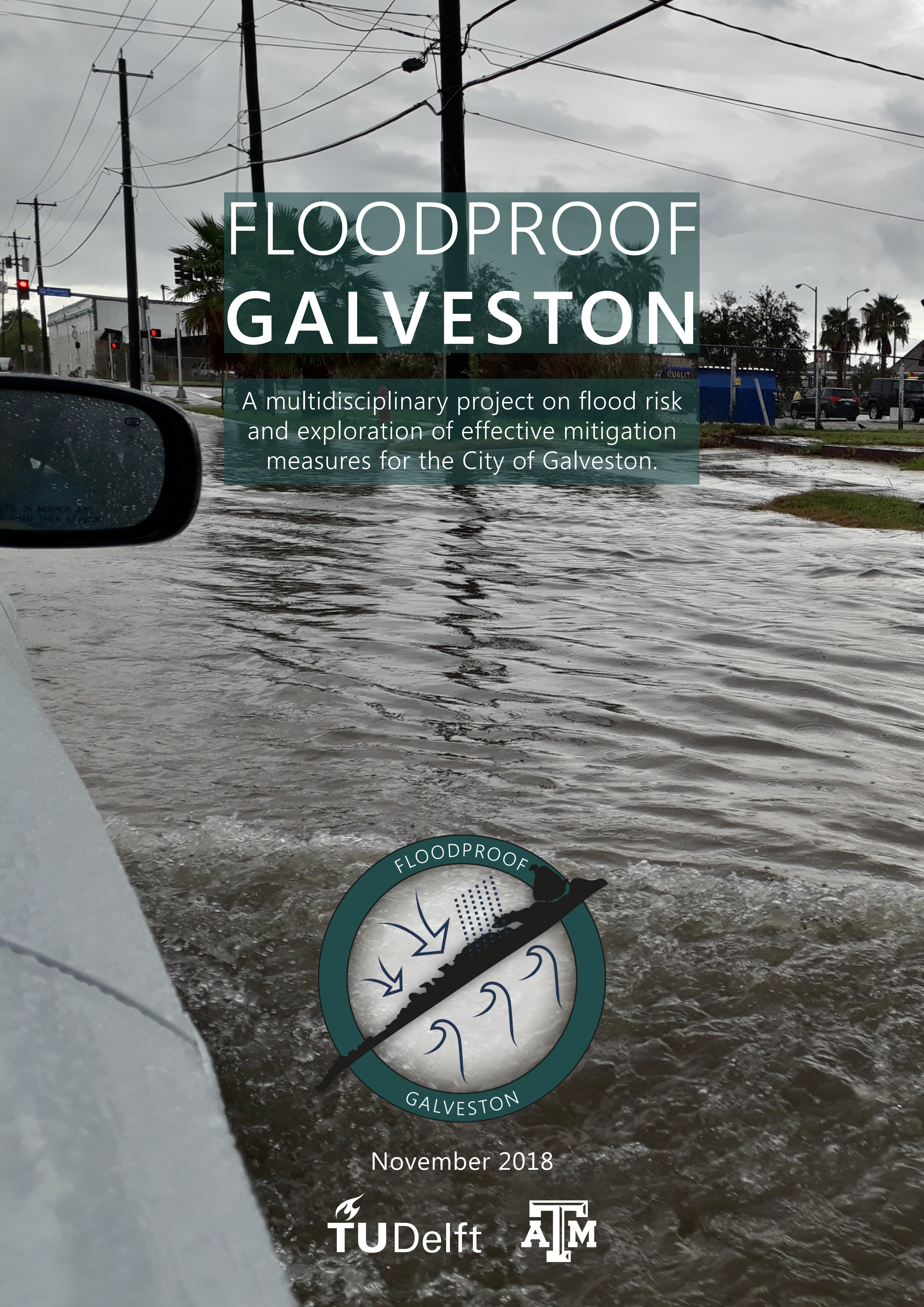

FLOODPROOF GALVESTON

A multidisciplinary project on flood risk and exploration of effective mitigation measures for the City of Galveston.

November 2018

Floodproof Galveston

A multidisciplinary project on flood risk and exploration of effective mitigation measures for the City of Galveston

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In close collaboration with:

TU Delft | Deltas, Infrastructures & Mobility Initiative

ATM CTBS
The Center for Texas Beaches and Shores

Nelen & Schuurmans

Lievense CSO
infra water milieu

Iv-Groep

Preface

This draft report is the concluding product of a research project on flood resilience of the City of Galveston, TX, USA. The research is part of the MSc program Civil Engineering and is conducted by a multidisciplinary group of students from the Faculty of Civil Engineering & Geosciences of the Delft University of Technology. The group, consisting of four students, contains three disciplines that are represented in this project: water management, hydraulic engineering and Integrated Design & Management (IDM). The combination of these disciplines allows for a more integrated approach than a single discipline would offer, although consensus on terminology is vital to prevent miscommunications. During the project, care was taken to clarify definitions and working methods to get all disciplines aligned.

The report is intended for those interested in pluvial, coastal and compound flooding issues in the City of Galveston.

We would like to express our gratitude to all parties that have contributed to this project. First of all our main supervisor Baukje Kothuis, who initiated the project and whose great support is highly appreciated by the group. We would also like to thank Dr. Brody of Texas A&M University for generously welcoming us and providing all necessary facilities and data to conduct this project. Thank you to our Dutch supervisors Frans van de Ven, Bas Jonkman, Erik van Berchum and Sander van Nederveen, who provided valuable feedback before, during and in the concluding phase of the project. We greatly value Sharon Tirpak's contribution to the hazard management section of this report. Furthermore, we would like to thank Antonia Sebastian, Carol Hollaway, Kayode Atoba and Russell Blessing for providing helpful information and data for our project. A final thank-you goes out to all residents who came to the residential stakeholder sessions, as their unique local insight proved to be valuable to our project.

Finally, we would like to thank our sponsors, whose efforts and financial assistance made it possible for us to carry out this project on location. A great thank-you to Nelen & Schuurmans for making available modelling software 3Di, and to DIMI, LievenseCSO and Iv-Groep for funding our project.

Galveston, Texas, United States of America, October 26th, 2018

Disclaimer

The information in this report is provided by the student-group Floodproof Galveston. It is intended to further scientific research, assist in increasing public knowledge and help in finding solutions for flood defense strategies. Conclusions are based on fieldwork, scientific research, literature studies and stakeholder interviews. The authors do not assume liability of any kind whatsoever resulting from any person's use or reliance upon the contents of this document.

Abstract

In the past, Galveston Island has suffered from several tropical storms and hurricanes. Some of them have had a tremendous impact on the City of Galveston and its inhabitants. Two recent hurricanes, Ike (2008) and Harvey (2017), caused significant damage and struck the city in different manners. While Hurricane Ike brought about high wind speeds and surge, Hurricane Harvey deposited extreme amounts of precipitation over the island.

There is a high probability that the City of Galveston will be struck again by a major hurricane. Hence, research is needed on mitigation measures that reduce the flood vulnerability of Galveston. More specifically, the simultaneous occurrence of surge and extreme precipitation is worth investigating, as currently little is known about the synergy between these aspects.

This report elaborates on how the risk of flooding in the City of Galveston can be mitigated, considering the influences of extreme pluvial, coastal and compound flooding.

In order to provide adequate mitigation measures, a vulnerability analysis is performed on the City of Galveston using hydraulic modelling software. Furthermore, a stakeholder and system analysis is done for all relevant stakeholders. Their respective interests, influence and interactions are mapped in a power-interest diagram and tube model. In addition, three residential stakeholder focus sessions were organized which provided valuable validation of the model and evaluation criteria for designs.

The flood vulnerability of the City of Galveston is not merely limited to a single area. Vulnerability maps and an inventory of critical infrastructure show that Galveston has various bottlenecks scattered around the city. A crucial result of the analysis was that flood risk issues in Galveston can be divided into two aspects: nuisance flooding by regularly occurring precipitation and flooding due to hurricanes. This distinction is reflected in the proposed mitigation measures, as they require a fundamentally different approach. While damage caused by nuisance flooding can be fully prevented with the proposed measures, damage resulting from hurricanes can at best be mitigated.

A comprehensive plan containing preliminary measures for both flooding scenarios is proposed for the City of Galveston. As part of this integrated plan, thirteen projects are defined which are elaborated in this report. Proposed measures to prevent damage originating from nuisance flooding include retention and infiltration of stormwater, discharge by pumps and raising frontier roads. Measures that mitigate damage due to hurricanes include breakwaters, retractable barriers and shelters for vertical evacuation.

The authors recommend that more stakeholders are actively involved in interactive design sessions to make the plan more inclusive. Furthermore, for more accurate designs a probabilistic approach is preferred to the deterministic approach used in this report. In addition, more work is needed to elaborate on the design proposals as presented in this report.

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List of Abbreviations

AIRP	Galveston Scholes Airport *(Stakeholder)*
AUDU	Audubon Houston/Galveston *(Stakeholder)*
AV	Avenue (road section)
COL	Galveston College *(Stakeholder)*
CPS	Coastal Protection *(System)*
DDC	Depth Damage Curve
DDF	Depth-Duration-Frequency (curve)
DEM	Digital Elevation Model
DRA	Drainage *(System)*
ECO	Economical *(Stakeholder)*
EDU	Educational *(Stakeholder)*
EPA	*see US EPA (Stakeholder)*
FED	Federal Government *(Stakeholder)*
FEMA	Federal Emergency Management Agency *(Stakeholder)*
FIRM	Construction Firms *(Stakeholder)*
GAIN	Galveston Association of Island Neighborhoods
GALV	Galveston City Council *(Stakeholder)*
GBF	Galveston Bay Foundation *(Stakeholder)*
GCBO	Gulf Coast Bird Observatory *(Stakeholder)*
GCC	*see GCCPRD (Stakeholder)*
GCCPRD	Gulf Coast Community Protection & Recovery District
GIS	Geographic Information System
GLO	General Land Office (Texas) *(Stakeholder)*
HOU	City & Port of Houston *(Stakeholder)*
IADC	International Association of Drilling Contractors
IDF	Intensity-Duration-Frequency (curve)
MOOD	Moody Gardens Theme Park *(Stakeholder)*
MSL	Mean Sea Level
NACO	Nature Conservancy *(Stakeholder)*
NAT	Natural *(Stakeholder) (System)*
NCC	Neighboring City Councils *(Stakeholder)*
NCOM	National Companies *(Stakeholder)*
N.D.	No Date
NHC	National Hurricane Center (NOAA)
NOAA	National Oceanic & Atmospheric Administration
NWS	National Weather Service (NOAA)
OFFA	Offatts Bayou, Teichmann Rd *(Stakeholder)*
PIER	Galveston Pleasure Pier *(Stakeholder)*
POL	Political *(Stakeholder) (System)*
PORT	Port of Galveston *(Stakeholder)*
PSU	Power Supply *(System)*
RAIL	Railroad Companies *(Stakeholder)*
Rd	Road (road section)
REC	Recreational *(System)*
RES	Residential *(Stakeholder)*
ROA	Road *(System)*
RORO	Roll-On-Roll-Off
RRO	Railroad *(System)*

SAF	Safety *(System)*
SEAW	Seawolf Park *(Stakeholder)*
SEW	Sewerage *(System)*
SMHI	Swedish Meteorological & Hydrological Institute
SOI	System of Interest
TAMU	*see TAMUG (Stakeholder)*
TAMUG	Texas A&M University at Galveston
TCEQ	Texas Commission on Environmental Quality *(Stakeholder)*
TSG	Texas State Government *(Stakeholder)*
TX	Texas
USA	United States of America
USACE	United States Army Corps of Engineers
US EPA	United States Environmental Protection Agency
UTI	Utilities *(Stakeholder)*
UTMB	University of Texas for the Medical Branch
WGI	*see WGIPOA (Stakeholder)*
WGIPOA	West Galveston Island Property Owners Association
WSU	Water Supply *(System)*
WWA	Waterway *(System)*
WWTP	WasteWater Treatment Plant

List of Symbols

C	Celsius
Dr	Drive (road section)
F	Fahrenheit
ft.	foot (feet)
ft^2	squared feet
hr.	hour
I-	Interstate Highway
in.	inch
in/hr	inches per hour
Inc.	Incorporated (company)
km/h	kilometer per hour
km	kilometer
km^2	squared kilometers
kt.	Kiloton
LCOM	Local Companies *(Stakeholder)*
LTD	Limited (company)
m	meter
m^2	squared meters
mi	mile
mi^2	squared miles
min	minute
mm	millimeter
mm/yr.	millimeters per year
mph	miles per hour
PM	Post-Meridian
St	Street (road section)
yr.	Year

1 Introduction

In the past, Galveston Island has suffered from several tropical storms and hurricanes (Roth, 2010). Some of them have had a tremendous impact on infrastructure, the City of Galveston, and its inhabitants. A major hurricane that struck Galveston in 1900 called “The Great Storm” resulted in extensive damage and triggered the construction of the Seawall. To this date, the Seawall still is the main coastal defense structure.

More recently, two major hurricanes hit the region. In 2008, Hurricane Ike passed over the island, causing devastating flooding in the city (Berg, 2009). This hurricane exposed Galveston to storm surge high surge levels in the Galveston Bay, creating water levels of 4.0 m (13 ft.) above MSL (Rego & Li, 2010). The bayside of the City of Galveston has a low elevation compared to the rest of the city, making it vulnerable to coastal flooding. The combination of high surge levels in the Galveston Bay and low elevation of the urban environment made drainage by gravity of rainwater into the bay impossible (Hanna, 2017). In 2017, Hurricane Harvey had different characteristics than Hurricane Ike. This hurricane produced an extreme amount of precipitation, which caused flooding in the streets of Galveston (Blake & Zelinsky, 2018).

Although major hurricanes are particularly impactful, common rainfall events during the hurricane season can already cause local flooding issues. These heavy precipitation events floods streets as the drainage system is not able to discharge when high tide occurs simultaneously (Hanna, 2017). This type of flooding is defined in this report as “nuisance flooding”.

In order to allow for a more focused approach, this project is spatially limited to the urbanized part of the City of Galveston. The shaded area in Figure 1 shows the area of interest. Although no comprehensive mitigation measures will be proposed for areas outside of the area of interest, these parts are still considered in the design phase. Concerns and interests of stakeholders outside of the area of interest cannot simply be ignored and will inform the designs.

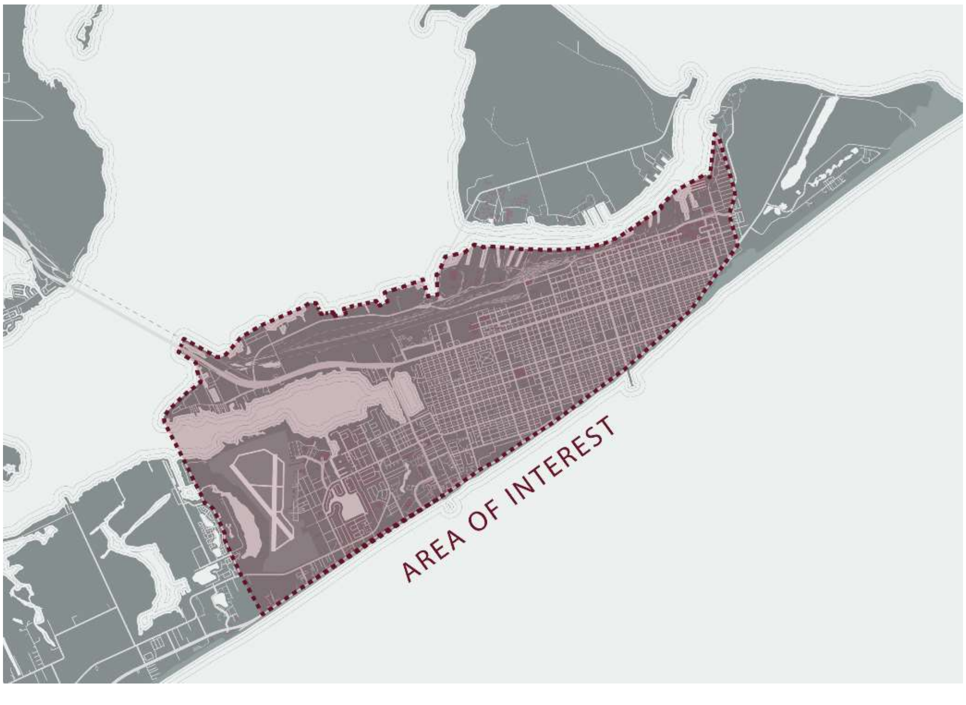

Figure 1 Area of interest

1 Introduction

The objective of this project is to investigate how flooding impacts the City of Galveston. Important subjects to investigate are the spatial and temporal scale of floods, as well as their causes. Furthermore, research is conducted on how flood related hindrance, damage and casualties can be mitigated. This is achieved by proposing a conceptual design which consists of an integrated set of projects.

In order to achieve our objective, the following research question is to be answered:

''How can the risk of flooding in the City of Galveston be mitigated considering the influences of extreme pluvial flooding, coastal flooding, and compound flooding?''

This report consists of two elements: an analysis and a first conceptual design proposal. Stakeholder engagement forms an important part of the input for design criteria. However, due to time constraints this is limited to residential stakeholders only. Furthermore, the project contains an analysis of all relevant stakeholders in the project, as well as an analysis of hydraulic and hydrological data. These analyses are combined into a risk and vulnerability map which greatly informs our design proposal. Due to time constraints, the integrated design has a limited level of detail. The design proposal is meant for preliminary purposes rather than an elaborate masterplan.

This report consists of nine chapters. Chapter 2 deals with the problem statement, in which the project goal is defined. Chapter 3 gives a description about the scenarios used. Several analyses are elaborated in chapter 4. In Chapter 5, designs & measures are discussed. Conclusions and recommendations are given in chapter 6.

2 Problem Statement

The issues this project aims to solve are defined. After this description the research question is addressed. This chapter concludes with an elucidation of which disciplines are involved in the Floodproof Galveston project and the methodology used.

2.1 Problem Description

The main issue in the City of Galveston is flooding due to extreme weather events, especially hurricanes. A hurricane event is associated with storm surge, intense precipitation, high wind force or a combination of these three. If this combination occurs, it is likely that compound flooding will be the result. This is currently the largest threat to Galveston Island.

However, nuisance flooding is a problem where Galveston's citizens are confronted with on a more frequent basis. Nuisance flooding can occur due to heavy rainfalls combined with either high tide or storm surge. These types of flooding are named pluvial flooding and coastal flooding, respectively. To protect the city against the latter type, measures were taken after the 1900 Storm. These measures involved building the Seawall and raising the City of Galveston, as is explained in Appendix A.8 Culture & History.

However, the Seawall does not protect the entire city from flooding. The main reason is an unequal elevation of the city. It has a downward slope from the southern part at the seawall towards the Port of Galveston in the north. Therefore, the northern part of the city is most vulnerable to flooding.

Due to the elevation differences on the island, water flows to lower lying areas and is retained there. This is especially a problem at Broadway, since Broadway is slightly elevated relative to connecting streets, as is shown in Figure 111 in Appendix A.1 Geography. It therefore actually functions as a small levee, where it blocks the water flowing from the southern part of the island towards the northern part. This causes streets to flood. Although drainage runs underneath Broadway, it cannot drain the city after a heavy precipitation event due to high tide. When high tide is passed, drainage capacity will increase again and water levels on the streets start dropping.

2.2 Research Question

In order to mitigate the problem of flooding, the following research question will be answered by the end of this report:

''How can the risk of flooding in the City of Galveston be mitigated, considering the influences of extreme pluvial, coastal, and compound flooding?''

To answer the research question, different research goals are formulated. These goals help gather and process information. An answer to this research question requires answering the following sub-questions:

- What are the locations of current protection structures, the regions of flooded areas and vulnerable locations?
- What are the causes of current flood related problems of the City of Galveston?
- What is the performance of the protection system of the city under the combination of past extreme events, hurricanes Ike (2008) and Harvey (2017)?
- What stakeholders are involved in this project and what are their interests?

- What are the concerns and demands of local residential stakeholders?
- What measures are available to minimize the probability of flooding and mitigate consequences in the event of flooding?
- What are the best-fit solutions for mitigating flood problems during extreme weather events?

Within this project, three disciplines combine their forces: Hydraulic Engineering, Water Management and Integral Design Management. Within these disciplines several topics are discussed. These are stated below.

The focus of Hydraulic Engineering on the project is:

- To analyze the coastal protection system;
- To investigate the influence of storm surge on the Seawall and the bayside of the island;
- To address the flood problems due to storm surge and wave impact in lower-lying areas.

From the view of Water Management, the project is on:

- Analyzing precipitation rates, runoff, storage and infiltration;
- Getting a qualitative and quantitative overview of water fluxes in the city (finding the water balance for Galveston);
- Creating a hotspot map of Galveston;
- Developing solutions that can prevent urban flooding.

From the point of view of Integral Design & Management:

- Stakeholders are analyzed to position their interests in the project;
- Hazard management is elaborated.

These topics are combined in a multidisciplinary design for the City of Galveston and the island.

2.3 Methodology

In the first weeks in Galveston fieldwork and orientating analyses are performed. The data following from the inventory and fieldwork is used in an analysis. The analysis consists of a stakeholder and system analysis, analysis to hydrodynamic parameters, a vulnerability scan and a water assignment. This forms a basis for the designs, which are a first impression of a possible course of action. A best-fit solution is chosen using a multi-criteria analysis (MCA). This MCA includes input requirements of residential stakeholders, technical feasibility and integration in existing infrastructure. The final chapter of the report contains conclusions of the analysis and designs, and recommendations for further research and design development.

3 Scenarios

This chapter elaborates on the scenario on which our analysis and designs are made. This forms a fundamental part of the report, as it stipulates boundary conditions and prospected changes to the environment. Four scenarios will be explained in this chapter, after which one is selected to form the basis for the design process. Section 3.6 Hydraulic Model 3Di is dedicated to explain the versatile hydraulic model (3Di) that is used to identify weak spots in the city.

Note: the four scenarios described below only discuss different hydrological conditions. Societal, economical and future projections are assumed to be equal for all cases and are discussed in Section 3.5 Selected Scenario in relation to the selected scenario.

3.1 Scenario I – Precipitation

The first scenario constitutes a heavy rain event in which the City of Galveston is exposed to severe precipitation with an intensity similar to that of Hurricane Harvey in September 2017 (see Figure 2). A local rain gauge near Nederland, TX recorded 1538 mm (60.58 in.) of total precipitation over 7 days (Blake & Zelinsky, 2018). This resulted in an average rain intensity of 9.1 mm/hr. (0.36 in/hr.), although higher intensities during the storm occurred and caused flash floods.

Depending on the tide, water can be drained relatively quickly by the storm drains, exposing the island primarily to short-term flooding. In this scenario, adequately storing and draining of precipitation is the primary challenge.

Figure 2 Urban flooding during Hurricane Harvey (Smialowski, 2017)

3.2 Scenario II – Storm Surge

The second scenario assumes a high tide plus storm surge comparable to that of Hurricane Ike in September 2008 (see Figure 3). In this case, the city is exposed to storm surge which threatens the built environment on all sides. Wave impact from the Gulf of Mexico on the Seawall is able to cause overtopping and flooding of the properties behind the Seawall. Moreover, the surge is able to flow into the Galveston Channel and flood the bayside of Galveston.

In this scenario, high wind speeds and storm surge are the main challenges to overcome.

Figure 3 Damage caused by Hurricane Ike (Harper, 2015)

3.3 Scenario III – Compound Flooding

This scenario assumes the simultaneous occurrence of both scenarios I and II: heavy precipitation is combined with a high tide and storm surge. This leaves the city vulnerable to flooding on both the bayside and Gulf of Mexico side while being unable to drain precipitation from the city. During high tide, discharge into the bay is not possible and a comparison to a bathtub can be made.

The main challenge in this scenario is to protect the built environment from coastal flooding, or at least mitigate damages and loss of life, while providing adequate opportunities for the rainwater to be stored or drained.

3.4 Scenario IV – Nuisance Flooding

A fourth scenario is considered in this report which is called nuisance flooding. Nuisance flooding is the type of flooding that occurs regularly. During the event heavy precipitation occurs simultaneously with high tide. So high water levels are present at both the south side and the north side of the island. Therefore, it is hardly possible to drain the rainwater in the bay. To let it infiltrate in the unsaturated zone of the soil is also difficult since the soil gets saturated pretty fast. Since water is collecting on the streets during a nuisance flooding event, traffic is being hindered. In conclusion, the nuisance flooding event shows the vulnerability of Galveston Island from four sides (see Figure 4).

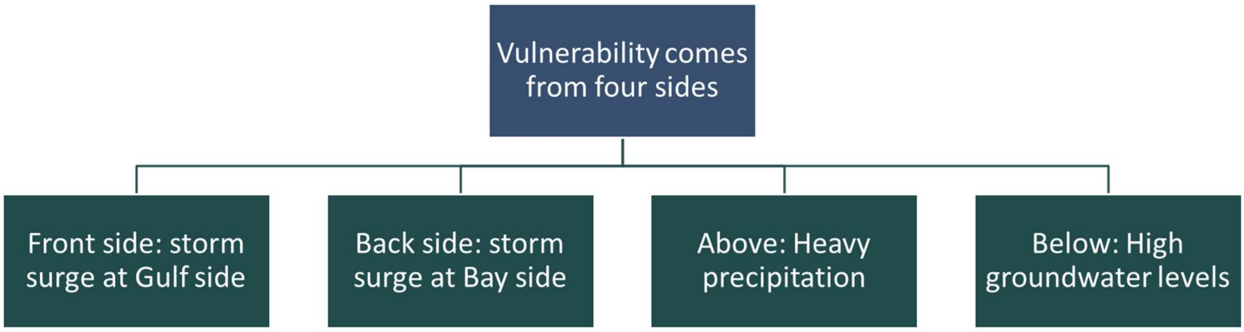

Figure 4 Vulnerable sides of Galveston Island during a Nuisance Flooding event

3.5 Selected Scenario

For the design of measures, Scenario III – Compound Flooding will be used. For a proper use of this scenario, the following data must be processed before they can be implemented in the model:

- Rainfall data according to future expectations. The IDF curves will be used to set up significant data;
- Analysis of the area of interest: land use, infiltration, drainage.

Besides extreme events as hurricanes, the focus is also on nuisance flooding as this is a more frequent issue and still causes significant hindrance and damage.

Hurricanes Ike and Harvey are combined to obtain a first analysis of the problems in the region. The surge levels of Ike and the rainfall data of Harvey have been implemented in the model. The results show a map of flooded areas and these results have been validated by the experience of residential stakeholders, as has been treated in Section 4.3 Vulnerability Analysis and Appendix C Residential Stakeholder Sessions. This will be the first step to make designs to increase flood resilience of the City of Galveston.

3.6 Hydraulic Model 3Di

In cooperation with Nelen & Schuurmans, a Dutch consultancy firm specialized in water issues in urban and rural environments, a hydraulic model has been developed which covers the entirety of Galveston Island. This model is based on the following input:

- A DEM of Galveston Island;
- A land use map;
- Boundary conditions for the sea and default water level;
- Discharge/infiltration capacity.

The model subdivides the island into grid cells which contain elevation data from the DEM and calculates whether flow can occur between cells using Saint-Venant shallow water equations. Furthermore, it applies land use data to assign (Manning) roughness coefficients to patches of land, which influence the flow resistance. Boundary conditions such as storm surge are added to the model to simulate Hurricane Ike-like tides. Lastly, a discharge value is added to compensate for drainage through the stormwater drains and infiltration losses.

This high-resolution model with pixel sizes of 10x10 m (~ 30x30 ft.) offers valuable insight into which spots in the city are the most vulnerable to flooding. As the model can handle precipitation, storm surge and a combination of the two, its versatility greatly helps to understand the consequences of compound flooding. The model is validated during the stakeholder sessions by comparing flooding experiences with the results produced by the model. This is further explained in Section 4.3.2 Stakeholder Engagement.

The model is used on multiple occasions throughout the project. The 3Di model returns a GeoTIFF GIS map with maximum inundation for any given scenario, which is needed in order to create a vulnerability map. This will be further elaborated in the analysis Chapter 4.3 Vulnerability Analysis.

4 Analysis

This chapter starts with an introduction of Hurricanes Ike and Harvey and the data of these hurricanes, which is used in the 3Di model. Then follows a system analysis and stakeholder analysis. Furthermore, a vulnerability analysis is performed, including a water assignment to calculate storage volumes. Hydrodynamic parameters *are defined for the design phase. The chapter concludes with a comparative analysis to hazard management for both the USA and the Netherlands. All assumptions and background data used for this analysis can be found in Appendices A.1 to A.9.*

4.1 Hurricanes

In 2008, Hurricane Ike passed over the island, causing devastating flooding in the city (Berg, 2009). This hurricane exposed Galveston to storm surge in the Galveston Bay, creating water levels of almost 4.0 m (13 ft.) above MSL (Rego & Li, 2010). The bayside of the City of Galveston has a low elevation compared to the rest of the city, making it vulnerable to coastal flooding. The combination of high surge levels in the Galveston Bay and low elevation of the urban environment made drainage by gravity of rainwater into the bay impossible (Hanna, 2017). For the scenarios, the storm surge during Ike is applied in the model. The storm has been treated in the paper of (Rego & Li, 2010). The storm surge is applied as an offshore boundary condition in the model. The data used shown in graph c in Figure 5, of which the measurement station is located at the north side of the Galveston Causeway bridge.

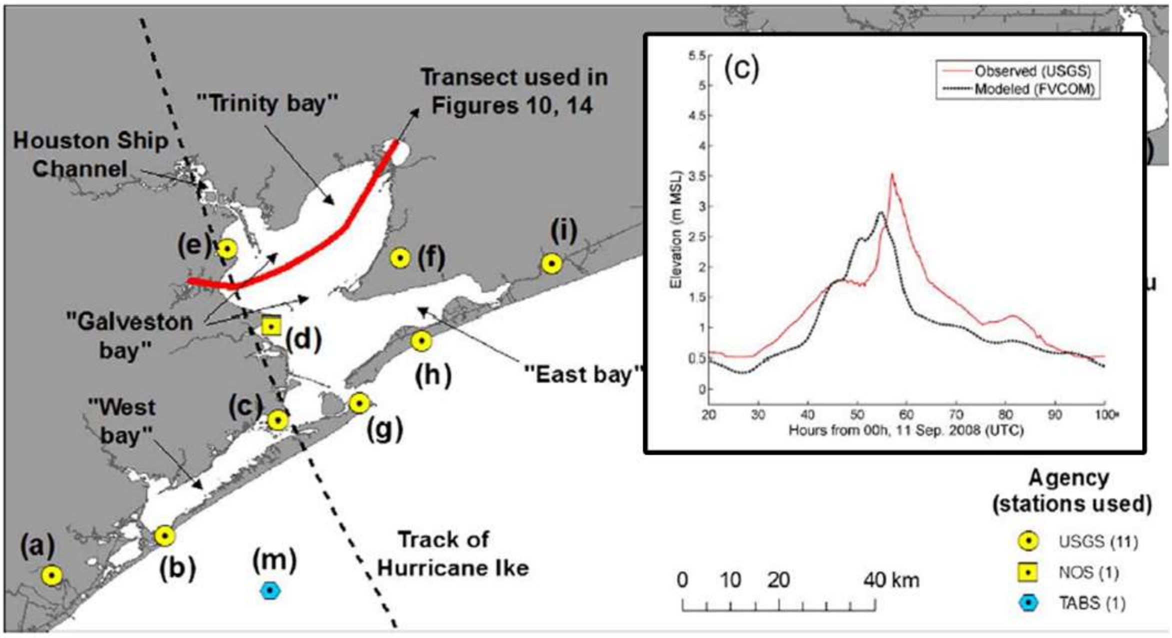

Figure 5 Storm surge during Hurricane Ike measured at location C (Rego & Li, 2010)

In 2017, Hurricane Harvey had different characteristics than Hurricane Ike. This hurricane produced an extreme amount of precipitation, which caused pluvial flooding in the streets of Galveston (Blake & Zelinsky, Tropical Cyclone Report Hurricane Harvey, 2018). The intensity of rainfall during Hurricane Harvey is used in the model. Within 7 days, an amount of 1538 mm (60.58 in.) rainfall dropped in Nederland, TX. The average rainfall intensity is 9.1 mm/hr. (0.36 in/hr.). However, higher intensities are used in the model to account for peak rainfall intensities.

4.2 System & Stakeholder Analysis

Within each project there are stakeholders. These are interest groups and interest systems interacting with the project, e.g.; individuals, groups, institutions, but also the natural environment. Expectations and demands of the project can be different for each stakeholder and the position of stakeholders compared to each other differs per project. Some stakeholders have more power than others, potentially giving them more direct influence early in the project. However, the importance of less influential stakeholders is not to be underestimated, as these parties can cause significant delays the implementation phase of the project. Also, some stakeholders might have more interest in flood resilience than others. Therefore, gathering information on stakeholders will help define boundary conditions and evaluation criteria for our design alternatives.

In this project, a distinction is made between five groups of general stakeholders as all stakeholders can be classified as part of one of these groups:

- Political stakeholders;
- Economical stakeholders;
- Residential stakeholders;
- Educational stakeholders;
- Environmental stakeholders.

It is acknowledged that residential stakeholders have a large interest in this project, since it concerns their living environment. To get more information on their view of flood related problems and their opinion on how these problems should or should not be solved, residential stakeholder focus meetings were organized. These meetings are elaborated in section 4.2.1 Residential Stakeholder Sessions.

It is important to analyze all groups of stakeholders mentioned above. Stakeholders are recognized to be part of a SOI (System of Interest), which consists of several subsystems. Stakeholders are coupled to one or more of these subsystems. The product of the amount of subsystems to which each stakeholder is coupled and the influence of each subsystem into the SOI, represents the amount of influence of each stakeholder in the project. This can subsequently be expressed as a combination of power and interest.

In this section system and stakeholder analyses are analyzed. After the section on the residential stakeholder sessions, the relationship between systems and stakeholders is explained. Thereafter, the System of Interest (SOI) is defined, after which subsystems are identified. Subsequently, stakeholders relevant to this project are described and linked to the subsystems. Finally, all elements described above are connected into a tube model, showing the elements and their relations to each other.

4.2.1 Residential Stakeholder Sessions

Three residential stakeholder focus meetings were organized to investigate the concerns that residents of Galveston Island have regarding flood risk and mitigation. These sessions served to clarify their values and stakes, and gave us an insight in their ideas about what measures they would like or dislike to see taken concerning their flood resilience. The residents who were involved, are representatives of:

- Galveston Association of Island Neighborhoods (GAIN);
- West Galveston Island Property Owners Association (WGIPOA);
- Residents from Offatts Bayou and Teichman Rd.

They were asked to express their experience, wishes and concerns regarding local flooding and flood mitigation in Galveston. The stakeholders were asked to draw the answers to the following questions on a topographical map and then explain their reasoning:

1. Where does it flood based on personal experience and why?
2. Where are protection measures from any kind not wanted and why?
3. Where are protection measures from any kind wanted and why?

Furthermore, the residents were asked to comment on various plans and ideas to protect the wider Houston-Galveston Bay region, presented over the past decades by universities, local organizations and the US Army Corps of Engineers, as well as the recent design alternatives presented to the citizens of Galveston in August 2018 by USACE Galveston. Their concerns about flooding in the City of Galveston in general, provided great insight into the main challenges from a local perspective.

The results of the three focus meetings have been summarized in aggregated maps in C Residential Stakeholder Sessions.

To accurately define the roles of stakeholders in a project, they are related to certain systems within a project structure. To accomplish this, System Engineering theory is used to make those distinctions. The theory is derived from (Wasson, 2015). One starts with defining a SOI, which is the system that is to be developed or improved. Within and around this SOI, several subsystems are coupled that have a particular influence on the SOI. This is visualized in a so-called Tube Model, which is shown in Section 4.2.5 System Overview and Figure 6.

When the SOI and subsystems are defined, the stakeholders are linked to these systems. Some stakeholders are linked to multiple systems, while others are linked to just a single system. The more systems a stakeholder is linked to, the more influence that stakeholder has on the SOI. With this information a Power-Interest Diagram is created, showing the position of stakeholders relative to each other based on two criteria: 1) the influence they have on a project, and 2) the interest they have in the project.

The information that results from the steps above form the basis for stakeholder implementation in the design phase of a project. With stakeholder input, improved testing criteria are developed, which will result in a design that is more integrated from a multidisciplinary perspective.

4.2.2 System of Interest

The System of Interest is defined as follows: Flood resilience of the City of Galveston

The flood resilience of the City of Galveston is currently considered to be inadequate and in need of improvement. Flood resilience implies the resistance to or the capacity of a system element to recover quickly from a flood event. The risk of flooding, defined as the probability of flooding times the consequences of flooding, is expanded with adaptability of the system element against the risk of flooding.

4.2.3 Subsystems

Two types of subsystems are classified: internal and external subsystems. They are further elaborated in this paragraph.

Internal Subsystems

Internal subsystems are directly related to the SOI. Any change in these systems will directly affect the SOI. These are listed in Table 1.

Table 1 Internal subsystems

Safety System	Contains measures, strategies and procedures that support safety and control processes during hazards, such as evacuation prior to hurricanes
Coastal Protection System	The system of coherent structures that protect the city and island against flooding due to storm surge and wave impact. The Seawall is part of this system
Drainage System	Contains the network of all pipes, drains and pumps that transport water from the streets due to rainfall towards the Galveston Bay, in which the water is being exposed

External Subsystems

External systems are systems that influence the SOI up to a certain level. Some subsystems have more influence than others. The subsystems considered in this project are listed in Table 2 below:

Table 2 External subsystems

Political System	Includes all administrative bodies on federal, state, and county (local) level. Included are all departments and organizations that operate on behalf of the government.
Nature System	Includes the natural areas, such as wildlife parks and city parks, as well as environmental quality management (air, water, soil quality)
Power Supply System	Contains the network of cables, sources and transformers that supplies electricity to users
Water Supply System	Contains the network of conduits and pumps, as well as the drinking water facility, which supplies water to users
Sewerage System	Contains the network of conduits and pumps, as well as the water treatment plant, which transports and cleans wastewater from users, and disposes it into the Galveston Bay
Recreational System	The set of entertainment industries and its users, such as theme parks and theatres
Road System	Contains the network of local, regional and national roads and highways, as well as its users
Railroad System	Contains the network of local, regional and national railroads, as well as its users
Waterway System	Contains the network of local, regional and (inter)national waterways, as well as its users. The City of Galveston is located along global shipping routes, which are part of this system

The relation to and influence of the external subsystems on the SOI is shown in Figure 6.

4.2.4 Stakeholder Involvement

Stakeholders have a major influence in a project and should be involved before defining requirements or designing anything. First, the stakeholders will be introduced, after which their stakes are explained and how they are coupled to the subsystems.

Stakeholders

There are various stakeholders with different interests. As was explained earlier, these persons and organizations can be divided in five categories: 1) political, 2) economical, 3) residential, 4) educational, and 5) environmental stakeholders. A complete list of all stakeholders and an explanation of their activities can be found in Appendix D Systems & Stakeholders. The stakeholders listed per category are shown in Table 3.

Table 3 Stakeholders involved in the project

Political Stakeholders

- Galveston City Council
- Texas State Government
- Texas General Land Office
- Federal Government
- US Army Corps of Engineers
- Neighboring City Councils
- Texas Commission on Environmental Quality
- US Environmental Protection Agency
- Federal Emergency Management Agency
- Gulf Coast Community Protection & Recovery District

Economical Stakeholders

- Local Companies
- (Inter)National Companies
- Port of Galveston
- Railroad Companies
- Utilities
- City & Port of Houston
- Galveston Airport
- Pleasure Pier Galveston
- Moody Gardens Theme Park
- Construction Firms

Residential Stakeholders

- Offatts Bayou, Teichman Rd
- Galveston Association of Island Neighborhoods
- West Galveston Island Property Owners Association

Educational Stakeholders

- Galveston College
- Texas A&M University at Galveston
- University of Texas for the Medical Branch

Environmental Stakeholders

- Nature Conservancy
- Audubon Galveston
- Galveston Bay Foundation
- Gulf Coast Bird Observatory
- Seawolf Park

Stakes
All stakeholders have interests in the project. The individual interests are listed in Appendix D Systems & Stakeholders. The general interests per category are stated below. These are assumed to be generally known.

Political interests
- To perform tasks that contribute to improvement and sustainable development of relations between residents, businesses and natural environment;
- To protect people against threats and assist during natural hazards;
- To make and execute laws, rules and regulations and guarantee that these will be respected.

Economic Interests
- To make profit by selling goods and services;
- To strengthen market position in the state, country, or worldwide;
- To facilitate recreation.

Residential Interests
- To improve safety against flooding without damaging personal value;
- To take care of people when needed (UTMB, Hospital).

Educational Interests
- To teach people about various disciplines;
- To enlarge the body of knowledge by conducting research and spreading knowledge.

Environmental Interests
- To protect and improve biodiversity in the Galveston Bay and the Gulf of Mexico;
- To protect species that are being threatened in the region.

Influence on Subsystems
As mentioned before, the linking of stakeholders to subsystems is useful to measure their influence on the SOI. The more links a stakeholder has, the more powerful this stakeholder is. In Appendix D Systems & Stakeholders, Table 63 shows the links between the stakeholders and the subsystems.

4.2.5 System Overview
Regarding the information described in the previous sections, the resulting system overview is determined, as well as the influence and power of the stakeholders.

Tube model

The Tube Model contains the SOI, internal and external subsystems, and the stakeholders linked to these subsystems. The Tube Model is shown in Figure 6.

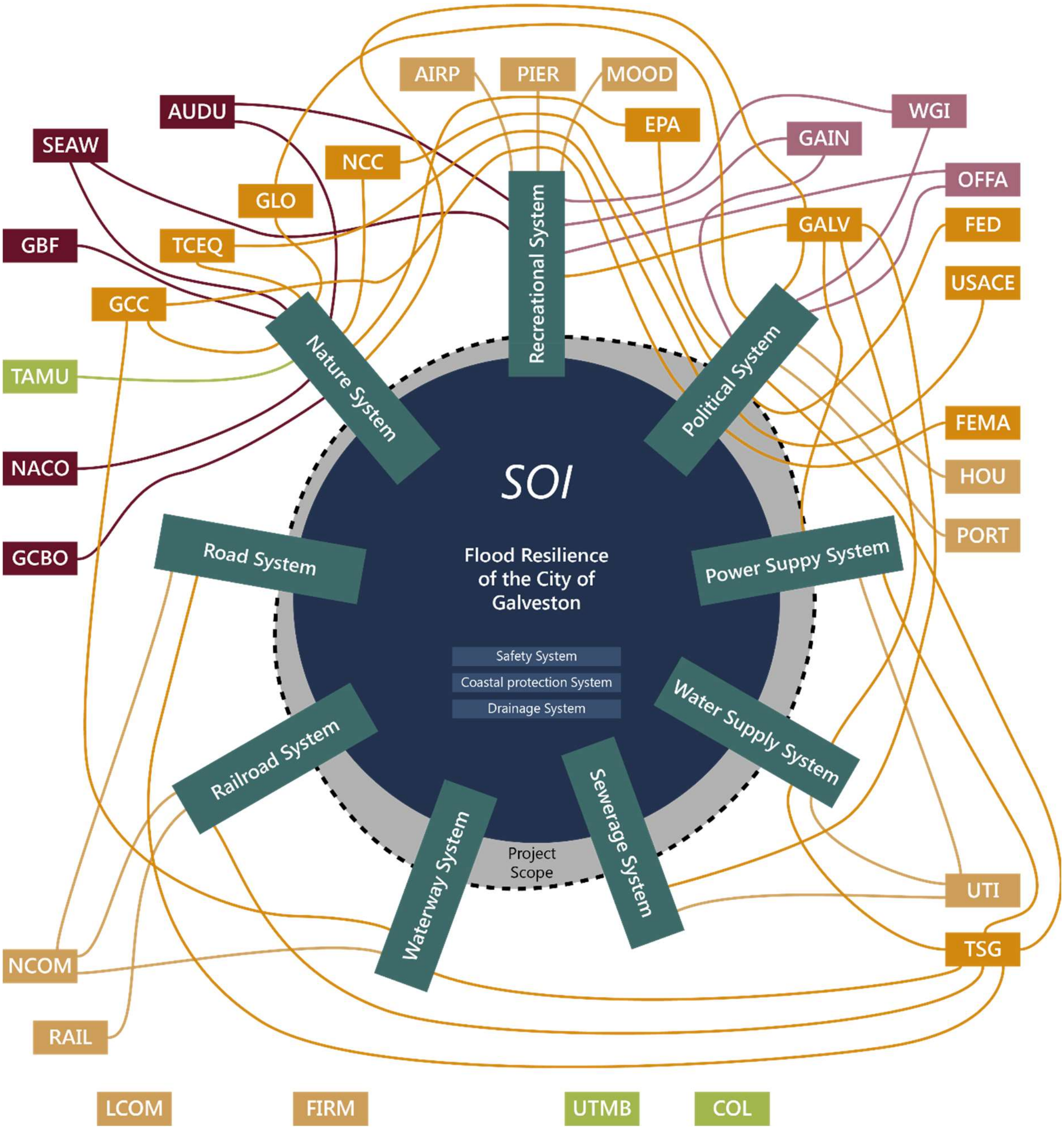

Figure 6 Tube Model

The nine subsystems all have a different amount of influence in the SOI. They also have a share in the project, which is visualized with the project scope. The political system has an average influence in the SOI, but a large share in the project scope. Therefore, political stakeholders have a large influence on decisions concerning designs in this project. The sewerage system has a large share in the SOI, and a relatively large share in the project as well. The recreational system does not have a large share in both the SOI and the project, compared to the other systems. As a result, stakeholders that are linked to the recreational system do not have large influence on the SOI and the project. In this way, the importance of the stakeholders involved in the project are determined.

Power & Interest Diagram

Now that the position of subsystems and stakeholders relative to the SOI are defined, the Power-Interest diagram shown in Figure 7 is made. This shows the power on and interest in the project stakeholders have relative to each other.

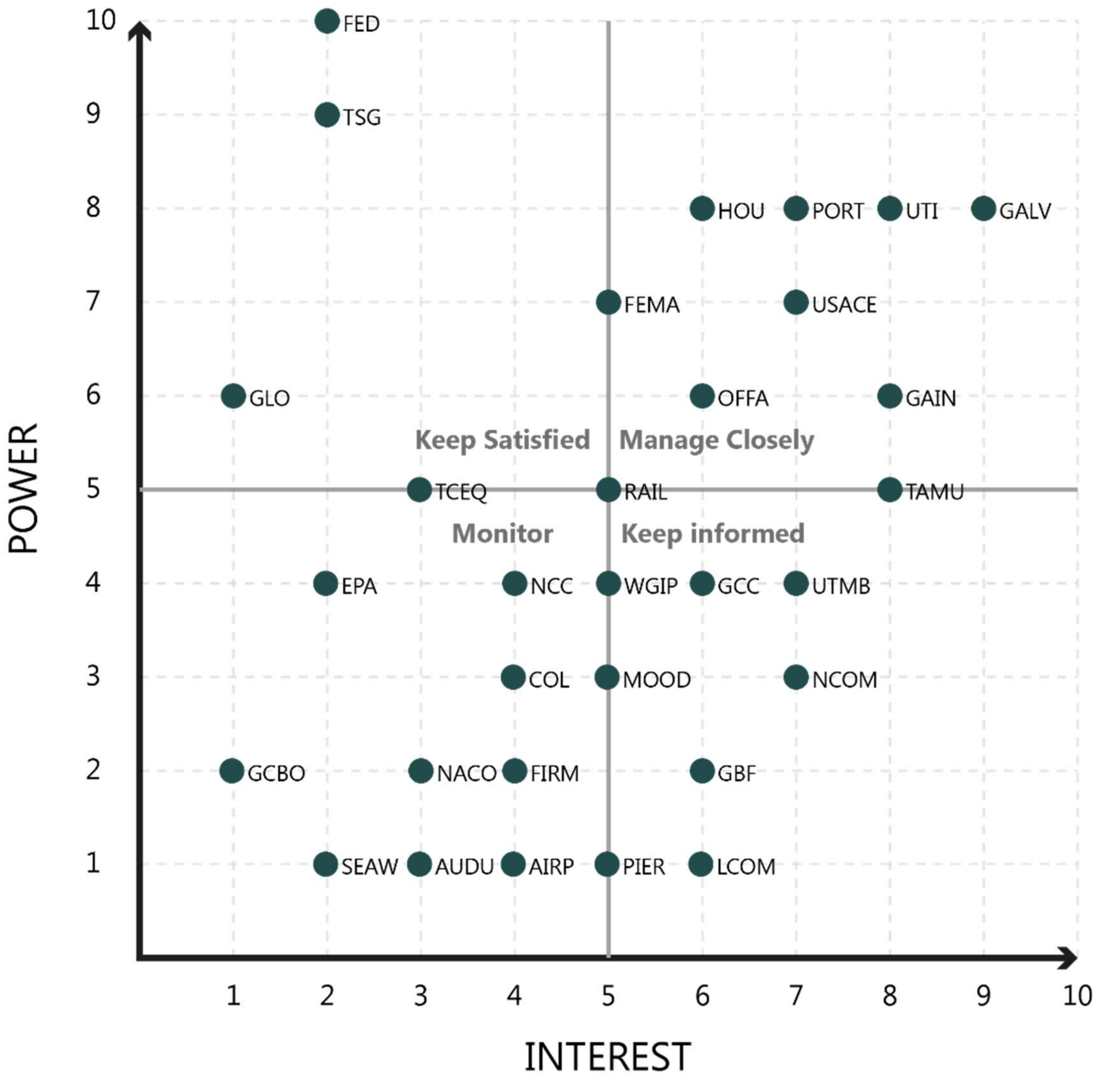

Figure 7 Power-Interest diagram

The explanation of the position of the stakeholders is summarized in Appendix D Systems & Stakeholders.

Some of the stakeholders with large influence in the project are: the Galveston City Council, the Port Authorities, and Residents. They have many reasons to want or not to want certain solutions for flood issues. Documentation of the stakeholder sessions with the three groups of residents can be found in Appendix C Residential Stakeholder Sessions. Herein, the most important reasons are explained why residents desire certain measures at a location or why not. These opinions will be considered in the design phase.

4.3 Vulnerability Analysis

In this section, a thorough analysis of the flood vulnerability of the City of Galveston is made, which will be guiding input for the design measures. The leading approach in this section is derived from the 'Handleiding Stresstest' (Buma, van de Ven, & Vos, 2014), which is a guide developed by the Dutch government for both assessing the climate vulnerability of cities and providing a framework for developing an adaptation plan. The stress test consists of two phases:

1. Conducting a vulnerability scan;
2. Creating an adaptation planning.

This section only covers the vulnerability assessment of this approach; the adaptation plan is covered later in Chapter 5 Design Measures. Five components are distinguished in this section: an initiative for the vulnerability scan, results from engaging stakeholders, identification vulnerable objects and critical infrastructure, creation of a vulnerability map and an explanation of the urgency for adaptation.

4.3.1 Initiative of the Vulnerability Scan

The initiative of the vulnerability scan involves obtaining a first overview of how vulnerable infrastructure is distributed across the City of Galveston. Hazard mitigation plans developed by the City of Galveston provide a comprehensive overview on vulnerable infrastructure (City of Galveston, 2012). Furthermore, during fieldwork trips an effort was made to map vulnerable infrastructure such as the Galveston County Jail. The reports of these fieldwork trips can be found in Appendix B Fieldwork. The hazard mitigation plans, combined with fieldwork experience, result in a map showing vulnerable infrastructure, which is presented in Figure 8. This figure is presented in a larger format in Appendix E.1 Vulnerability Map.

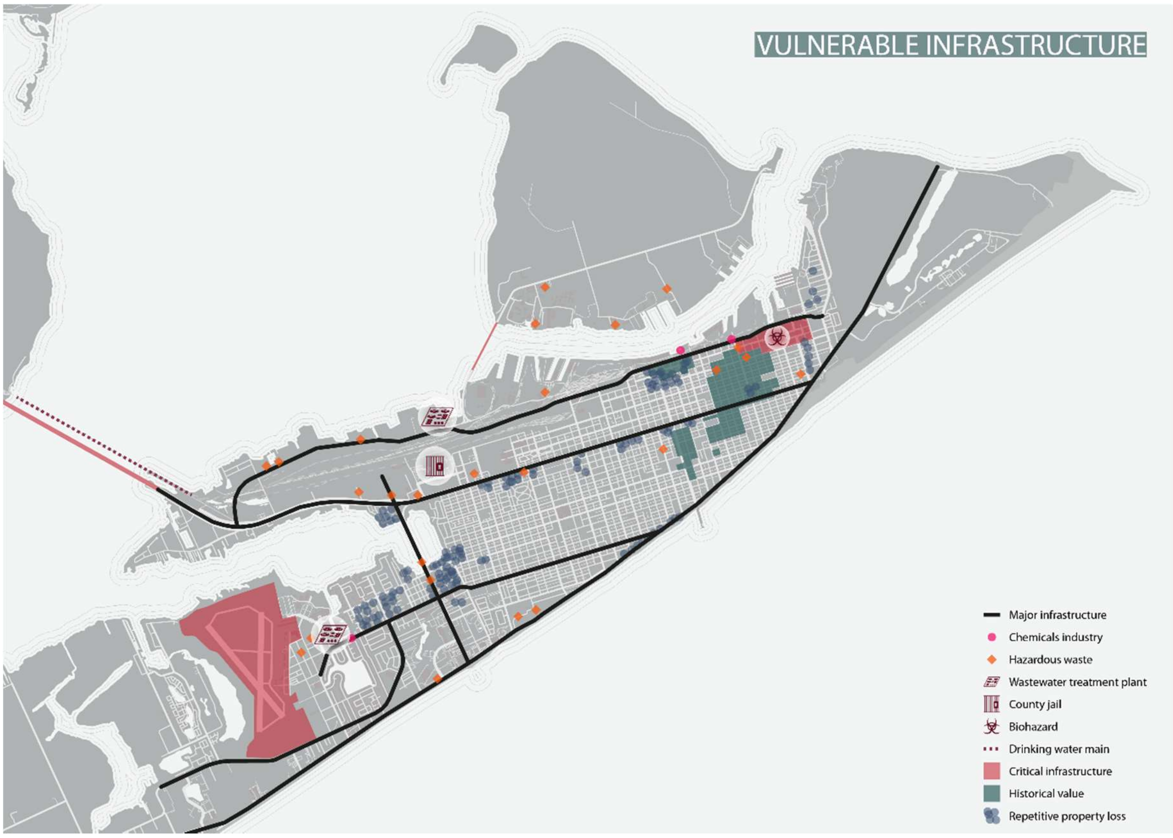

Figure 8 Map that shows vulnerable spots of the City of Galveston that were notified during fieldwork trips on the island

As can be seen in the legend of Figure 8, several types of vulnerable infrastructure and spots are identified. The major infrastructure is highlighted in black. This infrastructure is likely to be used during an evacuation for a hurricane. Pink dots indicate chemical industries and orange diamonds indicate places where hazardous waste is stored. They can cause large problems when flooded. The city has two wastewater treatment plants (WWTP). These two plants are marked as vulnerable spots in the map as well, just as the county jail on the island. On the east side of the city, UTMB is located. At their location on Galveston Island is a biolab that contains safes with a large amount of biologically hazardous substances. These facilities should be protected at all costs. Furthermore, the critical infrastructure is highlighted with a red shade. An example is the airport which can be used to evacuate people or receive goods after a hurricane hit the island.

