Building-with-Nature Solutions for Hurricane Flood Risk Reduction in Galveston Bay - Texas

Conceptual Design Study

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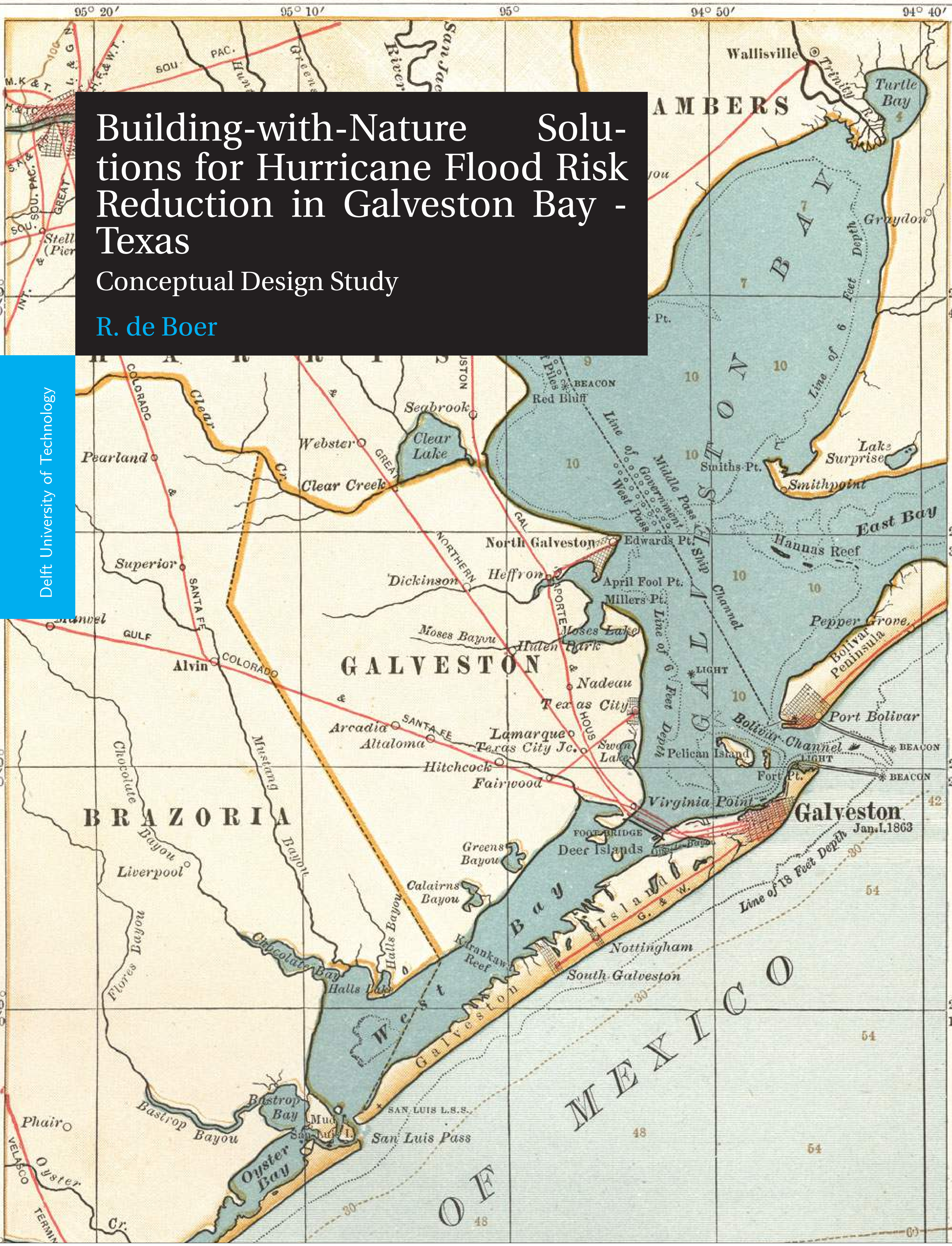

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Building-with-Nature Solutions for Hurricane Flood Risk Reduction in Galveston Bay - Texas

Conceptual Design Study

by

R. de Boer

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Master of Science
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***Cover image**: map of Galveston Bay, Texas, from circa 1900 (Source: 10th edition of Encyclopaedia Britannica)*

Preface

This report is the final MSc thesis as part of my Master's program Hydraulic Engineering, specialization Coastal Engineering, completed at Delft University of Technology. The research has been conducted in cooperation with Royal HaskoningDHV in Rotterdam. This thesis will be defended on September 22, 2015.

The main motivation for this thesis is Hurricane Ike, which struck the Upper Gulf Coast hard in September 2008. It showed that the Galveston Bay area is highly vulnerable to flooding. Since then several plans for flood risk reduction have been made of which the Ike Dike is an example. With this thesis I would like to tribute to the overarching goal of a safer and more sustainable Galveston Bay by focusing on opportunities for nature-based solutions for flood risk reduction.

I would like to thank the members of my graduation committee and in particular my daily supervisor Mathijs van Ledden. Their feedback, guidance and support throughout the project were indispensable. Furthermore I would like to acknowledge my colleagues at Royal HaskoningDHV, and especially my fellow students at the office with whom I shared pleasant moments of reflection. I would like to thank Leslie Mooyaart for introducing me to this company and the occasional advice about the topic and Sander Post for his help with the hydrodynamic modeling, which proved very helpful. Furthermore I would like to acknowledge the interdisciplinary graduation studio 'Delta Interventions' of the faculty of Architecture, Urbanism and Building Sciences for the cooperation and opportunity provided to perform a very useful excursion to Houston and Galveston Bay. Finally, I would like to thank Bas Jonkman and Mathijs van Ledden for helping me and four fellow students with the realization of a multidisciplinary MSc project in New York City in the second year of my Master. It kick-started the most important phase of my Master's program and proved to be very useful and successful to me and the team in many ways.

R. de Boer
Delft, September 2015

Abstract

The enormous damage caused by hurricane Ike in the year 2008 has been the main incentive for several structural flood risk reduction plans in the Houston-Galveston Bay area. One of them is the 'Ike Dike', a large-scale coastal barrier which closes Galveston Bay to prevent penetration of hurricane surges. A momentum gain for flood risk reduction plans enables opportunities for nature-based or Building-with-Nature (BwN) solutions in the area. However, no structured approach with respect to BwN for flood risk reduction has been followed for Galveston Bay yet. BwN focuses on working with processes of nature, promoting and using habitats and increasing the contribution to ecosystem services and other potential benefits. In order to apply this principle to flood risk reduction, more understanding of the hydrodynamic effect of BwN measures under hurricane forcing is required.

The main topic of this research is to explore the opportunities for BwN solutions for flood risk reduction in the Galveston Bay area. This study focuses on two aspects: flood risk and natural value. Thereby, the goal is to create solutions which add value to both aspects. Concerning flood risk, surge and waves are considered key processes because they contribute greatly to damage during hurricane conditions. In this study a conceptual design is made and evaluated by means of a qualitative evaluation and a quantitative evaluation. The qualitative evaluation involves two toolboxes. The quantitative evaluation involves a 2DH hydrodynamic model.

The Galveston Bay system is a large estuary, which is prone to hurricanes and vulnerable to flooding. Important variables that affect surge and waves inside Galveston Bay are fetch, depth, landfall location and hurricane surge at the open coast. Fetch and depth can be influenced by BwN measures. Galveston Bay is a productive ecological system and its most important habitats are wetlands (e.g. salt marshes) and oyster reefs. However, significant erosion of shorelines and wetlands in Galveston Bay as a result of relative sea level rise and insufficient sediment supply has been observed.

A BwN solution for flood risk reduction in Galveston Bay can consist of several elements or 'building blocks': nourishments, wetlands, oyster reefs and an eco-island. Oyster reefs are considered as three-dimensional structures. Moreover, an eco-island is defined as a large island with ecological development and e.g. recreational functions. These building blocks have been identified because they have the potential to reduce flood risk as well as provide natural benefits to the system.

In order to qualitatively evaluate these building blocks for Galveston Bay, a framework has been developed. This framework involves two toolboxes and the formulation of a global, conceptual BwN design. The toolboxes emphasize on flood risk and natural value of the building blocks. Simplified one-dimensional calculations, where possible, and qualitative literature are used to formulate the toolboxes. The potential effect of a building block is illustrated by a color classification and a description. The effect on flood risk is assessed for surge and waves. The effect on natural value is assessed for five relevant criteria. The framework has been proved to work well for evaluation of building blocks for Galveston Bay.

On the one hand, with respect to surge, the toolbox shows potential for a reduction of several decimeters to a meter in Galveston Bay for emerged nourishments which compartmentalize the Bay by limiting fetch and therefore wind set-up. The eco-island, however, is significantly less effective in surge reduction as water can easily flow around it. Wetlands and oyster reefs are considered not effective for surge reduction in Galveston Bay at all. On the other hand, with respect to waves, wetlands are promising for attenuating waves nearshore. However, wide stretches are required and the quantification of their effect is difficult due to various parameters like vegetation type, stem density and stem stiffness. At the shore, oyster reefs are effective in attenuating waves and reducing erosion as well, although the effect in hurricane conditions requires more investigation.

Concluding, the evaluation of the toolboxes shows that most promising flood risk reduction measures are least beneficial to the natural value in Galveston Bay and vice versa. The most effective design according to this qualitative evaluation method is a continuous emerged island that reduces peak water levels close to the

western and northwestern shore of the Bay. This can be combined with oyster reefs along the western shore until Texas City and wetlands at the foreshore of the Texas City Levee for wave attenuation and erosion reduction.

The qualitative evaluation showed promising solutions for surge reduction. However, quantification has been difficult. Therefore a hydrodynamic 2DH model has been created that incorporates the complex dynamics of a hurricane, two-dimensional flow mechanisms and the bathymetry of the Bay. This model is used to evaluate the system behavior and surge reduction measures for different hurricanes, with or without Ike Dike. Three hurricanes have been applied: a 'regular' Ike as reference hurricane, and two shifted Ike tracks in which landfall occurs to the southwest of Galveston. These two shifted hurricanes cause higher storm surge levels in Galveston Bay due to higher surge levels at the open coast and stronger onshore winds in Galveston Bay. The model has been calibrated with measurements of peak water levels during Ike. Although this model is a coarse resolution model with limited simulation time, its performance is acceptable.

Simulations show that peak surge levels of 3.5 - 7 m are expected in the Bay for different storms in the open Bay situation. However, in the case of a closed Bay (Ike Dike) peak surge levels are limited to 1.5 - 2.5 m. Surge measures are evaluated for three different areas of interest: West, Northwest or Houston Shipping Channel (HSC) and Northeast Bay. Outcomes of the model show that peak surge level can be reduced by emerged islands which are as continuous as possible. For an island to be emerged even in the worst simulated hurricane conditions an elevation of 6 m above mean sea level (MSL) is required. In that case, peak surge level reductions with a minimum of **0.5 m** and a maximum of **1 m** are expected with emerged islands in the West and the Northwest (HSC) for different storm tracks in the open Bay situation. The measures in the case with an Ike Dike are generally less effective in reducing peak surge levels. A final, optimized design for surge reduction is defined as the combination of a continuous island for West and Northwest (HSC), the two most economically valuable areas. This design is presented in Figure 1, along with results for peak water level reduction without Ike Dike.

The conclusion can be drawn that various limitations are found with respect to BwN solutions for flood risk reduction in Galveston Bay. Bwn solutions can significantly improve natural conditions in the Bay. However, they cannot eliminate flood risk in Galveston Bay, because a large emerged structure with a few open passages would reduce peak surge levels at the western and northwestern shore by a maximum of 1.5 m. The presented BwN design is a significant intervention in the system and might have limited benefits for natural value. Furthermore, flood risk reduction of BwN measures highly depends on whether an Ike Dike will be constructed and which storm is considered because the landfall location is highly influential to peak surge levels in the Bay. With respect to waves, oyster reefs and wetlands along the shore are considered to be promising measures as they clearly add value to the natural system, protect the shore and attenuate waves. However, the effect of these measures requires quantification. To reduce flood risk significantly, BwN solutions in Galveston Bay should be constructed alongside of hard flood protection structures.

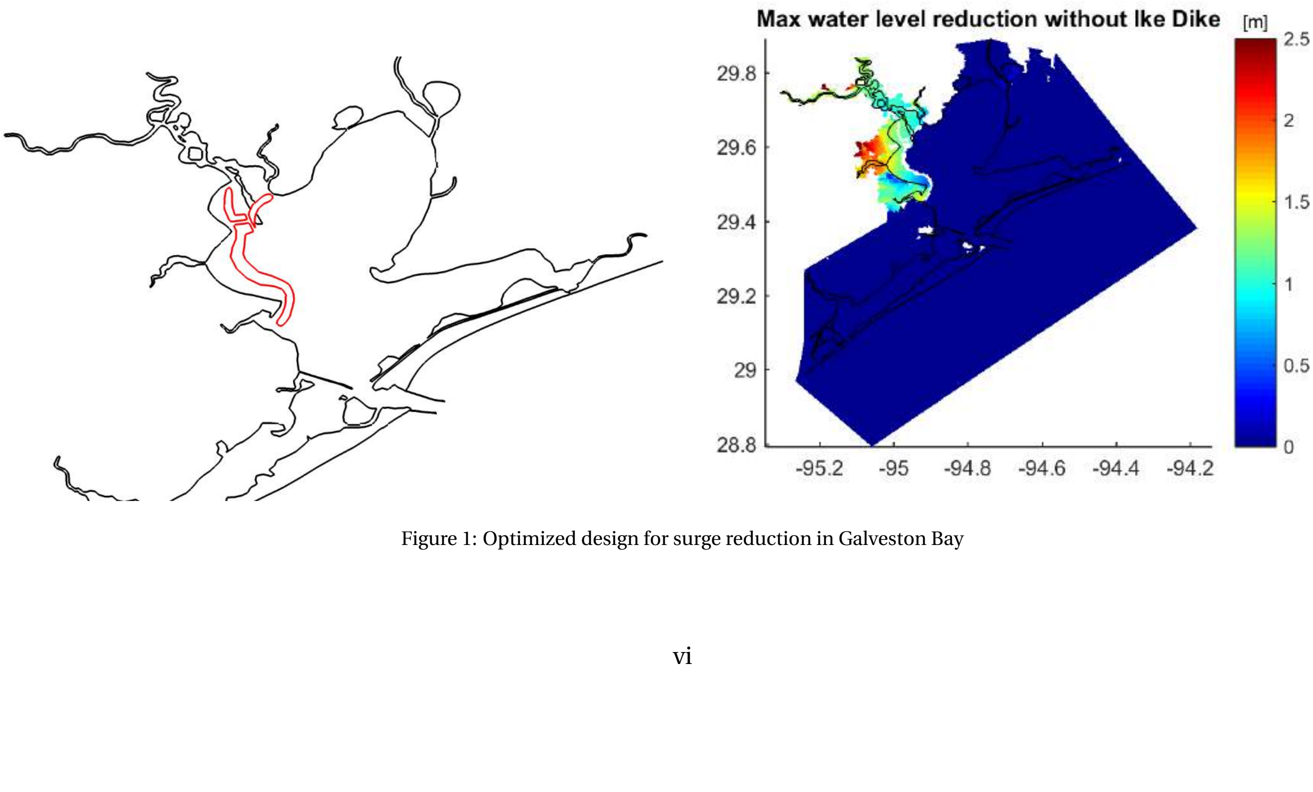

Figure 1: Optimized design for surge reduction in Galveston Bay

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Abbreviations

2DH	Two-dimensional horizontally (refers to hydrodynamic models to describe flow in depth-averaged water)
ADCIRC	ADvanced CIRCulation model
BwN	Building-with-Nature
DEM	Digital Elevation Model
D-Flow FM	D-Flow Flexible Mesh
EPA	United States Environmental Protection Agency
FEMA	Federal Emergency Management Agency
GBEP	Galveston Bay Estuary Program
GBF	Galveston Bay Foundation
GHMA	Greater Houston Metropolitan Area
GHP	Greater Houston Partnership
GIWW	Gulf Intracoastal Waterway
HSC	Houston Shipping Channel
MEOW	Maximum Envelope Of Water
MHW	Mean High Water
MLW	Mean Low Water
MSL	Mean Sea Level
NAVD88	North American Vertical Datum of 1988
NHC	National Hurricane Center
NOAA	National Oceanic and Atmospheric Administration
PAH	Port Authority of Houston
Rmax	Radius to maxium winds in a hurricane
(R)SLR	(Relative) Sea Level Rise
SLOSH	Sea, Lake and Overland Surges from Hurricanes
SSHWS	Saffir-Simpson Hurricane Wind Scale
SSPEED	Severe Storm Prediction, Education, and Evacuation from Disasters
TAMUG	Texas A&M University at Galveston
TPWD	Texas Park and Wildlife Department
TWDB	Texas Water Development Board
USACE	United States Army Corps of Engineers
USGS	United States Geological Survey
Vmax	Maximum sustained surface wind speed in a hurricane.

GLOSSARY

Barrier Islands . . . . Barrier islands are narrow, offshore deposits of sand parallel to the coast. Behind the barrier island a unique and productive estuary with low wave action present. Furthermore, barriers islands play a significant role in surge behavior inside semi-enclosed basins like Galveston Bay.

Building-with-Nature . . Concept of nature-based design which aims at working with processes of nature, use natural habitats and promote ecosystem services. Similar to the concepts of 'Engineering with Nature' (USACE) and 'Working with Nature' of PIANC.

D-Flow Flexible Mesh . . Flexible mesh compatible hydrodynamic software package of Deltares.

Fetch . . . . The length over which any given wind blows freely.

Forerunner Surge . . . . . An early rise in water level at the coast, starting at 24 hours before landfall of a storm. Induced by Ekman set-up from strong alongshore currents, and is most likely to occur in the case of a slow moving storm over a wide and gentle coastal shelf (Hope et al., 2013).

Ike Dike . . . . The Ike Dike is a proposed large-scale coastal barrier for Galveston Bay, Texas. It incorporates the 'coastal spine' principle to close off the Bay from penetrating surges and is based on the Dutch Delta Works.

MSL . . . . Mean Sea Level in and around Galveston Bay is defined as NAVD88 +0.18 m [0.6 feet] (NOAA, 2014)

NAVD88 . . . . The North American Vertical Datum of 1988 is a fixed vertical reference for elevations determined by geodetic leveling, established in 1991 (NOAA, 2014).

Risk . . . . Probability multiplied by the consequence of a certain hazard.

RSLR . . . . Relative Sea Level Rise is defined as the combined effect of land subsidence and sea level rise.

Storm Surge . . . . The rise of water commonly produced by an approaching storm. This effect is mainly driven by wind and atmospheric pressure.

Storm Tide . . . . The combined effect of storm surge and astronomical tides (National Weather Service, 2014).

Surge-Based Flood Risk . Surge-based flood risk is the potential for coastal hazards, such as storm surge and wave attack, to cause negative effects on human health, economy, social, environmental, cultural resources and infrastructure (National Research Council, 2014).

Wind Set-Up . . . . A difference in water level due to wind stresses. Water level tends to increase towards the downwind shore. Highest wind set-up occurs in shallow water.

1
INTRODUCTION

1.1. GALVESTON BAY

Galveston Bay is a large estuary located along the upper Texas coast of the Gulf of Mexico in the United States of America (Figure 1.1). Galveston Bay is the 7th largest estuary in the U.S., and it is located in the Greater Houston Metropolitan Area (henceforth GHMA) in which Houston, Pasadena, Texas City and Galveston are prominent cities.

Figure 1.1: Overview of the Galveston Bay region, Hurricane Ike's path and location of the proposed Ike Dike (Merrell, 2014)

The GHMA is a highly industrialized area with a large population. GHMA is one of the fastest growing metropolitan areas in the U.S. The positioning and viability of Houston can be linked to its proximity to Galveston Bay. Galveston Bay is an crucial driver for the economy of the GHMA. Valuable assets are the port of Houston, which is the second largest port of the U.S. (Port Authority of Houston, 2014), the petrochemical industry with several large oil refineries (Smith, 2013) and commercial (oyster) fisheries. Schiller (2011) states that around 900.000 people in the GHMA live between mean sea level (MSL) and the 2-meter elevation contour, and this number will likely increase (U.S. Census Bureau, 2012).

The Gulf of Mexico is frequently exposed to hurricanes and storm surge in the Atlantic hurricane season. The wide and gentle continental shelf with a slope of about 1:2000, see e.g. Jonkman et al. (2013) and Stoeten (2013), allows large storm surge at the coast. According to SurgeDAT the Upper Texas Coast is among the most surge prone areas (Needham & Keim, 2012). On average every 26 years a major hurricane (Category 3 or higher) makes landfall near Galveston Bay (Keim et al., 2007). The shore of Galveston Bay is not very well protected from surge attack, because only Texas City and the city of Galveston have an existing levee or seawall present (Blackburn, Bedient, & Dunbar, 2014). The combination of high economic activity, urbanized space, geography, absence of flood protection and climate make the area around Galveston Bay highly vulnerable to flooding. Economic losses due to hurricanes and coastal storms have increased over the past century, mostly due to the expanding population and development in most vulnerable areas, according to National Research Council (2014). Climate change poses an additional threat to Galveston Bay (National Research Council, 2014).

The fact that Galveston Bay is vulnerable for storm surge became clear when Hurricane Ike made landfall over Galveston on September 13, 2008 as a Category 2 hurricane. Besides the fact that Ike caused over 100 casualties in total (Berg, 2009), it was one of the costliest hurricanes in U.S. history. Damages caused by Ike in coastal and inland areas of the U.S. - mostly by storm surge - are estimated between $24.9 billion (Berg, 2009) and $29.4 billion (Perry, Eckels, & Newby, 2008).

1.2. BUILDING-WITH-NATURE OPPORTUNITIES FOR GALVESTON BAY

In the wake of Hurricane Ike several plans were developed to reduce hurricane flood risk[1] in the Galveston Bay area. In these plans a certain distinction can be made between proposed large-scale integral projects and (a system of) local measures. Examples of large-scale projects are the Ike Dike (Merrell, 2014; Merrell, Reynolds, Cardenas, Gunn, & Hufton, 2011) (Figure 1.1) and the Centennial Gate (Blackburn et al., 2014; Blackburn & Bedient, 2010). Furthermore, several small-scale measures were suggested by SSPEED (2015).

According to experts there is a growing demand for flood risk reduction in Galveston Bay (National Research Council, 2014). The American practice hints towards mitigating and recovering from storm surge instead of preventing storm surge (Bijker, 2007; National Research Council, 2014). More incentives are needed to improve pre-disaster risk management planning by means of giving attention to land use strategies with respect to flood risk (National Research Council, 2014). Recent developments around Galveston Bay indicate that large-scale protection projects like the Ike Dike are gaining momentum and federal support (Boyd, 2014; National Research Council, 2014).

Although adjacent to one of the most urbanized and industrialized areas in the nation, Galveston Bay itself is a complex and highly valuable ecosystem. It supports a wide variety of marine life (e.g. fish, shrimps, oysters and crabs) and habitats, because of its mixture of salt and fresh water. However, the system is under pressure due to human interference over the last centuries (Galveston Bay Estuary Program, 2014). It experiences problems with significant erosion and degradation of shores, wetlands & oyster reefs and problematic water quality.

There is an interest for nature-based flood risk reduction in the United States. For example an executive order of the Obama administration states that "an agency shall use natural systems, ecosystem processes, and nature-based approaches when developing alternatives for consideration, where possible" (Obama, 2015). A sustainable flood risk strategy has mainly attracted increasing interest due to multiple benefits it provides (Arkema et al., 2013; National Research Council, 2014). In general, "restoration of ecosystem features provide substantial ecological benefits and some level of risk reduction", according to National Research Council (2014). The fact that many issues are facing Galveston Bay and that flood protection in the area is increasingly desirable provides an opportunity for nature-based or 'Building-with-Nature' (BwN) principles.

[1] Surge-based flood risk is the potential for coastal hazards, storm surge and wave attack, to cause negative effects on human health, economy, social, environmental, cultural resources and infrastructure. It is defined as probability x consequence (National Research Council, 2014)

1.3. PROBLEM

Galveston Bay is at high risk with respect to coastal flooding due to hurricanes. Large-scale protection projects, such as Ike Dike and Centennial Gate are gaining momentum for federal support. Although several plans have been proposed, the **blind spot** in the plans is the exploration of the large-scale applicability of nature-based measures for hurricane flood risk reduction inside Galveston Bay. According to the National Research Council (2014), "the risk reduction of ecosystem features remains poorly quantified".

The current problem is that no structured, Bay-wide approach towards the design of nature-based measures for Galveston Bay has been followed yet. Therefore it is to date not known if nature-based measures are qualitatively, let alone quantitatively proven effective for flood risk under hurricane forcing in Galveston Bay. If such measures could improve the natural system and could provide flood risk reduction it would be a valuable combination.

1.4. OBJECTIVE AND RESEARCH QUESTION

The objective of this research is to design and evaluate nature-based measures that strive for improvement of the (ecology of the) natural system in day-to-day conditions and (ii) contribute to surge-based flood risk reduction in hurricane conditions for the Houston Galveston Bay area

The main research question of this thesis is:

What are the opportunities and limitations of 'Building-with-Nature' type solutions to reduce hurricane surge-based flood risk in the Houston Galveston Bay region?

Sub research questions are:

- What BwN measures might be applicable for the Galveston Bay area?
- How can several BwN building blocks be analytically assessed in a structured way on effectiveness against flood risk reduction (surge and waves) and natural value?
- Is it possible to create an effective 2DH model with limited simulation time that simulates the hydrodynamic behavior of Galveston Bay under hurricane forcing correctly?
- How does the system behave under hurricane forcing along different tracks and what consequences can be observed for different areas in the Bay?
- What design is considered to be effective for flood risk reduction?
- How effective are different design alternatives with and without Ike Dike?

1.5. METHODOLOGY

This thesis is a conceptual design study to investigate opportunities for BwN solutions for flood risk reduction in the Galveston Bay area, thereby focusing on flood risk and natural value. Therefore insight is to be gained into the natural system, the hydrodynamic behavior under hurricane forcing and different nature-based measures. However, the design is considered to be conceptual and is based upon concepts and functioning. No detailed designs and e.g. cost estimations are made. To assess whether or not nature-based measures are interesting, several steps are followed.

First step is a thorough analysis of the system and the nature of Galveston Bay. It is crucial to understand the hydraulics of Galveston Bay in daily and hurricane conditions. A BwN design can consist of several elements. As a results of analysis on the ecosystems of Galveston Bay and the 'Building-with-Nature' concept these elements can be identified. These elements are referred to as 'building blocks'.

In this study a conceptual design, composed of these building blocks, is made and evaluated by means of a qualitative evaluation and a quantitative evaluation.

In order to qualitatively evaluate these building blocks for Galveston Bay, a framework has been developed. This framework involves two toolboxes and the formulation of a global, conceptual BwN design. The toolboxes emphasize on flood risk and natural value of the building blocks. The potential effect of a building block is illustrated by a color classification and a description. Hurricane conditions are assumed and simplified calculations (following certain system assumptions) for idealized conditions are applied. The flood risk toolbox is created with hydraulic effect of all building blocks. Next, potential natural value of all building blocks is assessed according to 5 relevant criteria and summarized in the second toolbox. Outcomes of both toolboxes, together with an area analysis are used to formulate a global BwN design for hurricane flood risk reduction.

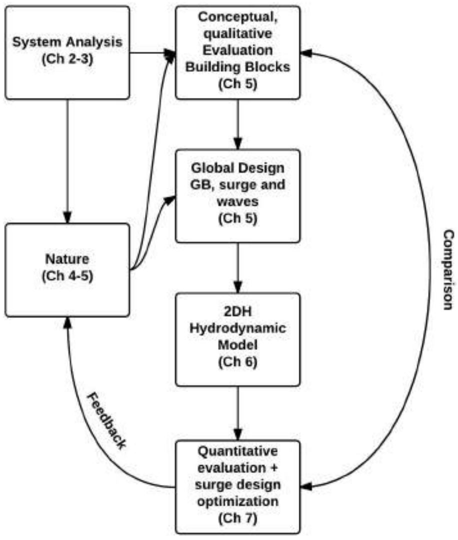


Figure 1.2: Schematized methodology

The quantitative evaluation involves a 2DH hydrodynamic model. This model is calibrated with observations of peak water levels during hurricane Ike and is used to assess the system behavior under hurricane forcing, for regular Ike and shifted tracks of Ike (of which one track is similar to Sebastian et al. (2014)). Subsequently it is used to assess the effect of surge reducing designs, with and without Ike Dike.

Based on outcomes of the simulations, a final design optimization is conducted. The final design with respect to surge reduction is presented. Moreover, final conclusions regarding opportunities and limitations of BwN for hurricane flood risk reduction are drawn.

1.6. REPORT OUTLINE

This thesis consists of 8 chapters, including this introduction. Chapter 2 gives a background overview Galveston Bay. Chapter 3 discusses the hydraulics of Galveston Bay, including hurricane characteristics for the area. Moreover, in chapter 4, the concept of 'Building-with-Nature' is introduced as well as suitable 'building blocks' for a BwN design. Chapter 5 deals with the qualitative evaluation of building blocks for the global conceptual design. Chapter 6 and 7 will introduce the 2DH hydrodynamic model and the outcomes of this quantitative evaluation. Chapter 7 finishes with the conclusions from the hydrodynamic simulation study and a final optimized design. Chapter 8 will conclude this thesis with the main conclusions and recommendations regarding BwN for flood risk reduction in Galveston Bay. Figure 1.2 depict these steps in the process as well.

The appendices are compromised of background information, equations and calculations. Appendix A corresponds to Chapter 2 and contains background information on Galveston Bay, including a literature review. Appendix B corresponds to Chapter 3 on hydraulics and Appendix C with Chapter 4 on BwN'. Appendix D is associated with Chapter 5 and Appendix E with Chapter 6 on the set-up of the hydrodynamic model. Finally, in Appendix F the complete simulation results of the hydrodynamic 2DH model analysis of Chapter 7 are presented. See Figure 1.3 for the structure of the report and the link between Chapters and Appendices.

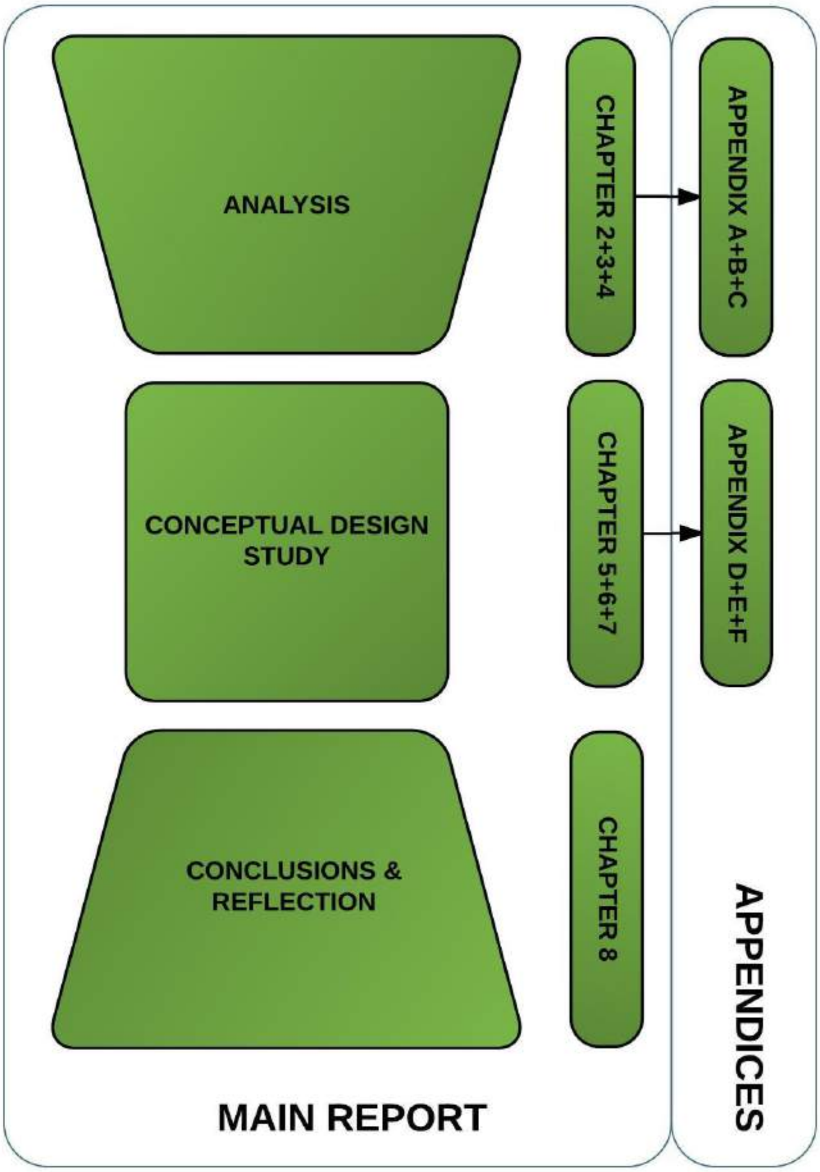


Figure 1.3: Report structure

2
Galveston Bay

The Galveston Bay area is generally referred by the area surrounding the Galveston Bay, including the Galveston Island and Bolivar Peninsula. This chapter deals with an analysis of the Galveston Bay area. Section 2.1 gives an introduction of Galveston Bay and its components and dimensions. Section 2.2 presents the processes occurring in the Bay, arranged from very long timescales (e.g. geology) to short timescales (e.g. tides). Section 2.3 gives an analysis of the ecosystems and trends, while Section 2.4 deals with hurricane characteristics, statistics and historic observations of Texas hurricanes. Subsequently, the practice of dealing with hurricanes and several recent flood protection developments, such as the Ike Dike, will be presented. All will be concluded by Section 2.7. For background information, of which some is not discussed yet, reference is made to Appendix A.

2.1. Galveston Bay Estuary

Galveston Bay has been important in Texas' history as it was home to Texas' earliest settlements. The port of Galveston became the most active port west of New Orleans and the largest city in Texas quickly after incorporation in 1839 (Galveston.com, 2013). The harbor of Galveston was moved to Houston after the devastating hurricane of 1900 ('The great storm') with an estimated present-day normalized damage of $700 million in which 6000-8000 lives were lost (Schiller, 2011; USACE, 1981). In the following decades, Houston experienced rapid growth.

Today, the port of Houston is the second largest in the U.S.A., with an annual cargo throughput of over 237 million tons (Port Authority of Houston, 2014). Also the harbor of Texas City and Galveston are large ports in the area (de Vries, 2014). Other important assets are the petrochemical industry, the medical and life-science (including the Texas Medical Center), the aerospace & aviation industry (NASA's Johnson Space Center is the centerpiece), tourism and (oyster) fishing are valuable industries (Greater Houston Partnership, 2014; Hodgin, 2007).

The GHMA is a highly industrialized area with a population of more than 6 million people, currently ranking fifth-largest metropolitan area in the U.S. (U.S. Census Bureau, 2012). Currently 4 million people live in in the 5 counties surrounding the Galveston Bay (Galveston Bay Estuary Program, 2014).

Galveston Bay is the largest estuary in Texas, with an estimated area of between 1399 km^2 [540 square miles] (Moretzsohn, Chávez, & J.W. Tunnell, 2014) and 1554 km^2 [600 square miles]. According to Pritchard (1967) an estuary is a semi-enclosed coastal body of water which has an open connection with the sea and within which saltwater is mixed with freshwater from runoff (Townend & Pethick, 2002). It is a typical drowned river valley, excavated by fluvial processes, which gradually flooded with rising sea level (Phillips, 2005; Rehkemper, 1969).

The bay consists of four sub-bays: East Bay, Trinity Bay, Galveston Bay (Upper and Lower) and West Bay. Galveston Bay and its elements can be seen in Figure 2.1. The shoreline length is difficult to define, because it depends on the scale of resolution for example (Lester & Gonzalez, 2011). Phillips (2005) uses a length of about 374 km [232 miles] but Lester and Gonzalez (2011) mentions a length of 1250 km [780 miles]. The first considers erodable shoreline, the latter features small-scale features as boat basins and service canals.

The average depth of the bay is about 2 to 3 meter [7 to 8 feet] (Armstrong, 1987; Lester & Gonzalez, 2011; Smith, 2013). Exceptions are the Houston Shipping Channel, which is 14 m [45 feet], and the Bolivar Roads Pass which has an average depth of 9 m and a maximum depth of up to 18 m (de Vries, 2014; Taylor et al., 2008). A depth elevation map of Galveston Bay can be seen in Figure 2.2. The overall shallowness of Galveston Bay, the deeper Houston Shipping Channel and dredge spoils banks along both sides of the channel can be seen.

Figure 2.1: Galveston Bay estuary and important elements (de Vries, 2014)

Galveston Bay is separated from the Gulf of Mexico by two barrier islands, the Bolivar Peninsula and the Galveston Island. These barrier islands are low (1-3 meter above MSL), narrow and straight (Stoeten, 2013). The barrier islands are composed of sand, whereas most soil in Galveston Bay is clay. Three inlets connect Galveston Bay with the Gulf of Mexico. The two major inlets are Bolivar Roads and the San Luis Pass (Figure 2.1). Bolivar Roads is 2.8 km wide and is an important shipping corridor towards the harbor of Houston. The third inlet is the Rollover Pass in the north. Galveston Bay is fed by several rivers delivering freshwater. There is an important relationship between bay waters and surrounding land. The estuary's physical, biological and chemical quality is linked to the quality and quantity of freshwater flowing into Galveston Bay (Galveston Bay Estuary Program, 2014). Runoff from watersheds plays an important role in bringing nutrients, organic matter and contaminants into Galveston Bay (Lester & Gonzalez, 2011).

Behind the barrier islands a unique, complex and productive estuary with low wave action and brackish water is present. A diverse range of marine and brackish habitats are supported, as well as unique plant and animal communities (Deltares, 2015a). Estuaries are areas of transition, for example between dynamics of the sea and the river, between saltwater and freshwater and between river and marine sediment (Deltares, 2015a). These transitional gradients are always dynamic. The result is a rich variety of habitats associated with diverse

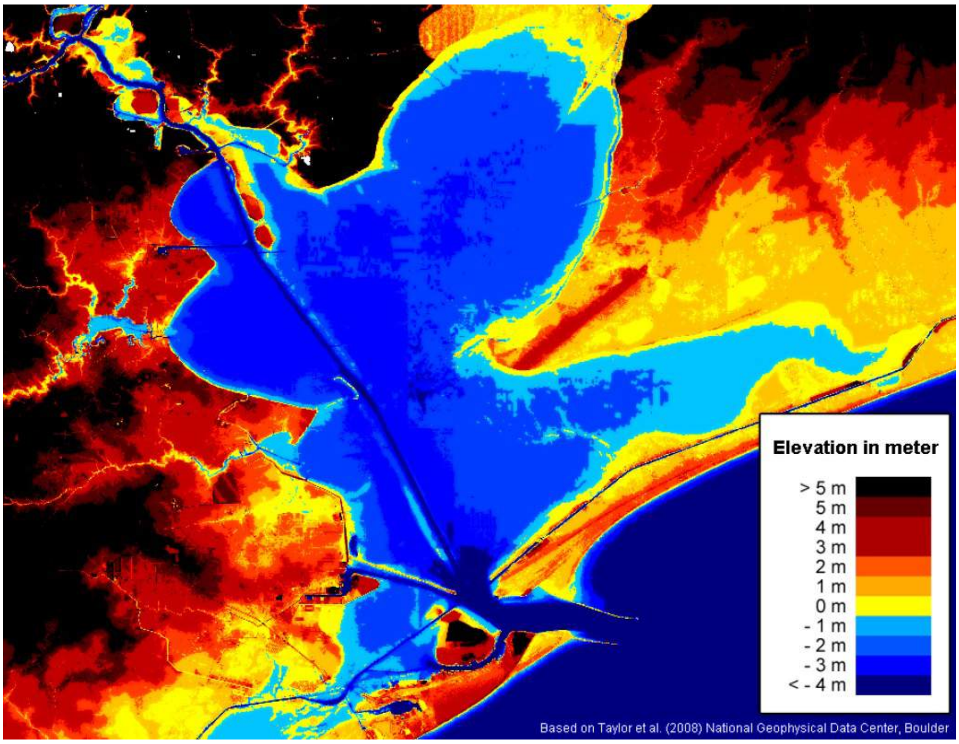


Figure 2.2: Depth elevation map of Galveston Bay, based on Taylor et al. (2008). (Stoeten, 2013)

animal and plant life (Deltares, 2015a).

2.2. GALVESTON BAY SYSTEM AND PROCESSES

2.2.1. GEOLOGY GALVESTON BAY

Galveston Bay as we know it now was being created during the last Ice Age, more than 18,000 years ago (Smith, 2013). As the last Ice Age came to an end, the earth warmed and sea level rose to the near present level, in a period of thousands of years (Phillips, 2005; Smith, 2013). Alongshore currents as a result of wave action deposited sediment along the new developed shoreline. This resulted eventually in the creation of the barrier islands around 2,500-5,000 years ago. Galveston Island shoreline started to retreat from around 1,200 years ago (Atkins Global, 2011).

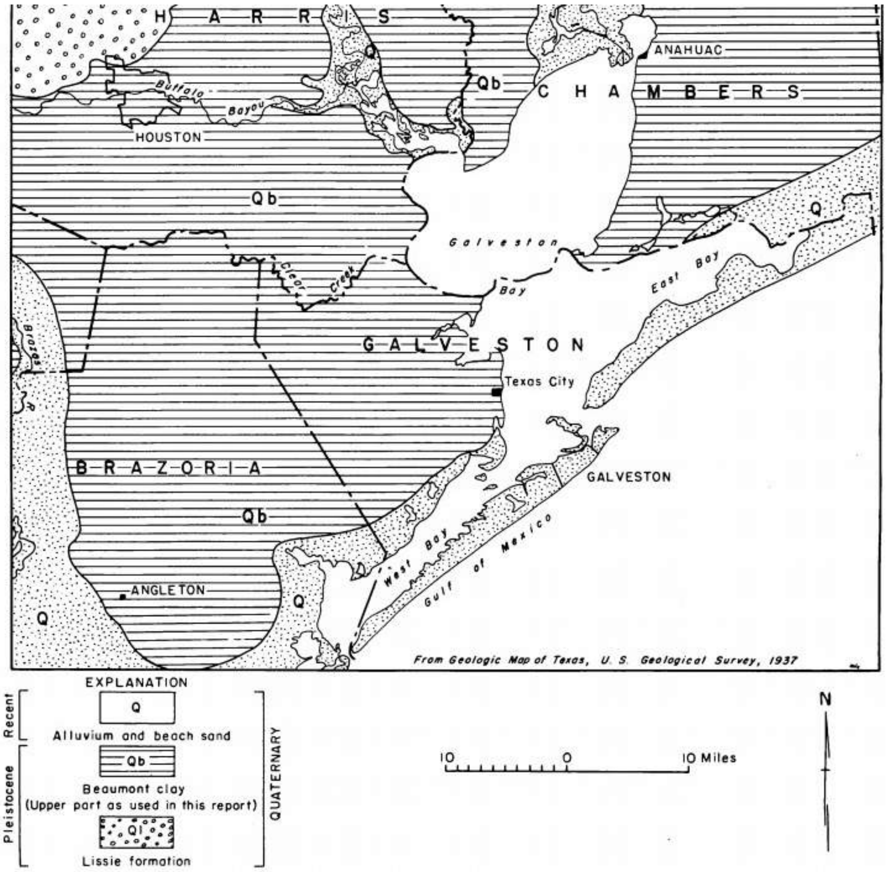
Galveston Bay has a micro-tidal range (0.35 m), and is wave dominant (Bosboom & Stive, 2013). This means that waves have shaped the barrier islands. Wave dominated estuaries are usually semi-mature in terms of evolution (OzCoasts; Geoscience Australia, 2013). Morphology can change rapidly over time due to e.g. infilling. Rodriguez et al. (2004) as well as Nichols (1989) prove that significant variability in coastal retreat, occurred during the Holocene[1], can be seen. This implies that morphology has been changing constantly. Sediment in wave dominated estuaries ranges from fine to coarse sands in the barriers and fine organic mud in the central basin (OzCoasts; Geoscience Australia, 2013).

A picture of geologic features of Galveston Bay can be seen in Figure 2.3. It is clear to see that the area contains Pleistocene[2] sediments such as mud, and that the barrier islands are formed by Holocene sand, probably originating from offshore. A cross-section of Galveston Bay, from the Trinity River delta to Bolivar Roads inlet can be seen in Figure 2.4.

[1]Holocene is the most recent geologic epoch that began at approximately 11,700 years BP and continues until now. The Holocene started after the last major Ice Age and has been a relatively warm period (University of California Museum of Paleontology, 2015)

[2]Pleistocene is the geologic epoch that spanned from 2.6 million to 11,700 years ago (University of California Museum of Paleontology, 2015)

Figure 2.3: Geologic map of Galveston Bay (Petitt & Winslow, 1955)



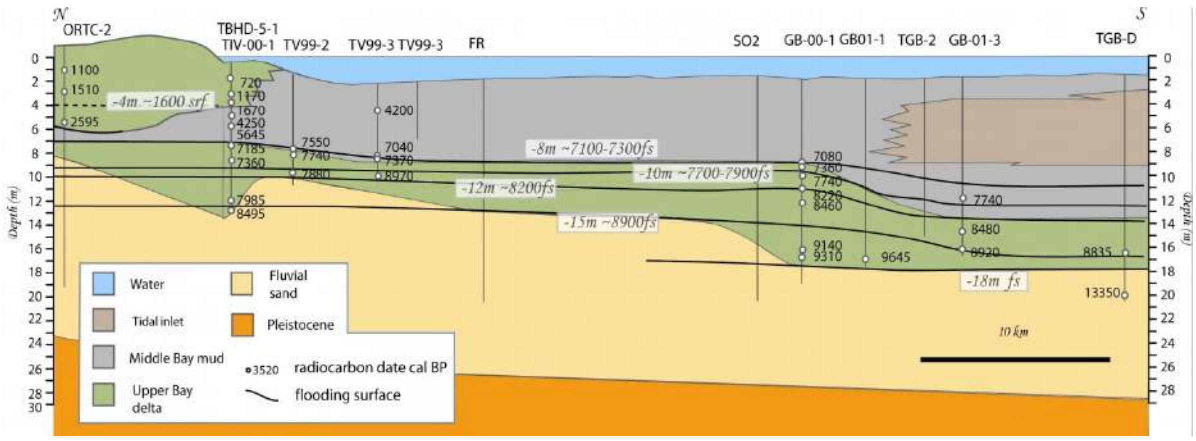


Figure 2.4: Cross-section of Galveston Bay from Trinity River delta to Bolivar Roads, compiled from a seismic line and drill cores acquired along the valley (J. Anderson et al., 2008)

2.2.2. MORPHOLOGY GALVESTON BAY

A wave-dominated estuary or lagoon, such as Galveston Bay, usually has certain geomorphological characteristics. It can be described as semi-mature, the morphology can change rapidly due to infilling. Nichols (1989) states that in general lagoons can be seen as sediment sinks destined to be filled as well, although a lot of lagoons on the Gulf and Atlantic coast of the U.S. have a near balance of accretion and relative sea level rise (henceforth RSLR)[3]. Nichols (1989), who investigated sedimentation rates and RSLR in lagoons, found that an accretionary deficit occurs in lagoons in general when the RSLR exceeds accumulation rates, observed in areas with rapid land subsidence or inadequate sediment supply, which is the case for Galveston Bay. According to Nichols (1989) Galveston Bay has a small accretionary suplus on the long term, which means it will start infilling eventually (Nichols, 1989). According to Nichols (1989) the short term negative accretionary difference can be fully attributed to human intervention resulting in high rates of RSLR. However, abovementioned analysis is based on RSLR projections which are out of date. Prof. John Anderson, an oceanographer from Rice University, states that RSLR currently is around 6 mm $^{-1}$ (Personal communication, March 2015). Sedimentation rates have been just over 1 mm year^{-1} (based on cores from Figure 2.4). This would suggest that Galveston Bay is not being infilled in the long term, because the negative accretionary deficit is around 5 mm year^{-1}.

Eyer (1985) investigated the morphological development of the Bolivar Roads inlet of the Galveston Bay, which is a micro-tidal, wave-dominated system. Galveston Bay contains both flood- and ebb-tidal deltas, comparable in size (Rodriguez, Anderson, & Bradford, 1998). Phillips (2005) states that satellite imaging shows sediment plumes both into and out of Galveston Bay through Bolivar Roads. Anderson (Personal communication, March 2015) states that there was a sizable flood-tidal delta prior to the present (see Figure 2.4), as well as a sizable ebb-tidal delta; see Figure 2.5 for a chart from 1856, where both tidal deltas can be seen. At that time the flood-tidal delta was already decreasing for several centuries.

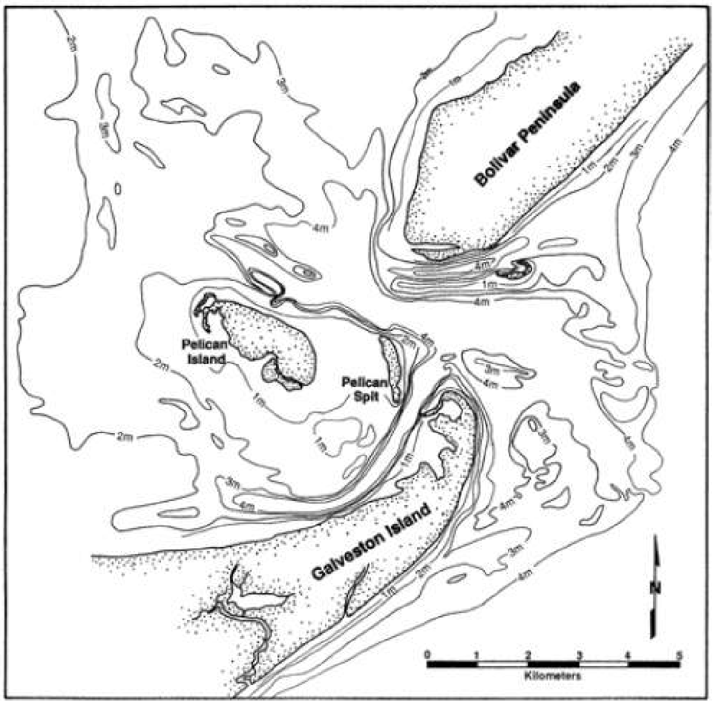


Figure 2.5: Tidal deltas of Bolivar Roads in 1856, before construction of the jetties (J. B. Anderson, 2007)

Eyer (1985) states that "in its natural state (pre-1890) Bolivar Roads inlet was geometrically stable and behaved like meso-tidal (tidal dominated) inlets, although it was micro-tidal and wave dominated. The well developed ebb-tidal delta was maintained by wind, tides and ebb flow enhancements due to 'Northers'[4](Ruijs, 2011), a large sediment supply and an ebb dominant asymmetry from a diurnal inequality of the tides and tidal phase

[3]Relative sea level rise or coastal submergence is the combined effect of sea level rise and land subsidence

[4]A Norther is a type of wind occurring in winter that accompanies the cold wave that follows the passage of a cyclone across the U.S. (Encyclopaedia Britannica, 1911)

lags in Galveston Bay". The North and South jetty enclosing the Bolivar Roads Inlet were built in 1890. Eyer (1985) also found that "the asymmetric flood-tidal delta migrated southward, because of Norther-generated wave and tidal current action". J. B. Anderson (2007) states that the inlet and flood-tidal delta complex migrated towards the West. In Figure 2.4 it can also be seen that this flood-tidal delta has decreased in size over the past centuries.

The present morphology is an interaction of tidal currents, alongshore currents and wind waves. These have all been disrupted as a result of extensive modification of the inlet, according to Eyer (1985) and J. B. Anderson (2007). For example "important changes in ebb-tidal delta were associated with repetitive cycles of channel abandonment by-passing". The biggest modification is the construction of the two jetties at Bolivar Roads. The main consequence of the jetties, is the fact that they trapped eroded sediment from the ebb-tidal delta and alongshore transport in locations where in natural conditions it would not have been accreted (Wallace, 2010).

The modern tidal-deltas of Bolivar Roads in Galveston Bay consist of mainly mud. However, some can be found in the center part of the tidal-delta (Rodriguez et al., 1998). Especially in the part just east of Pelican Island there is sand, the rest is buried beneath several feet of mud as a remainder of the old delta complex (J. B. Anderson, 2007). Additionally contaminated dredge spoils from the HSC were dumped on the ebb-tidal delta covering it partially (J. B. Anderson, 2007).

Rodriguez et al. (1998) state that an ebb dominance is still present. Anderson (Personal communication, March 2015) concludes that at least before 1890 an ebb-dominance was present from the fact that in the chart from 1856 both flood- and a sizable ebb-tidal deltas were present and the fact that the flood-tidal delta decreased over millennia (Figure 2.4). This would mean that sediment export out of the inlet would take place towards the ebb-tidal delta.

The system is probably out of morphological equilibrium, because of the high relative sea level rise rates and the fact that the system is highly impacted by humans. This statement is confirmed by prof. John Anderson (Personal communication, March 2015).

SAN LUIS PASS TIDAL DELTAS

The San Luis Pass inlet on the southwest end of Galveston Bay is the oldest natural deltaïc inlet of Texas. This means it has not been influenced much by humans, in contrast to Bolivar Roads (J. B. Anderson, 2007; Wallace & Anderson, 2013; Wallace, Anderson, & Fernández, 2010). San Luis Pass delta is a flood dominated delta, opposed to Bolivar Roads which is an ebb-dominated delta (at least before major modifications took place). However, both inlets have sizable ebb- and flood-tidal deltas.

2.2.3. CLIMATE CHANGE AND SEA LEVEL RISE

Human interventions have had a direct or indirect impact on Bolivar Roads, which is also reflected by climate change. The result of a changing climate is an increase in average temperature around the globe, and this subsequently results in sea level rise (henceforth SLR). Tide measurements and satellite altimetry suggests that sea level has risen 12-22 cm worldwide over the last century (Atkinson, McKee Smith, & Bender, 2013). The global projections show that the rate of SLR is accelerating (Atkinson et al., 2013). Worldwide projections for SLR range from 0.6-1.2 m for 2100 (IPCC, 2013), equal to around 6-12 mm year^{-1} on average (see Figure 2.6).

The fact that hurricanes especially or tropical storms in general will occur more frequently due to climate change has not been proven (Knutson et al., 2010). However, because of SLR coastal cities have an increased exposure to flooding. National Research Council (2014) states that although the total number of hurricanes is predicted to decrease in the 21st century, the intensity of hurricanes in general and the frequency of strong hurricanes may be increased by climate warming. The total number of strong storms is expected to increase. In the Atlantic basin, the increase in number of strong storms will outweigh the reduction in number of hurricanes resulting in an increase in potential damage by 2100 (Bender et al., 2010). High detailed modeling studies show that the intensity of hurricanes could increase with 2-11% by the year 2100 (Knutson et al., 2010). Knutson et al. (2010) also showed that the precipitation rate within 100 km of the center of the storm could increase with 20%.

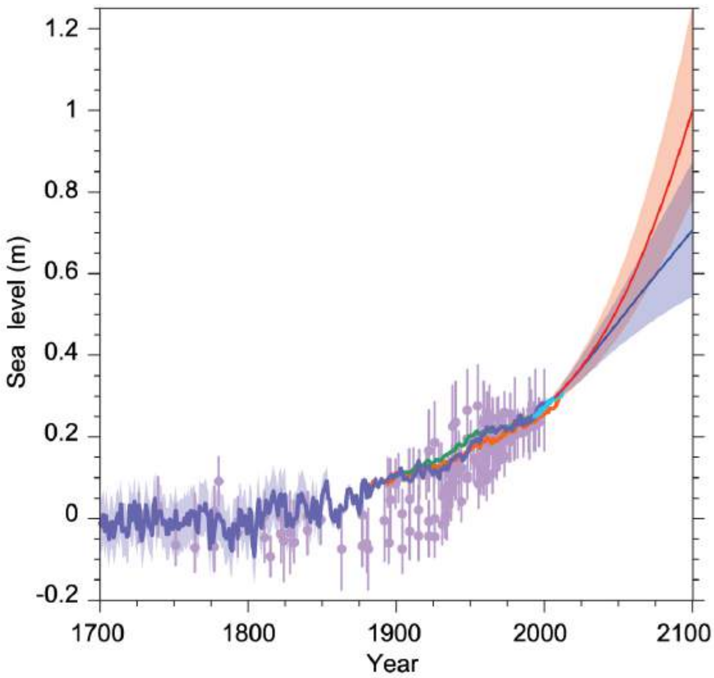


Figure 2.6: Combination of sea level data, central estimates and accompanying likely ranges for global sea level projections. Proxy data are shown in light purple, tide gauge data in blue. For the estimations, the red line shows projections for very high emission and the blue line shows projections for very low emissions (IPCC, 2013)

The Greater Houston Metropolitan Area has been greatly affected by land subsidence, perhaps more than any other metropolitan area in the world (Coplin & Galloway, 1999). Land subsidence in this area is caused by groundwater pumping and oil and gas extraction. According to Coplin and Galloway (1999), the phenomenon first occurred in the beginning of the 1900s in areas where oil, gas and groundwater were extracted. The trends in subsidence patterns shifted from the South to inland due to groundwater extraction for cities and the growing industry. The subsidence continued throughout the 20th century due to groundwater pumping. According to Lester and Gonzalez (2011) the surface around Galveston Bay has sunk as much as 3 m [10 feet] in some areas since 1906. A figure of the total subsidence in the region due to oil, gas and groundwater extraction can be seen in Figure 2.7. The land subsidence differs significantly locally over the region. Although rates of land subsidence have historically been high, they have been significantly decreased because of regulating efforts of the government.

RSLR is a relevant parameter because land subsidence is significant in and around Galveston Bay. Globally, RSLR has been 3.1 mm year^{-1} on average in the last two decades (National Research Council, 2014). An instrument of NOAA at Pier 21 in Galveston Bay recorded a RSLR of 0.6 m [2 feet] over the last 100 years, which equals around 6 mm year^{-1} over the last century (NOAA, 2014; Yoskowitz, Gibeaut, & Mckenzie, 2009). Phillips (2005) assumes projected annual rates of SLR between 1.4-3.2 mm year^{-1} and projected annual rates of RSLR between 7.6-10.3 mm year^{-1}. Ravens, Thomas, Roberts, and Santschi (2009) assumed a RSLR of 6.5 mm year^{-1}. These rates might be even conservative, looking at SLR projections from IPCC (2013).

2.2.4. ACTUAL EROSION IN GALVESTON BAY

The coast of Galveston Bay is experiencing erosion along barrier beaches and wetlands loss inside the estuary. Galveston Island Gulf shoreline has retreated for a long time (Figure A.5). Around 57% of Galveston Island's coastline has experienced erosion rates of 0.6 m year^{-1} or more in the past few years (Phillips, 2005). For the Bolivar Peninsula this number is 86%, and erosion rates of over 2 m year^{-1} are observed. A general alongshore transport in western direction can be found. The system is sand starved, as sand is in very short supply. The jetties in Bolivar Roads have trapped sediment from alongshore current and ebb-tidal delta and this starves the down-drift areas near Galveston Island even more (Wallace, 2010). Hard structures like the Galveston Seawall have exacerbated the erosion problem further west along the shoreline on Galveston Island (Wallace, 2010).

At the inside of the estuary Phillips (2005) states that "shoreline retreat of 1.5-3 m year^{-1} is common in recent

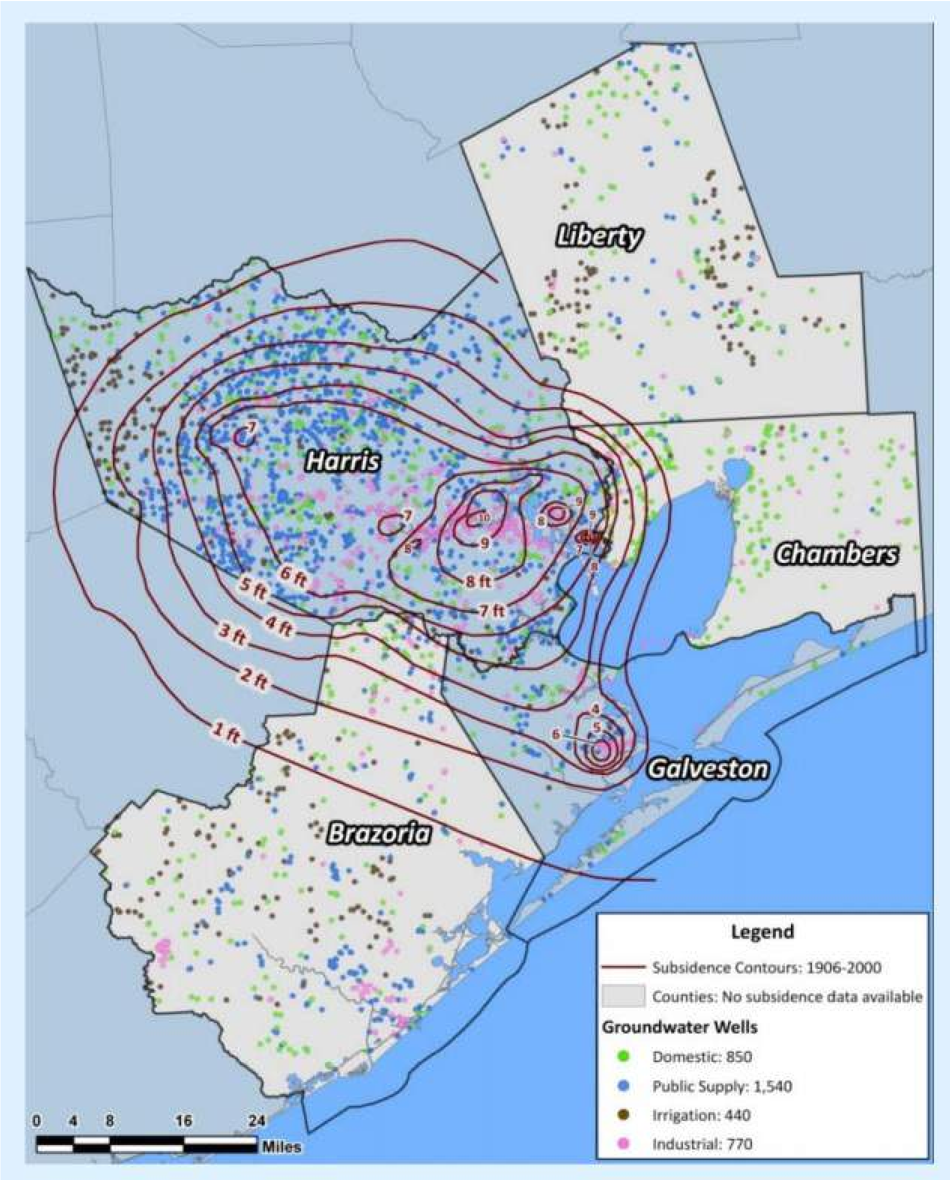


Figure 2.7: Overview of subsidence in Houston-Galveston region from 1906-2000, as well as the current groundwater wells. Data source: Harris-Galveston Coastal Subsidence District, 2008 and Texas Water Development Board, 2008 (Lester & Gonzalez, 2011)

years, and that conversion of wetlands to open water at a rate of 0.47 km^2 $year^{-1}$ has been documented for the Trinity Delta in the Northeast of the system". Other research states that the original wetlands in and around Galveston Bay have been eroding the last decades since 1990 at a rate of 0.3% per year (Galveston Bay Status and Trends, 2014). According to Ravens et al. (2009) the causes for wetland erosion in Galveston Bay could be wave action, insufficient sediment supply to keep up with sedimentation rates (also called infill rates or accretion rates). The sedimentation rates should compensate for RSLR. Ravens et al. (2009) researched the relative importance of these factors in Galveston Bay and states that the main reason for the erosion of wetlands is insufficient sediment supply to keep up with RSLR of 6.5 mm $year^{-1}$. A similar conclusion was made by Phillips (2005). He stated that "fluvial sediment inputs are insufficient to account for observed sediment infill rates in Galveston Bay (3.5 mm $year^{-1}$), and to keep pace with eustatic SLR (RSLR assumed to be 10.3 mm $year^{-1}$)". Thus Phillips (2005) calculates a deficit of around 7 mm $year^{-1}$. The conclusions from Phillips (2005) and Ravens et al. (2009) are in line with short-term conclusion of Nichols (1989) for Galveston Bay.

Although the main reason for erosion is insufficient sediment supply, erosion is still promoted by prevailing winds from the southeast in combination with long fetch length, especially on the western side of Galveston Bay (John Anderson, Personal communication, March 2015). In West Galveston, where inorganic sediment is limited it is harder for salt marshes (whom are mostly gone) to keep up with SLR in the future. Specifically wetlands are most susceptible for erosion in areas where the H80 wave height (80th percentile) is higher than 0.2 m, which the case for shorelines in West and East Galveston Bay (Figure A.8).

Additionally, the result of erosion can be seen as a vicious circle (Bregje van Wesenbeeck, Personal Communication, October 2014). The eroded natural shore will probably be removed to construct bulkheads or hardened revetments. These hardened shorelines will reinforce the erosion of the shoreline even more due to turbulent wave breaking and the absence of natural wave attenuation. This is especially the case on the urbanized western side of Galveston Bay.

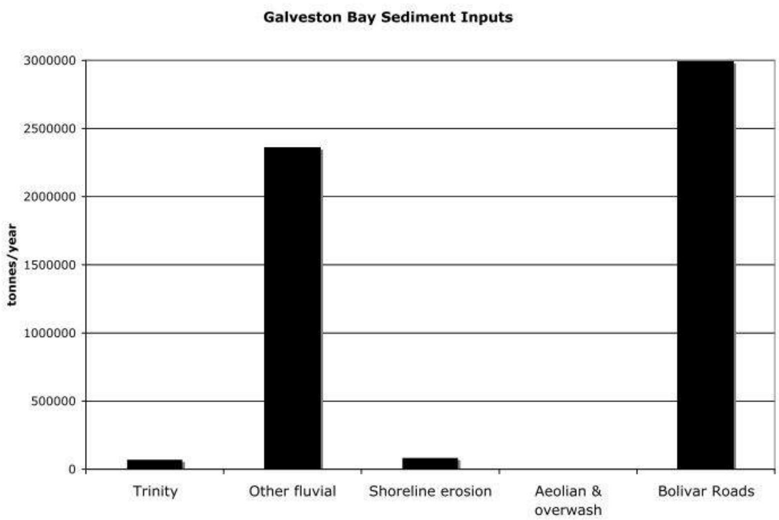
The sediment supply to Galveston Bay consists of three sources: 1. sediment from shoreline and wetland erosion, 2. coastal sediment input through Bolivar Roads, and 3. sediment from the Trinity river and the remainder of the watershed (see Figure 2.8). Given ample sediment supply, wetlands and shorelines can grow with sea level rise. In this case this sediment supply is insufficient, therefore erosion takes place and wetlands cannot grow with SLR. In the total sediment budget erosion is a significant source (Phillips, 2005). Current sedimentation rates are estimated to be around 3.5 mm $year^{-1}$ (Phillips, 2005). Phillips (2005) also calculated that the amount sediment needed to fulfill this estimation is 5.7 million tonnes.

Phillips (2005) states that overwash and aeolian inputs to the system are likely to be minor. This is confirmed by Wallace et al. (2010) and Wallace (2010). Hurricanes could have an impact on short-term sediment budget and cause coastal erosion, but they are found to cause minimal long-term sand sinks (Wallace, 2010).

Sediment input through Bolivar Peninsula could be a major source. Satellite images show sediment plumes in and out of Bolivar Roads inlet (Phillips, 2005). It is unknown how big this contribution is, but Phillips (2005) states that "because the fact that the tidal prism greatly exceeds the typical freshwater inflows, the importance of coastal sources to Galveston Bay is supported". It is estimated by Phillips (2005) at 3 million tonnes per year. Phillips (2005) furthermore states that "a significant portion of the incoming sediment is being transported beyond the the flood-tidal delta (presumably fine sediment) is likely to stay within the system".

Fluvial sediment supply, mainly from the Trinity River, is estimated to be 2.3 million tonnes per year. Whether the sediment supply from fluvial sources has been significantly modified by human interventions upstream is unclear, but Ravens et al. (2009) and Slattery and Phillips (2007) state that it is likely that deficit in sediment supply in Galveston Bay is related to sediment supply reductions to the Trinity River due to dam constructions. However, this theory is unsupported. Phillips (2005) states that human-caused interventions, such as dams and reservoirs upstream, are minor contributors to shoreline erosion. Also Wallace, Anderson, and Rodriguez (2009) state it even more firmly: "the popular conception that damming rivers has increased rates of erosion in unsupported, since fluvial sand delivery has in fact been relatively minimal over geologic time". It is unknown how much sediment is exactly going in or out of Galveston Bay. Both the sediment supply through Bolivar Roads and fluvial supply estimated by Phillips (2005) contain high uncertainties. See Figure 2.8 for an estimation of annual sediment inputs to Galveston Bay.

Figure 2.8: Estimated yearly sediment contributions to Galveston Bay (Phillips, 2005)



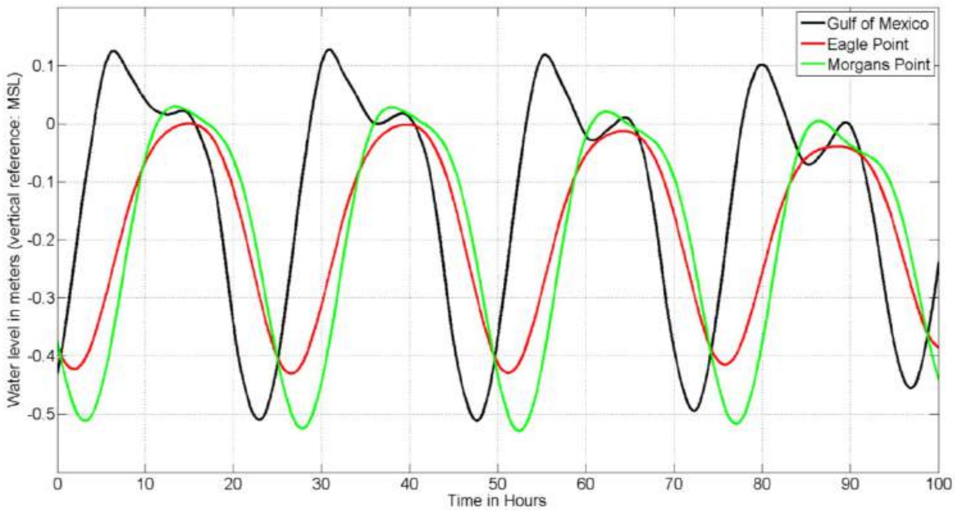
2.2.5. DAILY BEHAVIOR AND TIDES

Galveston Bay is a shallow, wind and wave dominated estuary with a low tidal range. Tides at open coast are mixed but predominantly diurnal and the mean tidal range is about 0.35 meter [1.16 feet] (Table 2.1). A plot of the tidal range in three different locations, of which 2 can be found inside Galveston Bay, is plotted in Figure 2.9. See Figure A.1 in Appendix A.1 for the locations of these observation points.

Table 2.1: Tidal ranges and propagation into Galveston Bay. Data source: NOAA (2014). (Jonkman et al., 2013)

Gauge	Mean Range	Diurnal Range	Phase difference (est.)
Pleasure Pier (Open Coast)	1.16 feet	1.67 feet	-
Eagle Point	1.02 feet	1.11 feet	+ 6 hour lag
Morgan's Point	1.13 feet	1.31 feet	+ 6 hour lag

Figure 2.9: Plot of tidal range and propagation into Galveston Bay. Data source: NOAA (2014). (Jonkman et al., 2013)



The tidal ratio between bay and Gulf is about 0.6 and observed phase lag is about 4 to 6 hours (Stoeten, 2013). The seasonal range of tides is 0.2-0.3 meter, with low range around August and December and high range around May and October (Stoeten, 2013), which is similar to the mean tidal range. Nichols (1989) mentions a residence time[5] of about 40 days.

[5] Residence time is defined as the time that a substance, in this case a water particle, spends within the physical system

A plot of the tidal current prediction at a location halfway inside Galveston Bay can be seen in Figure 2.10. The shape of the plot and the fact that the ebb current speed is larger than the flood current speed suggest that the tides in Galveston Bay are ebb-dominant (Bosboom & Stive, 2013). Similar plots can be created throughout Galveston Bay and at Bolivar Roads.

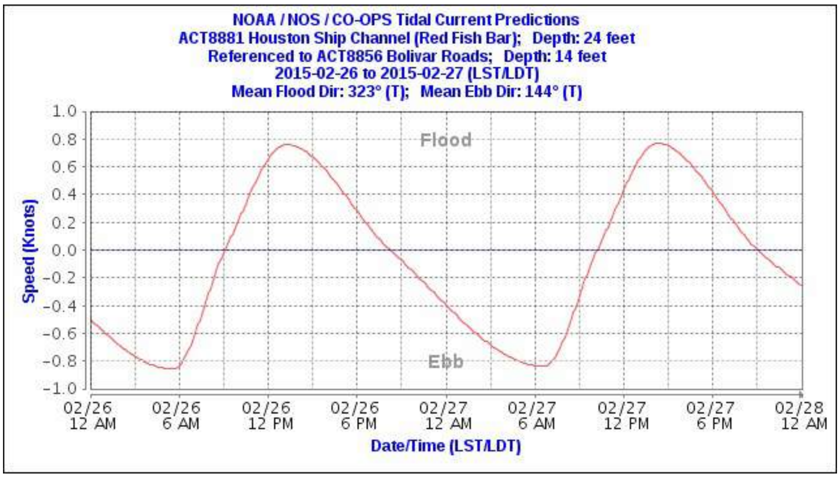


Figure 2.10: Tidal current predictions at the HSC near Redfish Bar (NOAA, 2014)

Three inlets connect Galveston Bay to the Gulf of Mexico: Bolivar Roads, San Luis Pass and Rollover Pass. Fresh water mixes with salt water from the Gulf of Mexico through these inlets. Bolivar Roads and San Luis Pass are responsible for respectively 80% and 20% of the tidal exchange (Lester & Gonzalez, 2011). Rollover Pass' tidal exchange is negligible (<5%) (Lester & Gonzalez, 2011; Matsumoto, Powell, Brock, & Paternostro, 2005). West Bay exchanges water through San Luis Pass, therefore it doesn't contribute to retention capacity of Galveston Bay for surge through Bolivar Roads. The tidal prism[6] is about 3.5 x 10^8 m^3 and flow velocities within channels are usually below 2 ms^{-1} (Jonkman et al., 2013; NOAA, 2014).

The bay is fed with freshwater by the San Jacinto River, Trinity River and numerous bayous. The watershed of the bay is about 85.000 km^2. The watershed stretches north from the GHMA past the Dallas-Fort Worth Metroplex. Half the population of the state of Texas currently lives in the Galveston Bay watershed (Smith, 2013). 54% of the watershed is accounted for by the Trinity River, the Jacinto River contributes 17% and creeks and bayous the remaining 29% (Phillips, 2005). Of the annual fresh water inflow, 5% flows through Rollover Pass, 20% through San Luis Pass and 75% through Bolivar Roads (Matsumoto et al., 2005). This is comparable to the tidal exchange through the inlets. Nichols (1989) calculated the flow ratio, which is the mean freshwater inflow during half a tidal cycle divided by the tidal prism, as 0.183 (Phillips, 2005). This leads to the conclusion that the tidal prism exceeds the freshwater inflow.

2.2.6. MORPHOLOGICAL ROLE OF TIDES

According to Townend and Pethick (2002), the role of tides is crucial in estuaries with a tidal range greater than 1 meter. This statement refers to the morphological feedback between tidal propagation and form of an estuary. Because the tidal range in Galveston Bay is around 0.35 m this theory suggests the role of tides is not crucial. Nevertheless, one theory seems to be influencing the morphological developments in the Bay to some extent.

TIDAL ASYMMETRY

The following theory can be found in e.g. Bosboom and Stive (2013). From Figure 2.10 it can be concluded that the tides in Galveston Bay are ebb-dominant. We also saw that an ebb-dominated flow can be found near the inlet, which would mean an increase in sediment volume in the ebb-tidal delta (Rodriguez et al., 1998).

In a system in morphological equilibrium, ebb-dominance would theoretically result in an export of coarse sediments (e.g. sand) out of Galveston Bay and an import of fine sediments. The reason for this is that the high water slack tide[7] takes longer than the low water slack tide (Figure 2.10). During high water fine sedi-

[6]Tidal prism is the total volume of water exchanged over a tidal cycle

[7]Slack tide is the period where current velocities reverse and tidal level is extreme (see e.g. Bosboom and Stive (2013))

ments have more time to settle on the bottom of the shallow estuary than during high water. Thus, less fine sediment can be transported out than in and import of fine sediment can be expected.

Anderson (Personal communication, March 2015) states the following: "the evidence suggest that Galveston Bay is trapping most of the sediment delivered to the bay". This is in line with the theory as described above and conclusions by Phillips (2005). As Figure 2.4 shows, there was a sizable flood tidal delta prior to the present. The present flood tidal delta has decreased in size, as shown in Figure 2.4. Prof. Anderson would suggest that net sediment movement today is out of the bay. He bases this conclusion on the observation that Figure 2.5 shows a sizable ebb tidal delta, which was vanished since the jetties around Bolivar Roads were constructed. The following hypothesis is formulated: it is expected that fine sediment is transported into and trapped by the Bay. The coarser sediment, sand which is present near the tidal deltas, on the other hand is moved from the flood-tidal delta towards the outer ebb-tidal delta due to ebb dominant asymmetry. Result is that the flood-tidal delta, consisting of more coarse sediment, is decreasing. Therefore coarse sediment is expected to be transported out of the Bay.

Whether or not a net sediment transport is in or out of the Bay is unknown. Expected is that fine sediment is being trapped into the Bay and coarser sediment is being transported from the flood-tidal delta out of the Bay. The most important fact remains that the infill rate is insufficient to keep up with high RSLR rates.

2.3. GALVESTON BAY NATURE AND ECOSYSTEMS

Galveston Bay supports a wide variety of marine life, such as fish, shrimp, oysters, crabs, birds, mammals and reptiles. It produces large quantities of recreational and commercial fish and shellfish. Galveston Bay is the second largest seafood producer after Chesapeake Bay and the biggest producer of oysters in the U.S. (Galveston Bay Estuary Program, 2014; Smith, 2013). Galveston Bay serves as a major nesting area for colonial waterbirds. These birds depend on the availability of food and suitable habitats, free from disturbance (Galveston Bay Status and Trends, 2014).

Galveston Bay system contains a variety of habitat types, ranging from open water to wetlands or marshes and upland coastal prairie. But also open-bay bottom, oyster reefs, seagrass meadows and intertidal mud flats (Galveston Bay Estuary Program, 2014; Lester & Gonzalez, 2011; Smith, 2013). Habitats are the ecological environments in which organisms live (Galveston Bay Status and Trends, 2014). They support wildlife, fish and plants by providing food, shelter and other resources needed for organisms to live. For the characteristic biodiversity of the system, a variety and abundance of habitats should be maintained.

The system in Galveston Bay is under pressure, like many similar systems worldwide. Lotze et al. (2006) state that "human impacts have worldwide depleted over 90% of formerly important species, destroyed over 65% of seagrass and wetland habitat, degraded water quality and accelerated species invasions". Some issues in Galveston Bay are: poor water quality, insufficient freshwater inflow, sea level rise (SLR) and land subsidence, erosion and conversion of wetlands to open water or urban and industrial space. As a result, large areas of habitats have been disappeared over the years. "Although natural processes are at work modifying the bay, the most visible changes have come at the hands of humans", according to Galveston Bay Estuary Program (2014). However the issues are less severe than they used to be. Land subsidence for example has been brought back to almost zero, the declining trend observed for wetlands and seagrass has been reversed due to restoration projects and water quality is improving. Still there is room for improvement for Galveston Bay (Galveston Bay Estuary Program, 2014; GBF, 2014).

Three important habitats in Galveston Bay are: (1) emergent wetlands (estuarine and palustrine), (2) seagrass meadows and (3) oyster reefs (Lester & Gonzalez, 2011). These three have been identified in 'The Galveston Bay Plan' for conservation and restoration efforts (Lester & Gonzalez, 2011).

