# DELFT DELTA DESIGN

## HOUSTON GALVESTON BAY REGION
## TEXAS, USA

EDITED BY
Baukje Kothuis
Nikki Brand
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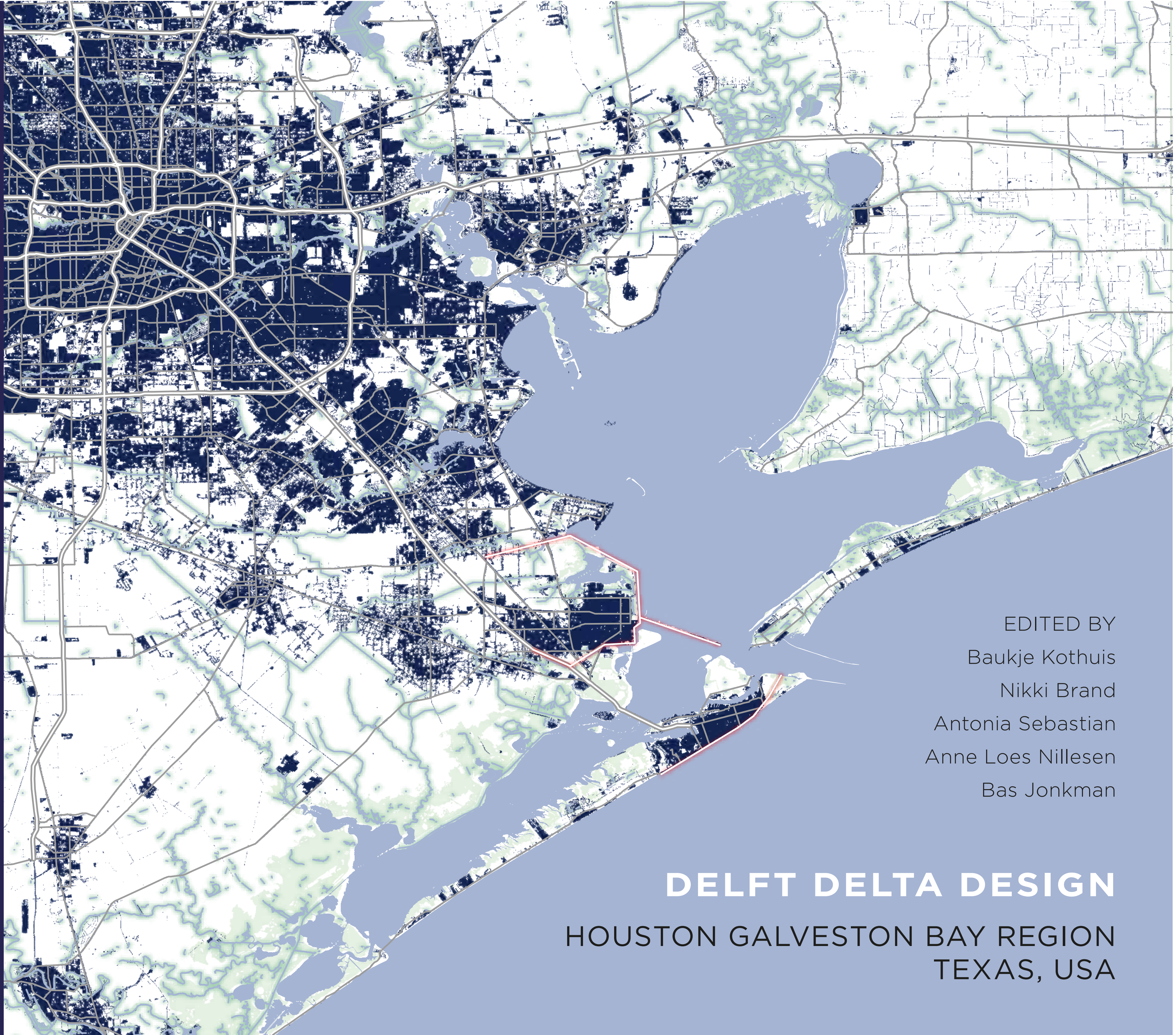


Kothuis, Brand, Sebastian, Nillesen, Jonkman (eds.) DELFT DELTA DESIGN HOUSTON GALVESTON BAY REGION

The authors



In 2008, Hurricane Ike devastated Bolivar Peninsula, narrowly missing the more heavily industrialized and populated areas in the region. In the aftermath of the hurricane, the Severe Storm Prediction, Education and Evacuation from Disasters (SSPEED) Center at Rice University in Houston, and Texas A&M University in Galveston (TAMUG) led initiatives to propose and design flood mitigation strategies.

In collaboration with TAMUG and the SSPEED Center, students and researchers at Delft University of Technology in the Netherlands have been investigating regional strategies for flood risk reduction. In this publication they and their Texas counterparts reflect on the research, design, and insight that has sprouted from this collective endeavor.

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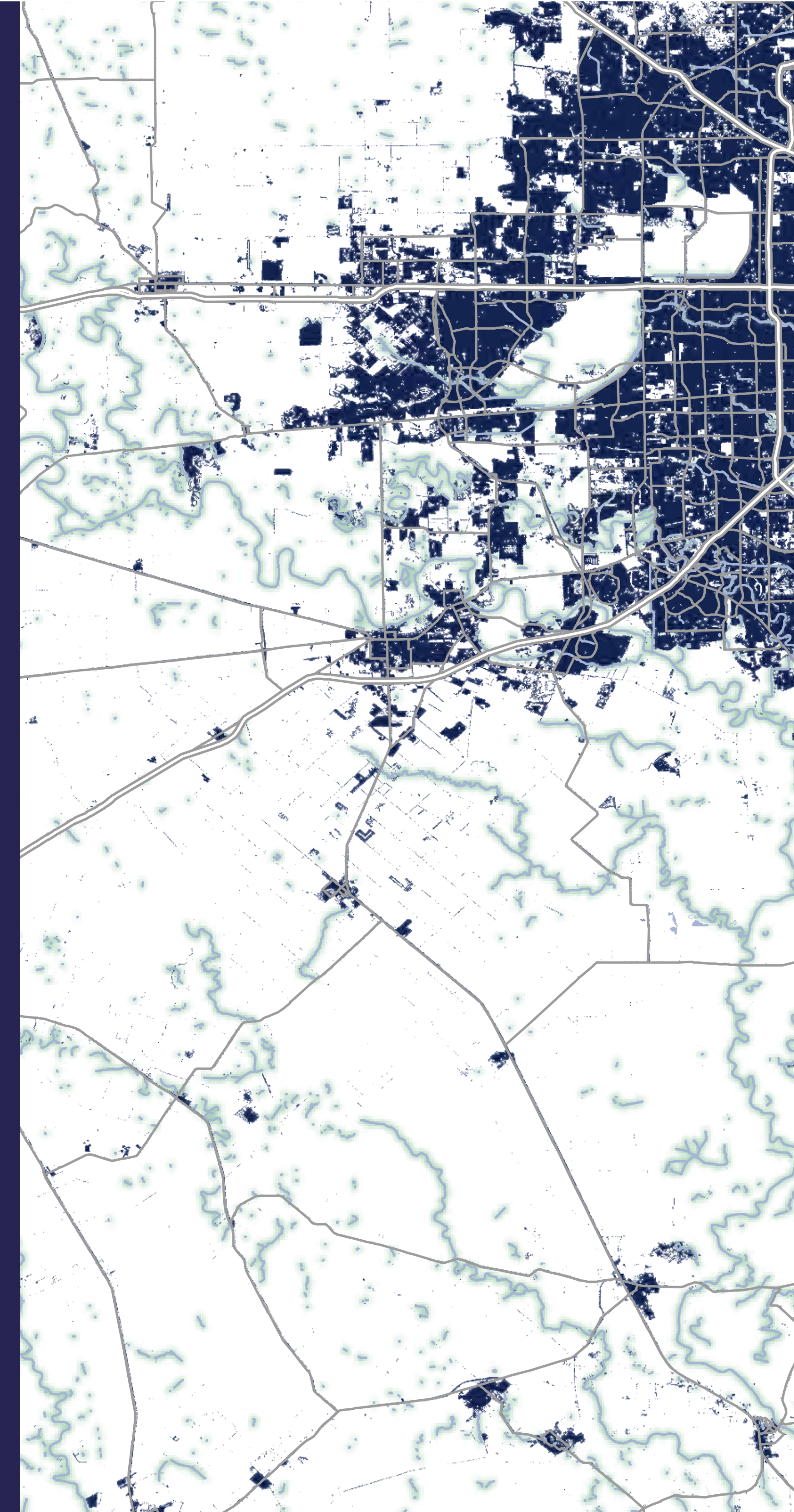

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## THE HOUSTON GALVESTON BAY REGION, TEXAS, USA

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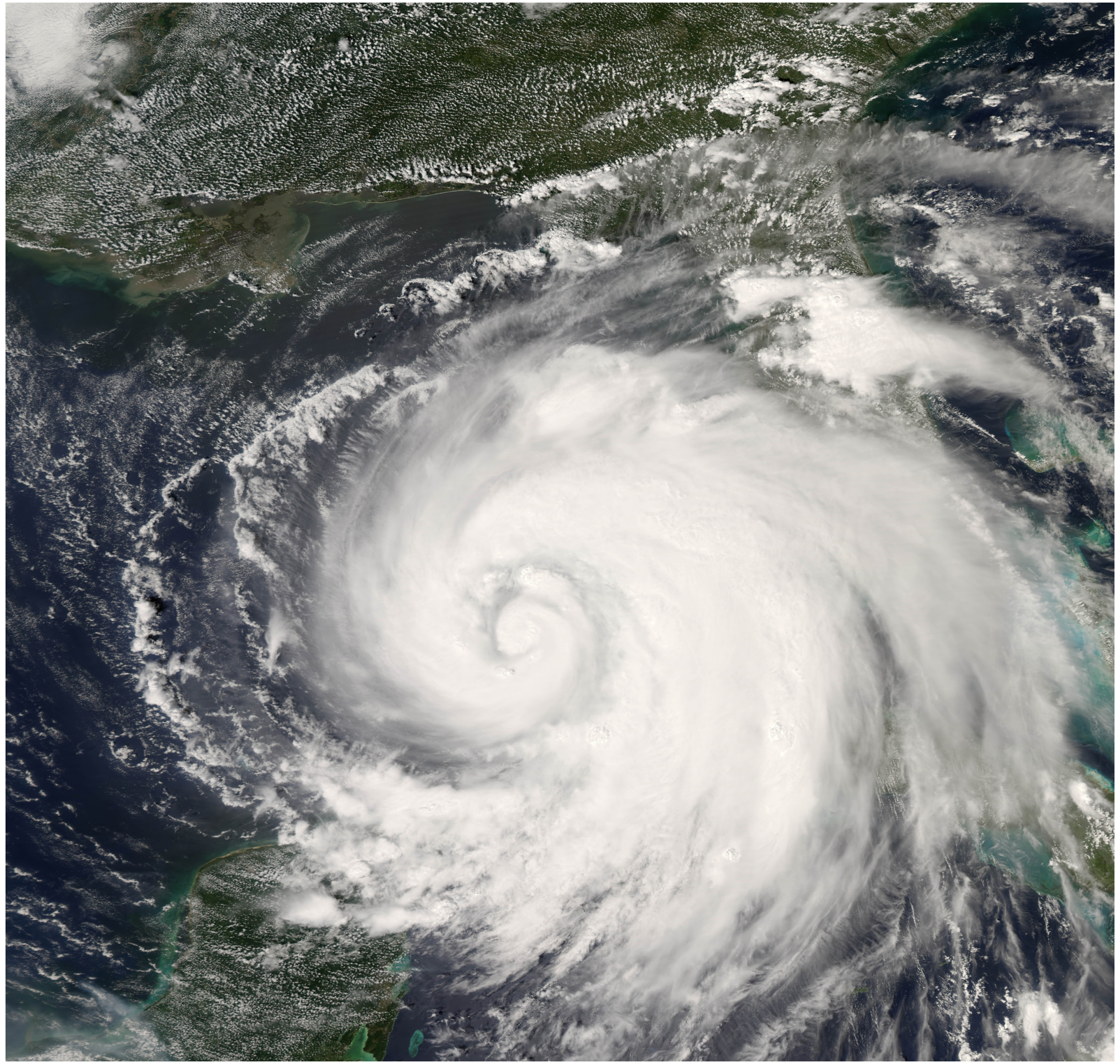


André Kuipers

# A PERSPECTIVE FROM OUTER-SPACE

## PREFACE

*Figure 1.*
*Hurricane Ike at 1:50 p.m. CDT on September 10, 2008.*
*(Photo Courtesy NASA)*

*Figure 2.*
*Dutch ESA Astronaut André Kuipers.*
*(Photo Courtesy Gagarin Cosmonaut Training Center)*


During the preparatory training for my travels to space, I spent a lot of time in Houston, Texas - for many the Valhalla of spaceflight. Actually, the Johnson Space Center is the place where we astronauts train as crews to work and live in the International Space Station ISS, which is the biggest technological construction ever built by humans. The flags at the entrance of the Space Center demonstrate clearly the international character of our work, bringing together many bright minds to address the huge challenges of sending humans to space.

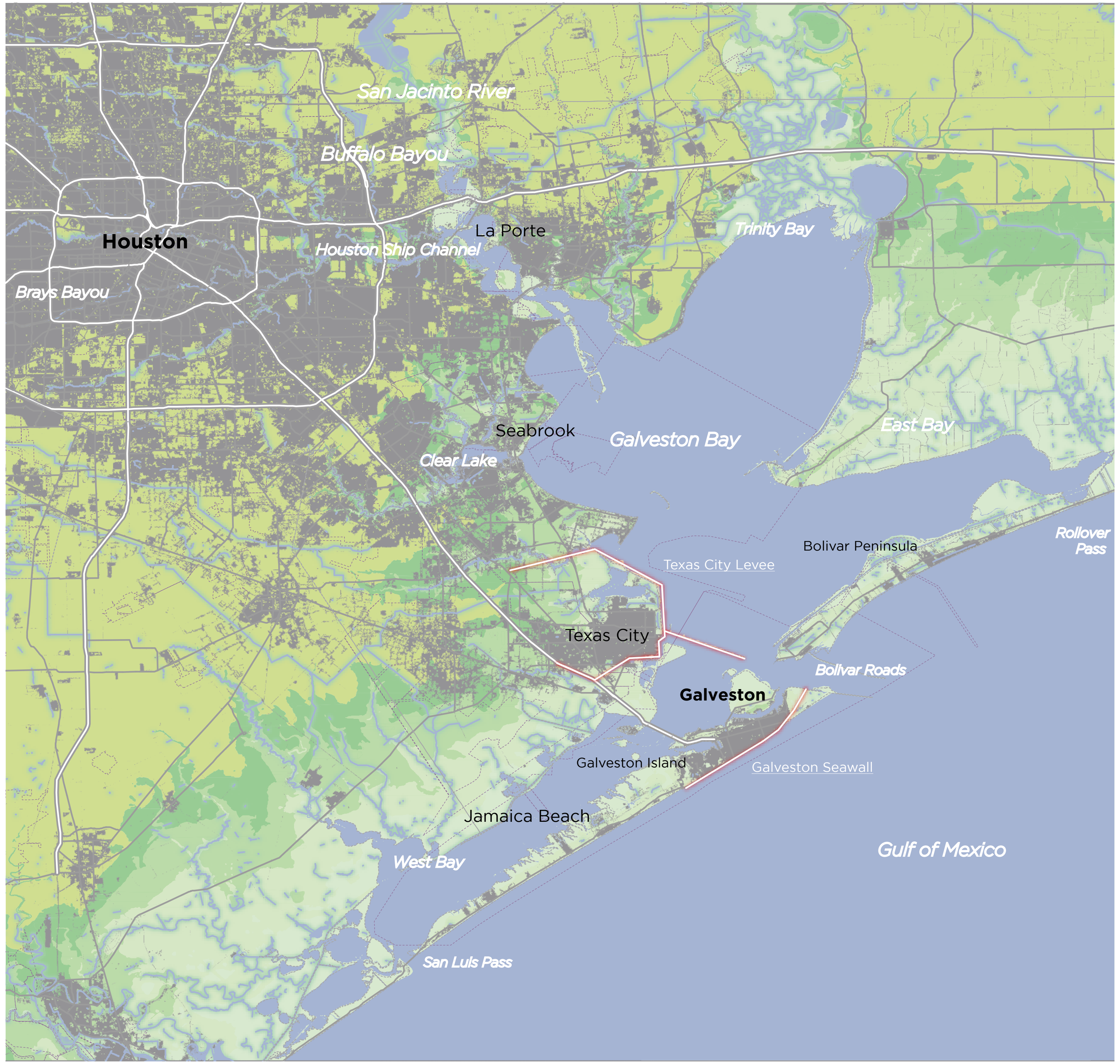
During my stays, I regularly drove down to Galveston for a walk on the beach. I liked the relaxed atmosphere of the place and often sat down for a fish lunch, with a view over the ocean. Children playing in the sand, some venturing into the water. How lucky I was not to have been around when Hurricane Ike struck with unbelievable power, in September 2008. When I returned, I witnessed the results of what looked to me like a war zone. Large parts of Galveston were flattened, caused by the destructive power of water and wind.

Are we able to protect ourselves from these fierce forces of nature? The answer to this question is even more important when we realize that these disasters will occur more often and become more violent as a result of climate change. Luckily, we have our human brain and the ability to work together in our attempts to protect ourselves from natural disasters on this scale.

Being an astronaut, I often get questions about my 'perspective'. By 'perspective' people often mean the view I had from space on the Earth, while orbiting our planet as a living satellite. Yet, there is another perspective that I had as an astronaut: the perspective on technology, science and people. On challenges, problems and innovation. During my two space missions I was privileged to work with some of the most passionate people imaginable. The smartest engineers, the brightest scientists, gifted inventors, and people who link out-of-the-box thinking to discipline and perseverance.

I recognize these qualities in many people who work in science at universities in both the Netherlands, like TU Delft, and in the United States. No matter whether they face technological challenges, scientific issues, or economically or socially relevant applications in the fields of architecture, urban planning, ecology and governance. People passionate about their work, who know it's essential to go one step further every time. Yet, to be able to achieve a common goal, one as incredibly complex as spaceflight or limiting flood risk, it's important to speak each other's language, both literally and figuratively, and transcend different cultures and reach out to different disciplines. Because all is related.

That is why I support international and interdisciplinary cooperation. It's a fantastic way to share findings, here and abroad, and face future challenges together.






# ACKNOWLEDGEMENTS

This book is the product of three years of intensive exchange between TU Delft and its partner institutions in the Houston Galveston Bay Region. This exchange was possible because of the admirable efforts of many people, both on and behind the stage.

For their generous financial, organizational, and personal support, the editors would like to thank Marcel Hertogh, Hans de Boer and Anna Molleman of the DIMI Infrastructure and Mobility Fund. Delft Infrastructures and Mobility Initiative (DIMI) is a platform for research and education in the field of water- and transport-related infrastructures and mobility. In DIMI research projects, scientists from different disciplines collaborate with stakeholders from governments, businesses, and knowledge institutions on finding integrated concepts to address present-day and future socio-technical issues.

We would also like to acknowledge financial support from the Dutch Technology Foundation, STW, which has facilitated the research presented by the Multifunctional Flood Defenses Program; and from the Netherlands-America Foundation (NAF) for a Fulbright Fellowship, which supported the PhD research of Antonia Sebastian in The Netherlands. For their assistance to student projects in the Hydraulic Infrastructure Design section we would like to thank Royal HaskoningDHV and Iv-Infra.

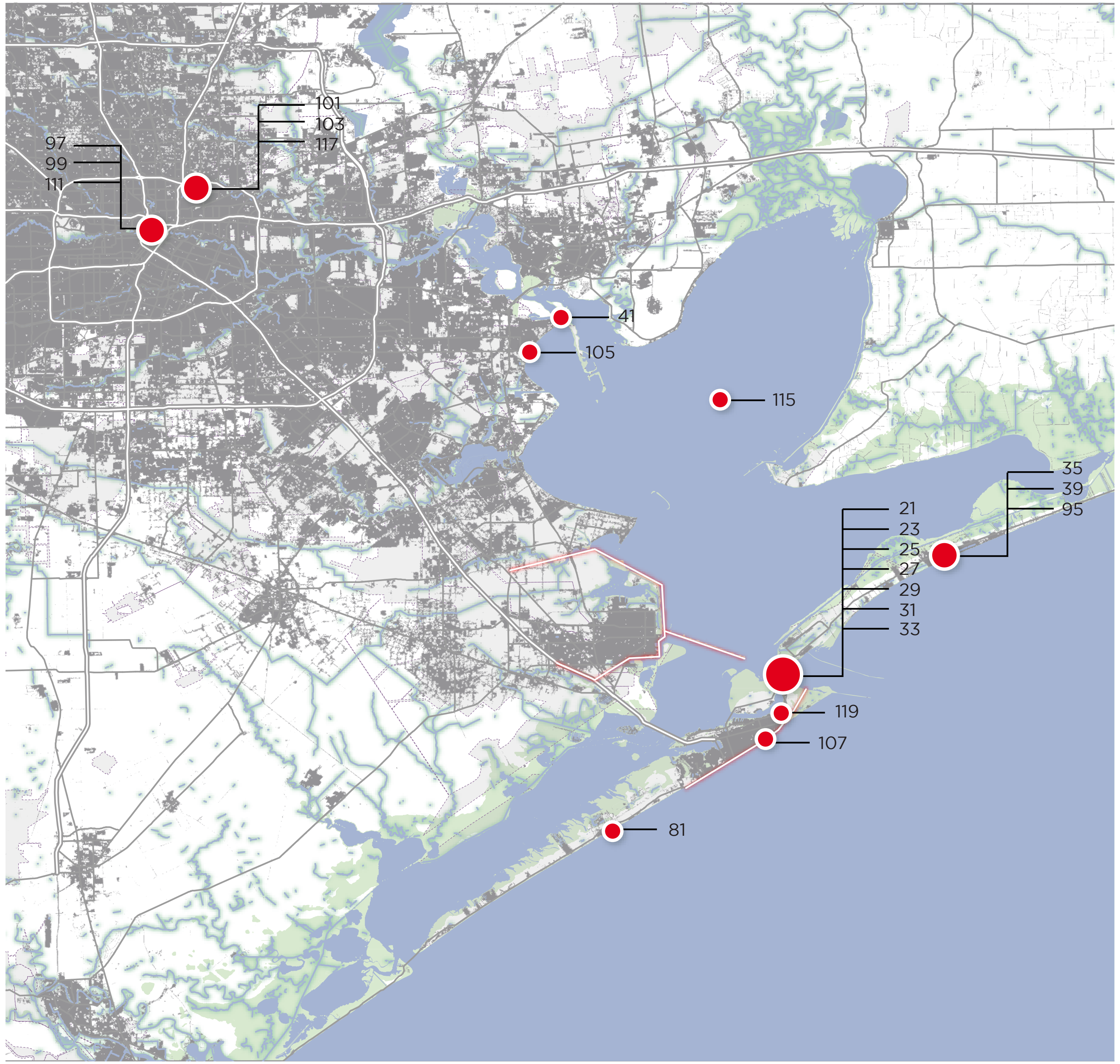
Many institutions in the Houston Galveston Bay Region have contributed their time and resources to make the research collaboration between The Netherlands and Texas, and thus this book, possible. We would like to specifically acknowledge Dr. Bill Merrell, Dr. Samuel Brody and Len Waterworth at Texas A&M University in Galveston; from Rice University, Dr. Phil Bedient, Jim Blackburn, Larry Dunbar and Charles Penland; and Tom Colbert from the University of Houston. They have not only been supportive of transatlantic research, but also visited the Netherlands multiple times and deepened our understanding of the Houston Galveston Bay Region's flood risk issue. Especially Tom's unwavering support to trans-disciplinary interaction has played a crucial role initially establishing the personal relations that were to be the foundation of this book. Last but not least, we would like to thank the other group members at our partner institutions for their unremitting and generous hospitality in Texas to both students and researchers from TU Delft.

The production of this book could not have been completed without a group of people moving outside of the boundaries of available hours and finances. We are deeply indebted to Cherie Coffman for her personal assistance at Texas A&M Galveston; Ad van der Toorn, Kasper Lendering, and Erik van Berchum for their organizational support at TU Delft; Gérard Brikkenaar van Dijk of the Netherlands Business Support Office for his hospitality; Alex Parvu and especially Steef Lifting for the design of the cover and help with the layout; Sören Johnson for the language edit; Lara Brand of Studio Wuft for providing the maps for this book; Helena Van Boxelaere and Defacto for sharing photos and images; and André Kuipers for his dedicated preface.

*Map on page 4:*
*Houston Galveston Bay Region:*
*Flood zones and topography.*

*Legend: see inside frontcover.*

*Map on page 6:*
*Houston Galveston Bay Region:*
*Wetlands contours and locations of site-specific projects and their page number in this volume.*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111
101
103
117
41
105
115
35
39
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21
23
25
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81



# CONTENTS

*Figure 3.*
*Hurricane Ike,*
*September 13th, 2008.*
*(Photo courtesy Joce-lyn Augustino, FEMA)*



Antonia Sebastian, Baukje Kothuis, Nikki Brand

# INTRODUCING DELFT DELTA DESIGN: MULTIDISCIPLINARY AND TRANSATLANTIC RESEARCH

## PROLOGUE

In 2008, Hurricane Ike made landfall near the Houston Galveston Bay Region (HGBR). Storm surge along parts of the coast exceeded 5m (16.4ft), but, in general, the storm is considered to have missed the heavily industrialized and populated areas of the region. In the aftermath of Hurricane Ike, researchers at Texas A&M University in Galveston and the Severe Storm Prediction, Education and Evacuation from Disasters (SSPEED) Center at Rice University in Houston led initiatives to propose and design flood mitigation strategies for the region. Together with Texas A&M University at Galveston and the SSPEED Center, students and researchers at Delft University of Technology (TUD) in the Netherlands have been investigating regional strategies for flood risk reduction.

This book highlights TUD-based research conducted by students and staff within the faculties of Civil Technology & Geosciences (CiTG), Technology, Policy & Management (TPM), and Architecture & the Built Environment (A&BE). The content of this book is organized into three sections: Hydraulic Infrastructure Design, Multifunctional Flood Defenses Program, and Delta Interventions Studio. The research contributions to each of the three sections are described in more detail below.

In the first section, Hydraulic Infrastructure Design, research ranges from probabilistic analysis of system boundary conditions to preliminary structural designs for storm surge barriers. The design of hydraulic infrastructures is often a multidisciplinary and integrated task, involving expertise from several departments within the faculty of Civil Engineering & Geosciences. Many of the students in this section chose to focus on the preliminary design of elements of a coastal barrier. These projects include the design of a moveable storm surge barrier across Bolivar Roads, both the navigational and environmental segments, and the proposed land barrier on Bolivar Peninsula. Other students investigated hydraulic structures within Galveston Bay, like the design of a Houston Ship Channel Barrier or mid-bay structures to reduce wind setup.

The second section presents work linked to the cross-disciplinary Integral and Sustainable Design of Multifunctional Flood Defenses (MFFD) Program. PhD candidates, postdocs and senior researchers address a variety of subjects, ranging from the political and governmental conditions for flood risk reduction to economic optimization of flood barriers; and from potential ecosystem services to varying concepts for nature-based flood risk mitigation. The contributions in this section depart from an integral systems approach and are primarily academic in nature. They are based on the principle that if interventions for flood risk reduction are to be effective, they should acknowledge multiple values and interests and perform several functions.

The third and final section, Delta Interventions Studio, presents the results of a multidisciplinary graduation studio based in the Urbanism Department of A&BE at TUD. Students from TPM, CiTG and A&BE participated in the studio, focusing on integrating flood mitigation strategies in the HGBR. The projects took a so-called ‘research-by-design’ approach to develop concepts for reducing flood risk, adapting architecture to the environment by integrating them into the urban fabric or by designing flood resilient architecture. In addition to considering a sites’ vulnerability to storm surge or urban flooding, all the projects aspire to heighten the spatial quality of the HGBR by increasing its recreational, environmental, and aesthetic appeal.

Each section ends with reflections written by senior experts from Texas and the Netherlands. These reflections not only highlight the significance of the research to date and identify remaining knowledge gaps, but also compare the cultural differences between flood risk reduction in Texas and the Netherlands, as well as reflecting the experts’ personal experiences with the issue.

The focus on the HGBR (known as ‘the Texas Case’ at TUD) has strengthened multidisciplinary research efforts between the faculties at TUD, as well as international, interdisciplinary research collaboration between TUD and universities on the US Gulf Coast. The urgent need for flood risk mitigation in the HGBR has been integrated into student education and academic research in the Netherlands, providing an excellent test bed for research in the field of natural hazards and risk mitigation. The projects included here range from pragmatic to bold, providing preliminary recommendations for hydraulic structures, coastal policy and governance, and architectural design that will help to address flood risk in the HGBR.

*Figure 4.*
*The Great Hurricane, Galveston Island, September 8th, 1900. (Image Courtesy Library of Congres, USA)*




Antonia Sebastian, Baukje Kothuis, Nikki Brand

# HISTORICAL HURRICANES AND RESPONSE IN THE HOUSTON GALVESTON BAY REGION

## PROLOGUE

The history of the Houston Galveston Bay Region has been marked by severe hurricanes and associated flooding. On average, a hurricane makes landfall on the upper Texas coast once every nine years. Since 1900, fifteen hurricanes have produced storm surge exceeding 1m (3ft) at Galveston Island, three of which produced surge in excess of 3m (9ft).

The HGBR's experience with coastal flood risk reduction can be traced back to the 1900 Hurricane, which, to this day, remains the storm of record for the upper Texas coast. On September 8, 1900, this Category 4 hurricane made landfall near Freeport, Texas, just southwest of the City of Galveston. At the time, the highest elevation on the island was around 2.5m (8ft). The New York Times reported Galveston Island covered by “a depth of [water] from six to twelve feet” (2-4 m). Approximately 8000 people died during the event and it remains the deadliest natural disaster in US history (Blake and Gibney, 2011). The hurricane prompted the construction of the Galveston Seawall, a concrete levee at the shoreline 5.2m (17ft) and, today, over 16km (10mi) long. To match the height of the seawall, buildings that had survived the hurricane were lifted and the island was back-filled toward the Bay. This massive reconstruction of the west end of Galveston remains one of the most extensive and impressive responses to hurricane flooding in the US during the 20th century.

In 1915, another large hurricane made landfall near Galveston producing in excess of 3m (10ft) of surge. While the seawall protected most of the City of Galveston at the east end of the island, storm surge and waves eroded the beach more than 100m (300ft) and caused scour along the seawall. During the 19th century, the City of Galveston had been one of the largest economic centers on the Gulf Coast, in direct competition with New Orleans. However, along with the discovery of oil and the booming cotton industry, the 1900 and 1915 hurricanes solidified the decision to build a deep-water channel in Galveston Bay and move the economic center of the region to inland Houston.

Over the next few decades, the region experienced a period of relative calm, punctuated by some smaller hurricanes, but none as devastating as in 1900 and 1915. In 1955, the US Army Corps of Engineers (USACE) and National Weather Service were authorized by Congress to conduct a hurricane study of the Texas Coast. This study determined that the most vulnerable location in the Galveston Bay Area was Texas City, prompting the design and construction of the Texas City Levee and Dike (Murphy & Geelan, 1965). Then, in 1979, the Galveston District undertook a comprehensive regional study to explore large-scale structural alternatives for flood mitigation, such as a coastal seawall and bayside barriers. Ultimately, none of the structural alternatives met all the requirements for federal involvement and none were further recommended (USACE 1979).

Since then, the population of the region has more than doubled, exceeding 4 million people by 2013. The Port of Houston, accessed by the Houston Ship Channel, has become one of the busiest ports in the world, and the associated industry is a major economic asset. Urban areas have sprawled outward toward the coast. Simultaneously, coastal wetlands and watersheds have been paved over, putting an increasing number of people and businesses at risk of flooding. Flooding of critical infrastructure - whether induced by both severe rainfall or storm surge - can potentially devastate the local and national economy, as well cause irreparable environmental damage to the Galveston Bay ecosystem (Burleson et al. 2015).

In 2008, Hurricane Ike served as a wake-up call for the region. While Galveston City was largely protected by the Seawall, water levels on Bolivar Peninsula exceeded 3.6m (12ft). Researchers estimate that the storm surge could have been 20% higher if the hurricane had made landfall 35 miles to the southwest (Sebastian et al. 2014). High water marks inside Galveston Bay were as high as 4.7m (15.5ft), causing severe damage along the western shore and on the back-side of Galveston Island. Apart from this, the hurricane dropped more than 30cm (12in) of rain in some areas causing severe flooding inland as well. Damages from the hurricane exceeded $29.5 billion making it the second costliest US hurricane on record (at the time) (Blake and Gibney 2011). The US Department of Energy estimated that 2.6 million people in Texas and Louisiana were left without power, some for more than two weeks.

Hurricane Ike prompted the flood risk in the HGBR to be reappraised, and new proposals for flood risk reduction to be considered. Today, the entire surge protection system for Galveston Bay consists of the Galveston Seawall (built between 1902 and 1904) and the Texas City Levee (built between 1958 and 1982), leaving the heavily populated west side of Galveston Bay and the Houston Ship Channel vulnerable to flooding from storm surge. The developed east end and bay side of Galveston Island and the homes on Bolivar Peninsula have also been left unprotected.

It is currently widely accepted that a system-wide approach should be taken to reducing flood risk in the region. To this end, local universities conduct extensive research and established international collaborations. In this book, researchers from TUD Delft were invited to present their contributions for pieces of a larger system for flood risk reduction in the HGBR.

# ONE | HYDRAULIC INFRASTRUCTURE DESIGN

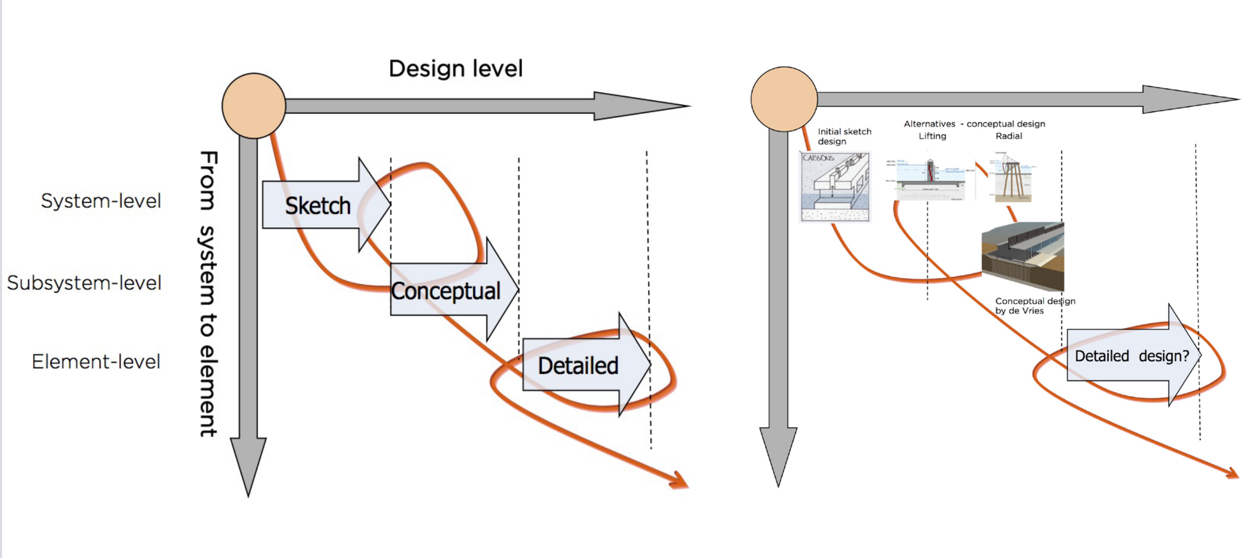


*Figure 5. Schematization of the design process. In the first design of a barrier for Bolivar Roads, a caisson type of barrier with vertical lifting gates – similar to the Dutch Eastern Scheldt Barrier in Figure 6 – seemed the preferred solution. However, in a later design step it appeared that the foundation would be critical, technically challenging, and very expensive. As a result, alternative barrier concepts with different foundations need to be explored. (Source of scheme: lecture hydraulic structures, TU Delft by Ir. A. van der Toorn)*

*Figure 6. Eastern Scheldt Barrier. (Photo Courtesy TU Delft)*



Sebastiaan N. Jonkman

# THE HYDRAULIC INFRASTRUCTURE DESIGN SECTION

## INTRODUCTION

*Prof. dr. ir. S.N. Jonkman is a professor of Integral Hydraulic Engineering at the Faculty of Civil Engineering and Geosciences at TU Delft.*

The Hydraulic Infrastructure Design section of this book presents studies of flood risk and preliminary designs for structural interventions in the Houston Galveston Bay Region (HGBR). Most of these projects were performed by students from the Hydraulic Structures and Flood Risk section of the Department of Civil Engineering at TU Delft. They are the result of a collaborative effort between stakeholders in Dutch and American academic institutions, the private sector, and local organizations. This cooperation was initiated in 2012, when architects, planners and policy analysts from TU Delft started to exchange ideas with colleagues from Rice University and the University of Houston on the planning and protection of the HGBR. Somewhat later, civil engineers from Delft started to work with the university of Texas A&M in Galveston on a coastal protection system that has some similarities to the Dutch Delta Works. Since the end of 2014, the two Texan academic groups have joined forces to develop an integral delta plan for their region. It will combine coastal and bay protection with structural and ecosystem interventions. The plan is to gain significant support from politicians and other stakeholders alike.

The section gives an overview of the Hydraulic Infrastructure Design projects completed to date. To produce a comprehensive design of coastal protection systems, it is essential to understand the hydraulics of the system. For this reason, Stoeten (p. 19) estimated the return periods of flooding and Ruijs (p. 21) investigated the effects of coastal interventions on the hydrodynamics of the Bay system.

Many of the student projects focused on structural elements of larger risk reduction systems for the region, which Merrell (p. 46) and Bedient (p. 48) describe. For example, one proposal to reduce the flow of storm surge into Galveston Bay is to build a storm surge barrier at the coast. The conceptual design of the coastal barrier is described by Lendering and Mooyaart (p. 23). Various students designed components of this barrier, such as the environmental section (De Vries, p. 25) and the navigational section of the gate across the Houston Ship Channel at Bolivar Roads (Karimi and Van der Toorn, p. 29). In addition, the dynamics and closure procedure was investigated (Smulders, p. 31), and the optimal elevation with respect to overflow and risk reduction was calculated (Rippi, p. 33). Students also explored innovative (non-traditional) barrier concepts that could be applied in the region. For example, Van Breukelen (p. 27) designed an inflatable barrier for Bolivar Roads, similar to the one already applied on a smaller scale in the Netherlands at the Ramspol storm surge barrier. Schlepers (p. 41) designed an elegant steel-truss structure to protect the Houston Ship Channel.

The final element of a coastal protection system would most likely include a 'land barrier' to prevent overflow into the bay. A student team prepared a first design for such a land barrier (Heeringa et al. p. 35), based on which Van Berchum et al. (p. 39) designed an alternative version. The chapter concludes with four reflections on the work done, the local context and planning, and the way forward. These are written by experts in the field (including Bill Merrell, Phil Bedient, and Mathijs van Ledden).

The designs presented in this section are based on the experience with the Dutch Delta Works and design methodologies taught at TU Delft. A successful hydraulic infrastructure system needs to be based on a sound analysis of the system and its required functionalities and qualities. Stakeholder inputs are also crucial. For example, the resulting designs of the storm surge barrier in Bolivar Roads are determined by both shipping requirements and environmental flows. The set of natural and societal boundary conditions will determine the design or solution space in which various alternatives can be explored.

The design of these infrastructures typically moves from a very general (sketch) design to more conceptual and detailed levels. This is not a linear, but rather an iterative process. Findings in later stages of the design, could force the designer to go back to the drawing board and make changes in earlier steps (Figure 5). This occurred, for example, in the design of the environmental section of the Bolivar Roads barrier (De Vries, p. 25).

One of the lessons from the Netherlands is that realizing large-scale coastal interventions takes many years and sometimes even decades. Similarly, the planning, design and evaluation of hydraulic infrastructure systems in the Houston Galveston Bay Region will require much more work in the future. The ideas presented in this book provide a first start of the development of a comprehensive risk reduction strategy for the region.

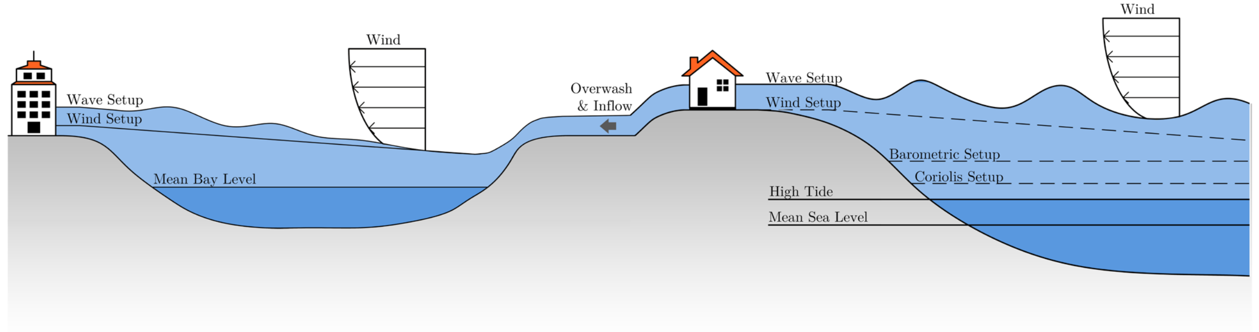


*Figure 7.*
*Contributions to storm surge height within the semi-enclosed bay system and at the open coast during a hurricane event.*
*(Stoeten 2013)*

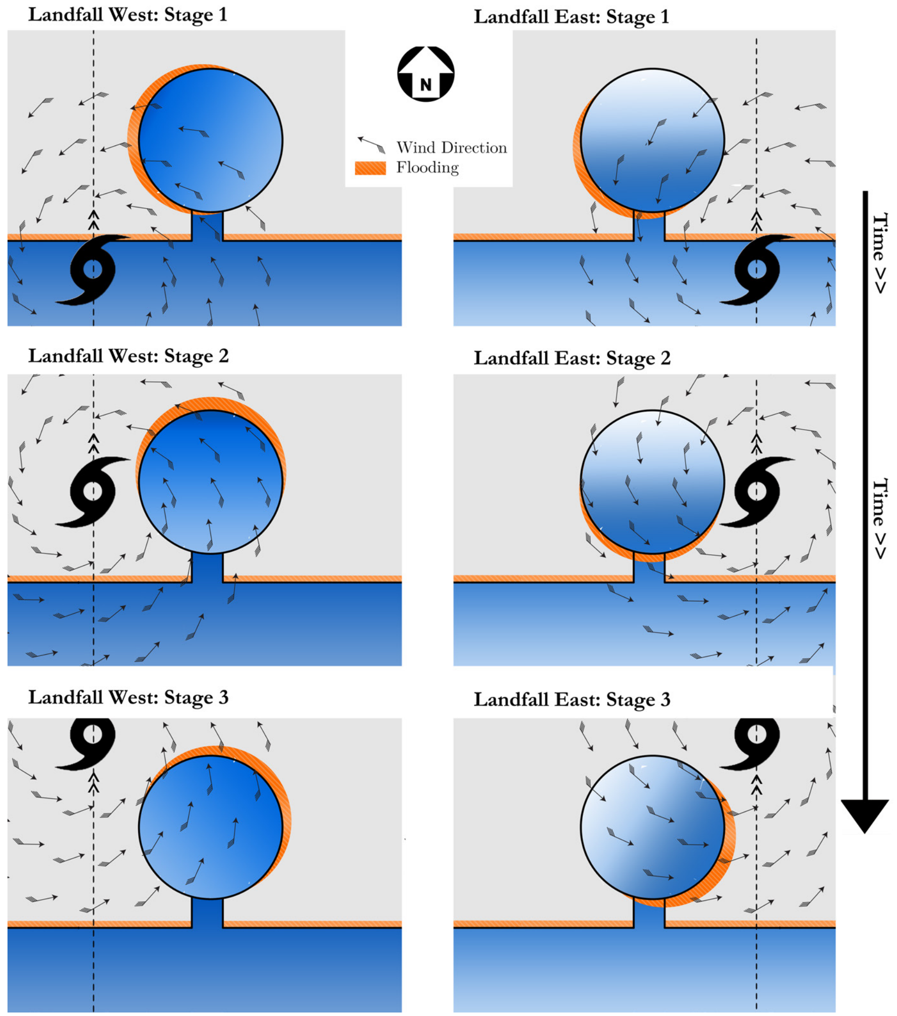


*Figure 8.*
*The influence of landfall location on local wind set-up within a semi-enclosed bay (dark blue indicates areas with higher storm surge).*
*(Stoeten 2013)*



Kasper Stoeten

# PROBABILISTIC DESIGN OF HURRICANE-INDUCED SURGE

## HOUSTON GALVESTON BAY REGION

*Ir. Kasper Stoeten graduated in 2013 from Delft University of Technology, faculty of Civil Engineering & Geosciences, department of Hydraulic Engineering.*

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*Ir. A. Willems, Iv-Infra*
*Prof. dr. S.D. Brody, Texas A&M University Galveston*

The most critical challenge facing the Houston Galveston Bay Region is reducing flood vulnerability. In the aftermath of Hurricane Ike (2008), several structural flood risk reduction measures were proposed; some advocate local solutions, whereas others advocate a regional approach. However, little is known about the return-period of storm surge height or the relationship between storm surge within Galveston Bay and storm surge at the open coast. This relationship could profoundly affect the performance of proposed local or system-wide solutions.
In this work,
1. a probabilistic model was developed to estimate the return probability of storm surge in a semi-enclosed bay system, and
2. a preliminary flood risk assessment was performed to assess the benefits of proposed structural flood risk reduction measures.

To assess bay behavior under hurricane forcing, a simple, behavior-oriented storm surge model was developed. The 1-D model couples meteorological forcing with hydrodynamic response to provide a preliminary estimate of storm surge within a semi-enclosed bay system. Hindcasts of historic events in the region show that the model provides a reasonable estimate of storm surge heights within Galveston Bay.

The validated model was then used to simulate a large number of synthetic events and determine the return period of surge at the open coast and at four locations within the Bay: north, south, east, and west. The results show that hurricane surge within the semi-enclosed coastal bay is highly sensitive to landfall location and that the difference between the return frequencies of surge levels at the open coast and within the bay is significant and may influence the selection of an optimal risk reduction strategy.

In the second part of this study, a flood risk assessment was performed to assess the benefits of three proposed structural flood risk reduction measures: the Coastal Spine, the Houston Ship Channel Gate, and an upgrade of the Texas City Levee. Preliminary results indicate that a system-wide strategy, such as the Coastal Spine, would yield the highest benefit in terms of risk reduction when a high safety level (e.g., 1/10,000 $yr^{-1}$) is adopted. For the same safety levels, local risk reduction strategies, like the Houston Ship Channel Gate or Texas City Levee upgrade, yield similar rates of return, but are less effective in terms of benefits. The analysis indicates that for lower safety levels (e.g., 1/100 $yr^{-1}$) local strategies are an efficient investment, whereas large-scale regional strategies are less economically advantageous due to high initial investment cost.

This thesis provides useful preliminary insights into the behavior of the system under hurricane forcing and supports a broader discussion of flood vulnerability within the Houston Galveston Bay Region. The rudimentary hydraulic model allows for a preliminary assessment of risk reduction strategies during the conceptual design stage. The model lacks spatial detail and should therefore not be used in later, more detailed design stages. For future research, extending to the model to 2-D would provide more accurate results of surge within the Bay.