4.3.2 Stakeholder Engagement

The goal of the vulnerability scan is to create maps that clearly show which spots on the island are most in need of adaptation. These are the so-called hotspots. However, to create such a hotspot map, various data is needed on characteristics of the City of Galveston. This data can partially be found in open sources. However, valuable knowledge cannot be found by using these open sources but can be obtained from local stakeholders. Therefore, it is important to involve these stakeholders in the conduction of the vulnerability scan of the City of Galveston. Furthermore, the stakeholders engaged in this project live on the island and provide unique local insight and knowledge.

Engaging stakeholders in three stakeholder sessions

To involve stakeholders in conducting the vulnerability scan, three stakeholder sessions were organized. These sessions took place on the 11th, 12th and 13th of September 2018, during which citizens from, respectively, GAIN, WGIPOA and Offatts Bayou & Teichman Rd were invited to share their concerns and ideas. Each of these stakeholder sessions was divided in three parts. During each part, the stakeholders were provided a map of Galveston Island and in this map they were asked to draw the following information:

- Part 1: Draw where water will be during pluvial, coastal and compound flooding according to your very own experiences;
- Part 2: Draw where you absolutely do not want any protection against these three types flooding;
- Part 3: Draw where you do want protection against these three types of flooding.

The maps that were created in the first part are important for validating the flood model that was described in Section 3.6 Hydraulic Model 3Di. The maps produced in part 2 and part 3 of the sessions will help during the design part in Chapter 5 Design Measures of the project. It will help to estimate which potential designs should be included or excluded in the elaboration of the designs, taking into account the notions of the stakeholders. The maps that were created by the stakeholders during the sessions are found in Supplements I, II, and III for Tuesday, Wednesday and Thursday, respectively.

To present a clear overview, a summary of all these maps has been made for the three different days of stakeholder meetings. Figure 9 shows the key findings for the stakeholder session organized on the 11th of September. Figure 10 displays the map produced by the stakeholders on September 12. The map displayed in Figure 11 shows the results of the session that was held on the 13th of September.

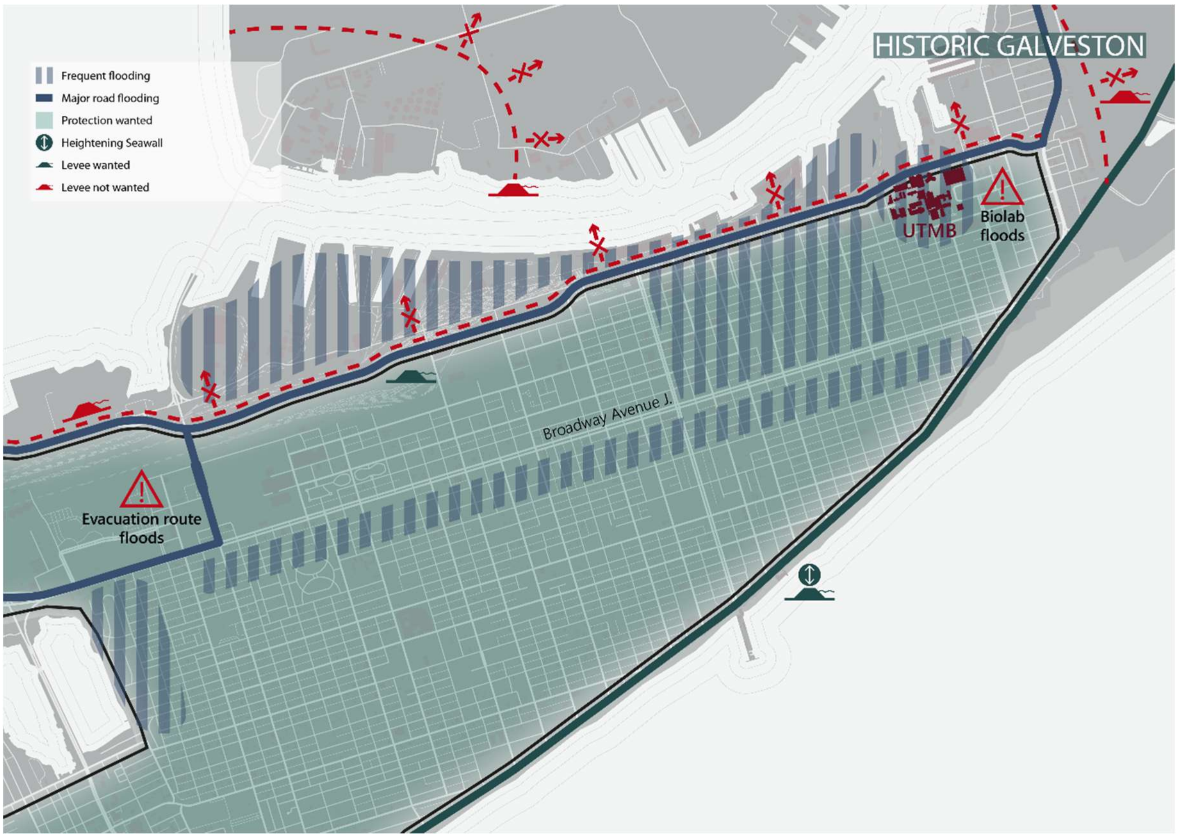

Figure 9 Summary of findings of session 1, where the stakeholders represented the citizens of GAIN

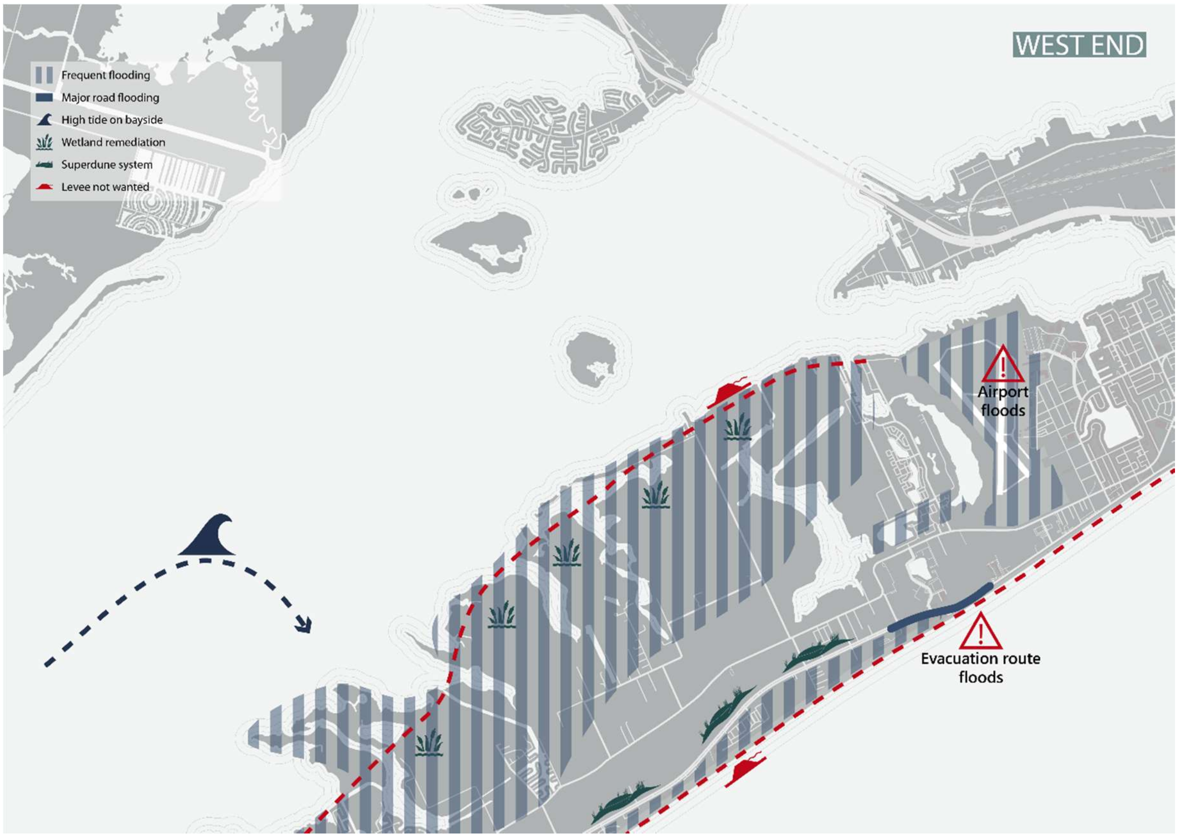

Figure 10 Summary of findings of session 2, where the involved stakeholders are citizens of WGIPOA

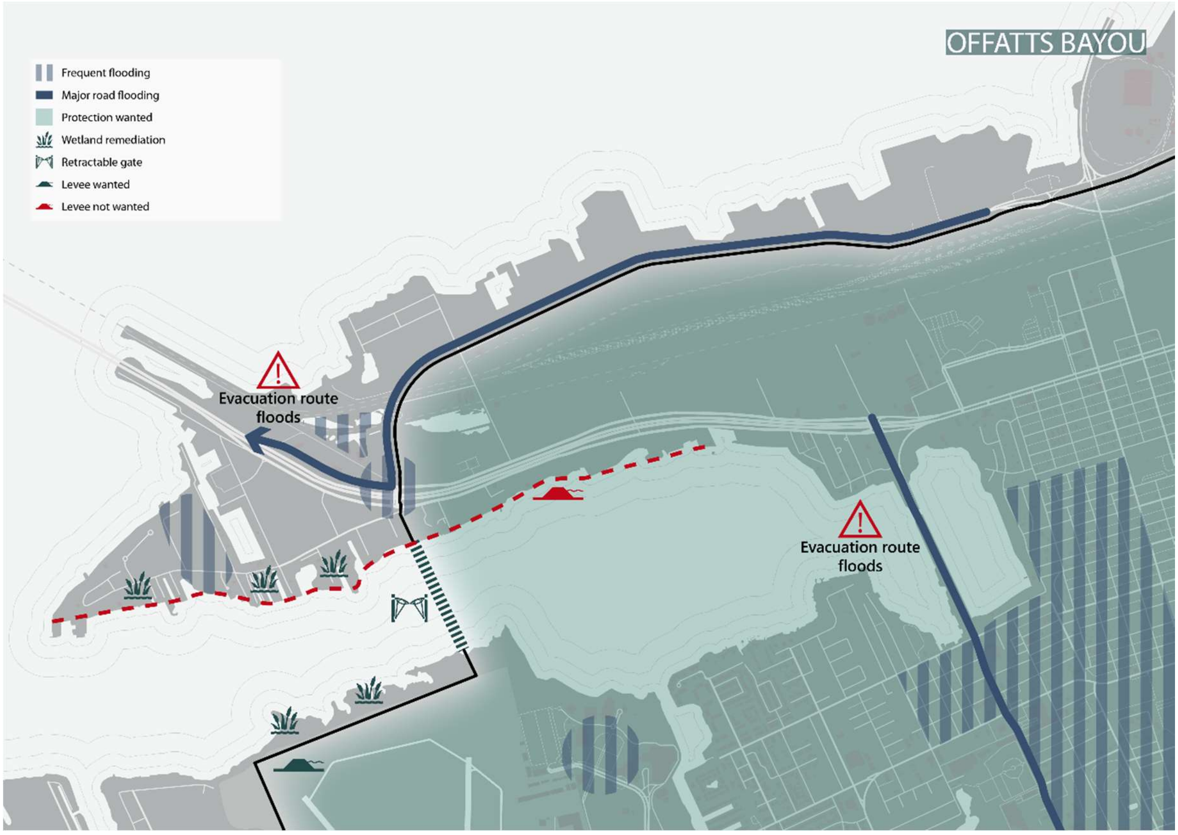

Figure 11 Summary of findings of session 3, where citizens of Offatts Bayou & Teichman Rd presented their concerns

4.3.3 Vulnerability Map

The ultimate goal of the vulnerability scan is to obtain a clear overview of the highest detrimental effects due to compound flooding. This overview is shown in a so-called hotspot map. There are multiple steps involved in the process of creating such a hotspot map. These steps are outlined in Figure 12, which is adapted from (van de Ven, 2018).

Firstly, a hazard map is created which shows the consequences of flooding for a given scenario. In this report, a map with the maximum water height above street level serves this purpose. Secondly, the inundation map is translated into a risk map by adding the damage sensitivity. Finally, by integrating the adaptability of the built environment a hotspot map is produced which shows the vulnerability of the city. This section continues with an explanation of how to perform all these steps in order to obtain the hotspot map.

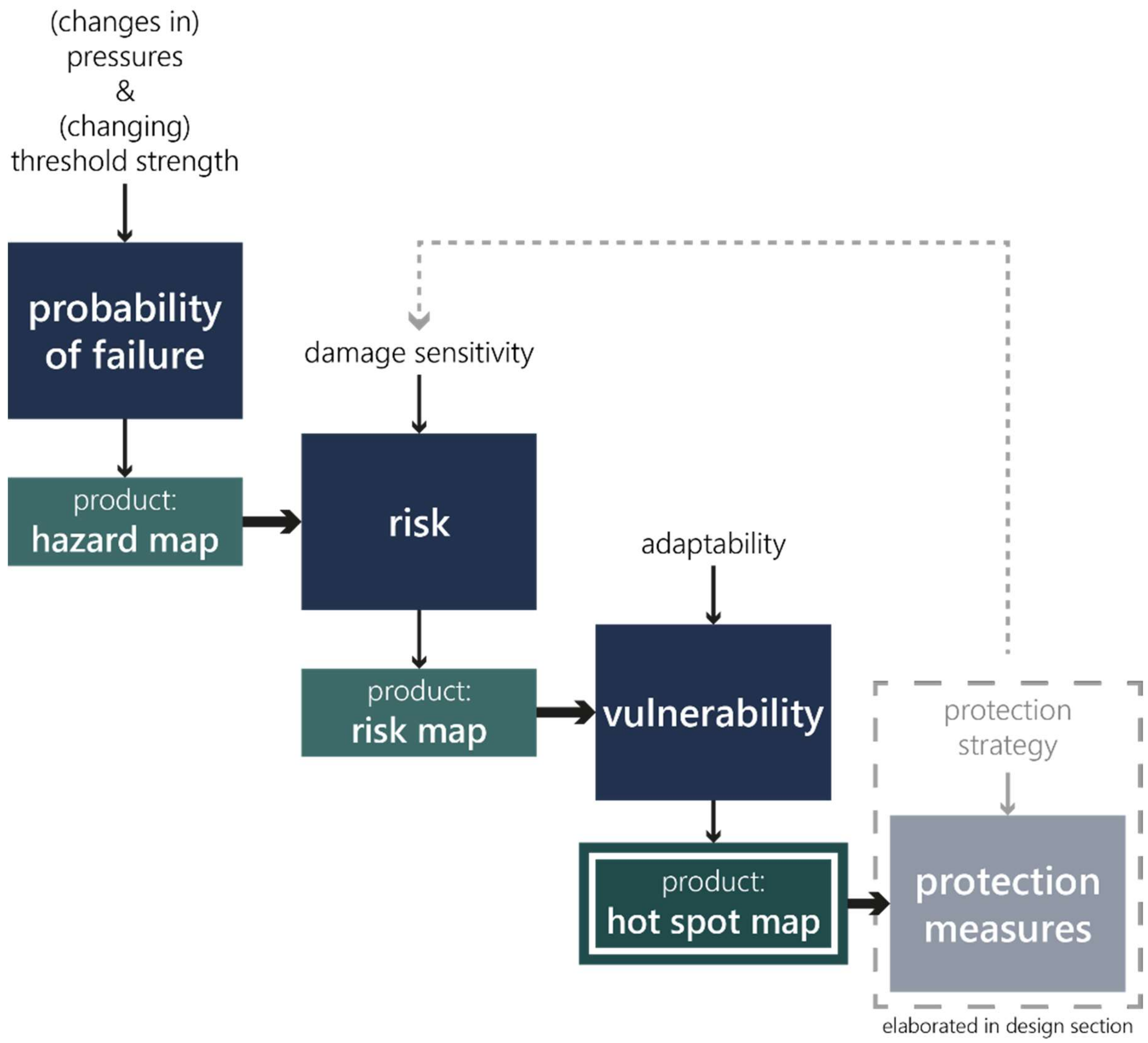

Figure 12 Steps to assess the vulnerability (adapted from (van de Ven, 2018))

Step 1: The hazard map

The first step in assessing the vulnerability is producing a hazard map of the City of Galveston in the event of compound flooding. More specifically, a map with spatially distributed maximum water depths over the city is required for an accurate estimate of flooding hazards. To this end a hydraulic model was created using 3Di software, which is explained earlier in Section 3.6 Hydraulic Model 3Di. This model is used to simulate the combined occurrence of both storm surge and heavy precipitation on the City of Galveston.

The maximum inundation level is calculated using a deterministic approach; the simultaneous occurrence of storm surge of Hurricane Ike (2008) and the precipitation of Hurricane Harvey (2017) is modelled. Taking a probabilistic approach is too time-consuming and therefore falls outside the scope of this project.

Figure 13 shows the result of the inundation modelling. The map shows the maximum inundation which occurred over the entire modelling time period, which is one day. The hazard map is available as an extended version in Appendix E.2 Hazard Map.

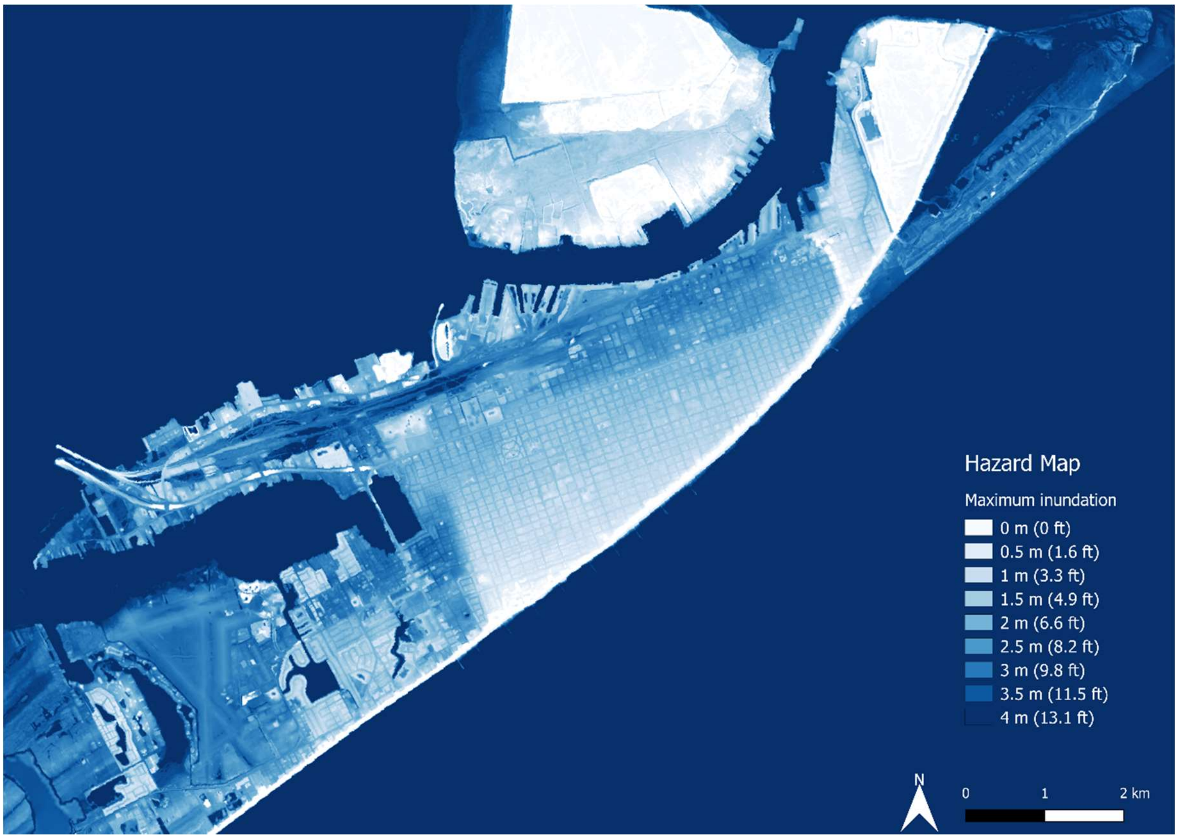

Figure 13 Hazard map of the City of Galveston

Step 2: The risk map

The next step involves adding property damage sensitivity, which will result in a risk map. Such a risk map highlights areas with the highest damage during the compound flooding scenario. Two steps are involved in producing a representative risk map that can be used for further analysis. First the percentage of property damage relative to the total property value is calculated using so-called depth-damage curves provided by the USACE and the Joint Research Center (JRC) of the European Commission. Secondly, this percentage is translated into an actual damage value using parcel value data.

The first step is finding representative depth damage curves. These are curves that show how much damage is done to a property or certain area in terms of percentage of the property or area value. This percentage depends on the flooding depth and is characteristic for a certain type of area or for a certain type of building. In this report, depth-damage curves that are produced by the USACE and the JRC of the European Commission are used to create the risk map. To create a proper risk map, distinction is made in between four building types / area types, being:

- Industrial zones, including the harbor and airport;
- Commercial zones, including the old historic city center;
- Single story buildings without basement;
- Multiple story buildings (2+ floors), without basement.

The depth-damage curves of the industrial and commercial zones are displayed in Figure 14; the ones for the single story and multiple story buildings are shown in Figure 15. Every depth-damage curve contains a trendline that goes through the values displayed in the depth damage curves. The data of the depth-damage curves is fitted best when using a higher order polynomial trendline.

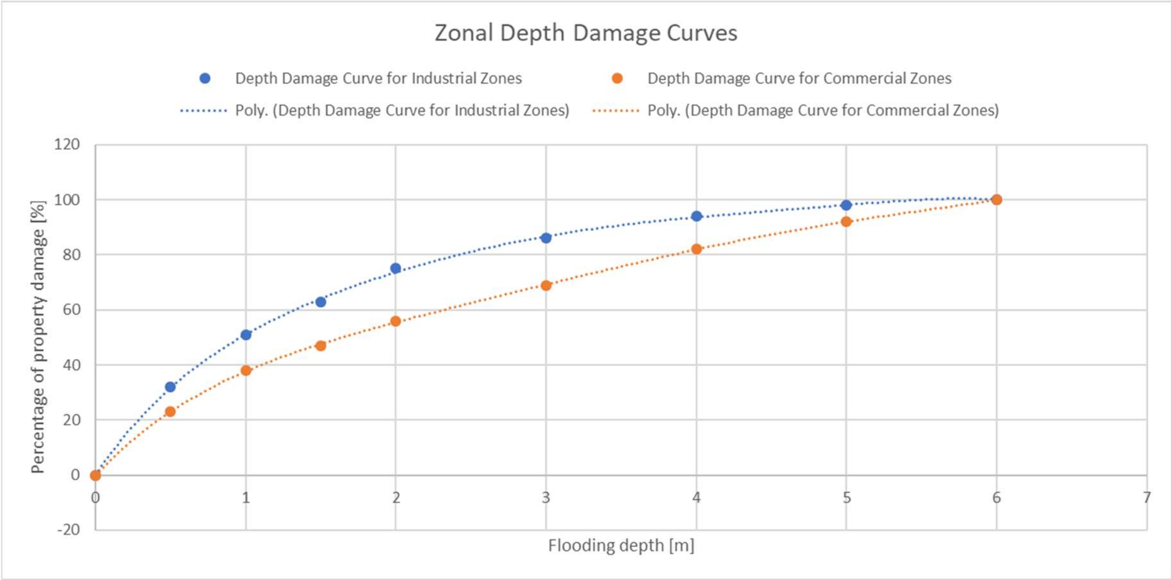

Figure 14 Depth Damage Curves for industrial and commercial zones, adapted from (Huizinga, de Moel, & Szewczyk, 2017)

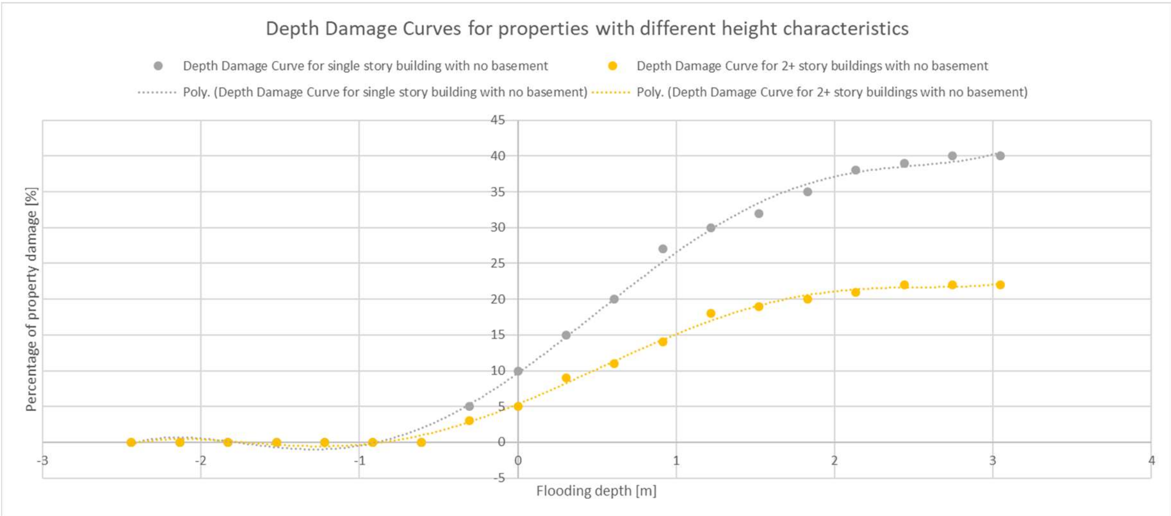

Figure 15 Depth Damage Curves for single and multiple story buildings without basements, adapted from (Davis & Skaggs, 1992)

The depth-damage functions shown in Figure 14 and Figure 15 are displayed individually in their respective Appendices H.1 Depth-Damage Curve for Industrial Zones, H.2 Depth-Damage Curve for Commercial Zones, H.3 Depth-Damage Curve for Single Story Buildings, and H.4 Depth-Damage Curve for Multiple Story Buildings. In these appendices, the equations of the fitted polynomial trendlines are shown as well.

It may be noticed that the depth-damage curves shown in Figure 15 start developing at negative flooding depth values. The reason for this is the usage of the same scale as the depth-damage curves for houses with a basement (Hollaway, 2018). Besides, it is curious that there are damage values at a flooding depth of 0 meters. This can be explained by the fact that there are damages accumulated to garages that are included in the building's damage estimate that are located at ground level. Another option is that damage already occurs to these buildings before water flows in (Hollaway, 2018).

The equations of the fitted polynomial trendlines are used to calculate what the percentage of damage of each property is. To get these results, the hazard map shown in Figure 13 is used as input. The second input is the land use map (see Figure 16) that shows which depth-damage curve applies to which area. After inserting the flooding depth in the trendline formulas of the representative curves, the percentage of property damage is obtained. Now, this percentage is multiplied with the actual parcel values on the island. These parcel values were transformed from shapefile to raster values beforehand. The resulting map is the risk map that is shown in Figure 17 and displayed at a larger extent in Appendix E.3 Risk Map.

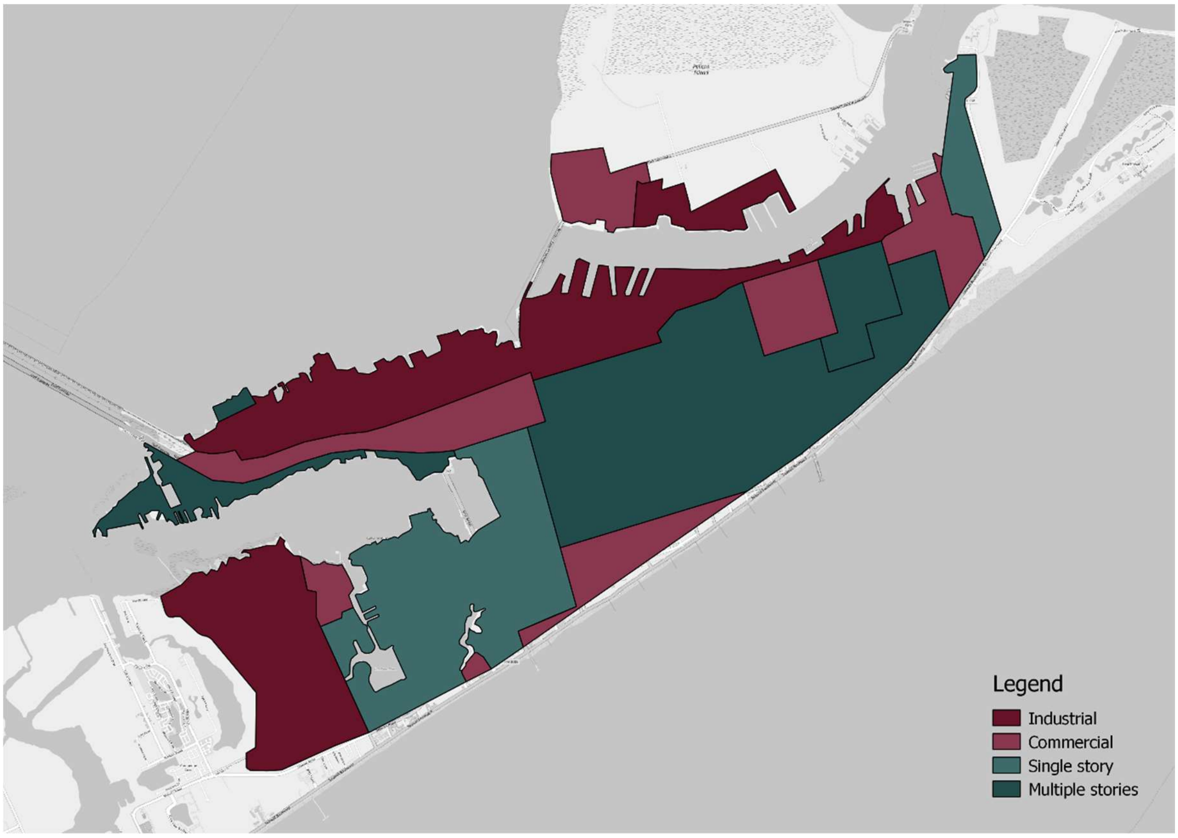

Figure 16 Land use map of the City of Galveston

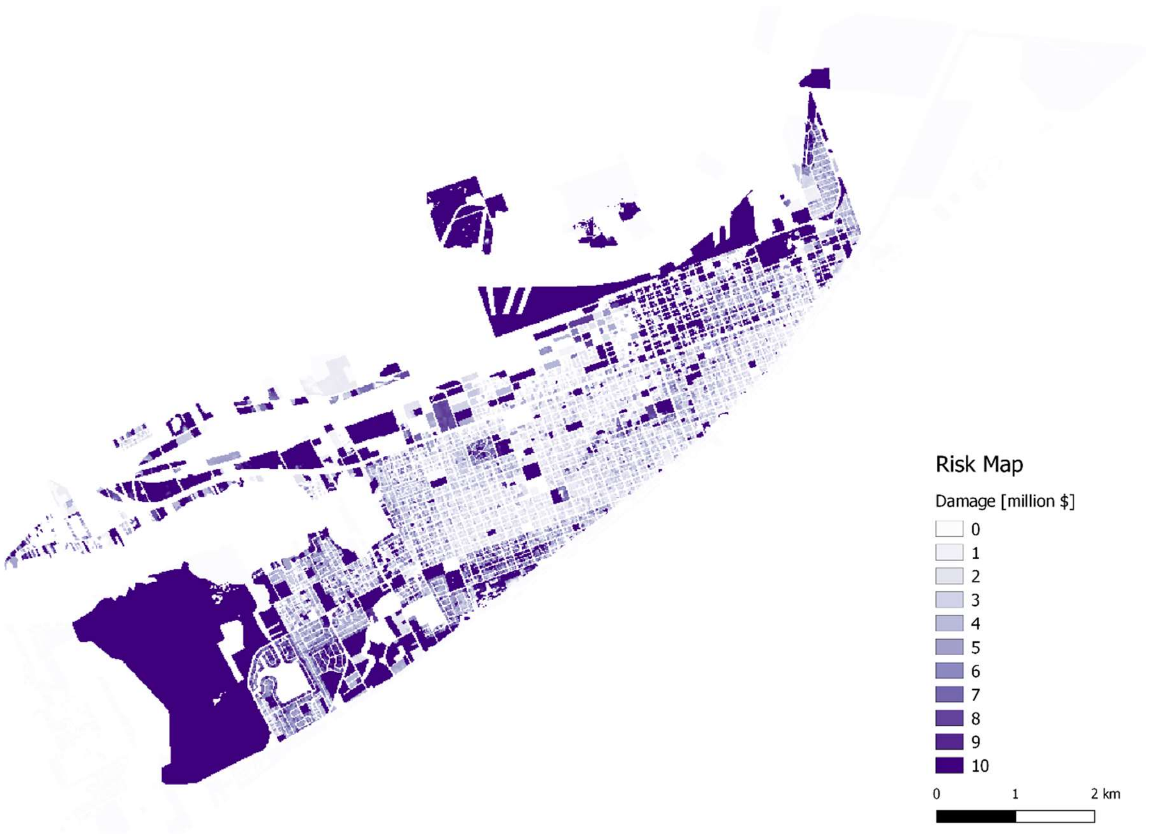

Figure 17 Risk map of the City of Galveston

Hotspot map

In order to create a hotspot map of the vulnerability of the City of Galveston, data is needed on the adaptability of the built environment. However, since the term adaptability knows many definitions, it is useful to clarify the definition of adaptability in this report. The following definition for adaptability is used: "The speeds and efforts in which adjustments are possible in the social practice and processes or physical structures of the current system to projected or actual changes of climate" (Deurloo, 2016).

To be able to judge the adaptability of properties, a few assumptions are made. One of these assumptions is that a property is highly adaptable when it has a high age, since they are more likely to be replaced by new buildings than younger ones. Properties with an age of 70 years and older are remarked as high-aged properties. Less adaptable are properties that are somewhat younger. Therefore, properties aged between 20 and 70 years old have been assumed to be adaptable on a medium level. The youngest buildings have been assumed to be least adaptable since they have recently been built.

Next, each property receives a value for its adaptability depending on its age, as described in the section above. The values for adaptability are displayed in Table 4.

Table 4 Values for adaptability for different properties

Age of property	Value of adaptability
age of property ≤ 20 years old	0.01
20 years < age of property < 70 years	0.5
age of property ≥ 70 years	1.0

It should be mentioned that this way of assigning values for adaptability is rough. It does, however, give a first overview of which properties in the area of research are more likely to be adaptable.

After assigning the adaptability values to each property (the white dots in the field displayed in the left picture of Figure 18), inverse distance weighting interpolation is used to obtain a raster map. In this raster map each cell now contains a value for its adaptability. Since the values are interpolated between 0.01 and 1.0, the raster map contains only cells with a value between these boundaries.

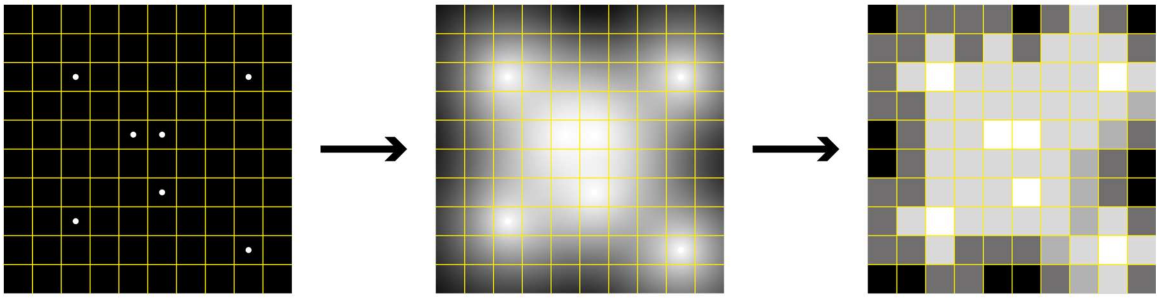

Figure 18 Visualization of inverse distance weighting interpolation of the properties' adaptability values

The last step to create a hotspot map that shows vulnerable spots in the city is to multiply the risk map, displayed in Figure 17, with the raster map that contains the values for adaptability. In Figure 19 the hotspot map is visualized, showing the most and least vulnerable spots in the City of Galveston.

Figure 19 Hotspot map of the City of Galveston

The hotspot map is shown at a larger extent in Appendix E.4 Hotspot Map.

4.3.4 Identifying Vulnerable Objects

The maps created by the residential stakeholders give valuable insight in their experiences with which parts of Galveston flood during a heavy rainfall event and high tide. However, these maps would be even more valuable with critical infrastructure depicted on them.

To create this map, annex 3 of 'Handleiding Stresstest' is used to obtain an overview of all vulnerable objects and infrastructure in and around the city. The table of annex 3 is shown in Appendix F Vulnerable Objects.

To mark vulnerable object, the fieldwork described in Appendix B Fieldwork is used. Pictures that were taken during the fieldwork show critical infrastructure and whether this is vulnerable or not. Furthermore, the hotspot map created and shown in Figure 19 is used to complete the overview of vulnerable objects.

In Appendix F Vulnerable Objects the classification of the various vulnerable objects of the City of Galveston can be found.

4.3.5 Urgency for adaptation

In order to fit measures in currently planned projects and provide an indication on where to start, the vulnerability map is overlaid with planned city improvements. The result are shown in Figure 20, followed by a short explanation below. The map shows windows of opportunity which are taken into consideration in the adaptation strategy.

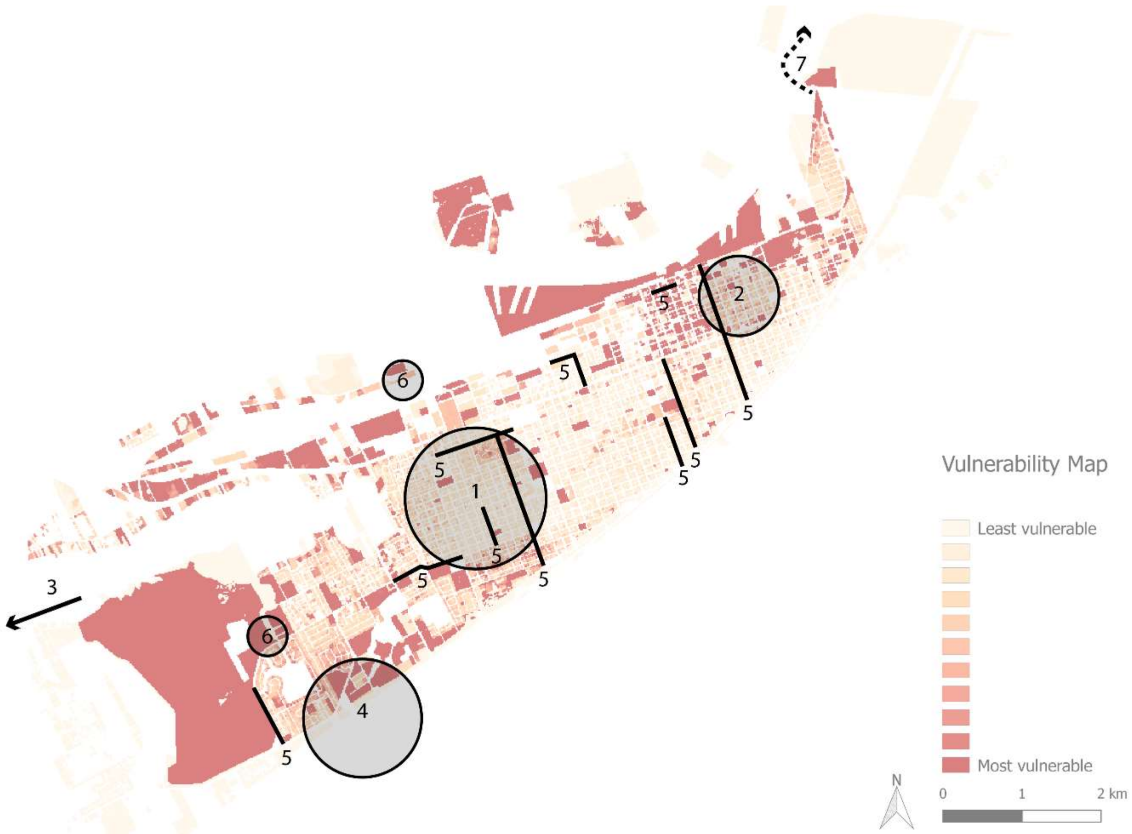

Figure 20 Planned city improvements

1. Redeveloping inner urban blocks for middle-income families:
   With the redevelopment of inner urban blocks, opportunities arise to incorporate water retention strategies in the building blocks;
2. Revitalizing historic urban core:
   When revitalizing the historic urban core, care must be taken to incorporate damage mitigation measures into the plans;
3. Expanding wetlands:
   Expanding wetlands will likely have a positive effect on reducing flood damages;
4. Babe's beach nourishment:
   Beach nourishment programs will expand the beaches and reduce the impact from wave action;
5. Road/drain improvements:
   In general, many roads need improvement and are therefore suitable for retrofitting;
6. WWTP improvements:
   An improved WWTP is better able to handle contaminations and will improve the water quality in the Galveston Bay;
7. Increase ferry capacity.

4.4 Water Assignment

This chapter focusses on the water assignment. The water assignment was developed by the Dutch Ministry of Transport, Public Works and Water Management in 2008 for the purpose of tackling flooding related to urban surface water, sewers and groundwater. In short, the water assignment can be split in three core tasks, as can be observed in Figure 21:

- Surface Water;
- Water Quality;
- Groundwater.

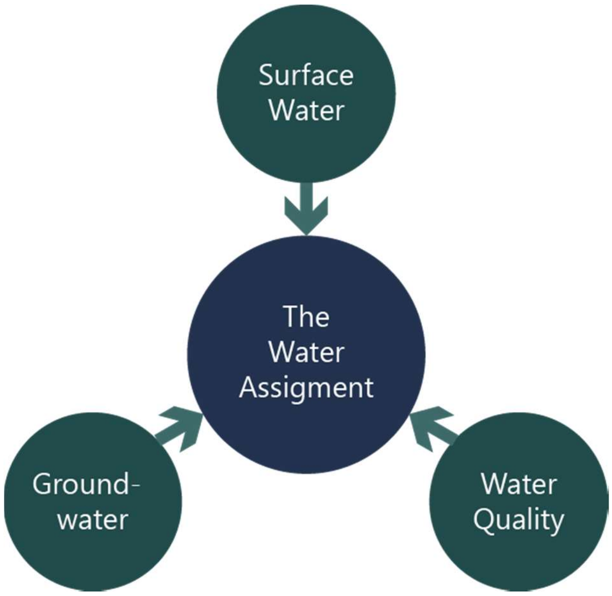

Figure 21 The three core tasks of the water assignment

These tasks will be elaborated separately in the following sections.

4.4.1 Surface water

This component of the water assignment aims to reduce flooding by providing sufficient storage capacity and discharge capacity. Furthermore, it considers mitigation of damage in case these capacities are exceeded.

The following steps are needed to determine the amount of required storage and the hydraulic discharge capacity (van de Ven, 2018):

1. Separate urban water from surrounding water;
2. Determine the drainage options;
3. Determine water level, freeboard, dH_{max};
4. Determine the needed storage;
5. What is considered storage;
6. Reduce damage when exceeding the design standard;
7. Hydraulic discharge capacity.

Step 1

The first step does not apply to Galveston, as the water system of Galveston cannot be considered to be segregated such as a typical Dutch polder. This step is therefore skipped.

Step 2

Step two considers the desired pattern of discharge. For instance, a city might want to drain excess water as quickly as possible to prevent coincidence with a slow release of water from upstream, rural areas. As Galveston does not drain to a river and the Galveston Bay has sufficient capacity to handle drained stormwater, this step can be skipped as well.

Step 3

Galveston does not currently enforce a freeboard, although it has been advised to consider setting a freeboard for properties that suffer repetitive flooding (City of Galveston, 2012). Perhaps in the future this will become relevant.

Step 4

The fourth step involves determining the required storage for the city. Critical to this approach is the understanding of exchangeability between storage and discharge. In case of a high discharge capacity, little storage is needed.

The amount of required storage is determined using Storage Discharge Frequency (SDF) curves. These are curves that show the relationship between a certain available discharge capacity and the required storage amount for several given design storms. They are used in urban areas to give an estimate on how much storage is needed in order to prevent flooding.

To create these curves much data is needed, which should be processed carefully. Two types of input are used: dynamic and static data. For dynamic input, a record of hourly precipitation and hourly evaporation rates are required of an area, spanning at least 30 years. For the static input, area characteristics regarding imperviousness, sewer layout and hydraulic conductivity of the soil have to be estimated.

Dynamic input

Monthly evaporation rates, retrieved from the website of the Texas Water Development Board (Texas Water Development Board, 2018), are interpolated to obtain hourly precipitation rates. Evaporation rates, assumed to be constant over the month, are converted to hourly rates using the distribution in Figure 22.

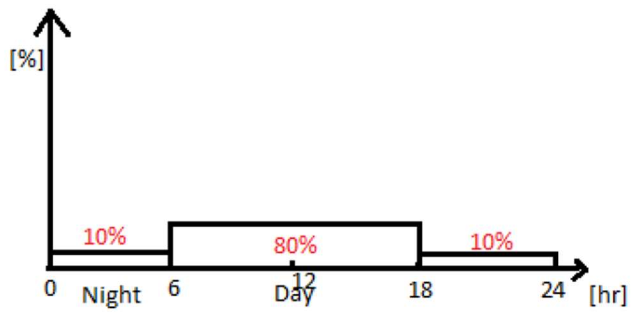

Figure 22 Distribution for converting daily precipitation rates to hourly rates (Zhang, 2018)

Precipitation data was downloaded from the National Centers for Environmental Information website (NOAA, N.D.). The gauge at Scholes International Airport provided a record of hourly precipitation data spanning at least 30 years.

Static input

Table 5 briefly explains the key assumptions regarding static parameters. The complete list with all used values can be found in Appendix G Static Parameters.

Table 5 Assumptions regarding static parameters

Paved roofs	Through map and field observation, an average building-to-plot ratio of 0.4 is assumed for all city plots; a ratio of 0.1 is assumed for industrial land use (including airport). With industry making up roughly 30% of the total land use, an average total percentage of paved roofs is calculated to be 31%. Twenty percent of the roofs are assumed to be disconnected from the sewer.
Closed paved (roads, etc.)	Road coverage is assumed to be 25% on city plots and 15% on industrial plots; 70% of the roads are thought to be disconnected from the sewer due to limited underground drainage.
Open paved (parking lots, etc.)	On city plots 5% is assumed to be open paved; for industrial plots this is 55%. It is further assumed that 80% is disconnected from the sewer.
Unpaved	An estimated 26% of the total land use is unpaved.
Open water	Open water makes up about 1% of the total land use.
Sewer system	Galveston has a dedicated stormwater drainage system.
Design standard of sewer system	Using the IDF curve displayed in Figure 118 in Appendix A.4 Meteorology, a design rainfall intensity of 49.53 mm/hr. (1.95 inch/hr.) is assumed for a T=2 years rainfall event.
Target open water level	This set to be 0 m (0 ft.) above MSL
Soil & crop type	As described in Appendix A.3 Geology, Galveston is situated on a loamy soil and mainly has grassy vegetation.
Groundwater	With a 6.4 meters (21 ft.) thick sandy layer and an assumed hydraulic conductivity of 10 m/day (33 ft/day), a drainage resistance of 64 days is calculated.

The final SDF curves are displayed in Figure 23 and Figure 24. For Galveston a design storm of T=2 years is of particular importance, as the civil infrastructure is designed for this event.

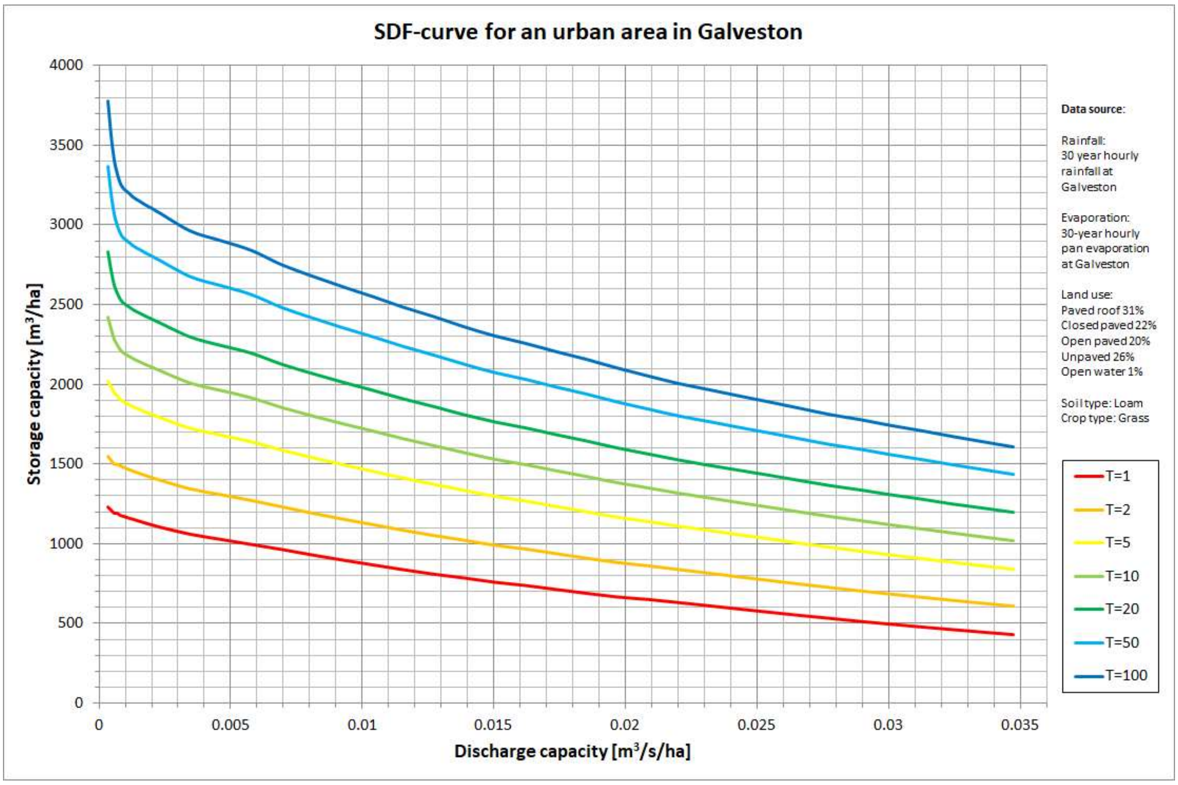

Figure 23 SDF curve showing the required storage capacity in m^3/ha (Zhang, 2018)

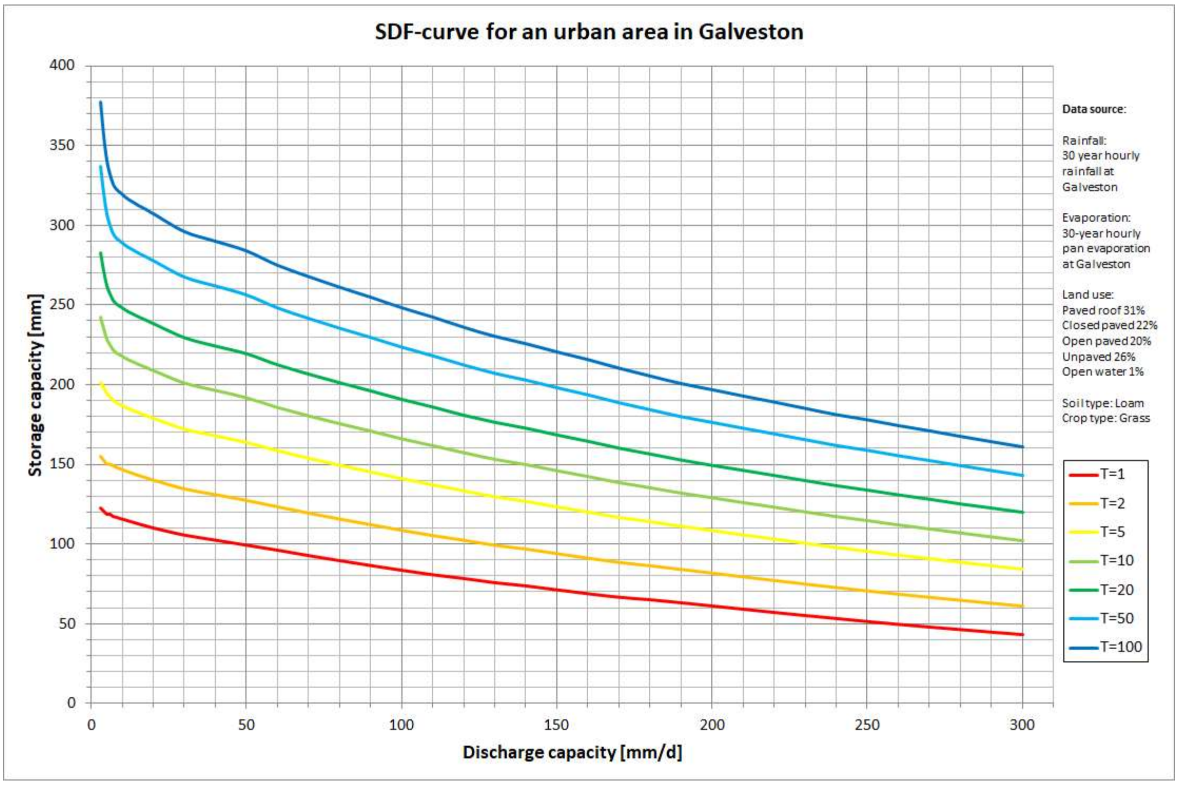

Figure 24 SDF curve showing the required storage capacity in mm (Zhang, 2018)

Step 5
This step considers the actual form of storage which is applied in the city. In case a dH_{max} is defined, the total open water surface area multiplied with the dH_{max} would give the total possible open water storage. However, as the dH_{max} is not defined, this approach is not straightforward. Storage on floodplains, in underground storage tanks on streets can also be considered to be effective.

