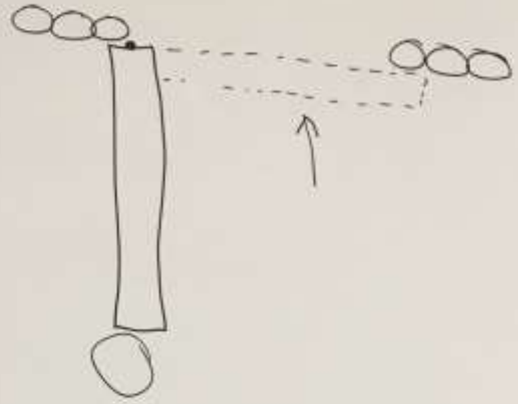


-

- PROVEN DESIGN
- GOOD RELIABILITY
- NAVIGATIONAL GATE
- CONNECTOR GATE — USE PIER/ISLAND FROM MAIN GATE OR LAND TO REDUCE BLOCKAGE
- SOME REVERSE HEAD CAPABILITY

Discounted Options

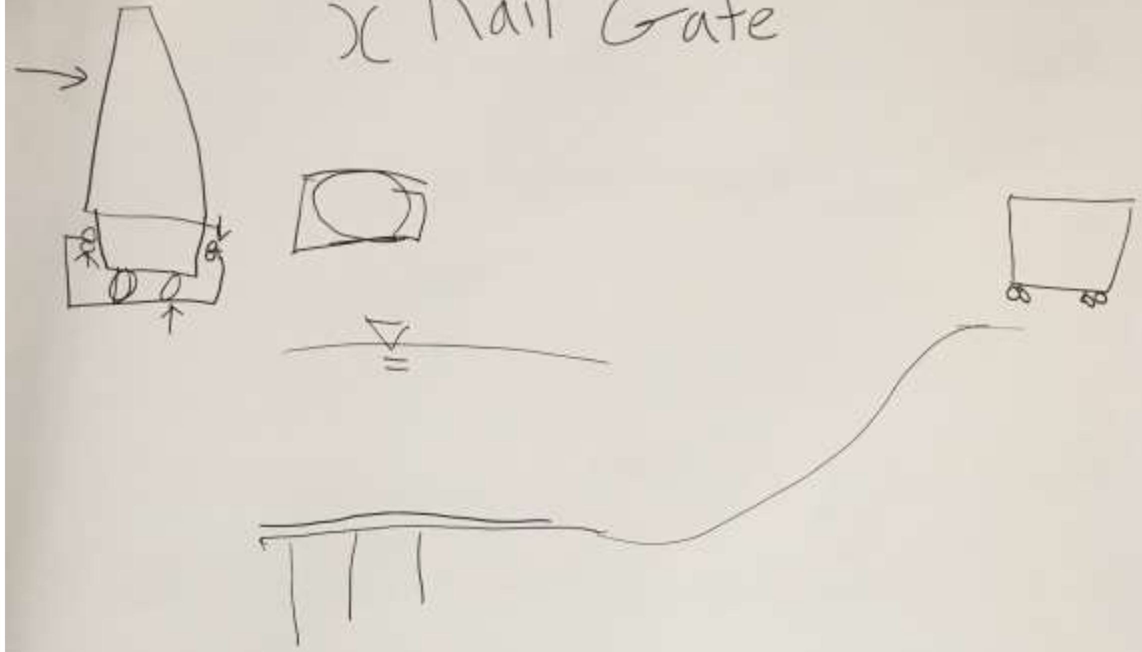
BARGE GATES



- –ve 2 x NEW ORGANS IN SENSE OF SCALE
- –ve CANNOT AUTOMATE
- –ve RELIABILITY – RISK.
- –ve DIVERS REQD BEFORE PLACING
- –ve OPENING – UNCONTROLLED
- \+ NO COFFERDAMS REQD

No

x Rail Gate



NOT Proven

Siltation

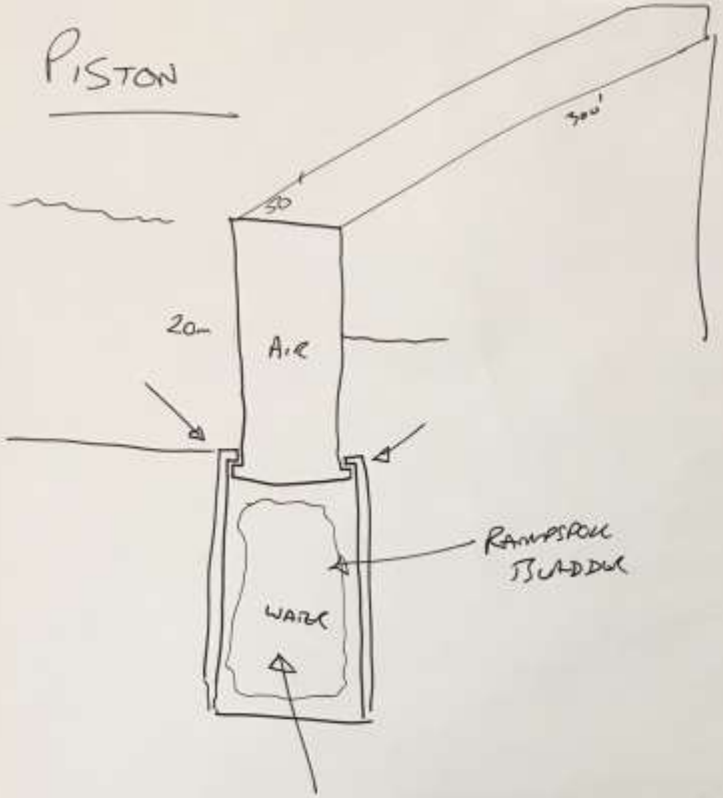
Moment

Risk OF Failure

NO

PISTON

BLOCKAGE = 0%

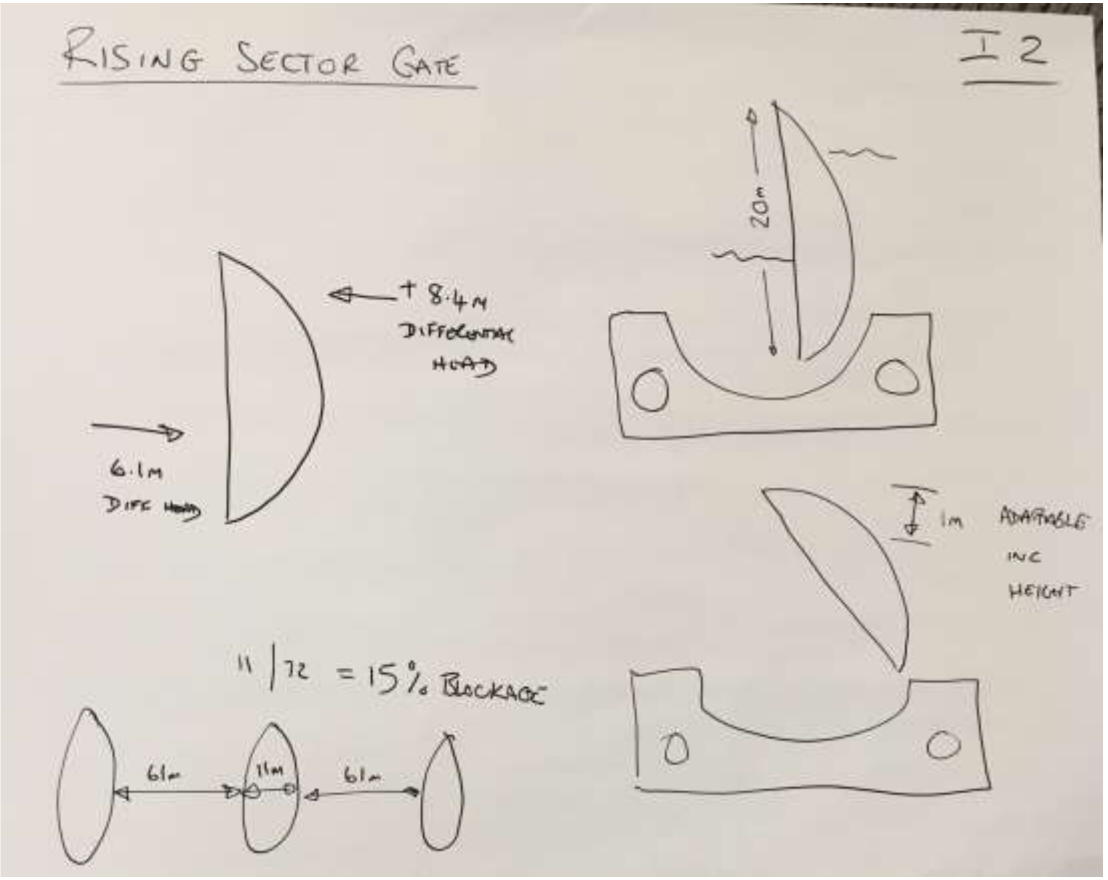


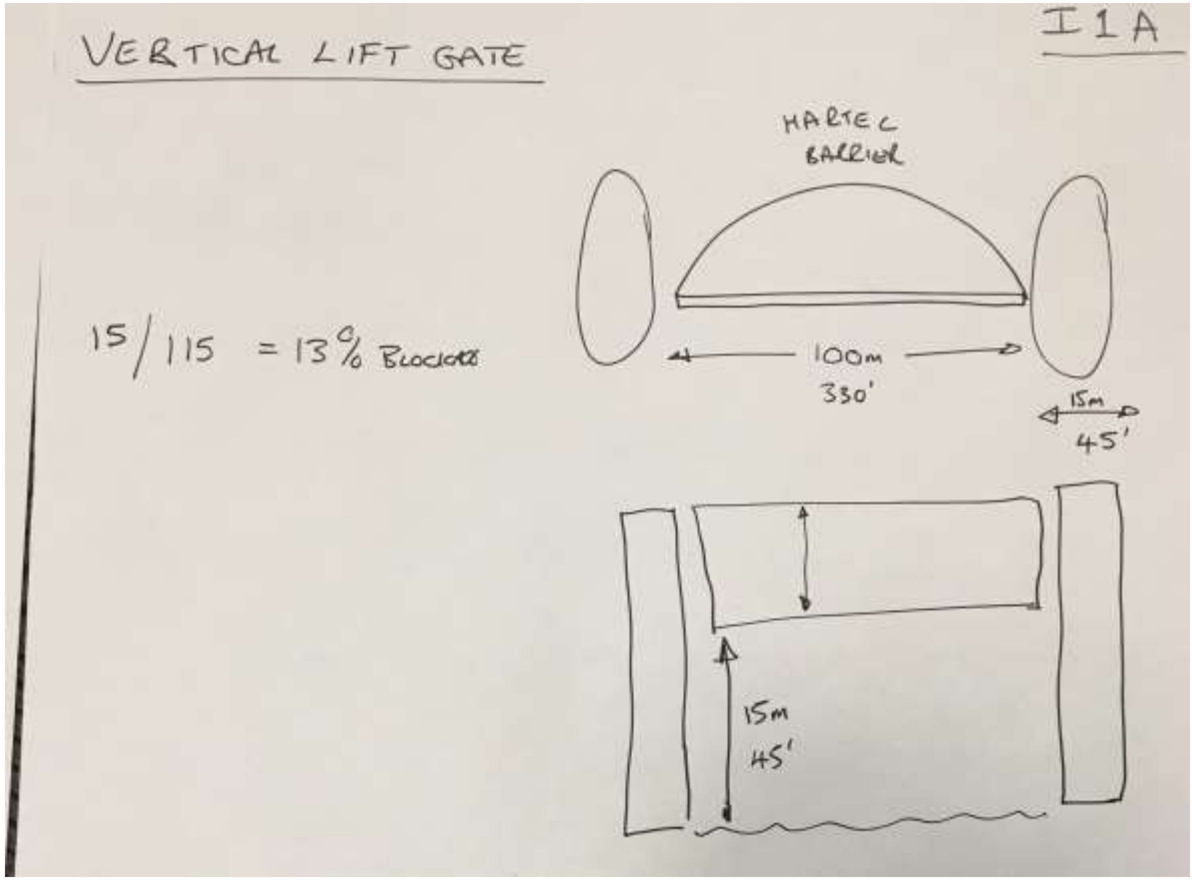
- CONSTRUCTION
- WHERE IS EQUIPMENT / PLANT
- NO BLOCKING
- NOT GOOD IN SHALLOW AS NEEDS BOYANCY
- MAINTENANCE — CONCERNS
- BLADDER COULD HELP SEAL
- VULNERABLE UNTIL GETS TO TOP
- RELIABILITY - UNPROVEN NEED A PROTOTYPE