2.3.1. HABITAT DESCRIPTION

WETLANDS

Wetlands play an important role in maintaining and protecting the estuary. Wetlands cover around 50% of the shoreline of Galveston Bay (Guannel et al., 2014). Two types of wetlands can be distinguished in and around Galveston Bay, estuarine and freshwater wetlands.

- Freshwater wetlands do not rely on tides. Freshwater wetlands lie inland of the bay, and are usually found in areas where rainwater accumulates, where rivers provide a source or where groundwater is exposed (Lester & Gonzalez, 2011).

- Estuarine wetlands can be classified into salt (or fringing) and brackish marshes and have an inter-tidal nature. They are located where saltwater of the ocean mixes with freshwater from the river and usually they are elevated around MSL. Therefore they will be inundated with every high tide.

Smooth cordgrass (Spartina alterniflora) is the dominant species found in the salt marshes (Lester & Gonzalez, 2011). At higher elevations Gulf cordgrass (Spartina spartinae) and marsh hay can be found, but they are more common in brackish marshes (Lester & Gonzalez, 2011). Furthermore Spartina patens can be found (Guannel et al., 2014). An example of a saltwater marsh can be seen in Figure 2.11. Wetlands act as a habitat for many species like fish, birds and shellfish (blue crab).

Figure 2.11: Salt marsh near Bayou Vista. Image courtesy: Earl Nottingham, TWPD (Galveston Bay Status and Trends, 2014))

Main reason for erosion is insufficient sediment supply for compensating RSLR. Other reasons for erosion are human interventions (land use, shoreline conversion and dredge and fill activities) and prevailing winds and waves from southeastern diction and long fetch (results in wetland loss on the western side of Galveston Bay). Additionally, Lester and Gonzalez (2011) state that invasive, exotic species are a thread to native wetlands in this area.

Wetlands have been eroding at high rates until approximately the 1990's. Since the 1950's almost 20% of the estuarine and saltwater wetlands have been lost (McPherson, Blackmar, & Heilman, 2015). After 1989 this trend slowed down and eventually reversed because of extensive restoration projects. Most restoration projects execute the wetland creation with dredged material from the Houston Shipping Channel. This method is the so-called beneficial use of dredged material.

SEAGRASS MEADOWS

Seagrass meadows can be established in areas where the water is shallow, clear, warm and where it has the right salinity. Also the water quality is an important parameter (Lester & Gonzalez, 2011). Seagrass meadows are rare in the Bay nowadays except for Christmas Bay. Only 0.1% of the Bay's bed consists of seagrass meadows (Guannel et al., 2014).

Once seagrass meadows flourished in locations along the western shore of the Bay, in the Trinity Bay and in West Galveston Bay (Lester & Gonzalez, 2011). Due to intense dredging and poor water quality these meadows disappeared except for West Bay. Overall almost 90% of the Bay's seagrasses has been lost (McPherson et al., 2015). The emergence of some new seagrass meadows is the indication that water quality is improving in the Bay, although the seagrass acreage is still very low.

OYSTER REEFS

Oysters, crabs, shrimp and finfish that were harvested from Galveston Bay are annually worth a combined \$19 million (EPA, 2007). Of these shellfish, oysters are most abundant. Their harvest accounts for nearly \$10 million annually (Galveston Bay Status and Trends, 2014). Of all the oysters harvested in Texas almost 70 percent comes from Galveston Bay.

Eastern oysters (Crassostrea virginica) are the dominant species in Galveston Bay. The eastern oyster feeds on plankton and algae, and therefore it needs flow and current of water to bring in nutrients. The oysters use gills to filter particles out of the water (TPWD, 2014a).

The oysters in Galveston Bay live in oyster reefs, which are 3-dimensional structures. Oyster reefs occupy currently around 6.5% of the Bay's bed surface (Guannel et al., 2014). Oyster larvae find a suitable place to attach by using tiny probing feet. Once settled, the oyster glues itself in place by a cement-like glue excreted by the foot, and stays there the rest of its life. Oysters can attach to almost everything, from boats to bricks or bottles, but prefers to attach to other oysters (TPWD, 2014a). Large clusters of live oysters and oyster shells form an oyster reef. The oyster reef habitat can form in shallow, salt or brackish water estuaries. Oyster reefs can be sub-tidal of inter-tidal. In winter months oysters can live out of the water for extended periods of time. Oyster reefs can grow vertically under the influence of SLR (Guannel et al., 2014). An example of an oyster reef can be seen in figure Figure 2.12.

Figure 2.12: Example of an emerged oyster reef in South Carolina (http://www.flickr.com)

Oyster are keystone species of Galveston Bay, which means the health of the bay depends on the health of oysters. This is because oyster reefs provide habitat, refuge and food for worms, crabs and fish. Over 300 aquatic species have been identified to use oyster reefs in some way (Robinson, 2014). Furthermore healthy oyster populations can filter large volumes of water and influence water clarity and plankton abundance. Oysters will accumulate pollutants and this combined with their lack of mobility makes them an important indicator for determining the health of the system (Galveston Bay Status and Trends, 2014).

Optimum water temperature for survival of oysters is about 68 - 86 °F [20-30 °C] and normal salinity range is 10 - 30 ppt (Robinson, 2014). In Galveston Bay the salinity is highest near Bolivar Roads, 25-30 ppt (Lester & Gonzalez, 2011). Oyster reefs in Galveston Bay are abundant in Middle Bay and East Bay and somewhat less abundant in West Galveston Bay due to higher salinity. They are more or less absent in upper bays due to inflow of freshwater. Oysters are a key indicator of adequate fresh water inflow because they require a certain salinity and temperature range to resist against predators and diseases. Figure 2.13 shows the locations of oyster reefs during an investigation by Powell, which was conducted for the Galveston Bay Estuary Program in 1991. Oyster reefs were mapped using pole sampling (E. Powell et al., 1994). It can be seen that most abundant oyster reefs are present in the middle of the Bay, remainders of Redfish Bar.[8]

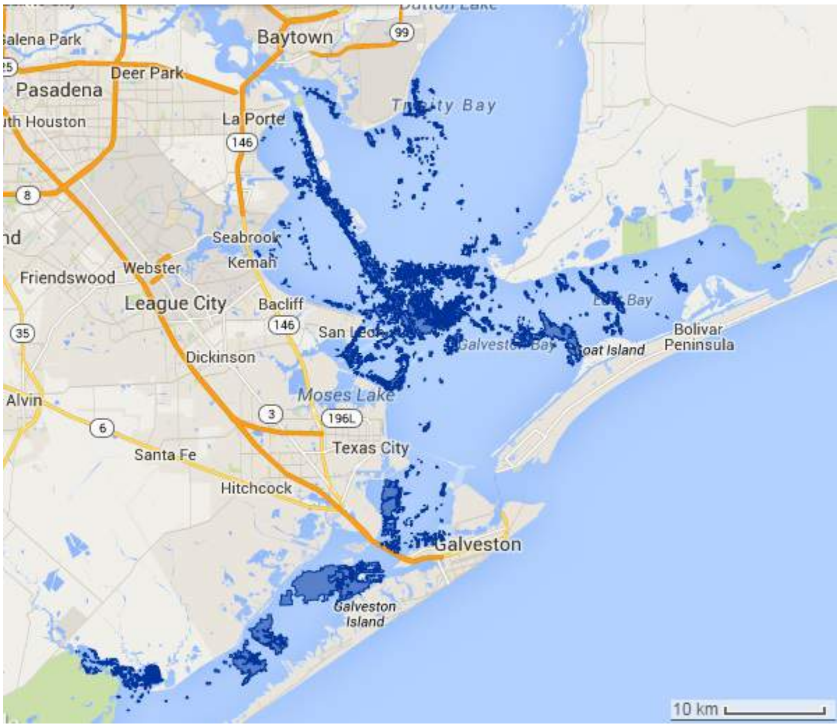


Figure 2.13: Distribution of oyster reefs in the Galveston Bay system. Based on E. Powell et al. (1994). (Texas General Land Office)

Oyster reefs have always changed in position and shape over time, following changes in salinity, circulation and plankton abundance. There used to be more oyster reefs in the Lower Galveston Bay, but due to changing salinity as a result of the deepening of the HSC these reefs migrated to the middle of the Bay (Lester & Gonzalez, 2011). Other important influences have been the construction of Texas City Dike which reduced circulation from Galveston Bay to West Bay significantly, channelization and dredge and fill operations.

The factor with biggest impact on the oyster reefs in Galveston Bay has been the commercial shell dredging for construction purposes and chemical industries. This shell dredging has removed reefs to a depth of 45 feet during the 1960's and 1970's (Lester & Gonzalez, 2011). Hurricane Ike destroyed an estimated area of 55-60% of productive oyster reefs by covering it by sediment and debris, according to the TPWD (Haby, Miget, & Falconer, 2009).

Since oyster reefs are an important economic driver for the Galveston Bay region, the oyster harvest industry plays a big role in the state of the reefs. Most oyster reefs are public reefs, but Galveston Bay is the only bay in the United States which has privately owned oyster reefs. 2,321 acres are controlled by private lease-holders. The lease-holders are mostly families which have been fishing the Galveston Bay waters since the beginning

[8] Redfish Bar was a widespread oyster reef of 9 miles long which stretched across Galveston Bay from West to East about halfway across the Bay

of the 20th century (Tresaugue, 2014). The expectation is that oyster shell dredging has been much worse than oyster fishery for the state of the oyster reefs. Because the areas with most heavily fished reefs have not varied much in size and shape.

Oyster reefs in Galveston Bay can be divided into natural reefs and reefs that have been created and maintained by humans. These human influences can be associated with placement of dredged material and clutch, modifications in current, oyster leases and gas industry development. These types of reefs account for a substantial fraction on the total reefs in Galveston Bay (Lester & Gonzalez, 2011).

All in all 5,000 acres [20 km^2], which is equal to approximately 16%, of historical oyster reefs have been lost. According to Grabowski et al. (2012) "the economic value of oyster reef services, excluding harvest, is between $5,500 and $99,000 per hectare per year. Therefore there is also an economic incentive to restore oyster reefs.

2.4. HURRICANES IN GALVESTON BAY

2.4.1. HURRICANE CHARACTERISTICS

A hurricane (also called tropical cyclone or typhoon) is a tropical storm of which the wind speeds exceed a certain value. The classification of hurricanes is done by the Saffir-Simpson scale[9]. Category 3 hurricanes and higher are considered major hurricanes (National Weather Service, 2014). Hurricanes occur in the tropics and sub-tropics, although not to close near the equator. It requires a warm ocean and humid atmosphere. A hurricane is a rotating tropical storm system with low pressures core and very high wind speeds. Wind velocities of over 120 km/h are classified as hurricane wind, but winds can exceed 240 km/h for very intense hurricanes. The lower limit of pressure in the core, the maximum hurricane intensity or Maximum Potential Intensity (MPI), is generally recognized as 880 mbar (see e.g. Stoeten (2013)). The atmospheric pressure and wind speed vary across the diameter of the hurricane, but profiles are roughly symmetrical (Figure 2.15). In the center of the eye pressure is lowest and winds can be calm. Highest wind speeds occur in the wall of the eye, where the gradient in pressure is steepest. A series of thunderstorms surrounds the core in a spiral of usually hundreds to thousands km in diameter. In the northern hemisphere region all tropical storms rotate counterclockwise (NOAA, 2014). See Figure 2.16 and Figure 2.15 for the characteristics and typical pressure and wind speed profile across the diameter of a hurricane.

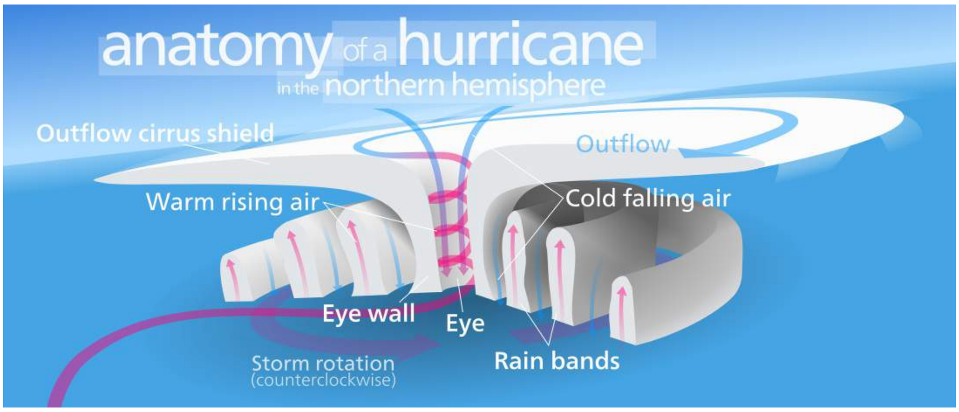


Figure 2.14: Schematic diagram of a hurricane on the Northern Hemisphere. Author: Kelvin Song, 2012 (wikipedia.com)

2.4.2. HAZARD OF HURRICANES

The Upper Gulf coast is prone to hurricanes. Combined with heavy rainfall and strong winds hurricanes are capable of producing storm surge and high waves, all at the same time. Therefore coastal regions, like Galveston Bay, are vulnerable to damage (to property, nature and even loss of life) from a hurricane. The Texas coast, together with Louisiana and Mississippi, experiences highest surges within the Gulf of Mexico, due to the wide and gentle continental shelf and the curve of the coast (Needham & Keim, 2012). Erosion and relative sea level rise may further enhance this hazard.

[9] Saffir-Simpson Hurricane Wind Scale: a 1 to 5 rating based on a hurricane's 1-minute averaged sustained surface wind speed (Schott et al., 2012)(Appendix A.2)

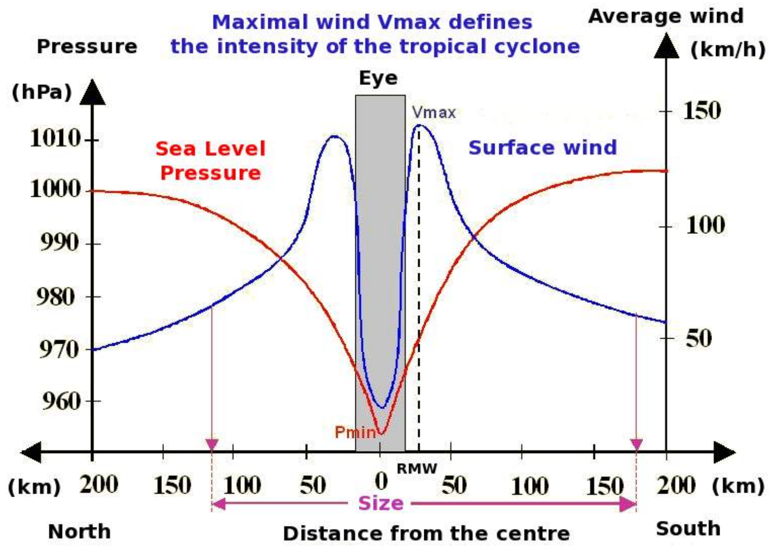


Figure 2.15: Typical wind speed and pressure profiles across the diameter of a Southern Hemisphere hurricane (meteo.fr)

The fact that hurricanes may inflict damage to nature, economy and property became clear by hurricane Ike, the most recent devastating hurricane that struck Galveston in 2008. Ike caused for about 30 billion dollars worth of damage and more than 100 casualties, of which 20 direct and 64 indirect (Roth, 2010). Inside Galveston Bay, more than 50% of the oyster reefs were destroyed by Ike because of sediment and debris smothering the live oysters (Galveston Bay Status and Trends, 2014; GBF, 2014; Haby et al., 2009), causing a reduction of 77% in projected yearly revenues for the Galveston Bay oyster industry (Haby et al., 2009). During Ike more than a half million gallons of oil (2 million liters) spilled into Galveston Bay and the Gulf of Mexico (Fox, 2008). Another example is a hurricane referred to as 'The Great Storm', which struck Galveston in 1900 and caused for $70 billion in present-day normalized damage (Pielke et al., 2008). Hurricane damage is always a risk in Galveston.

2.4.3. TEXAS HURRICANE HISTORY

The hurricane season for the Atlantic region, the time of the year in which the conditions are most optimal for hurricanes to occur, is between June 1st and November 30th. An analysis by Keim et al. (2007) shows that a hurricane hits the Galveston coast with an average return period of 8 years (see Figure 2.16). A major hurricane (category 3 or higher) makes landfall every 26 years on average (Keim et al., 2007).

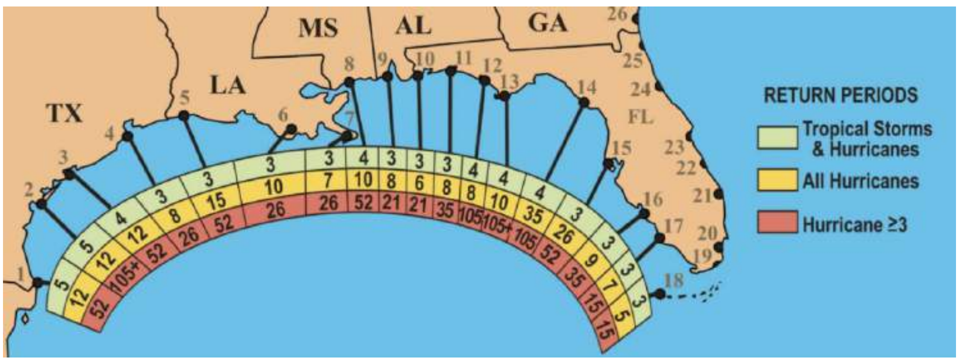


Figure 2.16: Return periods for tropical storms along the Gulf Coast of the U.S. Adapted from Keim et al. (2007) (Stoeten, 2013)

Texas exhibits a long history of hurricanes. Some of the most significant hurricanes ever to struck Galveston were Ike in 2008, the Great Galveston Hurricane (or The Great Storm) from 1900 and the Galveston Hurricane of 1915. Roth (2010) mentions a number of 64 hurricanes hitting the coast of Texas from 1850-2009 in 'Texas Hurricane History', an annual average of 0.4 per year. Hurricanes have been recorded since 1527, but prior to 1829 a relative lack of storms can be found due to sparse population and few surviving records (Roth, 2010). Stoeten (2013) states that prior to 1900 statistical records lack the accuracy required for modeling of storm surge. Therefore Stoeten (2013) made a statistical analysis of historic hurricanes affecting Galveston

Bay from 1900 to 2012. According to Stoeten (2013), 26 hurricanes made landfall within a 200 km radius from Galveston Bay between 1900 and 2012. He calculated the recurrence interval of hurricane intensity for a stretch of 400 km coast for the 26 hurricanes between 1900 and 2012, resulting in Figure 2.17.

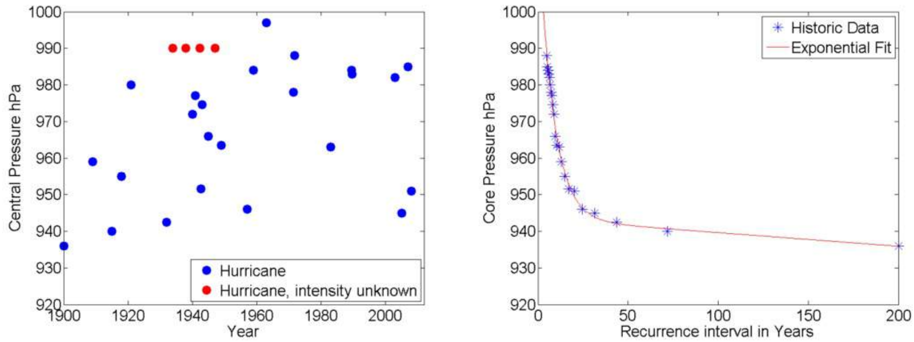


Figure 2.17: Recurrence interval of the core pressure in mbar within a 200 km distance from Galveston (right), over the period 1900-2012 (Stoeten, 2013)

IKE

Ike is the reference storm for many projects in the Galveston Bay area and the catalyst of almost all flood protection research efforts in the Bay area. Ike was a large and slow moving storm. It was nearly 1,000 km across and the radius to maximum winds was around 75 km at the time of landfall (NOAA, 2015). When Ike made landfall on September 13, 2008, it was a strong category 2 hurricane on the Saffir-Simpson scale (Appendix A.2). Measured wind speeds of hurricane Ike were around 40 m/s (Stoeten, 2013).

2.5. ESTIMATED VULNERABILITY OF GALVESTON BAY

The problem in Galveston Bay is clear: high vulnerability, low protection and high risk. A simple analysis in this section, based on water level return periods estimated by Stoeten (2013) and hurricane wave conditions, will endorse this.

Stoeten (2013) evaluated an order-of-magnitude estimate of return periods of surge at the open coast and within the bay with a 1D analytical model which calculated surge along 2 transects. Subsequently created a map of estimated inundations for these different return periods created using ArcGIS software (Figure A.14). It can be concluded that a 100 year event will flood most of Galveston Island and all of Bolivar Peninsula and some areas along the western end. The 1,000 year event will flood Texas City and some parts along HSC. The 10,000 year event will flood significant areas along HSC, which would probably result in high economic damage.

Using Figure A.14, the analysis is extended to calculate protection levels and required extra protection of specific areas in Galveston Bay. The principle used is that protection is required, no flooding is accepted. Figure 2.19 shows a figure with the results of an analysis of the safety levels inside Galveston Bay. The safety levels are determined as peak surge of a 1/100 year^{-1} storm, as simulated by Stoeten (2013). Added are plain wave heights which could be expected during a similar, 1/100 year^{-1} equivalent storm. Water levels and wave heights combined with the local elevations defined by Stoeten (2013), one can have an idea of which areas in the Bay are have a certain protection level. The situations with and without Ike Dike are presented. It should be noted that this is based on a very simple analysis with generalized numbers for surge and waves. Required protection level is determined by simply adding wave heights to surge heights to define a water level (similar to maximum water surface elevation). Wave heights used are outcomes of wave simulations of hurricane Ike, whom are consistent with data from literature for hurricane Ike of e.g. Hope et al. (2013).

It can be seen that for a 1/100 year^{-1} storm, according to this analysis, the combined effect of surge and waves would imply that West Bay and the Bay-side of Galveston are most vulnerable. In the current situation (no Ike Dike) the whole Galveston Bay, including the HSC, would require protection to prevent flooding. In the situation of an Ike Dike, West Bay and the bay-side of Galveston would require protection to prevent flooding.

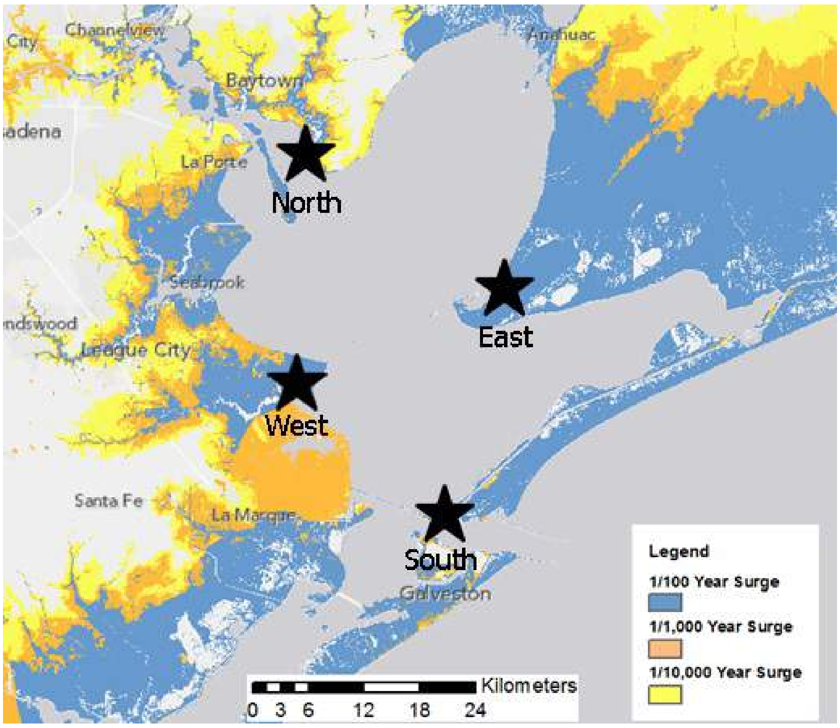


Figure 2.18: Inundation patterns for different return periods in Galveston Bay, as estimated with a 1D hurricane and flow model for Galveston Bay. Surge levels are combined with local elevation using ArcGIS software (Stoeten, 2013)

2.6. FLOOD PROTECTION FOR GALVESTON BAY

2.6.1. DEALING WITH HURRICANES IN THE USA

Current hurricane protection structures in the Galveston Bay region are the Texas City Dike and the Galveston Seawall (Blackburn et al., 2014). The rest of the area lies virtually unprotected from storm surge and waves, as opposed to e.g. New Orleans (LA), where levees and storm surge barrier have been implemented after hurricane Katrina.

The coastal region is divided into floodplains, managed by the US National Flood Insurance Program. The current standards for exceedance probability of water levels in the floodplains is 1/100 year^{-1}, like in the rest of the United States. The National Flood Insurance Program bases their policies on occurrence rate of floods in the future, and the impact of those floods (Warner & Tissot, 2012). However, floodplain maps do not account for erosion, relative sea level rise, degradation or settlement of levees, changes in storm climatology and effect of multiple storms, according to FEMA (2009). This suggest the floodplain classification system will not work properly in the near future. This is complementary to a statement of National Research Council (2014), whom states that "there is no solid basis of evidence to justify a default 1 percent annual chance design level. The 100-year flood criterion was established for management purposes instead of achieving an optimal balance between risks and benefits". It would be of great interest to all protection plans and the National Flood Insurance Program to estimate storm surge events and their likely impact as accurate as possible (Warner & Tissot, 2012).

On the other hand, for the Gulf Coast, the safety level of 1/100 year^{-1} is justifiable. This can be explained by a figure made by Philip Orton of the Stevens Institute in Hoboken, New Jersey (Figure 2.20). In the figure return periods of flood levels of the Netherlands, New York City and Mississippi are compared, based on three scientific articles. Because Texas is not part of the analysis, it is assumed that return periods for the Upper Texas Coast are comparable to those of Mississippi. From the figure it can be seen that the estimated water levels (flood height) for an event with a return period of 100 years in Mississippi is higher than in NYC or the Netherlands. Additionally, an increase in return period will have even much higher consequences in Mississippi with respect to water level as the gradient of the line is steeper. This is probably due to the extreme and variable nature of hurricanes, which are not present in the Netherlands. Therefore is a high return period (e.g. 1/10,000) much easier to maintain in the Netherlands than in USA in general and especially along the Gulf Coast.

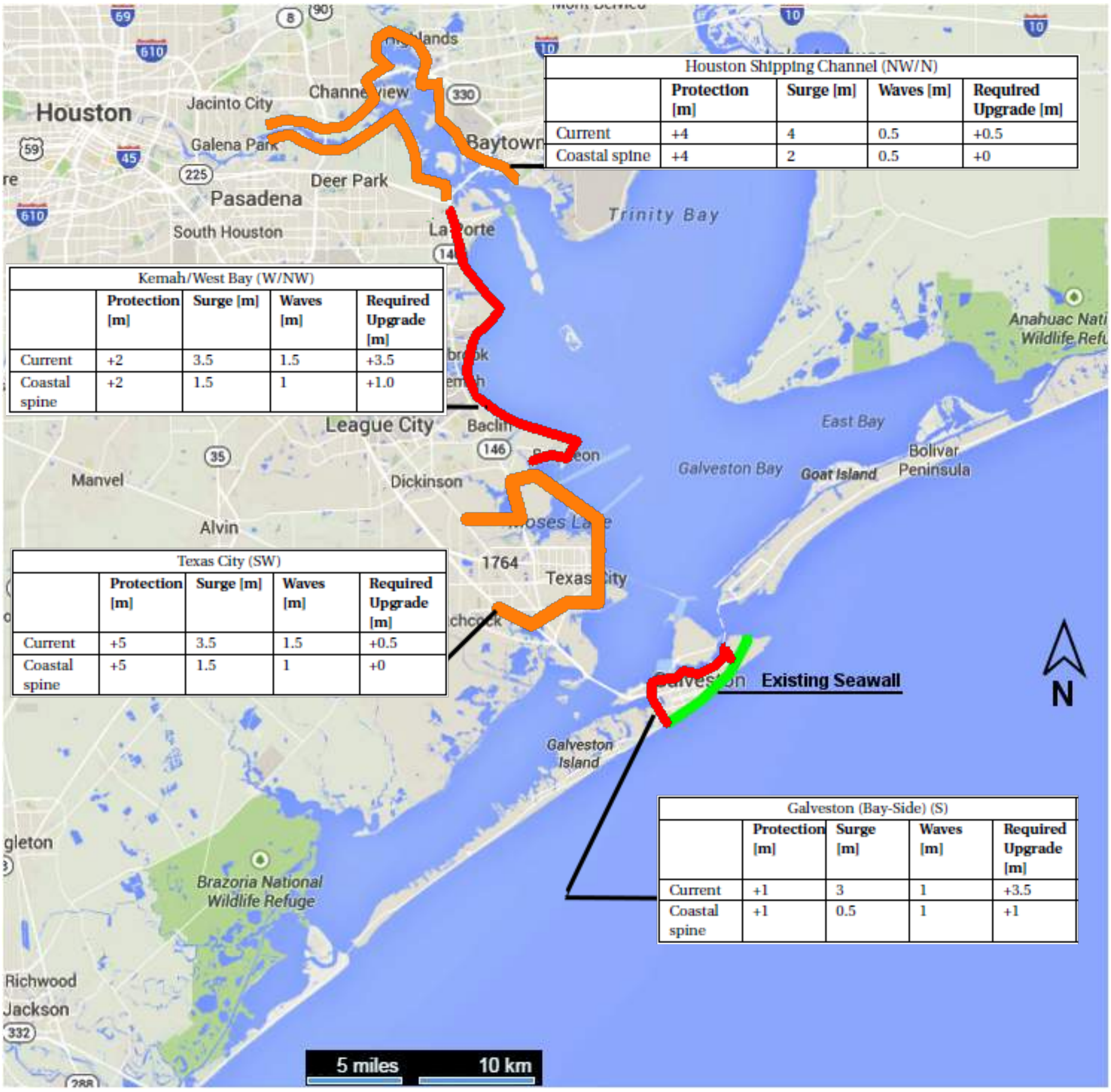


Figure 2.19: Protection levels and simplified required protection upgrade for four generalized areas of Galveston Bay for a 100 year design storm as defined by Stoeten (2013). Maps: Google (2014); Data water levels: Stoeten (2013); Data wave heights: Hope et al. (2013)

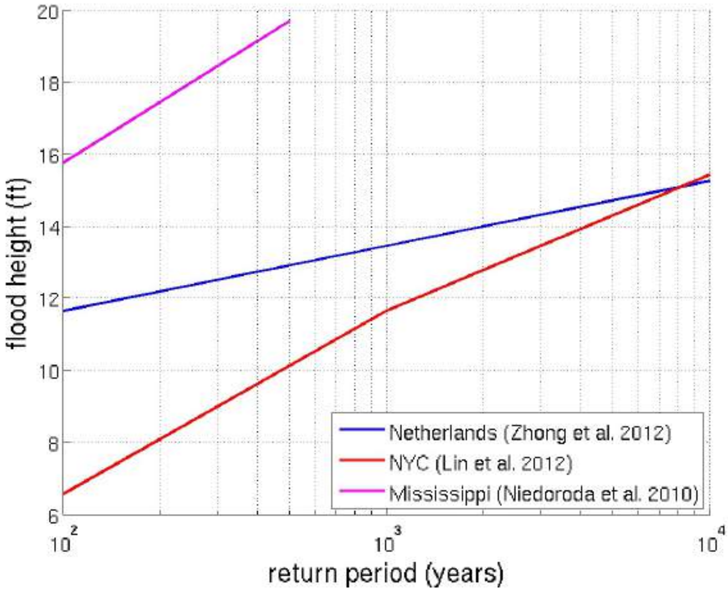


Figure 2.20: Hazards of the Netherlands, NYC and Mississippi (Philip Orton, Stevens Institute, Personal Communication, November 2013)

Policy makers in the U.S. focus on predicting flood hazards and mitigating the effects thereof (Bijker, 2007). This suggests that flooding is accepted, at least to some extent. Generally "strategies which reduce consequences of storms have documented high benefit-cost ratios, but are given less attention by the federal government", according to National Research Council (2014). However, the federal government is trying to move people out of the vulnerable areas of the 1/100 year floodplain, according to Antonia Sebastian (Personal Communication, September, 2014). When lands are damaged by storm surge, the government will try to buy out people that live there to create natural vegetation instead of urban area. Gradually the most vulnerable areas will turn into less urbanized areas. This has happened since the 1990's. Another example is given by Bates, Kundzewicz, Wu, and Palutikof (2008), whom state that "households with two flood-related claims are now required by the National Flood Insurance Program to be elevated by 2.5 cm above the 100-year flood level, or to relocate".

2.6.2. FLOOD PROTECTION PLANS FOR GALVESTON BAY

However, recent developments indicate that bigger flood protection projects are gaining momentum for federal support according to Harvey Rice, a writer for the Houston Chronicle (Personal Communication, October 2014). This is confirmed by Merrell et al. (2011) and Blackburn and Bedient (2010). The reason for this momentum gain could be the growth of Houston and its economic value and its big drivers like the port and the petrochemical industry. With accelerated SLR the region could be pressured even more because of its elevation and low protection level (Yoskowitz et al., 2009). Two distinctive different strategies are explained.

1. The Ike Dike proposition involves a closed Bay. The Ike Dike concept focuses on stopping the surge at the coast with a system of barriers on Galveston Island and Bolivar Peninsula and a barrier in Bolivar Roads Inlet (Merrell, 2014; Merrell et al., 2011). The barrier would consist of a movable, navigational section allowing ship traffic at normal conditions and a static, environmental section. A storm surge barrier in the inlet is required to prevent surge at the open coast from penetrating into Galveston Bay. This so-called coastal spine approach is based on the Dutch Delta Works. Schematizations of the proposed Ike Dike can be seen in Figure 1.1 and Figure A.16a. The Ike Dike aims at protecting the whole Galveston Bay from storm surge from the Gulf. However, significant local induced surge due to wind set-up inside the Bay can be expected.

2. This strategy proposes an open Bay with local measures along the perimeter of Galveston Bay (Figure A.16b). A large-scale barrier called the Centennial Gate in the North where the HSC enters the harbor, however, is the biggest structural component of this strategy (Blackburn et al., 2014; Blackburn

& Bedient, 2010). The strategy is composed around the fact that HSC is at very high risk because of its economic value. Other components are for example dredge spoils along the HSC, oyster reefs or a levee for the urbanized and vulnerable western shoreline of Galveston Bay. This strategy does not aim at protecting the whole Galveston Bay, but protects areas that are most vulnerable and economically valuable such as the industries along the HSC. If one also wants to protect all assets along the Galveston Bay e.g. dike heightening along the entire Bay will be necessary.

As of early 2015 research teams of both strategies made an alliance to combine their plans to form an integral plan to protect the Houston-Galveston Bay region. Their goal is to design an Ike Dike, combined with local measures in Galveston Bay to reduce surge-based flood risk in the region. Whether or not this is with a Centennial Gate is yet unknown. All components of the combined plan are displayed in Figure 2.21.

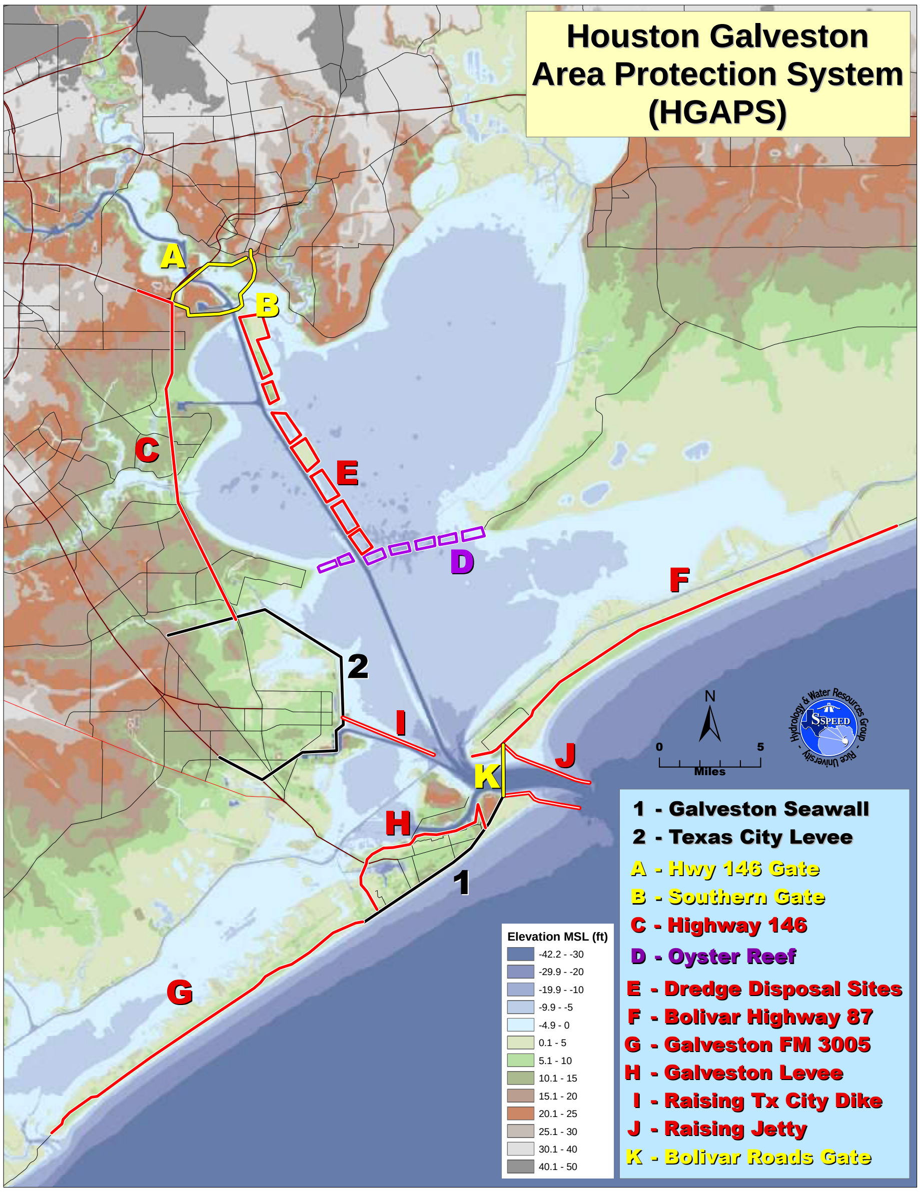


Figure 2.21: HGAPS: all components of the combined research effort to protect Galveston Bay (SSPEED, 2015))

2.7. CONCLUSIONS

Galveston Bay has been analyzed and relevant aspects within the system have been discussed in this chapter, with respect to the physical system, the natural system and flood protection plans for Galveston Bay. The following conclusions can be drawn:

- Galveston Bay is a micro-tidal estuary with an ebb-dominant asymmetry. Therefore it is expected that fine sediment is transported into and trapped by the system. The coarser sediments on the other hand are moved from the flood-tidal delta out of the Bay system. Erosion of shorelines, wetlands and seagrasses in Galveston Bay has been a result of relative sea level rise and insufficient sediment supply. The estimated sediment deficit is around 7 mm year^{-1}. The Upper Gulf Coast of Texas is prone to frequent hurricanes, on average a hurricane makes landfall every 8 years. A major hurricane with a category 3 or higher has a return period of about 26 years.
- Galveston Bay supports a wide variety of marine life (e.g fish, colonial birds and shellfish) and habitats. Three most important habitats in Galveston Bay are: wetlands, oyster reefs and seagrasses. Wetlands are under pressure but still present and seagrasses are rare in the Bay nowadays. On the other hand, oyster reefs are abundant in the Bay. The estuarine and saltwater wetlands have been disappearing by 20% since the 1950's up to now. After 1989, this trend slowed down and eventually reversed because of extensive restoration projects. Oyster reefs have historically been impaired as well. The main reasons have been commercial shell harvest and changing circulation and salinity patterns. Approximately 16% of historical oyster reefs has been lost.
- Although policy in the US generally focuses on mitigating effects of flood hazards, large-scale flood protection projects seem to be gaining momentum in Galveston Bay. Two distinctive strategies are a closed Bay (Ike Dike concept) or an open Bay with local measures, such as a barrier at the HSC in the North of Galveston Bay. Both strategies have been combined as of 2015 to integrally protect the Houston-Galveston Bay region. However, no systematic approach with respect to BwN measures for flood risk reduction has been followed yet.

These conclusions with respect to the system are an important step towards the next chapter, where the hurricane hydraulics of Galveston Bay will be discussed, and moreover to Chapter 4, in which BwN building blocks for Galveston Bay will be identified.

3

HURRICANE HYDRAULICS OF GALVESTON BAY

This chapter discusses relevant hydraulic characteristics with respect to hurricane conditions for Galveston Bay. It starts with a general hurricane surge description of observations ans hurricane parameters. Moreover, the mechanisms causing surge and waves will be discussed. Finally, the formulations to describe these processes are presented. The main focus is on the mechanisms surge and waves, because they contribute to hurricane damage to a great extent. Surge and wave action was significant on the western shore of Galveston Bay during hurricane Ike, evidenced by huge damage to structures like roads, rip-rap and piers. One third of the damage estimates for Harris County are associated with surge and waves (HARC, 2014b).

3.1. HURRICANE SURGE GALVESTON BAY

3.1.1. HISTORIC SURGE OBSERVATIONS

Hurricane induced storm surge is measured by water levels in- and outside of Galveston Bay. Observations inside Galveston Bay lead to increased understanding of Bay behavior during hurricanes. Figure 3.1 presents outcomes of an analysis conducted by NOAA (2014) of return periods of water levels at Galveston Pleasure Pier with a confidence interval of 95%. It can be seen that the water level for a return period of 100 years is around 2.6 m +MHHW (mean high high water). The 95% confidence interval is between 1.8 and 4.8 m +MHHW.

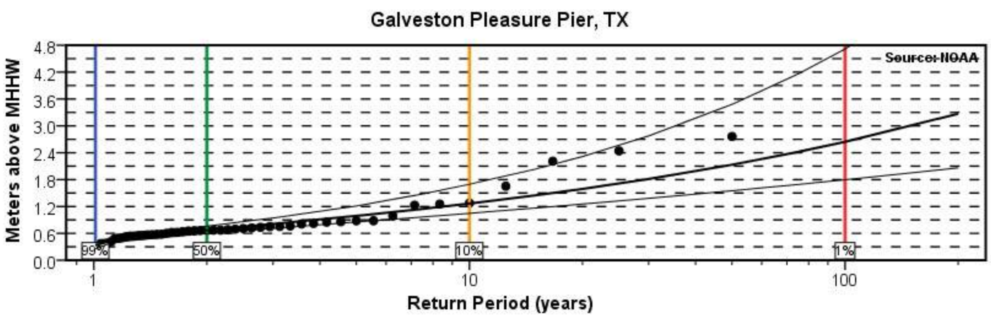


Figure 3.1: Return period of surge levels for Galveston Pleasure Pier (NOAA, 2014)

Table 3.1 presents historic peak surge observations near Galveston Bay of some significant hurricanes. Hurricanes of which data was insufficient such as the 1900 and 1915 hurricanes are not part of this table. The analysis has been conducted by Stoeten (2013). From Table 3.1 it can be seen that surge levels in the Bay are often different from surge levels at the open coast. It depends on the storm characteristics (e.g. landfall location) whether the surge in the Bay exceeds the surge at the open coast. From the table it is clear that this effect occurs for storms making landfall west of Galveston.

Table 3.1: Observed surge levels in and out of Galveston Bay for different recent hurricanes (Stoeten, 2013)

Hurricane	Cat	Landfall Location	Peak surge open coast	Peak Surge North Bay	Peak Surge South Bay
Carla (1961)	5	180 km West	3 meter	4 meter	3 meter
Alicia (1983)	3	50 km West	2.5 meter	4 meter	3 meter
Ike (2008)	2	0 km	4.5 meter	4.5 meter	3.5 meter
"Surprise" (1943)	2	30 km East	unknown	-1.5 meter	-1.5 meter
Cindy (1963)	2	50 km East	0.8 meter	-1 meter	1 meter
Rita (2005)	5	120 km East	1.5 meter	1 meter	1.3 meter
Andrew (1992)	3	200 km East	-	- 1.5 meter	1.5 meter

3.1.2. SURGE HURRICANE IKE

Highest storm surges during hurricane Ike were recorded along the Bolivar Peninsula, eastward of Galveston. Storm surges on Bolivar Peninsula were between 4-6 m (16-20 feet) (Berg, 2009) above NAVD 88[1]. Surge levels observed at Pleasure Pier in Galveston were 3 m +MSL (Stoeten, 2013). Due to the surge the barrier islands were completely overwashed and storm surge propagated inside Galveston Bay (Rego & Li, 2010). A plot of several hydrographs of different observations points in and around Galveston Bay can be seen in Figure 3.2. A distinctive feature of Ike was the large early rise of water prior to landfall called the forerunner (Kennedy et al., 2011), which can clearly be seen in the plot. This phenomenon will be explained later this chapter.

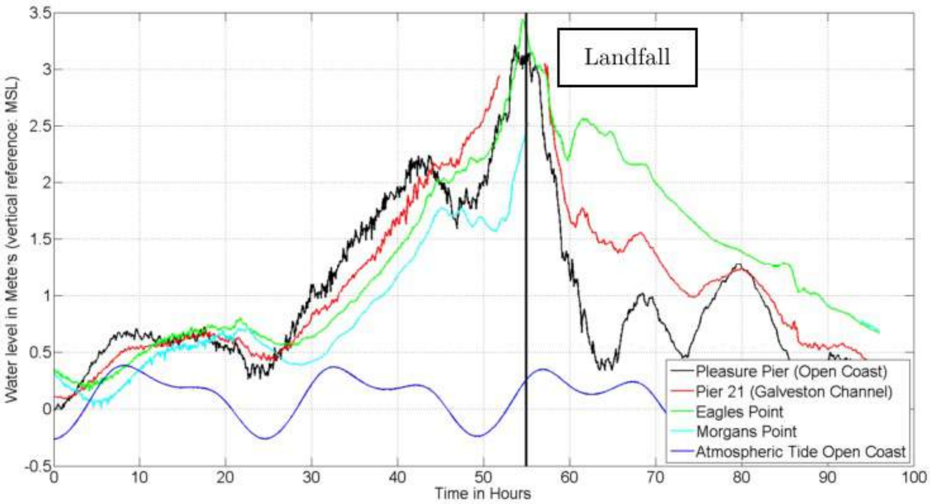


Figure 3.2: Hydrographs of observed water levels during hurricane Ike in 2008. Data: NOAA (2014) (Stoeten, 2013)

3.1.3. HURRICANE PARAMETERS AFFECTING SURGE

Hurricanes have certain parameters which influence the storm surge potential at the coast. It is a common fallacy that the well-known Saffir-Simpson Hurricane Wind Scale is the most optimal scale to describe potential surge height, as surge depends on many parameters. The following hurricane parameters are important for surge potential (see e.g. Needham and Keim (2012) and Resio and Westerink (2008)):

- Trajectory: the trajectory determines the time a hurricane spends over open water. The factor, angle and location of landfall all have influence on the surge a hurricane produces. The longer the hurricane is going over open water in a straight line, the higher the surge usually is.
- Forward Speed: it is shown that slow moving storms produce an increase in flooded volume but decrease peak surges, while faster moving storms generate a higher peak surge but travel less far inland (Rego & Li, 2009).
- Distance or radius to maximum wind speeds (size): larger storms produce highest surges (Resio & Westerink, 2008).

[1]NAVD 88 is the North American Vertical Datum of 1988. This is the vertical control datum of orthometric height established in 1991. It was established for vertical control surveying in the U.S. and based upon the adjustment of the North American Datum of 1988. In Galveston Bay NAVD88 is roughly equal to MSL (0.18 m difference) (NOAA, 2014)

- Maximum wind speeds (intensity): the Saffir-Simpson Hurricane Wind Scale(SSHWS) is the scale to classify the hurricane by wind speeds (Appendix A.2). Usually storms with higher wind speeds produce higher surges.
- Pressure under core: a lower pressure generally produces higher surge. The pressure under the core of a hurricane is highly correlated to its wind speeds, because wind speed is a result of a pressure gradient.

There are certain relevant coastal parameters as well as parameters of the hurricane itself. These are characteristics of the coast at the location of landfall. Some system parameters influencing surge potential are:

- Steepness of the continental shelf: usually a wide and gentle shelf produces higher surges. The Upper Texas coast has a relatively gentle (1:2,000) and wide shelf, causing high surges.
- Curve of the coast of the bay or estuary: inward curve of Upper Texas coast usually causes large surge heights. Because of that funneling effect, the water cannot 'escape' and gets piled up against the coastline.
- Frequency of hurricane strikes: this varies per region or state. We have seen that the Upper Gulf coast is very prone to hurricanes. Only Florida and Alabama have higher frequencies of hurricane strikes (Keim et al., 2007).

3.2. SURGE MECHANISMS OPEN COAST

Rego and Li (2010) state that storm surge at the coast is a complex relation between coastal geometry, bathymetry, wind and pressure forcing. The relationship with geometry is close, which implies that an exact representation of site dependent characteristics makes significant impact on accuracy of surge predictions.

Surges at the open coast are a combination of the following components, see e.g. Dean and Dalrymple (2004):

- Wind set-up: wind driven surge is inversely proportional to the depth. Water 'piles up' at the coast. This set-up is greatest on wide and gentle continental shelves. The wind driven set-up is usually the largest component of storm surge.
- Pressure driven surge: hurricanes have a low core pressure, which means the water surface is lifted. Usually this effect contributes to around 5% of the total surge(National Weather Service, 2014). General rule is a rise in water level of 10 mm for every mbar drop in pressure.
- Astronomical tides: strictly speaking not a component of storm surge, but a component of storm tide[2] and plays therefore a vital role. A higher water level is observed when a hurricane would strike for example during spring tide.
- Wave set-up: according to Weaver and Slinn (2004), "this is caused by the generation and release of wave momentum as waves shoal and break". Thus wave set-up is an effect of breaking waves on the total water level. This effect is especially significant for steep continental shelves, which is the case in Louisiana. During Katrina wave set-up was 2-4 feet (Irish & Cañizares, 2009; USNRC, 2012). And for Long Island, NY, Irish and Cañizares (2009) calculated a wave-induced set-up of about 15-35% of total storm surge. However, even for wide and gentle shelves like the shelf near Galveston Bay wave set-up could still be a significant component.
- Coriolis set-up (or Ekman set-up): occurs when strong currents flow along the shoreline due to the hurricane. Wind generates alongshore currents and due to a Coriolis force, net currents are rotated. The resulting current can only be balanced by a water level gradient.
  - *Ekman set-up due to Coriolis effect can be the cause for forerunners. The forerunner during Ike was a result of the Ekman set-up. Ekman set-up is most significant when the storm moves with moderate speed and the continental shelf is wide and gentle, as is the case for the Upper Texas coast (Kennedy et al., 2011).*

A graphic representation of the storm surge components is presented in Figure 3.3.

[2] Storm tide is defined as the water level rise due to the combined effect of storm surge and astronomical tides (National Weather Service, 2014)

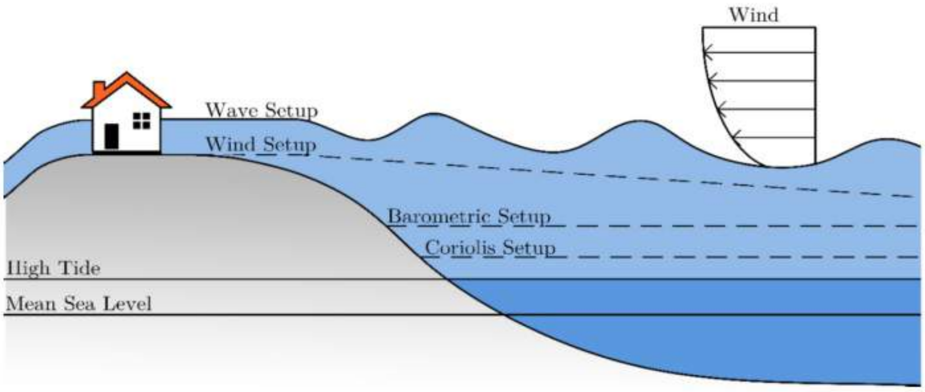


Figure 3.3: Hurricane storm surge components at the open coast (Stoeten, 2013)

3.2.1. FORERUNNER SURGE

Forerunner surge is a special phenomenon where an early rise in water levels is observed, up to several days prior to landfall. These *forerunners* typically have amplitudes under 1 m (Kennedy et al., 2011). Several explanations can be given for the occurrence of forerunners: barometric surge from lowered pressure, wave set-up, seiching modes and Ekman set-up (Kennedy et al., 2011). Not every hurricane event produces a forerunner, it is an infrequent phenomenon.

During Ike a large forerunner was observed, which arrived prior to landfall and started filling Galveston Bay at an early stage. Large forerunners were also present during the devastating 1900 and 1915 hurricanes, whose tracks were similar to the track of Ike (Kennedy et al., 2011). In the case of hurricane Ike the forerunner was special. It was large, with a peak of 1.4 m, and arrived 12-24 hour prior to landfall. Furthermore it was observed in large portions of the western Louisiana and northern Texas coast (Kennedy et al., 2011). It propagated as a free wave over the shelf. The long time-scale of the forerunner served to increase the water levels in estuaries with narrow inlets, like Galveston Bay. The Ike forerunner was induced by the Ekman set-up from alongshore currents propagating over a wide continental shelf. Coriolis force causes this currents to induce in a water level gradient (Bunpapong, Reid, & Whitaker, 1985; Kennedy et al., 2011). Ekman driven forerunners are most significant when a large storm moves over a wide shelf with a moderate forward speed Kennedy et al. (2011). All these criteria were met in the case of hurricane Ike at the Upper Gulf Coast.

3.3. SURGE MECHANISMS INSIDE GALVESTON BAY

Surge inside a semi-enclosed bay is a complex combination of the mechanisms inflow, overflow, wind set-up and wave set-up (Shen, Wang, Sisson, & Gong, 2006):

- Surge at open coast: the surge at the open coast determines the amount of inflow and overwash over the barrier islands and subsequently the surge levels inside the bay. These mechanisms are complex. The barrier islands (about 1-3 meters elevated above MSL) partly reflect the storm surge, and although they were overwashed they play a crucial role in reducting surge levels inside the bay (Rego & Li, 2010).
- Local wind set-up in semi-enclosed bay: the wind set-up is inversely proportional to the depth. Due to the rotating motion of the hurricane this wind set-up can induce 'sloshing' behavior.
- Wave set-up: waves transfer momentum which can contribute to total water levels (Resio & Westerink, 2008). This factor only occurs if waves break. Wave set-up is scaled with the significant wave height at breaking which depends on the steepness of the bed. Inside Galveston Bay wave set-up is assumed to be small, because wave heights are generally limited and the gentle slope (FEMA, 2008; Holthuijsen, 2007; Resio & Westerink, 2008; USNRC, 2012). Following e.g. Holthuijsen (2007), we see that the wave set-up can be considered as 0.15% of the incipient wave breaking height (1.5 m, see later this chapter), which leads to a wave set-up of around 0.2 m.

A schematic plot of hurricane surge inside a semi-enclosed bay can be seen in Figure 3.4.

Documentation and understanding on Bay behavior under hurricane conditions is not as good as under normal conditions. One of the reasons is that measurement equipment often breaks down during hurricane

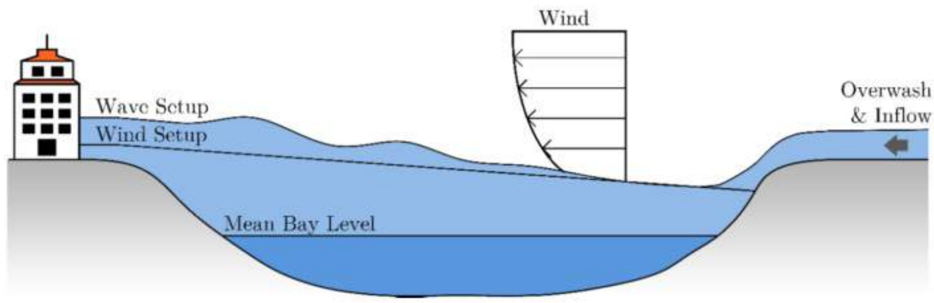


Figure 3.4: Hurricane storm surge in semi-enclosed bay such as Galveston Bay (Stoeten, 2013)

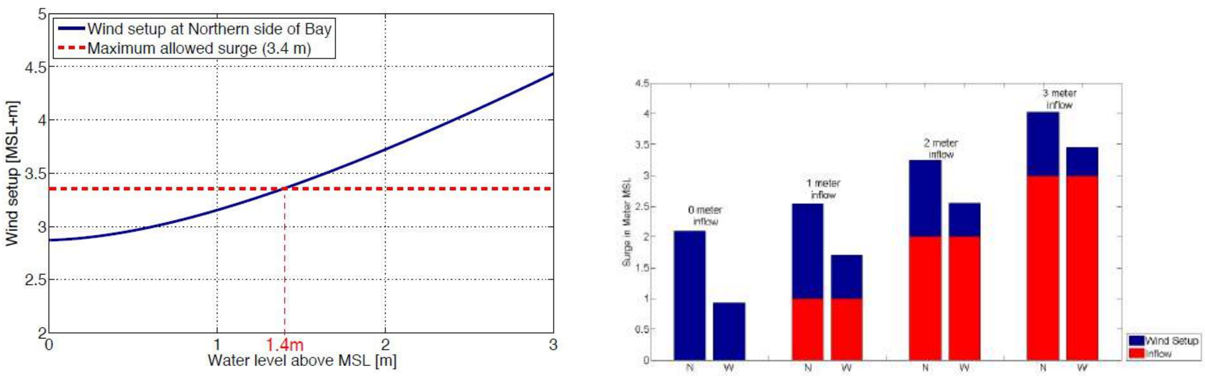
conditions and observations are scarce. Most modeling studies that investigated surge behavior inside the Bay, focus on peak surge levels, while some focus on dynamics of surge within bays.

Rego and Li (2010) state that barrier islands play a crucial role in Galveston Bay surge levels and that the bay would have experienced much higher (dangerously high) surge levels during hurricane Ike if the barrier islands would have been 45% of their current volume and would have two breaches (according to the writers this could be the result of a realistic erosion scenario). Rego and Li (2010) state this highlights the complex nature of the hurricane hydraulics in the Galveston Bay system.

3.3.1. BAY SURGE DYNAMICS

RELATION WIND SET-UP AND WATER LEVEL

Storm surge within Galveston Bay is a delicate balance between inflow and local wind set-up, which depends on wind velocity, fetch and water depth. The influence of local wind set-up on storm surge within semi-enclosed bays is found to be significant. Stoeten (2013) assessed the influence of the elevated water levels of the bay on the local wind set-up with elevated bay levels by 0-3 m. A similar assessment has been done by de Vries (2014). Both assessments used a different reference wind speed and water levels for the analysis. See Figure 3.5 for both outcomes.



(a) de Vries (2014)

(b) Stoeten (2013)

Figure 3.5: Sensitivity of wind set-up to different water levels, determined by Stoeten (2013) and de Vries (2014)

It is confirmed that relative wind set-up decreases with increasing total water depth. It can be seen that the relative increase in surge for each meter of extra water level increases exponentially. Wind set-up contributes around 25-50% to the total surge, with an absolute value of 1 to 1.5 m (Stoeten, 2013).

LANDFALL LOCATION

Surge levels inside the Bay are highly sensitive to landfall location. Due to influencing surge levels at the open coast and on the other hand influencing the local wind set-up in the Bay. Depending on the landfall location, the wind could either forcing water in or out of the Bay (Stoeten, 2013). A hurricane making landfall West of

Galveston will force water into the bay, and while moving onshore wind will shift from easterly, via southerly to westerly winds, subsequently influencing surge levels in the Bay. The opposite can be seen from a hurricane making landfall East of Galveston Bay. Such a hurricane will force water out of the Bay and while it moves onshore the wind shifts from easterly, via northerly to westerly direction affecting different area at the shore. See Figure 3.6 for these dynamics. These mechanisms can be clearly distinguished in observed surge levels in- and outside of Galveston Bay as well, which has been shown in Table 3.1.

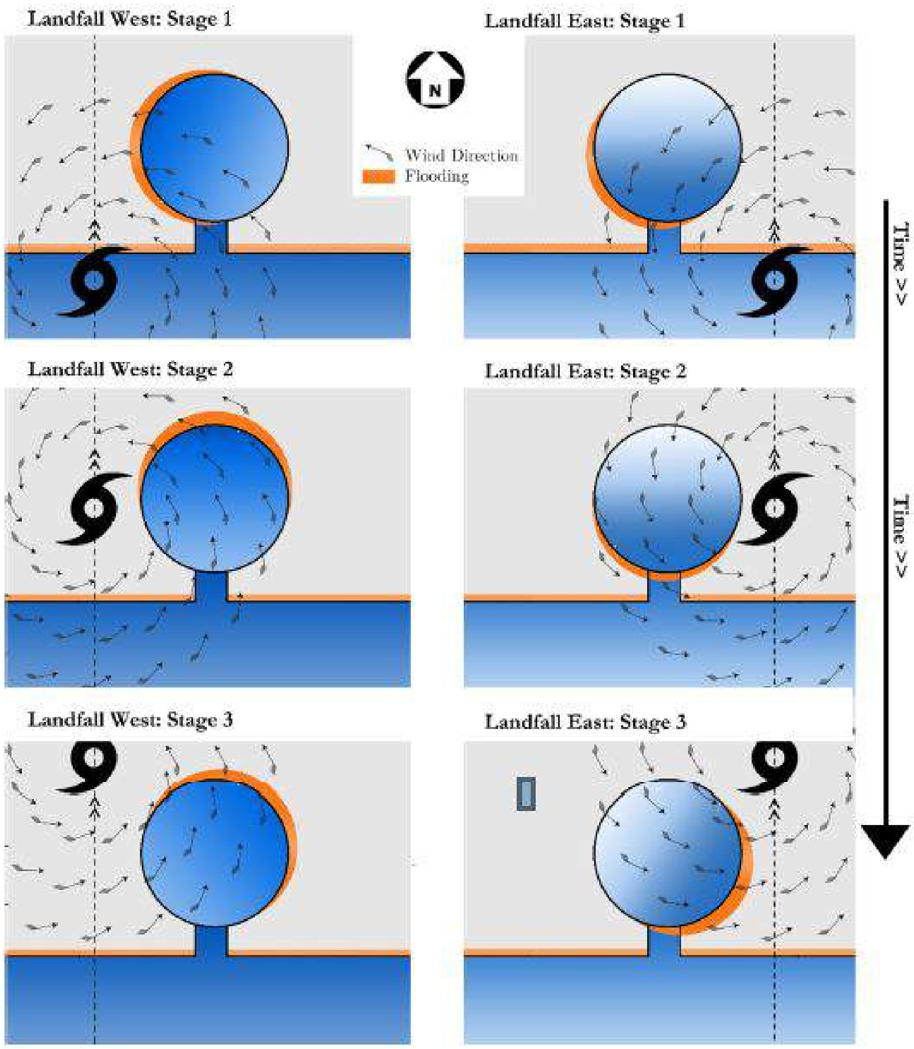


Figure 3.6: Influence of landfall location on surge and wind set-up in semi-enclosed basins (Stoeten, 2013)

Sebastian et al. (2014) investigated influence of landfall location on surge levels in the bay by shifting hurricane Ike while maintaining the angle of approach. They found that a shift of 40 km to the Southwest resulted in the highest surges in West and North Galveston Bay (highest risk involved), due to more intense shore-normal winds. This is what was expected from Figure 3.6 as well.

SLOSHING

Rego and Li (2010) investigated the behavior of Galveston Bay after hurricane Ike. They state that water level gradient due to wind set-up can change quickly. This phenomenon is called sloshing behavior and it could occur in semi-enclosed basins. According to Rego and Li (2010) this gradient along a transect east-west in Galveston Bay for hurricane Ike changed from 0.09 m/km westward to 0.08 m/km eastward within 5 hours. The magnitude of the gradient is an effect of the wind speeds of the storm, the path and bay geometry (Rego & Li, 2010). "The separation in time of these gradients is a direct result of hurricane's traveling speed", according to Rego and Li (2010). Thus the sloshing effect can be related to the storm's path instead of natural seiching of the Bay and is therefore a direct result of local induced wind set-up.

SEICHING

Although Rego and Li (2010) stated that the water surface gradient occurring during Ike was not seiching, this phenomenon could be an issue. Natural seiching of the basin can occur when the atmospherical fluctuation period matches the eigenperiod (or seiching period) of the bay. Temporal scales in the order of the seiching period might be possible and occurred in other systems like Lake Okeechobee and the Lake IJsselmeer before (de Jong, Bottema, Labeur, Battjes, & Stolker, 2006). According to Stoeten (2013) the eigenperiod of Galveston Bay is in the order of 2-4 hours. This can be approached by a simple analysis: the eigenperiod of Galveston Bay is roughly estimated to be around 4 hours ($d = 3m; l(lenght\,basin) = 40,000m; L(wave\,length) = 2 \cdot l = 80,000m \Rightarrow L/c = L/\sqrt{gd} = 4$ hours). Whether seiching is a problem for Galveston Bay should be investigated. Though it is not part of this thesis.

3.3.2. WIND SET-UP FORMULATIONS

ASSUMPTIONS

The following assumptions can be made with respect to the hydraulic system of Galveston Bay:

1. Hydrostatic pressure and incompressible fluid.
2. Shallow water is assumed for long waves (surge). This means the length scale of the water movement >> the water depth ($d << \frac{1}{20} \cdot L$).
3. Time to steady state wind set-up is assumed to be about 2 hours (see e.g. Dean and Dalrymple (1991); Stoeten (2013)).

As wind increases the water surface in a (semi) enclosed basin tilts and forms a slope upward towards the lee side of the wind. The resulting hydrostatic pressure results in a return flow. For constant wind, negligible pressure and sufficient duration, the steady state situation of the momentum equation remains (see Equation (B.1)). In that situation return flow is reduced (partly by bottom friction) and water levels builds up. If equilibrium has been reached, all wind shear stress has been transferred into a water level gradient and no flow towards the coast can be observed. In the one-dimensional steady state solution the hydrostatic pressure balances the wind stress (see Figure 3.7).

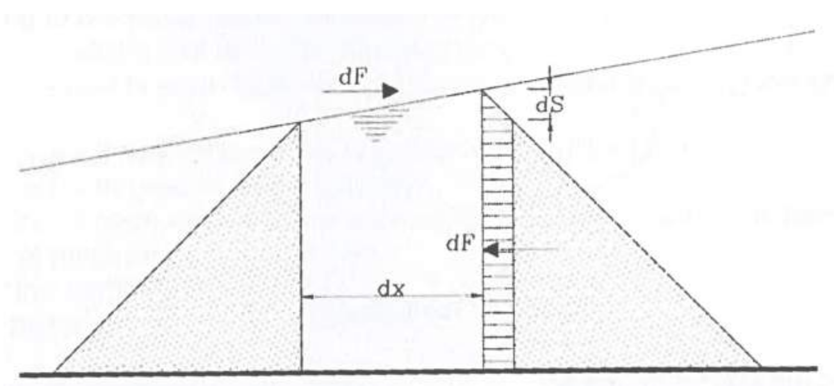


Figure 3.7: Balance of forces for wind set-up (Vrijling, 2011)

Re-writing Equation (B.1) into the equilibrium, steady state equation, therefore neglecting bottom shear stress, the one-dimensional wind set-up can be approximated by Equation (3.1):

$$\frac{d\eta}{dx} = \frac{\tau_w}{\rho_w g h} = \frac{\tau_w}{\rho_w g(\eta + d)} \tag{3.1}$$

where η is the wind set-up at a certain location and $d\eta$ is the total wind set-up over the transect length in [m] ($d\eta$ is equal to dS in Figure 3.7), τ_w is wind shear stress in [Pa], d is the water depth in [m], g is the gravitational constant in [ms^{-2}] and ρ_w is density of the water [kgm^{-3}]. The fetch length here (usually denoted by F) is dx in [m]. Wind set-up increases with increasing wind velocity or decreasing depth.

WIND SHEAR STRESS

The wind shear stress plays an important role in the occurring of wind set-up (see Equation (3.1)). In Equation (3.1) wind shear stress is represented by τ_w. This τ_w is formulated by Equation (3.2):

$$\tau_w = \rho_{air} \cdot C_D \cdot U_{10}^2 \tag{3.2}$$

Where ρ_{air} is the density of air and C_D is the wind drag coefficient. U_{10} is the surface wind velocity measured or estimated at 10 m elevation above the water surface. Usually for storm surge calculations at least the 10-minute (and preferably 30-minute) averaged wind speed is used (Deltares, 2015b; M. D. Powell et al., 2010). The reason for this is that the ocean responds to wind over longer time scales (NOAA, 2015). A derivation of the wind drag coefficient can be found in Appendix B.3.

FETCH LENGTH

Fetch is the distance to upwind coastlines. A representation of some different fetches for Galveston Bay can be seen in Figure 3.8. It shows that fetches for three different transects are around 30 km [19 miles].

Figure 3.8: Fetch lengths for three cross-sections in Galveston Bay. Maps: Google (2014)

DISCUSSION

- Steady state wind set-up in idealized conditions constant wind in time and space, symmetric basin, constant roughness and depth. Continuous wind for a long time is required to achieve the steady state wind set-up. Due to the dynamic hurricane character of a hurricane this assumption seems difficult to justify, especially at time of landfall. At the time of landfall hurricane winds can turn 180 degrees within hours. During Ike this happened in about 5 hours (Rego & Li, 2010)).

- The wind set-up formulation is valid if set-up does not exceed local depth (Stoeten, 2013).

- The wind set-up varies significantly with changes in local depth of the basin. The reason is that the result of constant blowing wind can be two components: a water surface gradient (like described by Equation (3.1)) and a horizontal current (when equilibrium is not yet reached). In steady state and with constant bottom, only wind set-up will occur. But for varying depth more horizontal current will occur and the wind set-up will not be constant.

3.4. WAVES

3.4.1. WIND WAVES OPEN COAST

Wind generated waves typically have periods of below 30 seconds and wavelengths between 0.1 and 1,500 m (Holthuijsen, 2007). Jin et al. (2010) simulated waves for combinations of storm surge and hurricanes classified by category. They found that wave height is generally linearly related to water depth (storm surge included) and is less dependent on wind velocity, at least for very high speed hurricane winds.

Estimated near shore wave heights for San Luis Pass obtained through SWAN simulations by Jin et al. (2010) can be seen in Figure 3.9 and Table 3.2. This analysis shows that the open coast could be exposed to very large waves during hurricane conditions. Note that both figures show maximum wave heights instead of the common used significant wave height H_s. During Ike the Bolivar Peninsula was indeed exposed to very high waves of around 6 meter (Berg, 2009). Sebastian et al. (2014) found by modeling Ike with a coupled ADCIRC and SWAN model that significant wave heights in the Gulf were as high as 7.5 m, but attenuated closer to shore. The slope of the continental shelf at Galveston is gentle, resulting in a dissipative environment. Breaking waves induce wave set-up which affects the water level.

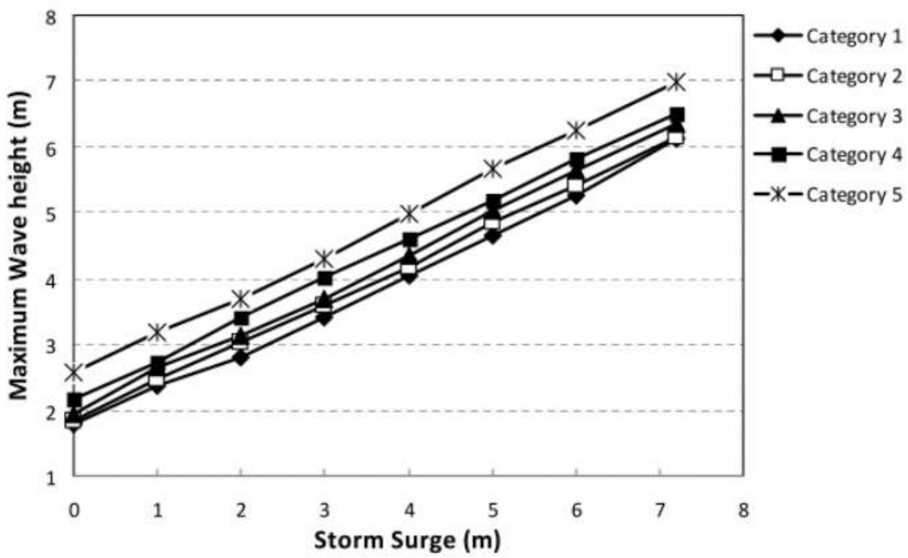


Figure 3.9: Estimated maximum wave height plotted against storm surge level at San Luis Pass for different hurricane categories (Jin et al., 2010)

Table 3.2: Estimated maximum wave heights at San Luis Pass (Jin et al., 2010)

Hurricane Scale	Storm Surge (m)							
	0	1	2	3	4	5	6	7.2
Category 1	1.78	2.38	2.81	3.41	4.03	4.66	5.26	6.13
Category 2	1.85	2.46	3.02	3.60	4.18	4.85	5.40	6.15
Category 3	1.95	2.66	3.14	3.69	4.35	5.03	5.63	6.36
Category 4	2.15	2.73	3.40	4.03	4.59	5.19	5.81	6.51
Category 5	2.57	3.19	3.69	4.30	4.98	5.67	6.26	6.99

3.4.2. WIND WAVES INSIDE THE BAY

Waves within Galveston Bay are most likely depth or fetch limited, depending on storm track and intensity (Stoeten, 2013). Waves will be lower than waves at the open coast, because of the sheltering behind the barrier islands and lower water depths. The Texas City Hurricane Protection was designed for a significant wave height of 1.5 m (A. B. Davis, 1966), while a significant wave height of around 6 m was observed at the coast during hurricane Ike (Berg, 2009).

According to Sebastian et al. (2014) wave heights inside Galveston Bay during Ike were limited to 2-2.5 m, and different simulations of hurricane Ike show a nearshore, significant wave height of 1-1.5 m. Wave height inside Galveston Bay due to generation by wind is directly related to the depth of the estuary, and has less relation to wind speed and fetch length. Waves will eventually diminish due depth-induced breaking when approaching the shoreline. For higher surge levels at the shore the waves will propagate further inland and potentially cause more damage. Wave set-up due to breaking inside Galveston Bay is assumed to be small. Furthermore, the offshore dynamic wave set-up is negligible in the Gulf of Mexico due to its gentle shelf (FEMA, 2008).

3.4.3. WAVE FORMULATIONS

ASSUMPTIONS

The following assumptions can be made with respect to the description of waves in Galveston Bay:

1. Shallow water is assumed for wind generated waves.
2. It is assumed that no waves from the open coast will penetrate into Galveston Bay due to the sheltered location behind the barrier islands and that all waves will be generated in the Bay locally.
3. For wave generation, an infinitely long and straight coastline is assumed.

Waves can be described by the linear wave theory for deep water or shallower, coastal waters (Holthuijsen, 2007). The linear wave theory is, like the SWE (Appendix B.1), based on a mass and a momentum balance. According to the linear wave theory, a propagating wave in deep water conserves energy.

The water particles experience an orbital motion when a wave passes, see Figure 3.10. The particle motions for deep water (linear theory) are circular. When a wave reaches shallower water the particle motions become more horizontal. When the water is shallow enough, the vertical motion can be totally ignored. In that case the wave can be described by the SWE. The motion of short waves in deep or coastal waters cannot be described by the SWE, because the orbital motion would be neglected. Waves in waters in between deep water (too shallow for the linear wave theory) and very shallow water (SWE) can be described by non-linear theories like the Boussinesq equations (Holthuijsen, 2007). These non-linear equations can include non-linear effects such as wave breaking.

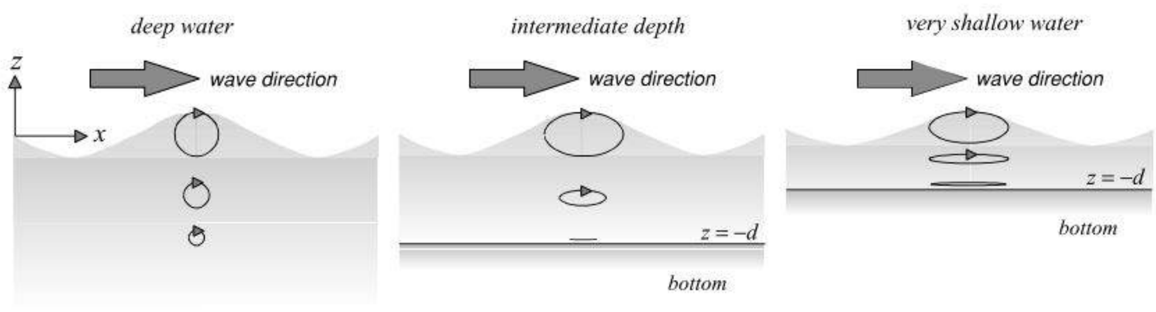


Figure 3.10: Orbital motion of waves in deep, intermediate and very shallow water (Holthuijsen, 2007)

It can be seen in Figure 3.11 that non-linear processes (breaking and e.g. wave-wave interactions) and depth related processes (bottom friction, refraction and breaking) become more important when approaching the shore. The processes reflection and diffraction are most significant for harbors where depth is less significant. Wind generation, propagation in the Bay (refraction, shoaling, diffraction and reflection) and dissipation (depth-induced breaking and bottom friction) for Galveston Bay will be discussed in this section.

Process	Oceanic waters	Coastal waters: Shelf seas	Coastal waters: Nearshore	Coastal waters: Harbour
Wind generation	•••	•••	•	○
Quadruplet wave–wave interactions	•••	•••	•	○
White-capping	•••	•••	•	○
Bottom friction	○	••	••	○
Current refraction / energy bunching	○/•	•	••	○
Bottom refraction / shoaling	○	••	•••	••
Breaking (depth-induced; surf)	○	•	•••	○
Triad wave–wave interactions	○	○	••	•
Reflection	○	○	•/••	•••
Diffraction	○	○	•	•••

••• = dominant, •• = significant but not dominant, • = of minor importance, ○ = negligible.

Figure 3.11: Relative importance of various wave processes in oceanic and coastal waters. Based on Battjes (1994). (Holthuijsen, 2007)

DISCUSSION

- The linear wave theory formulations for coastal waters ('waves feel bottom') from e.g. Holthuijsen (2007) can be applied assuming shallow water. This assumption might not be completely true (typical wavelength $L = 25 - 50m$, typical depth $d = 3m$).
- The assumption that no waves will penetrate into the Bay from the ocean might be unrealistic.

Figure 3.11 shows that the relative importance of wind generation in both oceanic and coastal waters is large. The formulation for wave growth during hurricane conditions in Galveston Bay is based on the Bretschneider equations (Holthuijsen, 2007). See Appendix B.2 for the full derivation of the wind wave formulations.

Short waves are generated by wind, which adds horizontal momentum in vertical direction to the water across the ocean surface (Holthuijsen, 2007). The formulations consider deep or depth-limited coastal water such as Galveston Bay. Formulations for the depth-limited cases are presented. To determine the significant wave height and wave period in coastal waters, Equation (3.3) and Equation (3.4) are used:

$$H = \tilde{H}_{\infty}\left[\tanh\left(k_3\tilde{d}^{m_3}\right)\tanh\left(\frac{k_1\tilde{F}^{m_1}}{\tanh\left(k_3\tilde{d}^{m_3}\right)}\right)\right]^{p}\cdot\frac{U_{10}^2}{g} \tag{3.3}$$

$$T = \tilde{T}_{\infty}\left[\tanh\left(k_4\tilde{d}^{m_4}\right)\tanh\left(\frac{k_2\tilde{F}^{m_2}}{\tanh\left(k_4\tilde{d}^{m_4}\right)}\right)\right]^{q}\cdot\frac{U_{10}}{g} \tag{3.4}$$

According to e.g. Holthuijsen (2007), the different formulations for deep and shallow water show that the most important parameter is the ratio of wind speed over the phase speed of the wave. The lower phase speed of the wave means that waves in shallow water will be higher compared to deep water waves. That is a fundamental difference between deep and shallow water wave growth. For the wave growth of waves, the depth is crucial in the formulation of wave growth. At higher depths, wave height will be higher.