Figure 9.
Mesh and bathymetry for 2D Model of Galveston Bay. (Ruijs 2011)

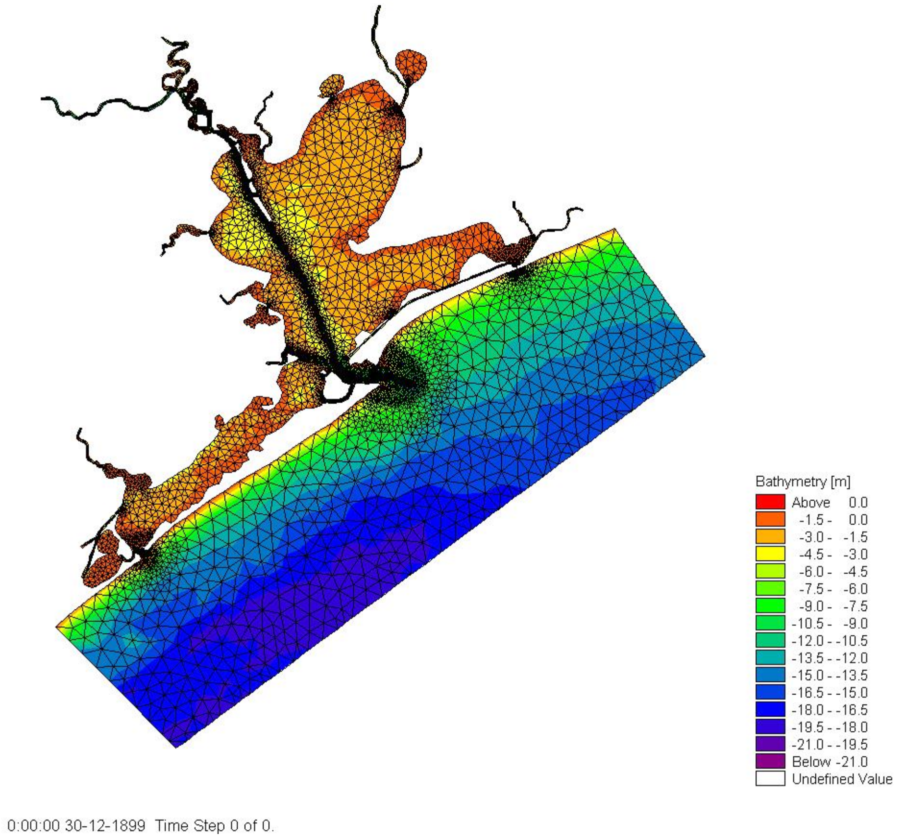
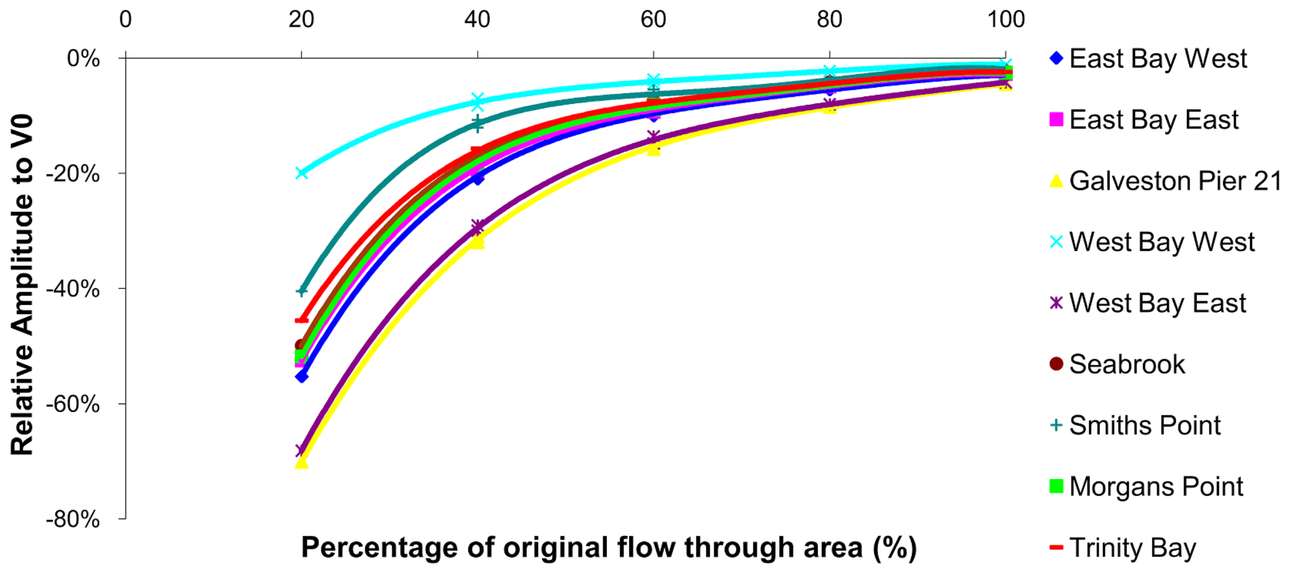



Figure 10.
Average decrease of tidal constituent amplitudes due to a decrease in flow area at Bolivar Roads for all water level recording stations. (Ruijs 2011)






Maarten Ruijs

# HYDRODYNAMIC IMPACTS OF A COASTAL BARRIER

## BOLIVAR ROADS

*Ir. Maarten Ruijs graduated in 2011 at Delft University of Technology, faculty of Civil Engineering & Geosciences, department of Hydraulic Engineering.*

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*Ir. A J. Lansen, Royal Haskoning DHV*
*Prof. dr. W. J. Merrell, Texas A&M University Galveston*

It is well known that storm surge barriers impact tidal flows in coastal estuaries, which can lead to environmental degradation of the ecosystem. This thesis analyzed the impact of the proposed Coastal Spine on the hydrodynamics, morphology, and water quality of Galveston Bay. A 2-D hydrodynamic model was constructed to quantitatively investigate the effect of the proposed surge barriers on the tidal prism, tidal range, and circulation in the Bay. The morphology, water quality and ecology of the Bay were qualitatively investigated by analyzing the results from the 2-D model in the context of existing literature and reference projects.

The results of the 2-D model indicate that the closure of Rollover Pass and partial closure of San Luis Pass would have a minor impact on water distribution inside Galveston Bay, while the construction of a barrier at Bolivar Roads would have a significant effect. During normal weather conditions, when the gates are open, the flow area through Bolivar Roads would be reduced by up to 40-60% due to the foundation of the surge barrier. The tidal prism and range would decrease by 20-40% and velocity currents would increase near the barrier, while decreasing inside Galveston Bay. Constricting Bolivar Roads would direct more ebb flow into the Houston Ship Channel and flood flow to the sides of the Bay.

The proposed barriers would reduce the tidal prism, tidal range, and velocity currents inside Galveston Bay. They would also block sediment inflow from the Gulf of Mexico. In response, sediment in marshes and flats is expected to redistribute to channels within the Bay. These morphological changes combined with the existing sediment deficit caused by sea level rise and subsidence would exacerbate retreat of the coastline and loss of marshes, wetlands, and tidal flats in Galveston Bay.

Restricting flow through the bay outlets would also increase the residence time of fresh water in the bay, resulting in decreased salinity and, potentially, an increased concentration of hazardous substances in Galveston Bay. The fine sediments in the bay would also settle sooner due to lower velocity currents in the bay, resulting in higher light transmittance. These changes, coupled with changes to the hydrodynamics and morphology, would cause loss of habitat and disturb the ecology.

In conclusion, the hydrodynamics and morphology of Galveston Bay would be significantly affected by the construction of a barrier at Bolivar Roads. For the increase of safety in the Houston Galveston Bay Region to outweigh the negative effects of the barrier on the habitats and the ecology, the impact of the Bolivar Roads surge barrier on the hydrodynamics and morphology of the Bay needs to be minimized. This can be accomplished by designing the Bolivar Roads surge barrier such that the flow area is reduced by less 20% or built using compartment dams to preserve the tidal range. Further analysis is needed to quantify the barrier's impact on sediment transport and the morphology of the system, as well as its effect on the existing habitat and ecological environment.

Figure 11.
*Conceptual navigational and environmental components of Bolivar Roads Storm Surge Barrier. (Image Courtesy DEFACTO)*

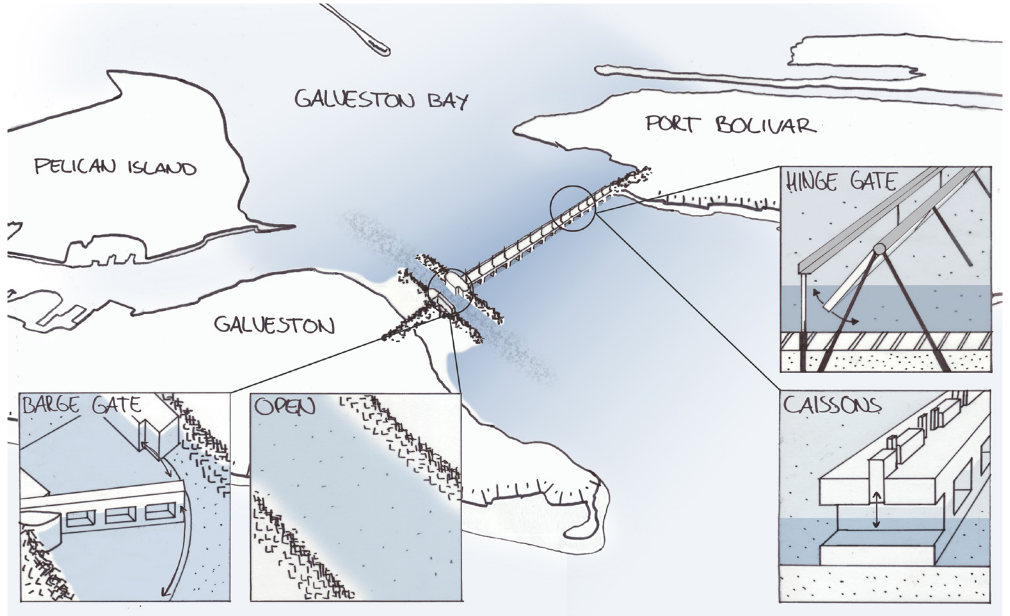


Figure 12.
*Proposed coastal spine and design elements. (Image Courtesy DEFACTO)*




Kasper Lendering & Leslie Mooyaart

# CONCEPTUAL DESIGN OF A COASTAL SURGE BARRIER

## BOLIVAR ROADS

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The initial conceptual design for the Coastal Spine consists of land barriers on Galveston Island and Bolivar Peninsula, a storm surge barrier across Bolivar Roads and at San Luis Pass. The storm surge barrier at Bolivar Roads should allow for environmental flows and shipping traffic to enter the Bay during normal conditions and close off Galveston Bay from the Gulf of Mexico during storm surge conditions. The hydraulic infrastructure research team at TU Delft, together with partners from the private sector, developed a preliminary structural design for the Bolivar Roads storm surge barrier.

The proposed Bolivar Roads storm surge barrier would be divided into a navigational section and an environmental section to maintain maximum tidal exchange through Bolivar Roads and preserve the unique ecology of Galveston Bay, as described by Ruijs (2011). Three design challenges were identified for the navigational portion of the Bolivar Roads surge barrier:

1. The large opening required for navigation during normal conditions (220m (722ft) to allow for Panamax ships);
2. Negative head due to counter-clockwise hurricane rotation over Galveston Bay, causing Bay water levels to be higher than Gulf water levels; and
3. Poor soil conditions making it difficult to properly transfer the horizontal forces to the soil layers underneath the barrier foundation.

Two conceptual navigation section options were initially investigated that address the design challenges: an open navigation section and a barge gate across the navigational channel. An open navigation section significantly reduces the cost of the barrier structure and, initially, it was hypothesized that restricting flow through Bolivar Roads (using an environmental barrier) would sufficiently reduce the volume of water entering Galveston Bay. However, in later hydraulic studies, the open section proved to be infeasible, or at least uneconomical, due to the high cost of bottom protection required to prevent erosion of the channel and scour near the environmental barrier (De Vries, 2014).

Thus, the barge gate proved to be the better design for the navigational section of the Bolivar Roads barrier. The project team completed a preliminary design of a steel barge gate which addressed all three design concerns. The navigational barge gate will be 220m (722ft) long to allow for Panamax ships. During negative head conditions, the barge gate - in contrast to a Maeslant-type sector gate, for example - will swing open on its own. Finally, a deep pile foundation, built using (pneumatic) caissons or cellular cofferdams, was designed to address the poor soil conditions.

Subsequent research explored the hydraulic boundary conditions at the barge gate and options for construction materials (Karimi, 2014; Smulders, 2014), as well as a design for the environmental section of the Bolivar Roads storm surge barrier (De Vries, 2014). Additional research is still required as the current designs can only be seen as a preliminary.

Figure 13.
*Cross-sectional view of barrier and forces due to positive head acting on caissons equipped with skirts (not to scale). (De Vries 2014)*

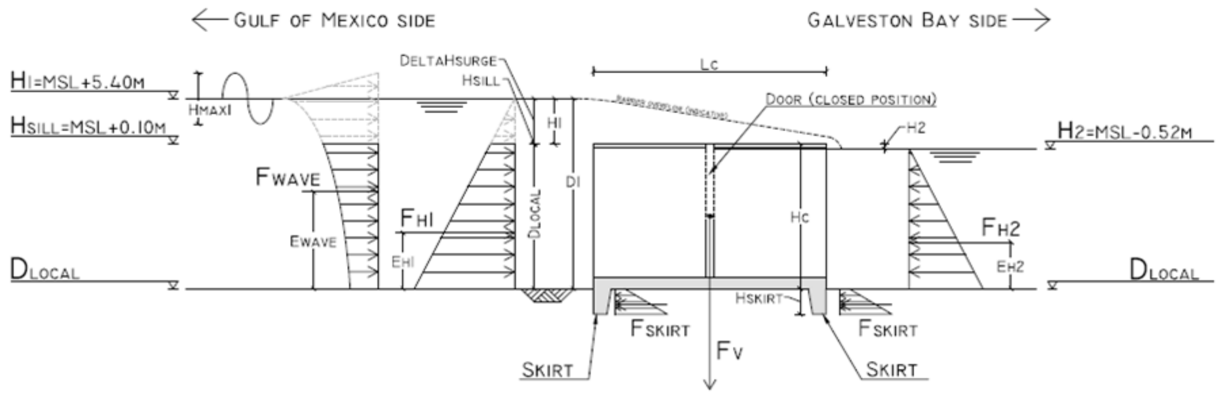
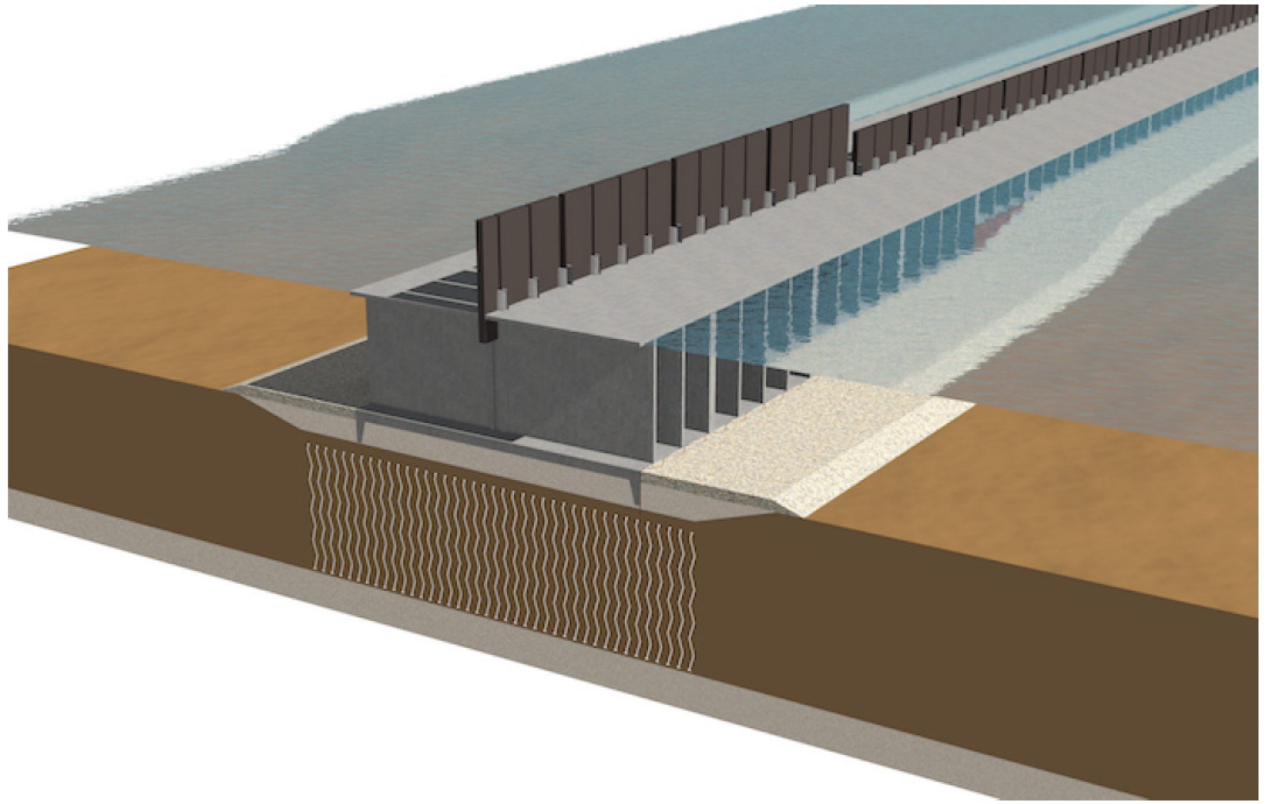



Figure 14.
*Cross section of the environmental section of the Bolivar Roads Storm Surge Barrier; caisson barrier with vacuum preloading soil improvement. (De Vries 2014)*





Peter de Vries

# DESIGN OF AN ENVIRONMENTAL SURGE BARRIER

## BOLIVAR ROADS

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The proposed Bolivar Roads Storm Surge Barrier has been divided into two parts: a wide deep opening to facilitate navigation and a more shallow, environmental section to preserve the ecology of Galveston Bay. In order to maintain the existing hydrodynamic processes described by Ruijs (p. 21), the environmental section must allow for sufficient tidal exchange between the Gulf of Mexico and Galveston Bay. The design must also address the poor soil and negative-head conditions described by Lendering and Mooyart (p. 23). In this thesis, a preliminary design was created for the environmental section of the surge barrier.

In the initial design phase, a preliminary analysis of Galveston Bay's retention capacity was undertaken. The Bay's retention capacity ensures the flood hazard along the Galveston Bay shores remains acceptable even if some volume of surge enters the Bay. It was determined that a surge-reduction barrier, which allows for overtopping, would be feasible at this location. This minimizes the initial investment costs since the barrier does not need to be constructed to retain the full height of surge. In this preliminary design phase, the environmental barrier was designed with a continuous retaining height of 0.1m (0.3ft) above mean sea level; however, in future research, the optimal barrier height should be determined based on a full cost-benefit analysis.

A multi-criteria analysis (MCA) was conducted to determine which barrier type was most suitable for the environmental section. Several barrier types were assessed based on their ability to retain surge, ability to deal with negative head, structural complexity, and total estimated life cycle costs. Based on these criteria, a shallow-founded caisson barrier with vertical doors was identified as the most appropriate design. In total, the barrier would have 338 gates each spanning 6.7m (22ft). The sill would follow the present bottom profile, on average 9.7m (31.8ft) below mean sea level. The barrier would decrease the flow area by 32%, meeting the 40% limit determined by Ruijs (2011).

During the foundation design it was concluded that the clay layers underneath the caissons would settle up to 3.7m (12.1 ft) in depth, which is unacceptable. Thus, four alternative foundation designs were drafted:
1. A shallow foundation using vertical drainage as soil improvement;
2. A shallow foundation with vacuum preloading as soil improvement;
3. A deep foundation with steel tubular piles;
4. A shallow foundation built after replacing the entire weak clay stratum with sand.

Given that underwater installation of vertical drains is expensive and there have been limited applications of this type of design, it was recommended that an alternative deep foundation should be considered in future design phases as it would solve the settlement issues by directly transferring the loads to the bearing sand layers. It is estimated that a technically feasible storm surge barrier could be constructed for both navigational and environmental sections in Bolivar Roads for between $2.7 and $4.0 billion.

Figure 15.
*Load distribution on rubber barrier due to positive head. (Van Breukelen 2013)*

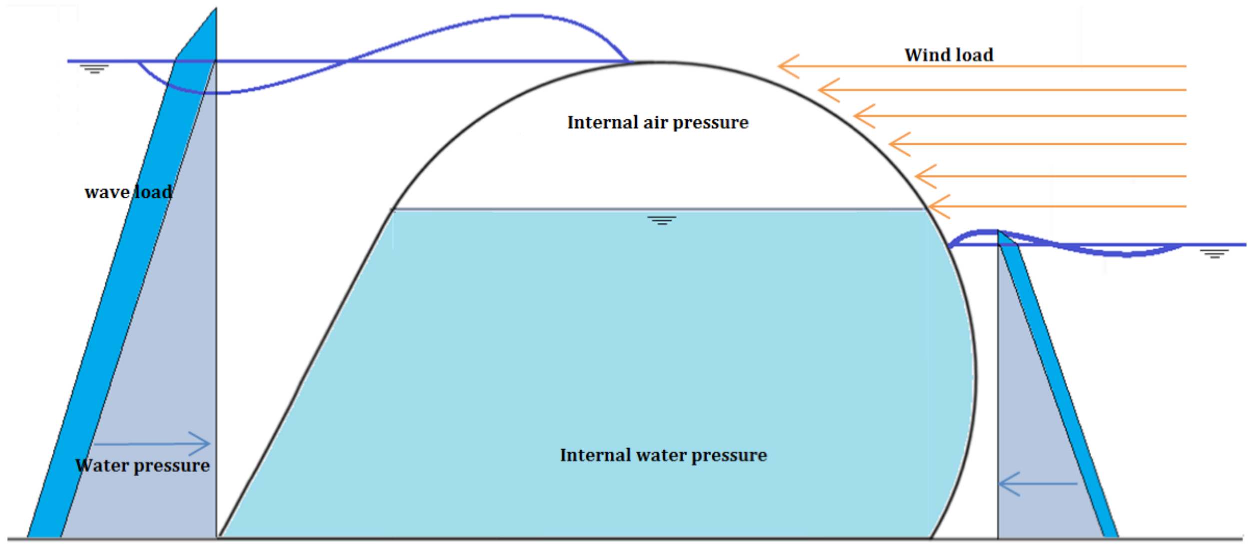
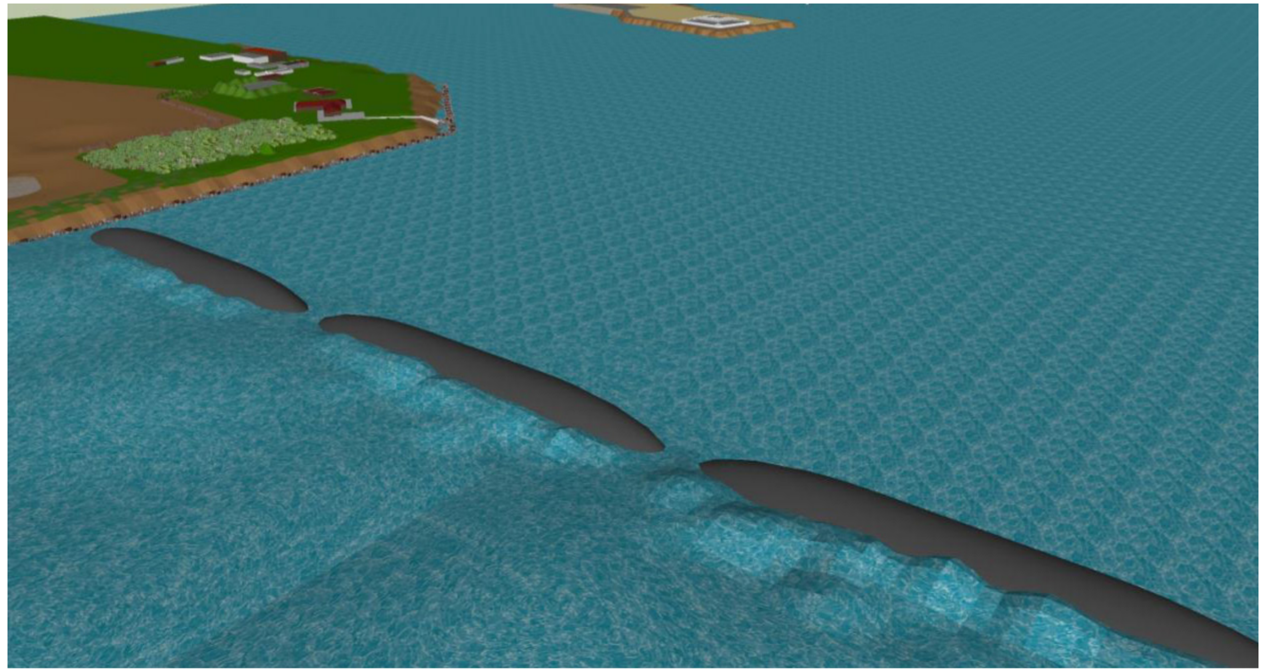



Figure 16.
*Inflatable rubber barrier without abutments designed for Bolivar Roads. (Van Breukelen 2013)*





Marjolein van Breukelen

# DESIGN OF AN INFLATABLE RUBBER BARRIER

## BOLIVAR ROADS

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If realized, the Bolivar Roads Surge Barrier will be the most expensive portion of the proposed Coastal Spine. An inflatable rubber barrier is one possible design that would meet navigational and environmental criteria and be more cost-effective than a hard structure. A large inflatable rubber barrier has been successfully built in Ramspol, the Netherlands, but it is a fraction of the size of what would be required for Bolivar Roads. The primary limitation to implementing large inflatable barriers is the high membrane force caused by stress concentrations in the sheet and dynamic loading. Even though existing rubber materials can withstand high loads, it is important to reduce the membrane forces. This can be achieved by limiting the number of folds and reducing peak stresses in the sheet when the dam is inflated.

In this thesis, two conceptual inflatable rubber barriers were developed and compared for Bolivar Roads. The first barrier is based on the existing inflatable dam at Ramspol, but has been improved and scaled up to allow it to be applied at Bolivar Roads. The second design is innovative and based on large-scale conditions. Ultimately, the second design was recommended for Bolivar Roads.

The first design consists of 7 inflatable dams, each with an approximate length of 250m (820ft). While shorter dam lengths reduce the probability of barrier failure, shorter lengths are infeasible at this location due to the flow-through requirement. The proposed design is an ellipsoid above the abutment and a half cylinder in the middle to minimize fold formation and peak stresses in the sheet; smaller abutment slopes were designed to minimize folds and peak stresses.

In the second design, an inflatable dam without abutments was generated. Since 100% closure is not required at Bolivar Roads (as discussed by De Vries (p.25)), water is allowed to flow between the inflatable dams. This design consists of 21 inflatable dams, each with a length of 100m (328ft), spanning the total width of Bolivar Roads. The shorter lengths increase the reliability of the barrier and are possible as no abutments are present in the waterway. Similar to the previous design, the ends of each inflatable dam are ellipsoid and the middle a half cylinder. The combination of the ellipsoid shape and the absence of connections with the abutments guarantee minimal folds and peak stresses in the sheet. This results in a better force transfer in the sheet, ensuring low peak membrane forces.

In both designs, folds and peak stresses in the sheet are significantly reduced compared to existing barrier at Ramspol. However, the second design provides better results than the first, due to the absence of connection with the abutments and the increased reliability which the larger number of shorter inflatable dams provides. For these reasons, the second design was chosen for the final design of the Bolivar Roads Surge Barrier.

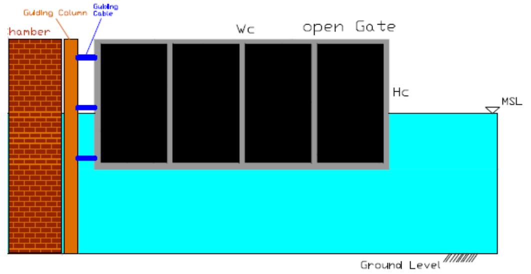


*Figure 17.*
*Open gate; cross section Galveston Island side, dimensions not to scale. (Karimi 2014)*

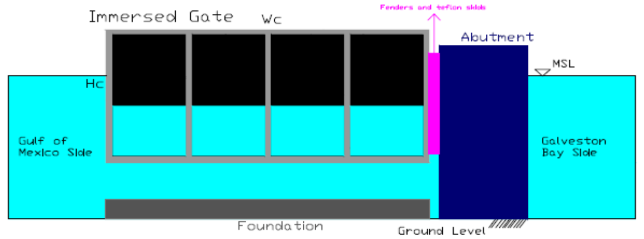


*Figure 18.*
*Ballasted gate during immersion; cross section Bolivar Peninsula side, dimensions not to scale. (Karimi 2014)*

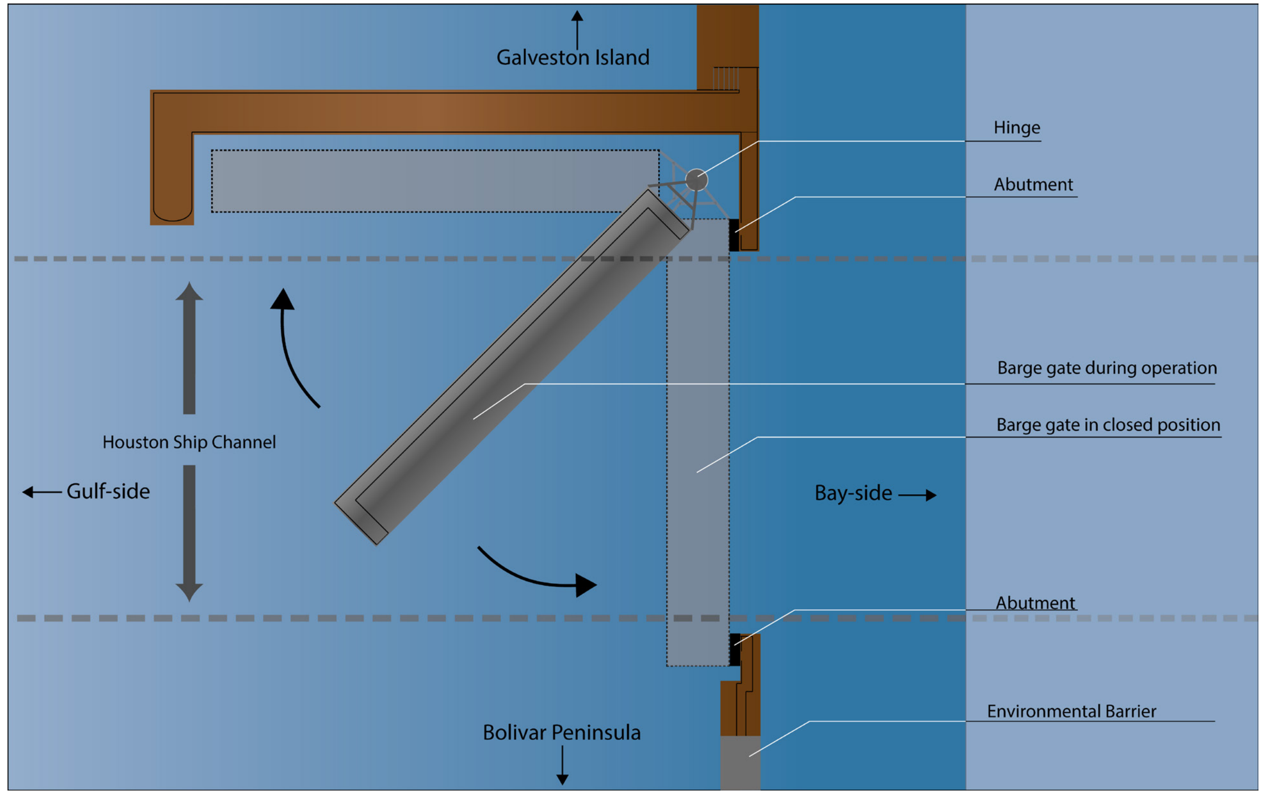


*Figure 19.*
*Plan of the barge gate; dimensions not to scale.*



Iman Karimi & Ad van der Toorn

# DESIGN OF A NAVIGATIONAL SURGE BARRIER

## BOLIVAR ROADS

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The challenge of designing and constructing a navigational surge barrier across Bolivar Roads is not only to bridge a free span of about 220m (722ft) using a single gate, but also to transfer the dynamic forces caused by high flow velocities during storm conditions to the piers and the deep pile foundation of the barrier. In this thesis, a preliminary design for the navigational section of the hydraulic barrier across Bolivar Roads was made using lightweight concrete (B65). The resulting design is not only strong, but also durable.

A multi-criteria analysis was used to determine which gate type would be suitable for the navigational section. Multiple gate types were considered, including a sector gate, flap gate, barge gate, inflatable gate, and parachute gate. The structures were evaluated based on criteria such as cost, maintenance, reliability, and realization. A floating barge gate was identified as the best option for the barrier, and a preliminary design was made based on system engineering. The design considered the main operational phases: opening, when the gate swings around one pier, landing, submerging, and re-opening.

The barge gate was designed to retain the full surge height of approximately 5.5m (18ft) above mean sea level. The barge would be a concrete caisson structure measuring 230m x 36m x 22.5m (755ft x 118ft x 73.8ft) and weighing approximately 71,000 tons. Due to the weak subsoil at Bolivar Roads, deep foundations were designed to transfer the large horizontal forces to the stronger soil layers below. These supports would comprise steel tubular piles filled with concrete. A preliminary design of the abutments yielded piers made of pre-stressed concrete each measuring 24m x 7m x 5m (79.7ft x 23.0ft x 16.4ft). Preliminary cost estimates indicate that a navigational barrier consisting of a concrete barge gate would cost around $300 million. The total estimated cost for the Bolivar Roads surge barrier (including the environmental and the navigational portions) is estimated to be between $2.3 and $4 billion.

Project management was also considering, including construction, maintenance and cost of the barge gate. The gate is designed to be constructed in a dry dock and floated to the site. This prefab concept is not only an advantage during construction, but could also be useful for maintenance. Based on the design undertaken in this thesis, a lightweight concrete barge gate could be a realistic, cost effective and durable option for the navigational portion of the Bolivar Roads Surge Barrier, though the dynamic behavior of the gate needs to be studied before the design can be finalized.

*Figure 20. Preliminary dimensions for the Bolivar Roads Navigational Surge Barrier. (Smulders 2014)*

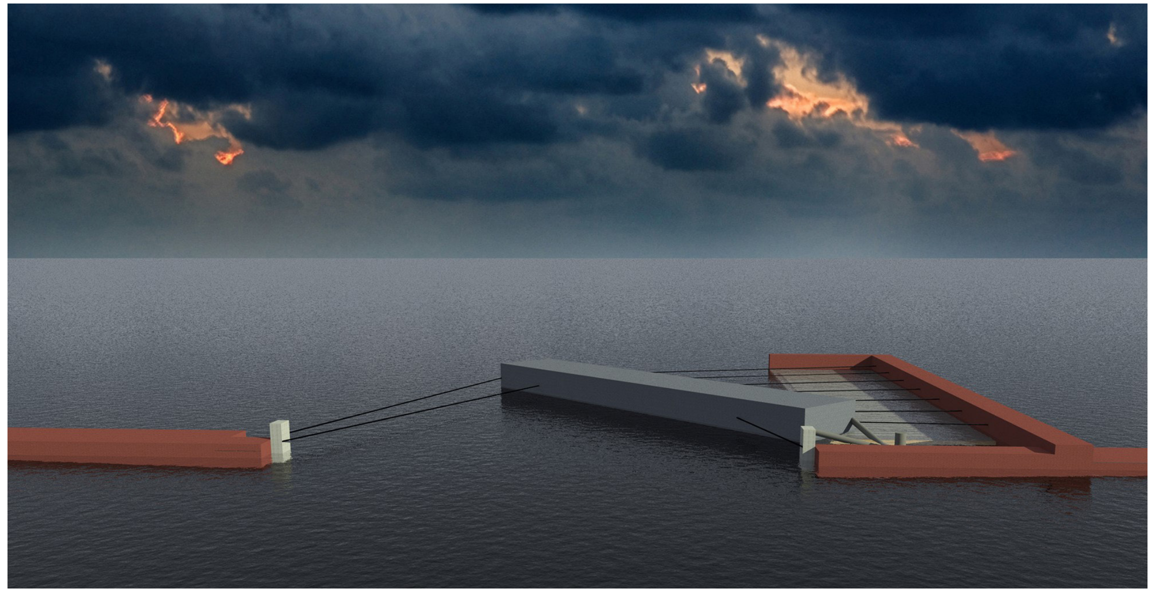
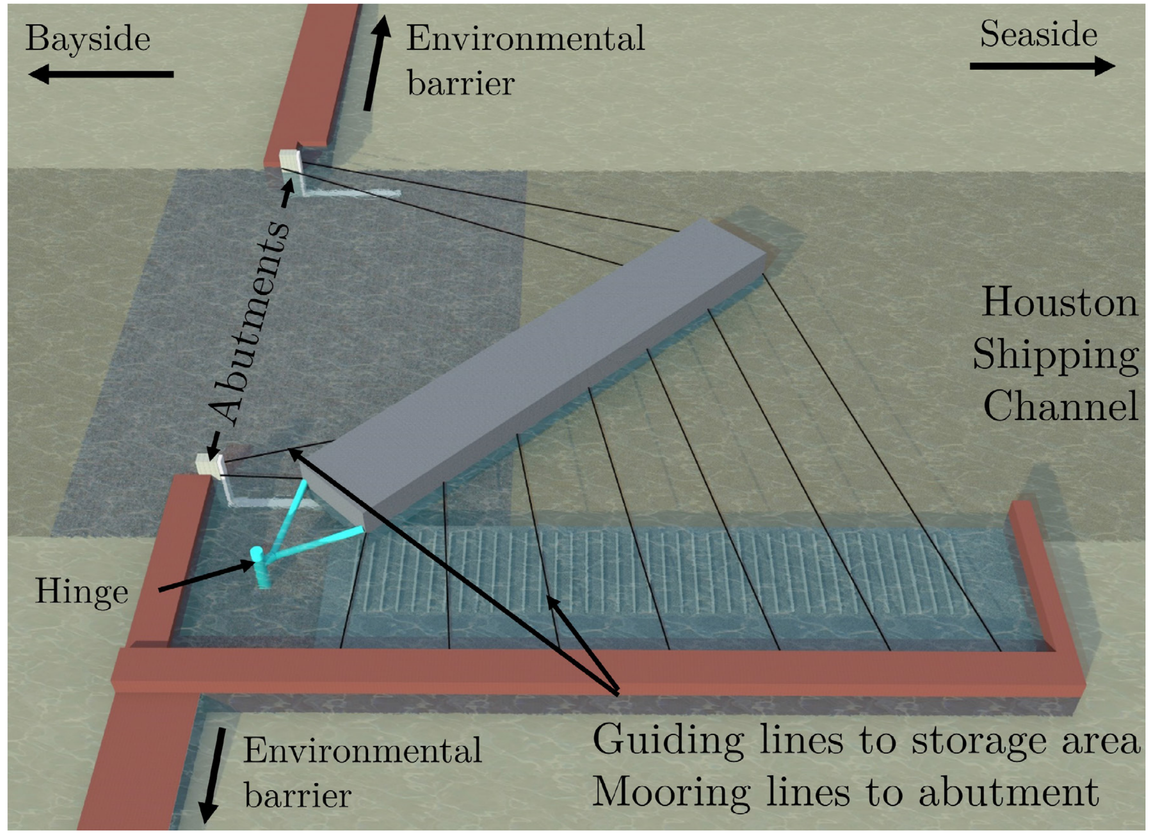


*Figure 21. Preliminary dimensions for the Bolivar Roads Navigational Surge Barrier. (Smulders 2014)*






Jor Smulders

# ANALYSIS OF NAVIGATIONAL BARRIER DYNAMICS

## BOLIVAR ROADS

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The proposed storm surge barrier at Bolivar Roads includes a navigational section for ship traffic and a wide shallow environmental section to maintain tidal exchange. Based on the preliminary design for the barrier presented by Lendering and Mooyaart (p.23), this thesis analyzed the dynamic behavior of the proposed barge gate and its response to wave and current excitation during a complete closing cycle.

In order to assess the technical feasibility of constructing a hydraulic barrier across Bolivar Roads, the closing cycle was divided into four individual phases: swing, submersion and landing, closed state, and negative head - the period during which water level in Galveston Bay exceeds the water level in the Gulf of Mexico. Recommendations were made for reducing the dynamic forces and excitation experienced during a closing cycle. In addition, the preferred material (concrete or steel) for each phase was identified.

Under normal conditions, the barge gate would be stored parallel to the channel. Thirty hours prior to hurricane landfall, the barge would be set afloat. The barge is designed to swing 90 degrees around a hinge, guided by anchor lines connected to the abutment and storage area. During the swing operation, the barge gate is governed by rolling. This motion can be reduced by introducing ballast water in the outer compartments of the barge or reconfiguring the anchor lines. Once closed, the barge is submerged using pumps and valves. In the closed position, the barge is supported at the ends, but a gap of 1m (3.3ft) is maintained above the channel bottom to avoid the construction of an expensive sill. The entire closure takes approximately two hours: one hour for swing and one for submersion and landing.

In the closed position, the motion of the simple supported barge is governed by torsion, vertical bending, and horizontal bending. Due to the high underflow velocity, the barge is prone to self-excitation in the vertical, horizontal and torsion directions. Multiple mechanisms, such as outflow in longitudinal direction or turbulence, can reduce the severity of this self-excitation. The first natural frequency in vertical bending is close to the peak of the wave spectrum. Under certain hurricane wind conditions, the bayside water level may exceed the seaside water level. For this, a stop block is required to ensure the barge does not slide off the abutment. Once the hurricane has passed the barge is set afloat and returned to the storage area.

During the dynamic assessment of the Bolivar Roads navigational barrier, unacceptable dynamic motions were encountered during the closed position. However, the addition of a stop block and ballast water, help to reduce these motions to an acceptable level. In this case, a concrete barge, such as the one described by Karimi, seems to be slightly more stable than a steel one, mainly due to the higher weight which can be achieved by increasing the amount of ballast water. In future design phases, the self-excitation should be tested in closed position using a scale model to determine the best mechanism for maintaining stability of the barrier.

*Figure 22.*
*Water level inside Galveston Bay as function of storm surge at the open coast for varying barrier height (1, 3 and 6 meters/ 3.3ft, 9.8ft, and 19.7ft). (Rippi 2014)*

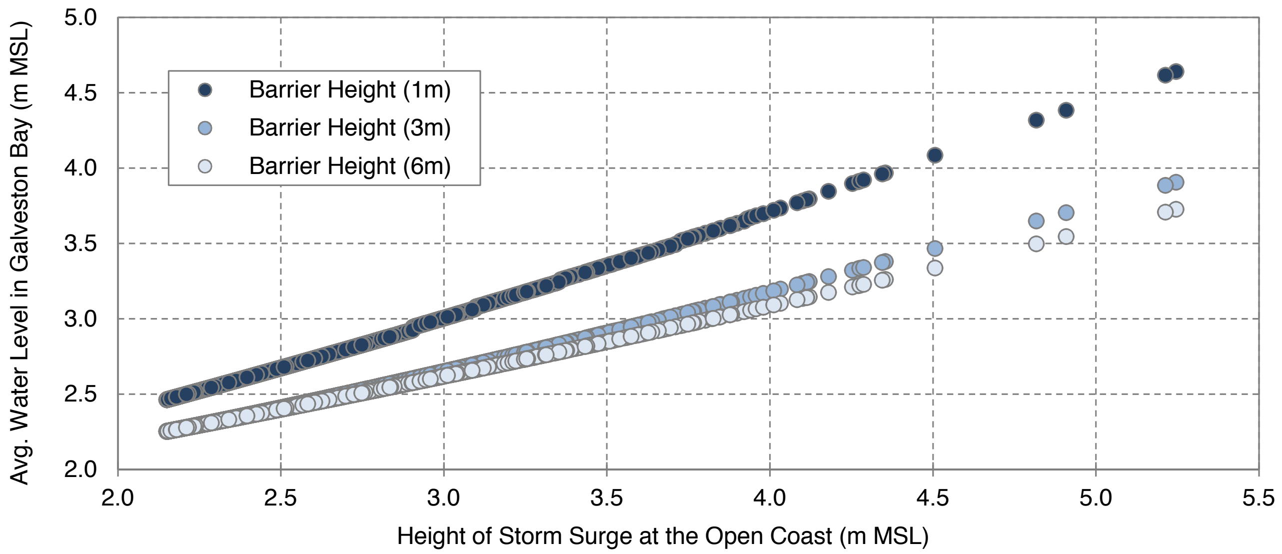
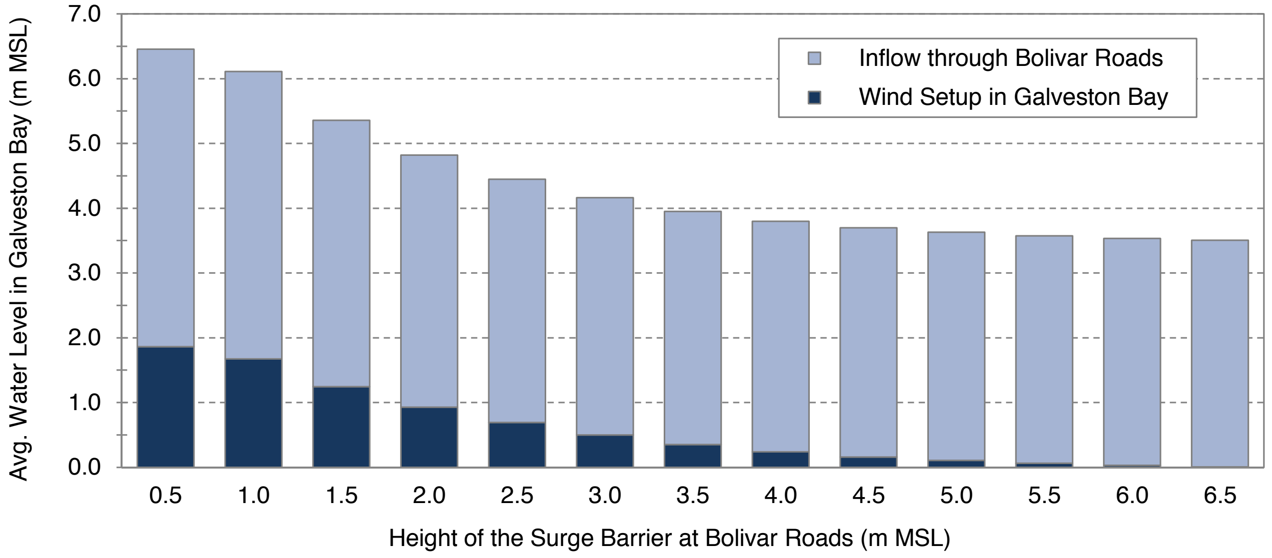



*Figure 23.*
*Relative contribution of inflow through Bolivar Roads and wind setup to total water levels inside Galveston Bay for varying barrier height (0-7 meters; 0-23 ft). (Rippi 2014)*






Katerina Rippi

# OPTIMIZATION OF SURGE BARRIER HEIGHT

## BOLIVAR ROADS

A major challenge for the proposed Coastal Spine is the design and construction of the Bolivar Roads Storm Surge Barrier. In prior studies, preliminary structural designs for the navigational and environmental portions of the barrier were developed. This project focused on identifying the cost-optimized barrier height based on surge risk reduction in the Houston Galveston Bay Region. To do this, a simplified, 1-D surge model was built to calculate water levels inside the Bay for varying barrier heights. The resulting water levels were used to estimate damage and associated flood risk reduction. Using this information, a preliminary cost-benefit analysis was conducted to determine the optimal surge barrier height.

The simple 1-D model was built based on the major physical components of surge and fundamental equations for wind setup. Using the model, a simple balance equation was derived relating the height of water inside the bay to that in the Gulf for barrier heights varying from 0 to 7m (0-23ft). Initial results indicated that increasing the barrier height reduced surge height in Galveston Bay, but that the relative impact of wind set up increased with increasing barrier height, primarily due to the reduced inflow through Bolivar Roads. Based on this analysis, the reduction of water levels in Galveston Bay can be optimized for a given barrier height and surge level; for example, for a peak surge of 5.2m (17 ft), the maximum water level reduction is reached at a barrier height around 4m (13.1ft).

