Applying best practices from the Delta Works and New Orleans to Galveston Bay

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Applying Best Practices From The Delta Works And New Orleans To Galveston Bay

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Cover photo: McKay, P. (2008, December) *A beach house on the Bolivar Peninsula near Galveston, Texas, destroyed during Ike*.

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SUMMARY

This report provides a comparison of the Dutch Delta Works, New Orleans and the Ike Dike concept. Methods of research include a study of literature, site visits and personal interviews.

Analyses on regional levels show that the three regions face similar natural threats. The combination of storm surge and local geography results in significant setup during storm events. Along the Gulf coast, the risk of storm surge combined with poor planning and rapid expansion has resulted in a large potential exposure to flooding. Recent research by the Louisiana State University (Needham, unpublished) shows that the Upper Texas Coast is the second most vulnerable stretch of coast along the Gulf of Mexico, when looking at storm surge.

After the disastrous floods in New Orleans (2005) and Galveston County (2008) neglecting flood hazards no longer seems to be an option. Nowadays an advanced system of levees and storm surge barriers protects New Orleans. The Ike Dike is a proposal for a coastal spine designed to protect the Galveston Bay Region, and Upper Texas Coast against storm surge and future sea level rise.

The Greater Houston Metropolitan area excels in growth. The annual growth of the population and the Gross Domestic Product significantly exceeds measured growth in both New Orleans and The Netherlands. Home to some of the largest refineries and the nation's largest tonnage port, Galveston Bay is a region of national strategic importance.

The strategy adopted to protect New Orleans and the Greater Houston Metropolitan originates from the renowned "Best Dutch Practices". All systems shorten the perimeter, keep the surge out of internal waters and ensure passage by using gated barriers. As opposed to New Orleans and The Netherlands, most of the Galveston Bay area is situated above sea level, and does not have a significant outflow of fresh water.

The Ike Dike concept makes use of existing technology to protect America's energy coast economies. Gated barriers similar to those used in the Delta Works and New Orleans ensure passage of ships and allow sufficient natural flow of water in order to preserve the ecology of the Bay. Natural looking levees similar to those found in The Netherlands provide an ecologically sound and visually appealing barrier on the islands. Possible solutions include a "levee-in-dune", a nourished natural dune or raising of the highway. The proposed crest height of the overtop-resistant barriers is NAVD +5.2 meter [17 ft], Ike level, and slightly below the required Base Flood Elevation level. The barrier keeps most of the surge out of the Bay, and thereby effectively prevents flooding by reducing water levels.

The effect of sea level rise and Climate Change on the recurrence intervals of storm surge is uncertain, although the consensus points at a lower recurrence interval for similar water levels. The growth of the Greater Houston Metropolitan is expected to continue, increasing the infrastructure at risk[1].

The Ike Dike protects all of the property surrounding Galveston Bay, including valuable assets along the Houston Shipping channel. At a cost of approximately 6 billion dollars, the Ike Dike requires a significant investment but offers protection to all communities, poor or rich.

[1] Risk is probability multiplied by expected damage

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GLOSSARY OF TERMS AND ABBREVIATIONS

CBA	Cost Benefit Analysis
DIVA	Dynamic Interactive Vulnerability Assessment
FEMA	Federal Emergency Management Agency
BFE	Base Flood Elevation
SRCC	Standard Regional Climate Center
GDP	Gross Domestic Product
HSDRRS	Hurricane and Storm Surge Risk Reduction System
IHNC	Inner Harbor Navigation Channel
MRGO	Mississippi River Gulf Outlet
MSL	Mean Sea Level
NAVD	North American Vertical Datum
NL	Netherlands
NOAA	National Oceanic and Atmospheric Agency
NWC	National Weather Center
Risk	Probability multiplied by expected damage
US	Unites States
USACE	United States Corps of Engineers
USGS	United States Geology Service

1 OUTLINE OF THE STUDY

Background

On September 13, 2008, hurricane Ike made landfall on Galveston Island, Texas. Wind and storm surge resulted in an estimated $24.9 billion dollars of damage (Berg, 2009). Ike's storm surge left almost no structure intact on the Bolivar Peninsula, and inundated the City of Galveston. Ike is the third costliest storm in U.S. history (Berg, 2009), and clearly demonstrated the regions vulnerability to hurricanes.

On February 1, 1953, a historically high storm tide flooded a significant part of The Netherlands. An area of over 1350 square kilometers [521 mi^2] was inundated and over 1800 lives were lost during this national catastrophe (NL-HaNA, 2006). In 2005 hurricane Katrina made landfall New Orleans. Katrina's storm surge caused over 50 levee breaches flooding the city and taking many lives. Hurricane Katrina is the single most costliest natural disaster in American history.

Both the 1953 flood in The Netherlands and the 2005 New Orleans flood triggered unprecedented political and societal responses. Within weeks the Dutch Department of Waterways and Public Works inaugurated the Delta Committee. The Delta Committee received one assignment; find a way to improve flood safety. In New Orleans catastrophic failure forced the U.S. Corps of Engineers to significantly improve and repair the existing system. Dutch engineers offered advice though a series of "Dutch dialogues". Both responses resulted in an advanced surge barrier system to keep future floods at bay.

Objective

The purpose of this study is to investigate the applicability of best practices in surge barrier engineering as seen in The Netherlands and New Orleans. This study tries to answer the following questions;

- What are the similarities and differences between The Netherlands, New Orleans and the Greater Houston Metropolitan on a regional level?
- What are the "best practices" applied in The Netherlands and New Orleans, and how can they benefit the Galveston Bay Area.
- What would a conceptual "Ike Dike" look like, based on these best practices?

Height levels are provided with respect to North American Vertical Datum (NAVD). Costs are converted to USD using an exchange rate of 1 euro to 1.3 dollar. Costs are normalized using the annual Producer Price Index (PPI) (Bureau of Labor Statistics, 2012).

Structure

The main section of this report consists of five individual chapters. This chapter outlines the study. Chapter 2 compares the three region. Chapter 3 clarifies the Ike Dike concept and gives an overview of the storm surge barriers in The Netherlands and New Orleans. Chapter 4 elaborates on the individual components of the Ike Dike, and concludes with a rough cost estimate. Chapter 5 introduces some thoughts on the sequencing of construction works. Chapter 6 presents the conclusion and recommendation.

2 REGIONAL COMPARISON

The purpose of this chapter is to give insight in regional similarities on geographical, economical and social aspects of the three regions. Special attention is given to the most important parameters as used in the discontinued Dynamic and Interactive Vulnerability Assessment (DIVA) Coastal Database (Vafeidis et al, 2008). The DIVA model was part of the DINAS-COAST effort to assess global vulnerability to flooding. These parameters include the Gross Domestic Product, population growth, elevation and possible threats.

Subsection 2.1, 2.2 and 2.3 discuss the three separate regions. Subsection 2.4 presents an overall regional comparison and conclusion.

2.1 The Netherlands

With over a third of land below mean sea level (PBL, 2007), flood control is an absolute necessity for The Netherlands. Over the centuries, windmills, dikes and polders[1] played an important role in Dutch history. The Netherlands has over 16 million inhabitants of which 9 million live in flood prone areas. (CBS, 2012). A sophisticated network of natural dunes, dams, levees and surge barriers protects those citizens and their property. The length of the shoreline is about 400 kilometers [250 mi].

Figure 2-1: Map of the Netherlands. Orange: below mean sea level (based on AHN, 2012).

Water management in The Netherlands is deeply embedded in history and present on multiple levels. Rijkswaterstaat, founded in 1978, is responsible for national water management and national flood protection. Water boards are responsible for the regional waterways and canals. The presence of water boards dates back to the 11th century making them one of the oldest Dutch governmental authorities. Water boards have their own, independent, source of income, citizens within the district of a water board pay a separate tax for local water management.

The governing hazardous events are northwesterly storms that occur on a frequent basis during autumn and winter. The shape of the coastline combined with the shallow North Sea can increase the surge to dangerously high levels. Hurricanes are not likely to occur in the Netherlands but hurricane force winds can occur. The correlation between high river discharge and storm surge is very low (Rijkswaterstaat, 1967).

[1] Area of low-lying land that has been reclaimed from water, often enclosed by an embankment.

The average macro-economic growth between 1980 and 2010 was 2.2% (CBS, 2012). During the same period the total population in the provinces of Zeeland, South-Holland and North-Holland grew by 13.4% (CBS, 2012). Approximately two-third of the GDP is generated in the flood prone western halve of The Netherlands (CBS, 2012). The annual spending on flood defense systems is 0.16% of the GDP (Ministerie van Financien, 2011).

Sea level rise is a threat to the future of The Netherlands. In a response to this new threat the second Delta Committee (2008) published a new long term flood control plan.