Step 6
As it is unlikely that the drainage infrastructure can handle severe weather events such as hurricanes, it is vital for the city to have measures in place that reduce damages when the drainage system is overloaded. This involves using streets for storage, protecting properties with removable barricades and protecting critical infrastructure from high water. Urban design plays a major role here as well, as the natural occurring topography should be considered when designing neighborhoods.

The designs, which will be introduced later, consider measures to mitigate damage in case the drainage system is overloaded.

Step 7
For the compound flooding scenario, discharge is assumed to be 0 as the high tide obstruct the sewer system discharging into the Galveston Bay. However, with a pump that constantly discharges water into the bay the required storage would be much smaller. Possible pumping solutions are considered and discussed in Section 5.9 Design 7: Water Storage and Discharge.

4.4.2 Water quality
Although the water quality is an important aspect of the water assignment, it falls outside the scope of this project due to time constraints. Nevertheless, water quality is considered during the design phase, as adverse effects on the water quality would be undesirable. Water quality is a criterion during the MCA (multi-criteria analysis).

4.4.3 Groundwater
Limited data is available that allows for a reliable assessment of the state of groundwater in the City of Galveston. No extensive, frequently updated network of standpipes exists. Currently available data consists of a general soil map of the island and scattered boreholes with data on the soil type. Although this provides sufficient information for a rough estimate on hydraulic properties such as hydraulic conductivity, it does not form a solid basis for designs. It would be worthwhile to invest in an extensive groundwater measurement network, since specific knowledge on the groundwater table and other hydraulic properties of the soil could open the way for opportunities otherwise missed. For instance, more emphasis could be placed on trying to infiltrate water locally instead of draining it as quickly as possible, if there is sufficient evidence to believe that the soil has a high potential for infiltration of stormwater.

During fieldwork as explained in Appendix B Fieldwork, saturated overland flow on grassy patches in between impervious areas was observed. However, it was not clear if the soil was indeed fully saturated over the entire area or that only the vegetated patches had a high groundwater table as only these were exposed to runoff.

4.5 Hydrodynamic Parameters

In this section, various hydrodynamic parameters are determined. These conditions are used as input for the designs in Chapter 5 Design Measures. The following conditions are analyzed: tidal elevation, extreme water levels (storm surge levels), offshore wave height, currents and sediment transport. The reference level, MSL, is first determined.

4.5.1 Elevation scale for datum level

The reference level is the level that enables all elevations on land and water to be compared to each other. In Figure 25 the datum levels for the USA are shown. Important datum levels are:

- Mean Sea Level MSL
- Mean Lower Low Water MLLW
- Mean Higher High Water MHHW

The reference level is chosen to be MSL. All other elevations are relative to MSL. In Table 6, the relation between the important levels are given.

Table 6 Datum levels relative to MSL (Mean Sea Level) (NOAA NGS, 2018)

Datum level	**Abbreviation**	**Elevation in m (ft.)**	**Elevation relative to MSL**
Mean Sea Level	MSL	0.338 (1.11)	n.a.
Mean Lower Low Water	MLLW	0.0 (0.0)	- 0.338 (- 1.11)
Mean Higher High Water	MHHW	0.622 (2.04)	+ 0.284 (+ 0.93)

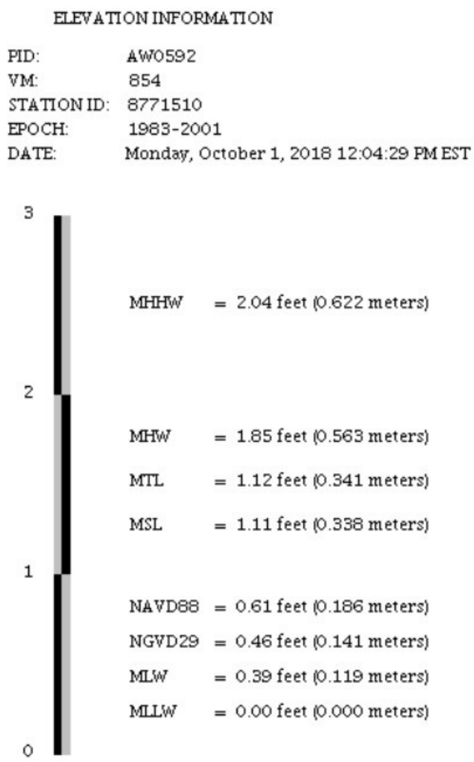

Figure 25 Datum level as a reference elevation for the water level (NOAA NGS, 2018)

4.5.2 Measurement gauges Galveston Island

Two measurement gauges are located near the City of Galveston, which collect data of wave height, wind characteristics, water levels and atmospheric characteristics. These gauges are located on the Galveston Pleasure Pier and at Pier 21, in the Port of Galveston. The water level data, retrieved from these gauges, is analyzed to determine significant water levels for designing protection measures. The data is gathered from (Station 8771510, 2018), (Station 8771450, 2018) and (Station 8771341, 2018).

4.5.3 Tidal Elevation

Along the coastline of the Gulf of Mexico, the tide has significant influence on the water level, currents and coastal processes. In Figure 26 the tidal elevation is plotted for a period of 48 hours, measured at Pier 21 in the port of Galveston on October 7th, 2018. The blue line shows several tidal constituents in the wave. There is a constituent that repeats after about 24 hours, and at least one constituent that repeats every 12 hours. The maximum elevation at this location is 0.5 m (1.8 ft.) above MLLW.

In Figure 27 the tidal elevation is plotted, measured at the North Jetty at Bolivar Peninsula, just north of the Galveston Bay entrance. This elevation is slightly larger, as the maximum elevation is at 0.6 m (2 ft.) above MLLW. The difference can be explained by the different locations of the gauges. The gauge at Pier 21 is in the middle of the Port of Galveston, covered from the Gulf of Mexico by the island. Another reason is the effect of water level variation due to wind or waves. This affects the water level at high tide, causing a higher water level than the tidal level only. The effects of wind and waves is also visible in the figures themselves. The red line is the measured water level, while the blue line represents the prediction.

In Table 7 the minimum and maximum values of the tidal elevation are summarized, as well as the relation of the maximum tidal elevation to MSL.

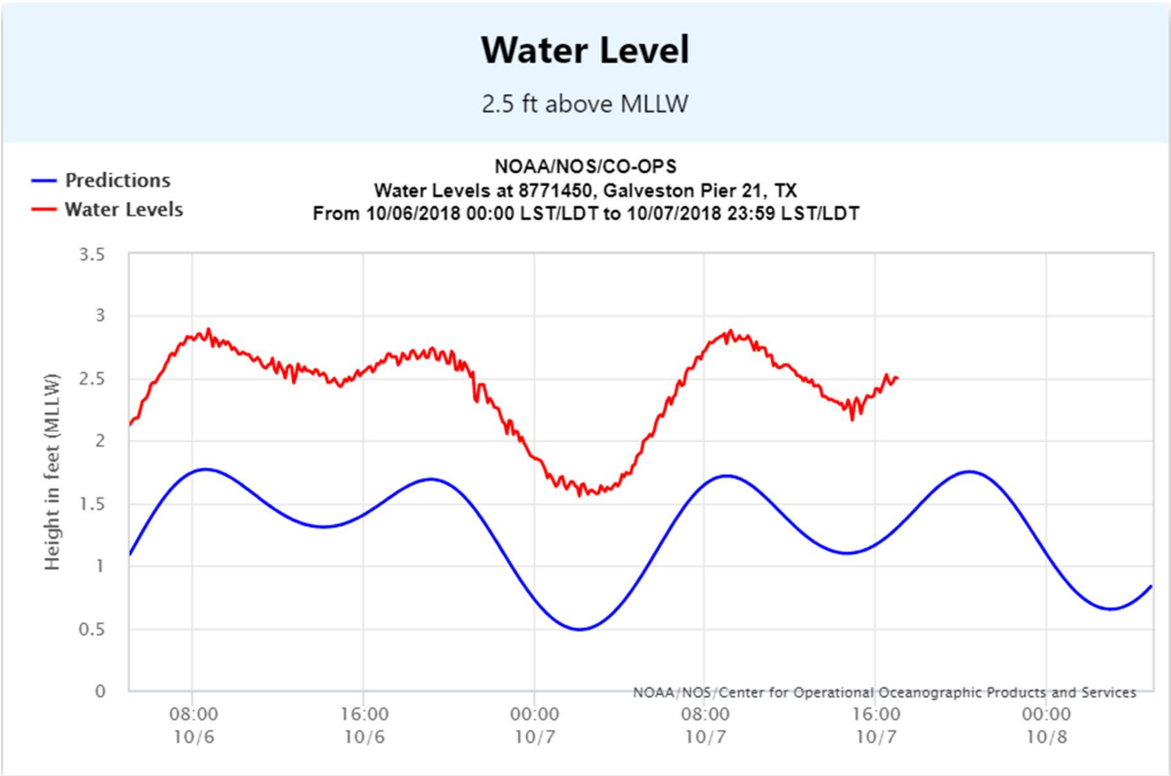

Figure 26 Tidal elevation of 48 hours on October 7th, 2018, measured at Pier 21 in the Port of Galveston (Tide Station 8771450, 2018)

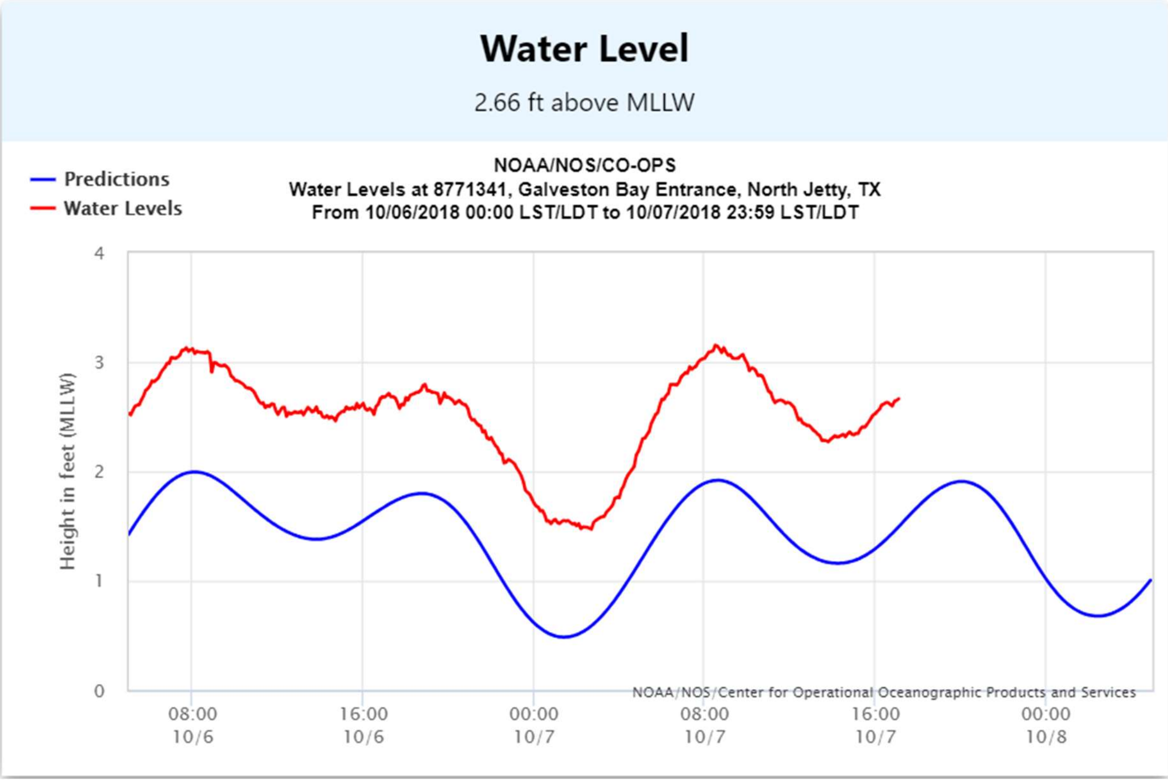

Figure 27 Tidal elevation of 48 hours on October 7th, 2018, measured at the North Jetty at Bolivar Peninsula (Station 8771341, 2018)

Table 7 Elevation of tidal wave relative to MSL for stations 8771450 and 8771341

Station	**PIER 21**	**North Jetty**
Maximum Elevation relative to MLLW in m (ft.)	0.55 (1.8)	0.61 (2.0)
Minimum Elevation relative to MLLW in m (ft.)	0.15 (0.5)	0.15 (0.5)
Maximum elevation relative to MSL in m (ft.)	0.21 (0.69)	0.27 (0.89)
Maximum elevation relative to MHHW in m (ft.)	- 0.07 (- 0.24)	- 0.01 (- 0.04)

4.5.4 Extreme water levels

For the stations on both sides of the island, the extreme water levels are determined.

Pleasure Pier (8771510)

Figure 28 shows the measured extreme water levels above MHHW (Mean Higher High Water), since late 1950s. The trendlines with different exceedance probabilities are shown from 1900 until 2020. The four trendlines have the same rate of increase over time, which is around 0.7 m (2 ft.) per 100 years (or 0.7 cm (1.8 in.) per year). The extreme water level for a probability of exceedance of a 100-year event is estimated to be 3.0 m (9.8 ft.) in the year 2040. The most recent large peak represents the water level during hurricane Ike in 2008.

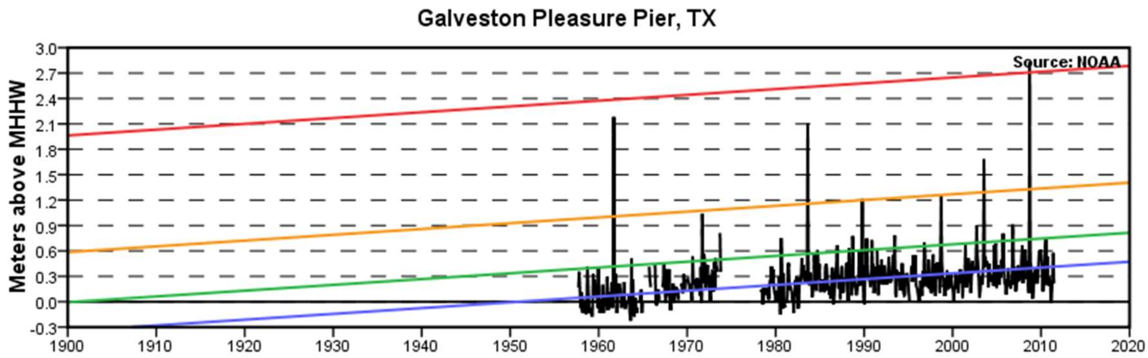

Figure 28 Extreme water levels including trendlines for different return periods for gauge at Pleasure Pier (Station 8771510, 2018)

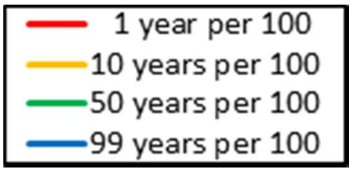

Figure 29 Legend of return periods used in graphs (Station 8771510, 2018; Station 8771450, 2018)

The return periods of these exceedance probabilities are plotted to a mean extreme water level above MHHW, including a 95% confidence interval, as shown in Figure 30. For a return period of 100 years the mean water level is 2.7 m (8.9 ft.), and the upper bound is 4.8 m (15.8 ft.) above MHHW. Thus, for this return period the water level of 4.8 m (15.8 ft.) has a probability of exceedance of 2.5%.

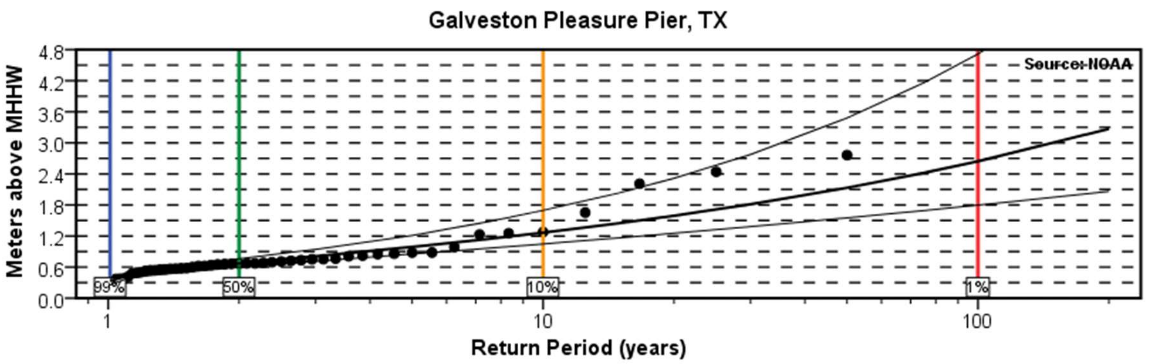

Figure 30 Exceedance probability curve for extreme water level for different return periods with 95% confidence interval for gauge at Pleasure Pier (Station 8771510, 2018)

The water levels vary throughout the year, for all return periods (see Figure 31). There is a peak in September, which can be seen as a consequence of the hurricane season. For a 1-year return period the variation is small, but for the 100-year return period the difference between September and October is 1.7 m (5.6 ft.).

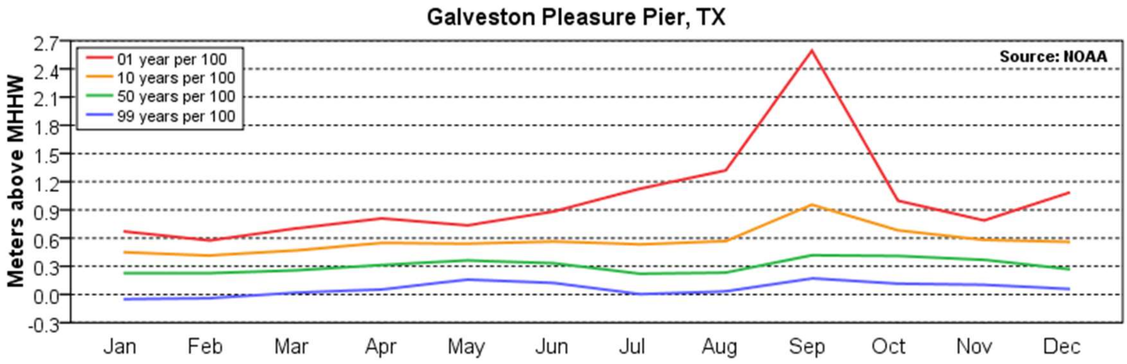

Figure 31 Seasonal variation of extreme water levels for different return periods for gauge at Pleasure Pier (Station 8771510, 2018)

Pier 21 (8771450)

For Pier 21 in the Port of Galveston more data is available. The red line represents the trendline for the 100-year return period. Since more data is available, the resulting trendlines are more accurate. The values, however, do not really differ from the measurements at the Pleasure Pier. The extreme water level in 2040 for a 100-year return period is expected to be 3.1 m (10.2 ft.). The data displayed in Figure 32 confirms these values.

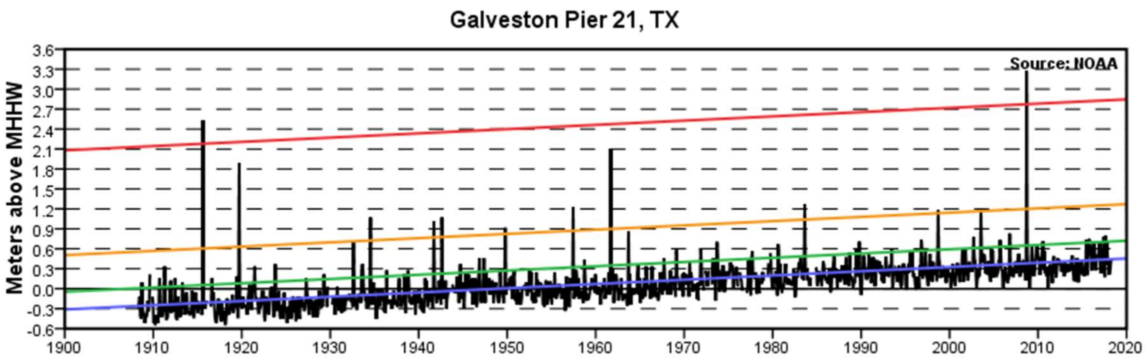

Figure 32 Extreme water levels including trendlines for different return periods for gauge at Pier 21 (Station 8771450, 2018)

From Figure 33, the mean extreme water level for a 100-year return period is 2.7 m (9 ft.). The upper bound is 4.6 m (15.1 ft.) above MHHW for the same return period.

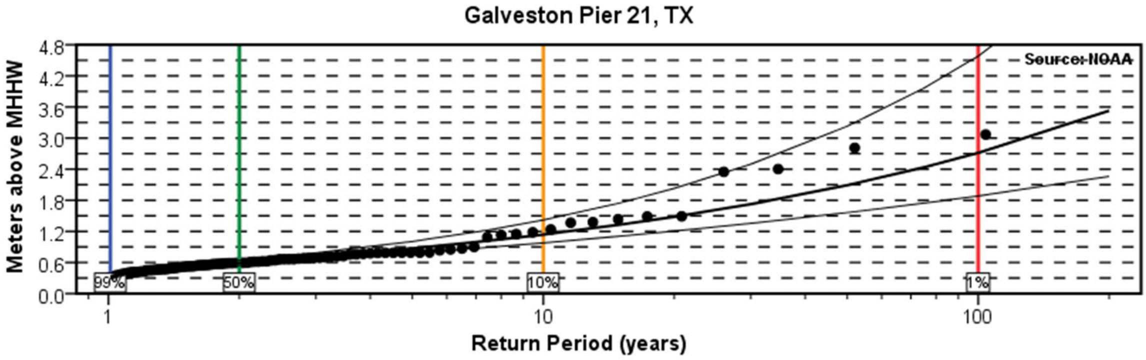

Figure 33 Exceedance probability curve for extreme water level for different return periods with 95% confidence interval for gauge at Pier 21 (Station 8771450, 2018)

As expected, the variation for larger return periods differs in September. Due to a larger record of data being available, the variation is less. Apparently, higher extreme water levels are expected to occur in August as well. In the past (before 1960), more hurricanes and large tropical storms have occurred in August, as the peaks show in Figure 34.

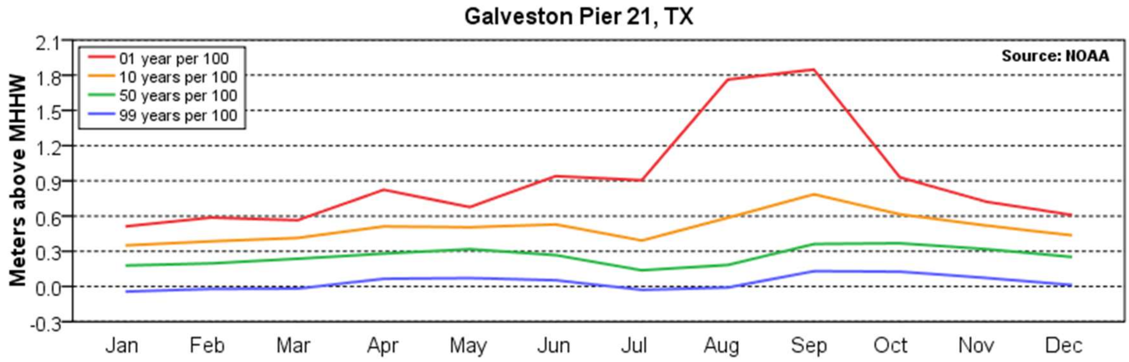

Figure 34 Seasonal variation of extreme water levels for different return periods for gauge at Pier 21 (Station 8771450, 2018)

The spread of the peaks of extreme water levels in Figure 28 and Figure 32 show the hurricanes and tropical storms that have affected the Galveston coastline since the twentieth century. For Galveston, the hurricane season starts around mid-August and ends at early October, which explains the seasonal variation in Figure 34. So for a 100-year return period the mean extreme water level is 0.8 m (2.6 ft.) above MHHW, except for the hurricane season between August and October. The mean extreme water level equals 1.8 m (5.9 ft.) above MHHW (125% increase).

4.5.5 Offshore wave data

From the NOAA, wave data has been gathered between May 1993 and December 2017. The measurement station is at buoy 42035, 22 miles offshore located in front of the Galveston Bay entrance.

The wave data was used to create a probability density function, shown in Figure 35, and a cumulative density function, shown in Figure 36. The probability density function gives the mean wave height and the spread of the different measured wave height. The cumulative density function shows the probability of exceedance for several wave height and the significant wave height (wave height exceeded by 1/3 of the waves).

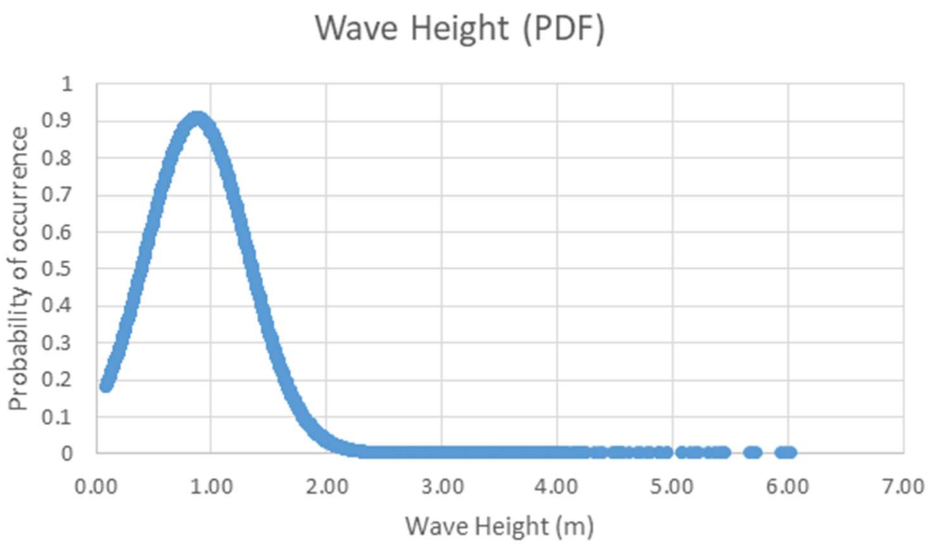

Figure 35 Probability Density Function of offshore wave heights. The mean wave height is 0.88 m.

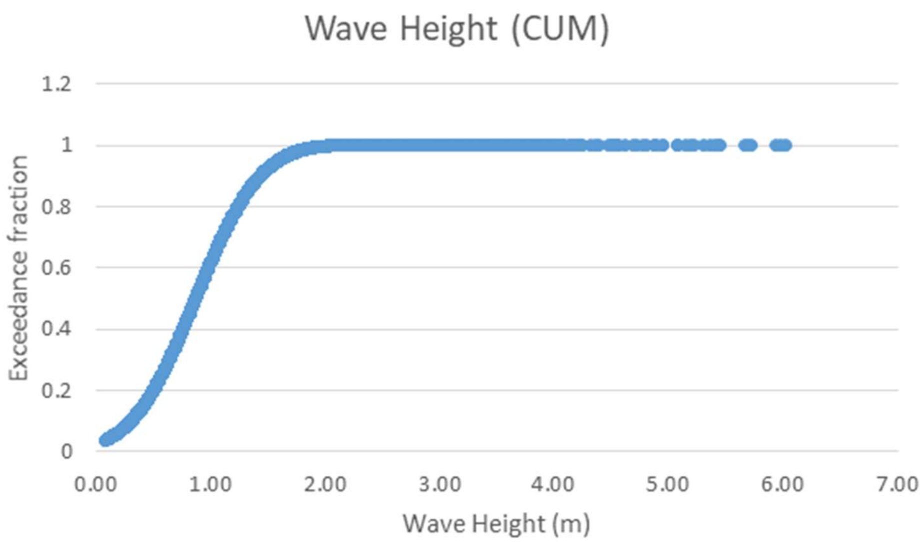

Figure 36 Cumulative Density Function. The significant wave height is 1.0 m (33% is larger than the significant wave height).

In Table 8 the wave heights for different probabilities of exceedance are shown. In the design phase, the wave height for a 2-year event is set to 1.0 m (3.3 ft.). The design wave height is not translated to a nearshore wave height due to time constraints.

Table 8 Wave heights for different probabilities of exceedance

	Wave Height (m)	Wave Height (ft.)
Minimum measured wave height	0.0	0.0
Maximum measured wave height	6.03	19.8
Mean measured wave height	0.88	2.9
Significant measured wave height	1.00	3.3
Wave height for 2-year event (exceedance probability = 50%)	0.88	2.9
Design wave height for 2-year event	1.00	3.3
Wave height for 10-year event (exceedance probability = 10%	1.40	4.6
Wave height for 100-year event (exceedance probability = 1%	2.00	6.6

4.5.6 Currents

The longshore currents at Galveston Island are mainly determined by the current patterns in the Gulf of Mexico. In Figure 37 these currents are represented. The Gulf of Mexico is the origin for the Gulf Stream to Northwest Europe. This origin contains warmer water, which improves the development of hurricanes. Near Galveston Island, a longshore current is moving southwest, with its origin in the Mississippi delta, near New Orleans, LA. This current moves to Tampico, Mexico.

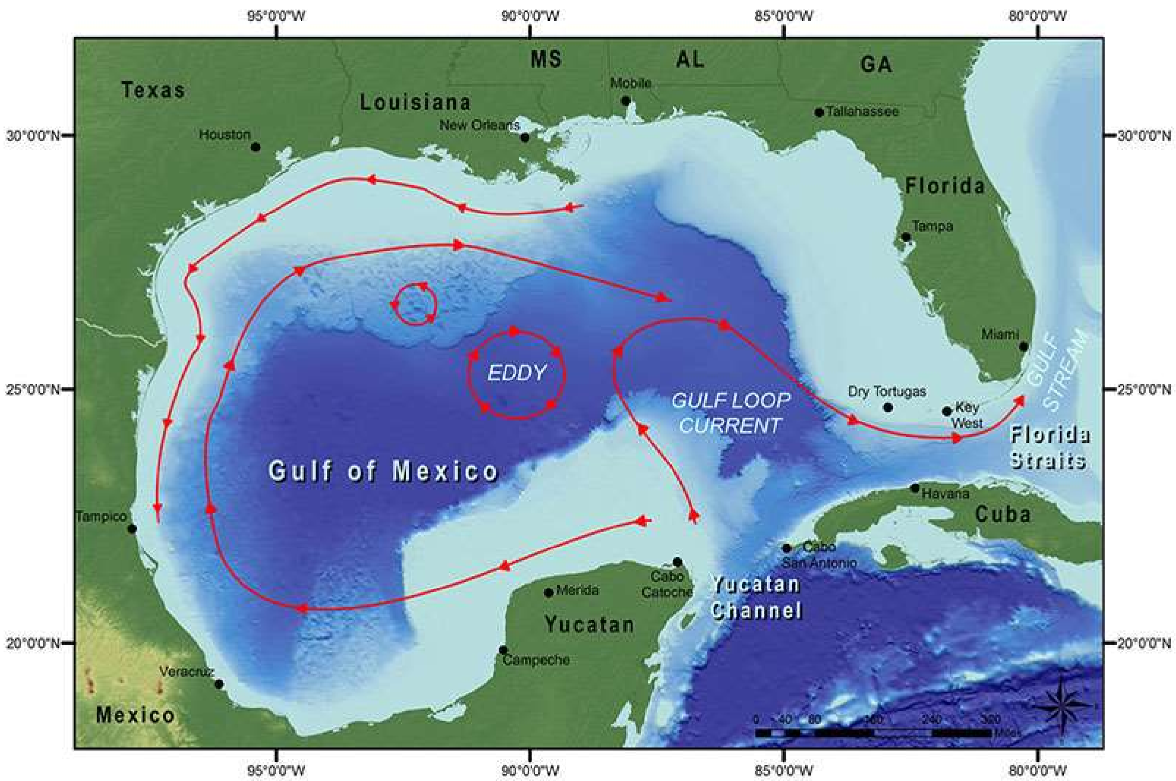

Figure 37 Basic currents in the Gulf of Mexico (NOAA OER, 2017)

4.5.7 Longshore sediment transport

The longshore current transports sediment from the Mississippi river along the coastline to Galveston and further. The direction of sediment transport and the current are the same, the magnitude of sediment transport depends on the magnitude of the flow velocity of the current. A higher flow velocity is able to transport more sediment. The variation in sediment transport gradients cause either accretion or erosion.

Erosion and accretion

For the section from Bolivar Peninsula to West Galveston Island the gradients in erosion and accretion are represented (see Figure 38). From this data, it is assumed that the east end of Galveston Island is growing (accreting), while the coast is eroding from the location where the Seawall starts along the beach westward (Frey, Morang, & King, 2016). This is because the Seawall is a hard concrete structure, which increases the flow velocity of the longshore current. At the end of the Seawall the erosion rate is the largest. The largest accretion rate is located at the east end of the island, where the South Jetty is constructed. This jetty retains the sand directly downstream of the structure. Besides that, the south end of Bolivar Peninsula is accreting, as the North Jetty is constructed here and prevents the sand from flowing into the Galveston Bay entrance.

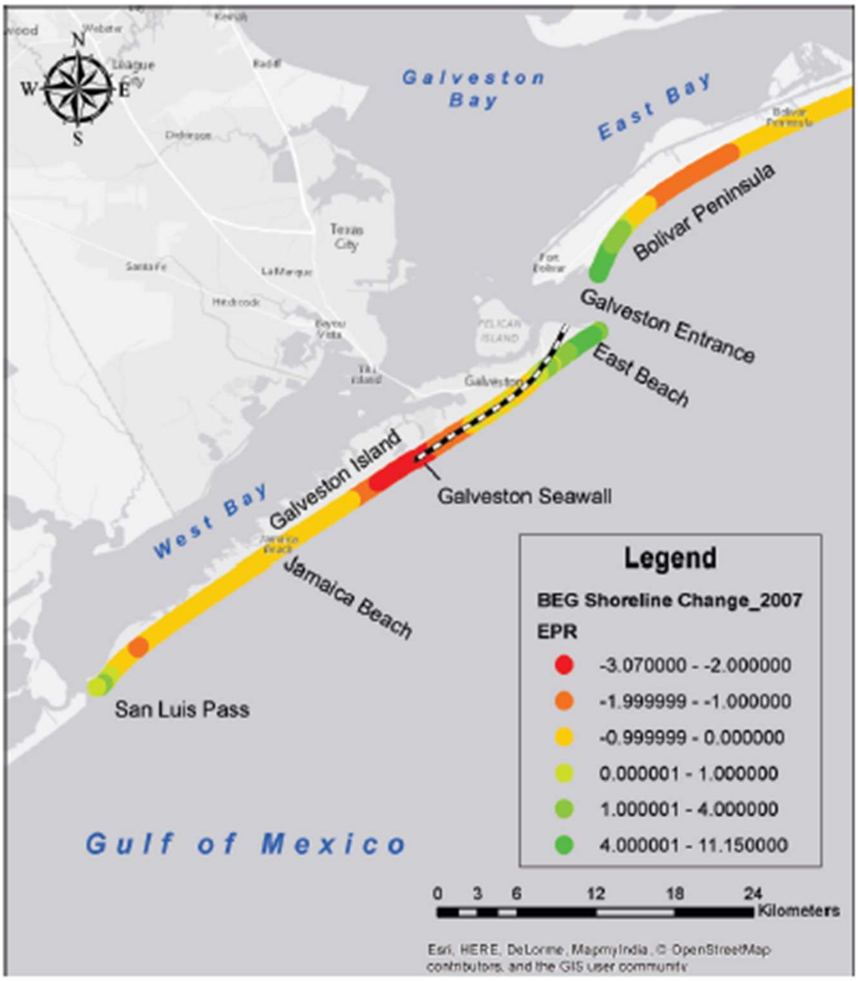

Figure 38 Erosion and accretion gradients for the coastlines of Bolivar Peninsula and Galveston Island, measured by USACE in 2007 (Frey, Morang, & King, 2016)

Sediment sources

Although a part of the Galveston coastline is accreting, the rate of erosion is larger and causes a shortage of sand for the coastline on the side of the Gulf of Mexico. To manage the coastline and reducing the net erosion rate, a supply of sediment is needed on an annual basis. For this sediment sources are needed, as at the coastline the longshore transport gradient is not sufficient. The USACE has proposed a number of sources that have sufficient supply for accretion of the Galveston coastline. Two of these sources are located offshore, on 55 and 110 km (34 and 69 miles, resp.) from the coastline (Frey A. , Morang, King, & Thomas, 2015).

In Figure 39 the sediment volumes are shown for different coastal sections. The net erosion and accretion volumes are shown for each section, as well as the sediment transport gradients between the sections. Most of the sediment is being transported southward, which confirms the direction of the net longshore current and net longshore sediment transport gradient.

Besides the offshore sediment sources, the east end of Galveston Island and west end of Bolivar Peninsula are suitable locations for sediment sources, according to the USACE (Frey A. , Morang, King, & Thomas, 2015). However, additional research to sediment sources is required to better manage the actual issues on erosion of the Galveston coastline.

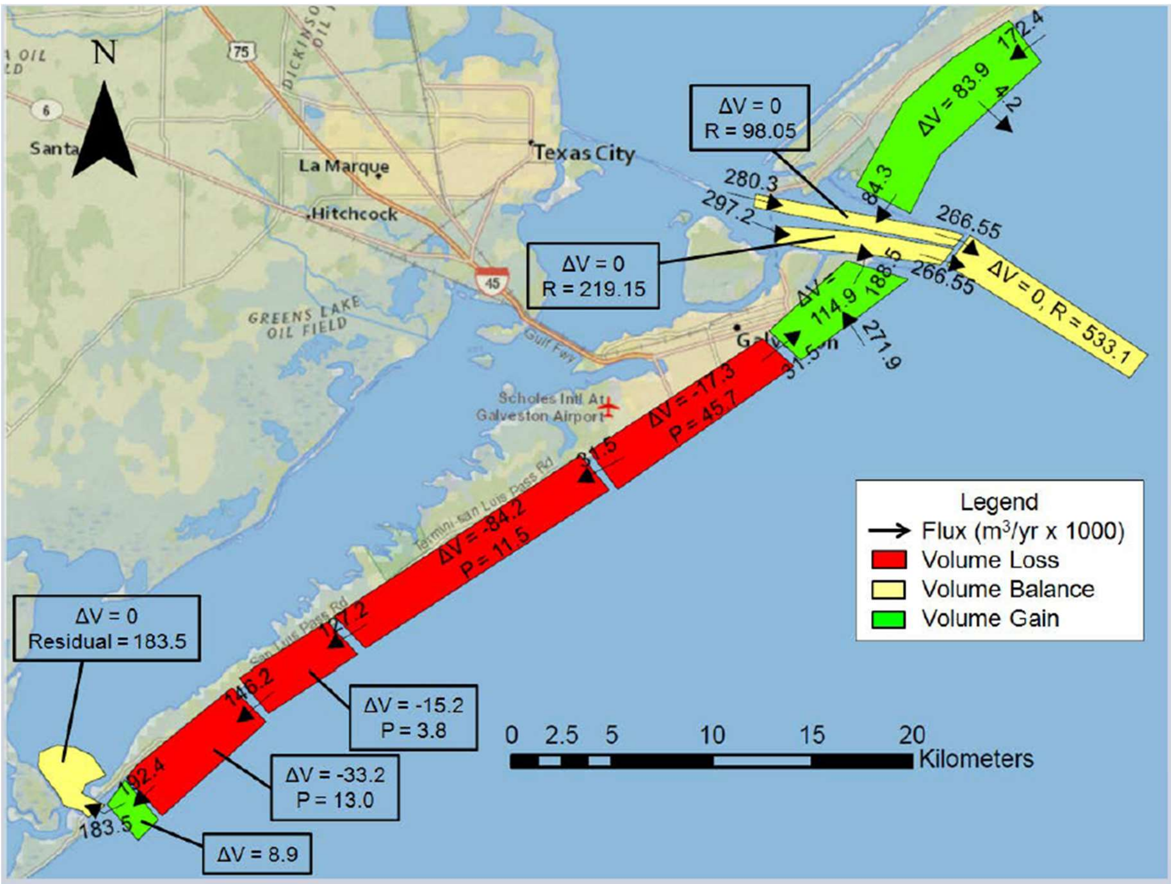

Figure 39 Sediment volumes that are needed to maintain the coastline. The fluxes represent the net sediment transport direction (Frey A. , Morang, King, & Thomas, 2015)

4.5.8 Significant data for designs

The significant values for the hydrodynamic parameters are shown in Table 9. Two return periods are used: a 2-year event for nuisance flooding and a 10-year event for storm impact. There is no specific return period for hurricanes, because additional research is required into return periods of different types of hurricanes. The design year is 2040, which gives expectations for the next 20 years.

The offshore wave height should be translated to a nearshore wave height. However, this is not possible due to time constraints. This is included in the recommendations in Section 6.2 Recommendations.

Table 9 hydrodynamic parameters for both 2-year return period and 10-year return period

2040		**2-year event**		**10-year event**	
Probability of exceedance	%	50%		10%	
		Level in m	Level in ft.	Level in m	Level in ft.
Reference level	MSL	0.0	0.0	0.0	0.0
High tide		+ 0.27	+ 0.89	+ 0.27	+ 0.89
Storm surge		+ 1.18	+ 3.88	+ 1.78	+ 5.85
Sea level rise		+ 0.16	+ 0.52	+ 0.16	+ 0.52
Wave height		+ 1.00	+ 3.30	+ 1.40	+ 4.59
Subtotal excluding waves		+ 1.16	+ 5.29	+ 2.21	+ 7.26
Subtotal including waves		+ 2.16	+ 8.59	+ 3.61	+ 11.85
Margin		+0.50	+ 1.64	+ 0.50	+ 1.64
Total excluding waves		+ 2.11	+ 6.93	+ 2.71	+ 8.90
Total including waves		+ 3.11	+ 10.23	+4.11	+ 13.49

4.6 Hazard Management

The approaches to hazard management in the USA and the Netherlands are discussed in this section. These approaches are compared in terms of flood risk, incentives to protect, protection measures and evacuation of flood prone areas.

4.6.1 Hazard Management in the USA

The United States has a broad perspective on hazard management. Most states suffer from different kinds of natural hazards, such as hurricanes, wildfires and earthquakes. The coastline of Texas suffers mostly from hurricanes; the region of Galveston is prepared to mitigate damages resulting from this type of hazard. The local and state governments have set up documents that describe the strategy before and during disasters and recovery procedures to mitigate the consequences of disasters.

In case of hazards

Two reports from FEMA (Federal Emergency Management Agency) are studied to gain a better view on how the Federal Government, the State of Texas and the local communities act in case of disasters. The National Incident Management System (FEMA, 2017) provides information on how to prepare for disasters and on how to act during disasters. This is done by explaining how the incident management system is built, how it works, what input elements are required and what output is given. The National Disaster Recovery Framework (FEMA, 2016) deals with the recovery strategy after disasters. Key elements in this report are the description of the organizational structure and the core capabilities that cover critical elements needed to ensure national preparedness. For more detailed information is referred to these documents.

Hurricanes cause extensive damage, which can be subjected to two distinct categories: damage due to flooding and damage due to wind force. Both are dangerous to people. Measures should be taken to protect people and properties. The primary measure is evacuation, the secondary measure is protection against flooding. However, the latter is difficult as it requires much time, effort and resources to determine the plan that would best protect people and property against intense flooding due to hurricanes. This is the reason why the focus has been on improving evacuation strategies. During the recovery stage the US Army Corps of Engineers (USACE) is assigned by FEMA certain missions, such as debris removal, ice and water distribution and restoration of electrical power to critical infrastructure, to assist in the post-hurricane phase (USACE, N.D.).

Role of USACE in Hazard Management

The USACE is responsible for maintaining the Nation's inland and coastal waterways flood risk management, including coastal storm risk management in the United States. They work closely together with FEMA, which is the federal organization that deals with the impact of natural disasters, such as hurricanes, on socio-economic and technical values. Non-Federal Sponsors, such as state agencies and local governmental entities identify a problem and then work with USACE to develop new plans to protect people from these hazards. These Non-Federal Sponsors provide financial help in executing the project. (Tirpak & Das, 2018). As an example, the Texas State General Land Office sponsors the project of Galveston Island (Coastal Study Texas, 2017)). When sponsors are found, the USACE can start the study, design or construction phase.

The USACE follows a set strategy to design infrastructure (Tirpak & Das, 2018). First, an analysis is done in the area to investigate what the problem is, what its causes are, and what types of solutions are possible. For the latter, they also do research in other countries, such as the Netherlands. After that, a feasibility study is made, including designs to solve or mitigate the problem. This is published in a public report, so that people are able to comment on the plans. When comments are gathered, the designs are adapted and finalized and a final report is sent to the Federal Government for approval by Congress. If approved and Congress provides funding, the USACE can start the project.

Evacuation of Galveston region

For the region of Galveston, annual reports are published to inform people what to do when a natural disaster will occur, especially for hurricanes. The documents are called Hurricane Guides and are found for the years 2016 and 2017, (Hurricane Guide 2016, 2016) and (NWS, 2017).

The Galveston region is evacuated when a hurricane is expected. To evacuate the region, a solid strategy is required to adequately move people out of harm's way. The Houston/Galveston region has developed an evacuation plan that shows the different evacuation routes to the mainland in the north and northwest, and a map showing different zones in the region, divided by zip-codes that show the vulnerability of that area for flooding. The zip-coded areas including evacuation routes are shown in Figure 40. The evacuation routes are heading north and northwest. The most vulnerable areas are near the coastline, where Galveston Island is most vulnerable.

People are warned by the National Weather Service of the National Oceanic Atmospheric Administration with text messages on their mobile phones. It depends on the strength of the hurricane if people are required to evacuate. If so, residents have to take measures to keep themselves safe and their property protected. A plan has been developed to guide people through this, as can be seen in Figure 41. The focus is to make sure that there are plenty of resources available (food, water, light sources) and that property is protected against wind force and flooding in the best way possible. If evacuation is required, plans to evacuate have to be prepared. Key questions to consider are the direction of evacuation, within which time window and what to bring along. Moreover, it is advised to make sure the property is safe by disabling all sources that can harm people and property, such as propane tanks and electrical devices. Assistance is not guaranteed for people that want to stay when evacuation is requested.

Recovery strategies and insurance

After hurricanes have passed the Galveston region, damage to property is to be expected. Most people in flood prone areas usually have insurance on property damage, so that large expenses are covered. Besides that, the federal government (FEMA) contributes to reconstruction of properties and infrastructure, in corporation with USACE (USACE, N.D.). Currently, the USACE is assigned to debris management, commodities distribution, temporary housing, temporary roofing, emergency power, infrastructure assessment and support to urban search and rescue.

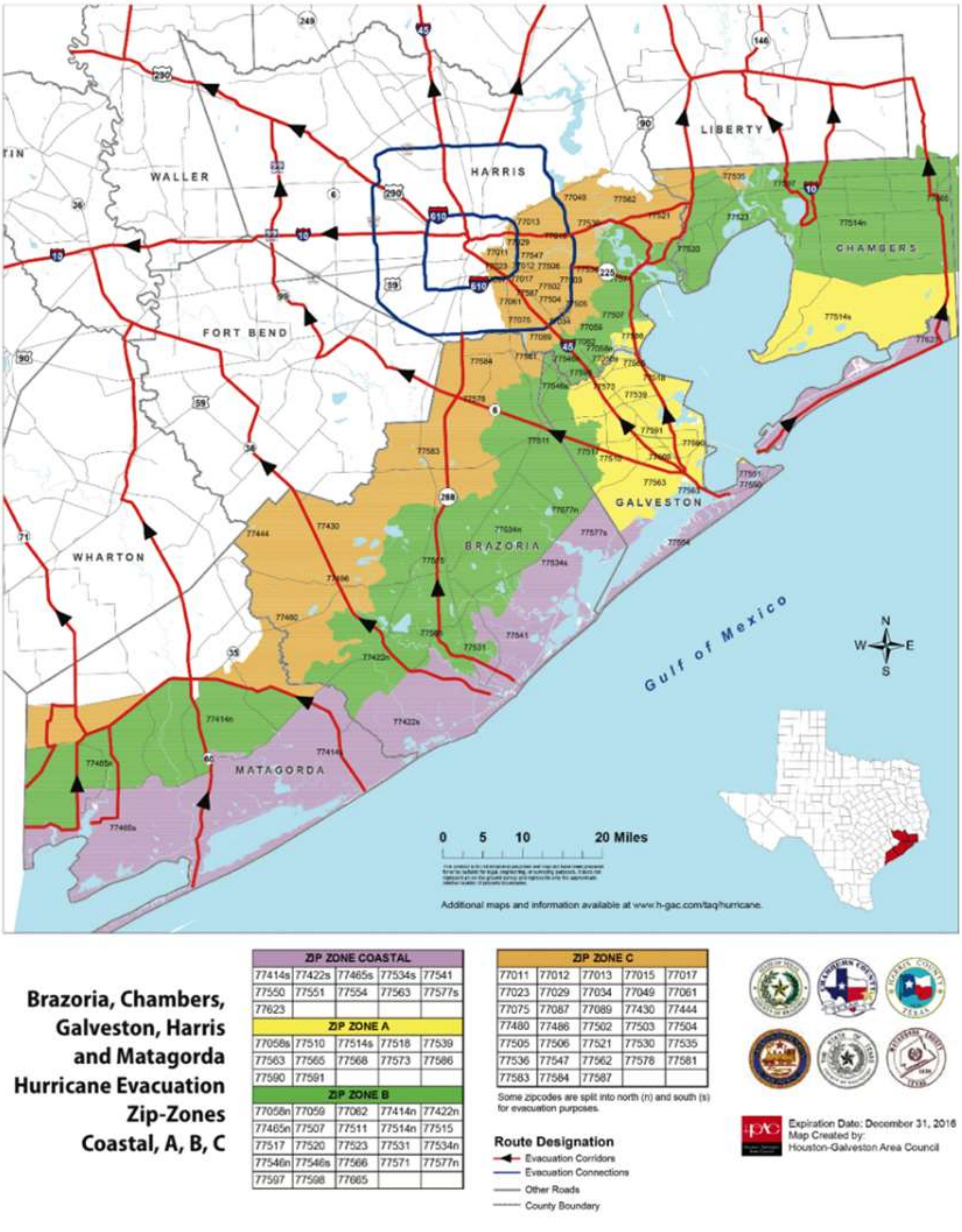

Figure 40 Zip Code areas including evacuation routes (Hurricane Guide 2016, 2016)

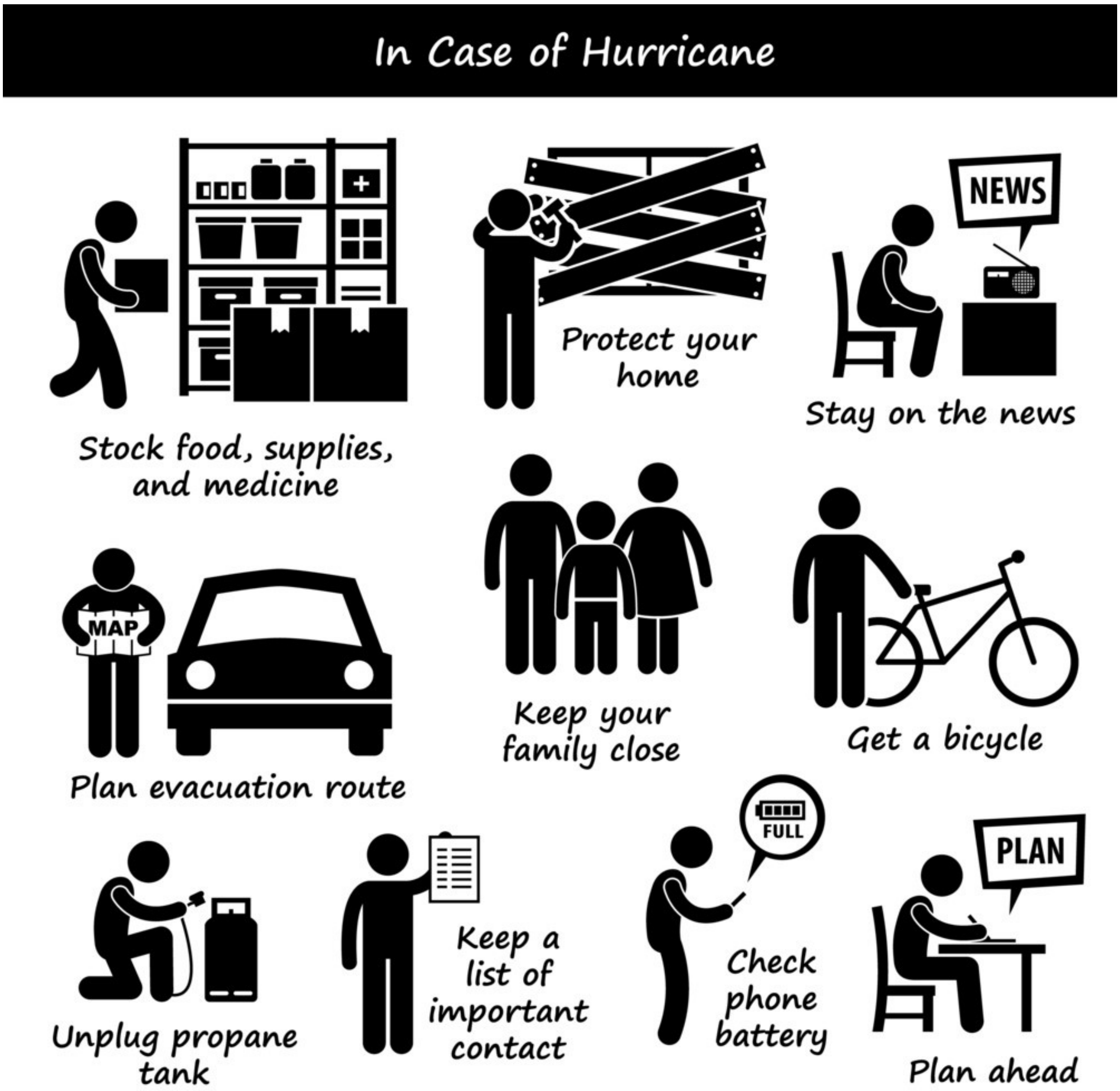

Figure 41 Hurricane checklist for residents and companies (123rf.com, N.D.)

4.6.2 Hazard Management in the Netherlands

The Netherlands has a preventive view on hazard management in general. The protection system for flooding is advanced and consists of various types of closure structures, hard and soft structures, and different policies of different regions. Rijkswaterstaat, the executing governmental body for management of infrastructure in the Netherlands, is responsible for the maintenance and monitoring of all flood defense structures. The construction of infrastructure is outsourced to other companies, who bid on projects. Rijkswaterstaat delivers a preliminary design and a program of requirements, after which the contractor is responsible for the final design and actual building.