To find the exceedance water levels inside Galveston Bay under varying hurricane con-ditions and barrier heights, a Monte Carlo simulation was run using the synthetic hurricanes created by Stoeten (2013). Cumulative probability distribution functions (CDFs) were derived for water levels inside Galveston Bay under varying barrier retaining heights between 0 and 7m (0-23ft). These water levels were used to estimate the highest potential damages in the region based on the inundation of residential and industrial properties. The benefit-cost ratio was determined based on the risk reduction (e.g., benefit) and the approximated investment cost of each barrier. Based on this calculation, the structure with the highest cost-benefit ratio has a height of 3m (9.8ft). A preliminary estimate of the optimal safety level and the barrier height were also calculated.

In this project, a simple relationship between water levels in the Gulf of Mexico and Galveston Bay was developed and used to find the optimal height of the barrier at Bolivar Roads. It is the first attempt to cost-optimize a structure for Bolivar Roads based on flood risk reduction. However, this preliminary approach has various limitations. While the 1-D model gives a preliminary indication of the volume of water entering the Bay via Bolivar Roads, a more accurate estimate would be obtained by applying a more sophisticated 2-D model to the system. In addition, the return period surge along an open coast needs to be understood more fully, and the acceptable level of risk in the Houston Galveston Region needs to be precisely determined. Together, these would permit a more definitive cost-benefit analysis.

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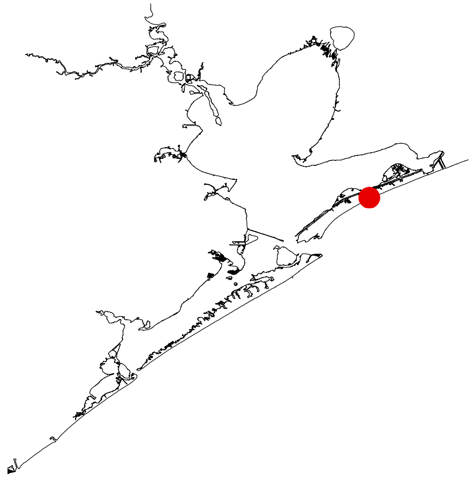
*Figure 24. Destruction of homes on Bolivar Peninsula by Hurricane Ike. (Photo Courtesy Jocelyn Augustino, FEMA)*



Tom Heeringa, Rolf Kelderman, Merijn Janssen, Geert Roukens, Refke Gunnewijk, Anniek de Milliano

# DESIGN OF A LAND BARRIER

## BOLIVAR PENINSULA



*A multi-disciplinary project by MSc students of Coastal Engineering (Merijn Janssen en Geert Roukens), Construction Management & Engineering (Tom Heeringa and Rolf Kelderman), and Transport, Infrastructure & Logistics (Refke Gunnewijk and Aniek de Milliano).*

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The risk of developing on Bolivar Peninsula was illustrated during Hurricane Ike (2008) when most of the established buildings were destroyed or washed away by storm surge. Since then, nearly half the homes have been rebuilt. The objective of this interdisciplinary team project was to develop an integrated land barrier and evacuation strategy for Bolivar Peninsula to protect residents and existing development and to reduce the volume of water overtopping the Peninsula during a hurricane event, thus also helping to protect the Houston Galveston Bay Region.

A detailed analysis of Bolivar Peninsula was conducted to determine the hydraulic boundary conditions of the system, the different stakeholders, their desired outcomes, and existing and potential evacuation strategies. Based on this analysis, three alternative levee concepts were developed: 'Lifeguard', 'Bolivar Boulevard', and 'Hands Off'. The 'Lifeguard' concept would consist of a levee on the beach with natural cover and would protect all of the existing development on the Peninsula. The 'Bolivar Boulevard' concept is based on the existing Galveston Seawall, a concrete T-wall at the Gulf-side of the island, which would be extended to protect the entire Peninsula. The 'Hands Off' concept consists of a levee located in the middle of the Peninsula, dividing it into two parts, one protected, the other unprotected, thereby preserving the existing beach and beachfront properties.

To choose the optimal levee concept for preliminary design, a multi-criteria analysis (MCA) based on thirteen criteria was undertaken to determine the optimal concept. The criteria were divided into four categories: economics (cost, indirect benefits, financing options), safety (evacuation capacity, structural reliability, reduction of flood area, footprint, risk perception), sustainability (ecology, ethical value, materials), and execution (maintenance and practicality). Based on these criteria, it was determined that the 'Hands Off' was the most appropriate concept for Bolivar Peninsula. It performed best in the categories economics, sustainability, and execution, and was second-best with regard to safety.

In the preliminary structural design, the optimal height of the barrier was determined based on the estimated cost of construction vs. flood risk reduction calculated by Stoeten (2013). From this, it was determined that the optimum barrier will protect against a once in 500 year flood. The resulting dike will be 5.8m (19ft) above mean sea level, 48m (157ft) wide, and 43km (26.7mi) long. The dike body will be constructed using sand-clay and allow for 10 l/m/s overtopping. A preliminary safety analysis based on piping, micro-stability, and slope stability indicated that the structure will not fail due to overtopping or wave attack. The structure itself will be wide enough to counteract piping underneath or through it; as a result, no seepage screens are necessary in the design. Finally, to connect the existing State Highway 87 on the Gulf-side of the dike with the new protected road on the bay-side of the dike, seven diagonal ramps were planned four miles apart. The estimated total cost of the structure is $500 million .

Based on the proposed dike design, a site-specific evacuation plan was developed for Bolivar Peninsula. The new dike will protect the bay-side of the island from flooding and the proposed road on the bay-side of the dike will allow more time to evacuate. To provide local shelter during small hurricane events, a large evacuation shelter is proposed on the bay-side of the Peninsula. Built to withstand hurricane force winds and flooding,

*Figure 25.*
*Cross-section of land barrier on Bolivar Peninsula; cross section and top view. (Janssen et al. 2014)*

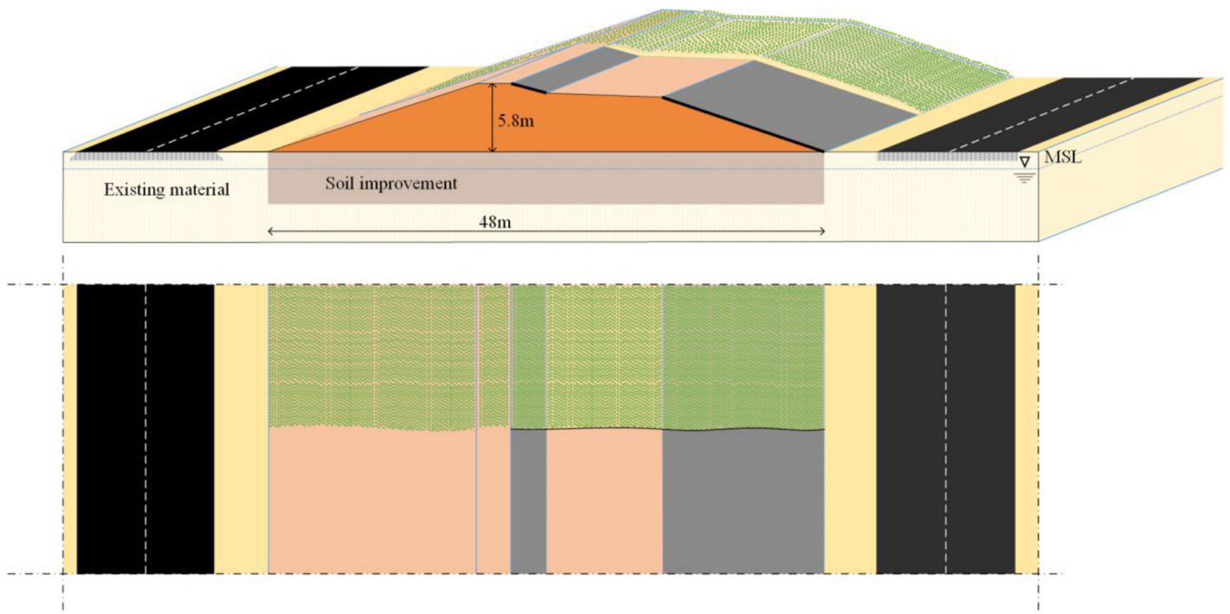
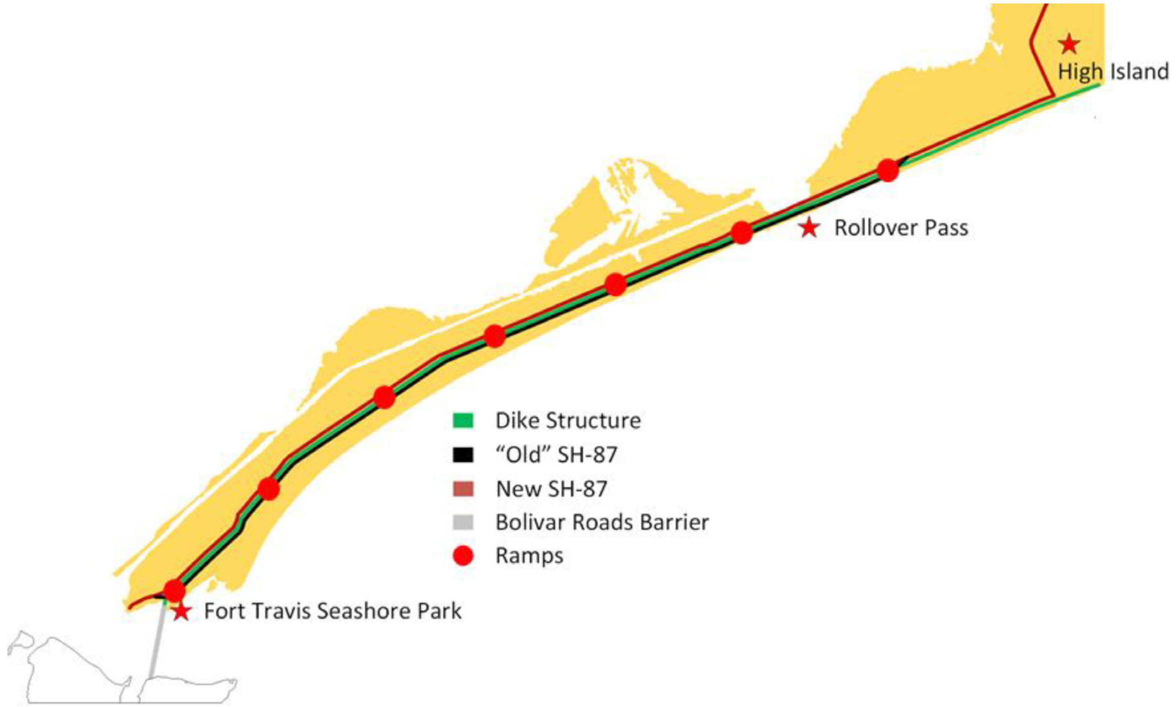



*Figure 26.*
*Alignment of proposed land barrier on Bolivar Peninsula. (Janssen et al. 2014)*






*This contribution is based on the findings of a multi-disciplinairy master project, executed by six master students from Delft University of Technology.*

*A multi-disciplinairy master project at the faculty of Civil Engineering & Geosciences, implies that different master disciplines work together on a project which they compose themselves; the location of the project is preferably abroad. MSc students work together in groups of four to six people, combining their knowledge gained. By collaborating with students from various disciplines, complex problems can be fully addressed and solved just like in corporate situations where employees often work within groups with a variety of disciplines to solve problems.*

*This group was on site in Texas from April 19th until July 19th, 2014.*

it will provide a temporary shelter for local residents and vacationers.

Even if the proposed dike is designed to withstand a once in 500 year storm surge from the Gulf-side, it cannot protect from other hurricane-related hazards, such as high winds or back-side storm surge driven by wind setup inside Galveston Bay. Thus, it will be necessary to evacuate the entire Peninsula during large hurricanes. The primary evacuation route will be via the proposed bay-side road toward High Island since the ferry between Bolivar Peninsula and Galveston Island cannot operate under hurricane conditions (+1.4m (4.6ft) above normal). From there, evacuees will travel north on State Highway 124 and then onto Interstate 10 West, sheltering in Houston or continuing towards Dallas.

A significant problem at Bolivar Peninsula is the lack of willingness of the residents and vacationers to evacuate during a hurricane, mainly because they are unaware of hurricane threats. Therefore, the main objective of the evacuation plan for Bolivar Peninsula was not only to develop the evacuation logistics, but also to influence the evacuation behavior and response to hurricane warnings. Educating residents, simplifying the evacuation decision process, and providing contact information have been included as necessary components in the proposed evacuation plan.

In the final phase of this project, a strategy was designed to convince critical stakeholders to support the project on Bolivar Peninsula, secure the necessary funding, and convince residents that they should evacuate. A stakeholder analysis was undertaken and four necessary activities were identified:

1. Increase awareness of the flood risk and consequences, and the necessity for evacuation;
2. Increase involvement of critical stakeholders in the project development and funding;
3. Increase collaboration between public officials, emergency managers, and the community;
4. Provide a viable preliminary design with acceptable cost-benefits.

During the project, many variables that will affect the design were not well-defined or were completely unknown. For example, the hydraulic boundary conditions and damage estimates were based on the preliminary return frequency water levels developed by Stoeten (2013). To improve the preliminary barrier design and evacuation strategy, the following parameters should be further investigated: subsoil conditions, storm conditions, surge heights, and minimum acceptable flood risk levels, investment and damage costs, applicability of the Dutch design formulas, variable structure height, construction materials, breakwaters, stakeholders, and evacuation demand.

This project resulted in a preliminary design for an integrated barrier design and an evacuation strategy for Bolivar Peninsula. It was determined that the optimal barrier should be located in the center of the peninsula and should protect against a once in 500 year storm. Along with the levee, a new road and evacuation shelter were also designed for the bay-side of the Peninsula. The proposed evacuation strategy includes a large educational component to promote awareness of hurricane risk.

Figure 27.
Artist impression of seawall partly covered in dune. (Courtesy of Defacto)

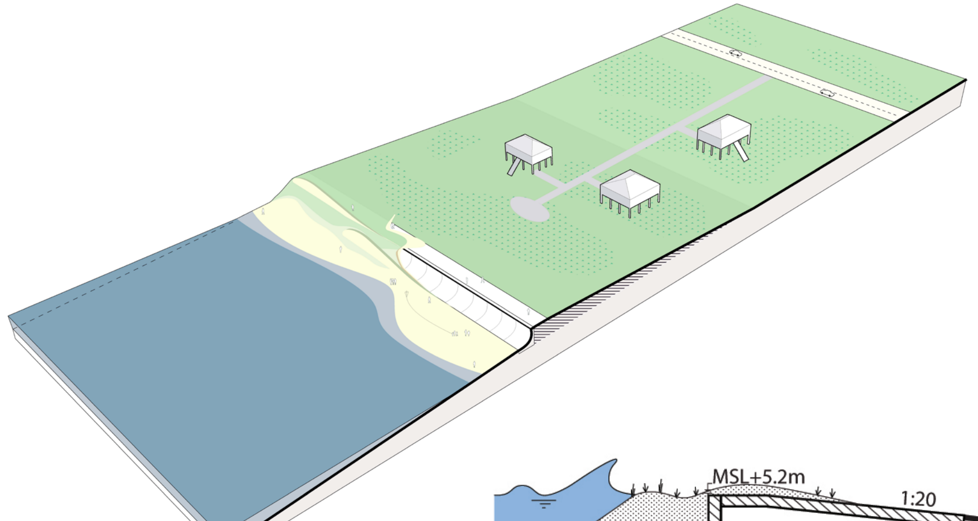


Figure 28.
Cross section of seawall alternative with dune coverage. (Courtesy of Defacto)

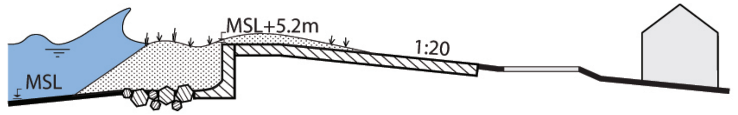


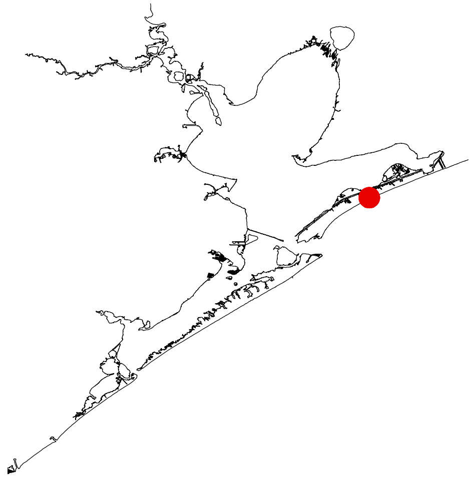

Figure 29.
Galveston Seawall. (Photo Courtesy Baukje Kothuis)




Erik van Berchum

# DESIGN OF A LAND BARRIER

## HOUSTON GALVESTON BAY REGION



*Ir. Erik van Berchum is a research engineer at Delft University of Technology, Faculty of Civil Engineering & Geosciences, department of Hydraulic Engineering..*

The land barrier is the longest element in the proposed Coastal Spine system. In its entirety, the barrier would stretch 90 kilo-meters (145 miles) along the coast between Freeport and High Island. It would be built on Bolivar Peninsula and Galveston Island, as well as along the Bluewater Highway south of San Luis Pass. Its purpose is to defend the Houston Galveston Bay Region from storm surge.

To develop a well-defined concept for the hydraulic design of the land barrier on Bolivar Peninsula, Galveston Island and along the Bluewater Highway, several steps were under-taken. The chosen alternative is based on the existing Galveston Seawall and com-bines its familiar look and height with the strength needed to protect the lives of the people living in the Houston Galveston Bay Region from hurricane-induced storm surges generated in the Gulf of Mexico.

The existing Galveston Seawall was built in the wake of the Great Hurricane of 1900 and has successfully protected the developed east end of Galveston Island for more than a century. The iconic Galveston Seawall will be extended to the west end of Galveston Island and built on Bolivar Peninsula to a height of 5.2m (17ft). Behind the seawall, a very gentle slope will lead the road back to normal level. Because of significant overtopping during extreme storm surges, extensive ground protection is needed to ensure stability; the structural elements of seawalls provide stability against surge and large wave over-topping volumes.

To help integrate the seawall in the landscape, the new portions of the seawall could be covered with sand or vegetation to resemble a natural dune. This concept has been applied in the Netherlands, as a so-called dike-in-dune (or levee-in-dune). This will entail higher construction and maintenance costs, but will also result in a somewhat higher landscape value, potentially resulting in economic gains through tourism or other recreational use. However, under high storm surges, this natural cover will vanish and the seawall will be exposed. To reduce costs, it would be possible to only cover the floodwall in residential and tourist areas.

An important conclusion is that it is not possible to design a structure that complies with all boundary conditions simultaneously. For example, if a dike height of 5.2m (17ft) is necessary, large forces and overtopping will also need to be accommodated in the design. This will result in a structural solution consisting of a hard seawall with a wide base to withstand the large hydrodynamic forces. Such a solution is relatively expensive and will have a drastic impact on the existing landscape of Galveston Island and Bolivar Peninsula.

Though it might be less visually appealing, another solution might be to increase the maximum allowable dike height. Overall, the land barrier needs to be studied further to determine an optimal solution. Future research could focus on the role of the land barrier in surge reduction in the bay (e.g., how much water flows over the barrier islands and how much this needs to be reduced), and optimizing the design based on engineering, costs and landscape integration.

*Figure 30. Navigational Surge Barrier at Houston Ship Channel. (Schlepers 2015)*

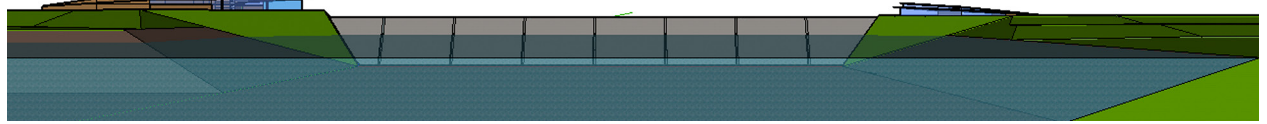
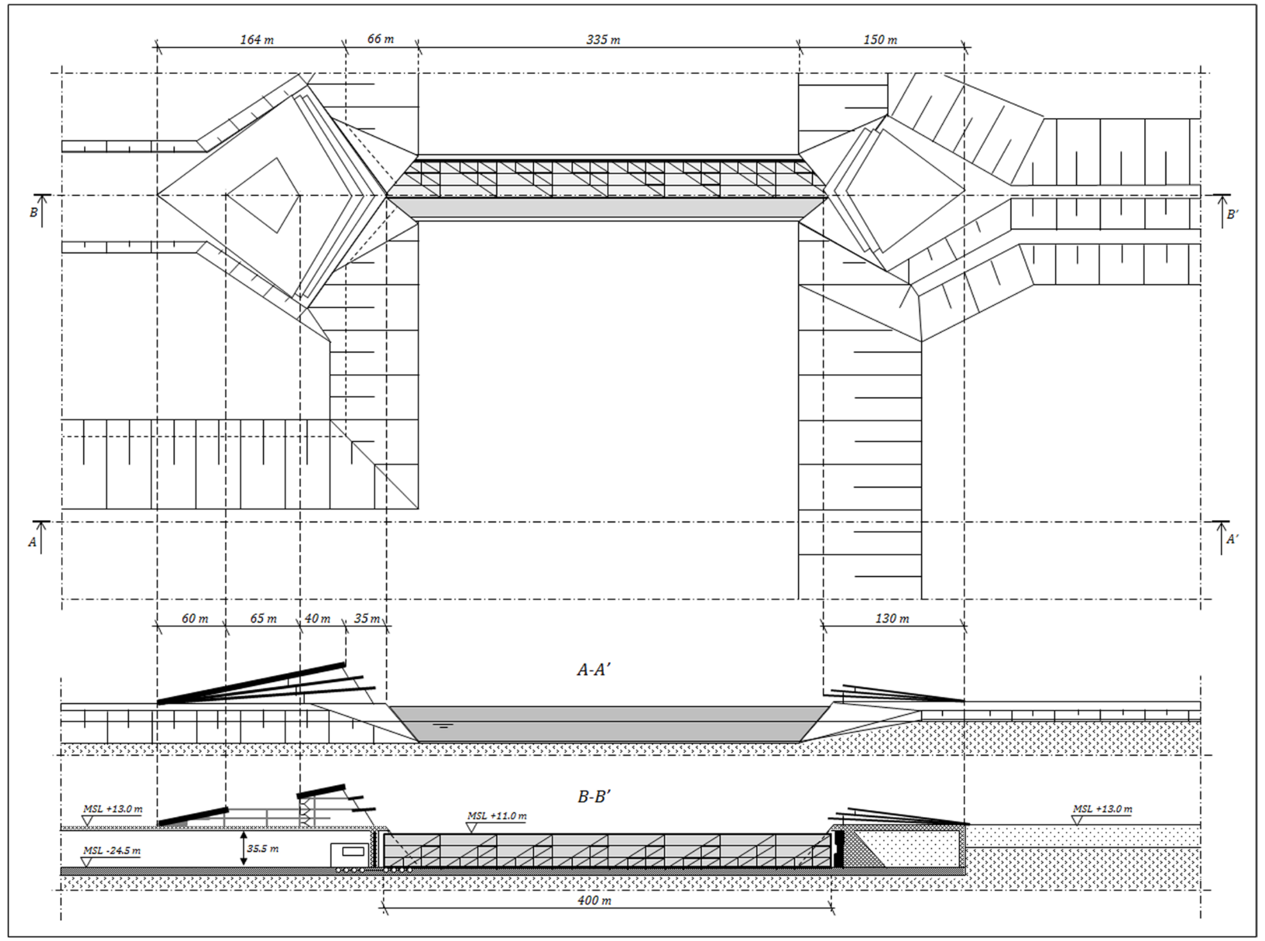


*Figure 31. Design of Navigational Surge Barrier. (Schlepers 2015)*




Martijn Schlepers

# DESIGN OF A NAVIGATIONAL SURGE BARRIER

## HOUSTON SHIP CHANNEL

The Houston Ship Channel (HSC) is home to the largest petrochemical complex in the US; flooding of the HSC industries due to storm surge could cause enormous economic and environmental damage in the region. Previous research has indicated that a storm surge barrier at the coast will not be sufficient to protect the HSC, since local wind setup will cause a significant residual surge in Galveston Bay. This thesis developed a preliminary design for a local storm surge barrier at the mouth of the HSC near Morgan's Point.

A brief stakeholder analysis determined the local requirements for the structure. The system and hydraulic boundary conditions were determined and the global design of a hydraulic barrier at Morgan's Point was developed, consisting of three levee sections, including environmental and navigational sections. The navigational section of the HSC barrier was then developed to a higher level of detail and recommendations for construction were made.

The hydraulic boundary conditions associated with a once in 1000 years storm event were estimated and used as maximum design loads for the structure. It was determined that this would be comparable to the storm surge conditions created by an Ike-like storm making landfall at San Luis Pass with wind speeds of 202 km/h (126 mi/h). The structure was given a design lifetime of 100 years, resulting in a probability of ultimate loading of $P_f = 1-e^{(-0.1)} = 0.095 = 9.5\%$ for its complete lifetime.

A multi-criteria analysis was undertaken to determine the most suitable gate type based on navigation, structure, hydrology, constructability, maintenance and aesthetics. The best structure was determined to be a horizontally moving gate, comparable to the design presented by Penland (2014). Inspired by that, a rectangular concrete door barrier, the foundation, and abutments were designed. The design was economically optimized by minimizing the amount of required material. Preliminary construction recommendations were also developed.

A secondary design was made to improve the horizontally moving gate; this alternative consists of a steel truss gate, which is lighter and more slender than the original barge gate, thus reducing the load to the foundation. For this alternative, a dry dock was included in the design, helping to integrate the hydraulic structure in the landscape.

These designs are a preliminary step towards protecting the Houston Ship Channel and the industries associated with it.

*Ir. Martijn Schlepers graduated in 2015 at Delft University of Technology, faculty of Civil Engineering & Geosciences, department of Hydraulic Engineering.*

*MSc Graduation Committee:*
*Prof. dr. ir. S.N. Jonkman, TU Delft*
*Ir. A. van der Toorn, TU Delft*
*Dr. ir. drs. C.R. Braam, TU Delft*
*A. Sebastian, TU Delft and Rice University*

Sebastiaan N. Jonkman

# PLANNING OF COASTAL RISK REDUCTION STRATEGIES

## REFLECTION

*Prof. Dr. ir. S.N. (Bas) Jonkman is a professor of Integral Hydraulic Engineering at the Faculty of Civil Engineering and Geosciences at TU Delft.*

It is an inconvenient truth that civilizations in coastal areas seem to implement the necessary risk reduction interventions only after major flood disasters. This was the case in the Netherlands after the 1953 storm surge disaster, in New Orleans after Hurricane Katrina (2005), and in New York after Sandy (2012). The question is what will be done in the Houston Galveston Bay Region (HGBR), which is at significant risk from hurricane induced flooding. When large areas with high densitiesof economic and societal value are at risk from flooding, flood prevention is an important element of effective risk reduction strategy. Examples of well-known flood protection systems include the Dutch Delta Works, implemented after the Netherlands' storm surge disaster (1953), and the hurricane protection system in New Orleans, built after Hurricane Katrina.

This section has described various engineering solutions and hydraulic infrastructure designed to reduce the coastal flood risks in the HGBR. Some of these projects were inspired by the Dutch Delta Works. While the Dutch do have substantial experience designing and building hydraulic structures, there is no standardized manual or framework for planning and designing large-scale coastal interventions or barriers.

While major dams and barriers in the Netherlands have been built in response to major flood events, their final designs were often shaped by societal demands, and economic and ecological requirements, rather than exclusively flood prevention. For example, after a major flood in the north of the country in 1916, a 32 km (19 mi) closure dam, the Afsluitdijk, was designed to protect Amsterdam and many other vulnerable areas. However, the construction of this barrier also created an enormous fresh water reservoir (Lake IJssel) and permitted surrounding land to be reclaimed for agricultural purposes.

The most famous example of flood control in the Netherlands is the Dutch Delta Works, built after the 1953 storm surge disaster to protect the southern portion of the Netherlands. The goal of the Delta Works was to provide a primary closed line of defense at the coast and to prevent future flooding from coastal storm surge; however, changing economic and societal values led to the incorporation of other functions and compromises in the design of hydraulic infrastructure. While ultimately more expensive, these barriers were also more innovative than anything previously built. For example, discussion over the environmental impacts of constructing a closed dam in the Eastern Scheldt in the early 1970s led to the design and construction of a partly open storm surge barrier that facilitates tidal exchange between the North Sea and the estuary. Similarly, the Maeslant barrier near Rotterdam was designed to maintain the navigation connection to Rotterdam and the hinterland.

The Dutch experience shows that the decision to build hydraulic infrastructure is largely a response to disasters (and the fear associated with high levels of flood risk). Yet, the planning and final design of these projects has been determined by other functions, and in response to societal requirements and desires. Many of the large-scale Dutch interventions for flood management in the 20th century (e.g., the Afsluitdijk, the Dutch Delta Works, 'Room for the River') can therefore be characterized as multi-purpose projects. While flood protection was (and still is) the most important objective, improving fresh water supply, creating better road connections, restoring nature, and promoting d economic development of reclaimed land have all been incorporated into their design as well. Similarly, in Texas, various functions and systems in planning and design coastal interventions need to be considered. The HGBR is home to a large economy, has one of the largest ports in the US, and is an important ecological area. Possible interventions should accommodate all these functions.

As part of the ongoing investigations, a first version of a framework to facilitate this planning effort was developed (see Figure 32). This framework considers three sub-systems: natural, infrastructure, and societal systems. The natural system includes the existing ecological and environmental processes in the region. The infrastructure system includes all the human interventions for flood risk reduction; these may include hard structures, such as barriers or sea walls, but could also be non-structural, such as the rehabilitation of wetlands or oyster reefs to reduce surge. And, finally, the societal system considers society's use of the environment (e.g., for navigation, industry, housing). The interaction between the three systems must be considered in the planning and design of flood risk reduction for the HGBR. For example, the hydrodynamic and meteorological processes (e.g., surge and winds) in the natural system provide the boundary conditions to the infrastructural and societal systems, whereas infrastructure can significantly impact the natural and societal processes of the system. A key issue in the final design of hydraulic infrastructure will be its impact on the natural and societal systems; for example, by reducing tidal exchange in an estuary which in turn might impact the economy. To facilitate the evaluation and decision-making, it will be key to provide insight in the level of risk reduction obtained by various inter-ventions and the associated costs and impacts on societal and natural functions of the system. Approaches, such as cost-benefit analysis and decision support tools highlighted in the reflection of Van Ledden (p. 44) can support this process.

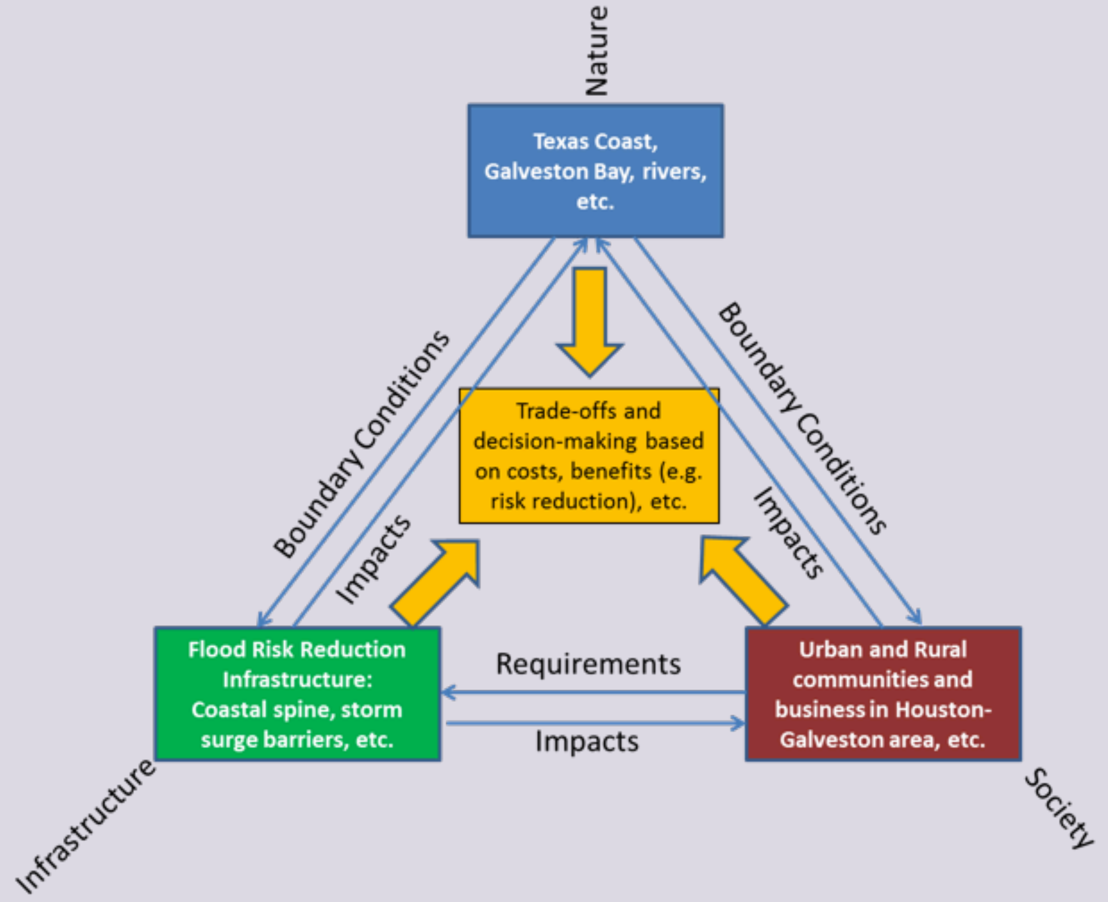



*Figure 32. Framework for the planning of strategies for flood risk reduction in the Houston Galveston Bay Region. (Jonkman et al. 2014)*

Many of the contributions included in this chapter address structural elements of a larger system to mitigate flooding in the HGBR. Most of them focus on elements of the coastal barrier, or coastal spine, but others examine features of other strategies for the region. Examples are the study by Schlepers on a barrier in the Houston Ship Channel (p. 41) and De Boer's research on building with nature solutions within the bay (p. 115). Eventually, it is expected that a number of strategic alternatives will be developed for the region as a basis for decision-making. Alternatives that are now being considered include the outer bay protection with a coastal spine and inner bay protection with a barrier near Houston and measures around the bay. More recently, an additional mid-bay system has been proposed by the SSPEED center. It is my expectation – especially given the significance of wind set up in the bay - that multiple lines of defense will likely be required. To achieve sufficient risk reduction and meet societal needs, the design could consist of a combination of structural protection elements, Building with Nature solutions, land use planning and emergency response measures. Over the past decades, the case of the Netherlands has demonstrated that large-scale coastal interventions can contribute to flood risk reduction and enhance societal, economic and environmental functions. This is also the key challenge for engineers and planners in Texas.

Matthijs van Ledden

# INTEGRATED HYDRAULIC INFRASTRUCTURE DESIGN

## REFLECTION

*Dr. ir. M. van Ledden is director Business Development Flood Risk Reduction, and Leading Professional Flood Hazards at Royal HaskoningDHV; and a lecturer of Hydraulic Engineering and Modeling at the Faculty of Civil Engineering and Geosciences at TU Delft.*

Hurricane Ike made it very clear in 2008: the Houston Galveston Bay Region (HGBR) would face a huge impact and an economic setback if a severe hurricane directly hit the region. Various modeling studies show that the situation could have been much worse in 2008 if a more intense hurricane had followed a more westerly path. As professor Merrell from Texas A&M rightfully pointed out after Hurricane Ike: “We dodged the bullet.” After Hurricane Ike, a substantial body of studies has been produced to unravel the flood risk challenge in the HGBR. The studies cover everything from mapping the coastal flood risk in the region to providing insight into practical solutions to resolve the classical challenge at hand: how does one protect a densely populated area against extreme coastal storms?

The coastal spine is one of the hydraulic infrastructure design concepts put forward to reduce flood risk in the Houston-Galveston area. Following the idea of shortening the coastline - as the Dutch did after 1953 - this coastal spine concept consists of a system of barriers on the existing peninsulas along the Texas coastline, but also with new barriers in the openings between Galveston Bay and the Gulf of Mexico. The various contributions from TU Delft described in this book are related to the concept of a coastal spine, touching on specific aspects or the design of a specific element. The majority of this work has been carried out by enthusiastic MSc students under supervision of both Texan and Dutch universities and private sector members. After reading the various contributions, the following is a personal reflection based on experiences in other parts of the United States, as well as in other flood-prone areas around the world.

From a helicopter perspective, it is striking to see the different approaches in New Orleans, Houston/Galveston and New York/New Jersey in the aftermath of the recent hurricanes Katrina (2005), Ike (2008) and Sandy (2012), respectively. After Hurricane Katrina, a massive and top-down program led by the US Army Corps of Engineers was successfully implemented in about 6 years; $14 billion (12.5 billion euro) was spent to achieve a 100-yr level of risk reduction. The approach in New Orleans resulted in a fundamental change of the flood protection system, with a greatly reduced line of defense achieved by closing off canals with various movable barriers (e.g., Lake Borgne & Seabrook barriers and the Western Closure Complex).

From a distant perspective, the response to Hurricane Ike in the Houston Galveston Bay Region seems to be at the other end of the spectrum and appears to be a very much bottom-up approach. So far, solutions have been proposed by various groups/academia in the region, but without strong coordination from the federal level. The proposed solutions vary from a coastal spine concept to a more localized solution along the perimeter of Galveston Bay. In the meantime, local measures have been taken to flood proof specific assets (e.g., hospitals). However, to date no federal funding has been allocated to implement the large-scale strategies.

Finally, the approach in New York/New Jersey seems to be somewhere in between those in New Orleans and the HGBR. Quickly after Hurricane Sandy, regional planning studies were initiated at state and federal levels (e.g., PlaNYC, North Atlantic Coast Comprehensive Study), and detailed engineering studies are now underway for different elements to improve the protection against flooding in the New York/New Jersey region. Local measures have also been taken to flood-proof critical infrastructure (e.g., subways, electricity grid, water sanitation plants, etc.). The approach in the New York/New Jersey area can probably be best characterized as a mixture of a top-down and bottom-up approach.

The difference in approach in the aftermath of the disasters in New Orleans, New York/New Jersey and the HGBR is intriguing. These storms hit densely populated areas in the same country and in about the same timeframe. However, the approach followed after each storm has been very different. Could this difference be related to the impact of the storm? Or do other factors play an important role? One hypothesis could be that a more top-down and large-scale intervention will only be followed if the impact of the storm is very dramatic (in terms of lives lost, displaced people, economic losses). Does this imply that another (bigger) hurricane needs to strike the Houston Galveston Bay Region before a large-scale intervention like the coastal spine (or another large-scale solution) is implemented? Or can such a large-scale intervention get sufficient support and traction so that it is implemented prior to the next big storm?



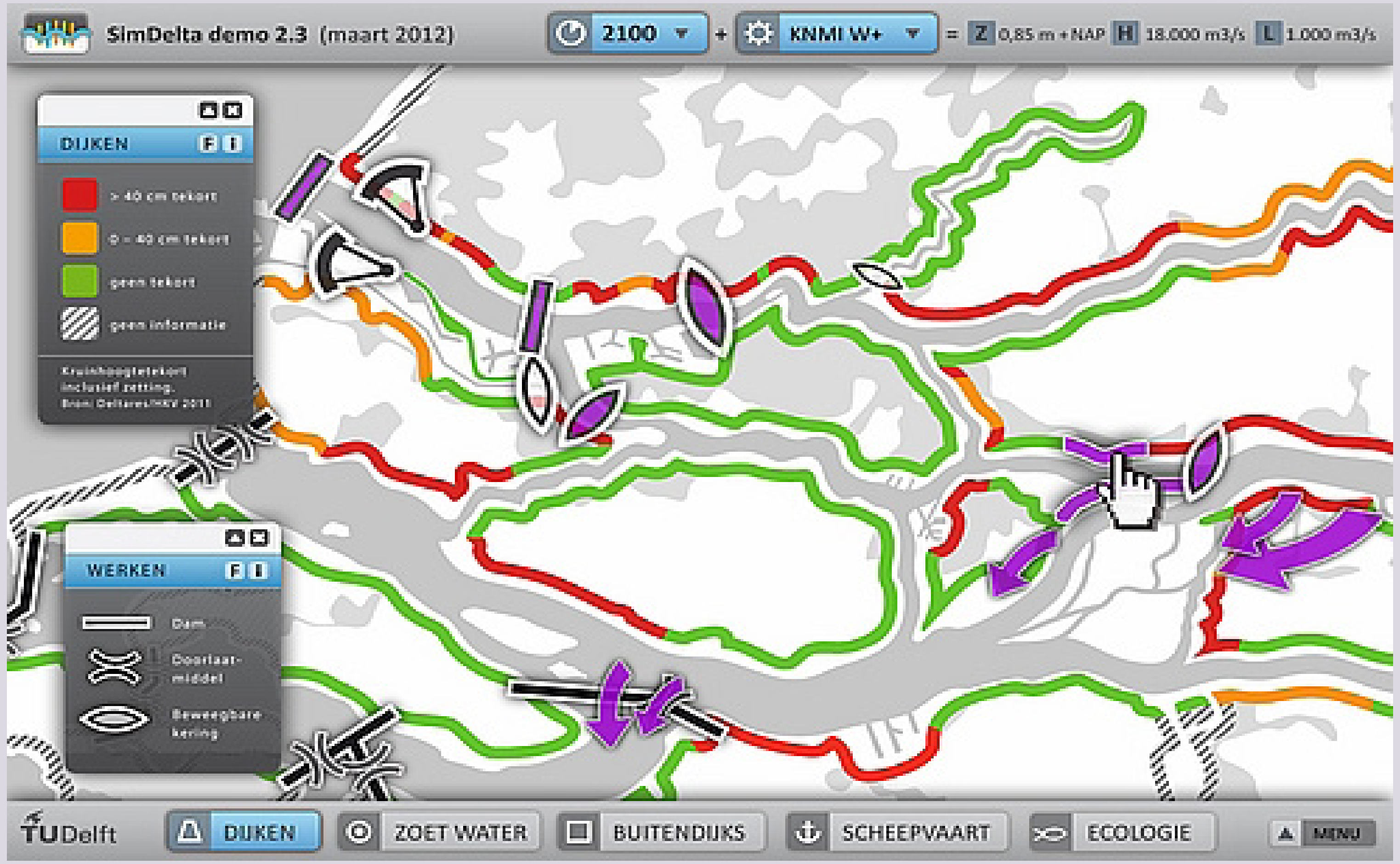



*Figure 33. Screenshot of Simdelta (developed by T. Rijcken, TU Delft) showing which levee sections are safe (green) and not safe (orange, red) in for a given intervention and future scenario.*

My recommendation for the HGBR would be to speed up the process of investigating the various strategic alternatives to better protect this area from flooding. Looking at the number of people potentially affected and also the economic value at stake, it makes sense to quickly decide upon a direction to follow to reduce risk before another (bigger) hurricane strikes the area. To aid in this decision-making process, an overarching platform where all potential solutions can be tested and visualized would be a great asset, not only to link the various research groups but also to communicate with the wider community. The value of such a tool has been shown in the ‘Room for the River’ and Delta programs in the Netherlands. A good example of an integrated assessment tool is the Simdelta ‘dashboard’ (Figure 33), which visualizes options for the Rotterdam area. The work presented in this book (e.g., hurricane analysis or designs/cost estimates of certain interventions) can serve as input for such an integrated tool for the Houston Galveston Bay Region.

William J. Merrell

# DESIGN OF A COASTAL BARRIER FOR THE HOUSTON GALVESTON BAY REGION

## REFLECTION

*Dr. W.J. Merrell is a professor in the Marine Sciences Department; and holder of the George P. Mitchell '40 chair at Texas A&M University at Galveston.*

Soon after Hurricane Ike (2008), I traveled to the Netherlands to discuss the concept of designing a coastal barrier to prevent massive storm surge from entering Galveston Bay. I was immediately struck by the many similarities between the two coastal regions as well as significant differences between Holland and the United States, especially the Houston Galveston Bay Region (HGBR). As evident in this section, hydraulic infrastructure design is strongly influenced by the nature of the flood hazard and the geography of the region. But, in the end, its implementation is driven by national and local public policy and a people's attitude toward flood risk. The more one works on flood risk reduction, the more one realizes the necessity for a comprehensive approach aimed at addressing all of these concerns. Ultimately, technical and scientific understanding must be folded into the complex political and social environment of the system.

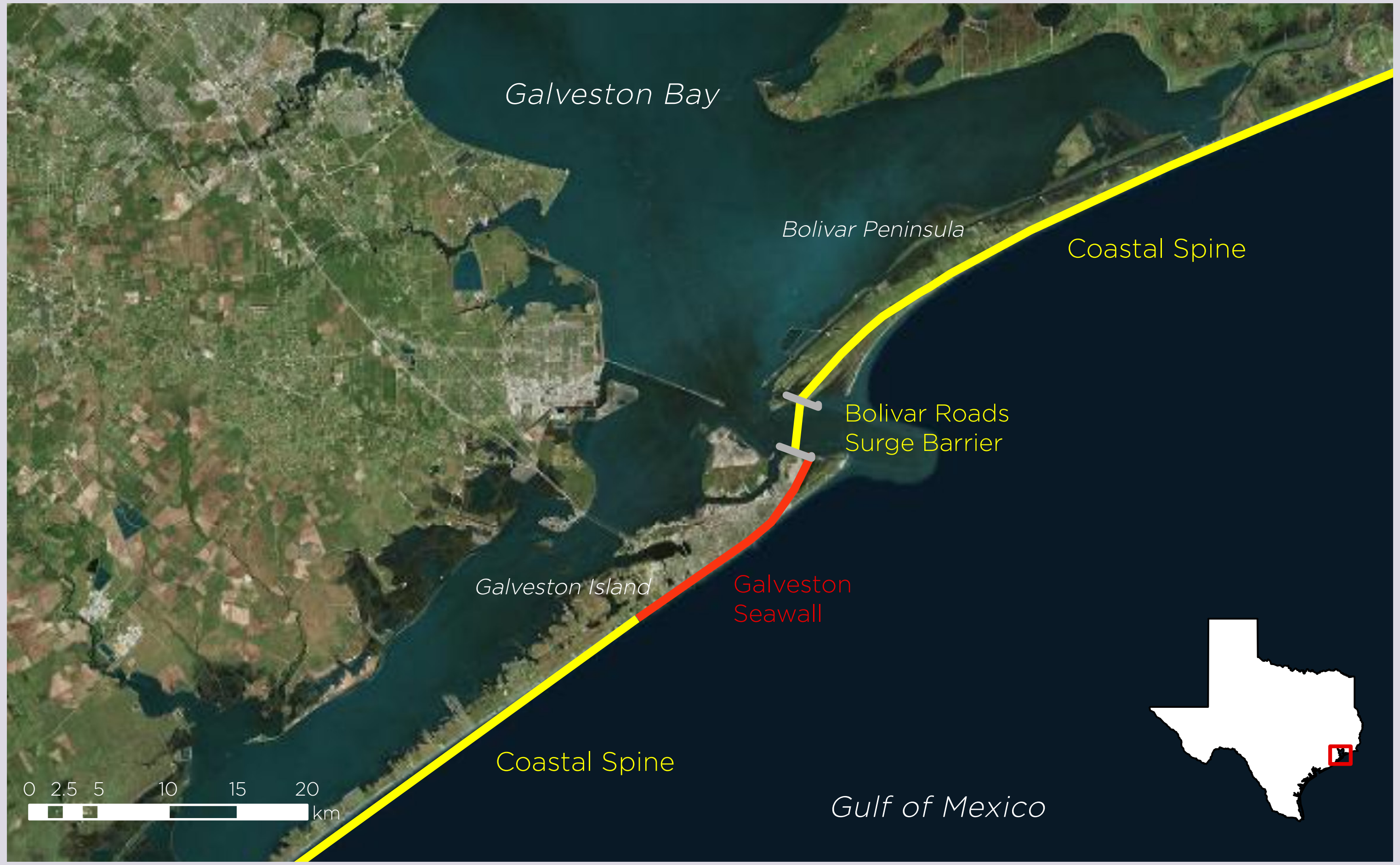
Before my trip to the Netherlands, I had reflected on the profound difference between the two countries' national strategies for addressing coastal flooding; the Dutch have always favored protection while Americans rely on recovery. As he picked me up at the airport, my Dutch host cheerfully noted that we were 3.4m (11ft) below sea level - this brought home how catastrophic the potential impact of massive coastal flooding is in the Netherlands, while it is usually 'only' disastrous in the United States. In the Netherlands, there are strong social values at work that benefit the continued development of its coastal infrastructure; the Dutch are a more orderly, risk adverse people who largely trust their government, while many Americans, especially Texans, are not only willing to tolerate a high level of risk, but also largely mistrust government intervention at all levels.