2.2 New Orleans

New Orleans, located in the Mississippi delta, is the largest city in the state of Louisiana. Because of its geographical location the New Orleans metropolitan area (Figure 2-2) is prone to flooding by Hurricanes, high river discharge and excessive rainfall. Surrounded by wetlands in the west, Lake Pontchartrain in the North, Lake Borgne in the East and the Mississippi river in the South possible threats may come from any direction. There is a high correlation between hurricanes and high water levels in the Mississippi River. According to the USGS (2012) strong winds and storm surge during Hurricane Isaac resulted in a momentary backward flow of the Mississippi river. A significant part of New Orleans is situated below sea level. New Orleans requires pumping to get rid of excessive water.

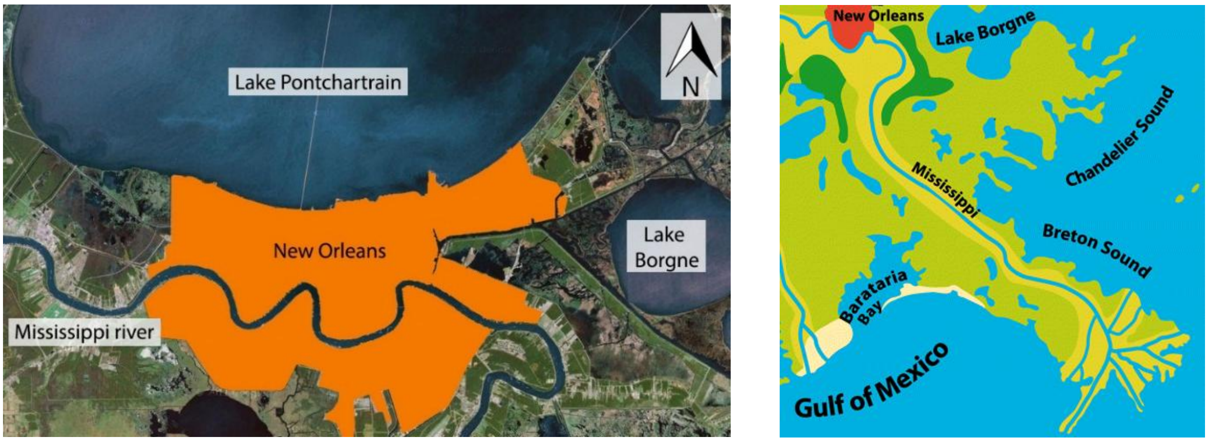

Figure 2-2: left: city of New Orleans (source: googlemaps). right: Mississippi river bird-foot (source: Texas A&M University)

Human intervention has greatly affected the course and shape of the Mississippi deltaic plain. Human efforts to prevent floods date back to the 18th century, whilst the past decade's oil exploration played an important role. Canalization of the river led to the so-called bird-foot (Figure 2-2) delta. Nowadays fresh water flows through the birdfoot towards deeper water as opposed to spreading out over the wetlands. As a result wetlands are degrading, increasing vulnerability to floods.

New Orleans is home to 350.000 inhabitants according to the Census (2010). After Hurricane Katrina the total population decreased by 29% between 2000 and 2010. Before hurricane Katrina there was a slight increase in population. The annual gross domestic product (GDP) of the New Orleans-Metairie-Kenner region is approximately 71.5 billion dollars (Bureau of Economic Analysis, 2011).

Measurements at Grand Isle, Louisiana, show that the average relative[1] sea level rise is 9.24 mm/year [0.35 inch/year] (NOAA, 2012).

[1] Land subsidence and sea level rise.

2.3 Greater Houston Metropolitan

The Galveston Bay estuary is a natural environment that offers a transition between fresh and saline water. The Gulf of Mexico is a micro tidal system and the tidal range is approximately 0.70 [2 ft] meter (Lester; Gonzales, 2002). The estimated surface area of the Bay is 1554 km^2 [600 mi^2]; the length of the shoreline is about 374 kilometer [232 mi] (Phillips, 2004). The inlets are tide governed and have a small net outflow into the Gulf. The yearly averaged fresh water inflow into Galveston Bay is approximately 430 m^3/s [15184 ft^3] (TWBH, 1981). The Trinity River is responsible for 54% of the fresh water inflow in the bay (Lester and Gonzales, 2005). Several other smaller rivers and bayous are responsible for the remaining inflow. Galveston Bay is an important source of oysters and shrimp and one of the most productive estuaries of the United States (TNC, 2012).

Galveston Island and Bolivar Peninsula are classical examples of barrier islands separating the Gulf of Mexico from Galveston Bay. The Islands are a popular holiday destination and are well populated. The average elevation is only 1 to 1.3 meter [3 – 4 ft] (National Geophysical Data Center, 2007) making the islands vulnerable to flooding.

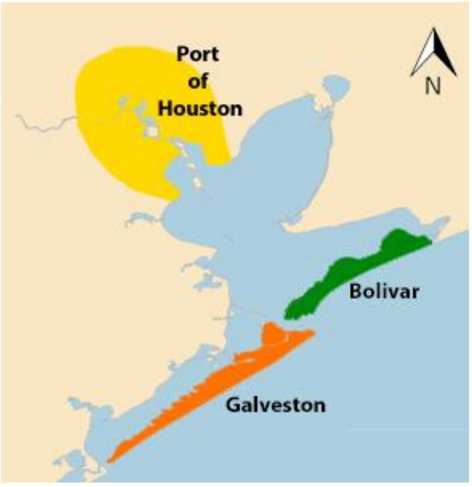

Figure 2-3: Galveston, Bolivar Peninsula and the Port of Houston.

The City of Galveston, population 50.000, is protected against flooding by a 17-foot high seawall on the Gulf side of the City. During hurricane Ike Galveston was flooded from Bay side because of high water levels in the Bay (see Appendix: A). The storm surge preceding a hurricane is able to penetrate into the Bay though the Bolivar Roads inlet, and to a lesser extent by washing over the unprotected barrier islands. Measurements by Kennedy et al. (2010) show that 15 hours before Ike's landfall the forerunner surge (Bunpapong, Reid, & Whitaker, 1985) already exceeded 2.2 meters [7.2 ft]. The early forerunner surge hampered evacuation efforts.

Located on the west-end of Galveston Bay, Texas city is home to a large petrochemical complex and deep-water port. A 27-kilometer [17 mi] network of levees and barriers protect the Texas City petrochemical complex against storm surges (USACE, 2012). Ike severely damaged the Texas City Dike. Texas City's guidelines prescribe that levees must be able to withstand a one in 100-year storm.

The Houston shipping canal, North of Texas City, connects the port of Houston to Galveston Bay. The port of Houston is the second largest port in the United States and its direct economic impact is estimated at 178.5 billion dollars a year (Martin Associates, 2011). The U.S. Coast Guard estimates that a one month closure of the port will cost the national economy $60 billion (USCG). The US Corps of Engineers (2008) expects container trade to expand significantly because of the ongoing expansion of the Panama Canal. There are no levees near the Port of Houston according to the National Levee Database (USACE, 2012).

Wind setup is the main contributor to surges in the Galveston Bay (Reid & Bodine, 1968). Wind setup combined with a higher-than-normal mean water level can lead to considerable flooding. The shape of the Galveston Bay amplifies the magnitude of the surge in the Bay. (Leatherman, 1983) According to Reid and Bodine (1968) the funnel shaped estuaries and bayous increase the surge to a level greater than on the open coast.

The average economic expansion of Texas exceeds the national economic expansion because of its rapidly expanding industry. The Greater Houston region has a GDP of 385 billion a year (Bureau of Economic Analysis, 2011). The average growth of the GDP during 2007 – 2011 was 2.36% per year. The average expected growth during 2012 – 2014 is 4.45% (Glassman, 2012). The economic expansion is expected to continue in the foreseeable future. The 10-county Greater Houston Metropolitan[1] (GHM) is one of the largest contributors to the economic growth of Texas (Greater Houston Partnership, 2012). The 10-county region includes the counties surrounding Galveston Bay. The total population of the Greater Houston area increased by 26.1% between 2000 and 2010 (Census, 2010).

Combining the FEMA flood maps (2011) with a height map of Galveston Bay (National Geophysical Data Center, 2007) and the population data of the five counties surrounding Galveston Bay (Census, 2010) gives some insight in the population at risk. Close to 725.000 people live within the 100-year flood boundary surrounding Galveston Bay. Approximately 686.000 inhabitants live in the 500-year flood zone surrounding Galveston Bay. Building regulations require a minimum floor elevation above the 100-year Base Flood Elevation (BFE) if they are within the 100-year floodplain.

Measurements at the Galveston Pleasure Pier show that the average relative sea level rise amounts to 6.84 mm/year [0.27 inch/year] (NOAA, 2012).

[1] The Greater Houston Metropolitan: Austin, Brazoria, Chambers, Fort Bend, Galveston, Harris, Liberty, Montgomery, San Jacinto and Waller County.

2.4 Comparing the three regions

This subsection analyses the similarities between the three individual regions. Table 2-1 shows a comparison of the level of protection and threats of the three regions. The Netherlands and New Orleans are classical delta systems, whereas Galveston Bay is best described as an estuary. The magnitude of the waves and surge is almost equal in Galveston and The Netherlands. The maximum wave height in New Orleans is mostly fetch limited because of the shape of the system. Wave height in New Orleans is relatively small.