There are ways to estimate the wave height of fully developed wave in a wave field (Vrijling, 2011). This is related to the moment when waves break, the steepness of the wave and the water depth. The individual and significant maximum wave height in a wave field can usually be estimated roughly from the depth of the water following Equation (3.5) and Equation (3.6) (Holthuijsen, 2007). The depth does play a role. The fetch does not play a role because this theory assumes fully developed waves:

$$\frac{H_{max}}{d} \approx 0.75 \Rightarrow H_{max} \approx 2.3m \tag{3.5}$$

$$\frac{H_{s,max}}{d} \approx 0.45 \Rightarrow H_s \approx 1.35m \tag{3.6}$$

3.5. CONCLUSIONS

Hydraulics of Galveston Bay, with special attention to hurricane conditions (surge and waves) has been discussed in this chapter. This is relevant to understand because BwN measures for hurricane flood risk reduction should affect these hydraulics to be effective. The following conclusions arise:

- The wide and gentle continental shelf of the Upper Gulf Coast allows for high surges at the coast. The 1/100 $year^{-1}$ observed surge level at Galveston Bay is around 2.6 m above MHHW.
- Storm surge in the Bay is highly sensitive to landfall location and resulting in onshore or offshore directed winds forcing water in or out of the Bay and causing different wind set-up patterns. A storm making landfall southwest of Galveston causes the water level inside Galveston Bay to be maximum due to higher surge levels offshore at Bolivar Roads and stronger, onshore directed winds in northern and western areas of the Bay. An important local effect of surge in the Bay is wind set-up. For wind set-up the fetch and depth are important variables. Ike caused a peak surge level of about 4.5 m on the northeastern side of Galveston Bay, while observations near Bolivar Roads inlet recorded a water level or 3.5 m. Distinctive feature of hurricane Ike was its large forerunner of about 1.4 m, prior to landfall of the hurricane.
- Wave heights in the Bay during hurricane conditions (high wind speed) are most likely to be depth limited, although dependent on wind speed and fetch as well. Significant wave heights during Ike in the Gulf of Mexico were as high as 7.5 m. Waves in Galveston Bay were limited to 2-2.5 m during hurricane Ike. Depth and fetch are important variables for the description of waves.

Conclusions with respect to both the system of Chapter 2 and the hydraulics of this chapter are important to identify suitable BwN building blocks for flood risk reduction in the next chapter.

4

Building-with-Nature Concepts and Building Blocks

Rhis chapter discusses the concept of 'Building with Nature', which will be incorporated into the conceptual design. A Building-with-Nature solution can consist of several elements or 'building blocks'. The final sections of this chapter identify four building blocks for Galveston Bay, on the basis of the Building-with-Nature concept and the area analysis.

4.1. Building-with-Nature Context

The concept of nature-based design has been used in engineering practices worldwide. According to van Wesenbeeck (2014), "there is a worldwide call for sustainability". Also the U.S. aims at incorporating nature-based design where possible (Obama, 2015).

The Dutch term of Building with Nature (henceforth BwN) has its origin in 1979, when Dutch engineer Honzo Svasek developed the concept. The starting point of the design approach was the use of physical processes to create new land and opportunities of new nature and recreation (de Vriend & van Koningsveld, 2012). The concept was further broadened by Ronald Waterman. He linked the concept to integrate coastal and delta strategies from 1980-2009 (IADC Dredging, 2010). In 2009 he published a book "Integrated Coastal Policy via Building with Nature" (IADC Dredging, 2010). Between 2007-2008 consortium EcoShape was formed, which initiated the 'Building with Nature' program. The program was supported by private and public parties. Ecoshape adapted the principles of Ronald Waterman. Worldwide, similar efforts can be distinguished, such as 'Engineering with Nature' by the USACE and 'Working with Nature' under the auspices of PIANC (Fredette & Bourne, 2014; IADC Dredging, 2010). The term nature-based flood protection is often used for abovementioned approaches as well.

"The EcoShape consortium consists of private parties, such as dredging contractors, equipment suppliers and engineering consultants and public parties, such as government agencies and municipalities, applied research institutes, universities and academic research institutes. The partners provide for co-funding of the program" (EcoShape, 2014). The program is currently conducting several pilot projects.

The goal of BwN is not to control nature, but understand and work with the processes of nature. Natural habitats and processes are being used and promoted. Then the estuary can deliver an increased level of diversity of ecosystem services, services that have been lost in many estuaries due to conventional engineering (Deltares, 2015a). It is stressed that BwN measures will be delivering ecosystem services most of the time, as it will be functional as flood protection a small percentage of the time.

Several interesting reference projects of BwN (or equivalent concepts) are discussed in Appendix C. General trend in those projects is that many wetlands and oyster reefs (including oyster reef breakwaters) restoration projects and (mega-)nourishments can be observed.

4.2. Ecosystem Services

An estuary is one of the most productive natural forms and is home to unique animal and plant communities (Deltares, 2015a). It provides ecosystem services valuable to abundant wildlife and to humans.

Ecosystem services are defined as "the benefits people derive from ecosystems, in this case an estuary", and they are usually categorized in four subcategories: provision, regulation, cultural (societal benefits) and support (beneficial for ecosystem itself) (Deltares, 2015a). An estuary like Galveston Bay delivers the following services (Deltares, 2015a):

1. Provision: actual products which are obtained from the estuary. Examples are the production of construction material or food.
2. Regulation benefits: for example coastal protection, water quality regulation, erosion control, flood control or carbon sequestration.
3. Cultural benefits: non-material benefits obtained from an estuary, such as recreational or educational benefits are regarded as cultural.
4. Support benefits: does not yield direct benefits to society, such as the provision of habitat and food for animals, nursery provision and nutrient cycles.

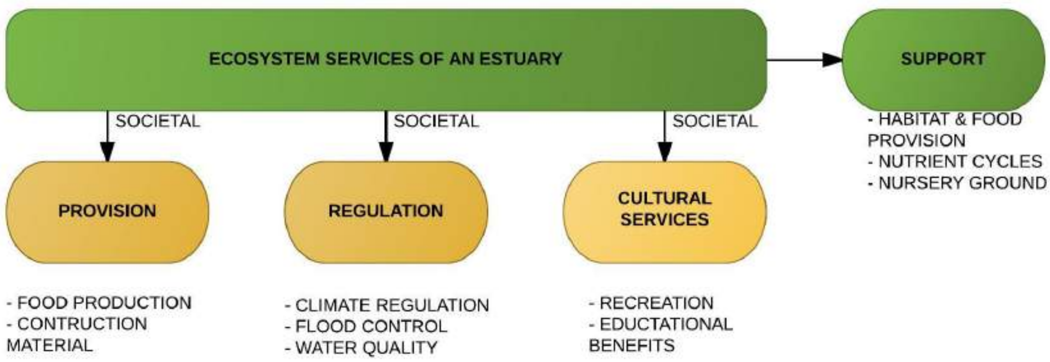


Figure 4.1: Ecosystem services. Based on e.g. Deltares (2015a) and Sangster (2015)

The three key habitats of Galveston Bay all provide several ecosystem services. These habitat services are mainly focusing on the regulation and support services of the estuary and will be discussed below.

Wetlands

Wetlands have important hydrological and ecological functions. They stabilize the sediment by retaining it and furthermore cause wave attenuation and trapping of sediment. They help maintain higher foreshores. Wetlands are valuable filter zones for polluted runoff from land as well as storage and sequestration of carbon trough photosynthesis (Acreman & Holden, 2013; National Research Council, 2014). Wetlands for example have the possibility to remediate after an oil spill (Antonia Sebastian, Personal Communication, September 2014). Constructed or stormwater wetlands ponds can even be constructed for stormwater treatment. Rainwater runoff from wetlands is released slowly and they could possibly be used for retention of stormwater. According to Guannel et al. (2014) wetlands can store millions m^3 of water, because of their-sponge like nature. However, large surface areas of wetlands would be needed to achieve that and for hurricane conditions this mechanism is considered irrelevant. Wetlands could provide a buffer between high-energy water and land (Galveston Bay Status and Trends, 2014), either for wave attack and they possibly reduce surge (surge can be increased as well). Wave height attenuation and sediment stabilization are considered to be the primary coastal protection service of wetlands (National Research Council, 2014). The services of wetlands can, even in the case of SLR, be delivered as long as they are allowed to migrate and are in healthy conditions (Guannel et al., 2014).

SEAGRASSES

Seagrass has similar characteristics as wetlands, except that it does not provide a buffer between land and water. Although usually present below MSL they could provide wave attenuation, sediment stabilization by the dense root structure and trap sediment (Deltares, 2015a). Though wave attenuation might be lower than wetlands. Seagrasses provide nursery grounds and can execute carbon sequestration and pollution and nutrient uptake.

OYSTER REEFS

Oysters have an important role of filtering the water in the bay from silt and contaminants like nitrogen (Galveston Bay Status and Trends, 2014; GBF, 2014). Furthermore oyster reefs could play an important role in carbon sequestration (Guannel et al., 2014; National Research Council, 2014), by storing it in their shells made of calcium carbonate. However, the shell production also causes the oyster to produce some carbon. Together with e.g. algae they can be very effective, long-term carbon sequesters (Hall, Risinger, Lutz, & Farlow, 2011). Oysters are keystone species of Galveston Bay, which means the health of the bay depends on the health of oysters. They play an important role in maintaining water quality in the estuary. Furthermore oyster reefs attenuate waves and therefore stabilize the shoreline and provide flood control and coastal protection. Generally shoreline stabilization is the most important potential service of oyster reefs, according to Grabowski et al. (2012). Guannel et al. (2014) states that oyster reefs can protect marshes from wave-induced erosion, and can continue to do so because they can grow vertically with SLR. The most important services coastal habitats of Galveston Bay can provide are summarized in Table 4.1 below.

Habitat / Service	Wetlands	Oyster Reefs	Seagrass Meadows
Flood control	Wave and possible surge attenuation	Wave attenuation	Wave attenuation
Coastal protection and erosion control	Sediment stabilization, soil retention and wave attenuation	Shoreline stabilization by wave attenuation	Sediment stabilization, soil retention and wave attenuation
Maintenance of marine life (fish, shellfish)	Provide habitat and nursery grounds for species	Provide food, habitat and nursery grounds for species	Provide habitat and nursery grounds for species
Water quality	Nutrient and pollution uptake and retention	Nutrient and pollution removal from the water	Nutrient and pollution uptake and retention
Carbon	Sequestration (store)	Sequestration (store)	Sequestration (store)

Table 4.1: Key habitats for Galveston Bay and important services they provide. Based on Guannel et al. (2014), Barbier et al. (2011), Lester and Gonzalez (2011) and Deltares (2015a)

In the BwN context habitats are often called ecosystem engineers. Though conventional, hard structures are likely to become more important for densely populated cities in delta areas, because many cities lack the space for nature-based risk reduction (National Research Council, 2014). Coupling nature-based with hard structures provides an effective strategy if space allows (National Research Council, 2014).

4.3. HABITAT RESTORATION PROJECTS IN GALVESTON BAY

4.3.1. WETLAND RESTORATION

According to McPherson et al. (2015), "beneficial use of sediment for restoration of wetlands and associated estuarine habitat within the Galveston Bay System is critical to the long-term sustainability and overall health of the bay". The USACE and Port Authority of Houston (PAH) used to dump dredged material from the HSC in designated disposal sitse offshore or next to the HSC on the open bay bottom. Nowadays some material being dredged from the HSC is used in so-called beneficial use projects, for example for wetland restoration. The Galveston District of USACE stated that in recent years this number is about 20% (Campbell, 2013). The total volume of dredged material in Galveston Bay is around 20-30 million cubic yards [16-23 million m^3]

(Campbell, 2013).

Wetland restoration efforts are carried out by several parties and organizations. In The Galveston Bay Plan the goal for creation or restoration for estuarine marshes has been set to 8,600 acres [35 km^2] (Lester & Gonzalez, 2011). Between 1996 and 2001 4,500 acres [18 km^2] of marsh has been restored. Restoration efforts occur on different scales, from a fraction of an acre to hundreds of acres. An example of a large-scale restoration is Atkinson Island in the North of the Bay.

4.3.2. OYSTER REEF RESTORATION

Oyster reef restorations can be designed in several ways. There are fairly new techniques that make breakwaters (physical barriers) into an ecosystem engineer (Dehon, 2010). It is a common engineering practice to design an oyster reef as sub-tidal or inter-tidal wave attenuating breakwater (Scyphers, Powers, Heck, & Byron, 2011). A breakwater is enhanced for the accumulation of oysters and oyster growth and the support of e.g. benthic species, by means of hard substrate which allows different organisms to attach an grow (Dehon, 2010). An oyster reef breakwater can be composed of e.g. bagged oyster shells, 'reef blocks' (rebar cages with oyster shell) or concrete 'reef balls' (special concrete elements for oyster accumulation) (Kroeger, 2012). An example of such a specific design is that of 'living breakwaters', which also focuses on a breakwater applicable for hurricane conditions (SCAPE Landscape Architecture PLLC, 2014), but more projects have been carried out.

In the beginning of and halfway the 1990's, several large oyster reef restoration projects have been carried out. However, from 2001 efforts have been limited (Lester & Gonzalez, 2011). In recent years, since 2009, TPWD restored a marginal amount of 230 acres [0.9 km^2] (TPWD, 2014b). However, since hurricane Ike, oyster reef restoration has regained interest. TPWD will conduct a large restoration project of 180 acres [0.7 km^2] soon (TPWD, 2014b). According to Grabowski et al. (2012), "the economic value of oyster reef services, excluding harvest, is between $5,500 and $99,000 per hectare per year. Reefs recover their median costs in 2-14 years". Probably economic value of oyster reefs is an added incentive for oyster restoration efforts.

4.4. BUILDING BLOCKS FOR GALVESTON BAY

The following elements or 'building blocks' for potential BwN solutions for hurricane flood risk reduction in Galveston Bay are identified:

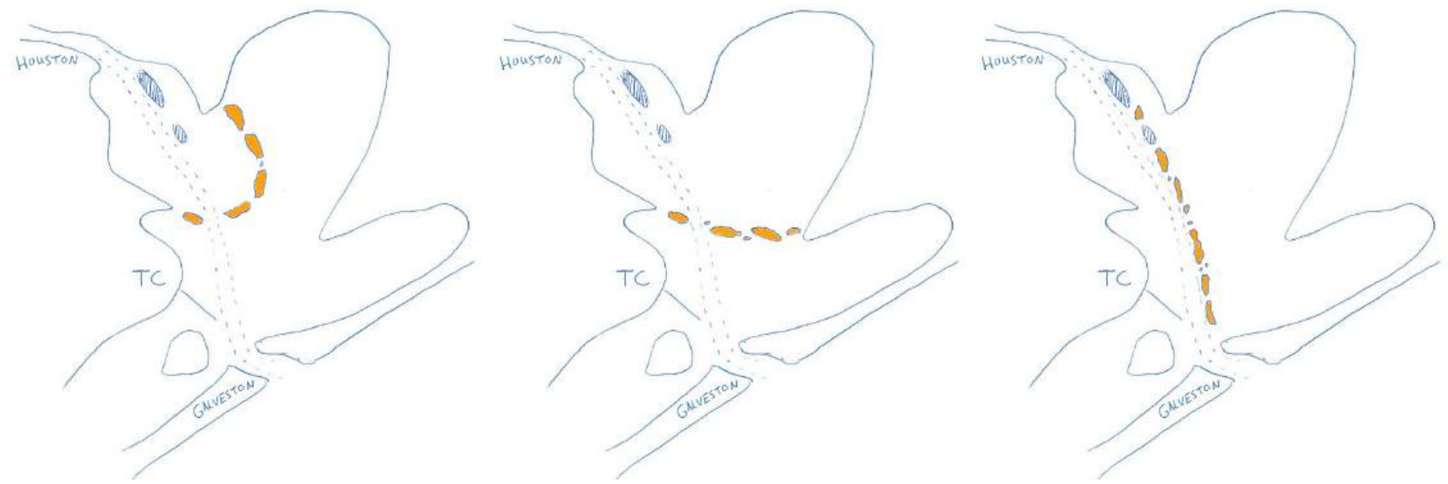
1. Nourishments
2. Wetlands
3. Eco-Island
4. Oyster Reefs

These building blocks have been identified because they have potential to add value to the natural system and contribute to flood risk reduction. All building blocks will be briefly discussed. Some sketches are merely included to give an impression of where it might be constructed. The scales, shapes or effect of these figures are not realistic because no calculations have been done at this stage. Other locations or configurations are possible.

4.4.1. NOURISHMENTS

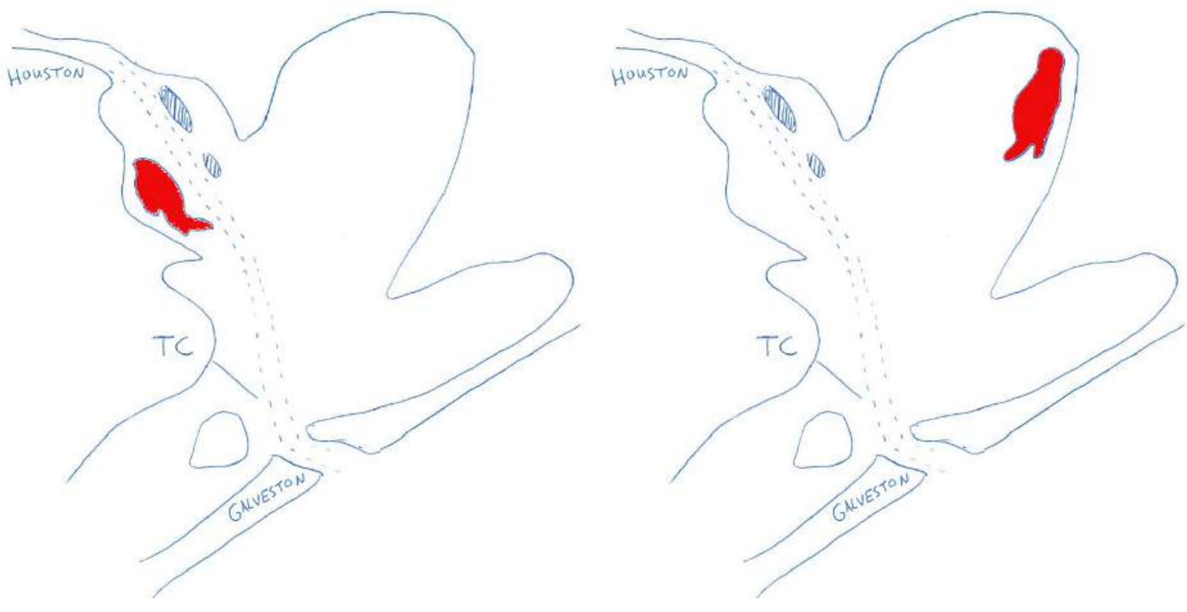
The system is sediment starved, and wetlands and shorelines are eroding due to insufficient supply and high (relative) sea level rise rates. A nourishment would supply the system with extra sediment to help preventing it from eroding. In combination with an Ike Dike it would be increasingly interesting to supply the inner system with sediment because the barrier will probably block sediment coming into Bolivar Roads (Ruijs, 2011). A nourishment is a placement of sediment (sand, silt or clay) at a certain location to replenish the foreshores. Nourishments can be constructed everywhere in the Bay, in one or more locations. Not known is how the system will exactly react to a nourishment. It is important to plan nourishments carefully and take into account oyster reefs and other valuable habitats near it, whom are negatively affected by extensive sediment loading. It depends on how and where it will be constructed whether it can be considered as BwN. If nourishments are located around MSL they could enhance the environmental quality by attracting certain benthic species, fish or birds. If nourishments are executed above MSL they will be islands and possibilities for ecology or recreational areas arise.

An option is to nourish in a conventional manner with small volumes close to the location in need of sediment. Another option is to construct a mega-nourishment, like has been done with the Sand Engine (Motor), Delfland or the Mud Motor, Wadden Sea in the Netherlands (EcoShape, 2014). In these projects natural processes are used to distribute a big volume of sediment into the system towards desired locations at the shore. It is unknown if such a mega-nourishment would be effective in the Galveston Bay. The configuration, size and location will determine whether a nourishment could be effective for hurricane flood risk reduction by reducing wind set-up. This effectiveness depends on the closing size and location and rotating character of the hurricane. See Figure 4.2 and Figure 4.3 for several possibilities of nourishments.



(a) Northwest Bay (b) Middle Bay (c) Along HSC

Figure 4.2: Sketches of possible strategically placed nourishment configurations, emerging as islands



(a) West (b) East

Figure 4.3: Sketches of possible mega-nourishments, not necessarily emerged

4.4.2. WETLANDS

Originally, wetlands have been present at 50% of the shoreline of Galveston Bay (Guannel et al., 2014). Low salt marshes are elevated around MSL and are flooded every tidal cycle. High marshes are elevated at higher altitudes and will be inundated during extreme high tide or storm surges. Both low and high marshes are present in Galveston Bay. In the U.S. it is common to restore wetlands in places where they have diminished. See Figure 4.4 for possible wetland configurations.

Note that it would be quite rigorous, unnatural and unrealistic (very large sediment volume) to completely fill Galveston Bay with wetlands. Restoration along the shoreline is more realistic, and there the wetland could be combined with for example a dike or levee to form a higher, natural foreshore (e.g. a living shoreline). Figure 4.4a and Figure 4.4b represent wetlands at the shore, although a clear gap can be distinguished. The gap is merely to indicate the present shoreline.

(a) West Bay Wetlands (b) East Bay Wetlands (c) Whole Bay Wetlands

Figure 4.4: Sketches of possible wetland options. Note that wetlands as foreshores are considered, the gap is merely included to distinguish the present shoreline

4.4.3. ECO-ISLAND

Instead of several nourishments one might think of one big eco-island. The island is always emerged and considered to be large. It would be an eco-island because it would offer a large area of ecological or environmental development, e.g. by the creation of degraded habitat area, nursery grounds for birds and fish and (eco)tourism. In that sense it could increase biodiversity in the bay. The island could be a bird sanctuary and is an interesting opportunity for bird watching tourism. The shores or intertidal areas of the island could consist of wetlands, seagrasses or oyster reefs. It should be noted that the term eco-island is by no means an official term.

The island could be effective for flood risk as wave breaking or wind set-up reducing measure because of its emerged character. A typical breakwater island would be a narrow and long strip, but the eco-island is considered to be a compact and large area. The reason is that an compact area is more effective for biodiversity (Gemeente Lelystad, 2013). In the right configuration it might be effective for flood risk reduction by reducing the fetch and thus wind set-up (when emerged during hurricane surge conditions). Furthermore this effect on surge might be enhanced by reducing the wind shear stress over a large area. Additionally it could act as a re-nourishing component or capture fine sediment like the Marker Wadden project in the Netherlands. See Figure 4.5 for an option of an eco-island in Galveston Bay.

4.4.4. OYSTER REEFS

The oyster reefs considered in this research are constructed oyster reefs and mimic the functionality of natural oyster reefs. The creation of artificial oyster reefs or habitat breakwaters has been conducted in Galveston Bay and other places before. An oyster reef (naturally or constructed) is doubted to be effective for hurri-

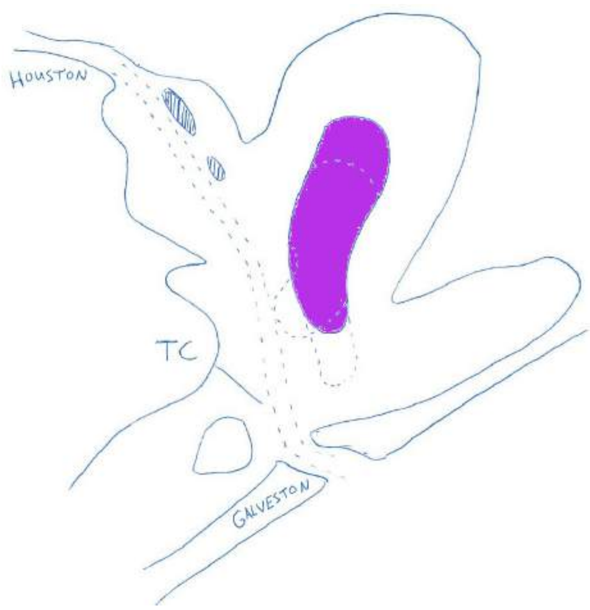
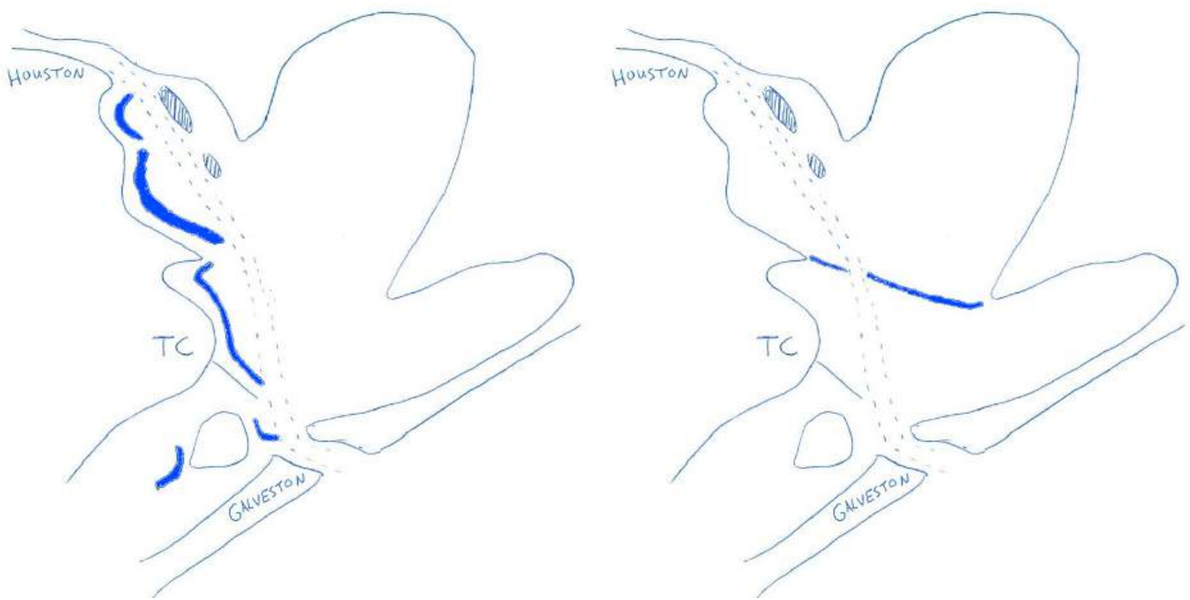


Figure 4.5: Sketch of a possible eco-island

cane wave attenuation, but delivers many ecosystem services in daily conditions. We have seen that there are designs that construct breakwaters (engineering structure), but designed in such a way it enhances habitat potential (oyster growth, shellfish etc). To be functional for flood risk reduction for Galveston Bay by breaking waves in hurricane conditions the oyster reefs breakwater are expected to be necessary.

Breakwaters along the shore or in the middle Bay section are possible. Along the shoreline they could preserve the foreshore, wetlands or flats, reduce erosion and attenuate hurricane waves. In combination with wetlands they can form a so-called living shoreline. See Figure 4.6 for an impression of possible locations for breakwaters in Galveston Bay. The construction of oyster reefs in the middle of the Bay is a option, although probably not effective for surge reduction or wave attenuation.



(a) West Bay (b) Middle Bay

Figure 4.6: Sketches of possible oyster reefs or oyster reef breakwaters

4.5. CONCLUSIONS

- BwN aims at understanding and work with processes of nature and to use and promote natural habitats. When such a solutions is successful, the estuary can deliver an increased level of diversity of ecosystem services.
- Ecosystem services habitats in Galveston Bay provide are: coastal protection - wave and possibly surge attenuation (surge increase is possible as well), erosion control, providing marine wildlife habitat, pollutant removal and carbon sequestration.
- Building blocks for possible hurricane flood risk reduction in Galveston Bay are: large-scale nourishments, wetlands, an eco-island and oyster reefs. Their functioning with respect to hydraulics and flood protection is investigated in Chapter 5.

5

Qualitative Evaluation of Building Blocks

This chapter describes the qualitative evaluation of the building blocks and a conceptual design. Focus is two-fold and lies on: surge-based flood risk reduction benefits and benefits to the natural system provided by the building blocks. Section 5.1 will present the framework and the following sections will describe in more detail how specific building blocks are evaluated with respect to both flood risk reduction and natural value. Finally, suitable conceptual design alternatives are formulated with the classifications from two toolboxes.

5.1. Framework for Qualitative Evaluation of Building Blocks

To evaluate the effect of building blocks on hurricane flood risk a framework is developed. The framework is presented in Figure 5.1.

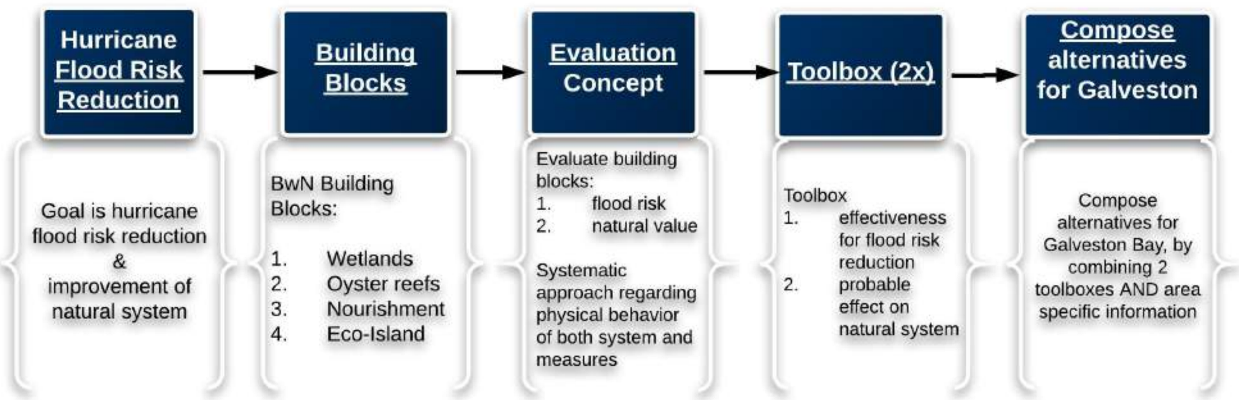


Figure 5.1: Framework for the qualitative evaluation of building blocks and the conceptual design of BwN measures for flood risk reduction in Galveston Bay

5.1.1. Flood Risk Reduction

A systematic approach will be followed to evaluate the physical behavior of the different building blocks in relation to the physical behavior of the system during hurricane conditions.

The following components are included in calculations and considerations:

- Local **wind set-up** (surge)

- Wind generated **waves**

Note:
Surge and waves are discussed because they are the biggest cause for damage and determines the effectiveness of a certain protection. Currents can be a significant mechanism during hurricane conditions, but it is not considered as a key mechanism for the effectiveness of a solution. It can determine if an alternative is suitable, how the design looks and therefore can be a criterion for choosing an alternative in a later stage.

Figure 5.2 depicts the modeling concept for both mechanisms wind set-up and waves. Nourishments will be quantitatively evaluated using simplified, 1D calculations. The three other building blocks will be qualitatively evaluated. Outcomes for both surge and wave height reduction for Galveston Bay are combined to form a flood risk reduction toolbox.

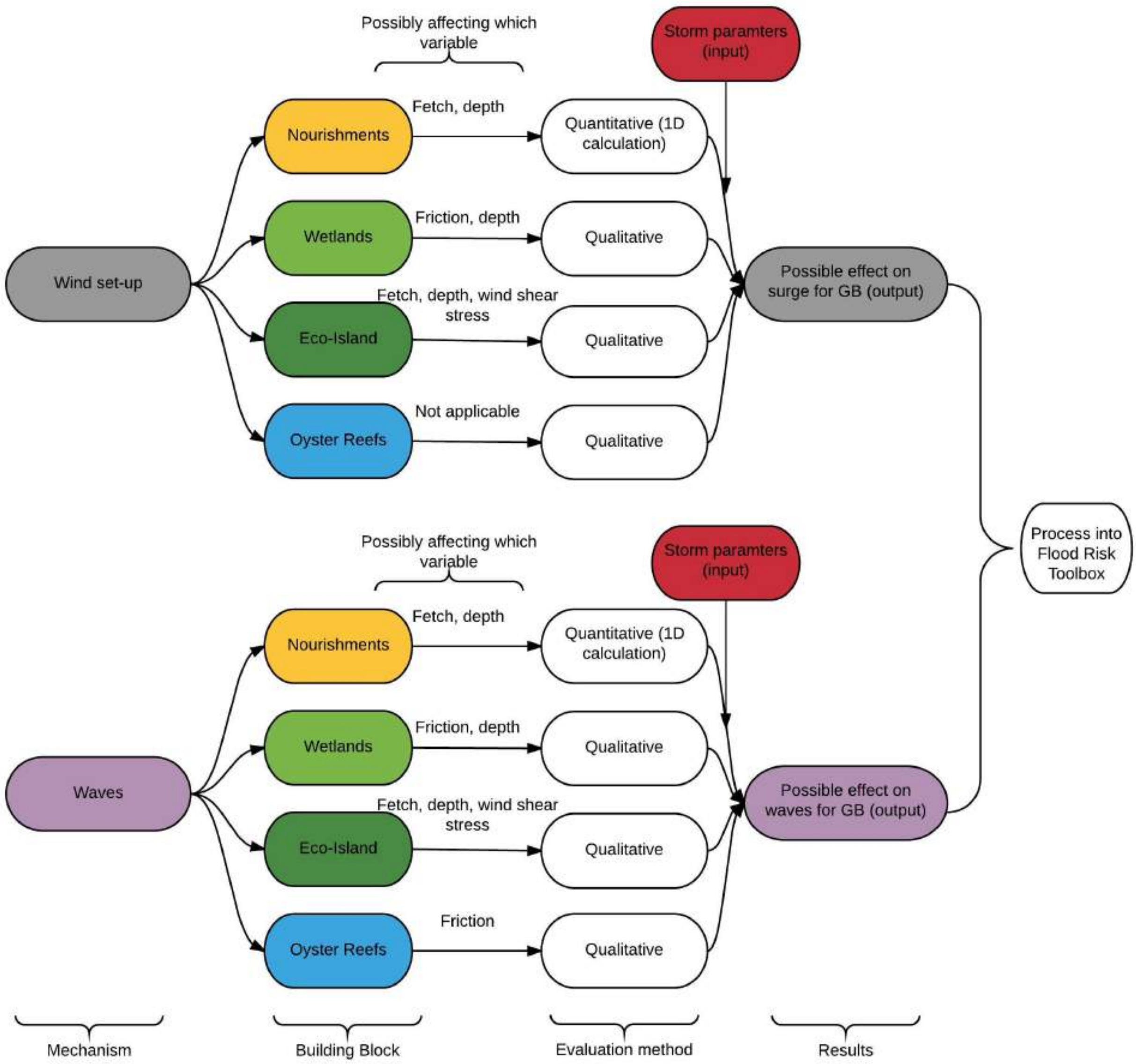


Figure 5.2: Evaluation Concept Flood Risk Reduction

TOOLBOX FLOOD RISK REDUCTION

To evaluate effectiveness a distinction has been made between a building block constructed in the center or along the shore of Galveston Bay. Both locations have different physical consequences. The toolbox for flood risk reduction of building blocks consists of the effect on storm surge and waves (for building blocks in the center or at the shore) and two additional columns: performance factors and additional functions. Performance factors are criteria which determine the performance of the measure to fulfill flood risk reduction. The additional functions are generally corresponding with additional ecosystem services the building blocks provide. All cells in the toolbox will be rewarded with a classification: positive effect (green), moderate effect (orange) or no/marginal effect (red). The classification for each building block will help formulating alternatives for Galveston Bay.

5.1.2. NATURAL VALUE

The effect of building blocks on natural value is qualitatively evaluated. Quantification is difficult, although several studies aim to quantify the ecological benefits of ecosystems. One of those studies is done by Guannel et al. (2014). For the qualitative evaluation, relevant criteria as an outcome of the area analysis of Galveston Bay are presented. These criteria are considered to be the main issues of Galveston Bay. Every building blocks is assessed for these criteria. The concept of evaluating natural value of building blocks is shown in Figure 5.3.

1. Erosion: how does the building block affect erosion issues or patterns?
2. Water quality: does the building block contribute to pollution and nutrient filtering, fine sediment uptake and carbon sequestration?
3. Ecology: does the building block support ecosystems, promote and/or enhance biodiversity and marine wildlife?
4. SLR: what is the the sensitivity of the building block to rising sea levels?
5. Match with autonomic behavior system: evaluation whether a measure is a realistic option, considering the autonomic development of the natural system.

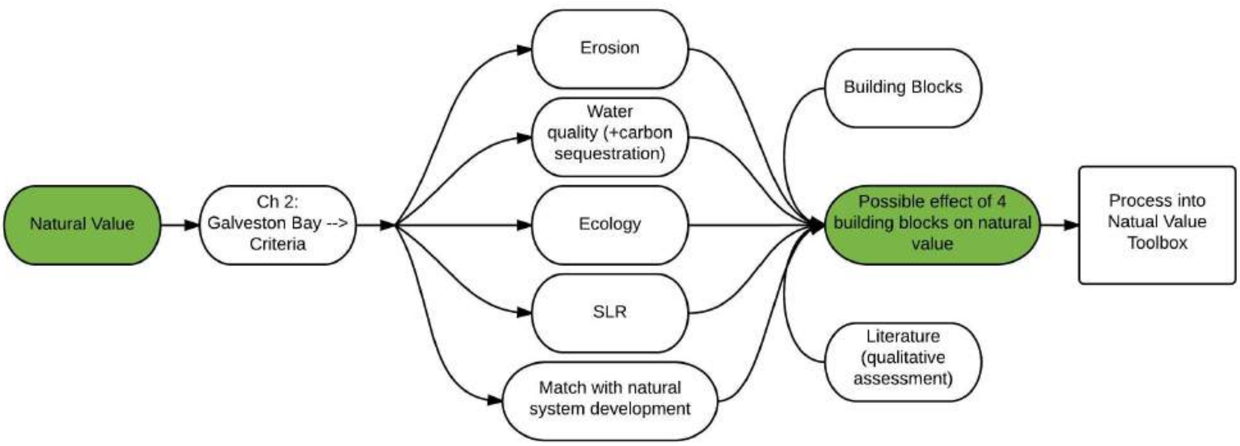


Figure 5.3: Evaluation Concept Natural Value

TOOLBOX NATURAL VALUE

Toolbox for natural value contains all the criteria mentioned above. All cells in the toolbox will be rewarded with a classification as well: positive effect (green), moderate effect (orange) or no/marginal effect (red). Natural value also depends on the scale and size of constructed building blocks. The classification for each building block helps formulating alternatives for Galveston Bay.

5.2. NOURISHMENTS

5.2.1. FLOOD RISK REDUCTION

If nourishments are emerged in the center of the Bay, they can be considered as islands. A row of connected, emerged nourishments could form barriers and create 'compartments' in Galveston Bay. The main function with respect to flood risk reduction of this type of nourishment would be limiting the **fetch**. It will be discussed how different configurations affect wind set-up and wave height. Also **depth** is a variable affected by a nourishment. This has mainly effect on waves, as wave can break over the nourishment. However, calculations will focus on fetch limiting mechanism. The hypothesis is that a set of offshore, emerged nourishments could be constructed in such a way that they can reduce water and wave levels at the shore.

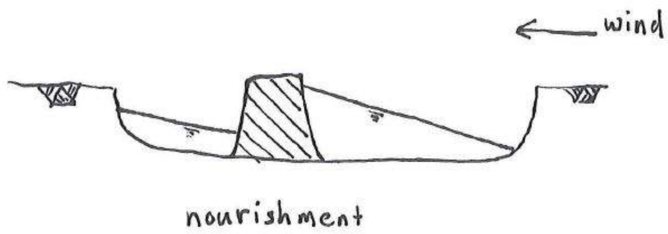


Figure 5.4: A schematic representation of the effect of emerged nourishments on the water level (wind set-up)

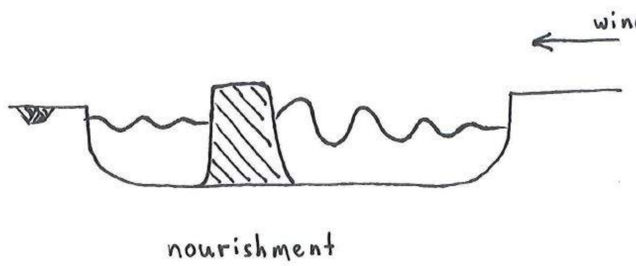


Figure 5.5: A schematic representation of the effect of emerged nourishments on waves

ASSUMPTIONS

Following assumptions apply to surge and wave calculations for emerged nourishments.

- A square basin is assumed with constant bottom depth. The tilting point of the water surface is located in the mean of the water surface.
- One-dimensional cross sections are considered.
- It is assumed that wind is long enough to achieve equilibrium set-up or full wave growth.
- Pumping mode applies to Galveston Bay for long waves like tide and storm surge, the bay can be schematized as a semi-enclosed basin (Stoeten, 2013). Inertia and resistance are negligible in the bay and the tide or surge propagates instantaneously. This assumption can be made when the basin is sufficiently short, thus $t_{\text{forcing}} >> t_{\text{bay}}$ (20 times bigger), in which t_{bay} is equal to L/c, according to e.g. Battjes (2000). This assumption seems reasonable for surge in Galveston Bay in engineering applications and has been validated by Stoeten (2013) for storm surge in the Bay. Sloshing behavior due to local wind set-up has its own dynamic.
- The created 'compartments' are semi-enclosed. They can fill or empty, but wind set-up and wave growth is added locally. This means emerged nourishments are considered closed and are emerged with respect to wind set-up.
- The average depth of Galveston Bay is assumed to be 3 m. The impacts of deep channels is assumed to be negligible due to large surface area of the Bay.

- Transects b and c in Figure 3.8 will be considered, representing wind directions southeast-northwest before landfall and southeast-northwest around landfall for a storm equivalent to hurricane Ike (landfall around Galveston).

- A constant and average value of inflow during hurricane conditions is assumed to be 3 m across the whole Bay, which is based on observed surge levels during hurricane Ike.

- The U_{10} for a forcing such as wind set-up represents a 10-minute or 30-minute averaged wind speed at the sea surface. For 1-minute winds a conversion factor of 0.81 (30-minute) or 0.9 (10-minute) is required according to e.g. M. D. Powell et al. (2010) and Deltares (2015b). In the case of Ike, around landfall measured 1-minute surface winds were over 40 m/s (Berg, 2009; NOAA, 2015), and according to Unisys Weather (2015) even 49 m/s [95 knots]. Therefore a U_{10} (which represents the 10-minute or 30-minute averaged surface wind speed) of 40 m/s is used.

- Wind drag coefficient C_D is assumed to be 0.0019, which is a result of the application of the new formulation as used in SWAN (Delft University of Technology, 2015).

- SLR in the calculations is assumed to be 1 m (IPCC, 2013).

A table with assumed constants like wind drag, air density and more can be seen in Table 5.1.

Emerged Nourishments Constants	
ρ_{air} $[kgm^{-3}]$	1.2
U_{10} $[ms^{-1}]$	40
U_{ref} $[ms^{-1}]$	31.5
$\tilde{U}$ $[ms^{-1}]$	1.2698
C_D $[-]$	0.0019
τ_w $[Pa]$	3.6841
ρ_w $[kgm^3]$	1025
g $[ms^{-2}]$	9.81
d $[m]$	3
$d_{inflow}{}^*$ $[m]$	6
d_{SLR} $[m]$	4
$d_{inflow+SLR}{}^*$ $[m]$	7

Table 5.1: Calculation constants for the 1D quantification of the wind set-up

In which d_{inflow} is the depth of the Bay with inflow for the scenario without an Ike Dike and d_{SLR} is the depth of the Bay for the scenario with SLR. $d_{inflow+SLR}$ is the depth of the Bay without Ike Dike and with SLR.

TEST DESIGNS

Fetch limiting nourishments affect surge and wave growth best if close to the areas which they need to protect. The reversed wind direction of transect c towards the Northeast would represent wind after landfall of the hurricane, but that direction is not considered in this calculation. Three test designs of emerging nourishments are formulated. These design will form the basis for the calculations. See Figure 5.6 for three test designs and the transects for which an idealized wind set-up and wave growth is calculated:

1. **Design 1**: *Archipelago Northwest*

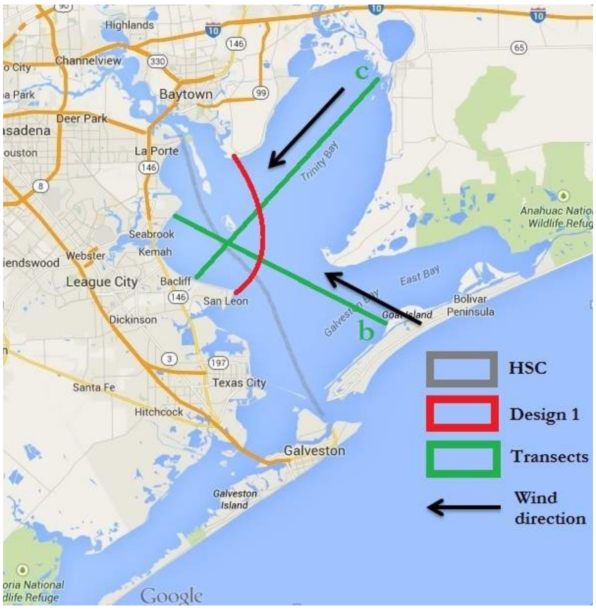
   This solution focuses on the northwestern area of Galveston Bay. Emerging nourishment design 1 will divide **transect b and c** in two parts of 20 km (upwind) and 10 km (downwind).

2. **Design 2**: *Archipelago Middle Bay*

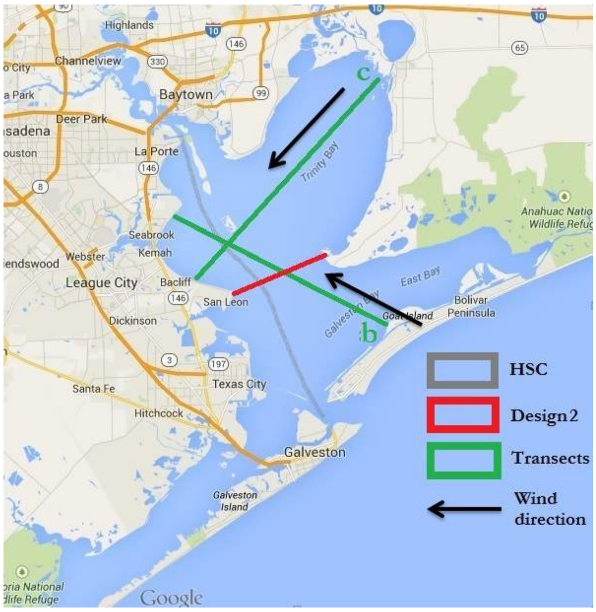
   East-West archipelago in the Middle Bay, where the span in Galveston Bay is smallest. This would affect South-North directed processes. The western side of the Bay is still exposed still for surge and waves, just like eastern side. Emerging nourishment design 2 will divide **transect b** in two equal parts of 15 km. **Transect c** is not being affected.

3. **Design 3**: *Archipelago along HSC*

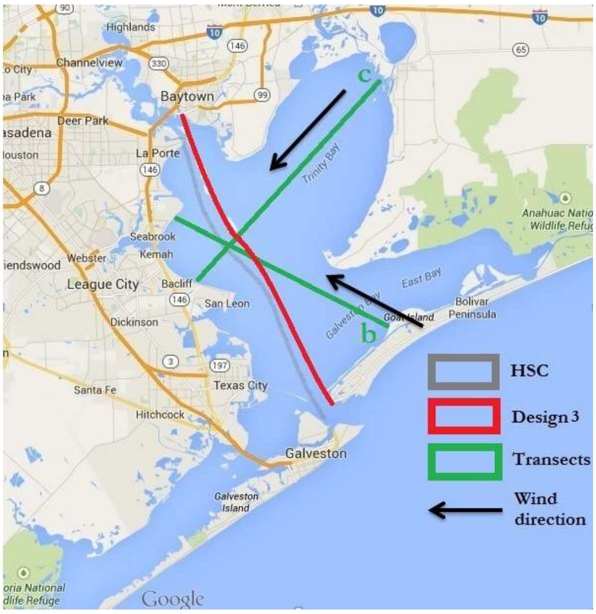
   This emerging nourishment would focus on the whole western part of the Bay. Extra advantage for construction is that dredged material from HSC can directly be dumped next to it, which means the travel distance is almost none. Design 3 will divide **transect b and c** in two parts of about respectively 22.5 km (upwind) and 7.5 km (downwind).



(a) Test design 1



(b) Test design 2



(c) Test design 3

Figure 5.6: Governing transects for 1D wind set-up and wave growth, with respect to test designs of emerged nourishments. Maps: Google (2014)

WIND SET-UP RESULTS

To determine the wind set-up, Equation (3.1) can be rewritten as:

$$\frac{dh}{dx} = \frac{\tau_w}{\rho_w g h} \tag{5.1}$$

in which h is the water level, which is equal to surge added to depth, $\eta + d$. The depth is a constant therefore the surge level and water level can be expressed as one another. The gradient (or derivative) of the water surface can be expressed in h or z, and the resulting surge over distance x is dh or dz, whom are equal.

If one integrates Equation (5.1), the following analytic expression arises which solves water levels as a result of wind set-up for every position x along a transect. It considers a non-linear wind set-up gradient:

$$h(x) = \sqrt{2(\frac{\tau_w}{\rho_w g})x + C_1} \implies \eta(x) = \sqrt{2(\frac{\tau_w}{\rho_w g})x + C_1} - d \tag{5.2}$$

in which C_1 is a differential constant. The calculations will be done with Matlab. Scenarios with and without Ike Dike (no inflow) and with and without SLR are simulated. This all results in 4 scenarios per test design, excluding a baseline scenario without implemented measures. In total 16 scenarios with measures are to be assessed. See Table 5.2 for the most relevant outcomes of the wind set-up calculations for the baseline and the three test designs for the scenarios with and without Ike Dike. For a complete overview of results including SLR, see Appendix D.1.

0: Baseline	**Downwind surge, transect b and c (Northwest and West) [m]**	**Difference with baseline [m]**
Open spine (d=6 m)	3.78	-
Closed spine (d=3 m)	1.54	-
1: Test design 1	**Downwind surge, transect b and c (Northwest and West) [m]**	**Difference with baseline, transect b and c [m]**
Open spine (d=6 m)	3.37	-0.41
Closed spine (d=3 m)	0.81	-0.73
2: Test design 2	**Downwind surge, transect b (Northwest) [m]**	**Difference with baseline, transect b [m]**
Open spine (d=6 m)	3.53	-0.25
Closed spine (d=3 m)	1.08	-0.46
3: Test design 3	**Downwind surge, transect b and c (Northwest and West) [m]**	**Difference with baseline, transect b and c [m]**
Open spine (d=6 m)	3.28	-0.60
Closed spine (d=3 m)	0.62	-0.92

Table 5.2: Results of 1D calculations for wind set-up reduction for emerged nourishments (baseline and test designs). Green color = significant reduction, orange = no or negligible reduction

WAVE RESULTS

For wave growth Equation (3.3) and Equation (3.4) will be used to calculate the significant wave height and period reduction behind the emerged nourishments. Depth induced wave breaking is not part of the calculations because a constant depth is assumed. The same as for the wind set-up calculation are applied. Waves heights from one direction are calculated. Therefore no contributions from different directions are into the wave height at a certain place, because the goal is to find the dependency of wave growth on fetch. See Table 5.3 for outcomes of the wave height analysis for baseline and three test designs for the scenarios with and without Ike Dike. For a complete overview of results including SLR and wave period reductions, reference is made to Appendix D.1.

SUMMARY

- The simple model estimates a surge level of 3.8 m (3 m water level raise and 0.8 m wind set-up) in the Northwest and West, which is fairly comparable to the results of Stoeten (2013). The water level is 1.5 m for the case with an Ike Dike (purely wind set-up).

0: Baseline	Wave height, transect b and c (Northwest and West) [m]	Difference with baseline [m]
Open spine (d=6 m)	2.46	
Closed spine (d=3 m)	1.57	
1: Test design 1	**Wave height, transect b and c (Northwest and West) [m]**	**Difference with baseline, transect b and c [m]**
Open spine (d=6 m)	2.28	-0.18
Closed spine (d=3 m)	1.56	-0.00
2: Test design 2	**Wave height, transect b (Northwest) [m]**	**Difference with baseline, transect b [m]**
Open spine (d=6 m)	2.40	-0.06
Closed spine (d=3 m)	1.57	-0.00
3: Test design 3	**Wave height, transect b and c (Northwest and West) [m]**	**Difference with baseline, transect b and c [m]**
Open spine (d=6 m)	2.15	-0.31
Closed spine (d=3 m)	1.55	-0.02

Table 5.3: Results of 1D calculations for wave height reduction for emerged nourishments (baseline and test designs). Green color = significant reduction, orange = no or negligible reduction

- The closer to the shore, the more effective the emerged nourishment is in reducing surge levels and wave heights. Therefore is test design 3 in this analysis most effective for the West and Northwest, design 1 is considered less effective and design 2 is considered not effective because it does not protect the western shore.
- Emerged, continuous nourishments in idealized open bay conditions can reduce surge levels by **0.5 m** at the western and northwestern shore. Almost 1 m surge reduction in West and Northwest might be possible in the case of an Ike Dike. Higher surge level reductions might be possible for different designs which are located closer to shore.
- Waves are indeed depth limited and can be considered almost fully developed in the shallow Bay, especially at low water depths. Emerged nourishments marginally affect wave heights, unless located at the shore.
- Emerged, continuous nourishments in idealized open bay conditions can marginally reduce wave heights by a maximum of **0.2-0.3 m** at the western and northwestern shore. With an Ike Dike, wave height reductions are negligible.
- During Ike a westward directed water level gradient of around 0.09 m/km is observed (Rego & Li, 2010). This conceptual calculation slightly underestimates the gradient for the current situation as it is 0.06 m/km. For a situation with Ike Dike the water level gradient from the calculation is 0.1 m/km. The assumption of constant wind to achieve steady state set-up is reasonable.

5.2.2. NATURAL VALUE

- Nourishments add sediment to the system, thereby replenishing shorelines which have been experiencing erosion. If effective, erosion of the shoreline will be reduced. There are two main ways to nourish, either replenish shorelines (sacrificial shoal) or nourish to help increase the infill rate (balancing the current sediment budget), thereby trying to reduce erosion of shorelines. If constructed as breakwater (shoal) sedimentation behind it should be enhanced due to low wave energy environment. It could even be constructed as sacrificial shoal in wave-exposed areas to help move sediment to the area behind it during certain high wave events.
- Nourishments will be neutral to water quality. They don't filter the water from pollutants and might even negatively impact turbidity if the nourishment is constructed with fine sediment.
- A nourishment will be classified as neutral with respect to ecology. It does not increase biodiversity directly, although a nourishment around MSL might function as tidal flat and it might help increase

habitat area for benthic species. On the other hand, sedimentation in proximity of the nourishment might bury some other habitats nearby.

- A nourishment is not considered a long term measure (in sense that it will be static for decades), because it is supposed to erode to replenish the system. Therefore it is not expected to be sustainable in the case of SLR. The nourishment will probably erode. Therefore would the nourishment need periodic maintenance or (eco-)engineering structures to keep it fixed and effective for hurricane flood risk reduction measure.

- A nourishment in the center of the Bay would be an unnatural element in the system, especially if emerged. Probably the nourishments will erode. But if effective as nourishment and reducing erosion rates, this would not be negative for natural system.

5.3. WETLANDS

5.3.1. FLOOD RISK REDUCTION

Wetlands possibly delay surge and reduce wave heights by energy dissipation due to increased **friction**. Wetlands increase friction by introducing two terms in the momentum balance due to vegetative resistance: due to bottom friction and due to drag throughout the water column (Loder, Irish, Cialone, & Wamsley, 2009). Therefore possible wave and surge attenuation depends on many factors, i.e. the stem diameter, stem density, stiffness and height of the vegetation. Friction by vegetation directly impacts the amount of momentum transfer of the flow (propagation of storm surge 'long wave') due to bottom stress. Elevation of vegetation impacts the momentum transfer due to both the bottom stress and vegetative drag (Loder et al., 2009). Elevation of wetlands (water **depth**) can play a role in the process of surge propagation and wave attenuation.

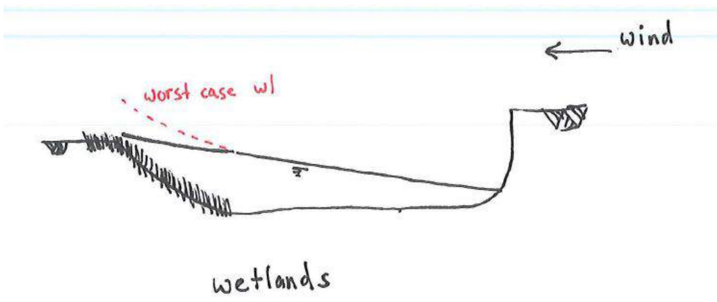


Figure 5.7: A schematic representation of the effect of wetlands on the water level (surge and wind set-up). Note that wetlands can also increase wind set-up and thus the water level for slow moving storms.

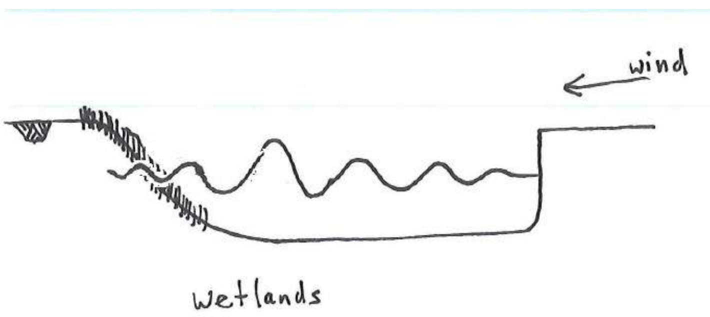


Figure 5.8: A schematic representation of the effect of wetlands on waves

SURGE

Literature on the effect of wetlands on surge has been reviewed, see Appendix D.2 for the complete review. The main findings will be presented below.

LITERATURE: EFFECT WETLANDS ON SURGE

- Frictional effects consist of both bottom stress and vegetative drag. These terms are introduced in the momentum balance.

- One effect of wetlands is to possible delay and attenuate a propagation surge by frictional effects. This effect could lead to surge reduction, especially for fast moving storms. In that case the propagation will be delayed reduced in height by frictional effects. Momentum equation balances between friction and water level gradient. Studies report water level reduction rates over a stretch of wetlands of 1 m per 4 km to 1 m per 25 km. The variability is very large and most studies focus on Louisiana.
- The second relative effect is elevation of wetlands on wind set-up, which might lead to higher surges for slow moving storms. The explanation is that eventually a steady state is present and no propagation can be observed anymore. Therefore friction doesn't play a significant role anymore and water level gradient will be balanced by wind stress in the momentum balance.
- If one would want to properly evaluate the effect of wetlands, numerical modeling in at least 2D (preferable even 3D) is needed and physical processes should be properly incorporated in the numerical modeling (especially drag forces introduced by vegetation), according to Wamsley, Cialone, Smith, Atkinson, and Rosati (2010).

WAVES

Literature on the effect of wetlands on waves has been reviewed, see Appendix D.2 for the complete review. The main findings will be presented below.

LITERATURE: EFFECT WETLANDS ON WAVES

- Wetlands attenuates waves by frictional effects induced by vegetation. Frictional effects consist of both bottom stress and vegetative drag of the stems. These terms are introduced in the momentum balance. Furthermore, wind shear stress is reduced if vegetation is emerged. However, this is unlikely in a hurricane event.
- Wave set-up (water level increase induced by momentum transfer due to breaking) is reduced significantly when waves are attenuated by wetlands.
- Factors which are important for wave attenuation are "vegetation characteristics, such as geometry, buoyancy, density, stiffness of the stems and spatial coverage, as well as hydrodynamic conditions, such as incident wave height, direction, period and water depth.
- Studies state that wave attenuation rates of around 1-5% per meter wetland are possible (see Figure D.2) (M. E. Anderson et al., 2011; Shepard et al., 2011), but assumed is that attenuation is exponential (most reduction in the first few meters of the wetland).
- Interactions are highly dynamic, therefore wave attenuation rates are very difficult to model or quantify. However, modeling vegetation roughness through the use of a dimensionless friction factor provides a reasonable estimate for the amount of wave attenuation through wetlands.
- Research on wave attenuation is mostly limited to small waves in or emerged or just submerged conditions, not large waves in totally submerged conditions (which would be the case during hurricane conditions). During a storm surge wetlands will be overtopped significantly and wave heights will be much higher than 1 m.

SUMMARY

- Reports show that surge reduction rates of 1 m/4 km to 1 m/25 km are possible, but surge increase over wetlands is possible as well. A fixed surge attenuation rate is impossible to define because of its dynamic and non-linear nature.
- Long stretches of wetlands are absent in Galveston Bay. Little surge propagation (i.e. Ike slow moving storm plus assumed pumping mode for surge) occurs and wind set-up could even increase the surge levels over the wetland. Therefore are wetlands considered to be **not effective** for surge reduction in Galveston Bay.
- Studies report that wave attenuation rates of 1-5 % per meter wetland can be achieved. Probably higher incident wave heights will be reduced at a higher rate.
- Wetlands are considered possibly **effective for wave reduction**. A width of at least **100 m** of wetlands at the shore of Galveston Bay is considered to significantly reduce wave heights at the landward edge of the wetland.

5.3.2. NATURAL VALUE

- Wetlands will not effect erosion in Galveston Bay on a global scale. Probably they will erode due to insufficient sediment supply, high SLR and wind waves, if not protected. If ample sediment supply or if constructed in a calm area they can be sustainable. In general wetlands do attenuate waves and do reduce erosion due to the reduction of undertow by vegetation, which is the main mechanism for erosion during storms (Guannel et al., 2015). Locally they can reduce erosion rates of shorelines, attenuate waves and capture and stabilize sediment by their vegetation and root structure.

- Wetlands are one of the most productive ecosystems in the world (Barbier et al., 2011), they filter runoff water before it flows into the Bay. They filter pollutants, nutrients, chemicals and fine sediments (Borsje et al., 2011). However, if the pollutant concentration in the filtered water is too high, the wetlands will degrade. This has happened in Galveston Bay in the past (Borsje et al., 2011). Wetlands can store and sequester carbon at high rates through the process of photosynthesis (Barbier et al., 2011). The anoxic nature of marsh soils carbon which is sequestered is shifted towards to long-term carbon cycle (1,000 years) as buried, slowly decaying peat (Barbier et al., 2011). In comparison, most ecosystems sequester carbon for the short-term (albeit not oyster reefs).

- Wetlands are considered good with respect to ecology. Wetlands are habitat area for a wide variety of fish, birds, plants and benthos and will increase biodiversity (EPA, 2005). It supports the esuarine ecosystem (of which a lot has been degraded in the past decades), with food and nursery grounds.

- Wetlands are able to grown with SLR, if sufficient sediment is supplied, as long as they are allowed to migrate inland and if they are in relatively healthy conditions. If wetlands are not allowed to migrate, their coastal protection value decreases as sea level rises. Fishing communities might benefit from SLR, if wetlands migrate as well (Guannel et al., 2014). In Galveston Bay sediment supply is insufficient, therefore is might be possible that wetlands will erode eventually. An option would be to protect wetlands with a breakwater to reduce wave-induced erosion, also one of the key mechanisms causing erosion. Furthermore there is, in some places, little room for the wetlands to migrate inland. These places would be unfit for wetland construction or restoration.

- Wetlands match with the development of the natural system, because wetlands are currently present in the system. This would not be unnatural to the system. However, erosion of wetlands is still an issue to remember, as well as room to migrate and wave action. Criteria for healthy wetlands are:

  1. Ample sediment supply
  2. Room to migrate under the influence of SLR
  3. Low wave energy conditions
  4. Limited pollutants in the water

5.4. ECO-ISLAND

5.4.1. FLOOD RISK REDUCTION

A so-called large eco-island would be constructed somewhere in the middle of Galveston Bay. The large area would be ideal for ecological development or recreational area. Like in the case of emerged nourishments, **fetch** of certain cross-section with respect to wind set-up will be affected by this measure to some extent. **Wind shear stress** can be affected as well, as for a large area wind shear stress is absent. Same assumptions apply as for the nourishments. However, the effect on wind set-up would be less than for a row of emerged nourishments, because an island will be confined to a certain area and water will be able to flow around it.

SURGE

For effect on wind set-up of an eco-island, reference is made to the section on flood risk reduction of nourishments (Section 5.2.1), because the possible effect of such an island would be to reduce local wind set-up. However, the effect will be less than for a row of emerged nourishments. Water can easily flow around it, making it less effective. Increasing the surface area will probably significantly improve surge reduction rates at the shore, because more water is retained. The closer to the shore which is chosen to protect, the better the fetch limited wind set-up is reduced.

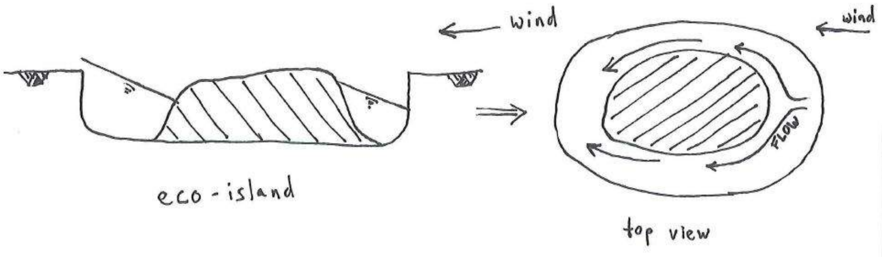


Figure 5.9: A schematic representation of the effect of an eco-island on the water level (wind set-up). Note that wind set-up reduction is less due to the face that water can flow around the island

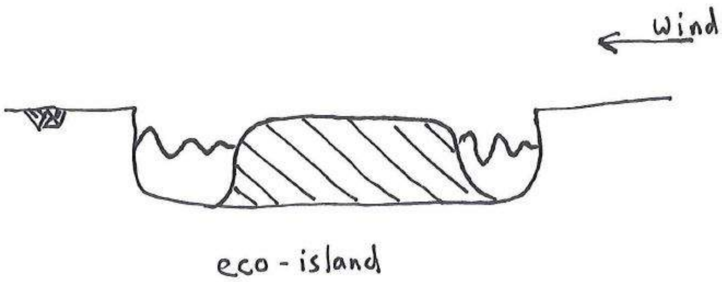


Figure 5.10: A schematic representation of the effect of an eco-island on waves

The fact that a large area where no wind shear stress is present could possibly affect the wind set-up on the lee side. The bigger the area, the more probable the effective for surge reduction with respect to wind shear stress reduction and subsequently wind set-up for the Bay is. But complex processes play a role, as water can flow around the island as well.

WAVES

With respect to waves the same holds as is the case for emerged nourishments. Additionally, as the island is confined to a certain area, waves can propagate around it making it unsuited for wave attenuation. With a big island the middle of the Bay waves at the shore will not be affected. Waves might be affected if island is constructed nearshore.

SUMMARY

- A large eco-island could be effective, as it affects wind set-up by means of fetch and wind shear stress reduction. However, it highly depends on the total surface area and location.
- Surge reduction will probably be lower than 0.5 m, except if the island is constructed nearshore.
- Wave height reduction will be marginal. An eco-island close to shore might be effective for specific areas along the shore.

5.4.2. NATURAL VALUE

- An eco-island is considered to be neutral for global erosion issues in Galveston Bay. However, the island could serve as mega-nourishment, but then it would have to be sacrificial to erode eventually. It is considered that the island itself is protected from erosion because of vegetation which stabilizes sediment.
- The eco-island has been qualified as neutral with respect to water quality. Vegetation or oyster reefs around the edges might marginally filter water from nutrients or pollutants. However, this effect depends very much on vegetation type and surface area.
- An eco-island would be very good with respect to ecology. It creates a large new surface area with (different) habitats and will support marine life. It is also recreationally interesting as it might serve as a bird paradise.

- The island would be not very sensitive to SLR. Probably some erosion will occur, but if constructed high enough this rate is manageable. If the edges are stabilizing living shorelines, such as oyster reefs or wetlands, even less erosion might occur.

- An island would not be compliant with the natural development of the system. There has never been an island in Galveston Bay.

5.5. OYSTER REEFS

5.5.1. FLOOD RISK REDUCTION

Oyster reefs are 3D structures capable of wave attenuation. **Bottom shear stress** and **depth** are the main variables affected by oyster reefs. Increased bottom shear stress is accomplished by increased bottom roughness and drag introduced by the reef (Styles, 2015). For oyster reefs usually a drag coefficient in modeling studies is used which is around 6 times larger than the coefficient for a sandy bed (Styles, 2015). Wave heights as well as wave energy will be reduced by the reef (Kroeger, 2012), which makes it potentially valuable during hurricane conditions. Surge reduction in not applicable due to permeability of oyster reefs, and will not be considered. Effect on wave heights will be qualitatively considered, giving the assumptions that the oyster reefs will be located close to the shore (within a couple hundred meters from the shore), can be emerged above MSL and are able to grow with SLR.

Oyster reefs can be constructed as breakwaters. It is not common to construct a breakwater specifically for hurricane conditions. But as waves in the Bay during hurricanes are limited to 1-2 m, it is considered to be possible to design a breakwater that attenuates these waves. To be effective for wave attenuation in hurricane conditions as well an oyster reef should be constructed as a conventional breakwater, but adapted for ecological functions with e.g. eco-concrete elements. The structure would be not just an oyster reef and would be emerged in daily conditions. It is unknown how oyster reef breakwaters react to storm damage. Grabowski et al. (2012) states that "the relative risk of storm damage to engineered and oyster reef structures needs to be considered". This reinforces the fact that the breakwaters would have to be designed for hurricane conditions as well. A breakwater for hurricane conditions would be robust and not dependent on living organisms, which is a valuable characteristic. It is considered a design of oyster reef breakwater to attenuate daily and hurricane waves in Galveston Bay and reduce erosion is possible. It is not within the scope of this research to develop or design such a breakwater.

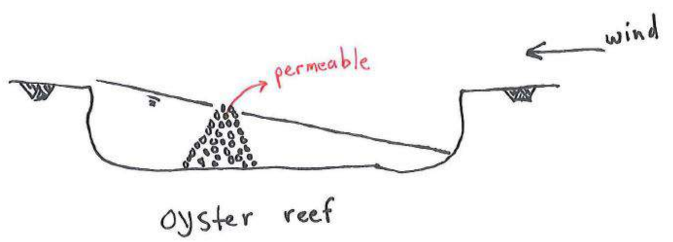


Figure 5.11: A schematic representation of the effect of oyster reefs on the water level

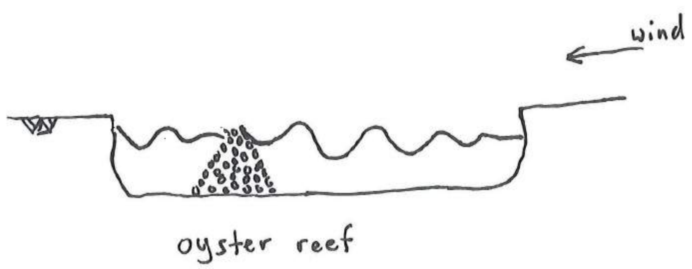


Figure 5.12: A schematic representation of the effect of oyster reefs on waves

WAVES

Waves lose energy while propagating over the reef and eventually break. Behind the reef or breakwater still water can be found with lower wave heights, and less erosion on a daily basis is expected to occur.

Kroeger (2012) investigated the benefits and impacts of two oyster reef restoration projects along the North Gulf Coast. High relief reefs of 0.5-1 meter is applied. The projects are expected to reduce the wave energy at least by 50%. Also, the investigator states that the reefs substantially reduce wave height and energy of waves in hurricane conditions (Kroeger, 2012). This has not been quantified.

SUMMARY

- Oyster reefs add friction and drag, which affects the bottom shear stress and is capable of attenuating waves.
- Oyster reefs are considered to be effective for wave attenuation and erosion, provided that they are constructed close to shore. Oyster reefs are expected to reduce wave heights around 50% for some restoration projects of high relief oyster reefs in daily condition waves (0.5-1 m). (Kroeger, 2012). However, probably wave heights and wave energy are reduced in hurricane conditions.
- The effectiveness for hurricane wave attenuation should be investigated. But, assumed is that a design of an oyster reef breakwater which is effective in hurricane conditions is possible.

5.5.2. NATURAL VALUE

- Oyster reefs at the shore reduce erosion. Therefore they can reduce erosion for Galveston Bay, especially around coasts where high erosion rates have been measured (where i.e. the H80 is over 0.2 m). However, the sediment deficit in that case is not expected to change. Oyster reefs are effective in protecting wetlands from erosion (Guannel et al., 2014).
- Oyster reefs are considered very good with respect to water quality. They can filter significant amounts of water (5 l/hour) if circulation is sufficient. Reefs filter the water from algae, nitrogen, sediment, organic matter, nutrients and chemicals (Grabowski et al., 2012). Additional result is a reduced turbidity of the water. They can sequester carbon dioxide by burying it in their shells (Grabowski et al., 2012). Hall et al. (2011) states that oyster reefs are "on a carbon per time per surface area basis, orders of magnitude more effective than grass based systems".
- Oyster reefs are considered to be very good for ecology. They provide habitat and food source for all sorts of marine life and bethic fauna (Grabowski et al., 2012). Oyster reefs are degraded habitats of Galveston Bay. An additional function might be enhancement of the conditions by wave attenuation along the edge of wetlands.
- Oyster reefs are not sensitive to SLR, as they can grow with SLR, provided that conditions are well (nutrients, salinity etc).
- Oyster reefs are a well-known habitat to the system, therefore it is compliant to the development of the natural system. Most oyster reef degradation in Galveston Bay was due to human impacts (shell harvest) or recent hurricane sediment load. Restored oyster reefs will be sustainable. Criteria for healthy oyster reefs are:
  1. A salinity of 10-30 ppt
  2. Proper circulation to bring in nutrients and phytoplankton
  3. Moderate sedimentation load. Although oyster reefs can filter sediment, too much sediment will be crucial. In that case oyster reefs will be buried with negative consequences (Wilber & Clarke, 2010).
  4. Spat availability to form new reefs and grow upward

5.6. SUMMARY OF QUALITATIVE EVALUATION

5.6.1. FLOOD RISK REDUCTION TOOLBOX

The resulting classification toolbox shows effectiveness of suitable BwN building blocks for hurricane flood risk reduction in Galveston Bay with respect to waves and storm surge (Table 5.4 on the next page). It is based on conclusions from this chapter and on e.g. M. Spalding, McIvor, Tonneick, Tol, and van Eijk (2014), USACE (2013a) and Guannel et al. (2014). The color of the cells represents a classification which has been assigned to the building block with respect to a certain mechanism (surge or waves). A building block which has a significant effect and contains few uncertainties is assigned with the color green. Orange means the building block could have an moderate effect on surge or waves, it has potential but contains some uncertainty. A red classification means the building block has marginal or no effect. This classification is merely an indication for the potential effect of the measure on surge and waves. Therefore, naturally, its ultimate effect depends on the scale and design of the measure.

It can be concluded that significant **surge** reduction is very difficult to accomplish for a measure which is not a continuous and integral structure (e.g. a dam). But there is potential for reduction of several decimeters to a meter for Galveston Bay. Surge is best reduced by more or less continuous emerged nourishments that compartmentalize the Bay. However, adequate quantification is difficult. An eco-island is expected to be significantly less effective. They both are far more effective if closer to shore, as fetch is the relevant affected variable. Wetlands or oyster reefs (breakwaters) are considered to be not effective for surge reduction in Galveston Bay.

Waves are generally better attenuated at or nearshore as they are depth limited in the shallow bay with high fetches under hurricane forcing. Wetlands are promising in reducing wave attack, but relatively wide strips are needed. Quantification is difficult due to wetland variables like vegetation type, density and stem stiffness and non-linearity of the processes. Not much is known how wetlands attenuate waves during hurricane conditions, and the width of a sufficient strip of wetlands may depend on hurricane erosion. The advantage of oyster reefs is that they can be constructed as conventional breakwaters which are adapted to optimize oyster attachment. At the shore, they are effective attenuating waves and reducing erosion on a daily basis. In hurricanes conditions a design of such a structure is assumed to be possible, but this should be thoroughly investigated. An oyster reef breakwater is considered a robust solution as it does not depend on organisms. Nourishments and an eco-island nearshore might be effective in attenuating waves in specific areas of the shoreline, especially if emerged.

Building Block	Location of BB	Effect on Flood Risk at shore		Performance Factors	Additional Functions
		Storm Surge	**Wind Waves**		
Nourishments	Center	If emerged, it can reduce fetch and affects local wind set-up. Wind-set is inversely proportional to depth. Therefore bay partition is relatively more effective for shallower Bay (e.g. in case of Ike Dike). **Surge reduction values of 0.5 meter in the West Bay and Northwest (HSC) shores** could be achieved for idealized**, 'continuous' and emerged nourishments** The closer to shore the bigger the effect. Only effective if emerged.	If emerged, fetch reduction --> affects wave growth. Waves are depth limited and wave height is proportional to depth. Waves are almost fully developed, especially for a shallow Bay. Therefore will **emerged nourishments** for idealized conditions **only marginally affect waves at shore.** The relative effect is bigger for higher depths (e.g. SLR) though.	• Elevation • Continuity • Distance to downwind shorelines • Surge level • Wave height • Length • Presence of closed coastal spine (wl during storm) • SLR • Current speed (during hurricane conditions)	• Replenishes the system with sediment/Erosion mitigation (sacrificial) • Protection from wave attack/Shore protection • Possible habitat if conditions apply and/or vegetated (wetland, mudflat)
	Shore	**Idem. The closer to shore, the bigger the effect** Only effective if emerged	At shore, where fetch is irrelevant. **nourishments are effective as breakwater (shoal), if emerged** Most effective if emerged		
Wetlands	Center	Miles needed to possibly affect propagating surge (4-25 cm/km) by friction (bottom friction + vegetative drag) **for GB: not effective for surge reduction** • Un-natural: no (long) stretches of wetlands in center or GB • Additionally: in GB little surge 'propagation' (due to pumping mode)	Several tens to hundreds of meters needed to reduce wave heights (1-5% per m + exponential decay) by friction (bottom friction + vegetative drag) **for GB: not effective for wave reduction at shore** • Un-natural: no wetlands in the center of GB	• Sufficient sediment supply • SLR and available space to migrate inland • Density (stems/m2) • Vegetation type • Vegetation height • Wetland elevation and continuity • Wetland area/width • Surge level • Wave height • Wave period • Storm duration and forward speed • (Storm) erosion	• Stormwater retention • Sediment stabilization • Shore protection • Provide habitat • Water quality • Carbon sequestration • Possible recreational value
	Shore	Miles needed to possibly affect propagating surge (4-25 cm/km) by friction (bottom roughness + vegetative drag) **for GB: no effect on surge** • If present, there are narrow strips of wetlands in GB	Several tens to hundreds of meters needed to reduce wave heights (1-5% per m + exponential decay) by friction (bottom roughness + vegetative drag) **for GB: assumed required width at least 100 meter**		
Eco-Island (island with large surface area for ecological development)	Center	Reduces fetch and wind shear stress and can affect wind set-up for certain transect. But confined area and water can flow around island. **Assumed surge reduction rates are smaller than for emerged nourishments,** but possibly effective in right location and with enough surface area. The bigger the island and the closer the shore, the bigger the effect.	Reduces fetch and wind shear stress. But **waves** are depth limited and will **not be or only marginally affected at the shore.**	• Elevation • Surge level • Wave height • Island surface area • Land coverage • Distance to downwind shorelines • (Storm) erosion	• Ecological diversification (biodiversity) • Possible sediment stabilization • Provide food and habitat • Aesthetic landscape • Possible recreational value
	Shore	**Idem. The closer to shore, the bigger the effect on surge**	At shore, where fetch is irrelevant. **eco-island could be effective as breakwater island**		
Oyster Reef Breakwater	Center	**No effect on surge** • Permeable	**No effect on waves at shore** • Oyster reef should be constructed at shore	• Wave height • Wave period • Surge level • Elevation/Crest height • Width • Roughness/Used material • Permeability • Proximity to the shoreline • Orientation • SLR • Sedimentation on reef (relevant if oysters provide functionality)	• Shore protection/stabilization by wave attenuation • Water quality (filters pollutants, nutrients and fine sediment) • Carbon sequestration • Provide food and habitat • Promotes economic (oyster) fisheries
	Shore	**No effect on surge** • Permeable	Oyster reefs increases bottom shear stress by bottom roughness and drag (drag coefficient is 6 times larger than for e.g. sandy bed). **Effective for wave attenuation.** If constructed as breakwater **possibly effective for hurricane wave attenuation**, provided that in close proximity to or at shoreline		

Table 5.4: Toolbox Hurricane Flood Risk Reduction of BwN Building Blocks for Galveston Bay. Legend: green = positive effect, orange = moderate effect, red = no or marginal effect

5.6.2. NATURAL VALUE TOOLBOX

The resulting classification toolbox shows the BwN building blocks for Galveston Bay and their effective natural value (see Table 5.5 on the next page). The toolbox is based on conclusions from this chapter and the ecosystem services of habitats of Galveston Bay (Table 4.1). The color classification works similar to the flood risk reduction toolbox. A building block which has a positive effect on natural value and contains few uncertainties is assigned with the color green. Orange means the building block could have an moderate or neutral effect on surge or waves, it has potential but contains some uncertainties. A red classification means the building block has no or even a negative effect on natural value. This classification is merely an indication for the potential effect of the measure on surge and waves, naturally its ultimate effect depends on the scale and design of the measure.