This has resulted in significantly different flood safety levels employed in the two countries. In the Netherlands, protection ranges between 1/4000 and 1/10000, whereas in the United States the highest level of protection is 1/500 years regardless of the regions' importance or vulnerability, or whether the flooding is coastal or riverine. Obviously, such differences in mandated protection levels influence the size, strength and even presence of protective hydraulic infrastructure in the two countries. Recently, this difference has begun to collapse. Since Hurricane Katrina (2005), the US national policy of reliance on recovery from flooding has started its slow demise with the move towards protection as evidenced by the construction of the Greater New Orleans Barrier and the aggressive federal response to Hurricane Sandy (2012). Despite this, flood risk reduction planning remains significantly and fundamentally different in the two countries.

Much of the research included in this section is based on a strategy of stopping storm surge at the coast, similar to the Dutch strategy adopted after the 1953 coastal flood catastrophe. However, the Dutch coastal barriers cannot simply be transferred to the HGBR, and new and innovated designs are required. There are major differences between the HGBR and the Netherlands that affect the hydraulic design of a coastal barrier, stemming both from the geography behind the barrier in each country and subtle, but important, differences in the storm surge and flood hazard. To state the obvious, much of the Netherlands is below sea level and has great economic importance; however, the storm surge experienced in the Netherlands is not nearly as high as that seen in the HGBR. In addition, internal surge within Galveston Bay can still cause residual flooding even with a coastal barrier in place.

A coastal barrier built to 5.2m (17ft) above sea level, the height of the Galveston Seawall, would offer a high level of protection from any hurricane that has made landfall near Galveston over the past 150 years. However, historical storm surge has exceeded 6.1m (20ft) at other locations in the Gulf of Mexico during very intense, but also very rare, hurricanes, such as Hurricane Camille (1969) and the Labor Day Hurricane (1934). If protection from these intense storms is desired, much more robust defenses are needed, requiring a higher coastal barrier or a lower coastal barrier combined with more complex, secondary lines of defense inside Galveston Bay. Thus, total protection becomes a complex tradeoff between the height of a coastal barrier and in-bay measures.

The hydraulic design considerations for a coastal barrier are complicated by the presence of Galveston Bay. Its large surface area and shallow depth allow internal surge to build up during hurricane events; fortunately, frictional effects limit the height of these surges to about the depth of the Bay (3.7m (12ft)) and most of the HGBR is above sea level. However, the presence of Galveston Bay may also benefit the design of a coastal barrier by acting as a huge retention pond to store rainfall-runoff or water that passes the barrier. Thus, the coastal barrier can be 'leaky' either by design or through barrier failure, increasing the barrier's safety factor.




*Map 3. Location of Coastal Spine.*

An important aspect of storm surge in the HGBR is the forerunner generated by the Coriolis force, a wide continental shelf, and a hurricane's intense cyclonic winds. Together, they create an Ekman wave that arrives ahead of the hurricane. Forerunners in Galveston Bay can arrive as early as 18 hours ahead of landfall and be several feet high, especially in the western portion of Galveston Bay. The coastal barrier would be operated in advance of the forerunner surge, significantly reducing the volume of water in Galveston Bay during a hurricane and helping to protect the HGBR. Many students have explored the operational aspects of the coastal barrier in their design.

While coastal surge is the primary common threat to both the Netherlands and the Houston Galveston Bay Region, there are important differences between the natural hazards and the geography. The Dutch have a long history of flood control and have built impressive hydraulic infrastructure to combat coastal flooding. Similarly, a coastal barrier in the HGBR will require both navigational and environmental sections, as well as a long land barrier. The lessons learned in Dutch design can be extrapolated to create new and innovative solutions for the Texas coast. The research highlighted in this book begins to address many of the regional differences and contains designs of water and land barriers that employ Dutch best practices, but are applicable to the hydraulic conditions in the HGBR. I'm particularly pleased that we were able to host many of the students at Texas A&M University at Galveston. We benefited greatly from their energy and enthusiasm as well as the technical knowledge demonstrated by their contributions to this book.

Philip B. Bedient

# DESIGN OF A HOUSTON-GALVESTON AREA PROTECTION SYSTEM (H-GAPS)

## REFLECTION

*Dr. P.B. Bedient is the Herman Brown Professor of Engineering in Civil and Environmental Engineering at Rice University; and Director of the Severe Storm Prediction, Education, and Evacuation from Disasters (SSPEED) Center.*

The concept for the Severe Storm Prediction, Education, and Evacuation from Disasters (SSPEED) Center arose in the wake of Hurricanes Katrina and Rita (2005). While neither hurricane made landfall in the Houston Galveston Bay Region (HGBR), their impacts were felt throughout the Gulf Coast. The objective of the SSPEED Center was to support university-based research and education related to severe storms and to gather the premier scientists conducting hurricane-related research on the Gulf Coast. When Hurricane Ike made landfall in 2008, the Center was poised to analyze the wealth of data that was collected during the event. Initially, research focused on preparation, response, and recovery in the region, including the use of evacuation and early warning systems. However, it quickly became apparent that the level of flooding seen during Ike could be much worse during a larger or more severe hurricane event; thus, a comprehensive regional strategy needed to be developed to mitigate flooding in the HGBR.

The HGBR is one of the largest metropolitan areas in the country and the Houston Ship Channel (HSC) hosts one of the largest petrochemical complexes in the world, serving as a major economic engine for the region and nation. The HSC's proximity to Galveston Bay makes it naturally vulnerable to storm surge created by extreme hurricanes. Flooding of the industrial areas along the HSC could potentially cause irreparable environmental damage to Galveston Bay, which provides valuable natural resources, ecological services, and recreational and commercial opportunities for the region. However, the complicated hydrodynamic (and political) nature of the system makes designing a storm surge mitigation strategy both a very difficult and interesting problem.

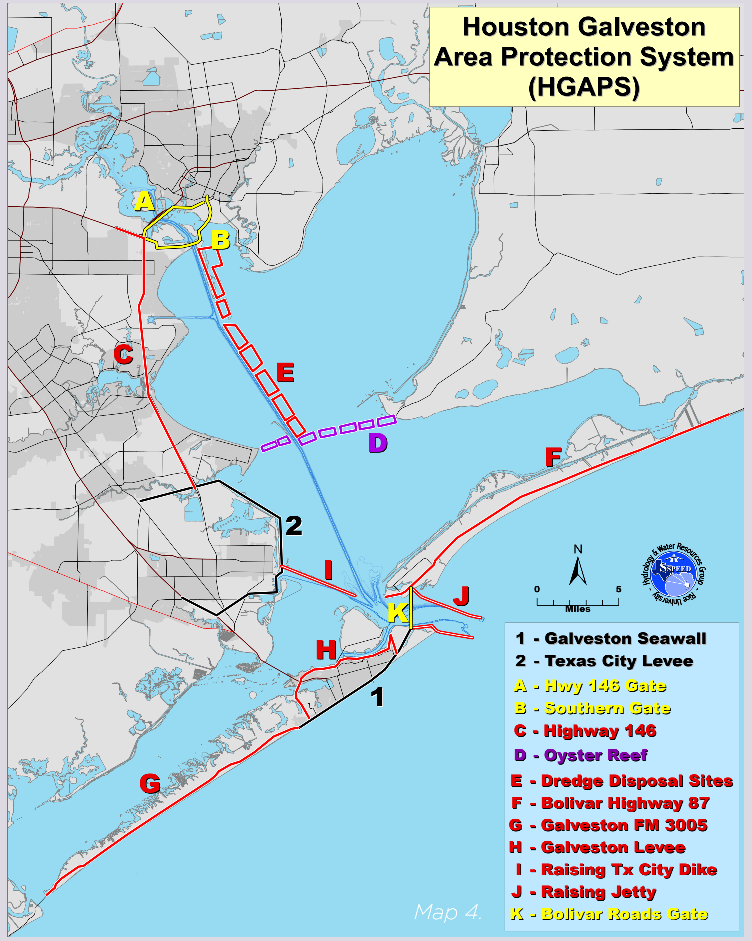
To protect the economic, environmental and social vitality of the region, the SSPEED Center is currently developing a comprehensive storm surge mitigation strategy, dubbed the Houston-Galveston Area Protection System (H-GAPS) (map 4 and 5, p. 49). This strategy is based on the belief that 'multiple lines of defense' are needed to protect the critical areas around Galveston Bay, especially the HSC. The system will include combinations of nature-based alternatives (e.g., oyster reefs, beach nourishment, wetland restoration) and structural alternatives (e.g., levees, flood gates, seawalls) to mitigate damages in the region.

Many of the components of the proposed strategy are in line with the coastal barrier proposed by the research team from Texas A&M University at Galveston. For example, in Alternatives G and F shown in Maps 4 and 5, existing roadways would be raised (or sand dunes would be built), which, when combined with the existing Galveston Seawall (Alternative 1) and a proposed flood gate at the coast (Alternative K), would form a continuous coastal barrier. The coastal barrier would provide an initial line of defense for the HGBR, preventing surge from overflowing Galveston Island and Bolivar Peninsula. However, for major hurricanes, wind setup within Galveston Bay will still create residual surge, potentially leading to damage in vulnerable areas. The complexity of the behavior of storm surge within the bay system merits additional consideration and requires a comprehensive approach that includes multiple levels of surge protection.

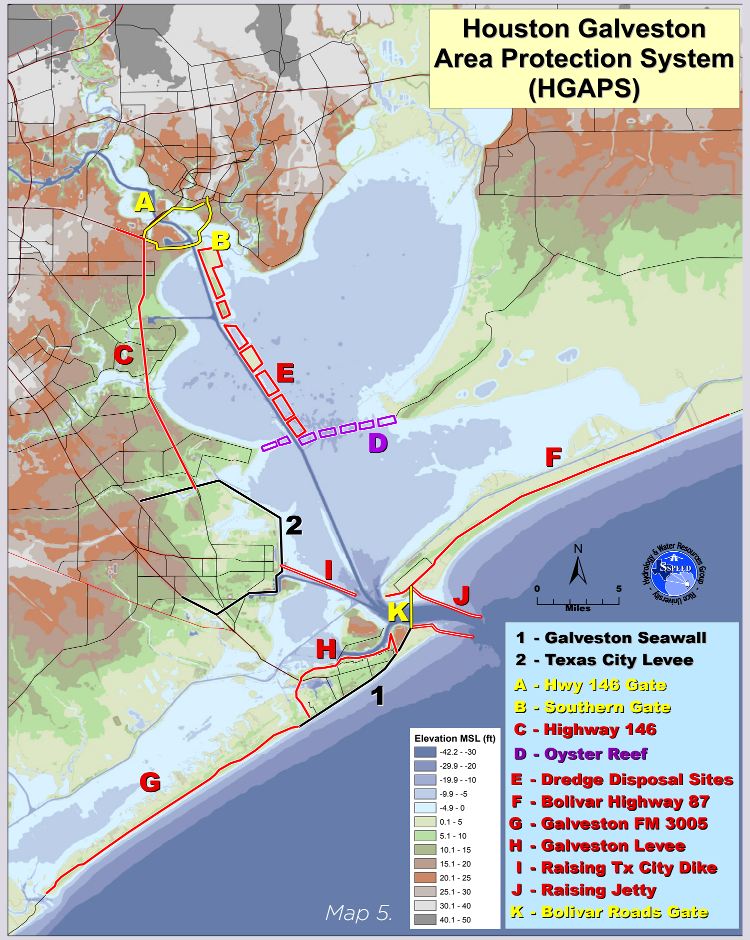
Possible alternatives for reducing wind setup inside Galveston Bay include extending existing dredge spoils or building levees inside the bay to compartmentalize it (Alternative D). These mid-bay alternatives would likely be combined with a hydraulic gate across the shipping channel (near D or E). For this alternative, major portions of the coastal spine along Galveston Island and Bolivar Peninsula may be needed for initial surge suppression. Other possible Galveston Bay storm surge protection alternatives include re-establishing oyster reefs or wetlands, which are vital in maintaining the Galveston Bay ecosystem and also dissipate wave action, preventing long-term shoreline erosion (State of the Bay, 2002). These various alternatives are being evaluated for surge reduction using the coupled ADvanced CIRCulation (ADCIRC) and SWAN Models for historical and synthetic hurricane events.

The hydraulic designs undertaken by the students at TU Delft demonstrate a very comprehensive approach to the complexities of the Galveston Bay system. In many ways, their conclusions are applicable both at the coast as well as to the interior Bay. For example, Stoeten and Rippi's preliminary probabilistic approaches show how a simple model can be used to gain insight into the hydraulic boundary conditions of the system. Similarly, De Ruijs' work demonstrates that any hydraulic barrier design must consider environmental flows to maintain the existing ecosystem, drawing conclusions from hydraulic






Map 4.




Map 5.

structures designed and built in the Netherlands. The information learned in these projects has already led to the development of innovative concepts that maintain circulation or reduce wind setup (e.g., environmental barriers or mid-bay solutions).

The lessons learned from the designs developed for the hydraulic barrier at Bolivar Roads can also be applied to the design of barriers in other locations. Any barrier that crosses the ship channel will have to include both a navigational section and an environmental section. Thus, Van der Toorn & Karimi and Smulders' analyses of gate operation and material gives insight into the feasibility of constructing and operating a hydraulic barrier that crosses the navigational channel. And, Schlepers' innovative steel design provides an interesting alternative to previously considered gate structures for the HSC. Similarly, the design of an environmental surge barrier by De Vries addresses some of the difficulties in maintaining environmental flows in the channel, while building a structure that will withstand high flow velocities. Finally, the inflatable gate design developed by Van Breukelen provides an interesting idea for in-bay situations. While the hydrodynamic forces at the coast are probably too large to sustain such a structure, the application of rubber barriers at other locations in the region merits further research (e.g., Clear Lake at Kemah).

The hydraulic structures developed for the HGBR will need to be coupled with advanced warning and flood prediction systems to address the complex problem of rainfall runoff and storm surge and the real-time operation of structures. To develop such systems, probabilistic analyses, as well as complex hydrodynamic models warrant further development. I have enjoyed the opportunity to interact with students from the Netherlands that have visited the HGBR and am enthusiastic about future collaboration with TU Delft; overall, the work by Dutch students was both impressive and comprehensive in covering many areas of hydraulic design, and when combined with the other projects from the Multifunctional Flood Defenses (MFFD) Program and Delta Interventions Studio, the body of work is an amazing collection of research on the problem of surge in Galveston Bay.

*Figure 34. Multifunctional flood defense design. (TU Delft Delta Interventions student work, Maike Warmerdam 2011)*



Matthijs Kok

# THE MULTIFUNCTIONAL FLOOD DEFENSES PROGRAM

## INTRODUCTION

*Prof. dr. ir. M. Kok is a professor of Flood Risk at the Faculty of Civil Engineering and Geosciences at TU Delft; and program leader of the 'Integral and Sustainable Design of Multifunctional Flood Defenses' research program, funded by the Dutch Science and Technology Foundation STW.*

The Multifunctional Flood Defenses (MFFD) research program is funded by STW, the Dutch national technology foundation. The foundation's objective is to achieve knowledge transfer based on excellent technical scientific research. The MFFD program is a collaboration between three Dutch universities (Delft University of Technology, Wageningen University & Research Center, and Technical University of Twente) and offers positions to twelve PhD candidates and four postdocs. It aims to advance the cutting edge scientific knowledge required to meet the upcoming challenges for flood mitigation in urban areas brought about by population growth, economic development, and climate change.

The program provides a framework for designing and maintaining multifunctional flood defenses, by linking comprehensive scientific research with on-the-ground projects. In addition to flood protection, multifunctional flood protection infrastructures fulfill societal functions like housing, recreation and leisure, ecology, mobility and transport, underground infrastructure; they are thus a functional part of their urban or rural environment. Multifunctional flood defenses have been implemented before, but to do this more efficiently, a number of questions must be answered regarding design, safety assessment, and management strategies. The ambition of the MFFD program is to address these research questions in order to remove the constraints that restrict the implementation of multifunctional flood defenses.

The focus of the program is to gain a deeper understanding of multifunctional flood defenses and to provide a foundation for their engineering, design, assessment, and management. The ultimate ambition is to substantially increase safety of these flood defenses, with the goal of a yearly failure probability less than $10^{-6}$.

The functions and pruposes of multifunctional defenses are investigated on regional and local scales for both urban and rural areas. Examples of functions in urban areas include infrastructure, real estate and leisure; examples of functions in rural areas include ecology, infrastructure, and recreation. Research is carried out on the safety assessment, hydraulic loads and strength of these defenses, and governance of multifunctional flood defenses in a complex environment with multiple users, multiple sets of administrative rules, and multiple legal frameworks. The flexibility and robustness of the defenses is investigated in an integral way, considering both economic and engineering perspectives. All the research projects in this program include case studies, which address the practical need for safe and multifunctional solutions and facilitate the integration of multidisciplinary knowledge.

The MFFD research program has the following objectives:

- To gain insight into the behaviour of multifunctional flood defenses during extreme storms, for example when facing extreme water levels and waves.
- To develop and design new principles of risk assessment methods for multifunctional flood defenses, in both urban areas (delta urbanism and architecture) and rural ones (landscape and ecology);
- To integrate technology for multifunctional and flexible flood defenses when developing urban and rural landscapes;
- To develop new governance and asset management principles for multifunctional flood defenses in the design phase, as well as in the management phase;
- To integrate new physical and safety knowledge into the design of multifunctional flood defenses;
- To include uncertainty in the design of multifunctional flood defenses (e.g., the uncertainty due to climate change or socio-economic developments).

The program is active in the period 2012-2016 and adopted the Houston Galveston Bay Region as one of its key cases. In the following section, several researchers connected and associated with the MFFD program present a multidisciplinary perspective on a diverse array of conditions and developments related to the Houston Galveston Bay Region.

Figure 35.
A bird's eye view on the Delanara-project at the west end of the Galveston Sea Wall. Beach nourishment is the product of a collaborative effort of the Park Board of Trustees, the City of Galveston, and the Texas General Land Office with the permission of three individual property owners. December 2014. (Photo courtesy Dustin Henry, Planning Department City of Galveston)

Figure 36.
January 2015. (Photo courtesy Dustin Henry, Planning Department City of Galveston)



Nikki Brand

# GALVESTON'S GOVERNANCE ARRANGEMENT FOR FLOOD RISK REDUCTION

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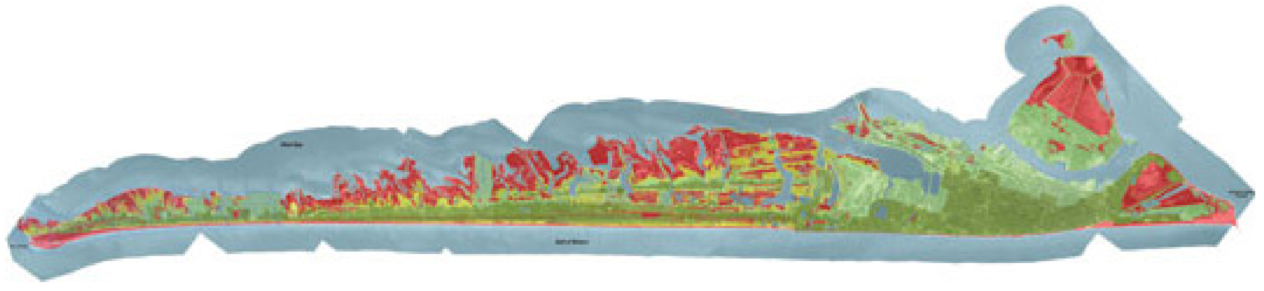
Over the last two decades, 'weak links' in the Dutch coastal flood defenses have been upgraded to meet higher safety standards. In contrast to existing structures, these upgraded flood defenses have been designed to address two issues: flood risk reduction and spatial quality enhancement (Heems & Kothuis, 2012). This has resulted in a variety of innovative designs for multifunctional flood defenses that cater to local government and stakeholder interests (Coastal Quality Studio, 2013). They range from 'hard' to 'soft', often sand-based, interventions and can be located landward, seaward or sur place. Although the decision-making process to address these weak links was complex and time-consuming, the resulting multifunctional flood defenses are celebrated by the public. The lessons learned from the design of Dutch multifunctional flood defenses can be applied in the search for strategies to reduce flood risk on Galveston Island.

Large spatial interventions have become increasingly harder to implement in the Netherlands due to the restraints imposed by planning procedures and public participation (Bosch & Van der Ham, 1998). Multifunctionality, identified through consultation with strategic parties, is a tool to align public and private interests, pool resources, gather support, and counteract potential opposition to a project. In the Netherlands, the consultation process is relatively straightforward since collective flood protection is institutionalized (Ministry of Transport, Public Works & Water Management, 2008). Rijkswaterstaat, the Dutch Ministry of Infrastructure and the Environment, prevents coastal erosion using dedicated national funds (Stive & Vrijling, 2010), while regional water boards maintain flood defenses using local tax-revenue. Any new spatial interventions to control flooding are translated into local municipal zoning plans, which are overseen by the province. Together, the municipalities and provinces represent the voice of the public. Formal public participation is organized via the procedures for permits at the municipal (local) level, or during open hearings of public agencies. While the choice of specific spatial intervention for flood control can be up for debate, the division of responsibilities among government agencies, the instruments available, and the sources of revenue are largely established.

To reduce flood risk for Galveston Island through spatial intervention - whether a soft sand-based strategy or a semi-hard land barrier like the Ike Dike - it would be helpful to identify Galveston's water governance arrangement. Understanding this is a first step to developing recommendations for a flood risk reduction strategy that is tailored to natural conditions and compatible with local governance. In-depth interviews with local representatives and experts on Galveston were conducted to provide an overview of involved agencies. Accompanied by desktop research, the interviews focused on features of government (public administration), water or flood risk reduction-policy, and planning. The latter two are interconnected with governance arrangements for flood risk reduction.

In order to identify Galveston's water governance arrangement, five factors were considered:
1. The nature of the involved agencies (private, public, single or multiple purpose);
2. Their role in water and spatial policy;
3. Their sources of revenue;
4. The recruitment of their officials; and
5. Their jurisdiction.

*Figure 37. Galveston Geo-hazard Map. (Source: Coastal and Marine Geospatial Lab of the Harte Research Institute for Gulf of Mexico Studies at Texas A&M University - Corpus Christi. Maps to be found on http://geohazards.tamucc.edu/Galveston/Gal_Small_rez.html; this map provided by the Bureau of Economic Geology, University of Austin)*



**Imminent Geohazard Potential**
Present Critical Environments: Salt and freshwater wetlands, including beaches, tidal flats, and marshes. Along Gulf of Mexico shoreline, including beaches and foredunes.

**High Geohazard Potential**
Future Critical Environments: Areas expected to become critical environments in 60 years' time (2062) if historical rates of relative sea-level rise and shoreline change continue and if development of restoration projects do not affect natural processes.

**Moderate Geohazard Potential**
Upland: Upland areas generally less than 5 feet above sea level that are not expected to become critical environments during the next 60 years (20620, but may be affected by storm surge caused by tropical storms or category-one-hurricanes.

**Low Geohazard Potential**
Island Core Upland: Centrally located upland areas generally more than 5 feet above sea level and not expected to become critical environments in 60 years' time (2062).

To analyze the governance arrangement, five factors were addressed:
a. Regional cooperation between authorities;
b. The degree of integration between the policy fields of spatial planning and flood risk reduction;
c. The funding of flood risk reduction;
d. The impact of private parties on policy; and
e. The role of public participation.

Preliminary findings indicate that several elements of Galveston's governance arrangement limit the opportunities for spatial intervention on or near the beachfront. Dedicated funding is limited, water and spatial planning are not integrated, and overall flood risk reduction is not institutionalized, as there is no agency that is clearly responsible and could take the lead. The most likely collective actor, the Texas General Land Office (GLO), has been sidelined, due to the Texas State Supreme Court ruling in the Severance v. Patterson case.

To start with, no local agency has been designated responsible for flood risk reduction, and no authority be identified as the preferred leading agency. Galveston's governance arrangement for flood risk reduction is composed of a variety of different local agencies, ranging from multiple purpose authorities (the City of Galveston and Jamaica Beach), single-purpose authorities (the Galveston Park Board of Trustees) and private, non-profit organizations (Galveston Economic Development Partnership, GEDP) and interest-based associations (for example, the West End Homeowners Association).

Agencies with some responsibility for flood risk reduction do so largely to serve another purpose. The Park Board, for example, safeguards the economic interests of tourism, for which the continued existence of the beach is essential. The same goes for the private, non-profit agencies that play a role consulting with the City, like the GEDP or homeowners associations. For them, flood control is an instrument to serve their economic interests. The only agency that includes safety from flooding among its directives is the Texas General Land Office, a state authority, rather than a local one (TGLO, 2014). However, their funds are limited and their allocation seems to be ad hoc, depending on requests by local partners, in accordance with the Coastal Erosion Planning Response Act (CEPRA).

Reliable funding for reducing flood risk is scarce. Though funding is available through the GLO, the City (4B sales tax) and the Park Board, their means are limited and state money is only made available in combination with local funds. The US Army Corps of Engineers (USACE), the federal executive agency that protects US navigable waters, only conducts so-called 'beneficial dredging projects' when a local party pays the incremental costs to nourish the beach with the dredging spoils. However, it seems the GLO, the City and the Park Board do not earmark money for flood risk reduction projects.

Leadership in flood risk reduction is scattered at best. Officials in all agencies are either publicly elected bi-annually (GLO, City) or, in the case of single-purpose authorities like the Park Board, appointed by the City Council.



Members of private non-profit organizations like GEDP and homeowners associations choose their own leaders. In sharp contrast with the Netherlands, it seems that the existence of 'additional' government institutions and non-profit organizations is explained by a desire to shield certain interests from the politics of short election cycles. Private parties seem to be more involved in governance of water and planning than in the Netherlands, because of political campaigning and organized public-private partnerships (PPP), like the GEDP, that are consulted during policy development. Although the development of the City's Comp plan included public participation, its general role remains opaque. This goes for both policy-making and granting permits. So far, it seems that the process of granting permits primarily brings federal environmental concerns to the table. As the US federal government considers the coastline as protected wetlands, its use is subject to section 404 of the Clean Water Act, which requires permits granted by the USACE. For discharge of dredged or fill materials on the coastline, Environmental Protection Agency (EPA) standards must be met (EPA, 2004).

While spatial planning does not limit development, it also does not promote spatial interventions which could reduce flood risk in an organized fashion. The integration of water and spatial policy seems minimal in the HGBR. Although the City of Galveston has Land Use Regulations (LDR) and building codes, these don't seem to be very effective. For example, the findings from the 2004 Galveston Island Geohazard Map were never translated into planning policy and new land use regulations for beach house construction and dune restoration in the coastal zone were removed from the 'revamped' regulations accepted by City Council in February 2015. Generally, 'grandfathering' applies to existing property. Supervision and enforcement by higher authorities, as is customary in the Netherlands, is lacking.

However, the biggest constraint to developing a comprehensive flood risk policy seems to be that jurisdiction on Galveston Island is a complicated matter. The City has jurisdiction over Galveston Island, with the exception of Jamaica Beach, which has its own local government. For designated locations, the responsibility for maintenance of public beaches is outsourced to the Park Board. Property owners near the beach sometimes contest jurisdiction of the Park Board, but the biggest confusion concerns the role of the Texas General Land Office. Traditionally, the GLO would be involved based on its ownership of the so-called 'wet' beach below the vegetation line, the submerged lands between mean high tide and Waters of the State. Also, it has the right of 'rolling easement,' which provides for obligatory public access to the beach as stated in the Open Beaches Act. However, after the Texas State Supreme Court ruled in favor of Severance in Severance v. Patterson in 2011, owners of property adjacent to the beach no longer have to accept obligatory public access (McLaughlin, 2013).

The Texas State Supreme Court ruling could bring flood risk reduction on Galveston Island to a complete standstill. Since public funds cannot be used to nourish private properties, the GLO has discontinued nourishment projects on the West End of the Island. If the precedent in Severance v. Patterson were applied to the entire Texas coast, the role of the GLO would be downsized in favor of a large group of individual landowners. In that case, identifying the parties with interests in the coastal zone will become even harder, and finding collective solutions for flood control even more challenging.

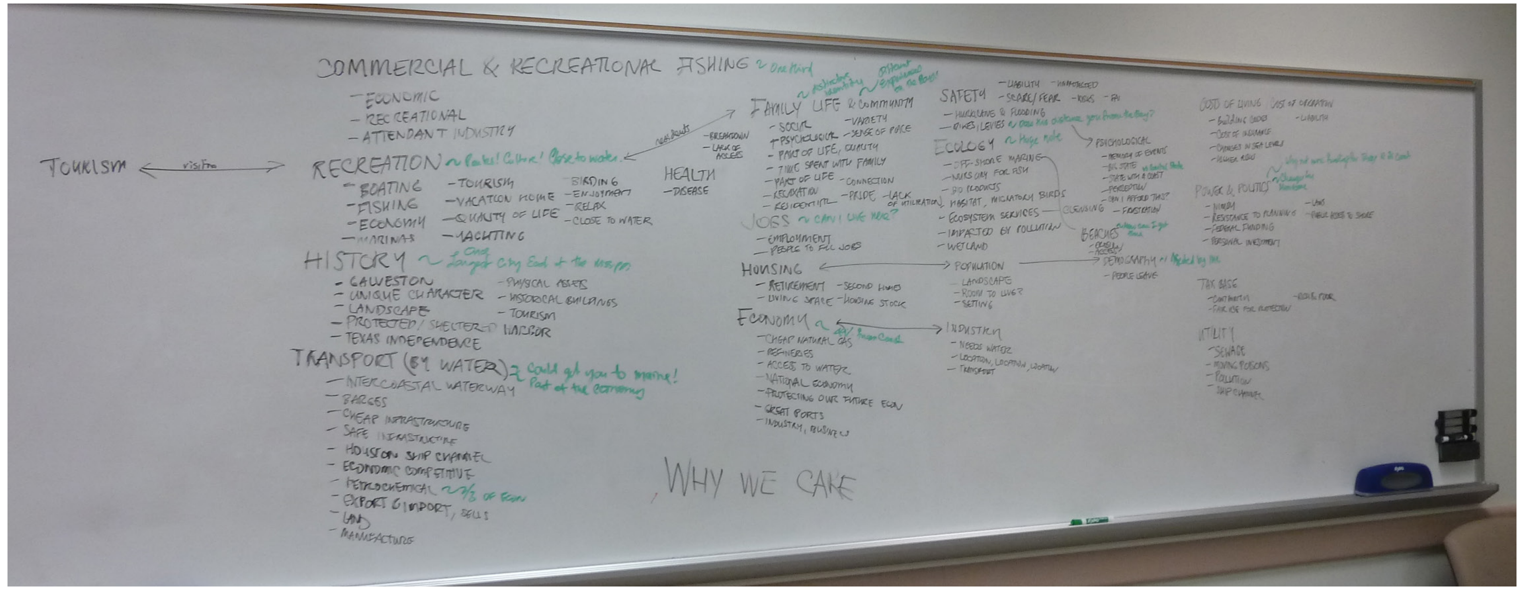
Nonetheless, there is good news, too. In spite of the confusion regarding jurisdictions, agencies occasionally succeed in implementing spatial interventions on behalf of flood risk reduction. This is demonstrated by the Delanara Project, where the beach on the western end of the Sea Wall is being nourished at the time of writing. Here the Park Board is nourishing the beach using funds from the GLO through a deal brokered by the City with three property owners. The City and the property owners agreed to replace the rolling easement with a fixed easement, meaning that the use of these properties will not be altered by changes in the coastal morphology. Here the obstacle of rolling easement has been overcome.

However, in order to facilitate collaborative partnership on a larger scale – and to come up with recommendations for a multifunctional flood risk reduction strategy – the relationship between agencies on Galveston Island needs to be clarified. As such two issues need to be resolved.

The first is the confusion regarding the legal demarcation line between the public and the private beach. As long as there is no legal consensus regarding the ownership of the wet beach and the GLO's role there, serious action by what is probably the most influential authority on Galveston's coastline will be hampered. It is possible that the GLO will ultimately be able to use its powers of eminent domain to take property for public use like the construction of a barrier. However, in a state dominated by traditional classical-liberal political values this seems unlikely and undesirable. The second issue that needs to be dealt with is the natural relocation of the demarcation line between public and private property due to erosion, and the rolling easement that follows it. The Delanara Project demonstrates that this obstacle can be overcome when the Park Board, the City and the GLO cooperate and strike a deal with individual property owners. An alternative to this time-consuming process could be to either come up with Texas-wide regulation addressing the rolling easement, or to fix the coastline with a regulatory Basal Coastline as has been done in the Netherlands.

*Figure 38. Systems and Values in the Houston Galveston Bay Region; as expressed by CIGAS workshop participants; October 2014, Houston/Seabrook, Texas, USA.*

*Figure 39. Galveston Bay, west bay shore residencies. (Photo Courtesy Baukje Kothuis)*






Scott Cunningham, Baukje Kothuis & Jill Slinger

# CONTESTED ISSUES GAME STRUCTURING APPROACH (CIGAS)

## GAME THEORY, REAL ACTORS AND VALUES IN THE HOUSTON GALVESTON BAY REGION

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In the contemporary context, any intervention for flood risk reduction in urbanizing deltas must meet the requirements of many different stakeholders. Although all stakeholders have a clear and common interest in enhancing safety from flooding, specific individual and organizational interests can diverge widely. Consequently, applying multiple valuation to flood risk reduction measures is a necessary strategy to meet the diverse needs, desires and requirements of the various stakeholders.

In the Houston Galveston Bay Region (HGBR) these different interests can be summarized under the labels people, economy and ecology (Blackburn et al., 2014; Sebastian et al., 2014). Each interest group focuses on a different functionality of the bay - for instance, some groups need space to develop businesses, while others demand a healthy environment, a place to live and work, or recreational facilities. Although these different functions can overlap, it is often unclear how to weigh them against each other.

In fact, the different stakeholders often even have difficulty finding a common venue in which they can meet each other and express and compare their respective interests and values. Too often these meetings result in strong disagreements about potential flood reduction solutions. Despite this, if a minimum satisfactory solution is to be achieved for all stakeholders, some form of commitment to joint action is required, however limited.

In such a context, the Contested Issues GAme Structuring (CIGAS) approach can be useful. CIGAS has been implemented to engage stakeholders in flood safety in the HGBR. The method, which is further detailed in the following section, strives to co-create insights into flood protection in the area. The approach is designed to provide solutions in situations where conflicting values and functional requirements cause conflicts. The CIGAS approach acknowledges that participants may differ in their interests and values, and consequently hold different opinions regarding solutions, in this case the choice of flood protection measures. The purpose of the approach is not to reach consensus, but instead to gain mutual insights regarding community values, and to explore and rate potential technological interventions for flood protection. Such insights are necessary, but not sufficient, to solve value conflicts regarding flood protection measures.

*Conduct of the Workshop*

The approach requires both an initial investigation, and also a stakeholder's workshop. The initial investigation involves a mixture of action research, system modeling, and game structuring techniques. Action research, building upon an anthropological approach, helps to remove artificial boundaries between researchers and the people they study. An action research approach also urges the researchers to recognize that they are acting upon, and thereby affecting, the systems they are studying. System modeling techniques employ a wide variety of methods for structuring and gaining insight into physical systems (Ackerman, 2012). Likewise, game structuring techniques provide an analogous understanding into the social world (Hermans and Thissen, 2009). Thus the initial investigation into physical and social systems provides the necessary input for a successful stakeholder workshop.

The stakeholder workshop was conducted over two days, and sixteen participants were invited. The workshop was held in two different cities in the bay area, Houston and Seabrook City. The specific findings from

*Table 1.
Three major coalitions of stakeholders - CIGAS Workshop October 2014, Houston/Seabrook, Texas, USA.
(Kothuis, Slinger & Cunningham 2014)*

| Three major coalitions of stakeholders - CIGAS Workshop October 2014 | | |
|---|---|---|
| **Local Interests** | **National Interests** | **Infrastructural Interests** |
| Environmental and Tourism Interests<br>State and Local Government<br>Citizens on the Water Front<br>Citizens in the Surge Zone | Federal Government<br>U.S. Army Corps of Engineers<br>Industrial and Port Interests<br>Flood Insurers<br>American People | Infrastructure Provision<br>Emergency Response Teams |

*Table 2.
Four outcomes on the Pareto Optimum - CIGAS Workshop October 2014, Houston/Seabrook, Texas, USA.
(Kothuis, Slinger & Cunningham 2014)*

| Four outcomes on the Pareto Optimum - CIGAS Workshop October 2014 | |
|---|---|
| **Outcome** | **Description** |
| An Enhanced and Rejuvenated Relationship with Nature | Flood protection is designed with principles of eco-tourism, and broad public access to environmental and recreational resources.<br>A priority is given to ecological health over safety and urban development. |
| Self-Reliant Communities | Flood protection is designed in multiple layers, with an emphasis on the needs and contingencies of local communities. A priority is given to individuals and communities to assess their own risk and develop their own appropriate responses. |
| The Over-Engineered Solution | Flood protection is designed to be comprehensive and all-encompassing. The resultant designs involve large and capital intensive structures which emphasize hard infra-<br>structure over soft. Safety is a high priority. |
| Waiting for the Next One | Flood protection is minimal, and primarily focused on industrial zones where there are obvious economic and environmental losses to be addressed. Urban expansion continues apace, with more and more citizens living and working in the flood zones. |



the workshop will be presented in the next section, but the six steps of the workshop are outlined here.

First, the key stakeholders need to be identified; participants are then invited to adopt the perspective of particular stakeholders for the remainder of the workshop. Second, the relevant systems and their problem contexts need to be identified, as well as the preferred outcomes of relevant stakeholders. Knowledge of the biophysical and social systems and the effects of infrastructure measures provide input to the process, providing bandwidths within which system responses occur. The third step involves collectively envisioning alternative possible flood protection measures; however, participants are asked not to consider the design or technical implementation of the defense. Instead, they are invited to think through the kinds of outcomes they would like to achieve as well as through the kinds of outcomes they would not like to occur. In the fourth step the participants are asked to consider - and rank - which of the identified outcomes would be preferred by their specific stakeholder. Fifth, the participants consider which concrete actions could be taken to achieve certain outcomes. In the sixth and final step, potential conflicts are addressed by identifying a design space of Pareto optimal solutions. A fuller description of the method is provided by Cunningham et al. (2014).

*Workshop Outcome and Follow Up*
The workshop aims to provide insight into the contested situation by exploring the following three central issues:

- 'Who is Affected by Flooding?'
  U.S. flood protection policy is highly de centralized, and generally oriented towards repairing damage rather than preventing flooding. Political mobilization is necessary to organize preventive measures, yet this can also exacerbate dispute as well. For this reason, it is critical to identify potential stakeholders and to recognize possible alignments in interest. Workshop participants identified eleven groups of stakeholders; in further discussion, participants grouped these stakeholders into three major coalitions (Table 1).
- 'What do the Stakeholders Care About?'
  Participants were then invited to think through the sorts of outcomes that they cared about most. Next, they were invited to consider a range of possible outcomes and resolutions of the current flooding situation, both good and bad. These took the form of 'rich pictures' of possible flood control measures and their impact on infrastructure, the economy, citizens, and the environment. Four of the seven scenarios discussed in the workshop are outlined below (Table 2).
- 'How are Stakeholder Values Embedded in the Outcomes?'
  After developing the outcomes (partially shown in Table 2), participants were invited to rate the outcomes according to the needs and priorities of each of the stakeholders. Not surprisingly, representatives of the different stakeholders favored the outcomes in differing degrees. The perceived alignment in priorities across stakeholders led to a recognition of coalitions and common interests, and also an appreciation of the issues on which the various coalitions diverge. The three resulting coalitions are shown by column in Table 1.

The workshop revealed irreconcilable differences between stakeholders in terms of preferred outcomes. Of course, these differences must be treated with care, since choosing a single outcome may favor one stakeholder at the expense of the other. The goal of the workshop is not to take sides, but rather to develop a common understanding of the problem and a commitment to further action. One possible route forward is to eliminate the lose-lose outcomes, enabling participants to focus on the wins. Possible winning solutions (for at least one of the identified stakeholders) are identified in Table 2. The workshop also addressed the themes of coalition formation, bargaining and stakeholder management. A full report of the workshop can be found in Kothuis et al. (2014).

The workshop participants and Rice University hosts acknowledged the importance of developing joint action. Just two weeks later, a platform for joint action was formed, and the workshop was widely acknowledged as a contributing factor. Furthermore, a follow-up workshop focusing more on functional engineering requirements is under consideration by local stakeholders, technical experts and industry leaders.

*Figure 40.*
*Lifted resideces on*
*Galveston Island.*
*(Photo Courtesy*
*Helena Van Boxelaere)*




Daniel Hogendoorn & Nikki Brand

# POLITICAL VALUES AND FLOOD RISK MANAGEMENT IN GREATER HOUSTON

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When a wave crushed conquistador Cabeza de Vaca's makeshift barge, and stranded him and his fellow survivors on an island along the Gulf of Mexico in 1527, he promptly christened the wave-battered island 'la Isla Malhado' - the Island of Doom. Thought to be modern day Galveston Island, the Isle has tempted fate ever since, facing regular hurricanes, and bracing for the accompanying surge flooding. In 1900, the vibrant harbor of Galveston was destroyed in what is still the deadliest U.S. natural disaster.

Galveston's destruction sparked life into the little town of Houston. Currently, the greater Houston metropolitan region has grown into the fourth largest metropolis in the United States. The largest U.S. energy hub, Houston sprawls relatively unregulated into flood-prone regions, where cutting off bayous and widespread paving has exacerbated floods and contributed to land subsidence. Of course, hurricane surge is not the only source of flooding. Torrential rainfall is also a chronic threat. But on average every fourteen years, homes, industry and biodiversity are threatened by catastrophic storm surge, with potential damages estimated in the tens of billions of dollars.

In such an economically vibrant yet flood prone region, one would expect – at least from a Dutch perspective – a public commitment to lower harm from flooding. In spite of the existing patchwork of flood-management institutions and strategies in the region, for over a century no comprehensive action has been taken to prevent harm from flooding. Contemporary proposals to address flood risk like the Ike Dike, the Centennial Gate and the Lone Star Coastal Recreational Area struggle for political support. This presents a puzzle. If need is high, and opportunity exists (Texas has consistent economic growth), why is there no real action? It could be that political values, prominent and deeply held preferences on the role and extent of government (Elster, 2007), hamper comprehensive policies or strategies that reduce flood risk.

How then, do existing strategies for flood risk reduction in Greater Houston reflect dominant political values? And what do these values imply for contemporary large-scale plans aiming to reduce risk? The conjecture that political values moderate the existing policies of collective actors was examined by a combination of desktop research and in-depth interviews with representatives involved in flood risk reduction in the Houston Galveston Bay Region. These policies include emergency planning, offering flood insurance, or plans to buy out damaged property. The following questions were considered:

a. What are the espoused political values of the region?
b. Which policies of flood risk reduction are enacted in Greater Houston?
c. Do the actual policies agree with the espoused values? (To evaluate this, the policies were translated into regional strategies based on how they reduce exposure to flooding.)
d. If the policies do not agree, how were they legitimized?

In political terms, Texas is an exemplary case of classical liberal political values (Texas Politics, 2014), favoring small government, low taxation, limited regulation, and strong liberties for individuals and businesses. Its current constitution, written in 1876, reflects these values. Despite a long list of amendments, the document was designed to be hard to change, with each change requiring voter approval. As a result, it has had a remarkably consistent impact on institutions in the

*Table 3. Policies for flood risk management in Greater Houston.*

| Policies for flood risk management in Greater Houston | | |
|---|---|---|
| **Actor** | **Character** | **Policies** |
| Federal Emergency Management Office (FEMA) | Public: Federal | National Flood Insurance Program (NFIP); Federal Disaster Assistance; National (Flood Insurance Rate) Maps; Mitigation Grant Funds |
| Flood plain administration | Public: locality, county | Regulating new development in the floodplain as identified by FEMA |
| Harris County Flood Control District (HCFCD) | Public: special purpose unit of state government | Building and maintaining of channel conveyance, storm water retention basins; buy out & demolition of vulnerable property |
| Office(s) of Emergency Management (OEMs) \| Houston StranStar | Public: partnership of four government agencies (locality & county) | Emergency management transportation; evacuation; awareness programs; informing (apps); Setting up contraflow traffic |
| Levee Improvement Districts (LIDs) in Fort Bend County | Public-private: political subdivision of the state | Alert system; building and maintaining of perimeter levee and flap gates plus pump stations adhering to FEMA standards |
| NGOs (Red Cross et al.) | Private | Emergency management (shelter, food); shadow-networks (agreements & contracting) |
| Houston Port Authority & Coast Guard | Public: city | Evacuating the ports; closing harbour; checking flood prone industries; debris removal |
| Texas General Land Office (TGLO) | Public: state | Easement in favour of public coastal access; regulating building to avoid flood damage; buyout & demolishing of damaged property |
| Texas Medical Center (TMC) | Private: coordinating body of 54 medical facilities and institutions | Radar-based alert system; improvement of storm water drainage; watertight doors and perimeter flood walls; berms & barriers; increased accessibility (sky bridges et al.); backup facilities |
| Private insurance companies | Private | Flood insurance for expensive properties outside scope of NFIP |
| US Army Corps of Engineers (USACE) | Public: Federal | Drainage; channelization; building of levee-systems; repair during events |



region. In the past century and a half, there have been hardly any ideological shifts, and it would be surprising to find policies that are incompatible with classical liberal values.

From local to federal level, a number of organizations enact regional policies, often radically different from each other. The majority of actors are public: the Texas General Land Office, Harris County Flood Control District, US Army Corps of Engineers, Federal Emergency Management Agency, Houston TranStar, Port of Houston, and various flood plain administrators. Levee improvement districts are considered to be public-private entities. Private actors involved in flood risk reduction include the Texas Medical Center, NGOs like Red Cross, and insurance companies. The most important private corporate actors, which contribute to risk and have the authority to respond to risks and take measures to prevent them, are the petrochemical industries located on the notoriously vulnerable Houston Ship Channel; however, they refused information requests.

The official policies of the cooperative actors were listed and subsequently categorized into regional flood risk reduction strategies, based on the intended result and the actions taken to achieve those results. We identified five strategies: (1) Information provision, (2) Evacuation, (3) Recovery, (4) Spatial adaptation, and (5) Flood control. As it turns out, each of these strategies requires more structural or intense government involvement.

The identified strategies demonstrate that the majority of existing policies reflect the predominant political values. As is often the case with comprehensive plans, these were not always coherent; in these cases, they were idiosyncratically adapted to reflect the political values, or were legitimized by exceptional circumstances.

Of the five regional flood risk reduction strategies, Information provision reflects the political value system of Texas, as government refrains from coercion but enables individuals. Evacuation also agrees, as the bulk of activities aim at coordination, leaving individuals with the choice whether to evacuate or 'hunker down'. The coercive elements of evacuation are limited to a well-defined period of time, high risk situations, and exceptional circumstances. Spatial adaptation relies on incentives such as largely-federal compensation (subsidies and buy-out) and permits instead of coercion. Flood control does not agree well with the political value system, but sometimes becomes palatable after a disaster, made more acceptable with Federal funding or presented as an 'add on' providing economic gain. Recovery, which relies on public money and government action, is also legitimized by exceptional circumstances.