The 1953 Flood

On February 1st, 1953, a large storm hit the southwest coast of the Netherlands, resulting in extreme storm surge in combination with spring tide. Extreme water levels, in combination with weak dikes and barriers caused over 500 breaches of dikes in the provinces of Zeeland, West-Brabant and Zuid-Holland and some dikes were completely swept away. An amount of 500 breaches occurred out of a total of 1000 dikes in the flooded region (Delta Committee, 1962). The maximum water level that was measured was 3.85 m above NAP (Normaal Amsterdams Peil), which is the Dutch reference level of MSL in the City of Amsterdam. During this event, more than 1800 people died.

This flood triggered a different attitude towards dealing with floods in the Netherlands, especially in the coastal areas. There was reason to protect an area, no matter the cost. Assuming sea level rise, subsidence of land, and growing population and economy after World War II, the risk of flooding became too large and consequences of flooding had a disastrous impact. Therefore, protection measures were designed.

The Delta Plan and Delta Works

After the final report in 1962, published by the (Delta Committee, 1962), the Delta Plan was launched, which contains several measures to protect the land against future flood risk. Some of the measures were:

- Shorten the coastline by closing of several inlets in Zeeland, for instance the Eastern Scheldt and the Haringvliet Lake;
- Increase and elevate dikes to prevent flooding; both the outer dikes and the inner dikes around cities;
- The design height for structures and dikes was set to 5 m above NAP; after some years this was changed to a design level with a probability of exceedance of 1 in 10,000 years.

These measures were combined in the Delta Works.

Evacuation of western regions

Due to the Delta Works, people in the Netherlands feel safe regarding flood risk. They are not aware of the possible risks and consequences of flooding or dike breaches, mainly because of the small probability of occurrence of flooding, which is 1 in 10,000 years (B. Kolen, 2017). Therefore, people do not know what to do when evacuation is actually needed.

When evacuation is necessary, the primary infrastructure to use is the road (Rijkswaterstaat, 2016). The highways from west to east are used, which are shown as red lines in Figure 42. The primary regions to evacuate when a storm is expected from sea, are the coastal regions. Unfortunately, this area is the most dense and vulnerable area of the Netherlands. Under different scenarios and time frames, it is not possible to evacuate everyone, as is shown in Figure 43. This is mainly caused by unpredictable human behavior and the limited capacity of the road network. The road network in the Randstad is too dense and consists of multiple layers of highways, regional roads and local roads. In the evacuation strategy, it is considered that connections between different road levels are closed to improve the evacuation flows to the East (Rijkswaterstaat, 2016). For most people, however, other evacuation options must be considered. There are possibilities for evacuation by railroad and vertical evacuation.

A report was published that describes the need for vertical evacuation in the vulnerable regions, since the evacuation fractions are too low (Kolen, Vermeulen, Terpstra, & Kerstholt, 2015). Many tall buildings are located in the cities in these areas, but research must be done to suitability and adaptability of these buildings. For more information about the opportunities and limitations is referred to their report.

Recovery after storms

Rijkswaterstaat stated that the Dutch Army must assist with evacuation and recovery when flooding occurs (Rijkswaterstaat, 2016). Roads are not accessible due to high water, but with the use of boats, airplanes and helicopters, people can still be reached.

Conclusion

Dutch hazard management is an advanced system when considering permanent safety measures against flooding. The Delta Works are one of the major protection systems for coastal flooding. However, if flooding still occurs, the Netherlands is only able to cope with the consequences to a limited extent, as:

- People are not aware of the risk and consequences of flooding;
- The infrastructure is inadequate to evacuate people from the most vulnerable areas in the western part;
- The alternative, vertical evacuation, is not sufficiently considered and thus not implemented in existing evacuation strategies.

Figure 42 Highways in the Netherlands. These roads are used for evacuation towards the east and southeast (Wegenforum, N.D.)

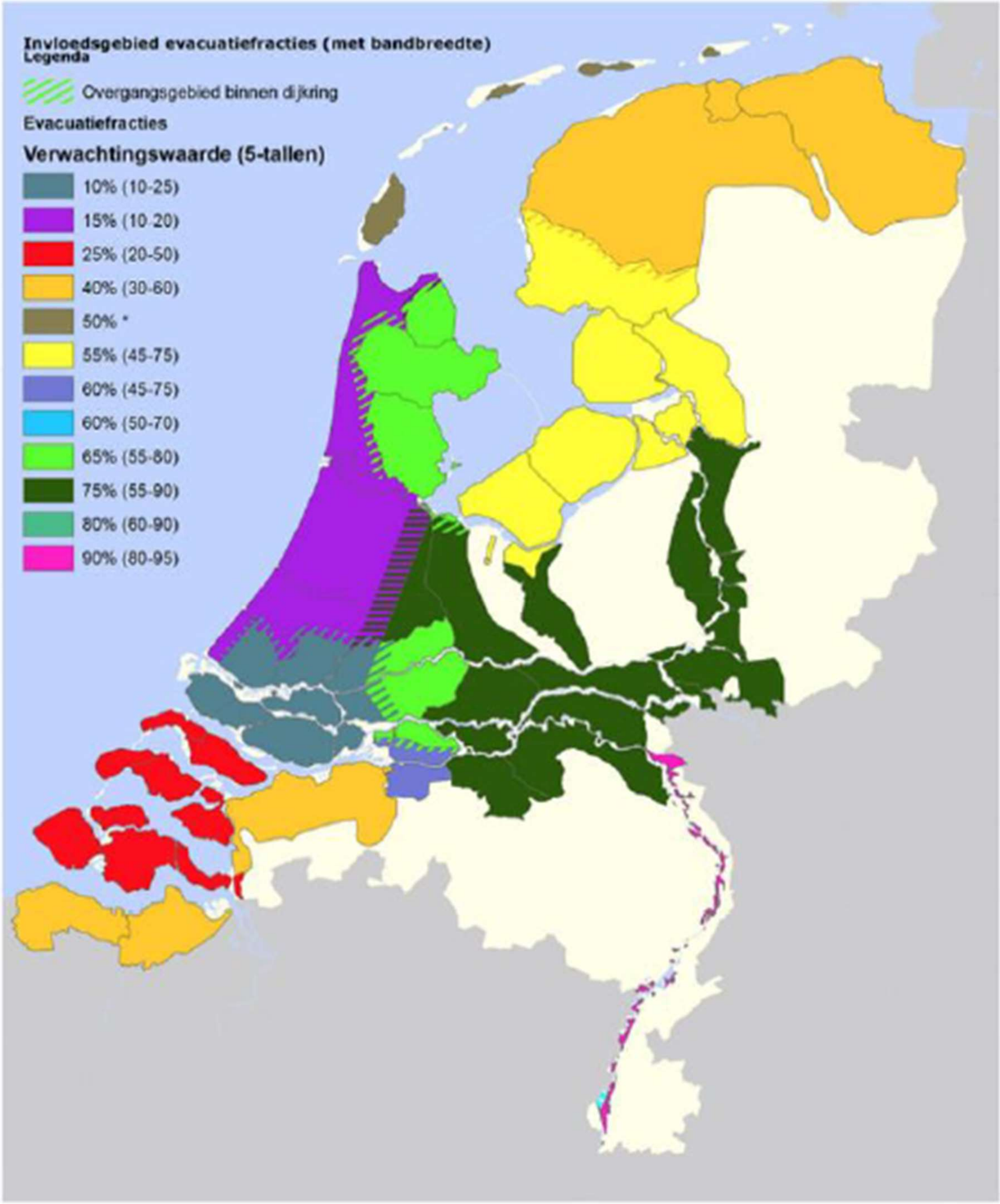

Figure 43 Evacuation fraction of different regions in the Netherlands. Colors display the percentage of people that are able to evacuate from the area. Only 15% of the people in the Randstad is able to evacuate in time. (Rijkswaterstaat, 2016).

4.6.3 Comparison Hazard Management USA-NL

The final step in this chapter is to compare hazard management of both countries. For the USA, the focus is on the Galveston region.

Comparison is done on the following items:

- Involved parties in coastal protection;
- Type of hazards and flood risk;
- Reasons to protect (historical events);
- Evacuation strategies;
- Recovery strategies.

Parties involved

In the USA the USACE is responsible for maintaining coastlines, inland waterways and flood risk measures. They work with Non-Federal Sponsors to develop plans to protect against flood risk and construct infrastructure. They receive missions from FEMA after a hurricane hits a coastal area. In the Netherlands, Rijkswaterstaat is responsible for maintenance and monitoring of infrastructure regarding coastal protection and inland flood protection. However, other companies construct the infrastructure, as Rijkswaterstaat assigns external parties to develop protection measures.

There are external companies actively involved in protecting areas against flooding in the Netherlands, while in the USA the USACE is the main party regarding flood risk measures.

Type of hazards and flood risk

While both the Netherlands and the USA suffer from large storms, the USA suffers from larger and more intense storms (hurricanes). High tide, storm surge and wave impact are common for both countries, as well as consequences due to intense rainfall. The causes of flooding are similar: intense rainfall and storm surge. The rate of occurrence of flooding depends on the infrastructure that is built to deal with flooding.

Reasons to protect

It is difficult to protect against hurricanes, as they have different characteristics and are not easy to predict well. After hurricane Ike (2008), the need for coastal protection was larger than ever before. Although the Seawall blocked most of the waves, storm surge caused a backflow towards the lower parts of the island along the bay. This caused enormous flooding in the city. However, adequate protection against storm surge would require too many resources, which are hardly available nowadays. The Netherlands has developed an extensive Delta Plan, including the Delta Works that protect the country against flooding from both the sea and the inland rivers. This plan was developed right after the 1953 Flood. The government did not want flooding to occur again, so all necessary resources were made available to protect the vulnerable areas.

The time in which measures were taken or have to be taken is different for both countries. Vital regions in the Netherlands were destroyed during the 1953 Flood, causing a united approach to protect the country. In the present era, it would be much harder to execute something similar to the Delta Works. This is one of the reasons why the USA are not willing to spend too much resources on protection of the Galveston region.

Evacuation
Instead of protecting regions, evacuation of these regions is the alternative. In the USA, evacuation is common for dealing with hurricane impact, as protection measures are simply too expensive and complex to construct. Each state has developed its own evacuation strategy for different hazards. When evacuation is necessary, people are required to leave. The main mode of transportation during evacuation is by car. The road network is developed in such a way that evacuation is optimized (reversed laning). Residents in the coastal areas in the Netherlands have never evacuated since the 1953 Flood. If that is necessary, only a fraction of the people is able to evacuate horizontally. Most people must evacuate vertically, into tall buildings. This requires a large supply of basic needs, such as drinking water, toilets and blankets. Most buildings in the coastal area are taller than the expected maximum water level in case of coastal flooding.

The USA is well prepared for evacuation for hazards, although alternatives should be considered and developed, for example vertical evacuation. The Netherlands are not well prepared for coastal flooding, as people feel safe behind the large coastal protection structures. Horizontal evacuation is limited, and would cause extreme congestion on the road network.

Recovery
In both countries, recovery strategies have been developed. The army is deployed to quickly access flooded areas and provide first aid.

Conclusion
The USA and the Netherlands can learn from each other. The USA has a well-developed evacuation strategy, and the Dutch protection measures against flooding are an example of long-term damage mitigation. Although the Netherlands is well protected, the country is not properly prepared for failure of the protection system. The USA have developed evacuation strategies that work well, but alternatives to horizontal evacuation should be developed to better protect citizens and mitigate property damage.

5 Design Measures

This chapter provides information on different potential designs. These designs are created while keeping the results of the performed analyses in Chapter 4 Analysis in mind. The chapter starts with an explanation of how the designs are created and evaluated. After this, each of the designs will be elucidated. At the end of this chapter a conclusion is provided where all created designs are displayed on.

5.1 The Design Process

This section describes what is involved in the design process of this chapter. Before any potential design is created, the location of where the design has to be implemented in will be highlighted. General information about what should be done at this location will introduce every design.

The next step of the process is to come up with a program of requirements. An overview is given that shows what requirements the different potential designs have and what the involved consequences are of these requirements. These consequences will be expressed in numbers. For example, a requirement is that a certain road should remain accessible during a heavy rain event has as consequence that it should be raised for a certain number of centimeters (or feet). The requirements are determined on the outcome of the residential stakeholder sessions and fieldwork experience.

It is important to give an overview of advantages and disadvantages of every potential design. Therefore, a list of these advantages and disadvantages will be given after the program of requirements.

When there are different potential designs possible, the best fit solution should be found. One way to do this is by scoring the alternatives by means of a multi-criteria analysis (MCA). To conduct such an analysis different criteria have to be chosen on which the potential designs have to be evaluated. The criteria and their explanation are shown in Table 10.

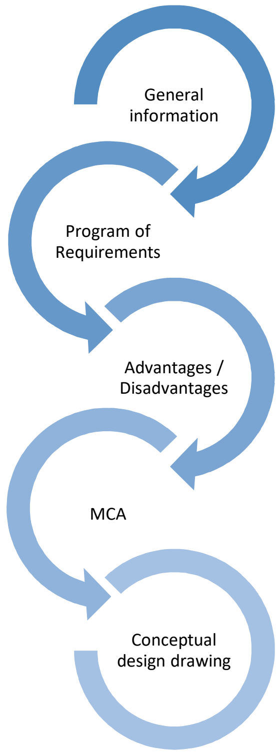

Figure 44 Strategy to gain a final design

As can be concluded from Table 10, the different criteria have different weights. It has been chosen to let the weights for the criteria vary from 1 to 5, where 1 is the lowest weight and therefore the least important and 5 is the highest weight and therewith most important.

In the last column of Table 10 the scoring is explained. Every design will be scored on every individual criterion by giving it a number with a range from 1 to 10. At all criteria it is explained what the lowest score 1 and the highest score 10 mean. Please pay attention that the complexity criterion is inversely related to the score. For example, if a design is complex, it will receive a low score. The other criteria are linearly related to the score.

Please note that not every design has multiple options. In these cases a MCA will not be conducted.

After the conduction of the MCA a best alternative is found. This alternative will be drawn in a conceptual design. This drawing is presented at the end of each section of this chapter.

Table 10 The explanation of the meaning and scoring of the different criteria used in the MCAs at the different designs included in this chapter, with their corresponding weights

Criterion	Explanation	Weight	Scoring
Complexity	The degree of how difficult it is to construct a potential design.	3	1: Very complex 10: Not complex at all
Durability	The life expectancy of a potential design.	5	1: Not durable at all 10: Very durable
Sustainability	The degree of how much the potential design meets the needs of the present without compromising the ability of future generations to meet their own needs' (World Commission on Environment and Development, 1987).	4	1: Not sustainable at all 10: Very sustainable
Aesthetics	The degree of how much the design is deemed to be beautiful.	1	1: Not aesthetical at all 10: Very aesthetical
Maintainability	The degree how easy it is to maintain a design when it has been constructed.	5	1: Not maintainable at all 10: Very maintainable
Preserving ecology	The extent of influence that a potential design has on ecology.	3	1: Not preserving ecology at all 10: Preserves ecology a lot
Effectivity	The degree of how well the design functions where it is designed for.	5	1: Not effective at all 10: Very effective
Multifunctionalit y	The extent to which a design fulfills multiple functions next to its main function.	2	1: Not multifunctional at all 10: Very functional
Adaptability	The extent to which a design is able to be adjusted in a later stadium.	3	1: Not adaptable at all 10: Very adaptable
Constructability	The extent to which a design can really be constructed.	4	1: Not constructible at all 10: Very constructible
Desirability	The degree of how well a design fits the wishes of local stakeholders.	5	1: Not desirable at all 10: Very desirable

5.2 Masterplan

As was found in 4 Analysis, flood risk issues in Galveston can be divided into two aspects: nuisance flooding by regularly occurring precipitation and flooding due to hurricanes. This subdivision is reflected in the proposed mitigation measures, as they require a fundamentally different approach. While damage caused by nuisance flooding can be fully prevented with the proposed measures, damage resulting from hurricanes can at best be mitigated.

However, in spite of the two different approaches, all designs elaborated in this chapter are designed to work together instead of acting as independent interventions. Considerations from all disciplines involved in this project are integrated into the proposed plan. Instead of hampering the design process, different approaches and values from all disciplines were exploited to conceive a more inclusive plan. Several synergies between designs are detailed below.

Critical evacuation infrastructure, vertical evacuation & evacuation by train

Critical evacuation infrastructure is raised to a level which prevents rapid flooding during a hurricane event. This network of roads is taken into account when considering options for vertical evacuation. It would be undesirable to have shelters in unreachable places. Furthermore, the location of a proposed train station is accessible via the main evacuation routes, extending the window of opportunity to evacuate citizens by train.

Combination of pumping capacity & storing water

As the land elevation on the northern part of Galveston is too low for discharge by gravity, pumping stations are proposed to keep the city dry during regular precipitation events. The pumping capacity influences the amount of storage needed to prevent inundation on the streets. Hence, the proposed measures in the neighborhood south of Broadway Av are designed while taking into account the discharge capacity of the pumps.

Breakwaters & raising roads

Breakwaters off the coast and in Offatts Bayou are designed to reduce wave impact on respectively the coast and Offatts Bayou properties. With reducing the wave height, a less increase in road elevation is required.

Airport & evacuation protocols

The airport is equipped with facilities to accelerate the initiation of recovery operations. Furthermore, the airport is connected to critical infrastructure to improve access to the city.

Building with nature solutions

Building with nature solutions on the western part of the island are strategically deployed to prevent the use of hard infrastructure such as levees.

Figure 45 shows the proposed integral design in which all measures work together to prevent damage due to nuisance flooding and mitigate damage during hurricanes. As a guide, the locations of all projects elaborated in this chapter are shown in Figure 46.

Figure 45 Integral design of mitigation measures

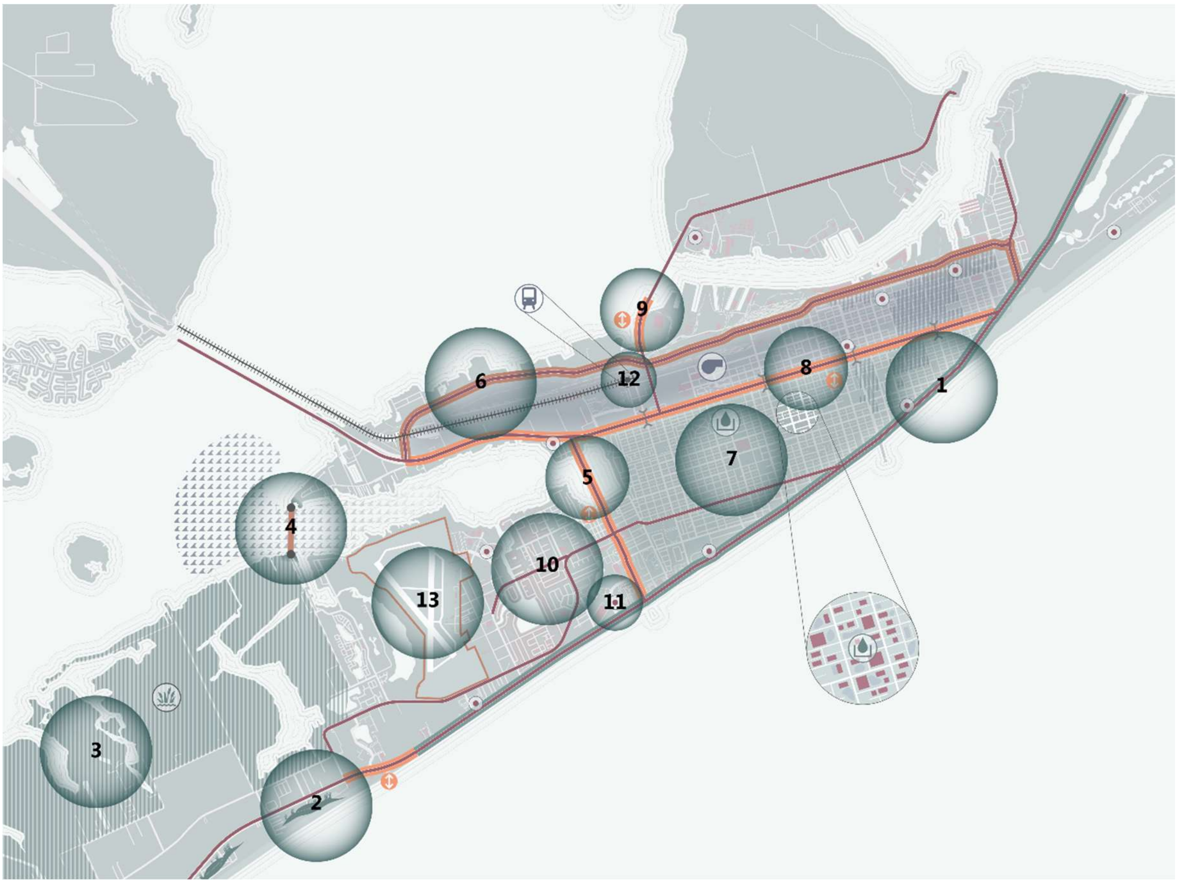

Figure 46 Locations of projects with their respective number

5.3 Design 1: Galveston Seawall

The Galveston Seawall is the primary defense of the City of Galveston against storm surge and wave impact from the Gulf of Mexico. Moreover, Seawall Boulevard, the road on top of the Seawall, is the main road along the beach side of Galveston. It is an important road during evacuation and is therefore marked as critical infrastructure. The current situation provides protection against storm surge and overtopping of most waves during a large storm event or hurricane event. However, an increase in intensity of storms and hurricanes is expected, as well as intensification of hydrodynamic parameters. This recommends adaptations to the Seawall and the coastline in front.

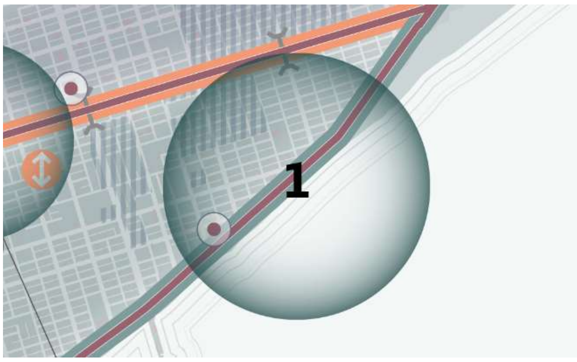

Figure 47 Location of the Seawall

5.3.1 Program of Requirements

The design for the Seawall should allow for elevation, while also preserving the social values of living on an island. An extension of the beach and other nature based solution can help in reducing flood risk, but are by no means capable of preventing flooding by themselves. However, these can help in reducing the required design elevation of the Seawall.

The Seawall does not need be elevated in order to reduce consequences of nuisance flooding, since these events mostly cause problems for the lower elevated areas of the City of Galveston. Although, the design should consider nuisance flooding. The design must not lead to problems on the Seawall during nuisance floods.

When the seawall is elevated, the road (Seawall Boulevard) is elevated as well to keep visibility on the beach and the sea. This results in an elevation difference with the side roads and properties along the Seawall. Adaptations are needed to remain safe transition of traffic flows from and to Seawall Boulevard.

Water from nuisance events needs to flow from the Seawall to lower areas. This sloping style road is recommended. It is preferred to have water on the Seawall flowing to the beach, to prevent nuisance flooding from causing damage to the houses and businesses located behind the Seawall. Water flowing into the city should be drained or stored in specified water storage areas as much as possible. Culverts can help in directing the flow of water.

Table 11 Requirements for Seawall

Requirement	Consequence
Seawall Boulevard needs to be available for traffic during a nuisance flooding event.	Seawall Boulevard needs to have a slope in the road to allow water to run off.
The Seawall needs to reduce the consequences of hurricane events from the Gulf of Mexico, present-day and future events included.	This is achieved by increasing its elevation, corresponding to a hurricane event with a larger return period than the return period of Hurricane Ike (more than 100 years).
Seawall Boulevard needs to allow drainage of water to the beach.	Water entrapped on Seawall Boulevard needs to be able to flow to the beach. This is achieved by having a slope in the pavement on the road, or by using culverts.
Seawall Boulevard needs to be accessible for traffic arriving from the side roads.	The elevation difference between Seawall Boulevard and its side roads cannot be too large. The interfaces need to be connected in a proper fashion.
Seawall Boulevard needs to have a limit in elevation compared to the surrounding area, to prevent visual obstruction.	The increase in elevation may not be larger than the visual height of the buildings at the Seawall.
Seawall Boulevard needs to be accessible as soon as possible after a hurricane event to recover quickly and perform rescue operations.	Seawall Boulevard must be accessible within 24 hours after the peak of the hurricane.
Climate change increases the hydrodynamic parameters: storm surge level, wave height and wind speed. These affect the maximum water level at the Seawall.	The design should be adaptable for future demands and requirements.
The Seawall and the beach are a touristic hotspot and people like to stay on or near the Seawall and the beach.	Extending the beach is an option with the improvement of the coastal protection system of the Seawall. Hence, social and ecological values are incorporated. This allows for a more desirable implementation.

5.3.2 Alternatives

The design alternatives implement measures to reduce the impact of flooding and adding different values to the design to make it more attractive. The design should be integrated into the surrounding as much as possible, aiming to prevent visual pollution under normal conditions. An added benefit to raising the Seawall is the accessibility for evacuation in the pre-hurricane phase and recovery in the post-hurricane phase.

Alternative 1: Rotating Barrier

The road section on the sea of Seawall Boulevard will have a hinge, allowing the top layers of the road to rotate upwards as can be seen in Figure 48. Hydraulic pumps will be placed and used underneath the road to assist in the rotation of the various sections. A temporary barrier is formed under an angle. The pump can be protected from water and waste by allowing only the bar to punch through the floor.

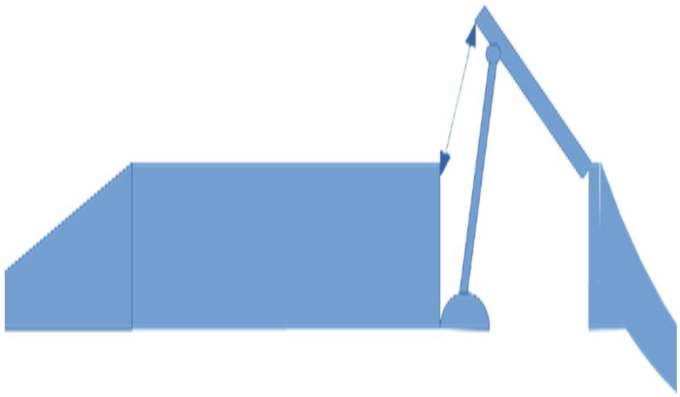

Figure 48 Sketch of Rotating Barrier for Seawall

Table 12 Advantages and disadvantages of rotating barrier for Seawall

Advantages	**Disadvantages**
Highly integrated	Maintenance of the hydraulic pumps requires access
Durable	Pumps need to be protected from water and waste
Flexible	

Alternative 2: Elevating the Galveston Seawall

The Galveston Seawall will be elevated further, as was done in the past. Seawall Boulevard will have to be elevated as well to enhance stability of the Seawall. This results in required adaptations to the intersections with its side roads and the houses as well as the businesses located alongside Seawall Boulevard as can be seen in Figure 49. Sediment is required to elevate the entire section and Seawall Boulevard has to be closed off to traffic temporarily.

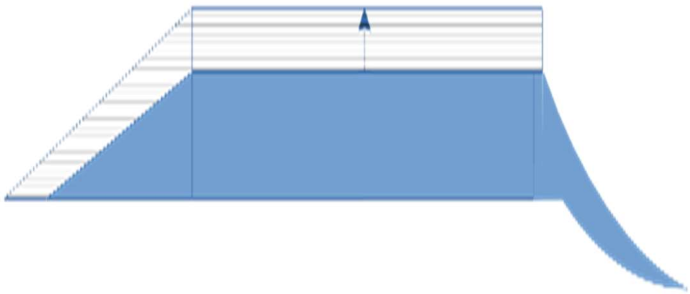

Figure 49 Sketch of elevation of Seawall

Table 13 Advantages and disadvantages for elevation of Seawall

Advantages	**Disadvantages**
Easy maintenance	Hindrance during implementation
	Not sustainable
	Requires adaptation of roads and buildings nearby

Alternative 3: Submerged Breakwater

Submerged breakwaters, shown in Figure 50, reduce wave impact on the coastline and provide an artificial habitat for species, for example oysters. This results in an improved resilient breakwater. Breakwaters have the ability to allow beaches to extend using natural processes of longshore and cross-shore transport of sediment. A breakwater does not prevent the Seawall and the city from flooding. It can, however, be used in a possible combination of measures. Visual pollution is limited when a combination of a submerged breakwater and small elevation of the Seawall is applied.

Figure 50 Submerged breakwater (Lech H Photography, 2012)

Alternative 4: Parking Garage Alternative

This solution is multifunctional as it provides parking spots, social and ecological values. It can provide an additional benefit to the City of Galveston, for instance by creating recreational facilities close to the beach. Since the parking garage consists of concrete, it is able to increase the strength of the Seawall.

Figure 51 Katwijk Garage Flood Defense Alternative (Flood Defences, N.D.)

Alternative 5: Do-Nothing

In this alternative, the situation is not adapted. This means flooding in occurrence with sea level rise will occur, but it is allowed to occur. Using different measures implemented throughout the City of Galveston, the excessive water is removed. Building along the Seawall will have to be adapted to higher flood levels, while the water flows to the lower areas. This alternative is included to compare the current situation with the alternatives and to show whether adapting the Seawall is a necessity.

5.3.3 MCA

Table 14 MCA of alternatives for Seawall

Criterion	Weight	Scoring Rotating Barrier	Result Rotating Barrier	Scoring Elevating Seawall	Result Elevating Seawall	Scoring Submerged Breakwater	Result Detached Breakwater	Scoring Parking Garage	Result Parking Garage	Scoring Do-Nothing	Result Do-Nothing	
Complexity	3	6	18	2	6	6	18	2	6	10	30	
Durability	5	8	40	7	35	8	40	9	45	2	10	
Sustainability	4	8	32	4	16	9	36	6	24	2	8	
Aesthetics	1	6	6	4	4	8	8	9	9	3	3	
Maintainability	5	6	30	10	50	4	20	4	20	8	40	
Preserving ecology	3	2	6	2	6	10	30	2	6	2	6	
Effectivity	5	8	40	8	40	6	30	6	30	6	30	
Multi-functionality	2	6	12	2	4	8	16	10	20	2	4	
Adaptability	3	6	18	8	24	8	24	2	6	7	21	
Constructability	4	6	24	2	8	7	28	2	8	10	40	
Desirability	5	8	40	4	20	8	40	9	45	2	10	+
Total score			266		213		290		219		202	

From highest to lowest scored, the alternatives are ranked:

1. Submerged breakwater
2. Rotating barrier
3. Parking garage
4. Seawall elevation
5. Do-Nothing

The Do-Nothing alternative is the least attractive solution, since it is not effective, durable and sustainable. In the long term it does not help solving the flood problems on Galveston Island.

Elevating the Seawall is an effective solution, which is durable and maintainable. However, it comes with difficulties regarding constructability, since Seawall Boulevard needs to be closed for traffic, buildings near the Seawall need to be adapted and care must be taken regarding stability of the structure.

A submerged breakwater is a desirable solution as it creates a more resilient coastline and supports sustaining the local ecology. The solution reduces wave impact, which contributes to less overtopping over the Seawall. It can be combined with other solutions.

The rotating barrier alternative is difficult to construct, since the Seawall structure needs to be adapted. Moreover, maintenance requires measures regarding accessibility to hydraulic pumps. However, the rotating barrier alternative is effective in reducing wave impact and blocking storm surge. Furthermore, the solution is durable and sustainable. It prevents permanent visual pollution.

The parking garage alternative scores high on multi-functionality. Furthermore, the durability of this design is high due to the fact it has a long lifespan. Downsides of this alternative are its complexity, adaptability and constructability.

5.3.4 Preliminary Design

The choice is made to design a combination of three of the alternatives: rotating barrier, submerged breakwater and a parking garage. The submerged breakwater is not visible from the beach and contributes to a more resilient coastline.

In normal weather conditions, the rotating barrier is closed. When a coastal flood warning is given, it opens and elevates the Seawall temporarily, as shown in Figure 52. The parking garage shown in Figure 52 is an additional feature of the design. The parking garage replaces the parking spots on the Seawall, which increases space for pedestrians. It provides additional stability to the Seawall, which is currently done by a retaining wall only.

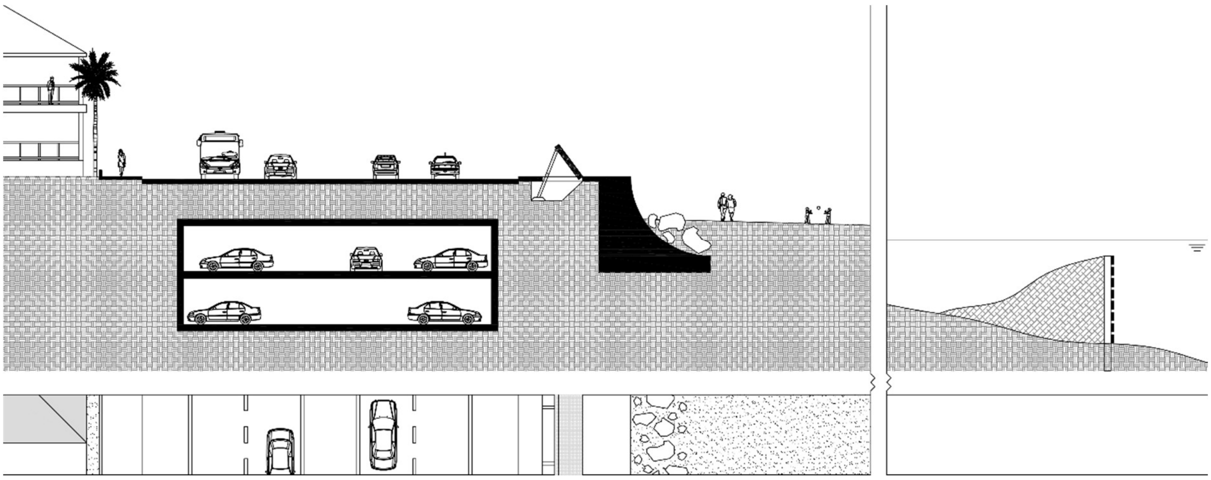

Figure 52 Preliminary design of a combined Galveston Seawall design, including a parking garage

5.4 Design 2: West Island Shore Protection

The combination of high tide and storm surge causes flooding on the western part of the island, as there is hardly any coastal protection. Moreover, this part of the coastline faces permanent erosion in the surf zone (see Figure 38). This is, amongst others, caused by the construction of the Seawall. The largest erosion rate occurs at the boundary of the hard structure (Seawall) and soft structures (dunes, beaches).

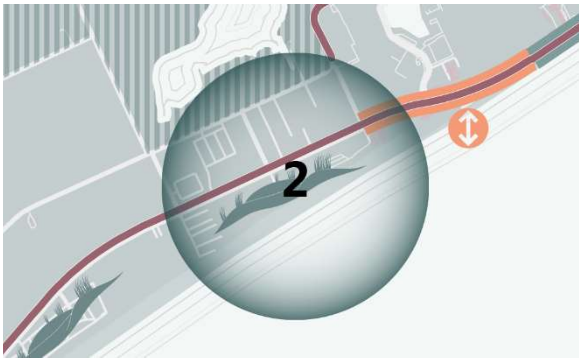

Figure 53 Location of West Island Shore Protection

5.4.1 Program of Requirements

The western part of the island must be better protected against storm surge and wave impact coming from both the sea and the bay. Wave impact is reduced by changing the profile of the beach slope, increasing roughness of the soil and install submerged breakwaters in front of the beach. Protection against storm surge is achieved by constructing levees or dunes between the beaches and the houses.

Table 15 Requirements for West Island Shore Protection

Requirement	Consequence
Erosion rate along beaches must be decreased	Permanent nourishment is required
Protection is needed against storm surge	Integration of dunes between the beaches and the houses to minimize flooding
Wave impact must be reduced	Submerged breakwaters are optional in the surf zone. Beaches are enlarged and beach slope is reduced, by nourishments.
Increase space for recreation	Enlarge the beach by nourishments

5.4.2 Advantages and Disadvantages

No multiple alternatives are designed, as one option is suitable to apply in this area. The advantages and disadvantages are summarized below.

Table 16 Advantages and disadvantages for West Island Shore Protection

Advantages	Disadvantages
Erosion rate is decreased	Visibility from houses to sea can be reduced
Beaches are enlarged for recreational use	Permanent (annual) nourishment is required
Protection of houses against storm surge by creating dunes	A large design return period of the hurricane requires higher dunes

5.4.3 Preliminary Design

To decrease the erosion rate, large nourishments are needed upstream of West Island. A possible location of a nourishment is in front of the Seawall, which will enlarge the beach southwest from the Pleasure Pier. The longshore currents transport the sediment towards West Island beaches.

The design criteria are based on a 10-year event. To reduce wave impact on the island, the dunes are elevated to a minimum level of 4.1 m (13.5 ft.) above MSL (see Figure 54 and Figure 55). The street level is 1.4 m (4.6 ft.) above MSL, which gives a net height difference of 2.7 m (8.8 ft.). From the second floor of the houses, one can still see the beach and the sea. The second measure for wave impact reduction is the construction of a sand bar in the surf zone to break waves and reduce wave impact on the dunes. The third measure is to enlarge the beach by nourishments, to create more room for recreation. The total design elevation is the sum of:

Table 17 Design values for dune height

High tide	+ 0.27 m MSL (+ 0.89 ft.)
Storm surge	+ 1.78 m MSL (+ 5.85 ft.)
Relative sea level rise	+ 0.16 m MSL (+ 0.52 ft.)
Wave height	+ 1.40 m MSL (+ 4.59 ft.)

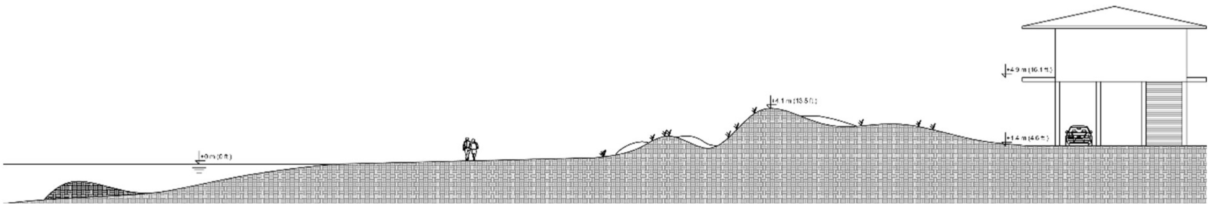

Figure 54 Overview of the measures to reduce the impact at the coastline of West Island: Heighten dunes, submerged sand bar and enlarging the beach

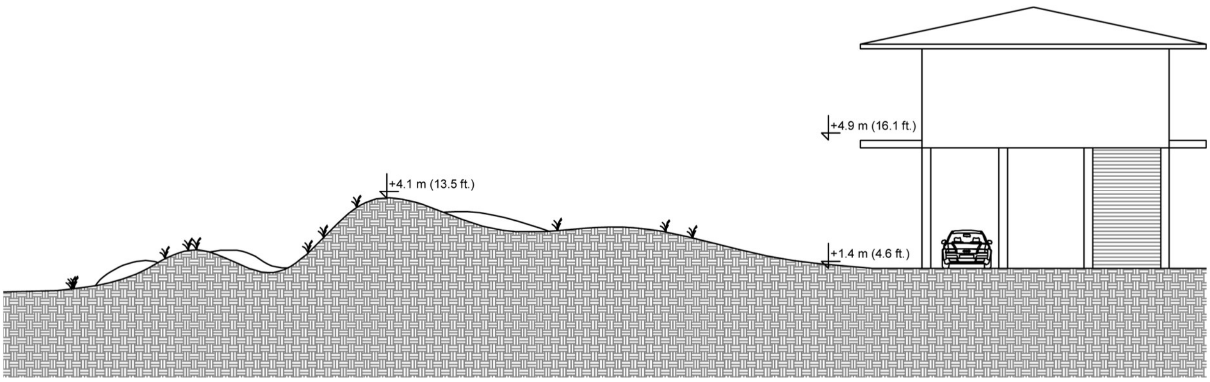

Figure 55 Zoom of dunes. The minimum height is + 4.1 m above MSL, which is 3 m higher than the streets behind the dunes.

5.5 Design 3: Wetlands on West Island

The western part of the island is low-lying and largely unprotected. From the bay, waves enter the backshore. Natural vegetation is already present in this region. The aim is to extend the area and use these wetlands as coastal protection of the western island along the bayside. Protection is needed against tide, surge, and waves. Especially surge and waves due to the backlash of a hurricane cause damage to the bay coastline.

Figure 56 Location of Wetlands on West Island

5.5.1 Program of Requirements

The wetlands must be able to reduce the impact of storm surge and waves. The main goal is to reduce the velocity of the currents caused by the waves and break the waves significantly to protect the houses on the West Island. Surge is defined an increase of the water level. To protect against surge a levee or similar is needed. As this is not desired, natural elevation of the wetlands is the preferred alternative: by creating islands and small hills that reduce incoming surge.

Table 18 Requirements for Wetlands on West Island

Requirement	Consequence
Wetlands must be able to break most incoming waves.	The soil friction must be increased by planting vegetation and elevating parts of the wetlands.
Type of incoming waves must be steered to reduce erosion in the surf zone.	The breaker parameter must be changed to generate spilling or surging waves (Holthuijsen, 2007). These waves are gentler and cause less erosion.
Protect Galveston island against incoming surge for a 2-year event.	The minimum elevation for a levee or small hill must be 1.6 m (5.3 ft.) above MSL, at minimum.
Building with Nature solutions are desired.	The use of oyster reefs in shallow waters improve the reduction of wave height and contribute to local economy.

5.5.2 Advantages and Disadvantages
No multiple alternatives are designed, as one option is suitable to apply in this area. The advantages and disadvantages are summarized below.

Table 19 Advantages and disadvantages for Wetlands on West Island

Advantages	Disadvantages
Preserving and improving ecology and biodiversity	No protection guaranteed against hurricane impact (waves, surge)
Reduce wave impact for smaller storms	Maintenance required as erosion still occurs
Expanding economic benefits, in particular fishery	

5.5.3 Preliminary Design
The combination of vegetation and level differences in the area reduces wave height and erosion rates. As there are already wetlands, the implementation of new and improved wetlands strengthens the area. Figure 57 shows a possible implementation of vegetation used for creating elevation differences. The use of oyster reefs has already been explained in Appendix A.5 Ecology; an example of an oyster reef project is shown in Figure 121.

Figure 57 Implementation of level differences in wetlands to reduce wave height (Waddenzee, 2016)

5.6 Design 4: Offatts Bayou Barrier

The entrance to Offatts Bayou at the western side of the City of Galveston is vulnerable to flooding. Flooding has not only occurred as a consequence of high storm surge, but also as a consequence of a hurricane backlash. This happened in the aftermath of Hurricane Ike and led to widespread damage.

In order to prevent storm surge and, especially, the backlash effect from causing a large amount of damage, not only at the Offatts Bayou West area but for the whole Offatts Bayou area, an obstruction at the entrance is required. The homeowners at Offatts Bayou West, however, have stated during the residential stakeholder sessions their appreciation of having an open view of the bayou, the ease of sailing into the bayous and the all-around island experience, and would like to keep it that way.

A design solution has to be determined which mitigates the largest amount of damages caused by hurricane events, while at the same time honoring the views of the (residential) stakeholders involved. Multiple design alternatives are elaborated in this section, followed by a multi-criteria analysis to assist in determining the best fit preliminary design solution.

Figure 58 Location of Offatts Bayou barrier

5.6.1 Program of Requirements

Table 20 Requirements for Offatts Bayou Barrier

Requirement	Consequence
Damage to properties around Offatts Bayou due to high water levels, whether caused by storm surge or hurricane backlash, needs to be minimized as much as possible.	Incoming waves need to dissipate, resulting in minimized damage.
Visual blockage for residents living along Offatts Bayou should be minimized.	The design should prevent a large amount of permanent visual pollution.
Residents living along Offatts Bayou should have access to open water.	The design should not permanently constrict Offatts Bayou, preventing citizens from reaching open waters.
Nature based solutions are preferred to hard solutions.	The design should try to incorporate a way to encourage ecological prosperity in the area.
The entrance of Offatts Bayou is almost 700 m (2300 ft.) wide, measured from 103rd street at the south bank to Teichman Point on the north bank. Water depth is for the most part 3.0 m (9.8 ft.) except for the dredged entrance channel, where the water depth is 6.0 m (19.7 ft.)	The design needs to consider the complete cross-section of the entrance, otherwise large erosion could occur in parts where water is allowed to flow through.
Abutments on both the north and south bank are required to put the barrier in place.	Some properties need to be bought out/moved or additional land has to be made (by disposing dredged material for instance).

5.6.2 Alternatives

Alternative 1: Inflatable barrier

To prevent wave impact on properties along Offatts Bayou an inflatable barrier is placed on the bottom of the bayou entrance. Under normal conditions the barrier is always located on the bottom of the bayou entrance, largely preventing visual obstruction. During high water, caused by storm surge or hurricane backlash, the barrier will be inflated with air and water, allowing it to block the entrance of the bayou. Thus it is able to dissipate the wave energy (waves, surge), which would otherwise affect the properties along Offatts Bayou.

The primary function of the barrier is thus to dissipate wave energy, resulting in damage prevention for the properties along the bayou. Since most properties along the bayou are on stilts (with varying elevation), a certain amount of flooding is allowed and thus it is an option to allow the barrier to overtop. As long as the flood rate in Offatts Bayou is reduced, damage is prevented. In combination with the design at the entrance of the bayou, a design to prevent flooding is implemented at 61st Street to minimize flooding into the city from the eastern part of Offatts Bayou.

A smaller height of the barrier also results in the way stations of the barrier to have smaller dimensions. These way stations are required to completely close off the bayou, otherwise too large of a momentum would occur in the barrier. Smaller dimensions of these way stations result in less visual pollution for the citizens of Offatts Bayou.

For the cross-section at the dredged entrance channel additional measures need to be taken since the water depth at this location is larger compared to the other parts of the entrance to Offatts Bayou. In Figure 59 the inflatable barrier at Ramspol in the Netherlands is shown. It is used to close off the Zwarte Meer from the Ketelmeer during high water to guarantee the flood resilience of the hinterland.

Figure 59 Ramspol barrier in the Netherlands (Rijkswaterstaat, 2017)

Table 21 Advantages and disadvantages of an inflatable barrier

Advantages	Disadvantages
Open waterways	The barrier is vulnerable to damages
Can dissipate wave energy properly	Maintenance work is complex
	Overtopping still takes place
	Requires stations between the different sections to span the entrance

Alternative 2: Floating barrier

This alternative design uses a floating barrier to block the wave impact and celerity into the bayou. It will float on the water and close the top part of the cross-section of the bayou entrance, while still allowing water to flow underneath. In this way the barrier reduces the flood rate of the bayou, resulting in a reduction of damage to the properties of Offatts Bayou. However, wave impact is highly reduced since waves break due to the floatable part of the barrier.

The barrier is normally stored off site and is only brought in and put into place during hurricane and other extreme storm surge events. The floatable barrier alternative requires additional measures to reduce the maximum momentum. If not, the barrier can break, be transported or undergo heavy damages. An example of a floatable barrier is shown in Figure 60.

Figure 60 Example of a floatable barrier (Dam-It Dams, 2018)

Table 22 Advantages and disadvantages of a floatable barrier

Advantages	**Disadvantages**
Can dissipate wave energy properly	Overtopping still occurs
Is not permanently present so, views of residents along Offatts Bayou are not blocked	Barrier must be stored at a facility when not being used
	Protection of the bottom of the bayou is needed to prevent soil erosion
	Requires additional research into the frequency of the wave and the floating barrier, to prevent resonance and stimulate wave dampening

Alternative 3: Ecological breakwater

This alternative utilizes the area's ecological aspects to create a combined barrier consisting of a movable gate and a breakwater, which is shown in Figure 61. Part of the barrier thus forms a permanent closure at the entrance of Offatts Bayou, while another part only closes when a hurricane event is imminent. The permanent part will span across the shallow parts of the entrance, creating a sheltered area to allow for wetland growth. This increases the overall flood resilience of the area. The movable part is located at the dredged entrance channel into the bayou. Under normal circumstances it is open, allowing for open water access. It closes during surge to minimize impact in the bayou. During its closed configuration, the bayou is no longer openly accessible.

This design aims to protect the bayou, while preserving the natural values which the residents value greatly and even creating more room to allow for ecological development. The movable part has various alternatives. It can be a horizontal closing gate or a vertical closing gate such as an inflatable barrier.

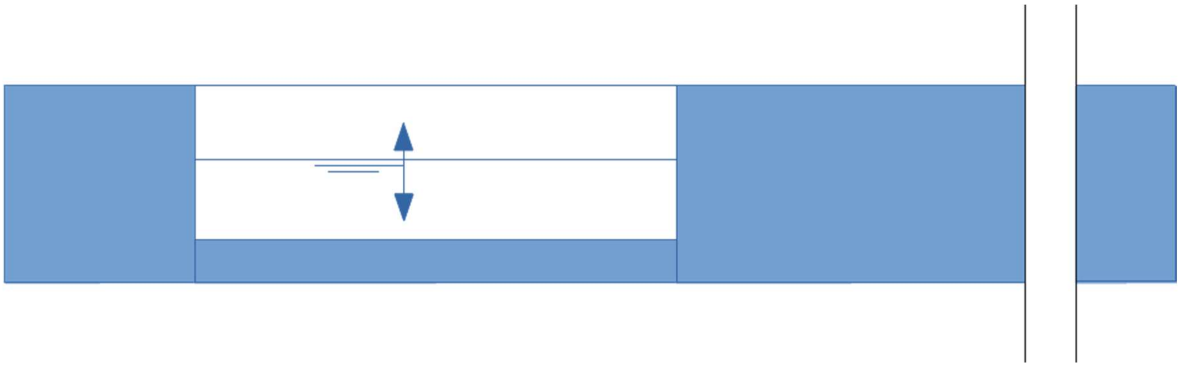

Figure 61 Impression of an ecological breakwater gate alternative

Table 23 Advantages and disadvantages of an ecological breakwater

Advantages	**Disadvantages**
Preserves and creates opportunities for ecological development	Closes of a part of the bay, however low the barrier may be it does change the view somewhat
Effective solution	Erosion occurs in the cross-section, especially near the navigation channel into the bay. The consequences of this erosion need to be determined
Requires minimal time to close the barrier	

5.6.3 MCA

Table 24 MCA for Offatts Bayou Barrier

Criterion	Weight	Scoring Inflatable Barrier	Result Inflatable Barrier	Scoring Floating Barrier	Result Floating Barrier	Scoring Ecological Breakwater	Result Ecological Breakwater	
Complexity	3	6	18	4	12	5	15	
Durability	5	5	25	5	25	9	45	
Sustainability	4	3	12	2	8	6	24	
Aesthetics	1	5	5	6	6	4	4	
Maintainability	5	4	20	7	35	6	30	
Preserving ecology	3	7	21	9	27	10	30	
Effectivity	5	7	35	5	25	9	45	
Multi-functionality	2	2	4	1	2	8	16	
Adaptability	3	1	3	9	27	7	21	
Constructability	4	6	24	4	16	6	24	
Desirability	5	6	30	7	35	7	35	+
Total score			**197**		**218**		**289**	

In terms of aesthetics and the preservation of the present-day experience of living near the Offatts Bayou, it is not possible to fully maintain the same view of the bay with either of these three alternatives. Every alternative (solution) will require some man made changes to the entrance of the bayou. With the inflatable and floatable barriers, some constructions will have to be put in place to span the length of the entrance of the bayou. It is not possible to create a barrier without these elements because it would result in too high stresses in the structure. The ecological breakwater alternative might require the most permanent structure in the entrance, but compensating for that will be the creation of new ecological areas for the citizens to enjoy.

The ecological breakwater is the most durable of the three alternatives because only a small part compared to the other alternatives requires moving parts. This means less vulnerable machinery need to be used compared to the others. The inflatable barrier is the alternative which is the hardest to maintain, simply because it is located on the bottom of the bayou entrance. The maintainability of the floating barrier alternative is highest because it can be placed on dry land.

The ecological breakwater is the most multifunctional one since it aims not only to protect Offatts Bayou from flood damage, but also to increase the chance for flora and fauna to develop in the area. This also gives it the highest score in preserving ecology. The adaptability of the floating barrier is deemed the highest, followed by the ecological barrier, this reasoning follows from the arguments of maintainability. It is chosen to make a preliminary design of the ecological breakwater.

5.6.4 Preliminary Design

The static part of the ecological barrier runs from the southern bank just north of 103rd street towards Teichman Point on the north bank and will end just south of the navigational channel. Figure 62 shows the original situation at the entrance of Offatts Bayou and Figure 63 shows the new situation with the ecological barrier in open configuration. Figure 63 also shows the new wetlands development, which are meant to increase the flood resilience of the bayou and provide amenities to residents living near Offatts Bayou. The locations of the wetlands are an indication.

Figure 62 Offatts Bayou: current situation

Both the permanently visible as well as the movable part of the barrier in closed configuration retain water. The movable part of the barrier will require an abutment on the northern bank at the entrance to the bayou and a connection to the static part of the barrier on the south side of the navigation channel. The static part of the barrier requires an abutment on the south bank at the entrance of the bayou.

In order to limit visual pollution the movable part of the barrier can consist of an inflatable barrier as described in the inflatable barrier alternative, or a horizontal translating gate. The gate requires additional room on the northern bank in the open configuration under normal conditions. Erosion occurs at the location of the gate due to the decreased area available for water moving in and out the bay. Bottom protection needs to be put in place in order to guarantee the structural stability of the barrier. Bottom protection along the breakwater and bank protection on both the south as well as the north bank are also required.

The static part of the barrier consist of a breakwater. It can be constructed using sand and stones or it can be made of wood. The breakwater is meant to function as a means to attract flora and fauna, such as oysters. The breakwater needs to be visually attractive and be part of the environment, providing shelter for species of animals and at the same time stimulate the growth of wetlands at both sides of the breakwater. The goal of this breakwater is to provide protection, while at the same time conserve the natural atmosphere of the area. Navigation from the southern bank towards the bay and open water is guaranteed by creating navigational channels through the wetland areas.

Figure 63 Offatts Bayou ecological barrier in open configuration

Figure 64 shows Offatts Bayou with the ecological barrier in closed configuration. This configuration happens only when a hurricane event (or other storm surge events) is imminent. This closes off the bayou and thus prevents navigation. However, during an extreme event such as a hurricane, navigation is not possible (or wanted) anyway.