NO

	NAVIGATION	RELIABILITY	ENV QUALITY	BLOCKAGE	S L RISE ADAPT	CONSTRUCT	CAP COST	O&M	TECHNOLOGY
VERTICAL LIFT I1A		✓	9	13	✓	✓		Above Water	
RISING SECTOR I2	✓	✓	13	15	✓	✓		Under	
I3 TAINTER GATE FALLING RADIAL		✓	13	15	✓	✓		Above Water	
(SECTOR) HINGED MITRE GATE *	✓	✓				✓			
BARGE GATE –					✓	✓			
FLAP GATE (VENICE) ?	✓	?		0	?	✓			
RAIL –	✓			0	✓	✓?			
PISTON –	✓			0		?			

Preferred Option



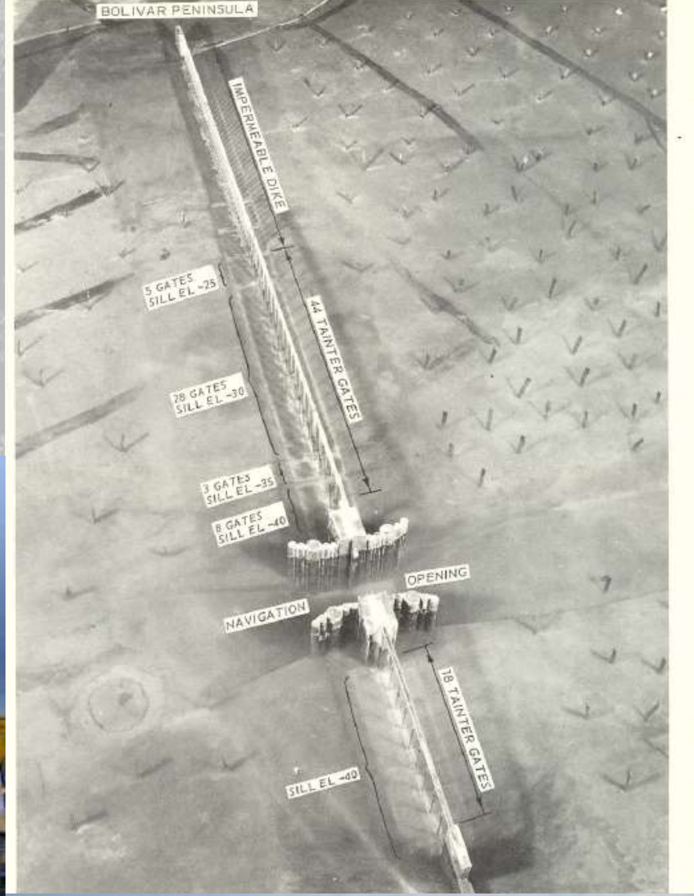


SHALLOW WATER GATE OPTIONS

(+3 TO -10 FT DEPTH GATES WITH 17 FT SURGE)

Coraggio Maglio

I-Storm Gate Workshop Galveston
Date: 19 March 2019



U.S. ARMY

US Army Corps of Engineers ®

WEIGHTING

Name:

			Design																	
			Shallow Draft																	
Criteria		**Weight %**	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
a	Blockage Ratio	15																		
b	Time to open and close	15																		
c	Alignment	0																		
d	Cost	15																		
e	Operation and Maintenance Cost	20																		
f	Reliability	go/no go																		
g	Adaptability	5																		
h	Constructability	5																		
i	Technology	5																		
j	Impact	20																		
k	Addn benefits	0																		

100

GATE STYLES DISCUSSED

Vertical

1. Vertical lift gates – proven technology, however large superstructure and associated blockage
2. Tainter gate – eliminate due to reverse head
3. Thames Barrier style – very expensive and large blockage and siltation

Bottom mounted

1. Flap gates (Mose) – uses buoyancy
2. Crest gate (using top mounted hydraulics) – simple, no superstructure, however entirely submerged as associated siltation issues
3. Bladder (inflatable) gate – proven technology, however large footprint and maintenance issues
4. Piston gate – not enough depth for buoyancy to work
5. Vertical rising gate – proven technology, however entirely underwater, sedimentation

Simple gate

1. Pivot gate – difficult to secure and potentially unreliable
2. Wicket gate – siltation, reverse head and weather effecting deployment, concerns with coastal environment
3. Stop logs – misalignment, weather effecting deployment and concerns with coastal environment
4. Flat panel drop-in gate (guillotine) – reliability concerns adverse coastal environmental conditions
5. Pre-Cast sluice (box culvert) – view shed issues and environmental considerations
6. Floating fixed barge gate – maintenance issues and siltation will be a problem.
7. Swinging Barge gate – simple, however deployment issues in weather

Innovative

1. Railroad – deployment issues in weather and no redundancy
2. Texas armadillo - deployment issues in weather and no redundancy
3. Curtain (membrane) gate

GATE STYLES DISCUSSED

Selected:

- Vertical Lift Gates
- Crest Gate
- Bladder (inflatable) Gate
- Vertical Rising Gate
- Pre-cast Sluice (box culvert)
- Swinging Barge Gate
- Railroad Gate
- Texas Armadillo

Eliminated:

- Tainter Gate
- Thames Barrier Style
- Flap Gates (Mose)
- Piston Gates
- Pivot Gate
- Wicket Gate
- Stop Logs
- Flat Panel Drop-in Gate
- Floating Fixed Barge Gate
- Curtain (membrane) Gate

VERTICAL LIFT GATE

Pros

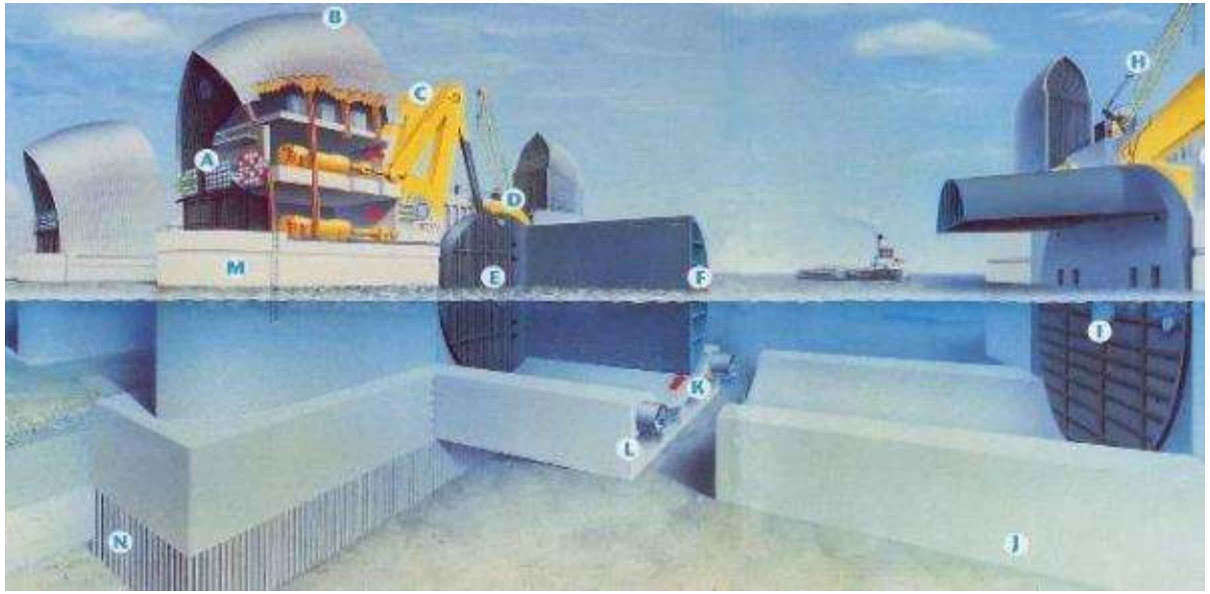
- Additional benefits: roadway on top
- proven technology able to manage reverse flows
- operated automatically
- Maintenance O&M lower
- Bubbler removes silts
- Quick deployment/lower operation time
- Can withstand negative head

Cons

- Blockage
- Larger concrete foundation
- Initial cost for construction
- Support columns
- Hazardous for small boat
- Small boat impact
- Limit to vertical height/clearance
- Build a sill
- Lowering mechanism
- $$$ steel

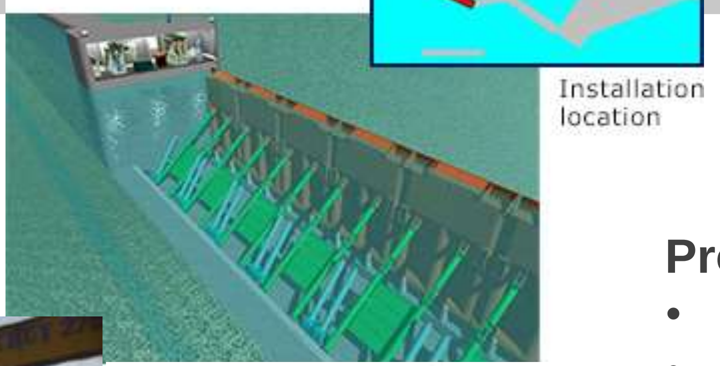
RISING SECTOR GATE (THAMES)