It can be concluded that both nourishments and an eco-island are generally considered to be neutral with respect to natural quality. Especially continuous, emerged nourishments could negatively impact circulation and subsequently ecology. Wetlands are good, they are a type specific habitat and they enhance ecology and increase biodiversity. However erosion due to SLR and daily wind waves might still be a problem, especially if wetlands are not protected. Oyster reefs are considered to be the best measure for natural quality. They are robust, sustainable, and they enhance ecology and increase biodiversity as well.

Building Block	Effect on Natural Value				
	Erosion	**Water Quality**	**Ecology**	**SLR**	**Match Autonomic Development System** (succes criteria)
Nourishments	Could add sediment to a starved system	Neutral, might increase turbidity	Neutral. If continuous could negatively impact circulation	Not supposed to be long-term solution. To be so, maintenance needed	Not type specific, but positive if effective against erosion
Wetlands	Globally won't affect erosion. Locally could reduce erostion rates compared to hardened shores	Good. Filters (runoff) water from pollutants, nutrients, chemicals and fine sediment. Plus they sequester carbon	Good. Restoration of (degraded) habitat for marine life (fish, birds, bethos and plants). Increases biodiversity	Inadequate if not protected. Insufficient sediment supply + high SLR	Ok, it's a type specific habitat, which is present in GB. But, erosion might be an issue. Success criteria: 1) ample sediment supply, 2) room to migrate, 3) low wave conditions and 4) limited pollutants
Eco-Island	Neutral, but could influence tidal prism	Neutral, but edges (e.g. wetlands or oyster reefs) could be filtering some water	Very good. Large surface with new habitats and huge biodiversity increase	Neutral to SLR, because large, emerged island. Edges could erode slightly	Not type specific. Never been an island in GB
Oyster Reefs	Effective at reducing erosion at shores and wetlands, especially for shores with H80 bigger than 0.2m	Very good. Filter large amounts of water from algae, nitrogen, sediment, nutrients and chemicals. And sequesters carbon	Very good. Provide habitat and food source for marine life and benthic fauna	Not sensitive to SLR, as they can rise with SLR (provided good conditions)	Type specific habitat. Human impacts have been degrading oyster reefs mainly. Success criteria: 1) salinity of 10-30 ppt, 2) proper circulation to bring nutrients & phytoplankton, 3) moderate sedimentation on top of reef and 4) abundant spat availability

Table 5.5: Toolbox Natural Value of BwN Building Blocks for Galveston Bay. Legend: green = positive effect, orange = moderate effect, red = no or marginal effect

5.6.3. COMBINATION TOOLBOX

A combined toolbox with the classifications with respect to flood risk and natural value is presented in Table 5.6. This toolbox gives quick insight in the effect of the building blocks for Galveston Bay. An interesting contradiction can be found regarding the effect on natural value and flood risk reduction. The building blocks that have most potential in reducing flood risk are generally considered as least good with respect to natural value and vice versa.

Building Block	Location of BB	Effect on Flood Risk at shore		Effect on Natural Value				
		Storm Surge	Wind Waves	Erosion	Water Quality	Ecology	SLR	Match
Nourishments	Center							
	Shore							
Wetlands	Center							
	Shore							
Eco-Island (island with large surface area for ecological	Center							
	Shore							
Oyster Reef Breakwater	Center							
	Shore							

Table 5.6: Combined Toolbox Natural Value and Flood Risk of BwN Building Blocks for Galveston Bay. Legend: green = positive effect, orange = moderate effect, red = no or marginal effect

5.7. CONCEPTUAL DESIGN

This section presents a conceptual design. This design will be a result of the outcomes of both classification toolboxes and area specific characteristics. Separate measures for surge and waves will be proposed because both mechanisms are significantly different. It could be an option to combine surge and wave measures, especially in West Bay.

5.7.1. AREA CHARACTERISTICS

A map of specific characteristics of Galveston Bay can be seen in Figure 5.13. For areas that are most susceptible to erosion (yellow shaded shore in the overview), reference is made to Figure A.8 in Appendix A. The area is divided into four potentially different areas for measures inside Galveston Bay which are identified base on Figure 2.19 and Figure 5.13. A protection from the following mechanisms is desirable for four areas in Galveston Bay. However, area East Bay is added to present a comprehensive analysis:

1. Texas City: Waves
2. West Bay (Kemah): Surge and Waves
3. Northwest (HSC): Surge
4. East Bay*: Surge (possibly)

* Area East Bay is added because it is vulnerable to flooding from surge. However, the area is highly rural and not urbanized. Therefore not much development is located at the shoreline. Moreover, waves during hurricanes in the East Bay area are considered not a major issue. Additionally, most shore is undeveloped which means it probably contains some natural protection from storm damage.

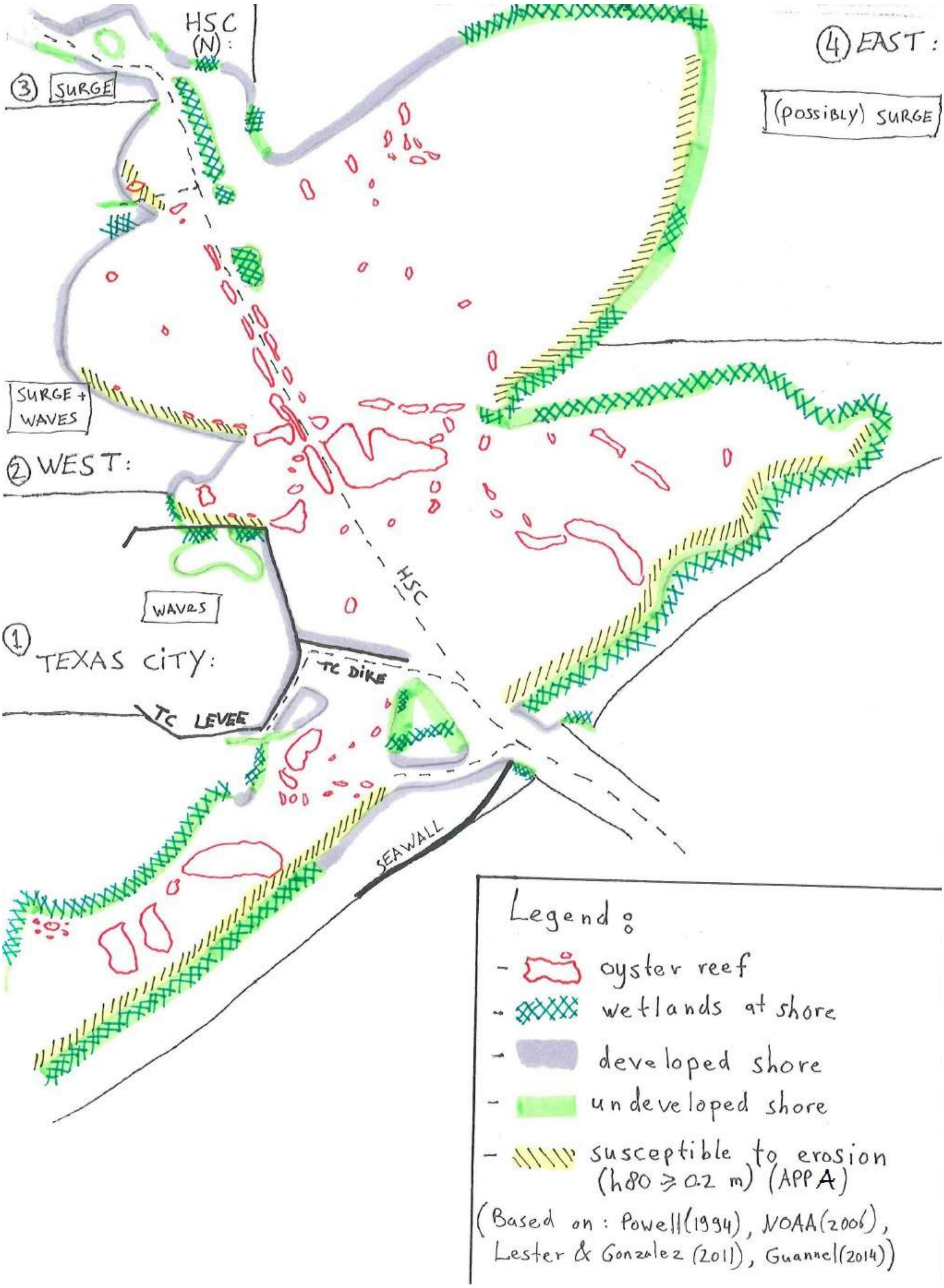


Figure 5.13: Area characteristics of Galveston Bay

5.7.2. DESIGN: WAVES

West Bay has an almost completely developed shoreline. No to little wetlands are present and large numbers of people have jetties for leisure boating. Therefore the choice has been made to protect this shoreline with **oyster reef (breakwaters)**. These can protect the developed and urbanized shoreline from wave attack and erosion. Because erosion is significant already, and a large part of the shore is susceptible to erosion, oyster reefs would be beneficial on a daily basis.

The Texas City Levee protects the city, but its current strength is questionable. During Ike, the levee was almost overtopped. High wave attack during hurricanes can threaten the levee. The levee is present at the shoreline, which means there is space for strengthening of the levee. The choice has been made to create **wetlands**, located at the foreshore of the levee to protect and strengthen it. It would attenuate waves and prevent erosion. During hurricane conditions the levee would endure less wave attack and run-up. In the northern part of the levee, where currently the highest H80 wave height occurs and the shoreline is most susceptible for erosion the wetlands at foreshore of the levee will be strengthened by an **oyster reef** to prevent erosion of the wetland itself and make an even more sustainable system. This is similar to a living shoreline concept. Something to consider would be constructing oyster reefs in East Bay to prevent daily erosion of the vulnerable wetlands, although it is not presented in this study. See the next Figure 5.14 for an impression of the complete wave design for Galveston Bay for all areas.

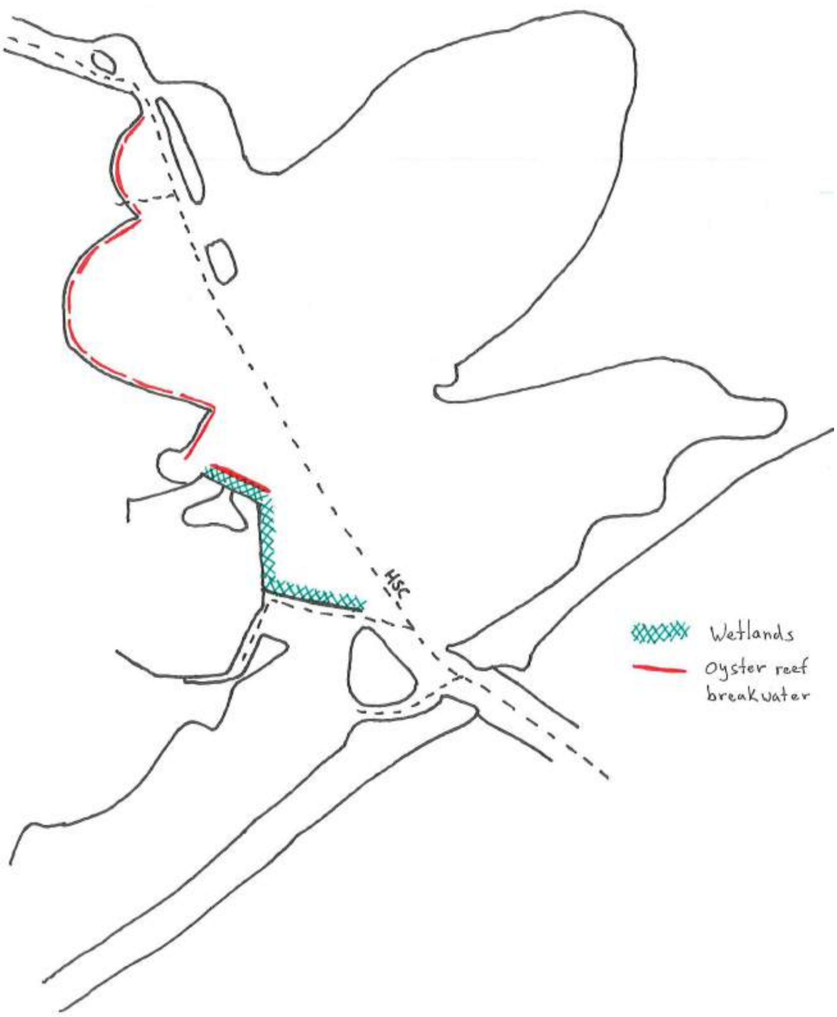


Figure 5.14: Conceptual BwN wave design for West Galveston Bay and the Texas City Levee

5.7.3. DESIGN: SURGE

It has been chosen to consider both **nourishments** and an **eco-island** for possible surge reduction measures. Both could add natural value, although this should be investigated thoroughly. The surge reduction potential of nourishments, especially emerged, is promising. In the West and East Bay space is available to construct measures. An advantage is that no shipping channels will cross. It will be difficult to reduce surge levels in HSC in the Northwest, because the HSC will always cross the measure. And because HSC is deep it is expected to carry most water towards the North, making the measure less effective. If constructed closer to shore, the reduction for all measures will be higher as fetch is the affected variable. An eco-island is less effective than emerged nourishments. A point of consideration is SLR, which could mean the solution is not durable, especially for nourishments.

Emerged nourishments can reduce surge for:

- Northeast Bay
- West Bay
- Northwest (HSC)

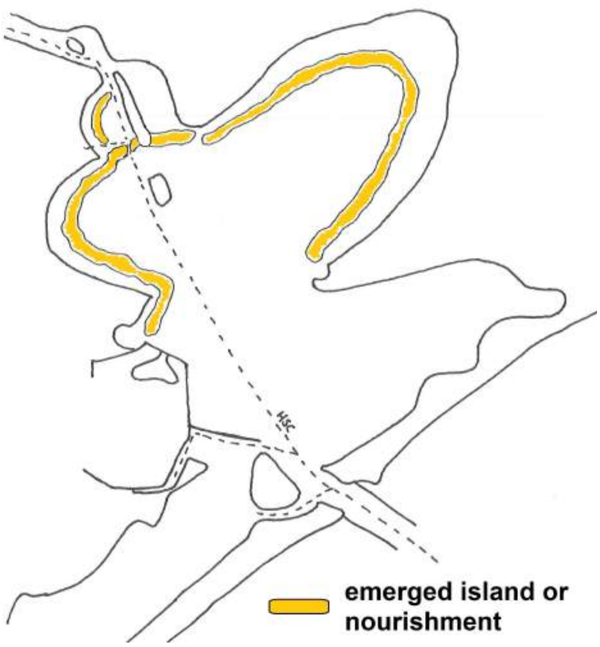
Eco-island can possibly reduce surge for*:

- Northeast Bay
- West Bay

* An eco-island is a large island. It is not considered here since it is unrealistic to construct it near the HSC in the Northwest.

See the following sketches (Figure 5.15 and Figure 5.16), for impressions of nourishment and eco-island designs for all areas combined. For all three areas a nourishment design is considered which is constructed as close as possible to the shore. In this chapter it was concluded that test design 3 was most effective for surge level reduction at the western shore. However, also this thesis show that emerged nourishment closer to the shore was more effective as fetch is more significantly affected. Therefore designs are located closer to shore and still is realistic option. The test designs of the 1D analysis in this chapter are omitted from now on, as those were merely for understanding of the mechanisms.

Figure 5.15: Conceptual BwN surge design, which consists of emerged nourishments for the areas West Bay, Northwest or HSC and East Bay (combined in one figure)



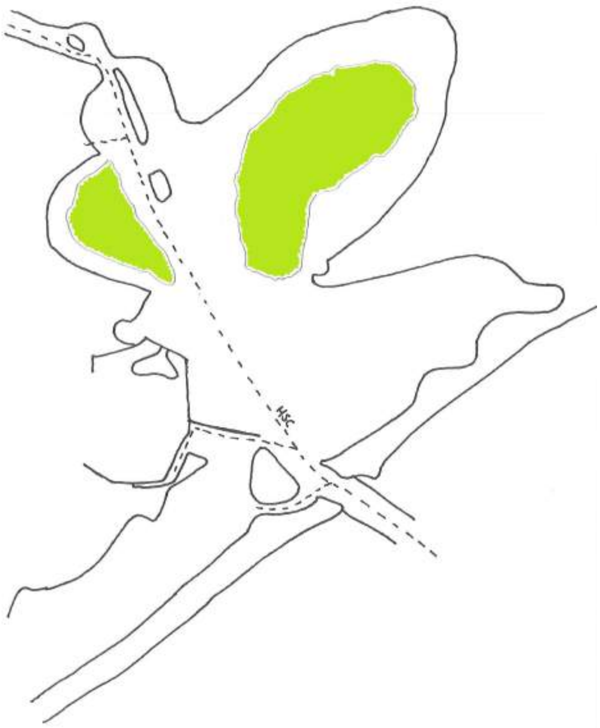


Figure 5.16: Conceptual BwN surge design, which consists of eco-islands for the areas West Bay and East Bay (combined in one figure)

Surge reduction methods are potentially interesting, but these highly simplified considerations are insufficient to draw conclusions. Also the continuous shapes that are considered are fairly unrealistic therefore some openings might be possible. How these openings between nourishments will be influencing the surge levels is unknown. The surge reduction strategies will be continued with a 2DH hydrodynamic study. Both eco-island and nourishments will be investigated, and thereby the abovementioned designs (Figure 5.15 and Figure 5.16) for three areas will be separately included in the model analysis. From now on, emerged nourishments for wind set-up reduction will be referred to as **emerged islands**, because such a structure is not considered a nourishment anymore. These islands might be considered as artificial barrier islands, although they would be located inside Galveston Bay.

6

SET-UP OF HYDRODYNAMIC MODEL

This chapter deals with the hydrodynamic 2DH[1] model, its relevance and set-up. The software package is D-Flow FM (Flexible Mesh) by Deltares (van Dam, Kernkamp, van der Pijl, & van Balen, 2015). Finally, this chapter discusses the calibration and method of use of the hydrodynamic model.

6.1. WHY A 2DH MODEL?

In the previous chapter we saw that with a simplified analysis it is hard to quantify the surge reduction benefits of certain BwN measures. A order of magnitude of the effect of a certain measure can be estimated, but processes during hurricane flow conditions are more complex. Therefore, the following listing states several reasons to use a hydrodynamic model:

- The hurricane forward speed and the rotating motion of the hurricane have not been implemented into the previous considerations. This is not described easily analytically.
- To incorporate complex bathymetry of Galveston Bay and two-dimensional processes. These are relevant when evaluating measures by implementation of barriers of any kind. It is absolutely crucial to determine two-dimensional mechanisms and processes to determine added value of measures. Stoeten (2013) made a probabilistic hurricane model to assess system behavior. His model showed good results. However, it only simulated along two one-dimensional transects, which means only 4 points could be assessed inside Galveston Bay. Complex bathymetry was not incorporated.
- In the previous chapter it was concluded that different areas of Galveston Bay have different options with respect to hurricane protection. High surges can be expected in West, Northwest (HSC) and Northeast. However, the differences between those areas are unknown.
- Stoeten (2013) describes sensitivity of surge levels in the bay to landfall locations of the hurricane. But how the landfall location exactly results in surge levels for our four interest areas is particularly interesting. Different tracks of Ik will be used to capture different peak surges in the areas.
- The case with an Ike Dike would be an interesting one to investigate. Currently, it is unknown how much exactly surge levels during hurricane conditions would be in case of a coastal spine. The effectiveness of building blocks with that scenario, needs assessment by a 2DH model. Also, the criterion that the local set-up must not exceed the local depth might be violated in case of a coastal spine, making the simplified considerations from the previous chapter unsuited. In that case a 2DH numerical model would be needed as well.

6.2. HYDRODYNAMIC MODELING CONCEPT

A 2DH hydrodynamic numerical model is used to asses the surge risk reduction capability of building blocks from the previous chapters. A hydrodynamic modeling suite is able to simulate flow conditions. This model

[1] 2DH means two-dimensional horizontally (see e.g. Battjes (2000)). 2DH models simulate horizontal two-dimensional and depth-integrated surface flow flow

needs site specific input, such as a domain, bathymetry, roughness and boundary conditions at the seaward boundaries. A computational grid, following certain qualifications should be applied. To simulate flow under hurricane forcing certain hurricane parameters can be transformed into pressure and wind speed varying in space and time, which is used by the model to force the flow. This has to be done prior to the flow simulation with a different model. The modeling concept of such a 2DH storm surge model can be summarized by the following figure. Output are flow and wind characteristics within the domain, for certain time span.

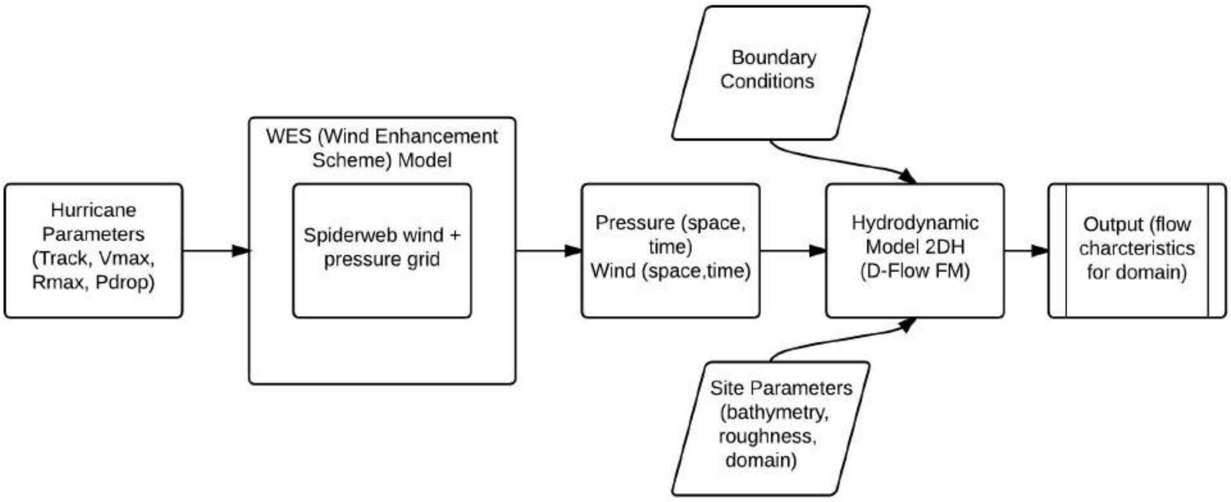


Figure 6.1: Modeling concept for the 2DH hydrodynamic hurricane model

The study uses the simulation of hurricane Ike, the catalyst of flood risk awareness in Galveston Bay. Therefore it is considered as the 'reference storm' for most modeling studies. Although it is not completely known, Ike conditions and surge levels are supposed to be quite comparable to the 1/100 year^{-1} return conditions, which is a good starting point for storm surge simulations and measures. Furthermore, observations of hurricane Ike are widely available. Different shifted tracks of Ike will be incorporated in the simulations. It is possible to couple flow simulations with wave simulations in a later stage. A wave model has not been included in this research.

6.2.1. HYDRODYNAMIC MODEL CHOICE

It has been chosen to use D-Flow Flexible Mesh (D-Flow FM) for the hydrodynamic modeling (van Dam et al., 2015). This simulation package by Deltares makes use of flexible meshes, which means curvilinear meshes combined with triangles or whatever form the user would want to use. D-Flow FM solves the 1D, 2D or 3D shallow-water equations (SWE). In this study focus lies on a 2DH model, in which the fundamental SWE (conservation of mass and conservation of momentum) are solved in the two-dimensional, horizontal domain, spatially averaged over water depth. D-Flow FM is expected to be the successor of several Deltares hydrodynamic modeling suites, such as Delft3D.

The reason this package has been chosen is that it is capable of rather quick and accurate mesh generation in geometrically complicated ares by the use of curvilinear and e.g. triangular meshes and efficient computation (Kernkamp, Van Dam, Stelling, & de Goede, 2011). Another reason was that a similar, unstructured grid of Galveston Bay has been created before by Ruijs (2011). The grid for this model was created using Mike. This grid was converted to a D-Flow FM grid and served as a starting point for the grid creation in this study. However, because Ruijs used it for a tidal simulation the grid needed major improvements to make it applicable for our hurricane surge simulations.

6.2.2. HURRICANE WIND AND PRESSURE FIELD MODEL

The 'Wind Enhancement Scheme' (WES), a program by Deltares to generate tropical cyclone wind fields is used as hurricane wind and pressure model (Deltares, 2015b). "The program computes surface winds and pressure around the specified location of a tropical cyclone's core and given a number of tropical cyclone parameters" (Deltares, 2015b). It uses a parametric model based upon Holland (1980), but adapted. The model has five hurricane parameters: track, radius to maximum winds, maximum wind speed, core pressure and current motion vector of the cortex (Deltares, 2015b).

6.3. MODEL SETUP

A small-scale model domain is used, to keep the study manageable and mainly the simulation time rather short. The domain is the same as used by Ruijs (2011). It extends from San Luis Pass to Rollover Pass, and the sea boundary is 25 km offshore. But, hurricanes induce large-scale motion across the Gulf Coast. To incorporate the large-scale effects of the hurricane the model will be forced with water level boundary conditions which follow from the ADCIRC and SWAN model, validated for Ike (Sebastian et al., 2014). Local effects will be captured by the use of hurricane wind and pressure field, varying in time and space and moving across the model domain. The simulation time is 3.5 days, from September 10, 2008 at 12.00 PM - September 14, 2008 at 12.00 AM (GMT). Hurricane Ike made landfall at September 13, around 7.00 AM (GMT).

The model uses an MDU (Model Definition Unstructured) file as the main file of a simulation. It contains geometric information and numerical and physical parameters. Some parameters included in the MDU file of the simulation will be discussed below. Output parameters will not be discussed. See Appendix E.1 for an example of an MDU file.

6.3.1. NETWORK

The network (in Delft3D known as grid) has been constructed by using a flexible mesh approach, combined with a curvilinear grid approach. In areas where flow is mainly occurring in longitudinal direction (deep channels) is a curvilinear approach applied to enhance simulation time. In general is a smaller grid size applied in areas with specific interest or small-scale bathymetry, in the channels and inlets. The channels are of specific interest since they are expected to move a proportional amount of water through the basin. Therefore it is tried to capture the depth of the channels, especially the HSC, sufficiently with curvilinear cells of 50 to 100 m wide (on a channel of about 300 m wide). The largest gridcells are around 3,000 m, and the smallest around 30 m. The total number of netnodes used is 25,447, the number of netlinks is 68,025. It has a maximum orthogonality of 0.048, which is considered good. The network's coordinated system is a spherical (lat, long) UTM zone 15 system. A spherical system is used because the spiderweb hurricane grid is only compatible with this kind coordinate system. It can be seen from Figure 6.2 that the network extends the sea-land boundary. The reason is that hurricanes cause inundation. Although the network extends the land-water boundary, observation points are defined at the shoreline to capture relevant water levels.

6.3.2. BATHYMETRY

A bathymetric dataset (or DEM: Digital Elevation Model) by Taylor et al. (2008) was used to supply bottom depth information to the network. This dataset has a resolution of 1/3 arc seconds, which is equal to around 10 m. This data has been reduced by a factor two in resolution, after which it would still match the grid resolution quite well. Vertical reference level is set to MSL.

A representation of the bathymetric dataset has been presented prior to this chapter (Figure 2.2). A figure of the grid with corresponding bottom depth values can be seen below, Figure 6.3. In the Galveston Bay jetties and levees are present that are not optimally incorporated into the bathymetric data, and especially in the coarse network. These geometric parameters are small-scale features and can be incorporated into the model through weirs (levees with limited height) or thin dams (levees with infinite height). To incorporate these important geometric parameters the following has been done. The Texas City Levee (Texas City Hurricane Protection) has been incorporated as a thin dam, infinitely high because its height is estimated to be around 7 m. The Galveston Seawall has a slightly lower crest height, and is therefore estimated as a weir with a crest at 5 m [17 feet] +MSL. The North and South Jetty and the Texas City Dike are simulated as weirs of respectively 0.5 and 1 m (estimated from bathymetric data).

6.3.3. NUMERICAL AND PHYSICAL PARAMETERS

The courant number in the simulations is automatically set to a maximum value of 0.7. The time step is automatically adjusted to satisfy the courant number. The courant number is a numerical parameter . A

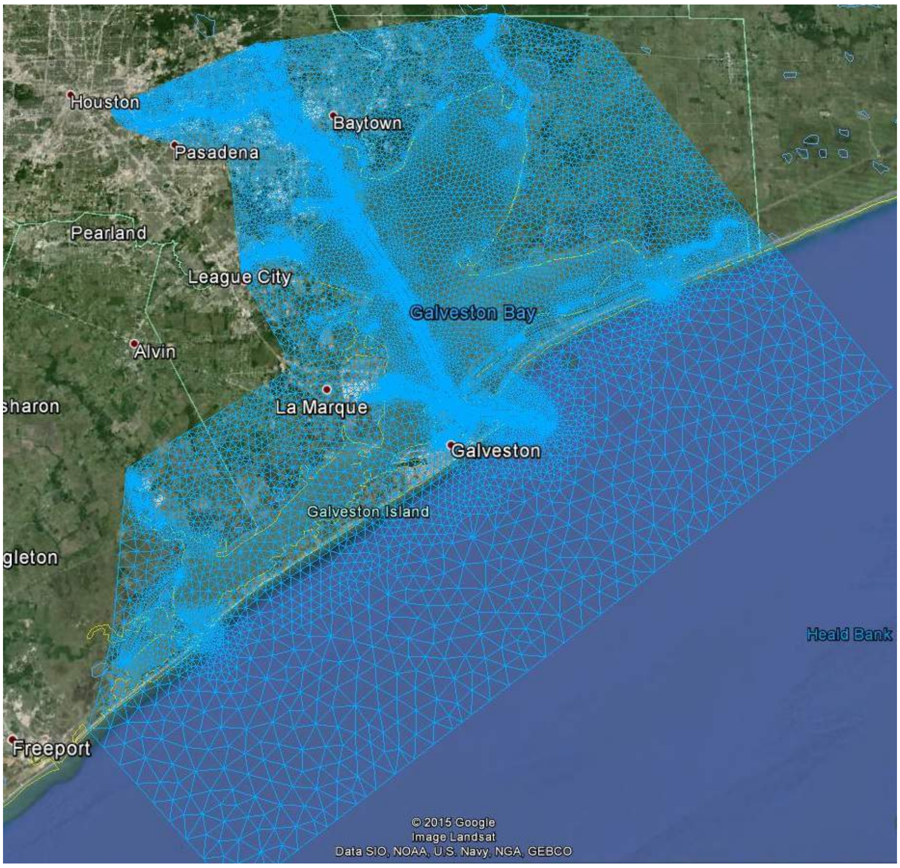


Figure 6.2: Galveston Bay network, plotted in Google Earth

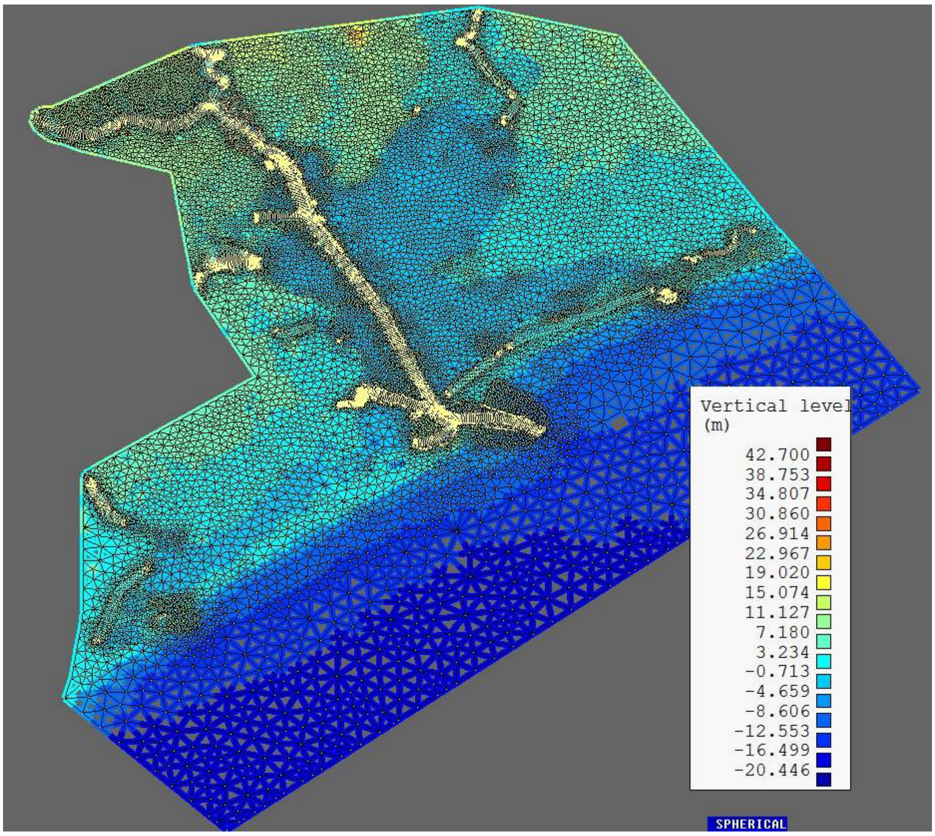


Figure 6.3: Grid with corresponding depth values. Units are [m], positive is above MSL, negative is below MSL

courant number of 1 or smaller usually yields stable solution. This criterion is called the CFL condition and is a necessary condition for stability of the numerical solution. An increased uniform eddy viscosity and eddy diffusivity of 10 m^2/s (default is 1) was chosen, because the model makes use of a coarse grid.

A unity friction Manning type coefficient has been set to 0.02 (default of D-Flow FM is 0.023), which can be explained by the fact that roughness below water is often represented by a roughness of 0.02 for the Gulf Coast and because Galveston Bay area contains fine sediments, which are more likely to be smoother. To specify roughness for different areas this can be specified in the EXT file. This has been done for all the area that are located above MSL. The roughness was the main calibration parameter. No other physical processes, such as salinity or temperature, are included.

6.3.4. EXTERNAL FORCING

An EXT file defines the external forcing of the model, such as boundary conditions and wind forcing through a spiderweb wind and pressure grid. See Appendix E.1 for an example of the EXT file.
The small-scale model is forced by water level time series at the seaward boundaries, simulated for hurricane Ike. This study was supplied with three water level time series of points close our seaward boundary. A graph of the water levels at those three points, is shown in Figure 6.5.

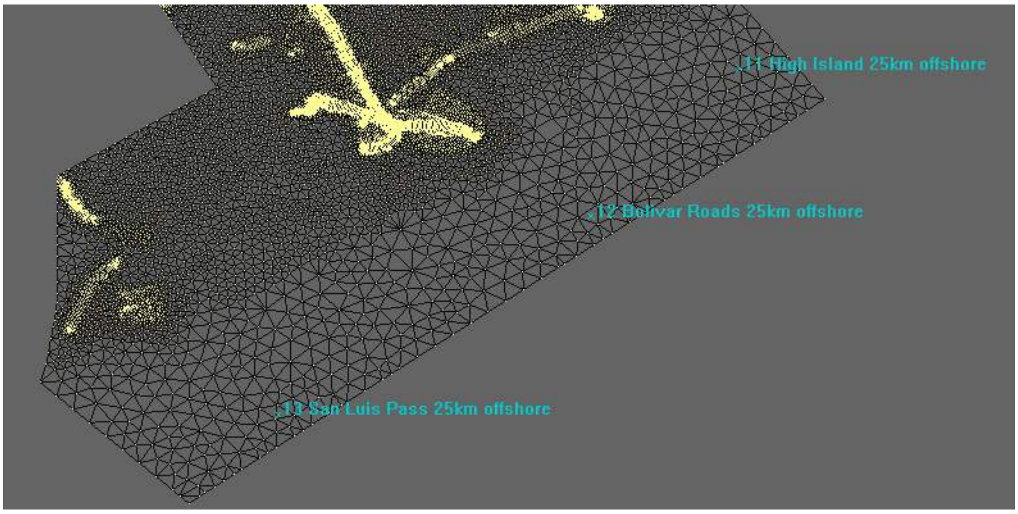


Figure 6.4: Water level points to force seaward boundary of the model

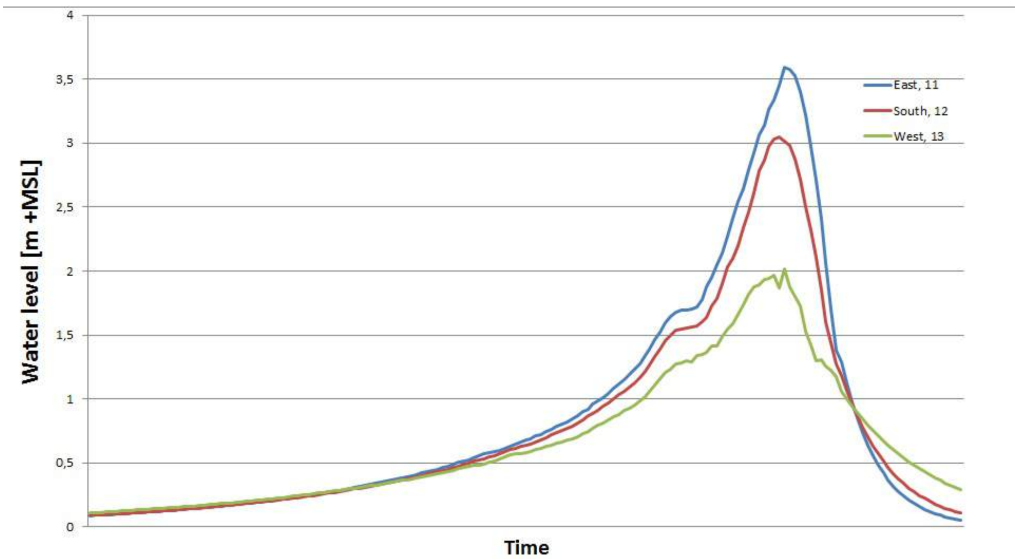


Figure 6.5: Water level time series of three points to force seaward boundary of the model

Water levels on the eastern side of the center of the hurricane are higher than at the western side, which is expected due to high onshore winds. From these three points, two are chosen to represent the boundary conditions during the simulation of the hurricane. From Figure 6.4 it can be seen that point 11 (Rollover Pass offshore) and point 13 (San Luis Pass offshore) are relatively close to our eastern and western boundary. Point 12 (Bolivar Roads offshore) is located at around one thirds of the distance from point 11 to point 13. From the Figure 6.4 it can also be seen that the peak water level (what were are especially interested in) is about 2/3 of the peak water level of point 13. Therefore a fairly linear water level gradient is expected between point 11 and point 13, both our domain boundaries. Point 11 is used to force the boundary at the eastern edge, point 13 is used to force the boundary at the western edge, and the southern boundary is linearly interpolated between those two water level time series.

The length of the time series was 2.5 days. However, this was manually to 3.5 days for simulation purposes. This has been done to capture the peak water levels in the whole bay. At the beginning of the data this is also extended, to lower the water level as close as possible to MSL (0.0 m). The initial condition of the water level is set to 0.09 m, which is equal to the lowest water level of the boundary conditions after extension. No tides are included in this water level time series, because we are merely interested in peak surge levels.

SPIDERWEB WIND AND PRESSURE GRID

With use of the program WES, incorporated in the DelftDashBoard toolbox of Deltares, a spiderweb hurricane grid is formulated. This grid simulates the size, form, and rotating motion of a hurricane. The grid is subsequently added to the simulation to capture wind and pressure effects (in our small-scale model mainly local effects).

A storm track for hurricane Ike from Unisys Weather (2015) is used (Figure 6.6). This track encompassed the location of the center of the hurricane (lat, lon) at a certain time, forming the track of the hurricane. Furthermore the maximum wind speed (Vmax; UNISYS uses 1-min sustained maximum surface wind speed data (Unisys Weather, 2015)) and pressure drop of the core (in millibar) at that time are included. Values of radius to maximum winds of Ike are added to this UNISYS track according to OFCL forecast data of NOAA (2015), which has been used by Hope et al. (2013) for the validation of their large-scale ADCIRC + SWAN model of hurricane Ike as well. This has been done to highlight to fact that Ike was a very large storm, which would lead to different flow and surge patterns in the Bay. Usually larger storms produce higher surges.

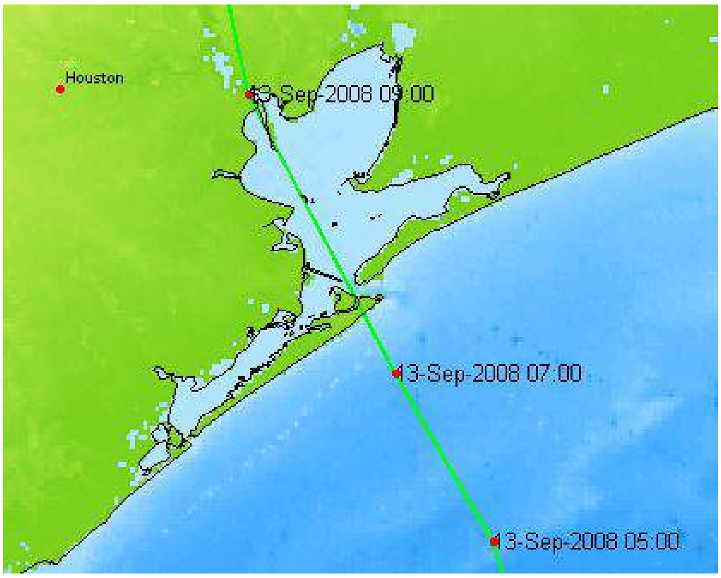


Figure 6.6: Track of hurricane Ike around landfall in Galveston. Date and time in GMT (Data source: Unisys Weather (2015); plotted in DelftDashBoard)

With these storm characteristics a spiderweb grid is produced on spherical coordinates (lat, lon). This is done with an enhanced Holland 80 model (Deltares, 2015b). The program transforms the maximum 1-min surface wind speeds into 10-min averaged surface wind speeds. For storm surge simulations it is advised to always use at least 10-minuted averaged wind speeds at the surface (Deltares, 2015b). The default size of a spiderweb grid was used, which is a 1,000 km in radius. This doesn't mean that the actual hurricane was of that size, it merely accounts for the gradual transition from 0 wind speed to hurricane wind speed at every point in time and space. This subsequently prevents a huge excitation when the wind enters the small-scale domain, which would lead to unwanted wiggles. The spiderweb grid proved to produce similar results to observed hindcast plots of wind speeds of Ike. See Appendix E.1 for a visualization of the spiderweb grid.

Wind Drag Coefficient

The effect wind has on exerting force on the flow depends on the wind drag, as discussed before. In the model simulation a wind drag coefficient is used as defined by Amorocho and DeVries (1980). It formulates an adapted version of the wind drag coefficient of Wu (1980) with an upper limit for high wind speeds of 0.00254 (wind above 26.8 m/s). This differs from the default wind drag expression which did not include an upper limit for high wind speeds. Reference is made to Appendix B.3 for the full expression of Amorocho and DeVries (1980).

6.3.5. Hurricane Ike Shifted Tracks

To simulate the effect of shifted Ike tracks, the hurricane is adjusted towards four different tracks. The angle of approach has been preserved as much as possible:

1. Shift 1: 25 km towards southwest (halfway Galveston Island, Jamaica Beach)
2. Shift 2: 40 km towards southwest (around San Luis Pass. Identical location as 'New Location', defined by Sebastian et al. (2014))
3. Shift 3: 25 km towards northeast (halfway Bolivar Peninsula)
4. Shift 4: 40 km towards northeast (around Rollover Pass/High Island)

The boundary conditions forcing the model were shifted in conjunction with the shift of the hurricane track. An assumption has been made how to shift the boundary conditions. It has been shown that the spatial variation in boundary conditions within the model domain is quite large (Figure 6.5). It is assumed that the eastern boundary of our domain experiences the highest surge levels for the regular hurricane Ike case. This assumption has been made because hindcast reports on hurricane Ike showed the highest measured surge were observed around High Island, or inland from that location (Berg, 2009). It is assumed that surge levels more eastward to High Island decrease linearly by the same rate as the increase between western and eastern boundary. At the western side the the assumption is made that the surge levels more westward of San Luis Pass (western boundary) will be reduced, but the reduction rate will be gradually decreased. The resulting water level boundary field is shifted in conjunction with the shift in hurricane track.

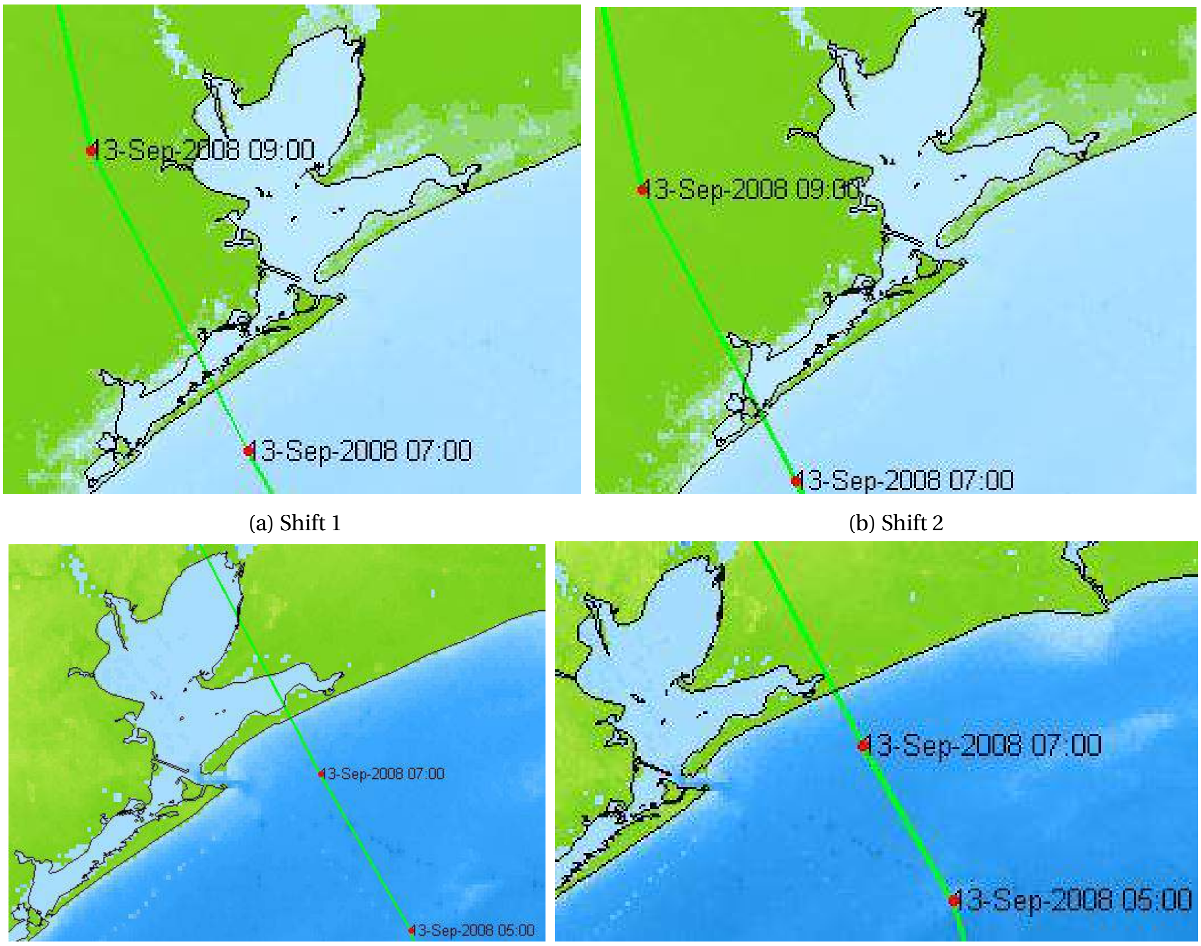
Thus, by shifting Ike westward, the boundary condition surge levels in front of the Bolivar Roads inlet will increase and the onshore winds in the the center part of the local domain of will generally be more direct and more intense. The expectation is that a westward shifted storm will induce peak levels in the Northwest (HSC), Northeast Bay (as is the case with normal Ike), thus a shift of the peak surge to the northwestern side. This is also what was found by Sebastian et al. (2014). And by shifting the storm eastward, the boundary conditions in front on Bolivar Roads will be reduced and wind in the center of Galveston Bay will generally be more offshore directed. The expectation is that with a eastward shifted storm the surge level in Galveston Bay will be a lot less severe. Furthermore is expected that West and Southwest are generally more directly affected and might experience Galveston Bay peak surges.

6.4. Calibration of the Hydrodynamic Model

Roughness and whether or not to place weirs at barrier islands have been the main calibration parameters of the hurricane Ike model. Furthermore the influence of Rmax (radius to maximum winds) and the wind drag coefficient have been investigated. It turned out the storm with increased Rmax (realistic simulation of Ike) and adjusted wind drag (lower drag for high wind speeds) produced the best results.

6.4.1. Calibration for Hurricane Ike

The model was calibrated with the use of measured data of hurricane Ike water levels. Two main data sources have been investigated, observations of water levels during hurricane Ike by USGS (East, Turco, & Mason, 2008) and NOAA Tides and Currents (NOAA, 2014). Stoeten (2013) mentioned that there are limited observations inside Galveston Bay. The reason is that measurement devices often fail during hurricanes. Therefore it



(a) Shift 1

(b) Shift 2

(c) Shift 3

(d) Shift 4

Figure 6.7: Shifted Ike tracks 1-4. Data source: Unisys Weather (2015). Plotted with DelftDashBoard

is difficult to calibrate the model. Only one NOAA point inside Galveston Bay was useful for calibration of the model (NOAA, 2014).

A total of 15 observation points was found to be suitable for calibration and inside the model domain. Of those points are 14 from USGS data and only 1 from NOAA data, and all points quite evenly distributed over the Bay (Figure 6.8). In the HSC in the North there is no sufficient observation of water levels unfortunately. Observation 'Manchester' of NOAA is a point located in the HSC. However, data from this observation is preliminary and not yet justified, according to the website of NOAA (2014). Although Berg (2009) mentions data from this observation point in his report, this data not used in this study because it was considered to be inadequate. All in all, no observation points in the Houston Shipping Channel were included. A plot with calibration points can be seen in Figure 6.8.

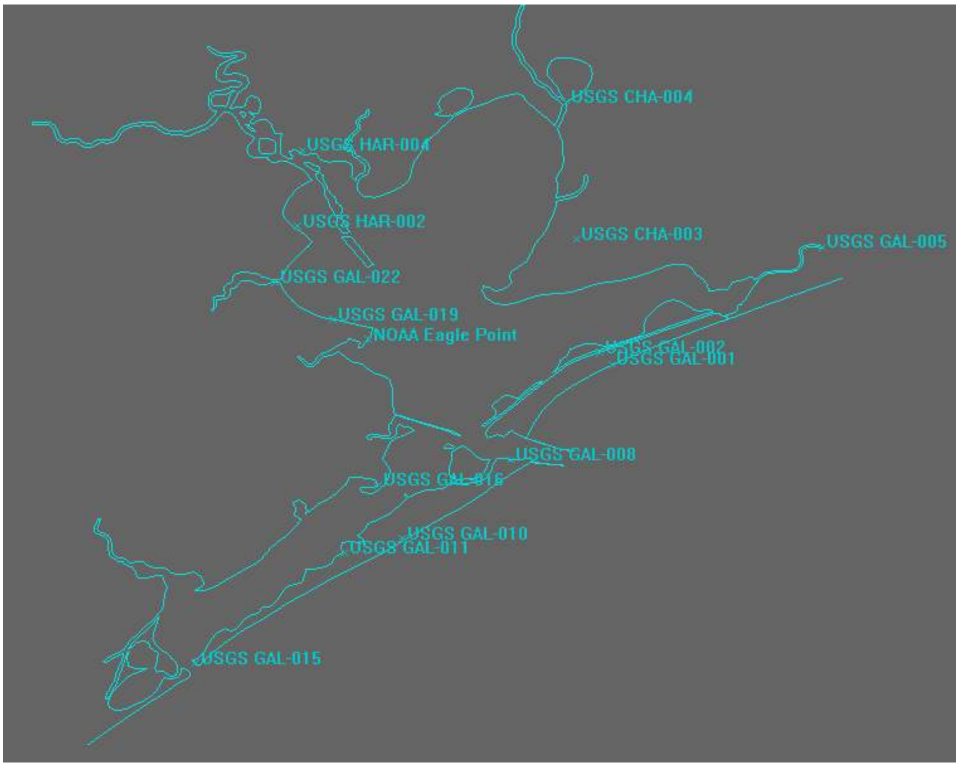


Figure 6.8: Locations of observation points of USGS and NOAA data in Galveston Bay for calibration of the model

The observation points of USGS outside Galveston Bay at the open coast (GAL-001, GAL-008, GAL-010 and GAL-015) and some time series inside Galveston Bay contained clear and significant wave interference, making the water level time series highly discontinuous and not well suited for calibration of the model because the peak water level could contain interference with a wave. Therefore these observations have been modified for the use of calibrating the model. The time series have been smoothed before extracting the peak water level. The 'rlowess' smoothing function of Matlab has been used, because it gave the best results. This function is a non-parametric locally weighted scatterplot smoothing. The result of one of the smoothed time series can be seen below. Note that this is not a complete time series, but it encompasses the peak water level.

After some iterations it was chosen to use a Manning roughness value below water level of 0.02 and a Manning value for land (thus above MSL) of 0.025 in the model. Hereby is all land considered, no distinction was made between different land classes according to e.g. Hope et al. (2013). The value of 0.023 gave best results comparing peak data to modeled peaks. It was expected that the roughess of land would have been higher, because usually wetlands, grassland or crops can be classified with a higher Manning value of 0.035-0.05, let alone urbanization (Table B.2 in Appendix B.4). But results of the calibration proved different in the case of this model with generalized roughness for all land areas. Scatter plots of a few calibration simulations are presented in Appendix E.2.

The model calibration is visualized using a scatter plot. This scatter plot contains modeled versus observed

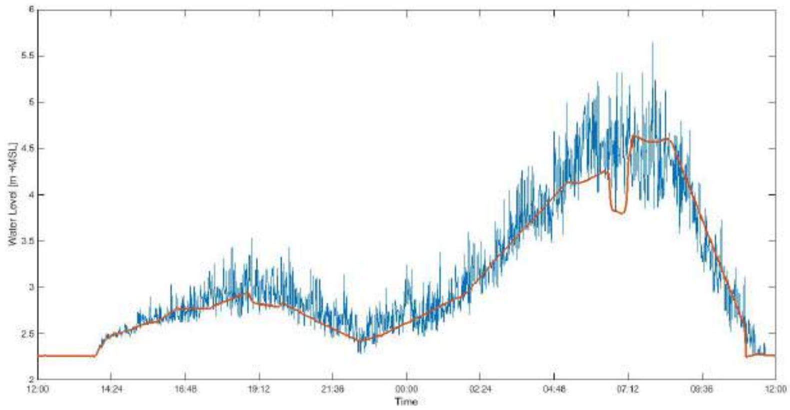


Figure 6.9: Smoothed observed water level time series, compared to the non-smoothed time series of USGS GAL-001 surge and wave site at the Gulf Coast of Galveston Bay

peak water levels for all 15 observation points in Galveston Bay. Only a scatter of peak water levels has been made, because peak water level is the variable of interest. There could be an error in the phase of the storm surge, this would not be captured by the calibration. If one wants to calibrate and compared the model even better with observations than possibly scatters of multiple points in time would be interesting. A scatter of the baseline (best calibrated model) has been included, Figure 6.10.

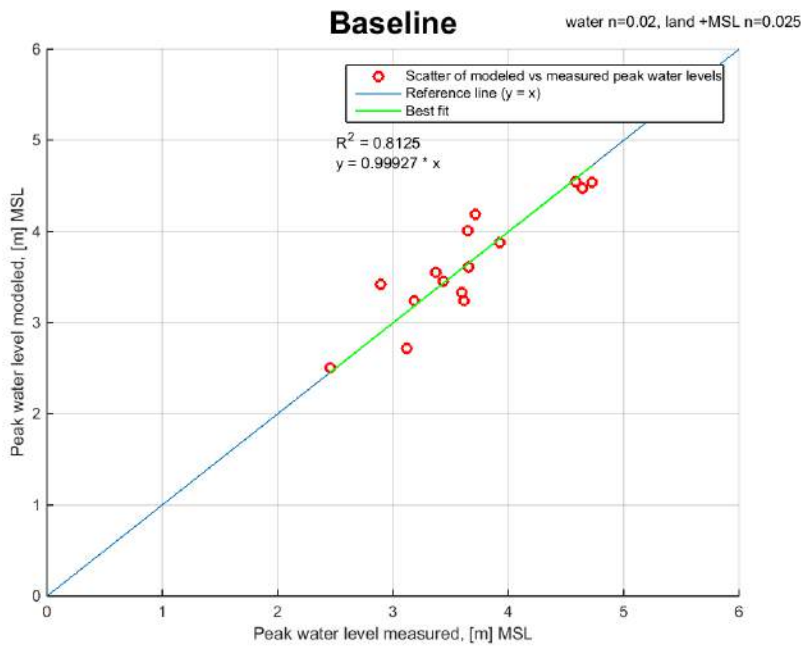


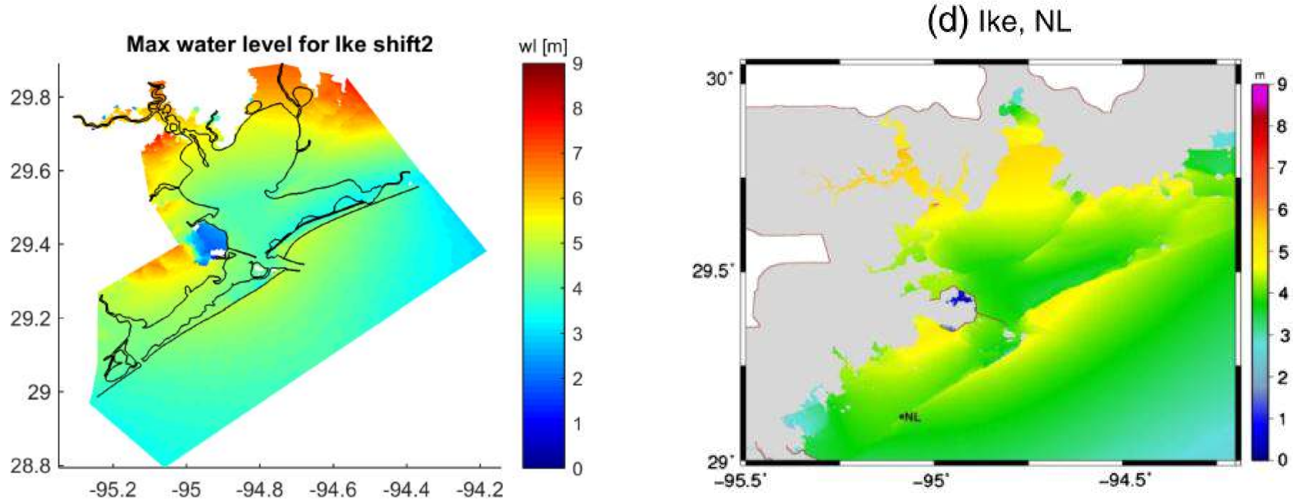
Figure 6.10: Scatterplot of modeled versus observed peak water levels in and around Galveston Bay [m] +MSL. R^2 represents the coefficient of determination. The green line represents the best fit through the scatter

From this figure is can be seen that calibration of the model is good. It has a relatively high R^2, which means the model can be used to predict the peak water levels in Galveston Bay for hurricane Ike. The maximum deviation from observed peak water levels is around 0.3-0.4 m. However, a high R^2 does not necessarily mean that the model reproduces the exact same peak surge levels as the observations. Therefore the best fit through the scatter is included as well as the equation of that fit. This equation gives information on how well generally the model predicts the peak surge observations.

Although it is a rather simple, coarse model with limited simulation run time, its performance is good. However, in the HSC the model underestimates the peak surge levels compared to modeling studies of Sebastian et al. (2014) and Hope et al. (2013). This difference is little over 0.5 meter, which is more than the largest observed errors for the calibration study (Figure 6.10).

6.4.2. CALIBRATION FOR HURRICANE IKE TRACK SHIFTED 2

An extensive calibration has not been conducted, but results from the model have been qualitatively compared with other results. The big assumption on how to vary the boundary forcing (result from large-scale motion across the Gulf) cannot be verified adequately, as no observations or model runs of exact the same shifts exist. We can compare one shifted storm with outcomes of simulation study by Sebastian et al. (2014), because one of both tracks are shifted towards the same location. The results of hurricane Ike shift 2 (40 km westward, landfall around San Luis Pass) can be compared to landfall location B or 'New Location (NL)' of Sebastian et al. (2014). The results are comparable. The outcomes of the simulations depict a water level of around 5.5-6 m above MSL for the HSC. Sebastian et al. (2014) found a similar value of 5.55 m. See Figure 6.11 for maximum water levels in the complete domain for both simulations.



(a) Maximum water level elevation for Ike shift2, simulated in this study

(b) Maximum water level elevations for Ike at 'New Location' (NL), simulated by Sebastian et al. (2014)

Figure 6.11: Comparison of maximum water level elevations for Ike track shifted 2 and 'New Location' (both tracks incorporate landfall at San Luis Pass)

Furthermore it was found that for the model outcomes of the shifted storms the adjusted boundary conditions played a significant role in influencing surge levels in the Bay. This means that surge levels in the bay are not merely dominated by winds and wind induced set-up, but but also significantly depend on increased water levels at the open coast. However, although for the westward shifted storms the relative importance of the wind becomes bigger, but still depend on open coast surge levels. Therefore the simulations of shifted tracks will be conducted with shifted (increased) open coast boundary conditions.

6.5. DISCUSSION

The model proved to provide good estimates of peak water levels in Galveston Bay during hurricane Ike. This is visualized by Figure 6.10, in which a maximum deviation from the measurements of about 0.4 m can be seen. However, some discussion can be held with respect to the improvement of the quality of the model:

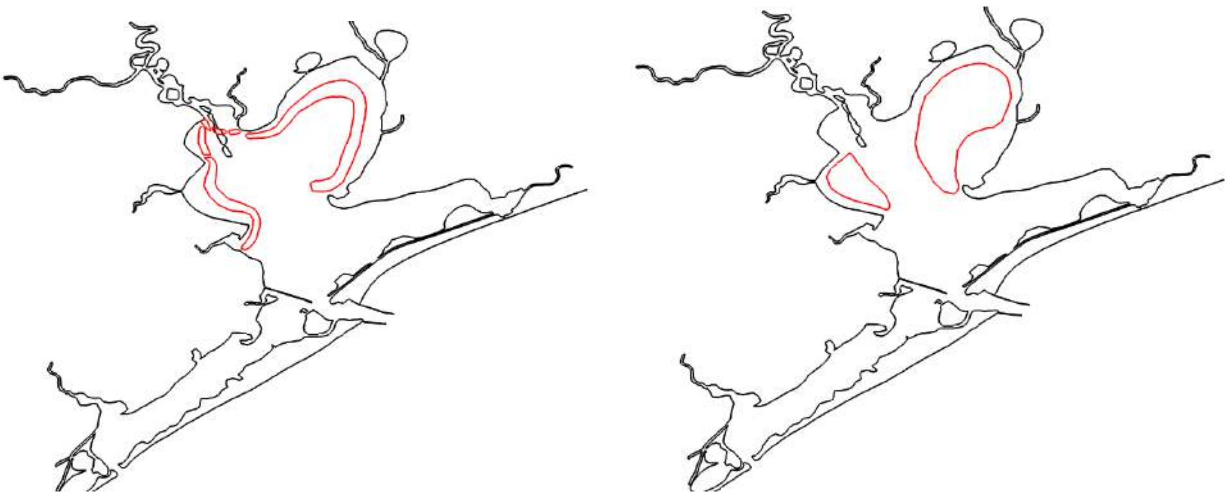
- Not many observations during Ike are recorded inside Galveston Bay. Almost all NOAA observation devices failed and did not capture a peak water level or provided data was unreliable. Therefore USGS data is used, of which only 11 observation points were located inside Galveston Bay. More observations would improve the calibration of the model.
- The grid resolution could be increased which would probably improve model results, especially near local, small-scale bathymetric features (e.g. barrier islands) and channels, especially when small-scale measures will be evaluated.
    - Result of the grid resolution might be the slight underestimation of the outcomes in the HSC in

the North, compared to other models. Because of grid resolution, the channel is enclosed by only one or two grid cells within its width. This would mean that the depth of the channel, which is locally very deep compared to surrounding areas, might be incorporated incorrect. Results for the HSC should be handled with caution.

In the next chapter the application of the hydrodynamic model will be discussed. Using the model, the following assessments will be done:

- Assess the behavior of the system under forcing of hurricane Ike, especially for the thee areas of interest for surge. The behavior of shifted Ike tracks will be assessed to investigate the sensitivity of landfall location and track of the hurricane on surge response in the Bay. Which tracks corresponds to a peak at what location?
- Assess the surge reduction of measures eco-island (for East and West possibly) and islands (for East, Northwest and West), as presented in Figure 5.15 and Figure 5.16. Thereby the goal is to reduce surge levels by at least 0.5-1.0 m (outcomes of simplified 1D analysis for respectively current and Ike Dike situation). Special focus lies on whether continuous emerged islands are required to be significantly effective in reducing surge level. Thereby different Ike tracks will be used to capture different peaks and investigate the sensitivity of tracks to surge reduction potential of the measures. Lastly, simulations with Ike Dike will be done to investigate whether a coastal spine would improve the surge level reduction of the BwN measures.

Designs like discussed in the previous chapter will be implemented in the model. See Figure 6.12 for a graphic representation of the shapes (polygons) that have been used to create measures in the model. The designs are implemented in the model by simply giving nodes of the network in a certain pattern (the design) a different z-value to mimic the elevation of the measure.



(a) Shapes for emerged island designs for three areas

(b) Shapes for eco-island designs for two areas

Figure 6.12: Overview of the shapes of proposed surge measures as they are simulated in the 2DH model

7

HYDRODYNAMIC MODEL SIMULATIONS

This chapter deals with the quantitative evaluation of the system behavior and the effect of surge reduction alternatives by means of the hydrodynamic 2DH model described. This chapter is divided into four sections. Section 7.1 deals with the simulated system behavior during hurricane Ike, with special interest for three areas of interest. A scenario with and without Ike Dike will be assessed. Section 7.2 discusses the behavior of the system under the forcing of two shifted Ike tracks. Section 7.3 presents results of surge reduction alternatives, separately for the three areas. A scenario with and without Ike Dike is assessed to investigate the relative surge reduction potential. An optimized design for Galveston Bay is presented in Section 7.4. Finally, Section 7.5 concludes the four previous sections.

Our three specific areas of interest - West, Northwest and Northeast - are represented by one location in the model domain for water level time series: respectively point 31, 48 and 65, see Figure 7.1. This is done to make the study as easily as possible and to compare simulations quickly. Point 31 is near Kemah, point 48 is located near the San Jacinto Monument in the Houston Shipping Channel and point 65 is near the village of Anahuac. All water levels are in [m] and referenced to MSL, in which a positive water level is +MSL. Time is referenced to GMT.

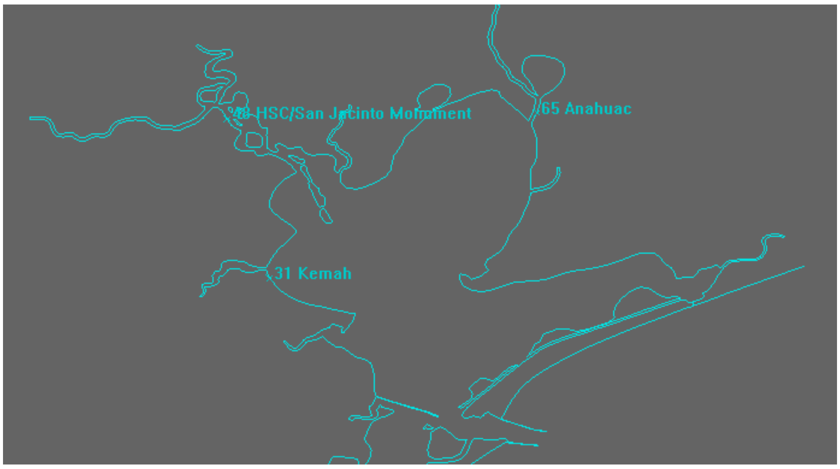


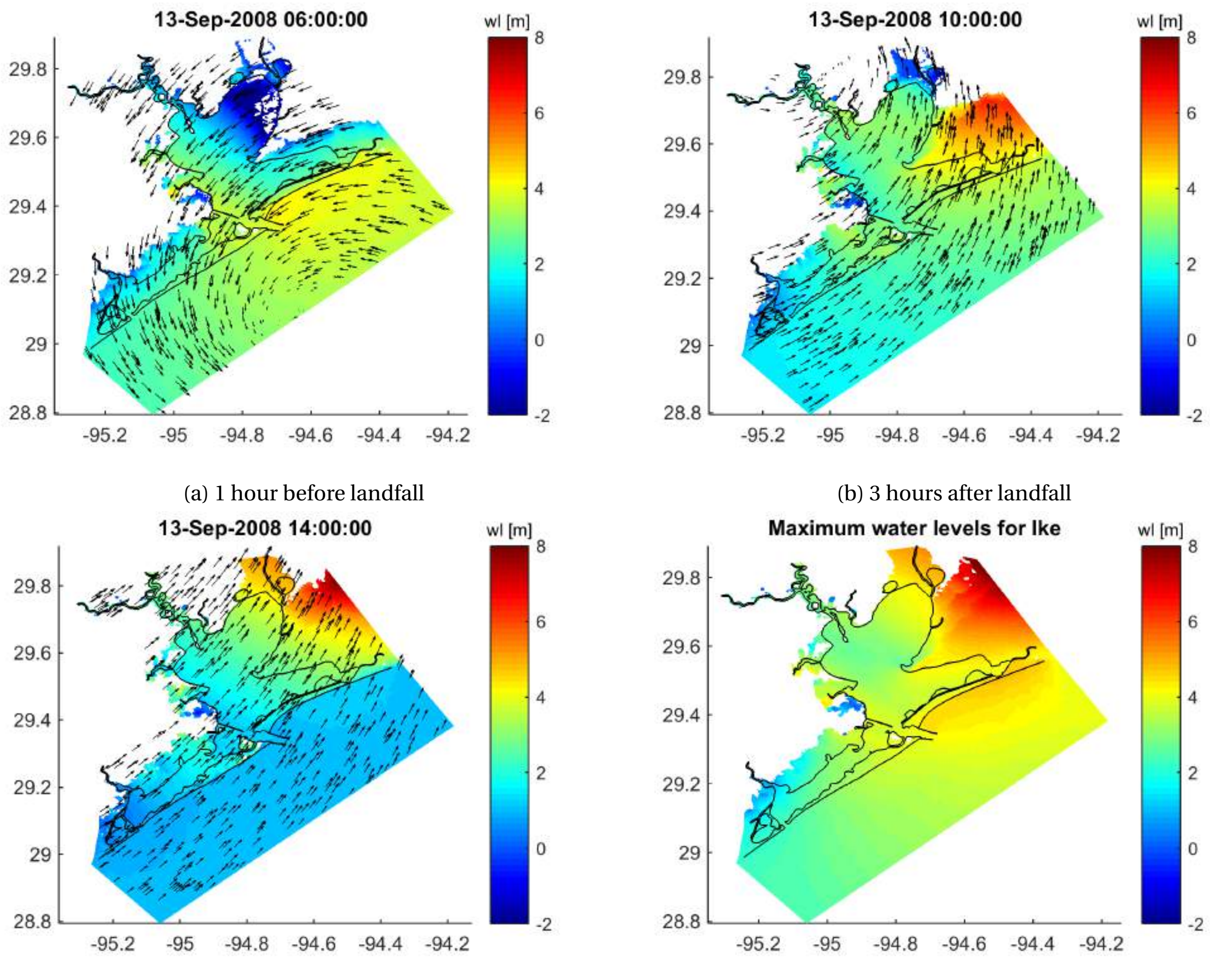
Figure 7.1: Locations of three observations points, which are representative for the three areas of interest

7.1. EVALUATION: SYSTEM BEHAVIOR FOR HURRICANE IKE

The results of the evaluation of system behavior in Galveston Bay under hurricane forcing are presented with three map plots of the water level throughout time, from just before to after landfall. The wind vectors are plotted in these maps as well. A fourth subplot is a map of maximum water level elevation throughout the complete simulation. Furthermore a graph with water level time series is presented for three observation points as discussed, in which landfall time is depicted as well.

7.1.1. BASELINE

A baseline scenario was simulated for the regular hurricane Ike. A plot of water level elevations throughout Galveston Bay at three moments around landfall and the maximum water level for the whole domain can be seen in Figure 7.2. See Figure 7.3 for a plot of the water level timeseries at the locations of interest. The local wind set-up effect can be clearly seen in the map plots. West experiences its peak of around 3.5 m before landfall due to easterly winds. Northwest(HSC) experiences a lower peak surge level of 2.8 m as it avoided direct strong winds. Northeast experienced the highest surge of the area, which is around 4.5-5 m. The reason is the direct onshore high wind of the hurricane when it has passed and the funneling effect of the Trinity Bay (Delta). An even much higher surge level of over 7 m can be observed (Figure 7.2d) on the eastern side of Galveston Bay inland of Chambers County.



(a) 1 hour before landfall

(b) 3 hours after landfall

(c) 7 hours after landfall

(d) Maximum water level elevation

Figure 7.2: Maps of water levels in Galveston Bay during Ike for 3 moments in time, from right before to after landfall and a map of maximum water level elevation

These results for Bay behavior are compared with results of the previously presented 1D calculations (see Table 7.1). The results were quite comparable for transect b, representing the easterly winds occurring before landfall. Peak surge in West were approximated at 3.8 m, with a 2DH simulation that result is 3.5 m. This means that for some areas, probably West and Northeast, at some point a steady state wind set-up occurs. The dynamics of the hurricane however, were incorrectly assumed. The assumption that transect b contributed to maximum steady state wind set-up in the Northwest was

Surge level [m] Baseline	West	Northwest	Northeast
1D	3.8	3.8	NA
2DH	3.5	2.8	4.5

Table 7.1: Comparison between 1D calculation and 2DH model: peak water levels for Ike

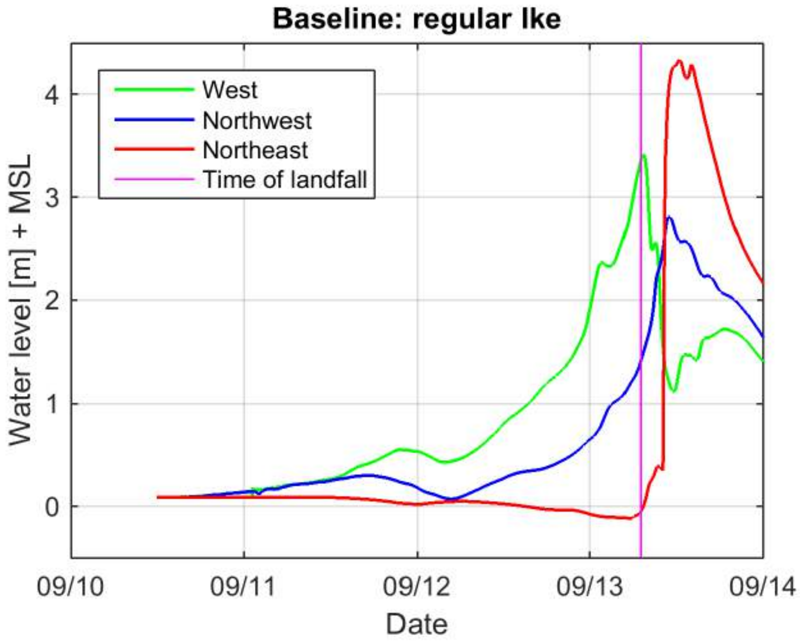


Figure 7.3: Time series of the water level during Ike at three observation locations of interest. Note that landfall is represented by the purple line. West = green, Northwest = blue and Northeast = red

wrong, as well as the fact that Northeast was not considered along transect c (the surge levels in the Northeast were highest in the bay during Ike). Because this level was observed later than for West, the Bay was probably already infilled to a bigger extent. Therefore surge level in the Northwest can be calculated with the simple calculation, assuming an increased water level. The surge levels in the Northwest never achieved steady state wind set-up during Ike because onshore direct wind was not as high as assumed. Therefore the surge levels in the Northwest were overestimated with the 1D calculation (3.8 m compared to 2.8 m). The conclusion is that the surge levels can be calculated reasonably with quite simple calculations and simplified geometry if the dynamics of a hurricane are correctly assumed (direction of wind affecting different areas) and if correct generalized water level increase and depth of the Bay are assumed.

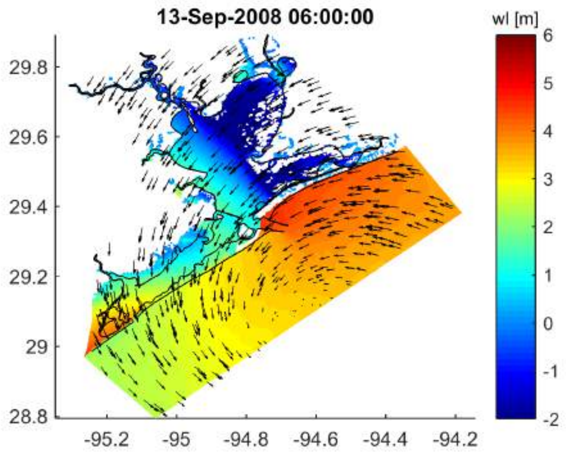
7.1.2. BASELINE IKE DIKE

An Ike Dike was implemented in the model as a 17 foot [5 m] high weir along the complete open sea coast of the domain. The height is the same height as the current crest height of the Galveston Seawall. The results of a simulation with hurricane Ike are presented, see Figure 7.4 and Figure 7.5.