Table 2-1: Threat and risk of The Netherlands, New Orleans and the Greater Houston Metropolitan.

	Risk [per year]	Threat	Surge height [meter]		Wave height [meter]	
Netherlands	1/4.000 – 1/10.000	Storm	5	[16.4 ft]	8 [1]	[26 ft]
New Orleans	1/100	Hurricane	4 - 7.4	[13 – 24ft]	2	[6 ft]
GHM	Not established	Hurricane	5	[16.4 ft]	7 [1]	[23 ft]

Table 2-2 shows the population levels and the Gross Domestic Product (GDP) of the three regions. The total population in New Orleans strongly decreased during the past 10 years. This sudden drop can be attributed to hurricane Katrina. In general the economic development and population growth in the Greater Houston Metropolitan exceeds the growth in The Netherlands and New Orleans.

Table 2-2: GDP and population development of The Netherlands, New Orleans and the Greater Houston Metropolitan.

	GDP (2010) Billion $	GDP Growth	Population in surge zone (2010)	Population growth (2000 - 2010)
Netherlands	704.1	2.2 %	9.000.000	5.1 %
New Orleans	71.5 [2]	2.2 % [2]	350.000 [2]	- 29 % [2]
GHM	385	4.45 % [3]	1.400.000	26.1 %

A significant part of New Orleans and The Netherlands is situated below sea level. In case of inundation or excessive rainfall pumps are required to prevent flooding. In New Orleans many pumps were damaged during Katrina, resulting in long duration flooding (USACE, 2011). A longer flood duration increases the risk of damage to specific construction materials because of saturation or mold. (FEMA, 2006) The Galveston Bay area features low laying barrier islands and marshes. According to the Texas 1/3 arc second DEM the Greater Houston Metropolitan does not contain inhabited areas that are below sea level (National Geophysical Data Center, 2007). Any excess water because of storm surge is able to run off freely. Long lasting floods are not likely to occur in the Galveston Bay area.

[1] Deep water wave height according to Jin et al (2010), near shore waves are lower because of depth induced breaking.
[2] Numbers influenced by hurricane Katrina
[3] Predicted growth 2012 - 2018

New Orleans is surrounded by marshes and wetlands. There are no significant wetlands or marshes in the Dutch coastal zone. Whereas wetlands can be very valuable nature wise, their ability to decease storm surges is uncertain. Often surge reduction is based on the US Army Corps of Engineers rule of thumb, 1 meter [3 ft] per 14.5 kilometers [9 mi] of marsh. (USACE, 1963) In reality, surge attenuation appears to vary widely (Resio and Westerink, 2008). According to Masters (2009) wetlands are only effective for small storm surges occurring within a limited timeframe. Wamsley et al. (2010) conclude that wetlands have the ability to reduce storm surge but that much depends on local bathymetry, topography and storm parameters. Dunes are another effective way to reduce storm surge. In The Netherlands active sand nourishment combined with natural beach reinforcement aids the growth of dunes.

Insuring flood risk in the U.S. is possible by means of the National Flood Insurance Program (NFIP). Established by the U.S. congress in 1968 this national insurance policy offers home and business owners the opportunity to purchase coverage for water damage. In contrast to the U.S. it is not possible to obtain an insurance on flood damage in The Netherlands (Consumentenbond, 2011). The National Disaster Damage compensation act offers a compensation in case of flooding. The National Disaster Damage act is more or less comparable to an obligatory national flood insurance. Table 2-3 sums up the conclusions of the previous paragraphs.

Table 2-3: Environment.

	Wetland / Marsh	Below sea-level	River discharge	Ongoing subsidence
Netherlands	No	Yes	Yes	Yes
New Orleans	Yes	Yes	Yes	Yes
GHM	Yes[1]	No	Some	Yes

The Netherlands, New Orleans and the Greater Houston Metropolitan area all face the threat of Climate Change. Climate Change influences the weather although it is not clear if hurricanes will be stronger or have a larger probability of occurrence in the future. Sea level rise remains a threat to the three regions, and the average yearly sea level rise is expected to increase during the coming decades. (Henson, 2008)

[1] Only inside Galveston Bay.

3 SURGE BARRIER SYSTEMS

This chapter focuses on the structural solutions applied after the flood disasters in the three regions described in chapter 2. Sections 3.1 and 3.2 elaborate on the already completed Delta Works and New Orleans HSDRRS. Section 3.3 explains the Ike Dike concept. Section 3.4 gives an overall comparison of the various systems and the individual barriers.

3.1 Dutch Delta Works

On February 1, 1953, the greatest catastrophe in recent Dutch history resulted in over 1800 causalities and immense economic consequences. Just weeks after the 1953 flood, the freshly installed Delta Committee received the task to investigate how to prevent such a catastrophe in the future.

The Delta Committee presented two possible solutions; improving the existing system of levees, or building a completely new system. The second alternative would imply closing several estuaries including the Eastern Scheldt estuary, and thereby reducing the length of surge barriers from 900 kilometers [560 mi] to approximately 200 kilometers [125 mi]. Improvement of the existing system proved to be very difficult because of presence of harbors, villages and infrastructure. In addition, a longer system of levees has a higher risk of failure because of the higher probability of weak spots. The new and shorter system was preferred over the improvement of the existing system (Deltacommissie, 1961).

Before 1953, levees were built as high as the previously known highest watermark. The Delta Committee proposed to determine the optimal safety level based on a cost benefit analysis (Dantzig, 1956). A higher surge barrier requires a larger investment and reduces the risk of flooding. By adding up the costs of the investment to the expected damage and by relating this total cost to a safety level, an optimum investment can be derived (Figure 3-1). This theorem assumes levees only fail because of overflow or breaching.

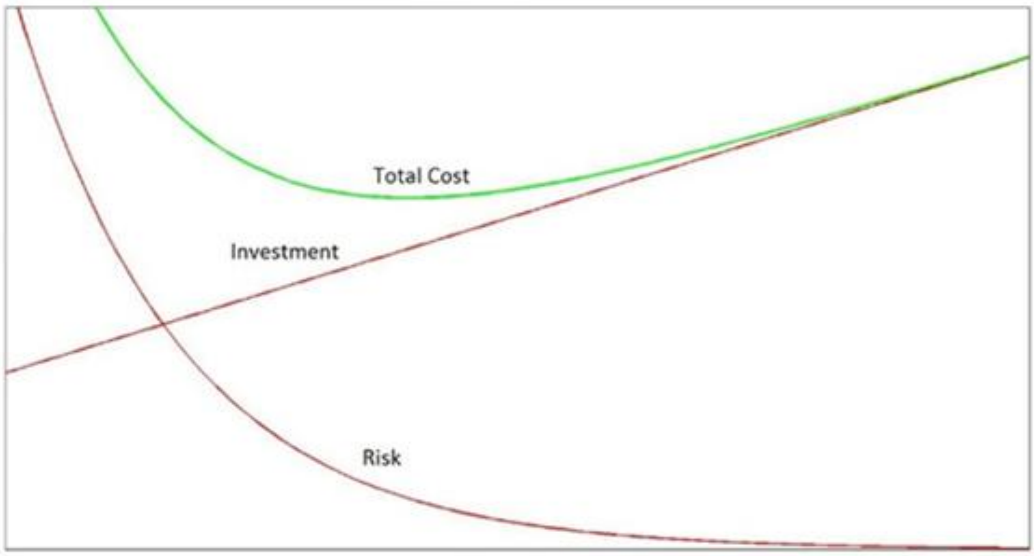

Figure 3-1: Cost Benefit with optimum (Dantzig, 1957) y-axis: cost x-axis: height of levee.

The Flood Defense Act (1996) formalizes the Dutch standards on flood safety and prescribes a required safety level based on the cost benefit analysis mentioned above. The estimated safety of the pre 1953 levee system was approximately 1:300 year storm (Deltacommissie, 1961). According to the Flood Defense Act (1996) the most valuable areas should be protected against a 1:10000 year storm. Less valuable compartments should have a safety level of 1:4000. Given the economic growth during the last decades, it is debatable whether this requirement is still sufficient (Eijgenraam, 2006).

The delta works as proposed by the Delta Committee were completed in 1997. The estimated present day value of the investment is $15 billion dollars. Figure 3-2 gives an overview of the Dutch Delta Works.

Figure 3-2: Dutch Delta Works (deltawerken.com)

The Eastern Scheldt (“Oosterscheldedam”) barrier is a compromise between an ecologically healthy system and reducing flood risk. Initially, the plan was to close off the estuary with a dam (Deltacommissie, 1961). After concerns were raised by environmentalists and fishermen the Dutch parliament opted for vertical lifting gate structures. Large pre-cast elements were used during construction. In total there are 62 flow openings of 40 meter [131 ft] each. The gates are up to 12 meters [40 ft] high and close once a year on average. The Eastern Scheldt barrier reduced the tidal prism by approximately 20% resulting in degrading intertidal flats (Adriaanse; van Zanten, 2008). The Volkerakdam forestalls fresh water inflow into the Eastern Scheldt. Nowadays, the Eastern Scheldt consists of several compartments. The compartments increase flood safety and play an important role in water control. A secondary function of the Eastern Scheldt barrier and most compartment dams is their use as highways.