Flood control and spatial adaptation, are politically ambiguous strategies, as are evacuation and recovery. The value of limited government is, however, abandoned when the action is temporary during a disastrous flood event, when it involves federal money, or when government action has a clear and direct economic gain.

What does this imply for contemporary large-scale plans? Whereas the Lone Star Coastal Recreational Area shares properties with spatial adaptation, the Ike Dike and the Centennial Gate are ambitious forms of flood control. Large-scale flood control will generally require permanent government services and taxes. To succeed, the plans must try to agree with political values (for example, by providing economic gain) or wait for exceptional circumstances. The political value of limited government is thus countered when exceptional circumstances – virtually always disastrous ones - lead to federal funding. An alternative route would be to finance flood control publicly through bonds, thus avoiding direct tax increases, as has already been suggested for the Centennial Gate. Another alternative would be to find a private actor to build and operate the Gate, with flood risk reduction as one of a variety of functions.

Flood risk reduction is too often seen as a purely technical affair with self-evident answers that should be able to convince an universal audience. This study shows that to reduce the harm of flooding, a more pragmatic approach is needed, one tailored to the local political values. By doing so, we can increase the chance of the proposed flood risk reduction plan being accepted.

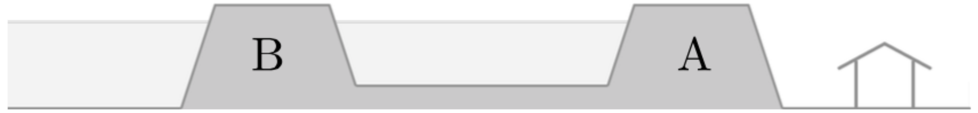


*Figure 41. Simplified cross section of a front defense (B) and rear defense (A).*


*Figure 42. Extreme water levels in case both defenses do not fail.*


*Figure 43. Extreme water levels in case the front defense is not present (either not built or washed away due to failure).*

*Figure 44. Texas City Levee. (Photo Courtesy KC10Chief)*



Guy Dupuits

# ECONOMIC OPTIMIZATION OF COASTAL FLOOD DEFENSE SYSTEMS

The Houston Galveston Bay Region (HGBR), like many other urbanized deltas, requires a variety of flood defenses. Deciding on the number of required defenses, and the safety level provided by these defenses, can be done by means of economic optimization. This entails finding a balance between investment costs and the risk reduction provided by these investments.

It is particularly interesting to integrate all relevant flood defenses in this calculation, because the safety level provided by one defense in a system can be influenced by the other defenses. Including and schematizing these reciprocal influences can lead to more precise determination of optimal safety levels. The goal of this study is to find both simple and fast methods to identify economically optimal safety levels for flood defenses in a coastal system, as well as proposing more comprehensive numerical frameworks for situations where a more detailed answer is required.

*Relevance & applicability for the HGBR*
The HGBR is a particular interesting case study, because of the significant economic value it represents, both on the barrier islands and on the mainland. Given this economic value, it makes sense that various areas in this region need flood defenses, but to what extent the existing flood defenses suffice or need to be strengthened or extended is up for discussion.

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Building defenses on or near the barrier islands will most likely reduce the risk inside the bay. The degree of reduction that is actually achieved will depend on the type of defenses built near the barrier islands, and the safety level these defenses provide. Both the type of defense and safety level affect the investment costs, but they also influence the achievable risk reduction.

Location is another important factor; it can influence costs of flood defenses and therefore the optimal choice for the type of defense and safety level. With such a large and diverse area as the Houston Galveston Bay Region, location adds another factor in the search for optimal flood defense systems.

This study focuses on capturing the influence of flood defenses on each other (interdependencies). This is initially worked out for simple characteristic cases, which helps us to define the issues involved in optimizing a larger coastal flood defense system. A simplified case can be found in Figure 41, with a front defense (facing the open water) and a rear defense, separated by a body of water.

Figure 41 shows housing behind the rear defense, which is what ultimately needs to be protected. In the situation with two defenses, two scenarios in which the rear defense could fail can be envisioned: either with or without the front defense continuing to function. This is shown in Figures 42 and 43, respectively.

Here we assume that a front defense can potentially reduce the probability of the rear defense failing. Coupling this risk schematization with investment costs for the front and rear defenses and taking potential flood damage into account, we can mathematically work out the optimal levels for both the front and rear defense.

Figure 41 represents a simplified case, and one that is not representative for the Houston Galveston Bay Region. Including additional housing on top of the front defense in Figure 41 would already be a better representation of the actual situation. Variations, such as the additional housing on top of the front defense, are logical additions for future work.

As the variations become more complex and additional influencing parameters are included, the step to numeric frameworks has to be made. Figure 1 could be extended by adding multiple rear defenses, or including flooding scenarios for different types of defenses. Future work should include these more complex scenarios.

*Figure 45.*
*Return to Galveston after Hurricane Ike. (Photo Courtesy Jocelyn Augustino, FEMA )*



Antonia Sebastian

# FLOOD MITIGATION IN MULTI-HAZARD COASTAL ENVIRONMENTS

Due primarily to advances in early prediction and warning systems, the number of deaths from flood events decreased significantly during the latter half of the 20th century. Conversely, the economic costs of coastal floods have risen exponentially. Unrestrained urban development has reduced the capacity of the coastal system for storing and accommodating rainfall-runoff, and led to greater economic consequences of both freshwater and saltwater floods. Recent hurricanes (e.g., Katrina, Ike, Sandy) have highlighted these costs and prompted the preliminary design of large coastal defenses to protect urban areas from surge-based flooding. However, the discussion surrounding the design of coastal defenses often neglects to consider the impact of future land use on freshwater flooding, and how this will change the flood landscape in the coastal zone.

Between 1978 and 2015, the National Flood Insurance Program (NFIP) paid over $3.8 billion (3.4 billion euro) in residential flood insurance claims in the three county area surrounding Galveston Bay (FEMA, 2015). Here, flooding is driven by rainfall-runoff or storm surge, or the simultaneous occurrence of the two. This research focuses on the flood landscape within the low-lying coastal zone on the west side of Galveston Bay. Preliminary results indicate that urban development of the coastal zone has contributed to the extent of flooding during hurricane events due to the interaction between the freshwater flood wave and storm surge. In the following paragraphs, the hydraulic concepts driving this research will be explained and preliminary criteria for the design of coastal flood defenses that protect from surge-based flooding, but also mitigate the negative impacts of urban development on the flood landscape, are presented.

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Much of the Houston Galveston Bay Region (HGBR) was rapidly developed during the 1960s and 70s, and growth in the coastal zone has continued steadily since the late-1980s. Currently, more than 1.6 million people live within the designated hurricane evacuation zones surrounding Galveston Bay and this number is expected to increase to 2.4 million by 2035 (H-GAC, 2011). The construction of vast swaths of impervious surface and widespread loss of wetlands, which usually store large volumes of water, has been shown to contribute to the size, intensity and frequency of freshwater flooding in the HGBR (Khan, 2005). Research has also shown that the amount of pervious land cover and open space surrounding existing development correlates strongly to the amount of flood damage experienced at the parcel level (Brody et al., 2014). As open space and pervious surface continue to disappear, flood damages in existing developments can be expected to increase.

In an effort to mitigate freshwater flooding, many of the bayous in the region have been channelized. Naturally, 'bayous' are slow moving, tidally influenced, brackish streams; they are rainfall-runoff fed and despite their normally languid behavior, quickly morph into raging rivers during heavy storms. While channelization of the bayous temporarily relieves local flooding, it can exacerbate flooding further downstream by increasing the volume of water within the channel and the speed with which the flood wave travels (Doubleday et al., 2013). As the region continues to grow and develop, additional channelization can be expected, facilitating future urban development and furthering a cycle of unsustainable flood mitigation.

In addition to freshwater flooding, the low-lying coastal zone is vulnerable to storm surge inundation during hurricane events. Much of the west side of Galveston Bay lies below 5m (16.4ft) and is at a higher risk than other parts of the region due to local wind setup in the Bay. In the 1960s, a levee was built to protect the industrial area of Texas City; still, no major storm surge mitigation has been built to protect the heavily developed and populated area between Eagle Point and Morgan's Point, and complete avoidance or retreat from the coastal zone is not feasible given the size of the urban population and existing infrastructure. This area has been widely recognized as one of the most difficult to address due to the many stakeholders and local interest groups, and growing population. In order to develop sustainable flood mitigation recommendations, it will be necessary to evaluate the relative risk of precipitation- and surge-driven flooding, as well as the impacts of land use and climate change on flood risk in the coastal zone.

Preliminary research indicates that while the economic consequences of surge-driven floods are significant, precipitation-driven floods occur, on average, more often, resulting in comparable annualized damages. For example, in a study of FEMA flood claims in the Clear Creek Watershed between 1999 and 2009, 43% of insurance claims were associated with Hurricane Ike (surge-driven flood),

Figure 46.
*Sustainable Mitigation requires Land Use Controls. (Sebastian 2015)*

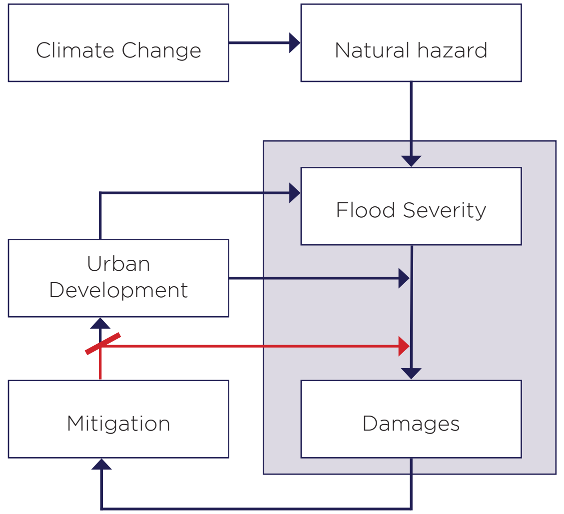


*Figure 47. The Evia neighborhood on Galveston Island which survived Hurricane Ike with virtually no damage. (Photo Courtesy Sullivan Brothers)*



37% with Tropical Storm Allison (precipitation-driven flood), and 20% with other precipitation-driven flood events) (Brody et al., 2013). However, when comparing the economic consequences of these events, precipitation-driven flooding only accounted for 49% of the total flood losses (Brody et al., 2013). While these events have been categorized as surge- or precipitation-driven, they, like most damage-inducing events in the coastal zone, are dual-hazard. In the development of flood mitigation strategies, it will be especially important to quantify the joint exceedance probability of storm surge and precipitation, since small increases in downstream elevation can have large consequences in upstream tributaries because outflow is restricted.

Current patterns of urban development and freshwater flood mitigation strategies in the HGBR coupled with rising sea levels will exacerbate the consequences of dual-hazard events and, potentially, the frequency with which they occur. As discussed previously, urban development can decrease the response time of a watershed to precipitation and increase the size and intensity of freshwater flooding. Current methods for mitigating freshwater flooding (e.g., straightening, channelizing) increase the speed with which a flood wave moves downstream. Because of this, precipitation falling on the upper portion of the watershed will move faster through the watershed decreasing the time separation between peak rainfall-runoff and peak storm surge and increasing the likelihood of severe peak on peak events.

The multi-hazard nature of highly urbanized coastal systems necessitates the design of comprehensive and sustainable flood mitigation strategies that consider the relationship between urban development and both precipitation-driven and surge-driven flooding in the coastal zone. Based on this preliminary conceptual assessment of hydro-meteorological hazards and flood behavior in highly urbanized coastal systems, sustainable flood mitigation strategies for the coastal zone should meet the following criteria:

1. Regional-scale storm surge mitigation structures should be designed with consideration of existing (riverine) flood mitigation strategies (e.g., channelization) and provide alternatives for future practices (e.g., Room for the River);
2. Structural flood mitigation solutions should maintain the existing values of the hydro logic system (e.g. flood storage);
3. Structural flood mitigation should be coupled with solutions at the parcel level to facilitate awareness and preparedness, and reduce damages (e.g., changes to building codes to encourage vertical avoidance, increase flood insurance premiums to encourage horizontal avoidance);
4. Structural flood mitigation solutions should include controls for land use development in the coastal zone and contributing watershed areas (i.e., no adverse impact).

Controlling development in the coastal zone is likely to be the most important component of any regional flood mitigation strategy. As discussed, urban development negatively impacts flood severity by increasing the volume of runoff and decreasing the response time of the watershed. In order to permanently mitigate expected losses in the coastal zone, proposals to manage flood risk in coastal watersheds must include measures to control urban development upstream and minimize hydrologic impacts of new development, as well as provide new development standards for downstream areas.

New standards for development in coastal watersheds should maximize set-backs from existing floodplains, maintain existing land cover and open space, and incorporate flood storage. These have been shown to be effective strategies for reducing the impacts of development on watershed hydrology and flood losses in the region (Doubleday et al., 2013; Brody et al., 2014; Brody et al., 2015). In the downstream portion of the watershed, particularly the areas below 5m (16.4ft) , repetitive loss structures should be removed and any new development in unprotected areas should be built to withstand hurricane flooding. One example of a hurricane proof community is the Evia neighborhood on Galveston Island (figure 47). Here, the land was elevated to 3.4m (11 ft) and structures were elevated to 4.0m (13 ft); excavated areas were repurposed as man-made wetlands/ponds to provide additional storage during flood events. This community experienced virtually no damage during Hurricane Ike (Patton, 2008). The science behind predicting and quantifying the impacts of flooding in the coastal zone has improved significantly in recent decades, ultimately reducing the lives lost from floods. However, the HGBR's capacity to fully mitigate the impacts of floods is hindered by coastal growth that has led to the reduction of natural buffers to flooding. Without restraints on urban development and new development standards, large-scale structural mitigation strategies will only provide temporary flood risk reduction, since, as more and more land is developed, the flood severity will again increase and expected damages will rise, creating a positive feedback loop and the need for continued mitigation, rather than a one-time investment in flood prevention (as seen in Figure 46).

Recent history has indicated that chronic precipitation-driven floods have the potential to cause annual repetitive losses, which due to their frequency, could exceed the annualized residential damages associated with hurricane-induced storm surge events in the HGBR. While it is important that the damages from storm surge are mitigated, it is also imperative that any regional- or large-scale storm surge mitigation strategies be coupled and integrated with current and future strategies for mitigating precipitation-induced flooding and the consequences of land use and climate change.

*Table 4. Concepts for flood risk reduction measures employed in the USA and The Netherlands, definitions and examples. (Kothuis 2015)*

| **Similar sounding concepts for flood risk reduction measures in the USA and The Netherlands** | | | |
|---|---|---|---|
| **Concepts commonly used in the USA** | | **Concepts commonly used in the Netherlands** | |
| Definitions | Examples | Examples | Definitions |
| **Structural measures**<br>'Products of planning, engineering design, and construction' (USACE) | - Levees<br>- Storm surge barriers and gates<br>- Dams<br>- Seawalls<br>- Groins<br>- Revetments<br>- Near-shore and detached break-waters | - Levees<br>- Dams<br>- Storm surge barriers<br>- Breakwaters | **Hard measures / Hard coastal defense**<br>'Coastal defense where the resistance is increased by use of hard materials (stone, basalt, concrete blocks)' (Ministry of I&E) |
| **Nonstructural measures**<br>'Products of public policy management and regulatory practices; may include pricing schemes, planning, engineering design, and construction' (USACE)<br>'Flood risk reduction measures that do not affect the flow of waters.' (USACE; NRC) | - Structure acquisitions or relocations<br>- Flood warning systems and preparedness planning<br>- Land use regulations<br>- Development restrictions<br>- Elevated development<br>- Managed retreat<br>- Evacuation<br>- Buyout and leaseback<br>- Flood insurance | - Beach sand nourishment<br>- Foreshore sand nourishment<br>- Mega sand nourishment (Sand Engine) | **Soft measures / Soft coastal defense**<br>'Coastal defense by means of sand. The dunes form a soft defense against flooding. Making use of the capacity to transform and recover (flexibility, resilience)' (Ministry of I&E) |
| **Natural Features (NF)**<br>'Features created through the action of physical, biological, geologic, and chemical processes operating in Nature' (USACE - ERDC) | - Barrier islands<br>- Dunes and beaches<br>- Oyster and Coral Reefs<br>- Wetlands and marshes<br>- Riparian corridors<br>- Maritime Forests and Shrub Communities | | |
| **Nature-Based Features (NBF)**<br>'Products of planning, engineering design, and construction, incorporating natural processes that contribute to coastal risk reduction and resilience' (USACE - ERDC)<br><br>*Note: Natural and Nature-Based Features are mostly referred to as combined concept, abbreviated as NNBF.* | - Barrier islands<br>- Dunes and beaches<br>- Oyster and Coral Reefs<br>- Wetlands and marshes<br>- Riparian corridors<br>- Maritime Forests and Shrub Communities<br>- Living Shorelines | - Creating new and restoring inter tidal habitats<br>- Making space for water (Room for the River) | **Nature-based Solutions (NBS)**<br>'Actions which are inspired by, supported by or copied from nature; and aim to address a variety of environmental, social and economic challenges in sustainable ways' (European Union) |
| **Green Infrastructure solutions (GI)**<br>'The natural or semi-natural systems that provide services for water resources management with equivalent or similar benefits to conventional (built) "grey" water infrastructure' (UNEP)<br>'The integration of natural systems and processes, or engineered systems that mimic natural systems and processes, into investments in resilient infrastructure' (USACE) | - Develop existing open space as natural flood storage<br>- Purchase and protect land in floodplains<br>- Transform vacant properties into open space, trails, community gardens, and parks<br>- Rain gardens<br>- Street swales<br>- Bioinfiltration<br>- Green roofs | - Gradual sand nourishment for the coast, reducing levels of damage to the ecosystem.<br>- Creating soft forebanks to mitigate wave impact<br>- Regrowth and restoration of mangrove forest | **Nature-based Engineering (NBE)**<br>'Combining flood protection and the recovery of the ecosystem' (Deltares) |
| **Engineering with Nature (EWN)**<br>'The intentional alignment of natural en engineer-ing processes to efficiently and sustainably deliver economic, environmental and social benefits through collaborative processes' (USACE - ERDC) | - Sediment retention engineering to facilitate wetland development<br>- Living shoreline creation through use of dredged material<br>- Engineering practices to enhance the habitat value of infrastructure | - Sand nourishment (Sand Engine)<br>- Create new dune landscapes<br>- Seabed landscaping<br>- Use of oyster reefs to protect tidal flats in estuaries<br>- Use of coral reefs, seagrass meadows and mangroves to prevent coastal erosion<br>- Attach habitat-promoting tiles to seawalls | **Building with Nature (BwN)**<br>'Proactive utilizing of natural processes and providing opportunities for nature as part of the infrastructure development and operation' (Ecoshape, Rijkswater-staat)<br>'Where nature is used to cope with the risks of waves and sea level rise' (Deltares) |
| **Working with Nature (WwN)**<br>'An integrated process which involves working to identify and exploit win-win solutions which respect nature and are acceptable to both project proponents and environmental stakeholders.' (PIANC) | - Environmental friendly river banks<br>- Creating a new tidal area<br>- River training structures: chevrons<br>- River Bendway Weirs<br>- Environmentally enhanced break-water toe blocks | | |



Baukje Kothuis

# BUILDING, WORKING, OR ENGINEERING WITH NATURE?

## SIMILAR SOUNDING CONCEPTS IN FLOOD RISK MITIGATION

Worldwide, many different concepts are used in flood risk reduction policy and measures, especially when it comes to involving nature and natural processes in the strategy. In Texas for example, commonly used terms are *Natural and Nature-Based Features* (NNBF), *Engineering With Nature* (EWN), *Working with Nature* (WwN), *Green Infrastructure solutions* (GI), and *Nonstructural Solutions* as opposed to *Structural Solutions*. Although these concepts are often mentioned simultaneously and sometimes even interchangeably, a closer look shows us that they differ significantly in features, functions and assumptions. This effect becomes even clearer in the context of international collaboration.

In the Netherlands, in the water management context a range of concepts is in vogue which at first seem similar: for example, *Nature Based Solutions* (NBS), *Building with Nature* (BwN) and *Soft Measures* as opposed to *Hard Measures*. The different terminology, as well as the different conceptual associations, can be a source of confusion. Moreover, this wide range of seemingly comparable, multi-interpretable concepts can become a serious impediment when it comes to making concrete plans (Bijker, 1995; Hajer, 1995). When it comes to implementing a project, differing initial interpretations of a concept often leads to disappointment, indignation, and worst of all, loss of mutual trust between stakeholders (Heems & Kothuis, 2012).

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In this study, we explore the concepts most commonly used in Texas and the Netherlands, and ask the following questions:
- Why did a range of concepts that incorporate nature, enter the flood risk debate in Texas, and why did these specific concepts enter the debate?
- Which concepts are used in current debate and policy on flood risk reduction in Texas and in the Netherlands? What do differences between these concepts signify?

Not surprisingly, after the disastrous flooding caused by Hurricane Ike in 2008, the first range of proposed flood risk reduction solutions all strongly aimed at keeping the water out of vulnerable areas. A well-known and proven method to achieve this goal is by using dikes, dams, closure gates and levees. As such expertise is often considered to be typically Dutch, research collaboration was sought and established with the Netherlands. Several alternatives were proposed, like shortening the coastline and installing storm surge gates. However, to qualify for the necessary Federal co-funding for any major flood risk reduction measure, not only is the proposal of an 'array of alternatives' (PR&G-WRDA, 2013:12-13) required but also strong local consensus for one solution. So far none of the proposed alternatives has satisfied all stakeholders in the region.

In order to develop a widely supported proposal, a broad range of solutions must first be presented. Most of the initial solutions proposed in the Houston Galveston Bay Region have been mono-functional, structural flood risk reduction measures, aiming to counter the storm surge. However, to accommodate the different desires of the various stakeholders, new strategies have been explored, combining these 'traditional' solutions with multifunctional measures that incorporate nature or natural systems. Well-known examples of such measures are the Dutch Sand Engine and the New Orleans Wetlands Restoration Plan.

Another incentive to explore multifunctional, nature-incorporating measures is a recent amendment to White House Executive Order 11988, entitled 'Establishing a Federal Flood Risk Management Standard and a Process for Further Soliciting and Considering Stakeholder Input' (EO 11988, January 30th, 2015). Whereas a set of alternatives was already required to qualify for federal funding for flood risk reduction, the amendment explicitly specifies the potential alternatives: 'Where possible, an agency shall use natural systems, ecosystem processes, and nature-based approaches when developing alternatives for consideration.' In this context, just as with the development of structural measures, experts from Texas and the Netherlands aim to collaborate to share expertise.

To study the features and functions of the different concepts used in the debate, the methods of document and discourse analysis, interviews, and participant observation were employed. First, we identified the actors in the water management debate. In the initial phases, developing alternatives for flood risk reduction, the leading actors come from knowledge organizations and government (at different levels). Governmental actors deliver policies, procedures and legislation, whereas knowledge providers focus on data, features and feasibility of the design. This paper considers the terminology and concepts currently used in the Netherlands by the Ministry of Infrastructure and Environment (I&E), the Department of Waterways and Public Works (Rijkswaterstaat) and the regional water boards; in the United States by the US Army Corps of Engineers (USACE), the Federal Emergency Management Agency (FEMA), the US Environmental Policy Agency

*Figure 48. Construction of Sand Engine along the Dutch Coast 2011. (Photo Courtesy Rijkswaterstaat/Joop van Houdt)*

*Figure 49. Sand Engine after completion in 2011. (Photo Courtesy Rijkswaterstaat/Joop van Houdt)*

*Figure 50. Sand Engine development by natural processes, 2014. (Photo Courtesy Rijkswaterstaat/Joop van Houdt)*

(USEPA) and the National Research Council (NRC); and in both countries in the scientific and knowledge providers, such as community universities, research institutes, engineering bureaus, and Non-Governmental Organizations (NGOs).

In the United States, a frequently used set of concepts is *Structural* and *Nonstructural Measures*. The National Research Council states that in USACE terminology, a structural project 'uses dams or levees to keep flood waters away from buildings and other infrastructure,' whereas a nonstructural flood risk reduction measure is one that 'does not store or divert flood flows away from an inhabited area' (NRC, 2004): in fact, it 'does not affect the flow of flood waters' (NRC et al., 2012). Generally speaking, structural measures modify the flood, while nonstructural measures modify the impacts of a flood. Nonstructural projects address 'how and where development might take place or how risks to existing development can be reduced by elevation, relocation, or other mitigation measures' (NRC, 2012; NRC, 2013). An important consideration is that developing nonstructural measures for flood risk reduction is generally the responsibility of state and local governments, and cannot be imposed by federal government (USACE, 2013). Major structural measures, however, often need federal funding, and therefore have to be approved by the US Army Corps of Engineers.

The counterpart of the US Structural and Nonstructural Measures might seem to be the *Hard* and *Soft Measures (or Solutions)* commonly used in the Netherlands. Hard and soft solutions originate in Dutch coastal policy, which is based on the adage 'Soft when possible, hard if necessary'. This is translated as 'move along as long as it's possible, offer resistance if nothing else is possible' (RW, 2012). Hard measures are indeed comparable to Structural Measures (see Table 1). However, Nonstructural Measures are not comparable to Soft Measures as Soft Measures explicitly do affect the flow of waters. Along the coast, the use of sand and sediment is currently central in this context. Initially, wetlands were also considered in the framework of this term (Capobianco & Stive, 2000): and in riverine areas, Soft Measures merely means providing extra space for floodwaters (I&E, 2011, 2014; RW, 2012). Although the Netherlands does not have a single catchall concept similar to the US Nonstructural Measures, the Dutch principle of multi-layer safety is related. Parts of the so-called second layer (i.e., spatial planning measures to mitigate flooding effects) and third layer (i.e., disaster management) comprise elements comparable to Nonstructural Measures. However, most of Dutch Hard and Soft Measures for flood risk reduction are aimed at the first layer: the prevention of flooding.

In a recent publication that aims to explain 'the full array of measures' for coastal risk reduction and resilience, USACE brings all measures back to four concepts. Apart from Structural and Nonstructural Measures, there are *Natural* and *Nature-based Features*. These connect another range of similar-sounding concepts in use in Texas and the Netherlands. Natural Features (NF) are those 'created through the action of physical, biological, geologic, and chemical processes operating in nature'; while Nature-based Features (NBF) are defined as 'products of planning, engineering design, and construction incorporating natural processes that contribute to coastal risk reduction and resilience' (USACE, 2013). In daily practice, it seems difficult to distinguish between the two, as the combined term and abbreviation is in general use: Natural and Nature Based Features (NNBF). These are meant to attenuate waves and provide other ecosystem services like habitat for animals, breeding grounds for fisheries, and sediment retention. But other functions are mentioned as well: e.g., tourism, recreation, water quality regulation, providing unique and aesthetic landscapes, and ecosystem diversification (biodiversity).

The Dutch concepts *Nature-based Solutions* (NBS) and *Nature-based Engineering* (NBE) sound similar to NNBF. NBS is used within the European Union to create a research and policy innovation agenda, primarily relating to sustainability and 're-naturing cities'. This concept correlates strongly with the US concept *Green Infrastructure Solutions*, which aims to provide services for water resources management and resiliency in cities. NBE, on the contrary, is concerned with flood protection and aims to combine protection with restoration of the ecosystem. This fundament relates to the three final concepts under consideration in this research project: *Building with Nature* (BwN), *Engineering With Nature* (EWN), and *Working with Nature* (WwN). These 'engineering' concepts differ greatly, although all three have roots in dredging. BwN is a prominent and much researched concept in the Netherlands, with the Sand Engine as its most famous example. BwN's aim is to reduce flood risk by developing infrastructure and proactively utilizing natural processes, providing opportunities for nature in the process (Ecoshape, 2012). The US concept EWN is defined as 'intentional alignment of natural and engineering processes' (USACE, 2015), which makes it sound very similar to BwN, since infrastructure obviously incorporates engineering. However, the context of EWN is much broader. Apart from flood risk reduction, EWN addresses the full array of water resources infrastructure, including restoration of aquatic ecosystems, water supply, generating hydroelectric power, and maintaining navigable waterways. WwN focuses on infrastructure for ports and navigation; flood risk reduction is not its core business. The projects must 'respect nature': the aim is to do 'no harm' to nature and to design projects that 'are acceptable for both project proponents and environmental stakeholders' (PIANC, 2011; Bridges et al., 2014). As a result of its no-harm policy, WwN may profitably restore or even create nature or ecosystems, but this is a secondary effect, whereas this is one of the explicit goals of both EWN and BwN.

Stakeholders in both the US and the Netherlands all explicitly mention multiple functions of the concepts discussed above. Strikingly, the same three functions are nearly always mentioned: economic, social, and ecological (or natural/environmental/ecosystem) functions. The goal of flood risk reduction in both countries is to protect benefits, interests, resilience, and development in three spheres: business, nature and people.

There is, nevertheless, a difference in hierarchy of functions of flood risk reduction measures between the two countries. In Texas, economic functions (business, jobs, ecosystem services) and ecological ones (protecting and restoring nature) are usually named first. Saving people's lives and livelihoods is not mentioned as the main aim, which could be explained by the fact that a hurricane comes announced and its damage is insurable. People have the opportunity to evacuate and return. In the Netherlands, on the other hand, evacuation is not an option, since a storm flood develops in hours instead of days and Dutch infrastructure hardly allows evacuation (Koolen, 2014). Furthermore, a major flood disaster is expected to demolish most crucial infrastructure to the point of no return (TMO, 2008). Additionally, flood insurance in practically unavailable in the Netherlands. Since people cannot flee nor recover, saving their lives and livelihoods is the first function of flood risk reduction measures in Dutch flood risk management policy. Only when this is accomplished does the function called 'spatial quality' appear: an opaque term that includes improving the local environment with natural features and enhancing the economy with recreational facilities.

From a governance perspective, including multifunctional nature-incorporating measures in flood risk reduction in the Houston Galveston Bay Region offers stakeholders the opportunity to combine diverse, previously proposed solutions into a new, integrated whole. For the time being, they seem to agree that measures that incorporate nature and natural systems and combine multiple functions could help to create the much needed broad local support necessary for federal funding. Nonetheless, researchers and local stakeholders, particularly those working together in international projects, must remain aware that seemingly similar concepts not only differ in content, but also in underlying assumptions and values. Recognizing and acknowledging these differences from the start can help to avoid undesired complexities, disappointment, or worse, loss of mutual trust, in later stages.

Figure 51.
Galveston Bay shore.
(Photo Courtesy
Jantsje van Loon-
Steensma)

Figure 52.
Galveston Bay
Wetlands.
(Photo Courtesy
Jantsje van Loon-
Steensma)




Jantsje van Loon-Steensma

# ECOSYSTEM SERVICES ALONG THE TEXAS COAST

## LONE STAR COASTAL NATIONAL RECREATION AREA

The Texas coast comprises an extensive delta of bays and estuaries linked to numerous rivers that drain rainwater from higher inland areas into the Gulf of Mexico, flanked by extensive wetlands consisting of salt, brackish and freshwater marshes, grass meadows, prairies, and forested wetlands and floodplain forests (Blackburn, 2004). These wetland habitats have adapted to recurring inundation by both riverine flooding and storm surges. Along the Upper Texas coast, a coastal chenier (an elongated stretch of historic beach ridge higher than the high tides) forms the border between the coastal plain and the Gulf. The coastline of the Mid-Texas coast consists of an elongated stretch of barrier beaches and islands (e.g., Galveston Island).

Like other deltaic areas, the Texas coast provides a broad range of ecosystem services (Hale et al., 2014). The coastal area offers space for human settlement and economic activities, provides food and other products for human use, it buffers floods and forms a retention area for fresh water, and offers opportunities for recreation and tourism. Furthermore, this wet sub-tropical coastal area harbors important ecological values and is part of the Central Flyway, the important route for migrating birds from North America to Middle and South America. The shallow bays and estuaries with their mud and sand banks are highly productive areas, with shrimps, crabs, oysters, fish, and abundant microscopic plants and animals. They form an important feeding area for wading birds and a stopover area for migrating birds. The coastal zone exhibits a graduation in wetlands, from those inundated by tides to those flooded by storm water and riverine flow year-round to those that are wet only during certain times of the year, and the related gradation from salt to freshwater marshes (flooded by rivers or heavy rainfall). It is this mosaic of wetland habitats and bottomland forest that attracts numerous birds. The Texas coast provides habitat for over 100 species of water birds, and many northern species winter on the Gulf Coast. Three of the top ten bird counts in the U.S. were found along the Texas coast. During spring migration, from late March until the end of May, several thousand birdwatchers visit the Texas coast. Visitors can observe and photograph spectacular concentrations of migratory birds and other wildlife, and they can fish, and hunt waterfowl (Blackburn, 2004).

In general, human settlements are situated on natural elevations, on strategic positions close to rivers (which are important transportation routes), and on the higher grounds along the bays and estuaries. Such sheltered locations offer some protection against recurring flooding from storm surges, heavy rainfall or hurricanes while also offering access to the benefits of the coastal environment. Except for a few intensively urbanized and industrialized areas like the greater Houston-Galveston Region (with its extensive oil refineries and petroleum-related chemical industry), the low-lying flood prone Upper and Mid-Texas coastal zone is sparsely inhabited. The likely 100-year surge is approximately 6.5 m (20 ft) (see Davis et al., 2014). Lower-lying areas close to the coast will also be inundated during storms more frequently. The habitats in this flood-prone zone - beaches and low dunes, wetlands, prairies, bottomland forest - are resilient to such incidental flooding, and may even dampen the waves and storm surge to some extent (Brody et al., 2007). The coastal zone thus forms a natural flood defense, which means that conserving it can be regarded as a non-structural flood protection strategy.

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*Figure 53. Brochure Proposed Lone Star National Recreation Area, (Source: National Parks Conservation Association)*


Wetlands inundated by coastal flood tides or flooding rivers are already protected for their biodiversity and habitat, for example, in the framework of the Ramsar Convention (Convention on Wetlands, 1987) and the U.S. Clean Water Act (Federal Water Pollution Control Act Amendments of 1972). Currently, a substantial part of wetland area and bottomland forest along the Upper and Mid-Texas coast is federal or state protected land (e.g., Texas Chenier Plain National Wildlife Refuge Complex, McFaddin National Wildlife Refuge, the Anahuac Refuge). The majority of the prairie land, on the other hand, is privately owned property, primarily used for ranching.

Although ranching affects its environment, this extensive type of land use has helped preserve the open prairie landscape. Grazing has probably even added to the biodiversity of this habitat by slowing down succession, preserving more species-rich succession stages, and (depending on the livestock density) inducing patchiness vegetation and structural heterogeneity. However, ranching has become economically less attractive in recent years. This means that some prairie area (including prairie wetlands) is no longer maintained for grazing purposes and is threatened by a change in land use, with suburbanization and fragmentation of this habitat. Some of the wet prairies are farmed for rice. Rice farming requires active management of the water system, and may affect the groundwater level and freshwater supply in nearby areas. In addition, the continuous removal of groundwater for industrial and municipal use in the urbanized Houston area has resulted in a change in groundwater level. At many places more groundwater is used than can be replenished by rainfall. This has not only affected wetland habitats but also resulted in soil subsidence.

The sandy strip adjacent to the Gulf is a popular destination for recreation and tourism. Along several stretches of the coast a number of beach houses have appeared, and the trend is continuing. These houses are built on stilts to protect them against coastal flooding and inundation by hurricanes. Sometimes the owners of these recreational houses also try to protect their property against flooding by stimulating dune formation. Nevertheless, after each hurricane a substantial number of the beach houses are severely damaged. Some stretches along the coast are even considered too risky for housing and are excluded from flood insurance.

The Houston Galveston Bay Region currently has around 6 million inhabitants. Concerns about the increasing pressure from population growth on the coastal habitats (i.e., urbanization, increasing demand for fresh water, need for recreation space) and from industrialization (i.e., pollution and deepening of shipping channels) has led to the idea of creating a coastal park to preserve the coastal zone with its mosaic of wetland habitats (Blackburn, 2013). This coastal park would conserve the typical Texan rural coastal landscape (as much as possible in its natural state), and enhance the development of an inundation-proof coastal zone. The ultimate goal would be to designate this a National Recreation Area. The proposed Lone Star Coastal National Recreation Area (LSCNRA) would include low-lying coastal areas (<6.5m (20ft) above mean sea level) in Chambers, Galveston, Brazoria and Matagorda Counties (in the area east and south of Houston). Such a park would provide opportunities for outdoor recreation like hiking, camping, kayaking, bird-watching, hunting and fishing for the inhabitants of the greater Houston area as well as for visitors, and could potentially boost the tourism-related economy.

However, the creation of the LSCNRA is a complex process, requiring the participation of many parties. The proposed reserve would comprise approximately 1.6 million acres, including some 220,000 acres from currently protected nature reserves (owned by the U.S. Fish and Wildlife Service, the U.S. Army Corps of Engineers, or the Texas Parks and Wildlife Department). The remaining area is privately held property, mainly prairie land used for ranching. Although the economic prospects of traditional ranching and farming are not very favorable, many landowners feel a strong connection with their land and are not willing to sell their property to nature conservation organizations (Winston Jones, personal communication Oct. 2014). Therefore, the challenge is to find economic incentives to encourage these landowners to voluntarily participate in the LSCNRA. The possibility of paying these landowners for the ecosystem services provided by their land in order to preserve the open prairie landscape is currently being explored (Davis et al., 2014). Next to traditional provision services, additional services might include buffering against storm surges, carbon sequestration, water purification, or restoration to compensate for the impact of regional economic development (Davis et al., 2014). An online platform for transactions that channels the benefits of individual conservation and restoration projects to buyers, called the Lone Star Coastal Exchange (LSCE) program, might provide a mechanism to deliver these incentives and benefits (Davis et al., 2014).

Creating an uninhabited (or sparsely inhabited) coastal park could be considered a non-structural hurricane damage mitigation strategy. Such a natural coastal landscape would provide a partial buffer against flooding of the inland zone. If, on the other hand, urbanization were to increase in the low-lying areas, this would most certainly lead to structural attempts to protect the built area against flooding. These measures would affect the ecological values of the coastal zone, and also require substantial funding. Another advantage of the coastal park is that it could easily be part of a combined regional strategy including structural measures, like a coastal barrier or a levee. Furthermore, the creation of the park would help reduce the pressure on coastal wetlands from sea level rise by providing space for a landward expansion of coastal habitats. Developing a coastal park is a no-regret flood protection strategy, and worth investigating further.

*Figure 54.*
*Galveston Island.*
*(Photo Courtesy*
*Helena Van Boxelaere)*



Helena Van Boxelaere

# AN INGRAINED COASTAL BARRIER ON GALVESTON ISLAND

## THE LANDSCAPE AS A COMPLEX OF BIOLOGICAL, PHYSICAL, AND CULTURAL SYSTEMS

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*Advisory panel for Texas Case:*
*Dr. B.L.M. Kothuis, TU Delft*
*Dr. A.D. Brand, TU Delft*

This study explores the design of a coastal barrier based on an in-depth understanding of the landscape system. Bringing together the major biological, physical, and cultural processes allows us to explore and develop designs that consider various landscape scales and multiple functions. For example, landward retreat of barrier islands, opportunities for combinations with evacuation routes, and clustering of crucial community facilities, might call for a barrier design located further away from the beach.

The landscape is usually visualized as a place, yet it can be better understood when we think of it as a process. Therefore 'the landscape is best described as a complex of biological, physical and cultural systems engaged in a process of perpetual becoming' (Murphy, 2005). These systems are outstandingly varied in the Galveston Bay area. An ecologically rich environment with fish, wildlife, birds, and vegetation arises when the fresh water of the Trinity River and San Jacinto River mixes in the shallow bay with the salt flux from the Gulf of Mexico. From a geo-morphological perspective, Bolivar Peninsula and Galveston Island have protective value for the bay and the coastal plain due to their small dunes. Although they are destroyed by major storms and shifted by landward migration of the islands, these dunes are repeatedly constructed by longshore sand transportation. On top of their ecological value, the barrier islands area are quite attractive for humans. The cooling breeze at the coast alleviates the humid subtropical climate, making Galveston a popular holiday or daytrip destination.

From these biological, physical and cultural perspectives, major and minor interactive processes on different scales and in different spheres can be identified in the specific landscape system of the Bay area. As a barrier island between the coast and bay, Galveston Island protects the bay and coastal plain from hurricane storm surges. It is both practical and realistic to increase this natural potential by adding an artificial coastal barrier to help stop the surge before it goes further. However, a coastal barrier has major regional and local implications for landscape processes. If this flood mitigation concept is designed based on these landscape processes, it can nevertheless result in a defense that is well integrated into the landscape system. Therefore, this study explores the design of flood mitigation concepts based on in-depth research of that system.

Three different strategies of flood mitigation are explored and designed in close relation to identified landscape processes:
- A concept for a protective dune barrier on the beach;
- A concept for a dike on the island;
- A concept for the protection of Galveston city combined with sand nourishment.

The design process has three steps:
- The landscape system is thoroughly analyzed and categorized;
- This is used for the initial development of the concepts named above and the basic design of the flood mitigation;
- The concepts constantly develop by further detailing the design and adding design details.

In order to create integrated multifunctional designs, it is important to deeply understand the relevant landscape processes and to create an understandable visualization of them. Ultimately, the illustrated designs are tested and related to the landscape system in a multi-layered mode, thus indicating their opportunities and limitations.

Matthijs Kok

# MULTIPLE SOLUTIONS FOR FLOOD RISK REDUCTION

## REFLECTION

*Prof. dr. ir. M. Kok is a professor of Flood Risk at the Faculty of Civil Engineering and Geosciences at TU Delft; and program leader of the 'Integral and Sustainable Design of Multifunctional Flood Defenses' research program, funded by the Dutch Science and Technology Foundation STW.*

The Multifunctional Flood Defense (MFFD) program facilitates research from an integral perspective: technical, landscape, financial and governance aspects are investigated in great detail. One of the cases the program has studied is the vulnerability of the Galveston Bay area: are multiple functions (such as improving ecological assets, houses, or other buildings) on and around flood defenses necessary to reduce the flood risk in Galveston Bay? The answer is: no, not necessarily. However, in my opinion, a multifunctional approach can help to design effective solutions for the reduction of flood risk. Not as a dogma, not with wishful thinking, but with sound engineering and an integral approach, as we advocate in the Delft Flood Risk Center at the TU Delft (DCFR).

The aim of the DCFR is to combine and share the knowledge on flood risk management throughout the several faculties of the TU Delft, in order to achieve an integral and broad approach to flood risk management in delta areas. In our view engineering (and other) solutions should meet social, economic and institutional requirements in order to be successful. The key elements of this approach are:

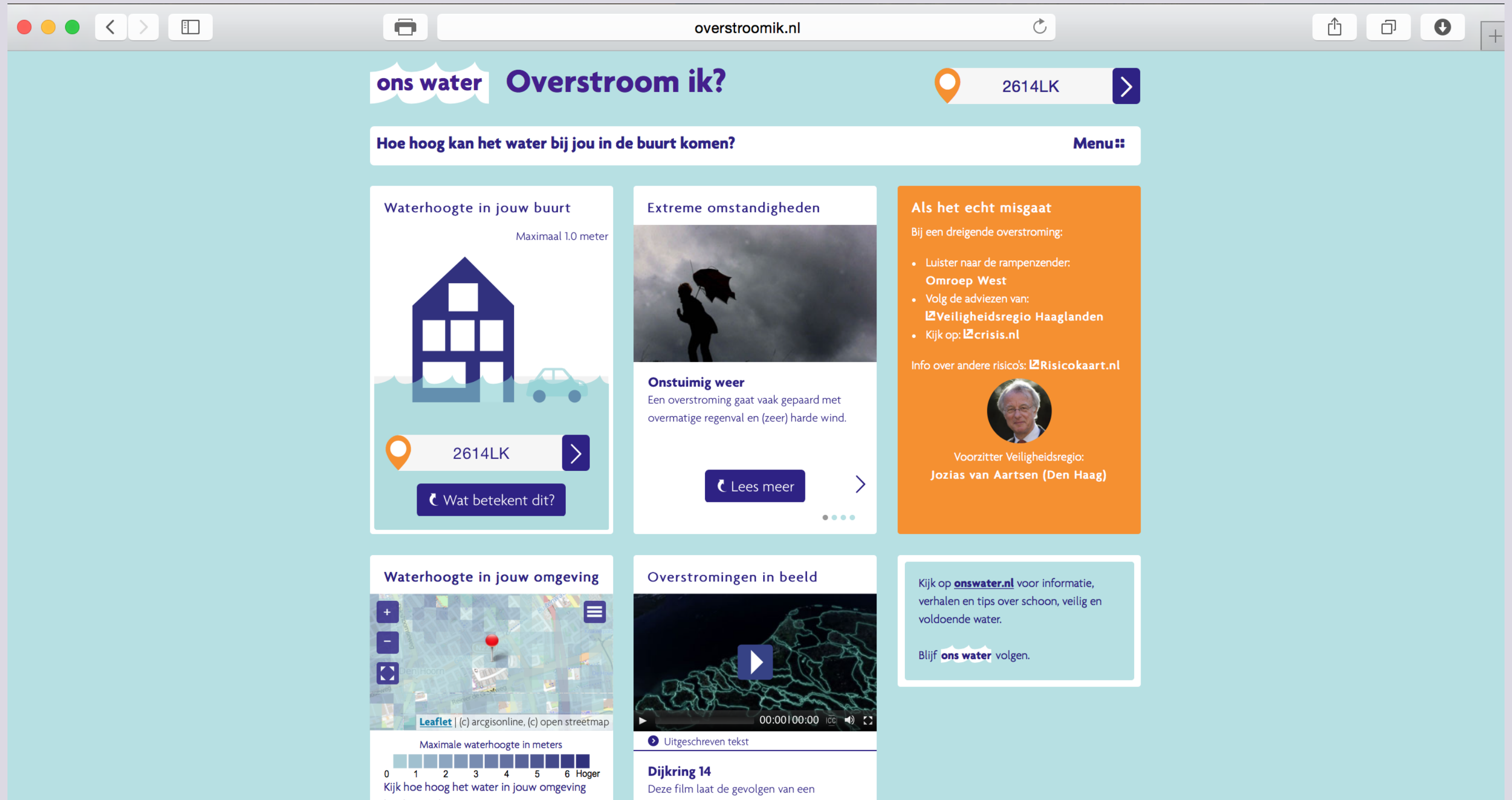
- Evaluate flood risk by assessing the probability of flooding and the consequences of flooding, using multiple scenarios. We know that, especially in densely populated delta areas, flood consequences may be severe, especially loss of life;
- Generate multiple alternatives for reducing flood risk, and assess each alternative for its reduction of flood risk, its costs, and its benefits. These assessments may also reveal how alternatives could benefit the ecological functions of the environment, or, for example, that it may be wise to improve evacuation plans.
- Open discussions in the public and private domain about the advantages and disadvantages of each alternative; and use these discussions to generate new combinations of alternatives;
- Find public and private funds to finance the most preferred alternative and to set safety standards in order to facilitate maintenance of the infrastructure. In the Netherlands, 50% of improvements of the dike system are covered by national taxes, with the remainder paid by taxes collected by local water boards. Depending exclusively on local investments would put too much pressure on the less densely populated areas of the country.

In October 2014, I met a delegation from Texas at the yearly closing of the Maeslant Barrier in Hoek van Holland, and was impressed by the wide variety of involved persons in the delegation. I spoke with mayors, but also with scientists and public servants. That is a good starting point of what we call *polderen* in the Netherlands. This typical Dutch word means talking with each other until we agree on a solution that is best for everybody (and not the best solution for one group alone). The word *polderen* comes from *polder*, which is reclaimed land that is still threatened by the sea (in California they call these areas 'islands', strangely enough).