The barrier is meant to break the incoming wave energy and allow for gradual flooding of the bayou. This means a reduction of the damage. The barrier could also be used to completely prevent flooding, but this would mean an increased height of the barrier and more stringent requirements to the materials of which the barrier would need to consist. This is due to the higher forces the barrier needs to resist in order to prevent flooding. A higher barrier, however, causes visual pollution and would not satisfy the requirements for the design.

Figure 64 Offatts Bayou ecological barrier in closed configuration

5.7 Design 5: 61^{st} Street

61^{st} St connects Broadway Av/Interstate 45 with the Seawall in the western part of the city. It divides Offatts Bayou and English Bayou by a bridge.

Figure 65 Location of 61st Street in the City of Galveston

5.7.1 Program of Requirements

The road must have a minimum elevation that guarantees no inundation occurs during regularly occurring events (nuisance flooding). Large parts of the street are already at an appropriate evelation. Moreover, the road should prevent English Bayou from flooding due to storm surge. The road is part of the evacuation network, so this function must be maintained in the pre-hurricane and post-hurricane phase.

Requirement	Consequence
Prevent flooding of road during nuisance flooding	Minimum elevation must be 2.6 m above MSL
Keep 61^{st} St accessible for evacuation	Integrate road in evacuation network
Through-pass between Offatts Bayou and English Bayou must remain possible	Opening required underneath bridge
Prevent storm surge in English Bayou	Block through-pass of currents underneath bridge

Figure 66 Requirements for 61st Street

5.7.2 Alternatives

Two alternatives are developed.

Alternative 1: permanent dike underneath 61^{st} St

The first option is to close the through-pass between Offatts and English Bayou. This prevents storm surge into the east bay. However, damage to the ecosystem is likely and access to Offatts Bayou and the Galveston Bay is not possible.

Figure 67 Impression of dike underneath 61st Street (Rijkswaterstaat, N.D.)

Table 25 Advantages and disadvantages of a dike underneath 61st Street

Advantages	Disadvantages
Blocks storm surge	Ecosystem is harmed
Region east from 61st St is protected	No access to Offatts Bayou possible from English Bayou

Alternative 2: Gate barrier

The second alternative is to use gates in front of the bridge at the side of Offatts Bayou, which are closed in case of storm surge. Access to Offatts Bayou is possible under normal conditions.

Figure 68 Impression of a gate in a barrier (Watersnoodmuseum, N.D.)

Table 26 Advantages and disadvantages of a gate barrier

Advantages	Disadvantages
Blocks storm surge	Structure of gates are visible
East region of 61st St protected	High maintenance cost
Ecosystem is maintained	High construction costs
Access to Offatts Bayou	

5.7.3 MCA

Table 27 MCA for barrier in 61st Street

Criterion	Weight	Scoring Permanent Dike	Result Permanent Dike	Scoring Gate Barrier	Result Gate Barrier	
Complexity	3	5	15	5	15	
Durability	5	4	20	6	30	
Sustainability	4	5	20	5	20	
Aesthetics	1	3	3	5	5	
Maintainability	5	6	30	4	20	
Preserving ecology	3	2	6	8	24	
Effectivity	5	4	20	5	25	
Multi-functionality	2	2	4	7	14	
Adaptability	3	6	18	4	12	
Constructability	4	6	24	3	12	
Desirability	5	4	20	7	35	+
Total score			**180**		**212**	

Both alternatives are complex to construct, as the road already exists. Large differences are not present, except for Preserving Ecology and multi-functionality as the gates contribute more to these criteria.

5.7.4 Preliminary Design

The option with gates is the best option in terms of preserving the ecosystem, accessibility of English Bayou and preventing storm surge in English bayou. The gates will close and block the incoming water when storm surge is expected. Under normal conditions boats are able to pass the bridge. The ecosystem is minimally impacted as water is still able to flow under normal conditions.

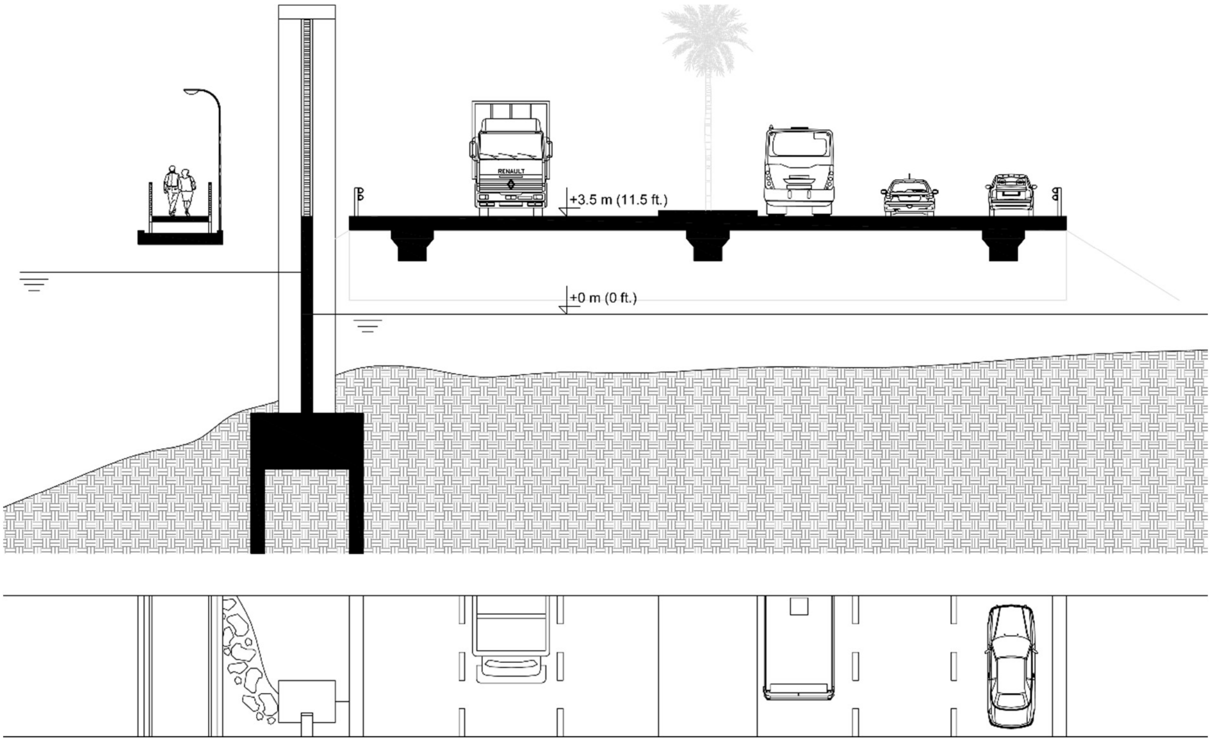

Figure 69 Cross section of bridge at 61st Street with gates at the side of Offatts Bayou. When gates are closed, water is not able to flow underneath the bridge

5.8 Design 6: Harborside Dr

Harborside Dr connects the Port of Galveston and the Gulf Freeway from Houston. In Figure 70 the western road section is shown, located between the Gulf Freeway and the crossing with 51st St. Harborside Dr runs up to Ferry Rd in the east of the city. The road floods when intense rainfall events occur. This road suffers much from nuisance flooding as it is on a low level compared to the surrounding area.

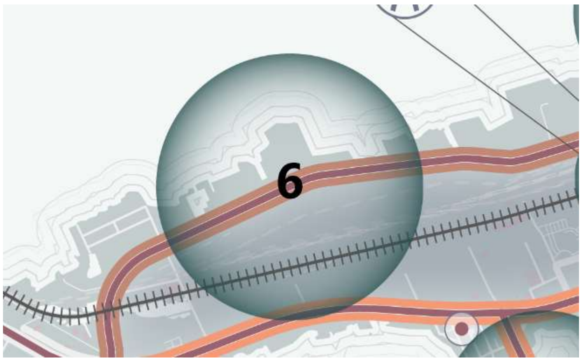

Figure 70 Location of Harborside Dr. This figure shows the west part only.

5.8.1 Program of Requirements

The road is elevated in order to prevent nuisance flooding during intense rainfall events. As a consequence, the road is still accessible for traffic. The road will block stormwater flowing from south to north, such as at Broadway Av. Drainage of water must remain possible to prevent nuisance flooding along the road. This is possible with application of a pump system alongside Harborside Dr. Due to the elevation of the road, it blocks storm surge and high tide that occurs with a 2-year event. Most buildings are protected against nuisance flooding since these are elevated compared to the roads.

The road is designed to reduce damage of property and infrastructure in low parts of the city, such as the historic core. Buildings in these parts are not elevated sufficiently to prevent flooding due to storm surge caused by hurricanes. Therefore, alternatives regarding protection against larger storm surge levels must be considered.

Harborside Dr is divided in 5 sections:

A. The crossing of Harborside Dr and the Gulf Freeway/Broadway St
B. Section between Gulf Freeway and 51st St
C. The crossing of Harborside Dr and 51st St/Pelican Island Causeway
D. Section between 51st St and Ferry Rd
E. The crossing of Harborside Dr and Ferry Rd

Section A must be elevated to prevent flooding at this crossing. However, this crossing includes a viaduct of the Gulf Freeway. If the crossing is elevated, the viaduct must be adapted as well. Section B is elevated, but contains issues regarding interfaces with the railroad tracks. These tracks must be elevated as well. Research to the possibilities for elevation of the railroad must be performed to integrate elevation of the road adequately. Section C consists of a set of viaducts that are connected at the crossing. These viaducts are already on a sufficient level. The connections with the lower elevated road sections of Harborside Dr, 51st St and Pelican Island Causeway must be adapted.

Section D is elevated, but has many side roads in the city around Downtown. These side roads must be connected to Harborside Dr Section E must be elevated to prevent nuisance flooding. The crossing connects Harborside Dr and Ferry Rd, which means that Ferry Rd must be elevated as well. This must be realized, as Ferry Rd is part of the evacuation network and connects Harborside Dr with Broadway Av and Seawall Boulevard.

Table 28 Requirements for Harborside Dr

Requirement	Consequence
Harborside Dr needs to be available for traffic during a nuisance flood event.	Harborside Dr needs to be elevated to a minimum height of 1.6 m (5.3 ft.) above MSL.
Harborside Dr needs to be fitted with measures that reduce the consequences of hurricane events from the bayside.	Harborside Dr has to reduce the flood rate of the areas directly present to the south. This can be achieved by allowing it to have an elevation higher than the elevation required for a nuisance event.
Harborside Dr needs to allow drainage of water to the bay.	The drainage system must be improved to accommodate run off underneath Harborside Dr.
Harborside Dr needs to allow drainage of water from the road to the sides of the road.	The drainage system must be improved to accommodate run off to the sides of the road, by creating ditches alongside the road, and remain a small sloped profile of the road.
Harborside Dr needs to be accessible for traffic arriving from side roads.	The elevation difference between Harborside Dr and its side roads cannot be too large.
Harborside Dr needs to have a limit in elevation compared to the surrounding area, to prevent visual obstruction.	The permanent elevation may not be larger than the visual height of street level. Alternatives in temporary structures must be considered.
Harborside Dr needs to be accessible as soon as possible after a hurricane event to recover quickly and perform rescue operations.	Harborside Dr must be accessible within 24 hours after the peak of the hurricane.
Climate change can increases the amount and intensity of rainfall. This expectation must be considered in the adaptability of the design.	The design should be adaptable for future demands and requirements.

5.8.2 Alternatives

Two alternatives are considered: a rotating barrier and a temporary placed barrier. Both barriers are implemented in a design that consists of elevation of Harborside Dr to 1.6 m (5.3 ft.) above MSL and the height of the barrier of 2.0 m (6.6 ft.). The total height of the protection measure is 3.6 m (11.8 ft.) above MSL, capable of blocking surge levels up to 3.6 m (11.8 ft.) above MSL and break waves that still overtop. The elevation of Harborside Dr prevents the road from nuisance flooding. Culverts are placed underneath the road to stimulate drainage of stormwater to the bay. Pumps are installed to discharge stormwater into the bay.

In times of hurricanes, the road is used for evacuation. This requires the minimum elevation that is applied, to ensure safe use of the road in the pre-hurricane phase.

Alternative 1: Rotating barrier

The rotating barrier is located in the road. During storms, these barriers are lifted by hydraulic pumps, creating a sloped wall that blocks water levels up to 3.6 m (11.8 ft.) above MSL. Overtopping waves are broken. The road can still be used.

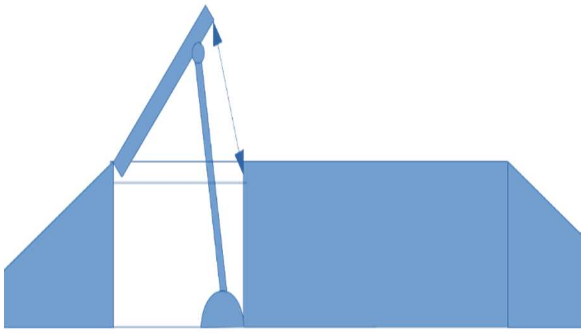

Figure 71 Sketch of Rotating barrier

Table 29 Advantages and disadvantages for rotating barrier

Advantages	**Disadvantages**
Highly integrated	Maintenance of hydraulic pumps requires access
Durable	Pumps need to be protected from water and rubbish
Flexible	

Alternative 2: Temporary placed barrier

The temporary placed barrier is placed in case storm surge exceeds the conditions of a 2-year event, which is 1.18 m (3.88 ft.) above MSL. The barrier consists of concrete walls that are placed in gullies. The placing of these elements is intensive and requires much time. The road can still be used.

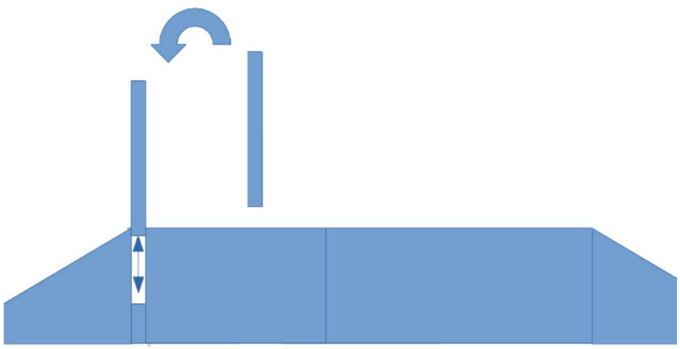

Figure 72 Sketch of temporary placed barrier

Table 30 Advantages and disadvantages for temporary placed barrier

Advantages	**Disadvantages**
Small impact	Requires much labor and time
Easy maintenance	Not durable
	Large dimensions required
	Storage needed for barriers

5.8.3 MCA

Table 31 MCA for Harborside Dr

Criterion	**Weight**	**Scoring Rotating Barrier**	**Result Rotating Barrier**	**Scoring Placeable Barrier**	**Result Placeable Barrier**
Complexity	3	3	9	5	15
Durability	5	5	25	2	10
Sustainability	4	4	16	1	4
Aesthetics	1	3	3	3	3
Maintainability	5	3	15	5	25
Preserving ecology	3	1	3	1	3
Effectivity	5	5	25	3	15
Multi-functionality	2	4	8	1	2
Adaptability	3	3	9	2	6
Constructability	4	2	8	5	20
Desirability	5	5	25	2	10
Total score			**146**		**113**

The rotating barrier alternative is more difficult to construct, since Harborside Dr needs to be adapted, including temporary lane closures. Measures have to be taken in order to have access to the hydraulic pumps for maintenance. The rotating barrier alternative is more effective in the long term, more durable and more sustainable compared to the temporary placed barrier alternative, since the temporary placed barrier alternative requires additional work to install and remove it for each storm. This is less desirable. In the long term, the rotating barrier is more profitable because it is a permanent structure.

5.8.4 Preliminary Design

Two types of configurations are shown in this section for the Rotating Barrier Design. The first configuration is the closed configuration in Figure 73, which is used under normal circumstances and in case of nuisance flooding. Figure 74 shows the closed configuration in detail.

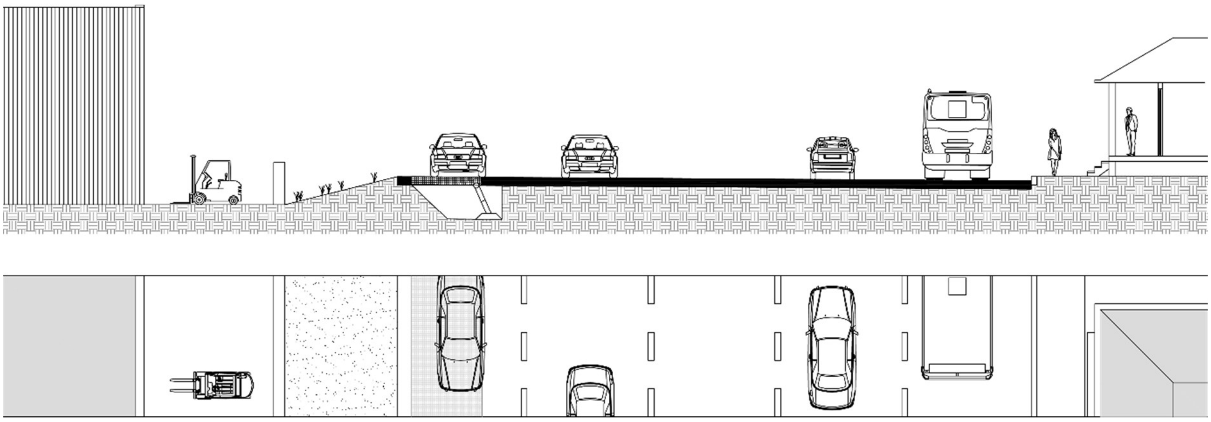

Figure 73 Rotating barrier in closed configuration

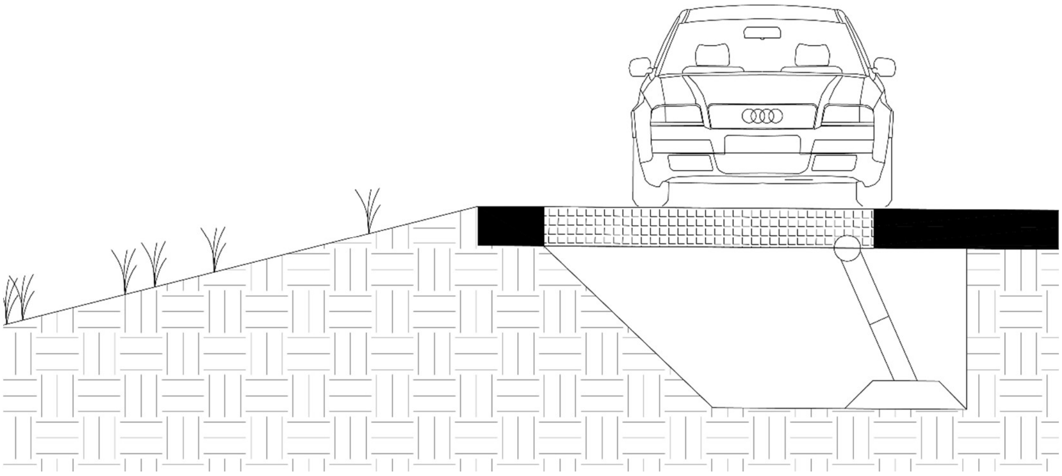

Figure 74 Detail of rotating barrier in closed configuration

In Figure 75 the open configuration of the design is shown. One lane cannot be used during this configuration. Other lanes are available for traffic. This supports the recovery operation after a flood event and allows for an extended evacuation period. The open configuration is shown in detail in Figure 76.

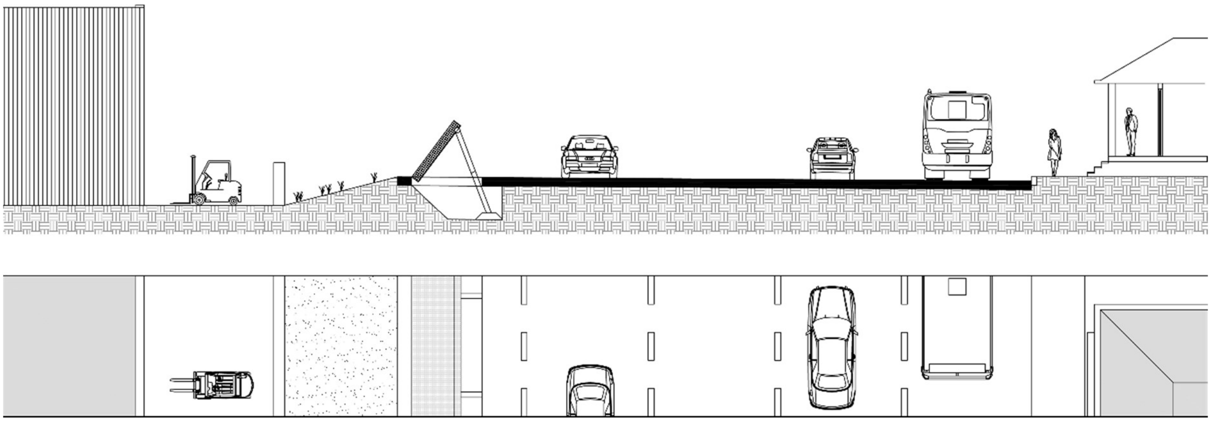

Figure 75 Rotating barrier in open configuration

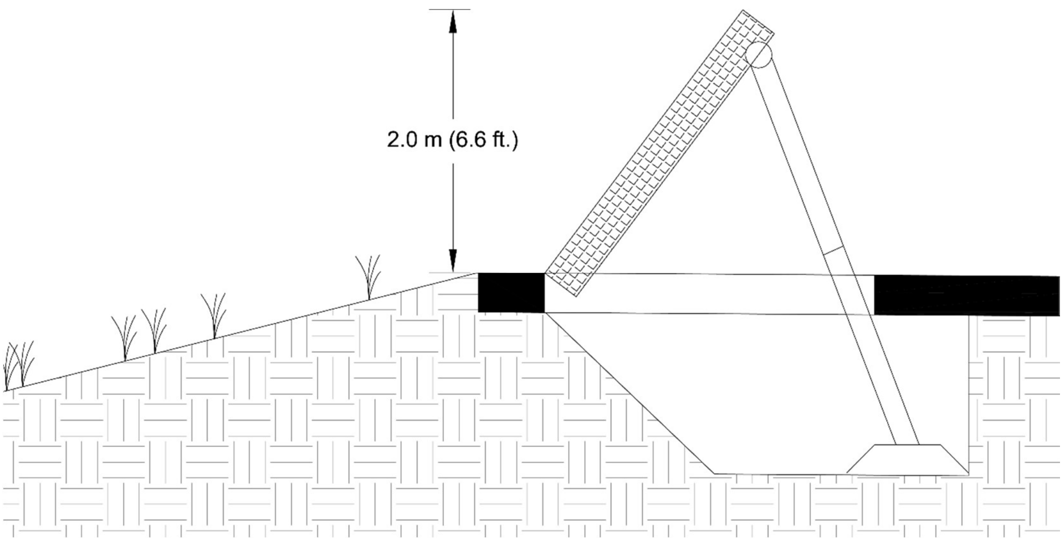

Figure 76 Detail of rotating barrier in open configuration

5.9 Design 7: Water Storage and Discharge

During the analysis phase, the water assignment for the City of Galveston was carried out. A relationship for storage, discharge and frequency (shown in Figure 24) is useful in the design phase. To be able to start thinking of measures that can be used to retain stormwater, it must be clear what the discharge capacity of the city is and what the rainfall return period is.

A return period of two years is used in Galveston to design the stormwater system. This means that the drainage system is able to handle this amount of water when a rainfall event with a return period of two years occurs. More rainfall than the design rainfall will cause flooding. However, there is no drainage possible when high tide occurs simultaneously with a 2-year rainfall event. Then streets start to flood anyway. To prevent this, discharge of stormwater must be possible when having a zero discharge capacity of the drainage system. By installing pumping stations the discharge capacity of the City of Galveston is enlarged, even when no water can leave the city through its drainage system.

The magnitude of the drainage capacity is a difficult to determine. A comparison with New Orleans is made for reference. After hurricane Katrina in 2006, the city of New Orleans started installing pumping stations. In this way the discharge capacity of the city was increased enormously. When stormwater starts collecting in the city and the threat for pluvial flooding is present, the pumping stations of the city are switched on. During the first hour of discharge, the system has a pump capacity of 25 mm/h (1 inch/h). After the first hour the capacity is 50% of the initial capacity (NOLA, 2017). In this way the pump system of New Orleans is theoretically able to discharge 318 mm (12.5 inch) stormwater in a day.

Options for retention of stormwater are still necessary with the application of a high discharge capacity. This becomes clearly visible from Figure 24 where the SDF curve for the City of Galveston is shown. Considering a two year rainfall event and a similar drainage capacity for the City of Galveston, it means that still 58 mm (2.3 inch) of stormwater must be retained in the city.

The drainage capacity for the City of Galveston does not have to be equal to that of New Orleans. To find an optimal combination of discharge capacity and stormwater storage capacity, studies must be carried out to find what is most economically favorable. A different pump with a higher capacity could for example be more expensive than creating more storage capacity. The conduction of such an economical study is beyond the scope of this project and will therefore not be carried out. However, different options for stormwater storage in combination with pumps are presented in this section.

5.9.1 Program of Requirements

Table 32 Requirements for Water Storage in the inner city

Requirement	Consequence
The design rainfall intensity is based on a 2-year event.	The design rainfall intensity is 76 mm/h (3 inch/h).
An optimum point for a combination of stormwater discharge and stormwater storage capacity should be found.	An economical study should be carried out to find this optimum. This is however out of the scope of this project.
The pumps installed in the pumping stations may not be flooded during both nuisance flooding and flooding due to a hurricane.	The pumps must be placed on a minimum height of 5 m (16.4 ft.) above MSL.
The scenario where streets are turning into rivers during nuisance flooding should be prevented.	Create stormwater storage capacity upstream of Broadway. Create discharge solutions downstream of Broadway.

5.9.2 Alternatives

A distinction is made in several types of solutions. First, solutions for enlarging discharge capacity are presented. Second, the stormwater storage solution is discussed.

Stormwater Drainage Solutions

Two possible stormwater drainage solutions are considered. The first one is creating capacity by installing pumping stations, and the second one is focused on updating the current drainage system.

Alternative 1: Installing Pumping Stations

With the installation of pumping stations, the drainage capacity of the city can be increased. Different options for pumps are possible, as well as different set-ups as pumps in parallel and in series. An example of pumps that could be used in a pumping station is shown in Figure 77.

Figure 77 Example of pumps that can be used in a pumping station (Demaclenko, 2018)

Table 33 Advantages and disadvantages of Installing Pumping Stations

Advantages	Disadvantages
Increase of drainage capacity to prevent nuisance flooding	Pumps are vulnerable and need protection in case of extreme weather
Quick recovery in the post-hurricane phase	Pumps require intensive maintenance
Makes drainage possible during high tide	
Different set-ups possible	

Alternative 2: Improving the current drainage network of the city

When improving the current drainage network of the City of Galveston, a new design can be made that makes it possible to drain the city during high tide as well. Hence, the capacity of the drainage system remains the same in situations with low and high tide and does therefore not drop to zero anymore. Figure 78 shows the installation of new concrete drainage pipes.

Figure 78 Installation of concrete drainage pipes (American Concrete Pipe Association, 2018)

Table 34 Advantages and disadvantages of improving the current drainage network

Advantages	Disadvantages
Makes drainage possible during high tide	Roads needs to be closed for construction of new drainage system
Part of old system can be re-used in new system	

Stormwater Retention Solutions

Multiple stormwater retention solutions are possible to make sure the peak flow coming from rainfall events is reduced. It is important to place these retention solutions upstream of the catchment area to guarantee peak flow reduction. Therefore, the region south of Broadway will be designed to have stormwater storage solutions. Multiple storage options are presented below.

Alternative 1: Water Squares

Water squares are squares that are located on a lower level than street level. They are able to store water in times of heavy rainfall events. Runoff water is collected in these squares and is released in the drainage system of the city when the peak flow has passed. Besides, a water square can be multifunctional. During dry weather it can for example be used as a play garden for children. Figure 79 displays three water squares that are located in Rotterdam in the Netherlands.

Figure 79 Water squares that can be found in Rotterdam, the Netherlands (Architectenweb, 2013)

Table 35 Advantages and disadvantages for Water squares

Advantages	**Disadvantages**
Water squares can have high capacity to store stormwater	Water squares require much attention when it comes to maintenance. It must be well cleaned after it has stored stormwater
Water squares can be multifunctional and also be used for recreational purposes	Children should be prevented swimming in the water squares when they are full of stormwater

Alternative 2: Infiltration crates

Infiltration crates can be installed underground to store water during peak flow. When peak flow is passed, the water collected in these crates can infiltrate in the soil. The capacity of a grid of these creates can be large. The installation of such a grid is shown in Figure 80.

Figure 80 Installation of infiltration crates (WaterWindow, N.D.)

Table 36 Advantages and disadvantages for Infiltration crates

Advantages	**Disadvantages**
No use of space above ground level	Maintenance work is complex, since the crates are located below ground level
Can be applied at different kind of places, e.g. parking lots, gardens and roads	Maintenance work is necessary to guarantee a high level of efficiency of the crates

Alternative 3: Rainwater barrels and rainwater fences

Rainwater barrels and rainwater fences are alternatives that are easier to install. People can install these measures in their own backyard. Many people must install these to gain a significant effect on storing rainwater. The capacity of a rain barrel for example is limited to 220 liters (58 US gallons) (Amsterdam Rainproof, 2018). A modern type of a rainwater barrel is shown in Figure 81. A rainwater fence is similar, but for this structure rainwater is captured in a fence.

Figure 81 Modern type of rainwater barrel (Rondomton, 2018)

Table 37 Advantages and disadvantages for Rainwater barrels and fences

Advantages	Disadvantages
Relatively cheap	Storage amount is limited
Easy to install	Can get damaged during freezing weather conditions
	Measure is only effective when multiple households install rainwater barrels or rainwater fences

Alternative 4: Unpaved gardens

Paved gardens prevent rainwater from infiltrating in the soil. Removing pavement in gardens, infiltration of rainwater to unsaturated layers is possible.

Table 38 Advantages and disadvantages for unpaved gardens

Advantages	Disadvantages
Supports prevention of nuisance flooding on local scale	An unpaved garden requires more attention when it comes to gardening
Relatively easy to implement	

Alternative 5: Infiltration trenches

Infiltration trenches are strips without a bottom that enable infiltration. The trenches are in direct contact with the subsoil, so the water that flows towards an infiltration trench is able to infiltrate and will eventually enter the unsaturated soil layer. A cross-section of an infiltration trench is shown in Figure 82.

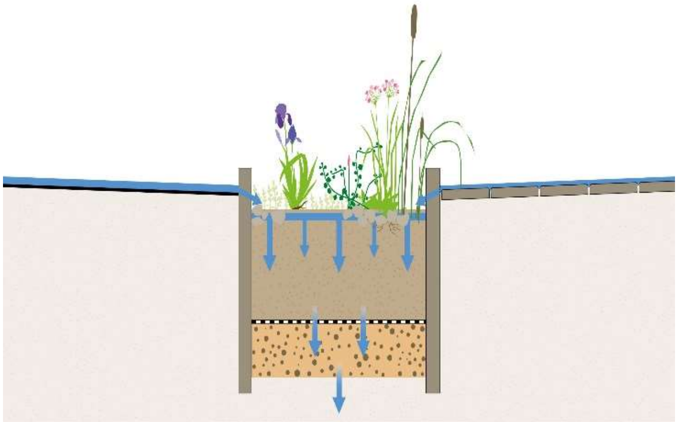

Figure 82 Sketch of an urban infiltration trench (atelier GROENBLAUW, 2018)

Table 39 Advantages and disadvantages for Infiltration trenches

Advantages	**Disadvantages**
An infiltration trench has a local impact and can therefore solve local problems related to pluvial flooding	Gutters that are located above ground level are needed to transport stormwater to the infiltration trenches
It unburdens the drainage system of the city	

Alternative 6: Permeable roads

By replacing regular roads by permeable roads, rainwater collected on these roads is able to infiltrate in the soil. It does not flow into the drainage system and therefore causes a decrease in load that the drainage system has to take. Especially roads that run through housing blocks are fit for this measure since heavy traffic is not using these roads. Figure 83 shows a parking lot with permeable concrete.

Figure 83 Parking lot with permeable concrete (Michon, 2018)

Table 40 Advantages and disadvantages for Permeable roads

Advantages	Disadvantages
It decreases the load on the drainage system of the city	This kind of pavement cannot be used on intensively used roads or parking lots due to risk of pollution
It can be applied in many different ways, e.g. in gardens, at roads and parking lots	Permeable roads can take a limited load of vehicles. Large vehicles can damage it
This kind of pavement gets less hot when than traditional pavement and asphalt when exposed to high temperatures	

Alternative 7: Intensive green roofs

Green roofs are roofs that have vegetation on it. The vegetation is planted on a substrate layer that makes sure vegetation can grow. Beneath the substrate layer, a filter is placed that makes it possible for collected rainwater to drain. Eventually the drained rainwater will be collected in the drainage system of the city. Since the vegetation on a green roof holds a part of rainwater, a green roof causes a delay in this drainage. A part of rainwater will not end up in the drainage system as this part will evaporate due to transpiration of the vegetation on the green roofs. A cross-section of a general green roof is displayed in Figure 84.

Figure 84 Cross-section of a general green roof (Besir & Cuce, 2018)

Table 41 Advantages and disadvantages for Intensive green roofs

Advantages	Disadvantages
Less water will flow from the roofs in the drainage system or to the streets, therefore less rainwater will end up as runoff	The load of an intensive green roof is high. Small houses are therefore not suitable for having intensive green roofs
Biodiversity of cities can be increased by installing intensive green roofs	Maintenance work on an intensive green roof is more difficult and more expensive than on an old-fashioned bitumen roof

5.9.3 MCA

A multi-criteria analysis is not performed for the different discharge and storage options for stormwater as described above. Choosing the best alternatives for the City of Galveston only makes sense when the optimal combination of discharge capacity and storage capacity is known.

5.9.4 Preliminary Design

Although a MCA was not performed, a preliminary design is created for a combination of measures that create extra discharge capacity for Galveston during high tide, and measures that can be used for stormwater retention. To increase the drainage capacity during high tide a design has been made for a pumping station. In this design it is acknowledged that the pumps have to be placed on a height of 5 m (16.4 ft.) to prevent flooding of the pumps in times of extreme weather events. The pumping station is shown in Figure 85.

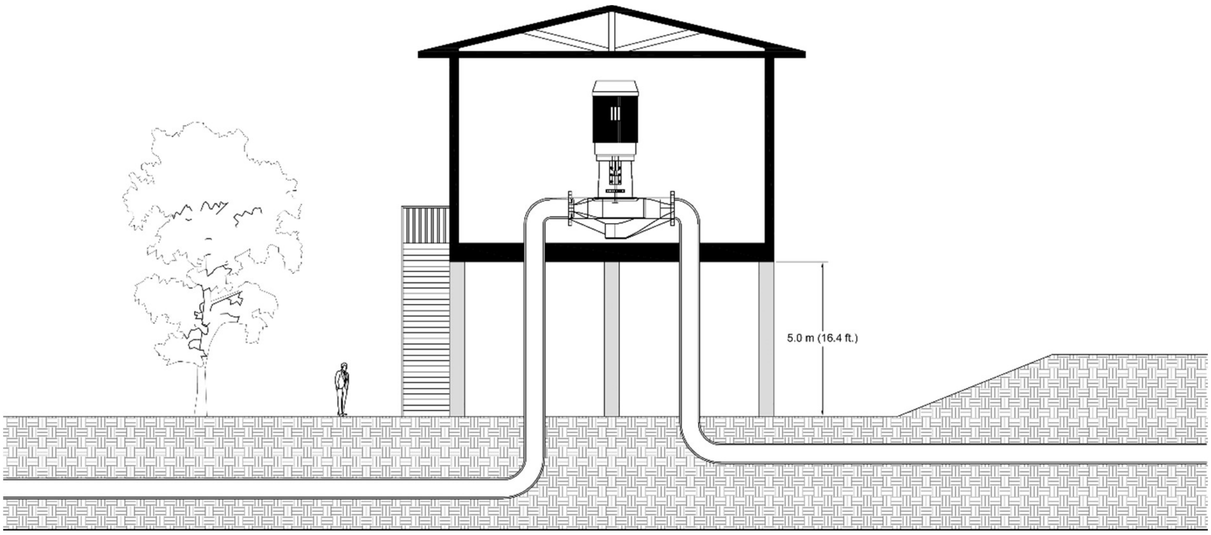

Figure 85 Preliminary design of a pumping station at Harborside Dr

For the design of stormwater retention, a single block of houses is analyzed. Different measures are located in this housing block. The City of Galveston has a typical American set-up with a grid system, so the design of this block can be applied for other blocks as well. The design is shown in Figure 86.

On the map dark colored plots are marked with a surface value. These are open plots that are suitable for storage of water by means of a water square. The amount of water storage possible in these areas depends on the depth that is used on each location. The total area of the open plots is 155,000 m^2 (1,669,000 ft^2.). If the squares have an average depth of 2.25 m (7.4 ft.), a total storage of 400,000 m^3 (14,126,000 ft^3.) is possible. It must be noted that it is not likely that all open plots are used for water storage.

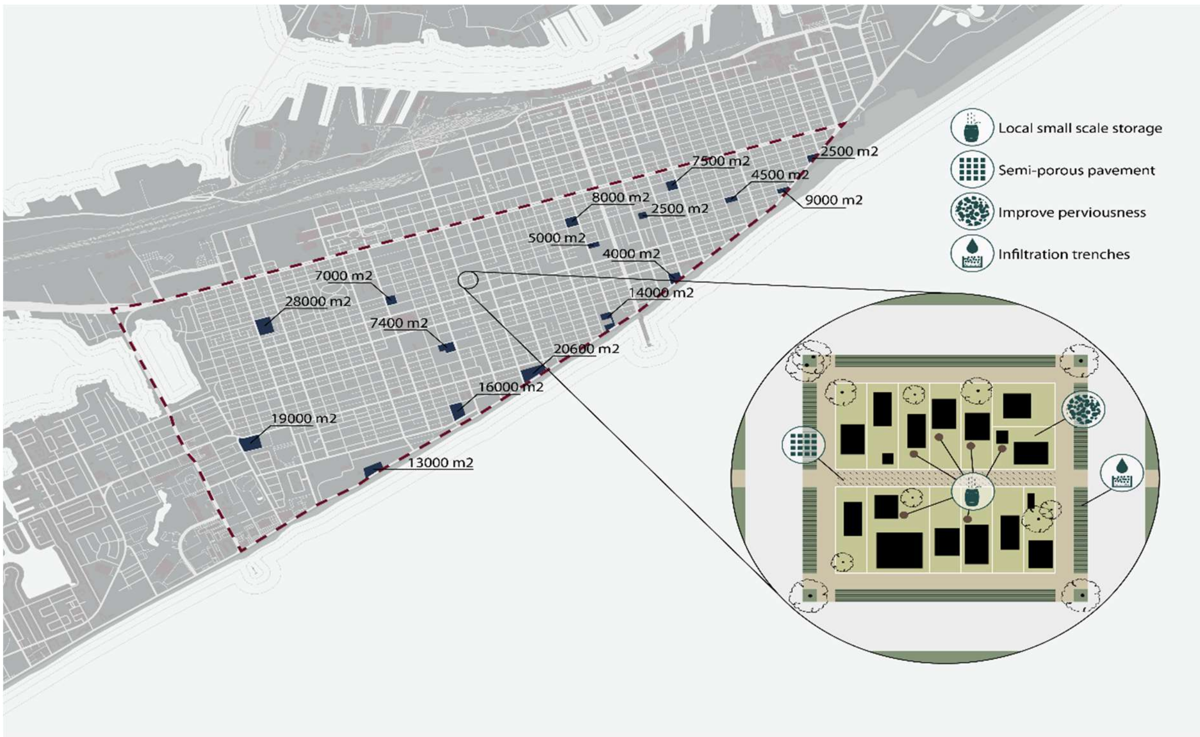

Figure 86 Preliminary design of stormwater retention options

In the lower right corner of Figure 86 a preliminary design of the stormwater retention options for a housing block are found. One can see that along the roads at the outside of the block infiltration trenches are placed. When the roads are slightly curved no gutters are needed to force the stormwater flow towards the infiltration trenches. The side road in the middle of the block gives residents access to their backyard. Nowadays these roads are mostly made of concrete. Replacing the material by permeable concrete improves drainage on these roads and a reduction of the water depth on the roads. In backyards two different alternatives are applied. People can install rainwater barrels or rainwater fences to store rainwater. Furthermore, gardens should be unpaved to make the infiltration flux larger and prevent flooding in backyards.

Intensive green roofs are not applied. These are too heavy for the majority of the roofs in Galveston. However, these roofs are an option for larger buildings that have stronger supporting structure for their roofs. Therefore, these supporting constructions are able to bear more load.

The last part of the preliminary design is the installation of infiltration crates. As is described above, these crates are placed underneath parking lots. Considering all surface for parking lots in Galveston, a total area of 475,000 m^2 (5,113,000 ft^2.) is found. An example of infiltration crates is the StormCrate from Brett Martin's. The capacity of their crates with dimensions of 1200 mm x 600 mm x 420 mm (4 ft x 2 ft. x 1.4 ft) is 0.3 m^3 (10.6 ft^3.) (Brett Martin, N.D.). When all parking lots contain the described infiltration crates, an amount of 200,000 m^3 (7,063,000 ft^3.) stormwater is stored.

In the end, it is possible to already store a high volume of stormwater when only considering the solutions of water squares and infiltration crates.

This is a preliminary design without a described recipe how much water should be stored at what location and how to store. The result of the economic study to develop the optimal combination of water storage and water drainage of the SDF-curve in Figure … will give an improved recipe for the storage or stormwater.

5.10 Design 8: Broadway Av

Broadway Av is the main artery of the City of Galveston. It is an extension of the Gulf Freeway from Houston and ends at the eastern end of the island at Seawall Boulevard. It is regarded as critical infrastructure, which means it must be accessible for traffic during nuisance flooding. Moreover, Broadway Av runs through the middle of the City of Galveston and currently blocks water flowing from the southern part to the northern part of the island during rainfall events. This causes flooding in the streets south of Broadway Av and as a consequence problems for traffic, businesses and properties occur.

Figure 87 Location of Broadway Av

5.10.1 Program of Requirements

The aim of this design is to elevate Broadway Av. The blockage of water from the south must be prevented. The water is then discharged to the north side into the bay.

Table 42 Requirements for Broadway Av

Requirement	Consequence
Broadway Av needs to be available for traffic during a nuisance flood event.	Broadway Av needs to be elevated to a minimum height of 2.1 m (5.3 ft.) above MSL.
Broadway Av needs to allow drainage of water from the southern city areas to northern city areas.	The drainage system must be improved to accommodate run off underneath Broadway Av.
Broadway Av needs to allow drainage of water from the road to the sides of the road.	The drainage system must be improved to accommodate run off to the sides of the road, by creating ditches alongside the road, and remain a small sloped profile of the road.
Broadway Av needs to be accessible for traffic arriving from side roads.	The elevation difference between Broadway Av and its side roads cannot be too large.
Broadway Av needs to be accessible as soon as possible after a hurricane event to recover quickly and perform rescue operations.	Broadway Av must be accessible within 24 hours after the peak of the hurricane.
Climate change can increases the amount and intensity of rainfall. This expectation must be considered in the adaptability of the design.	The design should be adaptable for future demands and requirements.

5.10.2 Preliminary Design

In the design Broadway Av is elevated to a minimum level of 1.6 m (5.3 ft.) above MSL, which creates a small barrier. This guarantees the availability of the road during nuisance flooding. The elevation of Broadway Av enlarges water storage capacity, which is not desirable during nuisance flooding. Therefore, culverts are placed underneath the road to allow water to flow from south to north. Pumping stations discharge the water into the bay. These pumps are located at several locations along the bay.

The heightened elevation of Broadway Av makes it possible to quickly recover after a hurricane event.

Next to the discharging function, the culverts also increase the water storage capacity, effectively this results in an extended time for evacuation and quicker recovery after a hurricane event.

Elevating Broadway Av results in a larger elevation difference between Broadway Av and side roads. These side roads need to be adapted as well.

Many of the houses and businesses along the driveway are on higher elevated properties. The connections between Broadway Av and the properties need to be constructed in such a way that excessive water runs from the properties into ditches along the road. As a consequence, Broadway Av will not flood because of water flowing from the properties.

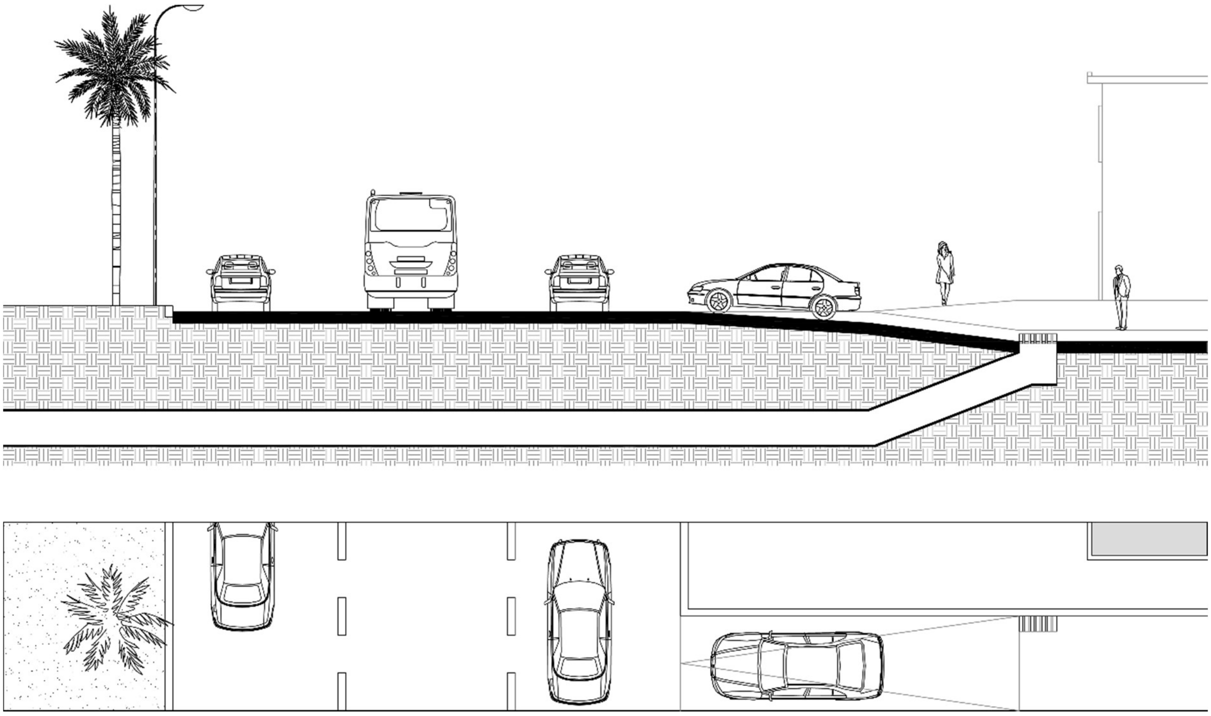

Figure 88 Preliminary design for Broadway Av

5.11 Design 9: 51st Street

The road section 51st Street North is located between Broadway Av and the bridge to Pelican Island, crossing Harborside Dr.

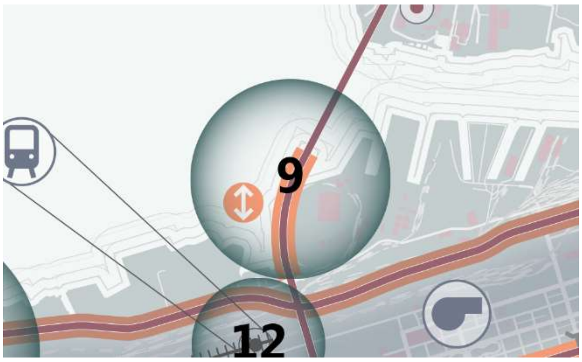

Figure 89 Location of 51st North, including the Pelican Island Causeway

5.11.1 Program of Requirements

This road section is part of the evacuation network. 51st Street is the only road access point to Pelican Island and it must be guaranteed that people can drive between Pelican Island and Galveston Island during events of nuisance flooding and in pre-hurricane phase.

Table 43 Requirements for 51st St North and Pelican Island Causeway

Requirement	Consequence
Remain accessible in case of nuisance flooding	Elevate road to level of reference of 2-year storm surge event including tide
Integration of road section in evacuation network	Connect road section to other evacuation roads and routes

5.11.2 Advantages and Disadvantages

Currently, there are no alternatives to compare. The road sections are elevated. The advantages and disadvantages of elevation of the road are shown below.

Table 44 Advantages and disadvantages of elevation of 51st St North and Pelican Island Causeway

Advantages	Disadvantages
Pelican Island remains accessible during nuisance flooding	The evacuation route remains accessible in pre-hurricane phase
The connection via 51st St between Harborside Dr and Broadway Av remains accessible during nuisance flooding	Accessibility is not guaranteed for more intense rainfall events

5.11.3 Preliminary Design

The road section of 51st St North, shown in Figure 90, is elevated to a level of 1.6 m (5.3 ft.) above MSL. This elevation withstands high tide and storm surge up to 0.9 m (2.9 ft.), which are the projected values for a 2-year event in the year 2040. The relative sea level rise is also included. Due to the elevation of the section between Broadway Av and Harborside Dr, ditches are created on both sides of the road. This is because the height difference of the road and the property along the road are almost equal. The ditches capture rainwater to prevent the road from flooding during regular precipitation events. The road section to Pelican Island in Figure 91 is elevated to 2.6 m above MSL. This part is impacted by waves as well. From the data presented in Section 4.5 Hydrodynamic Parameters, the wave height for a 2-year event is 1.0 m for a nearshore location. Although waves in the bay will refract and diffract, this is not considered in this report. The total elevation is the sum of:

Table 45 Design values for road elevation for 2-year event for 51st St North and Pelican Island Causeway

High tide	+ 0.27 m MSL (+ 0.89 ft.)
Storm surge	+ 1.18 m MSL (+ 3.88 ft.)
Relative sea level rise	+ 0.16 m MSL (+ 0.52 ft.)
Wave height	+ 1.00 m MSL (+ 3.30 ft.)

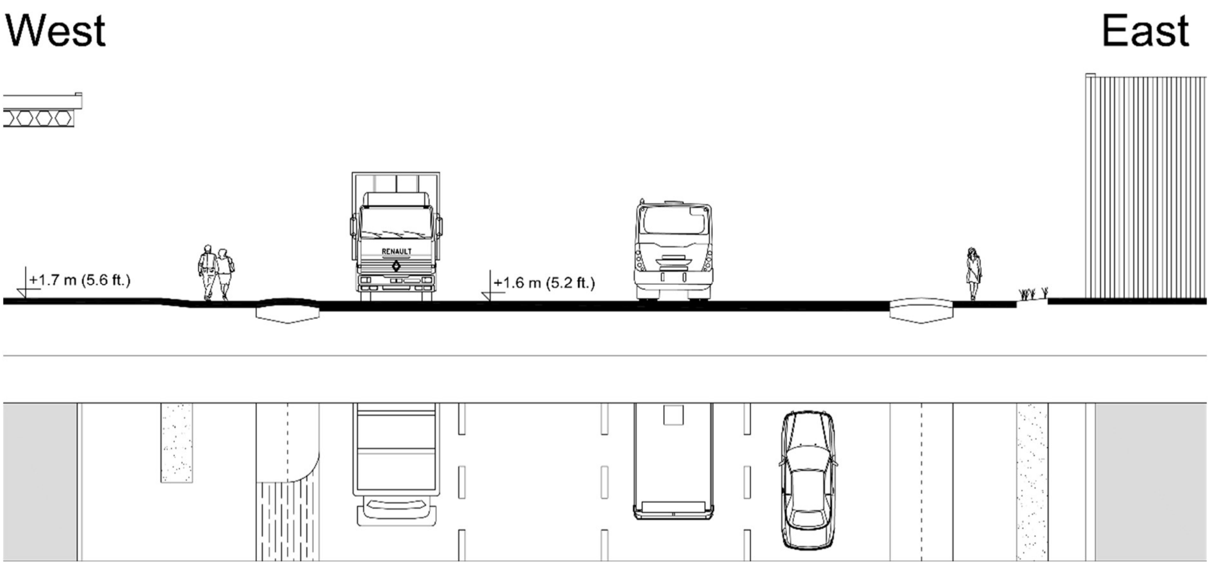

Figure 90 51st St between Broadway Av and Harborside Dr. The ditches next to the roads capture rainwater so that the road will not flood during nuisance flooding

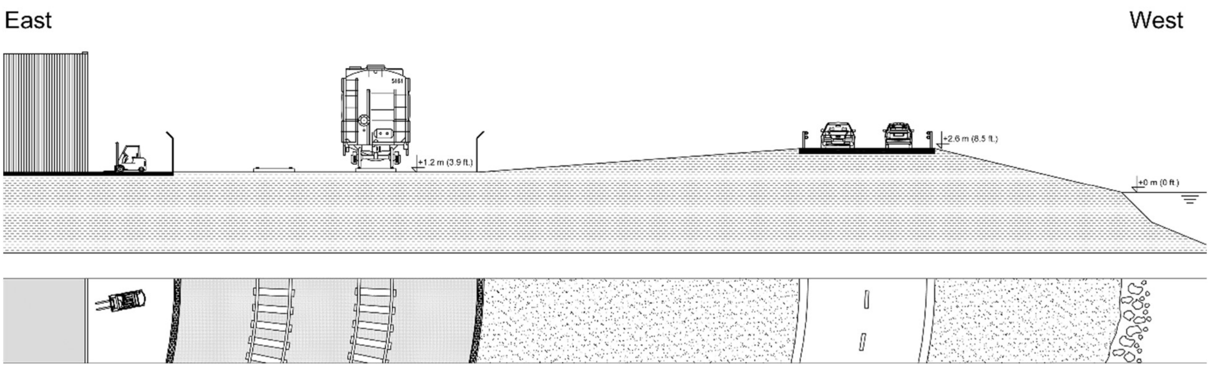

Figure 91 Access road to Pelican Island. The road is elevated to remain access to the Island and to ensure evacuation in the pre-hurricane phase

5.12 Design 10: Region 61st St – Airport

The vulnerability map displayed in Section 4.3 Vulnerability Analysis shows a high vulnerability of the Offatts Bayou precinct, which is located between 61st Street and Scholes International Airport. The high vulnerability value is largely due to extreme inundation levels which in turn are attributed to a general low elevation of the land (see Figure 111). As was found in the vulnerability analysis, Figure 8, this neighborhood is subject to repetitive flooding losses and requires measures to mitigate damages during future severe weather events.