Pros
- Proven technology
- Can allow vessel access

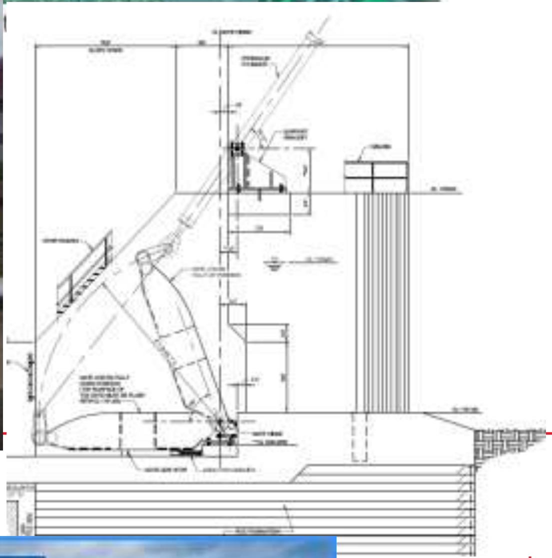


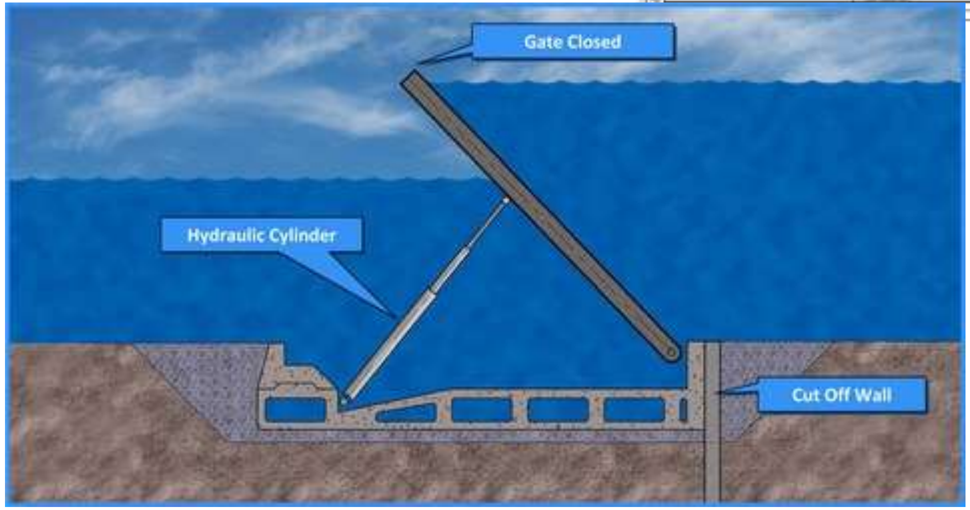
Cons
- High initial and O&M costs
- Large blockage
- Large footprint

CREST GATE



- Flood mitigation project in HoChiMinh City, Vietnam
- Flap Gate
- Construction: 2003





Pros

- simple
- no superstructure
- No viewshed issues
- Can be operated automatically

Cons

- Reverse head
- Maintenance issues
- entirely submerged thus siltation issues

BLADDER GATE (INFLATABLE)

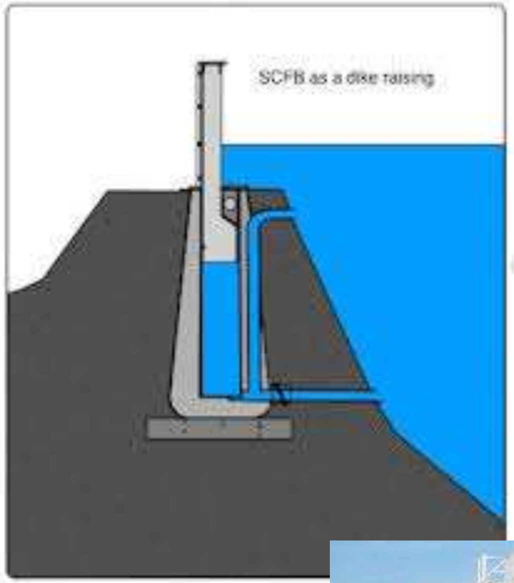
Pros

- proven technology
- cheap materials (build)
- reverse head
- Minimal blockage
- can be overtopped
- biofouling not an issue

Cons

- large footprint
- maintenance issue – replace in seals
- deflate time
- O&M cost
- Limited crest height

VERTICAL RISING GATE



Pros

- proven technology
- Minimal restriction
- No navigation impact
- blockage
- can be overtopped
- Reverse head

Cons

- Entirely submerged
- Sedimentation
- Potential initial cost

PRE-CAST SLUICE (BOX CULVERT)

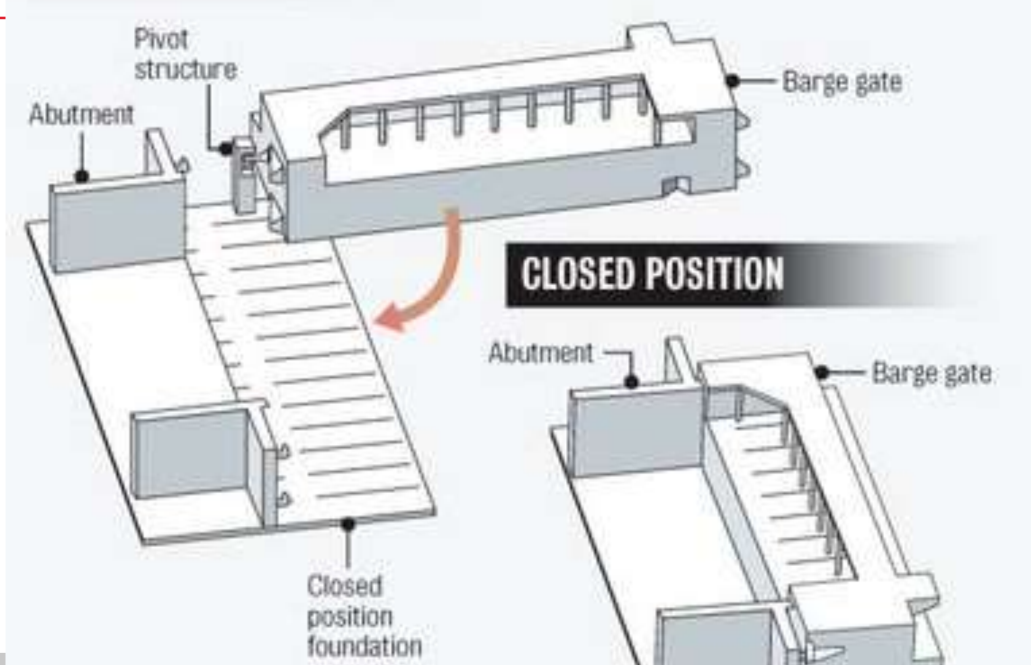
Pros

- great for roadway
- cheap
- easy to construct
- easy to operate
- low maintenance

Cons

- view shed issues
- environmental considerations
- more elements

SWING BARGE GATE



Pros

- Administration Transition / Program shift?
- ONBOARD ASA(CW) / ASA(IEE) / Secretariat
- FY18 Budget Testimony / adjust to new POTUS
- "Dirty Dozen" focus (mines/ACE/113/BEB's)
- REENERGIZE Joint Engineer Coordination
- CENTCOM AOR – Future of IRAQ/AFGHANISTAN

Cons

- Administration Transition / Program shift?
- ONBOARD ASA(CW) / ASA(IEE) / Secretariat
- FY18 Budget Testimony / adjust to new POTUS
- "Dirty Dozen" focus (mines/ACE/113/BEB's)
- REENERGIZE Joint Engineer Coordination
- CENTCOM AOR – Future of IRAQ/AFGHANISTAN

RAILROAD GATE

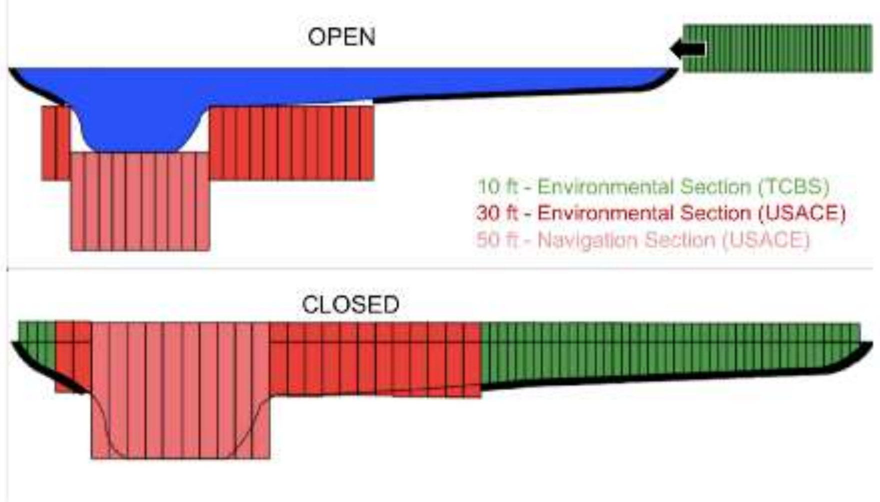


Figure 3: Concept of TCBS barrier integrated with USACE barrier.

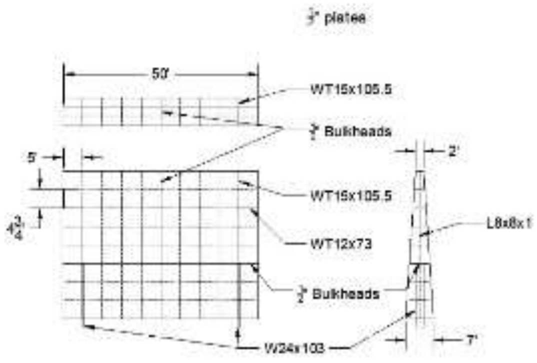
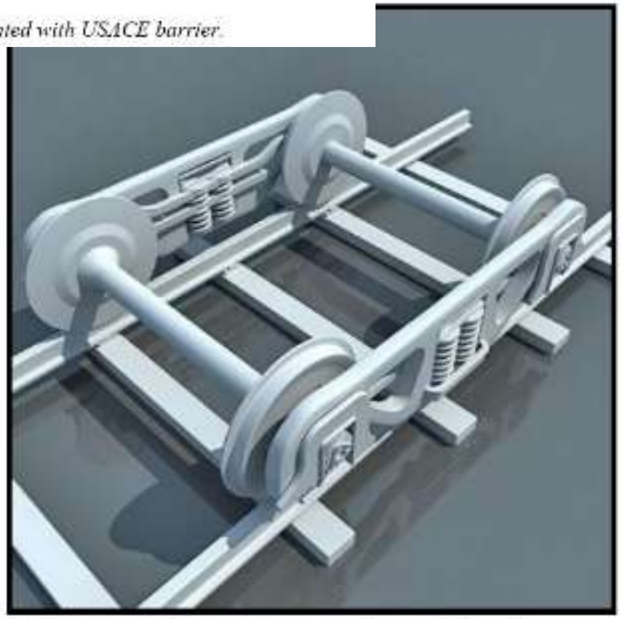


Figure 8: AutoCAD model of trapezoidal barrier section



5. Conceptual wheel system for each barrier segment [4].

Pros

- simple
- Minimum blockage
- Reverse head

Cons

- Deployment issues in weather
- Unproven technology
- O&M concerns with the sill

TEXAS ARMADILLO

Pros

- Best name ever
- Stored mostly out of water
- Minimal constriction?
- View shed
- O&M

Cons

- Crazy awesome
- Less vertical problems than VLG
- Untried/new tech
- Navigation impacts
- How to operate?