It has been shown that a dollar spent on preventing a disaster has much more value than a dollar spent on damage recovery. Even the International Red Cross has recently changed its policy: well known for their disaster response activities, they now also help to prevent disasters happening. In the Multifunctional Flood Defenses section of this book, several contributions refer to this so-called 'multi-layer safety' approach. Combining this multiplicity with potential multifunctionalities in the design phase seems a promising way to effectively develop integrated and sustainable flood defenses. To actively further this development, I hope that the exchange of knowledge and joint research between Dutch and Texan universities will become even stronger, especially on the following topics:

- Contribution to flood risk reduction of measures which improve the ecological situation. This might lead to win-win situations (see the contributions of Baukje Kothuis (p. 72) and Jantsje van Loon-Steensma (p. 76));
- Design of integrated flood defenses combined in an effective way with other functions, such as landscaping or recreation;
- Combining flood defenses might, from some points of view, some times be more interesting then using a single line of defense (see the exciting contribution of Guy Dupuits (p. 66)).
- Developing community information about the possible water depths at each location, for example in an 'app' (see Figure 55 for a Dutch example). A probability distribution of water depths is a promising tool to increase the risk perception among citizens, companies, public authorities and NGOs;
- Impact of pollution on Galveston Bay after a hurricane, with consequences for wildlife and humans.






The world is getting smaller and smaller, and local disasters become global issues: an earthquake in Nepal is news all around the world. To address this evolution adequately, international joint research between universities and cooperation between disciplines is, in my opinion, necessary. Let's not just discuss the problems, let's discuss the multiple solutions.

*Figure 55. Screenshot of Dutch app titled 'Will I Flood?' On the left, one sees the potential water depth of a flooded house in the area with zip code 2614 LK. In the middle of the screen one finds more information about extreme weather conditions. On the right, one finds recommendations about what to do in case of a flood, and a link to get information on other possible disasters.*

James B. Blackburn

# DEVELOPING A FLOOD DEFENSE SYSTEM: INTEGRATION OF MULTIPLE PERSPECTIVES

## REFLECTION

*Mr. J.B. Blackburn JD is a professor in the Practice of Environmental Law at the Department of Civil and Environmental Engineering at Rice University, Houston; and co-director of the Severe Storm Prediction, Education, and Evacuation from Disasters (SSPEED) Center.*

Developing a flood defense system for the Galveston Bay region is one of the more challenging and interesting problems that I have encountered in my career. Anyone who believes that they can arrive at a result without substantial input and assistance is slated for failure. And sometimes, that assistance comes from unplanned and unanticipated directions. Such was the case with many of the researchers that have contributed to this publication.

Antonia Sebastian is a graduate student from Rice who worked with us at the SSPEED Center and is now studying at TU Delft. She has done excellent work. She and Tom Colbert, an architecture professor from the University of Houston, insisted that I needed to spend time with a group of Dutch researchers who were interested in assisting us and the people of the region in finding solutions for the hurricane surge flood issues of the Galveston Bay region.

By following that advice, I have had the chance to meet and interact with many of the researchers contributing to the Multifunctional Flood Defense chapters and also have had the benefit of a guided tour through the Dutch coastal landscape and defense systems. Baukje Kothuis and Nikki Brand have been particularly helpful in assisting me in understanding the thinking and, perhaps more importantly, the attitude of the Netherlands toward flooding and flood abatement, including the evolution of thinking about flood defense approaches. The tour of the sand engine, the exploration of the Delta Works and the meetings with estuarine researchers studying the impacts of flood defense systems remain with me. I am grateful and appreciative of the effort expended to help me understand what has been done and what can advise the difficult task that we in the Galveston Bay region have in solving our hurricane surge flooding problem.

Here is a short summary of insights gained from these researchers. There is no problem too large to solve. There is no challenge that cannot be met. There is no answer that remains absolutely correct, and there are approaches, lessons learned and there are new approaches.



And while I must admit to thinking this way before I met Baukje and Nikki, the interaction with them opened me to being receptive to new ways of seeing my place. For that I am appreciative.

I want to emphasize a few aspects of the research products from my perspective. First, the work of Jill Slinger, Baukje Kothuis and Scott Cunningham was quite important in helping me see the Galveston Bay region differently. They conducted a workshop here in Houston that helped me, in my capacity as co-director of SSPEED Center, to better formulate the integration of social issues and public comments into solutions for surge flooding. We spent much time together as I showed them the ecosystems and settlements of Galveston Bay. It is always enlightening to see your region through the eyes of informed researchers from another place.

Similarly, the work of Jantsje van Loon-Steensma, Baukje Kothuis and Nikki Brand about integrating natural features into flood defense, and conversations with them on this, have proven quite useful. United States flood defense policy is changing from the ways of the 20th Century. New Principles and Guidelines for water-related projects have been issued by the President's Council on Environmental Quality and new flood design requirements have been issued by President Obama through revisions to Executive Order 11988. The integration of ecosystem services and natural design elements into structural and non-structural alternatives will be much more important in the future than in the past. These are issues that these researchers have explored in their work and in their writings. We will benefit from this work.

Finally, I want to emphasize that many challenges remain before us. We need to better understand impacts to and quantification of ecosystem services that may be lost to flood defense systems, just as we need to better integrate such services into design solutions. This will become a key issue given that Galveston Bay is among the most productive United States estuaries for fish and shellfish.We need to better understand how to balance costs and benefits of various alternatives. And we need better ways of integrating public comments and concerns into design solutions.

This research and my interaction with many of these researchers has been a highlight of the last year and will be for years to come.

*Figure 56. Recreational Area at Galveston Bay shore. (Photo Courtesy Helena Van Boxelaere)*

Samuel D. Brody

# THE NEED FOR PROTECTION BASED FLOOD MITIGATION STRATEGIES IN THE HOUSTON GALVESTON BAY REGION

## REFLECTION

*Dr. S.D. Brody is a professor at Texas A&M University; Department of Marine Sciences at Galveston, Department of Landscape Architecture & Urban Planning at College Station, George P. Mitchell '40 Chair in Sustainable Coasts, Director of the Center for Texas Beaches and Shores.*

Since Hurricane Ike in 2008, Texas A&M University at Galveston has participated in numerous Dutch-U.S. exchanges between students, faculty, and other flood researchers. What began as information gathering and in-depth discussions has evolved into a more formalized flood risk reduction program aimed at applying Dutch concepts to mitigate flood losses in the Houston-Galveston Bay Region (HGBR). These collaborations have sparked new ideas, designs, and strategies for flood mitigation. However, while we all contemplate how Dutch practices can be applied to reduce risk and associated flood impacts throughout the HGBR, one major difference in the overall policy approach in the two countries has become glaringly obvious: current U.S. policy is rooted in a recovery-based approach whereas the Dutch have systematically pursued a protection-based approach to flood risk reduction. Until decision makers in the U.S. and HGBR embrace a more proactive policy framework that seeks to protect communities from flood impacts in advance, many of the Dutch ideas laid out in this book will be difficult to implement.

One of the primary hurdles to changing US flood policy, is subsidized flood insurance. With the adoption of the National Flood Insurance Program (NFIP) in 1968, the US formally embraced a recovery-based approach to flood mitigation for both fresh and saltwater inundation events. This program was thought to be the most effective mechanism to provide the fiscal means to react and recover from an inundation event. The NFIP has grown tremendously and now offers federally-subsidized insurance to residents living within 24,700 participating communities. At the end of 2013, the NFIP had approximately 5.48 million flood insurance policies in force covering over $1.28 trillion (1.15 trillion euro) in assets.

As the cornerstone of flood mitigation in the U.S., the NFIP creates an expectation from the federal down to the household level that residential properties will flood, and that owners will incur damage, and need constant financial assistance to recover from their losses. This is a self-defeating strategy that has ultimately led to several unintended and undesirable consequences, including:



1. Subsidized insurance has made it more affordable to purchase a home in a flood zone and has increased overall household exposure to flood risk over the long term. Artificially-low insurance rates create an often-termed 'perverse incentive' to locate in risky areas because even if a home is flooded the resident will receive financial recovery assistance.
2. The NFIP has encouraged sprawling development patterns causing adverse environmental impacts in sensitive coastal areas. Subsidized insurance has enabled builders and homeowners to more affordably develop in flood-prone areas outside of traditional urban cores that have historically been left undeveloped.
3. Sprawling development in low-lying areas can change the spatial extent of floodplain boundaries faster than they can be officially mapped, thus putting downstream communities at greater risk. Older structures that have never flooded before or are outside of the 100-year floodplain boundary are increasingly reporting inundation and associated property damage.
4. The NFIP forces homeowners and communities into a constant repetitive loss and disaster-recovery cycle. Once a structure is flooded, insurance payouts require the owner to repair or rebuild in the same way (unless there is a local regulation that mandates structural change).
5. Repetitive and one-time insurance payments from the NFIP to homeowners have consistently exceeded the income generated from premiums; the NFIP has borrowed approximately $24 billion from the Federal Treasury to cover its deficit.

By contrast, a protection-based approach to flood mitigation, such as that employed in the Netherlands, focuses on avoiding losses ahead of a disaster event. Damage to property or other adverse impacts are considered to be failures of the system rather than expected consequences. Structural and non-structural flood mitigation techniques are implemented to eliminate (or minimize) risk of flooding, as well as incorporate contingencies if a disaster were to occur. Such an approach favors both systems-based structural interventions and land use planning techniques that seek to remove structures from or avoid building in areas most at risk.

Many Dutch-style strategies are put forth by the authors of this book. In particular, multifunctional flood defenses provide opportunities to protect communities from storm surge-based flooding while at the same time maintain and even enhance natural coastal systems. Working with natural functions and taking a systems approach to mitigation are cornerstone Dutch concepts that, if applied, could significantly reduce future flood losses across the HGBR. For example, the proposed 'Ike Dike', a storm surge barrier along the coast, would consist of the present Galveston seawall, sand covered revetments and extensions along the beaches of west Galveston Island and the Bolivar Peninsula, a small surge gate at San Luis Pass and a major gate system at Bolivar Roads. This coastal spine is designed to keep hurricane-induced storm surge out of Galveston Bay, but also provide recreational opportunities and restore dune systems along the coast.

*Figure 57. Rebuilding homes after Ike. (Photo Courtesy Jocelyn Augustino, FEMA)*

The authors of this book also note that vertical and horizontal avoidance strategies can also reduce flood risk, particularly when they are implemented through local development regulatory frameworks. For example, policies that focus new development away from flood-prone areas, such as clustering, density bonuses, transfer of development rights, and strategic placement of public infrastructure, can help protect future structures from damaging flood events. Spatially-targeted development strategies that set back from or create a buffer around areas most at risk to flooding tend to be most effective. By avoiding critical flood-prone areas, development and the associated placement of impervious surfaces can proceed without unduly compromising hydrologic functions. In particular, protecting naturally-occurring wetlands can lead to significant reductions in flood impacts, especially for precipitation-based events.

While the debate and study of multifunctional, protection-based flood strategies has begun, no concerted national policy exists with this focus, and local decision makers are constantly in competition with the insurance-based model. For example, local avoidance strategies and up-front investments to eliminate risk are contradicted by the availability of subsidized insurance and the assurance of rebuilding after a storm event. While insurance premiums are increasing and will eventually reach a more actuarial rate, the system itself needs to be fundamentally altered to embrace the concepts presented throughout this book. In the future, the system should include a more protective approach to flood risk reduction that focuses on eliminating the threat at the outset and integrating contingencies if flood damage were to occur. This shift in overall policy does not accept failure and places an emphasis on protecting residents ahead of a flood event. Above all, a protection-based approach is more in line with the idea of developing flood resilient communities over the long term.

Jill H. Slinger

# MULTIFUNCTIONAL FLOOD RISK MANAGEMENT

## REFLECTION

*Dr. ir. J.H. Slinger is an associate professor at Delft University of Technology at both Faculty of Technology, Policy & Management and Faculty of Civil Engineering & Geosciences; and a (visiting) professor at Rhodes University, Grahamstown, South Africa.*

The Houston Galveston Bay Region (HGBR) houses the largest petrochemical export harbor of the United States, is home to a diverse and ever increasing populace, and supports a thriving recreational industry. Despite a substantial reduction in freshwater flow and associated sediment transport into the bay over time, this Gulf Coast estuary supports a bio-geographically significant ecosystem characterized by extensive salt marshes, vast nursery areas for fish and invertebrate species, and habitats for rare bird species (see Van Loon-Steensma, p. 76). Although different views are held on balancing economic prosperity and environmental health in the Bay area (see Cunningham et al., p. 58), following the advent of Hurricane Ike in 2008 there is universal acknowledgement that hurricanes,

> 'the shadowy tempest that sweeps through space,
> a whirling ocean that fills the wall
> of the crystal heaven, and buries all'
> (William Cullen Bryant, 1854),

pose a threat to the future of the Bay area communities.

But, how do you move from acknowledging the threat (see Sebastian, p. 69) to developing workable decisions on flood risk management? Well, you move beyond the idea of a single solution, and embrace the concept of multilevel, multifunctional solutions. These are solutions that vary in spatial location and scale, that vary over time, and that work at different levels of aggregation for different groups of people. Moving to this kind of solutions is a complex task that requires the long term engagement of scientists, engineers, environmentalists and civil society in knowledge transfers to decision makers (Slinger et al., 2005).

This kind of transition is visible in the Netherlands, where we moved from conceptualizing flood defense as a single line of strong dikes and a closed coastline, to a more flexible coastal spine that explicitly includes nourished dune fields and an open storm surge barrier - the Eastern Scheldt - to try and accommodate the needs of nature as well as people. Today, the Netherlands has multiple layers of defense, and mega-, multi-year sand nourishments are used in 'Building with Nature' to protect the coast and manage flood risk. However, it must be emphasized that each of these solutions is embedded in governance arrangements in which engineers, environmentalists, and decision makers cooperatively undertake the task of flood risk management on behalf of Dutch citizens. Just as specific engineering solutions are not directly transferrable from one physical and biological environment to another, neither are the associated governance arrangements. To ensure that flood risk management solutions are effective, they must be embedded within the historical, cultural, physical and biological environment, as well as the existing governance context (see Hogendoorn & Brand, p. 63).

During my visit to Texas in October 2014, I was struck by the fiercely independent spirit of the people whom I met. Despite the diversity of their views regarding flood risk management in the immediate future, many common values were held, among them the desire to find a good Texan solution that does not include increased dependence on the national government, a strong and deep commitment to their communities and the Bay, pride in the pre-eminence of Houston as an export harbor, pride in the resilience of Galveston and the Houston area following hurricanes and river flooding in the past, and a strong desire to preserve their way of life, and the beauty and diversity of the environment. The central problem is determining appropriate solutions that conform to these underlying values. In the CIGAS workshop (see Cunningham et al., p. 58), the shared values of the diverse set of participants became clear, as did the option of aiming for benefit sharing or value-based solutions. The 'Building with Nature' concept - one of a plethora of similar sounding terms (see Kothuis, p. 72) - which involves using natural materials and processes to enhance the efficacy of engineering designs for flood defense, and preserving or restoring natural processes, was subsequently welcomed as a potential means of achieving such benefit-sharing. Further research on how this concept can be applied to flood risk management in the Houston Galveston Bay Region, will be undertaken jointly by Dutch and Texan scientists and engineers, providing a fruitful ground for collaborative learning in the future.

On a more personal note, I learnt many things through this project:
- Respect for a different way of being, a strong community-based independence that looks for solutions that fit the Texan context;
- To enjoy and value the beauty of the extensive salt marshes and beach systems of the HGBR;



*Figure 58.
Galveston Island coastal erosion.
(Photo Courtesy Helena Van Boxelaere)*

- That the environment-safety decision-making dilemma for flood prone coastal areas is universal;
- That scientists have an important role to play as brokers, and that their committed involvement over the long term is important in achieving sustainable solutions; and
- That scientific collaboration with counterparts at Rice University, Texas A&M Galveston and the University of Texas, Austin, is inspiring.

As a fellow scientist and nature-lover, I wish to thank Jim Blackburn in particular for his example in this collaboration. I thank him for his humility in first daring to share his deep concerns about the impacts of proposed flood defense measures on the bay ecosystem, then for making arrangements to involve Scott Cunningham, Baukje Kothuis and me, and for generously introducing us to so many colleagues, friends, and bay residents, some supporting and others opposing his personal views, and then stepping back to allow a dynamic of engagement to happen (see Kothuis et al., 2014).

In conclusion, I would urge all involved in decision making on flood risk management in the HGBR to seek to achieve a 'safe', ecologically and economically sound future through balanced benefit-sharing that reaches down into each of the communities in the Bay region.

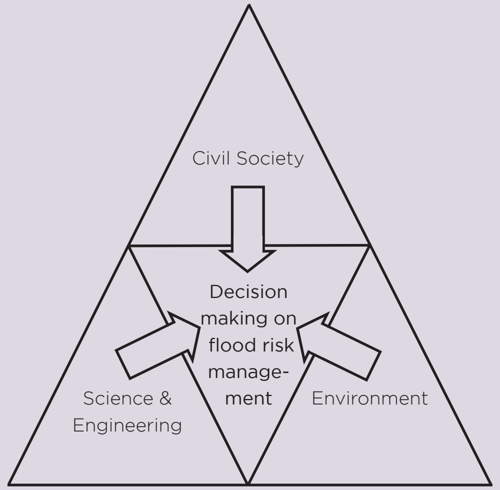
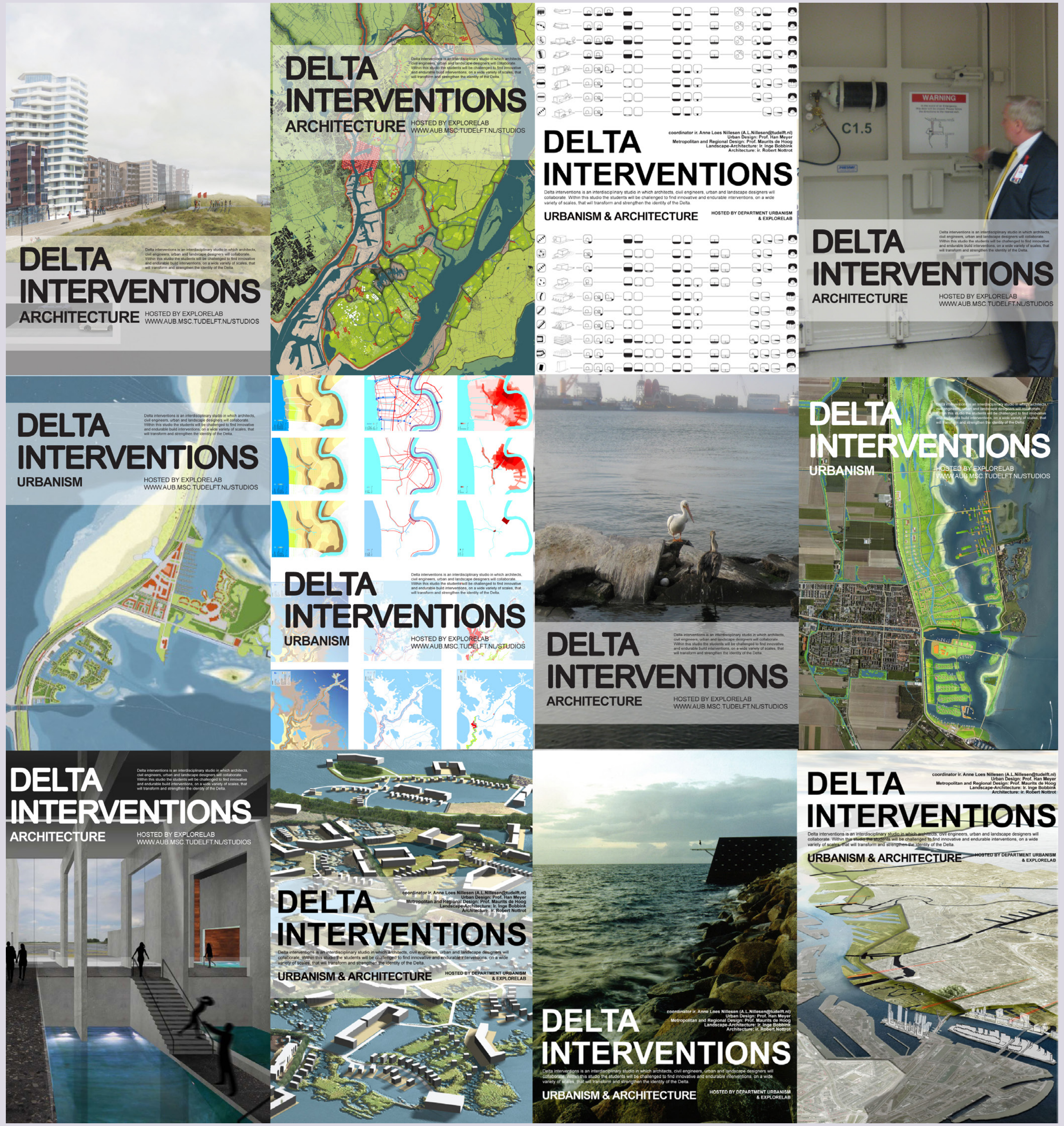



*Figure 59.
Decision making on flood risk management is underpinned by balanced, long-term engagement of civil society, environmentalists, scientists, and engineers; allowing knowledge from each source to inform decisions.
(Slinger, 2015)*

# THREE | **DELTA INTERVENTIONS STUDIO**






Anne Loes Nillesen

# THE DELTA INTERVENTIONS STUDIO

## INTRODUCTION

*Ir. A.L. Nillesen is a doctoral candidate at Delft University of Technology, Faculty of Architecture & the Built Environment; and coördinator of the TU Delft A&BE Delta Interventions Studio, an interdisciplinary MSc graduation studio focussing on water related issues.*

*Participating research teachers TU Delft DI Studio 2015:*

*Faculty of Architecture & Built Environment:*
*Prof. dr. ir. V.J. Meyer*
*Ir. A.L. Nillesen*
*Prof. ir. F. Palmboom*
*Dr. ir. E. Gramsbergen*
*Ir. K.P.M. Aalbers*

*Faculty of Civil Engineering & Geosciences:*
*Prof. dr. ir. S.N. Jonkman*
*Ir. A. van der Toorn*
*Ir. M. Voorendt*

*Figure 60.*
*Delta Interventions MSc Studio leaflet.*
*(Courtesy Anne Loes Nillesen)*

Delta Interventions is an interdisciplinary MSc graduation studio that deals with the development of delta areas worldwide. The studio was founded in 2010 as part of the Delta Urbanism research group of the Faculty of Architecture & the Built Environment at the TU Delft.

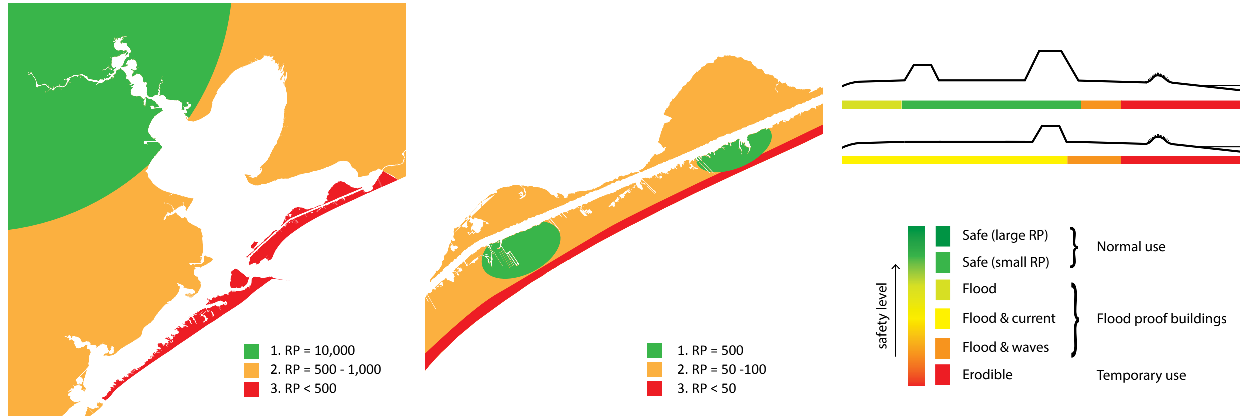
Deltas offer great opportunities for settlement and trading, but there is always the threat of water, which is increasing as a result of climate change. The studio focus lies on research and design projects that reduce flood risk and improve water management, while creating a new, strong and attractive urban delta landscape. The central question of the studio is how water management and spatial quality can be combined in innovative designs and strategies.

The studio initially focused on the Dutch Delta and later extended its vision to international deltas in Brazil, the United States and India. The 2015 studio included both the Houston-Galveston Bay Region and the Dutch IJsselmeer Region. The projects within these deltas can vary from large-scale concepts and strategies to small-scale designs or bottom-up interventions: from buildings, constructions, public works, outdoor spaces, to urban areas, landscapes and regions.

Delta landscapes display natural dynamics and ecological richness and are attractive places for settlement and for industry, trade and tourism. Their dynamics and complexity are challenging and require an interdisciplinary approach for designers of cities, infrastructures, policies and landscapes. Delta Interventions is therefore an interdisciplinary studio in which architects, urban designers, civil engineers, landscape architects and policy students work on a variety of individual projects.

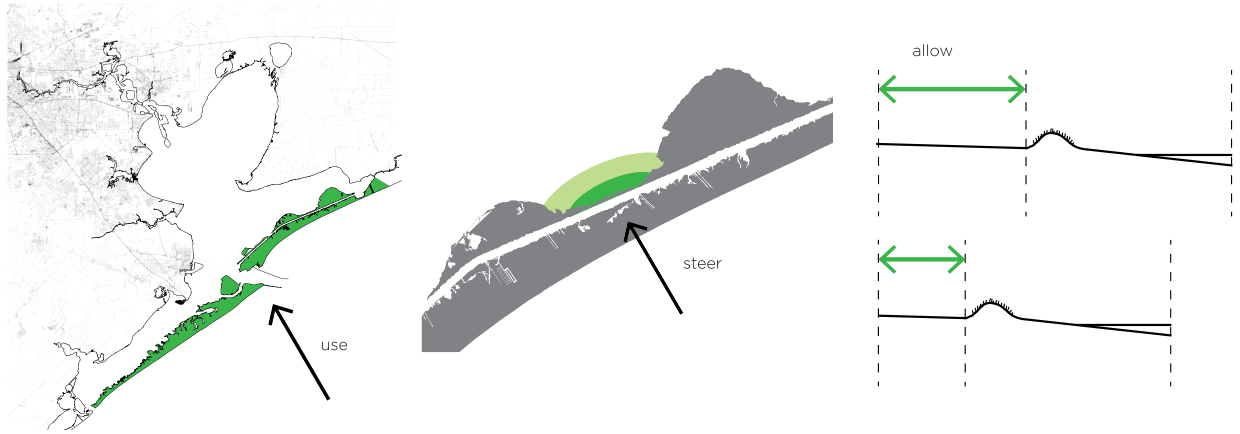
The core of the 2015 studio consists of architecture, urbanism and landscape design students from the Faculty of Architecture & the Built Environment, joined by two students from Civil Engineering and two from Technology, Policy & Management. In their graduation year, the students work on a joint research project that enables them to explore and understand the complex nature of the delta, followed by an individual design project in which they develop an intervention of their own choice into a concrete design proposal. This chapter presents a broad selection of these individual student projects.

Figure 61.
*Selective in space: A layered protection with strategic safety levels. RP = Return Period (Van den Ende, 2015)*



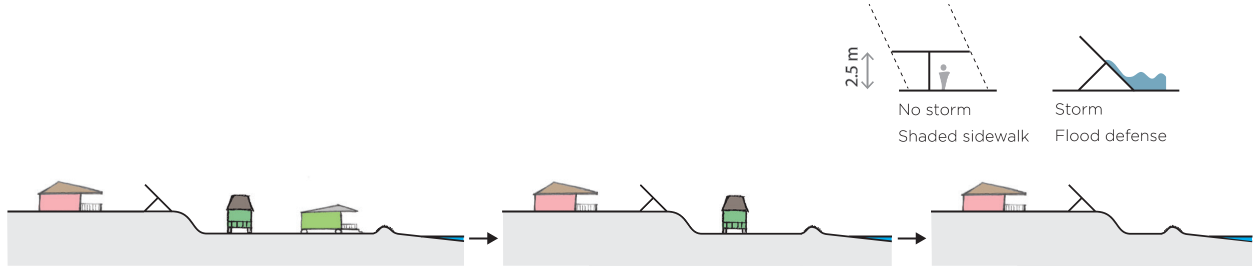

Galveston Bay | Bolivar Peninsula | Cross-section

*Figure 62. Change over time: Dynamic coastal protection. (Van den Ende 2015)*



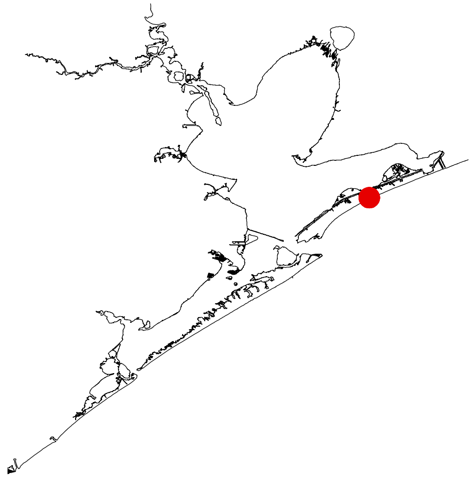

Galveston Bay | Bolivar Peninsula | Cross-section

*Figure 63. Design over time (Van den Ende 2015)*




Inge van den Ende

# A CHANGING DESIGN FOR BOLIVAR PENSINSULA



*Inge van den Ende is a MSc-student of Coastal Engineering at the Faculty of Civil Engineering & Geosciences of Delft University of Technology.*

*Tutors:*
*Ir. K.P.M. Aalbers, TU Delft*
*Ir. A. van der Toorn, TU Delft*

As the world increasingly looks to Dutch dikes as a model for coastal protection, the Dutch protection strategy itself is changing. First, it differentiates between areas by adapting the safety level to potential damage. Second, the focus has shifted from pure flood prevention to a combination of prevention and consequence-reducing measures. This new Multi-layered Safety (MLS) approach recognizes three layers that influence safety and flood damage:

1. Flood prevention,
2. Spatial planning (land use controls and building codes), and
3. Crisis management.

At the same time, plans for flood prevention for Houston and New York show that the US is moving from crisis management and spatial planning (in the form of building codes) to flood prevention. The current absence of flood prevention in the Houston-Galveston Bay Region offers an opportunity to design a form of flood protection that combines all layers of MLS equally, and to study what landscape architecture can add to the MLS approach.

As coastal processes are very dynamic, a coastal protection design will also change over time. A constantly relocating coastline, for example, results in a changing cross-shore profile. This kind of constant change is also addressed by landscape architecture, which considers changes over time due to growing vegetation, varying weather conditions and changes in land use. Hence a landscape design includes four dimensions: three spatial ones and time. The dimension of time is taken into account by planning and designing different time steps.

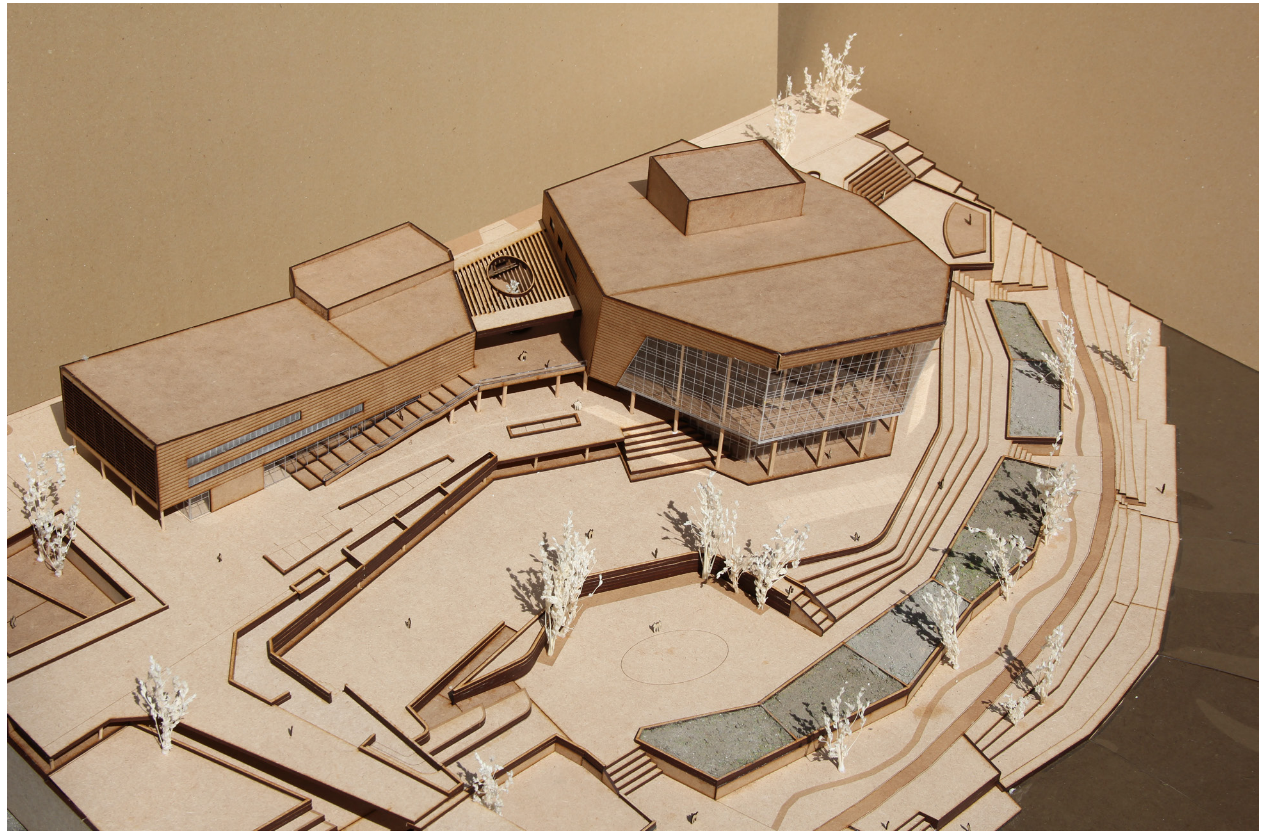
This approach has been applied to Bolivar Peninsula. By integrating landscape architecture and coastal protection design, we are able to create a design that allows, plans and uses the changes that occur over time. Designing different time steps into the design allows us to plan for, and use, the coastal changes. For flood risk reduction this means that space has to be reserved for future erosion, overwash sediment can be steered to a preferred location, and natural protection can be deployed. Flexible land use has to be enabled by applying, and enforcing, appropriate land use controls.

In the design for Bolivar Peninsula, an overtopping dike is combined with safe zones. The overtopping dike strengthens the natural protection the barrier islands, Galveston Island and Bolivar Peninsula, provide the Houston Galveston Bay Region. Partly raising the first layer of defense which these barrier islands provide against storm surge ensures that less water will enter the bay during a hurricane. The dike is combined with local 'safe zones', namely two low mounds with additional protection on the front. The tops of the mounds endure relatively low hydrodynamic loads, which allows these spots to be used for a variety of uses.

The combination of an overtopping dike and safe zones responds to coastline changes by steering overwash to the thinnest locations of the peninsula and allowing space for future erosion. To optimize this design, building codes will have to be adjusted to the different conditions that will be experienced at different parts of the structure: at permitting only expendable structures in the erodible area, wave proof or expendable structures in front of the mound, and current-resistant structures behind the overtopping dike.

Figure 64.
*Design of the cultural building complex on Buffalo Bayou. (Qian Cao 2015)*

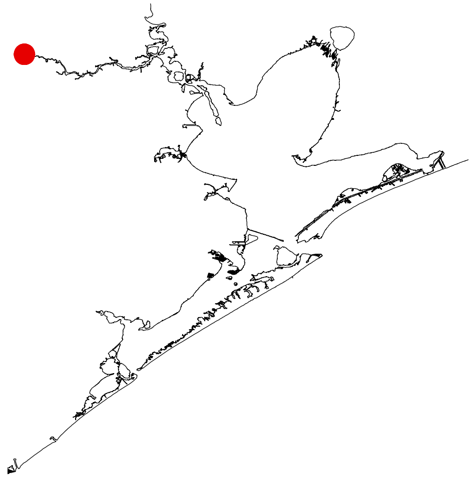
Figure 65.
*Model of the cultural building complex on Buffalo Bayou. (Qian Cao 2015)*





Qian Cao

# A CULTURAL BUILDING COMPLEX IN DOWNTOWN HOUSTON



Downtown Houston is the central business district of Houston. Buffalo Bayou, the body of water that gave birth to the Houston metropolis, runs through the area in the north. How can we take advantage of Buffalo Bayou to create a new attraction in Downtown Houston so it becomes more lively? What architectural programs can activate this site, and how can Buffalo Bayou contribute to this?

The strategic site for a new design is the current U.S post office located on the north bank of Buffalo Bayou. The building is owned by the United States Postal Service and houses a post office distribution facility, and an office building, both of which have been deemed obsolete to USPS operation.

Isolated by massive highways and the bayou, the site is underused and lacks proper connection to central Downtown. As a result of multiple bridges spanning the river channel, the waterfront of Buffalo Bayou has lost its role as a green public space. From an urban perspective, this site is a leftover space. Moreover, it faces flood risk resulting from high water levels caused by intensive rainfall. For example, in 2001, tropical storm Allison hit the White Oak and Buffalo Bayou area, resulting in the inundation of Downtown.

Since 2000, several studies have been conducted addressing downtown development, leading to several design plans. Among these, the Downtown Houston Development Framework defines an overall long-term vision for downtown in 2025. Though completed in 2004, the overall vision and recommendations are still valuable. According to the Development Framework, the US post office site has the potential to provide a mixed-use extension of the Theater District along the bayou.

The project proposed here seeks to re-develop the U.S post office site as part of a new master plan with residential buildings, a cultural building complex, and a cultural park along the Buffalo Bayou, which we hope can be a cultural and social catalyst for the entire Downtown Houston area.

To achieve this, Franklin Street and two highways connecting to Louisiana Street and Smith Street have to be removed. A new road network will be established by building a new west-east road on the original railway site, extending Bagby Street and transforming Congress Avenue into a pedestrian bridge. The cultural building complex will include an exhibition hall, an IMAX theater, and a performing arts center. The connection between the site and central downtown will be improved by providing cultural venues and ameliorating Buffalo Bayou.

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*Tutor:*
*Prof. dr.ir. F. Palmboom, TU Delft*

*Figure 66.*
*Layer-system approach:*
*Situation now (left), strategy (right).*
*(Brakel 2015)*

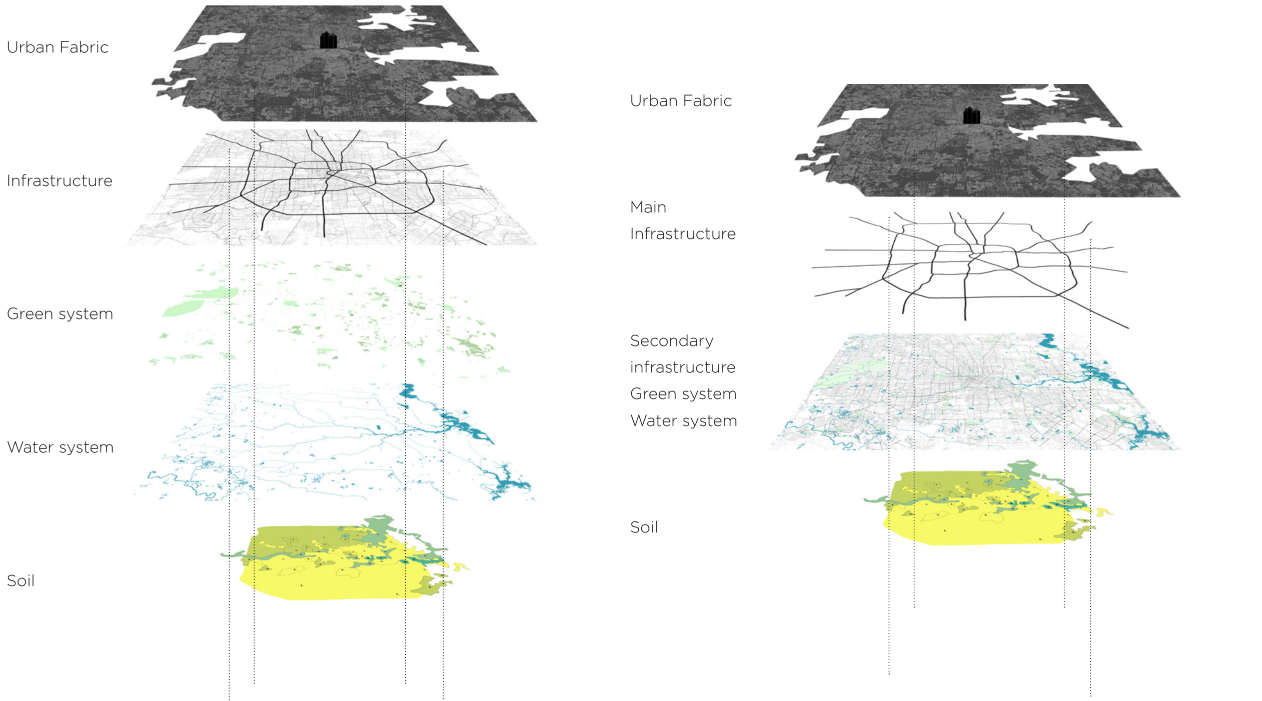
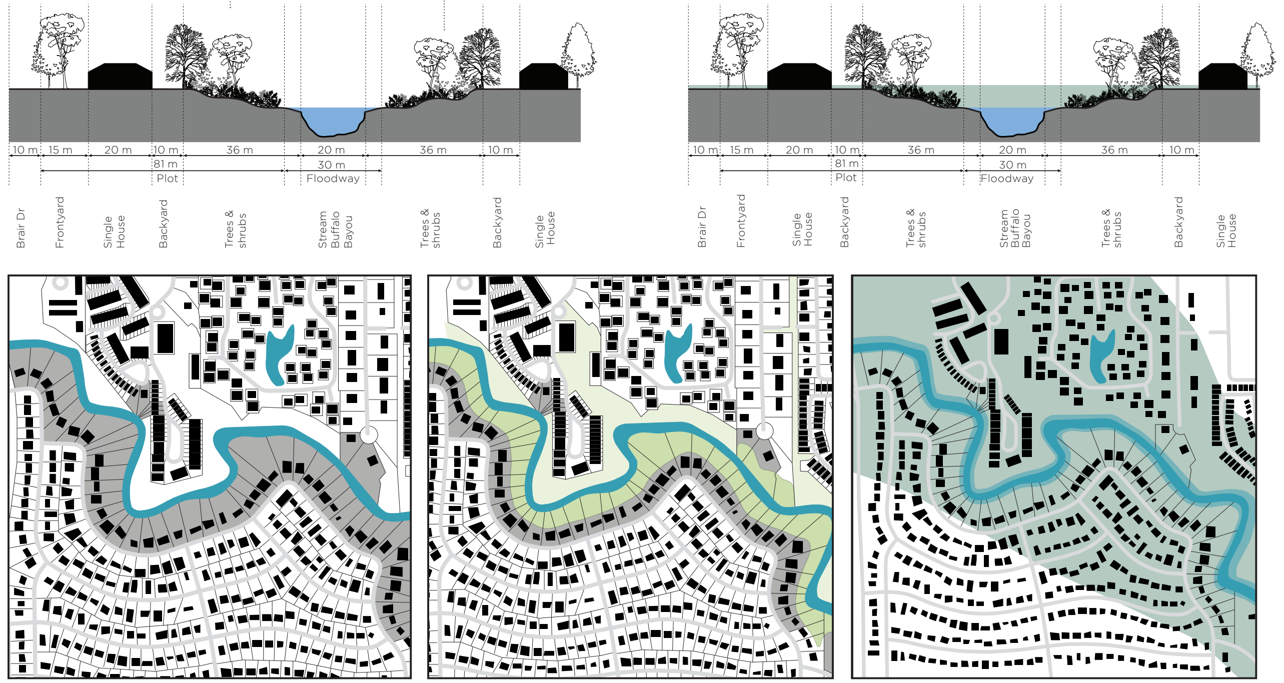



*Figure 67.*
*Focus-area Buffalo Bayou.*
*'No Man's land' can be 'Everyone's land'.*
*(Brakel 2015)*




Plots around Buffalo Bayou

Open space & potential greenway space

With 500 year floodplain



Sarah Brakel

# THE URBAN ECOLOGY OF DOWNTOWN HOUSTON

Houston is one of the fastest growing cities in the United States, and is already one of the five biggest metropolitan areas in the country. Due to this fast growth, a lot of land has been urbanized, which has led to a wide range of problems for the water network and ecosystems. Houston's climate is classified as humid subtropical, and hurricanes are an ever-present threat during the fall season. The climate and the fast growth of the metropolitan area combine to produce a higher flood risk around Galveston Bay, as well as inland along the rivers and canals.

A key site in Downtown Houston is Buffalo Bayou. This slow-moving river is the main waterway flowing from the east to the west through Houston, connecting Barker Reservoir in the east to Galveston Bay via the Ship Channel, which eventually connects to the Gulf of Mexico. Buffalo Bayou is fed by natural springs as well as the surface runoff from the surrounding urban fabric.

Because of its central location, Buffalo Bayou is a strategic site for intervention. Reducing flood risk can be done by absorbing rainfall and storm surge flooding into in the urban fabric around the Bayou. Soft borders from Buffalo Bayou should be extended into the urban fabric and vice versa to strengthen the interaction and the features of the 'Bayou City', but also to reduce flood risk while simultaneously restoring ecosystems. This will create a more sustainable and healthier environment for both humans and wildlife around Buffalo Bayou.

The shape of Buffalo Bayou forms the inner part of the city's grid, and this played a decisive role in the urbanization process of Houston. Buffalo Bayou lies in badly permeable soil, has a flat typography and has extensive natural floodplains. The urbanization of the watershed resulted in a large part of Houston's urban fabric being located in the natural floodplains. Due to the rapid urbanization since the mid twentieth century, changes were made in the watershed, which increased the level and intensity of flood events.

Next to this, the high percentage of paved surfaces in urban areas causes them to absorb and retain more heat. Increasing temperatures and the growth of 'heat islands' create problems for wildlife and their ecosystems. The Houston metropolitan area includes acres of diverse habitats, but land and water development means that these ecological areas are becoming increasingly threatened and fractured.

This research by design project aims to develop strategies that could be the trigger for a transformation of the wider area around the Bayou in the future. The Bayou itself is the leading feature in the applied layer-system approach, which aims at combining layers and systems to create an urban area that provides more ecological continuity and is less susceptible to flooding.