The New Waterway (“Nieuwe Waterweg”) is an artificial river mouth and an important navigation canal to the port of Rotterdam. The discharge is always higher than 1500 m3/s [53000 ft^3/s] to prevent salinization upstream, which would endanger the supply of fresh drinking water (Rijkswaterstaat, 2011). A floating sector gate barrier, The Maeslantbarrier, located near the mouth of the New Waterway, protects the city of Rotterdam against up to 5 meter [16.4 ft] stormtide. The barrier does not obstruct shipping. The barrier closes automatically when the predicted water level exceeds 3 meter [10 ft] above normal. The 360 meter [1180 ft] wide Maeslantbarrier consists of two floating gates and can be closed in 1.5 hours. The gates have closed once every ten years on average.

3.2 New Orleans Hurricane and Storm Damage Risk Reduction System

After Hurricane Katrina the Netherlands Water Partnership (NWP) was commissioned by the U.S. Army Corps of Engineers to carry out a research project named “A Dutch Perspective on Coastal Louisiana”. The purpose of this report is offering a Dutch perspective on reducing hurricane surge risk. Its main conclusions are (Dijkman, 2007);

- protect New Orleans by constructing a ring of levees around the city,
- make use of individual compartments to limit damage in case of failure,
- reduce the length of barrier system by closing canals with gates,
- improve health of marshlands and swamps to reduce surge and improve ecology, and
- close the connection between Lake Pontchartrain and Gulf of Mexico.

The $15.4 billion dollar HSDRRS barrier system, largely completed in 2008, satisfies all but the last point of advice. The total length of the system is reduced from 320 [200 mi] to 210 kilometer [130 mi] (Durham-Aguilera, 2011).

To reduce damage in case of failure three separate compartments divide central New Orleans. A system of levees protects the individual compartments against flooding. Movable Floodgates in the Inner Harbor Navigation Channel (INHC) and the Mississippi River Gulf Outlet (MRGO) provide safety and navigability. The navigable Seabrook surge barrier protects the Lake Pontchartrain entrance of the IHNC. The total system consists of three canal closure structures and four gated outlets (USACE, 2010). Four federal and 73 non-federal pumping stations prevent flooding during significant rainfall events (USACE, 2010). Lake Pontchartrain is still connected to the Gulf.

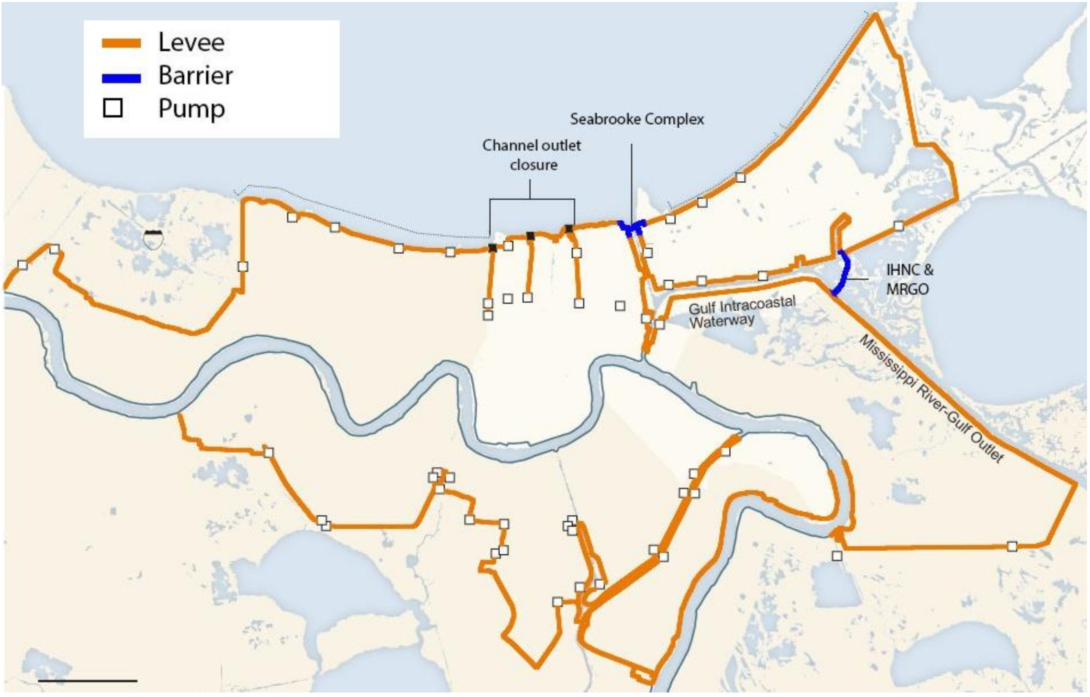

Figure 3-3: Map of the New Orleans HSDRRS Flood protection system. (Modified from NY Times)

The new system is designed to withstand the 1/100 year storm event in 2057. According to Jonkman et al. (2008) the estimated economically sound protection level for central New Orleans dike ring (compartment) would be of about of 1/5000 per year.

3.3 The Ike Dike

The damage caused by Hurricane Ike in 2008 motivates the Ike Dike proposal. Although Ike resulted in severe damage to the Galveston and the Bolivar Peninsulas, it did not cause severe damage to the Port of Houston and its refineries. A major hurricane with a "less fortunate" track might severally damage the critical industries along Galveston Bay resulting in a national catastrophe[1]. In this paper the proposed solution uses existing technology to prove the concept. Other techniques might be chosen for its final design. Based on lessons learned in The Netherlands and New Orleans, the Ike Dike should adhere to the following four principles;

- shorten the perimeter of the flood defense system as much as possible,
- keep the surge out of internal waters,
- use gated barriers to allow shipping, and,
- conserve and/or improve the ecology of the bay.

The initial surge preceding a hurricane causes increases water levels in the Galveston Bay. Channeling amplifies the wind-induced setup in the Bay. A higher surge requires a higher levee or barrier to obtain the same level of safety. Surge levels inside the Bay in general exceed surge levels outside the Bay. Surge levels in the Bay are expected to be significantly lower if the initial surge is kept out of the Bay. A combination of levees, floodwalls and gates on and between the barrier islands shorten the perimeter of the protected coastline whilst keeping the surge out of the Bay. By using the barrier islands as places to place levees the Ike Dike takes advantage of the regions geography.

One of the lessons learned in The Netherlands is that a complete closure has major implications on ecology. The Ike Dike ought to be a combination of an open and a closed system. It should allow free exchange of water, sediment and species between the Gulf of Mexico and the Bay. Movable floodgates should close off existing inlets during storm conditions. During normal conditions the floodgates allow free water flow and assure passage of large vessels. This is a similar strategy as used in New Orleans, and by the Dutch. The conceptual coastal spine consists of 100 kilometer [62 mi] of levees, and up to two gated passages (Figure 3-4).

Figure 3-4: proposed location of the coastal spine (source: W. Merrell, 2010).

[1] The Port of Houston is home to the nation's largest refineries and capable of producing up to 40% of the nation's petrol and chemicals.

On average a major hurricane makes landfall on the upper Texas shore every 15 years. Major hurricanes are classified as rare events because of their low frequency of occurrence. It is a challenge to relate a storm surge height to a long-term return period because of the limited number of events.

The Upper Texas Coastline is amongst the most surge prone areas according to SURGEDAT (Needham, unpublished), a historical storm surge database based on verified surge levels. The recurrence interval of a landfall on the Upper Texas Coast is equal to the average of the Gulf of Mexico (NHC, 2012). When looking at storm surge the Upper Texas Coast is the second most vulnerable coastline after the New Orleans delta. The estimated once per 100-year surge, obtained through a SRCC linear analysis, is 6.3 meters [21 ft]. The 100-year Base Flood Elevation (BFE) level on the Bolivar Peninsula, including wave action, is 5 to 5.5 meters [16.4 – 18 ft], depending on the distance to the shoreline (Institute for Business & Home Safety, 2009).

The probability of a significant surge somewhere on the Texas coastline is larger than the probability of a significant surge on the Galveston coast. This might explain the difference between the return period and surge height in the regional model of Needham (unpublished), and the local base flood elevation level.

During hurricane Ike portable depth gauges measured a still water height of NAVD+ 4.5 meter [15 ft] on the Bolivar Peninsula. The highest water marks collected ranged between 5.5 meter [18 ft] and 6.2 meter [20.5 ft]. (USGS, 2008)

The Ike Dike should be at least “Ike proof”. The design height and related return period of the surge is an important design question requiring further research. It is questionable whether the system should block the entire surge. A leaky system designed to withstand overtopping might prove to be a valid alternative. Because slight increase in water levels in Galveston Bay would not induce flooding. Table 3-1 gives an overview of important elevations.

