Multidisciplinary assessment of engineered dunes
West End, Galveston Island, Texas

L. Andringa
T.A. Eijkelkamp
T.T. Grolleman
O.A. Ophof
D.A.L. Schouten
X.P. Szadkowski

Multidisciplinary assessment of engineered dunes

West End, Galveston Island, Texas

by

L. Andringa
T.A. Eijkelkamp
T.T. Grolleman
O.A. Ophof
D.A.L. Schouten
X.P. Szadkowski

Student numbers:	L. Andringa	4454952
	T.A. Eijkelkamp	4354125
	T.T. Grolleman	4366484
	O.A. Ophof	4289250
	D.A.L. Schouten	4373650
	X.P. Szadkowski	4620836

Project duration:	February 10th, 2020 – April 10th, 2020	
Supervisors:	Dr. ir. M.G.C. Bosch-Rekveldt,	TU Delft, Construction Management Engineering
	Dr. B.L.M Kothuis,	TU Delft, Supervisor Texas projects
	Dr. E. Mostert,	TU Delft, Water Management
	Dr. ir. S. De Vries,	TU Delft, Hydraulic Engineering

An electronic version of this report is available at `http://repository.tudelft.nl/`.

Preface

Before you lies the report "Multidisciplinary assessment of engineered dunes for West End, Galveston Island, Texas". The basis of this report is a multicriteria analysis on engineered dunes that have been proposed by both United States Army Corps of Engineers (USACE) employees as well as by two TU Delft academics. The criteria upon which the alternatives were assessed in the multicriteria analysis reflect six different Master programs, at the Civil Engineering and Geo-sciences faculty, that our research team represents. It has been written to fulfill the requirements of a multidisciplinary project (MDP) at the TU Delft. We were engaged in researching and writing this report from February to April 2020.

The project was undertaken at the request of the Texas A&M University Galveston campus, where we had the privilege to be stationed in Spring 2020. The research was challenging, but our joint effort, extensive collaboration and communication has allowed us to answer the questions we identified. Fortunately, Dr. W.J. Merrell, Dr. S. Brody, Dr. J. Figlus, Dr. Y. Lee, C. Coffman and S. Parker, were always available on Galveston Campus and willing to answer our queries.

We hope you enjoy reading this report.

L. Andringa
T.A. Eijkelkamp
T.T. Grolleman
O.A. Ophof
D.A.L. Schouten
X.P. Szadkowski

Delft, April 2020

Abstract

The United States Army Corps of Engineers (USACE) is scheduled to present their solution for a storm surge barrier on Galveston Island in 2021 to congress for approval. A solution for an engineered dune system on the Galveston Island West End has been proposed, but storm surge models have shown that protection from this engineered dune only goes so far, moreover the search for a proper alternative that fulfills technical requirements and social political influences have proven to be challenging. This study aims to assess different dune alternatives, proposed in different reports, with a range of multidisciplinary criteria. The assessment of dune alternatives will also result in guidelines that should be considered for design, maintenance and governance aspects for an engineered dune barrier on Galveston Island. Using a multidisciplinary approach for the evaluation of the different dune alternatives, the following research question was formulated: To what extent do the various dune alternatives fit the requirements for a land barrier at the West End of Galveston Island, looking at both technical and sociopolitical aspects? In this context, technical requirements are defined as the storm surge- and rainfall coping capacities of the dune, i.e. against what kind of storm is the dune resistant. Social political influences are a combination of the perception by local residents that are directly influenced by the construction of a dune system, governmental forms of collaboration, and in provide an analysis of the maintainability of the dune alternatives using the storm surge capacities.

The different dune alternatives that have been assessed consist of the dune system proposed by the USACE and GLO (2018), the big dune system proposed by Galvez (2019) and the hybrid dune system as proposed by Muller (2017) and will hereafter be called alternative 1, 2 and 3 respectively. In this report a fourth alternative was introduced which is based on the hybrid dune system by Muller (2017) and consists of a clay core instead of a concrete core. Alternative 4 was chosen in order to simulate the difference between a concrete core and a clay core. Based on XBeach calculations, the storm surge coping capability of each dune was determined by projecting 10 year-, 50 year- and 100 year storms onto the dune alternatives. ArcGIS maps from the Galveston Island allowed for projection of flow patterns on the island in order to determine the rainfall coping capacity. An evaluation of sociopolitical aspects was based on a review of the literature on dune systems, forms of collaboration between governmental and private entities, and interviews with various respondents consisting of private individuals and companies, as well as governmental agencies involved in the process. Analysis of the various dune alternatives, based on multidisciplinary criteria, demonstrated that alternative 1 is completely flattened in 50 year storm events, whereas alternatives 2, 3 and 4 show a good storm surge capacity. All alternatives aggravate the current rainfall capacity at Galveston Island West End, because each dune system poses an obstruction that is not there currently. Alternatives 2 through 4 show a good enough storm resilience, requiring post-storm recovery maintenance while still providing a reduced but fair storm surge capacity. The sociopolitical results indicate that Galveston Island West End residents wishes are only safeguarded for alternative 1.

On this basis, the main recommendations are to perform tests upon the dune system alternatives regarding storm events occurring in succession, which is not unusual in the Gulf of Mexico. A combination of alongshore erosion rates from the Galveston Island and the effect of dune vegetation should be determined for the dune alternatives, since these aspects were not considered in this research. Further research is needed to identify the combined effects of rainfall and storm surge in order to get insights into the performances of a certain alternatives. Furthermore, the exact role including the desired storm surge capability should be well defined in order to determine which stakeholder wishes and influences are to be fully considered for the dune system design.

Contents

List of Figures

List of Tables

Acronyms

BEG   Bureau of Economic Geology
BFE   Base Flood Elevation

CBRA   Coastal Barrier Resources Act
CPRA   Coastal Protection and Restoration Authority

DDF   Depth-Duration-Frequency
DEMs   Digital Elevation Models

EEHDA   East End Historical District Association

FEMA   Federal Emergency Management Agency
FIRM   Flood Insurance Rate Map

GAIN   Galveston Association of Island Neighborhoods
GCCPRD   Gulf Coast Community Protection & Recovery District
GFDC   Galveston Flood Defense Coalition
GLO   General Land Office

H-GAC   Houston – Galveston Area Council's

IDF   Intensity-Duration-Frequency

LiDAR   Light Detection And Ranging

MAT   Mitigation Assessment Team
MCA   multicriteria analysis
MRM   Modified Rational Method
MSL   Mean Sea Level

NFIP   National Flood Insurance Program
NOAA   National Oceanic and Atmospheric Administration

PPP   Public Private Partnership

RFMC   Regional Flood Management Council
RLSR   relative sea level rise
RSLR   Relative Sea Level Rise
RWS   Rijkswaterstaat

SFHA   Special Flood Hazard Areas

TAMUG   Texas A&M University at Galveston
TAS   Texas Accessibility Standards
TCEQ   Texas Commission on Environmental Quality
TDLR   Texas Department of Licensing and Regulating
TFMA   Texas Floodplain Management Association
TU Delft   Delft University of Technology

USA   United States of America
USACE   United States Army Corps of Engineers
USEPA   US Environmental Protection Agency
UTMB   University of Texas for the Medical Branch

WGIPOA   West Galveston Island Property Owners Association
WWAO   Werkwijzer Aanleg Onderhoud

Conversion table of units

	SI - unit	Conversion to United state customary unit
Length	cm	$0.394in$
	m	$1.094yd$
	km	$0.621mi$
Area	cm^2	$0.155in^2$
	m^2	$1.196yd^2$
	km^2	$0.386mi^2$
Volume	cm^3	$0.061in^3$
	m^3	$1.309yd^3$
	$Liters$	$0.264\,Gallon$
Pressure	kPa	$0.145psi$

I

Introduction and analysis

1
Introduction

The coasts of the Gulf of Mexico have been ravaged by hurricanes for a long time. In Texas, the Island of Galveston (Figure 1.1) acts as a natural barrier against these brute forces of nature, providing cover for the Galveston Bay area, home to the largest petrochemical complex of the United States of America (USA) (Dyck, 2017). During Hurricane Ike in 2008 it became evident that the coping mechanisms against hurricanes and the storm surges that accompany them were insufficient. However, no additional measures have been taken. Plans have been created by professors and engineers to mitigate hurricane consequences, of whom Dr. W.J. Merrell, professor at Texas A&M University at Galveston (TAMUG), has been pushing to create the coastal spine, a combination of flood protection measures for the Galveston Bay Area and the barrier island itself. Several multidisciplinary studies have been conducted on varying aspects of this barrier system, and the United States Army Corps of Engineers (USACE) has proposed a tripartite plan to fulfill this need (USACE and GLO, 2018). Part of this proposal is a land barrier in the form of a dune system ranging from the City of Galveston up to the West End of the island, see Figure 1.1.

At the moment, the plan is in a time consuming preliminary design stage, open for response by the public. Previous researchers on the proposed dune system mainly focused on the protection against storm surge, among whom are Muller et al. (2018) and Galvez (2019). Although this is the primary function of the barrier, its protective value is only used occasionally. Other processes such as rainfall, maintainability and public opinion should all be taken into account in order to come up with an inclusive, acceptable, and feasible design, keeping in mind that protecting the underlying land should be its main function. Therefore a more integral approach is beneficial. In addition, a clear evaluation of the different available alternatives is absent.
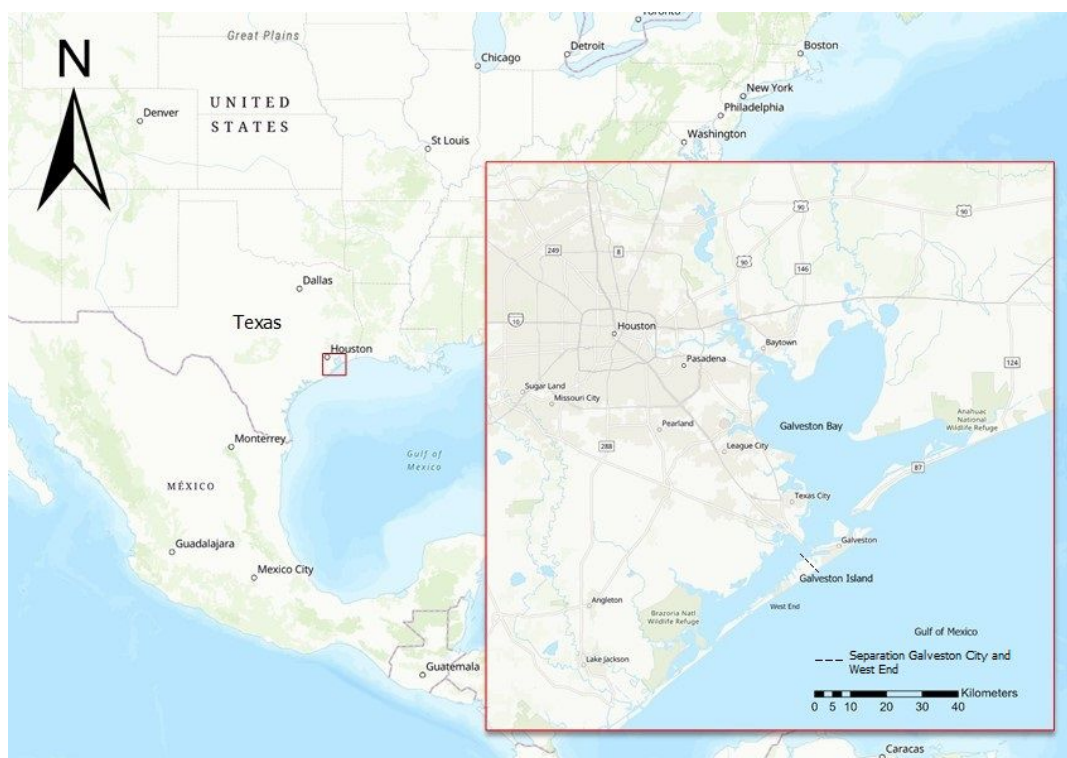
Figure 1.1: Galveston Island in the scope of the Gulf of Mexico.

The objective of this report is to evaluate four engineered dune alternatives in a multidisciplinary way. The purpose is to present recommendations for the design, maintenance and governance of the dune system. The research is focused on the proposed dune system on the Galveston Island West End. The dune system is part of the " "Coastal Texas Study", which calls for coastal storm resiliency measures to include surge gates, vertical lift gates, ring barrier, height extension of the seawall as well as beach and dune measures for the entire Galveston Bay area. This research focuses on the beach and dune measures of this plan for the West End of Galveston Island. The following research question was developed to achieve this objective:

To what extent do the various dune alternatives fit the requirements for a land barrier at the West End of Galveston Island, looking at both technical and sociopolitical aspects?

The following sub-questions have been defined in support of this main research question:

1 *What are the characteristics of the different alternatives for the proposed (hybrid) dune systems as a barrier at the West End of Galveston Island?*
2 *What are the main requirements for the land barrier at the West End when analyzing technical and sociopolitical criteria?*
3 *What guidelines should be considered for design, maintenance and governance for a future proof engineered dune barrier at the West End?*

This study sought to answers these research questions through a multicriteria analysis (MCA). Formulation of these criteria and the determination of their effects are the first steps. Next, the alternatives are tested on set criteria. Once the dune alternatives have been evaluated, conclusions are drawn regarding the different criteria. The scope of the evaluated criteria follows the disciplines within the research group. This means that the research includes an analysis into hydraulic processes and sediment transportation, the stormwater drainage impact and sociopolitical acceptance and visibility. The environmental impact of the barrier has been excluded from this project, although this is expected to possibly have effects on the outcome of this project. This exclusion is due to a lack of expertise within the team.

This report is divided in three parts. The first part consists of an area and problem analysis (Chapter 2) an analysis on dunes and the evaluated alternatives (Chapter 3), ending with an analysis on the different disciplines in Chapter 4. Part II consists of the methodology Chapter 5, in which the multicriteria analysis (MCA) is discussed and the results of this MCA (Chapter 6). The post processing of the results is done in part III, with the discussion in Chapter 7, the conclusions on the project (Chapter 8) and the recommendations for further studies (Chapter 9.

2

Area and problem analysis

In this chapter an analysis of the study area is provided. First, the geographical location is discussed. Next, the soil and sediment composition of Galveston Island is laid out. Following that, the history Galveston had with hurricanes is discussed, with an explanation on the processes governing hurricanes. Finally, the future plans regarding flood risk mitigation and the connection with this project are explained.

2.1. Geography

This section describes the location of the study area with respect to different scales.

2.1.1. Galveston Bay

The Galveston Bay complex consists of four sub-bays: Galveston Bay, West Bay, Trinity Bay and East Bay, of which Galveston Bay and West Bay are adjacent to Galveston Island. Galveston Bay can be considered shallow with an average depth of $2m$, which does not allow large ships to pass. Therefore, the Houston Ship Channel was dredged, which is $10m$ deep. (Encyclopaedia Britannica, 2017). This channel runs from Bolivar Road through the Galveston Bay towards the Port of Houston, interconnecting the ports of Houston and Galveston.

The Galveston Bay complex is surrounded by different small mainland communities. The bays and these communities together are known as the Galveston Bay Area. Galveston Island is not part of this area.

2.1.2. Galveston Island

Galveston Island is part of the state of Texas in the USA. It is located $3km$ out in the Gulf of Mexico, and functions as a barrier island, separating the Galveston Bay Area from the Gulf of Mexico. The island has an elongated shape, with a length of $46km$ stretching from the East-Northeast to West-Southwest, and varying in width of approximately 1 to $5km$ (Frey et al., 2016), see Figure 1.1.

Galveston Island is bordered by Bolivar Roads at the north-east side. This channel is the main navigation route into Galveston Bay and the Port of Houston, making it one of the busiest shipping entrances in the USA (Frey et al., 2016). The south-western area of the island is bordered by the San Luis Pass, a smaller entry into the Galveston Bay Area via West Bay. Galveston Island is surrounded by other islands: Bolivar Peninsula, located on the other side of Bolivar Roads; San Luis Island and Follets Island in the South-East and Pelican Island on the North. The latter belongs together with Galveston Island to the City of Galveston except for the town of Jamaica Beach.

2.1.3. Galveston Island - West End

The main residential and commercial part of Galveston is located at the eastern third of the island. This area is marked by the presence of the Seawall, a concrete wall parallel to the beach to protect residents against storm surge from the Gulf. See Section 2.3 for the historic background for the creation of the Seawall. This structure does not provide protection to the West End of the island, which stretches from the end of the Seawall down to San Luis Pass. Small residential areas can be found spread over this area, occasionaly adjacent to the beach. However, a large part of the West End is unpaved, including the Galveston Island

State Park. There is one main road that connects the whole island, which is San Luis Pass Road, that alters into Seawall Boulevard starting west from the Seawall (Google, 2020).

2.1.4. Elevation of Galveston Island

Figure 2.1 provides an overview of the elevation levels of Galveston Island. Note that the highest elevation in this map was capped at the elevation of the Seawall, as there were outliers of the elevation irrelevant for this study, mainly located on Pelican Island. The elevation of Galveston Island can be split into two sections:

1. The location with the highest elevation of the island can be found on the northeast side of the island, in the City of Galveston. The coast at this location is protected by the Galveston Seawall and the land laying behind the Seawall has been raised to the same level. Section 2.3 explains the reasoning behind the raising of the city of Galveston.

2. The elevation West End is much lower than the more populated northeast side of the Island. The whole section has an elevation slightly above Mean Sea Level (MSL), except for a few relatively low and unconnected dunes along the coast at the Gulf side.
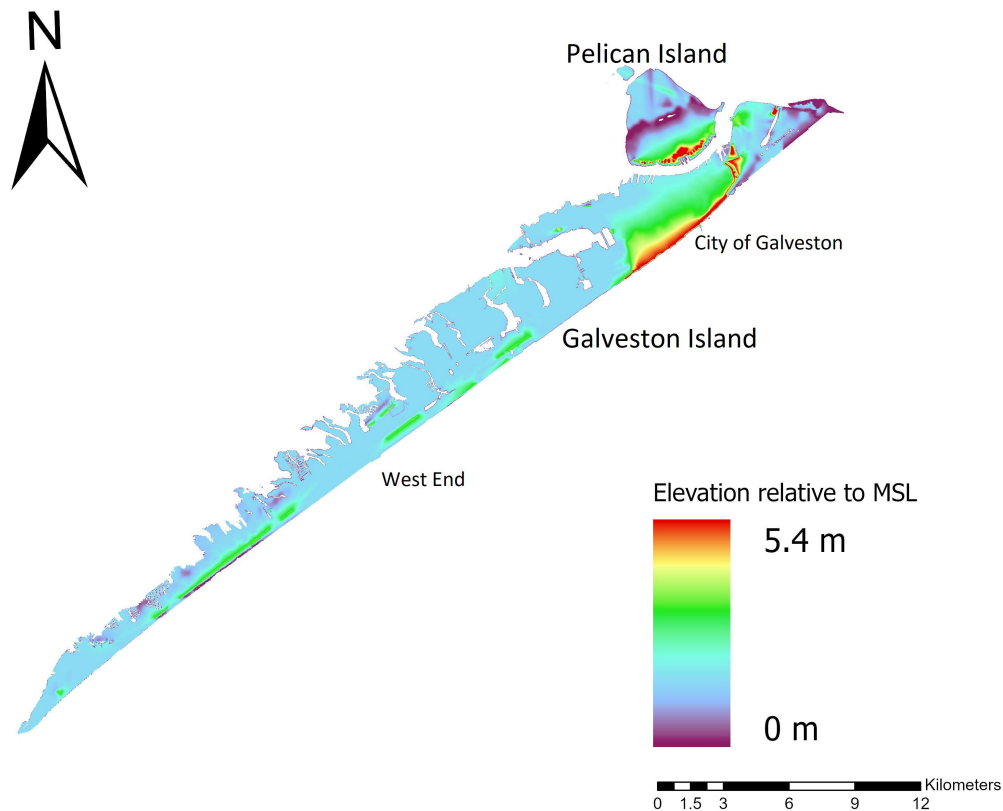
Figure 2.1: Elevation
levels of Galveston Island, relative to MSL. (United States Geological Survey, 2019)(United States Geological Survey, 2018).

2.2. Galveston and its history of hurricanes

Galveston Island has a history that is marked by hurricanes, due to its location in the Gulf of Mexico. This section provides an overview of three hurricanes that had a major impact on the current situation on the island.

1900: The Great Storm
On September 8th, 1900, Galveston Island was hit by a major hurricane, classified as Category 4 because

of its estimated maximum wind speeds of around $193km/h$. A storm surge of $4.8m$ struck the island when the storm made landfall, leading to an estimated total of over six thousand casualties. Based on this estimate, the storm, known in the area as "the Great Storm", is seen as the deadliest hurricane in US history. The damage on the island was enormous, including the loss of $3,600$ houses. This disaster has led to the iconic surge protection structure that is called the Seawall. The structure was finished in 1904. In addition, the entire City of Galveston was lifted, in order to improve flood resilience and stabilize the Seawall. This has led to the elevation differences as they are today: The highest point of approximately $5m$ is located directly behind the Seawall. The lowest point is located at the bayside, allowing drainage of the streets into the bay. (Ramos, 2013)

2008: Ike
Hurricane Ike struck at Galveston Island on September 13, 2008, after causing severe damage in Turks and Caicos, the Bahamas, Haiti, Cuba and the Cayman Islands. At the moment of landfall, Ike had an intensity of Category 2. The storm was surge dominant, inducing a storm surge that is estimated at $4.57m$ +MSL and overtopped the Seawall (Berg, 2009). The storm caused a tremendous amount of damage on Galveston Island: all the iconic piers in the Gulf were destroyed and approximately eighty percent of all the houses on the island were damaged. This included single family and vacation homes, but also public housing developments (Powell, 2018). Natural dunes had been completely flattened out as a result of wind and storm surge, allowing the sea water to come up to the houses. In general, Ike caused at least 83 fatalities in Texas and an approximated financial damage of $29 billion (Phan and Airoldi, 2015).

Ike was the last surge dominated hurricane that struck Galveston Island. Another process that intensified the damage on Galveston was the occurrence of a forerunner. This is an increase in water level several days before a hurricane makes landfall and typically has an amplitude under $1m$. However, the day before Hurricane Ike made landfall to the mainland, widespread inundation had already occurred (Kennedy et al., 2011b). Since Ike, new hurricanes have mostly caused flooding due to heavy rainfall.

2017: Harvey
From the 25th until the 30th of August, 2017, Hurricane Harvey stalled over Texas and caused intensive precipitation, which particularly ravaged Houston area from August 26 - 28 van Oldenborgh et al. (2017). The hurricane reached Category 4, while the rainfall event was an extremely rare event: the return period of the precipitation amount exceeded thousand years over a large area ($750mm$ over three days per year). The extreme precipitation event caused flooding in the streets of Galveston (Blake and Zelinsky, 2018).

It is estimated that the flooding impacted more than $100,000$ homes, with more than $80,000$ homes being flooded to a depth of at least $0.46m$ (FEMA, 2017a). Due to the fact that Hurricane Harvey was stationary inland for multiple days, it has been the most costly natural disaster in USA history with an estimated damage of $125 billion in total (NOAA, 2017)(NOAA, 2020c).