Scores - ALL PARTICIPANTS																							
			Shallow Draft								Intermediate Draft					Deep Draft				
	Criteria	Averaged Weight	1	2	3	4	5	6	7	8	11	12	13	14	15	21	22	23	24	25
a	Blockage Ratio	18.1	3.3	3.9	4.1	3.7	3.1	3.3	4.7	3.7	3.3	3.3	3.0	2.2	4.6	1.6	3.3	5.0	5.0	3.5
b	Time to open and close	8.4	4.3	4.0	3.7	4.5	4.2	2.0	2.6	3.0	4.5	4.3	4.2	3.8	3.9	3.5	4.2	4.2	4.0	4.0
c	Alignment	3.8	3.8	3.7	4.0	3.7	3.4	3.4	3.5	3.2	3.7	3.8	3.0	3.4	4.2	3.7	3.4	4.3	4.4	3.6
d	Cost	11.6	3.1	2.8	3.5	2.6	4.4	3.2	2.9	2.1	3.4	2.9	2.9	2.4	2.6	2.9	2.7	2.2	2.0	2.1
e	Operation and Maintenance Cost	10.4	3.7	2.4	3.1	2.4	4.2	2.5	2.4	2.2	3.9	2.9	3.4	3.1	1.9	4.2	3.0	1.4	1.5	2.1
f	Reliability and Redundancy	14.4	4.7	3.5	3.4	3.2	4.7	2.0	1.6	1.1	4.7	4.4	4.2	4.2	2.6	4.6	4.2	2.0	1.6	2.7
g	Adaptability	5.9	3.7	2.7	2.2	2.3	2.7	2.7	2.7	1.5	3.8	3.6	2.6	2.7	2.2	3.0	3.2	1.6	1.8	2.3
h	Constructability	8.8	4.0	3.5	3.4	3.1	4.2	3.3	2.8	2.1	3.8	3.5	3.1	3.3	2.9	3.4	3.2	2.5	1.7	2.0
i	Technology	8.8	4.7	3.7	3.6	3.5	4.5	3.2	1.8	1.1	4.6	4.2	4.0	4.0	2.9	4.5	3.3	2.7	1.3	2.5
j	Impact	9.4	3.1	3.3	3.3	3.9	2.5	3.1	3.3	2.7	3.1	3.3	2.9	2.6	3.8	2.2	3.1	3.6	3.6	2.9
k	Additional Benefits (Bonus)	1.7	2.5	2.0	1.6	2.0	2.8	1.2	1.6	1.3	2.6	2.0	1.9	1.8	1.8	1.6	1.8	2.0	1.9	1.8
			41.0	35.4	36.0	34.9	40.9	29.7	29.8	24.1	41.4	38.1	35.1	33.3	33.2	35.3	35.5	31.5	28.6	29.5

Scores - INVITED ISTORM PARTICIPANTS ONLY																							
			Shallow Draft								Intermediate Draft					Deep Draft				
	Criteria	Averaged Weight	1	2	3	4	5	6	7	8	11	12	13	14	15	21	22	23	24	25
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b	Time to open and close	9.2	4.5	4.0	3.9	5.6	4.1	1.7	2.4	3.3	4.5	4.6	4.5	4.1	4.3	3.4	4.4	4.4	3.7	4.2
c	Alignment	5.2	4.2	4.1	4.4	4.3	3.4	3.8	3.9	3.8	3.9	4.3	3.0	3.6	4.5	3.8	3.5	4.4	4.4	3.8
d	Cost	9.1	3.2	3.0	3.4	2.7	4.6	3.1	3.0	2.5	3.6	2.9	3.0	2.2	2.6	2.9	2.9	2.4	1.6	1.9
e	Operation and Maintenance Cost	11.9	3.7	2.5	3.3	2.6	4.5	2.6	2.1	2.3	4.2	3.1	3.8	2.8	1.9	4.3	3.4	1.5	1.1	1.9
f	Reliability and Redundancy	17.1	4.9	3.4	3.6	3.1	4.9	1.8	1.1	1.4	4.6	4.5	4.3	3.9	3.1	4.6	4.2	2.2	0.8	2.5
g	Adaptability	5.8	3.7	2.8	2.4	2.4	2.6	2.5	2.3	1.6	3.7	3.8	2.8	3.1	2.4	3.0	3.5	1.4	1.6	2.0
h	Constructability	10.3	3.9	3.8	3.4	2.9	4.2	3.4	2.7	2.2	3.9	3.5	3.2	3.2	2.9	3.4	3.2	2.6	1.1	1.4
i	Technology	9.7	4.9	4.1	4.1	3.8	4.4	2.9	1.8	1.3	4.9	4.5	4.2	3.9	3.4	4.8	3.8	2.9	1.0	2.3
j	Impact	6.1	3.2	3.2	3.6	3.4	2.8	3.2	3.1	3.0	3.4	3.4	3.1	2.9	3.6	2.6	3.3	3.4	3.0	2.8
k	Additional Benefits (Bonus)	3.1	2.4	1.8	1.4	1.8	2.7	1.1	1.1	1.4	2.6	1.7	2.0	1.9	1.4	1.5	1.4	1.4	1.2	1.5
			42.3	36.3	37.8	36.1	41.6	29.7	27.7	26.6	42.9	39.5	36.8	33.9	34.4	35.6	36.7	31.5	24.3	28.0

Scores - USACE, TAMU, and GCCPRD PARTICIPANTS ONLY																							
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b	Time to open and close	8.4	4.4	4.0	3.7	3.7	4.3	2.1	2.7	2.9	4.4	4.0	3.9	3.2	3.4	3.2	3.8	3.7	3.9	3.4
c	Alignment	3.8	3.4	3.1	3.4	3.1	3.1	3.0	2.8	2.5	3.5	3.3	2.8	3.0	3.8	3.5	3.1	3.8	4.1	3.3
d	Cost	11.6	3.2	2.9	3.3	2.6	4.2	2.9	2.7	1.6	3.4	2.9	2.7	2.8	2.8	2.9	2.7	2.3	2.4	2.5
e	Operation and Maintenance Cost	10.4	3.6	2.2	2.7	2.1	3.9	2.1	2.4	2.0	3.6	2.8	2.9	3.3	1.7	4.0	2.6	1.6	1.9	2.1
f	Reliability and Redundancy	14.4	4.6	3.6	3.4	2.9	4.6	2.2	2.1	0.8	4.8	4.4	3.8	4.5	2.5	4.6	4.1	1.6	2.2	2.3
g	Adaptability	5.9	3.6	2.9	2.2	2.3	2.8	2.9	2.9	1.5	3.8	3.3	2.3	2.5	1.9	3.1	2.9	1.7	1.9	2.3
h	Constructability	8.8	3.9	3.0	3.2	2.9	4.1	2.9	2.5	1.9	3.9	3.5	3.1	3.2	2.6	3.6	3.2	2.5	2.4	2.6
i	Technology	8.8	4.5	3.5	3.2	3.2	4.6	3.3	2.0	1.1	4.4	3.8	3.9	3.8	2.4	4.1	2.8	2.3	1.7	2.6
j	Impact	9.4	3.1	3.3	3.5	5.1	2.4	3.4	3.6	2.7	3.1	3.3	2.9	2.4	4.1	2.3	3.1	3.9	4.2	2.9
k	Additional Benefits (Bonus)	1.7	2.2	2.0	1.9	2.3	2.7	1.4	2.4	1.5	2.3	2.4	1.7	1.8	2.7	2.0	2.5	3.0	2.6	2.2
			39.8	34.7	34.7	34.0	39.7	29.3	30.9	22.3	40.5	36.8	32.9	32.4	32.9	35.4	34.3	31.3	32.2	29.9

Gate Selection Workshop: Coastal Texas Protection and Restoration Study

Notes

Table of Contents

Day 1
March 18th, 2019

Introduction

Purpose of workshop: We need to decide the type of barrier by the end of the week. The only topic to be discussed during this workshop is how to best close the inlet.

- How do we close the inlet?
- What is the best way to close the inlet?

Two step process:

1. Brain storm all of the ways that we can close the inlet.
2. Decide the best way to close the inlet.

Ranking needs to be determined after best ideas are selected. See design concept scoring sheet.

CTS Barrier Design Constraints

- Sill depth- deep, intermediate, and shallow draft sill depth. Structure must handle required depth and changing bathymetric condition.
- Hydrostatic load- structure must handle significant hydrostatic head difference
- Reverse head of 3ft
- Environment- to minimize the ecological impact. Cross section of the inlet must be maintained at least 70% of the current configuration. (27% or less blockage)
    - Salinity, sedimentation, and water quality considerations.
    - Inlet can be a good indicator of water quality.
- Openings in shallow water area necessary
- Potential deepening of intermediate areas
- Needs to not affect velocity
- Must have some shallows
- Operation time 24 hours is a max constraint
- Overtopping?
- Active gates that operate while the storm is still going
- Navigation – commercial navigation and recreational navigation need to be accounted for
- Impacting one of the three anchorages would mean having to mitigate by creating a new anchorage
- Goal is to reduce storm surge levels when barrier is closed
- Alignment
    - Looked at two different alignments
    - Alignment 2 is preferred after conduction ship simulation
    - Stay within Bolivar roads and Galveston Ship Channel
    - Realigning navigation is not preferable but is on the table

Ranking Criteria

Scoring 1-5

5- Best possible score

1- Lowest possible score

- Blockage ratio
- Time to open and close gate
- Alignment
- Cost
- Operation and maintenance
- Reliability and redundancy
- Adaptability
- Constructability
- Technology
- Impact

Consider certainty when ranking.

Discussion:

Q: This is focusing on the barrier type. How much freedom can we use/take with respect to location, dimensions, and type of design?

A: In terms of location, we are flexible. We have already looked into two alignments. We have identified that alignment 2 is slightly better than 1.

Let's constrain the location to tie into some part of Bolivar and Galveston Island. You cannot pass the GIWW (Gulf intercostal water way). But overall the movement of the alignment is open.

Q: Do you have an idea of moving the alignment out of these constraints?

A: There's not a lot of focus or analysis on the wave conditions. If you could move more inland with less direct effect with additional forces, you may create something form a structural point of view with a great design.

-We can try to find a barrier that can be constructed here. The objective is to find the barrier and the right barrier. The design score does not include the waves. In essence let's not only focus on the score, but use the score as a guidance to help select the best.

-purpose is to select the barrier that we can select and put a cost on.

-we do need to stay within this area. We do not want to go into the bay with the designs, it has been proven to not be cost effective.

Q: the criteria is missing navigation. Are you willing to sacrifice intermediate navigation? Should we include navigation as a part of the criteria?

A: this is a starting point and this criteria can be expanded as needed based on feedbacks.

Navigation is lumped into two categories: alignment and constructability right now. Hopefully in the team discussion we can find the pros and cons of each. The reason why it's put where it's at is because of commercial and goods navigation.

-recreational navigation needs to allow for fishing and sailboats

-it was planned/discussed to have a smaller spate gate for that recreational traffic.

-If we impact one of the anchorages we will need to create a new one. This is a part of the alignment criteria, to minimize the anchorage impact

Q: Do you require a certain reduction? What's the real purpose of the required effect of the barrier? Is that clear?

A: We closed the system and ran models of several storms and we found significant reductions in the wave heights and still water levels.

Q: How much can you allow for storm surge? Once you block the entire region you could have an effect, but there are already some protections in place. How bad is overtopping? Is that considered?