Table 3-1: Important height levels in NAVD88.

Level	Height
Mean Sea Level (MSL)	NAVD +0.5 meter [1.6 ft]
FEMA minimum floor level	NAVD +5 to NAVD +5.5 meter [16.5 - 18 ft]
Ike storm surge	NAVD +4.5 to NAVD +5 meter [15 - 16.5 ft]
Ike highest water mark	NAVD +5.5 to NAVD +6.2 meter [18 – 20 ft]

3.4 Comparing the Ike Dike with the Delta works and HSDRRS

The areas protected by the three individual barrier systems are densely urbanized areas with high economic values. In The Netherlands, New Orleans and Houston, navigable barriers provide access to important ports and waterways behind the barriers. In The Netherlands surge barriers are a compromise between an ecologically healthy system, and reducing flood risk. Restoration of marshland and improving ecology is an important part in reducing flood risk in New Orleans. The Ike Dike ought to change ecology as little as possible.

Table 2-1 taught us that the design conditions are more or less similar. The three systems are navigable and face a storm surge of approximately 5 meter [17 ft]. The Delta works, HSDRRS and Ike Dike follow most of the "Dutch best practices" as presented in Table 3-2. The Ike Dike concept does not make use of ring levees to divide the area into several compartments. Ring levees are effective in limiting flood damage by decreasing the area protected by a stretch of levee. Ring levees are most effective when the protected area is situated below sea level. A single beach would implicate flooding of the entire protected area. The Galveston Bay Region is does not contain areas that are kept dry using pump. In addition, one could look at Galveston Bay as a large retention pond in case of local failure. Ring levees are not required in the Galveston Bay Region.

Table 3-2: Similarities between Delta Works, New Orleans HSDRRS and the Ike Dike.

"Best practice"	Delta works	New Orleans	Ike Dike
Shorten perimeter	Yes	Yes	Yes
Keep surge out of internal waters	Yes	Yes	Yes
Close inlets with gates	Yes	Yes	Yes
Based on economic analysis	Yes	No[1]	Yes
Ring levees / Compartments	Yes	Yes	No

Galveston Bay is an estuary, not a delta. Galveston Bay features less inlets and channels as compared to The Netherlands and New Orleans, and there is no significant outflow of fresh water. In general, the system is less complex.

The Dutch Delta Committee advised to build a new barrier system as opposed to upgrading levees. Building a new system allows a shorter perimeter and does not require expensive land acquisition. The US Corps of Engineers upgraded and expanded the existing levee system in New Orleans requiring expensive land acquisition from private parties. In New Orleans, improving the existing system was the only option because of local geography. The Ike Dike makes use of beach and existing highways. If one raised the highways, some land acquisition is required.

[1] The HSDRRS is a direct result of hurricane Katrina, a cost / benefit analyses was made but not governing in the barrier / no barrier decision.

Table 3-3 gives an overview of the movable storm surge barriers. The cost estimates of the barriers are obtained through Dircke et al. (2012) and USACE. Section 4.5 presents a cost estimate of the required barriers. The Ike Dike sector gate is larger than the New Orleans Sector gates but smaller than the Dutch sector gates.

Table 3-3: Overview of movable storm surge barriers.

Barrier name	Type	Completed	Approximate value in 2010 [million dollar]	Width [m]	Hydraulic head [m]
Netherlands					
Maeslant barrier	Floating sector gate	1997	709 [1]	360	5
Easternscheldt barrier	Vertical lift gate	1986	5005 [1]	2400 [2]	5
Hartel barrier	Vertical lift gate	1997	100	148	3 [3]
Hollandse Ijssel barrier	Vertical lift gate	1958	127 [1]	80	5
New Orleans					
IHNC	Sector gates & floodwall	2010	1318 [1]	2900 [2]	7.5 [4]
Seabrooke	Vertical lift / sector gates	2010	165 [3]	130 [2]	4
Harvey	Sector gate	2010	43.2 [4]	25	4
Caernarvon	Sector gate	2010	20.2 [4]	18	9
Ike Dike					
Bolivar Sector gate	Floating sector gate	-	Chapter 4	180 - PANAMAX	5 [5]
Bolivar Barge gate (x2)	Vertical lift gate	-	Chapter 4	60	5 [5]
Bolivar inlet gates	Vertical lift gates	-	Chapter 4	2000 [2]	5 [5]
San Luis Pass gate	Vertical lift gate	-	Chapter 4	30	5 [5]
San Luis Pass inlet gates	Vertical lift gates	-	Chapter 4	800 [2]	5 [5]

[1] According to Dircke et al. (2012). Cost of IHNC is cost of entire structure.
[2] Consists of multiple smaller gates
[3] Spilling barrier design.
[4] According to USACE.
[5] Based on hurricane Ike and the height of the existing Sea Wall.

4 THE IKE DIKE:

This chapter contains a variant of the Ike Dike based on the principles of section 3.3. The most important principle is to keep the surge out of the Bay. The Ike Dike alternatives presented in this chapter represent preliminary and alternative concepts. These concepts are some of the possible solutions. The purpose of this chapter is to present a conceptual solution including a coarse cost estimate. Section 4.1 elaborates why the Ike Dike works. Sections 4.2, 4.3, and 4.4 treat the various elements of the Ike Dike. Section 4.5 gives a coarse cost estimate of the Ike Dike.

As stated in section 3.3 the Ike Dike should at least be able to withstand a surge equal to Ike's surge. In this chapter the Ike surge is used as the design surge for a conceptual Ike Dike. Elevations are given with respect to North American Vertical Datum (NAVD88). Mean sea level (MSL) is equal to NAVD +0.5 meter.

4.1 Wind setup and the Ike Dike

One of the most important tasks of the Ike Dike is to keep storm surge out of Galveston Bay. By keeping the storm surge out of Galveston Bay the water levels remain within acceptable levels preventing widespread flooding. Figure 4-1 shows a schematization of this principle.

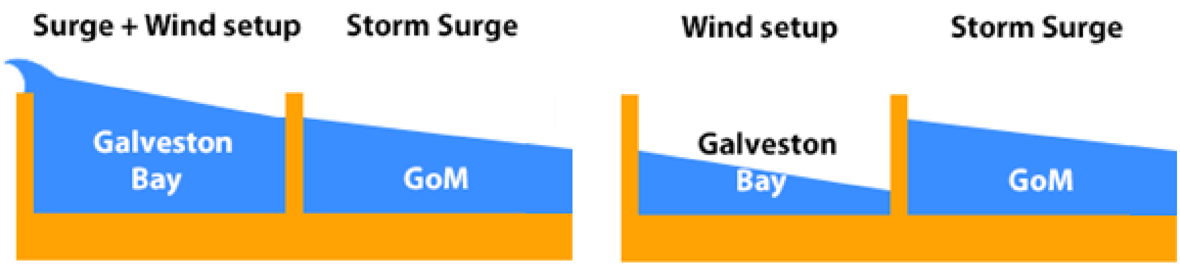

Figure 4-1: Schematized cross section of storm surge in Galveston Bay and Gulf of Mexico. Left: without barrier, Right: with barrier.

Wind setup is a function of the bottom roughness and wind shear stress at the surface. Bottom roughness slows down the backflow that compensates the wind driven surface current, and thus creates a setup. The effect of bottom roughness increases with a decreasing depth, resulting in a relatively larger surge in shallower water. The duration of a storm influences the total setup, a long lasting storm results in a larger setup. According to an often-used rule of thumb wind-setup rarely exceeds the average water depth. The basic wind-setup equation as published by Hellstrom (1970) supports this rule of thumb. Farrer (1957) derived empirical shear stress curves for hurricane wind tides on Lake Okeechobee. Lake Okeechobee is a hurricane wind prone shallow lake located North-West of Fort Lauderdale, Florida. Applying the formula of Hellstrom (1970) on Galveston Bay, using the empirical shear stress graphs of Farrer (1957), maximum fetch, category 3 hurricane winds and an average depth of 2.6 meter [8.5 ft] (Powell & Solis, 2011), a maximum wind induced setup of about 2 meter [7 ft] is found.

In general the duration of hurricane force winds is limited because hurricanes are fairly fast moving storms. The wind field associated with hurricanes is curved, not straight. Because of this curved wind field the fetch is smaller than the greatest possible distance. Wind setup on Galveston Bay, during hurricanes and with a closed Ike Dike barrier, is not expected to result in major flooding. Local variations might occur by channeling of the surge. More research on localized effects of wind setup is required.