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*Tutor:*
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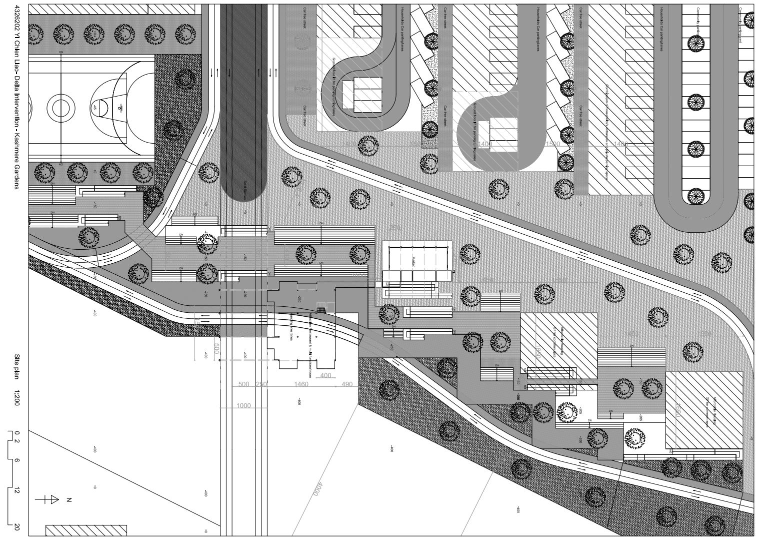


*Figure 68.*
*A site plan for*
*Kashmere Gardens.*
*(Yi Chien Liao 2015).*

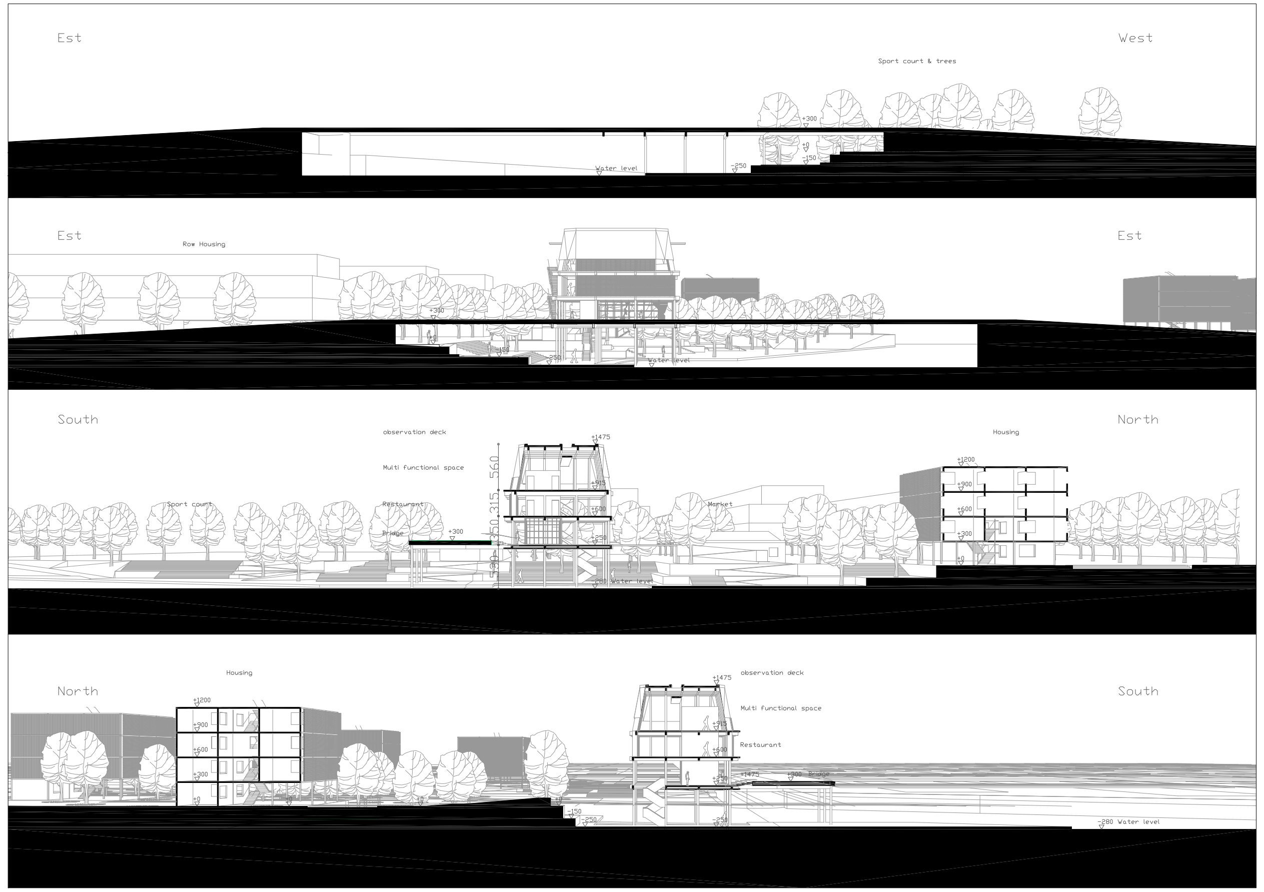



*Figure 69.*
*A section plan for*
*Kashmere Gardens*
*(Yi Chien Liao 2015).*



Yi Chien Liao

# FLOOD RESILIENT HOUSING IN HUNTING BAYOU

Houston is a delta city that includes several watersheds. The flat landscape, suitable for the construction of a sprawling city, brings along the danger of flooding as well. Storm surge and heavy rainfall result in regular flooding. Fast and efficient drainage via concrete channelization of natural bayous exacerbates the problem; there is little capacity for water storage and the reduced permeability of hard structures within the flood plains further increases flood risk.

In the lowest parts of the city, for instance in Kashmere Gardens, whole neighborhoods are threatened. Additionally, many bayous are lined with concrete, which limits people's access to the water. The plots between housing areas and bayous have become neglected, as the connection between human activity and the water has been lost. Such open spaces are badly maintained and lower the quality of the living environment. This double problem is especially noticeable in a low-lying and low-income neighborhood like Kashmere Gardens.

Isolated between industrial zones, highways, and railroads, Kashmere Gardens is a residential area for low-income residents located in a floodplain with 100-year flood risk. Amenities in the neighborhood are unorganized and poorly connected. Apart from the lack of connection with the water, Kashmere Gardens has a low quality housing stock. Inhabitants live in constant fear of being forced to move because of flood control interventions, or losing their property.

Problematic areas within the flood plain, especially along water streams in urban areas, can be redeveloped to re-emphasize the relation between the water and human activity. To investigate how this could be done, a typology study for restoring urban stream corridors was conducted, aiming to connect the urban fabric and the water in an ecology-friendly and flood-resilient manner. Additionally, we developed an architecture project for affordable housing along Hunting Bayou in the Kashmere Gardens neighborhood.

In the proposed project, Hunting Creek would be widened and deepened parallel to the main street in order to increase its capacity for water retention. This would also create a linear green corridor linking amenities. The relocation of houses due to widening and deepening of the creek would be compensated with new affordable and flood resilient housing along the linear waterfront park. Integrating housing with the waterfront park will improve the flood prone areas and upgrade the living quality in this neighborhood.

*Yi Chien Lao is MSc-student of Architecture at the Faculty of Architecture & the Built Environment of Delft University of Technology.*

*Tutor:*
*Dr. ir. E. van Gramsbergen, TU Delft*

*Figure 70.*
*A bird's eye perspective on downtown Houston with the proposed intensification centers in red. (Song-Ya Huang 2015)*

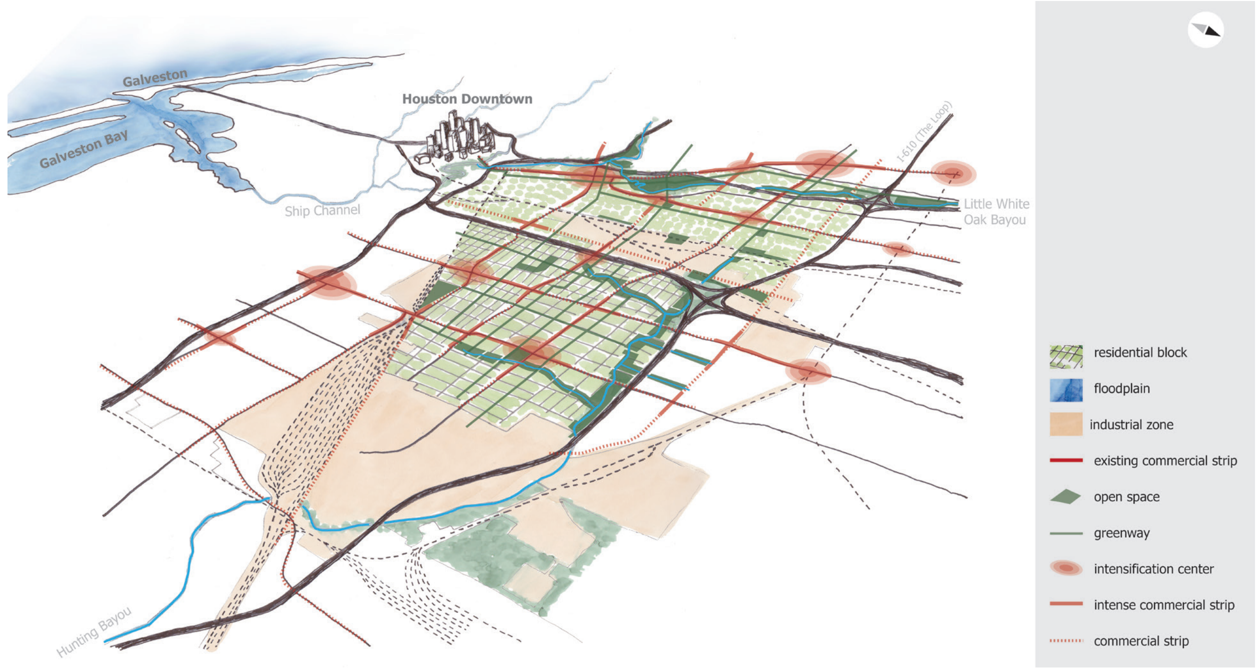



*Figure 71.*
*A bird's eye perspective with the flood plain singled out. (Song-Ya Huang 2015)*

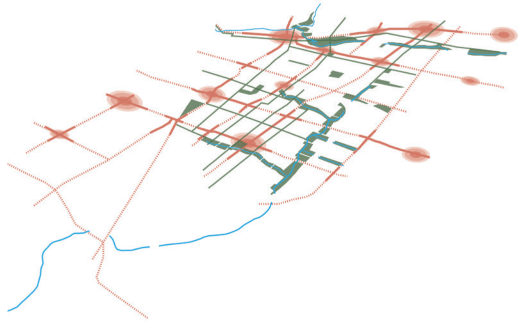


*Figure 72.*
*The intensification centers in relation to the water system. (Song-Ya Huang 2015)*

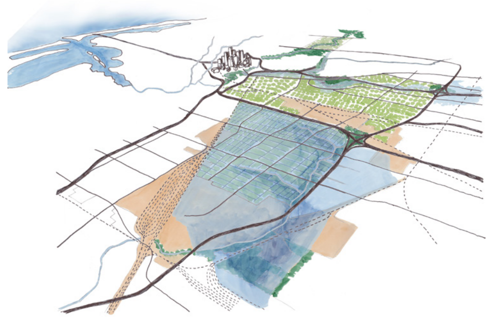
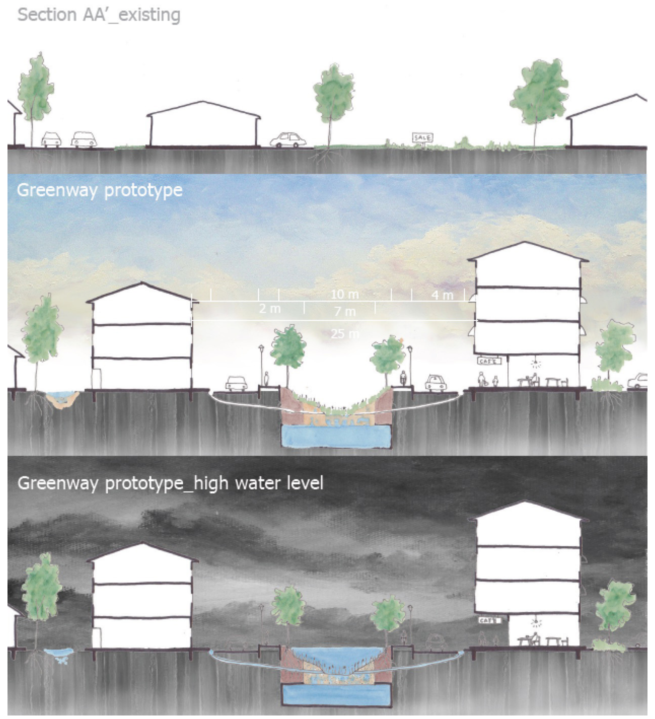


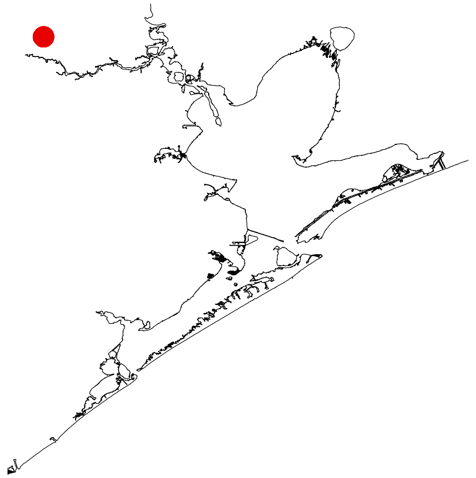
*Figure 73.*
*(far right) A prototype for the built environment of the intensification centers. (Song-Ya Huang 2015)*






Song-Ya Huang

# RECYCLING HOUSTON



*Song-Ya Huang is a MSc-student of Urbanism at Delft University of Technology, Faculty of Architecture & the Built Environment.*

*Tutor:*
*Prof. dr. ir. V.J. Meyer, TU Delft*

This project focuses on three urgent challenges facing Houston: flooding, urban sprawl and high automobile dependency. Despite the city's 4332 km (2691 mile) of drainage ditches, channels and bayous, the city still experiences regular flooding due to the combination of flat terrain and heavy rainfall. Urban sprawl and automobile dependency are closely related. First, the massive construction of highways has supported rapid expansion of suburban areas. Second, the sprawling urban structure requires continued use of the car. In order to become sustainable in the post oil era, spraw-ling urban areas will have to be transformed.

To achieve this, intensification is critical: heightening urban density should reduce both energy consumption and mitigate flooding. The livability of suburban neighborhoods will also benefit from the created synergy between improved water safety and reduced energy consumption. As flooding, urban sprawl and automobile dependency are interrelated, these challenges can only be addressed by an integrated intensification strategy that takes future trends and techniques into account.

Three questions arise when investigating how to enhance the sustainability of suburban Houston:

1. How can we intensify the suburban area by transforming the bayous and urban structure to reduce flood risk and provide alternatives for individual automobile use?
2. How can we transform suburban neighborhoods into mixed-use centers that can reinforce the quality of living, provide water storage capacity and still preserve the character of the neighborhood?
3. What are the prototypes of water interventions and urban forms that belong to the neighborhood; based on different scenarios and neighborhood characteristics?

The aim of the project is to provide an integrated strategy for intensification of the urban fabric. The project focuses on a suburban region located north of Downtown Houston, including Greater North Side, Kashmere Gardens, the Greater Fifth Ward and North East Houston. This threefold challenge facing suburban Houston - flooding, sprawl and automobile dependency - was addressed by an intensification strategy for the urban structure at the regional scale. As part of that regional strategy, interventions for three strategic hubs were developed. To conclude, we designed prototypes for both the water system and the intensified urban form.

The suburban intensification principles developed for Kashmere Gardens can be considered as representative for the entire region of Harris County.

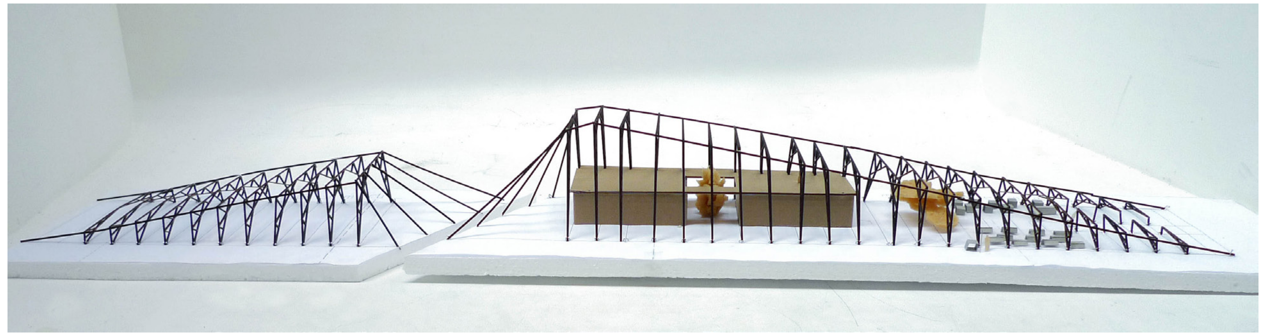


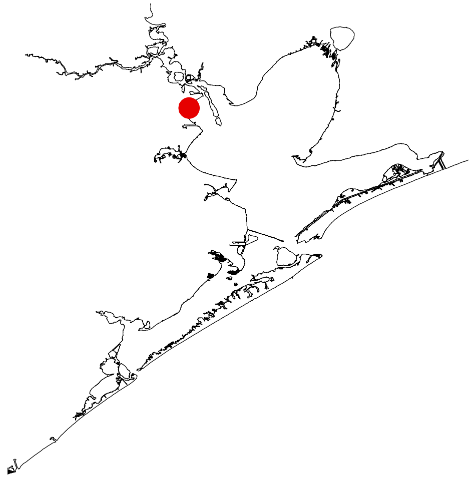
*Figure 74.*
*Model of a waterfront recreation complex for Sylvan Beach.*
*(Tsai Hsun Ho 2015)*

*Figure 75.*
*Bird's eye perspective of a waterfront recreation complex for Sylvan Beach.*
*(Tsai Hsun Ho 2015)*



Tsai Hsun Ho

# A WATERFRONT RECREATION COMPLEX FOR SYLVAN BEACH



*Tsai Hsun Ho is a MSc-student of Architecture at Delft University of Technology, Faculty of Architecture & the Built Environment.*

*Tutor:*
*Dr. ir. E.H. Gramsbergen, TU Delft*

Individual plots or industrial sites occupy most of the waterfront of West Galveston Bay, making the shore inaccessible and detracting from the Bay's natural beauty. This problem is not limited to the Houston-Galveston Bay Region. As of 2000, eighty percent of Americans were living in urban areas, and public space in many of these metropolitan areas is perceived as grossly inadequate.

One of the rare areas in the upper west side of Galveston Bay which does have public access is Sylvan Beach, located in La Porte. Until the Second World War, Sylvan Beach was a vibrant tourist attraction for Houstonians. After the war, and after the damage of several hurricanes, Sylvan Beach declined. Many people in the city of La Porte long to restore their town to its former glory as a tourist destination. At the moment, the beach itself is not very attractive to the eye and lacks connection with its direct environment.

As one of the very few public shores along the west bay, and the one closest to the city of Houston, the park is of geographical importance and has a lot of potential to serve both citizens and tourists. To achieve this, we designed a resilient building that offers recreational functions for the public such as space for fishing, bird watching, swimming and eating, plus a terminal for ferries from Houston and other parts of the bay.

The design of the recreation complex is based, first, on 3x3x3 map analysis. Overlapping maps of different categories, such as infrastructure, urban fabric, and landscape for different moments in time, permits us to study how these categories relate to each other, and see the changes through history and the development of the city. Second, we analyzed relevant architecture projects such as the beach park, water resilient architecture, wind resistant buildings and ferry terminals. Lastly, books about Sylvan Beach and La Porte provided detailed information about local development, showing the area's boom and decline. Together, these allowed us to determine an appropriate program for the site. The project responds to the lack of urban public space in the region and provides a solution that is water resilient and improves the quality of the waterfront.

The design of the waterfront recreation complex takes into account tidal fluctuations in the bay, and should withstand strong winds and a certain level of storm surge. For storm conditions, we assume that some form of coastal defense exists, reducing surge height and wave action. The complex consists of two sections, with the largest part located in the bay. A floating platform in the building follows the movements of the water.

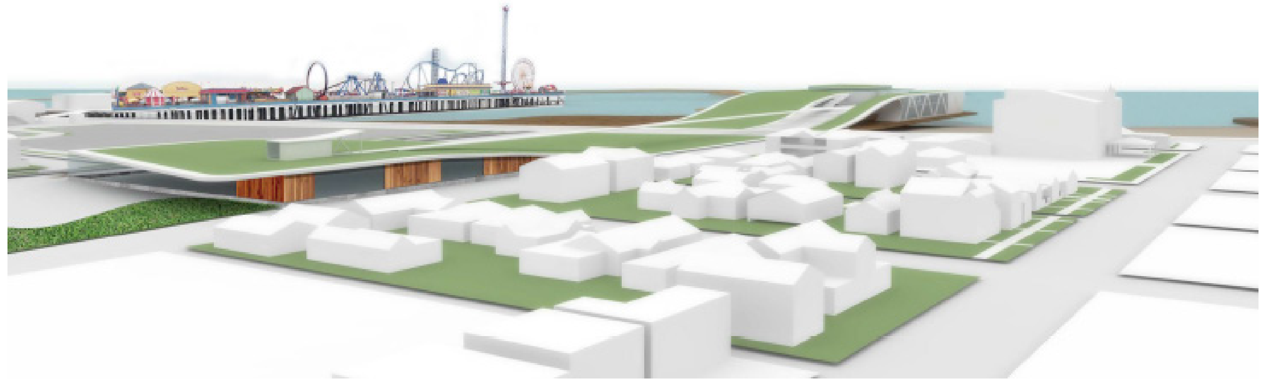


*Figure 76.*
*Bird's eye perspective of a seaward extension of Galveston at the intersection of 25th Street and the Seawall.*
*(Fangfei Liu 2015)*

*Figure 77.*
*Impression of the interior of a hurricane-resistant building within the seaward extension of Galveston.*
*(Fangfei Liu 2015)*



Fangfei Liu

# LIVE WITH THE WATER: GALVESTON GOES SEAWARD

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*Tutor:*
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Despite its sometimes sinister image, Galveston is a place with a strong local community; most people born on the island remain there for most of their lives. The barrier island has a rich history full of fascinating stories. There are two keys to the history of Galveston: urban development and protection from hurricanes.

While studying Galveston City, two boundaries catch the eye. The first one is the seawall, with the key word being linear distribution. The city has a close relation with the seawall. The seawall was built after the 1900 Galveston Hurricane. The construction process lasted for more than 30 years. Most local community activities take place along the 16 km (10 mile) seawall, which is also one of the most famous tourist attractions in Galveston. Many lines of activity are in turn arranged along the seawall: the Commercial line; Seawall Boulevard; Seawall Passage; Seawall; 'See-wall' (the world's largest and longest outdoor mural); the beach and the sea.

The second boundary is 25th Street, for which the key words are connection and balance. 25th Street is the boundary between the modern and historical parts of Galveston City. Galveston has the most intact collection of late nineteenth and early twentieth century buildings in the United States. To date 4 areas have been designated as local historic districts in the city, all on the eastern side of 25th Street. 25th Street is a north-south corridor that is both a commercial and residential street, and serves as a connection between Downtown and the Seawall. 25th Street and the Sea Wall pose two problems. First, although both ends of 25th Street have equal potential to develop, only the Downtown end fulfills its promise. Secondly, the construction of the high seawall is effective to reduce flood damages, but it brutally separates the city and the water.

The intersection of the two boundaries is a strategic site for Galveston. In fact, the site with the historical pleasure pier located at its center can be viewed as another historical district: its history can be traced back to the period between the wars, sometimes referred to as the 'Open Era', when Galveston was infamous for gambling and (illegal) alcohol. Although the majority of the buildings have been destroyed by hurricanes several times, the process of rebuilding never stops, which testifies to the value of the site.

People are attracted by water, but at the same time they are afraid of it because of the damage it may bring. Galveston could be brave and develop seaward. This is what the design proposed here, is inherently about.

The urban life of Galveston City and its tourism activities can be extended into and over the waterfront, in order to provide public space for Galvestonians to interact and tourists to enjoy their holiday. Thus recreational activities are concentrated at a specific recreational locus, instead of spreading them too thin along the trail on the seawall. At the same time, the balance along 25th Street can be recovered. The proposed project also provides different layers of water-related experience combined with different flood risk reduction strategies to meet future demands and challenges.

*Figure 78.*
*Figure 79.*
*Figure 80.*
*(this page)*
*An impression of the hurricane-resistant building from different angles.*
*(Fangfei Liu 2015)*

*Figure 81.*
*Figure 82.*
*(top opposite page)*
*The interior of the building.*
*(Fangfei Liu 2015)*

*Figure 83.*
*(bottom opposite page) The lay out of the building. The roof structure has been designed to withstand hurricane winds, while the open walls allow the natural landscape to enter the building.*
*(Fangfei Liu 2015)*

*Figure 84.*
*Bird's eye perspective on the leisure centre at Buffalo Bayou with dowtown Houston at its back.*
*(Kito Samson 2015)*

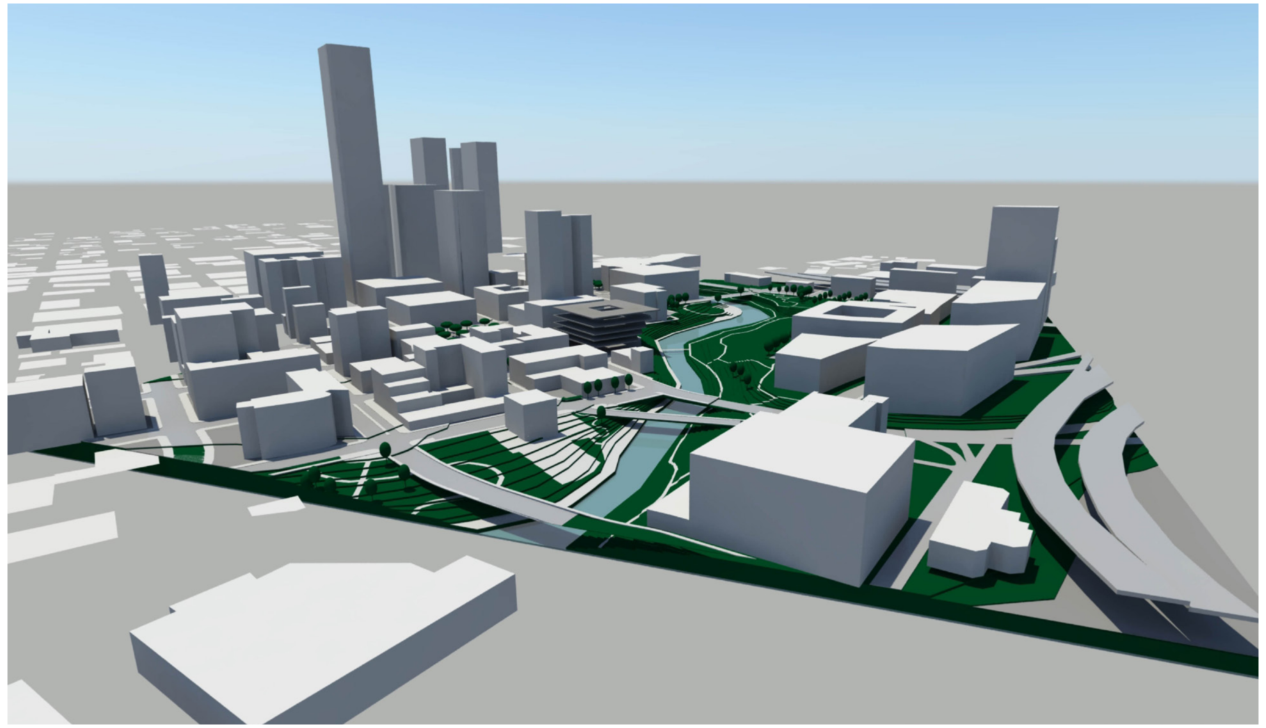
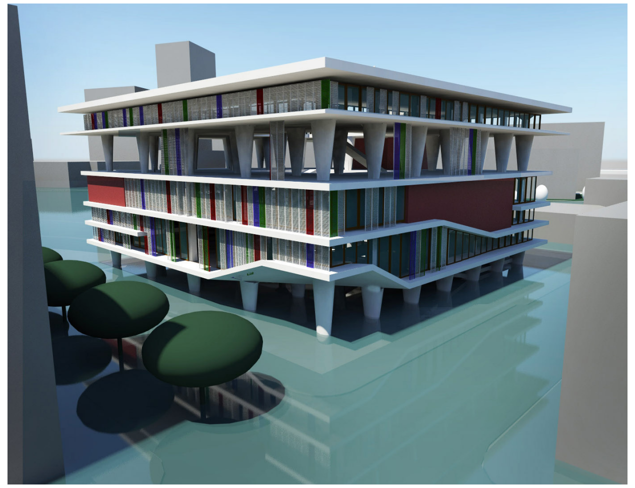


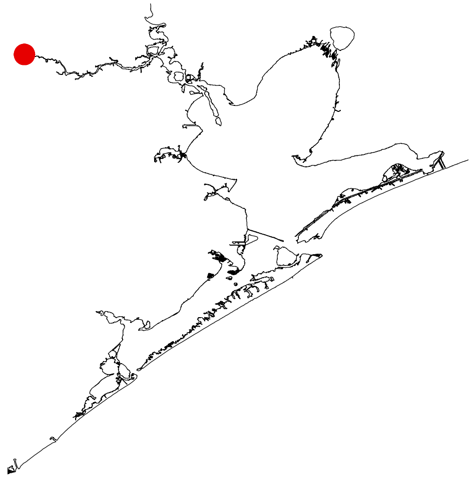
*Figure 85.*
*The leisure centre.*
*(Kito Samson 2015)*





Kito Samson

# A LEISURE CENTRE ALONG BUFFALO BAYOU



How can a common conception of the city of Houston be created through architecture? As a result of low density, car use, telecommunication, and Texas culture, no one really shares Houston. As Lerup (2011: 34) stated:

*'All of us have a unique view of the city we inhabit. But some cities are more conducive to undisturbed personal perception than others. Houston is such a city - the absence of shared space sees to this. Predominantly motorised and individualised [sic], Houston limits pedestrian and public experience to interior spaces - be it mall, arena, church or parking garage- where the city is always behind the horizon. Exterior space is dominated by the movement through it; whether parking tarmac, freeway, cloverleaf, frontage road, cul-de-sac. Houston is mine (and everybody else's), rarely to be shared, merely an extension of my driveway.'*

To promote human interaction and street life, the urban structure must have attractors and a certain level of density. In order to provide this in Downtown Houston, new buildings should replace the existing parking lots, parking garages and gas stations.

Downtown Houston is a strategic location for two reasons. First, the area is currently being revitalized. Local government is collaborating with the Kinder Foundation on a brand new development framework: the restoration of the Historical District, transformation of the waterfront along Buffalo Bayou and new tram lines. The densification of Downtown Houston will help the area to become pedestrian friendly, so people can share their city. Next to Buffalo Bayou, between the Theater District and Historical District, is a gas station. In the master plan, this place is designated to become a part of the Theater District with a cultural program.

Second, the Buffalo Bayou poses a problem to Downtown Houston because of persistent flooding. Houston lies on a moist prairie. Water cannot easily percolate through the gumbo soil. In such a setting, open pools would normally serve as evaporation basins, storing the water for several weeks. But increased asphalting and hardening of the surface hinder the environment's capacity to store this water. The water from rainfall runs directly into the bayous, leading to excessive peak discharges, after which it eventually runs into Galveston Bay. Additionally, water from the bay gets pushed up during tropical storms, raising water levels on the north side of the bay and blocking the water that needs to be discharged from the bayous. The water accumulates in the bayous until the banks overflow and flooding ensues (Lerup, 2011).

We propose a leisure center to take the place of the gas station; this would provide an attractor for Downtown Houston and complement the Theater District, providing Houstonians with a common experience. This facility has been designed bearing the location in mind. According to Harris County Flood Control District (2014), the water level on the flood plain will rise rapidly, but it will lower rapidly as well. This means the area will be flooded for a couple of hours rather than a couple of days. According to the Harris County Flood Warning System (2015), during flooding, water levels will reach 1 meter/3 ft (1 in 50 years) to 3 meters/9 ft (1 in 500 years). The new the leisure center should be able to cope with these water levels.

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Figure 86.
Bird's eye perspective on the leisure centre at Buffalo Bayou with dowtown Houston at its back.
(Kito Samson 2015)

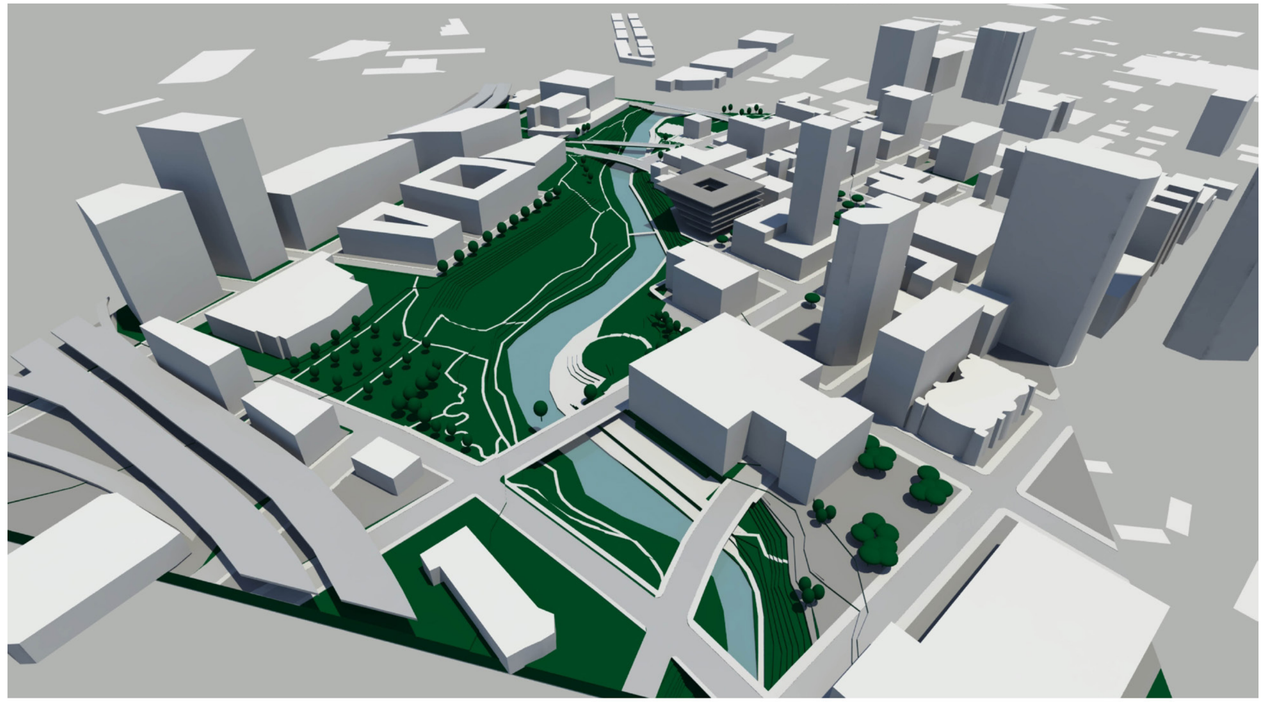


Figure 87.
The leisure centre and Buffalo Bayou during a flood event.
(Kito Samson 2015)

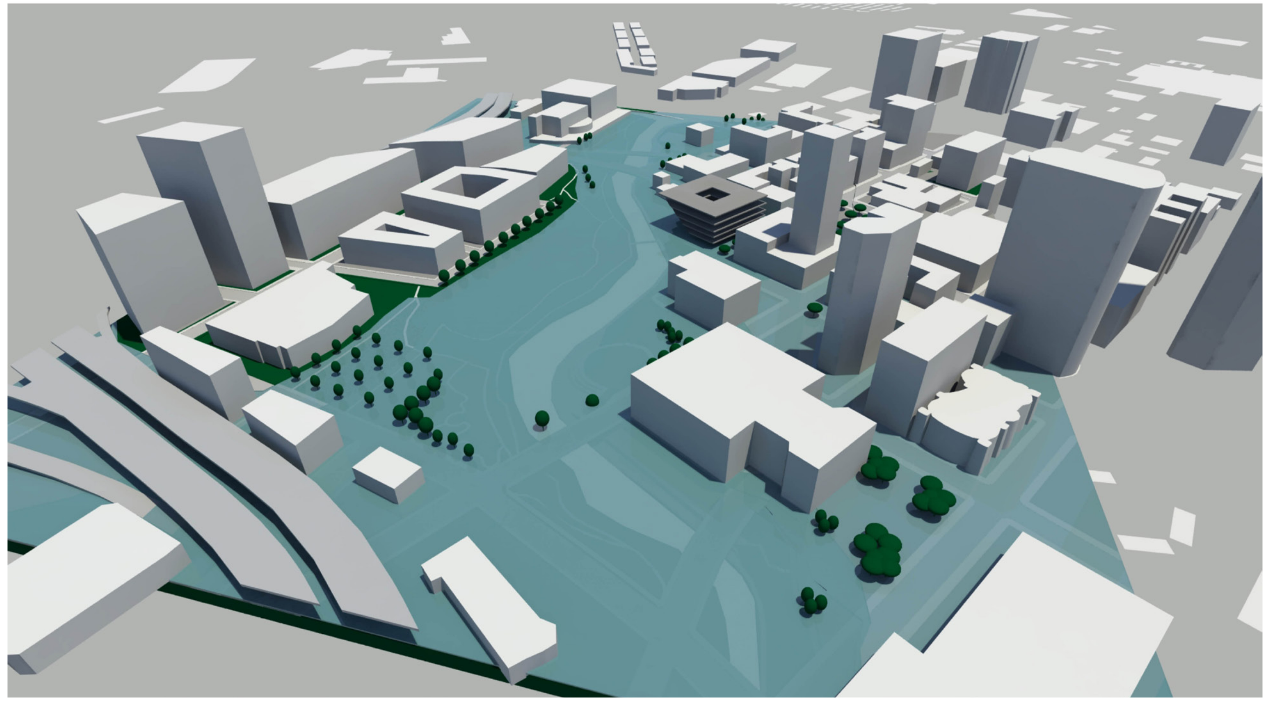


Figure 88.
(opposite page)
A model of the leisure centre at Buffalo Bayou.
(Kito Samson 2015)



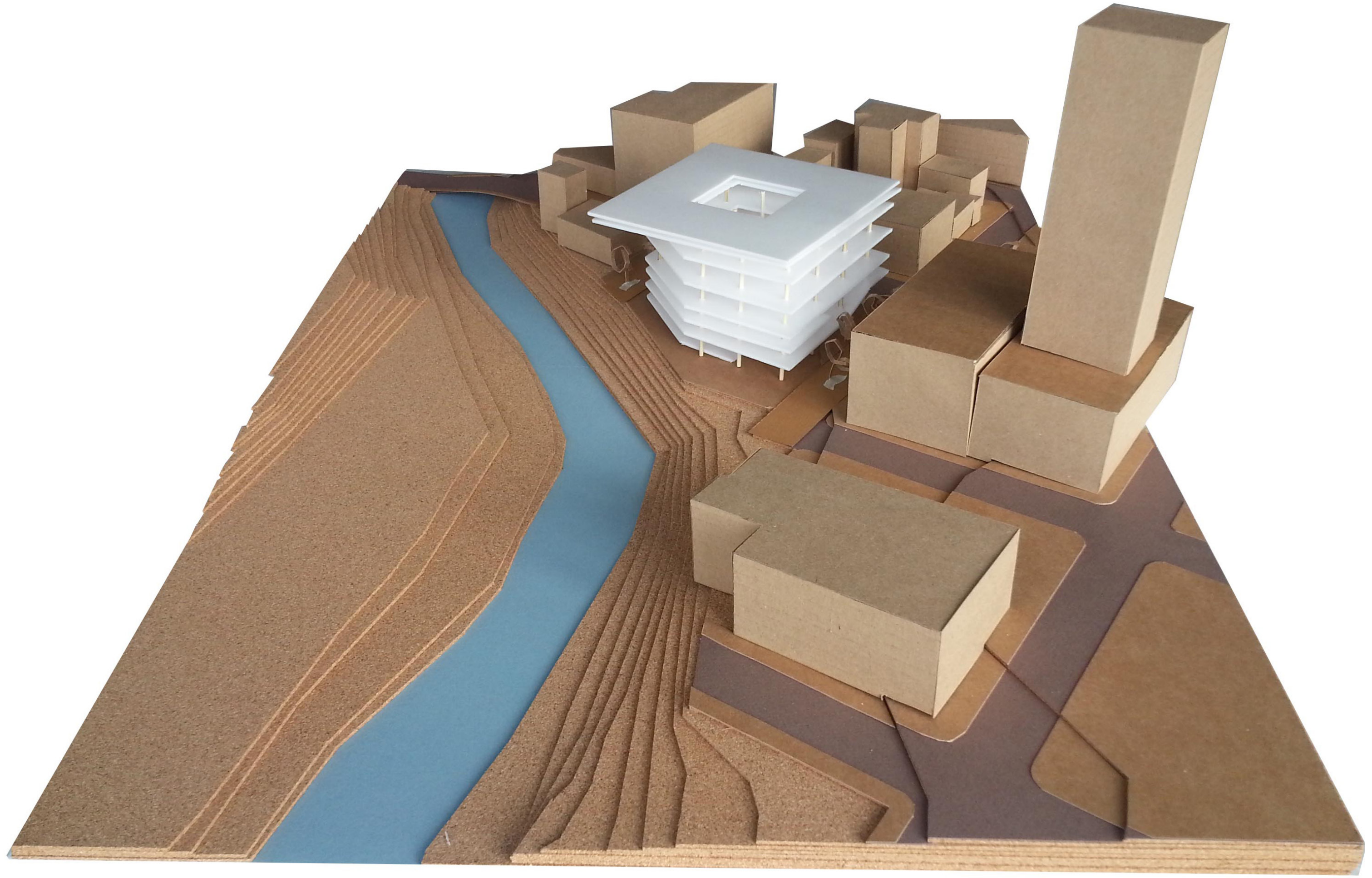


*Table 5.*
*Physical classification toolbox Building with Nature measures for flood risk reduction, Galveston Bay (GB). (De Boer 2015)*

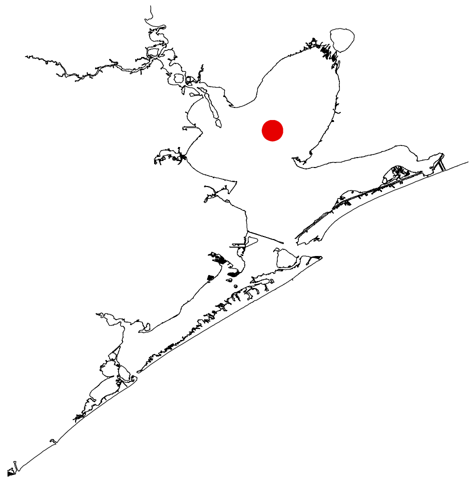
**Physical classification toolbox Building with Nature (BwN) measures for flood risk reduction, Galveston Bay, TX**

| **Building block** | **Location** | **Effect** | | **Additional functions** |
|---|---|---|---|---|
| | | **Storm surge** | **Wind waves** | |
| Bay partition (archipelago) or nourishment | Center | Reduces fetch and affects local wind set-up. Wind-set is inversely proportional to depth. Surge reduction values of 0.5 - 1 meter in the West and Northwest are possible for *idealized (closed)* conditions. | Fetch reduction and affect wave growth. Waves are depth limited and wave height is proportional to depth. Bay partition for *idealized (closed)* conditions will only marginally affect hurricane waves. | - Possible sediment stabilization<br>- Aesthetic landscape<br>- Could provide habitat |
| | Shore | The closer to shore, the bigger the effect. | The closer to shore, the bigger the effect. Nourishment affects hurricane waves at shore. | |
| Wetlands | Center | Miles needed to affect propagating surge (4 - 25 cm/km) by friction.<br>GB: no effect + not applicable.<br>* GB schematized as semi-enclosed bay with pumping mode for long waves (GB: no propagation takes place). | Several tens to hundreds of meters needed to reduce wave heights (1 - 5% per m + exponential growth) by friction.<br>GB: not applicable. | - Stormwater retention<br>- Sediment stabilization<br>- Shore protection<br>- Provide habitat<br>- Water quality<br>- Carbon sequestration<br>- Recreational value |
| | Shore | Miles needed to affect propagating surge (4 - 25 cm/km) by friction.<br>GB: no effect.<br>* GB schematized as semi-enclosed bay with pumping mode. | Several tens to hundreds of meters needed to reduce wave heights.<br>(1 - 5% per m + exponential growth) by friction.<br>GB: assumed required width at least 100 meter for hurricane waves. | |
| Eco-island (island with large surface area for ecological development) | Center | Reduces fetch and wind shear stress and will affect wind set-up.<br>Could be reducing surge at shore, if constructed in right location and with enough surface area. | Reduces fetch and wind shear stress and will affect wave growth.<br>But hurricane waves are depth limited and will not be or only marginally attenuated at shore. | - Biodiversity<br>- Possible sediment stabilization<br>- Provide food, habitat<br>- Aesthetic landscape<br>- Recreational value |
| | Shore | The closer to shore, the bigger the effect. | The closer to shore, the bigger the effect. | |
| Habitat breakwater (oyster reef) | Center | No effect.<br>* Permeable. | Not applicable.<br>* Should be constructed in close proximity of shore. | - Sediment retention/ stabilization<br>- Water quality<br>- Carbon sequestration<br>- Provide food, habitat |
| | Shore | No effect.<br>* Permeable. | If constructed as breakwater, effective for hurricane wave attenuation; provided that in close proximity to shoreline. | |



Robert de Boer

# BUILDING-WITH-NATURE MEASURES IN GALVESTON BAY



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The vulnerability of Galveston Bay to storm surge became obvious when Hurricane Ike made landfall at Galveston on September 13, 2008 as a Category 2 hurricane. Galveston Bay is a large estuary located along the Upper Texas coast of the Gulf of Mexico in the United States. It is adjacent to one of the most urbanized and industrialized areas in the nation, currently the fifth-largest metropolitan area in the US. Valuable assets include the Port of Houston, which is the second largest port of the US. (Port Authority of Houston, 2014), and the petrochemical industry with several large oil refineries (Smith, 2013). However Galveston Bay is also a complex and highly valuable ecosystem, which is highly under pressure due to (mostly human) impacts. Critical problems are

1. High erosion rates and habitat loss due to sediment starvation and sea level rise,
2. Water quality issues, and
3. Decreasing biodiversity due to habitat loss.

In the wake of Hurricane Ike, several plans were developed to reduce storm surge risk for the Houston Galveston Bay Region. According to experts there is a growing demand for flood risk reduction around Galveston Bay, and an interest for nature-based or 'natural' flood risk reduction in the United States as a whole (A.G. Sebastian, personal communication, September 2014). A blind spot in academic research has so far been the feasibility and effectiveness of measures for flood risk reduction inside Galveston Bay. Is it possible to both reduce flood risk and improve the natural system by implementing sustainable or natural solutions?

In order to design and evaluate the effectiveness of Building-with-Nature measures that improve the ecology of the natural systems in day-to-day conditions and contribute to flood risk reduction in hurricane conditions for the Houston Galveston Bay Region, a structured approach has been followed. The Ike Dike and sea level rise were used as sensitivity parameters to determine the resilience of the solutions. Preliminary conclusions from a simple, structured analysis are summarized in Table 5.

Specific measures (building blocks) considered to be suitable for Galveston Bay are wetlands, oyster reefs, habitat breakwaters, a spacious eco-island, an artificial bay partition (an archipelago of islands), and sand nourishments. The most important mechanisms for hurricane flood risk of Galveston Bay are inflow, local wind set up (which leads to sloshing behavior due to rotating winds as well) and waves on top of surge. The physical evaluation of these building blocks focused on reducing the load of the hurricane by addressing the surge and waves on top of it. The table plots the effects of these building blocks on surge and waves, as well where they should be placed and configured, and how large they need to be.

In this research project, the toolbox will be used to create integral designs, and to come up with a more thorough evaluation by means of a 2D hydrodynamic model. The emphasis will be to identify what building block will have the biggest positive effect on the natural ecosystem and reduce hurricane flood risk the most.

*Figure 89.
Frame 1: Dramatic destruction.
(Source: SSPEED Center 2010)*

*Figure 90.
Frame 2: High waters.
(Source: Rijkswaterstaat 2012)*

*Figure 91.
Frame 3: People-centric damages.
(Source: Ready.gov. 2015)*



An'An Denise Yam

# FRAMING FLOOD RISK: USE OF IMAGES IN COMMUNICATION

Traditionally, flood risk management has primarily focused on expert discourse and technical solutions. However, in the ongoing shift towards integrated flood risk management, flood risk communication plays an increasingly important role in bridging the gap between different actors. Using images can be a powerful communication tool, but this approach has not been widely studied in a flood risk context. This project deals with the use of images in the communication of flood risk to the public in the Houston Galveston Bay Region.