2.3. Hurricanes and tropical storms

Hurricanes and tropical storms are both part of the same generic category of weather phenomena, called tropical cyclones. These rotating and organized systems of clouds and thunderstorm originate over tropical or subtropical waters and have closed, low-level circulation. The main conditions for formation of such a system include an already existing weather disturbance, warm sea water, moisture in the air and relatively light winds. Most optimal conditions occur in the period between June 1st and November 30th, which is therefore called "Hurricane season".(NOAA, 2020c)

Tropical cyclones are categorized in three classes, depending on the maximum sustained winds of the system: tropical depressions ($62km/h$ or less), tropical storms (63-$117km/h$) and hurricanes ($118km/h$ or greater). Hurricanes can be subdivided into five categories based on their maximum sustained wind, according to the Saffir-Simpson scale. However, this scale does not account for possible catastrophic storm surge and heavy rain produced by the hurricane.

Storm surge is an abnormal rise in sea level, which accompanies a tropical cyclone. This is the result of low pressures at the water surface caused by the storm. If the pressure change is not too rapid, the water

level in the open ocean rises in regions of low pressure, and fall in regions of high pressure, so that the total pressure at some plane beneath the water surface remains constant. The theoretical rise of the water level is $10mm$ for $100Pa$ of pressure drop (Harris, 1963). Wind set-up, as a result of the heavy winds, only adds to this rise of the sea level.

Hurricanes may cause torrential rains and heavy storms. Typical characteristics of these tropical depressions are high intensity rainfall of long duration (e.g. several days) (Luxemburg and Coenders, 2017). Due to this duration, the total precipitation depth is generally higher than during regular precipitation events, even if intensities are lower. This relation is explained in Appendix C.1.3.

2.3.1. Climate change and relative sea level rise

Global warming is occurring roughly ten times faster than the average rate of ice-age-recovery warming (NASA, 2020). Besides a global rise in temperature, climate change is expressed in other ways as well. This is a worldwide sea level rise (Lundy, 2020). A positive feedback is created due to the warming of oceans, shrinkage of ice sheets, glacial retreat, decreased snow cover, ocean acidification and the decline of Arctic sea ice. With decreasing ice sheets comes the inability to reflect solar rays and the radiation is absorbed by the ocean, responsible for warming the ocean even further. Moreover, the warming of the oceans has lead to increased hurricane activity at Galveston Island. The intensity, frequency, duration and category of North Atlantic hurricanes have increased over time due to global warming. (Mann and Emanuel, 2006)(NOAA, 2020d)

The sea level rise has an effect on the environmental characteristics of Galveston Island (Mann and Emanuel, 2006). The sea level rise locally in the Gulf of Mexico is estimated from multiple measurements along the Galveston Pier 21 and Galveston Pleasure Pier. The expected sea level rise at Galveston Pier 21 and Galveston Pleasure Pier is determined to be around $6.5mm/year$ over a 100 year period with a 95% confidence interval. Besides the rise of sea level, Galveston Island is also subsiding due to continuous oil and gas extraction, which causes groundwater withdrawal to other aquifers. Subsidence is nowadays monitored to limit the groundwater withdrawal and enforce groundwater regulation in Galveston (Texas Living Waters Project, 2017).

2.4. Project scope

The combinations of the low elevation of Galveston Island explained in Section 2.1.4 with the history of hurricanes and rainfall in Section 2.3 show that the problem is not related to one single aspect. Hurricanes are a reoccurring problem in Galveston, necessitating a future proof solution that also takes into account relative sea level rise (RLSR) as indicated in Section 2.3.1.

Currently, the USACE is working on an integrated coastal barrier system of three segments to increase the flood risk safety of Galveston Bay. The plans are to create a storm surge barrier at the inlet of Galveston Bay, a ring levee in Galveston Bay and a dune system on Galveston Island and Bolivar Peninsula. In their proposal, this dune system is going to provide the role of a 'third line of defense'(USACE and GLO, 2018). The different segments are indicated in Figure 2.2.
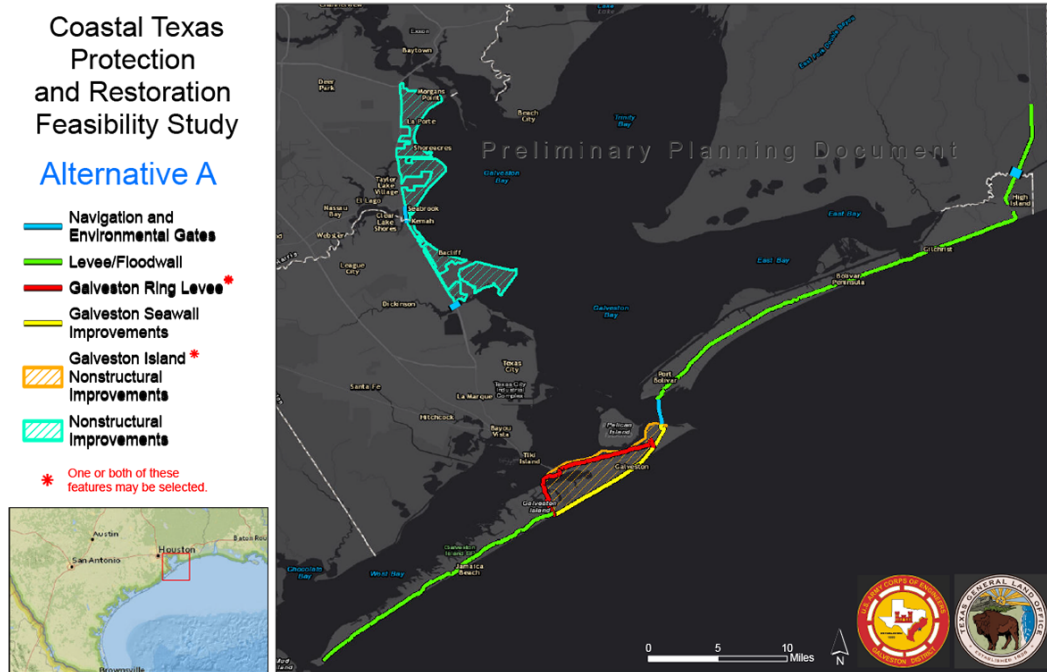
Figure 2.2: Proposal of the combined coastal spine.

This report focuses on the evaluation of dune system alternatives for the Galveston Island West End. Its primary function is the minimization of consequences in Galveston Island due to storm surge and waves, while also keeping the water out of Galveston Bay. This is also important, as the bay can be filled similar to a bathtub during a storm, possibly leading to devastating consequences for Galveston Island as well as affecting the whole Galveston Bay area.

The projected plan consists of the construction of a dune line from the end of the seawall on Galveston Island to San Luis Pass and is providing protection for both the adjacent residents as the Galveston Bay area. The construction itself remains a challenge, with the support from the federal government and the local residents being insufficient. The opinion and perception of the residents on the island differs, with residents concerned about hindrance of the sea view due to the projected construction of the dune system.

One of the main focuses of the USACE is to create support among different involved parties. It has proven to be challenging to integrate technical specifications that fit a certain amount of storm surge capacity with sociopolitical support to deliver a dune system design which is fit for purpose. Along with the proposed dune system by the USACE, two other dune system alternatives were proposed by TU Delft master graduates. An evaluation of these alternatives has not yet been conducted on the same criteria, as these plans have been developed in parallel. A comparison on the performance of the dune alternatives on storm surge coping capability, stormwater drainage impact, the maintainability and the sociopolitical acceptance can give insight into the performance of these alternatives.

A multicriteria analysis aids this comparison so that both technical and sociopolitical criteria are considered in a multidisciplinary way. This can support the USACE in creating a knowledge basis that the USACE can use on its way to the final proposition for the federal government. An analysis upon cross-shore processes of the dune upon 10, 50 and 100 year storms was performed and used to answer to what extent the various dune alternatives fit the requirements for a land barrier at the West End of Galveston Island.

3

Dunes

This chapter provides an introduction into various dune types and the functions of dunes. Furthermore, the different alternatives for the land barrier at the West End of Galveston Island are elaborated. The order of these alternatives listed is the order referred to in the remainder of the report. An overview of the alternatives is given in Figure 3.2.

3.1. Dune types

Sandy coasts around the world are diverse in terms of dynamics, morphology and vegetation. Coasts can consists of no dunes, while other coasts consist of dunes of $100m$ high or as low as $1m$ ((Martínez et al., 2013)). The latter, with dune heights varying around $1.5m$, reflects the dune type generally found along the West End of Galveston Island. Foredunes are situated on the backshore and formed by aeolian sand deposition in plants above the spring high tide line. On Galveston Island these are around $1m$ high. The vegetation on a dune can also differ. Dunes can be fully vegetated, giving more protection to erosion than a dune only consisting of sand (Martínez et al., 2013).

The dune system on Galveston Island includes the area from mean low tide line, to the landward limit of dune formation, which can be found at the property borders next to the dune. The sand material from offshore sandbars, typically within 15 to $30m$ from the shoreline, is deposited to the beaches along the Galveston coast that average 0.5 to $1m$ in the calm season (Howard et al., 2013).

3.2. Dune composition and functions

Aeolian sand deposition in plants slowly causes dunes to occur. The Galveston cross-shore coast is composed of the foreshore (wet beach), backshore (dry beach), foredune ridge, and backdune ridge, as can be seen in Figure 3.1. The foredune is the dune closest to the coastline. Its purpose is to absorb the initial brunt of a storm surge and dissipate wave energy. The backdune is the most landward dune, before property plot boundaries start. The dune system experiences daily harsh winds, frequent water inundation and can be affected by beach visitors. However, it remains fairly stable until a storm event occurs and serves for recreational purposes and as an important natural ecosystem (Howard et al., 2013).

Storm events cause high energy waves that wash against the base of the foredune, which disrupts vegetation and causes erosion of the dune face. Waves that return seaward carry the sand from the dune and deposit it back to offshore sand bars where it originated, and the cycle begins again. This process is described by undertow. Storm events that cause high velocity winds carry sand away from the shore in the direction of the Galveston Bay. This sand can not return naturally to the dune system and requires human intervention. This human intervention concerns the (post-storm) maintenance that is required to contain the storm surge capability of a dune system.
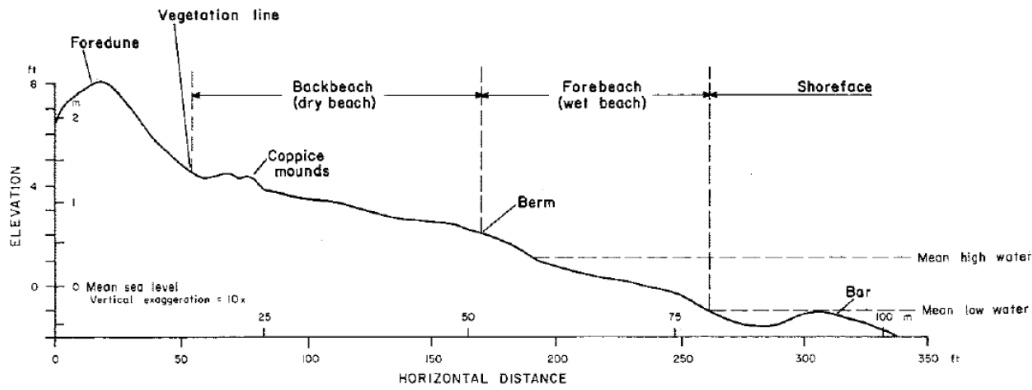
Figure 3.1: Beach profile at Galveston Island West End (Morton and Paine, 1985).

3.3. Hybrid dunes

If the availability of sand is a limiting factor for the creation of dunes, hybrid dunes can be a solution. This is a dune with a core consisting of an alternative material, thus keeping the appearance of a natural dune. Depending on the circumstances, the material substituting the sand in the core is a cheaper material such as clay, or a stronger and less erodible material such as concrete. An example of such a hybrid dune is the Hondsbossche Zeewering, stated in Appendix A.1. This used to be a dike, but currently has sediment on top of the dike, gaining a natural appearance of the structure, while also increasing the flood safety.

Research on hybrid dunes is limited, although the available results on this topic show that a hybrid dune performs well under certain circumstances. Results found by Muller et al. (2018) were: "By adding a sand cover over the seawall, maximum dissipation is spread over a larger cross-shore extent. This led to the reduction of the wave height at the face of the hybrid structure, as well as the generation of more wave-induced setup." As the sand supply is limited in Galveston and can prove to be costly, a hybrid approach may prove to be a solution on mitigation of flood risk on Galveston Island, while possibly being more effective than a sand dune. Besides a hybrid dune, more alternatives were considered in this project.

3.4. The alternatives

The different dune options considered in this research project are listed in the following sections.

3.4.1. The 0-option

The 0-option concerns an evaluation of the current situation on the West End of Galveston Island. The advantages and disadvantages of the 0-option were assessed for the current state of the West End of Galveston Island dunes. The 0-option provides protection, however an increase in stormwater drainage impact as well as intensity of storms and hurricanes is expected. Therefore the 0-option offers a baseline to compare the other alternatives with. An assessment for 50 years was done, as this compares well to the current plan by the USACE. An illustration of the option is given in Figure 3.2a.

3.4.2. Alternative 1: Twin dune system proposed by the USACE

The study team, consisting of the Texas General Land Office (GLO) and USACE is currently investigating a dune-and-beach system along the coast of the Galveston Island West End, from the end of the seawall till St. Luis pass. This alternative consists of a twin dune system, thus with two dunes next to each other,

varying in heights from 3.65 to $4.26m$ +MSL, as shown in Figure 3.2b. The USACE proposes a dune extension where the dune is placed from the dune foot on the residential side towards the sea. This means that the dune foot is going to extend the beach line seawards on locations where this is needed instead of moving properties back to make space for a dune. The protection system is based on a 50 years storm with a maintenance plan to re nourish the dunes every 5 year (Frey et al., 2016).

3.4.3. Alternative 2: Single dune proposed by Luis Galvez

Galvez (2019) has designed one dune with a height of $7.5m$ +MSL for his Master thesis at Delft University of Technology (TU Delft). This dune system was specifically designed in order to withstand a storm by the force of Hurricane Ike. The geographical position, the footprint of the dune on the island have not been taken into consideration by Luis Galvez. However, for this research an evaluation is done to what extend the dune fitted into the present geographical position on the West End of the island. The alternative is illustrated in Figure 3.2c.

3.4.4. Alternative 3: Hybrid dune with concrete core

Muller (2017) has undertaken research concerning the design of a hybrid dune system, with the seawall as a core of the dune and sediment on top of the seawall, creating a hybrid dune. This project was an additional thesis for the TU Delft. The concrete core dune system uses the same principle as Muller, by adding a concrete core to the dune system along the West End of Galveston Island. The concept of the idea of a hybrid dune is that it cuts costs by the decrease of volume in sand, while also requiring less maintenance after a major storm event or period of time compared to the other alternatives. See Figure 3.2d.

3.4.5. Alternative 4: Hybrid dune with clay core

This alternative consists of a clay-based core, in order to determine the difference between a hybrid dune with a clay-based core. It has the same dimensions as alternative 3 and thus uses the hybrid dune design of Muller (2017) as a basis. See Figure 3.2e.

3.5. Summary alternative characteristics

Data concerning the dune, core and slope dimensions from the dune alternatives were retrieved from the reports related to the different dune alternatives. Storm parameters and the dune profile were generated in different programs, as data was limited for alternative 1. Dimensions and design parameters for alternative 4 were based on the design parameters of alternative 3, except for the core which is made from clay.

Table 3.1 presents characteristics used for the testing of the different alternatives in this report. Fields show 'n.a.' (not applicable) if this is the case. Other fields state 'n.g.' (not given) if these were not given in the related dune alternative reports. Alternatives 3 and 4 state ranging dune bases, slopes and widths. These ranges are based on the report by Muller (2017). When these alternatives are discussed in this report, it is clearly stated whether a specific value was selected from this range or the full range was assessed. The range for the beach width for the 0-option reflects the currently varying beach width along the coast. Design characteristics used for the simulation of storm surge coping capability are given in Appendix H.

Table 3.1: Characteristics of the different dune alternatives

Characteristic		0-option	Alt. 1	Alt. 2	Alt. 3	Alt. 4
Dune crest	Level [$m\,w.r.t.\,MSL$]	+1.5	+3.7 & +4.3	+7.5	[+5.9,+7.6]	[+5.9,+7.6]
Dune base	Level [$m\,w.r.t.\,MSL$]	MSL	MSL	MSL	MSL	MSL
	Width [m]	[15,25]	56	100	[5,60]	[5,60]
Dune slope	[$-$]	varying	varying	1:3	[1:3.5, 1:10]	[1:3.5, 1:10]
Core slope	[$-$]	n.a.	n.a.	n.a.	1:5	1:5
Beach Width	[m]	[30,40]	75	100	[55,130]	[55,130]
Return period	[(-) year storm]	n.a.	50	100	100	100
Dune sediment	D_{50} [mm]	0.150	n.g.	0.1323	0.150	0.150
	D_{90} [mm]	0.187	n.g.	0.1869	0.187	0.187
	Clay [mm]	n.a.	n.a.	n.a.	n.a.	n.a.
Concrete core	Level [$m\,w.r.t.\,MSL$]	n.a.	n.a.	n.a.	+4.32	+4.32
	Height [m]	n.a.	n.a.	n.a.	5.2	5.2
	Width bottom [m]	n.a.	n.a.	n.a.	5	5
	Width top [m]	n.a.	n.a.	n.a.	1.5	1.5

(a) The 0-option.
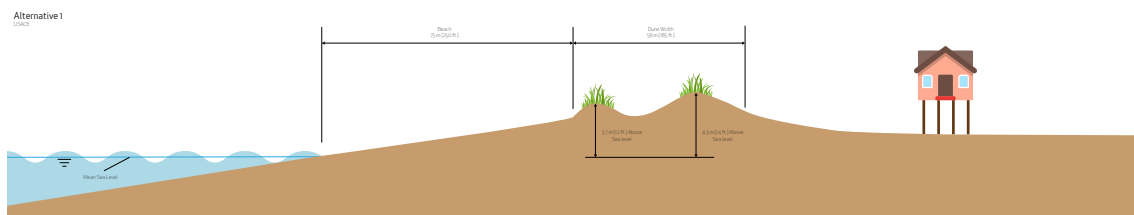
(b) Alt. 1: Twin dune system proposed by the USACE.
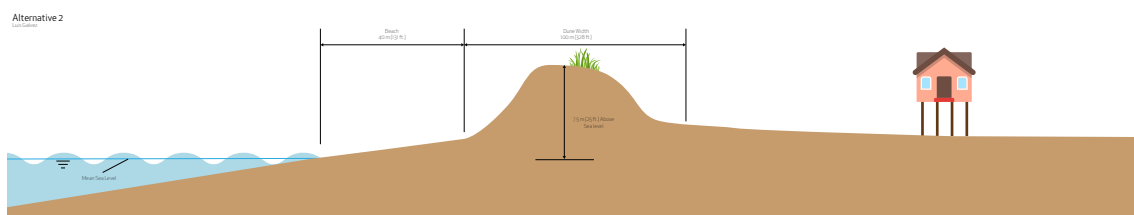
(c) Alt. 2: High single dune proposed by Luis Galvez.
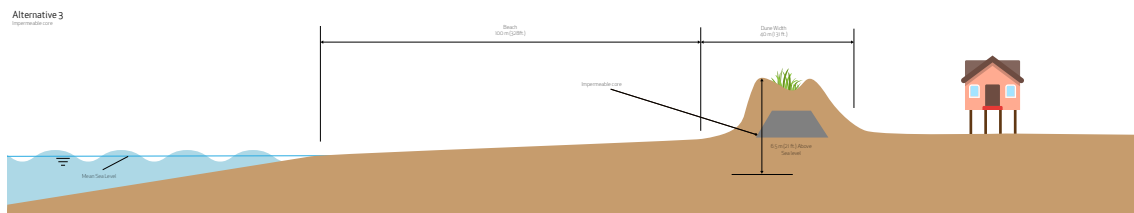
(d) Alt. 3: Hybrid dune with a concrete core.
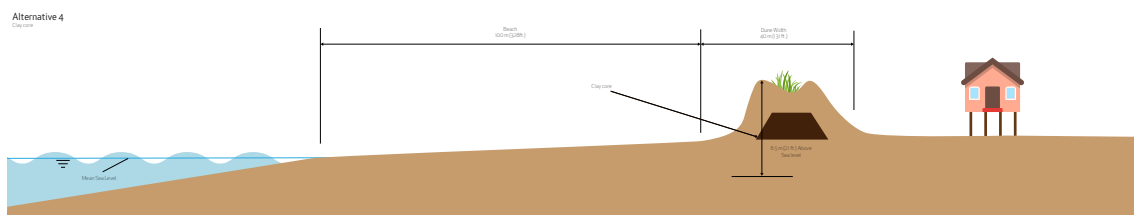
(e) Alt. 4: Hybrid dune with a clay core.

Figure 3.2: The different alternatives.

Analysis

This chapter provides an overview of the analyses that form the basis for the criteria used in the multicriteria analysis. These are a hydrodynamic process analysis (Section 4.1), a sediment analysis (Section 4.2), a hydrologic analysis (Section 4.3) and a sociopolitical analysis (Section 4.4).

4.1. Analysis hydrodynamic processes

This section describes different processes related to the hydrodynamic aspect of this assessment. The different equations used and a more extensive approach is listed in Appendix B.

When waves are propagating towards the coast, multiple processes occur. A wave spectrum consists of different waves with varying properties and processes. A distinction can be made between short, turbulence, very low frequency motions, mean flow and long waves. This is illustrated in Figure 4.1. The different timescales and the difference between the separation in the shoreface and the surf zone are illustrated in here. Short wave processes include wave set-down and set-up, energy loss due to wave breaking and wave shoaling. These processes differ with varying depth.
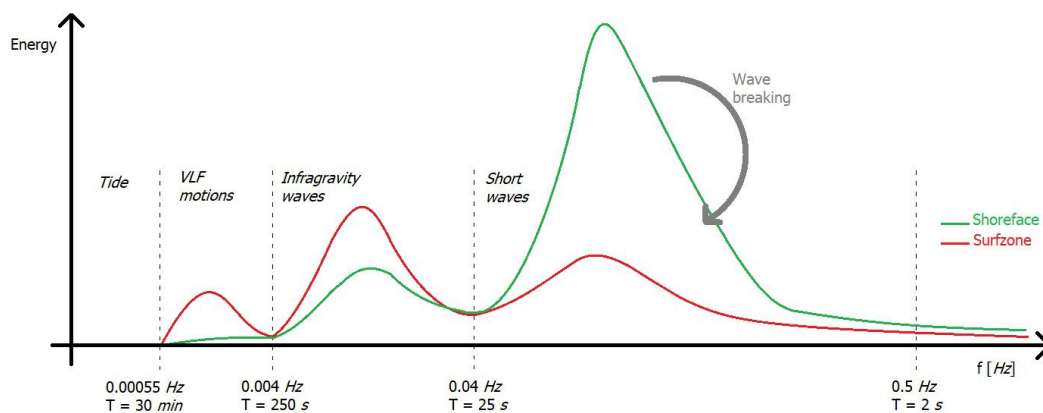
Figure 4.1: Separation of velocities based on timescale, from de Schipper (2019).

The green line represents the energy level at the shoreface and it can be seen that most energy is at the short wave frequencies. However, due to wave breaking, it can be seen that larger velocities are present at the lower frequencies and thus larger timescales at the surf zone. Therefore long waves play an important role in the erosion of dunes.

When waves arrive at the dune face, overtopping, overwash and inundation can be a result from this. Overtopping is the phenomenon where a discharge is occurring over the top of the dune and into the hinterland. Overwash is the event in which sediment is transported landward due to waves as a result of wave run-up or inundation. The mechanism of overwash was not calculated by itself in this research project, as the soil transport landward is difficult to predict requiring a scale model. Inundation is the natural process in which the hinterland is flooded and can be a result of continuous wave overtopping.