4.2 Bolivar Roads barrier

The Bolivar Roads inlet is one of the most important shipping corridors of the U.S. Gulf coast and allows vessels up to the Panamax size. In the near future local decision makers might wish to assure passage of the New Panamax vessels. A surge barrier in the Bolivar Roads would effectively keep the surge out of the Bay, reducing the total perimeter of the flood defense system by 374 kilometer [232 mi] (Phillips, 2004). A barrier in the Bolivar Roads Inlet influences the tidal prism and its morphology. Reducing the Bolivar Roads flow area by 40 to 60% will lead to a decrease of the tidal prism of 21 to 41% according to Ruijs (2011). Because of the smaller tidal prism, an increase in residence time, and a decrease in salinity can be expected. As in the Dutch case, a decreased tidal prism might result in degradation of the intertidal flats. During the past decades the volume of the Galveston Bay has increased because of dredging. (Galveston Bay National Estuary Program, 1994) Combined with the ongoing dredging of the Bolivar Roads inlet this increases the tidal prism. A surge barrier can mitigate this effect. It is up to the designer to choose an optimum, decrease or increase of the tidal prism is a choice. Further research is required.

The proposed Bolivar Roads barrier features a 180-meter [590 ft] wide floating sector gate barrier similar to the Maeslant barrier. Two vertical lifting gate barriers provide access for barges. Smaller vertical lifting gates, if required, will allow circulation of water but close the inlet in case of storm surge. See Figure 4-2.

Figure 4-2: Ike Dike: Bolivar Roads Surge Barrier. Barriers not on scale.

4.3 San Luis Pass barrier

The approximately 800 meter [2625 ft] wide San Luis Pass (Figure 4-3), located at the west end of Galveston Island, is responsible for about 20% of the tidal exchange of Galveston Bay (Lester; Gonzales, 2002). The tidal exchange is of great importance to oyster banks and the overall health of the Bay. The San Luis pass is a small boat corridor. The bridge limits the maximum size of the vessels to a width of about 10 meters [33 ft]. A vertical lift barrier ensures passage of small recreational vessels. A set of smaller vertical lift gate barriers allows tidal exchange.

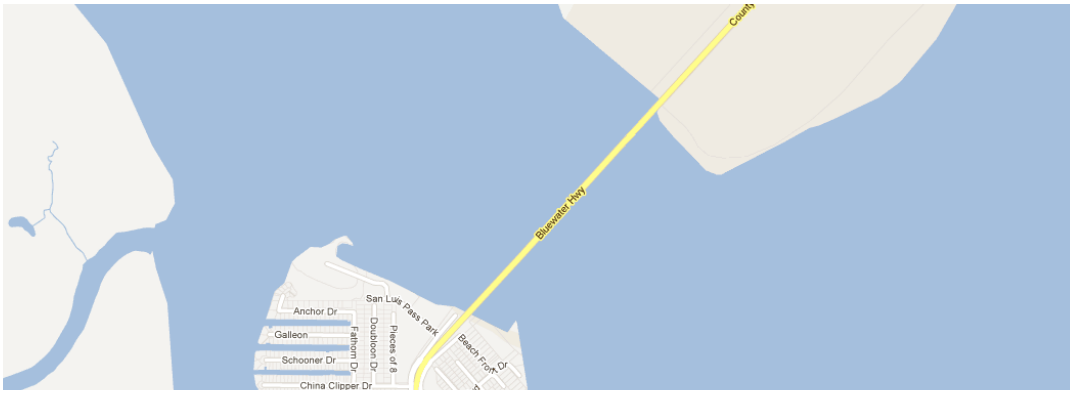

Figure 4-3: San Luis Pass and San Luis Pass Bridge. Width of the inlet is approximately 800 meter.

4.4 Barrier Island levees

This subchapter presents three conceptual Ike Dike levees. The purpose of these levees is protect the barrier islands, and to keep the water out of Galveston Bay. The total length of the coastal spine is about 90 kilometer [56 mi]. This does not include the existing Galveston Sea Wall. The beach on the Bolivar Peninsula and is an important tourist destination. Preserving the natural character of the beach is a key issue in these alternatives. A final solution could be a combination of the concepts described below.

4.4.1 Levee in dune

The “levee in dune” concept is a new Dutch concept that combines the structural integrity of a levee with the natural looks of dunes. A “levee in dune” is currently under construction near the Dutch cities of Noordwijk and Katwijk (Steetzel, 2010). The Ike Dike “levee in dune” concept consists a fortified core covered with sand and vegetation. The fortified core is not visible during normal conditions (Figure 4-4).

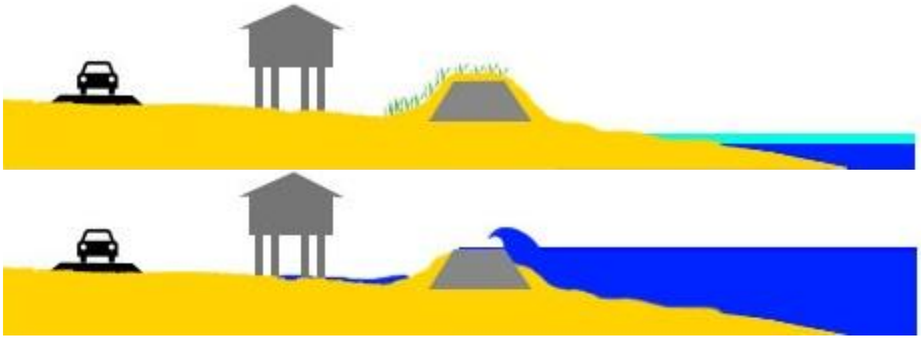

Figure 4-4: Levee in dune during normal condition (above) and design storm condition (below).

The proposed crest height of the solid core is NAVD +17 feet. A crest height of NAVD +17 feet does not affect ocean view since the current required stilt height of existing property exceeds NAVD +17 feet (Figure 4-4). In case of a serious storm, like hurricane Ike, waves will overtop the structure. The crest height is kept low on purpose; a low crest requires less material and does not obstruct view. The protection layer can be made of riprap, placed blocks, concrete or asphalt. Each alternative has its own strengths and weakness. An estimate of the required gradation or thickness, and its dominant method of failure is given below.

Riprap revetment

Riprap is a frequently used material in shore protection. Riprap is permeable and the dominant method of failure is movement of the individual grain. The required stone diameter is of the order of D_n50 = 1 meter [3 ft] (Pilarczyk, 1990) for a significant wave height of 1.8 meter [5 ft] (Kennedy, et al., 2010).

Placed block revetment

The dominant method of failure for placed block revetments is uplifting due to wave fronts and wave setup. Placed block revetments require a filter layer underneath the blocks. A permeable top layer and relatively impermeable filter layer leads to the most stable structure (Schiereck, 2012). The required thickness of the blocks is of the order of 0.6 meter [2 ft] (CUR, 1992).

Impervious layer revetment

Asphalt and concrete are often used as impervious layers in revetments. The dominant method of failure is uplifting caused by a head difference over the impervious layer. A filter layer is not required, asphalt can be placed directly on a sand core. The required thickness of asphalt on a 1:3 to 1:4 sand slope, using wave conditions from Table 2-1, is about 0.2 [8 inch] meter (Schiereck, 2012), (TAW, 2002).

Table 4-1: Advantages and disadvantages of levee in dune concept.

Advantages	Disadvantages
Looks natural	Between properties and beach
Strong, solid core	Expensive protection layer
All properties behind barrier	Hard structure
No land acquisition	

4.4.2 Dunes

The most natural looking way to keep the surge out of the bay is by using artificial dunes (Figure 4-5). Artificial dunes are created by beach nourishment, preferably in the shape of the existing dunes. Artificial dunes look and function as if a normal dune would.

Figure 4-5: Natural dune

Beach profiles are subject to frequent changes because of ever changing wave conditions. Beach profile behavior can be seasonal or episodic because of single storms with a severe magnitude. Research by Morton et al. (1994) show that micro-tidal wave-dominated sandy beaches on the Texas coast in general recover from storm events. Measurements show that lack of sediment supply hampered beach recovery on Galveston Island after hurricane Alice.

Dean and Kriebel (1984) have modelled the impact of storm surge on the beach profile. They conclude that increased water level during storm surge permits waves to break closer to the shore. Waves breaking closer to the shore than normal result in a beach profile that is out of equilibrium. In order to achieve an equilibrium situation sediment is redistributed by erosion at the shoreline and deposition offshore during high wave events (Dean & Kriebel, 1984). This is in accordance with Larson and Kraus (1994) who state that beach material is not lost during high erosion events. In general, storm events move sediment offshore towards submarine sand bars. Beach sediment is lost by over-wash during storm events, or by alongshore sediment transport in combination with a low supply of sediment. Changes in alongshore sediment transport can be the result of dams in rivers or coastal structures.

It is impossible to provide an accurate estimate of storm induced dune recession without numerical or physical modelling. Simulation of storm induced Beach erosion on the Florida coast show that a surge of 3.5 meter [11.5 ft] results in a dune recession of about 12.5 meter [41 ft] (Dean & Kriebel, 1984). The Galveston coast is different, and the storm surge is higher. The expected dune recession during an Ike like storm will probably exceed 12.5 meter [41 ft]. In order to provide safety against flooding without overwash conditions a natural dune solution requires a large width as compared to other solutions.

Table 4-2: Advantages and disadvantages of natural dune.