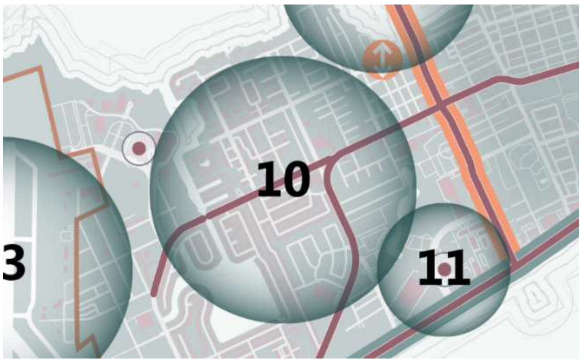

Figure 92 Location of region 61st Street-Airport (number 10)

5.12.1 Program of Requirements

For this neighborhood it is important to reduce repetitive flood damage and to make the built environment more adaptable to inundation. Furthermore, due to the current vulnerable situation, access to evacuation infrastructure is of utmost importance.

Table 46 Requirements for Region 61st Street-Airport

Requirement	Consequence
Repetitive flooding damages must be reduced.	A levee, raising of land or other measures are applied to permanently increase flood resilience.
All properties must have reliable access to evacuation infrastructure.	Infrastructure reaching into subdivisions must not flood quickly and should be raised.
Properties in this flood prone neighborhood should be adapted to deal with a high surge levels.	Dwellings in the area should be made adaptable to high surge levels, using floatable constructions or other solutions.

5.12.2 Alternatives

Four alternatives are considered.

Alternative 1: Ring levee

The first alternative is to build a ring levee around the precinct, connecting to the marina on the west and the Seawall on the south. Such a levee would provide permanent and reliable protection against surge levels but would largely block access to open water for waterfront properties.

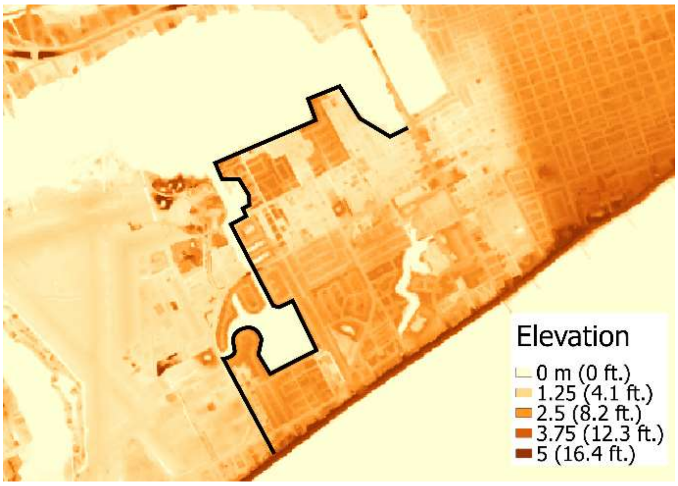

Figure 93 Sketch of a ring levee

Table 47 Advantages and disadvantages for Ring levee

Advantages	Disadvantages
Permanent protection against surge	Disturbing local hydrology
Reliable structure	Blocks access to open water

Alternative 2: Raising land

The second alternative consists of raising land that is currently considered to be vulnerable to flooding. As is shown on the DEM (see Figure 111), large parts in the northern half of the neighborhood are only 1 m (3.3 ft.) above mean sea level, while surrounding neighborhoods are at an elevation of roughly 2.6 m (8.5 ft.) above MSL. Raising the lower parts to an elevation of 2.6 m (8.5 ft.) above MSL would reduce the vulnerability of this neighborhood.

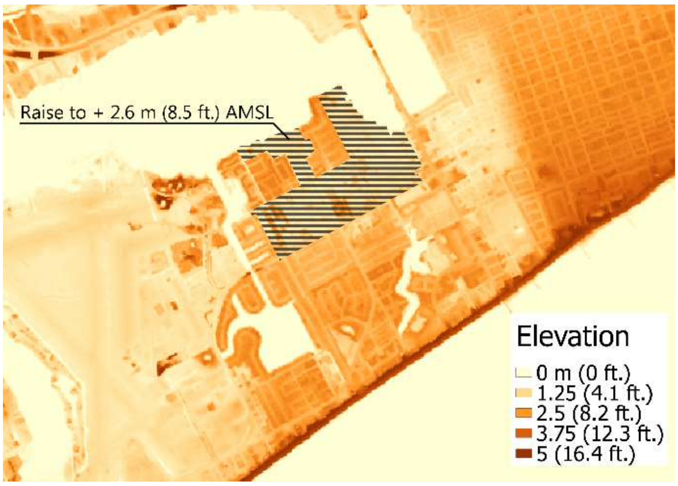

Figure 94 Sketch of raising land

Table 48 Advantages and disadvantages for raising land

Advantages	Disadvantages
Long-term damage mitigation	No immunity to flooding
Reliable	Long time span; not possible to execute immediately

Alternative 3: Raise evacuation infrastructure

The third alternative is to only raise evacuation infrastructure to ensure residents in this neighborhood have a safe evacuation route. This plan requires an analysis of the current neighborhood and evacuation needs. Once this is mapped, a suitable road network of evacuation infrastructure can be created.

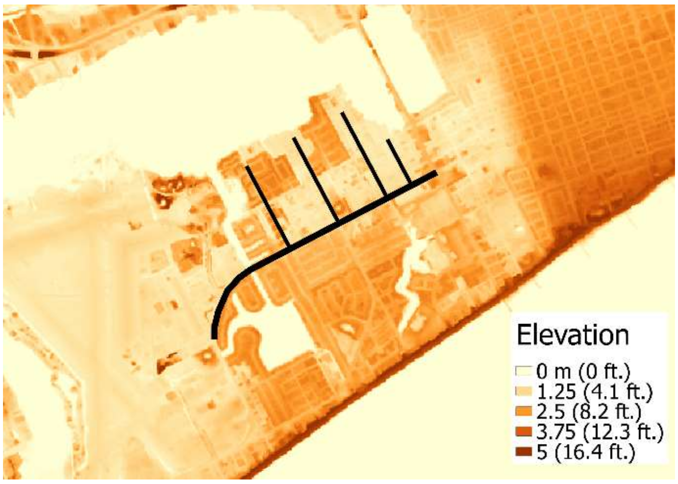

Figure 95 Sketch of raising evacuation infrastructure

Table 49 Advantages and disadvantages for raising evacuation infrastructure

Advantages	Disadvantages
Relatively small intervention	Does not protect properties from flooding

Alternative 4: Living on water

The fourth design alternative is focused on living with water rather than actually trying to keep it out. There are already many precedents of floatable homes such as the ones shown in Figure 96 (BinnensteBuiten, N.D.).

Figure 96 Precedent of floating homes (BinnensteBuiten, N.D.)

Table 50 Advantages and disadvantages for Floating homes

Advantages	Disadvantages
Sustainable living with water	No solution to current properties
Encourages awareness	Long time span; requires spatial planning
	Legislation could be an issue

5.12.3 MCA

Table 51 MCA for region 61st Street-Airport

Criterion	Weight	Scoring Ring Levee	Result Ring Levee	Scoring Raising Land	Result Raising Land	Scoring Raise Infrastructure	Result Raise Infrastructure	Scoring Living on Water	Result Living on Water
Complexity	3	1	3	1	3	8	24	5	15
Durability	5	8	40	8	40	4	20	8	40
Sustainability	4	7	28	7	28	7	28	10	40
Aesthetics	1	3	3	7	7	6	6	10	10
Maintainability	5	4	20	8	40	6	30	8	40
Preserving ecology	3	3	9	5	15	5	15	8	24
Effectivity	5	10	50	5	25	1	5	5	25
Multi-functionality	2	1	2	5	10	1	2	8	16
Adaptability	3	1	3	5	15	5	15	8	24
Constructability	4	1	4	5	20	10	40	4	16
Desirability	5	1	5	5	25	5	25	8	40 +
Total score			**167**		**228**		**210**		**290**

Floating houses score the highest, which is mainly due to high marks on multi-functionality, adaptability, aesthetics and desirability. However, because the surrounding land would remain extremely vulnerable to even small tidal variations, a general land raise is recommended as well. A ring levee scores low due to a high complexity and low desirability.

5.12.4 Preliminary Design

The design proposal consists of two components: raising land to reduce vulnerability to regularly occurring high tide and building floatable homes to deal with surges in a sustainable way. The soil has to be raised to an elevation of 2.6 m (8.5 ft.) above MSL. The realization of a breakwater project at the entrance of Offatts Bayou reduces local wave action.

An example of floating houses in the Netherlands is displayed below.

Figure 97 Floating house in Delft, the Netherlands (Steel Framing Holland, N.D.)

5.13 Design 11: Vertical Evacuation

Vertical evacuation is an alternative to horizontal evacuation and can also be a secondary choice for people who are stuck on the island. Horizontal evacuation is evacuation to other regions in the state or country. Vertical evacuation is evacuation in tall buildings which are made suitable for the accommodation of people.

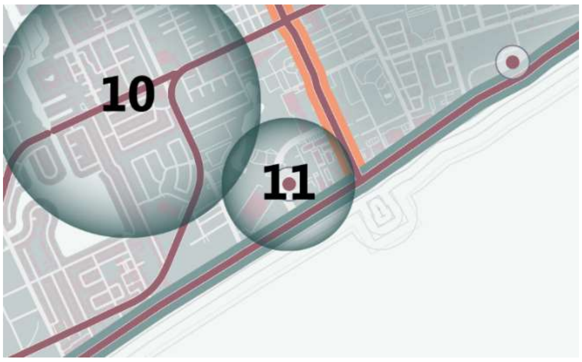

Figure 98 Location of building for vertical evacuation, shown at number 11

5.13.1 Program of Requirements

During a hurricane, the water level is elevated for a longer period of time, also known as storm surge. Surge levels last for days, which requires availability of basic human needs in buildings for vertical evacuation. Examples of basic human needs are drinking water, food, blankets, and sanitation. The buildings must be accessible for rescue services. People are likely to stay for multiple days. The locations must be adapted to accommodate larger groups of people.

A consideration is to compensate the owners of the buildings that are used as shelters since they make their buildings available to accommodate people.

Table 52 Requirements for Vertical evacuation

Requirement	Consequence
The buildings must be accessible for people.	People must be able to access the buildings by car, bike or public transportation. Shelters are preferably located next to critical evacuation infrastructure, as this improves accessibility.
People with disabilities must be able to make use of vertical evacuation.	Buildings must be adapted to accommodate people with disabilities, such as elevators, special beds and adapted sanitation.
The accommodation of pets must be possible.	Facilities must be suitable to accommodate pets.
The locations and facilities must be known beforehand.	Information about vertical evacuation must be supplied within the hurricane guide for each year.
Buildings must provide basic human needs.	The floors must be able to supply drinking water, food, and sanitation in sufficient quantities, for an expected group of people.
New buildings must be made adaptable for vertical evacuation.	Vertical evacuation must be a requirement that is stated in the building code.

Alternatives are not applicable to this design. Advantages and disadvantages are not determined.

5.13.2 Preliminary Design

In Figure 99 the buildings are marked that are suitable for facilitating vertical evacuation. Principles and Guidelines are described in two reports: Guidelines for Design of Structures for Vertical Evacuation from Tsunamis by (FEMA, 2012) and Randvoorwaarden Verticale Evacuatie Bij Overstromingen by (HKV, 2015). The guidelines presented by (FEMA, 2012) apply for tsunamis, but general information is also applicable for hurricanes. The conditions discussed by (HKV, 2015) apply for the Netherlands, but are also valid for the USA. However, each region requires adaptations on the guidelines and conditions to fit the evacuation strategy in the region.

Figure 99 Proposed buildings for Vertical evacuation

5.14 Design 12: Train Station

An alternative for evacuation is via railroad. When evacuation is needed, everyone leaves by car. This causes traffic congestion. The railroad extending into Galveston is part of the larger railroad network and connects Galveston Island to the Houston area and beyond. Although the railroad is suitable for diesel trains only (there are no overhead electricity lines available), these trains can still be used to transport people to the mainland. In Appendix A.9 Planned Developments, a development of a train route between Houston and Galveston was mentioned. If this route is actually being developed, the possibility of evacuation by train is part of the evacuation strategy.

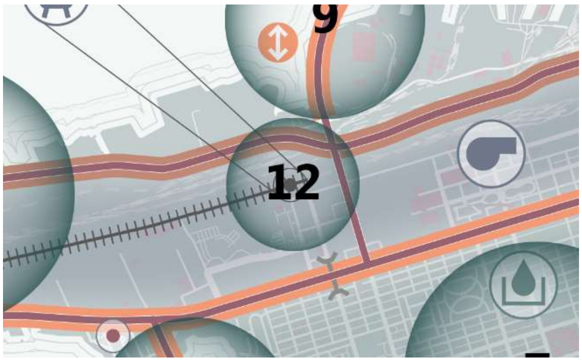

Figure 100 Location of train station

5.14.1 Program of Requirements

Table 53 Requirements for train station

Requirement	Consequence
The location must be accessible in the pre-hurricane phase	Station must be connected to the evacuation network. The station is preferably located next to evacuation infrastructure.
Multiple trains must be able to access the station simultaneously	More tracks are required.
The train station should be multifunctional and preferable a high building to accommodate vertical evacuation	Multiple floors are recommended. Top floors must be suitable for vertical evacuation.
The train station is not allowed to flood during nuisance flooding	The train station ground floor must be higher than the combined water level of mean water level, high tide and storm surge for a 2-year event (1.6 m (5.3 ft.) above MSL).

5.14.2 Alternatives

Two alternatives are considered.

Alternative 1: Temporary train station

The first alternative considers a temporary train station. The location of this train station should be within the elevated part of the city, so between the Seawall, Broadway Av, 61st St and Harborside Dr. The most suitable location is near 51st St between Harborside Dr and Broadway Av. Then the station is connected to the evacuation routes and elevated roads. Some companies at Harborside Dr must be cleared to accommodate necessary facilities, in particular access to the tracks. As this is a temporary measure, no buildings have to be built, only platforms are needed.

Figure 101 Location of temporary train station at Harborside Dr

Table 54 Advantages and disadvantages for temporary train station

Advantages	**Disadvantages**
Quick construction of platforms	Company property required to accommodate temporary station and get access to tracks
No additional buildings needed	Tracks are in flood prone area
No investments in railroad tracks needed	

Alternative 2: Permanent train station

In alternative 2, a location for a train station is at 51st St and Broadway Av. At the moment, this area is not used. However, railroad tracks must be built to connect the station to the existing railroad network. These tracks would cross private property and these must be acquired. Most of the existing buildings are storage facilities and movable homes. Another consideration is the required railroad bridge.

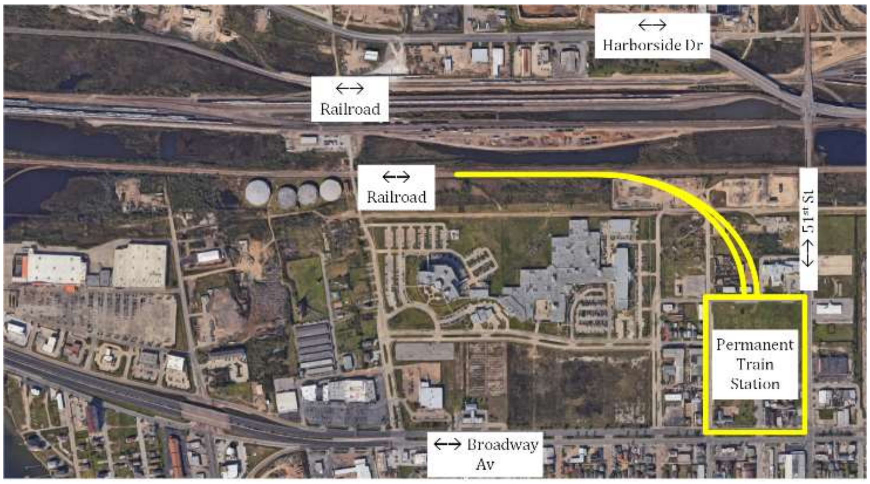

Figure 102 Location of permanent train station, including possible railroad tracks

Table 55 Advantages and disadvantages for permanent train station

Advantages	Disadvantages
Improved accessibility with the mainland and Houston	New railroad tracks must be constructed, as well as investments in electrification of railroad network
	New station must be constructed
	Railroad bridge must be improved
	Individual property is crossed

5.14.3 MCA

Table 56 MCA for Train station

Criterion	Weight	Scoring Temporary Station	Result Temporary Station	Scoring Permanent Train Station	Result Permanent Train Station	
Complexity	3	7	21	1	3	
Durability	5	4	20	7	35	
Sustainability	4	4	16	7	28	
Aesthetics	1	1	1	8	8	
Maintainability	5	7	35	6	30	
Preserving ecology	3	1	3	1	3	
Effectivity	5	6	30	8	40	
Multi-functionality	2	1	2	9	18	
Adaptability	3	7	21	3	9	
Constructability	4	9	36	3	12	
Desirability	5	4	20	7	35	+
Total score			**205**		**221**	

A temporary station is relatively easy and quick to construct and highly effective in evacuation strategies. A permanent train station and passenger connection between Galveston and Houston improves the connection to the mainland, but requires adaptations to existing infrastructure of railroad network and bridges and construction of new infrastructure. This will cost more effort and investments.

5.14.4 Preliminary Design

Although a permanent train station has a higher score, the net difference is hardly significant. The temporary station is preferred for now, as this solution is more effective on the short term and easier to implement in existing infrastructure and designs.

A permanent train station would be more effective if the passenger connection to Houston is approved and realized. Its location and connections to existing infrastructure is marked yellow in Figure 103.

Figure 103 Preliminary design of both alternatives. The temporary station is preferred

5.15 Design 13: Airport Recovery

The airport is strategically located behind the Seawall. In the post-hurricane phase, the airport can be used to quickly recover from hurricane impact. The US military forces can use the airport as a base to reach people and buildings for vertical evacuation and other locations in the city.

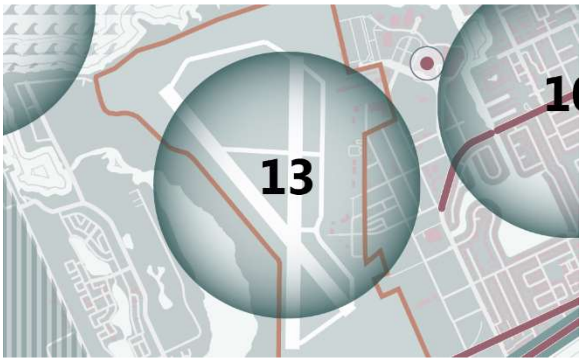

Figure 104 Location of the Airport

5.15.1 Program of Requirements

The airport must deal with the consequences of heavy rainfall and storm surge. During a hurricane event the airport will get flooded. Facilities should be available on the airport to pump the water into the bay right after the hurricane and clear the runways for airplanes and helicopters. Building a ring levee around the airport should be considered.

Table 57 Requirements for Airport

Requirement	Consequence
Quick recovery of airport runway and facilities right after hurricane event	Installation of pumps to discharge water into the bay to north of the airport
Elevate access road to Seawall to connect airport to evacuation network	Road must be higher compared to its direct environment to allow water to flow off the road
Protection of airport against storm surge	Building ring levee around airport to reduce damage (height will not be determined in this report)

5.15.2 Advantages and Disadvantages

Currently, there are no alternatives to compare. The primary function of the airport in case of hurricane events is recovery. The advantages and disadvantages are summarized below.

Table 58 Advantages and disadvantages of recovery using the airport

Advantages	Disadvantages
Alternative option to access the island after a hurricane event	Protection of airport facilities against water required
Fast supply of food, water and medicines to people by helicopters	Investments in pumps and elevation of access road
Transport of people to other locations (e.g. hospitals) at the mainland	If runway is damaged, the airport is inaccessible

5.15.3 Preliminary Design

From the airport, people and vehicles can access the city via the elevated roads (Seawall, 61st St, Broadway Av) to give first aid, as the yellow lines show in Figure 105. As most buildings are located along the evacuation roads, these can immediately be accessed. The access road between the airport and the Seawall must be elevated on the same level as Broadway Av and 51st St, which is 1.61 m above MSL.

The airport itself must be protected against flooding as well. Around the airport, a small levee is constructed, which protects the facilities and runways against small storm surge. In case of overtopping and intense rainfall, pump stations are available. In this way, the airport is quickly accessible by airplanes to give first aid.

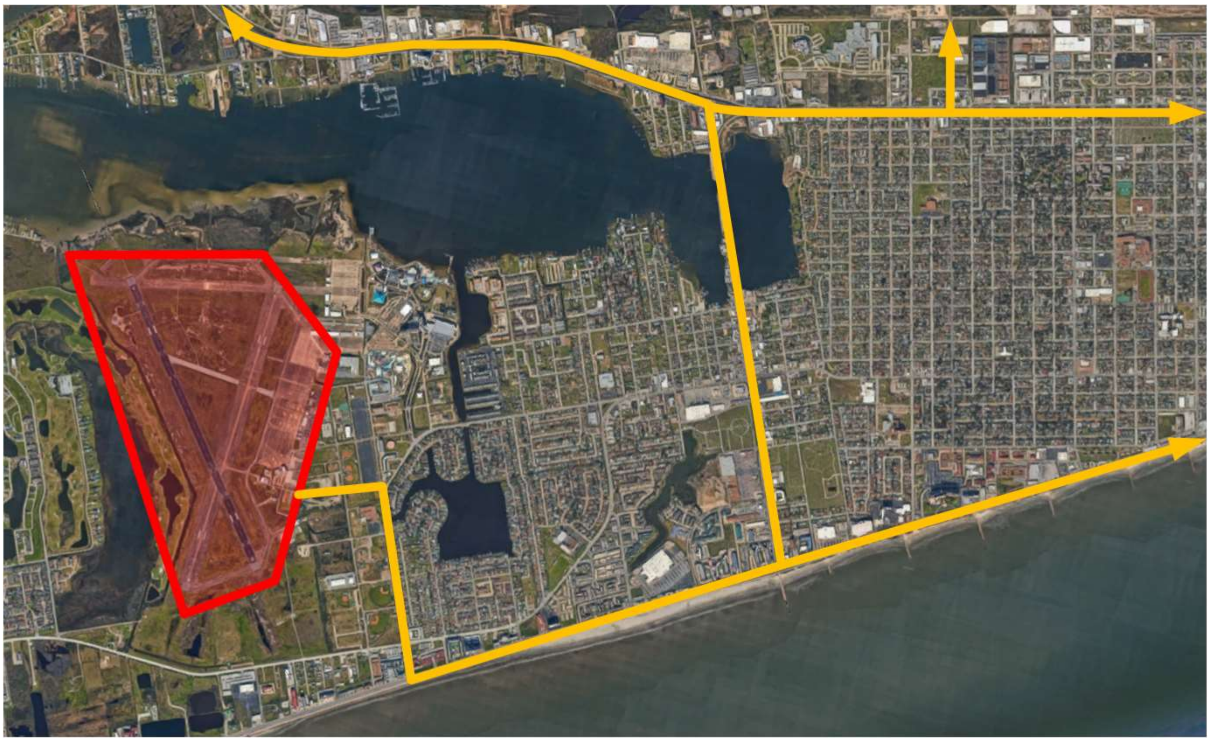

Figure 105 Access roads from the airport to different locations in the city, using the evacuation network

6 Conclusions & Recommendations

In this chapter the conclusions of the project are elaborated and advice and further research are explained in recommendations.

6.1 Conclusions

This project aims to investigate how the risk of flooding in the City of Galveston can be mitigated, considering the influences of extreme pluvial, coastal and compound flooding.

Vulnerability of the City of Galveston

The City of Galveston is found to have multiple vulnerable spots which are at risk of flooding, the most noteworthy cases being:

- <u>Scholes International Airport:</u>
  Its low elevation and high value for evacuation and recovery operations makes the airport vulnerable;
- <u>Historic urban core:</u>
  The presence of monuments and low adaptability of the built environment makes this area vulnerable to flooding;
- <u>The University of Texas Medical Branch at Galveston (UTMB):</u>
  A low elevation and the inclusion of a biolab makes the UTMB vulnerable to flooding;
- <u>The Port of Galveston:</u>
  The combination of high property values and the storage of dangerous substances makes the Port of Galveston vulnerable to flooding;
- <u>Offatts Bayou:</u>
  Low elevations of the shoreline in combination with aggravated wave height makes adjacent neighborhoods vulnerable to flooding;
- <u>Evacuation routes:</u>
  Many critical parts and junctions of evacuation routes flood regularly, disrupting evacuation and hindering recovery operations.

Flood risk issues in Galveston can be divided into two aspects: nuisance flooding by regularly occurring heavy precipitation events and flooding due to hurricanes (which can have a coastal and/or pluvial nature). This subdivision is reflected in the proposed mitigation measures, as they require a fundamentally different approach. While damage caused by nuisance flooding can be fully prevented with the proposed measures, damage resulting from hurricanes can at best be mitigated.

Design measures

An integrated set of mitigation measures is proposed that tackle both aspects of the problem related to flooding. All mitigation measures are schematically displayed in Figure 106. The main characteristics of measures for both aspects of the problem are elaborated below.

For nuisance flooding the focus lies on retaining, discharging and infiltrating rainwater and elevating shores and coastlines to prevent coastal flooding. The part of the City of Galveston south of Broadway Av will be equipped with measures that, collectively, can retain and infiltrate rainwater. Infiltration crates, water squares, infiltration trenches and replacing impervious infrastructure are the most important interventions. Multiple pumping stations are placed on the northern shoreline of the City of Galveston to discharge excess water into the bay. Harborside Dr, the eastern part of the Gulf Freeway and 61st Street will be raised to a level of + 1.60 m (5.3 ft.) above Mean Sea Level (MSL). This elevation is high enough to prevent coastal flooding during regular high tides (+1 ft. above MSL), considering a sea level rise of 0.16 m (0.5 ft.) per 20 years, up to the year 2040. Remediation of wetlands will reduce continuous erosion of bayside land.

As the amount of precipitation and the height of storm surge during hurricanes is too large to completely avoid damage and casualties, measures for this scenario are focused on evacuation, mitigation and recovery. Breakwaters off the coast of the Seawall and at the entrance of Offatts Bayou serve to reduce wave height and therefore diminish damage to properties. Critical evacuation routes are risen, and an emergency train service will be put in place to improve the evacuation capacity. Local shelters for vertical evacuation are strategically placed adjacent to heightened infrastructure throughout the city. Scholes International airport is fitted with a small levee and pump system to accelerate the initiation of recovery operations.

Figure 106 Proposed mitigation measures

Hydrodynamic parameters
Calculation of the hydrodynamic parameters has been performed on a deterministic basis. This means that single values are used for the design criteria. These values have been derived from measurements. For a good estimate of the exceedance probabilities. The parameter values must be determined on a probabilistic basis. This type of calculation includes the probability of occurrence and an uncertainty factor. The latter has not been included, because of a lack of data on both the amount of data per measurement station and the number of stations with sufficient data. Therefore more research to parameters for waves and storm surge must be performed.

System and stakeholders
The system and stakeholder analysis is not complete. An additional step must be performed to accurately translate the positions of stakeholders in the system to measurable requirements and wishes for the design process. This is done by determining the requirements and wishes of the

stakeholders and subsequently weigh these requirements and wishes according to the position of the stakeholders in the Power-Interest diagram (and Tube model). In this way the choice for a specific design is improved.

6.2 Recommendations

To provide more details on the proposed measures to reduce flood risk for the City of Galveston the following recommendations are suggested:

- Not only residential stakeholders should be involved in the project to make the designs more inclusive. Instead of organizing focus sessions for residential stakeholders only, it is advised to engage with other stakeholders as well. Governmental bodies, commercial and industrial stakeholders all can bring relevant and useful input, which leads to a better integrated design;
- Instead of only recording concerns of stakeholders, it is highly advised to engage with them actively in the design process. Tools for this are already available, such as the Adaptation Support Tool (AST) developed by Deltares for interactive design sessions in New Orleans. With such tools, stakeholders can actively contribute to the design process with the aim of creating a more integrated design;
- The requirements and wishes of all stakeholders must be determined and weighed according to the positions of stakeholders in the Power-Interest diagram and Tube model. This improves the list of requirements in the design phase and improves the choice for a specific design option.
- It is advised to develop a continuously monitored groundwater measuring network across the City of Galveston and perform soil surveys. This information would allow for more accurate designs regarding water storage and infiltration;
- The approach taken in this project uses deterministic modelling and calculation. However, to better consider climate change, it is advised to base design heights and discharge capacities on probabilistic modelling;
- The current proposed design measures should be elaborated and more research is needed before actual decision-making can be done. Furthermore, it is advised to conduct a more iterative design approach, as shown in Figure 107, where the design is evaluated against analysis conclusions, stakeholder input and hazard management strategies in multiple cycles;
- It is highly advised to consider and thoroughly investigate building phasing for any final design. There are windows of opportunities in conjunction with currently planned city improvement works which should be taken into consideration.

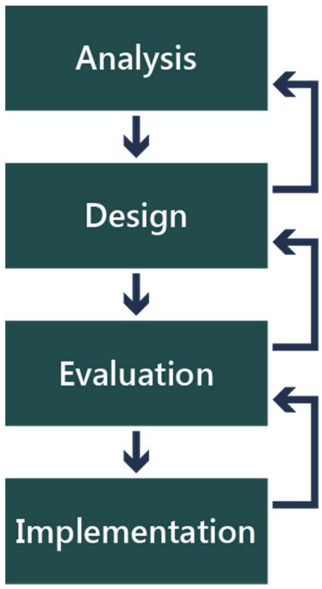

Figure 107 Advised iterative design approach

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Glossary

In this glossary a list of terms with their corresponding definition is presented. Since this project consists of multiple disciplines (Water management, Hydraulic Engineering and Integral Design & Management) it is important to acknowledge that these disciplines have different backgrounds and that terms can have varying meaning. To prevent misunderstandings, it is crucial to have the same understanding of relevant terms. This glossary displays interpretations of these relevant terms, as used in this report.

Term	**Interdisciplinary interpretation**
1900 Storm	Great Galveston Hurricane, Great Storm of 1900. The deadliest natural disaster in the U.S. history. The storm washed over Galveston Island, destroying it entirely.
1953 Flood	The 1953 North Sea flood was a major flood, affecting the Netherlands, Belgium, England and Scotland. The Netherlands experienced the most consequences in the form of casualties and property damage. This event started the development of the Delta Works in the Netherlands and storm surge barriers were also developed in the UK.
Adaptability	The speeds and efforts in which adjustments are possible in the social practice and processes or physical structures of the current system to projected or actual changes of climate. The extent to which a design is able to be adjusted in a later stadium.
Adaptation Plan	Plan or strategy with possible measures.
Aesthetics	The degree of how much the design is deemed to be beautiful.
Area Of Interest	The area on which the project is focusing.
Barrier	A structure or area hindering the flow of water. This can be both unwanted and wanted.
Basic Needs	Food, drink, shelter, sanitation, everything to survive a flood event during vertical evacuation.
Bathtub Comparison	An area functions as a bathtub. Water is retained within the area and cannot be discharged within a certain time span.
Bayside	The areas of the City of Galveston closest to the bay. The part of the area, road, structure which is facing the bayside.
Broadway Av	Broadway Avenue J, which is the main corridor for road traffic in the City of Galveston.
City of Galveston	Encompasses the whole of Galveston Island, with the exemption of Jamaica Beach.
Coastal Defense Structure	A structure which is intended to protect the coast from either flooding, erosion or both.
Coastal Flooding	Flooding due to high water levels. This can be a consequence of high tide, high waves and storm surge.
Coastal Protection System	A system which is intended to protect the coast from either flooding, erosion or both.
Coastal Storm Risk Management	Mitigation of probability and consequences due to storms.
Complexity	The degree of how difficult it is to construct a potential design.

Compound flooding	The event where flooding is caused by the combination of heavy precipitation and a high tide or storm surge.
Constructability	The extent to which a design can easily be build.
Cumulative Distribution Function	Probability of occurrence being equal to or less than a value for a parameter.
Delta Plan	Dutch strategy plan as a consequence of the 1953 Flood
Delta Works	Protection structures in the Netherlands, as part of the Delta Plan
DEM	Digital Elevation Model
Depth-damage Curves	Relation curve between water depth and the resulting damage.
Design Process	The process which is followed to create designs.
Desirability	The degree of how well a design fits the wishes of local stakeholders.
Dike	Levee, a long wall or embankment built to prevent flooding from sea or rivers.
Drainage System	Contains the network of all pipes, drains and pumps to transport water from the streets due to rainfall towards the Galveston Bay, in which the water is being exposed
Durability	The life expectancy of a potential design.
Dynamic Data	Variable set of data giving a range of output parameters.
Effectivity	The degree of how much the design does where it is designed for.
Flash Floods	Flooding occurring due to sudden intense precipitation.
Flood Hazards	Risk of flooding in an area
Flood Resilience	Rate of resilience against flooding
Flood Risk Management	Strategy of dealing with flood risk
Flood Vulnerability	Rate of vulnerability against flooding
Freeboard	Free vertical distance between ground level and surface water level.
GeoTIFF GIS map	Raster map file format
Hazard Management	Preventing, mitigation and recovery in pre-, peri-, and post-hazard phases.
Hazard Map	Map showing hazards
Horizontal Evacuation	Evacuation over ground
Hydraulic Model 3Di	Modelling hydraulic processes according to a deterministic approach
Levee	Dike, a long wall or embankment built to prevent flooding from sea or rivers.
Longshore	Along the coastline.
Maintainability	The degree of how easy it is to maintain a design, after it has been constructed.
Mean Sea Level	The sea level halfway between mean high and mean low sea level. It is the average level of the surface of the sea.
Multi-criteria Analysis (MCA)	Type of evaluating designs on different criteria.
NAP	Normaal Amsterdams Peil, datum level used in the Netherlands.
Nuisance Flooding	Flooding due to regularly occurring precipitation in combination with high tide
Pluvial Flooding	Flooding due to precipitation.
Power-Interest Diagram	Diagram showing the positions of stakeholders by their rates of power and interest.
Precipitation	Rainfall, Water which is present due to rainfall.

Preserving ecology	The extent of influence that a potential design has on ecology.
Probability Density Function	Probability of occurrence for one particular parameter.
Program Of Requirements	A list of requirements, which need to be met by design alternatives.
Rain Gauge	A measurement device, which measures the amount of precipitation within a certain time span.
Raster Map	Map containing pixel values
Return Period	Period of time that a particular event or parameter is occurring once.
Rijkswaterstaat	Dutch organization that is responsible for maintenance and monitoring of infrastructure.
Risk	Probability times consequence, expressed in values of money.
Risk Map	The map, which shows the areas with the highest risk of flooding.
Saturated Overland Flow	Overland run off due to saturated soil
SDF Curves	Storage Discharge frequency curve
Seawall	The Galveston Seawall. The present-day main coastal defense structure for the City of Galveston.
Sediment Transport	Transport of sediment due to the movement of water.
Significant Water Level	Water level that is exceeded by 1/3 of the measured water levels.
Significant Wave Height	Wave height that is exceeded by 1/3 of the measured wave heights.
Spread of Data	The distance a typical value has from the mean of the dataset. Can imply the total of distances from all the data points.
Stakeholder Analysis	Analysis of stakeholders involved in the project.
Stakeholders	People and parties with interests, involved in the project.
Standpipes	Vertical tubes in soil to measure ground water level
Static Data	Fixed input parameters giving one output parameter.
Sustainability	The degree of how much the potential design meets the needs of the present without compromising the ability of future generations to meet their own needs' (World Commission on Environment and Development, 1987).
System	Set of elements
Systems Analysis	Analysis of several systems and their relation to each other
Systems Engineering	Systems engineering is a field of engineering and engineering management, focusing on the design and management of complex systems.
System Of Interest (SOI)	The system that is to be improved. The project goal is to change, build or improve this system.
Tube Model	Visualization of system and stakeholders and their relation to each other.
Variation	It shows the extent of variability in relation to the mean of the a certain value. Variance.
Vertical Evacuation	Evacuation by using the vertical elevation of buildings or areas. Considered as an option in flood prone regions.
Water Assignment	Analysis to water storage needed in an urban area.
Wave Analysis	The analysis of wave data used to acquire useful values for design purposes.
Wave Impact	An amount of damage which a wave does in an area. The action of a wave coming forcibly into contact with a structure, beach, area.

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A.1 Geography

Galveston Island and City of Galveston

Galveston Island is located in the state of Texas in the United States of America (see Figure 108). It forms a sand-barrier island on the southeast coast of Texas and the Gulf of Mexico, 70 km (44 mi.) to the southeast of Houston (TSHA, 2018). The island used to be a marsh divided by several bayous. It has a length of about 46 km (29 mi.) and a width of approximately 1 to 5 km (0.6 to 3 mi.), varying along the length of the island. Furthermore, Galveston Island runs parallel to the coast of Texas 3 km (2 mi.) out with an orientation of the long axis from east-northeast to west-southwest at an angle of 235° (Frey, Morang, & King, 2016).

The north-eastern part of the island is bordered by the Bolivar Peninsula with the Galveston Entrance Channel in between, which is the main navigation channel into Galveston Bay. This channel is one of the busiest shipping entrances in the United States (Frey, Morang, & King, 2016). The south-western part of the island is bordered by San Luis Island (and Follets Island) with the San Luis Pass in between, which provides a second smaller entryway into the bays behind Galveston Island. Between Galveston Island and Pelican Island, which borders on the northern side, runs the Galveston Channel (Google Maps, 2018; TSHA, 2018).

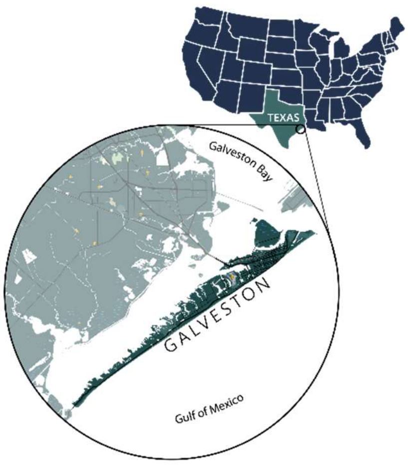


Figure 108 Location of Galveston Island

The entire island, excluding the town of Jamaica Beach, is part of the City of Galveston. The eastern third of the island, which functions as both the residential and commercial heart of Galveston, is protected by the Galveston Seawall, as shown in the zoning map in Figure 109. Moreover, this part of the island was raised following the Galveston Hurricane of 1900. The western part has “limited development of single-family beach homes, subdivisions, and condominiums, interspersed with undeveloped areas” (Frey, Morang, & King, 2016; GTHC, 2004). Note: the western part of the island is not shown here, the full zoning map of Galveston can be found at (City of Galveston, 2018).

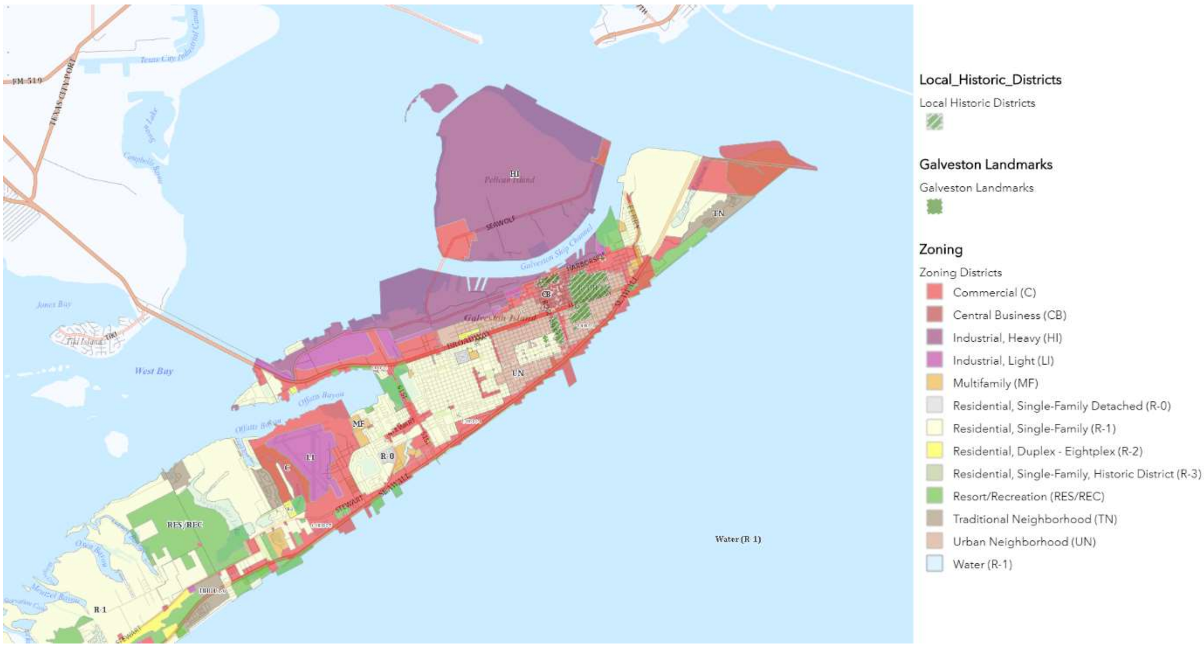


Figure 109 City of Galveston Zoning map (City of Galveston, 2018)

Galveston Bay Area

Circling Galveston Island are multiple bays that, amongst other functions, contain habitats for flora and fauna, provide ship channels to access the ports in both Galveston and Houston, and facilitate recreation and a satisfactory living experience as illustrated in Figure 110.

The Houston Ship Channel (HSC) runs between Galveston Island and Bolivar Peninsula through the Galveston Bay into Houston. The channel is used by ocean-going vessels as well as inland barges between the Ports of Houston and Galveston and the Gulf of Mexico (TSHA, 2018). The navigation channel is shown in Figure 110, as well as the waiting areas of ships in the Gulf of Mexico.

Figure 110 Location of the various bays around Galveston Island and the ship routes in the bay (OpenStreetMap, 2018; KILN, 2018)

Elevation

The Island of Galveston has a downward gradient from the Seawall towards the bayside. This is due to the island being a natural barrier island in a dynamic environment, resulting in a differentiating coastline. Moreover, measures have been taken to increase the elevation of various parts of the island, which also result in elevation differences. One of those measures is the Galveston Seawall, the primary protection against surge from the Gulf of Mexico. A map of the elevation of the City of Galveston is shown in Figure 111 (West Island not included). The elevation is relative to MSL in meters, where 1 m equals 3.3 ft. Figure 25 is used as a reference point for MSL. The datum levels are based on measuring station 8771510, which is present on the Galveston Pleasure Pier (NOAA NGS, 2018).

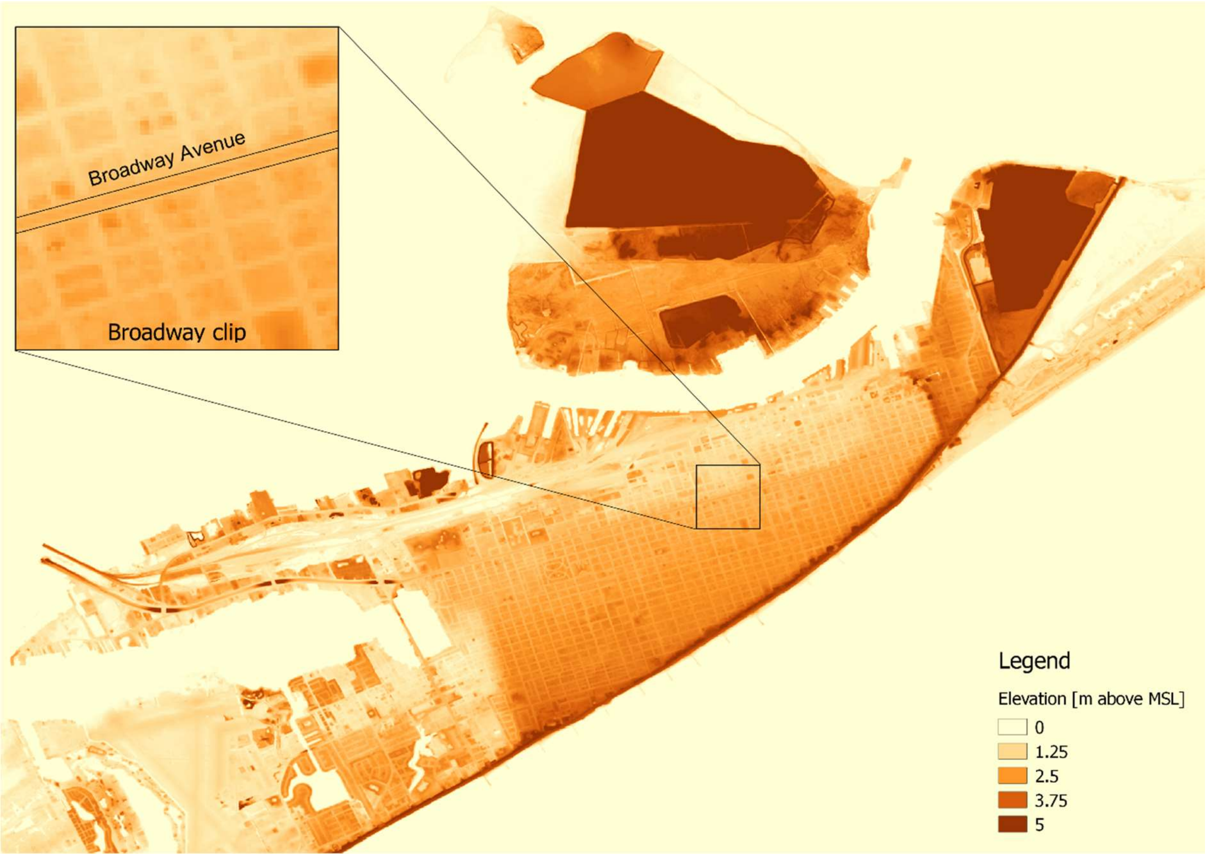


Figure 111 Elevation Map City Galveston

People have built their homes on mounds to protect their properties from flooding, which is another reason why variations in elevation exist.

A.2 Demography

Demography is the study of the size, structure and distribution of populations, as well as variations in population, both spatial and temporal. Different criteria can be used to differentiate in populations. These criteria include amongst other education, income, property value, house ownership, age, gender, etc. Demography can have an influence on mitigation measures considered for flood problems in the City of Galveston. Elderly people may need more assistance during an evacuation for example, but value of properties and population densities also have an influence on risk.

Population

The population of Galveston amounts to about 50,000 people. The age distribution of the population is shown in Figure 112. The median age of the population is 37. With a total area of 561 km^2 (219 mi^2) this results in a population density of 479 per km^2 (1227 per mi^2).

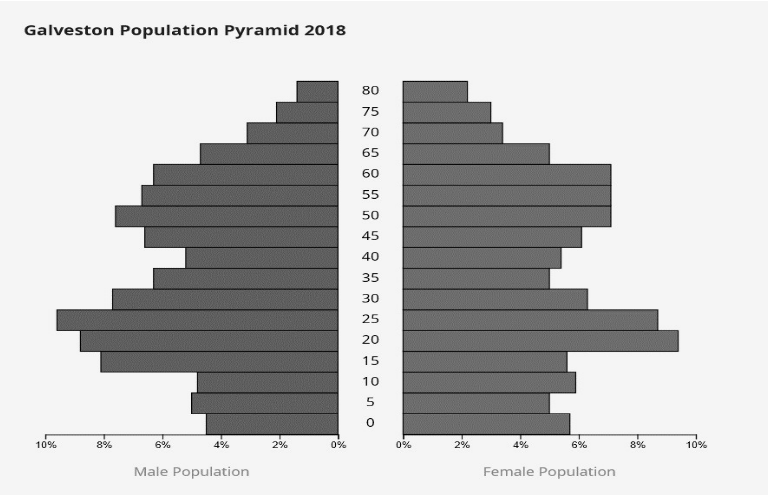


Figure 112 Population Pyramid Galveston (World Population Review, 2016)

Income per Household

The median household income equals $42,216 and the poverty rate is about 22.8%. When looking at the island there is a certain distribution of income per island area. This can be seen in Figure 113.

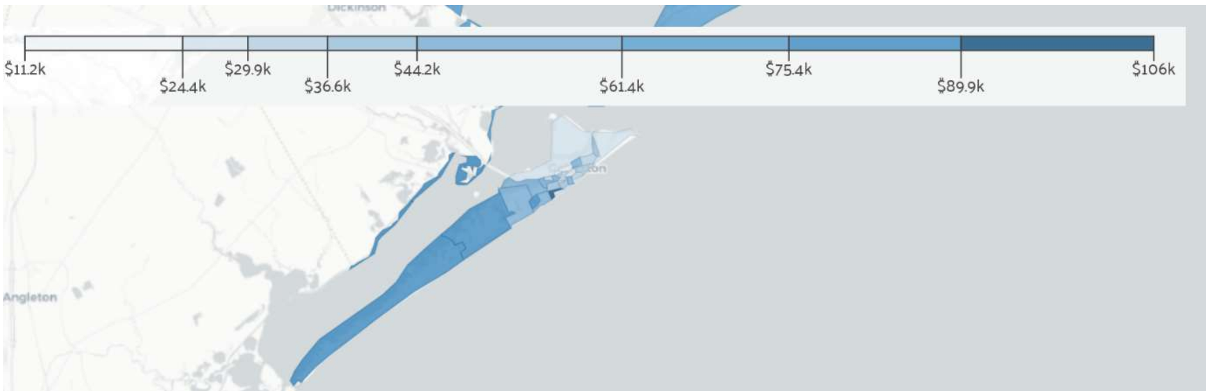


Figure 113 Distribution of median household income (Data USA, 2016)

Property Value

The average property value on Galveston Island is $154,400 with a large share of the houses having a value over $100,000 (Data USA, 2016). In Figure 114, a distribution of the property value of the island is shown. These values have influence on the impact part of determining the risk of compound flooding. This is further elaborated in Section 4.3 Vulnerability Analysis.

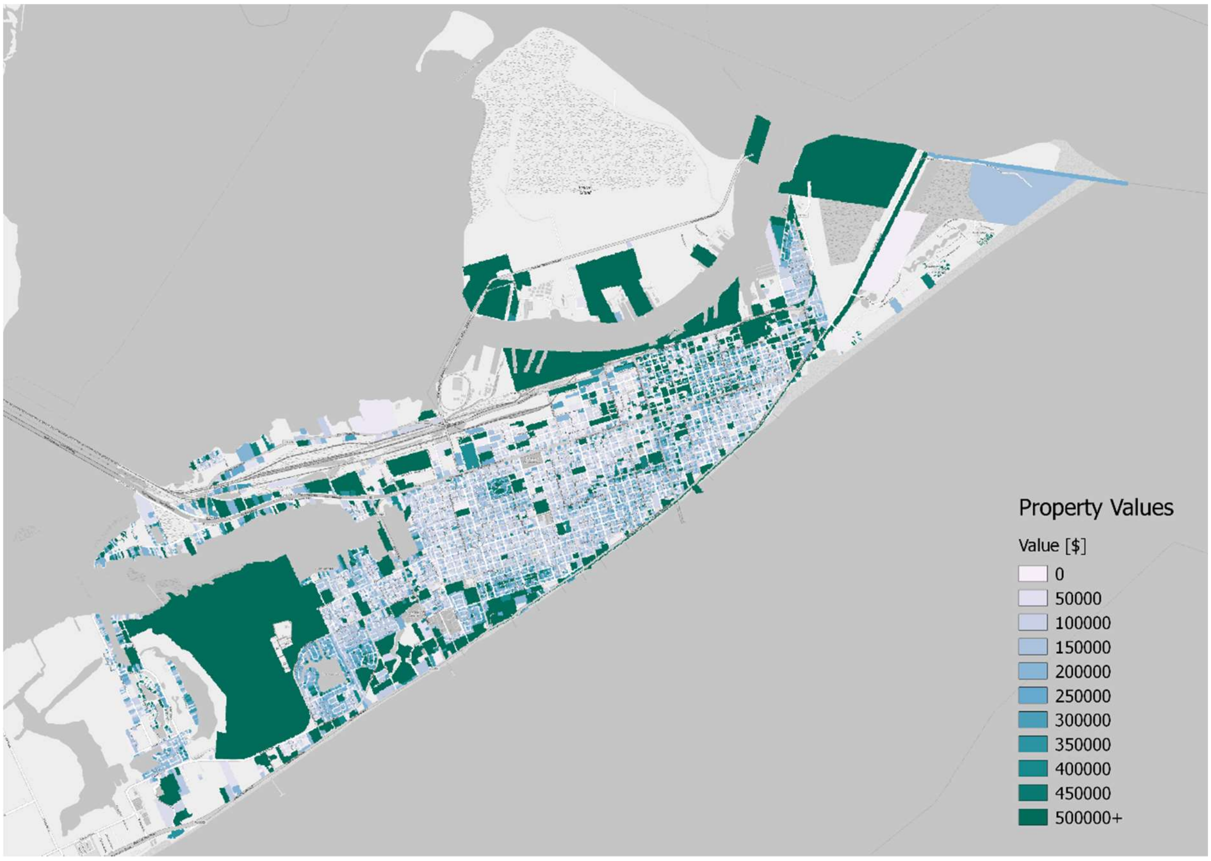


Figure 114 Property Values of the different houses in the City of Galveston

A.3 Geology

Consistency of Soil

The soil of which Galveston Island consists is generally classified as a mix of Mustang-Galveston type of soil. The bayside of Galveston Island consist of a Placedo-Tracosa-Veston soil mix, while Pelican Island largely consists of Ijam type soil. This means that most of Galveston Island consists of sand, which is rapidly permeable, but it can be both poorly drained to excessively drain. Pelican Island, however, is largely clay, as is displayed in Figure 115 (U.S. Department of Agriculture, 1988). For more information, reference is made to the Soil Survey of Galveston County (U.S. Department of Agriculture, 1988).