A: That's another discussion we need have to decide how much we can allow before failure.

Q: Are there some constraints for open and closure times?

A: We talked about that on the boat yesterday. The coast guard sees a storm coming and they have to start making decisions on when to close the port. Having a system that gives flexibility to begin closure without cutting off navigation is another aspect to consider. If I can close it off in sections and then make the final closure at the end that would be best.

Q: Can you give us a steer? What are the absolute parameters? Then we will design your gate system to meet that.

A: Around 30% constrictions we see significant impact on the bay.

-Reverse head needs to be considered in this case.

-The graph of the simulation shows that its effect to keep it closed for the entire event. If we can open it after, then the negative head will never happen. The solution is right around the lines crossing.

-The limitation of the reverse head should also be a criteria for intermediate and shallow depths.

-Time as a parameter should be better defined for tomorrow's discussion.

- O&M costs are very important it is often forgotten or neglected
- Potential road put on the structure for O&M access
- If something is not reliable then it should be eliminated
- Reliability should be changed to a yes or no option (5 or 0)
- Impact of foundation on the bay bottom will have to be mitigated because the footprint is so large. Changing criteria to direct impact condition.
- Also scour protection

Criteria A: Blockage Ratio

- Reduction in cross section: maximum reduction of inlet cross section where ideal condition would not significantly alter the current configuration and minimize the environmental impacts
- Q: how much blockage could we get in the shallows? Do you know or have constraints?
- A: I don't know the bottom and top velocities number on the top of my head to give you a direct answer.
- We need to make sure there's a shallow water opening that maintain relatively close velocities to what's happening now
- I didn't think the percentage was equally weighed from deep vs shallow blockage.
- The deeper section may be more effective in terms of hydrodynamics.
- Q: Would it be okay to make some of the shallow parts deeper? Excavate those regions?
- A: Maybe… it depends on how much deeper you want to go. It's not just that its shallow the slower velocity is also important if you can keep the slower velocity and make it deeper then maybe. But we do need to maintain some shallow water for the organisms living in those areas.
- The intermediate area could possibly be deeper, but that shallow region should remain shallow.
- Q: Can you look at the cross sections and give a cut off of where the areas are that need to remain shallow?
- A: it's difficult to say how much of the shallow water we need. We need to model the plan sand stud the impacts. We need to minimize the impact on the shallow water.
- When the groups are working together, we need to consider the depth that is next to you. How we look at shallow to intermediate and intermediate to deep is important.
- Q: 570ft to 1200ft wide gate?
- A: the 1200ft width is what we think would be necessary to maintain at speed two way traffic. This is also to account for future expansion and larger ships.

- We did ship simulations with the increase in velocity inside the gate. We even with the width of 1200ft we saw some crashes.

Criteria B: Operation Time

- Maybe we should differentiate the speeds between the deeper part and shallow part.
- It's more effective to open quickly the deeper part. The ship channel is the most important.
- From an environmental standpoint it is still more efficient to have a quicker open/close time. The shorter the closure the less the environmental impact.
- Q: Did the navigation industry give us a hard number?
- A: It takes 48 hours for them empty the Houston City Ship channel. You can't keep the navigation gate closed for that long without causing a negative impact.
- Operation time. Close the lesser impact gates first, but this is all during a storm surge. Environmental impacts need to be considered. Closure time is all for big storm and big events.
- YANKEE: 24 hours prior to gale force winds, there will be no pilot service available
- We want to be able to manage the water levels within the bay to eliminate the reverse head and possibly for other purposes.
- If the deep channel gate closes last, it should be the most reliable design
- Anything greater than 24 hours for navigation gate is off limits because of the pilot boats

Criteria C: Alignment

- How to reduce the length of the alignment
- Moving the anchorage areas closer to the gate makes it harder for the ships to utilize the areas; shoaling in anchorage area due to relocation
- Minimize ship collision
- Minimize impact to anchorage area
- Maximize ship turn over to Galveston channel
- Tie-in to reduce flanking
- Q: Is there any hard constraint aside from tying in the islands?
- A: No.
- Q: Is there a way to separate the criteria into two groups?
- A: The more criteria, the more details and complicated.
- Re-aligning navigation should stay on the table until we look at the pros and cons
- The closer we put the anchorage area to the gate, the maneuverability of the ship becomes a concern. Currently they can pull in and out of the anchorage area themselves.
- The alignment cannot impact Fort Travis. It's a historical fort that cannot be touched.
- Q: If you pull the alignment forward how does that effect the head?
- A: We'd have to evaluate that.
- The barge lanes don't start until the GIWW

Criteria D/E: Cost/ Operation & Maintenance (O&M) Cost

- O&M cost needs to be as low as possible because the public sponsor will be paying for it
- Certainty of cost would be huge factor upon determining the score here
- It might be an idea to try to add these two costs. It would be good to calculate the total cost of ownership. You need the team and money for operation and maintenance
- Navigation will dictate. To get the scheme through and approved, in a way you end up doing what you have to do. The way that we look at this cost, change always acquires cost. Capital cost, constructability, and O&M.
- Low cost but high maintenance isn't ideal. We cannot assign a value for construction cost yet. We should plan how to manage change that will come later as a way to better keep within the budget.
- We're trying to make a decision that will change as little as possible
- Q: In terms of maintenance for the entire alignment. Would it be possible to have a roadway along the gates?
- A: Yes. Not only is there a possibility, but if we put a road on top of it we can cost share.
- We need to understand how do we get to this type of gate to maintain it? Water borne or land based? Think in your groups about how you need to reach the gate.
- Roads- Maybe you can sell this road to someone in the area

Criteria F: Reliability & Redundancy

- System can be reliably closed within the required time limit
- The ability to inspect critical members for O&M
- Consider the difference between O&M (ownership) cost for GLO and capital costs at the beginning
- Possibility to cost share if a road is built along the alignment of the gate
- We NEED a reliable barrier. Anything not reliable should not be an option.
- Q: Do you have a reliability requirement for this barrier?
- A: There is not a Corps wide reliability. It is based project to project and study to study.
- Our system should have maintenance parameters. Maybe perform all maintenance operations outside of hurricane season. Or maybe limit the operation that can be performed during different times of the year.
- Let's change this to a Yes or No. Is it reliable or not? (for scoring the criteria)
- This becomes a constraint now and not a criteria.
- 0 or 5 scoring? Anything with a 0 score in a section will be eliminated as a possibility
- FEMA standard of 1%

Criteria G: Adaptability

- Degree of adaptability- ideal condition will be structure that can be adaptive to future changes in channel bathymetry, future sea level rise & subsidence, and expansion of HSC (Houston Ship Channel)

- For the sea level rise scenarios, the height of the barrier is an important factor.
- Two main factors: sea level rise and HSC expansion
- Q: Do we have a number for the sea level rise?
- A: For all of our analysis we use the intermediate sea level rise.
- There is not one answer within the structure. Certain parts can be others not as much. We tend to build structures for a conservative level.
- Q: what about the cost of the adaptability. Maybe it is possible to make it adaptable with a higher cost.
- A: we need to decide as a group which factors are the most important and how each criteria is weighed.
- Q: how much overtopping do you let onto what part of the system?
- A: we could decide that overtopping should not be addressed on the gate when we have 76 mile stretch elsewhere.
- Engineering reliability is different from flood reliability
- WE can include life cycle in cost and O&M

Criteria H: Constructability

- Maximize the HSC operation during construction
- If you cannot maintain navigation during construction it is a 0
- Can you build it and keep navigation where it is or build it and provide a different route for navigation?
- Can you sequence the build where you can never dam off more than 30%?
- Cost aspect- how do you go about construction and the mitigation during construction
- Construction methods should be considered also
- Direct impacts of any staging areas are also a concern
- Temporary impacts on ecology need to be mitigated
- Concerns of contractors: getting workers and supplies to site
- Construction sequence plan

Criteria I: Technology

- Proven technical/innovative approach
- Non US made items need exemptions
- Technology and adaptability go hand in hand
- Are we working on the same scale where proven technology has been applied? Something to be mindful about.
- Someone needs to be able to stand up and say that the system is affective/will work and that closure will not affect the ecology.
- The chief of engineers will sign off on this and be the one to say that the design will work

Criteria J: Impact

- Foundation footprint and indirect impacts
- Overall the foundation performance of any kind of gate is feasible
- We do not have a challenging geotechnical condition here. Any driven pile type will work here.
- Any direct impact of foundation on the environment as well as any indirect impacts on the bay due to closures
- Goal is to minimize the impacts
- The more changes being made to the bay bottom then more mitigation will be required
- Critical habitat for piping plover. Moving gulf-ward can affect the endangered species.
- Direct and indirect impact
- We combine our direct and indirect impacts.
- Indirect impacts are stemming from the cross sectional input
- This topic is a catch all for environmental impact
- Piles are driven deeper than initial clay layer and therefor is not a concern with regards to feasibility

Discussion/ additional criteria:

-Additional benefits could be another criteria added to the ranking like adding bonus points

-Risk of collision seems to be a major factor

-Environmental impacts during construction and environmental impacts during operation

-Operations during storm?

Q: How do we deal with the shipping lanes?

A: If we went to a two structure system you'd have a backup for if one fails. The discussion then becomes having a gate structure for two different systems.

-Consider the other benefits for two gates

-Are we talking about two lanes at all times? So then do we need three?? What happens when you need major maintenance and that part of the shipping channel is closed?

Afternoon Session

Criteria Modifications

- Operation time: hard constraint anything longer than 24 hours in not acceptable
- Alignment: life cycle cost is added

- Reliability: anything not reliable is now 0
- Constructability: expanded
- Impacts: direct and indirect impacts
- New Criteria: additional benefits

Break out into Shallow, Intermediate, and Deep groups

Shallow Group Discussion

- Definition -10ft to 0ft for shallow draft
- Elevations: from -10ft to 17ft
- Navigation:
    - Are we allowing navigation through our gates?
    - Not in the shallow region.
- For the current alignment look at recreational traffic.
- We are not designing for navigation for these gates
- Possibly don't allow navigation through most of it and allow them to cross only in certain locations

- Will we have to make provisions for some form of recreation traffic?
- No, as long as we coordinate it through the intermediate group.