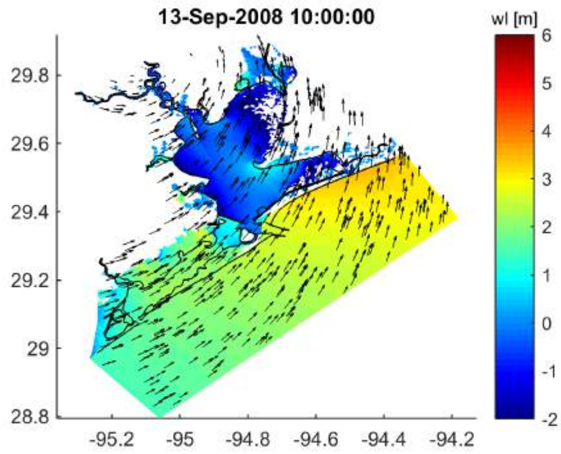
Surge level [m] Baseline: Ike Dike	West	Northwest	Northeast
1D	1.5	1.5	NA
2DH	1.5	0	1.7

Table 7.2: Comparison between 1D calculation and 2DH model: peak water levels for Ike with Ike Dike

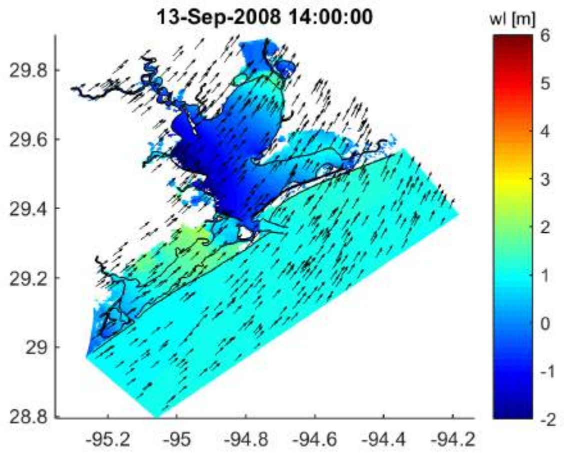
With an Ike Dike in place, surges of around 1.5 m would occur in the Bay, as seen in both the West (1.5 m) and Northeast (1.7 m) of the Bay (see Figure 7.4 and Figure 7.5). The HSC is not affected and does experience hardly any raise in water level at all. The surges that can be observed in the shallow Bay are merely composed of local wind set-up. Therefore a clear set-down of around 2 m in the East of the Bay can be distinguished before landfall as well. These results are compared with results from the simple calculations that were made before. Like in the case without coastal spine the results for West (before landfall) are comparable with the outcomes of the simulation, they both are 1.5 m. This means the 1D calculation gives reasonable surge level results for a coastal spine situation. However, this provided that the right direction of the wind has been assumed. The conclusion can be made that for the 1D calculation the correct average depth assumption for Galveston Bay was made. Comparisons between the 1D and 2DH outcomes for the baseline scenario with regular Ike and an Ike Dike implemented are presented in Table 7.2.



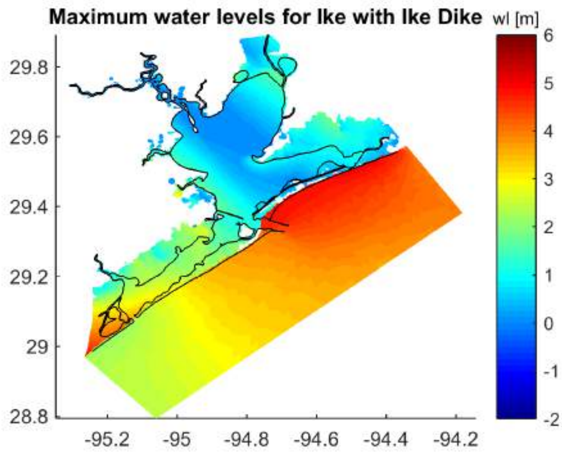
(a) 1 hour before landfall



(b) 3 hours after landfall



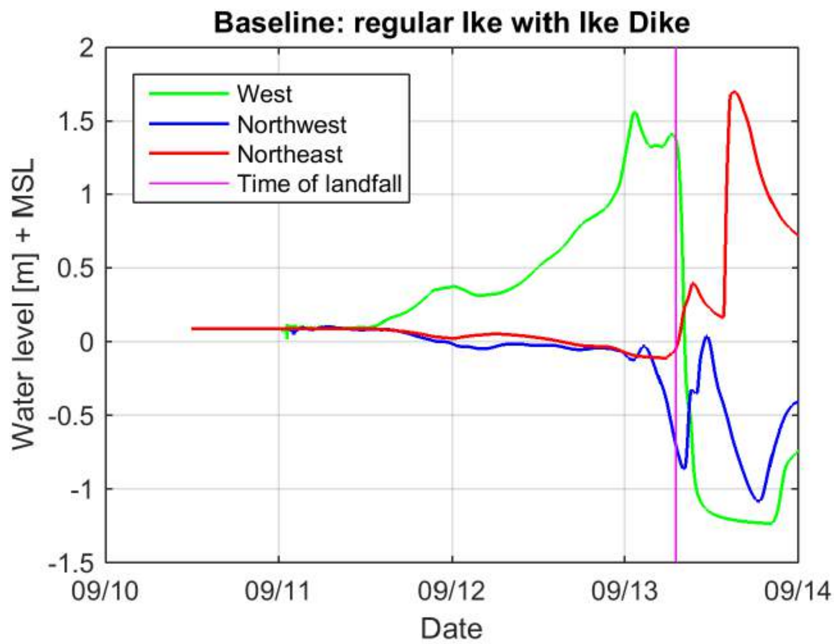
(c) 7 hours after landfall



(d) Maximum water level elevation

Figure 7.4: Maps of water levels in Galveston Bay during Ike for 3 moments in time from right before to after landfall and a map of maximum water level elevation, simulated with an Ike Dike (coastal spine) in place

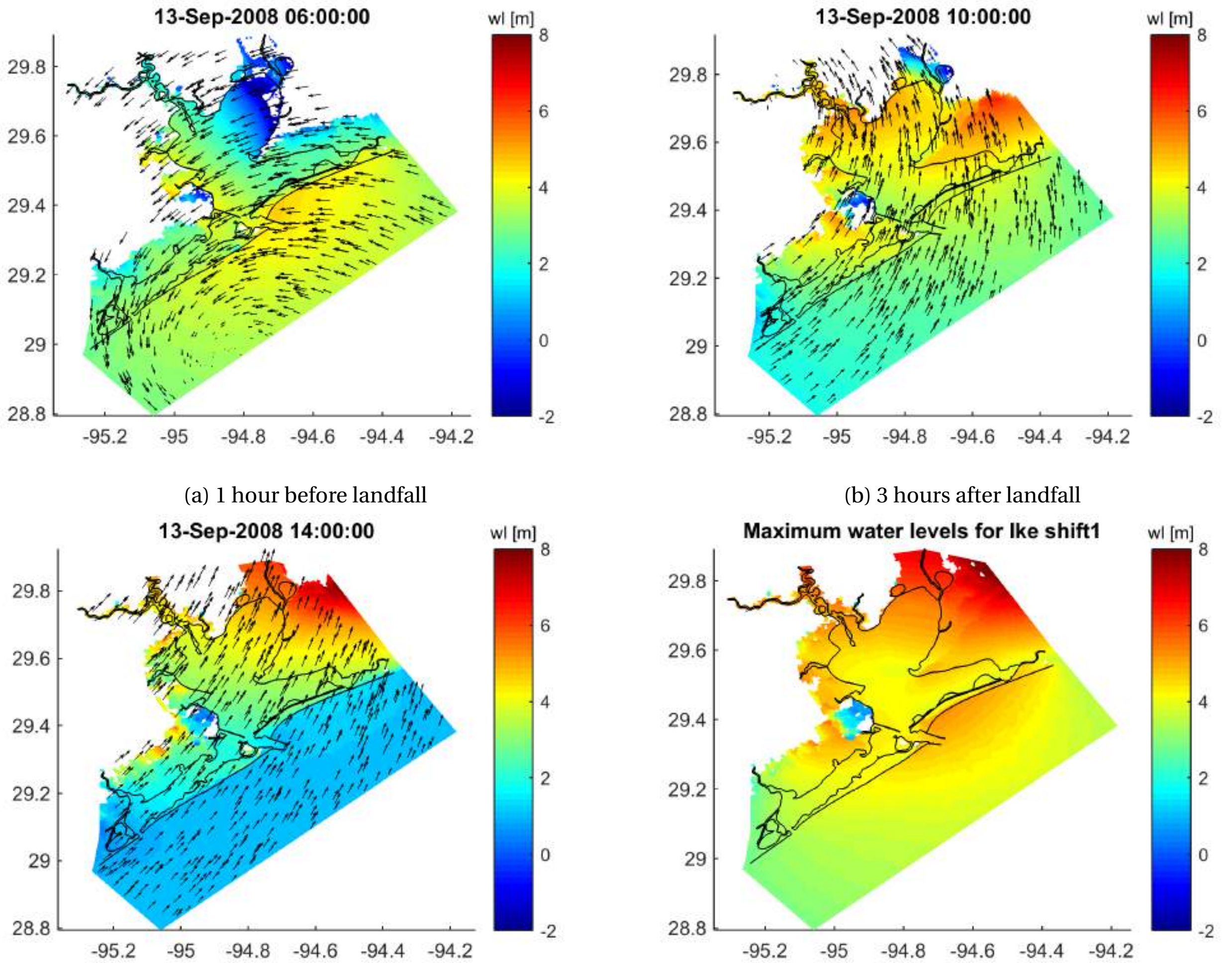
Figure 7.5: Time series of the water level during Ike, simulated with Ike Dike (coastal spine) at three observation locations of interest. Note that landfall is represented by the purple line. West = green, Northwest = blue and Northeast = red



7.2. EVALUATION: SYSTEM BEHAVIOR FOR SHIFTED IKE TRACKS

It has been discussed in the previous chapter that four different shifted tracks of hurricane Ike have been applied to the model (Figure 6.7). The goal was to induce different peak water levels in the three areas of interest. Two shifts towards the Northeast were applied, whereby surge levels in the Bay in general were lower compared to surge levels for regular Ike. This is because the winds are generally directed towards the West and Southwest, driving water out of the Bay. The HSC endured almost no surge for these two hurricane tracks. Therefore, these shifted storms are neglected and not used in simulations.

Two shifts towards the Southwest are increasing surge levels in the Bay, which has been most significant in the areas West and Northwest (because Northeast already experienced rather high surge levels during regular Ike). Northeast and Northwest both experienced more direct strong winds. The hurricane tracks (shift 1 and 2) resulted in higher peak surges than regular Ike for all three areas. Shift 1, shifted 25 km in southwestern direction, led to highest surge levels for the Northeast Bay, due to very high and direct onshore winds after landfall, although difference in peak surge level for Northeast between shift 1 and shift 2 is insignificant. Shift 2 (equivalent to 'New Location' storm of Sebastian et al. (2014)), resulted in overall peak surge level in Galveston Bay. This is due to easterly and southeasterly, strong, onshore winds before and just after landfall. Outcomes for both shift 1 and shift 2 will be presented in Figure 7.6 to Figure 7.9. Results for both Ike shift 1 and 2 in combination with an Ike Dike can be found in Appendix F.1.



(a) 1 hour before landfall

(b) 3 hours after landfall

(c) 7 hours after landfall

(d) Maximum water level elevation

Figure 7.6: Maps of water levels in Galveston Bay during Ike shift 1 (landfall at Jamaica Beach) for 3 moments in time from right before to after landfall and a map of maximum water level elevation

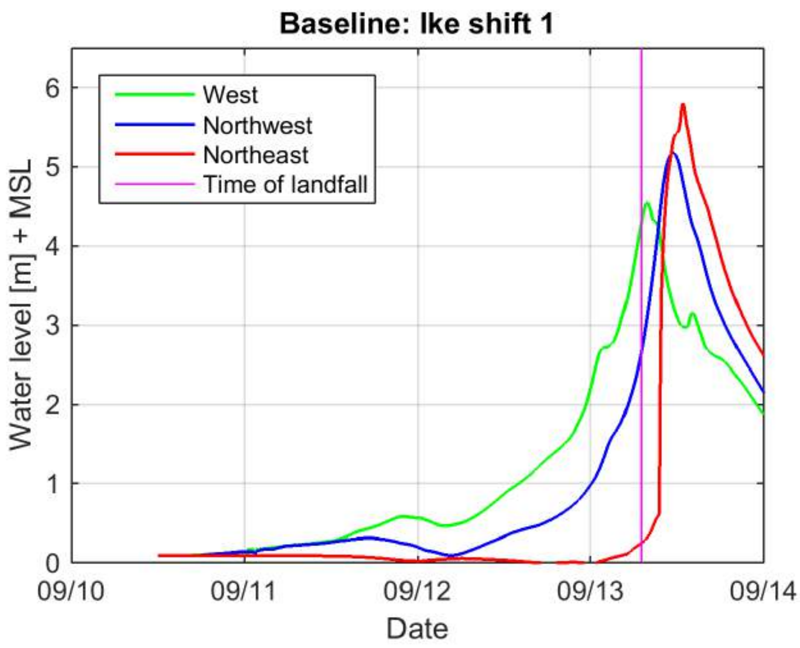
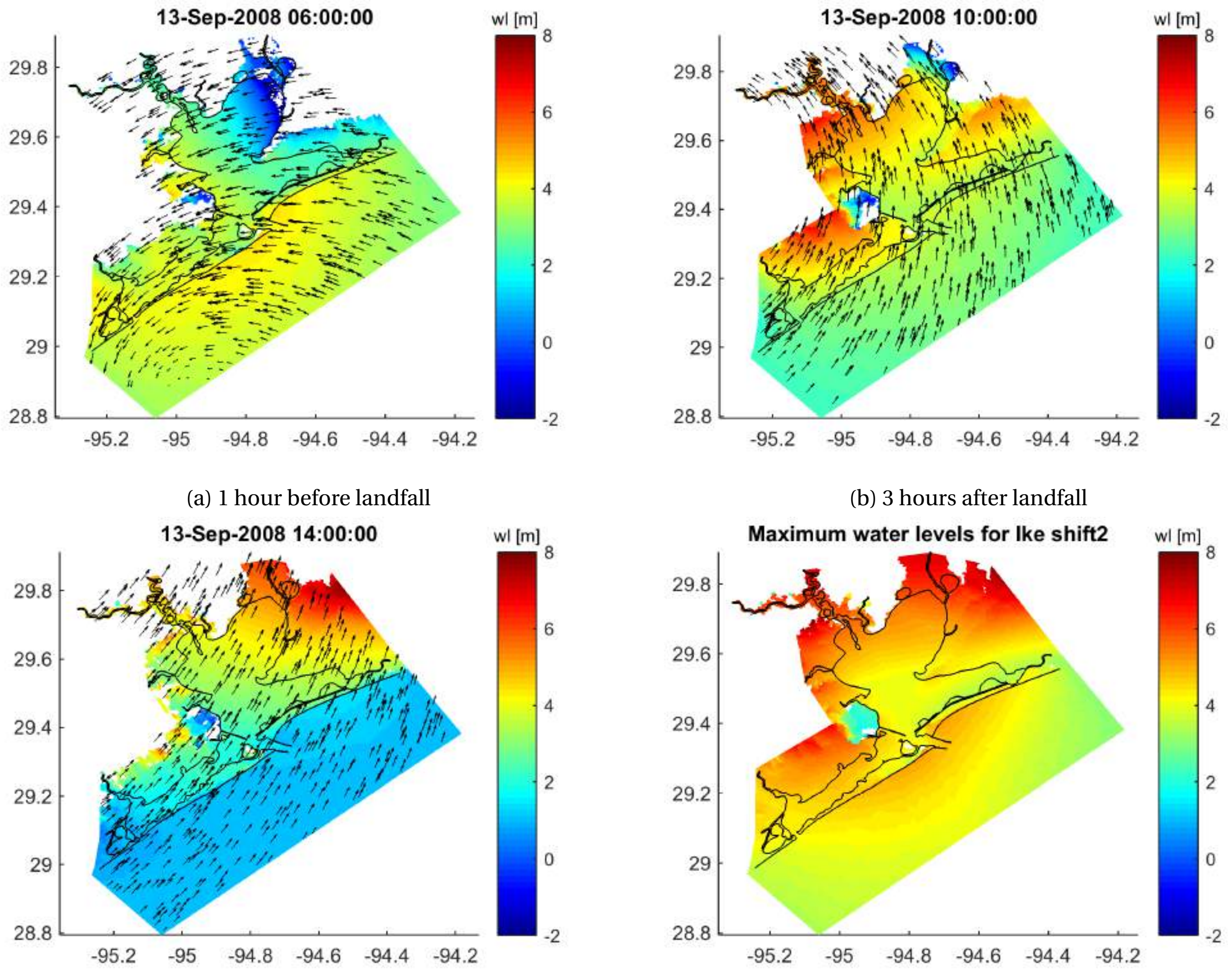


Figure 7.7: Time series of the water level during Ike shift 1 at three observation locations of interest. Note that landfall is represented by the purple line. West = green, Northwest = blue and Northeast = red



(a) 1 hour before landfall

(b) 3 hours after landfall

(c) 7 hours after landfall

(d) Maximum water level elevation

Figure 7.8: Maps of water levels in Galveston Bay during Ike shift 2 (landfall at San Luis Pass) for 3 moments in time from right before to after landfall and a map of maximum water level elevation

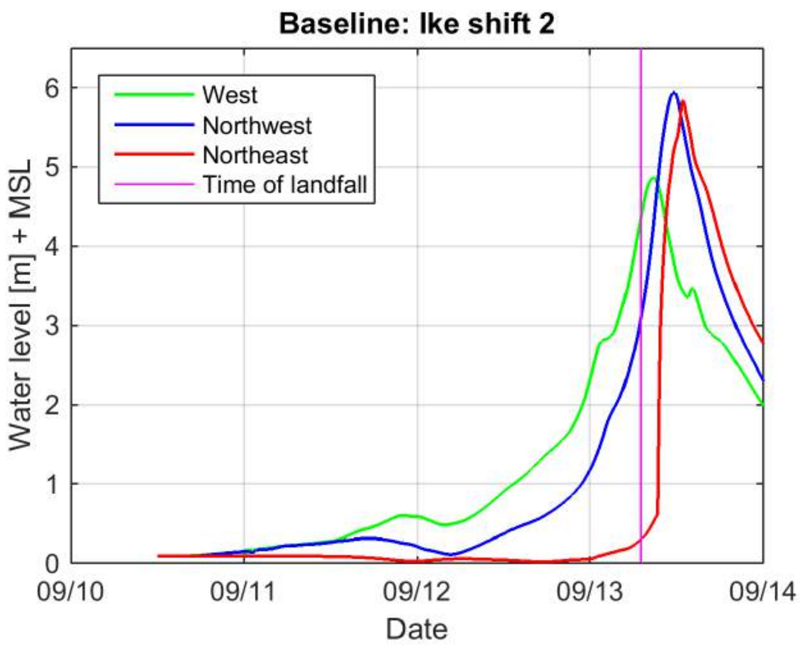


Figure 7.9: Time series of the water level during Ike shift 2 at three observation locations of interest. Note that landfall is represented by the purple line. West = green, Northwest = blue and Northeast = red

It can be seen that surge levels are significantly higher than for regular Ike (compare Figure 7.2 with Figure 7.6 and Figure 7.8). Easterly and southeasterly winds drive surge into the Bay around landfall and start wind set-up towards the northwestern shore. After landfall the northeastern directed winds drive water towards the Trinity Bay in the East. Note also that the representative points for Northwest and Northeast might not even experience highest surges as the piling up effect of the strongest, directly onshore directed winds is very strong. Surge levels of over 7 m in the HSC and the Trinity Bay will probably be observed for both tracks.

7.3. EVALUATION: SURGE REDUCTION ALTERNATIVES

The three areas (West Bay, Northwest (HSC) and Northeast Bay) will be assessed by a measures intended to reduce surge at the shoreline of that area. Designs for West and Northwest will be assessed with regular Ike and Ike shift 2. Northeast will be evaluated with regular Ike and Ike shift 1. The highest surge is observed on a different moment in time for each area due to rotating motion of the hurricane. Therefore the measures for the three areas will be separately evaluated (see Figure 5.15 and Figure 6.12b, whom depict an overview of the designs). Later in this section considerations will be given on the effect of combined measures.

An important choice is the **elevation** of the designs. After some iterations it can be concluded that for regular Ike a height of **3 m +MSL** for both islands and eco-islands is necessary to be able to reduce surge significantly. A necessary elevation of **+6 m** for hurricane Ike shift 1 and 2 is considered because surge levels in the Bay will be significantly higher during those two storms. Basically, this means the islands have to be emerged in hurricane conditions. All results in this section are assessed with designs with the abovementioned elevations.

The emerged nourishments will be referred to as islands, as stated previously in this thesis. Two options are considered: a completely continuous and long island, **design continuous** (this island is as continuous as possible, e.g. the shipping channels will never be hindered and the island is not fixed to the shoreline) and several islands separated by channels every few miles, **design open**. For eco-islands two designs, one in the West and one in the Northeast are made (Figure 6.12b). Influence of the roughness of the island due to e.g. vegetation on surge levels behind it is significant. Therefore a higher Manning value of 0.035 will be applied on the island. Assumed is that the islands are vegetated (see Table B.2 in Appendix B). The outcomes of the island and eco-island alternatives will be discussed on the basis of most relevant results, the complete results are presented in Appendix F.2. The results of the evaluation of measures are presented with a map of maximum water level elevation throughout the complete simulation and a map with the reduction of maximum water level which can be accomplished by an implemented measure for that scenario. Furthermore a graph with water level time series is presented for the observation point which represents the areas of interest, in which landfall time is depicted as well.

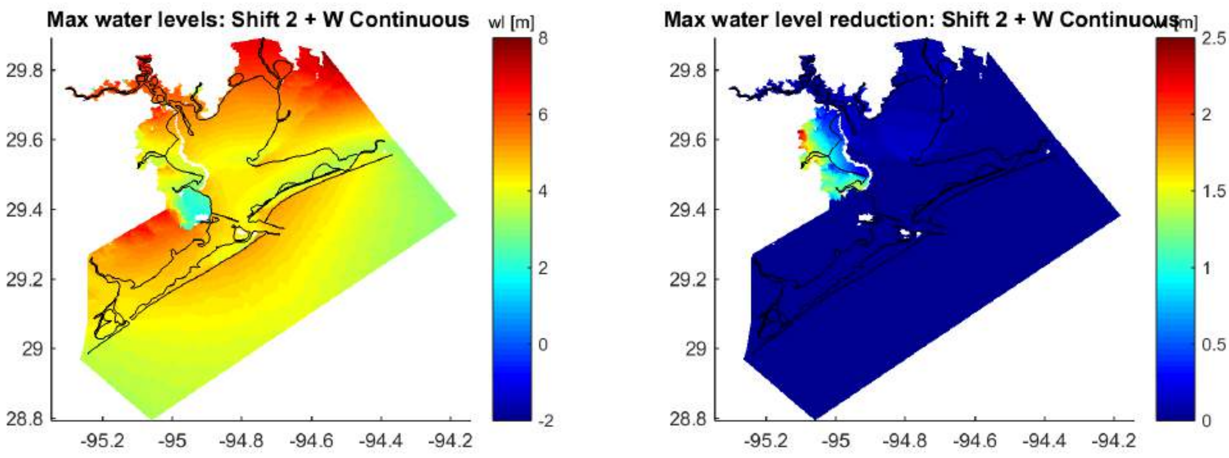
7.3.1. ISLANDS WEST

For reducing peak surge levels in the West the islands is located close to the western shore, around 3-4 miles from the western shore. They are considered to be feasible in terms of space and oyster reefs in the area. Both designs continuous and open, as implemented in the model, are presented in Figure 7.10. The design option open is in the West most realistic because a continuous emerged nourishment is probably a significant intervention due to extensive boating in this part of the Bay and water circulation issues.

Figure 7.10: Design options West continuous and West open, as implemented in the model

WEST DESIGN CONTINUOUS

The design continuous is the most effective measure for the West. Results for Ike shift 2 are presented in Figure 7.11 and Figure 7.12. It can be clearly seen that West design continuous is very effective at reducing the peak surge level by around **0.9 m** for hurricane Ike shift 2. An equivalent effect of 0.9 m can be observed for hurricane Ike as well. Furthermore it can be seen from Figure 7.12 that the peak surge level is delayed. However, it could mean that water behind the islands is also released more slowly, which might cause negative impacts.



(a) Maximum water level elevation

(b) Maximum water level reduction for measure

Figure 7.11: Maximum water level and maximum water level reduction in Galveston Bay during Ike shift 2 for West design continuous

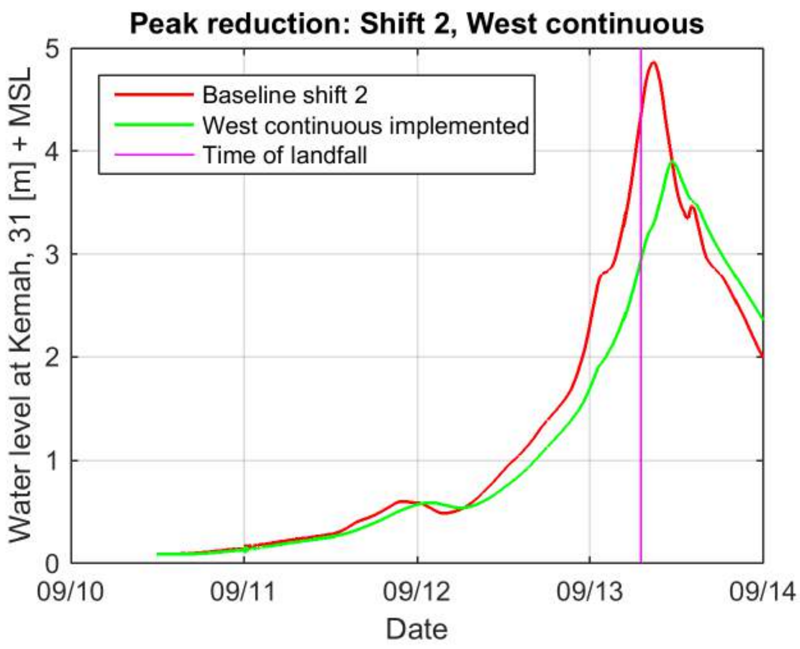


Figure 7.12: Time series of water levels during Ike shift 2 for West design continuous compared to Baseline in West, 31 Kemah. Measure implemented = green, Baseline = red

WEST DESIGN OPEN

Design open is obviously less effective than a closed design. The results for an open design show that islands are hardly effective at reducing peak surge levels (see results in Appendix F.2). For hurricane Ike peak surge level in West is reduced by **0.2 m**, for shift 2 this is **0.4 m**.

7.3.2. ISLANDS NORTHWEST

Both designs options continuous and open, as implemented in the model are presented in Figure 7.13. Due to short construction length only one extra channel is created for the open design. However, this open design is considered the most feasible design. Results for a continuous design with Ike shift 2 are presented in Figure 7.14 and Figure 7.15. Results of other scenarios are presented in Appendix F.2.

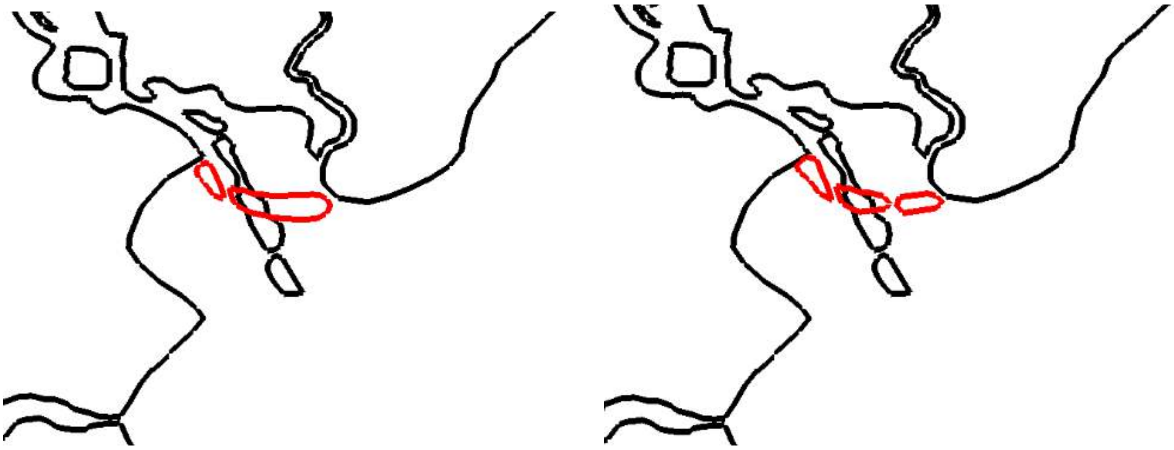
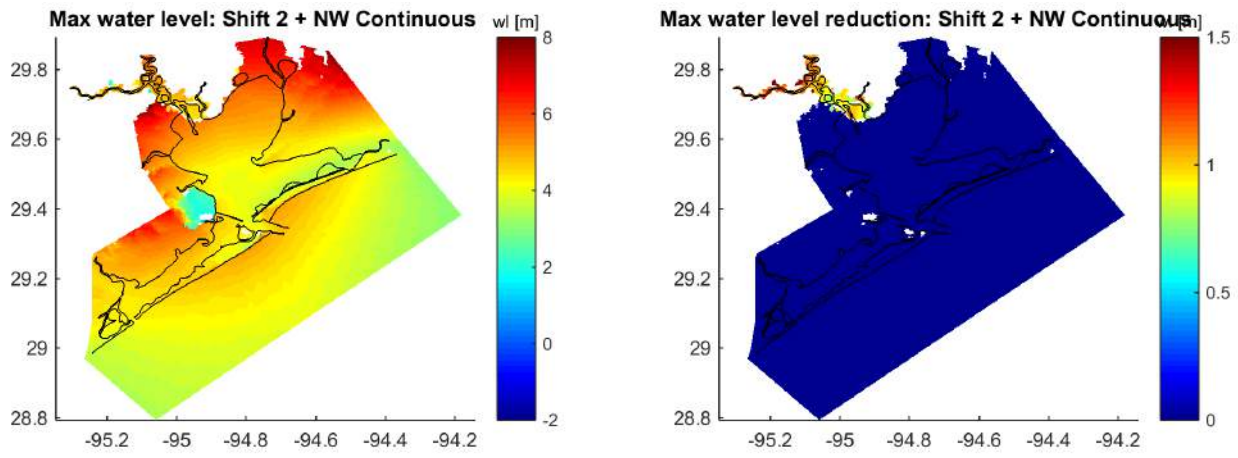


Figure 7.13: Design options Northwest continuous and Northwest open, as implemented in the model

NORTHWEST DESIGN CONTINUOUS

The design continuous (as continuous as possible) is the most effective measure for the Northwest. From Figure 7.14 and Figure 7.15 it can be seen that peak surge reduction for shift 2 is **1.0 m**. For regular this peak surge reduction is **0.4 m**.

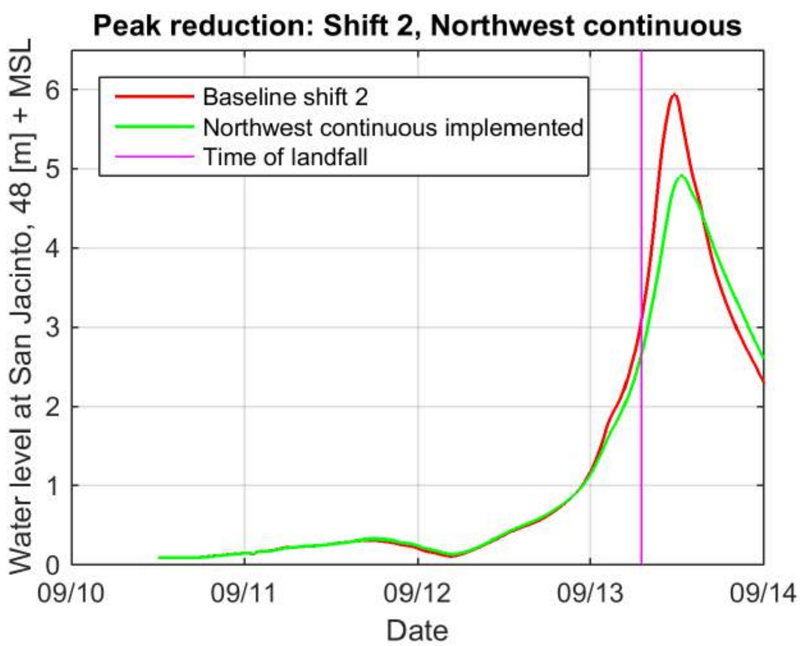


(a) Maximum water level elevation

(b) Maximum water level reduction for measure

Figure 7.14: Maximum water level and maximum water level reduction in Galveston Bay during Ike shift 2 for Northwest design continuous

Figure 7.15: Time series of water levels during Ike shift 2 for Northwest design continuous compared to Baseline in Northwest, 48 San Jacinto Monument. Measure implemented = green, Baseline = red



NORTHWEST DESIGN OPEN

It can be seen that for Northwest design open the peak surge will only be marginally reduced. For regular Ike this reduction is only around **0.3 m**. Again, the absolute effect of the design with Ike shift 2 is much bigger, because for Ike shift 2 peak surge reduction is about **0.8 m**. Although the peak surge reduction for a continuous solution is better, the difference between a continuous island and open islands with one extra channel is not significant. The reason for this observation is probably because the presence of the HSC which much deeper than surrounding Bay area and carries most water to the North, causing the influence of the extra channel to be minimal on peak surge levels in the Northwest.

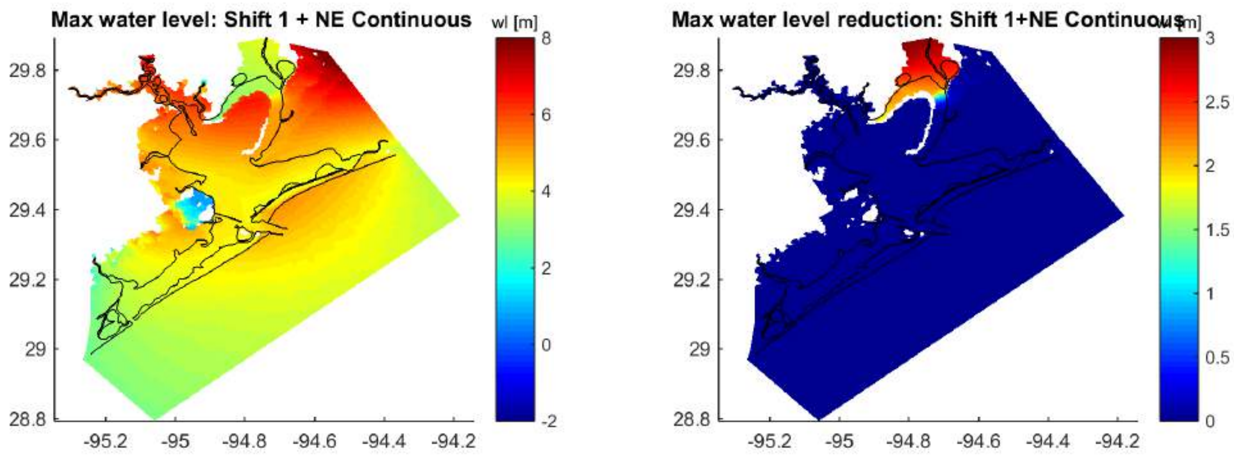
7.3.3. ISLANDS NORTHEAST

The island is located close to the eastern shore. Both design options continuous and open, as implemented in the model, are presented in Figure 7.16.

Figure 7.16: Design options Northeast continuous and Northeast open, as implemented in the model

NORTHEAST DESIGN CONTINUOUS

See Figure 7.17 and Figure 7.18 for the results of the Northeast design continuous during Ike shift 1. It can be seen that Northeast design continuous is very effective at reducing peak surge levels. During Ike shift 1 the peak surge level is reduced by **2.2 m** and during Ike by **0.8 m**.



(a) Maximum water level elevation

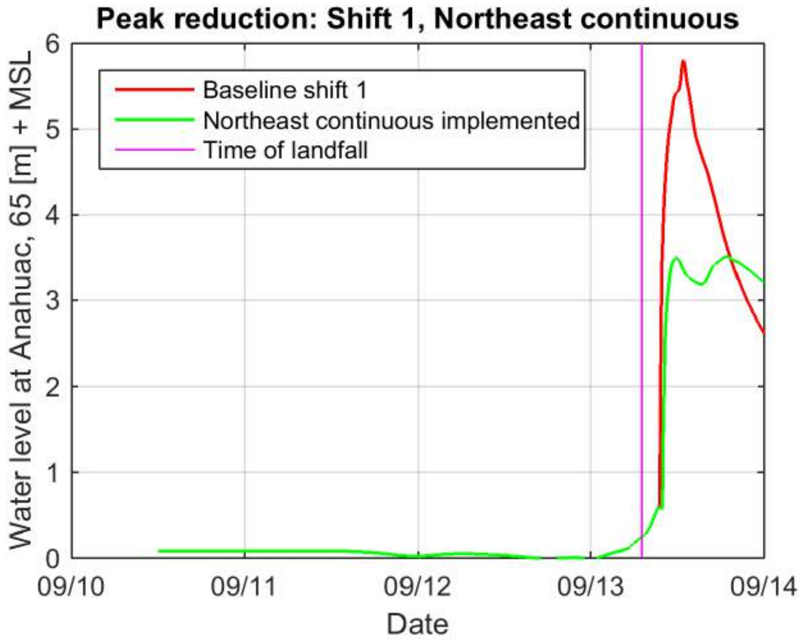
(b) Maximum water level reduction for measure

Figure 7.17: Maximum water level and maximum water level reduction in Galveston Bay during Ike shift 1 for Northeast design continuous

NORTHEAST DESIGN OPEN

The results show that an open design is still rather effective, with a peak level reduction **0.6 m** for regular Ike and **1.2 m** for Ike shift 1.

Figure 7.18: Time series of water levels during Ike shift 1 for Northeast design continuous compared to Baseline in Northwest, 65, Anahuac. Measure implemented = green, Baseline = red

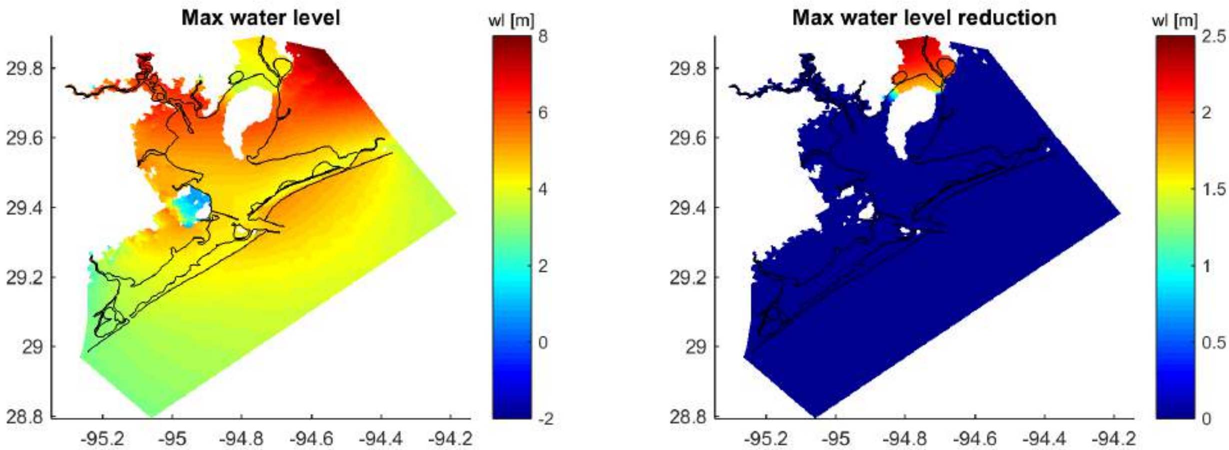


7.3.4. ECO-ISLANDS

An eco-island placed in West Bay **marginally** effects peak surge level. It even amplifies surge levels at shore in the case of Ike shift 2. The reason is that there is probably too much space for the water to flow around the island. Because of this marginal effect no results are shown.

ECO-ISLAND NORTHEAST

For a big island in the Northeast of the Bay it has been found that peak surge level reduction is **1.3 m** for hurricane Ike and **1.7 m** for Ike shift 1. The reason for this high reduction might be that a part of the Bay can be almost closed by the island, making the peak surge level reduction very effective. See **??** for map results for the eco-island with Ike shift 1.



(a) Maximum water level elevation

(b) Maximum water level reduction for measure

Figure 7.19: Maximum water level and maximum water level reduction in Galveston Bay during Ike shift 2 for West design continuous, simulated with Ike Dike

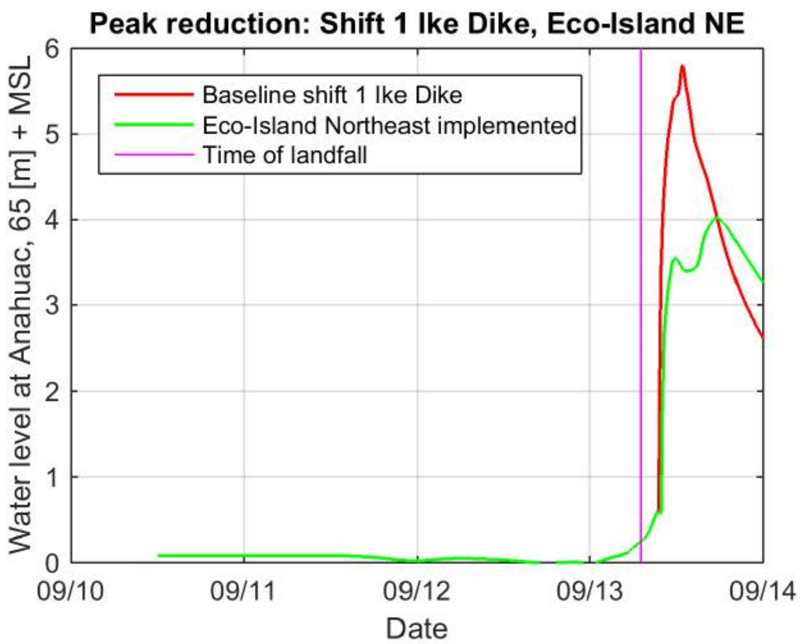
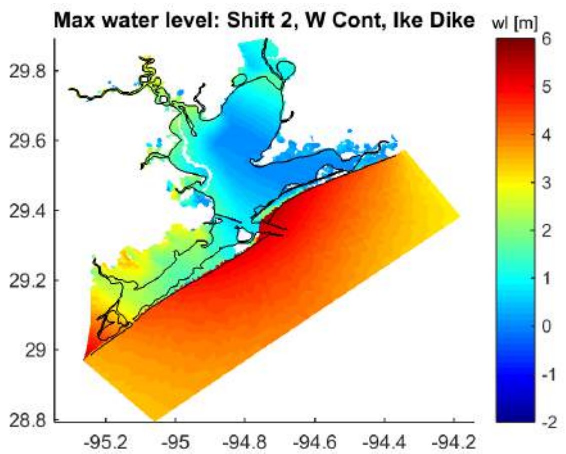


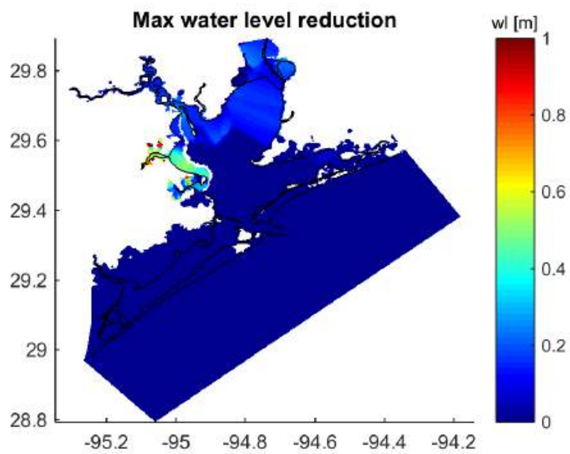
Figure 7.20: Time series of water levels during Ike shift 1 for eco-island Northeast compared to Baseline in Northeast, 65, Anahuac. Measure implemented = green, Baseline = red

7.3.5. SURGE REDUCTION ALTERNATIVES WITH IKE DIKE

All the designs in this chapter have been simulated with an Ike Dike in place. The 1D conceptual model showed us that the relative effect of fetch reducing measures might be higher because the surge in the case of a coastal spine is completely composed of wind set-up in the absence of inflow through Bolivar Roads and overflow over the peninsulas. The results will be briefly discussed in the next section. Two examples of outcomes for designs West and Northwest continuous are presented here, see Figure F.26-Figure F.31. For complete outcomes of the simulations with Ike Dike reference to Appendix F.3 is made.



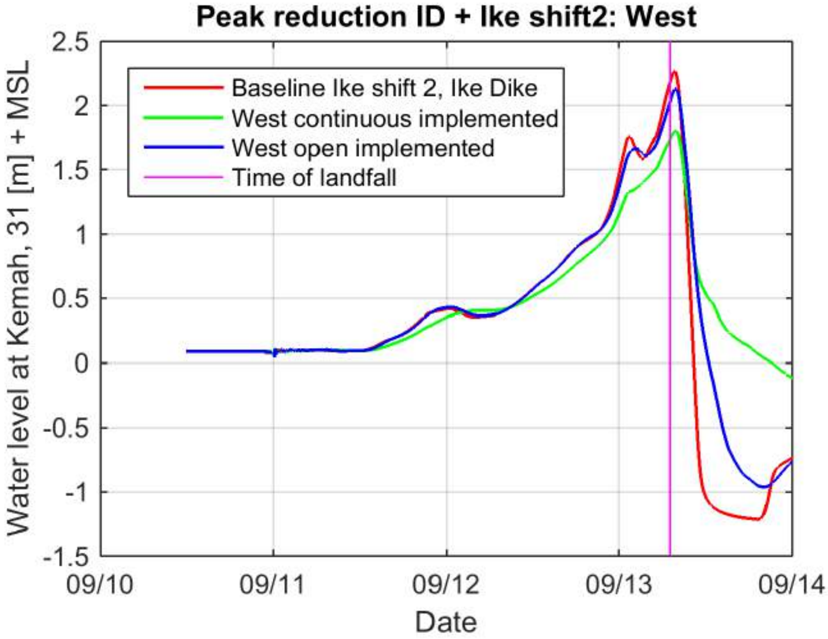
(a) Maximum water level elevation

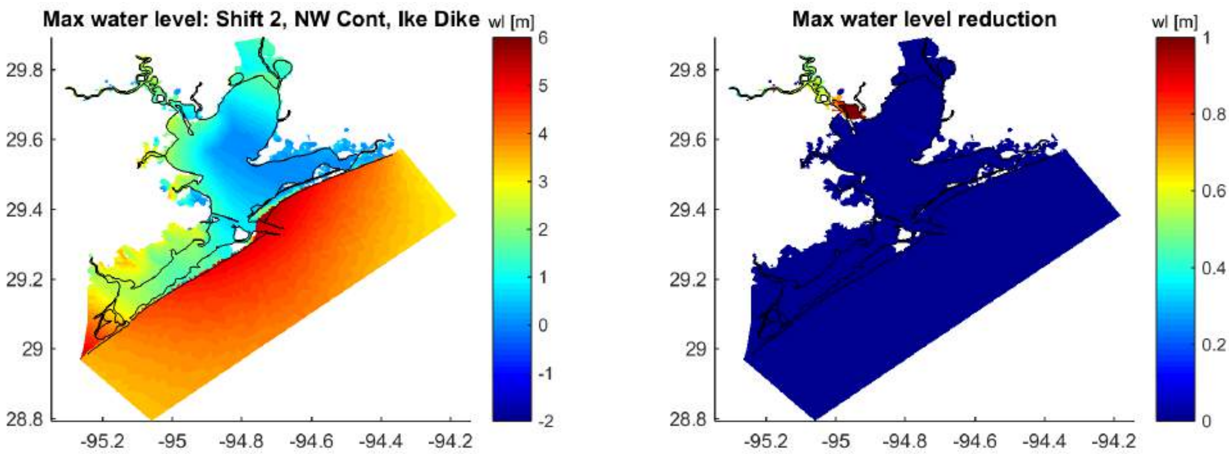


(b) Maximum water level reduction for measure

Figure 7.21: Maximum water level and maximum water level reduction in Galveston Bay during Ike shift 2 for West design continuous, simulated with Ike Dike

Figure 7.22: Time series of water levels during Ike shift 2 for West design continuous compared to Baseline, in Northwest, 31 Kemah, simulated with Ike Dike. Design continuous = green,Design open = blue, Baseline Ike Dike = red





(a) Maximum water level elevation

(b) Maximum water level reduction for measure

Figure 7.23: Maximum water level and maximum water level reduction in Galveston Bay during Ike shift 2 for Northwest design continuous, simulated with Ike Dike

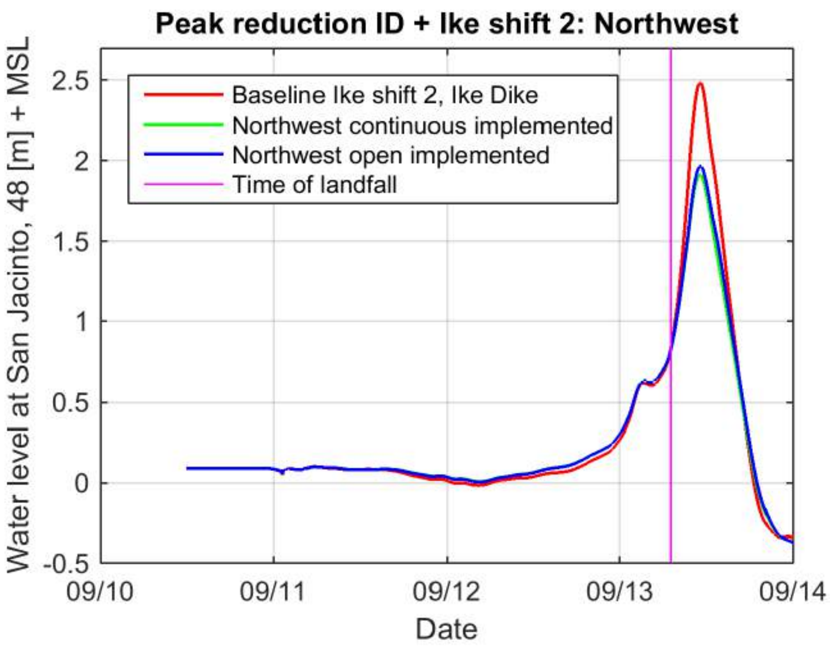


Figure 7.24: Time series of water levels during Ike shift 2 for Northwest design continuous compared to Baseline, in Northwest, 48 San Jacinto Monument, simulated with Ike Dike. Design continuous = green,Design open = blue, Baseline Ike Dike = red

7.3.6. SUMMARY SURGE REDUCTION RESULTS

A summarizing table with all discussed results is presented in Table 7.3. Results of all three island alternatives and two eco-islands are shown. The peak surge levels for baseline scenarios without alternatives implemented inside Galveston Bay are presented as well as an absolute and relative peak surge reductions of every alternative. The relative reduction depicts the percentage reduction with respect to corresponding baseline scenario. The outcomes of the simplified 1D analysis were as follows: 0.5 m peak surge reduction for the current open situation and 1.0 m peak surge reduction for an Ike Dike situation. In Table 7.3, it is considered to be a significant surge reduction if it accomplishes at least 0.8 m reduction, moderate is it is between 0.4 and 0.8 m peak surge reduction and marginal means a peak surge reduction of below 0.4 m. Not applicable means it is not simulated. The relative peak surge reduction gives insight into the surge reduction compared to the surge level of the baseline scenario without measure implemented. The classification is meant to give quick insight in the effectiveness of different measures in different scenarios and hurricanes, therefore it is not a decisive criterion.

From Table 7.3 several conclusions can be drawn. Peak surges can be reduced in different areas by fetch-limiting measures. For all areas the islands require to be emerged and as continuous as possible to be most effective. It can be seen that West and Northwest continuous are most effective measures. An eco-island is only effective for peak surge reduction in the Northeast but requires a very large, emerged surface area that almost closes off this part of the Bay.

In general, a shifted hurricane track towards the Southeast (25 or 40 km) induces higher inflow and higher direct wind set-up for West, Northwest and Northeast. For Northeast this relative increase in peak surge levels is less (because Ike already caused high surge levels in the Northeast) and is mainly caused by increase in inflow from the open coast surge. The measures are more effective in the case of a shifted track compared to the regular Ike track. This is most significant especially in areas where inflow as well as wind set-up can be reduced due to closure of a part of the Bay (Northeast and to some extent, Northwest). It can be concluded that the inflow from the open coast plays an important role in the peak surge level reduction of measures, because measures will retain inflow as well as reduce wind set-up.

The measures are very sensitive to the presence of an Ike Dike. With an Ike Dike in place the local surge levels are merely composed of wind set-up. The differences in surge in the Bay between regular Ike and shifted tracks are therefore less significant. In the case of Ike Dike, islands in the Northeast (open or continuous) and Northwest is considered to be significantly effective, whereas islands in the West are much less effective. However, the absolute effectiveness of the measures is less significant compared to the case without Ike Dike.

Peak Surge Levels [m] +MSL (from 2D hydrodynamic simulations)			No Ike Dike			Ike Dike		
			Hurricane Ike	Hurricane Ike Shift 1 (25 km southeast)	Hurricane Ike Shift 2 (40 km southeast)	Hurricane Ike	Hurricane Ike Shift 1 (25 km southeast)	Hurricane Ike Shift 2 (40 km southeast)
Baseline scenarios, no alternatives implemented		West	3.4	4.5	4.9	1.6	2.1	2.3
		Northwest	2.8	5.2	5.9	No surge	1.6	2.5
		Northeast	4.3	5.9	5.8	1.7	1.8	1.7
Peak Surge Reduction (relative) [m] +MSL								
Surge alternatives implemented	Continuous Islands	West	0.9 (26%)	NA	0.9 (18%)	0.3 (19%)	NA	0.5 (22%)
		Northwest	0.4 (14%)	NA	1.0 (17%)	No surge	NA	0.9 (37%)
		Northeast	0.8 (19%)	2.2 (38%)	NA	1.3 (76%)	1.2 (67%)	NA
	Open Islands	West	0.2 (6%)	NA	0.4 (8%)	0	NA	0.2 (9%)
		Northwest	0.3 (11%)	NA	0.8 (14%)	No surge	NA	0.6 (24%)
		Northeast	0.6 (14%)	1.2 (27%)	NA	1.3 (76%)	1.2 (67%)	NA
	Eco-Island	West	0	NA	0	0	NA	0
		Northeast	1.3 (30%)	1.7 (29%)	NA	0.5 (29%)	0.6 (33%)	NA

Table 7.3: Results of all 2DH simulations for surge reduction alternatives. Legend: Green = significant peak surge level reduction; orange = moderate peak surge level reduction; red = marginal or no peak surge level reduction; NA = not simulated

This highlights the fact that the measures are never completely continuous. However, the relative surge (relative to peak surge for the corresponding baseline scenario) level reduction of measures in the case with an Ike Dike is marginally higher, which stresses that wind set-up is the most relevant mechanism in the case of an Ike Dike. Note that surge levels in the case of an Ike Dike are much less than without Ike Dike, making the requirement for measures unnecessary. Only West Bay and East Bay might experience some inundation, the Houston Shipping Channel will not be jeopardized by floods.

To investigate the influence of measures on other areas four simulations have been conducted with a combination of all three emerged island designs. The expectation was that peak surge level reduction might be a higher for a combined measure due to an increase in of retaining area, thereby decreasing surge levels (inflow and wind set-up) in all areas. This is indeed the case, peak surge level reduction is higher in all areas for a combined measure, although this is not a significant amount.

1D VS 2DH RESULTS

Previously in this report a simplified 1D calculation has been made to investigate to potential effect of fetch limiting islands in the Bay. These results can be compared to the results of the 2DH simulations, which can be seen in Table 7.4. This table only shows results for a continuous measure in the West with hurricane Ike, because the winds of the hurricane prior to landfall create the most simple situation in the Bay with (steady-state) wind set-up. It can be seen that 1D results are not similar to 2DH results. In the 1D analysis it was assumed that a measure is closed with respect to wind set-up. However, a water level increase behind the measures was assumed to mimic the fact that the measure can never be completely closed. In the 2D analysis the measures were constructed as continuous as possible. The 'compartment' behind the measure will not be filled completely due to open coast surge, like was assumed in 1D analysis. This has been a wrong assumption, therefore the 1D analysis underestimates the reduction in the open Bay situation. However, for Ike Dike it appears that measures are not continuous enough to completely stop wind set-up. Thus, this results in an overestimation of reduction in the 1D analysis.

Surge reduction [m] by most optimal continuous measure	No Ike Dike	Ike Dike
	West	West
1D	0.4	0.7
2DH	0.9	0.3

Table 7.4: Comparison between 1D calculation and 2DH model: peak surge reduction in the West by a continuous island, with and without Ike Dike

7.4. DESIGN OPTIMIZATION

Although we saw that measures in the Northeast can significantly impact peak surge levels, this part of the Bay has a very low flood risk due to low consequences if flooding occurs. Almost no people live there and almost no buildings are located near the shore of that area. Therefore little risk (consequences x probability) is present. Additionally we have seen that measures that could be effective at reducing the surge height, are very large structures. Therefore Northeast Bay is neglected in the design of surge reducing measures and will not be included in the following considerations. Areas West and Northwest (HSC) will be considered because of high economic value and high populations, which means these areas would benefit from flood risk reduction. We have discussed before that generally the Northwest (HSC) is inundated when surge rises to above +4 m +MSL and West is inundated with water level above +2 m. In the current situation without Ike Dike, West and Northwest (HSC) would require protection from surge. In the situation with an Ike Dike, properties along the HSC are not threatened and only the western shore of Galveston Bay is at risk due to low elevation. It has been shown that only continuous, emerged islands can be considered effective for significant peak surge reduction.

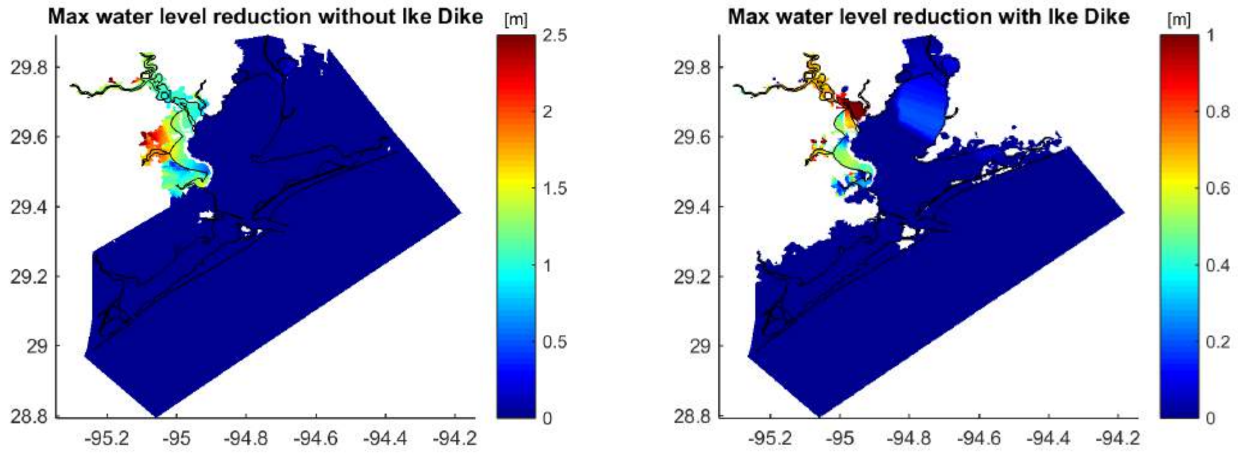
DESIGN

The optimized design (with respect to surge) is a combination of continuous islands in the West and Northwest of Galveston Bay. See Figure 7.25 for a graphic presentation of the design. This design is simulated with shift 2 for both the situations with and without Ike Dike. In the analysis of separate measures West and Northwest proved most effective in the case without Ike Dike. However, in the case with Ike Dike, the continuous measures in the Northwest proved to be fairly effective in reducing surge as well, whereas West in that case was significantly less effective.

Figure 7.25: Optimized design for surge reduction in the West and Northwest of Galveston Bay

Results of the simulations for Ike shift 2 with and without Ike Dike are shown in Figure 7.26. In the West peak surge reductions of **1.6 m** for the case without Ike Dike and of **0.5 m** for the case with Ike Dike are estimated. For HSC in the Northwest these estimated reductions are respectively **1.2 m** and **0.7 m**. It can be clearly seen that, although the measures are not completely continuous, they are very effective at reducing peak surge levels in the West and Northwest for a big hurricane like Ike shift 2. Even with an Ike Dike, the reduction can be considered significant, especially in the Northwest. It can also be seen that the optimized (combined) design shows better results for surge attenuation in West and Northwest than results of separate designs, probably simply because more water is retained by the design.

However, such a design requires a high volume of sediment, due to high construction length and high elevation of the islands of +6 m MSL. A quick assessment can determine the amount of sediment would be require to construct this design. See Figure 7.27 for an schematic presentation of a possible cross-section of the island. It is based on a side slope for the island of 1:3 for sediment under water.



(a) Maximum water level reduction without Ike Dike

(b) Maximum water level reduction with Ike Dike

Figure 7.26: Maximum water level reductions in Galveston Bay for the optimized design during Ike shift 2, simulated with and without Ike Dike

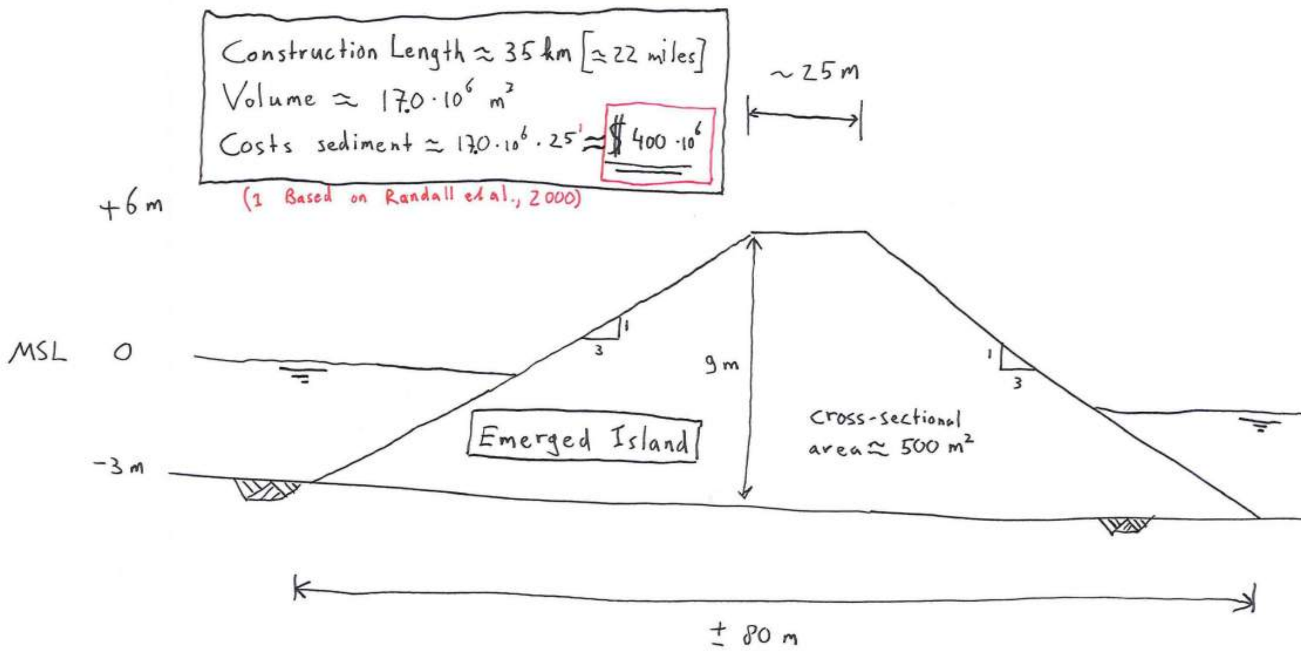


Figure 7.27: Sketch of the cross-section and an estimation of the sediment volume and the sediment costs of the optimized design

Depending on the crest width the measures could require up to 10-20 million cubic meters of sediment. In this study it is estimated to be 17 million cubic meters (see Figure 7.27). Randall et al. (2000) estimate the costs of manufactured soil for the beneficial use of dredged material for the Texas GIWW (near Galveston Bay) at \$17-26 per cubic meter. With this estimation the the total costs of the sediment required for the design can be estimated (see Figure 7.27). It is estimated at around 400 million dollar.

This design has to be further optimized and evaluated. For example ecological consequences, high current velocities in the channels, (technical) feasibility and costs should be thoroughly investigated. For example very high current velocities of **3-5 m/s** can be observed through the channels between islands.

7.5. CONCLUSIONS

- During hurricane Ike West experiences direct onshore winds prior to landfall causing peak surge to be around 3.5 m. Slowly the Bay is being infilled due to open coast surge. After landfall onshore wind shifts and the highest surge (4.3 m) is observed in the Northeast due to southwesterly winds. The Northwest (HSC) is not directly affected by high wind speeds and only experiences a surge level of 2.8 meter. It is possible with a simple 1D calculation to estimate surge levels in different areas of the Bay reasonably, provided that the correct wind direction of the hurricane and increased water level in the Bay due to open coast surge are assumed. The 1D calculations proved to underestimate the peak surge reduction for continuous fetch-limiting measures in the current situation and overestimated the reduction for the situation with Ike Dike.

- Shifted hurricanes towards the Southwest are significantly increasing surge levels in the Bay due to increasing inflow from the open coast surge and higher onshore directed winds, especially in the West and Northwest. Peak surge levels of around 5 m are found in the West, whereas peak surge levels of over 6 m can be observed in the Northwest and Northeast.

- Peak surge level can be reduced by emerged, continuous islands. Emerged during the worst simulated hurricane conditions requires a elevation of the islands of 6 m +MSL. For higher surge storms (shifted Ike 1 and 2 in this analysis), the surge reduction measures are more effective. For a situation with Ike Dike the effectiveness of measures generally is less effective, highlighting the fact that measures in this form are never completely continuous. From Table 7.3 it can be seen that continuous West and Northwest are the most effective measures. Peak surge reductions of over **0.5 m** with a maximum of **1 m** are possible for these islands. West is most effective without Ike Dike, whereas Northwest is still effective in the case with Ike Dike.

- An optimized design of a combination of continuous islands West and Northwest is presented. It is possible to achieve **1.6-1.2 m** surge reduction without, and **0.5-0.7 m** reduction with Ike Dike during Ike shift 2 in respectively the areas West and Northwest (HSC). A quick assessment showed that 10-20 million cubic meter sediment would be required for the construction of this design, which could cost up to $400 million dollar in this area. However, thorough investigation and optimization of this measure is required in terms of feasibility, ecology and cost-benefits.

8

Conclusions and Recommendations

8.1. Conclusions

This thesis explores the opportunities for Building-with-Nature solutions for hurricane flood risk reduction in Galveston Bay.

Galveston Bay is a large, micro-tidal estuary with an ebb-dominant tidal asymmetry. Most important habitats in Galveston Bay are oyster reefs and wetlands, although significant erosion and wetlands in Galveston Bay as a result of relative sea level rise and insufficient sediment supply has been observed. Galveston Bay is prone to hurricanes and vulnerable to flooding. Surge and waves are considered key processes contributing to flood risk, because they contribute greatly to damage during hurricane conditions. Important variables that affect surge and waves in Galveston Bay are fetch, depth, landfall location and hurricane surge at the open coast, of which fetch and depth can be influenced by BwN measures. Waves are generally depth limited in the Bay under hurricane forcing.

A BwN solution for flood risk reduction in Galveston Bay can consist of several elements or 'building blocks': nourishments, wetlands, oyster reefs or eco-engineered oyster reef breakwaters and an eco-island. The latter is a large island with ecological development and e.g. recreational functionality. Oyster reefs are considered as three-dimensional structures. These four building blocks have been chosen because they have the potential for flood risk reduction as well as provide natural benefits to the system.

A framework has been developed for the qualitative evaluation of building blocks for Galveston Bay. This framework involves two toolboxes and the formulation of a global, conceptual design. The toolboxes emphasize on flood risk and natural value of the building blocks. Simplified one-dimensional calculations, where possible, or qualitative literature are used to formulate the toolboxes. The potential effect of a building block is illustrated by a color classification and a description. The effect on flood risk is assessed for both surge and waves. The effect on natural value is assessed for five relevant criteria. It was proved that the framework works well for quick, qualitative evaluation of building blocks for Galveston Bay.

With respect to surge, the toolbox shows potential for peak surge reduction of several decimeters to a meter in Galveston Bay for emerged nourishments which compartmentalize the Bay, by limiting the fetch and thereby the wind set-up. An eco-island, however, is significantly less effective in reducing surge as water can easily flow around it. Wetlands and oyster reefs are considered not effective for surge level reduction at all. On the other hand, with respect to waves, wetlands are promising in reducing for wave heights nearshore. However, wide stretches are required and quantification of their effect is difficult due to existing variables like vegetation type, stem density and stem stiffness. At the shore, oyster reefs or eco-engineered oyster reef breakwaters are effective in attenuating waves and reducing erosion, although the effect in hurricane conditions requires more investigation.

Concluding, the evaluation of the toolboxes shows that most promising flood risk reduction measures are least beneficial to the natural value in Galveston Bay and vice versa. The most effective design as outcome of this qualitative evaluation is a continuous emerged island close to the western and northwestern shore of the Bay to reduce peak water levels. This can be combined with oyster reefs along the complete western shore up until Texas City and wetlands at the foreshore of the Texas City Levee for wave attenuation and erosion reduction.

The qualitative evaluation shows promising solutions for surge reduction. However, quantification has been difficult. Therefore a hydrodynamic 2DH model has been created that incorporates the complex dynamics of a hurricane, two-dimensional flow mechanisms and the bathymetry of the Bay. This modes is used to quantitatively evaluate the system behavior and surge reduction measures for different hurricanes, with or without Ike Dike. The model has been calibrated with measurements of peak water levels during Ike. Although this model is a coarse resolution model with limited simulation time, its performance is acceptable.

Simulations show that peak surge levels of 3.5 - 7 m are expected in the Bay for different storms in the open Bay situation. However, in the case of a closed Bay (Ike Dike) peak surge levels are limited to 1.5 - 2.5 m. Comparison between results from 2DH model simulations and the outcomes of the simple calculation of the qualitative evaluation shows that it is possible with simple, 1D calculations to estimate surge levels in different areas of the Bay reasonably. However, it is important to incorporate the dynamics of the storm (right directions of maximum winds) and an increased water level due to open coast surge correctly. Moreover, this comparison shows that the effects of surge reduction by BwN are more difficult to estimate with 1D calculations, because 2D mechanisms play a significant role. That is why outcomes of the 1D calculation for continuous and emerged islands underestimated the surge reduction for the open Bay situation and overestimated the reduction in the case with Ike Dike.

The most promising BwN surge reduction alternatives from the qualitative evaluation are assessed with the 2DH model. Peak surge can be reduced by emerged islands which are as continuous as possible (but never attached to the shoreline and shipping channels are always unobstructed). For the islands to be emerged even in the worst hurricane conditions simulated a height of 6 m +MSL is required (on an average Bay depth of 3 m). Peak surge level reductions with a maximum of **1 - 1.5 m** at the shore are possible for different storm tracks with emerged islands in the West and the Northwest (HSC). The measures are more effective for higher surge levels in the Bay. Highest simulated surge levels in Galveston Bay in the case of an Ike Dike are not high enough to jeopardize the banks of the Houston Shipping Channel or the Texas City levee, the economically most valuable areas. However, some inundation of the western shore will occur. Therefore the western shore of the Bay would benefit from surge reduction measure in the situation with an Ike Dike. On the other hand, simulation results show that BwN measures are generally less effective in the case with an Ike Dike, especially in the West. A final, optimized design for surge reduction is the combination of a continuous island for West and Northwest (HSC), the most economically valuable areas. This optimized design reduces peak surge levels in the West and Northwest of the Bay by 0.5 - 0.7 m in the situation with Ike Dike, and 1.2 - 1.5 m in the situation without Ike Dike. However, this design should be further optimized with respect to ecological consequences, (technical) feasibility and costs and benefits.

The main research question of this study was:

> **What are the opportunities and limitations of 'Building-with-Nature' type solutions to reduce hurricane surge-based flood risk in the Houston-Galveston Bay region?**

Building-with-Nature measures cannot completely eliminate the flood risk problem in Galveston Bay. However, they can significantly improve natural conditions in the Bay. On the one hand, surge reduction is merely achieved with almost continuous and emerged islands. The presented optimized BwN design is a significant intervention in the Galveston Bay system, requires a high sediment volume and might have limited benefits for natural value. This BwN design results in a maximum peak surge reduction of 1.5 m at the western and northwestern shore. Moreover, effectiveness of all measures depends on whether an Ike Dike will be constructed and on which hurricane and landfall location are considered. On the other hand, with respect to waves, oyster reefs and wetlands along the shore are promising BwN solutions, as they clearly add value to the natural system, protect the shore and attenuate waves. However, to reduce flood risk in Galveston Bay significantly, BwN solutions should be constructed complementary to hard flood protection structures, like e.g. an Ike Dike and/or levees inside the Bay.

8.2. Recommendations

Recommendations from this research are as follows:

- A conceptual design study is presented in this report. It is recommended to improve the **design optimization** for the Building-with-Nature for hurricane flood risk reduction in Galveston Bay. It is important to know whether the BwN solution is feasible with respect to e.g. morphological development of the system, ecological consequences, stakeholders and economic interests, costs, constructability and technical feasibility. Because the emphasis in the 2DH analysis was on surge, combinations of surge and wave designs should be further investigated. Also combinations of BwN with hard structures should be thoroughly investigated as this is probably the most optimal solution to completely eliminate the flood risk problem and add ecological value to Galveston Bay. Lastly, the design of eco-engineered oyster reef breakwaters should be investigated and optimized.

- It is recommended to conduct a thorough **cost-benefit analysis** for the optimized BwN designs for hurricane flood risk reduction in Galveston Bay. This cost-benefit analysis must consist of:

  - Quantification of **ecological benefits** of the building blocks and designs. How will the system react to certain measures and what are the consequences for the ecosystems of Galveston Bay? The ecosystem services should be included and quantified, like has been done by e.g. Guannel et al. (2015). Furthermore the economic quantification of the ecosystem services provided by the measures should be assessed, like done by e.g. Barbier et al. (2011). It is desirable to expand the 2DH hydrodynamic model for an estimation of ecological benefits. Furthermore it is recommended to create a sophisticated morphological model to investigate the morphological development of the system and the morphological effects of the Building-with-Nature measures. Finally, water quality could be included into the model to simulated the effect of measures on circulation and salinity patterns in Galveston Bay.
  - The **flood risk benefits** of the BwN designs should be quantified by means of a proper flood risk assessment. What does a certain surge reduction mean in terms of risk reduction? Therefore the flood damage of surge and waves and wind damage corresponding with the return periods of a certain hurricane should be estimated. To accomplish this, detailed land use data and damage estimates are required. Furthermore it is desirable to expand the 2DH hydrodynamic model and improve its resolution. The inclusion of waves in the model to evaluate wave height reduction of measures will further improve the analysis, as wave set-up due to breaking waves (albeit assumed small) will be a part of the simulated surge levels. Therefore, would inclusion of waves make the surge predictions more adequate as well.
  - A thorough **cost estimation** of the optimized BwN designs should be made to finish the cost-benefit analysis. It is currently unknown what the costs of the proposed measures are and whether they are outweighed by the benefits of the measures. This cost estimation should be made in a later stage, when a possible design for Galveston Bay is optimized.

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Appendices

A

Galveston Bay Background

Information in this chapter is based on literature and discusses background information on Galveston Bay.

A.1. Galveston Bay Literature Review

This section discusses Galveston Bay's history, its characteristics and economic and environmental aspects. The characteristics of Galveston Bay can be summarized in three words: people, business and nature. This combination makes the estuary highly valuable.

A.1.1. Map Galveston Bay

Map of Galveston Bay with locations of some NOAA observation points from NOAA (2014).

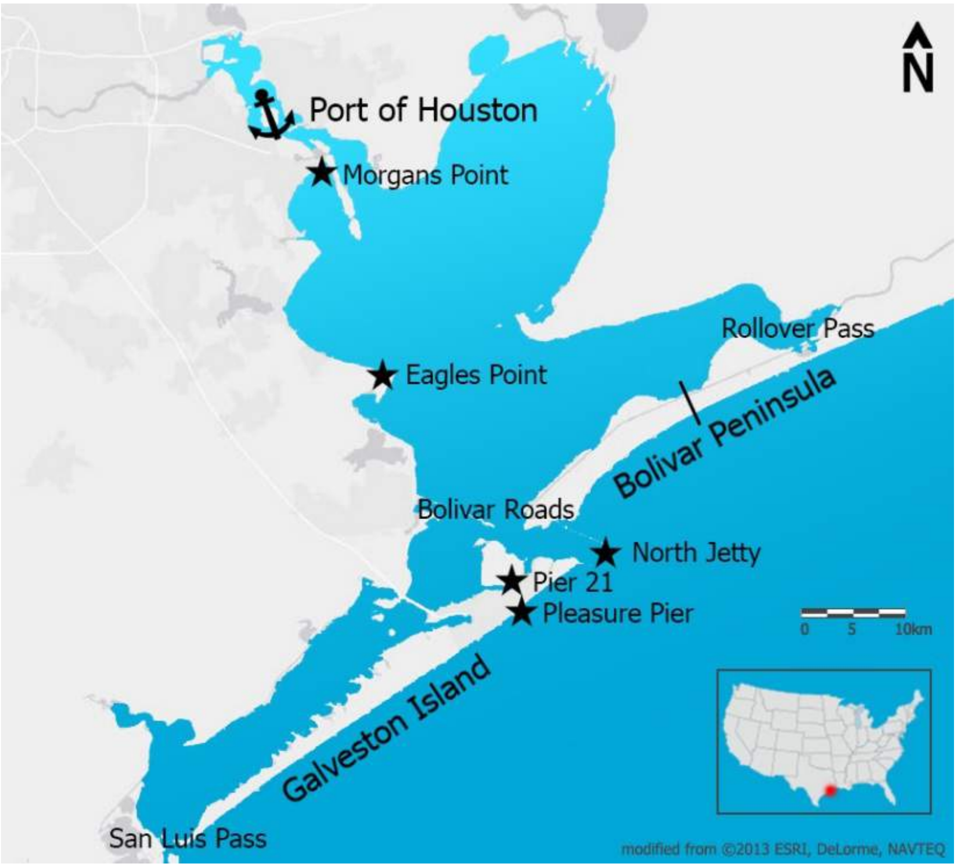


Figure A.1: Map of Galveston Bay and NOAA observations points (Stoeten, 2013)

A.1.2. HISTORY GALVESTON BAY (PEOPLE AND BUSINESS)

Earliest fossilized bones and artifacts around Galveston Bay were found between 14,000 and 8,000 years ago (Smith, 2013). These archaeological findings indicate that people had been using resources of Galveston since that time (Galveston Bay Estuary Program, 2014). First nomadic people used the bay area for hunting wildlife and harvested shellfish. From that point forward the Galveston Bay environment was modified by the harvest, production of shell mittens and introducing plants from other ecological environments (Galveston Bay Estuary Program, 2014). First known permanent inhabitants of the area were found between 5,000 and 7,000 years ago (Smith, 2013). Galveston Island was home to earliest settlers from Europe, since 1528 when a shipwrecked Spanish explorer landed on the island (Galveston.com, 2013; Smith, 2013). Later, Galveston was named after a Spanish governor and general Bernardo de Galvez by Spanish explorer Jose de Evia in 1786 during his charting of the Upper Gulf Coast (Galveston.com, 2013). Around 1800, the settlers exploited the biological and physical resources of the Galveston Bay. The city of Galveston was incorporated by the Congress of the Republic of Texas. During this period, Galveston was thriving as Texas' largest city and the port of Galveston quickly became the most active port west of New Orleans (Galveston.com, 2013). By that time the Bay itself was subjected to big alterations already, as navigation channels were made and dredged material was deposited.

In 1900 a devastating hurricane struck the Galveston Island. This storm was henceforth called 'The Great Storm' or 'Great Galveston Hurricane'. The storm caused between 6,000 and 8,000 casualties (on a population of around 37,000 people) and is known to be the most deadly storm in U.S. history (Galveston Newspapers, 2014; Galveston.com, 2013). Estimated present-day normalized damage is more than $70 billion (Pielke et al., 2008). After the storm, measures were undertaken to prevent future damage. The entire city of Galveston was raised by 8 feet [2.4 m] by jacking up 2,000 building and filling up with sand from the bay, and the concrete Galveston Seawall with a crest height of 17 feet [5.2 m] was constructed to prevent surge from entering the city of Galveston (Casselman, 2009; Galveston Newspapers, 2014; USACE, 1981). Many businesses, including the major port of Galveston, moved inland to Houston (Smith, 2013). The harbor of Houston took over the position of most important port of the area and grew with time to the second largest port of the U.S. as it is today. With growth of the port, the HSC was continuously dredged deeper to the depth of about 45 feet [13.7 meter]. In the decades after 1900, the GHMA grew out to be the fifth largest metropolitan area in the U.S., and still grows fast (Lerup, 2012; U.S. Census Bureau, 2012). Rapid industry and population growth occurred from the end of the 40's (1948) with the development of high-tech industries like air conditioners, elevators and high-rise buildings (Lerup, 2012). But also during the 70's and 80's population grew explosively (Galveston Bay Estuary Program, 2014). Much of the region's growth is attributed to the discovery of oil in the Gulf of Mexico and the construction of the HSC (Galveston Bay Estuary Program, 2014).