Wave overtopping is calculated on its own in this research project. Despite the imminent threat of wave impact on dunes, knowledge and modeling capabilities are limited on these topics Figlus et al. (2011). Because of this, an indication is made with the use of equations from Van der Meer (1988), which relate to hard structures. Nevertheless, it enables a comparison on wave overtopping between the different alternatives. The magnitude of overtopping over a structure is important for the dune design and a more relevant parameter than wave run-up is: it gives an insight of the rates of the running water of the hydraulic structure into the hinterland. The maximum allowable overtopping for a sandy slope is 1 liter per second per meter width.

It is known that spatial gradients in net sediment transport rates result in changes in the coastal morphology (Bosboom and Stive, 2015). However, there is still much research to do about the interaction between hydrodynamics and sediment. The process responsible for offshore migration of sediment is the undertow. This is the return flow compensating for the onshore directed waves and migrates over the bottom floor, stirring up and moving sediment. In the surf zone these velocities are highest: due to shoaling, the waves are high and the water is shallow.

When waves hit the bottom of the toe side of the dune, erosion can occur, transporting the sediment offshore due to the undertow process. The offshore movement of sediment can start a process in which the top of the dune erodes as well: the dune can become unstable due to the bottom sliding away, which causes a collapse of the dune face. The criterion for this collapse is that the local dune slope angle is larger than the equilibrium slope (van Rijn, 2013). The collapse of sediment from the top to the bottom of the dune face is called avalanching.

The processes listed in the previous paragraphs, except for the overtopping are included in the modeling tool XBeach. This program was used in this project. More information about the model specifications of the different alternatives are given in Appendix H.

4.2. Sediment analysis

This section describes dominant processes related to sediment around Galveston. Additionally, sediment management and its impact on coastal development in the area are discussed.

4.2.1. Sediment management in Galveston Bay

Three sources of sediment input in Galveston Bay have been identified, which are fluvial input, input from transport through Bolivar Roads or coastal and marine sources derived from barrier island overwash and shoreline erosion (Phillips, 2005). The current sediment accumulation cannot be exactly determined and brings difficulties due to sources of bed disturbance and has a mean sediment accumulation rate that has been estimated on $3.5mm/year$ (Phillips, 2005).

The container vessels in the worldwide transport industry have always increased over time and this asks for deepening and widening dredging operations. Recently, the channel to the port of Houston has been widened and new plans are set in order to deepen the approach channel to $13.7m$ and widen it to $162m$. Together with the accumulation in Galveston Bay, this asks for continuous dredging operations.

4.2.2. Coastline development at Galveston Island

According to Phillips (2005), 57% of the shoreline of Galveston Island experiences erosion rates of at least $0.6m/year$ in recent years. The erosion and land loss has increased over the years, as well in Galveston Bay due to human interactions, such as the impoundment of the Trinity and other Texan rivers.

The shoreline is measured every year by the Bureau of Economic Geology (BEG). Since 2000, Light Detection And Ranging (LiDAR) surveys have been conducted. The shoreline position and the beach and dune volume can be estimated from these data. Over time, these surveys are conducted, together with coast-wide surveying (Bureau of Economic Geology , 2020). The recent coastal trends found from these data and surveying are illustrated in Figure 4.2. As can be seen from the figure, accretion occurs on the

outer ends of the island and the rest of Galveston Island suffers from erosion. The maximum erosion occurs at the southern end of the seawall, where five hundred meters from the seawall the coastline regression between 2000-2019 has been $-1.98m$ every year.
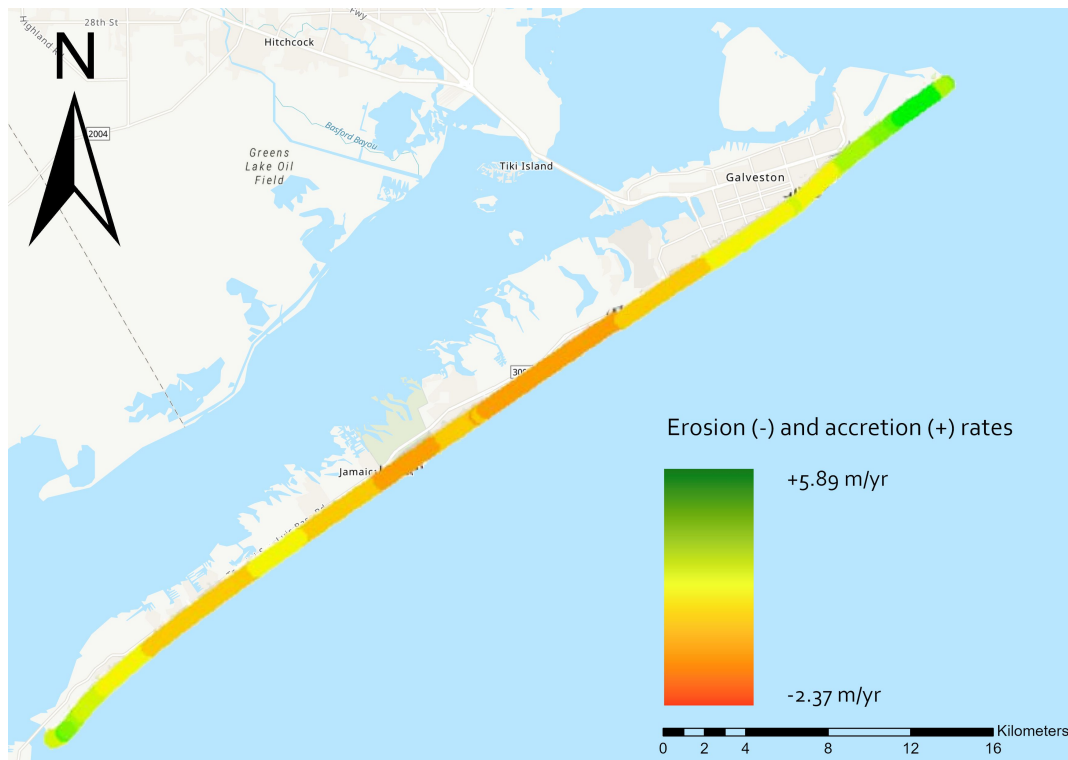
Figure 4.2: Shoreline trends West End Galveston Island, (Bureau of Economic Geology , 2019)

Since the early 1900s littoral flow of sediment has been blocked. This is due to the construction of the jetties at the entrance to Galveston Bay in that time. (Kent, J., 2019). Because of this blockage eddies form in the longshore current, with accretion as a result at the East Beach. From Stewart Beach westward, the erosion rates have averaged from 1.5 to $3.0m/year$ for the last fifty years. Thus, the island suffers from serious erosion threats with short beaches (Lee Jr., 2017).

4.3. Hydrological analysis

This section discusses the main findings that are hydrologically relevant for the design and maintenance of a dune system as a future land barrier. This analysis was performed in four steps. First, the components of the water balance for the relevant system were determined. Secondly, potential effects of the creation of a land barrier were reported. Thirdly, components relevant to these effects were quantified. Lastly, potential mitigation measures for negative effects were analyzed. The water balance and the relevant dominating components are specified in Appendix C.1. An analysis into the current situation and problems related to drainage and quality of rainwater at the West End of Galveston Island can be found in Appendix C.2.

4.3.1. Hydrological issues and potential effects of a land barrier

This research primarily focuses on water that sits on top of the soil. Therefore, the relevant system is bounded by the ground level. The resulting dominant hydrological processes are precipitation, evaporation, infiltration and runoff. Galveston Island is prone to a lot of precipitation all year round, with a yearly average precipitation depth of $1100mm$ and a peak in September, due to hurricane season (U.S. Climate Data, 2020). Infiltration and storage in the unsaturated zone are very limited, due to the high groundwater

table of 0 to $15cm$ below ground level and the poorly drained soil type Mustang (Howard et al., 2013). Additionally, the urban areas at the West End decrease infiltration possibilities even more (US EPA, 2003). Evaporation rates drop during rain events as well. The combination of these circumstances results in high runoff volumes that need to be either stored or drained away, but residents of the West End report frequent flooding and ponding, even after moderate rainfall (Figlus and Song, 2019). This indicates that drainage of rainwater is not performed properly. In addition, the City of Galveston states that all new developments must drain North to Galveston Bay, and prohibited drainage to the beach area (City of Galveston, n.d.). Nevertheless, Figlus and Song (2019) showed that various areas drain rainwater towards the Gulf, potentially causing health risks due to a relatively high concentration of pollutants that is common for urban runoff.

The future land barrier will close off the current drainage outlets onto the beach. This can lead to obstruction of drainage paths, potential improvement of runoff quality due to filter capability and to seepage that could cause nuisance. In order to analyze potential obstructive effects, a runoff analysis was performed. Potential obstruction and impact on quality were taken into account in the multicriteria analysis. This research did not include an analysis into seepage, and was therefore left out of the multicriteria analysis. However, Appendix C.4 provides potential mitigation measures for all mentioned potential effects, including seepage, and discusses suitability in a qualitative way.

4.3.2. Runoff analysis

The Modified Rational Method (MRM) was applied in order to quantify runoff volumes on the West End. This method uses precipitation depth, catchment area and a runoff coefficient and results in generated runoff volumes. This runoff coefficient is typical for every specific catchment, and depends on catchment characteristics such as topography, soil type and land use. For a detailed explanation of the MRM, see Appendix C.3. This section only shows the main results.

Usage of ArcGIS Pro software allowed to delineate catchment areas that drain towards the beach and their respective drainage locations onto the beach. In total, 71 catchment areas could be identified. The total area that drains towards the beach can be seen in Figure 4.3, the main contributing areas and their specific outlet locations can be seen in Figure 4.3b. Table 4.1 provides an insight into runoff volumes for these five outlet locations, based on a rainfall depth in $24h$ during storms with a return period of 2 year, 10 year, 25 year, and 100 year. As can be seen, these five catchment areas generate approximately half of the total runoff volume.

Table 4.1: Catchment areas and runoff coefficients for the areas draining towards the Gulf.

ID	W [dd]	N [dd]	Area [$*10^5 m^2$]	Runoff coefficient [-]	$V_{T=2year}$ [$*10^4 m^3$]	$V_{T=10year}$ [$*10^4 m^3$]	$V_{T=25year}$ [$*10^4 m^3$]	$V_{T=100year}$ [$*10^4 m^3$]
P1	29.2387645	94.8773063	2.6	0.41	1.3	2.3	3.1	4.5
P2	29.2366557	94.8799596	7.7	0.45	4.4	7.6	10.1	15.0
P17	29.1955323	94.9489356	2.6	0.49	1.6	2.7	3.6	5.4
P27	29.1700789	94.9913450	3.1	0.49	1.9	3.3	4.4	6.5
P29	29.1490334	95.0262873	2.0	0.50	1.3	2.2	2.9	4.3
Total main contributors			17.9	0.46	10.6	18.1	24.0	35.8
Other catchment areas			19.5	0.51	12.7	21.7	28.8	42.9
Total			**37.4**	**0.49**	**23.3**	**39.8**	**52.9**	**78.7**
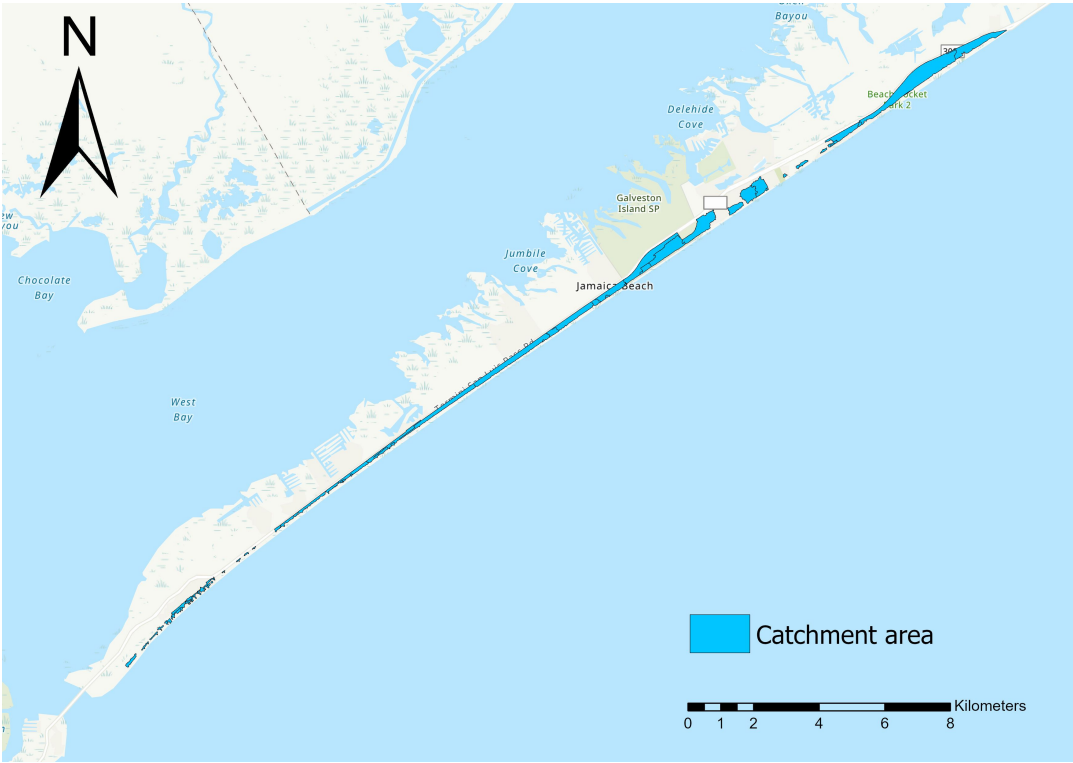
(a) Total area of the West End that drains towards the beach.
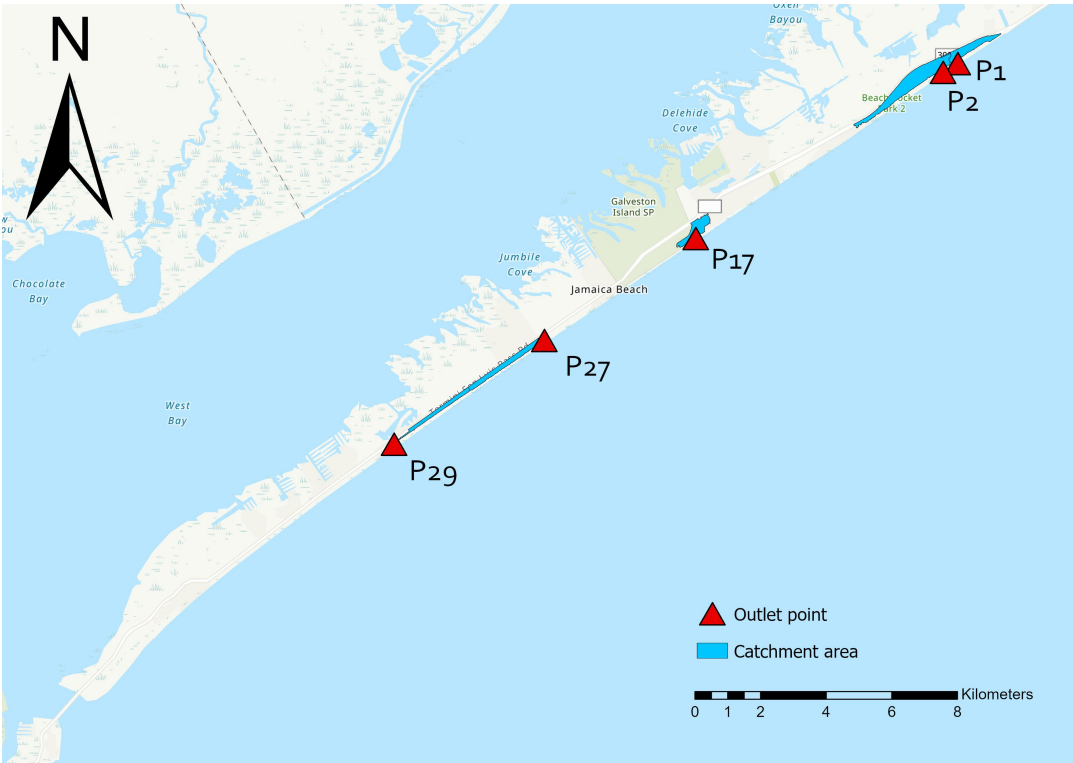
(b) Five main contributing catchment areas and their outlet locations at the West End.

Figure 4.3: Contributing areas that generate runoff volumes and drain towards the Gulf

4.4. Sociopolitical analysis

This section provides an analysis on the combination of social and political factors to the implementation of a coastal flood protection. Firstly the demography and economy are further elaborated. This is followed by an analysis of the stakeholders and the form of governance.

4.4.1. Demography

Demographic data provides insights about future infrastructure needs, resource allocation and demand for municipal and other services of a community. This section discusses demographic trends with regard to property values along the West End and the origin of homeowners. It is important to acquire general knowledge about Galveston City, but also to determine what groups of people are affected by the construction of a dune system. Demographic data on the West End are discussed in this section. The Houston bay area demographics are not discussed in this research, because this falls out of the scope of this project. For this purpose general demographic data on Galveston City is given and an analysis of property values and where residents have registered for the Galveston Island West End area, were made in order to determine who are going to be directly affected by the construction of an engineered dune system. For this purpose five cross sections on the West End have been made, see Appendix D. The interface between the dune system alternatives and demographic data mentioned in the following subsections, are discussed in Chapter 7.

City of Galveston
The population of the City of Galveston has grown since the first USA census in 1850. However, after Hurricane Ike in 2008, a population drain that started in the early 1960s accelerated (World Population Review, 2020). Galveston's population dropped from its peak population of $67,175$ that was recorded in 1960 to $47,000$ by 2010. Recent estimates show that the population has edged upward since, by almost 6% since the last census of 2010 to a population of $50,457$ according to the most recent U.S. census estimates (United States Census Bureau, 2020). The population density is $3,175$ per km^2 which is nearly thirteen times higher than the Texas average and fourteen times higher than the national average. The median age in Galveston is 39.4 years, which is similar to the United States median age of 37.9 years. In Galveston City, 83.8% of the population is over 18 years of age and 15.5% of is 65 years and older. 73.7% speak English and 20.9% speak Spanish. Galveston City is inhabited by mostly White Americans. According to the 2018 USA Census Bureau estimates, the population of Galveston City was White American 74.1%, Black or African American 18.3%. The rest of the Galveston City population are composed of other races like American Indian, Asian or Native Hawaiian. The median household income (in 2018), was $\$44,902$, in comparison to the United States median household income $\$61,937$.

Galveston Island West End
$8,769$ people live on Galveston Island West End (Texas Demographics by Cubit, 2020), which is almost 20% of the total Galveston Island population. The median Age on the Galveston Island West End is 48.5 years, which is an increase of 10 years compared to Galveston City as a whole, meaning there is an increase in senior residents on the Galveston Island West End. 90.9% is U.S. born, 80.7% of which lived in the same house last year. From a total of $3,733$ households on the West End of Galveston Island, 86.5% are households without children. The median household income (in 2018) was $\$73,242$, in comparison to the Galveston City median household income of $\$44,902$ (Texas Demographics by Cubit, 2020). The average household income is $\$106,901$. During the year an owner occupation rate of 64.9% is present on the Galveston Island West End, a little over a third is renter occupied. The average property value along the coast is $\$601,250$, see Appendix E. Just under 10% of residents along the coast are registered as residents in Galveston City. 8.2% of the residents are registered in other states than the State of Texas. From the 91.8% of Texas state registered home owners, just over 46% are registered in the city of Houston.

4.4.2. Economy

A description of local economics is addressed in order to get a general understanding of the project area.

Galveston City
The economy of Galveston employs $22,000$ people. The largest industries in Galveston are:

- Health Care & Social Assistance (3,931 people);

- Accommodation & Food Services (3,421 people), partly related to tourism;

- Educational Services (2,635 people).

The healthcare industry is driven by the University of Texas for the Medical Branch (UTMB). It serves the inhabitants of Texas with specializations and takes care of people from the entire state of Texas. Galveston City is home to the Galveston National Laboratory, which is one of the two sophisticated high containment research facilities in the U.S. serving as a critically important resource in the global fight against infectious deceases (Tourism Economics, 2018). The highest paying industries are Utilities ($95,893 per year), Wholesale Trade ($58,700 per year), and the Mining, Quarrying, Oil & Gas Extraction ($58,036 per year) (United States Census Bureau, 2020).

Tourism is an integral part of the Galveston Island economy with a visitor spending of $872 million in 2018. Tourism on Galveston Island generated $177 million in tax revenues in 2018 (Tourism Economics, 2018). Employment and income in Texas and Houston continue to grow faster than the U.S. rates and are likely helping to drive tourism on Galveston Island. The city is home to the largest cruise ship terminal in Texas, and the 11th-largest in the world, with just under one million visitors in 2018. The Port of Galveston in general provides an annual economic impact of more than $2.3 billion and is thus a significant contributor to the local, regional and state economies (Tourism Economics, 2018).

4.4.3. Stakeholder analysis

The process of building a land barrier draws from a wide range of knowledge across various sectors: from science and research, through planning and design, to engineering and construction. Stakeholders should be involved as soon as possible in the design phase as they influence the outcome of a project de Ridder (2009). Figure 4.4 summarizes the stakeholder identification, which is further elaborated in Appendix F. The results from the multidisciplinary project of Rooze et al. (2018) were used for this map. The stakeholders are divided into political stakeholders, economical stakeholders, residential stakeholders, environmental stakeholders and educational stakeholders.
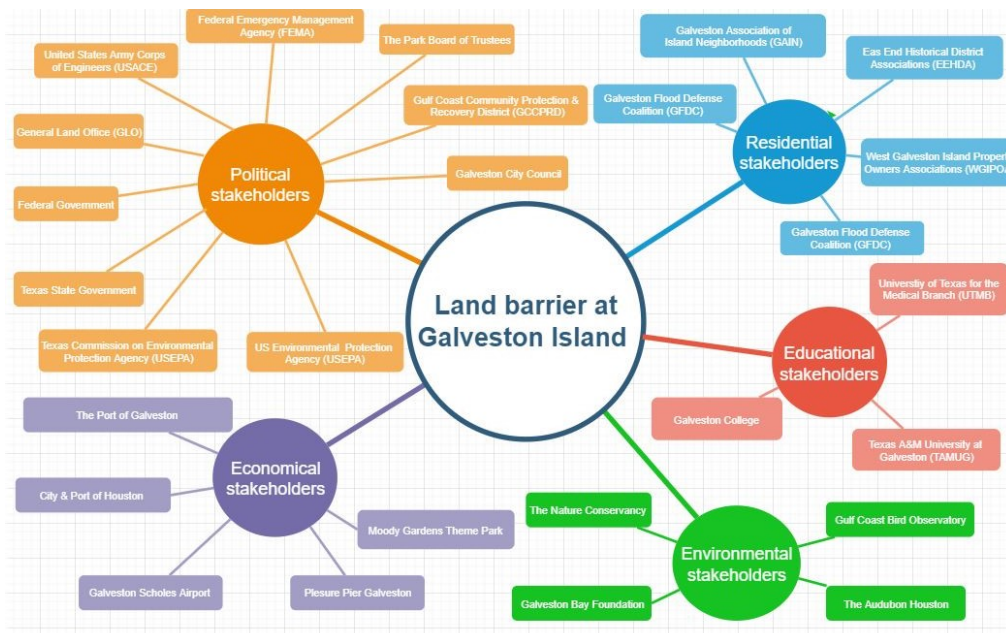
Figure 4.4: Stakeholder map Galveston Island.