Specifications:

- 1000ft in length. 10ft deep
- Probably a series of gates
- Beaumont Clay

Break out of teams-

Team 1:

- Charles Schelpe
- Tycho Busnach
- Carla Kartman
- Len Waterworth
- Deidra Dittmar

Team 2:

- Badre Enam
- Alexis Bragg
- Victor Gonzalez
- Michael Vanderzanden
- Mike Diaz
- Nola Canann

Team 3:

- Travis Creel
- Gerard Gillen
- Chris Sallese

- Jen Morgan
- Kelly Burks-Copes

- Would like to get three design ideas
- Focus on gate structures themselves not the land tie ins

Team 2 notes

- If we dredge will the section be considered intermediate instead

- Vertical lift gate:
    - Total of 150ft per gate
    - 75ft wide base
    - 20 gates
    - 33% blockage
    - We can have a roadway on top for
    - With thicker piers
    - Piers can be constructed on land and then brought into the location
    - Huge concrete foundation with a tower and needs to hold machinery
- Wicket gate (manual or automated):
    - Normally angled back
    - Proven (older technology)
    - Would be down for a long period of time. Silting would be a concern.
    - Cranes can bring in a panel to a slotted area in the piers
    - Since its shallow enough you could set barges on top of it
    - How to address scour?
    - Scour protection can be placed around
    - Need for concrete piers somewhere between 50-70ft
    - Foundation: 8ft diameter high pile with concrete foundation for the hinge itself. Maybe 60-70ft deep into the bed

- Flat panel gate
    - Maybe 27ft panels like a large stop logs as a flood gate
    - Make it in segments that are interlocking
    - Not all have to be 27ft in height
    - Similar foundation to the wicket.
    - 30 panels, 100ft long each
    - 3 crews. 10 panels per crew. With 10 hours to close the gate per crew.
    - Time: how long will it take to drop into place from the crane
    - This would need to be installed early. If the hurricane is too close and the wind speed it strong enough this is not viable
    - One in New Orleans
- Tainter gate

    - Wench system to pull gate up
    - Hydraulics also for redundancy
    - Reverse head- this gate type is not good for the reverse head condition
    - Can open gate if you notice reverse head condition forming
    - Platforms for maintenance
    - No navigations
    - Bottom seal- concrete bottom
    - Foundation- will need concrete slab with piles below
    - Doesn’t have to be that tall
    - A lot of concrete
    - 120ft span with 20ft piers
- Barge gates
    - Float it in
    - Make the bottom wider

Environmental: Flat panel and barge

O&M: vertical lift gate, tainter gate, and mechanical wicket gate

Group Discussion

- Vertical lift gate
    - Variety of lengths and combinations
    - Can create a favorable ratio of pier to gate width
- Floating
- Rail
- Texas Armadillo
- Rolling Tainer
- Bladder
- Barge Gates
- Stop Logs/ Pins
- Piston Gates
- Pre Cast Drop Ins
- Pivot Gate
- Wicket Gate
- Do Nothing
- Take out portion of seawall and make disposal area a bypass
- Inflatable dam
- Rising sector gate
- Rams bowl

What are we looking for in these gates?

- Sill:
  - minimum influence on the bed profile
  - hard sill (limited footprint)
  -
- Navigation:
  - Ideally would allow small navigation
  - Can limit the disturbance by creating certain paths that must be taken for navigation
- Scour protection:
  - Velocities that are environmentally friendly
- Footprint
  - Minimize
- Flow velocity
  - Less piers and less of a footprint
  - Not dealing with reverse head

<u>Criteria Review</u>

Time (10%)

- Close them 96 hours in advance
- When you close the environmental gates, how does that effect the velocities in the other areas
- This needs to be done in time for redundancy measures

Blockage (20%)

- Since we're closing off a small cross sectional area, is this that important?
- This is a critical area for critters
- How much that can be blocked off here also depends on the intermediate and deep water design
- From a hydrodynamic perspective it doesn't really matter
- 27% or less of the cross sectional area of the overall system can be covered

Alignment (0%)

- Doesn't affect us that much in shallow region

Construction Cost (15%)

O&M cost (20%)

Reliability and Redundancy

- If it's not reliable then it's not an option

Adaptability (5%)

- We're not being adaptable to navigation
- Adaptable for future sea level rise

- Small stretch

Constructability (5%)

Technology (5%)

- Proven or more innovative
- Innovation doesn't really determine gate selection

Impact (20%)

- Environmental impacts outside of blockage
- Direct and indirect impact
- Innovation in indirect impacts

Additional benefits (0%)

- The shallow is probably the best place for these additional benefits

Item	Weighted Percentage
Blockage	15
Time	15
Alignment	0
Cost	15
O&M	20
Reliability	No go/go
Adaptability	5
Constructability	5
Technology	5
Impact	20
Additional benefits	0
Total	100

Types of gates:

Vertical Gates

- Vertical lift gates
    - Cons: larger concrete foundation
- Tainer gate
    - Cons: not designed for reverse head
- Tames barrier
    - Cons: the depth, price, siltation

Bottom mounted

- Flap gate
- Crest gate
- Ladder gates
- Piston gates

Simple

- Pivot
- Wicket gate
    - Cons: hard to deploy, siltation, reverse head
- Stop logs
- Flat panel drop in gate
- Pre cast sluice gate
- Floating fixed barge gates
-

Innovative

- Self-propel
- Railroad
- TX armadillo

Intermediate Group Discussion

Intermediate gate -20- -40

Vertical lift gate with recreation vehicles able to pass

- Length, longest segment
- Maximize hydraulic cross-section and be able to allow small and medium vessels
- Barge gates are very labor intensive
- List of requirements
    - Recreational gate fishing, sailboat
    - Barges (fueling) must pass 125 ft width
    - 3000 ft length
    - 20 ft – 40 ft
    - Top of gate: 17 ft (may adjust)
- At least one gate must be 38 m
- Preference to not have a gate on Galveston side
- Don't really want fishermen to "play chicken" with larger vessels
- Intermediate Gate on Galveston 800'
- Discussion of Thames Design consideration (Raising Sector) 14% blockage
    - Possible solution
    - Could be expanded
    - Float in piles were unpopular in New Orleans? (6-12m)
    - 40 ml steel
    - Proven success in the Thames system
    - 7 m tidal distance
    - Usual 8.4 m head and 6.1 m in other direction
    - Low ecological impact from flow
    - 70m with 13 gates would cover the whole distance?
    - Would have to be modified for hurricane conditions
- Seepage cutoffs?
- Vertical lift gate 1
    - 100 ft gate width
    - 50' gate height
    - 300 ft width is possible?
    - 20 m tower 20' wide 20%
    - Could block visibility unless the gate is risen even higher
    - Possible migratory bird impacts and temporary marine life impacts (dolphins)
    - Structure is above the water
    - Longer will decrease blockage but create more stresses on the gate and tower
    - Need another larger gate for sailing boat
    - Reliability and proven O&M "gravity works"
- Vertical Gate Proposal 2
    - 100 m long gate
    - Curved gate

- 15m island width > 13%
  - Need different gate for recreation craft
  - Reliability ok – "Gravity works"
  - Road?
- Barge Gates
  - Tug puts in cable to winch it closed, on a hinge, pinned down to resist reverse head
  - Hydraulic resistance
  - O&M is difficult, closing and opening is complex and cannot automate
  - Risky reliability
- High dollar guesses can help sell it as it is optimized
- Venice Gate design
  - Air or hydraulic
  - Suitable for very calm water
  - Connection between flap gates could be the structural weak point
  - Gates could be replaced easily
  - Siltation will become a major concern would need a way to remove silt effectively
  - Would have to be designed for turbulent stormy conditions
  - Would require hydraulic investigation, untested reliability
  - 0% blockage
  - Positive to navigation
  - Can be designed to cope for wind loads
- Sector Gate/ Hinged Mitre Gates
  - New Orleans included with other designs for Recreational and Navigational ships
  - Proven Design
  - Reverse Head resilience limited
  - Use blockages from other island
  -
- Student
  - Train placed from land slid onto sill in 10 ft water
  - The train is rolled into place
  - Sill is held in with H beams
  - Seepage between the cars
  - Wheels in the sill itself to help
  - 10 ft width current design but could
  - Very heavy
  - Not proven or tested
  - Siltation
  - Moments and overturning
  - If one element fails the whole thing may fail
  - Maintenance on land is preferable
  - Maintenance in the sill is problematic but designs have been discussed to mitigate siltation and debris
- Fulium Radial Gate / Tainter Gate
  - For shallow water

  - Blockage Percentage - ???
  - Rotates up to the open position
  - Similar to Thames
  - Reliability- good
  - Enviornmentaly same as vertical lift
  - Lower wind loading
  - Not navigable?
- Piston
  - No blockage
  - 300' long
  - Piston fits into a 50' sleave in the seabed
  - Filled with water in the cavity or bladder to help with the seal at the lip
  - The wall itself is filled with air
  - Not good for shallow water
  - Maintenance Unknowns
  - Channel is deep
  - Equipment location
  - Not proven – Needs a prototype
  - Vulnerable until fully deployed
  - Reliability
  - Possible use of hydraulics instead of inflated bladder
- Barge Gate is not recommended
- Venice Gate is theoretically possible
- Vertical Lift Gate – N, R, 13, A, C
- Tainter Gate – R, 13, A, C
- Rising Sector (Thames) – N, R, 14, A, C
- Piston – N, 0, ?
- Venice Flap Gate – N, ?, 0, ?, C
- Rail Gate – N,
- Barge Gate --
- Mitre Gate – N, R

Deep Group Discussion

1. Floating sector gate
2. Rising sector gate
3. Roller gate – knocked out because of reliability
    a. Rolls out from dry storage
    b. Would need roller gates twice the size as any in use now
    c. Scale jump too large to be a viable choice
4. Vertical drop gate – knocked out because of reliability and constructability
    a. Recessed into seafloor
    b. Gate would need to be at least 85 feet, so the chamber would need to be very deep
    c. Sediment will be deep into the chamber and hard to remove
5. Flap gate
6. Piston gate
    a. If the piston gate is obstructed by growth / bottom debris, what do you do if it won't open before a storm?
    b. Very difficult to access pistons

Day 2
March 19th, 2019

Intermediate Solutions

Vertical lift gate

- Spans of 100m with 15m piers with 9 gates
- Lift to 15m
- "recreational gate"
- Pros:
  - Reliable
  - Maintenance
  - Reverse head
  - 13% blockage
- Cons:
  - Impacts on Navigation due to reduced visibility
  - Additional benefits: can have a road

Vertical lift gate (In study)

- Pros:
  - 15% blockage
- Cons:
  - A lot of steel
  - Solid structure loss of visibility
  - Environmental concerns for marine life
  - Adaptability: sill is clearly set on the bottom
  - Non navigable (Tainter Gate)
  - Staggered placement with structure in between to stop leakage. To Minimize blockage.
  - Originally a big block of concrete
- Optimization study would need to be conducted to find appropriate length of the gates
- Or perhaps an innovation in material technology
- Vertical Lift Gate would need to be 75 ft to accommodate sailboats?
- Normalize the depth or profile the structure

Rising Sector Gate

- 13 gates
- 20m depth of the gate
- 61m in span size up to 70m span
- Pros:
  - Proven reliability
  - 15% blockage
  - Up to 8.4m differential head
  - Up to 6m reverse head
  - Adaptability: over rotating can increase the height
- Cons:

Tainter Gate

- Pros:
  - Reliability- good
  - Visibility is okay
- Cons:
  - Environment- shade same as vertical lift
  - Less wind loading
  - Doesn't allow for navigation

Flap gate (Venice gate)

- With this work with the tide here?
- Wind?
- Maximum differential head 15ft
- Each gate flaps individually
- Pros:
  - No blockage
  - O&M is okay
  - Won't interfere with navigation
- Cons:
  - Concern of debris
  - Silt will be an issue
  - Part is proven but not the whole
- Negative head isn't an issue
- Access tunnel for O&M

Hinged Sector Gate

- Pros:
  - Proven design
  - Good reliability
  - Common
  - Can be used in combination with another gate type
  - Navigation gate
- Cons:
  - Needs land

Gates that will not work

- Barge gates
  - Cannot navigate
- Rail gate
  - Land based gate

  - Not proven (risky)
  - Siltation problems
  - Moments around it would be very high
  - Risk of failure
- Piston
  - Construction
  - Where is equipment?
  - 0% blockage
  - Concerns for moment and forces
  - Reliability unproven

Chosen option by group: Combination of rising sector and vertical lift gates

Discussion:

- Main priority was to limit blockage
- Q: Is wind force a factor?
- A: the truss is curved to take the loading. But the loading should be checked.
- Vertical lift gate- depending on the bearings on the side, it may not be able to operate due to the differential head
- Q: How do we perform major maintenance?
- A: Vertical lifting will allow for roads and we can have roads from A to B.
- The rising sector gate has that built in adaptability for 3ft rise. The vertical lift gate can be added onto for adaptability.
- Q: Cost in O&M?
- A: The rising sector gate would be more expensive because it is more complex. Parts are in the water. Vertical gate is out of the water all of the time and has a cheaper O&M, where equipment can be stored above water.
- Q: closing time?
- A: closing time in theory can be done with those structures at any time in the tide. This gives it flexibility. Vertical rising 12 minutes, rising sector about 30 minutes. Vertical lift can always drop by gravity if anything happens.
- Q: redundant?
- A: rising sector can be operated on either side or even both with two tunnels.