A.1.3. LAND USE GALVESTON BAY (PEOPLE)

Houston has grown and still is growing rapidly (Brody, 2014; Lerup, 2012). According to Lerup (2012) there is little zoning in Houston, which results in urban sprawl[1] of Houston and surrounding cities.

A general map of land use in the Houston-Galveston area can be seen in Figure A.2. This map shows all land uses for the area. For example developed land, pasture, forest, different wetlands and unconsolidated shores can be distinguished. It can be seen that most wetlands (estuarine or tidal wetlands) are located near the ocean shore, and palustrine wetlands are present in the delta near the inflow of the Trinity River in the northeast of the bay. Furthermore it can be seen that most developed land is located on the western side of Galveston Bay (cities of Houston, Texas City and Galveston). This western shoreline is usually hardened and in some places there are private jetties present. Most industrial and urban activities take place on the western side and almost all people in the GHMA live on the this side of Galveston Bay and on Galveston Island. Result is that large numbers of people live inside the 1/100 year floodplain.

The eastern side of the Bay consists of pasture, coastal and upland prairies, cultivated crops for agricultural use and forested land (Lerup, 2012). Except a couple of villages, not many people live on the eastern side of Galveston Bay. Most coastline around Galveston Bay originally consisted of wetlands (Houston Wilderness, 2014; USGS, 2013).

[1] Urban sprawl is the expansion of human populations from the urban central areas towards low density communities on the countryside. Spreading out over a large area in an irregular way. These communities usually do not have many functions (e.g. residential) and are often car dependent (Frumkin, 2002)

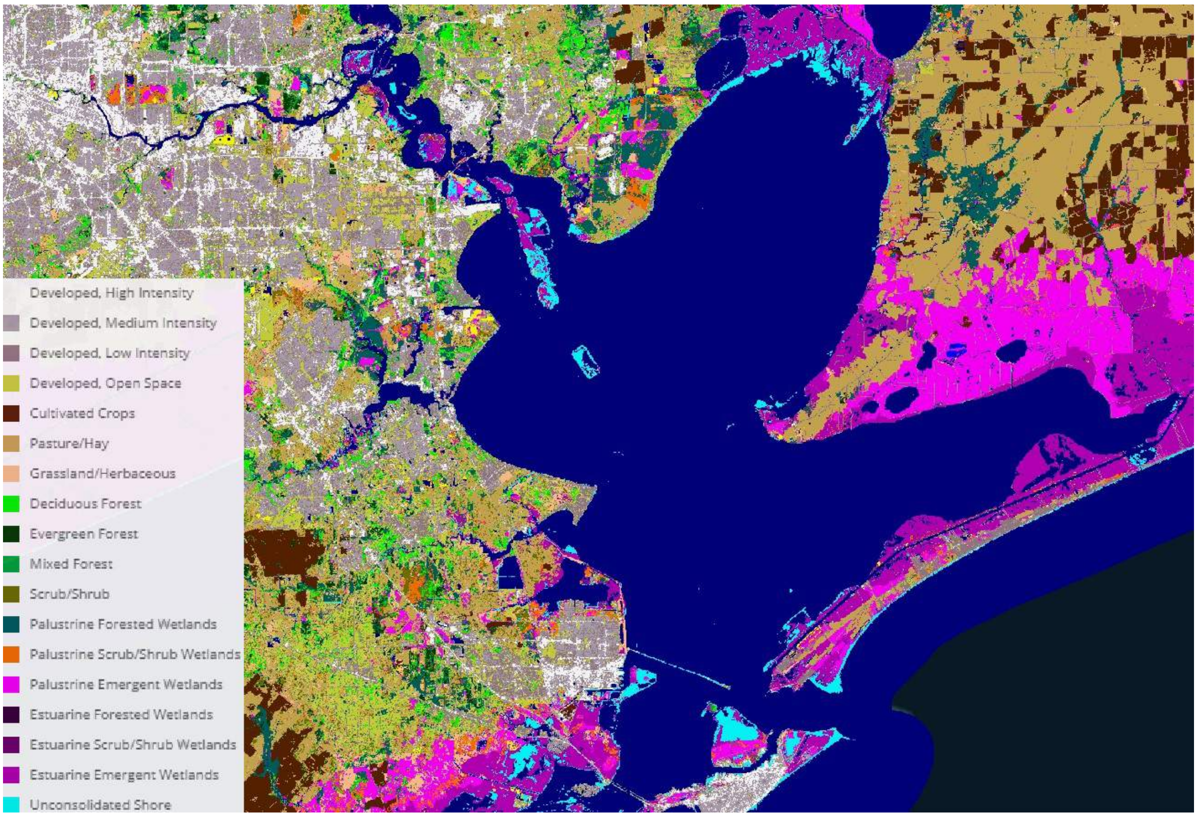


Figure A.2: Land use in the Houston-Galveston Bay area (NOAA, 2014)

The shoreline around Galveston Bay has been modified extensively, with reaching implications. See Figure A.3 for a state of the Galveston Bay shorelines as of 1995. "Shoreline modifications involve conversion of shoreline and near-shore habitat from a sloping, vegetated, natural state to an abrupt vertical land-water barrier" (Lester & Gonzalez, 2011). This has great environmental impacts, such as erosion, decrease in ecological value and the inability to grow with SLR. As of 1995, almost 28% of the shoreline has been developed, especially on the western side (Lester & Gonzalez, 2011).

A.1.4. ECONOMY GALVESTON BAY (BUSINESS)

The Galveston Bay area has a high economic activity and hosts some important industries. Houston is among the top (high-tech) manufacturing cities in the U.S. (Greater Houston Partnership, 2014). Most important assets are the port of Houston and the petrochemical industry. Additionally, the medical and life-science industry (including the Texas Medical Center), the aerospace & aviation industry (NASA Johnson Space Center), tourism and fishing are valuable industries (Greater Houston Partnership, 2014; Hodgin, 2007). While Houston is recognized for its petrochemical industry, renewable energy technology is growing (Greater Houston Partnership, 2014).

The port of Houston is a 25 mile [40 km] complex built along the Houston Chip Channel in proximity of Galveston Bay. It is just a few hours away from the Gulf of Mexico. With annual cargo throughput of over 237 million tons the port is the second largest port in the U.S. and the sixth largest in the world, based on total tonnage (Port Authority of Houston, 2014). Martin Associates (2012) estimated the direct economic impact of the port to be 178.5 billion dollar and HSC-related businesses contribute more than 1 million jobs throughout Texas. The petrochemical manufacturing industry of Houston and Texas City is a 15 billion dollar industry (Port Authority of Houston, 2014) and is the largest of the nation and the second largest in the world (Smith, 2013). In this complex about 1/3 of the oil refining of the U.S. takes place.

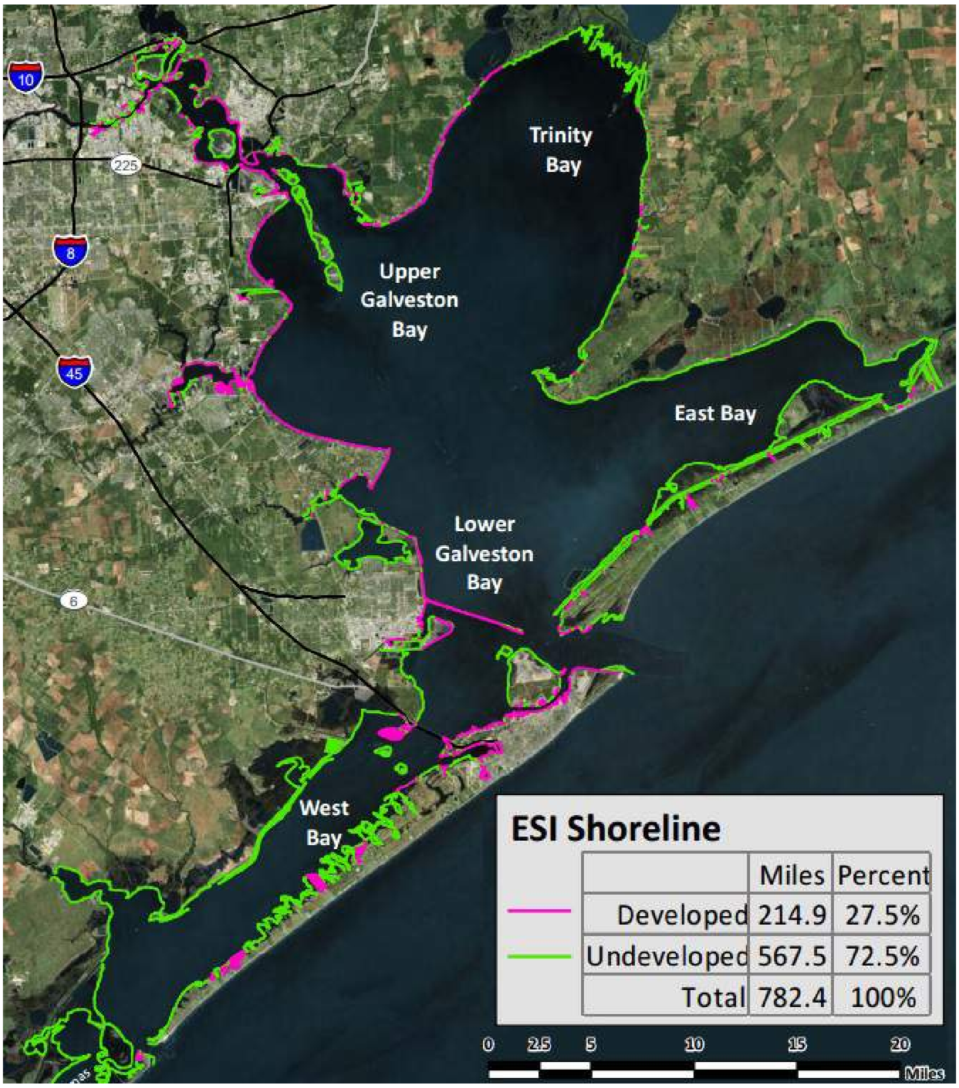


Figure A.3: Galveston Bay shoreline development. Data source: BEG (1995) (Lester & Gonzalez, 2011)

Besides the Port of Houston, the ports of Texas City (ranked 11th in the U.S. with 58 million tons cargo) and Galveston (41st with 14 million tons) are valuable drivers for the economy around Galveston Bay as well.

According to Smith (2013) almost all commercially and recreationally important fisheries in the Gulf of Mexico are dependent upon estuaries like Galveston Bay. Galveston Bay is the most productive bay in Texas and only trailing Chesapeake Bay nationwide (Smith, 2013). Shrimps accounts for nearly half the Galveston Bay seafood harvest and Galveston Bay produces more oysters than any single water body in the U.S. (Galveston Bay Estuary Program, 2014). According to the EPA the recreational and commercial fisheries in and around Galveston Bay contribute over $3 billion annually and it also supports 40,000 jobs in the area (Galveston Bay Estuary Program, 2014).

It may be clear that due to the economy - maritime and (commercial) fishing activities -, navigability in Galveston Bay is very important at all times.

A.1.5. GALVESTON BAY SYSTEM

GEOLOGY GALVESTON BAY

The starting point of Galveston Bay as we know it was during the last Ice Age, more than 18,000 years ago (Smith, 2013). As the last Ice Age came to an end, the earth warmed and sea level rose to the near present level in a period of thousands of years (Phillips, 2005; Smith, 2013). Alongshore currents due to wave action along the new developed shoreline deposited sediment, starting around 6,000 years ago (Ricklis, 2009; Rodriguez et al., 2004; Smith, 2013). First creating sand bars, waves and currents continued to bring sediments forming the barrier islands (Bosboom & Stive, 2013). In addition rivers, the Trinity River and the Jacinto River, washed coarse sediment from the watershed that built up the barrier islands. Eventually the barrier islands were created, Galveston Island around 5,000 years ago and Bolivar Peninsula around 2,500 years ago respectively (Ricklis, 2009; Smith, 2013).

Barrier islands are usually created when a certain set of criteria is met. The tidal range should be low, the system should be wave dominated, the continental shelf should preferably have a gentle slope, there should be ample sediment supply to form the barrier and a stable sea level should be present. All these conditions were met in Galveston Bay with the formation of the two barrier islands (NOAA Office for Coastal Management, 2014). Figure A.4 shows a typical model of a Texas barrier estuary. Several typical land forms can be seen: an old delta front, a bay, a barrier island and an active inlet (Atkins Global, 2011).

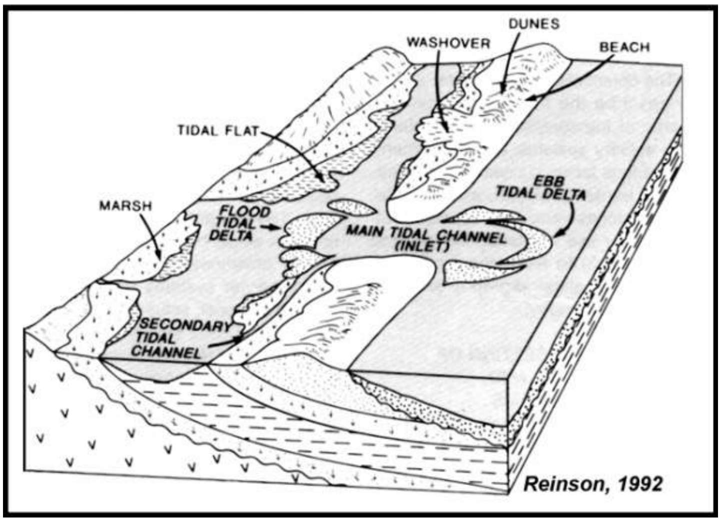


Figure A.4: Typical barrier island estuary system and coastal environment (Atkins Global, 2011)

The area contains Pleistocene sediments such as mud, and that the barrier islands are formed by recent, Holocene sand. A cross-section of Galveston Island can be seen in Figure A.5.

The deeper soil layers in the Galveston Bay area have been investigated by Petitt and Winslow (1955). They found that the area is underlain by a Pleistocene Beaumont clay layer which consists of mostly clay and sand.

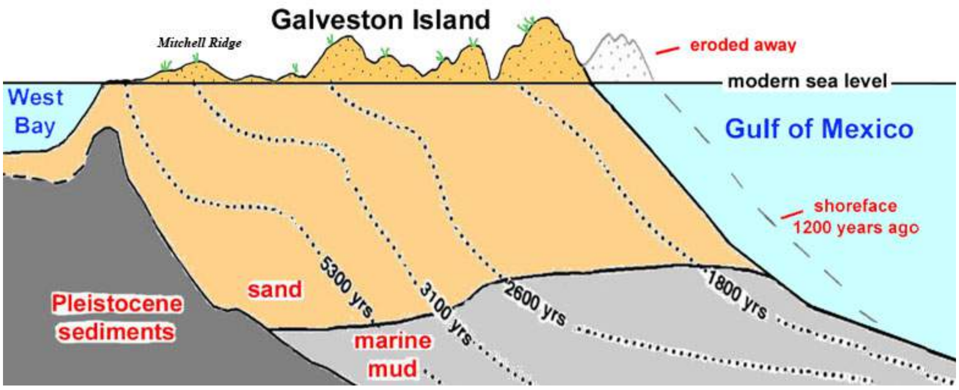


Figure A.5: Cross-section of Galveston Island. Adapted from: Rodriguez et al. (2004) (Ricklis, 2009)

These sediments are mostly of deltaic or alluvial origin and have been deposited during the Pleistocene period. These clay layers cover at least the first 150m over the soil. Below, a more sandy layer can be found, the Alta Loma sand layer, which is formally a part of the Beaumont clay layer as well. This layer covers roughly 50 meters, and sits on top of the Pleistocene Lissie clay layer (Petitt & Winslow, 1955).

INLETS

Bolivar Roads is 2.8 km wide, 15 m deep at maximum and is an important shipping corridor towards the harbor of Houston (Figure 2.1). Bolivar Roads is enclosed by two jetties to protect and retain the deep waterway (de Vries, 2014). In the future Bolivar Roads may facilitate even larger vessels. The different depths can be distinguished from a plot of three different cross-sections of the Bolivar Roads inlet in Figure A.6.

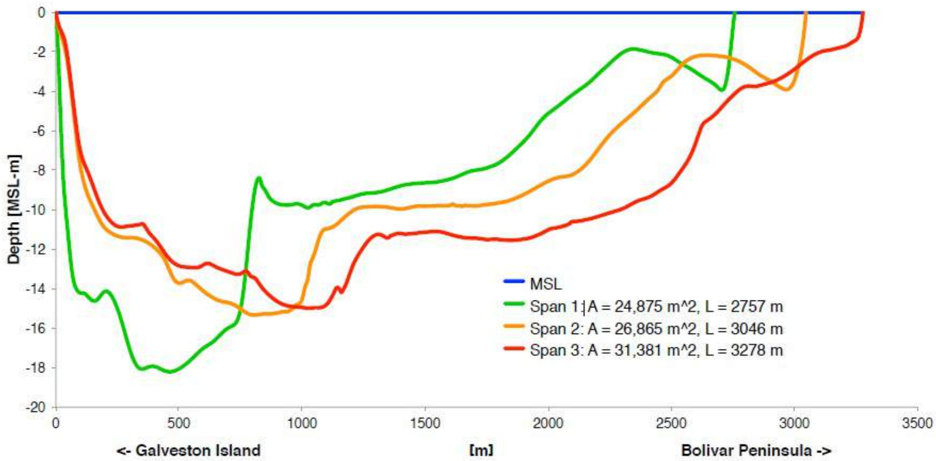


Figure A.6: A plot of three different cross-sections in Bolivar Roads Pass (de Vries, 2014)

San Luis Pass is located at the southwest end of Galveston Island (Figure 2.1) and connects the West Bay with the Gulf of Mexico and is 900 m wide and on average 2 m deep (de Vries, 2014). It is responsible for about 15-20% of the tidal exchange with the Gulf of Mexico.

Rollover Pass is a artificial inlet of 60 m wide and is negligible for tidal exchange. It is located at the northeast end of Bolivar Peninsula. The pass was constructed to improve fishing in the bay, but due to erosion problems, the Texas General Land Office is considering to close the inlet once again (de Vries, 2014).

TIDES

Galveston Bay is a shallow, micro-tidal, wave dominated estuary with a predominantly diurnal tidal range of about 0.35 meter. The tidal ratio between bay and Gulf is about 0.6 and observed phase lag is 4 to 6 hours. The tidal prism is 3.5 x 10^8 m^3. Residence time of a water particle is generally 40 days (Phillips, 2005).

Freshwater Inflow and Runoff

The main source for fresh water inflow into Galveston Bay is the Trinity River. This river accounts for 54% of the total drainage area of Galveston Bay (Phillips, 2005; Smith, 2013). The second river debouching in Galveston Bay is the San Jacinto River, accounting for 17%. The rest of the inflow is accounted for by numerous bayous and streams. The total fresh water inflow varies strongly, but yearly average is assumed to be $1.7 \cdot 10^{10} m^3$, which is equal to $540 m^3/s$ (Matsumoto et al., 2005).

Wind

Two dominant wind directions can be found in Galveston Bay, due to seasonal variations. Dominant directions are the southern/southeasterly and northerly directions (Ruijs, 2011). Persistent southern and southeasterly winds occur in summer from March to November. The prevailing wave direction is from SSE and SE as well, resulting in a westward directed alongshore sediment transport at the coast. In winter short-lived and strong northerly winds occur due to Northers. See Figure A.7.

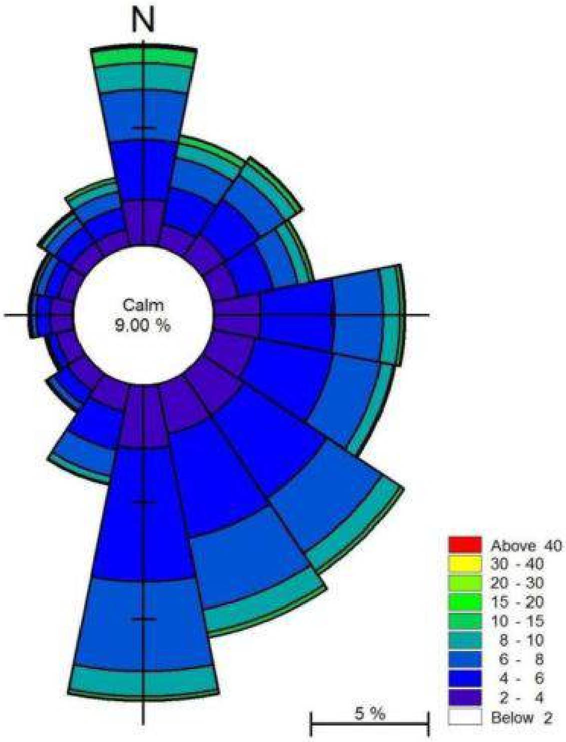


Figure A.7: Wind rose for the Galveston Bay Area from 1983-2006. Data source: NOAA (2014) (Ruijs, 2011)

Harter, Figlus, and Dellapenna (2015) state that "although the winds from SSW and SW occur more regularly, a proportionally greater percentage of peak winds (above 10 m/s) are from the north", representing the Northers.

80th Percentile Wave Height

Marshes exposed to a 80th percentile significant wave height (H80) greater than 0.2 m are more susceptible to erosion than others (Guannel et al., 2014). Kroeger (2012) formulates the same threshold as a median significant wave height (H50) of 0.15 m. A map of locations of the H80 wave height in Galveston Bay can be seen in Figure A.8.
Yellow and red areas are potential areas to be protected in general.

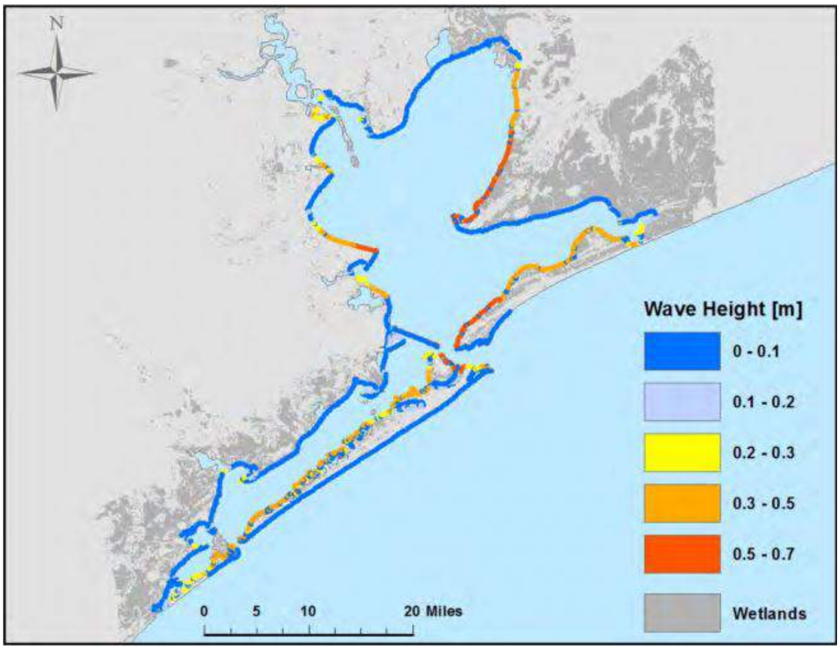


Figure A.8: A map with the 80th percentile significant wave height (H80) for Galveston Bay. Shores and especially wetlands exposed to an H80 of over 0.2 m are most susceptible to erosion (Guannel et al., 2014)

A.1.6. GALVESTON BAY ECOSYSTEM (NATURE)

HABITAT DESCRIPTION

Galveston Bay, adjacent to one of the most urban and industrialized areas in the nation, is also a complex and highly valuable ecosystem, important for the state of Texas and nationwide. The barrier islands of Galveston Bay ensure this unique environment of relatively low wave energy and brackish water. Without barrier islands ecosystems probably would have been different. Inflow of fresh water from rivers and bayous brings in nutrients, sediments and organic material into the bay to fuel the food chain and replenish the wetlands and other ecosystems (GBF, 2014; Ricklis, 2009). Galveston Bay supports a wide variety of marine life. Galveston Bay serves as a major nesting area for colonial waterbirds. These birds depend on the availability of food and suitable habitats, free from disturbance (Galveston Bay Status and Trends, 2014).

PROBLEMS

Although the natural value of Galveston Bay is significant, the system is under pressure. Some issues in Galveston Bay are: poor water quality, insufficient freshwater inflow, sea level rise (SLR) and land subsidence, subsequently erosion and conversion of wetlands to open water or urban and industrial space. Galveston Bay has been an important resource for people around it for thousands of years.

WATER QUALITY

Water quality in Galveston Bay is an issue and one of the key problems of the estuary. Since the beginning of the last century water pollution has become a problem (Lester & Gonzalez, 2011). In 1967 federal investigators identified the HSC as the estuary with most significant water pollution observed in Texas. From that moment corrective measures have been initiated to improve water quality (Lester & Gonzalez, 2011). Generally, water quality has been good in recent years. Problems related to water quality are point and non-point source pollution, chemical and petroleum product spills from barges and industry (EPA, 2007). Point source pollution has been regulated strongly since the 70's and has resulted in substantial improvement (Galveston Bay National Estuary Program, 1995). But non-point source pollution is still significant. This is attributed by runoff from the highly urbanized space (residential lawns, industrial ares, gas stations) and failing septic tanks (EPA, 2007). Harmful contamination due to non-point source pollution is the fecal coliform bacterium. An additional problem is the turbidity of the water in the bay, caused by fine sediments in suspension. Galveston Bay naturally turbid due to fine sediments and shallow depth, but dredging, fisheries and erosion enhance this (EPA, 2007). Increasing turbidity could have negative effects ecology.

The following analysis will discuss an assessment of the actual water quality in Galveston Bay EPA (2007). It is based on data collected by the Texas Park and Wildlife Department (TPWD) and the U.S. Environmental Protection Agency National Coastal Assessment (US EPA/NCA) from 28 stations, which was sampled in 2000 and 2001. Water quality is generally rated poor, based on the NCA survey results and guidelines (EPA, 2007). The index of this NCA survey used 5 indicators: DIN, DIP, chlorophyll a, water clarity and dissolved oxygen. An overview of the water quality index data points can be seen in Figure A.9. Sediment quality is fair to poor (EPA, 2007). Sediment in the upper part of the HSC exceeds concerned levels for chemicals as PCB's, DDT, toxic dioxin (all toxic, organic matter) and some heavy metals, although improving (EPA, 2007; Lester & Gonzalez, 2011). Overall the Galveston Bay is classified as fair. Benthic index is rated fair and the fish tissue contaminants index is rated good to fair (EPA, 2007). See Figure A.10 for a table of overall quality of Galveston Bay, based on the four indices.

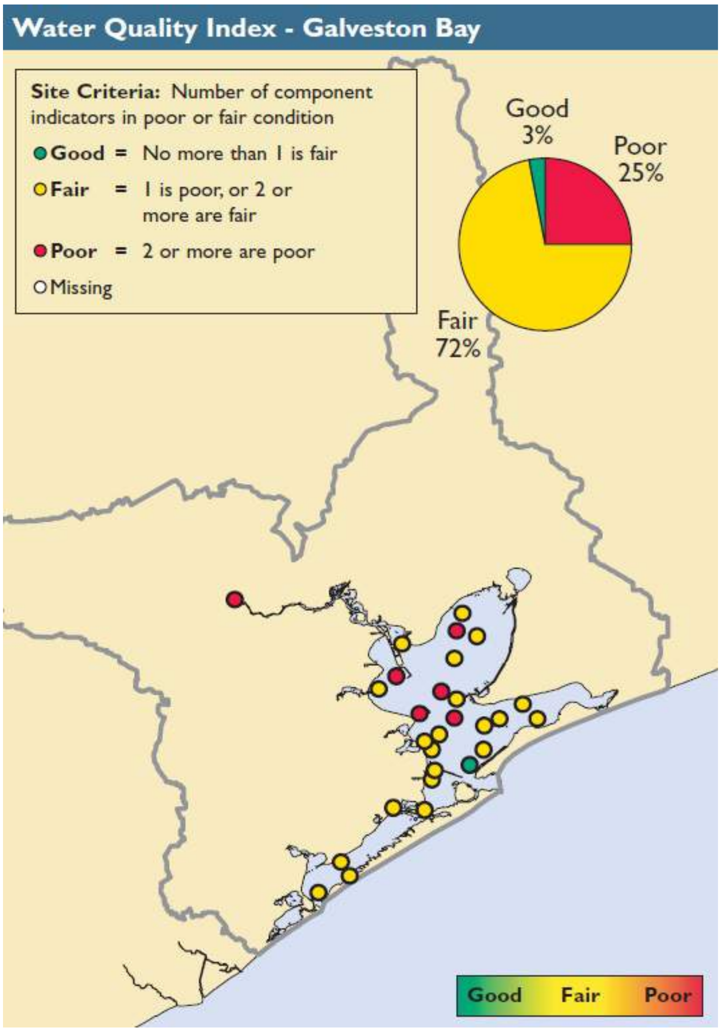


Figure A.9: Water quality index for Galveston Bay in 2000 and 2001. Data source: U.S. EPA/NCA (EPA, 2007)

Water quality has consequences for oyster harvest. Oysters will accumulate pollutants and this combined with their lack of mobility makes them an important indicator for determining the health of the system (Galveston Bay Status and Trends, 2014). A result of this can be seen in Figure A.11. Certain areas are depicted for oyster harvest, while other areas are restricted or forbidden to harvest oysters because of water quality issues. This permanently or conditionally closed area is over 50% of the total area (Galveston Bay National Estuary Program, 1995), mainly due to the fecal coliform, non-point source contamination.

Salinity trends in Galveston Bay which have been found to be dynamic and complex. No clear trend can be distinguished, as it depends very much on period and location. However, it can be said that more saline water penetrates to the Upper Bay area and that current velocities are increased because of the deepening of the HSC.

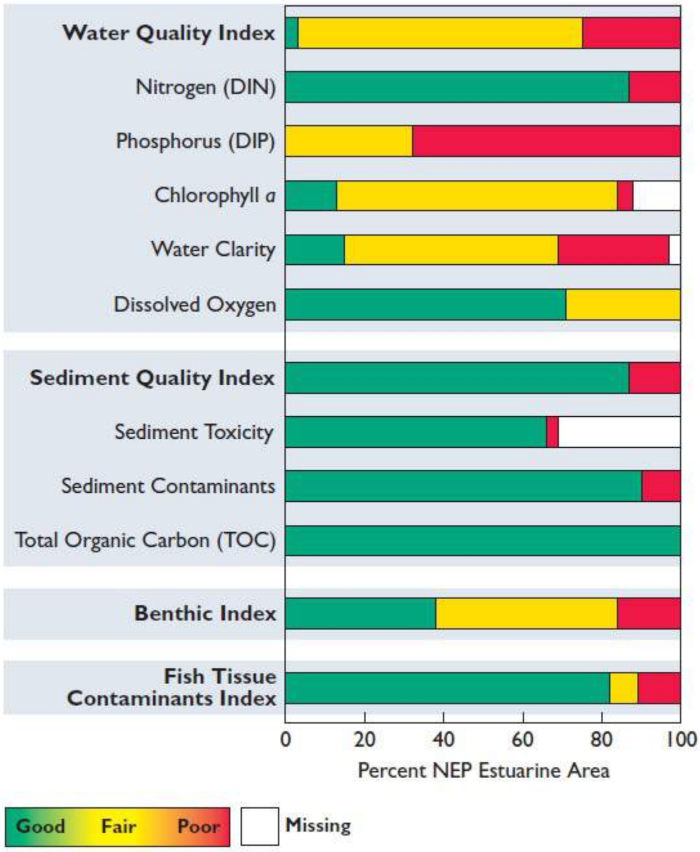


Figure A.10: Overall quality Galveston Bay: percentage of Galveston Bay area achieving each classification for all four indices and associated components. Data source: U.S. EPA/NCA (EPA, 2007)

An additional thread for the water quality is the possibility of an oil spill. The risk of an oil spill is ever-present because of the large quantities of petrochemical complexes in the proximity of Galveston Bay and oil tankers sailing the HSC. Every year an average of 275 oil spills occur in Galveston Bay (HARC, 2014a). Shipping vessels are the biggest contributor to this number. Oil spills are usually small in volume, the average is 100 gallons per spill and most spills are minor spills of less than 1 gallon (HARC, 2014a). Oil spills impact ecosystems because petroleum is toxic to organisms, and it evaporates and will become air pollution (HARC, 2014a). The heavier components will wash upon shore or sink to the bottom. In March 2014 there was a large oil spill from a tanker in the HSC. This spill of 168,000 gallons [636 m^3] is the largest oil spill ever recorded in Galveston Bay (HARC, 2014a).

HABITAT ACREAGE

WETLAND TRENDS

The main reason for wetland loss is insufficient sediment supply to keep up with relative sea level rise. The conversion of wetlands to urban, industrial, infrastructural and agricultural land use, dredge and fill operations and invasive species threatening the wetland flora play an additional role in this process. Erosion and overwash due to hurricanes is not necessarily negative for the natural system, as the overwash deposits could turn into wetlands at the backside of barrier islands (J. B. Anderson, 2007).

Trends in wetland distribution are based on an analysis by Lester and Gonzalez (2011). Focus lies on estuarine and salt marshes, because they form the edge between the water and land of Galveston Bay. Although freshwater marshes acreage decreases at a much higher pace than estuarine wetlands, they are less interesting for this research because they lie more inland (Lester & Gonzalez, 2011).

The area of estuarine wetlands has been evaluated several times. Different studies are hard to compare due to the fact that different areas are considered and different surveying methods have been applied. Table A.1 displays acreage and change in acreage in estuarine emergent wetlands for an area covering 30 quads of the Lower Galveston Bay watershed. The table is based on data from a land cover classification done for the

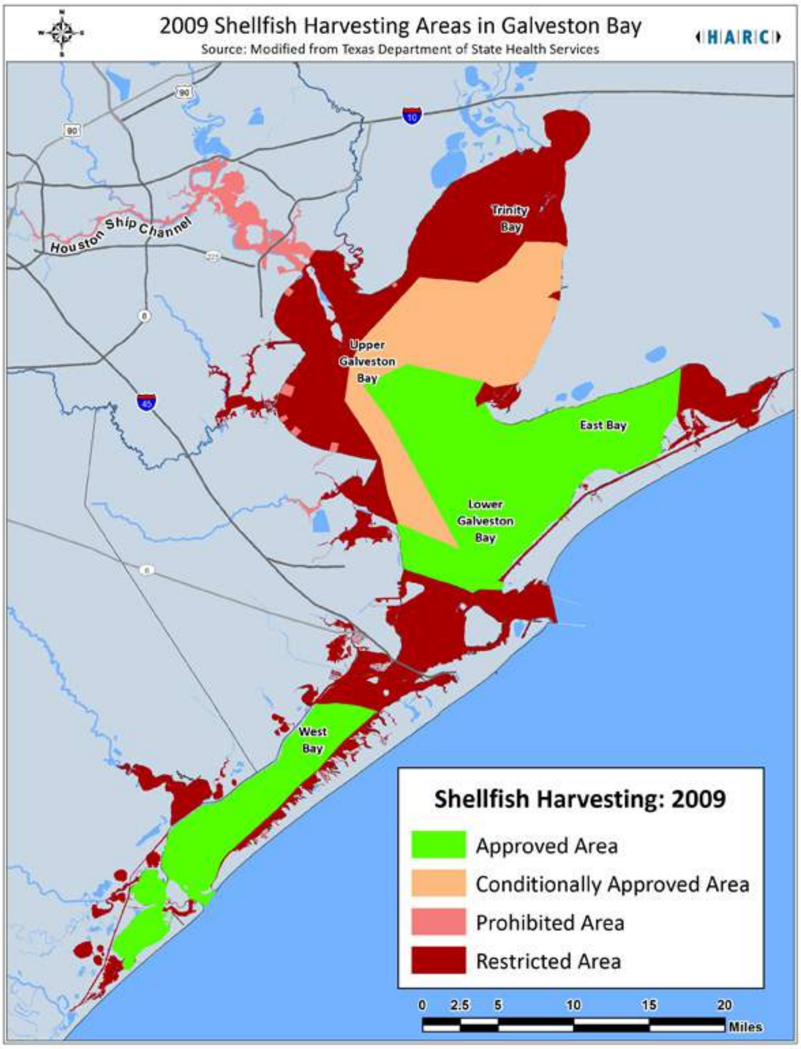


Figure A.11: Map with shellfish harvest area classifications in Galveston Bay (Galveston Bay Status and Trends, 2014)

Galveston Bay Estuary Program by White et al. in 1993 (Lester & Gonzalez, 2011).

	Acres [km^2]					
Wetland classification	**1953**	**1979**	**1989**	**Total change ’53-’89**	**Annual change ’53-’89**	**Percent change ’53-’89**
Estuarine emergent	117,640 [476]	105,880 [428]	108,160 [438]	-9,480 [38]	-256 [1]	-8%

Table A.1: Historic trends in estuarine emergent wetland acreage in 30 quads of Lower Galveston Bay. Data source: White et al., 1993. Adapted from Lester and Gonzalez (2011)

More recent trends can be seen in Table A.2. This table is based on analysis of NOAA C-CAP data from 2006 for the same 30 quads near Galveston Bay between 1995 and 2005 (Lester & Gonzalez, 2011). Comparisons between different studies and data sets is very difficult due to mostly methodological and geographical differences (Lester & Gonzalez, 2011). However, similar trends can be seen. The loss of estuarine wetlands has been slowed down significantly and eventually reversed since 1989, see Table A.1 and Table A.2. The reason for this trend according to Lester and Gonzalez (2011) is probably the regulatory protection under the Clean Water Act as well as the numerous restoration efforts.

	Acres [km^2]				
Wetland classification	**1996**	**2005**	**Total change ’96-’05**	**Annual change ’96-’05**	**Percent change ’96-’05**
Estuarine emergent	120,893 [489]	123,168 [498]	+2,275 [9]	+228 [1]	+2%

Table A.2: Recent trends in estuarine emergent wetland acreage in 30 quads of Lower Galveston Bay. Data source: NOAA C-CAP, 2006. Adapted from Lester and Gonzalez (2011)

The same data from NOAA can be processed for the 5 counties in the Lower Galveston Bay watershed, which covers a slightly bigger area than the first study discussed. The result can be seen in Table A.3. This table shows a net gain of estuarine wetlands of only 199 acres [0.8 km^2] which is smaller than observed from Table A.2. Acres of loss due to urban or industrial development, which is bigger for the 5 counties, are compensated by gains in wetlands due to restoration.

	Acres [km^2]				
Wetland classification	**1996**	**2005**	**Total change ’96-’05**	**Annual change ’96-’05**	**Percent change ’96-’05**
Estuarine emergent	163,029 [660]	163,228 [661]	+199 [1]	+20 [0.1]	+0%

Table A.3: Recent trends in estuarine emergent wetland acreage in 5 counties around Galveston Bay region. Data source: NOAA C-CAP, 2006. Adapted from Lester and Gonzalez (2011)

OYSTER REEF TRENDS

The analysis on oyster reef trends arises from the report of Lester and Gonzalez (2011). Some oyster reefs in Galveston Bay have persisted throughout time. Other oyster reefs have been disappearing or changing the past decades, changing position and shape as a result of human and natural changes in the system (Lester

& Gonzalez, 2011). The factor which has had most impact on the oyster reef system is the commercial shell dredging for construction and chemical industries. This has removed reefs to a depth of 45 feet during the 60's and 70's (Lester & Gonzalez, 2011).

Some areas with most heavily fished reefs have not varied much in size and shape. Most oyster reef losses have been in areas which were closed due to health protections (E. Powell et al., 1994). The conclusion can be made that oyster fishery might even enhance reef growth. One of the reason could be shell movement off the edges of the reef.

Most important circulation influences have been the loss of Redfish Bar due to the HSC, the construction of Texas City Dike which reduced circulation from Galveston Bay to West Bay significantly, channelization and dredge and fill operations. The HSC has increased the saline water to penetrate more northward. Therefore more oyster reefs could be productive in the north of the bay. Furthermore the widening of the HSC exposed buried shell. The provision of this substrate enhanced oyster settlement, over 2,500 acres [10 km^2] has been developing along the the channel (Lester & Gonzalez, 2011; E. Powell et al., 1994). This can be seen in Figure A.12. Nowadays most reefs are detached from the shoreline due to land subsidence and shoreline retreat (E. Powell et al., 1994).

Some oyster reef degradation might be induced by increased suspended sediment loading, for example due to dredging activities or hurricanes (Wilber & Clarke, 2010). Therefore dredging activities should be carefully planned and monitored to avoid these effects. Not much is known about this factor in oyster reef loss in Galveston Bay. Hurricane Ike destroyed an estimated area of 55-60 % of productive oyster reefs by covering it by sediment and debris (Haby et al., 2009). This loss is estimated at 6,000-8,000 acres [24-32 km^2] (Hons & Robinson, 2010; Robinson, 2013). To restore this oyster habitat to pre-Ike conditions is estimated at $300 million (Robinson, 2013).

Original oyster surveys started around 1850. Three extensive studies have been conducted, by Turney (1958), by Benefield and Hofstetter (1976) and by E. Powell et al. (1994), of which measurements were conducted in 1991. Since 1991 no oyster survey study has been performed. A overview with oyster reef maps from the 50's and the 90's can be seen in Figure A.12. Large differences can be seen in the acreage ares of oyster reefs. One reason is that oyster reefs changed significantly during the period in which shell dredging was permitted. The area where Redfish Bar once was located can be observed in both surveys, but the abundance of reefs has been shifted from west to east of HSC (Lester & Gonzalez, 2011). E. Powell et al. (1994) recorded a much larger area of oyster reefs. Two main reasons can be discussed. Technology was improved, therefore more positive classifications were found especially in deeper water and some oyster reefs have been extended or improved in the 40 years since surveys were conducted by Turney in 1958 (Lester & Gonzalez, 2011).

Summary All in all Galveston Bay has lost over 5,000 acres [20 km^2], which equals around 16%, of its historical oyster reefs (NFWF, 2013). Today around 22,760 acres [92 km^2] of public reef and 2,321 acres [9.4 km^2] of private reef are present in Galveston Bay (Robinson, 2014).

RESTORATION OF HABITAT

BENEFICIAL USE OF DREDGED MATERIAL

Material which is being dredged from the HSC is used in so-called beneficial use projects. An example of such a project is the Houston-Galveston Navigation Channels (HGNC) project, authorized by Congress in 1996 (Aspelin & Krueger, 2007; USACE, 2013b). It is a large beneficial use project and can be considered as the start of this beneficial use of dredged material. The goal was to use dredged material from HSC, which was dredged deeper and wider, for beneficial use to solve placement area capacity problems. Until that time dredged material was simply placed next to the channel, on the open bay bottom. That was not going to be accepted anymore, because of environmental concerns for Galveston Bay. Beneficial use is strongly correlated with wetland restoration projects.

The Galveston District of USACE stated that in recent years about 20% of dredged material is used in beneficial sites (Campbell, 2013). A map of a 50-year plan from 1996, which is still in use, can be seen in Figure A.13.

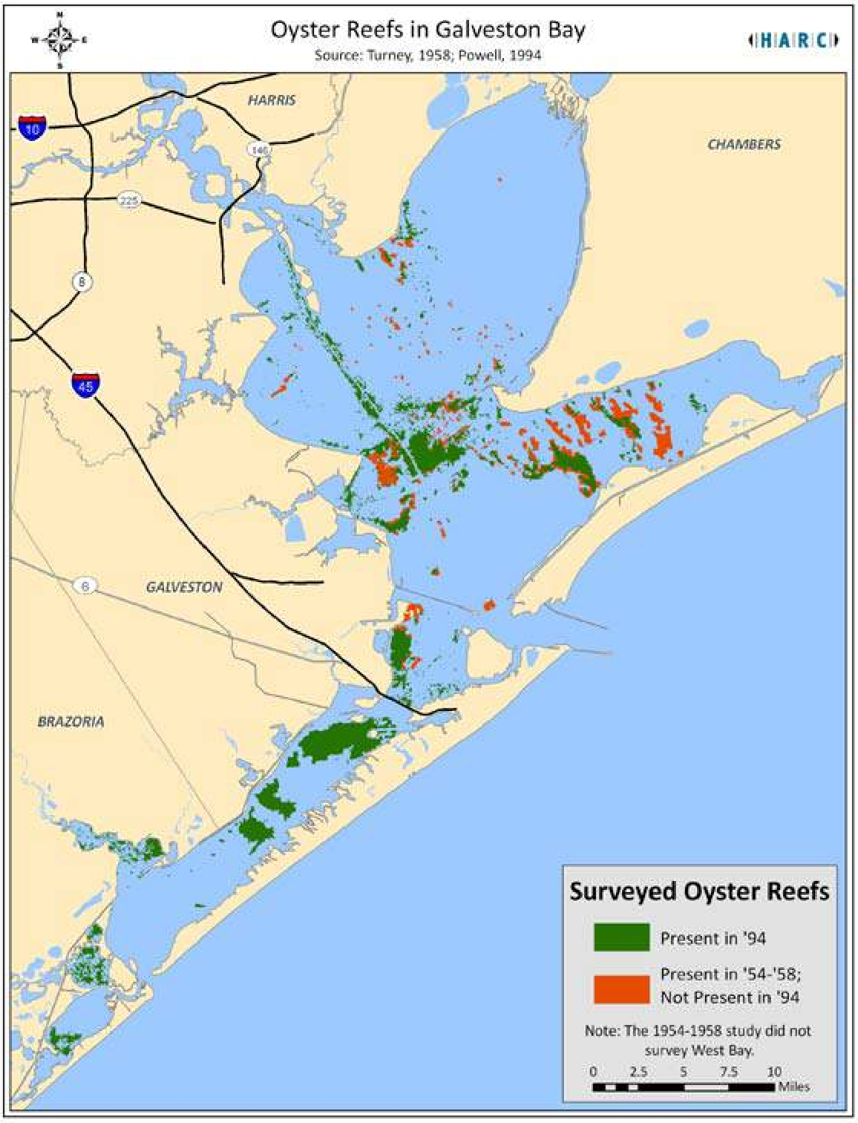


Figure A.12: Oyster reef location changes in Galveston Bay, 1954 to 1992. Data source: Turney (1958), Rehkemper (1969) and E. Powell et al. (1994) (Galveston Bay Status and Trends, 2014)

The different beneficial sites for dredged material and wetland restoration from 1996 can be seen.

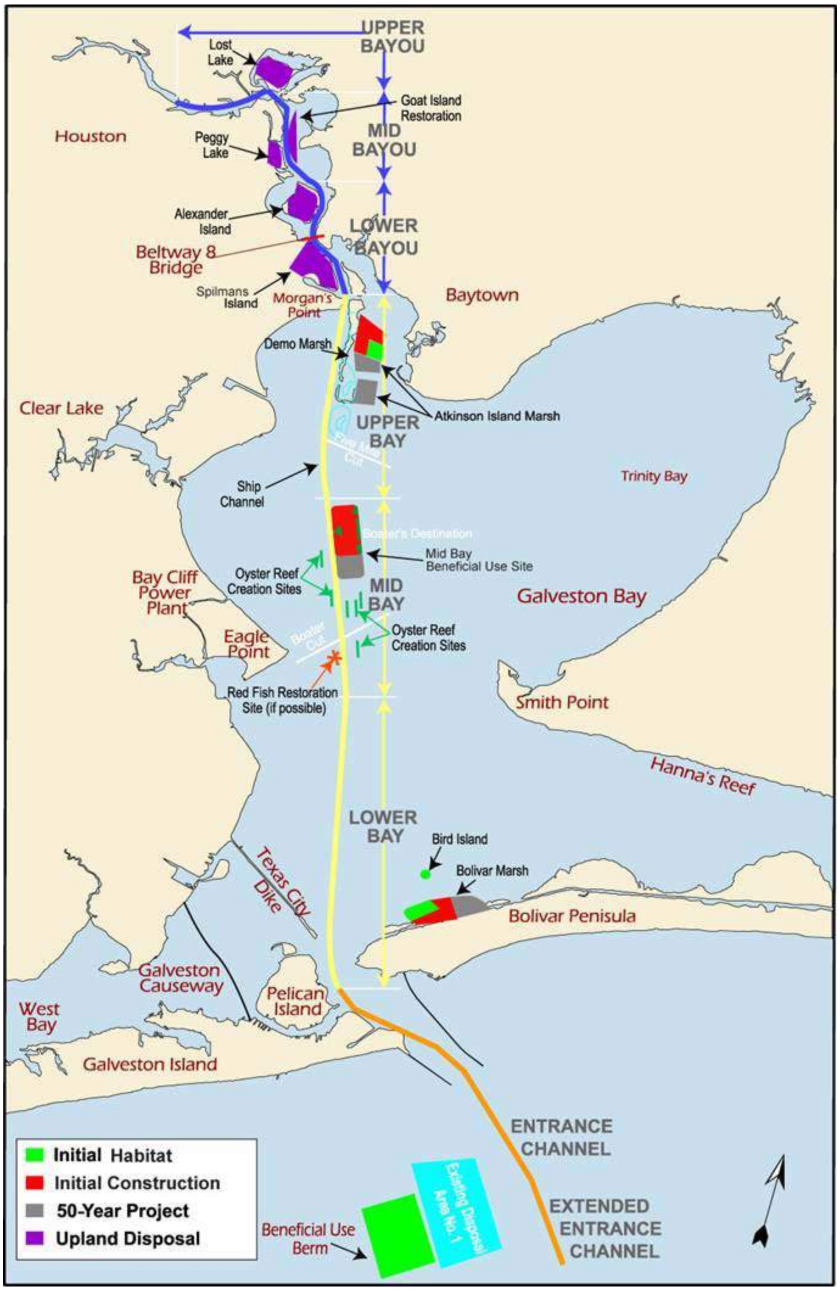


Figure A.13: 50-year plan for beneficial use of dredged material from Houston Shipping Channel, 1996 (Aspelin & Krueger, 2007)

WETLAND RESTORATION

Wetland restoration is strongly correlated to the use of dredged material by the USACE and PAH. The goal of restoring 8,600 acres has not been reached yet, but efforts will continue. Restoration efforts occur on different scales, from a fraction of an acre to hundreds of acres. The most significant sites were on submerged land belonging to the State or dredge disposal sites of the USACE or PAH (Lester & Gonzalez, 2011).

A.2. SAFFIR-SIMPSON HURRICANE WIND SCALE

The table of the Saffir-Simpson Hurricane Wind Scale can be seen in ??, which is reprinted from de Vries (2014). The scale is usually based on 1-minute averaged surface wind speeds Schott et al. (2012), but supplemented with the 10-minute wind speed according to Stewart (2008).

Cat.	Maximum 1-min wind speed	Maximum 10-min wind speed	Types of damage due to hurricane winds
1	74-95 mph 64-82 kt 119-153 km/h 33-42 m/s	66-85 mph 57-74 kt 106-137 km/h 30-38 m/s	Very dangerous winds will produce some damage: Well-constructed frame homes could have damage to roof, shingles, vinyl siding and gutters. Large branches of trees will snap and shallowly rooted trees may be toppled. Extensive damage to power lines and poles likely will result in power outages that could last a few to several days.
2	96-110 mph 83-95 kt 154-177 km/h 43-49 m/s	86-98 mph 75-85 kt 138-158 km/h 38-44 m/s	Extremely dangerous winds will cause extensive damage: Well-constructed frame homes could sustain major roof and siding damage. Many shallowly rooted trees will be snapped or uprooted and block numerous roads. Near-total power loss is expected with outages that could last from several days to weeks.
3	111-129 mph 96-112 kt 178-208 km/h 50-58 m/s	99-115 mph 86-100 kt 159-185 km/h 44-51 m/s	Devastating damage will occur: Well-built framed homes may incur major damage or removal of roof decking and gable ends. Many trees will be snapped or uprooted, blocking numerous roads. Electricity and water will be unavailable for several days to weeks after the storm passes.
4	130-156 mph 113-136 kt 209-251 km/h 58-69 m/s	116-137 mph 101-119 kt 186-220 km/h 52-61 m/s	Catastrophic damage will occur: Well-built framed homes can sustain severe damage with loss of most of the roof structure and/or some exterior walls. Most trees will be snapped or uprooted and power poles downed. Fallen trees and power poles will isolate residential areas. Power outages will last weeks to possibly months. Most of the area will be uninhabitable for weeks or months.
5	>157 mph >137 kt >252 km/h >70 m/s	>138 mph >120 kt >221 km/h >62 m/s	Catastrophic damage will occur: A high percentage of framed homes will be destroyed, with total roof failure and wall collapse. Fallen trees and power poles will isolate residential areas. Power outages will last for weeks to possibly months. Most of the area will be uninhabitable for weeks or months.

Table A.4: Saffir-Simpson Hurricane Wind Scale. Based on Schott et al. (2012) and Stewart (2008). Reprinted from de Vries (2014)

A.3. SYSTEM BEHAVIOR UNDER HURRICANE FORCING

Historic events and simulations show that the northern Bay area and the HSC may be subject to even higher surges than Galveston Island and Bolivar Peninsula, especially when landfall location is to the West of Galveston (Sebastian et al., 2014). SLOSH and ADCIRC simulations indicate that storm surge of over 11 meter should be possible in the northern Bay area (Blackburn et al., 2014; Jonkman et al., 2013).

A.3.1. THESIS STOETEN

For his MSc thesis Stoeten (2013) created a 1D model to calculate surge levels and associated return periods inside Galveston Bay along 2 transects based on a probabilistic hurricane model. Subsequently he investigated the most optimal risk reduction measure for Galveston Bay. The objective was to i) gain insight in the behavior of Galveston Bay under hurricane conditions, ii) obtain an order-of-magnitude estimate of return periods of surge at the open coast and within the bay and iii) derive the optimal risk reduction strategy for Galveston Bay.

Outcomes are that especially West Bay (Seabrook and Kemah) and the Bay-side of Galveston are highly vulnerable because of local geography and low elevation. Table A.5 shows estimated surges levels for Galveston Bay, with and without Ike Dike. The estimated surge levels without coastal spine are comparable to results from other simulations by Sebastian et al. (2014). Table A.6 shows estimated protection levels for Galveston Bay.

Table A.5: Simulated surge heights for the 1/100, 1/1,000 and 1/10,000 year^{-1} (Stoeten, 2013)

1/100 yr^{-1} water level elevation.

ID	Simulation	Open Coast	North	South	West	East
S1	1. Baseline	3.9 m	4.2 m	2.9 m	3.6 m	3.4 m
S2	2. Coastal Spine	3.9 m	1.8 m	1.1 m	1.4 m	1.0 m

1/1,000 yr^{-1} water level elevation.

ID	Simulation	Open Coast	North	South	West	East
S1	1. Baseline	4.9 m	5.5 m	3.8 m	4.7 m	4.5 m
S2	2. Coastal Spine	4.9 m	2.8 m	1.8 m	2.2 m	1.8 m

1/10,000 yr^{-1} water level elevation.

ID	Simulation	Open Coast	North	South	West	East
S1	1. Baseline	5.4 m	6.4 m	4.4 m	5.7 m	5.3 m
S3	2. Coastal Spine	5.4 m	3.5 m	2.3 m	3.0 m	2.5 m

Table A.6: Estimated level of protection, based on simulations (Stoeten, 2013)

Location	Inundation when: (estimated)	Estimated Safety level
Galveston (bay-side)	WL > 1 meter MSL	25 - 50 yr^{-1}
Galveston (ocean-side)	WL > 4.5 meter MSL	100 yr^{-1}
Texas City	WL > 5 meter MSL	100 yr^{-1}
Houston Ship Channel	WL > 4 meter MSL	100 yr^{-1} - 500 yr^{-1}
Kemah (west bay)	WL > 2 meter MSL	25 - 50 yr^{-1}

Table A.5 and Table A.6 are combined with the elevation of Galveston Bay resulting in Figure A.14, a map of estimated inundations for different scenarios created using ArcGIS software. It can be concluded that a 100 year event will flood most of Galveston Island and all of Bolivar Peninsula and some areas along the west end. The 1,000 year event will flood Texas City and some parts along HSC. The 10,000 year event will flood significant areas along HSC, which would probably result in large economic damage. Least protected are Kemah and the bay-side of Galveston. Stoeten (2013) also calculated safety levels of Galveston Bay, based on his probabilistic simulations. These levels, based on surge levels only, are ranging from 25-50 year^{-1} for Kemah and Galveston (Bay-side) to 100^{-1} for Texas City and Galveston (Ocean-side) and 100-500 year^{-1} for the Houston Shipping Channel (Stoeten, 2013). This analysis does not include waves, which means that safety levels in reality might even be lower.

Stoeten (2013) proved that Galveston Bay is highly vulnerable to flooding. The 1/100 year^{-1} inundation pattern suggests most industrial areas are protected, while residential areas are exposed. Analyzing the 1/1,000 year^{-1} inundation pattern, industrial exposure significantly outweighs the residential exposure. Preliminary results show that the Ike Dike approach reduces storm surge within the bay. Documentation and understanding on bay behavior under hurricane conditions is not as good as under normal conditions. One of the reasons is that measurement equipment often breaks down during hurricane conditions. Stoeten (2013) stated that his model should be validated with observations or a model of Galveston Bay to be fully confident about its performance.

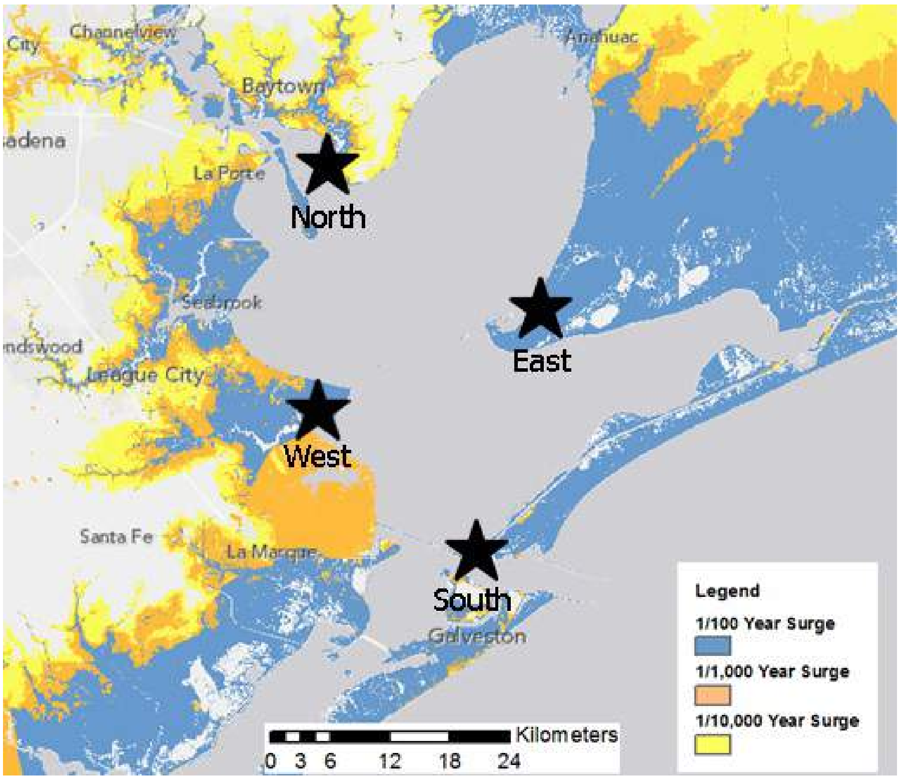


Figure A.14: Estimated inundation patterns for different return periods, estimated with a 1D hurricane and flow model for semi-enclosed basins (Stoeten, 2013)

A.4. OPPORTUNITIES FOR FLOOD PROTECTION IN GALVESTON BAY

Design strategies to counter flood disaster can be dealt with in several ways. When reducing the probability of occurrence of a flood for example, one could think of reducing the source of the hazard, the exposure or the vulnerability. Reducing the source of the hazard is not possible for the case of a hurricane flood, as one cannot prevent a hurricane from occurring. Reducing exposure is related to limiting interface between hazard source and impacted shore (people and property) and reducing vulnerability is aiming to increase resiliency of impacted people and property, therefore enabling them to withstand the hazard with success. This research focuses on the first layer of defense, namely the prevention or reduction of flood risk by reducing probability. Within this probability reduction focus lies on reducing probability of exposure (not of the hazard itself or vulnerability of society).

A momentum increase for large-scale flood protection can be observed in Galveston Bay, due to vulnerability, lack of protection and high value at risk (economy, people). In general, flood risk reduction interventions cannot remove risk at all, but will reduce it to an acceptable level of residual risk (M. D. Spalding et al., 2014), which is explained by Figure A.15.

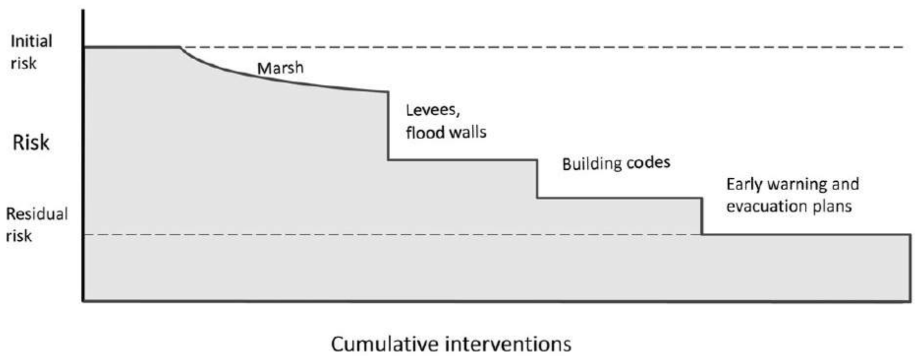


Figure A.15: Risk reduction measures (M. D. Spalding et al., 2014)

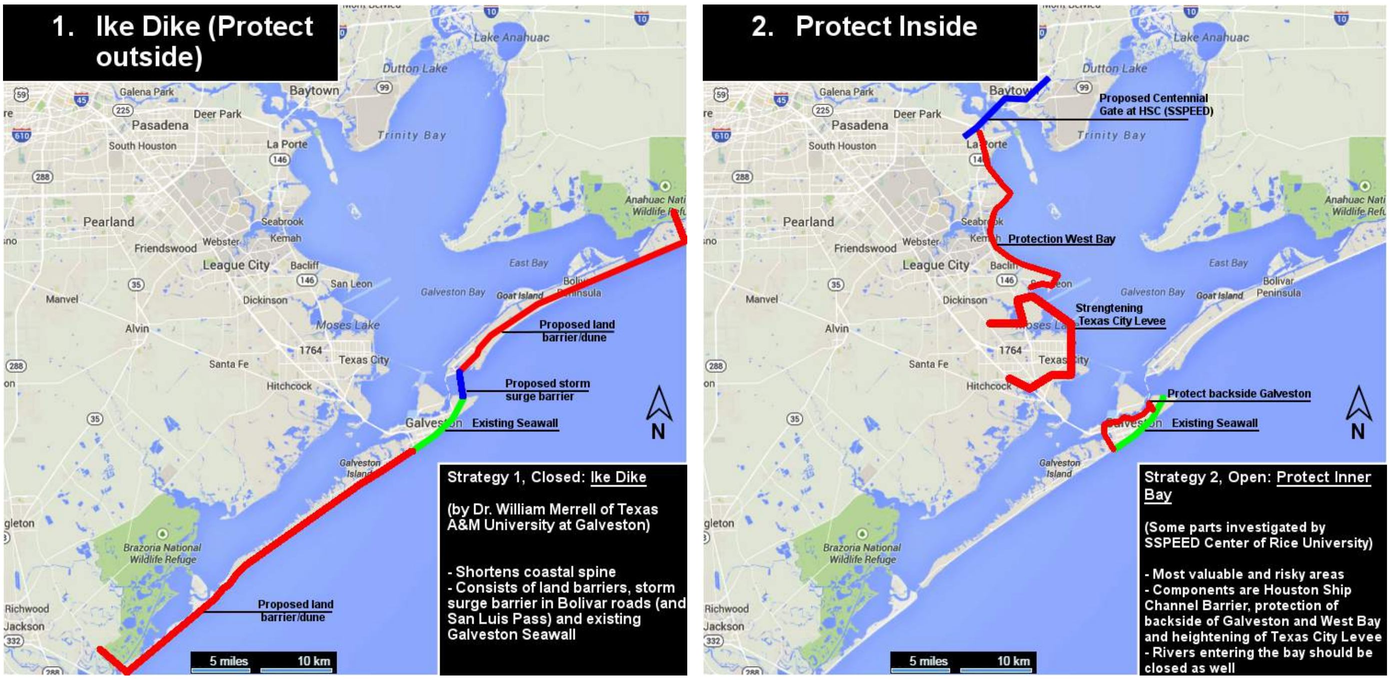
The natural system of Galveston Bay is already under pressure and it is unknown if proposed plans like the Ike Dike will have an increased impact or not, making Galveston Bay particularly interesting for sustainable or nature-based measures. According to the National Research Council (2014), "restoration of ecosystem features provide substantial ecological benefits and some level of risk reduction". Coupling nature-based with hard structures provides an effective strategy if space allows, because many cities lack the space for pure nature-based risk reduction (National Research Council, 2014). M. D. Spalding et al. (2014) and M. Spalding et al. (2014) state that ecosystems typically need to be implemented alongside a suite of other measures, like engineered, social, cultural and legal measures to form a cumulative intervention (Figure A.15).

A.5. STUDIES AND PLANS FOR GALVESTON BAY

The damage caused by Ike brought the topic flood protection to the attention of local people and parties.

These are two of the proposed strategies (Figure A.16):

1. A large-scale coastal spine approach, the Ike Dike, has been proposed and some aspects of its design and effect has been investigated. The Ike Dike is a concept which focuses on stopping the surge at the coast with a system of barriers on Galveston Island and Bolivar Peninsula and a barrier in Bolivar Roads Inlet
2. Localized approach one large-scale and several smaller-scale measures has been proposed. The large-scale component is the Centennial Gate at HSC. If one also wants to protect all assets along the Galveston Bay e.g. dike heightening along the entire Bay will be necessary.



(a) Strategy 1: closed

(b) Strategy 2: open

Figure A.16: Two distinctive strategies for flood risk reduction of Galveston Bay. Maps: Google (2014)

Combinations of both strategies can be considered as well, for example nature-based solutions could be combined with a conventional structure like the Ike Dike. As of early 2015 researchers of both strategies made an alliance to combine their plans to form an integral plan to protect the region (Figure 2.21).

A.5.1. STUDENT THESES

Multiple theses arose from the Ike Dike plan (1) and Centennial Gate (2), conducted by students from both TAMUG and Delft University of Technology (henceforth TU Delft). The most important studies prior to this thesis will be discussed:

- For his MSc thesis at the TU Delft, de Vries (2014) conducted a design study for the storm surge barrier of the environmental section in the Bolivar Roads inlet.
- Two Capstone projects of TAMUG (Cox, Davis, Hennigan, & Robichaux, 2013; Z. Davis, Flores, Szempruch, & Thomas, 2010) investigated the design of the storm surge barrier in Bolivar Roads as well.
- Janssen et al. (2014) looked at the design of the Bolivar Peninsula barrier as part of their MSc multidisciplinary project at the TU Delft.
- For his MSc thesis at TU Delft, Ruijs (2011) researched the impact of a partial closure of the inlet on Galveston Bay's hydrodynamics, morphology and water quality by means of a 2D hydrodynamic model.
- Like Ruijs (2011), Stoeten (2013) focused on the effect of the Ike Dike for the behavior of the system in normal and hurricane conditions, instead of the design of the barrier itself, for his MSc thesis at the TU Delft.
- A finished MSc thesis by Jor Smulders of the TU Delft assessed the dynamic behavior of the Bolivar Roads navigational barrier.
- For his MSc thesis, Martijn Schlepers (2015) of TU Delft conducted a design study for the Centennial Gate (storm surge barrier) near at the HSC in the North.

THESIS RUIJS

Ruijs (2011) investigated the effect of a storm surge barrier in Bolivar Roads on the daily conditions of Galveston Bay. He found that a reduction of 40% of the flow area results in a 9% decrease in tidal amplitude and discharge. This subsequently would not impede navigation (due to increased current velocities) in daily conditions. Furthermore Ruijs (2011) expects the tidal prism to decrease as a result of the inlet restriction. This could cause a two-fold increased erosion of the shorelines of the Bay. On the one hand, due to the fact that current velocities in the Bay will decrease the tidal channels will be filled to restore equilibrium. Because of the blockage of Bolivar Roads sediment to fill the channels will originate from the Bay itself, shorelines and wetlands. Thirdly, the reduction in prism and thus tidal range could result in a decrease of inter-tidal area altogether.

Sediment deficit is expected to increase due to blockage in Bolivar Roads and reduced tidal prism, residence time is expected to increase and salinity is expected to decrease significantly. Not known is how the Ike Dike affects the system hydrodynamics and water quality under hurricane conditions. See Table A.7 for the outcomes of Ruijs (2011) as well as an estimation of the tidal response due to a partial closure of Bolivar Roads inlet made by Jonkman et al. (2013).

Table A.7: Tidal response to partial closure. Based on Ruijs (2011). (Jonkman et al., 2013)

Situation	**Cross-section (μA_s^*)**	**Tidal response in Galveston Bay**
Current	28,000 m^2 *Bolivar Roads: 22, 000 m^2* *Other: 6, 000 m^2*	90% of incoming tide (estimate)
40% closed	16, 000 m^2 *Bolivar Roads: 13, 000 m^2* *Other: 3,000 m^2*	(Ruijs: 80% of original) 72% of incoming tide
60% closed	12,000 m^2 *Bolivar Roads: 9, 000 m^2* *Other: 3, 000 m^2*	(Ruijs: 61% of original) 55% of incoming tide

* actually cross-section multiplied by flow coefficient

The assumption Jonkman et al. (2013) made to create this table was the following: friction and inertia in Galveston Bay itself are neglected (small-basin approximation), meaning the water levels inside Galveston Bay are equal at every moment in time. This approximation leads to the 'rigid-column approach' or 'pumping mode'.

The way the system behaves in a daily context is an important parameter, especially for large infrastructural plans like the Ike Dike or a nature-based measures inside Galveston Bay. A possible barrier or any other solution has to allow sufficient tidal exchange to preserve the ecosystems present in Galveston Bay (Jonkman et al., 2013).

A.5.2. LSCNRA

The Lone Star Coastal National Recreation Area (henceforth LSCNRA) is a plan initiated by the SSPEED Center. The goal of this plan is to recognize the Upper Gulf Coast as a designated as National Recreation Area. This means the area will be a preserved ecosystem and will be protected (SSPEED, 2011). The economic driver is enhance recreation (such as bird watching) and natural resource value trading (Jim Blackburn, Personal Communication, December 2014). Another benefit, according to SSPEED (2011), would be to serve inland communities as a buffer against flooding and function as part of a larger coastal protection system. It is unlikely that is will act as a storm surge buffer, especially because the parks are in areas more west and east of Galveston Bay and wouldn't protect Galveston Bay. But the project will probably create awareness about nature and flood risks and will probably have economic benefits. According to The Harbinger Consulting Group (2011) the estimated economic impact of the National Recreation Area by the tenth year of operation could be as much as $192 million in local sales, $69 million in personal income and support over 5,000 jobs. By that time it could attract 1.5 million people annually as well (The Harbinger Consulting Group, 2011).

According to Antonia Sebastian (Personal Communication, September 2014) the LSCNRA was probably going to be accepted by Congress in Spring 2015.

B

Hydraulics

B.1. Shallow Water Equations

If one applies the assumptions stated in the report, the flow in the system can be described using the simplified 1D shallow water equations (SWE). The SWE are equal to the depth averaged Navier-Stokes equations to describe fluid motion. Long waves in shallow water can be described with these equations, no vertical motion occurs in these conditions. Reference is made to Appendix B.1 for the full shallow water equations.

The 1D momentum equation (conservation of momentum) in x-direction (normal to shore), as derived by e.g. Dean and Dalrymple (1991) and reprinted from Stoeten (2013), is:

$$\frac{\delta q_x}{\delta t} = -\frac{h}{\rho}\frac{\delta p_\eta}{\delta x} - h \cdot g \cdot \frac{\delta \eta}{\delta x} + \frac{\tau_w - \tau_b}{\rho} \tag{B.1}$$

Where q_x is the flow rate or depth integrated discharge per unit width in [m^{2}s^{-1}], h is the water depth with surge in [m], ρ is the density of water [kgm^3], p_η is the barometric pressure in [hPa], g is the gravitational acceleration [ms^{-2}], τ_b [Pa] is the bottom shear stress and τ_w is the wind shear stress. Advection is already neglected in this formulation and friction is accounted for by wind shear and bottom shear stress.

This momentum transfer holds if there is motion of the fluid, thus momentum transfer.

The continuity equation (conservation of mass) reads, e.g. Battjes (2000) and Zijlema (2012):

$$\frac{\delta \eta}{\delta t} + \frac{\delta uh}{\delta x} = 0 \tag{B.2}$$

With η is the surge in [m] and uh equals the depth integrated flow rate q_x in [m^{2}s^{-1}].

Several simplifications of the SWE are possible for different situations of long waves in which assumptions can be made or extra terms can be neglected.

B.2. Wind Waves

B.2.1. Wind Generation (Sverdrup-Munk-Bretschneider)

Assumed is that wave growth starts with a undisturbed sea surface. Figure 3.11 shows that the relative importance of wind generation in both oceanic and coastal waters is significant. A similar approach as described here, has been followed by Aarnink, de Boer, Evers, Kruis, and der Valk (2013).

Short waves are generated by wind. The wind adds horizontal momentum in vertical direction to the water across the ocean-atmosphere surface (Holthuijsen, 2007). A purely idealized situation considers deep water, constant and infinite wind and straight infinitely coastline (see **??**). At short fetches waves grow rapidly, this is called *young sea state*. As fetch grows, the growth slows down and wave speed of the longest waves approach wind speed. At a certain moment, a phenomenon called *fully developed sea state* can be observed

(Holthuijsen, 2007). A formulation for depth-limited case for coastal waters like Galveston Bay is presented. One-dimensional linear concepts were used for this formulation.

In this section it is assumed that the coastline is infinitely long. For the duration it is assumed that 2 hours is sufficient to achieve a maximum wave height. The depth is not taken infinitely because of the average depth of Galveston Bay is 3 m (Holthuijsen, 2007). This means that the wave height is dependent on sustained wind speed)which is usually measured at 10 meters above the water surface), water depth and fetch length. This is shown by the Sverdrup-Munk-Bretschneider method for all sea states (Holthuijsen, 2007) (see Equation (B.3) and Equation (B.4)):

$$\tilde{H} = \tilde{H}_\infty \tanh\left(k_3 \tilde{d}^{m_3}\right) \tanh\left(\frac{k_1 \tilde{F}^{m_1}}{\tanh\left(k_3 \tilde{d}^{m_3}\right)}\right) \tag{B.3}$$

$$\tilde{T} = \tilde{T}_\infty \tanh\left(k_4 \tilde{d}^{m_4}\right) \tanh\left(\frac{k_2 \tilde{F}^{m_2}}{\tanh\left(k_4 \tilde{d}^{m_4}\right)}\right) \tag{B.4}$$

where $\tilde{H}$ is the dimensionless wave height, $\tilde{T}$ is the dimensionless wave period, $\tilde{d}$ is the dimensionless water depth, $\tilde{F}$ is the dimensionless fetch length, $\tilde{H}_\infty$ and $\tilde{T}_\infty$ are the limit values for deep water and k_1, k_2, k_3, k_4, m_1, m_2, m_3 and m_4 are calibration parameters that have to be determined from observations.

The formulas for the dimensionless parameters are given by Equation (B.5), Equation (B.6), Equation (B.7) and Equation (B.8) (from e.g. Holthuijsen (2007)):

$$\tilde{H} = \frac{gH}{U_{10}^2} \tag{B.5}$$

$$\tilde{T} = \frac{gT}{U_{10}} \tag{B.6}$$

$$\tilde{d} = \frac{gd}{U_{10}^2} \tag{B.7}$$

$$\tilde{F} = \frac{gF}{U_{10}^2} \tag{B.8}$$

Young and Verhagen (1996) added two extra parameters, p and q, to control the transition from a young sea state to a fully developed sea state better (**?**). These coefficients are determined by Breugem and Holthuijsen (2006). This gives the following result:

$$\tilde{H} = \tilde{H}_\infty \left[\tanh\left(k_3 \tilde{d}^{m_3}\right) \tanh\left(\frac{k_1 \tilde{F}^{m_1}}{\tanh\left(k_3 \tilde{d}^{m_3}\right)}\right)\right]^p \tag{B.9}$$

$$\tilde{T} = \tilde{T}_\infty \left[\tanh\left(k_4 \tilde{d}^{m_4}\right) \tanh\left(\frac{k_2 \tilde{F}^{m_2}}{\tanh\left(k_4 \tilde{d}^{m_4}\right)}\right)\right]^q \tag{B.10}$$

Table B.1 shows the values of the coefficients found by Young and Verhagen (1996), and modified by Breugem and Holthuijsen (2006) for all sea states and all water depths. With Equation (B.9) and Equation (B.10) and Table B.1 the wave height can be calculated for different fetch lengths.

To determine the significant wave height and wave period, respectively H and T, Equation (B.9) and Equation (B.10) have to be rewritten to Equation (3.3) and Equation (3.4).

According to Holthuijsen (2007), the different formulations for deep and shallow water show that the most important parameter is the ratio of wind speed over the phase speed of the wave. It must be noted that the *fully developed sea state* will be almost unrealistic because very long fetches would be needed to reach it (Holthuijsen, 2007). And these formulations are valid for idealized conditions.

Coefficients	
k_1	4.14×10^{-4}
k_2	2.77×10^{-7}
k_3	0.343
k_4	0.10
m_1	0.79
m_2	1.45
m_3	1.14
m_4	2.01
p	0.572
q	0.187
$\tilde{H}_\infty$	0.24
$\tilde{T}_\infty$	7.69

Table B.1: Coefficients to represent idealized wind-wave growth in depth-limited water (Holthuijsen, 2007)

B.2.2. Wave Propagation

When a wave propagates towards shallower water with a gentle sloping bottom, its wave length will decrease. The phase speed of the wave will correspondingly decrease:

$$c = \sqrt{\frac{g}{k} tanh(kd)} \tag{B.11}$$

Where k is the wave number, which is characterized as $2 \cdot \pi / L$ and L is the harmonic wave length.

The wave experiences depth-induced phenomena shoaling, and refraction and diffraction and possibly reflection when propagating through the Bay (Figure 3.11). The processes shoaling and refraction are caused by horizontal variations in water depth. Shoaling generally increases the wave amplitude as the waves propagate towards shallower water, and is caused by conservation of energy decreasing wave celerity (Holthuijsen, 2007). Diffraction is caused by a change in amplitude of the wave, particularly occurring in the shadow line of obstacles like islands (Holthuijsen, 2007). Diffraction and reflection are most important in harbors.

Waves in coastal waters are much more challenging to model or describe than in e.g. oceanic waters, because the propagation is much more complex and the processes of generation, dissipation and non-linear interactions are increased in number and complexity (Holthuijsen, 2007). This means the linear wave theory is limiting the correctness of the solution. Furthermore the processes of (surf) breaking and bottom friction are added to the system.