Advantages	Disadvantages
Natural looking solution	Between properties and beach
Easy to construct	Large surface area
No land acquisition	Uncertain behavior

4.4.3 Raising highway

The existing Galveston Seawall combines transportation with flood safety. A major advantage of this approach is that evacuation routes will remain accessible during flood events. By raising highway 87 on Bolivar, or the San Luis Pass road on Galveston Island a similar approach is used. Raising the highway requires some land acquisition, and driver safety requires some attention. In addition this concept leaves property outside of the protected zone when applied in the denser populated areas. Raising the highway could be a viable alternative in the less dense populated areas of the island, for instance the east part of Bolivar Island.

Figure 4-6: Raising the highway.

Table 4-3: Advantages and disadvantages of raising the highway.

Advantages	Disadvantages
Evacuation route does not flood	Leaves many unprotected
Strong levee	Large structure
	Expensive
	Some land Acquisition required

4.5 Rough cost estimate

This section gives a cost estimate of the Ike Dike. Detailed information on the costs of surge barriers is very limited resulting in a very coarse estimate. Subsections 4.5.1 and 4.5.2 respectively give a cost estimate for the gates barriers, existing sea wall upgrade and a surge suppression system on the barrier islands. Subsection 4.5.3 gives an overview of the total cost.

4.5.1 Cost estimate of storm surge barriers

According to Hillen et al. (2010), the estimated unit price per meter width of any type of storm surge barrier ranges between 0.5 and 2.7 million euro. Important factors in determining cost are local soil properties, hydraulic head and the desired height. Based on Table 3-3 the cost of a sector gate barrier ranges between $1 and $2 million dollar per meter [3 ft] width. The cost of a vertical lift gate barrier ranges from $0.5 to $1.5 million dollar per meter [3 ft] width. Table 4-4 gives an overview of the barriers required for the Ike Dike. The required width of the shipping channel determines the width of the sector gate.

Small vertical lift barriers adjoining the navigable barriers ensure sufficient flow into Galveston Bay. These simple barriers are located in water depths of up to 3 meter [10 ft]. Estimated cost ranges between 1 and 1.5 dollars million per meter width, depending on the complexity of the implementation. Total cost of the Bolivar Roads and San Luis Pass Surge barrier is estimated at 2.1 to 3.4 billion dollars.

Table 4-4: Overview of movable storm surge barriers required for the Ike Dike.

Barrier Name	Type	Approximate value in million $	Width [m]	Hydraulic head [m]
Sector gate	Floating sector gate	180 – 360	180 [1] [590 ft]	5.2 [17 ft]
Barge gate (x2)	Vertical lift gate	30 – 90	60 [195 ft]	5.2 [17 ft]
Bolivar Flow	Vertical lift gate	1000 – 1500	2000 [1.25 mi]	5.2 [17 ft]
San Luis Pass gate	Vertical lift gate	10 – 30	20 [66 ft]	5.2 [17 ft]
San Luis Flow	Vertical lift gate	800 – 1400	800 [0.5 mi]	5.2 [17 ft]

[1] Based on current width of channel and PANAMAX vessels.

4.5.2 Cost estimate of levees

Reports on the average unit price of levees are very scarce. The available cost estimates are usually coarse because of the lack of data and large differences between individual projects. The primary sources of data are the reports by the IPCC CZMS (1990) and Hoozemans et al. (1993). Linham et al. (2010) compared the cost estimates of the IPCC CZMS (1990) and Hoozemans et al. (1993) with the actual unit costs. In these studies the estimated cost per kilometer is only a function of the length.

Table 4-5 gives a cost estimation of levees as obtained from Hoozemans et al. (1993). Hoozemans et al. used the IPCC CZMS (1990) and added the estimated cost of sea level rise. The estimated cost is based on a “Dutch” levee with a height of MSL+5 meter [16.5 ft]. The average price of a new levee in San Francisco, in 2008, was $5650 per meter [3 ft] (2010 price level) (Heberger, Cooley, Herrera, Gleick, & Moore, 2009). Linham et al. (2010) suggest that the unit prices of Hoozemans et al. (1993) significantly over-predict the actual cost of constructing levees. It is suggested that the average Dutch levee is expensive as compared to the average levee. The cost of the Ike Dike levees is estimated at $6000 to $10000 per meter [3 ft].

Table 4-5: Unit costs per meter of levee according to Hoozemans et al. (1993) corrected to 2010 price levels.

Measure	Unit cost per meter [3 ft] in US$ (2010)
Stone protected sea dike[1]	6700 - 12660
Clay covered sea dike	3720
Dune	6700

The price of beach nourishments is volatile and highly dependent on the price of fuel, steel and the availability of dredgers. Table 4-6 contains an estimate of the cost of beach nourishment. Based on these numbers the cost of nourishment on the Texas Coast should be of the order of 10 to 15 dollars per cubic meter.

Table 4-6: Unit cost of beach nourishment.

	Unit cost in US$ per m^3 material (2010) [2]	Reference
Deltares	9.1 – 11.7	(Deltares, 2010)
IPCC CZMS	4.94 – 9.88	(IPCC, CZMS, 1990)
Dutch chamber of statistics	9 – 10	(Algemene Rekenkamer, 2009)
USA	8 – 16	(Linham, Green, & Nichols, 2010)

[1] Depends on toe level. Low: toe at NAVD +0 meter, high: toe at NAVD -5 meter.
[2] Exchange rate: 1 euro = 1.3 dollar.

4.5.3 Rough cost estimate

The estimate cost of the Ike Dike is 3.0 to 4.5 billion dollars (2012 price level). This number includes the cost of design and construction of levees and barriers. This number does not include the cost of initial studies and additional studies that do not directly relate to the individual structures. An example of a study that is not included in the unit price of a barrier is a study on the ecologic consequences of the total system. This number also does not include the cost of project management, land acquisition, or political processes.

An estimate of the total cost of the Ike Dike project would be a figure somewhere close to $6 billion dollar, however much depends on decisions made during the design process. As pointed in in Section 3.3 the Ike Dike can tolerate much more overflow than the Delta Works and New Orleans Barrier, which protect land below sea level. Six billion is significantly less than New Orleans. The Ike Dike does not require as much land acquisition or as many hard structures as the HSDRRS. In addition, the Ike Dike does not require pumping stations.

5 SEQUENCING CONSTRUCTION

The Ike Dike concept consists of levees and barriers. This chapter focusses on the preferred order of construction, and the necessity of both barriers and levees. The physics of the Ike surge are discussed in Appendix A, it can be summarized into two individual stages;

Stage 1: forerunner surge fills up the bay.
Stage 2: surge starts to overtop islands.

The Bolivar Roads and San Luis Pass barriers keep the surge out of the Bay during stage one and two by preventing flow through the inlets. The proposed levee system on Galveston Island and Bolivar Peninsula prevents wash-over during stage two.

The effectiveness of a levee system without surge barriers in the inlets is questionable. Figure A-1 (Appendix A) shows us that the forerunner surge resulted in widespread inundation, whilst not causing any over-wash. A levee system will protect property against wave-action and storm surge from the Gulf of Mexico. Without a barrier gate the islands are still at risk of being flooded from the bay side.

The effectiveness of a system without levees, and with a barrier at the Bolivar Roads inlet depends on flow over the islands during a significant storm event, and its impact on Bay water levels. A coarse estimate is obtained by combining USGS gauge data near Crystal Beach (USGS, 2008), see Appendix A, with a simplified broad crested weir formula [1] (Ankum, 2002). The width of the modelled weir is based on alongshore water levels as found in a historical SLOSH runs (NHC, 2012).

$$Q = 1.7 * width * hydraulic\_head^{3/2} \quad [1]$$

This coarse calculation does not take into account roughness or erosion. It is expected that a larger head level difference will results in higher flow velocities and significantly more erosion. Results are plotted in Figure 5-1. Based on this coarse calculation and the apparent risk of extreme erosion on the barrier islands a surge barrier without levees is not recommended. Recommended sequence of construction is to complete the inlet barriers after completing the levees.

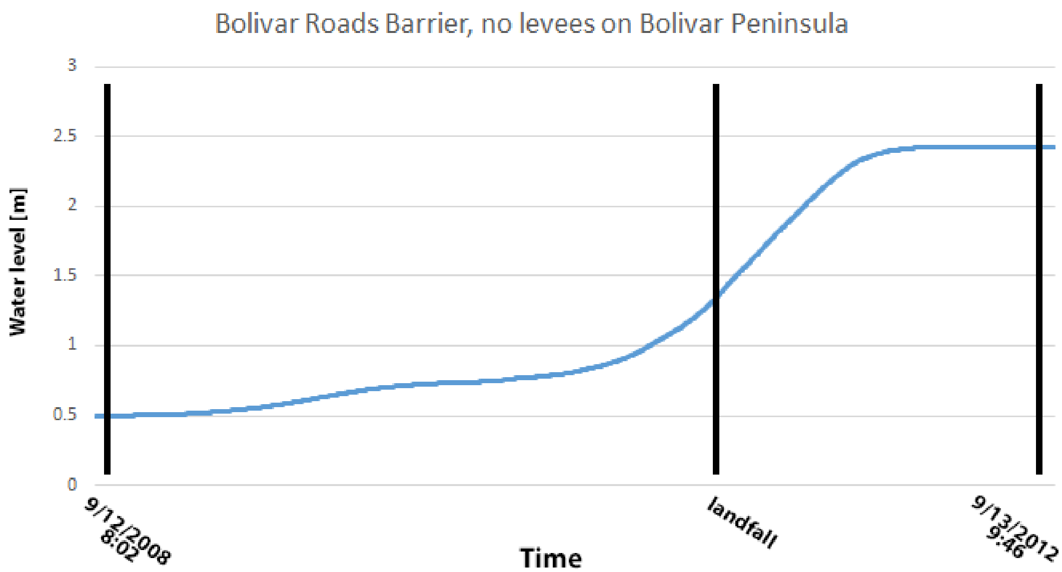

Figure 5-1: Simulation of water level in Galveston Bay during Ike with closed Bolivar Roads inlet.