Framing refers to the way in which a communicator presents an issue or event to an audience by placing it in a specific 'field of meaning'. It is clear that flood risk can be communicated in different ways and within different frameworks. The focus of this project was to understand how images of flood risk are related to the viewers' risk perceptions. We based our approach on construal level theory, and propose that a viewer's initial perception of flood risks is based on their psychological distance to flooding. This perception will affect their response to images and different frames of flood risk. While the viewer's perception can influence their response, the reverse can also happen, with images and framing changing a viewer's risk perception.

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In this study, we investigated how flood risk in the Houston Galveston Bay Region are communicated. The flood risk frames intended and used by local flood risk practitioners were contrasted against how the public interpreted the messages. Interviews were conducted with practitioners who have experience in public communication in a variety of settings, while the public's perceived frames of flood risk were determined using the Q method, an approach to determine subjectivity in respondents' perceptions in a statistically interpretable way. A random sample of residents of Houston and Galveston City was created, and participants were asked to sort a deck of 24 flood risk-related images based on the perceived impact.

Findings show a mismatch between the type of images frequently used by practitioners and those that resonate with the public. Practitioners generally use technical images (often maps or graphs of modeling output) to communicate the severity of flood risk and the urgency of addressing them. Such images could be seen as abstract and psychologically distant to the viewer. Conversely, the public is attracted to images that portray the negative outcomes of floods, which concretize flood impact for them. In fact, three distinct frames were found that involved the public: dramatic destruction (see Figure 89), high waters (see Figure 90), and personal loss (see Figure 91). Images that fit such frames are better at capturing the public's interest and conveying a sense of importance. These frames provide insight into the way the public could be engaged in flood risk discussions.

The effectiveness of flood risk communication could be improved by aligning the practitioners' and public's frames of flood risk. For example, affective images portraying flood impact could be deliberately integrated into technical images. The level of affect should be as specific and personalized as possible to increase the public's sense of personal relevance and responsibility. However, portrayal of risks should also be balanced with accompanying solutions, to prevent unnecessary fear-mongering.

Despite the small survey sample, this project identified multiple frames in the public perception; presumably, even more frames could be uncovered in the larger population. Flood risk communication can be improved with the thoughtful use of images and framing, and these lessons could be transferred to contexts beyond the Houston Galveston Bay Region and even to risk communication in other fields.

*Figure 92.*
*UTMB's sanatorium consists of two parts: a main body on the dike with two platforms on piles, plus shelters that float upward during a flood event. The shelters can be loosened from the platform if need be. (Dichao Wang 2015)*

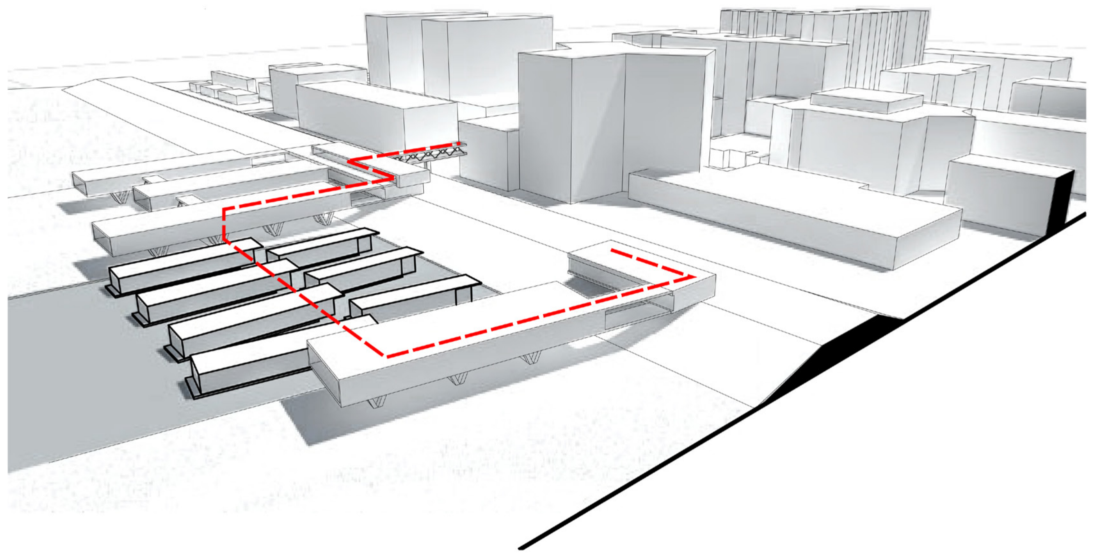
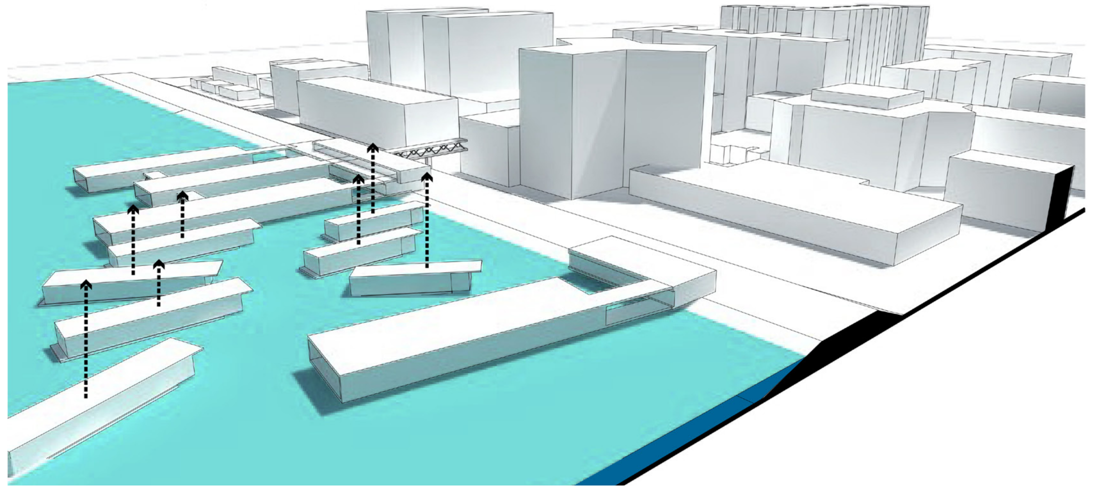


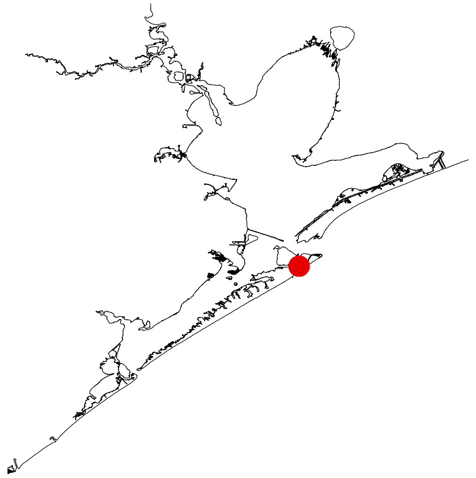
*Figure 93.*
*UTMB's sanatorium during a flood event. (Dichao Wang 2015)*





Dichao Wang

# A WATERFRONT SANATORIUM FOR UNIVERSITY OF TEXAS MEDICAL BRANCH, GALVESTON



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*Tutor:*
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Galveston's year-round supporting industries, the harbor and health care facilities, both faced serious challenges after the economic devastation brought by Hurricane Ike in 2008. Reconstruction of the harbor area, damaged by storm surge and leftover sediment, has cost millions of taxpayer dollars. Due to the consistent threat of flood damage. University of Texas Medical Branch Galveston (UTMB) experienced a decline in the number of patients. In the 2009 Galveston Economic Recovery and Rebuilding Report, local community leaders announced a district restoration plan including investment in supporting industries, recovery of infrastructure, and reinforcement of flood risk reduction measures. According to the plan, a total of $2.4 billion (2.15 bilion euro) needs to be invested in the restoration of Galveston, with $600 million (538 million euro) allocated to UTMB.

The urban fabric of Galveston consists of four main areas: the port, residential neighborhoods, the university campus, and natural wetlands. The famous Strand Historical District and the UTMB campus form the heart of the city. This project considers options for a site located in the northern coastal area of the city close to the UTMB campus, next to the port on the east, with natural wetlands on the west. The connection between the site and the campus is split by Harborside Drive. At present, the site is used primarily as parking lot for UTMB, with a cruise terminal on the Bay, where cruise ships occasionally dock. In the district restoration plan, the site is allocated to UTMB, and a nuclear magnetic resonance facility is also planned dockside.

Although the waterfront could offer many qualities, it is currently regarded as the 'back side' of UTMB campus. For Galveston as a whole, both the northern and the southern coastal strip lack a quality waterfront: the port occupies the northern strip, and the Galveston Sea Wall cuts off the southern strip from the Gulf.

The project, a waterfront complex, extends past Harborside Drive, facing Pelican Island. The complex consists of two elements: a sanatorium and a training facility, both of which supplement UTMB's existing facilities. In general, Texas has an aging population, and measures have to be taken to accommodate senior health care. A sanatorium will also strengthen Texas' lead in top health care facilities. According to UTMB's management, a training facility for interns and resident practitioners to get practical experience beyond the classrooms and academic settings is also required. The waterfront complex will meet these requirements.

The design assumes that storm surge will be reduced by the construction of both the Ike Dike along the Gulf of Mexico, and the Galveston Levee as projected in SSPEED's HGAPS proposal, which are designed to stop surge from the Bay. In order to construct the Galveston Levee, Harborside Drive will need to be elevated.

Nevertheless, in order to meet the requirements of flood risk reduction, the new building was designed to be amphibious. The part of the building located on the waterside of Harborside Drive has been designed to float under storm conditions. Under regular circumstances, it will be used as a sanatorium and training center, whereas during floods it will transform into a temporary rescue facility with floating shelters. The other part, which spans Harborside Drive, is designed to resist storm surge.

Han Meyer

# TOWARDS A COMBINATION OF ENGINEERING AND DESIGN

## REFLECTION

*Dr. ir. V.J. Meyer is a professor of Urban Design and Delta Urbanism at the Faculty of Architecture & the Built Environment at Delft University of Technology.*

The student projects presented in this book show a series of interesting possibilities for the future of the Houston Galveston Bay Region, looking for solutions which substantially improve the quality of urban space and the landscape, as well substantially reducing flood risk and offering new ways of dealing with floods. This double aim is the essence of what we call 'Delta Urbanism': looking for 'smart combinations' to create attractive conditions for human settlement in deltaic environments, taking into account both environmental and ecological conditions, and addressing safety, flood risk reduction and fresh water supply. The invention and exploration of new 'smart combinations' is exactly what might be expected of a new generation of engineers and designers, especially when we recall the original meaning of engineering: 'the art of ingenious solutions'.

An important ambition of the Delta Interventions studio is to make students familiar with interdisciplinary approaches, which are necessary to be able to design and implement 'smart combinations'. Both in practice and in education, it is difficult to develop these interdisciplinary ways of thinking and working. This is partly the result of different organizations with different codes, administrations and budgets. But more fundamental are the different ways of thinking, in particular the difference between an 'engineering' approach and an 'architectural' one. Mark Maier and Eberhardt Rechtin explain this difference in their book *The Art of Systems Architecting* (2000), with engineering taking a basically deductive approach while architecture is characterized by an inductive approach. Engineers are trained to try to understand the larger picture, the system, and to invent a principle which can change or manipulate the system as a whole, and 'translate' this principle to the scale of an individual project. Architects tend to start with a local experiment and try, based on their experience with the project, to define some more general rules for the larger picture. Neither approach is superior: the important thing is to acknowledge that this difference exists. Maier and Rechtin emphasize that really sustainable and resilient approaches are characterized by a combination of the engineering and architecture approach. In what sense do we recognize this difference in the work of the students, and did we succeed in combining both approaches in the studio?

The projects of the architecture students are quite varied. The project of Tsai Hsun Ho (p. 104), a waterfront recreation complex for Sylvan Beach, is a very specific project for a specific site, but with the aim of influencing the awareness of Houstonians that they live in a deltaic environment. It makes the bay and the beach accessible, emphasizes the pleasure and joy of living near the water, and clarifies the need to be prepared for high tides at the same moment. It is not a building with a principle that should be repeated everywhere; the quality of the building is its uniqueness, which can contribute to make the building an icon for Houston and Houstonians.

The projects of Qian Cao (p. 96) and Kito Samson (p. 110) for new public buildings in the central district of Houston have a different character. Both try to deal with the combination of accessibility and publicness of the building and making it flood proof by elevating it. The result is buildings that are not separated from the system of public streets, but which add an extra dimension to the public character of the street. Currently, Downtown Houston is a boring area, with streets dominated by closed fronts of parking garages and without any exchange between buildings and streets. The designs of Cao and Samson show that, when elevating a building to make it flood proof, the elevation itself can play a function to create contact zones between the interior and exterior of the building, and hence improve the quality of the public space. The two buildings can be considered as variations on a principle, one which can be applied in different forms in different places in Downtown Houston. Adding these elevated buildings would enrich the central district of Houston, making the district more flood-proof and at the same time making it more interesting to spend some time there.

The projects of the civil engineering students have another approach. Especially the project of Robert de Boer for Building with Nature (p. 114) is an example of an attempt to understand the whole system of water, floods and natural processes of currents, sediment transport and silting in Galveston Bay, and to exploit these natural processes in a way which should result in a safer situation as well as a sustainable ecosystem. The question is how this approach will influence a local situation, for instance the edge of the bay where Tsai Hsun Ho located her waterfront recreation complex. It would be interesting if these two students joined efforts and explored how their projects can profit from each other.

The project of Inge van den Ende (p. 94) on the Bolivar Peninsula is perhaps one of the most interesting projects from the engineering as well as from the architectural perspective. She explores how a general (Dutch) principle (the 'multilayered safety' principle) can be applied to the Houston coastline in a way that also leads to a more interesting architectural and landscape environment. She seems to be able to combine both approaches in one design.

The projects of Song-Ya Huang (p. 102)and Sarah Brakel (p.98), both urbanism students, are examples of a search for principles that can be applied in the whole urbanized area of Houston. Both explore a specific district next to a bayou, and try to design a series of interventions and building regulations that should lead to a long-term transformation of the whole district. These interventions should lead to a new type of urban environment, which suffers less from flood events, and where the bayou has a new central position. Since Houston is interlaced by bayous, the approach might be applied in various ways in other districts.

It is not difficult to imagine other combinations of different projects, especially projects with a more deductive approach and those with a more inductive approach: not only combining the recreation complex of Tsai Hsun Ho with the Building with Nature project of Robert de Boer, but also the public buildings of Qian Cao and Kito Samson with the urban designs of Song-Ya Huang and Sarah Brakel, the Bolivar Peninsula project of Inge van den Ende with the Galveston project of Fangfei Liu (p. 107), and so on.

Overall the student projects presented in this book deliver a rather comprehensive picture of a possible future for Greater Houston. And perhaps their work brings us pretty close to what Maier and Rechtin consider a really sustainable and resilient approach.

*Figure 94.*
*A multifunctional Barrier Building Complex for Rockaway Peninsula, New York. (Courtesy of X. Sun)*

Thomas M. Colbert

# MULTIDISCIPLINARY VIEWS OF GALVESTON BAY

## REFLECTION

*Dr. T.M. Colbert is an associate professor at the Gerald D. Hines College of Architecture at the University of Houston, Texas.*

In June of 2014 it was my great good fortune to visit the Delft University of Technology to attend a review of student and faculty coastal planning research and design work including, to my great delight, a brilliant presentation by one of the recently announced Finalists for the international Rebuild By Design competition. After a full afternoon with the students and faculty, I was greatly impressed by the range and thoughtfulness of responses to the challenge of protecting urban areas against flooding, while making cities and urban regions better places to live. When I then heard that the Houston Galveston Bay Region had been selected as the subject for the 2015 Delta Interventions Studio I couldn't have been more delighted. I imagined the same talent that I had just witnessed being directed at my own region, where the threat of flooding and the need for coastal and spatial planning couldn't be greater. I was not to be disappointed. As you have seen in the previous pages of this book, an impressively diverse range of thoughtful research and well-developed design projects has been put forward in only two semesters.

The Houston Galveston Bay Region is an especially challenging and deserving subject for such a studio. The region is highly susceptible to hurricane-related tidal surge and rainwater flooding from tropical storms. Its rapidly growing metropolitan area contains approximately six million people, the most important international port in the United States, and perhaps the largest collection of petrochemical refining, storage and transmission networks in the world, and yet it is almost completely unprotected against flooding hazards either by land use planning or structural measures. The reason for this apparent failure of reason is the State of Texas' radical devotion to the idea that less is more where government is concerned, combined with protracted political squabbles about what to do. In short, we have been too busy arguing to look the problem squarely in the face.

While studios in Texas and Louisiana have examined these issues on a regular basis, the Delta Interventions Studio has brought unique resources to bear on the problem. The most important of these resources are a completely fresh and well-informed international perspective and a profoundly well-integrated multi-disciplinary point of view and team structure. Independence from any association with the politics of our region combined with familiarity with a wide range of historical precedents for these problems is extremely important as well. But, it is the depth of integration of diverse disciplines that is the most unique aspect of this the Delta Interventions Studio and the one that seems most responsible for the extraordinary diversity of solutions that were proposed for Galveston Bay.

It is no longer so unusual in university settings for disciplinary silos to be broken down in applied research teams. Subjects as complex as coastal and spatial planning require it. Hydrology and other aspects of civil engineering, urban planning and architecture, environmental and political sciences are all essential to the field. Even geophysics is foundational for this essentially multi-disciplinary field. In the United States, in studios, lecture and seminar courses it is possible, although still quite unusual, to engage smaller groups of multi-disciplinary faculty in coursework; however, it is almost unheard of for a graduate design studio to incorporate so many diverse faculty and students from different disciplines working together. To have so many distinguished faculty from different branches of Engineering, Architecture, Urbanism, and Technical Policy and Management working together with a team of students pursuing degrees in coastal engineering, architecture, urbanism, and systems engineering and policy analysis is a remarkable academic and pedagogic achievement.

The result of this collaboration, under the able leadership of Anne Loes Nillesen, has been the impressively wide range of projects that are recorded in this book. Each project taken on its own provides an independent and well-informed look at the problems and opportunities facing the Houston Galveston Bay Region. From proposals for the development of flood-resilient social housing along a tributary bayou to spatial planning for a barrier island, and building with natural measures inside Galveston Bay, we are given a new understanding of the region. Taken together this collection of projects provides us with a fresh vision of the region - one that is independent of political debates and that concentrates on opportunities as much as problems.

The problems of rainwater and surge tide flooding in the Houston Galveston Bay Region are unprecedented in their scale and complexity. It seems apparent that no single answer to these problems will be adequate to that challenge. Rather, multiple answers must be found, each operating at different scales and with different implementation mechanisms. Since it is clear that many of the answers to these challenges are not yet dreamed of, what is needed by the professional, political, and academic communities of the Houston Galveston Bay Region is informed speculation about land use and architecture as mitigation tools. This will stimulate creative debate, help to unearth new ideas, and permit convincing strategies to be developed.

Using design as a research tool, the Delta Interventions Studio has made a substantial contribution to the understanding of the Galveston Bay Region, an understanding that may well play an important role in the development of solutions to the many pressing problems we are facing. Who knows which of these design proposals may influence future decision-making? In any case, the studio has made a substantial contribution to graduate level teaching and pedagogy. By bringing together so many disciplines at such a high level, including faculty and students who were involved in this two-semester program, it has set a high standard for multi-disciplinary education, one that is likely to be emulated in universities around the world.

*Figure 95. Student design for a watchtower - Water approach. (Courtesy Tom Colbert)*

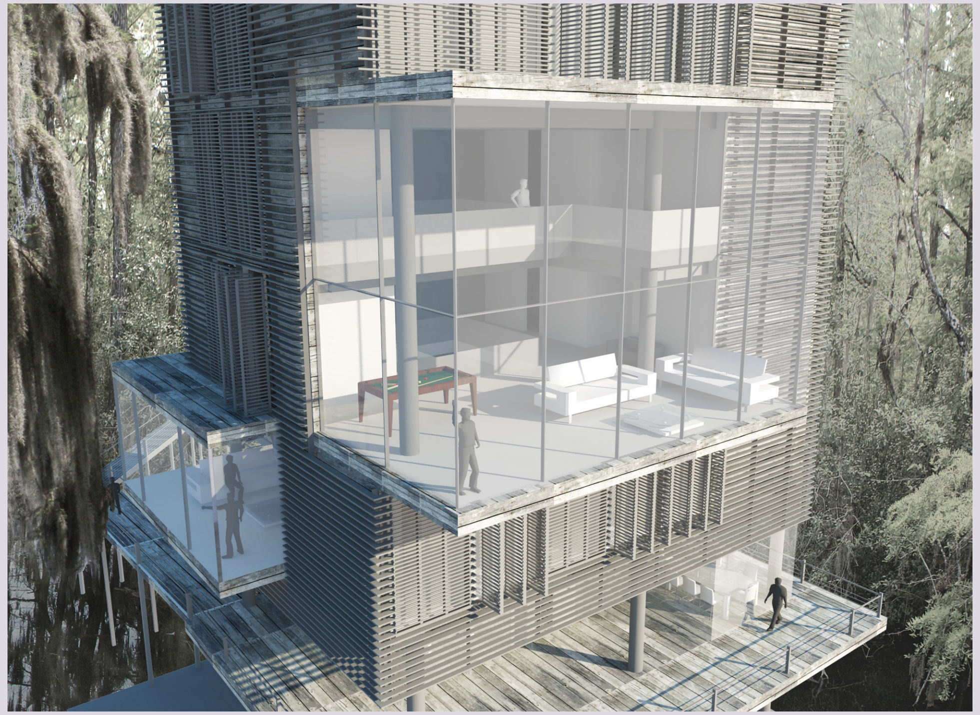


*Figure 96. Student design for a watchtower - Swamp. (Courtesy Tom Colbert)*

Galen Newman

# DUNE INTEGRATION FOR GALVESTON ISLAND: ISSUES AND OPTIONS

## REFLECTION

*Dr. G. D. Newman is an assistant professor of Landscape Architecture & Urban Planning at the Hazard Reduction & Recovery Center of Texas A&M Galveston.*

Coastal storm damage and related flooding threatens the Texas coastline regularly. With nearly 40 significant hurricanes since 1900, coastal Texas experiences a hurricane every five years, and a major storm every 15 years, on average. The Ike Dike is a projected storm surge protection system which is intended to protect the Houston-Galveston Metropolitan Area from a 10,000 year storm event. It is named after Hurricane Ike, a category four hurricane that occurred in 2008, resulting in 84 casualties and over $19 billion (17 billion euro) in damages. The proposed barrier infrastructure extends parallel to Galveston Island to protect the port of Houston, the second-busiest port in the US. The barrier system consists of a set of sector and sluice gates on each side of Galveston Island and a fortified linear dune (the emphasis of this reflection) which creates a protective spine the length of Galveston Island.

Current approaches in the US favor structural or mechanical solutions for surge protection, which can increase the opportunity to develop areas where floodrisk currently hinders development. Structural approaches typically involve physical construction to resist the threats of floodwaters; these include seawalls, levees, dams, channels, elevated buildings, sector and sluice gates, and revetments. These can significantly diminish the visual quality of the existing landscape, they can be costly, and they are prone to structural failure. Outside the Netherlands, however, there are few examples of a combination of structural and non-structural approaches. Non-structural approaches seek to guide development away from flood vulnerable areas through land conservation policies and/or other non-developmental measures. Effective flood management programs utilize a mixture of techniques tailored to the different and unique conditions of each local area.

Currently, over half of Western Galveston Island is composed of wetland area (56.3%), much of it saltwater marsh (24.6%). Overall, green space is the dominant land use on the site (61%), with residential (32%), commercial (1%) and beach area (6%) also occupying considerable tracts of land. Current beach widths on the island average approximately 200ft (61m.) This could make dune integration difficult in developed areas, as this is much smaller than average widths of other beaches such as San Diego, California (320ft/98m), Miami, Florida (370ft/113m) or a typical beach in the Netherlands (600ft/183m). Proposed dimensions for the Galveston dune are approximately 115ft (35m) wide by 20ft (6m) high. In developed areas near the coast, this would lead to nearly all of the existing beach line being consumed by the barrier. In addition, existing residential structures are around 30-40ft (9.1-12.2m) high and unless the dune is well integrated, it could have negative scenic and social effects. This leads to eight options for dune integration to be explored:

1. Beach Maximization - Considering the relatively low amount of beachside land, dune placement should seek to maximize existing beach widths. In places where future development may occur, the dune should be strategically located to provide ample beach space for future residents. Areas with existing development must seek to maintain existing beach dimensions as much as possible. Beach nourishment and expansion strategies are especially encouraged in these areas.

2. Cross Dune Accessibility - Dune-to-structure connections for existing development should be dependent on owner preference. Connections with stairways, ramps and/or boardwalks can be made from the second or third stories of each residence; these could in corporate privacy structures but still increase beach access. Vehicular access to the beach should also be maintained.

3. Parallel Connections - While cross-dune connections are important, linkages along, or parallel to, the dune are also necessary. Bike lanes, walkways, existing trail connections, and spaces for commercial activities should also be considered.

4. Erosion Control - The fortified dune should be covered with native plantings to protect its stability. It is important to reduce sedimentation loss on the coastal side of the dune through the strategic planting of species with fibrous root systems. Decreased erosion will also reduce dune maintenance costs over time.

5. Leakage Detention - A series of existing small scale, linked wetlands or excavated areas should be installed behind the fortified dune. These wet ponds are designed to retain some volume of water at all times, but they can also be used to absorb storm surge that may overtop the dune.

6. Habitat Preservation - Existing state and local parks, ecological niches, and open space are encouraged for conservation to aid flood attenuation purposes. These areas will be protected by the dune and can help buffer the surrounding developed and developing communities.

7. Tourism Enhancement - Community-based tourism enhancement should be explored as opportunities for economic development. The dune should be designed to promote coastal tourism opportunities, open up existing communities, and celebrate the culture of the island.

8. Recreational Opportunities - Increased population, development and tourism make public space such as parks and beaches essential venues for recreational activities. Innovative passive and active recreational offerings and increased outdoor opportunities should be designed with the dune to contribute to the local economy and generate job opportunities.

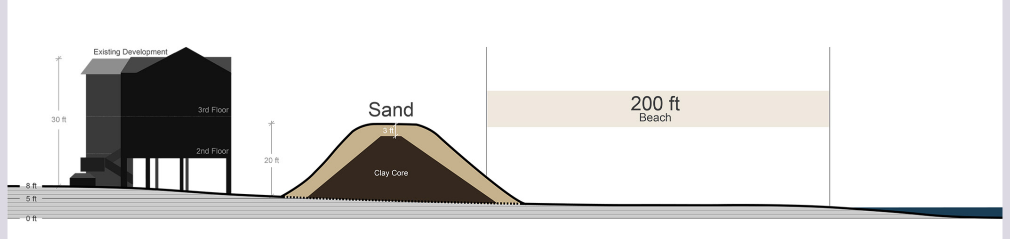
The Ike Dike will unavoidably alter the physical landscape of Galveston. The proposed dune system should seek to retain the current local conditions as much as possible, utilizing open space to help attenuate flooding from storm surge, providing erosion control measures to decrease sedimentation losses from surge by planting fibrous-root species, and providing a connective spine for existing parks, open spaces, and green spaces.

As a hybrid approach using structural and non-structural mechanisms for flood protection, three salient points should be considered for successful dune integration. First, placement of the dune must strive to maximize beach space. Approaches for expanding the beach over time should also be considered. Second, non-structural solutions for surge protection should be maximized. This will create a green space network to help protect the island while providing ecosystem services. Enhancing the ecology of the island will also help to detain overtopped surge. Third, incorporating human functions across and along the defense structure will make the barrier a line of social activity which will link developed areas and the coastline, increase recreation and tourism, and provide a pedestrian connection along the entire coastline.

*Figure 97. Dune Integration. (Courtesy Galen Newman)*

*Figure 98. Projected Dune Dimensions. (Courtesy Galen Newman)*

*Figure 99. Dune Connections. (Courtesy Galen Newman)*




Anne Loes Nillesen

# A RICH DIVERSITY OF BUILDINGS BLOCKS FOR A COMPREHENSIVE FLOOD RISK REDUCTION STRATEGY

## REFLECTION

*Ir. A.L. Nillesen is a doctoral candidate at Delft University of Technology, Faculty of Architecture & the Built Environment; and coördinator of the TU Delft A&BE Delta Interventions Studio, an interdisciplinary MSc graduation studio focussing on water related issues.*

The focus in the Delta Interventions studio lies on exploring the opportunities for combining spatial and flood risk reduction interventions into one integrated design. The initial Delta Interventions and Delta Urbanism projects focused on the Dutch Delta. Later on, the scope was expanded internationally and came to include research and student projects in several deltas worldwide, including the Houston-Galveston Bay Region in 2015. When creating integrated designs and strategies, regardless in which delta, essential strategic choices have to be made about the scale and type of intervention.

Especially on the regional scale - for instance in the Houston Galveston Bay Region or the Dutch Rijnmond-Drechtsteden region - an essential choice has to be made between a probability-reduction strategy and a consequence-reduction strategy. Both strategies can be supported by different flood risk reduction measures, either on the regional scale (e.g., storm surge barriers, dike rings, evacuation strategies, or major land elevations) or the local scale (e.g., flood proof buildings, shelters, and local dikes or quays).

In the past years, the studio and research group has conducted many research-by-design projects within the Dutch context, exploring the spatial opportunities related to different large-scale choices for flood risk protection, varying from a closed delta protected by a network of storm surge barriers, an open delta focusing on dike rings in a natural and open estuary, to strategies based on local-scale consequence-reduction measures. However interesting and valuable the contributions of these research-and-design projects, they were mainly perceived as theoretical exercises, since a regional protection strategy of probability reduction has already been selected and implemented in the Dutch Delta.

What makes the Houston Galveston Bay Region interesting, is that this major choice for a regional flood risk protection strategy is still being debated. This makes the research and design projects performed by the Delta Interventions students of wider interest, potentially contributing to future strategy development and decision-making. For the Houston Galveston Bay Region, a wide variety of flood risk reduction measures can be considered for a regional flood risk protection strategy. The student projects explore a wide range of options, including combined approaches ranging from probability reduction to consequence reduction.

From the urban perspective, the projects demonstrate a focus on addressing urban sprawl and improving the spatial quality of specific sites. The projects predominantly focus on the local scale of a building, or the design of a specific public space. On this local scale, many projects employ the changing water levels related to floods as a leading design principle. Thus, the frequency of water level fluctuations becomes an important design parameter. We see a cluster of projects around the bayous, an area subject to water fluctuation caused by both extreme flood events as well as the more frequent intense rainfall events. Each of the projects demonstrates, in its own way, how the creation of flood proof buildings and public spaces can improve the water storage capacity while reducing the impact of floods events, at the same time improving the spatial composition or quality of the city.

Other projects focus solely on an extreme flood event. We see different approaches, such as improving the seawall, building a natural barrier, or hurricane- and flood-proofing buildings. Focusing on an extreme event introduces the challenge of balancing the investment to be made, in relation to the low predicted return period of the flood event.

The rich diversity of student projects presented in this book can be seen as local scale components and showcases for alternative regional flood risk reduction strategies for the Houston Galveston Bay Region. Formulating and further exploring comprehensive regional flood risk protection strategies in an integral way is where the main challenge remains. The projects presented in this book demonstrate the effectiveness of an integrated design approach, as well as offering insights for water management policy in the Houston Galveston Bay Region.

*Figure 100. View from Galveston Harbour. (Photo Courtesy Anne Loes Nillesen, 2015)*

Nikki Brand, Baukje Kothuis, Antonia Sebastian

# COMBINING TRADITIONS OF FLOOD RESPONSE

## EPILOGUE

The research by design presented in this book addresses flood response and mitigation for the Houston Galveston Bay Region. The authors did not explore what causes flooding or how it affects peoples' lives and livelihoods, but rather what flood risk reduction strategies are feasible, and how they can be designed within the wider context of the region's physical and political environment. Most of the contributors to the Hydraulic Infrastructure Design Section focus on elements of regional-scale structural solutions, while those within the Delta Interventions Section explored improvements to the built environment at the level of neighborhoods and individual plots. The contributors to the Multifunctional Flood Defenses Section analyzed combinations of solutions, as well as the application of different strategies within the existing political and economic system of the region.

The majority of the contributors to this book have been trained in the tradition of Dutch flood mitigation practice, which dates back hundreds of years. Given the success of large-scale structural solutions to coastal flooding in the Netherlands, like the Dutch Delta Works, Dutch expertise is often called upon after major flood events. However, Galveston Bay is not Lake IJssel, Texans are not Dutch, and hurricanes are no westerly gales. This book shows Netherlands-based researchers eagerly learning from their experiences in Texas – where new and innovative approaches are required to address flooding in a different and complex environment.

In many ways the Houston Galveston Bay Region has provided a unique location to advance TU Delft-based design. The diverse challenges regarding planning and design stimulate researchers to find answers to new problems at different scales, thus offering many opportunities to learn. This design environment inspired research projects across different scales and disciplines, which, when viewed as a body of research by design, illuminate certain topics to be addressed in future research:

1. The regional-scale flood risk posed by hurricane-induced storm surge inspires large-scale structural solutions. However, the dynamic behavior of storm surge in Galveston Bay presents a unique design challenge for hydraulic engineers: large-scale structural solutions designed to reduce surge at the coast will not fully mitigate the effects of local wind setup within the bay itself. Thus, a combination of structural solutions coupled with local interventions will be necessary, which requires an innovative approach that addresses design challenges at different scales.

2. Hurricane-induced flooding has two drivers: storm surge and rainfall-runoff. In low-lying coastal watersheds, surge-based flooding is exacerbated by torrential rainfall and the failure of the built environment to accommodate it. This, too, requires a more intrinsically combined approach. One that enhances the design of structural and non-structural solutions that both accommodate rainfall-runoff and adapt the built environment to mitigate flood losses.

3. The environmental impact of large-scale interventions on Galveston Bay and the barrier islands is still relatively unknown. Also, the potential application and long-term effectiveness of nature-based solutions merits additional research. Nature-based solutions, like the Sand Engine in the Netherlands, or the enhancement of coastal wetlands within the structure of the proposed Lone Star National Recreation Area, have the potential to provide both quality of life and economic value to the region, while at the same time reducing flood risk.

4. Possibly the most complex design challenge encountered in this book is how to match future flood response and mitigation with the cultural and political environment of the Houston Galveston Bay Region. While local perceptions, mindsets, and traditions may for a large part determine what will be a feasible approach to reducing flood risk, many crucial questions remain unanswered. How to balance economic, social, and environmental criteria? What are potential strategies for stakeholders to join forces to develop a broadly supported plan? What are means of support and funding, not only to build a system for flood response, but also to maintain, manage and fund it over time?

Trans-Atlantic knowledge transfer regarding flood risk reduction, obviously, is not one-way traffic. While the Dutch can provide expertise regarding 'first layer' safety based on large-scale preventive measures to the Houston Galveston Bay Region, 'third layer' safety measures, such as evacuation planning and flood insurance, have matured in Texas. These provide inspiration to enhance flood risk awareness of Dutch citizens in the absence of recent major flooding. It seems likely that the fruitful grounds to jointly develop alternatives for flood risk reduction in the Houston Galveston Bay Region are somewhere in the middle between the traditions of Dutch and Texan flood mitigation practice.

Ultimately, this book is not about how the Houston Galveston Bay Region should respond to its complex flood risk challenge, but rather how it could respond. The contributions in this book suggest that the exploration of a potential effective and efficient multiple lines of defense strategy that combines structural and non-structural measures may be worthwhile to pursue. However it is up to those who actually live in the Houston Galveston Bay Region to decide what solution and design should be chosen. This book hopes to inspire them.

*Figure 101.*
*Annual test-closing of Maeslant Barrier in The Nieuwe Waterweg, shipping route to port of Rotterdam. (Photo Courtesy Rijkswaterstaat/Bart van Eyck)*



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*Figure 102. Multifunctional flood defense The Hague-Scheveningen Boulevard: a dike protected by a widened beach and concealed beneath an undulating pedestrian- and bicycle-friendly esplanade. (Photo Courtesy Rijkswaterstaat/ Harry van Reeken)*




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*Figure 103.*
*Galveston Seawall,*
*Pleasure Pier, and*
*sargassum built up.*
*(Photo Courtesy*
*Baukje Kothuis )*




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# COLOPHON

DELFT DELTA DESIGN
HOUSTON GALVESTON BAY REGION, TEXAS, USA

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| | |
|---|---|
| P.B. (Phil) | Bedient, page 48 |
| E. (Erik) van | Berchum, page 41 |
| J.B. (Jim) | Blackburn, page 84 |
| R. (Robert) de | Boer, page 115 |
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| A.D. (Nikki) | Brand, p. 11; 55; 63; 129 |
| M. (Marjolein) van | Breukelen, page 27 |
| S.D. (Sam) | Brody, page 86 |
| Q. (Qian) | Cao, page 97 |
| T. M. (Thomas) | Colbert, page 122 |
| S.W. (Scott) | Cunningham, page 59 |
| E.J.C. (Guy) | Dupuits, page 67 |
| I. (Inge) van den | Ende, page 95 |
| R. (Refke) | Gunnewijk, page 35 |
| T. (Tom) | Heeringa, page 35 |
| D.N. (Daniel) | Hogendoorn, page 63 |
| T. (Tsai Bubu) | Hsun Ho, page 105 |
| S.Y. (Song-Ya) | Huang, page 103 |
| M. (Merijn) | Janssen, page 35 |
| S.N. (Bas) | Jonkman, page 17; 42 |
| I. (Iman) | Karimi, page 29 |
| R. (Rolf) | Kelderman, page 35 |
| M. (Matthijs) | Kok, page 53; 82 |
| B.L.M. (Bee) | Kothuis, p. 11; 59; 73; 129 |
| A. (André) | Kuipers, page 3 |
| M. (Matthijs) van | Ledden, page 44 |
| K.T. (Kasper) | Lendering, page 23 |
| Y.C. (Yi Chien) | Liao, page 101 |
| F. (Fangfei) | Liu, page 107 |
| J. (Jantsje) van | Loon-Steensma, p. 77 |
| A. (Anniek) de | Milliano, page 35 |
| W.J. (Bill) | Merrell, page 46 |
| V.J. (Han) | Meyer, page 120 |
| L. (Leslie) | Mooyaart, page 23 |
| G. (Galen) | Newman, page 124 |
| A.L. (Anne Loes) | Nillessen, page 93; 126 |
| K. (Kasper) | Stoeten, page 19 |
| K. (Katerina) | Rippi, page 33 |
| G. (Geert) | Roukens, page 35 |
| M. (Maarten) | Ruijs, page 21 |
| K. (Kito) | Samson, page 111 |
| M. (Martijn) | Schlepers, page 39 |
| A. (Toni) | Sebastian, p. 11; 69; 129 |
| J.H. (Jill) | Slinger, page 59; 88 |
| J. (Jor) | Smulders, page 31 |
| A. (Ad) van der | Toorn, page 29 |
| H. (Helena) | Van Boxelaere, p. 81 |
| P. (Peter) de | Vries, page 25 |
| D. (Dichao) | Wang, page 119 |
| A.A. (Denise) | Yam, page 117 |

In 2008, Hurricane Ike devastated Bolivar Peninsula, narrowly missing the more heavily industrialized and populated areas in the region. In the aftermath of the hurricane, the Severe Storm Prediction, Education and Evacuation from Disasters (SSPEED) Center at Rice University in Houston, and Texas A&M University in Galveston (TAMUG) led initiatives to propose and design flood mitigation strategies.

In collaboration with TAMUG and the SSPEED Center, students and researchers at Delft University of Technology in the Netherlands have been investigating regional strategies for flood risk reduction. In this publication they and their Texas counterparts reflect on the research, design, and insight that has sprouted from this collective endeavor.

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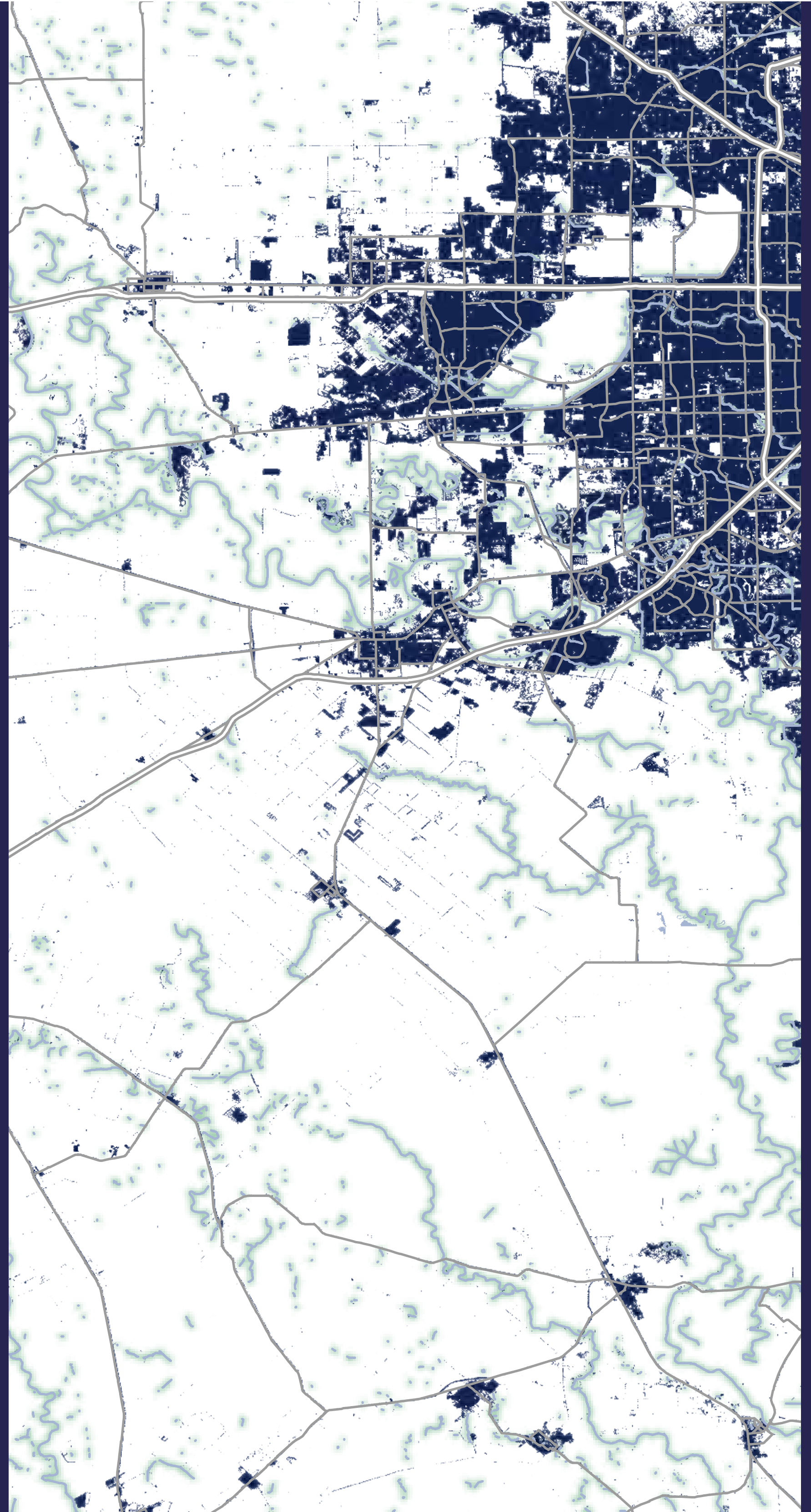
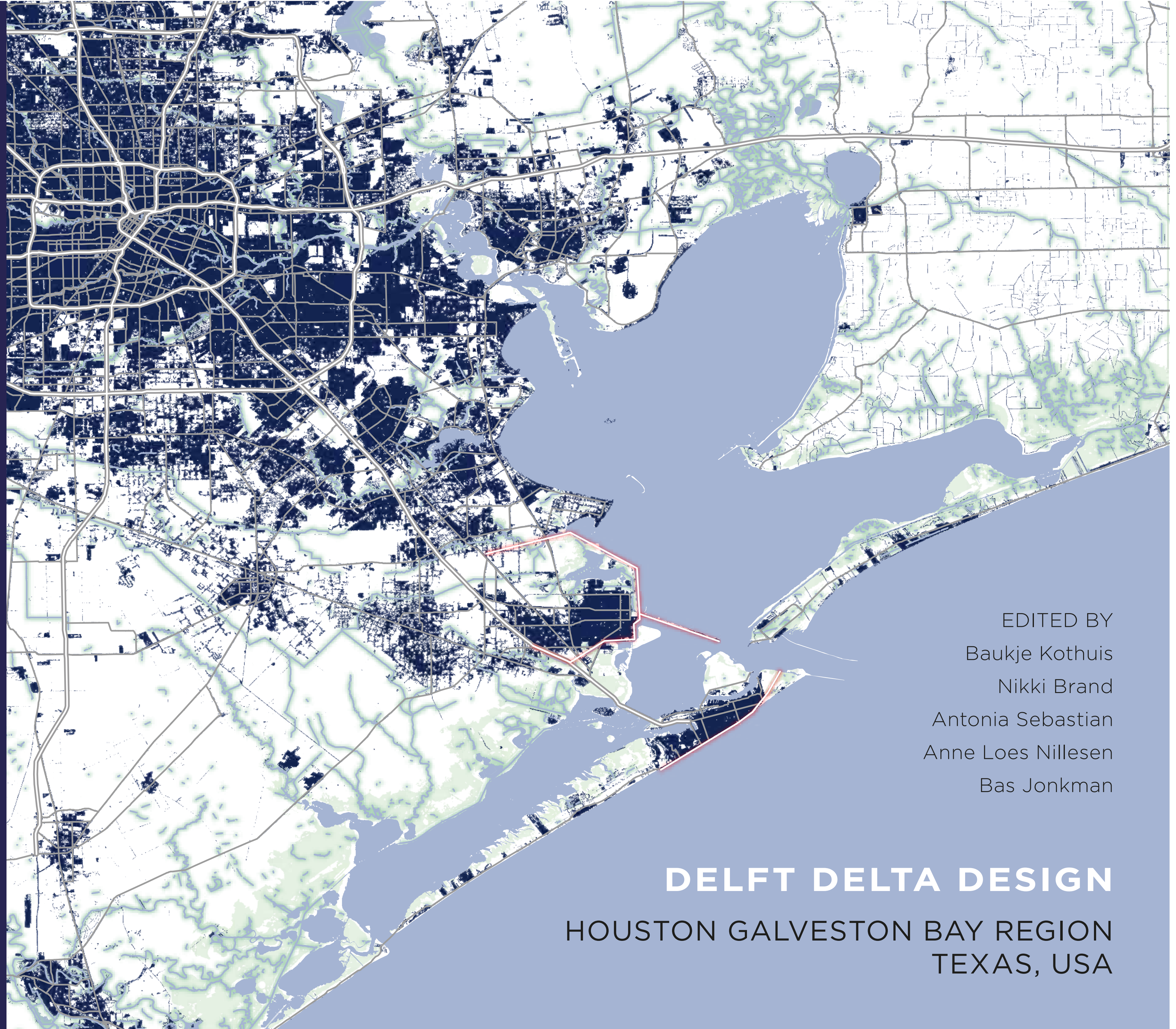


Kothuis, Brand, Sebastian, Nillessen, Jonkman (eds.)

DELFT DELTA DESIGN

HOUSTON GALVESTON BAY REGION



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# DELFT DELTA DESIGN

## HOUSTON GALVESTON BAY REGION
## TEXAS, USA

ENVIRONMENTAL CONDITIONS AND HUMAN ACTIVITIES

**Urbanization & infrastructure**

- Levee
- Urban development
- Primary road network
- Secondary road network

**Environment**

- Bodies of water
- Elevation zone </= 1 meter
- Elevation zone 1 - 3 meter
- Elevation zone 3 - 5 meter
- Elevation zone 5 - 7 meter
- Elevation zone > 7 meter
- Wetlands

**Administrative boundaries**

- County
- City

**Projects**

- # Project location with pagenumber