It is important to incorporate the stakeholders of Galveston Island, so that local support is generated. Therefore stakeholders have been interviewed to gain their perspectives on the construction of a dune system. These include government agencies, private consulting firms, research institutions, non-profit organization and residents. A further elaboration on the responses of the stakeholders can be found in Appendix F.2. A summary consists of the following items:

- The land barrier does not negatively influence the architectural integrity, the cultural tourism or local (industrial) business on Galveston Island.

- The public access of the beaches need to be maintained.

- The every day value of the people on Galveston Island need to preserved.

- A land barrier need to prevent storm surge from overflowing the West End to provide extra safety for the residents.

- Any form of protection need to reduce the Galveston's flood insurance premiums. More information about the National Flood Insurance Program (NFIP) can be found in Appendix G.2.2.

- Any form of protection provides also benefits for non-hurricane problem flooding.

4.4.4. Forms of governance

The analysis on the forms of governance, as further elaborated in Appendix G provides a clear distinction between the priorities set with regard to the USA and the Netherlands. Dutch form of governance with regard to flood risk measures has a standard federally-funded budget and focus on maintenance. Where in USA it has often been based on a protect based budget by local funding. The challenge that arises is to connect technical knowledge with social political decision making.

Finding an all-encompassing proceeding is impractical, because of the many differences between and within countries. However, there are vast elements in the form of governance which could be useful. The USA need to introduce a federal flood protection standard for federally-funded projects. With as purpose to reduce disaster costs by avoiding future damages, save taxpayer dollars over the long-term, preserve coastal flood plains and safeguard people and property. In Appendix G.3 an advise is formed in with emphasis on the form of governance with relation to future flood risk reduction measures in the USA.

The findings from the sociopolitical analysis were used in Appendix K to define boundary conditions for the sociopolitical acceptability of the proposed alternatives.

II
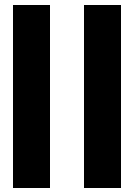
Methodology and results

<div align="right">

5

</div>

Multicriteria analysis

A multicriteria analysis (MCA) was used to assign value to the alternatives, based on the obtained information in the previous chapters. A MCA is a method to assign the value of certain alternatives relative to each other, based on discrete criteria. First, the general system for the criteria is explained. Next, the general rating system for the critera the criteria that determine the value of each alternative and their governing parameters are formulated and elaborated, and the outline of the final scoring table is given. Finally, the lack of weight factors is explained.

5.1. Rating system

Each alternative was tested on the parameters given in Section 5.3. The results were evaluated and based on these results a final score was given to each alternative on how it fulfills the function of each criterion. There were three possible scores each alternative could receive for each parameter: a positive score, a negative score or a neutral score, respectively represented by a '+', '-', and a '0'. All scores were given based on the impact each alternative had on each criterion in the current situation during the total lifetime of the structure.

As the parameters for each criterion were evaluated separately, it is imminent that the situation occurred in which one of the parameters of the criterion received a different score than the others. To offer clarity in these situations, the following rules were formulated to the scoring of the criteria, which range from highest to lowest priority:

1. If one or more parameters of a criterion received a negative ('-') score, the criterion automatically received a negative score as well.
2. If the parameters of a criterion only had a positive ('+') and neutral ('0') scores, the criterion received a positive score.
3. If all the parameters of a criterion had the same score, the criterion received this score as well.

The reasoning behind rule one was as follows: no mater how an alternative positively scores on some of the parameters of a certain criteria, the fact that it negatively affects one of the parameters of criteria is enough to give a negative score to the said criteria. Rule two was based on the logic that a neutral impact of a parameter on a criterion is no impact at all, and therefor does not impact the score of a criterion. Rule three was inherent and thus needs no further explanation.

5.2. Outline of the scoring table

The scoring table of the final results are in the form of Table 5.1, with the symbols '+','-', and '0' filled in the blank spaces of the table.

Table 5.1: Scoring table of the final results.

Criteria	0-option	Alt. 1	Alt. 2	Alt. 3	Alt. 4
Storm surge coping capability					
Erosion during normative event					
Wave overtopping capability					
Stormwater drainage impact					
Obstructive impact					
Quality impact					
Maintainability					
Maintenance approach					
Sociopolitical acceptability					
Fitting of the dune					
Effect on the line of sight					
Accessibility					

5.3. Criteria of the MCA

The criteria that were chosen for the MCA are inherent to the expertise of the research group, as well as based on the views and needs put forward during interviews and meetings with stakeholders.

The capability to cope with storm surge is the leading criterion when evaluating different alternatives, due to the nature of the project. It can be described as a boundary condition that the alternatives have to meet, in order to function as a barrier. However, this does not mean other criteria should not be considered. It is hypothesized that an increase in storm surge coping capability of an alternative leads to a decrease of its ranking regarding to other criteria. An increase in height or width of the current dunes could result in less rainwater drainage capabilities, higher maintenance costs and a disconnection between the beach and the homes behind the dune system.

By taking the previous statements into account, the four criteria determining the role of the land barrier for the coastal spine were chosen as: *the Storm surge coping capability*, *the Stormwater drainage impact*, *the Maintainability* and *the Sociopolitical acceptability*. For each criterion, the specific method for determining the value and the corresponding parameters is given in a separate appendix, respectively appendices H, I, J and K.

5.3.1. Storm surge coping capability

This criterion describes the primary function of the structure. Contrary to the other criteria, sea level rise was taken into account for this criterion. This is due to the fact that a rise of sea level has a direct impact on this criterion, whereas the other criteria are only indirectly affected by this phenomenon. The parameters used for the grading of this criterion are listed below:

- **Erosion during normative event**
  The erosion rates were determined with the use of XBeach. Modeling the alternatives resulted in an outcome in what manner the alternatives handle different kinds of design storms. If these rates were too high for an alternative, it resulted in a negative score on this parameter.

- **Wave overtopping capability**
  If the wave overtopping rates for an alternative reach a certain level, the dune system can become unstable and the flow of water into the hinterland can ultimately result in inundation. Thus, lower wave overtopping rates resulted in a positive score for this parameter.

5.3.2. Stormwater drainage impact

Heavy rainfall is a major issue in the region. This criterion describes the effect the different alternatives have on stormwater induced issues. The parameters used for the grading of this criterion are listed below:

- **Obstructive impact**
  Any continuous dune system results in the accumulation of rain water on the back (non-Gulf) side of the dune. This phenomenon is called ponding and also depends of the materials used in the dune system. A lower volume of water ponding on the back side of the dune resulted in a positive score for this parameter.

- **Quality impact**
  The quality of the runoff from the back side of the dune system to the gulf is positively influenced by an increase of the filtering capability due to the presence of a dune. Thus, alternatives with a higher filtering capability received a positive score for this parameter.

5.3.3. Maintainability

The maintainability of the alternatives depends on the amount of maintenance that is required during the post-storm recovery maintenance that is needed after a storm surge.

- **Maintenance approach**
  The sole parameter that determined the score for this criterion was the maintenance approach. Two types of maintenance are of importance for the land barrier, post-storm dune recovery, and regular beach & dune nourishment. Alternatives that require regular sand nourishment, but have a good post-storm resilient design (meaning that the dune remains some storm protection after a first storm event) were valued with a positive score.

5.3.4. Sociopolitical acceptability

Differences in perception of the structure between people have been found. Therefore, this criterion describes the acceptance of people with regard to their political beliefs and social class. Sea level rise was not taken into account in this criterion, as the current regulations used as input data are based on the current sea level. The parameters used for the scoring of this criteria are listed below:

- **Fitting of the dune**
  Alteration of the current coastline at the West End is not favorable. Thus, alternatives affecting the current coastline the least received a positive score for this parameter.

- **Effect on the line of sight**
  Any alternative, except for the 0-option, raises the elevation of the land in front of the houses along the beachfront and thus blocking the view over the Gulf. Alternatives having more effect on the line of sight received a negative score for this parameter.

- **Accessibility**
  The Texas Open Beaches Act (TGLO, n.d.) states that the public should have unrestricted access to the beaches of Texas along the Gulf. Thus, any alternative should have a way to provide access to the beach in front of the dune system. Texas General Land Office (2011) provides guidelines on how to comply with the Open Beaches Act. The public of Galveston Island West End is afforded access to beached by dune walkovers. More information about dune walkovers can be found in Appendix N.1. Alternatives complying with these guidelines received a positive score.

5.4. Absence of weight factors

No weight factors were given to the criteria due to this research having an advising point of view instead of being of a judgmental nature. Although it is inherent to a storm surge barrier that the storm surge coping capability is the governing criterion in any sort of analysis, the distribution of the exact weight factors to the criteria is a whole study by itself.

6

Results

This chapter provides an elaboration of the results of the study, starting with the general results, followed by the description of the results of the criterion maintainability, sociopolitical acceptance, storm surge coping capability and stormwater drainage impact.

6.1. General results

The general results show how the proposed alternatives score with regard to the criteria. An overview of the results of the criterion and the attached parameters is given in Table 6.1. The results of each criterion are elaborated in Section 6.1.1, Section 6.1.2, Section 6.1.3 and Section 6.1.4. The general results are further discussed in Chapter 7.

Table 6.1: Scoring table of the final results.

Criteria	0-option	Alt. 1	Alt. 2	Alt. 3	Alt. 4
Storm surge coping capability	**-**	**-**	**+**	**+**	**+**
Erosion during normative event	-	-	+	+	+
Wave overtopping capability	-	0	+	+	+
Stormwater drainage impact	**-**	**-**	**-**	**-**	**-**
Obstructive impact	0	-	-	-	-
Quality impact	-	+	+	+	+
Maintainability	**0**	**0**	**+**	**+**	**0**
Maintenance approach	0	0	+	+	0
Sociopolitical acceptability	**+**	**-**	**-**	**-**	**-**
Fitting of the dune	+	-	-	0	0
Effect on the line of sight	+	+	-	-	-
Accessibility	+	+	-	+	+

6.1.1. Storm surge coping capability

The quantitative results obtained from the XBeach model runs, grouped by the intensity of a 10 year storm, 50 year storm and a 100 year storm can be found in Appendix O.1. The validation of the process of XBeach are described in Appendix L. It can be concluded that the 0-option and alternative 1 do not perform well under conditions with a lower return period than 10 year storm. The 0-option caused also the largest over-topping rates. Therefore this alternative is rated with a '-'. The Wave overtopping capability of Alternative 1 is graded with a '0', because it has not too damaging consequences. However, the storm surge coping capability of alternative 1 is still graded with a '-'. Alternative 2, 3 and 4 have been rated with a '+', since these alternatives are able to withstand the heavier storms as well as withstanding the overtopping.

6.1.2. Stormwater drainage impact

An extensive description of the results of the parameters Obstructive impact and Quality impact can be found in Appendix O.2. From the results it can be concluded that all the alternatives do not perform well under the parameter of stormwater drainage impact. For the 0-option, this is due to low runoff quality affecting beach water. For the various alternatives of the dune barrier, this is due to obstruction of drainage paths, leading to an increase in ponding volumes on the inner side of the dunes. Therefore all the alternatives are rated with a '-'.

6.1.3. Maintainability

A description on Maintenance approach can be found in Appendix O.3. The most important aspect for the evaluation of the maintainability was determined by the amount in which a dune system could naturally recover due to storm surge driven events that were discussed and modeled in this research, thus the storm surge coping capability of the dune is an important factor in the evaluation of the maintainability. Comparison of the results shows that the 0-option and alternative 1 scored a '0', meaning both alternatives can naturally recover after 10 year storms, but not after 50 year or bigger storm events. Alternative 2 and 3 scored positive, due to the fact that these alternatives scored well on retaining storm surge capabilities and needing relatively little artificial maintenance. This also holds for alternative 4; however, the alternative was assigned a '0', because of the unknown behavior of the clay core.

6.1.4. Sociopolitical acceptability

The results of the parameters Fitting of the dune, Effect on the line of sight and Accessibility are further elaborated in Appendix O.4. From the results it can be concluded that only the '0-option' performs well under the criteria of sociopolitical acceptance. This indicates people do not like anything to change on the current situation. According to the results, alternative 2 does not perform well under the criteria of sociopolitical acceptance. Meaning it does not fit or meet the requirements as set by the Texas Beach Accessibility Guide. On top of that it also blocks the landscape view of properties on the first line after the dune, so alternative 2 is valued with a '-'. Alternative 3 and 4 have scored well on Accessibility and neutral on Fitting on the dunes. However, the criterion received a negative score, because it provide visual block to the homeowners of the first line after the dune.

III
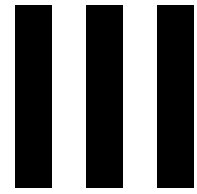
Discussion, conclusion and recommendations

7

Discussion

7.1. General interpretation results

Looking at the results, the different alternatives score well on different parameters; none of the alternatives received a positive score on each of the four criteria. This will inevitably lead to a discussion on prioritization. In this research, storm surge coping capability was determined to be the leading criterion, or, even stronger, a boundary condition. This means that a certain elevation is required for an alternative to fulfill its role as a land barrier at all. Building an alternative which is lower than the required elevation seems to be a wrong investment, since it would not able to function as a coastal defense system. However, this research did not determine this exact elevation, but rather assessed four proposed alternatives upon different criteria.

According to the applied XBeach model, the higher dunes are able to withstand high intensity storms, such as Hurricane Ike. This is in contrast to the 0-option and the alternative proposed by the USACE. The XBeach model output plots showed large amounts of eroded sand and overtopping rates for these alternatives. This would mean a destruction of the entire island and generating problems for the Houston industrial and metropolitan area. When the profile flattens, Galveston Island loses its function as a barrier island for the Galveston Bay. With an increased fetch and more water flowing into the bay, Houston industrial and metropolitan area could face devastating consequences. The construction of a dune would limit this overtopping rates and the flattening of the dune system. A dune with a higher level of safety offers more protection for reoccurring storms in a limited space of time, as post storm maintenance is required less.

An explanation for these major damages is the fact that the 50 year design storms have a surge level which is almost as high as the dune elevation itself. Combined with the given wave heights this would automatically lead to an overwash regime (Asbury H. Sallenger, 2000). Furthermore, it can be seen in the resulting profiles for the 0-option and alternative 1 for high intensity storm that the wave height does not decrease very much when it approaches the surf zone, which would normally be the case. This is due to the fact that the profiles are already flattened after a short period, causing the waves not to break and lose height. Due to the fact that these alternatives face large sand losses, they did not score well for the 'maintainability' parameter. As expected, these dunes would have to be built up again after a storm event, which would result in excessive maintenance costs.

A striking finding is that the 100 year storm gave a less eroded sand volume than the 50 year storm with a long duration. This implies that the duration of a storm, at certain water levels, has a big influence on the level of damage.

The 0-option and alternative 1 show, as expected, good scores for the Effect on line of sight and the Accessibility. These alternatives are not going to block the sea view and are not projected to have any problems providing beach access. The alternatives with a larger elevation, alternative 2, 3 and 4, do not score well for these criteria. The designed elevation of these alternatives is simply larger than the first floor's elevation of the houses close to the beach. The dune with the largest elevation, alternative 2, scores worst on Accessibility due to the fact that the beach would be difficult to access. The other high elevation dunes, alternatives 3 and 4, would face difficulties providing beach access but this would be solvable.

A distinction was made between a hybrid dune with a concrete core and one with a clay core. The hybrid dune system was introduced in order to save costly sand and to still have a certain defense structure after a severe storm has hit the coast. Muller (2017) showed that a hybrid system performs better than a single sea wall, in terms of reducing the wave height. Despite the fact that the concept of a hybrid dune is relatively

new, and not much could be said about the differences in a technical sense, there are some differences in acceptability and maintainability of these options. People would prefer to see a concrete core instead of a clay hope after a storm event, according to a few Galveston officials. However, clay is wider available and moreover cheaper than building a concrete core. Alternatives 3 and 4 have good scores for Maintainability, since less sand has to be renourished after a storm event. However, even more sand could have been saved by reducing the depth of sand cover and achieve greater level of risk reduction for the hardened core options. More runs should have been done with successive hurricanes and different forms of hybrid dunes in order to find an optimum in this case.

In contrast to the other criteria, no distinction could be made between alternatives by scoring them on their drainage capacity. The score on Stormwater drainage impact is negative for all alternatives. In the current situation, a significant area drains urban runoff and the related pollutants towards the Gulf coast. The presence of a dune barrier reduces discharge on the beach and can provide filter possibilities, improving on beach water quality. The down side of this favorable consequence is a large increase in volume of ponding water. In the current situation, ponding and flooding already occur frequently at the West End, and increased volumes would severely aggravate experienced issues.

Interpretation of the results for stormwater drainage impact shows very small daily discharges through the dunes. This leaves approximately all runoff as ponding volume, disregarding the intensity of precipitation. Although both stormwater drainage and storm surge calculations were performed using extreme events, issues related to stormwater volumes will aggravate for very regular rain events as well. Due to the frequency of occurrence, these issues are closer related to the daily value of the dune system rather than the protective value in case of an extreme event, and the construction of a dune system can therefore generally lead to a decrease in quality of everyday life. Solutions for these drainage issues should be incorporated without affecting the storm surge coping capability of the barrier in order to create a suitable design for the land barrier. Appendix C.4 lists and evaluates potential solutions that could be incorporated in the design. This evaluation showed that implementation of a dune infiltration system could potentially be a valuable solution to deal with drainage issues, but impact on the protective function of the barrier against storm surge is still to be analyzed. In general, spreading volumes over the area instead of canalization towards a single outlet point can reduce issues at these outlet locations.

One has to keep in mind that the dune system should have one main function: providing a certain level of safety against potential hurricanes, not only for Galveston Island itself but also for the entire underlying area. The daily value of this dune system should also be taken into account but should be secondary to the main function. The daily value refers to the impact of the dunes on people's daily lives. A dune blocking the sea view or a dune causing the beach to be non accessible means negative impact on daily life for example. However, a more socially accepted design scores less on storm surge coping capability aspects and vice versa.

The stakeholders at the West End of are considered as part-time Galveston Island residents and have wishes that contradict the main purpose of the dune system by prioritizing aesthetics over functionality. These people are willing to take the risk that their surroundings could be flooded and hurricanes cause damage to their properties. Regardless of the dune system that is chosen eventually, it is important to clearly state the boundary conditions for a dune system. What is its purpose, which area will be protected by it (only the Galveston Island, or the Bay area), who will benefit and how, are questions that should have clear answers. This information is vital for stakeholder prioritization. Some stakeholders need only to be informed, others need to be actively involved in the process. The latter consists among other things of the decision makers and the financing institutions. An advise on the governance strategy is given in Appendix G.3.

If the dune system would have a major role in the proposed coastal defense system for the entire area, which is claimed by the USACE, alternative 1 would perform better on the Storm surge coping capability and the Stormwater drainage impact. Alternative 1 has been modeled in XBeach as if it is a model on its own, without the other aspects of the tripartite plan. It is unknown how this plan functions altogether and how the different parts of the plan function independently and thus the decision was made to model the dune system as it is a separate plan. Furthermore, when scoping to the entire Galveston Bay area, stakeholders on the West End of Galveston should not be considered as a priority stakeholder group. It is, however, inevitable that this leads to great resistance from these local residents.

In the following section the general research limitations are pointed out. The limitations per criterion can be found in Appendix P.

7.2. General limitations

- The stakeholder analysis is a biased to social acceptability from only a part of the residents of the entire Galveston Bay area. This is due to the fact that mostly people from the island have been taken into account. People, not owning any houses close to the beach, would care less about the effect on the line of sight requirements and value protection as more important than aesthetics. The main concern of the inhabitants of the island is whether the dune system negatively influences the architectural integrity, cultural tourism or impede the local (industrial) businesses and is able to prevent water flowing into their area. However, the plans are projected to positively influence the local businesses as well: the Port of Houston is nation's number 1 port for exports, thus flood protection is vital to protect an essential part of the economy of the USA.

- The method for calculating dune volume can greatly underestimate the true volume requirement for the alternatives in which the coastal line is advanced seaward. The obtained volume should be added to the volume required to advance seaward the entire nearshore beach system a distance X.

- The absence in this research to investigate the influence of the proposed alternatives to the ecology is a big limitation. The research team was aware of the fact that any form of protection would have influence on the ecology. Due to the lack of expertise to provide a thorough study on this subject, there is decided to leave this subject out of the study scope.

- No model runs or tests have been executed with the combined effects of rainfall and storm surge. Most of the time, hurricanes not only cause large storm surge levels at sea, but also cause heavy rainfalls. In this research, these topics have only been examined separately.

- In this research the initial construction costs of each alternative have not been taken into account, whereas this could give valuable information while comparing the alternatives.

- Weight factors should be added to the different criteria and parameters when choosing one alternative from the assessment. However, the level of safety would have received a weight factor significantly larger than the other criteria, due to the fact that, in the first place, a dune system should be able to withstand severe storms.
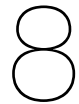
8
Conclusion

This research aimed to identify the effect of technical and sociopolitical aspects of different dune alternatives for the Galveston Island West End. For this purpose, the dune alternatives proposed by the USACE, and the alternatives proposed by two TU Delft master graduates (L. Galvez and J. Muller), were evaluated using different criteria. A process-based numerical model, XBeach was used to conduct an assessment of the storm surge coping capacity, ArcGIS calculations were used to conduct an assessment on the rainfall coping capacity of the dunes. Furthermore, interviews with individuals, companies and governmental agencies in combination with a literature review led to insights into sociopolitical criteria. To conclude this report, the research questions are stated again.

To what extent do the various dune alternatives fit the requirements for a land barrier at the West End of Galveston Island, looking at both technical and sociopolitical aspects?

Three sub-questions were formulated in support of this main research question. These sub-questions are listed and the answers allow to come up with an answer for the main research question. The first two sub-questions directly support the main research question, the third sub-question provides guidelines that were formulated in support of further research regarding the main research question.

1 What are the characteristics of the different alternatives for (hybrid) dune systems that have been proposed as a barrier at the West End of Galveston Island?

Four different alternatives were distinguished and their characteristics were described in Chapter 3. Alternative 1 is the latest proposal of the USACE, which consists of a twin-dune system with two sand dunes. The highest crest has a height of $4.26m$ +MSL. Alternative 2 is a single sand dune with a considerably larger height of $7.5m$. This alternative was proposed by Luis Galvez. Alternative 3 is a hybrid dune with concrete core, with a total height of $6.5m$. Alternative 4 is similar to alternative 3, but with a clay core instead of concrete. Its height is the same as for alternative 3.

2 What are the main requirements for the land barrier at the West End when analyzing technical and sociopolitical criteria?

The main requirements for the land barrier were formulated as follows:

- The land barrier should be able to withstand storm surge in order to protect Galveston Island and the Galveston Bay area. This means that the overflow rate into the Island and the Bay is limited.

- The construction of a land barrier should not lead to an increase in problems related to rainfall at the West End.

- The required post-storm dune maintenance should be minimal in order to maintain a decent storm surge capacity.

- The land barrier should be accepted and supported by various stakeholders, considering a purposeful stakeholder prioritization.

- The organizational approach needs to be an holistic project-operating system in order to improve the performance on predictability and maintenance.