6 CONCLUSION AND RECOMMENDATION

Conclusion

A preliminary analysis of the Ike Dike concept shows that a coastal spine effectively reduces flood risk by keeping the surge out of Galveston Bay. Based on experience gained in The Netherlands and New Orleans adopted to protect the Greater Houston Metropolitan originates from the renowned “Best Dutch Practices”. The Ike Dike shortens the perimeter, keeps the surge out of internal waters and ensures passage of ships and ecosystem function by using gated barriers

A regional analysis shows that the Galveston case is stronger than the New Orleans case. The Greater Houston Metropolitan Area excels in economic and population growth, and is of national strategic importance. An analysis of local geographic features shows that the problem is less complex than the problem encountered in New Orleans and The Netherlands.

The proposed Ike Dike should at least withstand another “Ike like” hurricane. The system can be somewhat leaky, using Galveston Bay as a retention pond. The concept only works when both levees and gates are constructed. A coarse analysis shows that it is preferable to build the levees first.

The estimated cost of structural parts of the Ike Dike is $3.0 to $4.5 billion dollars, depending on design decisions. An estimate cost figure of the entire project amounts to about $6 billion.

The Ike Dike coastal spine protects all and reassures economic development of the region by lowering the risk of flooding.

Recommendation

The large scale and corresponding large investments of the Ike Dike requires a thorough cost benefit analysis. The relation between the predicted economic growth and the used discount rates requires special attention.

The proposed Ike Dike has a large potential impact on society. It is recommend to perform a study of the social benefits of the barrier.

The effect of local geography on storm setup requires further research.

Galveston Bay is a unique ecological habitat and an important nursery for many types of marine life. The ecology of Galveston Bay is of utmost importance and the influence of the Ike Dike on the ecology of the bay requires a thorough study.

With near-consensus among scientist on the effects of Climate Change and its relation to global sea level rise and hurricanes special attention should be given to the effects of Climate Change on the Ike Dike and Galveston Bay.

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Appendix A. Hurricane Ike's surge

Understanding how Ike's surge behaved is a key question in any design for a storm surge barrier along the Galveston Coast. According to Berg (2009) the surge from hurricane Ike was preceded by smaller yet significant forerunner surge, flooding important evacuation roads. According to Kennedy et al. (2011) the forerunner surge as registered during Ike is the result of the Ekman setup. Forerunner surges only occur on wide shallow continental shelves, like the Louisiana Texas shelf, in combination with a large and slow moving storm.

Prior to landfall of hurricane Ike the USGS deployed portable water level gauges along the Galveston coast. Figure A-1 shows measurements obtained by two gauges deployed on the beach (red) and bay side (blue) on the Bolivar Peninsula near Crystal Beach (USGS, 2008). LiDAR images obtained prior to and after hurricane Ike show that the height of Bolivar Island varied between 2.5 and 3 meter (USGS, 2008).

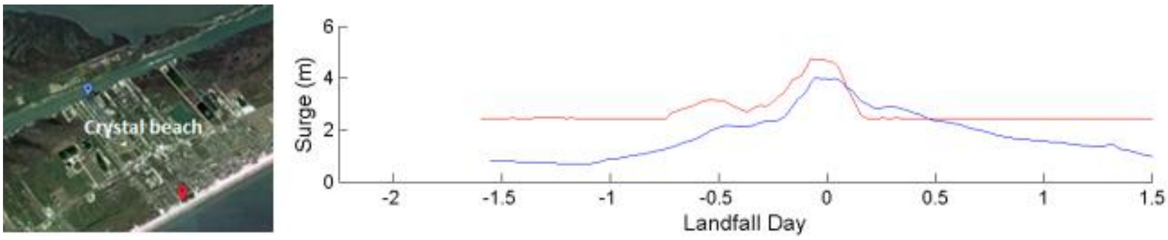

Figure A-1: Measured water levels near Crystal Beach during Ike. (Kennedy et al., 2010)

Figure A-2 shows a pre Ike LiDAR image of Crystal Beach. The combination of the gauge data and LiDAR imagery shows that Bolivar Island endured flooding from the bay side during the forerunner stage. Overwash did not occur until a few hours prior to landfall when the height of the storm surge on the open coast exceeded the height of the dunes on the barrier islands. According to FEMA (2009) scour hole depth near piles varied between 10 and 25 centimeter. Gauge data from Figure A-1 shows that the head level difference between the ocean and bay side was of the order of 0.5 to 1 meter during the storm. Kennedy et al. (2010) state that the majority of damage on the Bolivar Peninsula was caused by wave action. A head level difference of 1 meter over 2 kilometer results in a flow
velocity of about 1m/s when the overflow is simplified to uniform open channel flow with a Manning roughness coefficient of 0.025. Based on these conclusions, and images of the area after hurricane Ike the flow velocity over the barrier islands appeared to be rather limited.

During the initial phase of flooding, the islands were inundated "from behind" because of increasing water levels in the bay. A few hours prior to landfall the surge height on the open Bolivar coast exceeded the height of coastal defenses resulting in over wash. The Galveston Seawall protected the Gulf of Mexico side of the city, it did not prevent flooding from the bay.

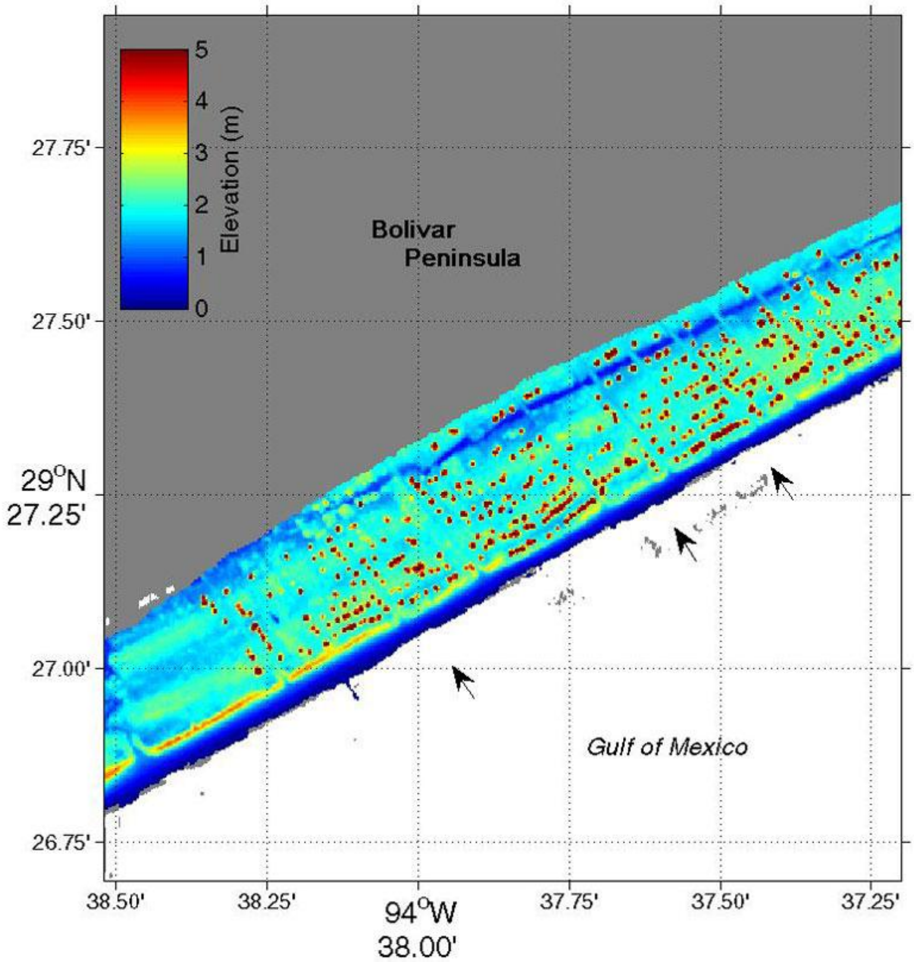

Figure A-2: LiDAR image of Bolivar Peninsula near Crystal Beach (USGS, 2008)

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