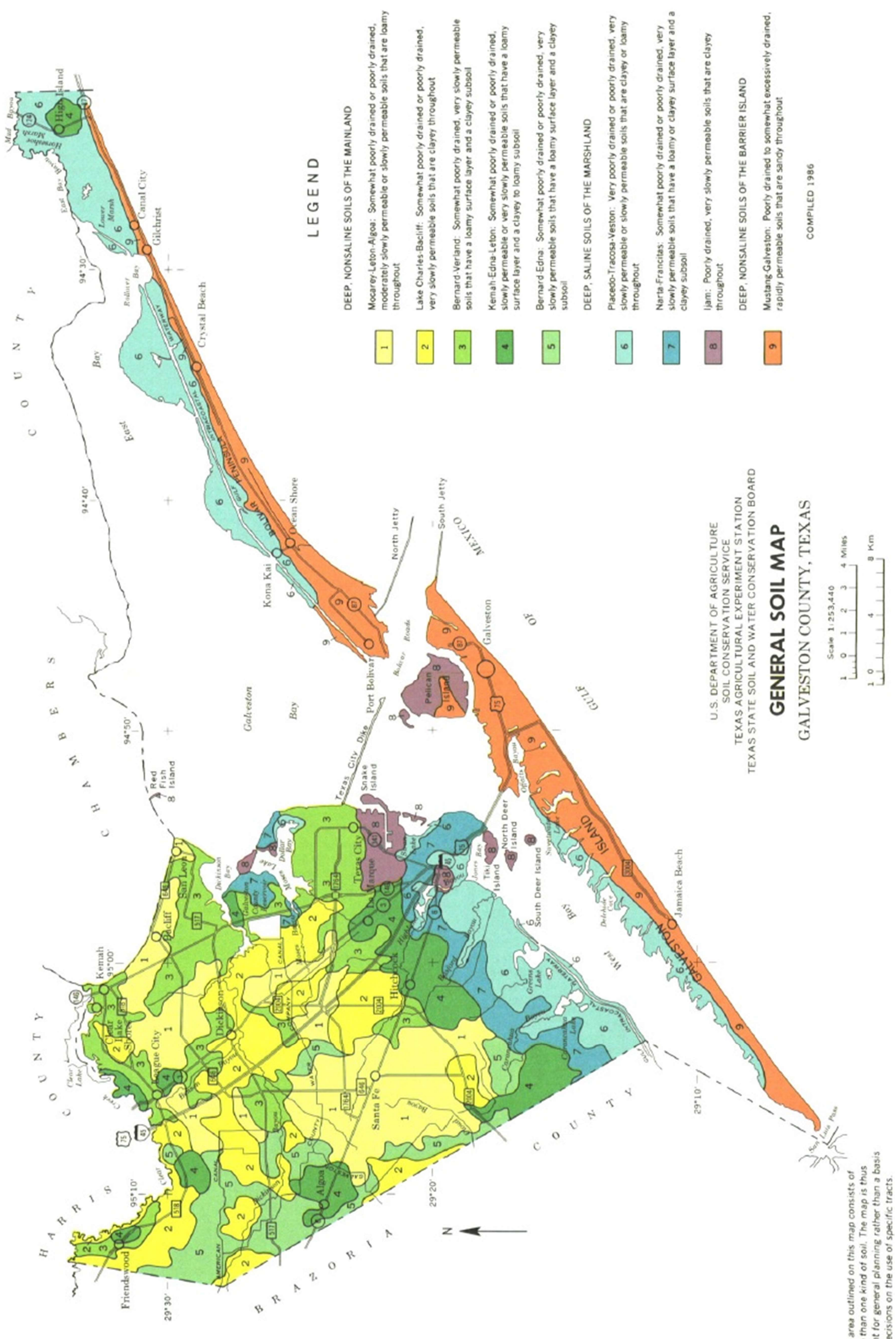


Figure 115 General Soil map of Galveston County (U.S. Department of Agriculture, 1988)

A.4 Meteorology

Within meteorology, the subjects of climate, rainfall and extreme events are of particular interest.

Climate

The City of Galveston is located on 29° latitude which means that it is located in a subtropical climate. Most of the year the temperature is above 21 °C (70 °F), combined with a high humidity of almost 90% (U.S. Climate Data, 2018).

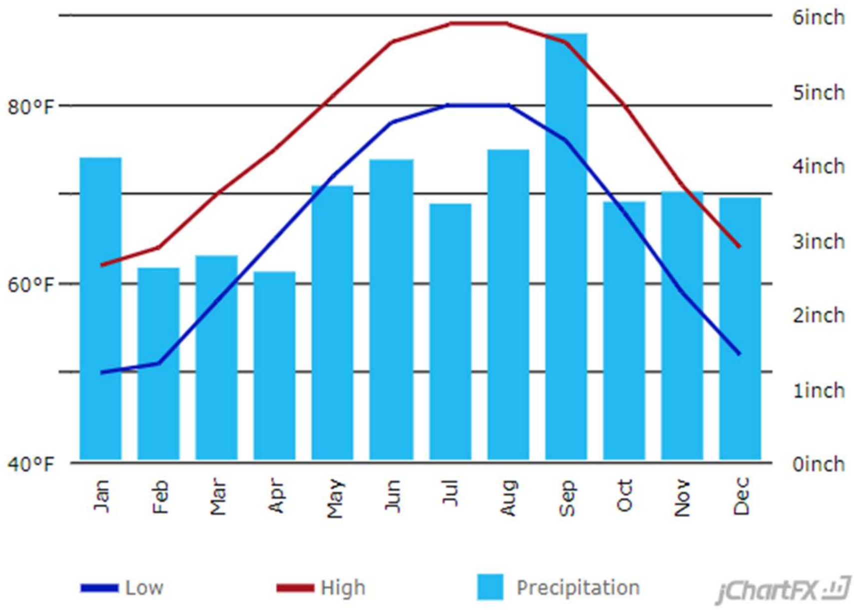


Figure 116 Monthly rainfall and minimum and maximum temperatures for the City of Galveston (U.S. Climate Data, 2018)

From Figure 116, it can be concluded that average low and high temperatures are varying respectively between 10 to 32 °C (50 and 90 °F) throughout the year. Average rainfall is low from February through April and high in September. Hurricane season runs from mid-August until late October, with its peak in September. In Figure 117, the wind directions are shown. The dominant wind direction is southeast.

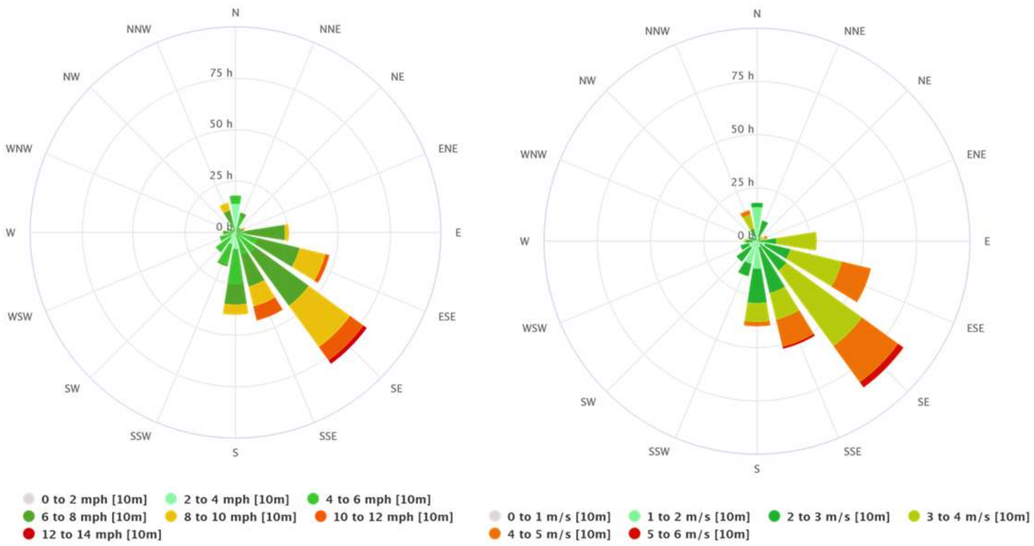


Figure 117 Wind roses in mph (left) and m/s (right). The main wind direction is southeast (Meteoblue, N.D.)

Rainfall

A particular problem in the region is the intense rainfall during hurricane season. Large amounts of rainfall occur several times during this season and are problematic to the city, even without the occurrence of a hurricane.

Infrastructure was designed to cope with specific amounts of rainfall, but the system does not suffice due to increasing intensity and ageing infrastructure. Hydrological research is carried out to obtain so-called Intensity-Duration-Frequency (IDF) curves (NWS N. , 2017). Figure 118 shows IDF curves for Harris County. The assumption is made that the IDF curves of Harris County are also valid for Galveston County, since these counties are close to each other.

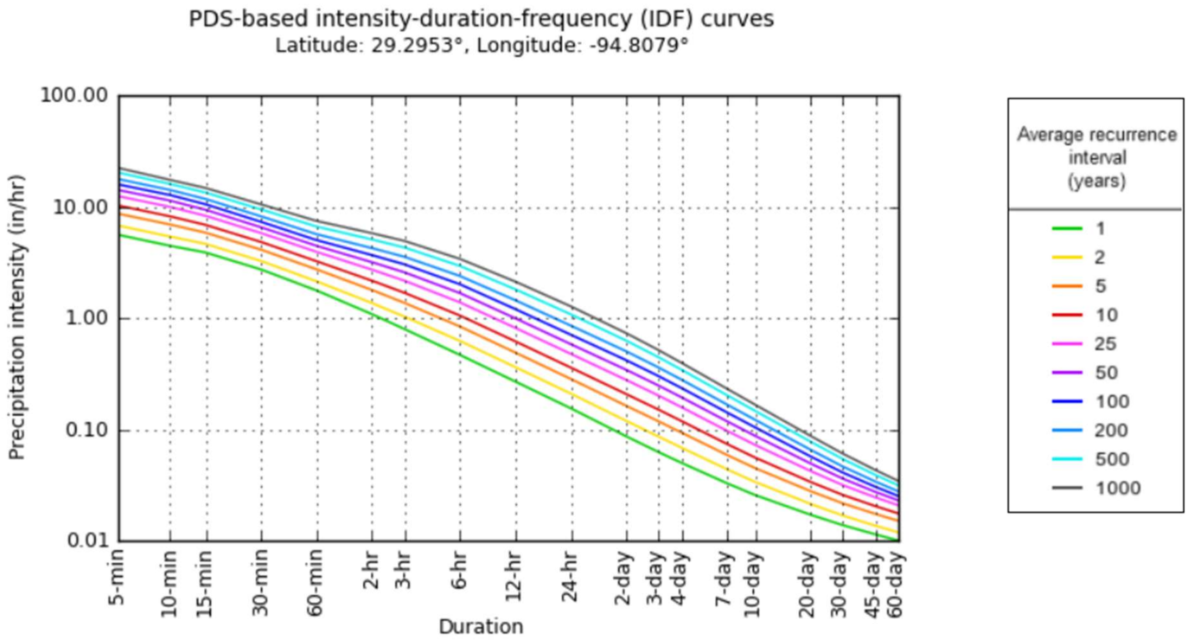


Figure 118 IDF curves for Harris County, TX (NWS N. , 2017)

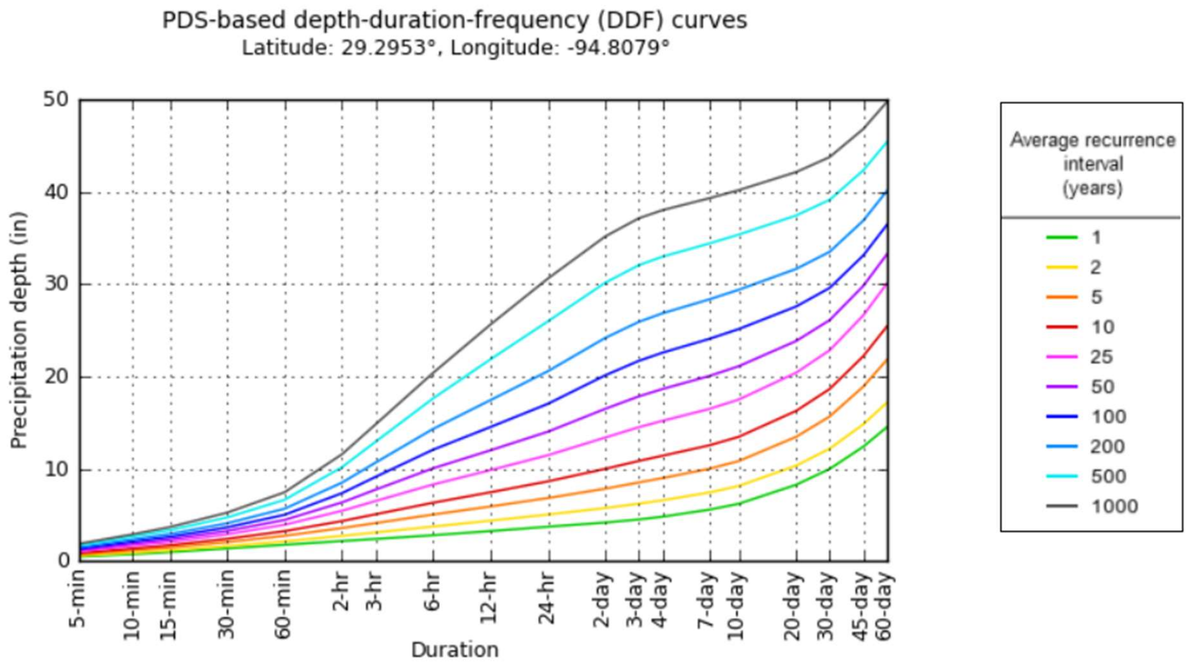


Figure 119 DDF curves for Harris County, TX (NWS N. , 2017)

IDF curves can be used to design infrastructure to prevent flooding. Rainfall intensity decreases as the duration of the precipitation event increases. For larger return periods the intensity and duration increase. For creating an IDF curve a Depth-Duration-Frequency (DDF) curve is needed, which represents the actual depth during a rainfall event. In Figure 119, the DDF curves are shown for Harris County. To convert a DDF to an IDF curve, the actual rainfall depth should be divided by the event duration.

Extreme events & hurricanes

Intense rainfall events occur several times a year. In Appendix B Fieldwork two of these events are described that happened in the first week of September 2018. During these events the rainfall intensity exceeds the design rainfall intensity, therefore streets get flooded. Usually, a maximum of 76 mm (3.0 in.) precipitates and results in nuisance flooding.

During tropical storms the rainfall often lasts multiple days. The intensity is somewhat less, but the overall precipitation depth is actually higher due to a longer duration. This is also observed in the DDF curves in Figure 119, which represent a larger amount of precipitation for longer durations of events. Tropical storms also bring another important hazard: storm surge. Surge is created by low pressure fields and strong winds. A normal pressure is around 1010 mbar, but this drops to 970-990 mbar in the inner parts of the storm field, causing the sea level to rise some feet. A decrease of 1 hPa (1 mbar) in air pressure lifts up the water level 1 cm (0.4 inch) (SMHI, 2014). A pressure drop equal to 30 mbar gives 30 cm (1 ft.) of surge. If water level rise due to wind speed is added, the total storm surge can add up to multiple meters above MSL.

A hurricane causes intense wind fields and low pressure fields. Wind speeds can reach over 130 km/h (80 mph), creating large waves and high storm surge levels. Air pressure can drop to just 940 mbar, causing at least a sea level rise of 70 cm (2 ft.). Hurricanes are divided into 5 categories by the Saffir-Simpson Hurricane wind scale (NHC, 2018), and are rated based on sustained wind speed. Each category includes a range of storm surge, rainfall intensity (IDF) and depth (DDF), and level of damage. Most of the hurricanes are either dominated by storm surge or intense rainfall. The last two hurricanes that had a significant impact on the Galveston region are Ike (cat. 3, 2008), which was surge-dominated, and Harvey (cat. 4, 2017), which was rainfall-dominated. These two hurricanes are input criteria for the scenarios in Chapter 3 Scenarios and design process in Chapter 5 Design Measures later in this report. The Great Storm of 1900 is also being considered, however, there is little data from that event. Only damages are known and the measures that were done after the storm.

A.5 Ecology

Flora & Fauna

The Galveston Bay hosts several habitats that add to the biodiversity of the region. These provide shelter for plants and animals and are part of Galveston Island. They are important to the region, as they provide, amongst others, aesthetics, biodiversity, jobs (fishing and tourism) and they can add to the stability and protection of the coastal region. In the Galveston Bay area four key types of coastal habitats can be identified. These are the freshwater wetlands, the saltwater wetlands (and saltmarshes), the underwater grasses and the oyster reefs (Galveston Bay Report Card, 2018).

Wetlands (and saltmarshes), under the right circumstances, develop on the border between land and aquatic environments (see Figure 120). They fulfill various functions such as serving as a buffer for tides and surges, reducing shoreline erosion and filtering runoff. Moreover, they slow the flow of water and thus allow sedimentation to occur. This will add to accretion of new land.

Figure 120 Wetlands near Teichman Road, Galveston, Texas (Photo courtesy of authors)

Underwater grasses develop in shallow water with enough light penetration to allow photosynthesis to happen. Underwater grasses provide habitat for fish and shellfish, as well as a natural buffer for water quality due to the oxygen they produce.

Oyster reefs develop in the mud on the bay floor. These reefs provide a natural solid bottom in the bay and filter the water in Galveston bay, providing an improvement of water quality. To the fishing industry oysters are important as well, both for their meat as well as their shells. Oysters can also function as wave energy dissipaters, adding to the reduction of the wave energy and thus reducing the impact of waves on the coastline (see Figure 121).

Figure 121 Oyster Reef Restoration project (Galveston Bay Foundation, 2018).

The open bay waters of Galveston are also of great importance because plants and fish are living there which sustain, amongst others, shrimp. These are commercially important in the region (Texas Parks and Wildlife, 2018). Another point of interest are the jetties. These mostly fulfill the function of preventing shipping channels from filling with sand and silt, but they have an added function of providing food and shelter for various species. The nearshore waters in the area are used for placing artificial reefs in order to attract species that would otherwise not be present in the region. These reefs provide a commercial benefit and add to biodiversity (Texas Parks and Wildlife, 2018).

The Galveston Bay area does not only provide a habitat for marine life, but also provides food and shelter for mammals and birds. These animals add to the biodiversity of the region and also sustain tourism in the region (i.e. bird spotting).

Use of Nature in Engineering

Next to their ecological importance, local flora and fauna are useful in engineering. They provide alternative solutions or are supplemental to existing solutions to problems affecting human society. It is still researched to what extent certain species have influence on wave energy reduction, but wave impact reduction has been proven. Measures against wave impact using flora and fauna are being implemented. These measures do not only protect against wave impact for example but also implement values from a societal and ecological point of view, for example the oyster restoration project shown in Figure 121.

Building with Nature (in the USA better known as Natural and Nature Based Features, but it boils down to the same principle) solutions cannot always be used. Some solutions are simply unable to solve the problem, others are financially not feasible or bring too much risk with them. Using this philosophy, however, results in a shift from the traditional engineering perspective and will help in realizing a holistic approach, where values for people and planet are integrated (Building with Nature, 2018; IADC, 2017). An example is shown in Figure 122, where a Sand Engine is installed along the Dutch coast and used to protect and nourish the beaches of the Dutch coast.

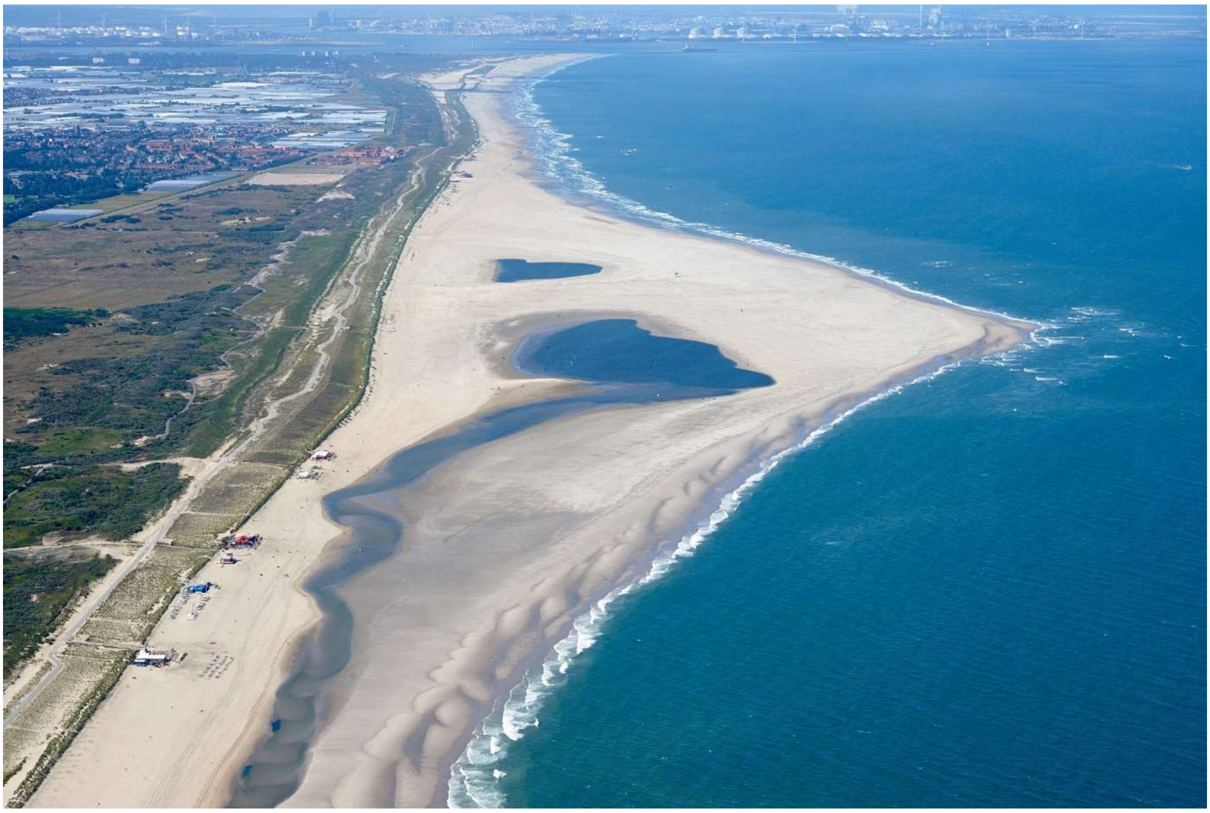


Figure 122 The Sand Engine near Kijkduin, The Netherlands (De Zandmotor, 2018)

A.6 Climate Change

Effects of Climate Change

The Earth's climate has been changing throughout history. In the last 650,000 years there have been seven cycles of glacial advance and retreat. Most of these changes are caused by small variations in the Earth's orbit that effect a change in the amount of solar energy the planet receives.

The current trend of global warming is of significance because ever since the mid-20th century, global warming occurs at an unprecedented rate over decades to millennia. Figure 123 illustrates the change in global surface temperature relative to 1951-1980 average temperatures (NASA, 2018).

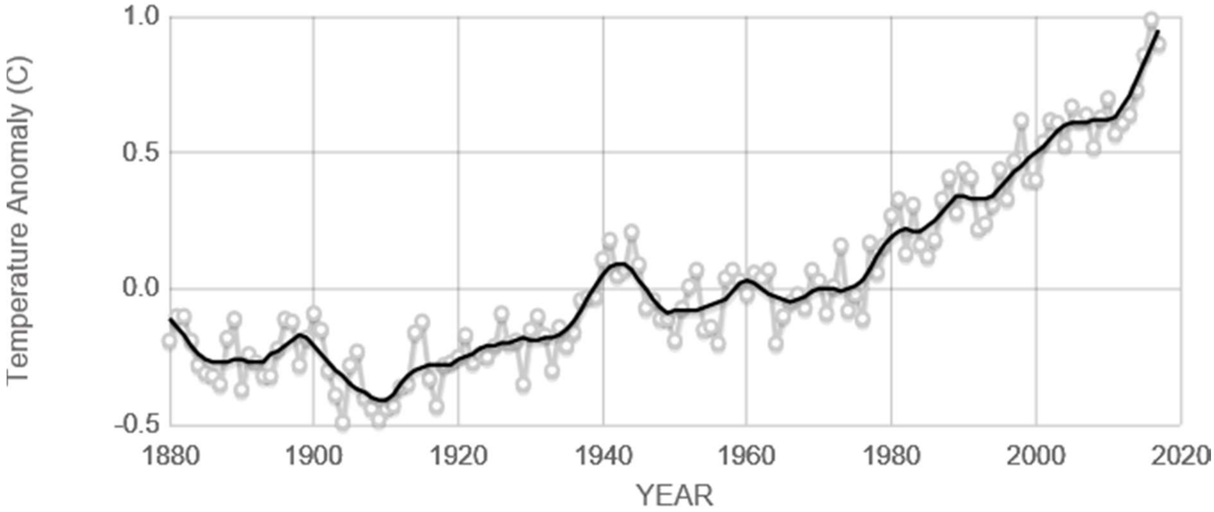


Figure 123 Relative change in global surface temperature (NASA, 2018)

Multiple events and data suggest that current warming is occurring roughly ten times faster than the average rate of ice-age-recovery warming (NASA, 2008). Some of the changes, which are happening due to climate change, are:

- Global temperature rise;
- Warming of the oceans;
- Shrinking ice sheets;
- Glacial retreat;
- Decreased snow cover;
- Sea level rise;
- Declining Arctic sea ice;
- Extreme events;
- Ocean acidification.

Influence of climate change on Galveston Island

Of the aforementioned changes in climate, the warming of the oceans and sea level rise have an effect on the environmental characteristics of Galveston which are relevant to this project. The other changes have an effect as well, but these fall outside the scope of this report.

The warming of the oceans lead to increased hurricane activity (Emanuel & Mann, 2006; NASA, 2018): 'The intensity, frequency and duration of North Atlantic hurricanes, as well as the frequency of the strongest (Category 4 and 5) hurricanes, have all increased since the early 1980s'.

The change in sea level will also have an influence on the environmental characteristics. The local sea level rise is being measured at two locations: one location is at the Galveston Pleasure Pier and the other is at Galveston Pier 21. Figure 124 shows the sea level rise derived from multiple measurements along the Gulf of Mexico.

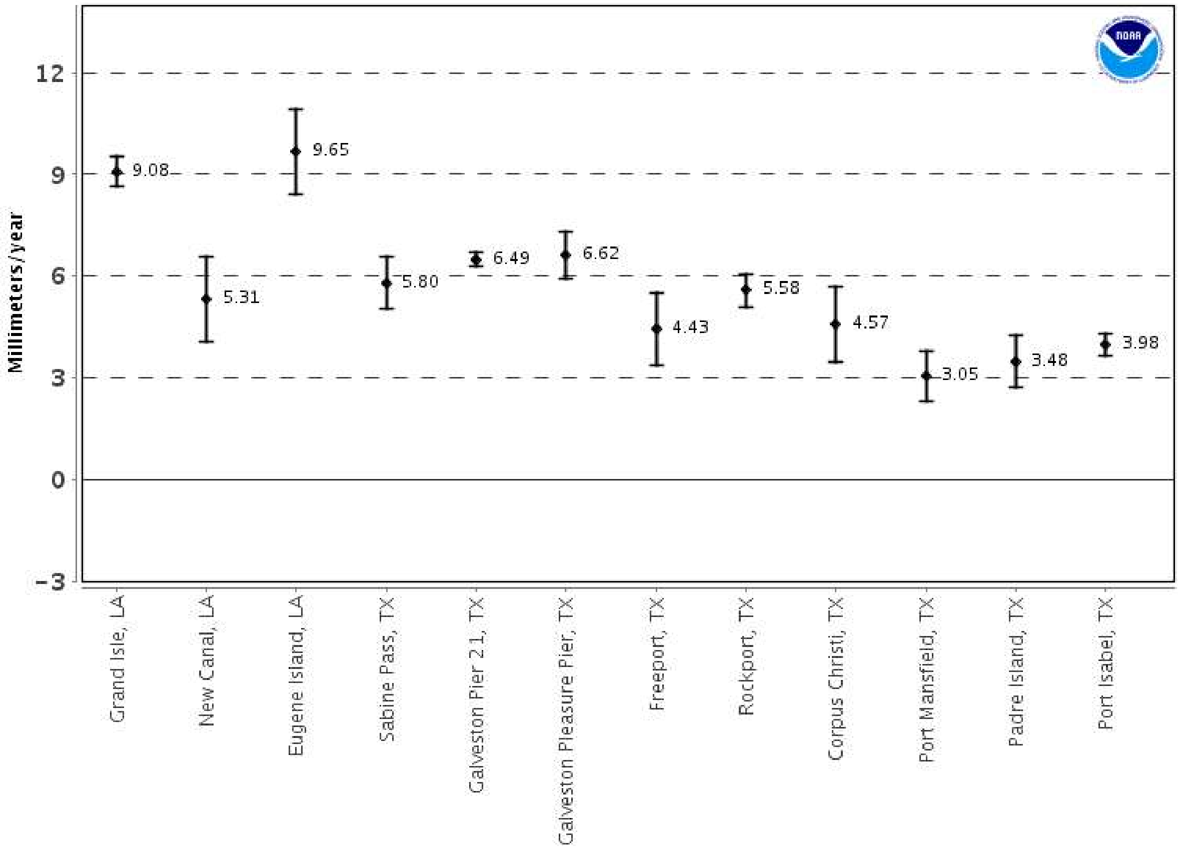


Figure 124 Sea level rise per year (NOAA NOC, 2018)

The NOAA Tides and Currents website also shows the 95% confidence intervals for the values of the sea level rise at the measurement points on Galveston Island. The expected sea level rise as measured at Galveston Pier 21 and at the Galveston Pleasure Pier are respectively 6.49 mm/yr. with a 95% confidence interval of +/- 0.23 mm/yr., which is equivalent to a change of 2.13 feet in 100 years and 6.62 mm/yr. with a 95% confidence interval of +/- 0.69 mm/yr., which is equivalent to a change of 2.17 feet in 100 years (NOAA NOC, 2018). The size of the confidence interval is dependent upon the amount of data available and the time in which this data is measured.

A.7 Economy

In this section, the following subjects are elaborated: transportation (road, railroad and waterway), industry, and shipping.

Road

The Island of Galveston is accessible by road from two directions. The main road access to the island and the City of Galveston is via the Interstate Highway 45 from the City of Houston. This is a 2x3 lane freeway, which connects the island to the mainland with a large bridge and enters the city in the northwest corner at Teichman Rd. The second access road is the San Luis Pass Rd and Bluewater Highway in the southwestern section of the island, which connects the island with the City of Freeport. A third access route is from Bolivar Peninsula using the ferry towards the northeast corner of the city.

The road network in the city is a grid, which is a typical layout for U.S. cities. On top of the Seawall a 2x3 lane road is located, which serves as an important road in the network. This is also the case for Broadway Av, an extension of the I-45, which goes further towards the east part of the city.

Railroad

For transportation of goods the Galveston Railroad (GSVR) is used. The GSVR provides a Class 3 terminal and switching railroad service with its headquarters in Galveston. It primarily services the Galveston Port and various industries by transporting cargo over the railroad bridge between the Port of Galveston and the mainland around Houston. The railroad network is used for freight trains only, there is no commuter traffic by railroad (TSHA, 2018). The railroad network consist of 51 km (32 mi.) of tracks at Galveston on a total area of 20 hectares (50 acres).

Other ways to access the island

There are also other modes of transportation in and out of Galveston. West from the city the Galveston Scholes Airport is located. This airport used to be of military nature, but nowadays it is for recreational use. However, the airport runway is suitable for larger planes, such as regular passenger airplanes and it can also accommodate helicopters. This could make the airport useful for other purposes, such as evacuation during natural hazards.

Furthermore, the Port of Galveston includes both a cruise terminal and Roll-On-Roll-Off (RORO) terminals, so that visitors can access the island by ship as well.

Industry

The Port of Galveston is important for both the mainland and offshore activities. Major companies and activities in the port are:

- Royal Caribbean International Cruise Terminal; vessel fleet “of the Seas”;
- Carnival Cruise Line Terminal; vessel fleet “Carnival”;
- ADM Grain; large grain export company;
- Savage Sulfur Services LTD; distributor of dry sulfur;
- Texas International Terminal; multi-modal terminal for storage and distribution of both dry and liquid bulk;
- Ports America Inc.; Terminal for RORO and Breakbulk;
- Fresh Del Monte Produce Co; Distributor of fresh goods;
- AET Offshore Services Inc.; offshore cable positioning;
- G&H Towing; tug boats services;
- Gulf Copper Dry Dock & Rig Repair; maintenance of offshore rigs.

Galveston also boasts a fishing industry, where part of the caught fish is consumed in the city and part of it is exported. The fishery port is located in the east part of the port. Next to the fishery port the yacht port is located. This is a private port for residents.

In Figure 125 and Figure 126 an overview is given of the percentage of employment in Galveston, both for fulltime local civilian labor as well as part time and seasonal worker labor.

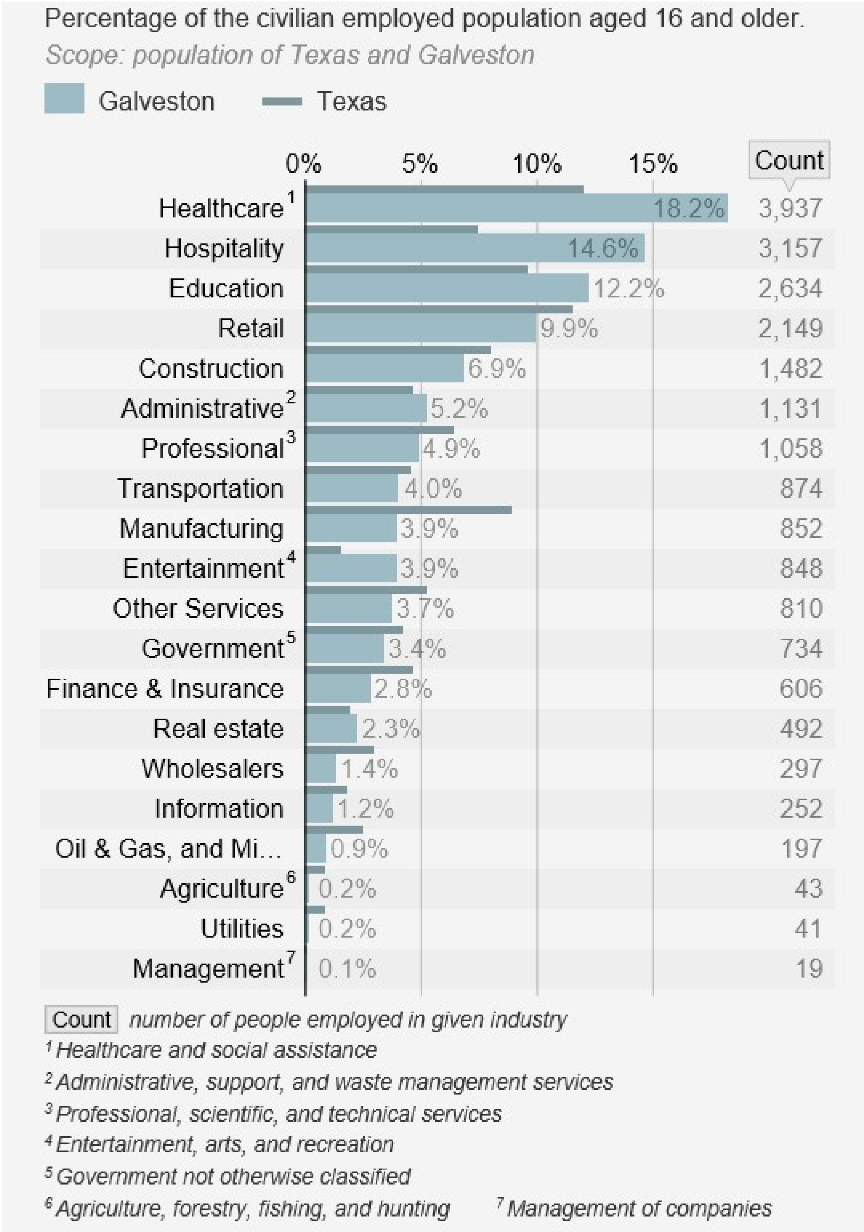


Figure 125 Employment per branch of industry (Statistical Atlas, 2018)

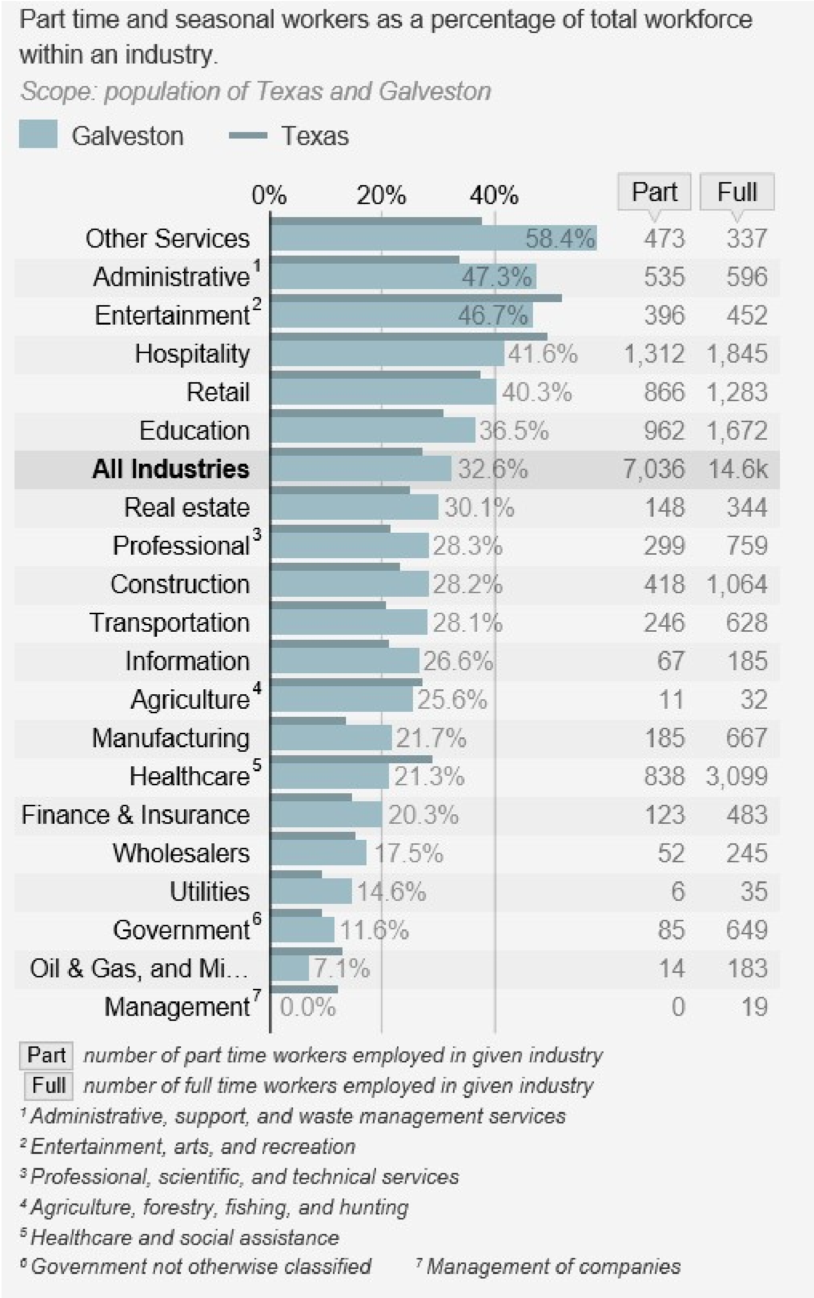


Figure 126 Seasonal workers per branch of industry (Statistical Atlas, 2018)

Medical Industry

As shown in Figure 125 and Figure 126, the healthcare industry makes up a large part of the total employment on Galveston. The University of Texas Medical Branch at Galveston (UTMB) is a major academic health center. It is the main hospital in the region of Galveston Island, Bayou Vista and Texas City. A large part of UTMB focuses on research in diseases. Part of UTMB is the World Reference Center for Emerging Viruses and Arboviruses (WRCEVA), which is a large, diverse collection of many different emerging viruses and viral reagents. It was founded in the early 20th century to understand viral ecology, epidemiology, and pathogenesis (UTMB Health, 2018).

Shipping

The Port of Galveston is one of the main ports in the region. The port is located on the north side of Galveston Island with facilities and some properties located on Pelican Island. The Port of Galveston's facilities are located 15 km (9.3 mi.) from the open sea at the entrance to Galveston Bay in the Galveston Channel. The Galveston Channel has an authorized minimum depth of 13.7 m (45 ft.) and is 366 m (1200 ft.) wide at the narrowest point. The port is part of the Gulf Intracoastal Waterway, see Figure 127, which is part of the larger Intracoastal Waterway, marked in red.

Figure 127 Gulf Intracoastal Waterway (Captain John, 2018)

The port has experienced an increase in ships docking as well as an increase in revenue. The total income from Operations increased by 22.8% (see Table 59). The total tonnage has also increased by 46.8% implying not only cruise terminal operations (9.6% increase in passengers) are increasing but also the amount of cargo increased. An annual maintenance dredging project is underway to dredge the port area and the Galveston Channel (Port of Galveston, 2018). The dredged material is scheduled to be deposited on Pelican Island with a volume of 112,390 m^3 (147,000 yd^3).

Table 59 Port of Galveston Financial Revenue up to and including July 2018 (Port of Galveston, 2018)

Port of Galveston/GPFC					
Year-To-Date Operating Revenues as of 7/31/18					
	July '18 Actual	July '18 Budget	July '17 Actual	Over (Under) Budget %	Over (Under) Prior Year %
Switching and Storage Cars - GRI	498,341	306,689	306,689	62.5%	62.5%
Wharfage	2,601,931	1,802,460	1,879,059	44.4%	38.5%
Passengers	7,163,695	6,838,297	6,689,553	4.8%	7.1%
Parking-Cruise Operations	4,274,059	3,814,531	3,706,558	12.0%	15.3%
Dockage	2,730,474	1,968,433	1,814,536	38.7%	50.5%
Lay Dockage	1,197,946	493,884	508,581	142.6%	135.5%
Ship Service Revenues	3,192,890	2,947,568	2,469,763	8.3%	29.3%
Real Estate	2,304,834	2,243,633	2,165,659	2.7%	6.4%
Security Cost Recovery	724,331	529,032	461,046	36.9%	57.1%
Terminal Access Fee	533,202	520,800	535,030	2.4%	-0.3%
Revenue Producing Services & Misc.	198,620	91,430	156,739	117.2%	26.7%
Total Income From Operations	25,420,323	21,556,757	20,693,213	17.9%	22.8%

A.8 Culture & History

A brief historical overview including critical events regarding flooding of Galveston Island and the City of Galveston is given. This historical overview is followed by a section on the culture of Galveston.

History of the City of Galveston

The Nineteenth Century

During the nineteenth century the City of Galveston was famous for its port. The port was used to trade goods, especially cotton. Besides, the Port of Galveston used to be the entrance to Texas for European immigrants (Galveston City Council, N.D.).

Throughout the century both the economy and population of Galveston kept on growing. Due to this growth it became one of Texas' most important cities. Galveston was not only famous for its growth, but also because of the fact that various novelties were introduced in Galveston. One of these novelties was the first daily newspaper of the state of Texas (Galveston Regional Chamber of Commerce, N.D.).

The 1900 Storm

On September 8 of the first year of the twentieth century, a category 4 hurricane hit Galveston Island. With estimated maximum wind speeds of 193 km/h (120 mph) and a storm surge of 4.8 m (15.7 ft.) it devastated the City of Galveston. The amount of human lives that was claimed by The Galveston Hurricane of 1900 is estimated to be over 6,000 (Ramos, 1999). However, other estimates are mentioned. The damage done to properties was calculated to be 30 million US dollars, including the loss of 3,600 houses (see Figure 128). This makes the Galveston Hurricane of 1900 the worst and deadliest hurricane in US history (Ramos, 1999).

Figure 128 A devastated City of Galveston after the 1900 Hurricane (Waxman, 2017)

The years after the storm

After this disaster, the Central Relief Committee was elected. The main task of this committee was to make sure that Galveston would recover. This involved ensuring that most urgent needs were available for the survivors of the hurricane. Furthermore, the committee made it possible to build and repair houses on Galveston Island (Ramos, 1999).

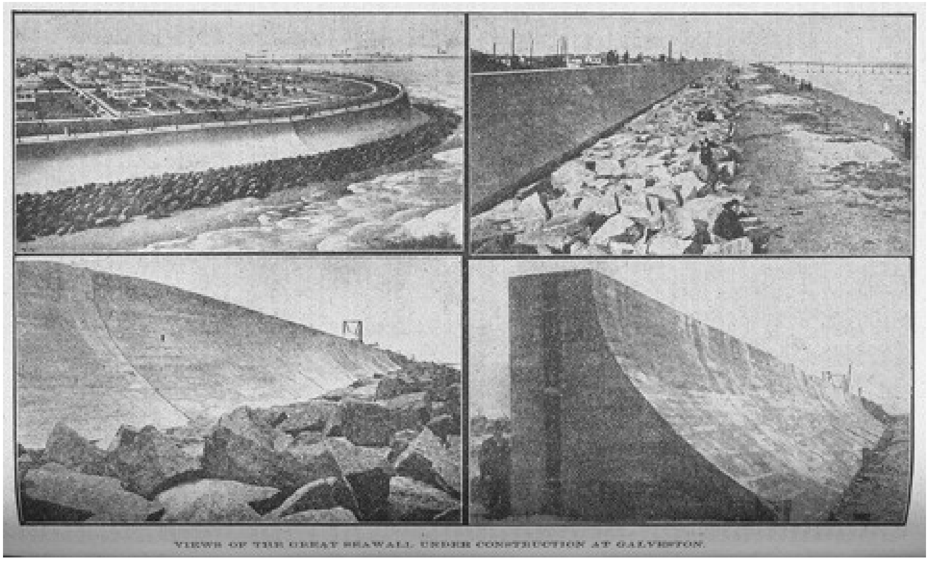


Figure 129 Construction of the Seawall in 1904 (Ramos, 1999)

Their next mission was to protect the City of Galveston from a new possible disastrous hurricane. Engineers appointed by the committee advised to protect Galveston in a two-phased recovery plan (Ramos, 1999). The first phase would involve building a concrete structure at the southern side of island to halt the force of incoming waves. This structure is better known as the Seawall. The construction of it began two years after the 1900 Storm and was completed in 1904 (see Figure 129). With a height of 4.9 m (16 ft.) relative to MSL, it protects the City of Galveston from wave impact.

The second phase of the plan was to raise the entire City of Galveston (Ramos, 1999). This was done because of two reasons: to further enhance flood resilience and to stabilize the Seawall. Without this sand fill, the Seawall would not have any solid support at all.

In the end, the city was lifted under a gradient of $6.7E^{-4}$ (Ramos, 1999), where the highest point is located directly behind the Seawall with a raise of 5 m (16.4 ft.). The lowest point is located at the bayside. In this way the streets of the City of Galveston could drain directly into the bay.

The second half of the Twentieth Century

Protected by its Seawall and elevated land, Galveston had the opportunity to grow again. Therefore, the 1960s and 1970s mark a flourishing period for Galveston. During these years, numerous educational institutes, among which Texas A&M University, were established on Galveston Island. Furthermore, the first container terminal in the Port of Galveston opened in these years.

Hurricane Ike and recent history

On September 13, 2008 hurricane Ike hit Galveston Island. It has been the most devastating hurricane since the 1900 Storm to hit the island. Many homes were destroyed when Ike raged over Galveston. However, after the hurricane the people of Galveston started to rebuild their city. And with success, because still every year millions of tourists come over to see their city and island (Galveston Regional Chamber of Commerce, N.D.).

The tenacious culture of Galveston

Despite the amount of damage the City of Galveston suffered from various hurricane events, its citizens would never give up rebuilding it. This is exactly what happened after hurricane Ike too. Not only houses were rebuilt after the hurricane had disappeared, also cultural buildings were repaired rapidly. Only a year after Ike hit the island, the Galveston Art League was rebuilt and ready to show new art exhibitions again (Walrath, 2015). This shows how tenacious Galveston's community is and how determined they are to rebuild their lives after a major disaster.

To prepare themselves for a new storm event, most houses were rebuilt on stilts as can be seen in Figure 130. This results in these dwellings being more flood resilient than the ones that are not on stilts. However, there are still houses on stilts that make use of the ground floor which may inundate with a next large storm event.

Figure 130 Houses that are built on stilts on the West End of Galveston Island (Photo courtesy of authors)

A.9 Planned Developments

In order to create a viable adaptation strategy, it is important to list and map city works and developments planned by the Galveston City Council and other institutions. Any proposed strategy should consider current and future works, as failure to do so can result in lost opportunities and wasted capital.

Galveston has a zoning plan which outlines the permitted land use. For reference, the zoning map is displayed in Figure 109.

This section of the inventory considers the following aspects: general strategic goals of the City of Galveston, plans for housing, plans for natural resources, planned drainage system improvements, other planned infrastructure and disaster planning.

Strategic Goals of the City

As outlined in the City of Galveston Comprehensive Plan, also known as Comp Plan (HDR Engineering, 2011), the vision defined for the City of Galveston is "*Galveston is a livable city on a sustainable island, a community that demands excellence*". According to the Comp Plan, the City of Galveston faces a decreasing permanent population and a wide disparity of household incomes.

Several highlighted general points of action from the Comp Plan are:

- Having a higher share of permanent residents in the city demography;
- Providing better access to the many cultural and natural assets Galveston Island offers;
- Increasing resilience to natural hazards by reducing vulnerabilities and planning a response;
- Providing middle-income housing to create a more diverse city.

Housing

An advisory report created by the Urban Land Institute argues that in general the housing stock is ill-maintained. They state that the historic neighborhoods offer few housing options due to limited new constructions and poor maintenance of historic buildings (Urban Land Institute, 2009).

The general goal regarding housing development as outlined by the City of Galveston is described as: "*Expand the Availability of Quality Housing to Meet the Needs of a Diverse Population and Build Strong Neighborhoods to Enhance Community Character.*" (HDR Engineering, 2011). In short, the objectives that arise from this goal primarily focus on two aspects which are relevant to mitigating flood risk:

1) Providing suitable housing for middle-income families and seniors. As the area protected north of the Seawall is largely urbanized, opportunities for middle-income housing mainly lie within redeveloping urbanized blocks in the inner city (HDR Engineering, 2011). Also, additional middle-income housing opportunities should be created west of the Seawall.
2) Revitalizing and enhancing the urban and historic neighborhoods. As can be observed in Figure 109, a significant portion of the urban core is labeled as 'historic urban neighborhood', which implies that revitalizing this area and mitigating flood risk is a large part of the assignment. Furthermore, reinvestment in properties should be encouraged by means of financial incentives.

Natural Resources

The goal for natural resources is formulated as: "*Preserve and Protect the Sensitive Natural Resources of Galveston Island, the Galveston Bay Estuary, and the Gulf of Mexico.*" (HDR Engineering, 2011). First of all, the City of Galveston seeks to protect and restore the dune system of the island in order to stabilize the Gulf coast.

Furthermore, the Galveston wetlands are a point of interest. New development should have minimal impact on existing wetlands and restoration of wetlands on Galveston Island should be encouraged to prevent degradation of the ecosystem.

A recurring beach nourishment program is underway at the location of Babe's Beach in order to provide material to the accreting ends of the island (City of Galveston, 2018). New developments planned across Galveston Island pose a threat to sensitive natural resources. Therefore, it is necessary to create a network of permanently protected open space.

Drainage System & Hydraulic Measures

The City of Galveston completed a Stormwater Master Plan in 2003, which provides recommendations on pressing issues regarding drainage. This Stormwater Master Plan identified the existing drainage system to be insufficient. Even with the assumption of a clean and debris free system, there is insufficient capacity (Dannenbaum Engineering Corporation, 2003). Considering in sandy and silty sediments leaves the system with even less capacity. The Stormwater Master Plan proposes storm drain improvements at many locations; main recommendations include the installation of larger drain pipes and replacing culverts.

As outlined in the Capital Improvement Plan, there is a continued effort to clear roadside ditches of sediments in order to ensure a high drainage capacity. Furthermore, the following improvements in the city are planned (City of Galveston, 2018):

- Replacing and upsizing the storm drain in Church Street from 35th Street to 37th Street;
- Replacing inlets and undersized laterals in conjunction with street improvement projects;
- Replacing and upgrading storm drain in 18th Street from Shipping Channel to Av N.

In addition, a range of culvert and storm drain replacements around the city is scheduled through 2023.

Other Infrastructure

The City of Galveston, although already being less dependent on private automobiles than neighboring counties, aims to expand the share of other modes of transportation (HDR Engineering, 2011). There is particular interest in creating a high-speed railway to the mainland, which would reduce congestion on highways. Also, a rail line would support the creation of a modern, walkable urban district (Urban Land Institute, 2009).

Another challenge is the management of port, industrial and cruise ship traffic (HDR Engineering, 2011). This requires separation of industrial traffic from other sources and providing sufficient, attractive parking options for cruise ship traffic.

The City of Galveston wishes to expand the role of the Bolivar ferry, as it is a critical transportation link that also serves as a tourist attraction and provides for an interesting gateway to the island (HDR Engineering, 2011).

There is much work to be done in order to bring the quality of the roads on Galveston Island up to standard. As much as 23.7% of all streets in the City of Galveston scored below "satisfactory" (City of

Galveston, 2018). Some improvements have been carried out in recent years; the rest is planned to be completed by 2020.

Disaster Planning

The goal of the City of Galveston regarding disaster planning is: "*Prepare the City for Disasters that Could Adversely Affect the Health, Safety, and General Welfare of Residents and Visitors*." (HDR Engineering, 2011).

The Comp Plan clearly states that disaster planning programs should be closely coordinated with other plans regarding development and conservation. This implies that for a solid disaster plan, integrating the built and natural environment is essential. It is further argued that the integrity of the Seawall should be protected and that non-coastal land loss should be addressed (HDR Engineering, 2011).

B Fieldwork

In the first week of the project, from September 3rd until 9th, two rainfall events occurred which were more intense than regular rainfall events. As a consequence, flooding occurred in most streets, which gave a good validation of data that was gathered during preparation. Three days of fieldwork are summarized in this appendix.

Monday September 3rd – Flooding

Due to intense rainfall for 24 hours, local flooding occurred in the streets of Galveston. The sewers are not able to transport this amount of water and there are no other buffers available in the city. The streets fulfil this function (see Figure 131).

Figure 131 Flooding in 56th street, seen from Broadway Av (Photo courtesy of authors)

The streets have a downward sloping profile to the sides. However, the quality of the road was found to be insufficient: cracks and holes are common and some potholes were a few feet deep. It is not easy to estimate the depth of each pool, which makes it dangerous for vehicles to drive through them. This is the reason the municipality closes the roads with barricades when they flood (see Figure 132).