The different alternatives identified in sub-question 1 were assessed based on the first four criteria identified in sub-question 2. This allowed to answer the main research question.

The 0-option and the alternative proposed by the USACE do not meet the main requirement to prevent storm surge from overflowing Galveston Island into the Bay. Both alternatives completely flatten out for a 50 year storm event. This shows that action should be taken with respect to the current situation, but the twin-dune design does not meet storm surge capacity for a 50 year storm in its current form. The other, higher alternatives 3, 4 and 5 perform better.

Rainfall capacity was evaluated with the requirement not to aggravate the current rainfall capacity at Galveston Island West End. None of the dune alternatives met this requirement. Due to obstruction of drainage paths, all alternatives led to an increase in ponding volume. Solutions to solve this issue need to be properly designed and might lead to an increase in beach water quality.

The requirement for maintainability is related to erosion of beach and dunes and mainly focuses on the post-storm recovery maintenance. In case of a storm surge event, alternative 1 completely washes away, while alternatives 2, 3 and 4 show low amounts of erosion. Therefore, less sand is needed for restoration of the dune to its current state. Alternative 2 and the hybrid dune alternatives are preferred for this criterion due to their performance.

Sociopolitical acceptability was analyzed with a focus on the residents of the West End. For them, the height of the dune is a limitation. Therefore, lower dunes score better on this criterion than higher alternatives. Nevertheless, only the 0-option completely fulfills the requirement in the way it was assessed in this report. This resembles the opinion of the people the research team has spoken to: local residents would prefer to keep things as they are.

From the results it can clearly be concluded that alternative 2 with a height of $7.5m$ scores well on storm surge coping capability, but that this results in difficulties regarding accessibility, fitting and effects on the line of sight. This puts an emphasis on the importance of the role of this barrier. Priorities should be clear in order to determine the height that still fulfills the main function of the barrier.

Based on the conclusions of the main research question, the third sub-question can be answered. The third sub-question is stated once more and answered accordingly.

> *3 What guidelines should be considered for design, maintenance and governance for a future proof engineered dune barrier at the West End?*

The guidelines were formulated as follows:

- The main purpose of the land barrier is to prevent storm surge from overflowing the West End of Galveston Island, as a part of a complete coastal spine that protects the Bay area in case of a hurricane. This primary function requires certain minimum dimensions to guarantee the desired level of storm surge capacity for the area that is to be protected. This report did not quantify these dimensions, although it did show that the current design of the USACE does not withstand a 50 year storm. As a guideline, a dune with a significant higher elevation is advised by the research team.

- The final plan for the dune barrier should include a solution for increased ponding volumes due to obstructed drainage paths. This can be done by the capture and redirection of stormwater or incorporation of drainage solutions into the design of the dune system. The latter seems to be particularly interesting because diversion of stormwater is a very large and costly operation.

- Regardless of the dune system chosen eventually, it is advised to clearly define the area that is to be protected from storm surge events by a dune system on Galveston Island. A clear definition of the dune system protection allows for a clear stakeholder prioritization. All stakeholders can and

need to be involved in the process, though some only require to be informed and others require to be actively involved in the design process. If the dune system should have the role of defending the whole Galveston Bay area from severe floods during storm surge events, stakeholders on the Galveston West End should not be considered as priority stakeholder group.

9
Recommendations

This chapter consists of recommendations regarding improvement of further research on an optimum design for the dune system at the West End of Galveston Island.

- It is recommended to consider and thoroughly study on the impact of any of the proposed alternatives on the ecology of the Galveston Island West End. It is advised to focus on the beach salinity, beach circulation and effects on specific fishing industries (such as shrimp, oysters) and native species to Galveston Island, for example the sea turtles and dolphins. An outcome on these effects can ultimately result in a comparison between these alternatives on ecological scale.

- A cost evaluation for both the construction and maintainability of the dune system alternatives should be made in order to make a monetary evaluation.

- The effect of a clay core inside a hybrid dune should be tested and evaluated, in order to determine if the assumptions that were made in this report (that clay reacts similar to the concrete core), were correct or incorrect.

- A combination of alongshore erosion rates from the Galveston Island and the effect of dune vegetation should be determined. An evaluation of the alongshore erosion consequences should be modeled for the different proposed alternatives, in order to determine how much artificial dune restoration would be needed to retain the preferred storm surge coping capacities. Consequently, these results can be used to determine the costs required for maintenance. This includes regular and post-storm recovery maintenance for each dune alternative.

- It should be made clear what the exact role of the dune system would be. How much water should it retain? How much risk would this reduce for the entire area? With the answers on these questions a better substantiated stakeholder prioritization could be set up.

- The alternatives should be tested upon hurricanes occurring in succession, which is not unusual in the Gulf of Mexico. This test provides insights in how the various alternatives perform reoccurring hurricanes. It is expected that in these tests the alternatives with a solid core is going to perform better than the ones without, since a certain level of protection, given by the hardened core, is projected to remain.

- In further studies, it is important to not only take into account stakeholders from the Galveston Island but make the stakeholder scope as large as possible. Only then the bigger picture could be mapped well and certain opinions could be placed in a better perspective.

- Tests with different depths of sand cover should be executed, in order to gain more knowledge about the performance of the hybrid dune option. Also research should be done on an optimum shape of the hardened core. Furthermore, the exact effects of a hybrid dune system on processes close to the dune should be figured out as well as the potentials of a hybrid clay core system. Different scale models can give insights about the optimum performance of a hybrid dune.

- In further studies it is recommended to inspect more transects across the island instead transects limited to five in this study. This is projected to result in varying conditions and thus requiring a solution best fit for every set of conditions.

- It is recommended to execute model runs or tests with the combined effects of rainfall and storm surge in order to get insight into the performances of a certain alternative on this criterion.

Bibliography

B.F. Almarshed. Hydrodynamic design conditions from measured data. Technical report, Texas A&M University, Galveston, 2015.

G.J. Arcement Jr and V.R. Schneider. Guide for selecting manning's roughness coefficients for natural channels and flood plains united states geological survey water-supply paper 2339. *Water-supply Paper*, 2339, 1989.

Jr. Asbury H. Sallenger. Storm impact scale for barrier islands. *Journal of Coastal Research*, 16(3): 890–895, 2000.

Atelier Groenblauw, 2018. Infiltratiestroken met bovengrondse opslag. Retrieved from Amsterdam Rainproof: `https://www.rainproof.nl`.

A. Atreya and J. Czajkowski. Graduated flood risks and property prices in Galveston County. *Real Estate Economics*, 47(3):807–844, 2019.

R.G. Bailey. *Ecosystem geography: from ecoregions to sites*. Springer Science & Business Media, 2009.

M. Bakker, 2018. Principles of Geohydrology Notebook 1: Principles of Groundwater Flow. `https://www.brightspace.tudelft.nl`.

R. Berg. *Tropical cyclone report: Hurricane ike (al092008), 1-14 september 2008*. National Hurricane, Center, 2009.

E.S. Blake and D.A. Zelinsky. Tropical Cyclone Report: Hurricane Harvey. Technical report, National Hurricane Center, 2018.

J. Bosboom and M.J.F. Stive. *Coastal Dynamics I*. 0.5. Delft Academic Press, 2015.

M. Burchell, B. Hunt, and W. Price, 2013. Dune Infiltration Systems for Reducing Stormwater Discharge to Coastal Recreational Beaches. `https://content.ces.ncsu.edu/`.

Bureau of Economic Geology , 2019. Shoreline Change Map. `https://coastal.beg.utexas.edu/shorelinechange2019/`.

Bureau of Economic Geology , 2020. The Texas Shoreline Change Project. `https://www.beg.utexas.edu/research/programs/coastal/the-texas-shoreline-change-project`.

C. Jones. *Coastal Construction Manual: Principles and Practices of Planning, Siting, Designing, Constructing and Maintaining Residential Buildings in Coastal Areas*. Diane Publishing, 2001.

V.T. Chow. *Open-channel hydraulics*. McGraw-Hill Book Co., New York, 1959.

City of Galveston. City of Galveston Master Drainage Plan. Technical report, City of Galveston, 2003.

City of Galveston. Drainage Design Criteria. Technical report, City of Galveston, n.d.

J. Clark. *Coastal zone management handbook*. CRC press, 1995.

T.G. Cleveland, D.B. Thompson, and X. Fang. Use of the Rational and Modified Rational Method for Hydraulic Design. Technical report, Texas Tech University, 2011.

Coastal Protection and Restoration Authority of Louisiana. Louisiana's comprehensive master plan for a sustainable coast. *Coastal Protection and Restoration Authority of Louisiana, Baton Rouge*, 2012.

Coastal Wiki, 2020. Sand transport. `http://www.coastalwiki.org/wiki/Sand_transport`.

G.W. Crenwelge, E.L. Griffin, and J.K. Baker. *Soil survey of Galveston county, Texas*. US Department of Agriculture, Soil Conservation Service, 1988.

H.A.J. de Ridder. *Design and Construct in Civil Engineering, Lecture Notes CT5981*. Delft University of Technology, 2009.

M. de Schipper, 2019. CIE4309 Coastal Dynamics 2, Lecture Notes.

Delta Committee, 1962. Final Report of the Delta Committee. `http://publicaties.minienm.nl/documenten/rapport-deltacommissie`.

Deltacommissie, 2008. Working together with water; a living land builds for it's future. findings of the deltacommissie. `www.deltacommissie.com`.

Deltares, n.d. XBeach Open Source Community. `https://oss.deltares.nl/web/xbeach/`.

N. Dhakal, X. Fang, T.G. Cleveland, and D.B. Thompson. Revisiting modified rational method. pages 751–762, 2011.

Division of Watershed Management. Chapter 5: Computing stormwater runoff rates and volumes. *New Jersey Storm water Best Management Practices*, pages 5–22, 2004.

J.P. Doody. *Sand Dune Conservation, Management and Restoration*. Springer Science and Business Media, 2012.

M. Dyck, 2017. Port of Houston: The Nation's Largest Petrochemical Complex . `https://www.ocean-insights.com/article/port-of-houston-the-nations-largest-petrochemical-complex/`.

Encyclopaedia Britannica, 2017. Galveston Bay. `https://www.britannica.com/place/Galveston-Bay`.

Li Erikson, Magnus Larson, and Hans Hanson. Laboratory investigation of beach scarp and dune recession due to notching and subsequent failure. *Marine Geology*, 245(1-4):1–19, 2007. ISSN 0025-3227. doi: 10.1016/j.margeo.2007.04.006.

FEMA, 2016. National Disaster Recovery Framework .

FEMA. Historic Disaster Response to Hurricane Harvey in Texas. *HQ-17-133*, 2017a.

FEMA, 2017b. National Incident Management System.

J. Figlus and Y.K. Song. Galveston Beach Rainwater Runoff Investigation. Technical report, Texas A&M University at Galveston, 2019.

J. Figlus, N. Kobayashi, C. Gralher, and V. Iranzo. Wave-induced overwash and destruction of sand dunes. *Coastal Engineering Proceedings*, 1(32):sediment.34, Jan. 2011. doi: 10.9753/icce.v32.sediment.34.

G. Fleit. *Numerical modeling of complex free surface flows*. PhD thesis, "Budapest University of Technology and Economics", 06 2015.

A.E. Frey, A. Morang, and D.B. King. Galveston Island, Texas, Sand management strategies. Technical report, US Army Engineer Research and Development Center Vicksburg United States, 2016.

Galveston Central Appraisal District, 2020. Galveston Central Appraisal District Property value. `http://www.galvestoncad.org/`.

Galveston County, 2017. Galveston County Dune Protection and Beach Access Plan. `https://glo.texas.gov.html`.

Galveston Island Park Board of Trustees, n.d. Galveston Island Beaches, Real-Time Beach Watch Advisories. `https://www.galvestonbeachinfo.com/conditions.asp`.

L. Galvez. Dune Based Alternative to Coastal Spine Land Barrier in Galveston Bay. Technical report, Delft University of Technology (TU Delft), 2019.

GLO. Coastal Erosion Planning & Response Act. Technical report, Texas General Land Office, 2016-2017.

Google, 2020. Google maps. `https.//www.google.nl/maps/place/Galveston`.

D.L. Harris. *Characteristics of the hurricane storm surge*. 48. Department of Commerce, Weather Bureau, 1963.

C. Harter, J. Figlus, and T. Dellapenna. The role of hurricanes on the morphological evolution of a sediment-starved barrier island along the upper texas coast: Follets island. 07 2015. doi: 10.1142/9789814689977_0005.

Hoonhout, B., 2015. XBeach User Manual. `https://xbeach.readthedocs.io/en/latest/xbeach_manual.html`.

K. Howard, K. Laverty, and N. Ekstrom. *Galveston Island Sand Dunes Maintenance Manual*, 2013.

I-STORM, 2020. International network for storm surge barriers. `https://www.i-storm.org`.

Vexcel imaging, 2020. Aerial photographs from Galveston Island. `https://www.vexcel-imaging.com/`.

B. Keim, R. Muller, and G. Stone. Spatiotemporal patterns and return periods of tropical storm and hurricane strikes from texas to maine. *Journal of Climate - J CLIMATE*, 20, 07 2007. doi: 10.1175/JCLI4187.1.

A. Kennedy, A. Asce, U. Gravois, S. Asce, and B. Zachry. Observations of landfalling wave spectra during hurricane ike. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, 137, 05 2011a.

A. Kennedy, U. Gravois, B. Zachry, J. Westerink, M. Hope, J. Dietrich, M. Powell, A. Cox, R. Luettich, Jr, and R. Dean. Origin of the hurricane ike forerunner surge. *Geophysical Research Letters - GEOPHYS RES LETT*, 38, 04 2011b. doi: 10.1029/2011GL047090.

Kent, J., 2019. A Double Edged Sword for Anglers.

C. Kousky and L. Shabman. Policy nook:"Federal funding for flood risk reduction in the US: Pre-or post-disaster?". *Water Economics and Policy*, 3(01):1771001, 2017.

J. Lee Jr. City of Galveston Dune Protection and Beach Access Plan. Technical report, Coastal Strategies Group, LLC, 2017.

L.Tanner, C. Jones, D. Low, and W. Wilson. Floodplain Management Regulations, Building Codes, and Standards Mitigation Assessment Hurricane Ike. *Mitigation Assessment Team Report*, 2013.

M. Lundy. Climate change and the nuclear option. *Berkeley Scientific Journal*, 23(1), 2020.

W.M.J. Luxemburg and A.M.J. Coenders, 2017. CIE4400 Hydrological Processes and Measurements, Lecture Notes.

M.E. Mann and K.A. Emanuel. Atlantic hurricane trends linked to climate change. *Eos, Transactions American Geophysical Union*, 87(24):233–241, 2006.

M. L. Martínez, J. B. Gallego-Fernández, and P.A. Hesp. *Restoration of Coastal Dunes*. Springer, 2013.

M. Michon, 2018. Grasbetonstenen. Retrieved from Amsterdam Rainproof: `https://www.rainproof.nl`.

R.A. Morton and J.G. Paine. *Beach and Vegetation-Line Changes at Galveston Island, Texas: Erosion, Deposition, and Recovery from Hurricane Alicia. Geological Circular 85-5.* University of Texas at Austin, Bureau of Economic Geology, 1985.

MRLC Consortium, 2011. 2011 National Land Cover Database - Multi-Resolution Land Characteristics Consortium. `http://www.mrlc.gov/`.

J.R.M. Muller, 2017. A hybrid solution for the galveston seawall. Additional thesis, TU Delft.

J.R.M. Muller, J. Figlus, and S. Vries. Xbeach simulation of hybrid coastal protection: A galveston seawall test case. *Coastal Engineering Proceedings*, 1:100, 12 2018. doi: 10.9753/icce.v36.papers.100.

R.A. Muller. A synoptic climatology for environmental baseline analysis: New orleans. *Journal of Applied Meteorology*, 16(1):20–33, 1977.

NASA, 2020. Global Climate Change: Vital Sings, Global Temperatures. `http://climate.nasa.gov/scientific-consensus`.

NOAA, 2007a. Galveston, Texas Coastal Digital Elevation Model. `https://www.ncei.noaa.gov/metadata/geoportal/rest/metadata/item/gov.noaa.ngdc.mgg.dem:403/html`.

NOAA, 2007b. Coastal elevation models. `https://www.ngdc.noaa.gov/mgg/coastal/coastal.html`.

NOAA, 2007c. Relative Sea Level Trend. `https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=8771510`.

NOAA, 2017. Billion-Dollar Weather and Climate Disasters: Overview. `www.ncdc.noaa.gov/billions`.

NOAA, 2020a. National data buoy center. `https://www.ndbc.noaa.gov`.

NOAA, 2020b. Galveston Temperature and Precipitation Climate Graphs. `https://www.weather.gov/hgx/climate_graphs_gls#2019`.

NOAA, 2020c. What is the difference between a hurricane and a typhoon? `https://oceanservice.noaa.gov/facts/cyclone.html`.

NOAA, 2020d. Relative Sea Level Trends for Tropical and Gulf of Mexico. `https://www.ncdc.noaa.gov/cdo-web/results`.

NOAA Atlas 14, 2014. Point Precipitation Frequency Estimates: TX.

J.G. Paine. Subsidence of the texas coast: inferences from historical and late pleistocene sea levels. *Tectonophysics*, pages 445–458, July 1993.

I. A. Penn and G. B. Pennix. *Records management handbook*. Routledge, 2017.

A. Perrone, 2019. The design of risk sharing to promote cooperation. Master thesis, TU De;ft.

T.Q. Phan and E.M. Airoldi. A natural experiment of social network formation and dynamics. *Proceedings of the National Academy of Sciences*, 112(21):6595–6600, 2015.

J. Phillips. A sediment budget for Galveston Bay. Technical report, University of Kentucky, 2005.

Port of Galveston, n.d. The Port of Galveston is opened for many of your needs. `https://www.portofgalveston.com/240/onlinespecial?gclid=Cj0KCQjwj7v0BRDOARIsAGh37iqWBFWoy1ESR36EbTUjybEaFR5aw6gZ6_KdIkoevk-b7qEBHMRfcjUaAl9MEALw_wcB`.

N. Powell. 10 years after ike, galveston has bounced back but questions remain on island's long-term survival. *Houston Chronicle*, Sep 2018.

M.G. Ramos. Galveston's Response to the Hurricane of 1900. *Texas Almanac. Accessed January*, 11, 2013.

J. Rijke, S. van Herk, C. Zevenbergen, and R. A. Room for the River: delivering integrated river basin management in the Netherlands. *International Journal of River Basin Management*, 10(4):369–382, 2012. doi: 10.1080/15715124.2012.739173.

Rijkswaterstaat, 2016. Verhoog de waarde van je project, Value Engineering. `www.rijkswaterstaat.nl/`.

Rijkswaterstaat, 2019. Toekomstige opgave rijkswaterstaat: Perspectief op de uitdagingen en verbetermogelijkheden in de gww-sector. `https://www.rijksoverheid.nl/documenten/rapporten/2019/06/11/toekomstige-opgave-rijkswaterstaatl/`.

D. Rooze, M. van Hugten, N. Huijsman, and N. Kok, 2018. Floodproof Galveston: A multidisciplinary project on flood risk and exploration of effective mitigation measures for the City of Galveston. Multidisciplinary project, TU Delft.

Henrik Rye, Oistein Johansen, Ismail Durgut, Mark Reed, May Ditlevsen, and ERMS JIP. Erms report no. 21: Restitution of an impacted sediment final report. Technical report, ERMS, 08 2006.

J. Scata. A new flood protection standard for the us flooding problem. *Natural Resources Defense Council, Mar*, 13, 2018.

G.J. Schiereck and H.J. Verhagen. *Introduction to Bed, bank and shore protection*. Delft Academic Press, 2016.

Texas A&M / DEM Risk Area maps, 2020. Risk area maps. `https://tamug.edu/ctbs/web-tools.html`.

Texas A&M at Galveston, n.d. Texas A&M University at Galveston is the source for all things "ocean-oriented" at Texas A&M University. `https://www.tamug.edu/`.

Texas Coastal Atlas, 2020. Overall hazard risk score. `https://portal.texascoastalatlas.com/buyersbwhere/riskdescription.html`.

Texas Demographics by Cubit, 2020. Texas Cities by Population. `https://www.texas-demographics.com/cities_by_population`.

Texas Department for Licensing and Regulation, Weather Modification, n.d. Weather Modification: Frequently Asked Questions.

Texas General Land Office. Texas Beach Accessibility. Technical report, George P.Bush Commissioner, 2011.

Texas Living Waters Project, 2017. Understanding subsidence in the Houston-Galveston region. `https://texaslivingwaters.org/groundwater/subsidence-houston-galveston-region/`.

TGLO, n.d. In Texas, public access to Gulf Coast beaches is not just the law, it is a constitutional right. `www.https://glo.texas.gov/coast/coastal-management/open-beaches/index.html`.

The Texas General Land Office, n.d. The Republic of Texas Created The General Land Office in 1836. `https://www.glo.texas.gov//`.

The University of Texas at Austin, 2017. Geologic Wonders of Texas. `http://www.beg.utexas.edu/UTopia/coastal/coastal_rock.html`.

The University of Texas Medical Branch, n.d. The University of Texas Medical Branch at Galveston. `https://www.utmb.edu/`.

Tourism Economics. The Economic Impact of Tourism on Galveston Island, TX. Technical report, Oxford Economics company, 2018.

TU Delft. *SwanOne User Manual, V1.3*, 2018.

TxDOT. Hydraulic Design Manual. Technical report, Texas Department of Transportation, 2019.

United States Census Bureau, 2020. Galveston City, Texas Demography. `https://data.census.gov`.

United States Department of Agriculture. Part 645 Construction Inspection National Engineering Handbook, Chapter 11: Drains and Filters. Technical report, United States Department of Agriculture, 2016.

United States Geological Survey, 2018. USGS NED 1/3 arc-second n30w095 1 x 1 degree IMG 2018. `https://viewer.nationalmap.gov/basic/#productSearch`.

United States Geological Survey, 2019. USGS NED 1 arc-second n30w096 1 x 1 degree ArcGrid 2019. `https://viewer.nationalmap.gov/basic/#productSearch`.

U.S. Climate Data, 2020. U.S. Climate Data. `https://www.usclimatedata.com/`.

US EPA, 2003. Protecting Water Quality from Urban Runoff. `https://www.epa.gov/npdes/npdes-stormwater-pollution-additional-documents`.

US EPA, n.d. Water Enforcement. `https://www.epa.gov/enforcement/water-enforcement`.

USACE. Galveston Island, Texas, Sand Management Strategies. Technical report, USACE, July 2016.

USACE and GLO. Coastal Texas Protection and Restoration Feasibility Study. Technical report, USACE, 2018.

J.W. Van der Meer, 1988. Rock slopes and gravel beaches under wave attack. Doctoral thesis, TU Delft and Delft Hydraulics Communication.

J.W. van der Meer. Application and stability criteria for rock and artificial units. *Dikes and Revetments: Design, Maintenance and Safety Assessment*, 01 2017.

L. van Kerkhoff and V. Pilbeam. Understanding socio-cultural dimensions of environmental decision-making: A knowledge governance approach. *Environmental Science & Policy*, 73:29–37, 2017.

G. J. van Oldenborgh, K. van der Wiel, A. Sebastian, R. Singh, J. Arrighi, F. Otto, K. Haustein, S. Li, G. Vecchi, and H. Cullen. Attribution of extreme rainfall from Hurricane Harvey, August 2017. *Environmental Research Letters*, 12:124009, 12 2017. doi: `10.1088/1748-9326/aa9ef2`.