B.3. Wind Drag Coefficient

The wind drag coefficient C_D is the representation of the friction of the water surface. Its value is higher for higher wind speeds, because the water surface is considered to be more rough due to waves. The coefficient is usually empirically determined, a commonly used expression is the relation by Wu (1980) (see e.g. Holthuijsen (2007)):

$$C_D = \begin{cases} 1.2875 \times 10^{-3} & for \quad U_{10} < 7.5 m/s \\ (0.8 + 0.065 \cdot U_{10}) \times 10^{-3} & for \quad U_{10} \geq 7.5 m/s \end{cases} \tag{B.12}$$

A similar expression is the formulation of Amorocho and DeVries (1980), which is an adapted version of the formulations of Wu (1980). It introduces an upper limit of the wind drag for higher wind speeds due to a smooth layer of foam:

$$C_D = \begin{cases} (0.8 + 0.065 \cdot U_{10}) \times 10^{-3} & for \quad U_{10} < 26.8 m/s \\ 2.54 \times 10^{-3} & for \quad U_{10} \geq 26.8 m/s \end{cases} \tag{B.13}$$

According to Delft University of Technology (2015), recent developments have shown that for very high wind speeds of $> 20 m/s$ the wind drag is overestimated by these empirical formulations Equation (B.12), even with the formulation of Amorocho and DeVries (1980). This is certainly the case for hurricane wind speeds, which are $40 m/s$ or higher. "It appears that the drag coefficient increases almost linearly with wind speed up to approximately $20m/s$, then levels off and decreases again from $35m/s$ to rather low values at $60m/s$ wind speed" (Delft University of Technology, 2015). A fit of the wind drag by some authoritative studies is defined as:

$$C_D = (0.55 + 2.97 \cdot \tilde{U} - 1.49 \cdot \tilde{U}^2) \times 10^{-3} \tag{B.14}$$

With $\tilde{U} = U_{10}/U_{ref}$ and $U_{ref} = 31.5m/s$, which is the velocity at which the drag is maximum according to Delft University of Technology (2015). Drag values following from this new expression are 10-30 % lower for high wind velocities and 30% lower for hurricane wind velocities (Delft University of Technology, 2015). This formulation (Equation (B.14)) is used in the latest SWAN version.

The wind shear stress can also be reduced by emerged vegetation which has an effect on the wind velocities at the surface. According to Reid and Whitaker (1976) the wind shear stress can be altered by a sheltering coefficient S, which is then added to the equation of the win shear stress Equation (3.2) (Loder, 2008).

B.4. BOTTOMS SHEAR STRESS

The bottom shear stress affects both the momentum and energy transfer. Therefore, it is a term in the momentum balance. It is essentially a transfer of energy and momentum from the orbital movement of water particles to turbulent movement in the boundary layer (Holthuijsen, 2007). It depends on both flow velocity (or wave characteristics) and bottom roughness, according to the *Manning* formulation for uniform flow (Stoeten, 2013). This formulation uses a quadratic flow velocity and is most widely used for approximation of vegetated flow (Loder, 2008). Holthuijsen (2007) mentions an empirical relation of Collins (1972) for determining bottom shear stress for waves, with a quadratic term for bottom velocity.

B.4.1. ROUGHNESS

The bottom roughness is usually represented by a Manning, Chezy or Nikuradse value. Bottom characteristics might be affected by waves or flow (Holthuijsen, 2007). For example a sandy bottom may develop ripples.

Different types of bottoms have different roughness. A bottom with vegetation as present in nearshore areas in Galveston Bay for example would have a higher roughness value, which is represented in higher Manning values as well. A table with standard Manning values for different types of beds and can be found in Table B.2. This is GAP data for Louisiana from USGS and provides a lot of detail in different wetland variations. Common types for Galveston Bay wetlands are fresh, intermediate, brackish and saline marsh with associated Manning values of 0.055-0.035.

Manning-*n* values for LA-GAP classification.

LA-GAP class	Description	Manning *n*
1	Fresh marsh	0.055
2	Intermediate marsh	0.050
3	Brackish marsh	0.045
4	Saline marsh	0.035
5	Wetland forest—deciduous	0.140
6	Wetland forest—evergreen	0.160
7	Wetland forest—mixed	0.150
8	Upland forest—deciduous	0.160
9	Upland forest—evergreen	0.180
10	Upland forest—mixed	0.170
11	Dense pine thicket	0.180
12	Wetland scrub/shrub—deciduous	0.060
13	Wetland scrub/shrub—evergreen	0.080
14	Wetland scrub/shrub—mixed	0.070
15	Upland scrub/shrub—deciduous	0.070
16	Upland scrub/shrub—evergreen	0.090
17	Upland scrub/shrub—mixed	0.080
18	Agriculture–crops–grass	0.040
19	Vegetated urban	0.120
20	Nonvegetated urban	0.120
21	Wetland barren	0.030
22	Upland barren	0.030
23	Water	0.02–0.045

Table B.2: Manning n-values according to the GAP classification for Louisiana (Bunya et al., 2010)

C

Building with Nature Reference Projects

The following projects and/or locations have similarities with the Galveston Bay case and could therefore be interesting reference material for this study.

C.1. Marker Wadden, Lake Markermeer

The project "Marker Wadden" is a project carried out by the Dutch foundation Natuurmonumenten (Natuurmonumenten, 2014). It involves the construction of a big archipelago of islands of nature in the Lake Markermeer, a former part of the Dutch Zuiderzee. Nowadays, the lake has been cut off from the Wadden Sea and experiences extreme turbidity due to wind waves in the shallow lake (2-4 m deep) (Natuurmonumenten, 2014). Marine wildlife suffers from this high turbidity in Lake Markermeer. To tackle this problem and to enhance natural value in this lake, the plan Marker Wadden was designed.

The plan is to build an artificial island with the use of clay and silt from the Lake Markermeer, near the Houtribdijk. The island will be a swampy area with marshes, natural shores and shallow zones and strives to boost the ecology and wildlife in the area. It aims at reducing the high turbidity in the lake. Also recreation will be enhanced and watersport fans and nature enthusiasts will benefit from the project. An impression of the plan can be seen in Figure C.1.

This could be an interesting project for Galveston Bay because of the high turbidity in the lake and the abundance of fine sediment. However, for Galveston Bay it is unknown how bad ecology suffers from high turbidity.

C.2. Mud Motor, Wadden Sea

The idea of the "Mud Moter" is to improve the growth of salt marshes in the Wadden Sea near Koehool, Friesland by a mega-nourishment, like the Sand Engine along the Dutch North Sea coast (EcoShape, 2014). The concept makes use of the present tidal sediment transport capacity (EcoShape, 2014). The coastal system at the project site consists mainly of fine sediments, just like Galveston Bay. Interesting goals for this project, according to EcoShape (2014) are:

"The dumped sediment is expected to be transported by natural processes further into the area. The extra input of sediment is expected to lead to the formation and extension of salt marshes. This would yield three favorable effects:

1. Less re-circulation towards the harbor, hence less maintenance dredging
2. Promotion of the growth and stability of salt marshes, improving the Wadden Sea ecosystem
3. Stabilizing the foreshore of the dykes, and therefore less maintenance of the dyke"

An interesting comparison with Galveston Bay is the fact that this solution makes use of sediment transport capacity of the system. It introduces sediment which is required to replenish the salt marshes. This could be

Figure C.1: Artist impression of Marker Wadden in birds-eye view over the area, view from Enkhuizen in the Northwest (groot-waterland.nl)

an interesting option for Galveston Bay as well, because the Bay has experienced high erosion rates over the past decades. Sediment from dredging could be used for this purpose. However, the expectation is that extra sediment from outside of the system is necessary to make the wetlands sustainable (in other words, to keep pace with RSLR).

C.3. OYSTER REEFS, EASTERN SCHELDT

Ecoshape is carrying out a pilot of the construction of oyster reefs in the Eastern Scheldt. The purpose of these oyster reefs is to prevent erosion of the tidal flats. To accomplish this, 2D oyster reefs on the tidal flats are being constructed to prevent sediment from washing away. Oyster reefs dissipate wave energy near the bottom and retain sediment.

The oyster reefs are constructed using shallow steel nets or gabions filled with oyster shells (de Vriend & van Koningsveld, 2012; EcoShape, 2014). Live oyster larvae will attach themselves onto the shells, forming a closed reef. A picture of the reef can be seen in Figure C.2.

Figure C.2: Oyster reef in the Eastern Scheldt (dutchwatersector.com)

A different pilot of oyster reef construction consisted of a 3D reef to prevent shoaling of the tidal channels. The oyster used for this test was the Pacific Oyster. 3D reefs were created, similar to the Eastern Oyster present in Galveston Bay (de Vriend & van Koningsveld, 2012). The 3D reef structures are effective in dissipating wave energy en prevent underlying sediment from erosion (de Vriend & van Koningsveld, 2012). A 3D oyster reef would be more interesting for Galveston Bay.

C.4. WETLAND RESTORATION PROJECT JUMBILE AND CARANCAHUA COVE, GALVESTON BAY, TEXAS

This section discusses two wetland restoration projects in Galveston Bay along wave-exposed perimeters. Coalescing, sacrificial sand mounds were constructed to help increase wave-induced sediment transport into the marsh and to help protect from direct wave exposure, allowing vegetation to become densely established (McPherson et al., 2015). These soft mounds are constructed as an alternative to the conventional hard shoreline protection structures such as rock breakwaters or geotextile tubes, usually constructed along the wave-exposed perimeters of the marsh complex (McPherson et al., 2015).

The project has been a success and therefore a sand ridge or mound along the wave-exposed perimeter as alternative for a conventional hard structure should be continued to be considered in projects (McPherson et al., 2015). This is an interesting option for marsh restoration at shorelines which are highly exposed to waves.

C.5. NATURE-BASED BREAKWATER ISLANDS, FORT PIERCE MARINA, FLORIDA

A project carried out by the USACE is the construction of a breakwater to protect the Fort Pierce Marina after it was destroyed by hurricane Frances in 2004 (Czlapinski, 2013; RBD, 2014). The challenge was to protect it from a 100 year storm with a sustainable solution under difficult site and regulatory conditions (Czlapinski, 2013).

The project included mangrove enhancements, oyster recruitment, shorebird habitat, artificial reefs and seagrass habitat. In total, 15 acres of island and 21 acres of habitat were constructed (divided over 12 smaller islands and 1 bigger peninsular structure) (RBD, 2014). The construction of the peninsular island consisted of T-groins made of geotubes and armor stone. Sand dunes are in the center and oyster recruitement and mangroves at the leeward side of the structure (Czlapinski, 2013). See Figure C.3 for an impression of the project (which is not finished yet).

Figure C.3: Pierce Marina Breakwater Islands (Source of figure: Flint Industries)

C.6. MARSH TERRACING, SOUTHERN LOUISIANA

In Southern Louisiana a technique is applied to create marshes in shallow water of 1 to 2 feet deep. It converts sub-tidal non vegetated bottom into wetlands or marshes (RBD, 2014). The technique is called terracing: piles of sediment (2 feet out of the water) were constructed in v-shape to create calm conditions regardless wind conditions and capture sediment and enhance marsh growth. Smooth cordgrass was planted on top of the islands to prevent erosion. Construction was finished in 2003, total construction area is 6,000 acres. See

Figure C.4 for an impression of the terraces.

Figure C.4: Marsh terracing for marsh creation in southern Louisiana (FWS.gov)

C.7. DEADMAN'S ISLAND OYSTER BREAKWATER, GULF BREEZE, FLORIDA

Deaman's Island consists of 7 acres of oyster reefs and 8 acres of seagrass marshes. This restoration project (study site for USACE, NOAA and other parties) addressed the loss of habitat due to the impact of shore development. Salt marsh habitat acreage at this site was drastically decreased due to erosion. A new breakwater, consisting of natural resources such as oyster reefs, is proposed to reduce erosion. The new 850 feet breakwater is composed of so-called Ecodiscs, made of fossilized and recycled oyster shells, is placed in 5 feet deep water (RBD, 2014). These Ecodiscs are considered an ecological alternative to riprap armoring. The structure will also provide a marine habitat for fish and marine animals and protects existing coastal habitats.

C.8. LIVING BREAKWATERS, REBUILD BY DESIGN, STATEN, ISLAND, NEW YORK

A team of SCAPE Landscape Architecture, Parsons Brinckerhoff, Stevens Institute and more participated in the rebuild by design competition for rebuilding the New York, New Jersey region after superstorm Sandy (SCAPE Landscape Architecture PLLC, 2014). In particular the location of interest is Staten Island, New York.

Staten Island is vulnerable to erosion and wave action. The team designed a line of so-called living breakwaters to buffer against wave action and erosion. The living breakwater consists of certain elements that have complex forms to attract oysters and that could act as a habitat for (fin)fish, shellfish and lobsters. The design of the project explores a mix of sub-tidal beds and breakwaters which are emerged above the high water level (RBD, 2014). See Figure C.5 for an 3D artist impression of the living breakwater.

The interesting aspect of the project is its multifunctionality. On the one hand it is a breakwater, on the other hand it is an habitat area, with oysters, shellfish and fish. For Galveston Bay this is also an interesting option. This project is interesting for shores which are exposed to wave action and experience erosion rates, which is the case in Galveston Bay.

C.9. BLUE DUNES, REBUILD BY DESIGN, NEW YORK

A team consisting of main parties WXY, West 8 and Stevens Institute participated in the rebuild by design competition, New York (WXZ; West8; Stevens Institute, 2014). RBD (2014) states that "In searching for a regional 'soft' solution that would benefit all affected communities, the team used models, developed by the Stevens Institute of Technology, of storm surges, ocean currents, and dynamic tidal exchanges between the

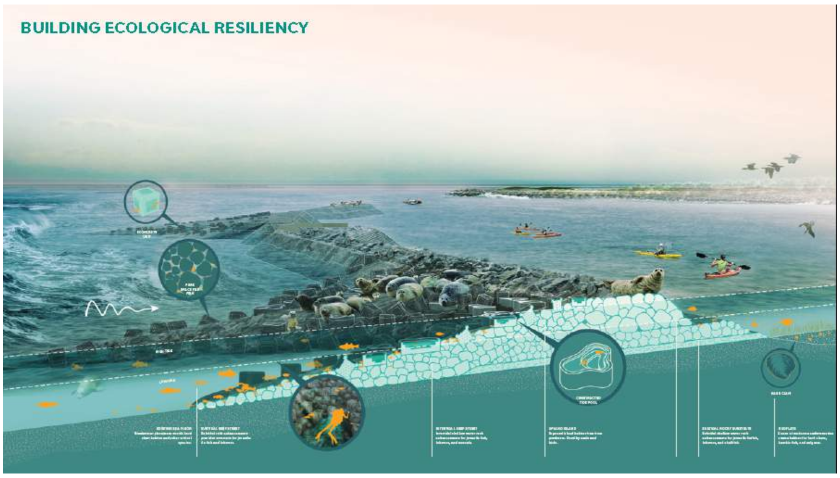


Figure C.5: Living breakwaters proposal for "Rebuild by Design competition" by SCAPE, Parsons Brinckerhoff and Stevens Institute (RBD, 2014)

Long Island Sound and the New York/New Jersey harbor estuary to evaluate the effectiveness of natural systems to reduce the height of storm surges. This could be seen as a example of BwN, as it seeks to work with processes of nature and strives for a sustainable solution(WXZ; West8; Stevens Institute, 2014).

The result is the large project "Blue Dunes", consisting of artificial barrier islands constructed 6-10 miles offshore from New York and New Jersey. This is supposed to result in the scale of annual savings for flood insurance that can expect investment nationally. See Figure C.6 for an impression of the proposal. The islands with dunes are alleged to protect the region from surges and waves which would result in added economic value for New York and New Jersey and provides additional ecological function with e.g. low energy waters for marshes on the leeward side. The dunes provide a potential coupling with offshore wind energy and recreation. This project is still a proposal and is far from being designed or constructed. The project should cost around 50 million dollar and is supposed to be in construction within 5 years (WXZ; West8; Stevens Institute, 2014).

Figure C.6: Blue Dunes proposal for "Rebuild by Design competition" by West8, WXZ and Stevens Institute (Source of figure: west8.com)

D

Conceptual Evaluation Flood Risk of Building Blocks

D.1. Quantitative 1D Evaluation of Nourishments

D.1.1. Surge

Results of wind set-up calculations will be presented in Table D.1-Table D.4. The base situation is the situation in which no test design is implemented. Results of the baseline situation and the three designs will be shown and differences with base situation are highlighted. Note that surge levels are presented with respect to MSL. This means that the depth, corresponding to a surge level of 0 m, is 3 m.

0: Baseline	**Downwind surge, transect b (Northwest) [m]**	**Downwind surge, transect c (West) [m]**
Open spine (d=6 m)	3.78	3.78
Closed spine (d=3 m)	1.54	1.54
Open spine + SLR (d=7 m)	4.69	4.69
Closed spine + SLR (d=4 m)	1.97	1.97

Table D.1: Results of 1D calculation for emerged nourishments with respect to surge: baseline situation

1: Test design 1	**Downwind surge, transect b (Northwest) [m]**	**Difference with baseline, transect b [m]**	**Downwind surge, transect c (West) [m]**	**Difference with baseline, transect c [m]**
Open spine (d=6 m)	3.37	-0.41	3.37	-0.41
Closed spine (d=3 m)	0.81	-0.73	0.81	-0.73
Open spine + SLR (d=7 m)	4.32	-0.37	4.32	-0.37
Closed spine + SLR (d=4 m)	1.51	-0.46	1.51	-0.46

Table D.2: Results of 1D calculation for emerged nourishments with respect to surge: test design 1

2: Test design 2	**Downwind surge, transect b (North-west) [m]**	**Difference with baseline, transect b [m]**	**Downwind surge, transect c (West) [m]**	**Difference with baseline, transect c [m]**
Open spine (d=6 m)	3.53	-0.25	3.78	0
Closed spine (d=3 m)	1.08	-0.46	1.54	0
Open spine + SLR (d=7 m)	4.47	-0.22	4.69	0
Closed spine + SLR (d=4 m)	1.71	-0.26	1.97	0

Table D.3: Results of 1D calculation for emerged nourishments with respect to surge: test design 2

3: Test design 3	**Downwind surge, transect b (North-west) [m]**	**Difference with baseline, transect b [m]**	**Downwind surge, transect c (West) [m]**	**Difference with baseline, transect c [m]**
Open spine (d=6 m)	3.28	-0.60	3.28	-0.60
Closed spine (d=3 m)	0.62	-0.92	0.62	-0.92
Open spine + SLR (d=7 m)	4.24	-0.45	4.24	-0.45
Closed spine + SLR (d=4 m)	1.39	-0.58	1.39	-0.58

Table D.4: Results of 1D calculation for emerged nourishments with respect to surge: test design 3

D.1.2. WAVES

Results of wave growth calculations will be represented in Table D.5-Table D.8. Results of the baseline situation and the three designs (wave heights and periods all the way downwind of the transect, thus in the West or Northwest) will be presented and reductions with respect to the base situation are highlighted. Note that wave heights are given with respect to the water surface, thus including surge levels. Because for baseline, test design 1 and 3 the transects are exactly the same is for those test designs only one of those transects shown. For test design 2 only transect b is shown, because transect c is not affected in this test design.

0: Baseline	**Wave height, transect b, c (Northwest, West) [m]**	**Wave period, transect b, c (Northwest, West) [s]**
Open spine (d=6 m)	2.46	5.89
Closed spine (d=3 m)	1.57	4.54
Open spine + SLR (d=7 m)	2.71	6.24
Closed spine + SLR (d=4 m)	1.89	5.06

Table D.5: Results of 1D calculation for emerged nourishments with respect to waves: baseline situation

1: Test design 1	**Wave height, transect b, c (Northwest, West) [m]**	**Difference with baseline, transect b, c [m]**	**Wave period, transect b, c (Northwest, West) [s]**	**Difference with baseline, transect b, c [s]**
Open spine (d=6 m)	2.28	-0.18	5.48	-0.41
Closed spine (d=3 m)	1.56	-0.00	4.54	-0.00
Open spine + SLR (d=7 m)	2.42	-0.29	5.57	-0.67
Closed spine + SLR (d=4 m)	1.86	-0.03	5.01	-0.04

Table D.6: Results of 1D calculation for emerged nourishments with respect to waves: test design 1

2: Test design 2	**Wave height, transect b (Northwest) [m]**	**Difference with baseline, transect b [m]**	**Wave period, transect b (Northwest) [s]**	**Difference with baseline, transect b [s]**
Open spine (d=6 m)	2.40	-0.06	5.78	-0.11
Closed spine (d=3 m)	1.57	-0.00	4.54	-0.00
Open spine + SLR (d=7 m)	2.59	-0.12	5.98	-0.25
Closed spine + SLR (d=4 m)	1.89	-0.01	5.06	-0.00

Table D.7: Results of 1D calculation for emerged nourishments with respect to waves: test design 2

Note that results are fairly comparable to outcome of the very simple Equation (3.6) by Vrijling (2011), in which fully developed waves are assumed, not influenced by fetch or wind speed but by depth. With d=3 m $H_s \approx 1.4m$. Or with inflow (d=6 m) $H_s \approx 2.7m$. Right at the shore the wave heights will always be lower due to

3: Test design 3	**Wave height, transect b and c (Northwest and West) [m]**	**Difference with baseline, transect b and c [m]**	**Wave period, transect b and c (Northwest and West) [s]**	**Difference with baseline, transect b and c [s]**
Open spine (d=6 m)	2.15	-0.31	5.17	-0.72
Closed spine (d=3 m)	1.55	-0.02	4.52	-0.02
Open spine + SLR (d=7 m)	2.25	-0.46	5.21	-1.03
Closed spine + SLR (d=4 m)	1.82	-0.07	4.90	-0.16

Table D.8: Results of 1D calculation for emerged nourishments with respect to waves: test design 3

depth-induced breaking. You can see that for a shallower Bay the waves can be regarded as fully developed, but with a Bay with inflow (e.g. during hurricane conditions) the waves are not yet (almost) fully developed.

D.2. Qualitative Evaluation of Wetlands

D.2.1. Literature Wetlands for Surge Reduction

It should be noted that most research focuses on the wetlands in Louisiana. The situation in Texas is different but processes are similar.

The possible effect of wetlands on surge is twofold, they can have accomplish a reduction of a propagating surge by friction and the affect the local wind set-up. Vegetation of wetlands increases friction and reduces surface winds. The resistance helps to slow down and reduce the speed and height of the surge which propagates as a long wave. Furthermore because of the elevation of the wetlands around MSL the wind set-up might be influenced as well (Loder et al., 2009).

Several (modeling) studies have been conducted to evaluate the effectiveness of wetlands for storm surge reduction. Empirical data and numerical models show that wetlands can play a role in reducing surge peaks (Loder et al., 2009), but it depends on many factors and better validation should be done (Masters, 2014). Modeling efforts have been done with numerical 2D models and simplifications regarding wetlands (e.g. Loder et al. (2009); Wamsley et al. (2010)). Usually wetlands are considered as continuous with an constant friction rate and the changes in landscape due to storm passes are not considered in studies (Wamsley, 2007). It looks like only stretches of several miles wetland could affect surge significantly, because wetlands are elevated around MSL and will be significantly overtopped by a large surge, but do add friction (bottom stress and vegetative drag) to the system.

Typically the rate at which wetlands attenuate storm surge is expressed as a constant rate, but the situation is much more complex (Masters, 2014; Resio & Westerink, 2008; Wamsley et al., 2010). An example is such an attenuation rate is 1 m per 14.5 km marsh, from a report of the U.S. Army Corps based on empirical data of inland penetration for seven storms in southern Louisiana between 1909 and 1957 (Resio & Westerink, 2008). But considerable scatter can be found, then attenuation ranges from 1 m for 20 km to 1 m for 7 km (Resio & Westerink, 2008) or even 1 m per 60 km to 1 m per 5 km (Wamsley et al., 2010). Similar observed attenuation rates for e.g. hurricane Rita can be found, varying from 1 m per 25 km to 1 m per 4 km (Wamsley et al., 2010). Subsequently modeling simulations by Resio and Westerink (2008) show a maximum attenuation ranging from 1 per 11 km to 1 m per 19 km for western Louisiana during hurricane Rita.

The reality is much too complex that it can be expressed as a constant attenuation rate, implying a simple balance between gradient of water level and bottom friction (Resio & Westerink, 2008). The inland penetration of storm surges over wetlands is complex interaction between several factors including momentum balance; the landscape (bathymetry, local geometry/structures and wetland characteristics) and storm characteristics (size, forward speed, duration, intensity and track) (Resio & Westerink, 2008; Wamsley et al., 2010).

Increased roughness causes the surge to slow down. The frictional effects influence both the horizontal and vertical structures of currents (Resio & Westerink, 2008). The friction can be seen as a bottom friction and flow drag due to vegetation (Loder et al., 2009; Wamsley et al., 2007). In 2D modeling studies the flow drag can be only approximated by increasing the bottom friction of the model (Wamsley et al., 2007), and this is mostly done by a certain associated Manning n value. Recent studies applied 2D storm surge models with a vegetation-induced friction Manning coefficient (Loder et al., 2009; Wamsley et al., 2010). Many studies develop an artificially high Manning friction coefficient (n) to take into account both bottom friction and vegetative drag (Loder, 2008) (see also Table B.2 for different values of Manning's n). According to Sheng, Lapetina, and Ma (2012) "this 2D approximation, however, fails to adequately account for the complex flow over and within vegetation in storm conditions". Therefore Sheng et al. (2012) used a 3D model with explicit drag forces introduced by the vegetation (Sheng et al., 2012).

The roughness can cause the surge to delay and reduces surge or delays arrival time landward of the wetlands (Wamsley et al., 2010). The dominant momentum balance is then the friction balanced with the water level gradient. Therefore this is only the case if the storm surge is truly propagating, thus in motion. Friction process may slow the surge's advance, but the movement of water can divert toward another location, and subsequently can cause for a local increase of surge there (Wamsley et al., 2010). Increased friction could also lead to a steepening of the surge front as it propagates (Resio & Westerink, 2008). The degree of reduction of surge does also depend on duration of the forcing and the waves (Resio & Westerink, 2008).

For storms with long duration the dominant momentum balance changes. The wind stress is balanced by a water surface gradient (like with wind set-up), which leads to an increase in surge level landward of the wetlands (Resio & Westerink, 2008). Thus sometimes wetlands even increase storm surge, because of duration, elevation and the sort of shoaling effect (storm surge gets pushed up, water cannot go anywhere because of elevation) (Loder et al., 2009). Some sort of equilibrium or steady state has been occurred in which motion and therefore friction doesn't play a role anymore. Therefore a rise in elevation of wetlands may even lead to larger surge levels, particularly during severe surge events which are slow moving.

It can be concluded that a long stretch seems necessary, if applicable at all for Galveston Bay. We know that the processes of wetlands reducing surge are very complex and that also the storm surge models which estimate the attenuation of the surge are not validated enough yet. Wetlands will be most effective on surge reduction for weaker, fast moving storms where clear surge propagation is occurring Masters (2014); Wamsley et al. (2010).

D.2.2. LITERATURE WETLANDS FOR WAVE REDUCTION

Wetlands at the shoreline can attenuate wave heights (M. E. Anderson et al., 2011; Shepard et al., 2011). Wind waves will be much more attenuated during low-energy events than storm surge events (National Research Council, 2014), and attenuation during storm surge events is less investigated (M. E. Anderson et al., 2011). Wave attenuation is regarded the primary coastal risk reduction function of wetlands, although quantitative effects are not fully understood yet (National Research Council, 2014). Numerous models exist that look for a relation for the interactions between waves and submerged vegetation (Augustin, Irish, & Lynett, 2009). Literature on wave attenuation is mostly limited to small waves in or emerged or just submerged conditions, not large waves in totally submerged conditions which would be the case during storm surge conditions (Shepard et al., 2011; Wamsley et al., 2010). However these waves that are most frequently impacting the wetlands (Shepard et al., 2011).

Wetlands introduce friction, both frictional drag due to vegetation as well as bottom friction (Shepard et al., 2011). Both terms are introduced in the momentum balance (Loder et al., 2009). Furthermore the vegetation reduces surface winds, which means usually the waves don't grow over the wetland (McIvor, Spencer, Möller, & Spalding, 2012; Wamsley, 2007). While a wave passes through the wetland vegetation wave energy or height will be reduced by this friction, through work performed on the plants (Augustin et al., 2009). M. E. Anderson et al. (2011) mentions factors which are important for wave attenuation are "vegetation characteristics, such as geometry, buoyancy, density, stiffness of the stems and spatial coverage, as well as hydrodynamic conditions, such as incident wave height, direction, period and water depth" (M. E. Anderson et al., 2011; Augustin et al., 2009). The wave vegetation interactions are highly dynamic, and because of these dependencies and the variety of coastal wetlands the variability of wave attenuation is large (M. E. Anderson et al., 2011). An extra benefit of wetlands is the fact that wave set up due to wave height reduction in the shallow water limit can be reduced by two-thirds due to vegetation (Dean & Bender, 2006). The same holds for wave run-up at the landward edge of the wetland.

First, two specific wave attenuation studies will be discussed.

Because the variability of wave attenuation is very large, according to Mendez and Losada (2004) "trying to define a generalized behavior of the 'plant-induced dissipation' is absolutely impossible". Therefore it would be desirable to define adequate modeling of wave attenuation along vegetation stretches (Mendez & Losada, 2004). Mendez and Losada (2004) developed an empirical model for wave transformation on vegetation fields, and included wave damping and breaking over the vegetation fields on variable depths (Mendez & Losada, 2004). The model is validated with experimental data. It has been shown that influence of vegetation on the wave propagation not only on the plant height, but also the width of vegetation, as well as higher plants result in higher dissipation (**?**). The model depends on a single parameter which is similar to the drag coefficient and it showed reasonable accuracy in reproducing root-mean-square wave height transformation observed in experimental data (Mendez & Losada, 2004).

Augustin et al. (2009) did laboratory experiments to represent wave attenuation for emergent and near emergent conditions, focusing on common salt and estuarine marsh plants Spartina Alterniflora. The data is analyzed using linear wave theory to identify a bulk drag coefficient and with a non-linear model to identify friction factors for representing wetland vegetation (Augustin et al., 2009). Experiments showed that emergent conditions attenuated wave more than near-emergent conditions (Augustin et al., 2009). See also Figure D.1, intuitively this may sound correct as well. Wave attenuation appeared to be most depended on ratio of stem length to water depth and stem density (Augustin et al., 2009). Augustin et al. (2009) states that "modeling vegetation roughness through the use of a dimensionless friction factor was found to provide a reasonable estimate for the amount of wave attenuation that may occur through wetland marshes".

Next, two studies whom present an overview of wave attenuation studies will be discussed.

M. E. Anderson et al. (2011) provides a literature overview of wave dissipation by vegetation such as wetland plants. Wave attenuation is mostly studies in low-energy environments, nonetheless studies present methods to quantify vegetation induced attenuation for model and design (M. E. Anderson et al., 2011). Many field studies have been performed to quantify wave energy dissipation. High variability has been found due to different plant species, wave conditions and coverage of vegetation (M. E. Anderson et al., 2011). Average wave reductions range from about 1 to 5% per meter vegetation. The wave heights were found to reduce exponentially, that means the most rapid decay happens in the first few meters (M. E. Anderson et al., 2011). For example, "Knutson et al. (1982) reported a 20% wave height reduction per m within the first 2.5 m while Möller and Spencer (2002) reported values of 1.14% and 2.12% per m within the first 10 m for two transects" (M. E. Anderson et al., 2011). Laboratory studies reported attenuation rates ranging from 0.83-1.67% per m for 400 stems/m^2 to 5% per m for 600 stems/m^2 (M. E. Anderson et al., 2011). Unlike the effect of stem density, the influence of wave height was found to be less clear, although some conclusions were that an increase of wave attenuation can be found for higher incident wave heights (M. E. Anderson et al., 2011). The physics how stems of vegetation attenuates waves can be seen in Figure D.1.

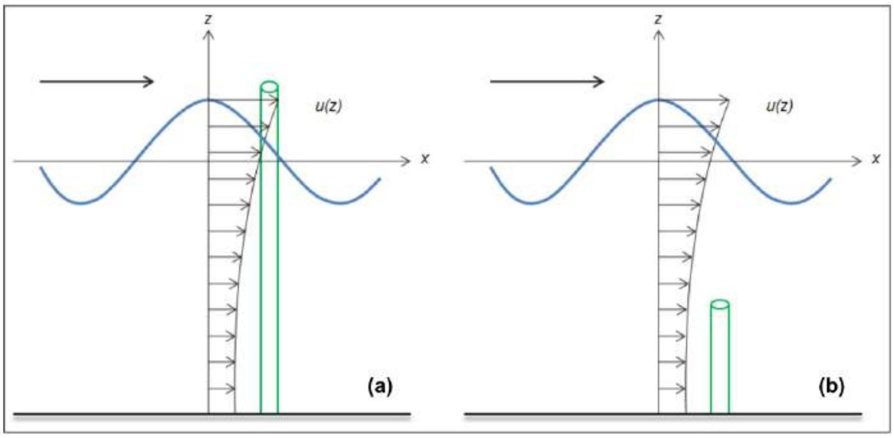
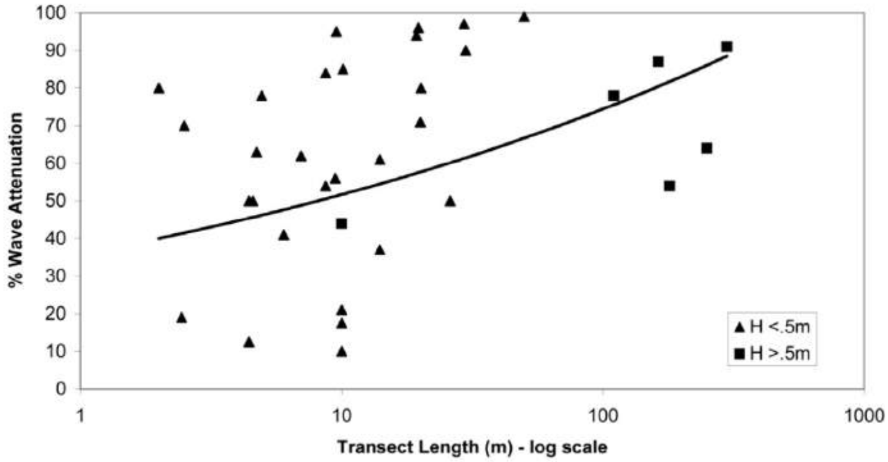


Figure D.1: Particle velocities versus emergent (a) and submerged (b) stems of vegetation (M. E. Anderson et al., 2011).

Wave forces work on the stems, inducing drag. Horizontal water particle velocities are largest near the crest of the wave as a wave passes. The highest velocities are impeded as stems approach the surface of the water, leading to greater drag and wave dissipation (M. E. Anderson et al., 2011). "Wetlands may be less effective in attenuating waves during storm events due to submergence, but study suggest that even a relatively low rate of wave reduction across wetlands can be substantial when applied over long distances", according to M. E. Anderson et al. (2011). Concluding, it can be said that generalizing wave-vegetation interactions is extremely difficult. Therefore modeling is necessary to quantify benefits of vegetation on storm damage, and thus wave-vegetation hydrodynamic formulations, which account for the influence of plant structure on wave attenuation through a calibration variable, often C_D, have been developed and these foremost methods describe dissipation by vegetation fairly good (M. E. Anderson et al., 2011). But these empirical, analytical and numerical models require calibration.

Lastly, a study of Shepard et al. (2011) will be discussed. Shepard et al. (2011) reviewed the current evidence for the specific processes of wave attenuation by vegetation. Shepard et al. (2011) states that "observation intervals for the wave attenuation studies ranged from a single wave to an extended time series of waves with wave amplitudes ranging from millimeters to just under one meter". It was found that 10 studies compared wave attenuation in vegetated and unvegetated areas. All of those studies concluded that wave attenuation is greater across marsh vegetation than inter-tidal mudflats. Wave attenuation rates increased with marsh transect length. For short transects attenuation rates are highly variable, but even in within the wetland edge significant attenuation can occur (Shepard et al., 2011). The same conclusion was made by M. E. Anderson et al. (2011). See Figure D.2 for the generalized increase in wave attenuation.

Figure D.2: Reported wave attenuation rates through wetlands versus wetlands transect length. H = incident wave height. (Shepard et al., 2011)



Shepard et al. (2011) futhermore states that "the effects of storms appear to be more complex". For example, increasing wind and wave energy were frequently correlated with lower wave dissipation rates (Shepard et al., 2011). But it is considered a research gap that storm surge and dissipation for large waves (> 1 m) are not well understood.

E

SET-UP OF HYDRODYNAMIC MODEL

E.1. MODEL SET-UP

E.1.1. SPIDERWEB WIND FIELD

An example of the wind field with the wind velocity magnitude at 5:00 GMT on September 13, 2008 can be seen in Figure E.1. This figure can be compared to Figure E.2, although a time shift of 30 minutes is present between both wind fields. It can be seen that both wind field are similar in size and in wind velocity magnitude.

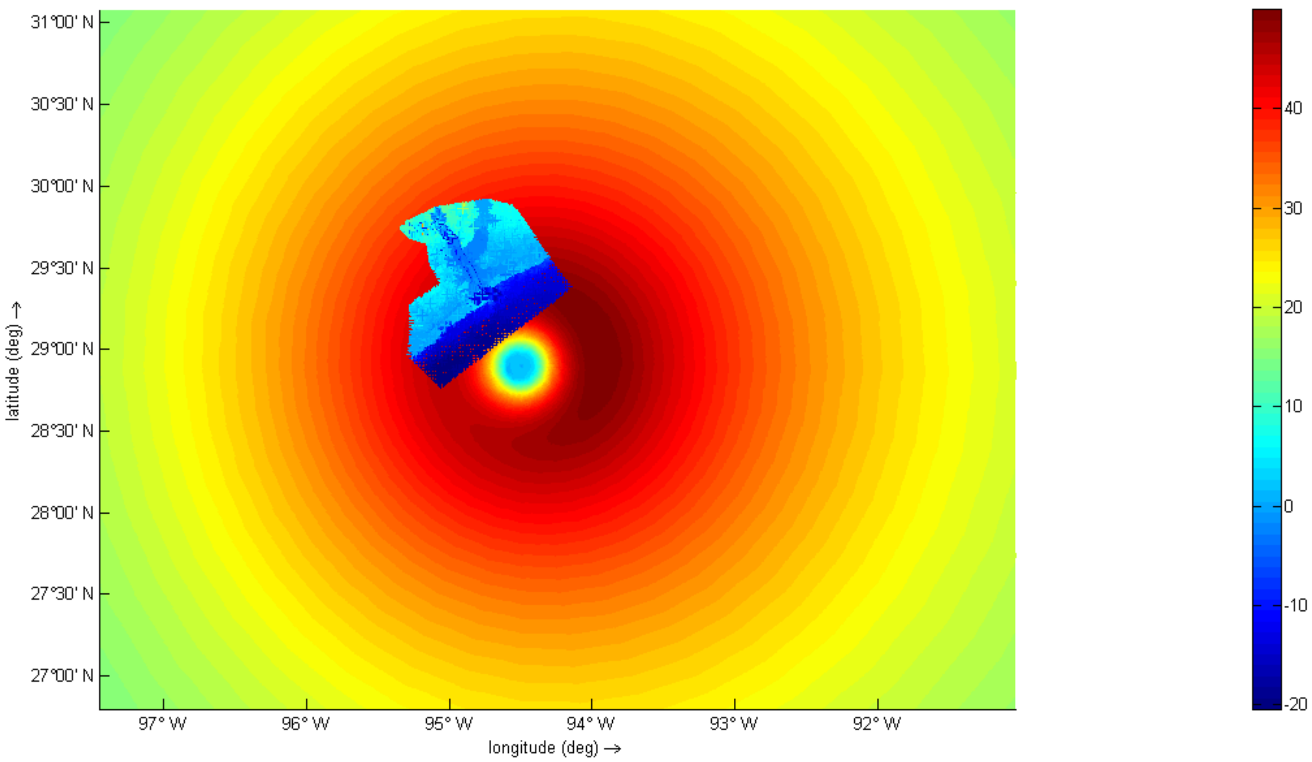


Figure E.1: Simulated wind field at 5:00 on September 13

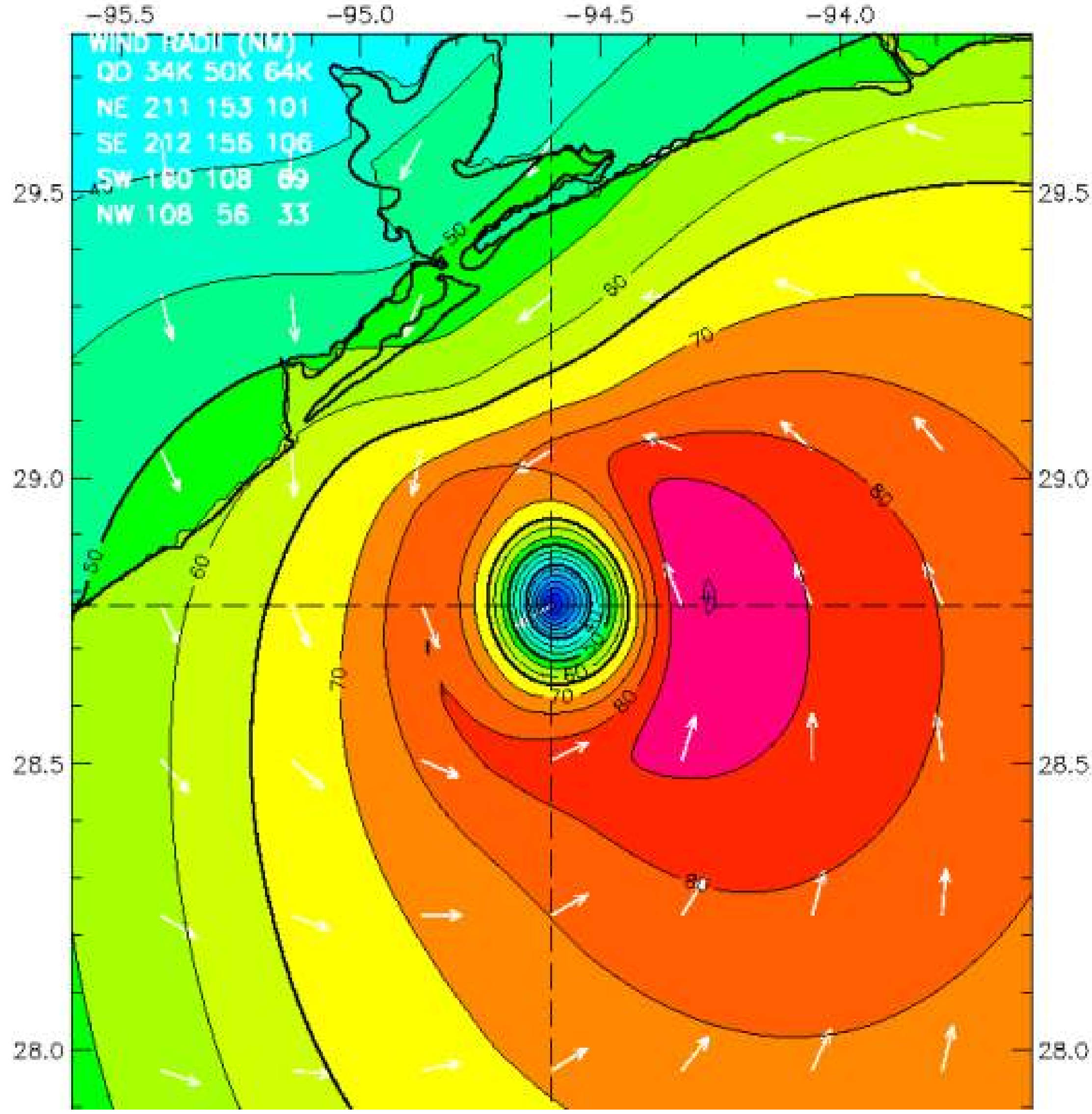


Figure E.2: Sustained wind field at 4:30 on September 13 (NOAA, 2014)

E.1.2. MDU FILE

mdu.txt

```
BASELINE

# Generated on 21:58:03, 25-06-2015
# Deltares, D-Flow FM Version 1.1.125.37607, Dec 15 2014, 18:58:06


[model]
Program = D-Flow FM
Version = 1.1.125.37607
MDUFormatVersion = 1.01 # File format version. Do not edit
this.
AutoStart = 0 # Autostart simulation after loading
MDU or not (0=no, 1=autostart, 2=autostartstop).


[geometry]
NetFile = gb_msl_wgs84_flow links removed_net.nc # *_net.nc
BathymetryFile = # *.xyb
DryPointsFile = # Dry points file *.xyz, third column
dummy z values, or polygon file *.pol.
WaterLevIniFile = # Initial water levels sample file
*.xyz
LandBoundaryFile = # Only for plotting
ThinDamFile = TClevee_thd.pli # *_thd.pli,
Polyline(s) for tracing thin dams.
FixedWeirFile = weirs_fxw.pliz # *_fxw.pliz,
Polyline(s) x,y,z, z = fixed weir top levels (formerly fixed weir)


VertplizFile =
first Z =nr of layers, second Z = laytyp
ProflocFile =
profile refnumber
ProfdefFile =
for all profile nrs
ProfdefxyzFile =
for all profile nrs
Uniformwidth1D = 2.
specified bij profloc
ManholeFile =
WaterLevIni = 0.089
Bedlevuni = -5.


# *_vlay.pliz), = pliz with x,y, Z,
# *_proflocation.xyz) x,y,z, z =
# *_profdefinition.def) definition
# *_profdefinition.def) definition
# Uniform width for 1D profiles not
# *...

# Initial water level
# Uniform bottom level, (only if

bedlevtype>=3, used at missing z values in netfile
BedlevType = 3 # 1 : Bottom levels at waterlevel
cells (=flow nodes), like tiles xz, yz, bl , bob = max(bl left, bl right)

# 2 : Bottom levels at velocity
points (=flow links), xu, yu, blu, bob = blu, bl = lowest
connected link

# 3 : Bottom levels at velocity
points (=flow links), using mean network levels xk, yk, zk bl = lowest

connected link
```

```
points (=flow links), using min
connected link

points (=flow links), using max
connected link
PartitionFile =
AngLat = 29.
Coriolis
AngLon = 0.
0=Greenwich
Conveyance2D = 1

2:K=analytic-1D conv, 3:K=analytic-2D conv
Nonlin2D = 0
ibedlevtype = 3 and Conveyance2D>=1

[numerics]
CFLMax = 0.7
AdvecType = 3

# 4 : Bottom levels at velocity
network levels xk, yk, zk bl = lowest

# 5 : Bottom levels at velocity
network levels xk, yk, zk bl = lowest

# *_part.pol, polyline(s) x,y
# Angle of latitude S-N (deg), 0=no
# Angle of longitude E-W (deg),
# -1:R=HU,0:R=H, 1:R=A/P,
# Non-linear 2D volumes, only icm

# Max. Courant nr.
# Adv type, 0=no, 1= Wenneker,


qu-udzt, 2=1, q(uio-u), 3=Perot q(uio-u), 4=Perot q(ui-u), 5=Perot q(ui-u)
without itself
TimeStepType = 2 # 0=only transport, 1=transport +
velocity update, 2=full implicit step_reduce, 3=step_jacobi, 4=explicit


Page 1

BASELINE

Limtypmom = 4 # Limiter type for cell center
advection velocity, 0=no, 1=minmod,2=vanLeer,3=Kooren,4=Monotone Central
Limtypsa = 4 # Limiter type for salinity
transport, 0=no, 1=minmod,2=vanLeer,3=Kooren,4=Monotone Central
Icgsolver = 4 # Solver type , 1 = sobekGS_OMP, 2 =
sobekGS_OMPthreadsafe, 3 = sobekGS, 4 = sobekGS + Saadilud, 5 = parallel/global
Saad, 6 = parallel/Petsc, 7 = parallel/GS
Tlfsmo = 0. # Fourier smoothing time on
waterlevel boundaries (s)
Slopedrop2D = 0. # Apply droplosses only if local
bottom slope > Slopedrop2D, <=0 =no droplosses
cstbnd = 0 # Delft-3D type velocity treatment
near boundaries for small coastal models (1) or not (0)
Jaorgsethu = 0

[physics]
UnifFrictCoef = 2.0d-2 # Uniform friction coefficient, 0=no
friction
UnifFrictType = 1 # 0=Chezy, 1=Manning, 2=White
Colebrook, 3=idem, WAQUA style
UnifFrictCoef1D = 2.0d-2 # Uniform friction coefficient in 1D
links, 0=no friction
UnifFrictCoefLin = 0. # Uniform linear friction coefficient
for ocean models (m/s), 0=no
Vicouv = 10. # Uniform horizontal eddy viscosity
```

```
(m2/s)
Dicouv = 10. # Uniform horizontal eddy
diffusivity (m2/s)
Smagorinsky = 0. # Add Smagorinsky horizontal
turbulence : vicu = vicu + ( (Smagorinsky*dx)**2)*S, e.g. 0.1
Elder = 0. # Add Elder contribution

: vicu = vicu + Elder*kappa*ustar*H/6), e.g. 1.0
irov = 0 # 0=free slip, 1 = partial slip using
wall_ks
wall_ks = 0. # Nikuradse roughness for side walls,
wall_z0=wall_ks/30
Rhomean = 1025. # Average water density (kg/m3)
Idensform = 0 # 1=Eckard, 2=Unesco, 3=barocin case
Ag = 9.81 # Gravitational acceleration
TidalForcing = 0 # Tidal forcing (0=no, 1=yes) (only
for jsferic == 1)
Salinity = 0 # Include salinity, (0=no, 1=yes)
Temperature = 0 # Include temperature, (0=no, 1=only
transport, 5=heat flux model (5) of D3D), 3=excess model of D3D

[wind]
ICdtyp = 3 # ( ),1=const, 2=S&B 2 breakpoints,
3= S&B 3 breakpoints, 4=Charnock constant
Cdbreakpoints = 0.0008 0.00254 0.00254 # ( ), e.g. 0.00063 0.00723
Windspeedbreakpoints = 0. 26.8 60. # (m/s), e.g. 0.0 100.0
PavBnd = 101325.0000000 # standard air pressure (because
Gapres = 101325.0000000 # idem

[time]
RefDate = 20080905 # Reference date (yyyymmdd) in 00:00
GMT
Tzone = 0. # Data Sources in GMT are
interrogated with time in minutes since refdat-Tzone*60
Tunit = M # Time units in MDU (H, M or S)
DtUser = 120. # User timestep in seconds (interval
for external forcing update & his/map output)
DtMax = 30. # Max timestep in seconds
DtInit = 1. # Initial timestep in seconds
AutoTimestep = 1 # Use CFL timestep limiter or not
(1/0)
TStart = 7920. # Start time w.r.t. RefDate (in
TUnit)
TStop = 12960. # Stop time w.r.t. RefDate (in TUnit)

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BASELINE

[restart]
RestartFile = # Restart file, only from
netcdf-file, hence: either *_rst.nc or *_map.nc
RestartDateTime = # Restart time (YYYYMMDDHHMMSS), only
relevant in case of restart from *_map.nc


[external forcing]
ExtForceFile = galvestonbay.ext # *.ext


[output]
OutputDir = # Output directory of map-, his-,
rst-, dat-and timings-files, default: DFM_OUTPUT_<modelname>. Set to . for no
dir/current dir.
ObsFile = galvestonbay_obs.xyn # *.xyn Coords+name of
observation stations.
CrsFile = galvestonbay_crs.pli # *_crs.pli Polyline(s)
definining cross section(s).
HisInterval = 120. # History output, given as "interval"
"start period" "end period" (s)
XLSInterval = 3600. # Interval (s) between XLS history
```

```
FlowGeomFile = # *_flowgeom.nc Flow geometry file in
NetCDF format.
MapInterval = 3600. # Map file output, given as
"interval" "start period" "end period" (s)
MapFormat = 1 # Map file format, 1: netCDF, 2:
Tecplot, 3: netCFD and Tecplot
RstInterval = 151200. # Restart file output, given as
"interval" "start period" "end period" (s)
WaqInterval = 3600. # Interval (in s) between Delwaq
file outputs
StatsInterval = 0. # Interval (in s) between simulation
statistics output.
TimingsInterval = 0. # Timings output interval
TimeSplitInterval = 0X # Time splitting interval, after
which a new output file is started. value+unit, e.g. '1 M', valid units:
Y,M,D,h,m,s.
MapOutputTimeVector = # File (.mpt) containing fixed map
output times (s) w.r.t. RefDate
FullGridOutput = 0 # 0:compact, 1:full time-varying grid
data
Wrihis_structure_gen = 0 # Write general
structure parameters to his file (1=yes, 0=no)
Wrihis_structure_dam = 0 # Write dam parameters
to his file (1=yes, 0=no)
Wrihis_structure_pump = 0 # Write pump parameters
to his file (1=yes, 0=no)
Wrihis_structure_gate = 0 # Write gate parameters
to his file (1=yes, 0=no)
Wrimap_waterlevel_s0 = 1 # Write water levels for
previous time step to map file (1=yes, 0=no)
Wrimap_waterlevel_s1 = 1 # Write water levels to
map file (1=yes, 0=no)
Wrimap_velocity_component_u0 = 1 # Write velocity
component for previous time step to map file (1=yes, 0=no)
Wrimap_velocity_component_u1 = 1 # Write velocity
component to map file (1=yes, 0=no)
Wrimap_velocity_vector = 1 # Write cell-center
velocity vectors to map file (1=yes, 0=no)
Wrimap_upward_velocity_component = 1 # Write upward velocity
component on cell interfaces (1=yes, 0=no)
Wrimap_density_rho = 1 # Write flow density to
map file (1=yes, 0=no)
Wrimap_horizontal_viscosity_viu = 1 # Write horizontal
viscosity to map file (1=yes, 0=no)
Wrimap_horizontal_diffusivity_diu = 1 # Write horizontal
diffusivity to map file (1=yes, 0=no)
Wrimap_flow_flux_q1 = 1 # Write flow flux to map


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BASELINE

file (1=yes, 0=no)

Wrimap_spiral_flow = 1 # Write spiral flow to
map file (1=yes, 0=no)
Wrimap_numlimdt = 1 # Write the number times
a cell was Courant limiting to map file (1=yes, 0=no)
Wrimap_taucurrent = 1 # Write the shear stress
to map file (1=yes, 0=no)
Wrimap_chezy = 1 # Write the chezy
roughness to map file (1=yes, 0=no)
Wrimap_wind = 1 # Write wind velocities
to map file (1=yes, 0=no)
EulerVelocities = 0 # 0:GLM, 1:Euler
velocities

[trachytopes]
TrtRou = N # Include alluvial and vegetation
roughness (trachytopes), (N=no, Y=yes)
```

```
TrtDef = *.ttd # Filename including trachytope
definitions
Trtl = *.arl # Filename including distribution of
trachytope definitions
DtTrt = 60 # Updates trachytope roughness at
specific time interval

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```

E.1.3. EXT FILE

ext.txt

```
galvestonbay

* QUANTITY : waterlevelbnd, velocitybnd, dischargebnd, tangentialvelocitybnd,
normalvelocitybnd filetype=9 method=2,3
*
: salinitybnd
filetype=9 method=2,3
*
: lowergatelevel, damlevel, pump
filetype=9 method=2,3
: frictioncoefficient, horizontaleddyviscositycoefficient,
advectiontype, ibotlevtype filetype=4,10 method=4

*
: initialwaterlevel, initialsalinity
filetype=4,10 method=4
*
: windx, windy, windxy, rainfall_mmperday, atmosphericpressure
filetype=1,2,4,7,8 method=1,2,3
*
: shiptxy, movingstationtxy
filetype=1 method=1
*

* kx = Vectormax = Nr of variables specified on the same time/space frame. Eg.
Wind magnitude,direction: kx = 2
* FILETYPE=1 : uniform kx = 1 value 1 dim array
uni
* FILETYPE=2 : unimagdir kx = 2 values 1 dim array,
uni mag/dir transf to u,v, in index 1,2
* FILETYPE=3 : svwp kx = 3 fields u,v,p 3 dim array
nointerpolation
* FILETYPE=4 : arcinfo kx = 1 field 2 dim array
bilin/direct
* FILETYPE=5 : spiderweb kx = 3 fields 3 dim array
bilin/spw
* FILETYPE=6 : curvi kx = ?
bilin/findnm
* FILETYPE=7 : triangulation kx = 1 field 1 dim array
triangulation
* FILETYPE=8 : triangulation_magdir kx = 2 fields consisting of Filetype=2
triangulation in (wind) stations
*
* FILETYPE=9 : polyline kx = 1 For polyline points i= 1 through N
specify boundary signals, either as
* timeseries or Fourier components or
tidal constituents
* Timeseries are in files *_000i.tim,
two columns: time (min) values
* Fourier components and or tidal
constituents are in files *_000i.cmp, three columns
*
period (min) or constituent name
(e.g. M2), amplitude and phase (deg)
* If no file is specified for a node,
```

```
its value will be interpolated from surrounding nodes
* If only one signal file is
specified, the boundary gets a uniform signal
* For a dischargebnd, only one signal
file must be specified
*
* FILETYPE=10 : inside_polygon kx = 1 field
uniform value inside polygon for INITIAL fields
*
* METHOD =0 : provider just updates, another provider that pointers to this
one does the actual interpolation
* =1 : intp space and time (getval) keep 2 meteofields in memory
* =2 : first intp space (update), next intp. time (getval) keep 2
flowfields in memory
* =3 : save weightfactors, intp space and time (getval), keep 2
pointer-and weight sets in memory
* =4 : only spatial interpolation
*
* OPERAND =O : Override at all points
* =+ : Add to previously specified value
* =* : Multiply with previously specified value
* =A : Apply only if no value specified previously (For Initial fields,
similar to Quickin preserving best data specified first)
Page 1


galvestonbay

*
* VALUE = : Offset value for this provider
*
* FACTOR = : Conversion factor for this provider
*

********************************************************************************
******************************

QUANTITY=waterlevelbnd
FILENAME=boundarysea_1west.pli
FILETYPE=9
METHOD=3
OPERAND=O

QUANTITY=waterlevelbnd
FILENAME=boundarysea_2south.pli
FILETYPE=9
METHOD=3
OPERAND=O

QUANTITY=waterlevelbnd
FILENAME=boundarysea_3east.pli
FILETYPE=9
METHOD=3
OPERAND=O

QUANTITY =airpressure_windx_windy
FILENAME =Ike_080910_1200_Rmax_radius1000.spw
FILETYPE =5
METHOD =1
OPERAND =O *wind

QUANTITY=frictioncoefficient
FILENAME=peninsulas.pol
FILETYPE=10
METHOD=4
OPERAND=O
VALUE=0.025 *roughness

QUANTITY=frictioncoefficient
FILENAME=mainland1.pol
FILETYPE=10
```

```
METHOD=4
OPERAND=O
VALUE=0.025 *roughness

QUANTITY=frictioncoefficient
FILENAME=mainland2.pol
FILETYPE=10
METHOD=4
OPERAND=O
VALUE=0.025 *roughness

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```
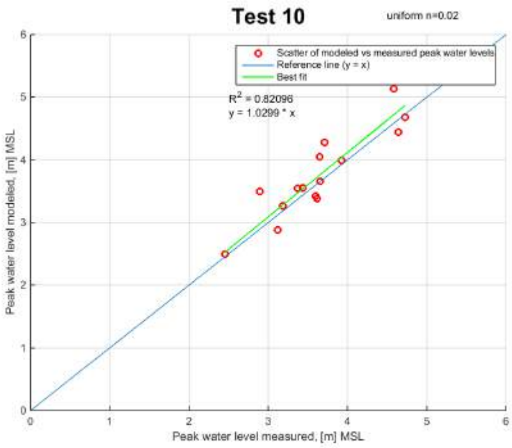
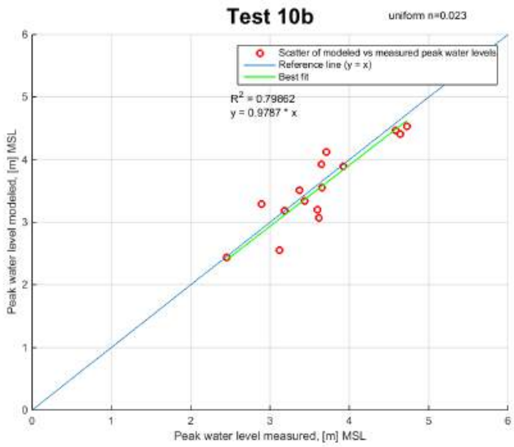

E.2. MODEL CALIBRATION FOR HURRICANE IKE

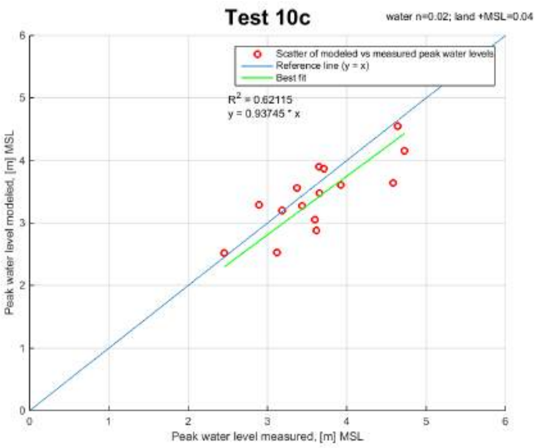
See Figure E.3-Figure E.4 for scatters of test simulations, which was a part of the calibration study below. Note that simulation "Test 10g" is missing because it is equal to the "Baseline" simulation, which is already presented in the main report.



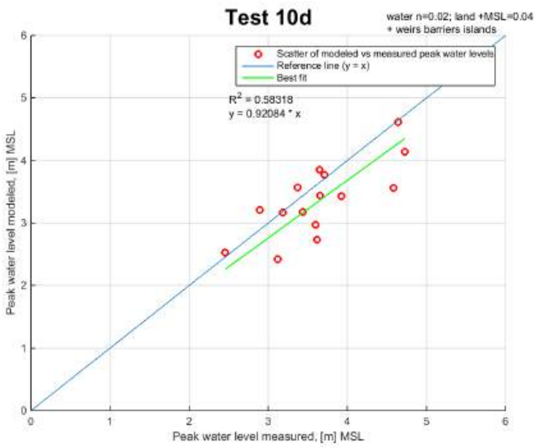
(a) Test 10



(b) Test 10b

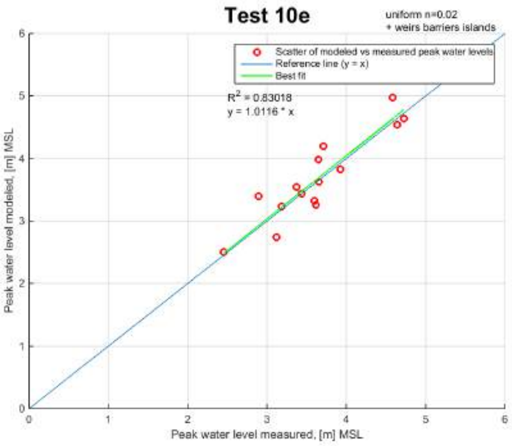


(c) Test 10c

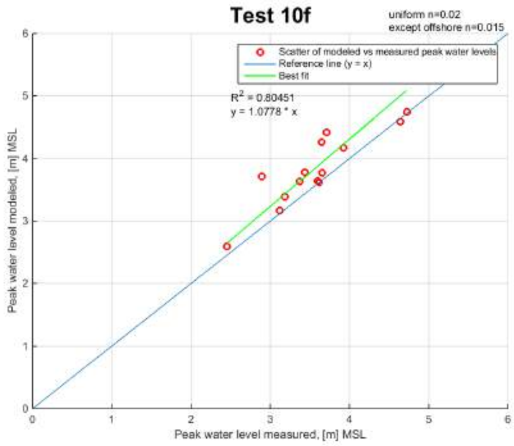


(d) Test 10d

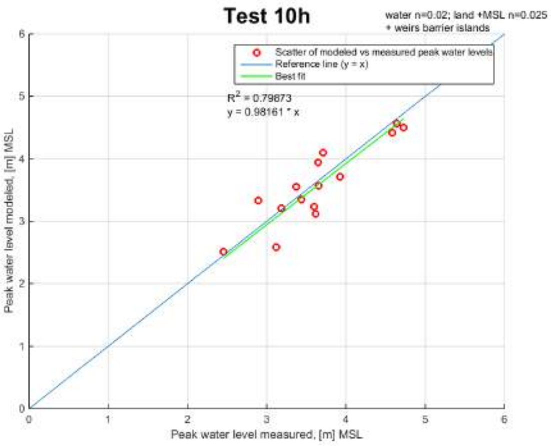
Figure E.3: Test simulation scatter plots of observed versus modeled peak water levels for Galveston Bay, a part the calibration of the model. (Part 1)



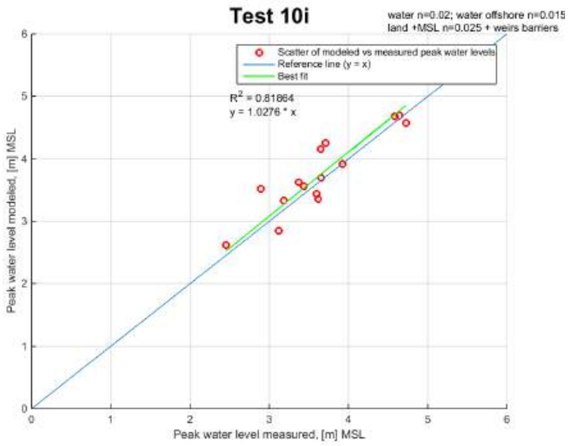
(a) Test 10e



(b) Test 10f



(c) Test 10h



(d) Test 10i

Figure E.4: Test simulation scatter plots of observed versus modeled peak water levels for Galveston Bay, a part the calibration of the model. (Part 2)

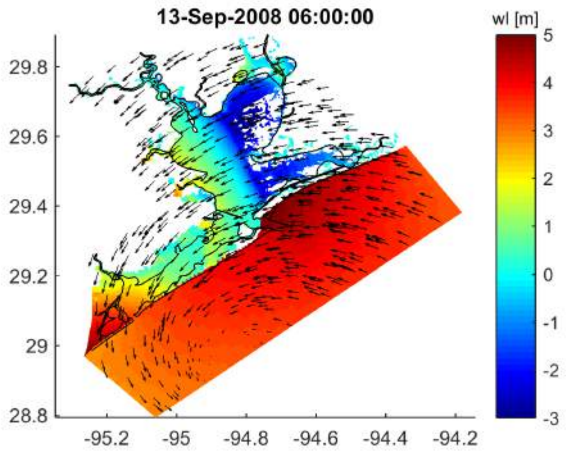
F

Hydrodynamic Model Simulation Results

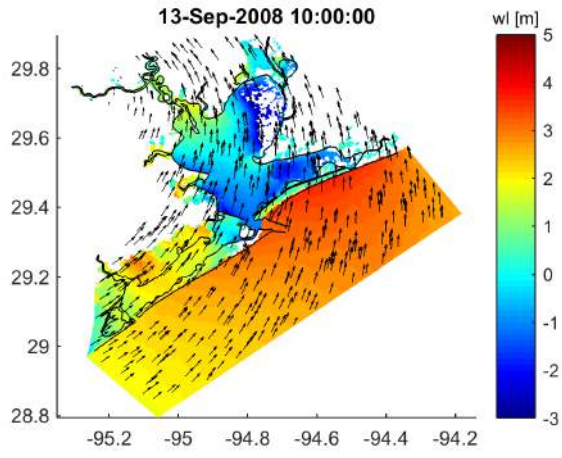
F.1. Shifted Ike Tracks with Ike Dike

Results for both hurricanes shift 1 and shift 2, simulated with Ike Dike, are presented in Figure F.1-Figure F.4.

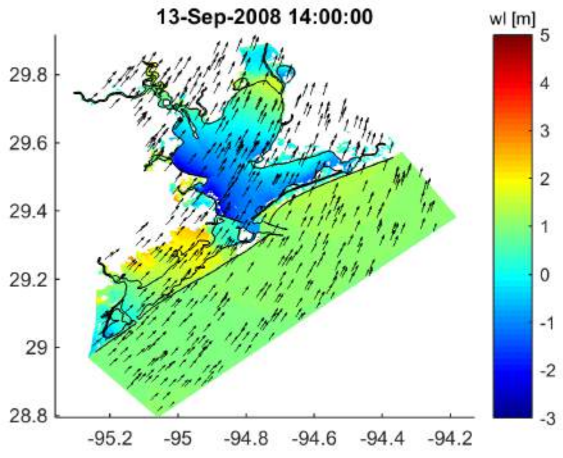
The rotating motion of the wind direction of the hurricane can be clearly seen in these plots. For Ike shift 1 West experiences direct onshore winds first, then Northwest and lastly Northeast when the hurricane has passed. For shift 2 the patterns are similar except the fact that the Northwest experiences even stronger winds. The surge levels are, compared to regular Ike, significantly higher. The surge levels rise up to around 2 m for shift 1 with peak surge in the West and up to almost 2.5 m for shift 2, with a peak in the Northwest (HSC).



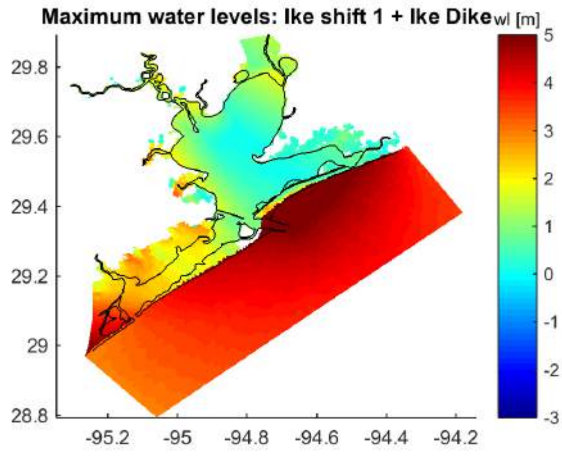
(a) 1 hour before landfall



(b) 3 hours after landfall



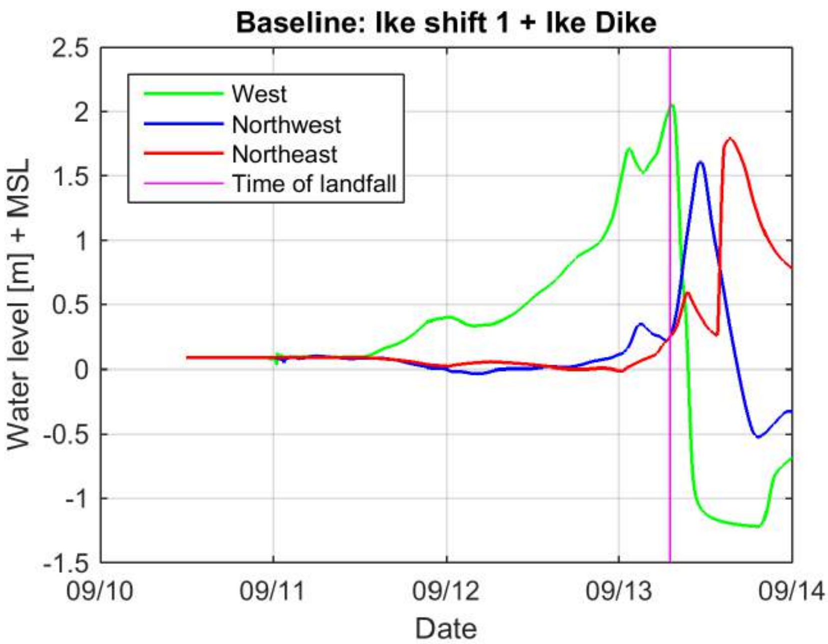
(c) 7 hours after landfall

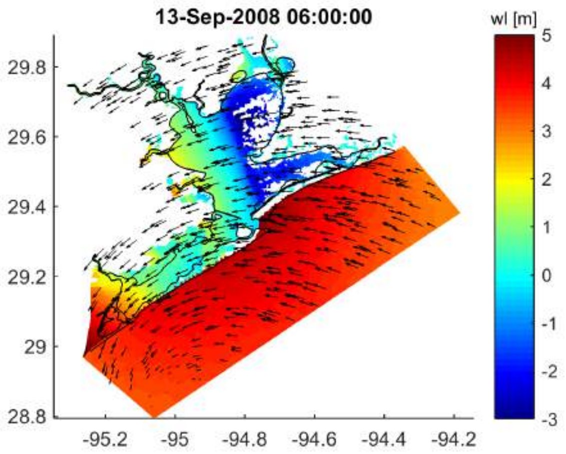


(d) Maximum water level elevation

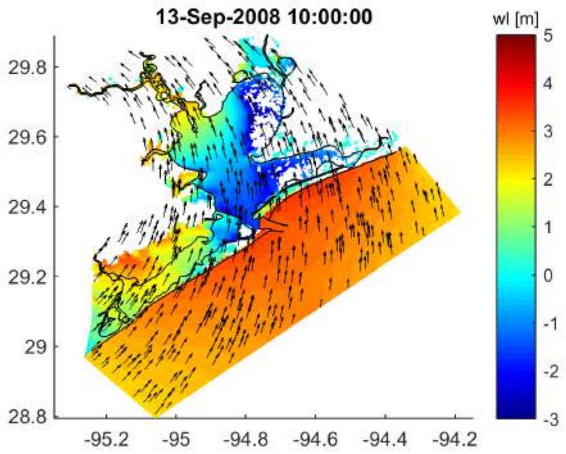
Figure F.1: Maps of water levels in Galveston Bay during Ike shift 1 (landfall at Jamaica Beach) for 3 moments in time from right before to after landfall and a map of maximum water level elevation, simulated with an Ike Dike (coastal spine) in place

Figure F.2: Time series of the water level during Ike shift 1, simulated with Ike Dike (coastal spine) at three observation locations of interest. Note that landfall is represented by the purple line. West = green, Northwest = blue and Northeast = red

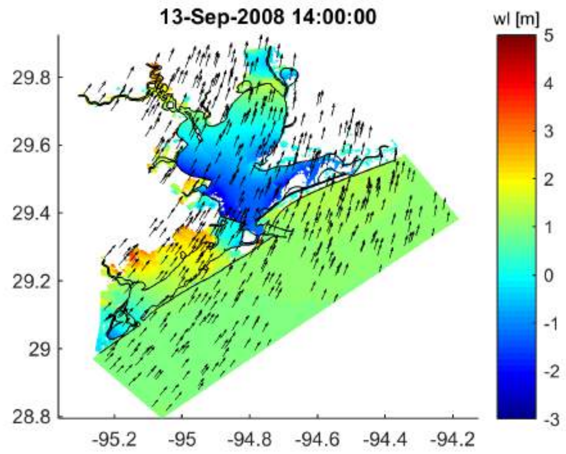




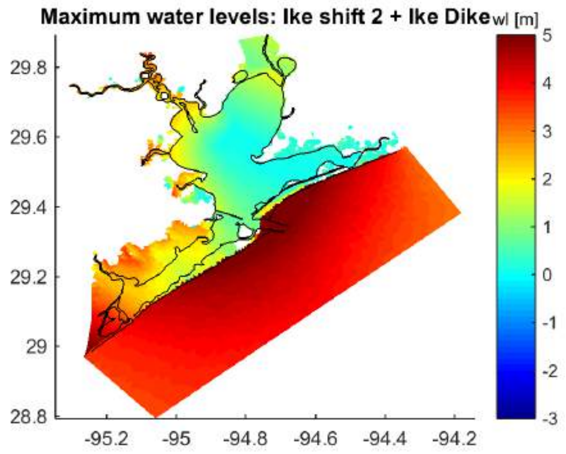
(a) 1 hour before landfall



(b) 3 hours after landfall



(c) 7 hours after landfall



(d) Maximum water level elevation

Figure F.3: Maps of water levels in Galveston Bay during Ike shift 2 (landfall at San Luis Pass) for 3 moments in time from right before to after landfall and a map of maximum water level elevation, simulated with an Ike Dike (coastal spine) in place

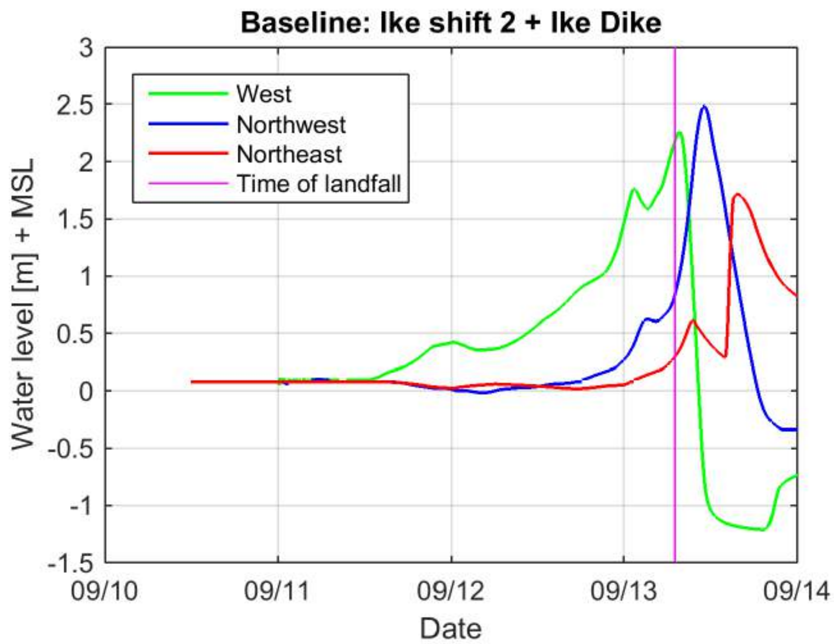


Figure F.4: Time series of the water level during Ike shift 2, simulated with Ike Dike (coastal spine) at three observation locations of interest. Note that landfall is represented by the purple line. West = green, Northwest = blue and Northeast = red

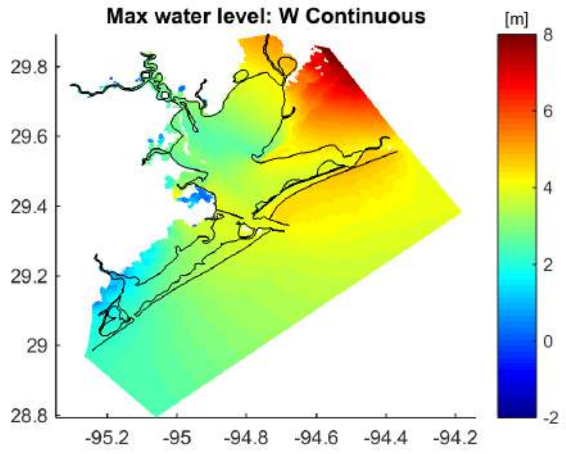
F.2. SURGE ALTERNATIVES

F.2.1. ISLANDS WEST

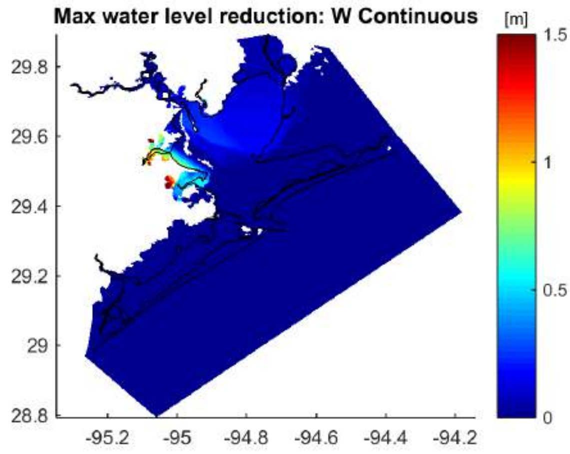
WEST DESIGN CONTINUOUS

IKE

Design continuous simulated with hurricane Ike, see Figure F.5 and Figure F.6.