Deep Draft Solutions

Constraints

- Large ships (navigation must be maintained)
- Size of gate
- Blockage dependent on blockage of the other sections

- One island onshore – Needs to divert shipping channel

Reducing closure

- Channel closure was the biggest impact of the deep draft
- Mitigation options:
    - One island onshore
        - Needs diverted shipping channel
        - Possibly a leisure craft canal landward of dry-dock
    - Barrier located at wider channel- modelling needed to confirm benefit
    - Split navigation channel in two or three- overlapping islands
    - Barrier design with no islands- or smaller piers
    - Extend deep draft into the intermediate
    - Deeper channel- includes ship increase adaptability
    - New chipping canal through peninsula

Floating sector gate

- Pros
    - Time to open is under 2hrs
    - Alignment- can be very wide
    - Reliability-proven
    - Proven technology at the scale needed
    - O&M in dry- easy to access and low deterioration
    - Construction- up to design
- Cons
    - Reduced CSA
    - There needs mitigation or other parts of structure to be very low constriction
    - Largest footprint

Rising sector gate

- Pros
    - Blockage ration is low (15%)
    - Time to open is under one hour
    - Can work with any alignment
    - Reliability is proven
    - Impact
    - O&M cost- has to be taken out of water
- Cons
    - Main negative is that it has ne been tried at this scale (about three times the size of Thames Barrier)
    - Not available as one signal opening (although group consensus was two or three is better anyway)
    - Has to be removed from water to maintain

- Cost approx. 1.5 times the Thames
- Q: The foundation needed is more or less than the floating sector?
- A: These have a small island to transfer the loads, so the pile cap will need to be a bit bigger. Might the same amount or more.

Float Mechanical Flap gate

- Venice type
- Pros
  - Blockage can be 0%
  - Time to open is quick
  - Can work with any alignment
- Cons
  - Inspections and maintenance
  - Whole structure is under water

Rising Piston gate

- Pros
  - Blockage can be zero
  - Time to open
  - Any alignment
- Cons
  - Inspection and maintenance
  - Unproved tech
  - Very deep construction
  - Potentially hidden components

Vertical drop gate

- Pros
  - Low blockage ratio (15%)
  - Time to open
  - Any alignment
- Cons
  - Inspection and main,
  - Most of the structure is under water
  - Very deep construction
  - Potential hidden components

Q: did you talk about the cost?

A: not really because of the unproven technology

Key comparisons

- Comparison depends on which criteria is the most important
- Cross sectional area
    - Best: Flap gate and Piston
    - Mid: Rising sector and vertical lift
    - Worst: floating sector
- Proven Technology
    - Best: floating sector- proven at the scale we need it
    - Mid: rising sector and flap- proven but not at this scale
    - Worst: piston and vertical drop
- Navigation Channel width
    - Best: Flap and Piston
    - Mid: Floating Sector
    - Worst: Rising sector and vertical drop
- Deterioration, inspection, and maintenance
    - Best: floating sector
    - Mid: rising sector and vertical drop
    - Worst: flap and piston

Discussion

- Q: Silt and dredging?
- A: We did not discuss the pros and cons of dredging for those options.
- For siltation each gate would have different options on how to combat that. It's more of a design issue rather than a show stopper for the gate selection.
- The rising sector gate can take an amount of silt and actually cut its way through it.

Shallow Draft Solutions

- +3 to -10 elevation
- 17ft surge

Weighting for criteria

			Design																	
			Shallow Draft																	
	Criteria	Weight %	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
a	Blockage Ratio	15																		
b	Time to open and close	15																		
c	Alignment	0																		
d	Cost	15																		
e	Operation and Maintenance Cost	20																		
f	Reliability	go/no go																		
g	Adaptability	5																		
h	Constructability	5																		
i	Technology	5																		
j	Impact	20																		
k	Addn benefits	0																		
		100																		

Gate Styles Discussed

(Red- eliminated as an option)

Vertical

1. Vertical lift gates – proven technology, however large superstructure and associated blockage
2. Tainter gate – eliminate due to reverse head
3. Thames Barrier style – very expensive and large blockage and siltation

Bottom mounted

4. Flap gates (Mose) – uses buoyancy
5. Crest gate (using top mounted hydraulics) – simple, no superstructure, however entirely submerged as associated siltation issues
6. Bladder (inflatable) gate – proven technology, however large footprint and maintenance issues
7. Piston gate – not enough depth for buoyancy to work
8. Vertical rising gate – proven technology, however entirely underwater, sedimentation

Simple gate

9. Pivot gate – difficult to secure and potentially unreliable
10. Wicket gate – siltation, reverse head and weather effecting deployment, concerns with coastal environment
11. Stop logs – misalignment, weather effecting deployment and concerns with coastal environment
12. Flat panel drop-in gate (guillotine) – reliability concerns adverse coastal environmental conditions
13. Pre-Cast sluice (box culvert) – view shed issues and environmental considerations
14. Floating fixed barge gate – maintenance issues and siltation will be a problem.
15. Swinging Barge gate – simple, however deployment issues in weather

Innovative

16. Railroad – deployment issues in weather and no redundancy
17. Texas armadillo - deployment issues in weather and no redundancy
18. Curtain (membrane) gate

Vertical lift gate

Pros	Cons
Additional benefits: roadway on top	Blockage
Proven technology	Larger concrete foundation
Able to manage reverse flows	Initial cost for construction
Operated automatically	Support columns
Maintenance	Hazardous for small boat
O&M lower	Small boat impact
Bubbler removes silts	Limit to vertical height/clearance
Quick deployment/lower operation time	Build a sill
Can withstand negative head	Lowering mechanism
	Cost of steel

Crest gate

Pros	Cons
Simple	Reverse head
No superstructure	Entirely submerged
Can be operated automatically	Siltation
No view shed issues	O&M

Bladder gate (inflatable)

Pros	Cons
Proven technology	Large footprint
Cheap materials (build)	Adaptability
Reverse head	Deflate time
Blockage (minimal)	O&M cost
Can be overtopped	Limited crest height
Bio-fouling not an issue	

- Blockage approx. 5%
- Can handle head, however the footprint increases with the height
- Proven with the 3m

Vertical Rising (like St. Petersburg)

Pros	Cons

Proven technology	Entirely underwater
Minimal reduction to cross section	Sedimentation
Won't disrupt navigation	Cost (initial)
Blockage	
Can be overtopped	
Reverse head	

Precast Sluice (box culverts)

Pros	Cons
Great for roadway	View shed issues
Cheap	Environmental considerations (marine life trying to pass)
Easy to construct	More elements
Easy to operate	
Low maintenance	

- Hydraulic jump can cause heavy flows. Scour protection would be required.
- Environmentally- this is not sound the concern for marine life is too great
- Might be an option to come into the island with shallow water
- This ties into the ground
- This has a larger aerial footprint, but it's very similar to any bridge
- The size of the boxes can be adjusted and easy to order in a variety of dimensions
- Siltation could be a consideration for maintenance

Swinging barge gate

- Pros
- Cons
    - Deploying them in bad weather
- When can the gates be deployed? We can potentially close these gate 48 hours before. In terms of reliability and use of the barge gate, it's all man power.

Railroad

Pros	Cons
Simple	Deployment issues in weather
Minimum blockage	Limited use
Reverse head	O&M concerns with the sill

- A series of large casions
- Little redundancy
-

Texas Armadillo

Pros	Cons

Stored mostly out of water	“Crazy Awesome”
Minimal constriction?	Less vertical problems than VLG
View shed	Untried/new tech
O&M	Navigation impacts
	How to operate

- A giant net that would be very rigid and close
- Like half an Armadillo shell
- Concave gate
- Rigidly pinned on either side

Discussion

- For shallow system, possibly we close it down completely
- A: that’s a no go for environmental concerns
- Q: which system best maintains the natural environment
- A: the Box culvert design
- Q: how would you prevent the biofouling form the oysters on the box culvert?
- A: we wouldn’t. it would be a maintenance piece for cleaning it
- The boxes (sluice culverts) are also used in Louisiana for coastal protection
- Natural grade dictates the gate selection in this region
- Q: did the shallow group consider to arc the alignment of the gate or zig zag it
- A: we didn’t look at that very closely. A lot of the gate types resolved for the need of that.
- Navigation considerations and crashing needs to be better looked into

- Q: Preferred options for each group?
- A: Shallow- Culvert Box (sluice gate)
- A: Deep- Floating Sector
- A: Intermediate- Combination of rising sector and vertical lift gates

Afternoon Session

Shallow:

- Sluice Gate (box culverts) ranked first
- Vertical Lift gate ranked second
- Begin with box culverts in shallow, then transition into the vertical lift gate for the deeper part of the shallow possibly. Or even make larger box culverts.
- The length is the item that will have the most environmental/ecological damage

Intermediate:

- Vertical lift gate, rising sector, and tainter gate are all viable options
- Eliminate tainter gate due to tie ins to shallow and deep

Deep:

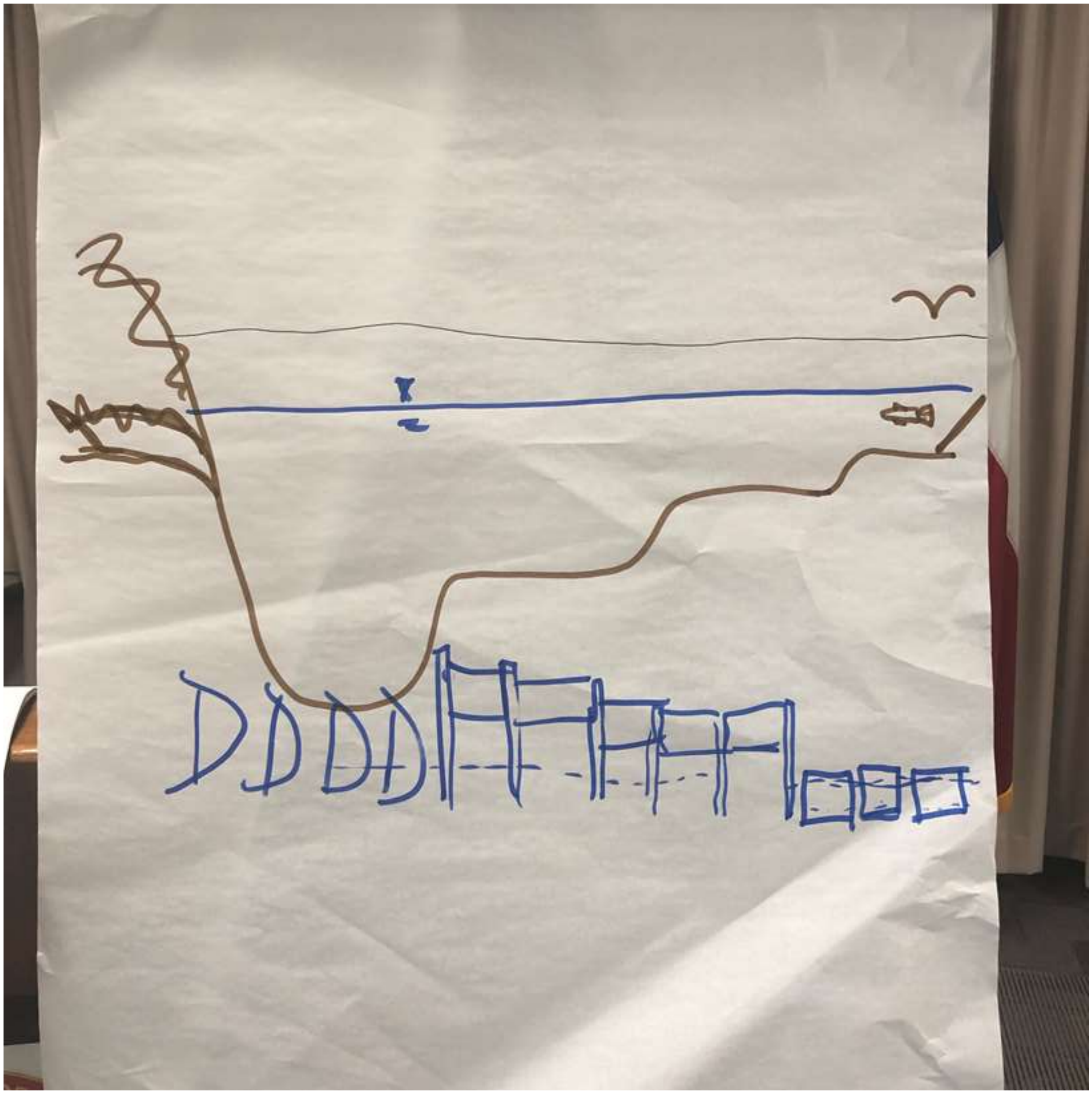
- Rising sector gate and Deep sector gate are ranked the best

Discussion

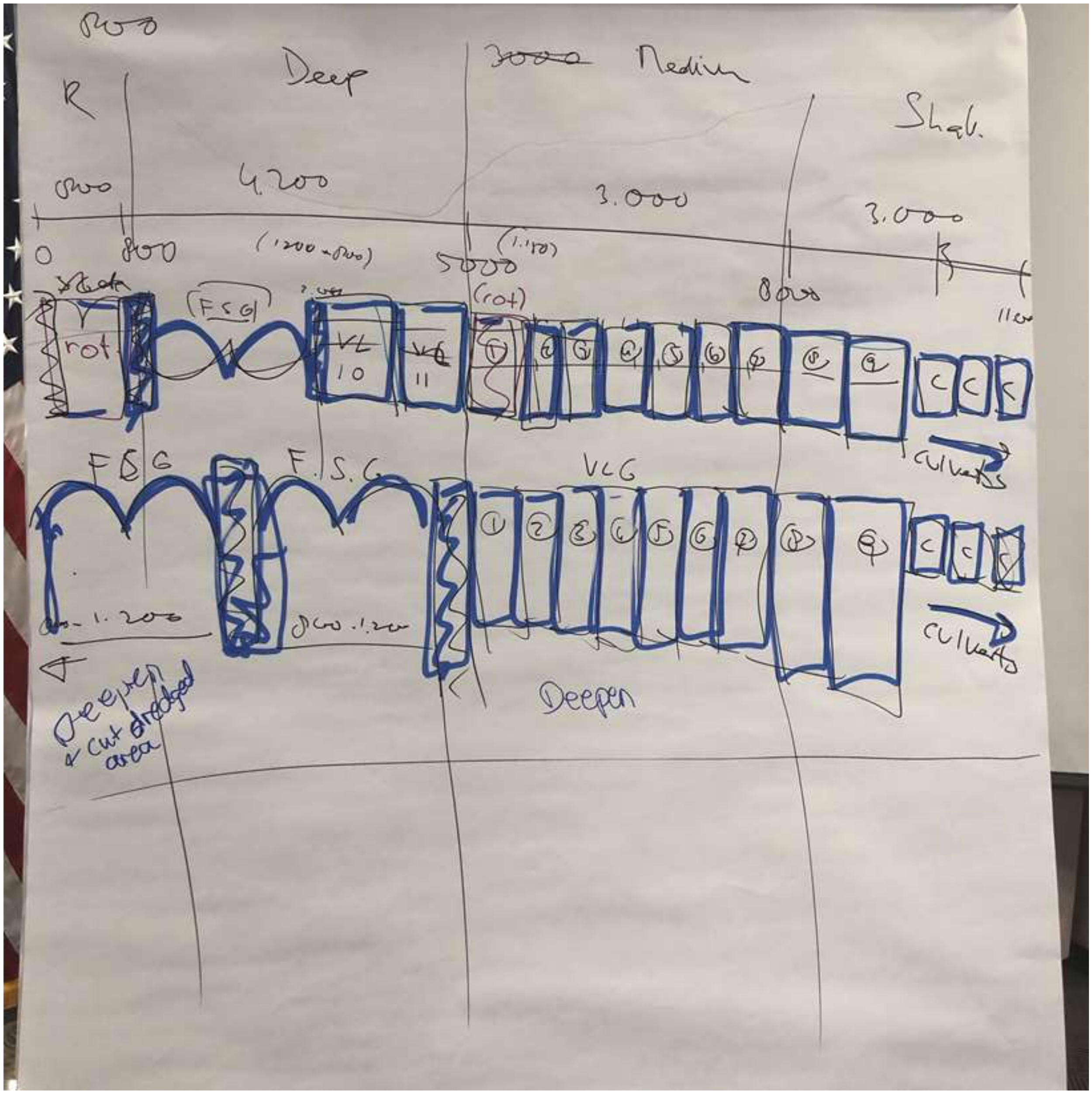
- Try to limit the amount of gate types
- Are we looking for a few larger gates? Or more smaller gates?
- Q: Additional benefits what are those?
- A: I only really considered roadways as a benefit.
- Q: Should we eliminate any criteria?
- A: No. We should keep all of the criteria.
- Q: How do we take the next step in choosing among the remaining?
- A: Start putting alternatives together and make various combinations.
- Should add boundaries as to how many combinations we look at.
- We need to visualize it have a diagram that shows the transitions in bathymetry and gates. These gates also need to look pretty.
- The intermediate gates: the Vertical lift gate might not be able to pass the recreational vessels
- Maybe 4 passages through the deep draft
- Concern about a less reliable barrier because the main focus is selling the blockage percentage to the public. All parameters need to continually be considered not just the one.

Design Configurations

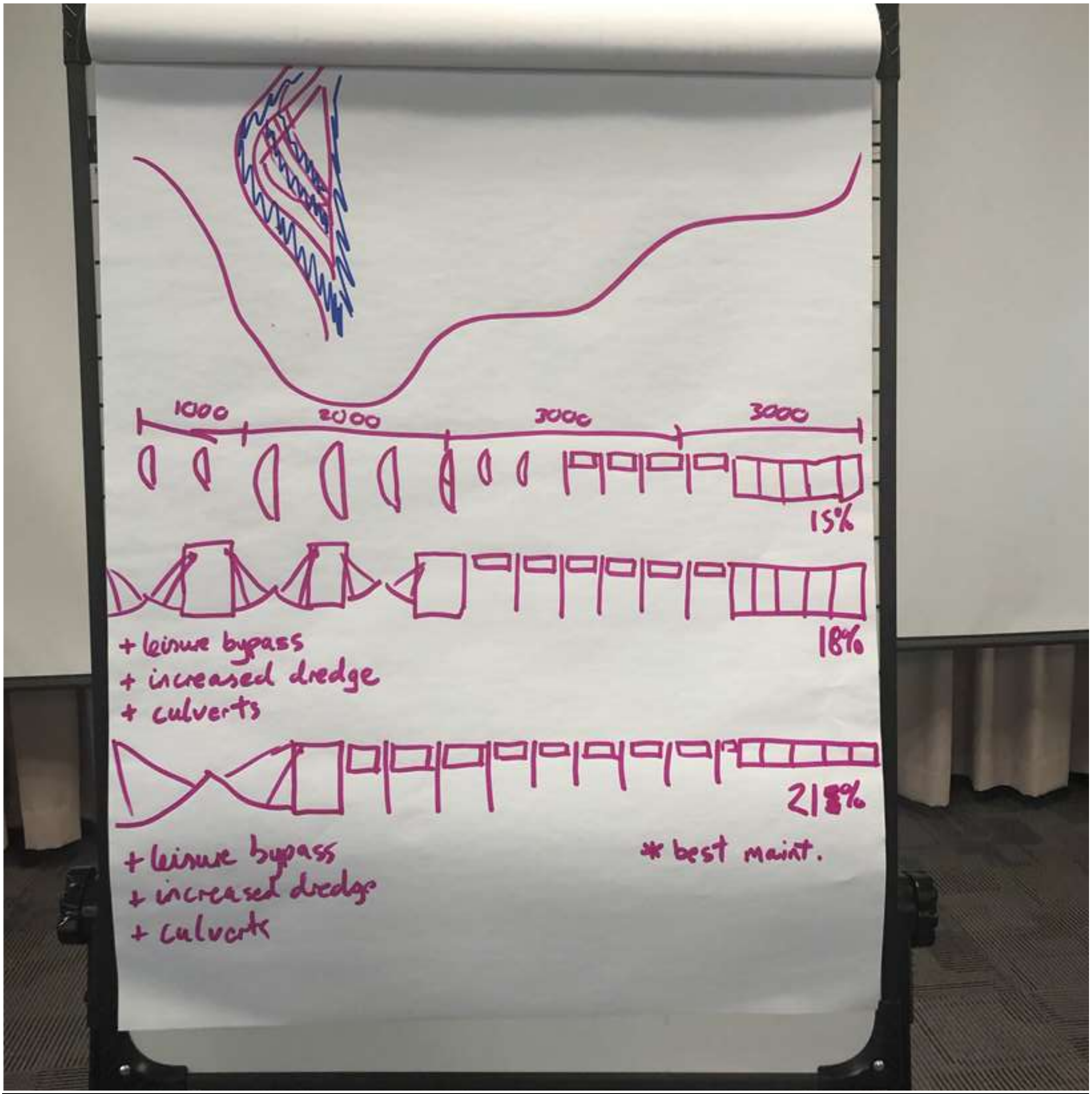
Shallow Group Configuration:



Intermediate Group Configuration:



Deep Group Configuration:

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