Figure 132 Streets closed for traffic due to flooding. This is common for most streets in the city (Photo courtesy of authors)

These barriers are on every corner along Broadway Av and other main access roads. The city is divided in many neighborhoods and these are not on the same ground level. Downtown is lower than areas near the seawall. Also, Broadway Av is somewhat higher elevated than connecting streets. Further to the east, Broadway Av is less accessible due to its lower elevation. In the west at 61st street, 3 lanes are accessible, but near 45th street just 1 lane to the east is available for vehicles. Figure 133 and Figure 134 show flooding at 51st street, where the water depth reaches up to 0.6 m (2 ft.).

Figure 133 Flooding at the crossing of Broadway Av and 51st street (Photo courtesy of authors)

Figure 134 Flooding in 51st street (Photo courtesy of authors)

Properties are largely spared from flooding, due to their high elevation. Water is discharged primarily by drainage conduits, and when rainfall intensity becomes too large the streets function as a buffer.

Due to flooding, it was not possible to go further east over Broadway Av than near 45th street as all lanes were flooded from that point.

Wednesday September 5th – Beach & Seawall

The goal of this fieldwork trip was to conduct an exploratory study on the Galveston Seawall and basic coastal processes that occur here. An overview of the conditions on location are visible in Figure 135.

Figure 135 Galveston Beach, as seen from the Seawall (Photo courtesy of authors)

From the beach, ships are visible at open sea waiting for permission to enter the Bay and Houston Ship Channel, as visible in Figure 135. Also oil rigs are visible far at sea. Several breakwaters and piers divided the beach into long stretches. The most well-known pier is the Galveston Pleasure Pier at 25th Street (Figure 136).

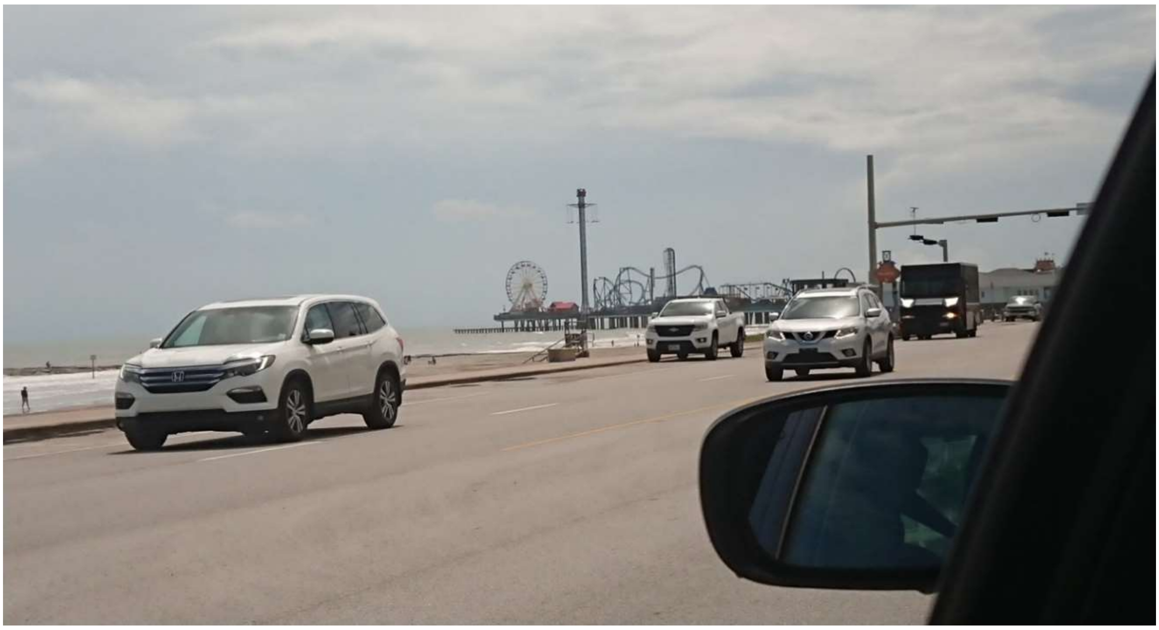


Figure 136 Galveston Pleasure Pier, as seen from the east on the seawall (Photo courtesy of authors)

The beach stretches along the entire seawall and further along the island to the west. Figure 137, Figure 138 and Figure 139 show the beach at the convention center. The seawall is visible as a steep, concrete slope. On the seawall the road is located.

Figure 137 Galveston Island Convention Center near 57th street (Photo courtesy of authors)

Figure 138 Galveston Beach to the northeast (Photo courtesy of authors)

Figure 139 Galveston Beach to the southwest (Photo courtesy of authors)

Several local bars are located on the piers (Figure 140). During hurricane Ike (2008), some of these bars were lifted by waves and storm surge and deposited on the island.

Figure 140 One of the piers along the beach (Photo courtesy of authors)

The Seawall is a curved concrete wall with large rocks in front (see Figure 141). The height of the wall is about 2.2 m (7.2 ft.) above upper beach level. Vegetation is also observed, which is a source for birds to gather food.

Figure 141 The Seawall (Photo courtesy of authors)

Figure 142 A panoramic view at the convention center (Photo courtesy of authors)

Thursday September 6th – Flooding

On Thursday September 6, 2018, Galveston Island was confronted with heavy rainfall. Figure 143 shows the sky was looking quite threatening that morning. The characteristics of the two distinctive kind of clouds that can be seen on the picture are different.

The dark front of clouds that can be seen in the top of Figure 143, have a low elevation. This is the type of clouds that can be associated with short intense rainfall events. During these events, rainfall is highly local and not spread over a large area. This results in concentrated precipitation and can therefore easily cause nuisance flooding problems, since the drainage capacity is not large enough to get rid of the rainwater.

The light grey colored clouds, which can be seen at the horizon of the picture shown in Figure 143, have different characteristics. These clouds are located on a higher elevation and usually hold little or no rainfall. Furthermore, the extent of rainfall events from these types of clouds is much larger than the range of the dark grey colored clouds.

Figure 143 Dark clouds hanging above Galveston, photo taken on Broadway (Photo courtesy of authors)

The picture shown in Figure 144 shows the view on the Galveston Bay from the northeast end of the Seawall Boulevard during the afternoon of September 6th. As can be concluded from the picture, a heavy rainfall event is taken place above the bay, while on land, it is raining less intensively. Therefore, a possible conclusion could be that the amount of precipitation is heavily influenced by open water bodies, such as the Galveston Bay as could be seen in Figure 144.

Figure 144 Intense rainfall above the Galveston Bay, photo taken on the northeast end of the Seawall Boulevard (Photo courtesy of authors)

Figure 145 shows the situation after the intense rainfall event of the day has ended. As can be concluded from the picture, 51st Street is now completely submerged. The drainage that is located there is simply not capable of taking that much water. The most important reason to explain this has to do with the tide. During high tide, Galveston Island has no possibilities to drain water on the island. This can only be done during low tide. Therefore, when the drainage system has filled itself completely with stormwater, it starts overflowing and flooding start to occur. However, when high tide is over and the water level in the Ship Channel is dropping, the island starts to drain.

Figure 145 After some time has passed, 51st Street is completely inundated (Photo courtesy of authors)

The area that was most hit by the nuisance flooding on September 6 was the northern side of the island, including Harborside as can be observed in Figure 146. The reason why the highest water levels on the streets can be found here can be found when having a look at the elevation of Galveston Island. This is a gradient with the highest level at the southern side (Seawall Boulevard) and goes down towards Harborside Dr, where it is on its lowest. So, all water that is collected on the streets will flow naturally towards Harborside Dr and starts accumulating there.

Figure 146 Flooding on Harborside Dr (Photo courtesy of authors)

Moreover, it was noticed that the few grassy patches in between impervious areas were unable to infiltrate stormwater runoff. The soil was locally saturated, which forced the water to run off into the drains. Figure 147 shows an image of such an occurrence.

Figure 147 Local saturation of the soil (Photo courtesy of authors)

C Residential Stakeholder Sessions

Introduction

As was described in Section 4.2.1 Residential Stakeholder Sessions, three residential stakeholder sessions were organized to gain more insight in flood issues in Galveston. The main findings for each session are summarized below.

All observations described in this Appendix represent those of residential stakeholders and not those of the authors.

General comments

During the focus meetings, residents gave multiple general comments related to flooding.

Inadequate infrastructure is the main cause of nuisance flooding. The drainage system is not able to drain the water to the bay and ocean because of two reasons:

1. The conduits are not built to manage large amounts of water over such a short time period;
2. The amount of water that can be discharged in the bay depends on the bay water level, so tidal elevation.

To compensate the lack of discharge capacity of the drainage system, streets have a temporary storage function in case of heavy rainfall. When the drainage system is able to discharge the water, flooding depth will decrease rapidly. However, the rate of discharge depends on the tidal elevation.

The comments that are most useful for the design process, are listed below.

- After Hurricane Ike (2008), Broadway Av has been elevated a couple of feet (1 ft. = 0.3 m) to avoid flooding of the main access road to the city. This road is an extension of Interstate 45, and thus important in case of evacuation. This has caused an increase of number of flooding events in the streets south of Broadway Av, as water that is flowing towards the harbor is now blocked;
- Most houses on the island have been built on stilts or on elevated parcels to mitigate damage from flooding. The streets in the city are lower than the ground floor of the houses;
- People secure their house against flooding by building on stilts and having insurance in case of damage. When flooding occurs, some people do evacuate.

Comments on ring levee of USACE

Since the 1960s USACE has developed strategies to reduce flooding due to storm surge around Galveston Island and in the Galveston Bay. Since the beginning one of the options has been the design of a ring levee to protect the city. However, the exact location of such a structure was never determined, except for the fact that the Seawall is part of this ring levee. According to several residents, a ring levee will have the following negative impacts on the city:

- A ring levee will block access and visibility to the bay and natural habitat. The ring levee would close off Offatts Bayou from the Galveston Bay, which prevents residents to sail to the Galveston Bay;
- Another issue is mobility. When evacuation is required, a levee will give hindrance between properties and roads;

- A ring levee will not solve flooding due to rainfall. Therefore, pumps are required. However, residents are not sure about the reliability of those pumps and are concerned about consequences if they fail.

There are also comments on the current ring levee designs by USACE:

- Stakeholder input is lacking. Residents and other parties are not involved in the process, while local knowledge is key information for the design process;
- Residents believe the City of Galveston has to pay for measures and not receive federal funding.

Areas of flooding

Session 1: GAIN

Areas that flood regularly are the historic urban core, the area around UTMB, the industrial plots north of Harborside Dr, the neighborhood east of English Bayou and the general area south of Broadway. Harborside Dr and parts of 51st Street and Broadway are important evacuation routes that flood regularly.

Session 2: WGIPOA

Frequent flooding of the wetlands on the bayside of Galveston Island degrades the ecosystem and reduces protection against wave action. Furthermore, the airport and surrounding areas flood regularly, as well as land between Termini-San Luis Pass Road and the Gulf of Mexico. A part of Termini-San Luis Pass Road near the end of the Seawall floods rapidly, making evacuation more difficult.

Session 3: Residents of Offatts Bayou and Teichman Road

Plots on Teichman Road generally have a low elevation, which makes them vulnerable to flooding. Furthermore, flooding on both sides of the Galveston Causeway occurs regularly. The neighborhood south-east of English Bayou floods often, mainly due to its low elevation. Important evacuation routes also flood regularly, such as Harborside Dr and 61st Street.

Protection not desired

Session 1: GAIN

Industrial plots north of Harborside Dr should not be included in a ring levee design. These parties have indicated not to be interested in protection by a levee, as this would impede their business. Furthermore, areas east of UTBM should not be protected as these are not part of the urban core. Finally, while protection for the Texas A&M Galveston campus would be accepted, further protection of Pelican Island is undesirable.

Session 2: WGIPOA

Hard protection measures such as concrete walls or levees are not desired on both the Gulf of Mexico side and bayside of Galveston Island.

Session 3: Residents of Offatts Bayou and Teichman Road

Most properties on Teichman Road and around Offatts Bayou have access to open water, which is one of the major reasons for residents to settle here. A fixed levee is not desired as this would undermine access to open water and would also block the view on the Bayou.

Protection desired

Session 1: GAIN

The urban core in between Harborside Dr and the Seawall should be properly connected against flooding, as the built environment is not adapted to inundation on the streets. Furthermore, raising the Seawall with multiple feet would improve protection against coastal flooding. Also, it is wanted to protect UTMB since flooding of their biolab is unwanted.

Session 2: WGIPOA

Natural protection systems on the Gulf of Mexico side are desired. Examples of so-called super dunes were received well. Remediation of wetlands on the bayside of Galveston Island is desired, as this would be a natural intervention to improve flood resilience.

Session 3: Residents of Offatts Bayou and Teichman Road

The urban core of the City of Galveston should be protected against floods. As Offatts Bayou needs to be closed off for proper protection of the city, a moveable gate is preferred. This gate would be open during normal circumstances. Furthermore, remediation of wetlands along the shores of Offatts Bayou would reduce wave impact.

Conclusions

The findings of the three stakeholders are summarized in Figure 9, Figure 10 and Figure 11.

According to the resident consulted, most people on the island are aware that they live in a flood prone area and accept this risk. The main reasons for residents to live on Galveston Island are the natural environment, life at the coast and local activities: fishery, boat rides and more. These are important tourist attractions. The people living in the City of Galveston highly value the natural environment, which cannot be found in the larger cities at the mainland. When measures negatively influence these values, people will leave. This underlines the importance of taking stakeholder input into account during the design phase.

D Systems & Stakeholders

Stakeholders

The explanation of stakeholders and their mission or activities are summarized in this section.

Political Stakeholders

Galveston City Council

The Galveston City Council is responsible for local planning, execution, and maintenance of public work in the city. They also manage and perform organizational and administrative tasks.

Texas State Government

The State Government of Texas is the government on state level. They have the jurisdiction to implement their own laws within the boundaries of the Federal Government.

Texas General Land Office

The Texas General Land Office is a department within the Texas State Government. They are responsible for managing land and natural resources.

Texas Commission on Environmental Quality

The Texas Commission on Environmental Quality is a department within the Texas State Government. Their mission is to protect and improve human health and natural resources.

Gulf Coast Community Protection & Recovery District

The Gulf Coast Community Protection & Recovery District is an organization that is addressing the risks of storm surge during hurricanes. It works closely with the Texas General land Office, however, it is not a governmental department.

Neighboring City Councils

Neighboring cities have influence on politics in the project. Plans and strategies that are designed will have impact on the cities around the City of Galveston, such as Bolivar Peninsula and Texas City.

Federal Government

The Federal Government (Washington DC) is the overall governmental administration that makes laws for all states. They set up boundaries in which state governments should act.

United States Army Corps of Engineers

The US Army Corps of engineers is responsible for the designing, building, and financing of infrastructure, such as roads, railroads, and flood defense structures. They are the counterpart of Rijkswaterstaat in the Netherlands.

United States Environmental Protection Agency

The US Environmental Protection Agency is an organization within the federal government. The agency is responsible for the protection of human health and the environment. They also assist with preparation and recovery for natural disasters, such as hurricanes.

Federal Emergency Management Agency

The Federal Emergency Management Agency is responsible for coordination of assistance when a disaster occurs. The agency assists when local authorities lack the resources to deal with emergencies. The Governor of the State has to initiate ‘a State of Emergency’ in order to receive assistance.

Economical Stakeholders

Local & National Companies

Local Companies are active in the City of Galveston. Examples are grocery stores, bakeries, and maintenance shops. Also fishery is a local business and provides many jobs.

National and International Companies have other stakes and should be considered separately. Examples are the businesses in the harbor, such as the oil and drilling companies and ADM Grain, as well as the cruise terminal.

Port of Galveston

The Port of Galveston is owned by the municipality and is managed by the Board of Trustees of the Galveston Wharves. The Port is independent and does not receive funding. The Port of Galveston consists of the Galveston Ship Channel, the southern embankment of Pelican Island, and the northern embankment of the Island of Galveston. The Port is able to handle various types of cargo including dry bulk, RORO, and liquid bulk. Since 2017, the cruise terminal is the 4th busiest terminal in North America.

City & Port of Houston

The City of Houston is the first large city near Galveston and the 4th largest city of the United States. The Port of Houston is much larger than the Port of Galveston, and they have strong economical bonds.

Railroad Companies

The two largest railroad companies, BNSF and Union Pacific, transport goods between the Port of Galveston and the mainland. Transportation of petrochemicals, grain and parts of wind turbines are most common.

Utilities

Utilities are the companies that supply and maintain the water supply system, power supply system and other municipal systems in the city.

Construction Firms

Construction companies build houses, offices, and parts of infrastructure.

Galveston Scholes Airport

This airport used to be a military base. Nowadays it is used for private flights and recreational activities, such as skydiving. The airport is useful for evacuation during natural disasters.

Pleasure Pier Galveston

At 25th street and the seawall, the Pleasure Pier is located with lots of attractions. It is partly constructed on the beach and above the sea, and it is highly valued by the city and tourists.

Moody Gardens Theme Park

This theme park is located near the airport. It attracts thousands of people every year. It is owned by the Moody Foundation, which is a large institution on the island for over a century.

Residential Stakeholders

Three associations joined interactive sessions in which they could share their experience of flooding on Galveston Island. The outcomes of these sessions can be found in Appendix C Residential Stakeholder Sessions.

Galveston Association of Island Neighborhoods

The Galveston Association of Island Neighborhoods represents the residents of Downtown Galveston. This roughly is the area located east from 51st street. This part of the city is flooded quickly as it is the area lying lowest.

West Galveston Island Property Owners Association

The West Galveston Island Property Owners Association represents the residents on the western part of the island, from the airport onwards. This part of the island is not protected by the seawall, nor by any dunes. Flooding occurs easily as ground level is less than 1 m (3 ft.) above sea level.

Offatts Bayou, Teichman Rd Residents

The residents of Offatts Bayou and Teichman Rd are located in the northwestern part of the City of Galveston, near the Interstate 45. This area is sensitive to flooding as it is surrounded by water and barely above sea level. The area is located along the bay, but tide and surge are changing the water level continuously.

Educational Stakeholders

Texas A&M University at Galveston

Texas A&M University is a large public university with a satellite campus at Pelican Island. The Center for Texas Beaches & Shores is part of the university. This faculty performs research to coastal processes and management and has a large interest in coastal developments at Galveston Island.

University of Texas for the Medical Branch

This institution has both a hospital and a research center. It is the largest hospital in the City of Galveston and surrounding cities. The research center is specialized to worldwide diseases and has a biolab containing many samples of diseases.

Galveston College

Galveston College is an institution with a variety of disciplines, such as Engineering and Health Sciences. It is located in the City of Galveston.

Natural Stakeholders

Nature Conservancy

The Nature conservancy is primarily addressing the importance of preserving habitat in the Galveston Bay, protecting freshwater basins, and improve health of the Gulf of Mexico.

Galveston Bay Foundation

The Galveston Bay Foundation strives to improve the biodiversity and health of the Galveston Bay.

Gulf Coast Bird Observatory

The Gulf Coast Bird Observatory focuses on creating a healthy ecosystem with abundant space for birds to survive and thrive around the Gulf of Mexico and beyond.

Audubon Houston/Galveston

The Audubon is an organization that has multiple locations, including a center in Galveston. It focuses on the conservation of bird species that live in the region.

Seawolf Park

Seawolf Park is a warfare center at the east of Pelican Island. Its main attraction is the USS Seawolf, a military vessel from World War II.

Individual Interests

The individual interests of the stakeholders are listed in the table below.

Table 60 Individual interests

	Stakeholder	Interest
POL	**Galveston City Council**	Managing and improving well-being of and local development by residents and businesses, creating safe areas and protecting citizens from hazards.
	Texas State Government	Being responsible for implementing and execution of laws on state level and managing governmental cases on state level.
	TX General Land Office	Managing and protecting land use an natural resources Invest profits in primary education.
	Texas Commission on Environmental Quality	Perform research to improve environmental quality of air, land and water in Texas.

	Gulf Coast Community Protection & Recovery District	Improve safety against natural hazards by studying storm surge and impact on coastlines.
	Neighboring City Councils	Measures implemented for the Galveston region should not harm the regions of other cities.
	Federal Government	Responsible for implementing and execution of laws for all states and managing governmental cases.
	US Army Corps of Engineers	Create infrastructure that improves current transportation networks and coastline defenses.
	US Environmental Protection Agency	Perform research to improve environmental quality of air, land and water in the United States.
	Federal Emergency Management Agency	Properly operate prior to, during and after natural hazards and assist victims where possible.
ECO	**Local Companies**	Making profit by selling goods and services.
	(Inter)National Companies	Making profit by selling goods and services, expand businesses, and strengthen market positions.
	Port of Galveston	Making profit by distributing goods and services and cooperating with other ports to gain a better position in North America.
	City & Port of Galveston	Making profit by distributing goods and services and cooperating with other ports to gain a better position in North America.
	Railroad Companies	Making profit by transporting goods between the Port of Galveston and the mainland.
	Utilities	Providing services by managing water and power supply systems, as well as drainage and sewerage systems.
	Construction Firms	Making profit by building infrastructure.
	Galveston Scholes Airport	Providing services to residents and businesses to make profit. Be able to assist during evacuation and in post-hurricane phase.
	Pleasure Pier Galveston	Entertaining people and making profit to reinvest in the pier.
	Moody Gardens Theme Park	Entertaining people and making profit to reinvest in the theme park.
RES	**Galveston Association of Island Neighborhoods**	Improve safety against flooding without impeding personal values, such as visibility and accessibility.
	West Galveston Island Property Owners Association	Improve safety against flooding without impeding personal values, such as visibility and accessibility.
	Offatts Bayou, Teichman Rd	Improve safety against flooding without impeding personal values, such as visibility and accessibility.
EDU	**Texas A&M University Galveston**	Enlarging the body of knowledge on coastal processes and development and spreading current knowledge.
	University of Texas of the Medical Branch	Taking care of people in the hospital (also a residential interest). Doing research to health sciences to improve social healthiness.
	Galveston College	Teaching people in variety of disciplines.
NAT	**Nature Conservancy**	Preparing plans and proposals to improve the natural habitat in the Galveston Bay region.
	Galveston Bay Foundation	Preparing plans and ideas to improve biodiversity in the Galveston Bay.
	Gulf Coast Bird Observatory	Protecting birds and their habitats around the Gulf of Mexico.
	Audubon Galveston	Taking care of and preserve bird species in the region.
	Seawolf Park	Educating people about Seawolf Park, its mission and history.

Abbreviations Systems & Stakeholders

For simplicity in tables and figures, abbreviations of systems and stakeholders are used. They have been listed below. The abbreviations are also found in the List of Abbreviations.

Table 61 Abbreviations of systems

Subsystem		**Subsystem**	
SAF	Safety System	**WSU**	Water Supply System
CPS	Coastal Protection System	**SEW**	Sewerage System
DRA	Drainage System	**REC**	Recreational System
POL	Political System	**ROA**	Road System
NAT	Natural System	**RRO**	Railroad System
PSU	Power Supply System	**WWA**	Waterway System

Table 62 Abbreviations of stakeholders

Stakeholder		**Stakeholder**	
GALV	Galveston City Council	**NCC**	Neighboring City Councils
TSG	Texas State Government	**FED**	Federal Government
GLO	Texas General Land Office	**USACE**	US Army Corps of Engineers
TCEQ	Texas Commission on Environmental Quality	**EPA**	US Environmental Protection Agency
GCC	Gulf Coast Community Protection & Recovery District	**FEMA**	Federal Emergency Management Agency
LCOM	Local Companies	**NCOM**	(Inter)National Companies
PORT	Port of Galveston	**HOU**	City & Port of Houston
RAIL	Railroad Companies	**AIRP**	Galveston Airport
UTI	Utilities	**PIER**	Pleasure Pier Galveston
FIRM	Construction Firms	**MOOD**	Moody Gardens Theme Park
GAIN	Galveston Association of Island Neighborhoods	**TAMU**	Texas A&M University at Galveston
WGI	West Galveston Island Property Owners Association	**UTMB**	University of Texas for the Medical Branch
OFFA	Offatts Bayou, Teichman Road	**COL**	Galveston College
NACO	Nature Conservancy	**GBF**	Galveston Bay Foundation
GCBO	Gulf Coast Bird Observatory	**AUDU**	Audubon Galveston
SEAW	Seawolf Park		

Stakeholder Involvement in Subsystems

Table 63 Stakeholder involvement in subsystems

	SAF	CPS	DRA	POL	NAT	PSU	WSU	SEW	REC	ROA	RRO	WWA
GALV	V	V	V	V	V	V	V	V	V			
TSG		V		V		V	V			V	V	V
GLO				V	V							
TCEQ				V	V							
GCC		V		V	V							V
NCC				V	V							
FED	V			V								
USACE	V	V		V								
EPA				V	V							
FEMA	V	V		V								
LCOM	V											
NCOM	V	V								V	V	V
PORT	V	V		V								
HOU	V	V		V								
RAIL											V	
UTI			V			V	V	V				
FIRM												
AIRP	V		V						V			
PIER		V							V			
MOOD									V			
GAIN	V	V	V	V					V			
WGIP	V	V	V	V					V			
OFFA	V	V	V	V					V			
TAMU		V	V		V							
UTMB	V											
COL		V	V									
NACO		V	V		V							
GBF		V			V							
GCBO					V							
AUDU					V				V			
SEAW					V				V			

Power VS Interest Diagram

The Power VS Interest diagram is shown in Section 4.2.5 System Overview. For each stakeholder, their position in the diagram is explained.

Manage Closely

- Galveston City Council
  The city council creates and approves plans to improve flood resilience, which makes them vital.
- Utilities
  Utilities are responsible for maintenance of power and water supply, and drainage and sewer systems. Any plans to improve flood resilience will affect these systems.

- Port of Galveston
  The Port has a strong position in the city, as it delivers both jobs and income. Losing port activities is harmful to people and the city.
- City & Port of Houston
  Houston is the largest city near Galveston and has strong economical bonds with the Port of Galveston.
- US Army Corps of Engineers
  The USACE designs infrastructure and builds it. These designs must fit in the plans, which makes them an important stakeholder.
- Galveston Association of Island Neighborhoods
  One of the residents associations that live in the city. Residents have a say in planning and design. The GAIN is located Downtown, which is one of the most vulnerable spots (see Figure 19).
- Offatts Bayou, Teichman Rd
  The second group of residents that live in a vulnerable part of the city.

Keep Satisfied

- Federal Government
  The federal government sets up the boundaries in which local governments can operate. It is not common to cross those boundaries.
- Texas State Government
  The Texas Government has to approve plans and designs that are beyond the boundaries of the City of Galveston. They must be kept satisfied in order to use those plans.
- TX General Land Office
  The General Land Office manages parts of land, also on Galveston Island.
- Federal Emergency Management Agency
  FEMA is responsible for financially supporting to states that suffered from disasters. Improving flood resilience will have an effect on the budgets of FEMA.
- TX Commission on Environmental Quality
  The TCEQ aims to maintain environmental quality on the island. Plans of the city council should not harm this.
- Railroad Companies
  The railroad is the most important connection to the mainland for the Port. Railroad companies want to make profit and have a strong position in the market.

Keep Informed

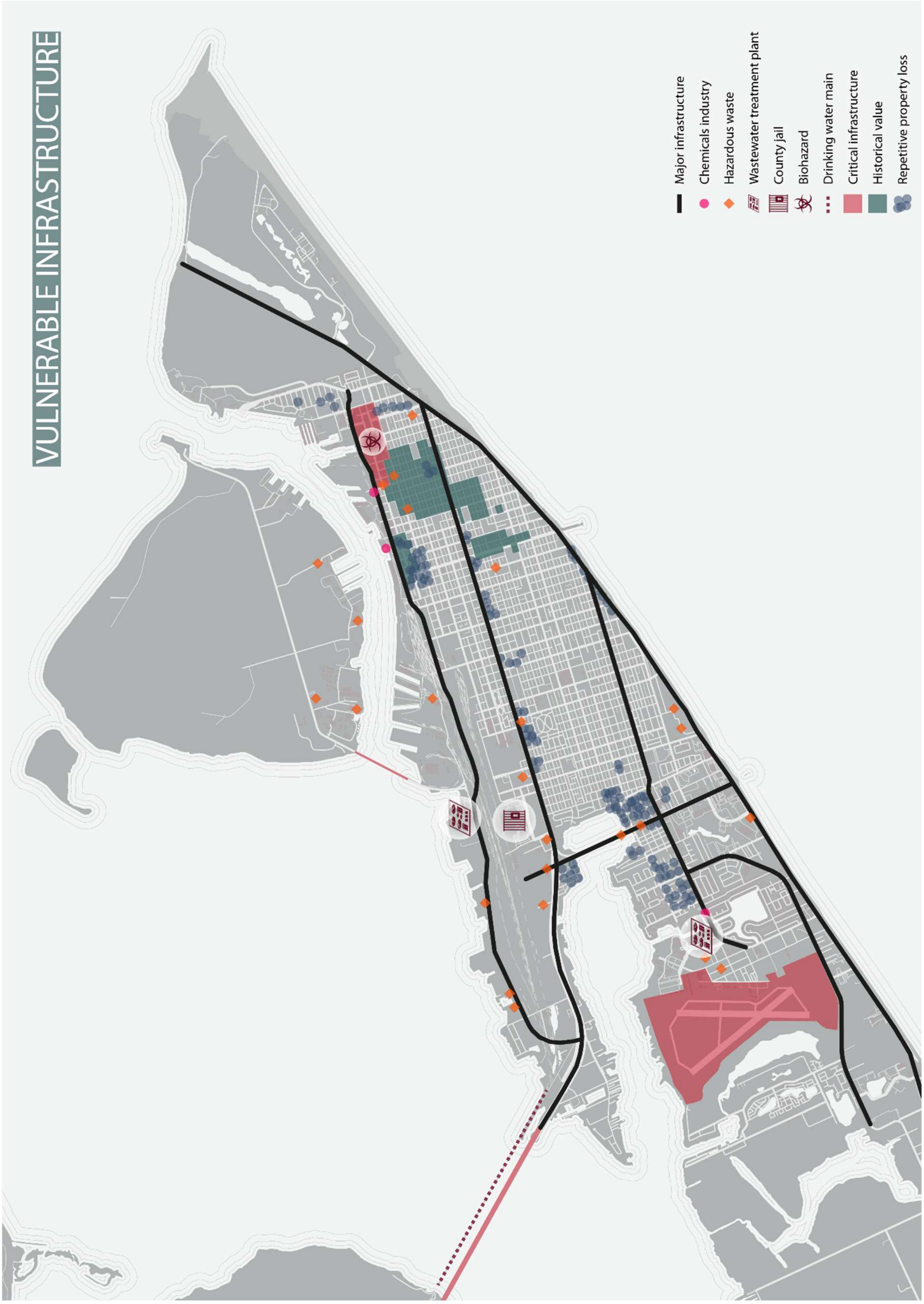
- Texas A&M University
  TAMUG is highly interested in coastal processes and development. They must be informed to be able to extend their knowledge and do more research.
- University of Texas for the Medical Branch
  The UTMB is the largest employer of the island. It is both a hospital and a research center with highly valued activities. They should be informed about any plans and designs.
- National/International Companies
  Companies are dependent on customers on the island, as well as connections to the mainland. Designs that will affect these groups will affect the livelihood companies to continue their businesses.
- Gulf Coast Community Protection & Recovery District
  The GCCPRD is supporting the state government with doing research on storm surge and protection measures. They should be informed about the progress of the city council

- Local Companies
  Local companies are dependent on customers on the island. Designs that will affect these groups will affect the livelihood of companies to continue their businesses.
- Galveston Bay Foundation
  The Galveston Bay Foundation is improving the environmental quality of the bay and should therefore be informed.

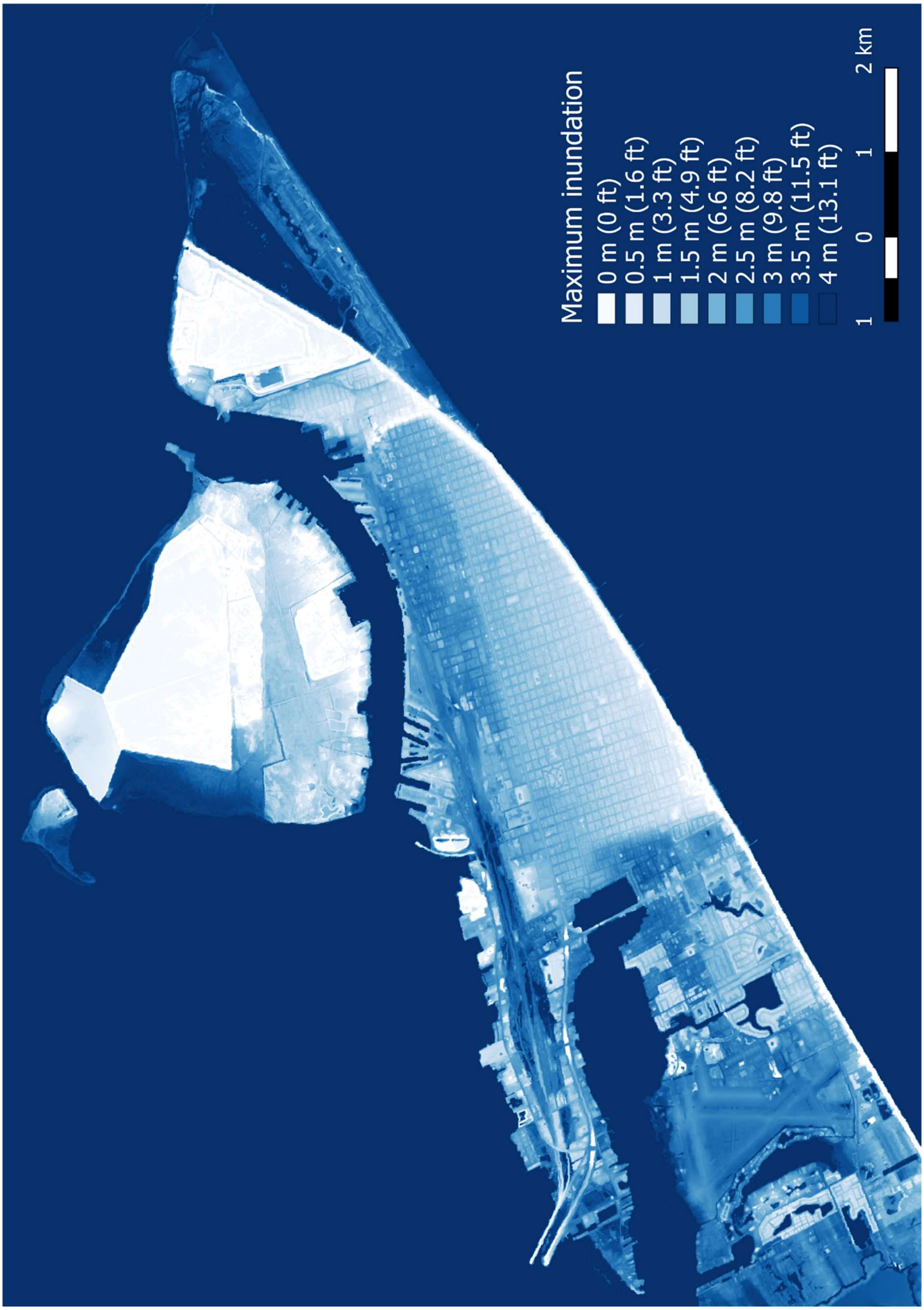
Monitor

- US Environmental Protection Agency
  The US EPA performs research to environmental quality for all states and therefore has little influence on local level.
- Neighboring City Councils
  Neighboring cities should be monitored, as they do not have large influence.
- Galveston College
  Galveston College offers employment, but does not play a large role in the project.
- West Galveston Island Property Owners Association
  The WGIPOA is the third residents association, but is located on the west end of the island. This area falls outside the scope of the project and is therefore considered to be less important for measures in the city.
- Moody Gardens Theme Park
  Moody Gardens may be interested but has no large influence on the project.
- Nature Conservancy
  The Conservancy aims to protect natural environment, but has little power.
- Construction Firms
  The construction firms do not have power to influence the project.
- Pleasure Pier Galveston
  The Pleasure Pier should be considered when designing along the seawall, but monitoring is sufficient.
- Galveston Scholes Airport
  The airport is interested in the project, as it is located on the edge of previous designs, but has little influence on the project.
- Gulf Coast Bird Observatory
  The GCBO has little influence on and interest in the project.
- Audubon Galveston
  The Audubon has little influence on and interest in the project.
- Seawolf Park
  Seawolf Park has little influence on and interest in the project.

E.1 Vulnerability Map



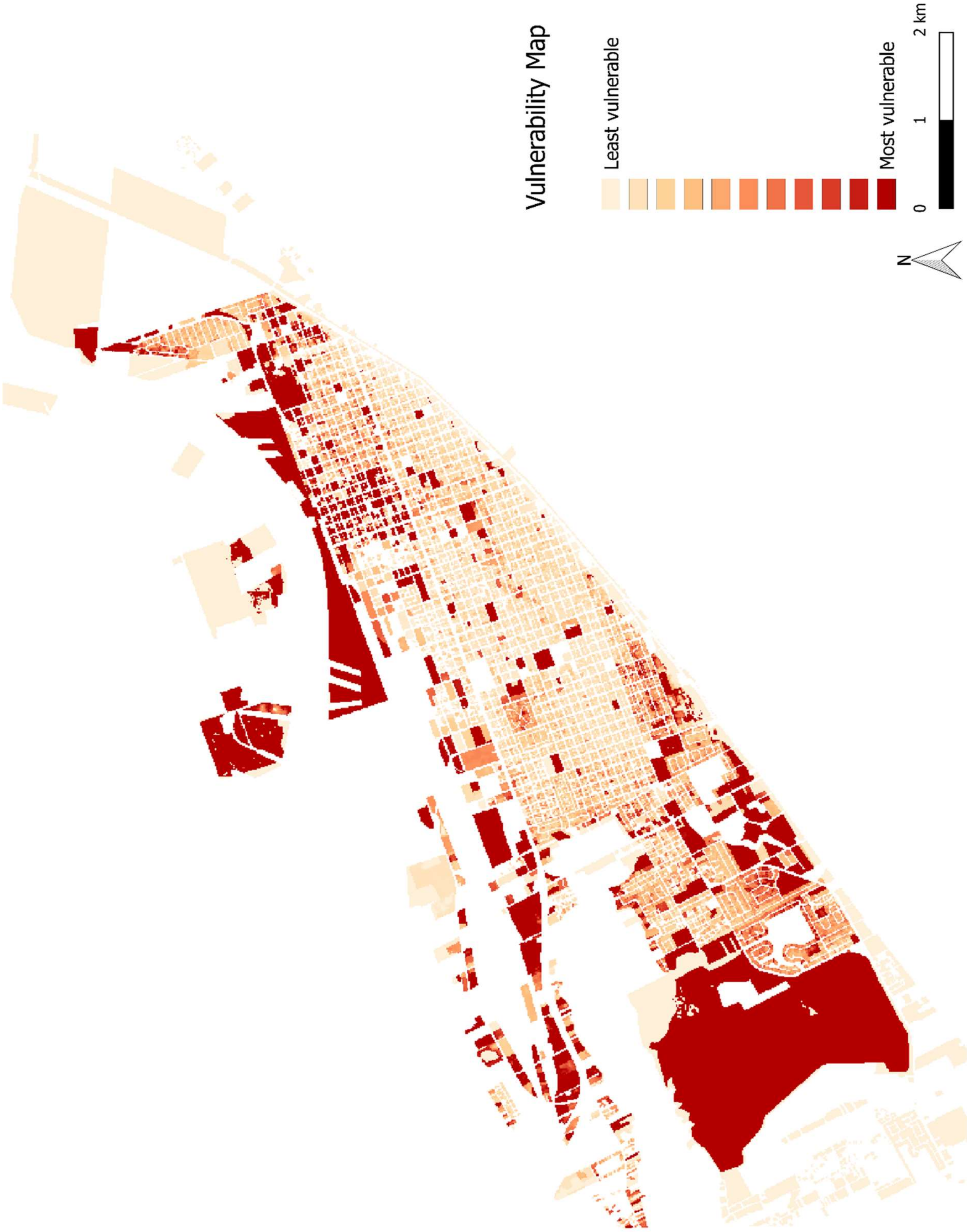
E.2 Hazard Map



E.3 Risk Map


Risk Map
Damage ($)
0
1300000
2600000
3900000
5200000
6500000
7800000
9000000
1e+07

E.4 Hotspot Map



F Vulnerable Objects

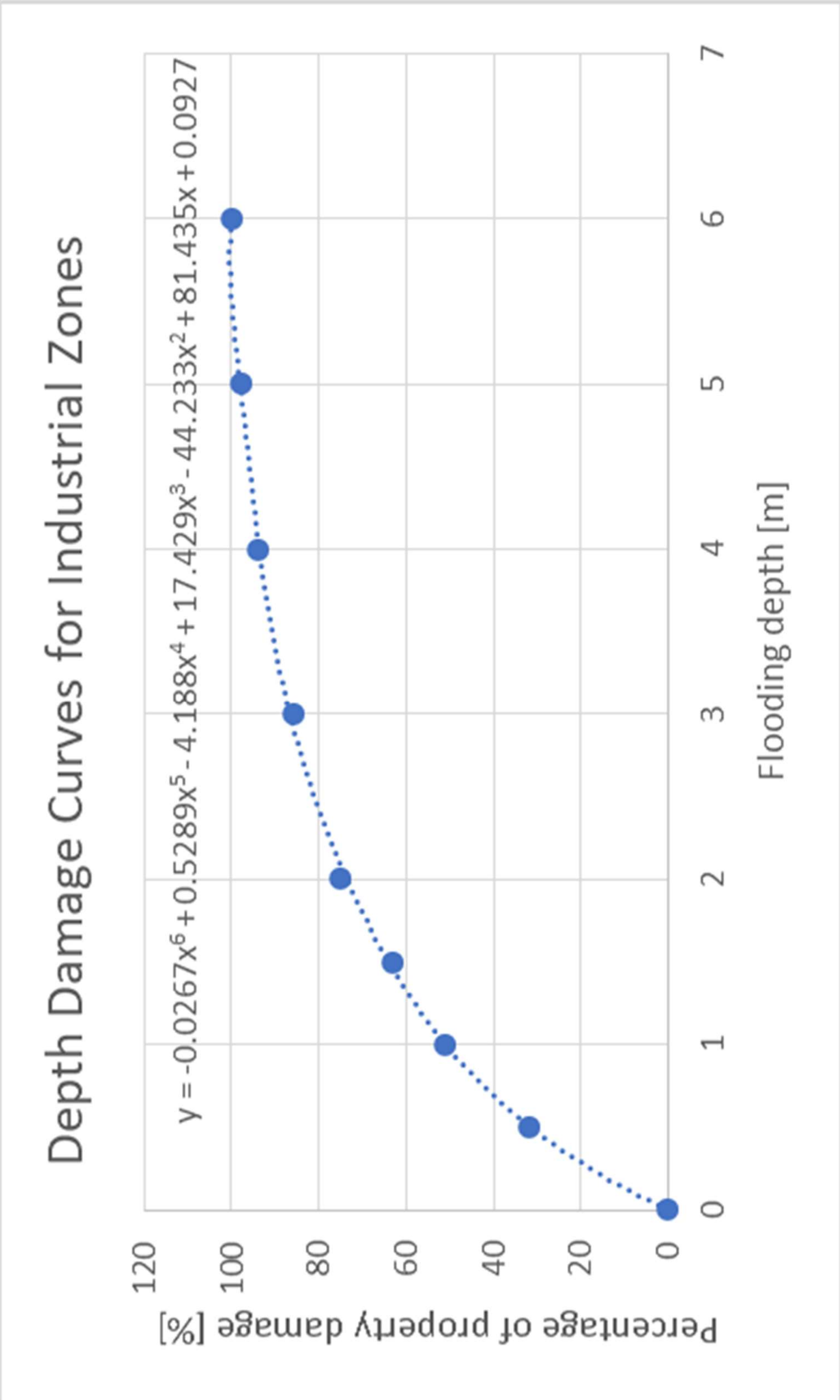
Objects, groups, networks	Water safety
Mobility	
Main roads	•
Neighborhood (access roads)	•
Tunnels and underpasses	•
Waterways	
Subway	
Railways	•
Stations	
Train-emplacement / transfer stations	•
Utilities	
Drinking water extraction points	
Drinking water reservoirs	
Drinking water distribution network	•
Power plants	
Transformer / substations	•
District distribution stations	
Gas distribution and measurement stations	
Gas distribution network	•
Telephone - transmission masts (+ power supply)	
Telephone / internet- power stations and distribution boxes	•
Telephone / internet cables	•
Emergency power plants and network	
CAI & Fiber optic panels and distribution boxes	•
CAI & Fiber optic cables / internet	
District heating plant	
Distribution stations district heating	
Landfill	•
Objects	
Police stations	•
Fire stations	•
Hospitals / clinics	•
Production centers and storage serums and medicines	•
City halls	•
Water board houses (crisis centers)	
Radio (disasters) transmitters	
Barracks and other military objects	•
Crisis centers / alarm and coordination points	
Storage of food and emergency provisions	
Parking cellars / garages	•
IT centers (server hubs)	
Navigation posts shipping	
Electronic payment transactions center	
Ground, pumps	
Sewage treatment plants and sewage pumping stations	•
Museums and monuments	•
Factories and storage of hazardous substances	•
nuclear substances (also radiotherapy)	
storage and transhipment of explosive substances, LPG, fuel	
Waste processing companies	
Companies working with hazardous substances	•
Vulnerable groups	
Physically and mentally handicapped	•
Senior citizens	•
Sick, nursing and care homes	•
Prisoners	•
Children, pregnant women	•
Zoo	
Pets (shelter for dogs and cats)	

G Static Parameters

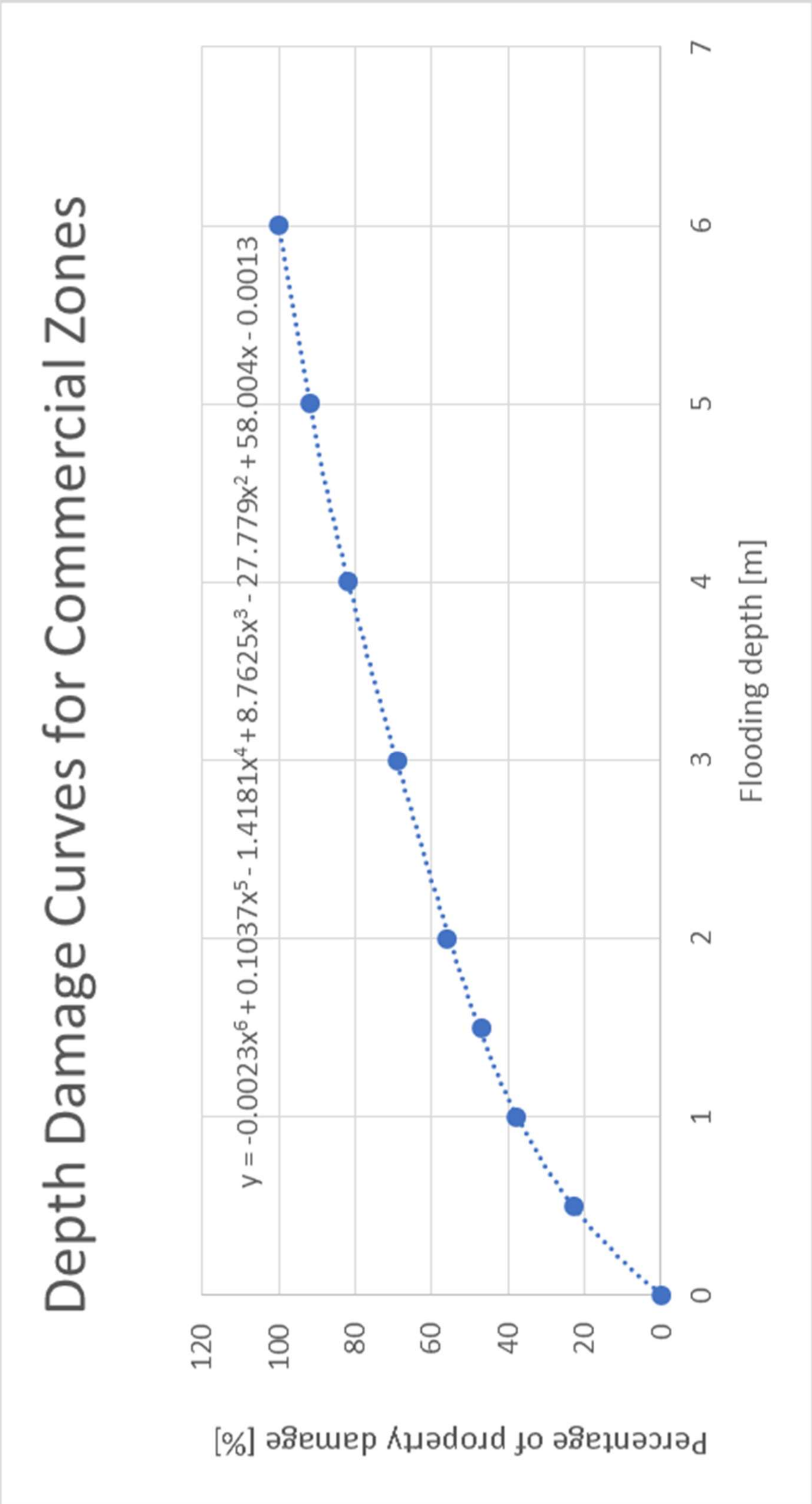
Total Area	31968751	m2
Land use fraction		[-]
Paved roofs	**31**	[%]
part of buildling above GW	75	[%]
part disconnected from sewer	20	[%]
Closed paved	**22**	[%]
part disconnected from sewer	70	[%]
Open paved	**20**	[%]
part disconnected from sewer	80	[%]
Unpaved	**26**	[%]
Open water	**1**	[%]
part of OW above GW	80	[%]
Sewer system		[-]
Storm Water Draiange System	100	[%]
Combined sewer system (MSS)	0	[%]
Design standard of sewer system		
Design rainfall intensity of sewer system (above which sewer overflow on the street occurs)	49.53	mm/hr
Design rainfall intensity of sewer system (above which combined sewer overflow to the open water occurs)	0	mm/hr
Target open water level	0	m-SL
Soil type	10	
Crop type	1	
Groundwater information		
drainage resistance (from shallow GW to open water) (w)	64	d
initial GWL	0	m-SL
Seepage from shallow GW to deep GW		
Constant downward flux Qs (negative-upward)	0	mm/d

Interception storage capacity on the surface		depth
Paved roof	1.6	mm
Closed paved	1.6	mm
Open paved	1.6	mm
Unpaved	20	mm
Open water	X*1000	mm
Infiltration capacity		
Open paved	1	mm/d
Unpaved	48	mm/d
Storage capacity in sewer system		
SWDS	2	mm
MSS	9	mm

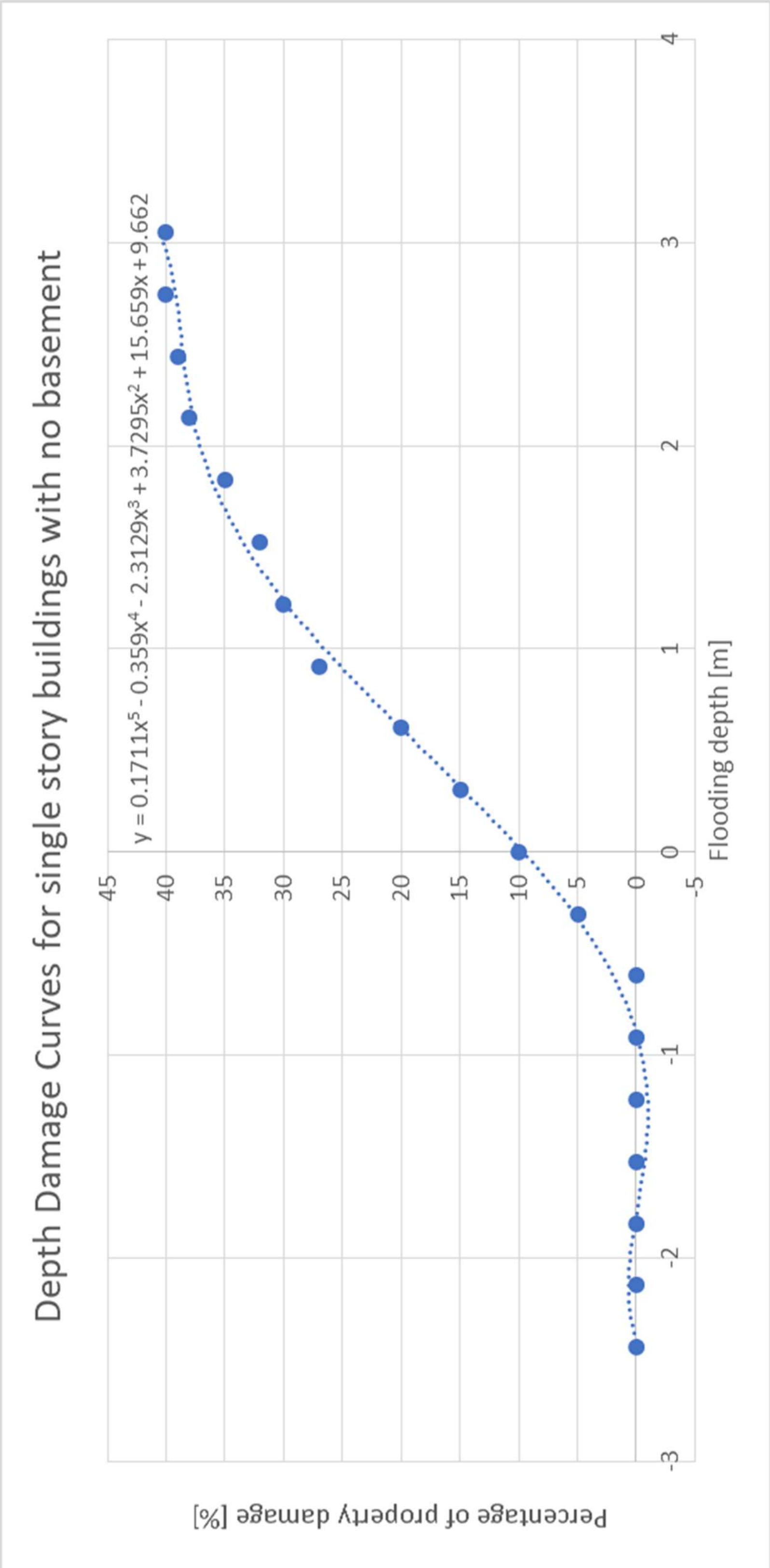
H.1 Depth-Damage Curve for Industrial Zones



H.2 Depth-Damage Curve for Commercial Zones



H.3 Depth-Damage Curve for Single Story Buildings



H.4 Depth-Damage Curve for Multiple Story Buildings