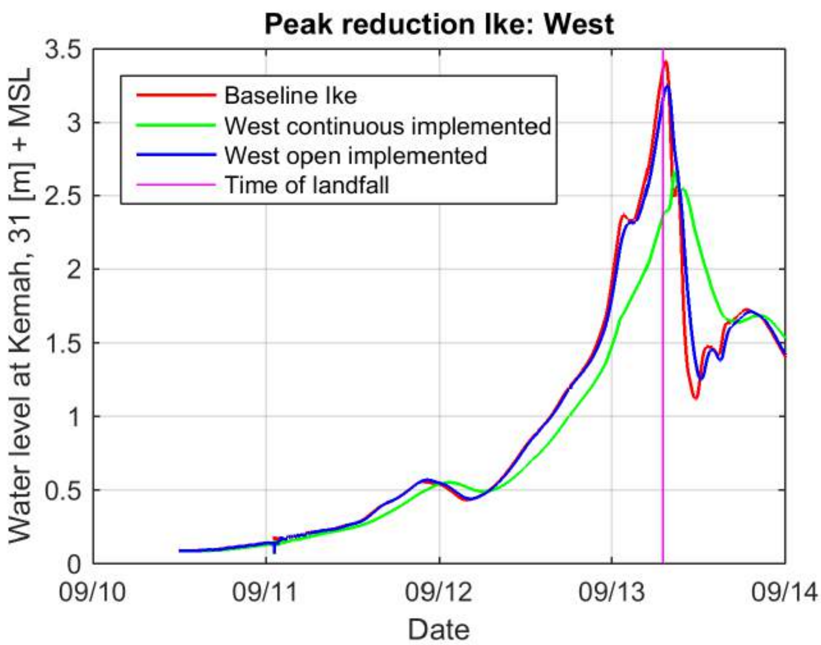
(a) Maximum water level elevation



(b) Maximum water level reduction for measure

Figure F.5: Maximum water level and maximum water level reduction in Galveston Bay during Ike for West design continuous

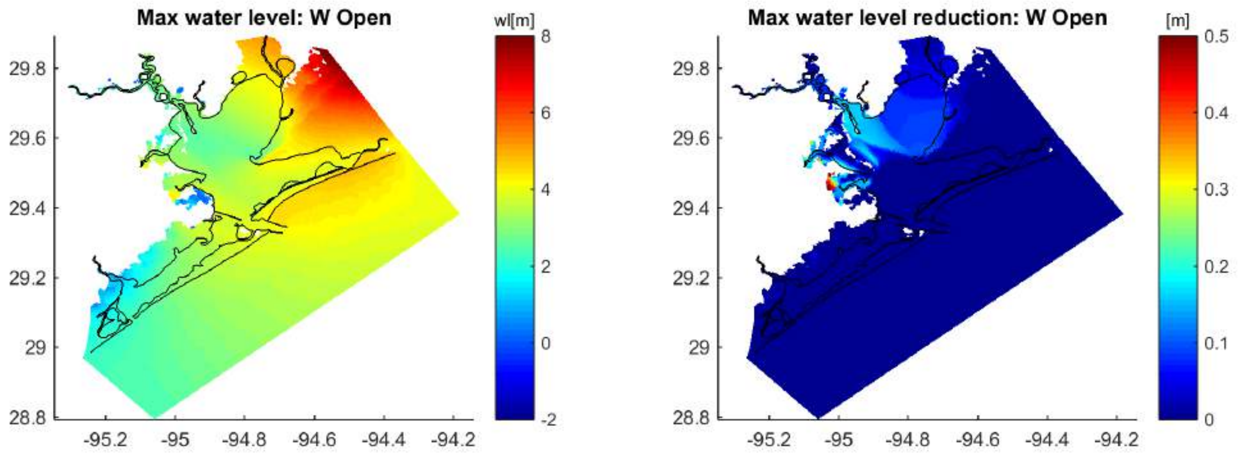
Figure F.6: Time series of water levels during Ike for West design continuous compared to West design open and Baseline Ike in West, 31 Kemah. Measure implemented = green, Baseline = red



WEST DESIGN OPEN

IKE

Design open simulated with hurricane Ike, see Figure F.7 and Figure F.6.



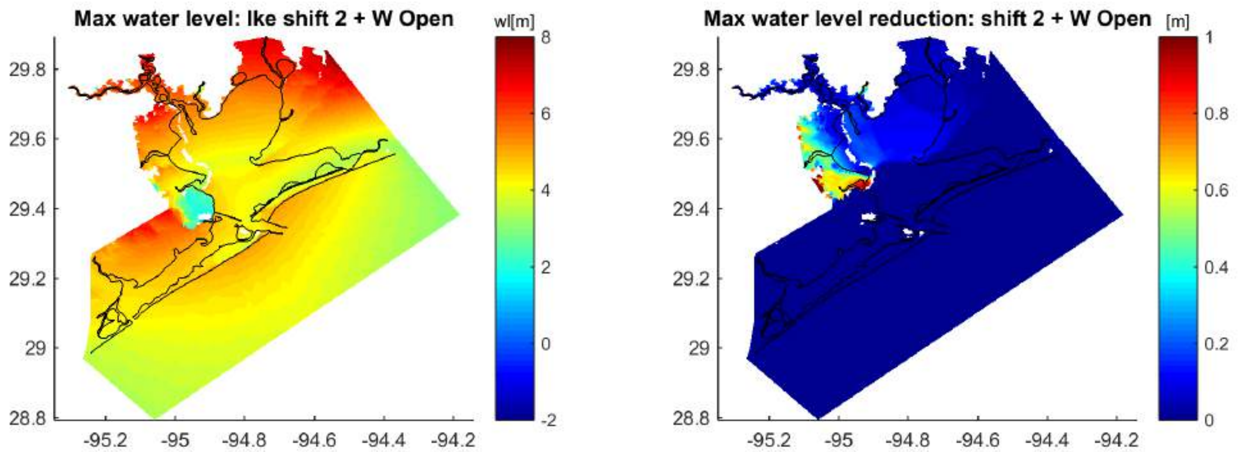
(a) Maximum water level elevation

(b) Maximum water level reduction for measure

Figure F.7: Maximum water level and maximum water level reduction in Galveston Bay during Ike for West design open

IKE SHIFT 2

Design open simulated with Ike shift 2, see Figure F.8 and Figure F.9.



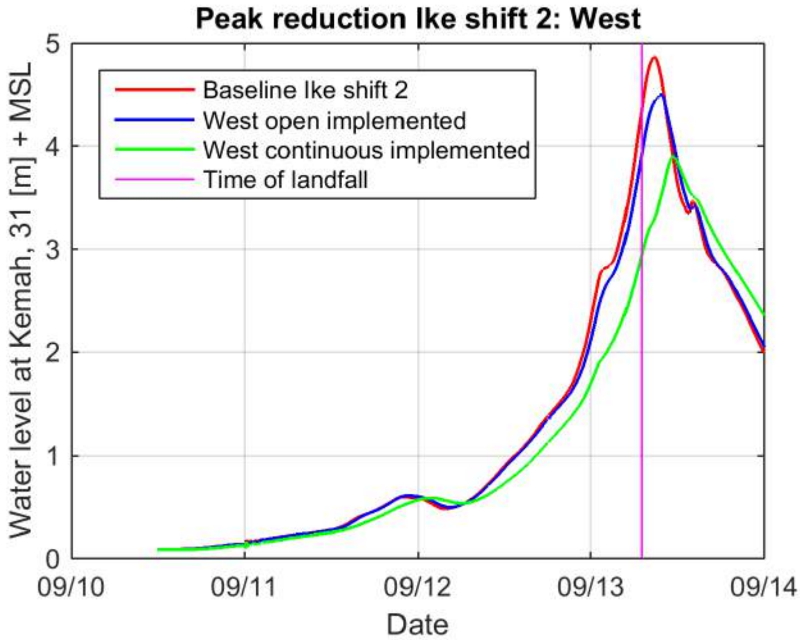
(a) Maximum water level elevation

(b) Maximum water level reduction for measure

Figure F.8: Maximum water level and maximum water level reduction in Galveston Bay during Ike shift 2 for West design open

These results clearly show that an open design is much less effective at reducing surge heights than a continuous design. For hurricane Ike, surge level in Kemah is reduced by **0.2 m** and for Ike shift 2 **0.4 m** (wind set-up is relatively more important).

Figure F.9: Time series of water levels during Ike shift 2 for West design continuous compared to West design open and Baseline in West, 31 Kemah. Design continuous = green, Design open = blue, Baseline = red



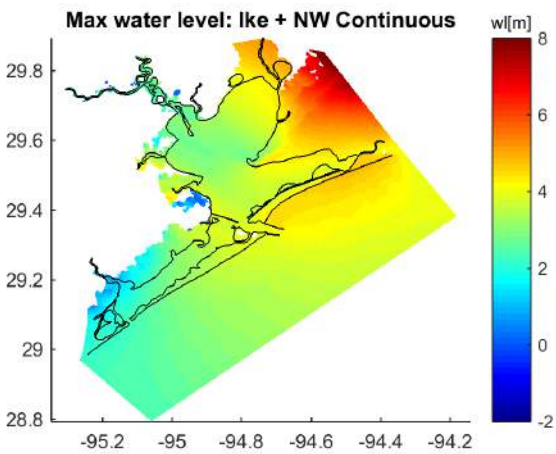
F.2.2. ISLANDS NORTHWEST

NORTHWEST DESIGN CONTINUOUS

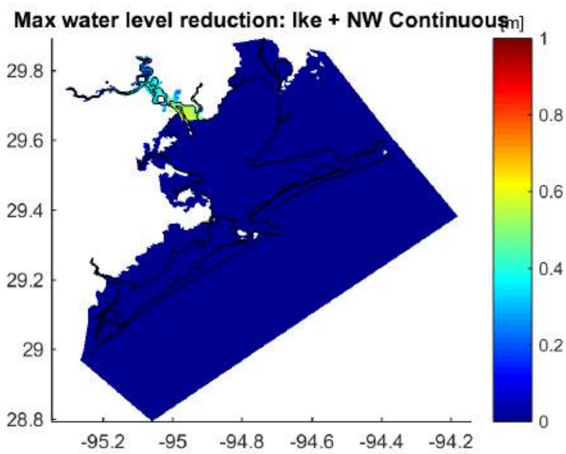
Design continuous with Ike shift 2 has been discussed in the main report. Here, results for design Northwest continuous with hurricane Ike will be presented.

IKE

For results of a design continuous simulated with hurricane Ike, see Figure F.10 and Figure F.11 below.



(a) Maximum water level elevation



(b) Maximum water level reduction for measure

Figure F.10: Maximum water level and maximum water level reduction in Galveston Bay during Ike for Northwest design continuous

NORTHWEST DESIGN OPEN

IKE

For results of design open simulated with hurricane Ike, see Figure F.12 and Figure F.11.

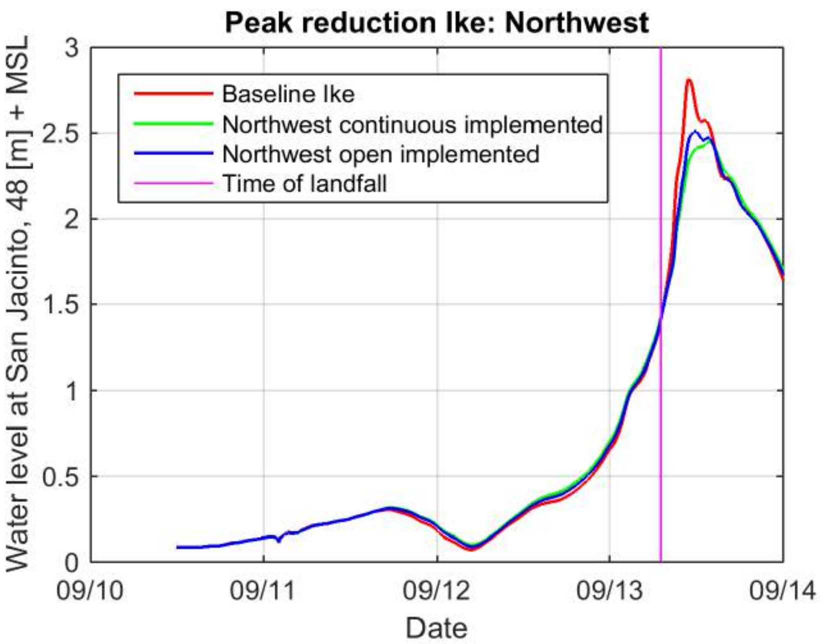
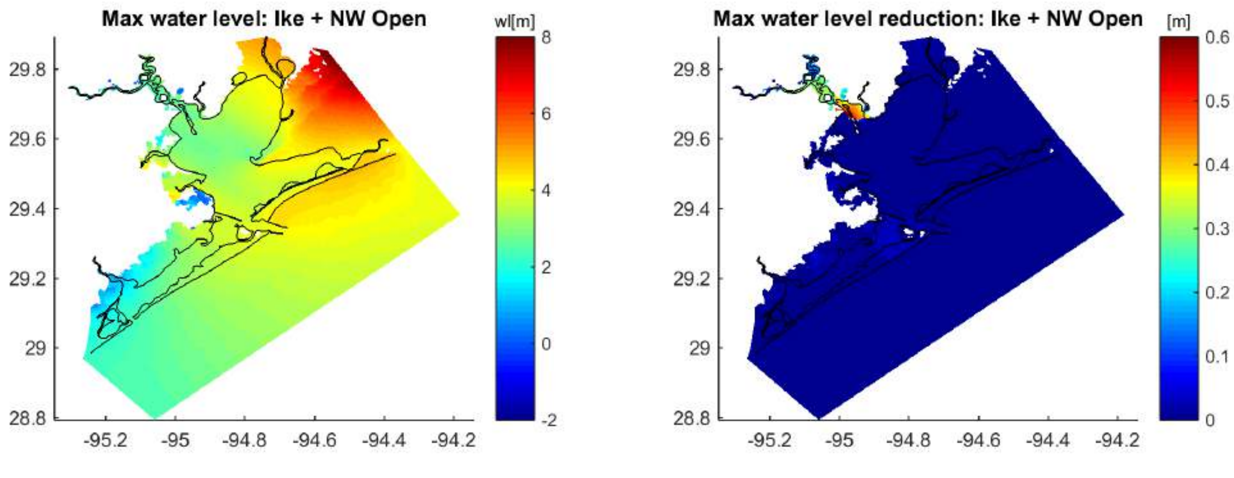


Figure F.11: Time series of water levels during Ike for Northwest design continuous compared to Northwest design open and Baseline Ike in Northwest, 48 San Jacinto Monument. Design continuous = green, Design open = blue, Baseline = red



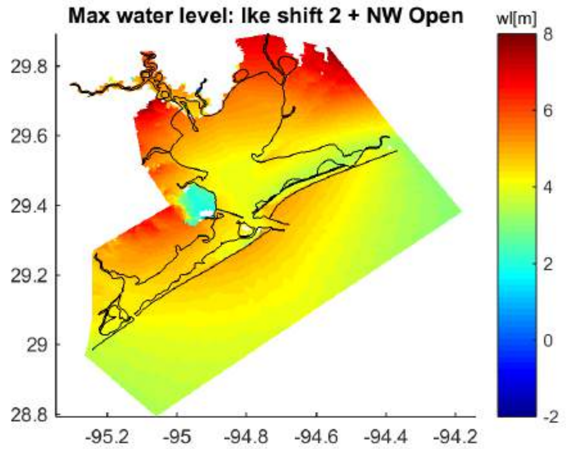
(a) Maximum water level elevation

(b) Maximum water level reduction for measure

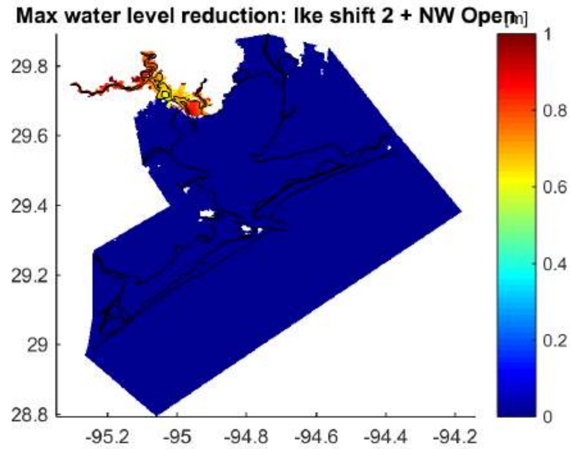
Figure F.12: Maximum water level and maximum water level reduction in Galveston Bay during Ike for Northwest design open

IKE SHIFT 2

For results of design open simulated with Ike shift 2, see Figure F.13 and Figure F.14.



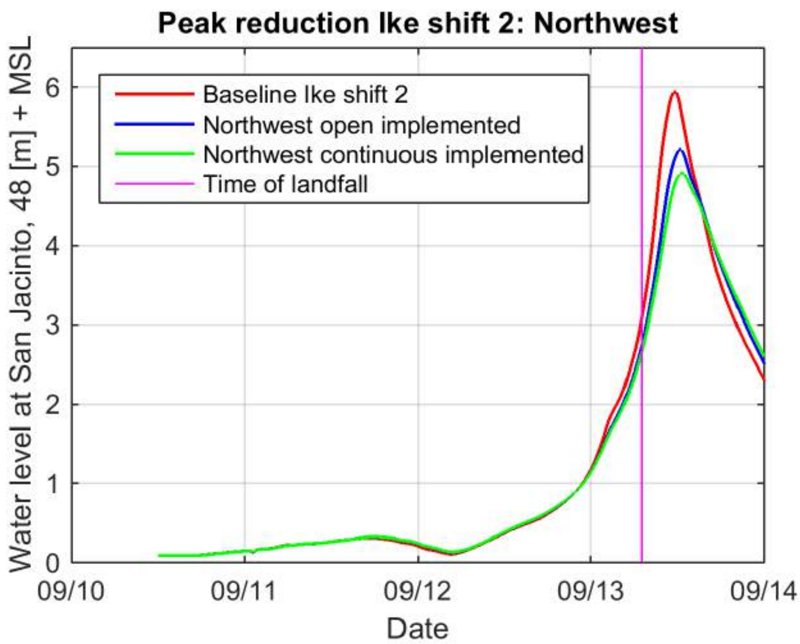
(a) Maximum water level elevation



(b) Maximum water level reduction for measure

Figure F.13: Maximum water level and maximum water level reduction in Galveston Bay during Ike shift 2 for Northwest design open

Figure F.14: Time series of water levels during Ike shift 2 for Northwest design open compared to design continuous and Baseline in Northwest, 48 San Jacinto Monument. Design continuous = green, Design open = blue, Baseline = red



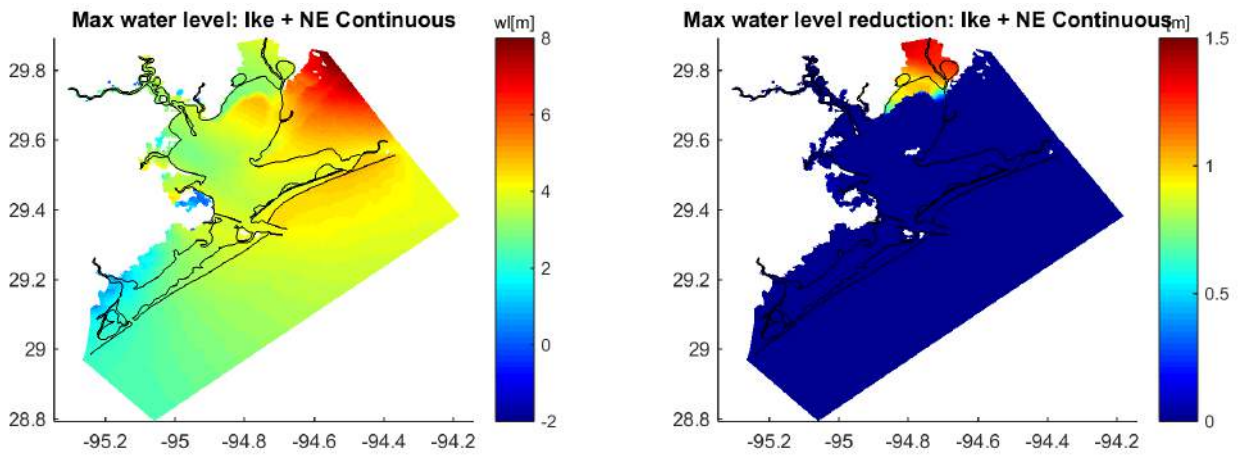
F.2.3. ISLANDS NORTHEAST

NORTHEAST DESIGN CONTINUOUS

Result for Ike shift 1 have presented in the main report, therefore only results for regular Ike will be discussed.

IKE

For results of design continuous simulated with hurricane Ike, see Figure F.15 and Figure F.16.



(a) Maximum water level elevation (b) Maximum water level reduction for measure

Figure F.15: Maximum water level and maximum water level reduction in Galveston Bay during Ike for Northeast design continuous

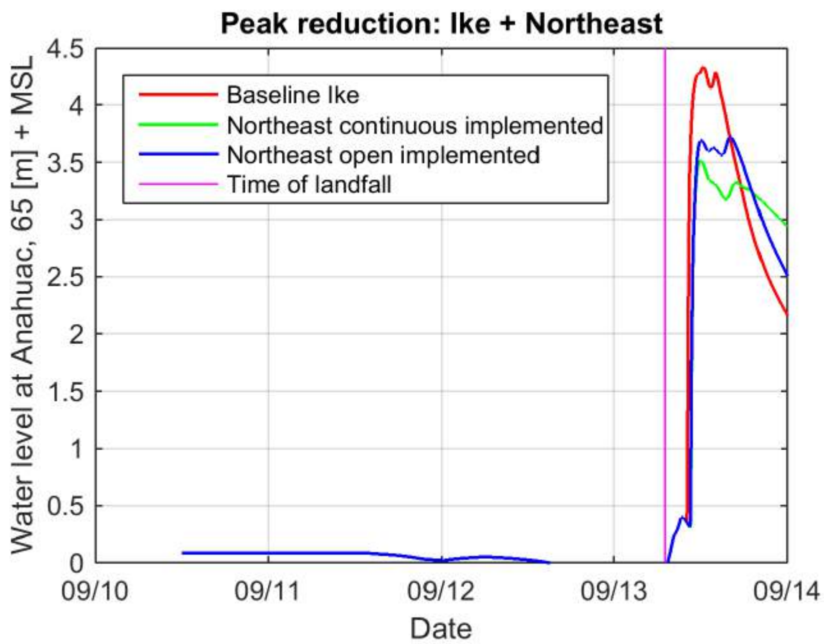
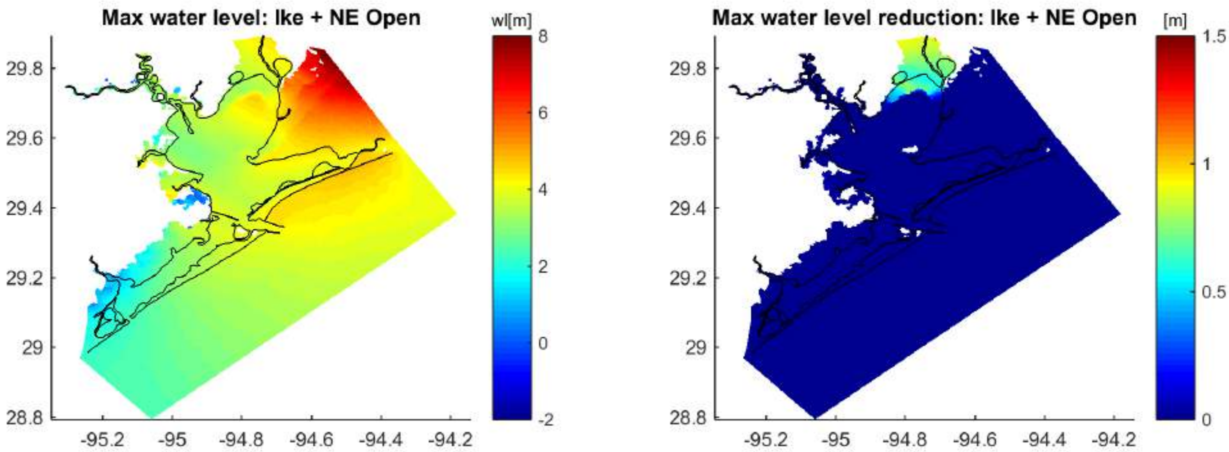


Figure F.16: Time series of water levels during Ike for Northeast design continuous compared to design open and Baseline in Northeast, 65 Anahuac. Design continuous = green, Design open = blue, Baseline = red

NORTHEAST DESIGN OPEN

IKE

Design open simulated with hurricane Ike, see Figure F.17 and Figure F.16.

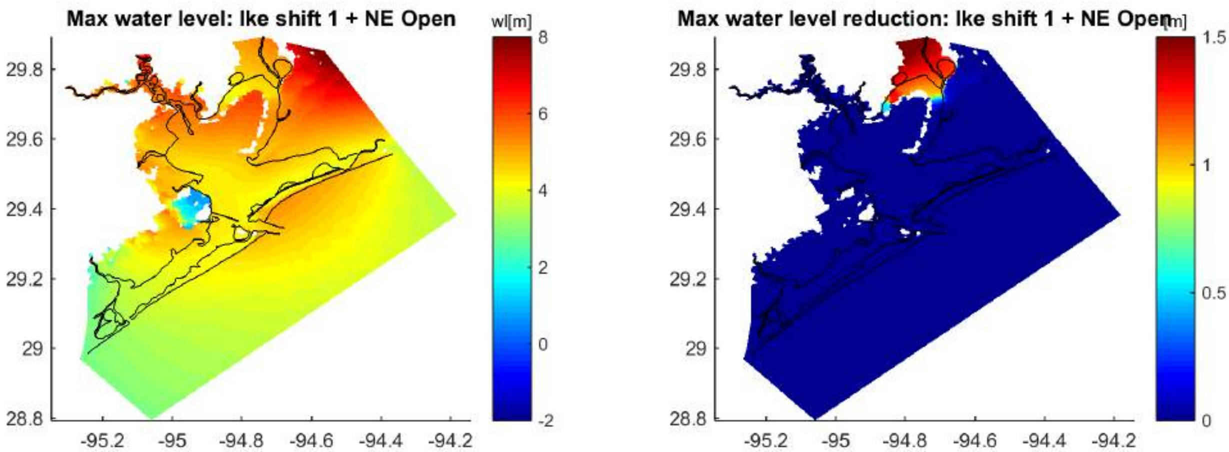


(a) Maximum water level elevation (b) Maximum water level reduction for measure

Figure F.17: Maximum water level and maximum water level reduction in Galveston Bay during Ike for Northeast design open

IKE SHIFT 1

Design open simulated with Ike shift 1, see Figure F.18 and Figure F.19.



(a) Maximum water level elevation (b) Maximum water level reduction for measure

Figure F.18: Maximum water level and maximum water level reduction in Galveston Bay during Ike shift 1 for Northeast design open

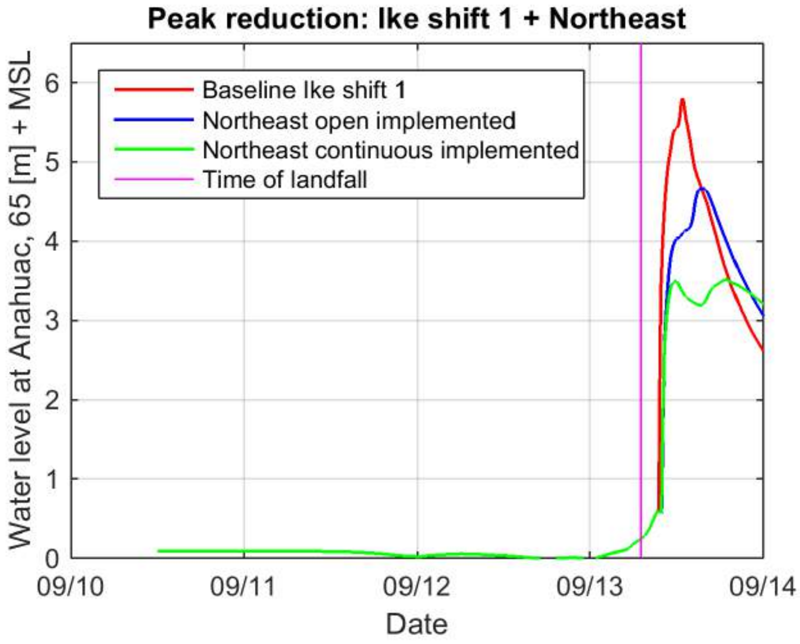


Figure F.19: Time series of water levels during Ike shift 1 for Northeast design open compared to design continuous and Baseline in Northeast, 65 Anahuac. Design continuous = green, Design open = blue, Baseline = red

F.2.4. ECO-ISLAND WEST

IKE

Eco-island West simulated with hurricane Ike, see Figure F.20.

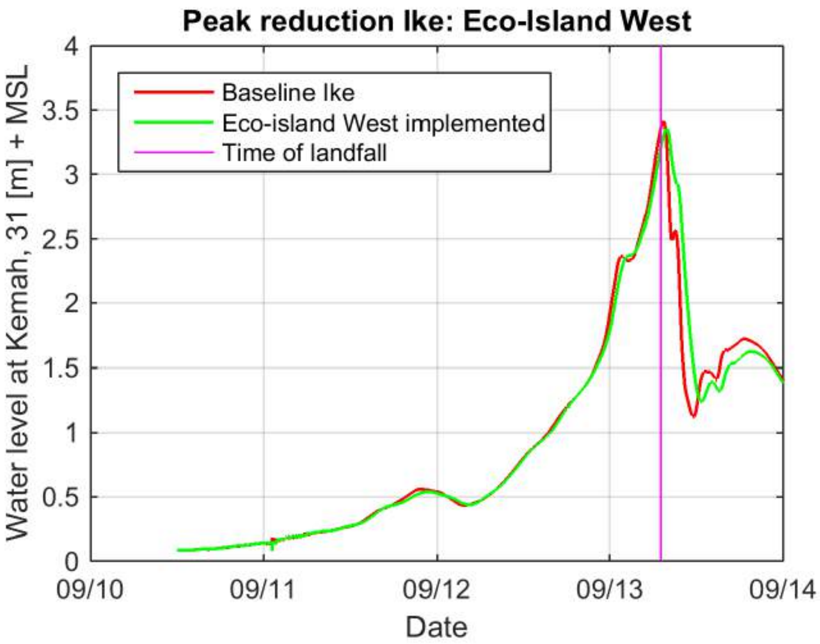
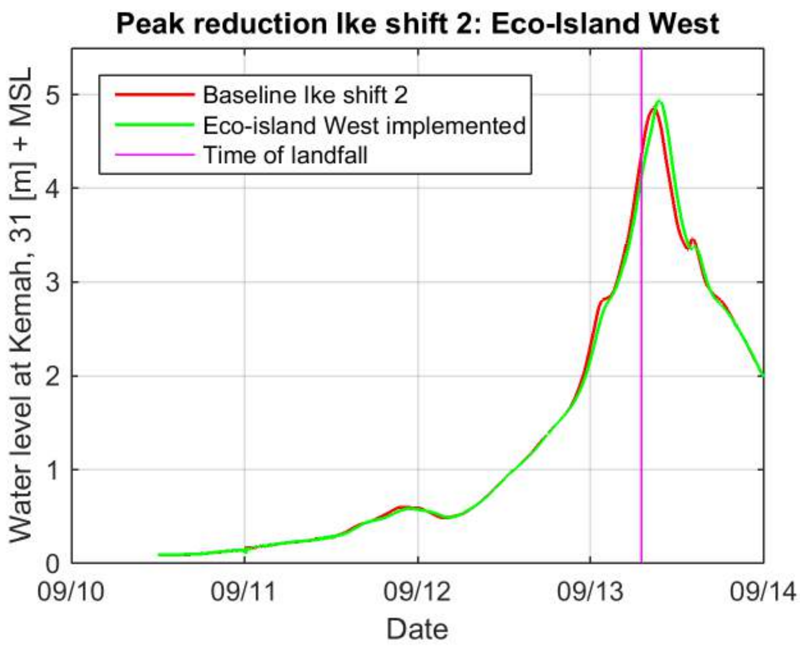


Figure F.20: Time series of water levels during Ike for Eco-Island West and Baseline in West, 31 Kemah. Measure implemented = green, Baseline = red

IKE SHIFT 2

For results of eco-island West simulated with hurricane Ike shift 2, see Figure F.21.

Figure F.21: Time series of water levels during Ike shift 2 for Eco-Island West and Baseline in West, 31 Kemah. Measure implemented = green, Baseline = red

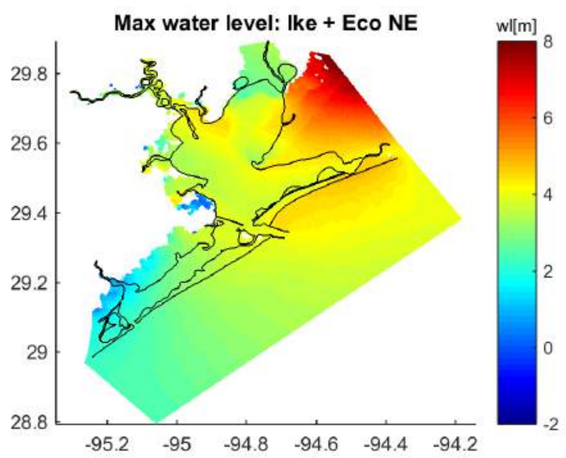


F.2.5. ECO-ISLAND NORTHEAST

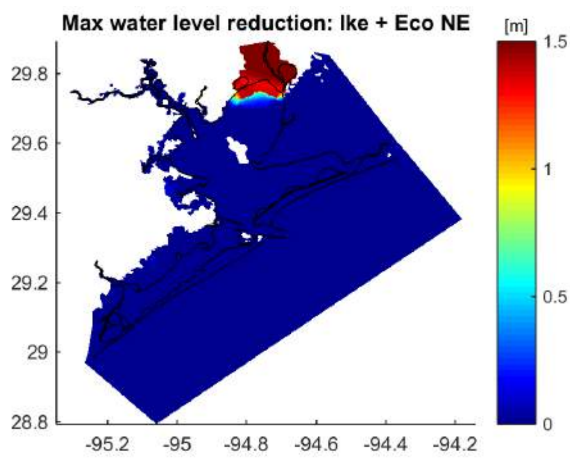
Only results for hurricane Ike will be presented, because Ike shift 2 has already been presented in the main report.

IKE

Northeast simulated with hurricane Ike, see Figure F.22 and Figure F.23.



(a) Maximum water level elevation



(b) Maximum water level reduction for measure

Figure F.22: Maximum water level and maximum water level reduction in Galveston Bay during Ike for Eco-Island Northeast

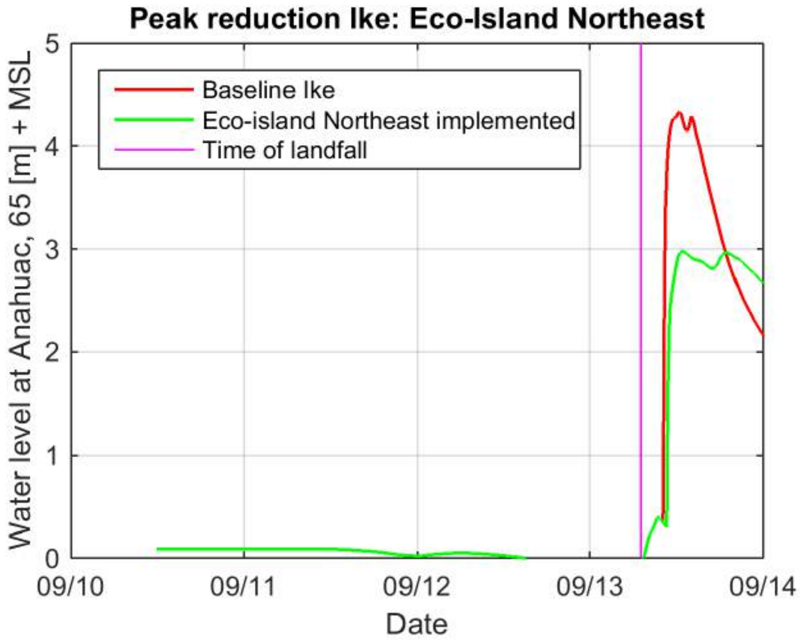


Figure F.23: Time series of water levels during Ike for Eco-Island Northeast and Baseline in Northeast, 65 Anahuac. Measure implemented = green, Baseline = red

F.3. SURGE ALTERNATIVES WITH IKE DIKE

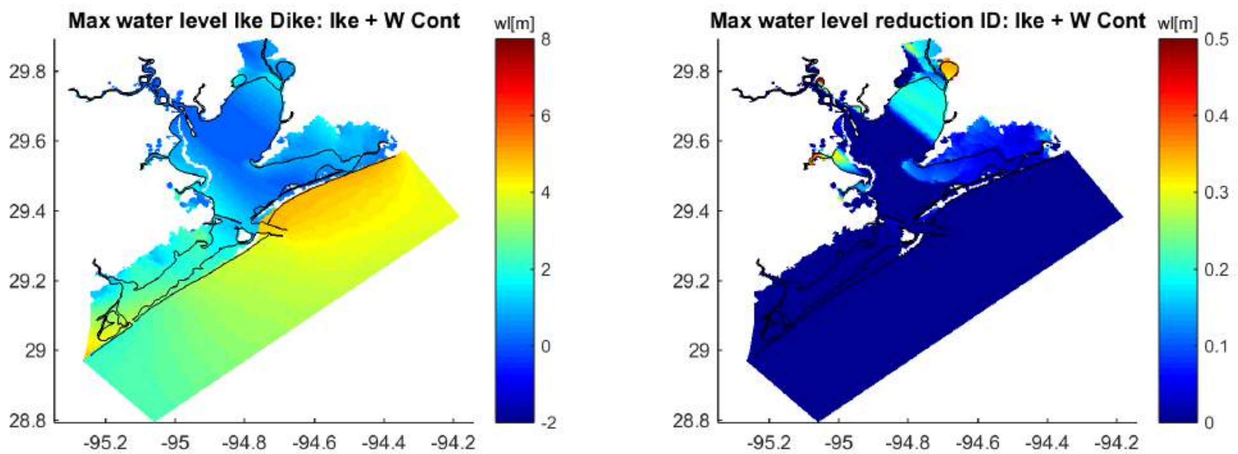
All results for islands and eco-island designs with an Ike Dike in place will be presented in this section.

F.3.1. ISLANDS WEST IKE DIKE

WEST DESIGN CONTINUOUS

IKE

For design continuous simulated with hurricane Ike, see Figure F.24 and Figure F.25.



(a) Maximum water level elevation

(b) Maximum water level reduction for measure

Figure F.24: Maximum water level and maximum water level reduction in Galveston Bay during Ike for West design continuous with Ike Dike

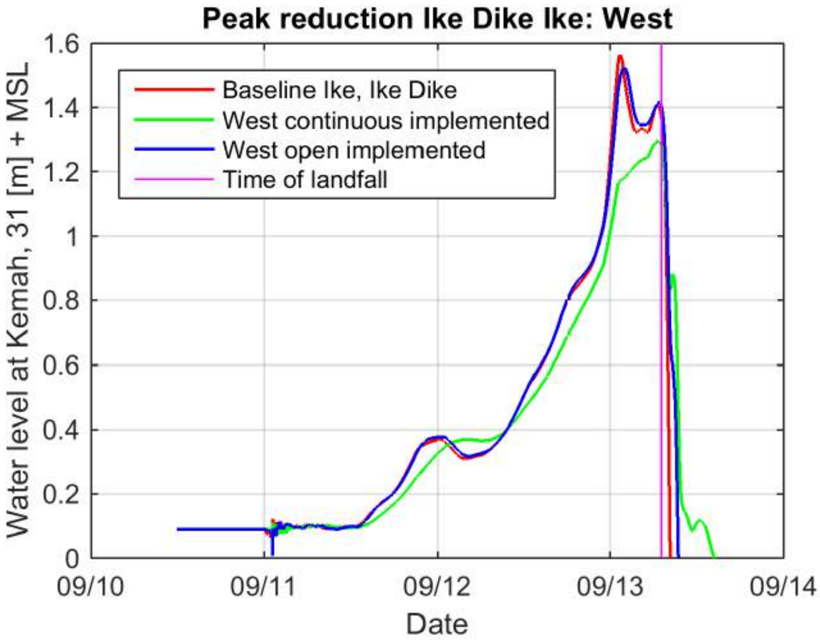
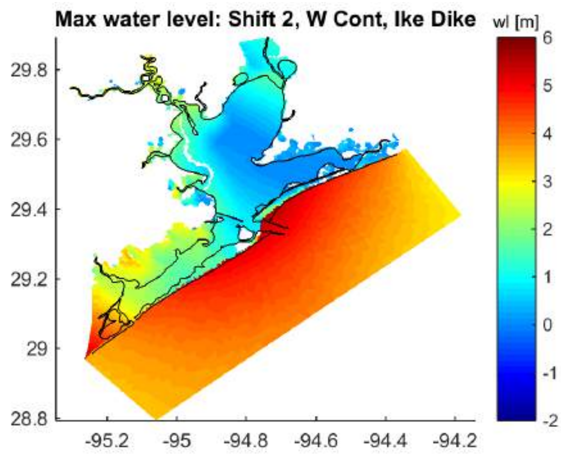


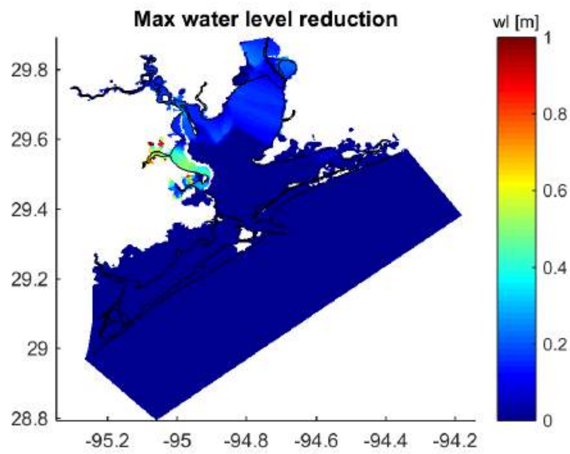
Figure F.25: Time series of water levels during Ike for West design continuous, design open and Baseline Ike Dike in West, 31 Kemah. Design continuous = green, Design open = blue, Baseline Ike Dike = red

IKE SHIFT 2

Design continuous simulated with Ike shift 2, see Figure F.26 and Figure 7.22.



(a) Maximum water level elevation



(b) Maximum water level reduction for measure

Figure F.26: Maximum water level and maximum water level reduction in Galveston Bay during Ike shift 2 for West design continuous with Ike Dike

It can be seen that West design continuous is expected to reduce surge by around **0.3 m** for hurricane Ike and **0.45 m** for Ike shift 2 in the case of an Ike Dike, which is far less effective than the simulations without Ike Dike have shown.

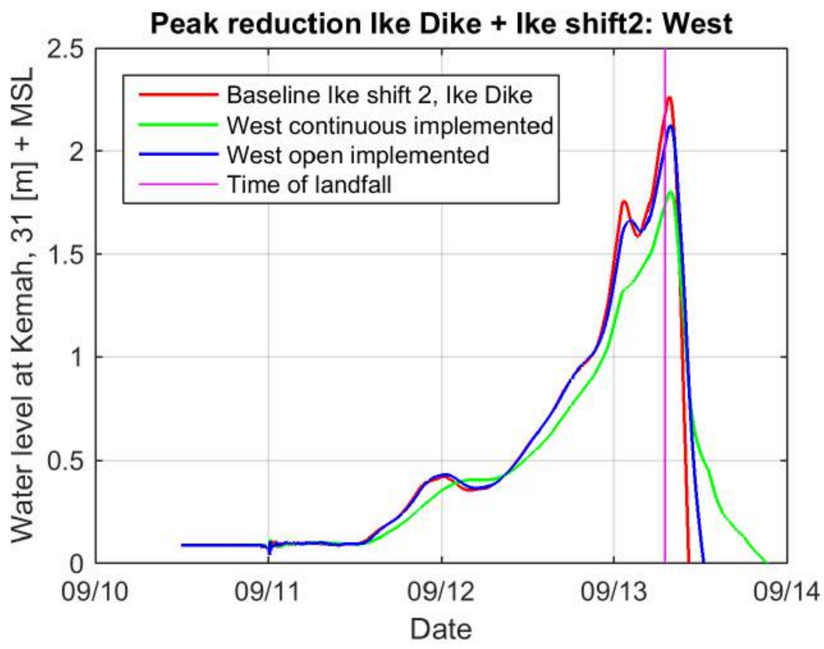
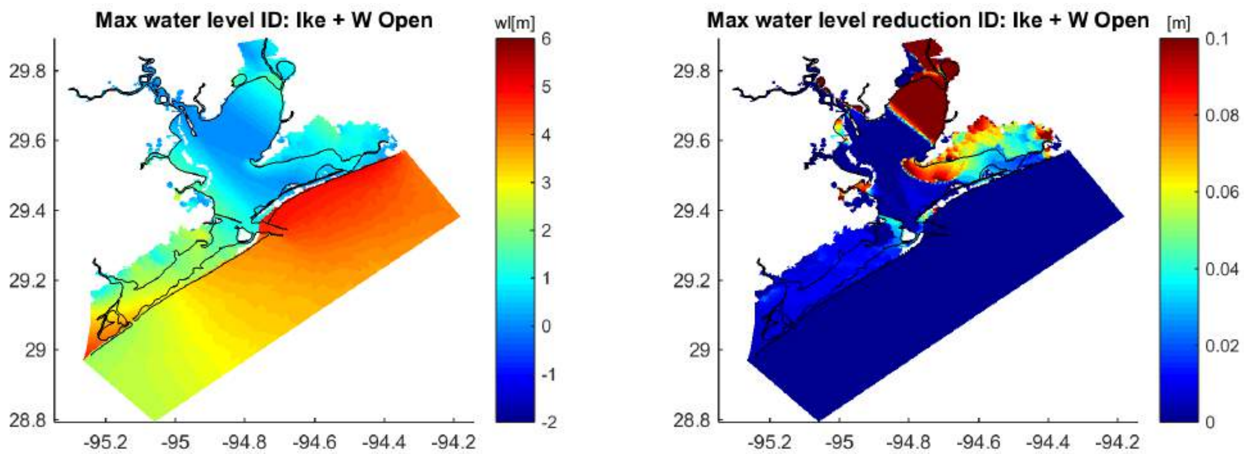


Figure F.27: Time series of water levels during Ike shift 2 for West design continuous, design open and Baseline with Ike Dike in West, 31 Kemah. Design continuous = green, Design open = blue, Baseline Ike Dike = red

WEST DESIGN OPEN

IKE

Design open simulated with hurricane Ike, see Figure F.29 and Figure F.25.



(a) Maximum water level elevation

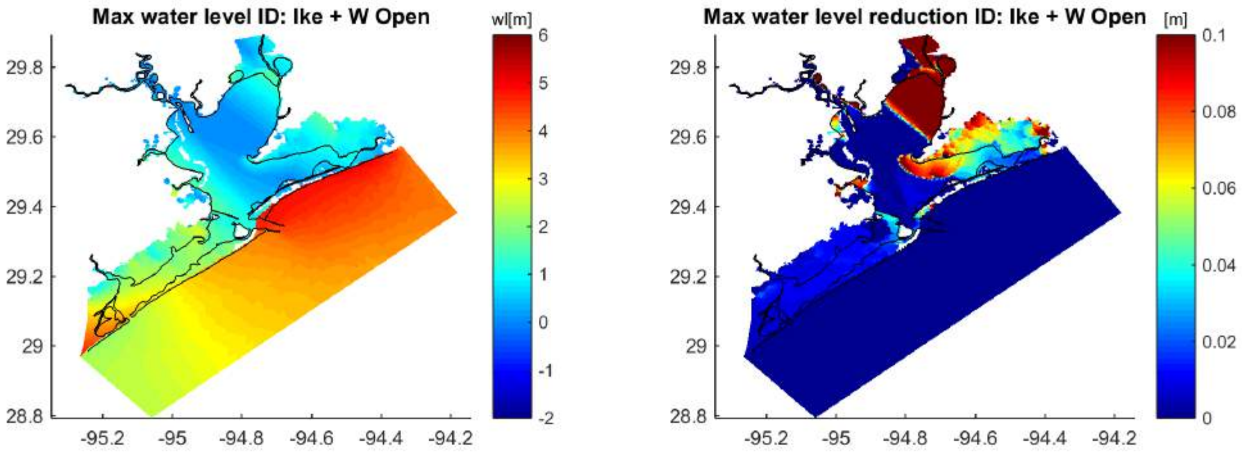
(b) Maximum water level reduction for measure

Figure F.28: Maximum water level and maximum water level reduction in Galveston Bay during Ike for West design open with Ike Dike

IKE SHIFT 2

Design open simulated with Ike shift 2, see **??** and Figure F.27.

These results show that an open design is hardly effective at reducing surge heights induced by wind set-up with an Ike Dike in place, for both storms. For hurricane Ike surge in Kemah is reduced by **0.05 m**, for shift 2 this reduction is **0.15 m**. The effect of design open is even much less than design continuous. Compared to simulations without Ike Dike the results show even less surge reduction by West alternatives with Ike Dike.



(a) Maximum water level elevation

(b) Maximum water level reduction for measure

Figure F.29: Maximum water level and maximum water level reduction in Galveston Bay during Ike shift 2 for West design open with Ike Dike

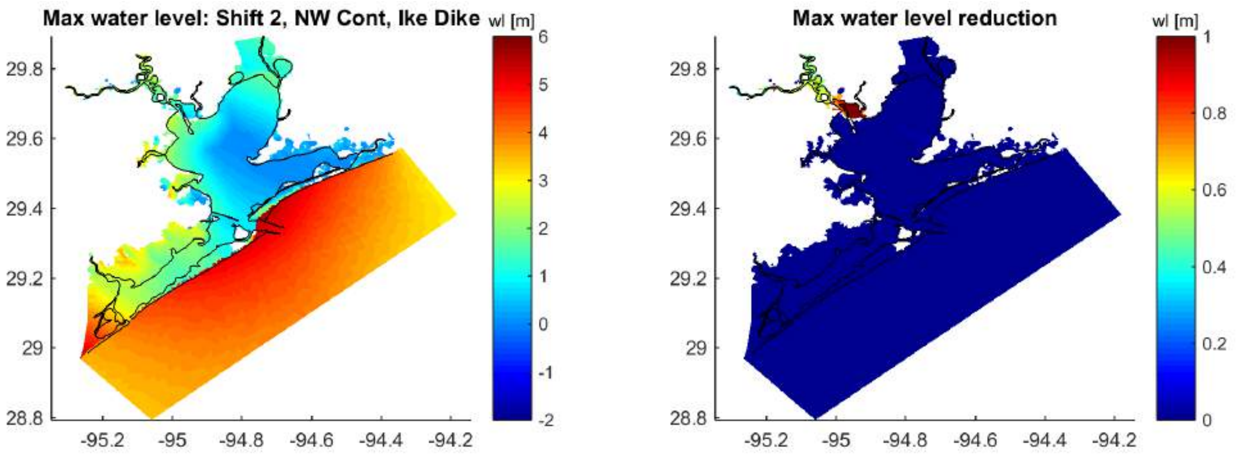
F.3.2. ISLANDS NORTHWEST IKE DIKE

Since hurricane Ike with an Ike Dike does not cause for any surge in the Northwest (blue line in Figure 7.5), only results for Ike shift 2 will be presented.

NORTHWEST DESIGN CONTINUOUS

IKE SHIFT 2

Design open simulated with Ike shift 2, see Figure F.32 and **??**.



(a) Maximum water level elevation

(b) Maximum water level reduction for measure

Figure F.30: Maximum water level and maximum water level reduction in Galveston Bay during Ike shift 2 for Northwest design continuous with Ike Dike

The absolute surge reduction for Northwest design continuous for Ike shift 2 is **0.55 m**.

NORTHWEST DESIGN OPEN

IKE SHIFT 2

Design open simulated with Ike shift 2, see Figure F.32 and Figure F.31. The absolute surge reduction for Northwest Design Open for Ike shift 2 is **0.55 m**.

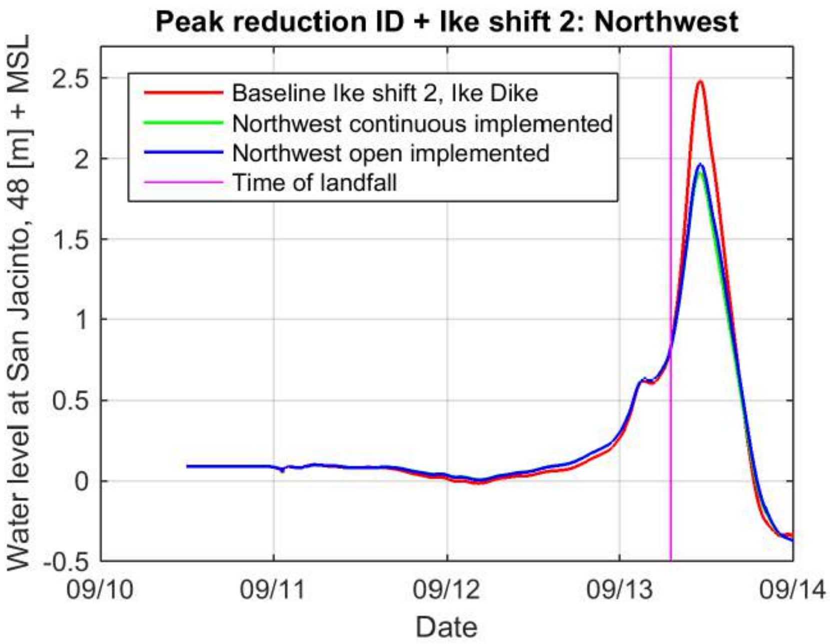
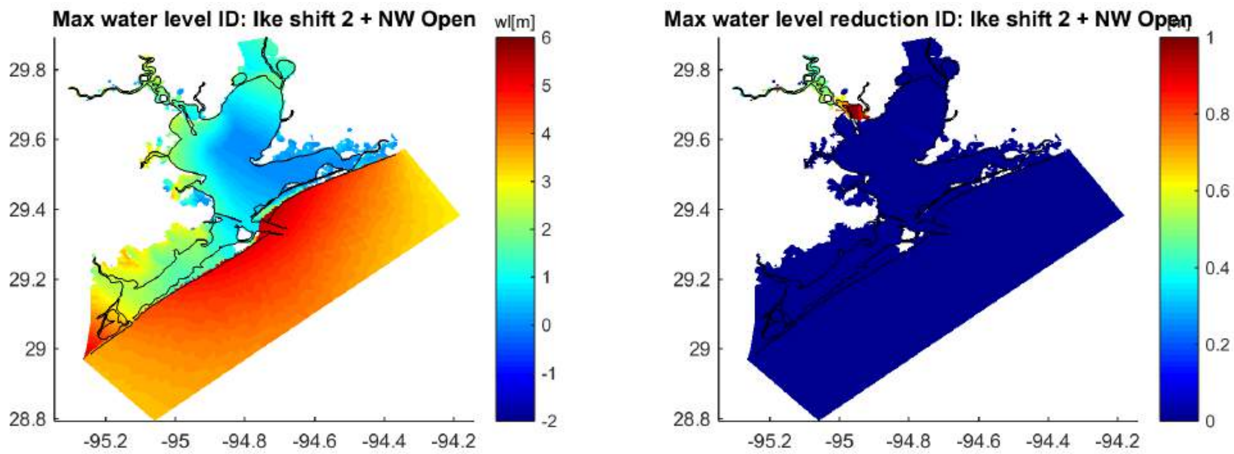


Figure F.31: Time series of water levels during Ike shift 2 for Northwest design open, design continuous and Baseline with Ike Dike in Northwest, 48 San Jacinto Monument. Design continuous = green, Design open = blue, Baseline Ike Dike = red



(a) Maximum water level elevation

(b) Maximum water level reduction for measure

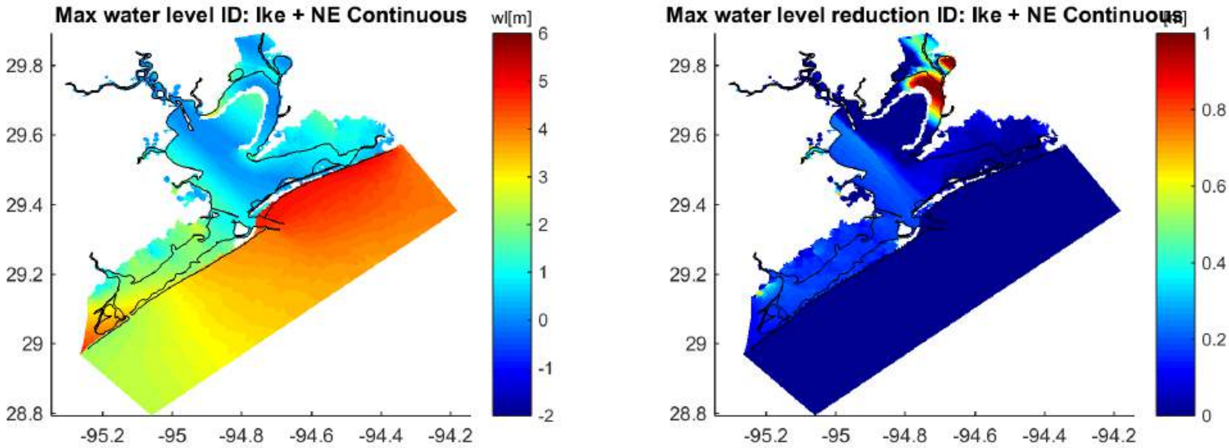
Figure F.32: Maximum water level and maximum water level reduction in Galveston Bay during Ike shift 2 for Northwest design open with Ike Dike

F.3.3. ISLANDS NORTHEAST IKE DIKE

NORTHEAST DESIGN CONTINUOUS

IKE

Design continuous simulated with hurricane Ike, see Figure F.33 and Figure F.34.

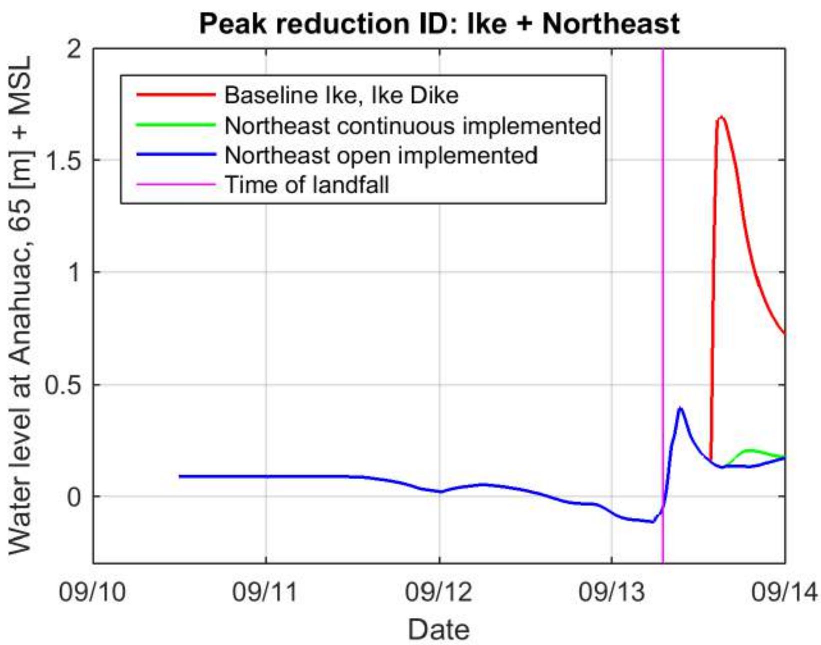


(a) Maximum water level elevation

(b) Maximum water level reduction for measure

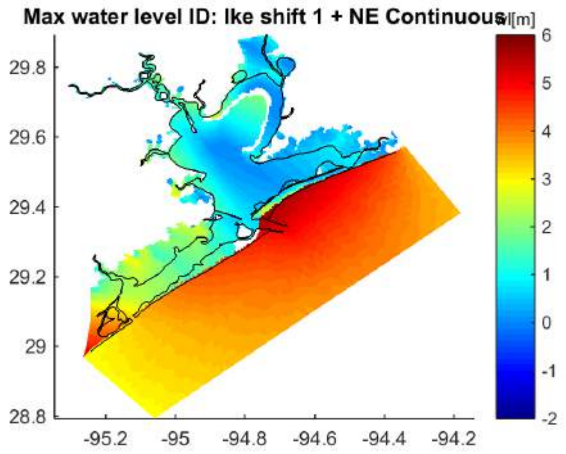
Figure F.33: Maximum water level and maximum water level reduction in Galveston Bay during Ike for Northeast design continuous with Ike Dike

Figure F.34: Time series of water levels during Ike for Northeast design continuous, design open and Baseline Ike Dike in Northeast, 65 Anahuac. Design continuous = green, Design open = blue, Baseline Ike Dike = red

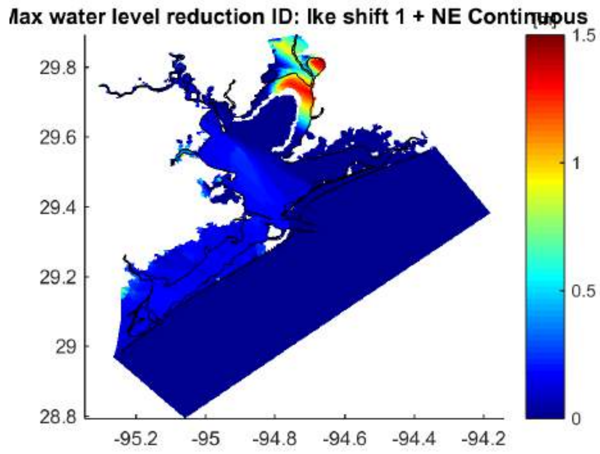


IKE SHIFT 1

Design continuous simulated with Ike shift 1, see Figure F.35 and Figure F.36.



(a) Maximum water level elevation



(b) Maximum water level reduction for measure

Figure F.35: Maximum water level and maximum water level reduction in Galveston Bay during Ike shift 1 for Northeast design continuous with Ike Dike

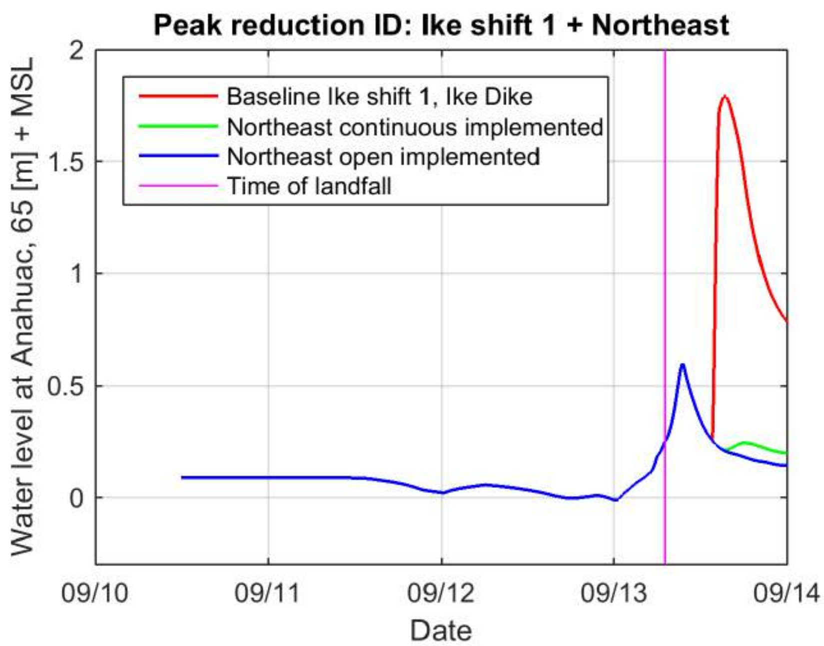


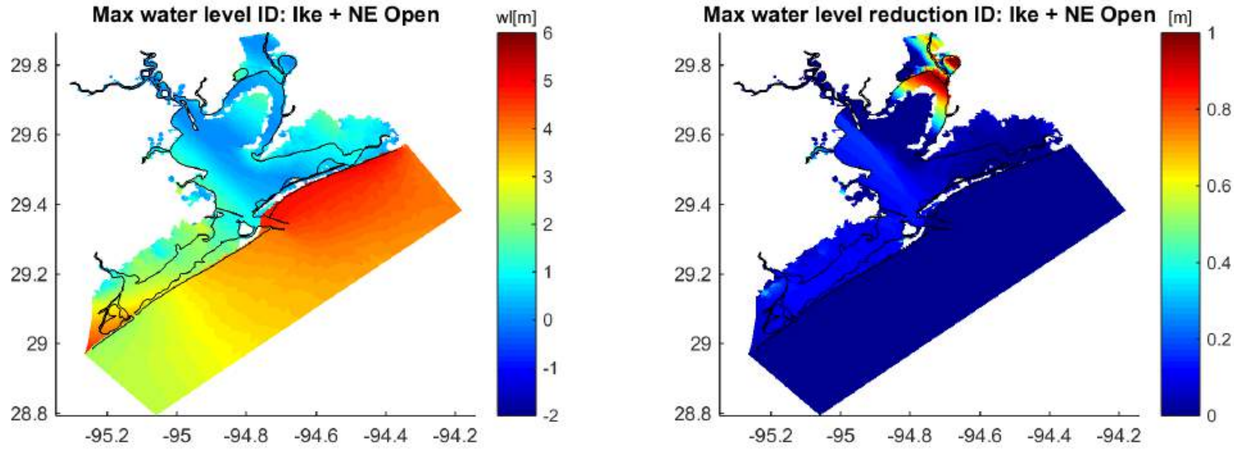
Figure F.36: Time series of water levels during Ike shift 1 for Northeast design continuous, design open, and Baseline Ike Dike in Northeast, 65 Anahuac. Design continuous = green, Design open = blue, Baseline Ike Dike = red

It can be seen that Northeast design continuous is very effective at reducing peak surge levels in the case of Ike Dike, although the absolute reduction much less than in the case without Ike Dike. But the relative reduction is higher. Absolute peak surge reduction for Ike of **1.3 m** and for **Ike shift 1 of 1.2 m**.

NORTHEAST DESIGN OPEN

IKE

Design open simulated with hurricane Ike, see Figure F.37 and Figure F.34.



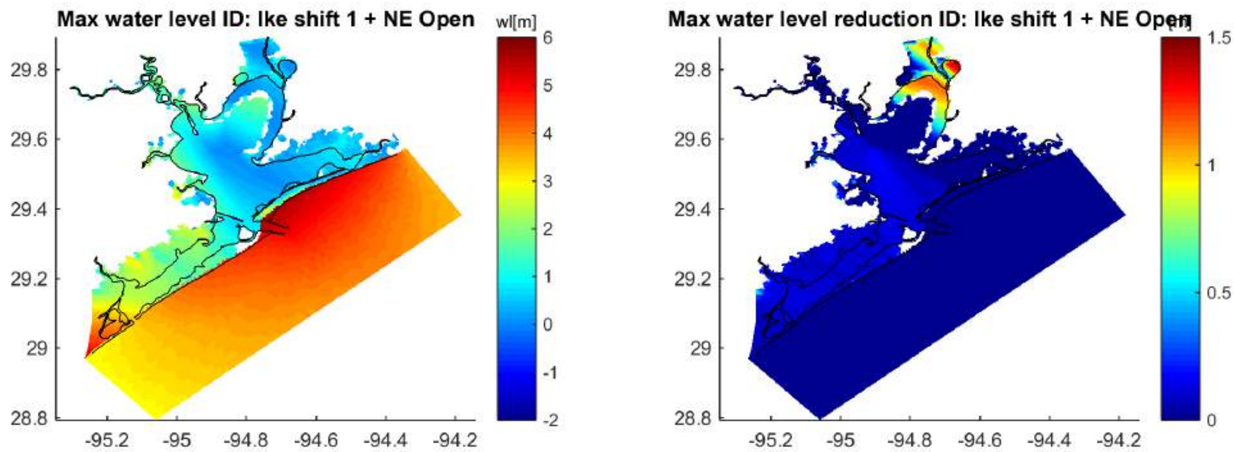
(a) Maximum water level elevation

(b) Maximum water level reduction for measure

Figure F.37: Maximum water level and maximum water level reduction in Galveston Bay during Ike for Northeast design open with Ike Dike

IKE SHIFT 1

Design open simulated with Ike shift 1, see Figure F.38 and Figure F.36.



(a) Maximum water level elevation

(b) Maximum water level reduction for measure

Figure F.38: Maximum water level and maximum water level reduction in Galveston Bay during Ike shift 1 for Northeast design open with Ike Dike

These results show that an open design is exact as effective for peak surge reduction in Anahuac as a continuous design, with a peak surge reduction of **1.3 m** for Ike and **1.2 m** for Ike shift 1. Apparently does an open design have no effect on surge in Anahuac. The difference of these results compared to the case without Ike Dike are not big. The following trend can be observed. An open design and a continuous design are both effective. For hurricane Ike the effectiveness of the alternatives generally increases in case of Ike Dike, for Ike shift 1 the effectiveness generally decreases.

F.3.4. ECO-ISLAND IKE DIKE

ECO-ISLAND WEST

Only water level time series of the observation point 65, Anahuac are shown, no maps of maximum water levels or water level reduction.

IKE

For eco-island West, simulated with hurricane Ike, see Figure F.39.

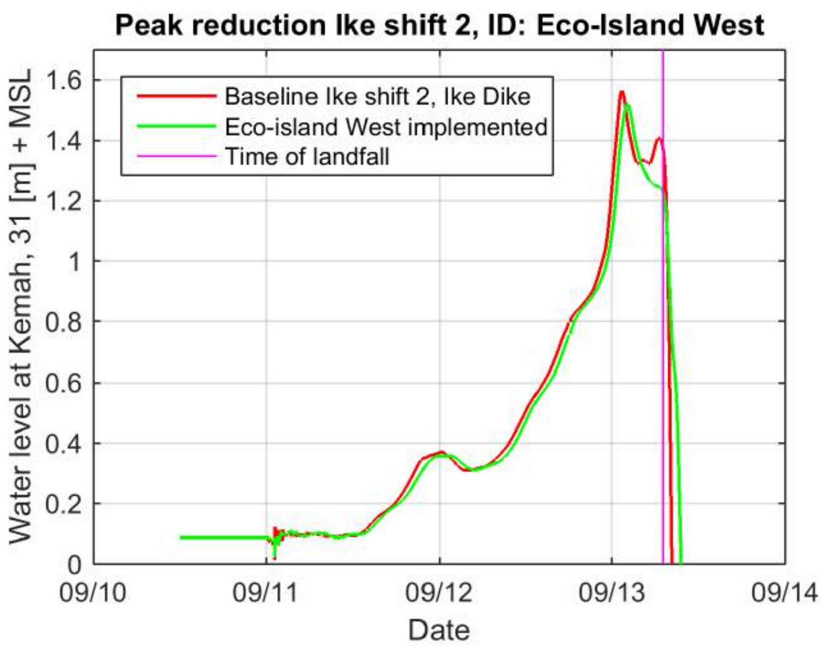


Figure F.39: Time series of water levels during Ike for Eco-Island West and Baseline Ike Dike in West, 31 Kemah. Design implemented = green, Baseline Ike Dike = red

IKE SHIFT 2

For eco-island West, simulated with hurricane Ike shift 2, see Figure F.40.

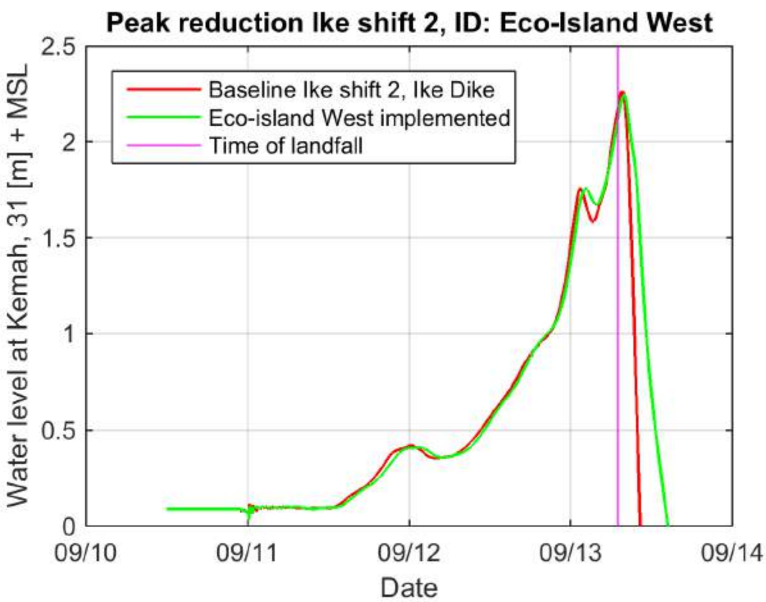


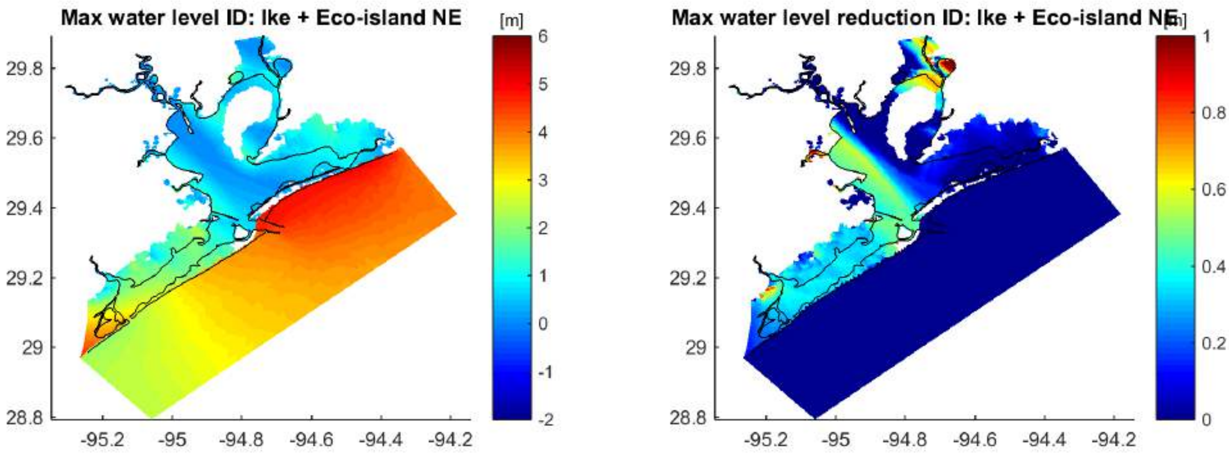
Figure F.40: Time series of water levels during Ike shift 2 for Eco-Island West Ike Dike and Baseline Ike Dike in West, 31 Kemah. Design implemented=green, Baseline Ike Dike=red

For results eco-island West simulated with hurricane Ike shift 2, see Figure F.40. This design, eco-island West does not effect peak surge in the West for both storms Ike and Ike shift 2. Therefore no difference is observed compared to the situation without Ike Dike.

ECO-ISLAND NORTHEAST

IKE

For an eco-island in the Northeast, simulated with hurricane Ike, see Figure F.41 and Figure F.42.

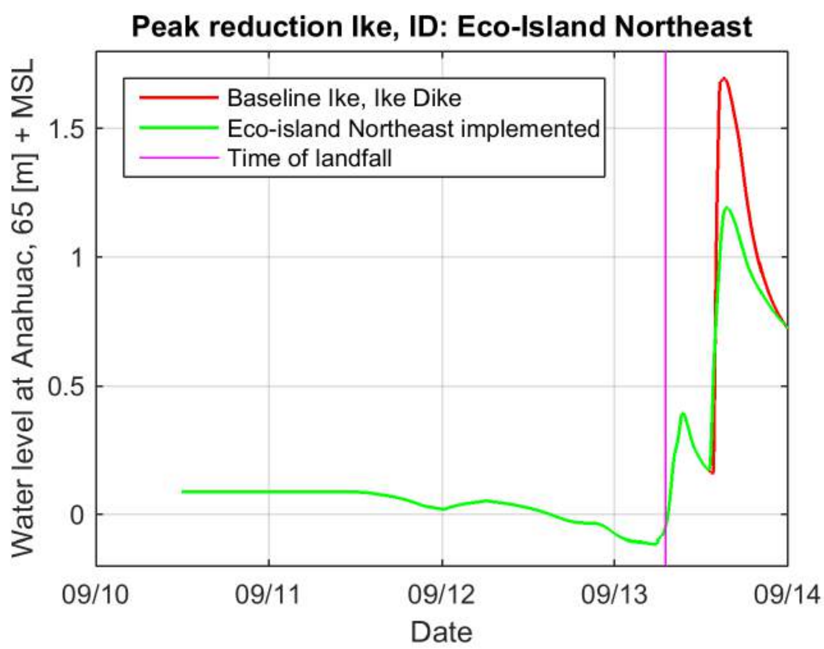


(a) Maximum water level elevation

(b) Maximum water level reduction for measure

Figure F.41: Maximum water level and maximum water level reduction in Galveston Bay during Ike for Eco-Island Northeast with an Ike Dike

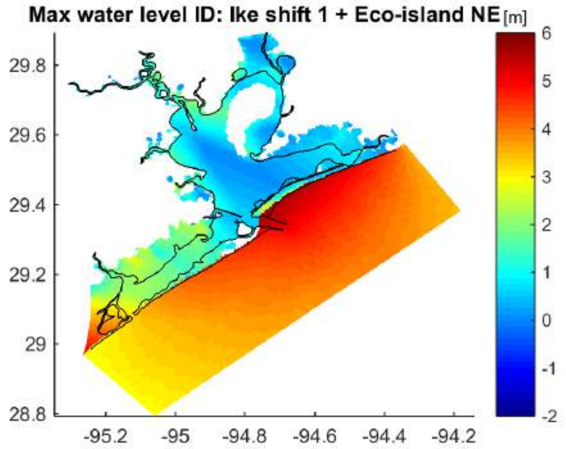
Figure F.42: Time series of water levels during Ike for Eco-Island Northeast and Baseline Ike Dike in Northeast, 65 Anahuac. Design implemented = green, Baseline Ike Dike = red



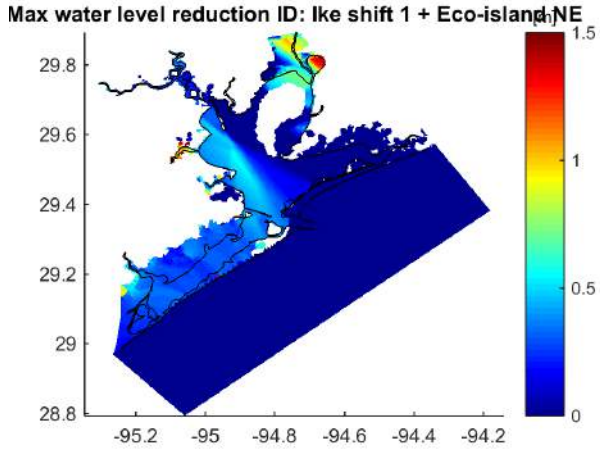
IKE SHIFT 1

For an eco-island Northeast, simulated with hurricane Ike shift 1, see Figure F.43 and Figure F.44.

The peak surge reduction is **0.5 m** for hurricane Ike and even **0.6 m** for Ike shift 1. Absolute differences compared to the situation without Ike Dike are found to be significant. However, the relative surge reduction in the case with Ike Dike is higher.



(a) Maximum water level elevation



(b) Maximum water level reduction for measure

Figure F.43: Maximum water level and maximum water level reduction in Galveston Bay during Ike shift 1 for Eco-Island Northeast with an Ike Dike

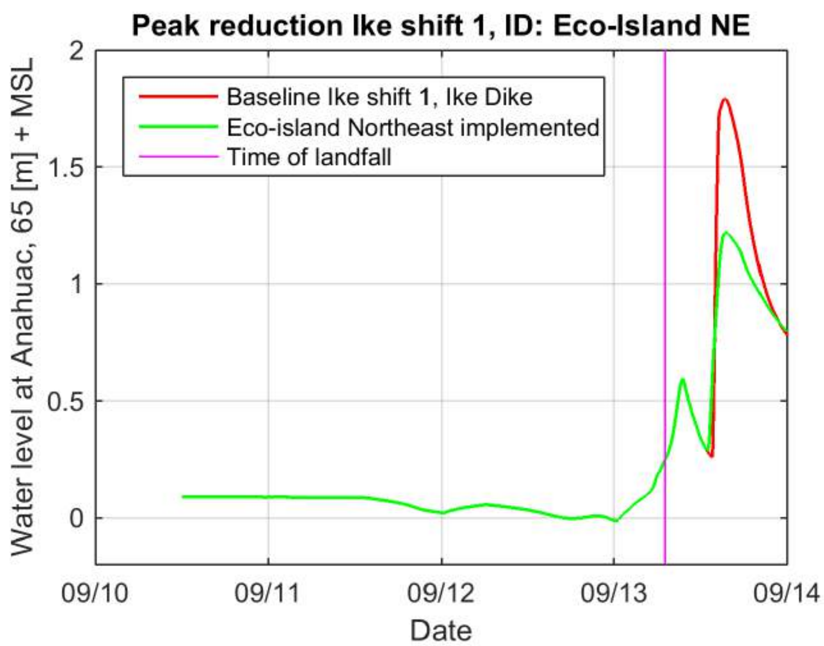


Figure F.44: Time series of water levels during Ike shift 1 for Eco-Island Northeast and Baseline Ike Dike in Northeast, 65 Anahuac. Design implemented = green, Baseline Ike Dike = red