L. C. van Rijn. Erosion of coastal dunes due to storms. Technical report, Leo van Rijn sediment, 2013.

Waternet, n.d. Amsterdamse Waterleidingduinen - Hoe het duin het water zuivert. `https://awd.waternet.nl/beleef/waterzuivering/`.

Witteveen+Bos, 2016. Hondsbossche en pettemer zeewering nederland. `www..witteveenbos.com/nl/projecten/hondbossche-en-pettemer-zeewering-nederland/`.

World Population Review, 2020. Galveston, Texas Population 2020. `http://worldpopulationreview.com/us-cities/galveston-population/`.

S. Xian, Lin N., and H. Kunreuther. Optimal house elevation for reducing flood-related losses. *Journal of hydrology*, 548:63–74, 2017.

A

Reference projects

This appendix consists of several projects that are relatable to aspects of the study. This can be on the level of policy, construction and added value.

A.1. Hondsbossche Zeewering

The Hondsbossche and Pettemer Zeewering is a $5.5 km$ long dike along the North Sea in the Netherlands. Its original layout originates from 1880 and the structure did not meet the safety standard for wave overtopping. The reinforcement plan of the dike was created: this plan consisted of a beach in front of the dike. The hybrid solution of a soft measure to reinforce an existing hard structure is an innovative concept. Over 40 million m^3 of sand has been deposited to create a beach that reduces the overtopping of the existing dike. Maintenance of the coastline for 20 years is implemented in this project (Witteveen+Bos, 2016).

A.2. Room for the River programme

The Room for the River programme is the Dutch approach to solve risk for flooding within the Netherlands Rijke et al. (2012). The Room for the River programme used nine nature-based solutions to lower water levels and was a large success due to its strong institutional co-operation and public support. This new governance approach was adopted by the Ministry of Infrastructure and Environment and Rijkswaterstaat (the executive arm of the Dutch Ministry of Infrastructure and the Environment, which is responsible for the design, construction, management and maintenance of the main infrastruture facilities in the Netherlands).

The recently established Delta Programme (2009-2015) is using Room for the River as an example for developing integrated strategies and governance. Rijke et al. (2012) states that Room for the River plays an important role in a transition to integrated river basin management in the Netherlands. As t has overcome the gap between practical implementation of integrated river basin management and strategic policy. This is done by introducing the following four process factors (leadership, capacity building and demonstration, public engagement and research) to enable an integrated approach through stimulating multi-level governance approaches and collaborative approaches which are required for integrated water management.

A.3. I-STORM, International Network of Storm Surge Barrier

The I-STORM network unites public administrations of countries that build, manage, operate and maintain moveable storm surge barriers. The network aims to share and exchange experiences and knowledge on operations and maintenance of large movable storm surge barriers in order to optimise the management of barriers in an innovative way. I-STORM helps its members to accomplish the highest levels of operational safety and reliability to protect people and property against severe floods I-STORM (2020).

The I-STORM network is founded in 2006, as a joint initiative of: Rijkswaterstaat, Waterboard Groot Salland (the Netherlands) and Magistrato alle Acque di Venezia Nuova (Italy) I-STORM (2020), Environmental Agency (UK) and St.Petersburg barrier authority of the Ministry of Regional development (Russion Federation). Recently barrier managers from New Orleans (USA) and Emssperrwerk (Germany) have been

participating in some of the network activities. Since the I-STORM network was established in 2006, several activities have been taking place. Each year an Annual Conference is organised during which barrier managers meet and discuss different topics of similar interests.

The I-STORM network works according to the principles of a Community of Practice and therefore cuts across political barriers and interests. The members of I-STORM are all responsible for storm surge barriers. From this mutual interest, they share and exchange concerns, problems, successes and lessons learned. Looking to enhance their knowledge. The members find that interacting regularly with peers from similar organisations abroad helps build their understanding and expertise on large moveable storm surge barriers I-STORM (2020). Working together, they develop practices that help to establish a common knowledge. Passion and commitment for the operations, maintenance and development of storm surge barriers is what holds the network together.

A.4. Louisiana's Comprehensive Master Plan for a Sustainable Coast

Louisiana's Comprehensive Master Plan for a Sustainable Coast was initiated by Coastal Protection and Restoration Authority (CPRA) of Louisiana to evaluate the performance of potential protection and restoration projects on the Louisiana Coast for the next 50 years (Coastal Protection and Restoration Authority of Louisiana, 2012). CPRA is established as Louisiana's single state entity with authority to develop, implement, and enforce a comprehensive coastal protection and restoration Master Plan.

A.4.1. Importance of coastal protection & restoration

The endurance of Louisiana's communities and economy is deeply connected to the health of the coast and its wetlands. To this end, the State of Louisiana and its partners are planning and building a comprehensive, coordinated suite of projects to simultaneously reduce risks to communities and infrastructure while also enhancing the surrounding coastal habitats and natural resources.

The sustainability of coastal Louisiana requires the restoration of natural processes that drive land building in the Mississippi River Delta and ensuring that measures taken to reduce flood risks are integrated properly. Through the Coastal Master Pan, the state of Louisiana continues to develop and refine a systems-based approach to protect and restore Louisiana's coast. This approach involves building a network of projects that work together to reduce flood risk to communities and industries, restore wetlands and natural resources, and support the livelihoods of those who live and work along the coast.

If no action is taken to protect the coast, Louisiana's culture, economy, and environment will compute experience widespread negative impacts. Coastal Master Plan seeks to address these impacts and make people, businesses, industries, and the environment more resilient. There has never been a more critical time to make meaningful progress to preserve our wetlands and communities depend on them.

A.4.2. Innovation in research and planning

In order to address the land loss crisis, the state is helping to create innovative solutions, drawing upon a wealth of homegrown expertise in planning, design, engineering, and science. Much of these work is happening at the Water Campus in Baton Rouge – an 'incubation hub' where world class experts convene to develop new technologies and techniques to address the problem. These innovation not only serve to address challenges facing the coast, but they are also generating a knowledge base that can be exported to other areas of the world facing similar challenges with coastal issues.

The Coastal Master Plan is designed to provide the leadership needed to save Louisiana's coast. The plan sets forth goals and objectives that reflect the key issues affecting people in and around Louisiana coast. The approach to coastal protection and restoration is founded on state-of the-art science and analysis

through the Coastal Master Plan, as well as studies on the effects of projects in local areas. Coastal Louisiana is also developing the technological tools and expertise to lead such research and planning efforts around the nation and world.

Monitoring
Following the construction of a project, continuous study of conditions, performance, and impacts are crucial to understanding the success of specific coastal restoration and protection strategies. Monitoring involves frequent documentation of the properties and outcomes of the project, the conditions of the infrastructure involved, as well as changing environmental conditions and human activities that could influence project performance. This process serves to guide and optimize planning and design for future restoration projects, and to adjust current projects as needed.

Operations and Maintenance
Once a project is constructed, it undergoes continuous operation and maintenance processes that vary depending on project size, type, and location. Protection project require constant maintenance and are operated according to specific protocols. Restoration projects that involve modifications to natural hydrology may require breaching and degrading of spoil banks and earthen containment levees. Barrier Islands typically include vegetative plantings and sand fences that require routine maintenance and replacement.

Data collection
In addition to building projects, CPRA is investing in progressive, long-term monitoring activities that measures change along our coast and evaluate the overall effectiveness of Louisiana's coastal protection and restoration efforts. Robust monitoring ensures a comprehensive network of coastal data collection activities is in place to support the continued development, implementation and adaptive management of the coastal protection and restoration program.

Adaptive Management
It is not possible to predict with certainty how the Louisiana coast will change under future coastal conditions, with or without additional risk reduction and restoration projects. Adaptive Management means using the best available technical, ecological, economic, and social information to capture and incorporate lessons learned, improve future plans and projects, and optimize operations of existing projects.

A.5. Dune infiltration system in Kure Beach, North Carolina

A dune infiltration system (DIS) is an example of a measure to loose stormwater runoff based on infiltration. Three of these systems were implemented at Kure Beach, North Carolina.

A.5.1. Function

All information in this paragraph is derived from Burchell et al. (2013).

The DIS is designed as a chamber with an open bottom. Stormwater runoff is diverted into these chambers via discharge pipes. Water from the chambers infiltrates the soil, spreading out laterally and mixing with groundwater. Pollutants in the stormwater can be filtered between sand particles, improving on quality of the water that finally reaches the ocean. Overflow pipes are installed for excess flow as a result of heavy storms.

The system relies on infiltration. Therefore, the ability of the soil to transport water is important for proper functioning of the DIS. Values for hydraulic conductivity k preferably are in order of 10 to $100 m/d$. Ideally, the annual mean water table is at least $1m$ below the surface.

A.5.2. Performance

At Kure Beach, these systems were designed to drain catchment areas up to approximately $35,000 m^2$. Infiltration areas vary on the number of chambers and the catchment area to which the system is connected. Data on overflow volumes are available. Overflow is seen as untreated discharge.

A.5.3. Cost

Cost varied between $4,500$ and $7,200$ per $10,000 m^2$ catchment area, depending on the amount of impervious surface. Larger runoff volumes lead to a larger chamber and more discharge pipes.

B

Hydrodynamic processes

In this chapter the physical processes, which were resolved by the XBeach model and were used in the analytical calculations, are elaborated. Simplifications and assumptions relevant for the processes and equations are described in the different sections. When describing the wave action from different wave angles, it is important to note that the situation is simplified to processes with an angle of incidence of 0 degrees, thus normally incident on the coast.

B.1. Short wave processes

B.1.1. Wave energy and radiation stress

The total energy balance for waves is given in Equation B.1. When waves propagate towards the coast, their energy is typically dissipated with a decrease of water depth, with wave breaking as a result.

$$\frac{\delta E}{\delta t} + \frac{\delta}{\delta x}\left(Ec_g\cos\theta\right) + \frac{\delta}{\delta y}\left(Ec_g cos\theta\right) = S - D \tag{B.1}$$

In which:

E is the wave energy $[J]$

c_g is the group celerity $[m/s]$

θ is the angle of incidence

S is the source term of energy $[J]$

D is the dissipation term of energy, induced from white capping and bottom friction $[J]$

Waves change their momentum through in- and outflow of momentum with the particle velocity or via a net wave-induced pressure force (Bosboom and Stive, 2015). The depth-integrated and wave averaged flow of momentum is called the radiation stress, S_{xx}. The radiation stress in cross-shore direction (x-direction) can be described as follows in Equation B.2 (Bosboom and Stive, 2015).

$$S_{xx} = (n - \frac{1}{2})E + n\cos^2\theta E \tag{B.2}$$

In which:

n is the ratio of group velocity and phase velocity $[-]$.

Ratio n is represented in Equation B.3.

$$n = \frac{c_g}{c} \tag{B.3}$$

In which:

c is the wave celerity $[m/s]$

The ratio n increases from $\frac{1}{2}$ to 1 from deep to shallow water, according to linear wave theory as seen in Equation B.4.

$$n = \frac{1}{2} + (1 + \frac{2 \cdot kh}{\sinh(2 \cdot kh)})$$
(B.4)

In which:

k is the wave number $\frac{2\pi}{L}$ $[rad/m]$

h is the water depth $[m]$

The radiation stress in longshore direction (y-direction), S_{yy} and the shear stress S_{xy} are described as follows:

$$S_{yy} = (n - \frac{1}{2})E + n\sin^2(\theta)E$$
(B.5)

$$S_{xy} = S_{yx} = n\cos(\theta)\sin(\theta)E$$
(B.6)

With a normal angle of incidence, thus $\theta = 0$, the radiation stress terms result to be:

$$S_{xx} = (2n - \frac{1}{2})E$$

$$S_{yy} = (n - \frac{1}{2})E$$

$$S_{xy} = S_{yx} = 0$$

Gradients in the radiation stress produces a net force. This is the wave-induced force and in x-direction this is described by:

$$F_x = -\left(\frac{\delta S_{xx}}{\delta x} + \frac{\delta S_{xy}}{\delta y} \right)$$
$$= -\left(\frac{\delta S_{xx}}{\delta x} \right) \quad \text{for normally incident waves}$$
(B.7)

B.1.2. Wave set-down and set-up

When waves approach the shore, the group number increases in intermediate water depths to one. This effect also increases the cross-shore gradient of the radiation stress. Further offshore, the group number in deep water is constant and thus the radiation stress is too. The result is a net force offshore when S_{xx} increases, see Equation B.7. As a result the water level onshore is slightly lower than the water level off shore, called set-down. This balance in forces can be described by:

$$F_x = -\frac{dS_{xx}}{dx} = \rho g h \frac{d\overline{\eta}}{dx} = \rho g(h_0 + \overline{\eta})\frac{d\overline{\eta}}{dx}$$
(B.8)

In which:

$\overline{\eta}$ is the mean elevation [m]

B.1.3. Wave energy dissipation - wave breaking

When waves approach the shore, a critical height of the wave for a certain depth is reached. Waves higher than this critical height are going to break, which results to energy loss in the wave spectrum. Wave breaking can be approximated the criterion from Miche (Equation B.9) and is estimated in respectively in deep and shallow by:

$$\left[\frac{H}{L}\right]_{max} = 0.142 \cdot \tanh(kh)$$

$$\left[\frac{H}{L}\right]_{max,deep} = 0.142 \tag{B.9}$$

$$\left[\frac{H}{L}\right]_{max,shallow} = 0.142 \cdot kh \approx 0.88 \cdot \frac{h}{L}$$

For the shallow water approximation, the breaker criterion, γ, is approximated by Equation B.10, which relates the wave height to the water depth:

$$\gamma = \left[\frac{H}{h}\right] = \frac{H_b}{h_b} \approx 0.88 \tag{B.10}$$

In which:

H is the wave height $[m]$

H_b is the breaker wave height $[m]$

h_b is the breaker depth $[m]$

The bed slope influences the breaker height. The Iribarren parameter is related to the bed slope and wave steepness:

$$\xi = \frac{\tan(\alpha)}{\sqrt{S}} = \frac{\tan(\alpha)}{\sqrt{H_0/L_0}} \tag{B.11}$$

In which:

S is the wave steepness $[-]$

$\tan\alpha$ is the steepness of the beach $[-]$

H_0 is the wave height in deep water $[m]$

L_0 is the wave length in deep water $[m]$, which can be approximated with linear wave theory:

$$L_0 = \frac{gT_p^2}{2 \cdot \pi} \tag{B.12}$$

In which:

T_p is the peak wave period $[s]$

For different ranges of the Iribarren number, different types of breakers apply. This is illustrated in Figure B.1

Spilling	Collapsing
$\xi < 0.5$	$3.3 < \xi < 5$
Plunging	Surging
$0.5 < \xi < 3.3$	$\xi > 5$
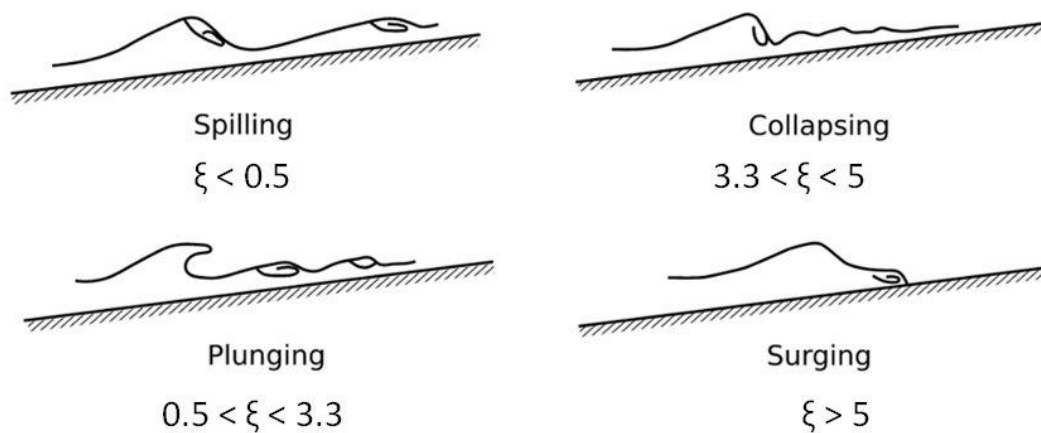
Figure B.1: Breaker types and corresponding Iribarren numbers, edited from Fleit (2015).

B.1.4. Shoaling

If waves move towards a coast while the water depth gets gradually shallower, shoaling will occur (Bosboom and Stive, 2015, p. 160). As the waves approach the coast, deep water conditions decrease as shallow water conditions increase. In other words, the wave propagation speed will decrease, as it gets negatively affected by the decreased water depth. This follows from linear wave theory, represented in its most simplified form in Equation B.13.

$$c = \sqrt{gh} \tag{B.13}$$

In which:

g is the gravitational acceleration on earth, equal to $9.81 m/s$

The expression for wave energy is given in Equation B.14.

$$E = \frac{1}{8} \cdot \rho g H^2 \tag{B.14}$$

In which:

ρ is the density of water, for salt water this is equal to $1025 kg/m^3$

Wave energy can also be expressed as in Equation B.15:

$$E = Dnc \tag{B.15}$$

In which:

D is equal to the wave energy per surface area $[J/m^2]$

As the waves travels toward the coast, the wave energy remains the same. This is represented in Equation B.16, with a substitution of Equation B.14 into Equation B.15. In this and the following equations, subscript o and n represent the "offshore" and "nearshore" situation respectively.

$$H_o^2 n_o c_o = H_n^2 n_n c_n \tag{B.16}$$

Rewriting Equation B.16, with a substitution of Equation B.13 for the wave celerity, n_o to its offshore value $\frac{1}{2}$ and n_n to its nearshore value 1, results in Equation B.17.

$$\frac{H_n}{H_o} = \sqrt{\frac{1}{2} \cdot \left(\frac{h_o}{h_n}\right)^{\frac{1}{4}}} \tag{B.17}$$

Thus it can be concluded that the wave height increases as wave approach an increasingly shallower coastline. This is the phenomenon known as shoaling. Note that the used equations in this section are a simplification, used to qualitatively explain the phenomenon of shoaling.

B.2. Long wave processes

As discussed in Section 4.1, long wave motions play a significant role in the erosion of dunes. These motions are discussed in this section. Long (infragravity) waves are generated by variations in wave height in time and space (i.e. wave groups). The radiation stress varying on wave group timescale is given by:

$$S_{xx}(x,t) = (2 \cdot n - 0.5)E(x,t) = (2 \cdot n - 0.5)(\bar{E} + \hat{E}cos(\Delta \omega t - \Delta k x)) \tag{B.18}$$

In which:

E is the total time varying wave energy $[J]$

$\bar{E}$ is a constant wave energy $[J]$

$\hat{E}$ is a fluctuating wave energy $[J]$

ω is the radial frequency $[degrees/second]$

This formula includes, in addition to Equation B.2, the variations of wave energy on the same wave group timescale of the bichromatic waves. The response of the surface elevation under the wave group is given by:

$$\eta_{l,b}(x,t) = \frac{-(2 \cdot n - \frac{1}{2})}{\rho(gd - \frac{\Delta\omega^2}{\Delta k^2})} \tilde{E}(x,t) \tag{B.19}$$

In which:

$\eta_{l,b}$ is the surface elevation induced by the bound long wave $[m]$

$\tilde{E}$ is sum of the variations in wave energy in the wave group $[J]$

The minus sign indicates a reverse relation between the wave energy and the surface elevation. Note that the closer the last part of the denominator gets to gd, the larger the long wave amplitude gets.

When wave groups enter the surf zone, wave breaking reduces the groupiness. The bound long waves get decoupled from the wave groups and transform into freely propagating long waves. The speed of these free long waves is no longer controlled by the propagation speed of short wave energy, instead they propagate with the speed given by the dispersion relation. As the wave length of the long wave is very long in shallow water, this celerity matches $c = (gh)^{0.5}$. There is a difference between the depth-dependency of bound long waves and freely propagating waves. The depth-dependency of the bound long wave is given by:

$$\hat{\eta}_{l,b} \approx h^{-5/2} \tag{B.20}$$

The depth-dependency of the freely propagating wave is given by:

$$\hat{\eta}_{l,f} \approx h^{-1/4} \tag{B.21}$$

This results in a difference between the amplitude of the incoming and reflective long wave, which can be seen in Figure B.2.
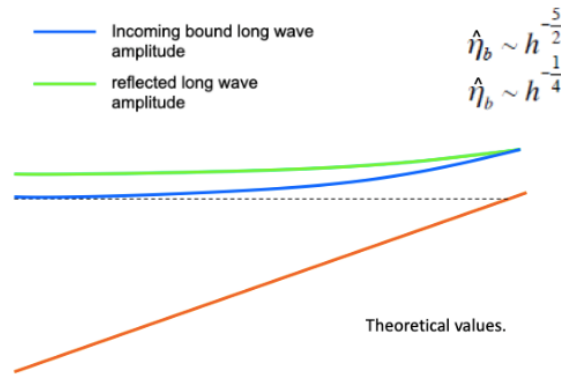
Figure B.2: Amplitude change near shore, edited from de Schipper (2019).

B.3. Wave overtopping, overwash & inundation

A severe storm can damage the dune and even result to destruction of the dune system. Wave overtopping can be a result of a storm with high surge and wave height. As discussed in Section 4.1, overwash is not calculated on its own, but processed in XBeach. The soil transport itself is evaluated in Appendix B.4.

The general description of the overtopping quantity is given by Equation B.22:

$$Q = a \cdot \exp\left(-b \frac{R}{\gamma_{overtopping}}\right) \tag{B.22}$$

In which:

Q is the dimensionless overtopping:

$$Q = \frac{q}{\sqrt{gH_s^3}} \sqrt{\frac{H_s/L_0}{\tan\alpha}}$$

R is the dimensionless freeboard:

$$R = \frac{h_c}{H_s} \frac{1}{\xi}$$

h_c is the crest height, which is the difference in height between the maximum height of the dune alternative and the storm surge level $[m]$

$\gamma_{overtopping}$ is the combined factor for the berm , roughness and incoming angle of attack, which is set to $1[-]$

B.4. Bed load and sediment transport

In this section the key elements of sediment transport are briefly discussed. The magnitude of sediment transport is for the most part dependent on the sediment properties: grain size, density and settling velocity. The settling velocity is an important characteristic of a particle: it says something about the time it takes for a particle to settle. The two important basic equations, which apply to the forces on a sediment particle are given in Equation B.24 and Equation B.23:

$$F_G = (\rho_s - \rho)g\left(\frac{\pi}{6}D^3\right) \tag{B.23}$$

In which:

F_G is the downward directed gravity force on a sphere $[N]$

ρ_s is the mass density of the particle $[kg/m^3]$

ρ is the mass density of the surrounding fluid $[kg/m^3]$

D is the particle diameter $[m]$

g is the acceleration of gravity $[m/s^2]$

$$F_D = \frac{1}{2} \cdot C_D w_s^2\left(\frac{\pi}{4}D^2\right) \tag{B.24}$$

In which:

F_D is the upward directed drag force $[N]$

C_D is the drag coefficient $[-]$

w_s is the particle fall velocity $[m/s]$

Sediment can only be transported if the shear stress τ_b, exerted by the waver movement, is larger than the critical shear stress $\tau_{b,cr}$ of a particle. If this is the case, the particles move or roll. The Shields parameter θ_{cr} is used in the Shields curve to indicate whether a sediment particle moves or is in rest. The Shields parameter is given by Equation B.25:

$$\theta_{cr} = \frac{\tau_{b,cr}}{(\rho_s - \rho)gD} = C \tag{B.25}$$

In which:

C is a constant, which has to be determined experimentally

In Figure B.3 the plotted line indicates initiation of motion. A value for the Shields parameter higher than this band means movement of particles, whereas the area underneath the band indicates no motion. On the x-axis the Reynolds numbers is plotted.
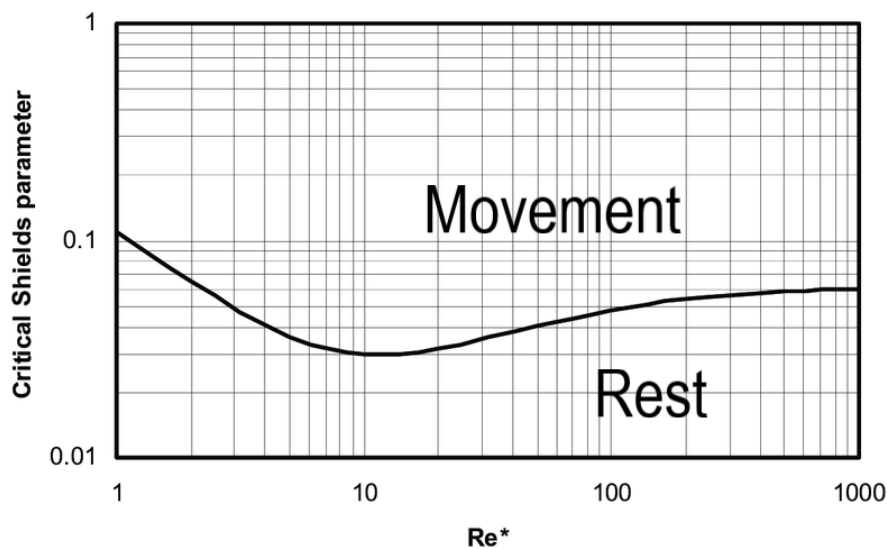
Figure B.3: Shields curve, edited from Rye et al. (2006).

It is important to note that there are two different modes of sediment transport: bed load and suspended load. The bed load consists of the particles which are transported close to the bed, whereas suspended load consists of the sediment particles suspended in the water without any contact with the bed. In Figure B.4 the distinction between suspended en bed load can be clearly seen. Moreover, the velocity and concentration profile of the sediment particles in the vertical direction are also visible.
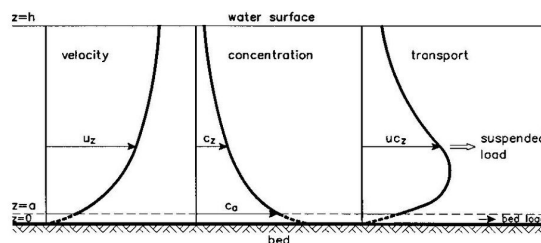
Figure B.4: Bed load versus suspended load, from Coastal Wiki (2020).

B.5. Avalanching

Avalanching can occur due to two different failure nodes, which are shear type and beam type failure. Shear failure is expected to occur for the process when the weight of the overhang due to dune foot erosion (notching) exceeds the shear strength of the sediment. It slides down as indicated in Figure B.5.a,b. Beam type failure occurs when the tension cracks develop landward of the face of the dune and the failure block either rotates Figure B.5.c or slides downward Figure B.5.(Erikson et al., 2007)
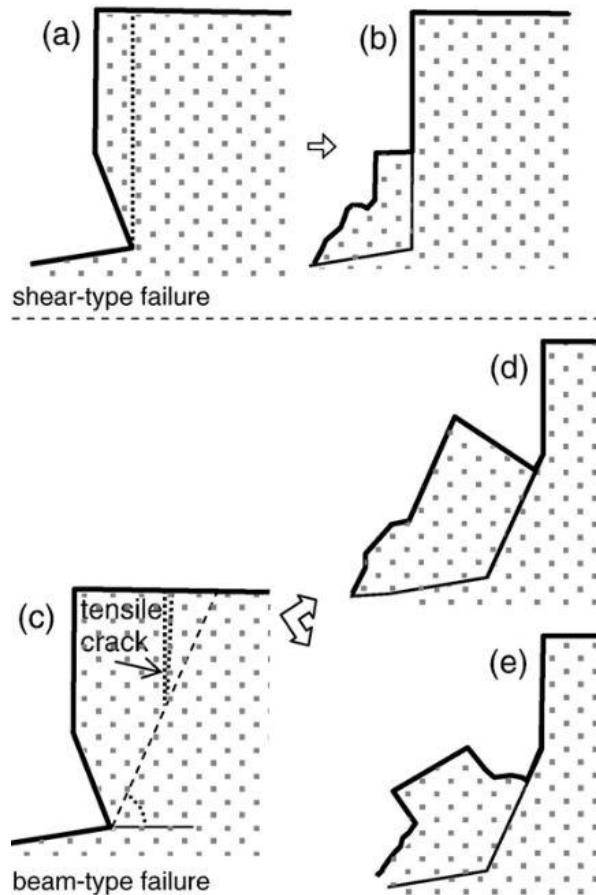
Figure B.5: Failure nodes avalanching , showing shear- and beam-type failure mechanisms Erikson et al. (2007).

B.6. Stability of waves, protection without sand cover

The stability for breaking waves can be described using the equations determined by Van der Meer (1988). From this equation the critical significant wave height for the specific damage level and other breakwater specifics, H_{sc}, can be determined. These equations are given in Equation B.26:

$$\frac{H_{sc}}{\Delta D_{n50}} = 6.2 \cdot P^{0.18} \left(\frac{S}{\sqrt{N}} \right)^{0.2} \xi^{-0.5} \quad \text{(plunging breakers)}$$

$$\frac{H_{sc}}{\Delta d_{n50}} = 1.0 \cdot P^{-0.13} \left(\frac{S}{\sqrt{N}} \right)^{0.2} \xi^{P} \sqrt{\cot\alpha} \quad \text{(surging breakers)}$$

(B.26)

In which:

D_{n50} is the median nominal rock size diameter [m], which is related to d_{50} by (Schiereck and Verhagen, 2016, p.358):

$$D_{n50} \approx 0.84 \cdot D_{50}$$

P is the porosity of the structure [-]

S is the damage level [-]

N is the number of waves [-]

Δ is the relative density [-]

The calculation of the relative density Δ is given in Equation B.27

$$\Delta = \left(\frac{\rho_s - \rho_w}{\rho_w} \right) \tag{B.27}$$

In which:

ρ_w is the density of saline water, equal to 1025 kg/m^3

ρ_s is the density of the solids [kg/m^3]

The transition between the two equations in B.26 is found by equating them, which results in Equation B.28:

$$\xi_{trans} = \left[6.2 \cdot P^{0.31} \sqrt{\tan\alpha} \right]^{\left(\frac{1}{P+0.5} \right)} \tag{B.28}$$

B.7. Analytical approach wave overtopping and stability of waves

This section consists of multiple calculation steps to ultimately come to the wave overtopping rates and the critical significant wave height for the concrete and clay cores.

B.7.1. Iribarren numbers

The Iribarren numbers for the different options and probabilities need to be determined in order to calculate the wave overtopping and critical significant wave height for the different options. The Iribarren number is determined from the wave steepness S and the slope of the dune, as given in Equation B.11. The wavelength can be determined from linear wave theory, as described by Equation B.12 and with the input values of Table H.1 for the different probabilities:

$$L_{0,10} = \frac{g T_{p,10}^2}{2 \cdot \pi} \qquad L_{0,50} = \frac{g T_{p,50}^2}{2 \cdot \pi} \qquad L_{0,100} = \frac{g T_{p,100}^2}{2 \cdot \pi}$$
$$L_{0,10} = 194.45\ m \qquad L_{0,50} = 100.67\ m \qquad L_{0,100} = 100.67\ m$$

Resulting in a wave steepness of:

$$S_{10} = H_{s,10}/L_{0,10} \qquad S_{50} = H_{s,50}/L_{0,50} \qquad S_{100} = H_{s,100}/L_{0,100}$$
$$S_{10} = 0.0244 \qquad S_{50} = 0.0606 \qquad S_{100} = 0.0654$$

The Iribarren numbers can be calculated from the different slopes of the dunes:

$$\xi_{10} = \frac{\tan\alpha}{\sqrt{S_{10}}} \qquad \xi_{50} = \frac{\tan\alpha}{\sqrt{S_{50}}} \qquad \xi_{100} = \frac{\tan\alpha}{\sqrt{S_{100}}}$$

The slope α has been calculated over the whole toe side of the dune and has been summarized in Table B.1.

Table B.1: Slopes of the different dune alternatives.

	0-option	Alt. 1	Alt. 2	Alt. 3	Alt. 4
α	0.0327	0.155	0.159	0.149	0.149
ξ_{10}	0.209	1.00	1.03	0.961	0.961
ξ_{50}	0.133	0.63	0.651	0.609	0.609
ξ_{100}	0.128	0.611	0.627	0.587	0.587

B.7.2. Wave overtopping

Wave overtopping discharges per m width q can be determined with Equation B.22 and B.3. The significant wave height is taken from Table H.1. Combining the latter two equations results in an expression for q:

$$q = Q\sqrt{gH_s^3}\sqrt{\frac{H_s/L_0}{\tan\alpha}}$$

$$q = a\exp\left(-b\frac{R}{\gamma_{overtopping}}\right)\sqrt{gH_s^3}\sqrt{\frac{H_s/L_0}{\tan\alpha}}$$

Now the dimensionless freeboard R needs to be calculated. An expression for this is the following:

$$R = \frac{h_c}{H_s}\frac{1}{\xi_{probability}}$$

$$R = \frac{h_{max,alternative} - SSL_{probability}}{H_s}\frac{1}{\xi_{probability}}$$

The different crest heights are given in Table B.2.

Table B.2: Crest heights for the different options and probabilities.

	0-option	Alt. 1	Alt. 2	Alt. 3	Alt. 4
$h_{c,10}\,[m]$	1.87	3.66	6.86	5.86	5.86
$h_{c,50}\,[m]$	-1.11	0.68	3.88	2.88	2.88
$h_{c,100}\,[m]$	-2.13	-0.86	2.86	1.86	1.86

For the parameters a and b it is key to know whether the breaker is a plunging or surging breaker. As the Iribarren numbers are $<< 5$, it can be said that the breaker functions as a plunging breaker, meaning that a equals 0.067 and b equals 4.75. The overtopping rates were calculated with the previously computed input parameters in this Appendix. A negative crest height resulted in high overtopping rates and these are left out of the results. The resulting overtopping rates in l/s per m width are given in Table B.3. The overtopping rates for the concrete or clay core have also been determined. Compared with the hybrid core option, the only change is the maximum height, which is $2.2m$ lower than with sand on top of the core.

Table B.3: Overtopping rates in $l/s/m$ width per probability.

	0-option	Alt. 1	Alt. 2	Alt. 3	Alt. 4	Core only
$q_{1/10}$	362	110	6.85	11.9	11.9	118
$q_{1/50}$	-	2039	49.6	126	126	2086
$q_{1/100}$	-	-	206	544	544	-

B.7.3. Stability of waves, hybrid dunes

From Equation B.26 the critical significant wave height for the different hybrid dune options can be determined. This specific wave height is calculated from a specified number of waves and a damage level that has been reached, which are 3000 waves and a damage level of 2. This corresponds to a damage level for initial damage (van der Meer, 2017). This level is a precautionary level, as the quality of the concrete and clay core cannot be guaranteed and might have been damaged due to different failure processes, out of the scope of this research project. The cohesion of clay and the strength of concrete has not been taken into account, which is the reason that both nominal diameters have been set on the nominal diameter of the sand on the dune. Furthermore, the density of the solids is assumed to be $2650 kg/m^3$, which is a typical design value for the material.

One Iribarren number has been set for design purposes. This is ξ_{10}, resulting in the smallest wave heights. The input values for the calculation of the significant critical wave height are given in Table B.4.

Table B.4: Input parameters stability waves concrete core.

Parameter	Symbol	Value
Damage level [-]	S	2
Median stone diameter [mm]	D_{n50}	$0.84 \cdot 0.150 = 0.126$
Number of waves [-]	N	3000
Permeability concrete [-]	$P_{concrete}$	0.6
Permeability clay [-]	P_{clay}	0.1
Slope factor of the core [-]	α	0.16
Relative density [-]	Δ	$\frac{2650-1025}{1025} = 1.59$

$$\frac{H_{sc}}{\Delta D_{n50}} = 6.2 \cdot P^{0.18} \left(\frac{S}{\sqrt{N}} \right)^{0.2} \xi^{-0.5}$$

$$H_{sc} = \Delta D_{n50} \cdot 6.2 \cdot P_{material}^{0.18} \left(\frac{S}{\sqrt{N}} \right)^{0.2} \xi_{10}^{-0.5}$$

$$H_{sc} = 0.126 \cdot 6.2 \cdot P_{material}^{0.18} \left(\frac{2}{\sqrt{3000}} 0.961^{-0.5} \right)$$

Table B.5: Critical significant wave height for the concrete and clay core.

	Clay	Concrete
H_{sc} [m]	1.07	1.47

Hydrologic analysis

C.1. Hydrological processes

In this section the hydrological processes relevant for the design and maintenance of the land barrier are discussed. For this purpose, the different components that are relevant for the water balance of Galveston Island are explained.

C.1.1. Climate

The climate at Galveston Island is classified as subtropical, the climate type that prevails in all Gulf Coast states (Bailey, 2009). This climate comes generally with hot and humid summers, and cold to mild winters. Figure C.1 shows the monthly precipitation depth and maximum and minimum temperature for Galveston throughout the year. Low and high temperatures vary between 10 to 32°C (or 50 to 89°F). There is no observable dry season, which is common for a subtropical climate (Bailey, 2009). Hurricanes and tropical storms are common in this region. Muller (1977) classified these storms as a specific weather type for the region, highlighting their frequency of occurrence.
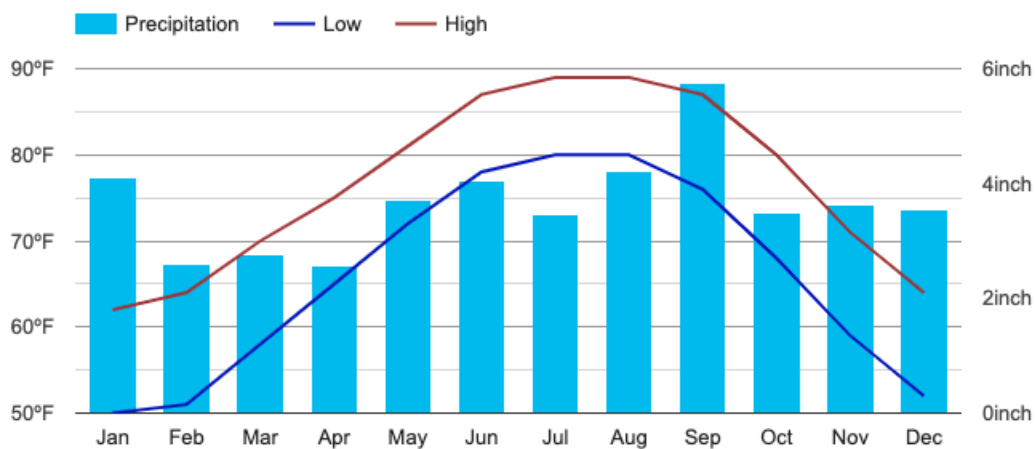
Figure C.1: Monthly precipitation depths in inches and minimum and maximum temperatures in °F for Galveston Island (U.S. Climate Data, 2020)

C.1.2. The water balance

The water balance is a quantitative way to analyze hydrological fluxes for a specified area, based on conversation of mass. This law implies that the total difference between the incoming and outgoing fluxes of a system is equal to the change in storage within that system. In general, this can be expressed by Equation C.1:

$$\Delta S = Q_{in} - Q_{out} \tag{C.1}$$

In which:

ΔS is the change in storage $[m^3/s]$ or $[m]$

Q_{in} is the sum of the incoming fluxes $[m^3/s]$ or $[m]$

Q_{out} is the sum of the outgoing fluxes $[m^3/s]$ or $[m]$

The water balance is applicable on a system bounded in space by a specific area and bounded in time by a specific duration. Therefore, all components $[m^3/s]$ can be expressed in unit of height $[m]$ by dividing each component by the area $[m^2]$ and the duration $[s]$. This research primarily focuses on water that sits on top of the soil. Therefore, the system is bounded by the ground level and hydrological processes that take place in the ground (e.g. groundwater flow, percolation) are not discussed.

Q_{in} is primarily determined by precipitation at Galveston Island, due to the relatively small area and intense rains. By neglecting the subsoil hydrological processes, Q_{out} is dominated by evaporation, infiltration and runoff.

C.1.3. Precipitation

Galveston Island receives high precipitation depths, with a yearly average of approximately 1100mm and a peak in September (see Figure C.1). This peak coincides with hurricane season, but high precipitation depths can be observed regardless of the occurrence of a hurricane. Based on data provided by the National Oceanic and Atmospheric Administration (NOAA), precipitation depths of 75-100mm in one day are not uncommon during most years (NOAA, 2020b). In general, lifting of air is the most important mechanism that results into precipitation. Different lifting mechanisms can be distinguished: convection, orographic lifting, frontal lifting, cyclones and convergence. Convective clouds are the predominant cloud type during the warmest eight months of the year (March-October) in Texas, and are therefore responsible for the largest part of the precipitation (Texas Department for Licensing and Regulation, Weather Modification, n.d.). According to Luxemburg and Coenders (2017), intensities of convective rainfall events can be very high locally, but duration is generally short. The drier period between February and April still receives approximately 65mm of precipitation each month, which can be considered significant.
One way to address precipitation rates is in the form of Intensity-Duration-Frequency (IDF) or Depth-Duration-Frequency (DDF) curves. IDF-curves relate the intensity of a precipitation event to the duration and return period of the event. Higher intensities for the same duration have larger return periods. This curve therefore varies for different return periods. A DDF-curve is based on a similar mechanism, relating precipitation depth to duration and return period. The precipitation depth is obtained by multiplying the intensity and duration. These curves can form a basis for the design of drainage infrastructures, using the precipitation characteristics that belong to the return period of interest. The curves are developed based on historic data.

The IDF- and DDF-curves belonging to Galveston Island are given in Figure C.2. These curves were developed based on data of Scholes Field Weather Station, located at Scholes Airport. As can be seen, intensities decrease when the duration of the shower increases.
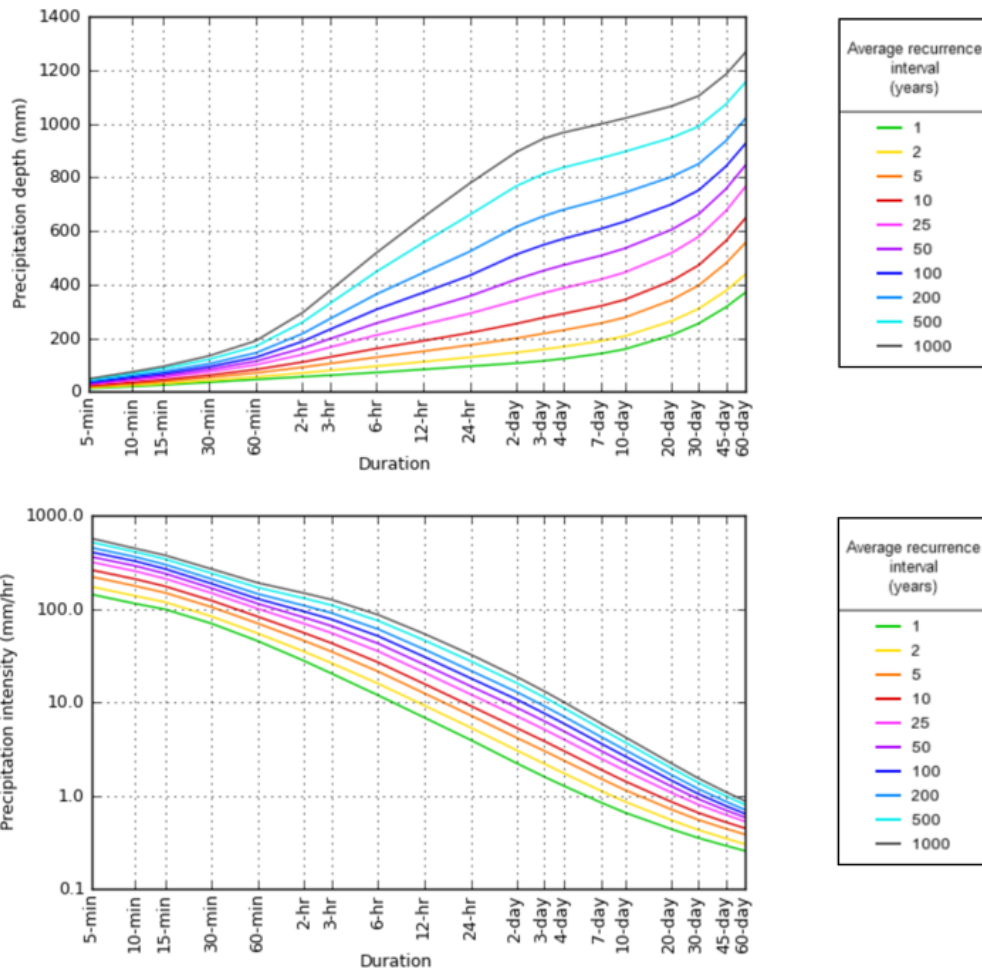
Figure C.2: Depth-duration-frequency curves (top) and
intensity-duration-frequency curves (bottom) for Galveston Island (NOAA Atlas 14, 2014).

C.1.4. Evaporation

Evaporation is generally determined in mm/d, and rates depend on evaporation surface, solar radiation and atmospheric conditions such as relative humidity and temperature. Dry, sunny weather provides ideal conditions for water to evaporate. Rain events however lead to a drop in evaporation rate, due to the decrease of temperature and the increase of relative humidity.

C.1.5. Infiltration

Infiltration is the process by which water on the ground surface enters the unsaturated soil. Infiltration rates are influenced by soil characteristics, soil moisture content, land cover and slope.

Soil type
Figure C.3 shows soil types at Galveston Island. The dominant soil type at Galveston Island is a Mustang - Galveston mixture. Only at the bayside, the soil consists of a Placedo - Tracosa - Veston soil mix (Crenwelge et al., 1988). According to the study of Crenwelge et al. (1988), the soil is rapidly permeable but poorly to somewhat excessively drained. The latter means that the soil is saturated frequently. The Galveston Park Board, the governmental entity that is amongst others responsible for maintenance and supervision of the beaches, classifies the dominant soil type as Mustang Fine Sand, stating that this type

of soil is "generally described as having a 0 to 1% slope in topography, poorly drained ... due to the high water table (found at 0 to 15.6cm), and very low available water capacity" (Howard et al., 2013).
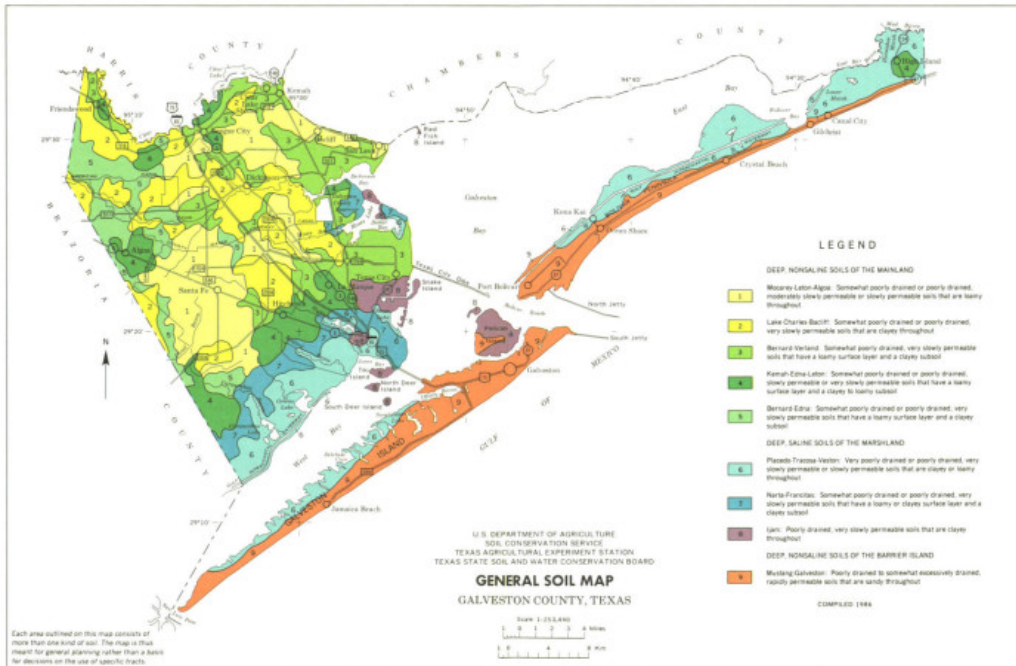
Figure C.3: Geology of the Galveston County (Crenwelge et al., 1988).

Land cover
Infiltration rates are higher in natural landscapes compared to urban areas. Much of the land surface in (sub)urban areas is covered by buildings and pavement, which do not allow rain to soak into the ground. The West End is less densely developed than the main residential area, but urbanized areas still affect infiltration potential.
Because of the high groundwater table, Galveston Island possesses over a very small storage availability in the soil. In combination with a significant area with developed land cover and a poorly drained soil, this leads to very low infiltration rates.

C.1.6. Runoff

Due to low infiltration rates and evaporation rates during rainfall events, a large part of the rainfall is transported above the surface in the form of overland flow. Extensive drainage systems are designed to convey these increased amounts of runoff (US EPA, 2003). The lack of infiltration capability and evaporation during rain events results in large runoff rates on Galveston Island.

C.2. Stormwater at the West End

Part of the City of Galveston is connected to a separate storm sewer as its primary conveyance system, but this part is limited to the area East of Scholes Airport and North of Seawall Boulevard. The West End and Pelican Island generally are not equipped with a storm sewer, but rely on open channel collector systems with culverts and/or bridges, and some supplemental sewer systems (City of Galveston, 2003).

The report "Drainage design criteria", published by the City of Galveston (n.d.), informs and outlines rules about drainage related requirements applicable on developments on Galveston Island, from which the

most important aspects are listed below:

- A design storm with a return period of 25 years is used as a criterion for both the sewer and open systems;

- All new developments must drain North to Galveston Bay, or connect to an existing drainage system that drains to the north side of the island. Drainage to the Seawall or beach areas is prohibited;

- New structures cannot interfere with existing drainage possibilities.

C.2.1. Drainage related problems at the West End

Figlus and Song (2019) mentions frequent ponding and flooding as the main problem reported by residents, even after moderate rainfall events. This was confirmed by residents that were interviewed for this research. In their report further show current areas that drain towards the Gulf beach instead of draining North as prescribed by City of Galveston (n.d.), resulting in potential health risks due to deep scour channels that might lead to injuries and runoff with a low water quality affecting the beach. The quality of runoff is discussed in the next paragraph.

C.2.2. Stormwater runoff quality

Stormwater runoff collects and transports various kinds of pollutants during the route towards the final discharge location, especially in the initial runoff period. In case the runoff is discharged untreated, these pollutants end up in the receiving water body. These uncontrolled stormwater discharges can therefore pose a significant threat to public health (US EPA, n.d.). Urbanization increases the variety and amount of pollutants that is carried by stormwater runoff, including toxic chemicals, pesticides, nutrients, viruses, bacteria and heavy metals. (US EPA, 2003)

At Galveston Island, coastal water quality is monitored by measuring levels of the bacterial indicator enterococcus (Galveston Island Park Board of Trustees, n.d.). Indicator organisms are often used to assess water quality. An increase in measured level of enterococcus is commonly seen after heavy rainfalls and lasts approximately 24 hours.

C.2.3. Consequences of a dune system

The creation of an artifical dune system can have a significant impact on the drainage conditions on Galveston Island. This section describes possible effects on the hydrological situation, and potential mitigation options for negative effects.

Potential effects
Possible effects include:

- Obstruction of current drainage paths for stormwater to the beach. Water would have to move through the dunes to reach the beach. This might increase drainage time and therefore increase issues related to ponding and flooding on the inner side of the dune.

- Possible filtering capability of a dune. For example, dunes are used to filter drinking water in the Netherlands (Waternet, n.d.).

- Seepage out of the dune, which could cause nuisance. Seepage is groundwater that comes to the soil surface induced by a difference in hydraulic head. This might happen with rainwater falling directly on the dune. Seepage from seaside to the inner side is not expected, because the water levels that could cause the necessary difference in hydraulic head only occur for a very short period of time (e.g. storm surge). However, sea level rise might affect this in the future.

C.3. The Modified Rational Method

This appendix provides a detailed description of the Modified Rational Method (MRM) applied on the West End of Galveston Island. The MRM allows to estimate stormwater runoff volumes, as a function of rainfall depth, catchment area and runoff coefficient. This method is an extension on the Rational Method, which uses rainfall intensity to estimate peak discharges and was originally developed for sizing drainage structures (Dhakal et al., 2011). Since the Rational Method is not based on a total storm duration, but rather a period of rain that produces the peak runoff rate, the method cannot compute runoff volumes unless the user assumes a total storm duration. This adjustment was made in the MRM, with the assumption that the duration of peak-producing rainfall is also the entire storm duration (Cleveland et al., 2011). This allows the development of runoff hydrographs with either a triangular or trapezoidal shape, depending on the duration of the storm compared to the time of concentration.

The MRM uses the following equation:

$$V = cDA \tag{C.2}$$

In which:

V is the total runoff volume $[m^3]$

c is the runoff coefficient [-]

D is the total precipitation depth $[m]$

A is the contributing catchment area $[m^2]$

The MRM is applicable on drainage areas less than approximately $800,000 m^2$ with generally uniform surface cover and topography (Cleveland et al., 2011). The method does not account for any storage in the drainage area; any available storage is assumed to be completely filled. Further assumptions are a uniform rainfall intensity throughout the duration of the storm and a uniform distribution of rainfall over the contributing drainage area.

C.3.1. Contributing catchment area

Identification of the total contributing catchment area A was performed using the hydrology toolset in ArcGIS PRO based on the Digital Elevation Models (DEMs) provided by the U.S. Geological Survey. The spatial elevation differences obtained from the DEM were used to determine the direction and accumulation of runoff streams, creating a stream network from higher points at the island towards the beach and the Bay. Stream networks were created using the D8-approach, modelling flow directions from a particular cell to the adjacent cell with the largest elevation drop and hence the steepest downward slope. Based on flow accumulation, streams could be ordered based on the Strahler number, which allows to show hierarchy in the stream pattern. Emerging streams receive an order 1. In case a stream with stream order 1 merges with another stream with order 1, the resulting stream has order 2. In case two streams of unequal number merge, the resulting stream receives the highest of the two orders. This results in a pattern as shown in Figure C.4. Relevant outlet points were specified based on the stream order map. An outlet point was considered relevant if a stream would reach the beach through this point with a stream order of at least 2. Based on this network and the related outlet points, individual catchment areas A_i that drain towards the beach could be delineated. A detail of this resulting stream network and contributing catchment area can be seen in Figure C.5. The sum of all individual catchment areas A_i is equal to the total contributing catchment area A.
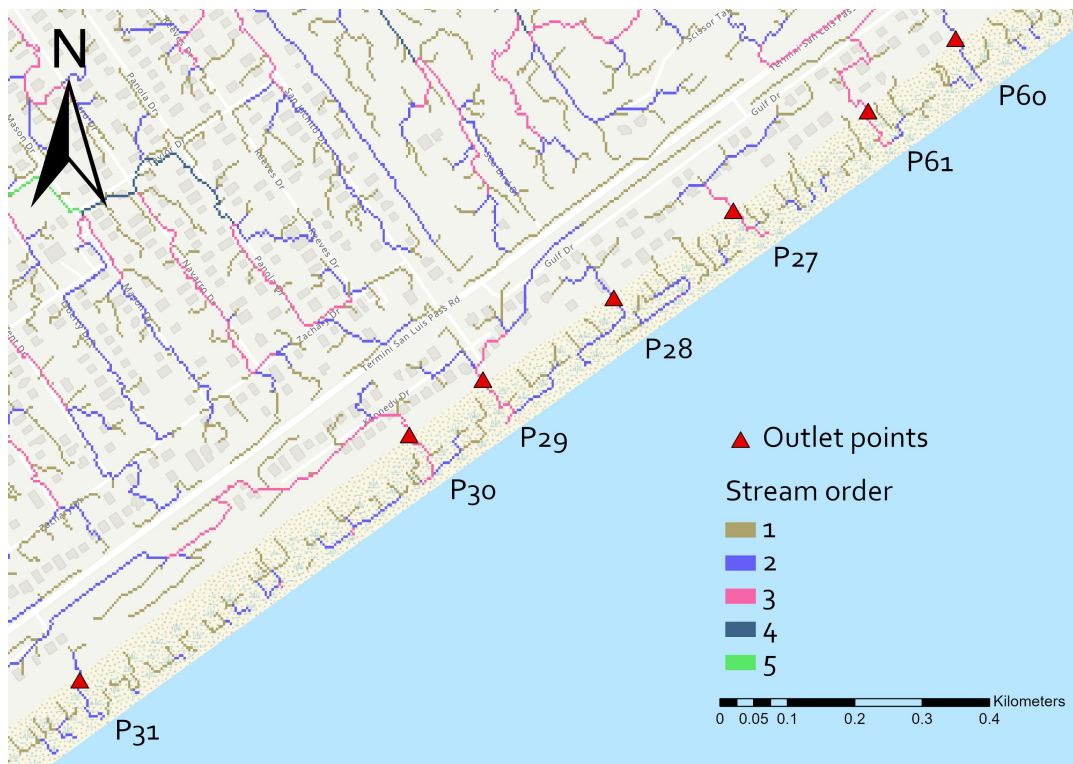
Figure C.4: Detail of stream order map, with allocated outlet points.
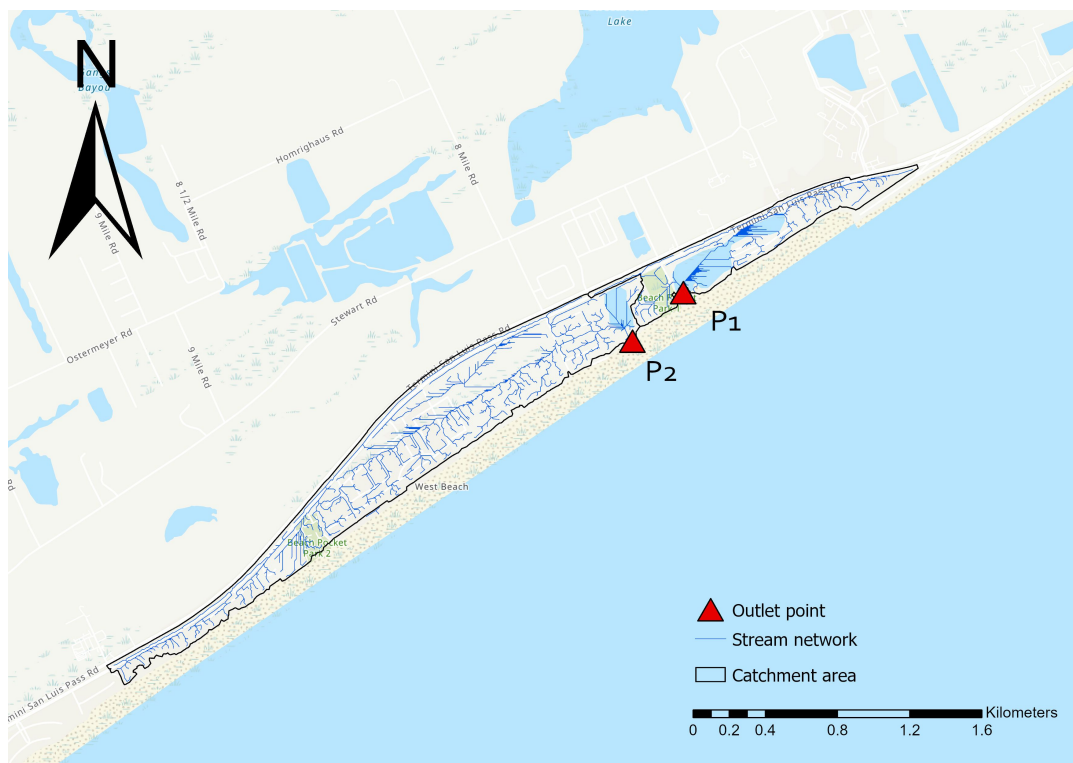
Figure C.5: Catchment areas 1 and 2, their respective outlets P1 and P2, and the stream network.

C.3.2. Runoff coefficient

The runoff coefficient c is used to denote the fraction of rainfall that runs off immediately. The runoff coefficient is characteristic for every specific catchment and is based on catchment characteristics such as topography, soil type, vegetation and land use. c is close to zero for high permeable soils with large infiltration capacities, and goes towards 1 for increasing slope and surface imperviousness. In this research, the runoff coefficient for each catchment area was determined based on land use, using Table C.1 with values for c based on land use that are provided by City of Galveston (n.d.).

Table C.1: Runoff coefficients used by City of Galveston (n.d.), based on land use.

Land use	c [-]
Undeveloped Areas	0.30
Minimum Developed Areas	0.55
Commercial areas	0.90
Lots smaller than $650m^2$	0.90
Extensively paved/impervious surfaces	0.90

Table C.2: Land uses, runoff coefficients used in this research, and percentages of the total area.

Land Cover	%	Runoff coefficient [-]
Shrub/Scrub	0.1	0.2
Woody Wetlands	0.1	0.2
Open Water	1.0	0
Developed, High Intensity	2.4	0.9
Developed, Open Space	6.0	0.55
Barren Land	14.0	0.3
Developed, Medium Intensity	17.0	0.9
Herbaceuous	17.4	0.2
Emergent Herbaceuous Wetlands	19.3	0.2
Developed, Low Intensity	22.7	0.55

The 2011 National Land Cover Database by MRLC Consortium (2011) was used to generate land use data. According to these data, the land use at the West End is governed by barren land, varying kinds of developed areas and herbaceuous areas. Land uses, their percentage of the total area, and related runoff coefficients that were used in this research can be seen in Table C.2. See Figure C.6 for a detailed view on the land use map that was used to obtain these runoff coefficients. Developed areas were divided into either minimum developed area (low intensity or open space) or extensively developed area (medium or high intensity).
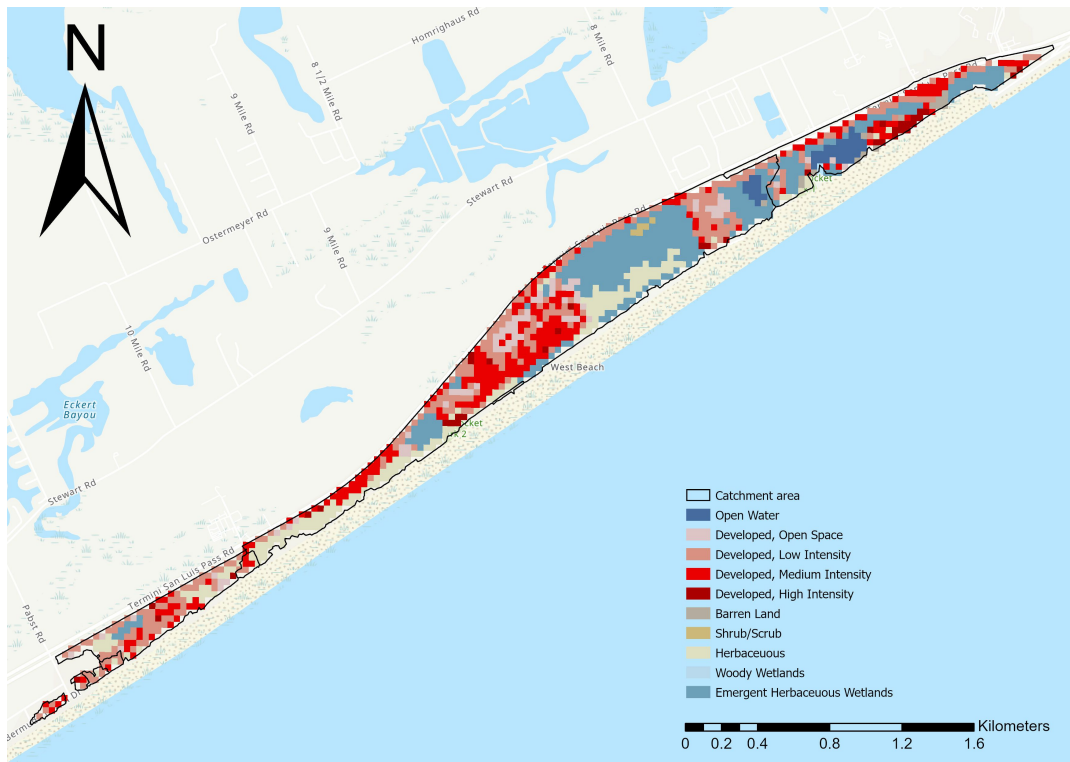
Figure C.6: Catchment areas 1 and 2 and their land use based on MRLC Consortium (2011).

A weighted runoff coefficient can be calculated for subcatchment areas that are governed by multiple land uses with the following weighting formula (TxDOT, 2019):

$$c = \frac{\sum_{j=1}^{n} c_j A_j}{\sum_{j=1}^{n} A_j}$$

(C.3)

In which:

c is the weighted runoff coefficient [-]

A_j is the area for subcatchment j [m^2]

c_j is the specific runoff coefficient for subcatchment j [-]

n is the total number of subcatchments [-]

C.3.3. Precipitation depth

The MRM uses precipitation depth D as an input to generate runoff volumes. The values for return period, depth and duration for precipitation events at Galveston Island shown in Figure C.2 are used in this research. Division of Watershed Management (2004) states that the 2, 10 and 100-year rainfall events are of primary concern for stormwater quantity analysis, due to their potential to cause either aggravate downstream erosion and/or flooding. These three events were therefore evaluated in this research. Additionally, a 25-year rainfall event was evaluated, because this is the principle design criterion for drainage systems at Galveston Island (see Appendix C.2). Normally, the time of concentration is used in the Rational Method to determine the duration of interest. This is a measure for the time that is needed for runoff to flow from the most hydraulically remote point of the drainage area to the point under investigation (Figlus and Song, 2019). This measure is of particular interest for estimating peak runoff discharges to allow proper design of

drainage measures, but this research was primarily focused on peak runoff volumes to quantify the impact of the land barrier. The relevant timescale is therefore not the concentration time, but the retention time due to the land barrier, which depends on infiltration as the dominating outgoing flux if outlet points to the beach are closed. The typical time scale for infiltration has the same order as hydraulic conductivity, which is days. (see Appendix I). Therefore, a rainfall duration of $24h$ was selected. Combining selected return periods and duration resulted in the values that are shown in Table C.3.

Table C.3: Rainfall depths in mm for 24 hour duration and various return periods.

	$T = 2years$	$T = 10years$	$T = 25years$	$T = 100years$
$D[mm]$	128	219	291	433

C.3.4. Generated volumes

The above steps result in generated runoff volumes during $24h$ for 2, 10, 25 and 50 year rainfall events.

C.4. Potential measures

As a result of the dune, increased volumes of ponding water and seepage out of the dune might cause issues. A couple of mitigation measures exist to reduce nuisance. Possible mitigation measures for increased volumes of ponding water are:

- Leave openings in the dune system at the current outlet points to allow drainage towards the beach.

- Allow drainage towards the beach by implementing draining possibilities in the dune design, e.g. application of drains from the inner side to the seaside.

- Improve current drainage system to divert drainage from relevant areas to the Bay side.

- Implementation of a dune infiltration system (see Figure C.7a. Such a system includes a storage basin in the dune system, capturing runoff and let it infiltrate slowly into the soil. See Appendix A.5 for more info.

- Implementation of different alternatives to improve infiltration on other locations, e.g. infiltration basins or trenches (see Figure C.7b.

- Implementation of permeable pavement to reduce runoff volumes (see Figure C.7c.

Possible mitigating measures for seepage are:

- Catch seepage on inner side of the dune system. In the current situation, this is performed with so-called wetlands on the inner side of the natural dunes Figure C.8a.

- Application of toe drains to control seepage and prevent erosion of the toe Figure C.8b.

- Application of chimney drains to control seepage. This might as well prevent horizontal flow along impervious layers, such as clay or concrete cores Figure C.8c.

(a) Chambers of a dune infiltration system (Burchell et al., 2013).
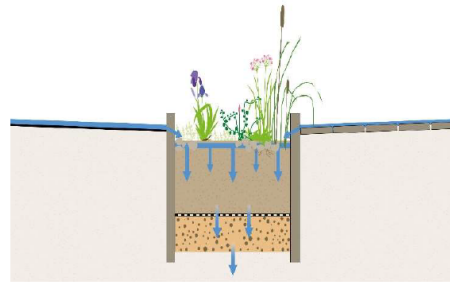
(b) Schematic of an infiltration trench (Atelier Groenblauw, 2018).

(c) Example of permeable pavement on a parking lot (Michon, 2018).

Figure C.7: Examples of mitigation measures to cope with high ponding volumes

(a) Current wetlands on the inner
side of the dunes on the West End (own picture). (Burchell et al., 2013).
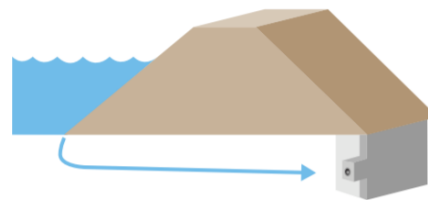
(b) Typical
design of a toe drain (United States Department of Agriculture, 2016).
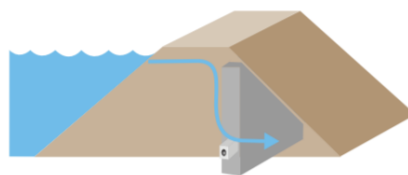
(c) Typical design of a chimney drain (United States Department of Agriculture, 2016).

Figure C.8: Examples of seepage measures

C.4.1. Evaluation of mitigation measures

The runoff volume analysis was a large part of this research. On the contrary, seepage was left out of the research. Therefore, suggested measures to reduce issues related to the large ponding volumes are discussed more extensively compared to the ones for seepage. Nevertheless, some suggestions to reduce

and control seepage were made as well.

Mitigation measures to reduce ponding volume
The different alternatives were evaluated based on three criteria: impact on ponding volume, impact on runoff quality and potential impact on other criteria of the research, namely storm surge coping capacity, sociopolitical acceptance and maintainability. Measures are rated with '+' if the effect is positive, a '-' if the effect is negative and a '0' if there is no significant effect. 'u' means that the effect is yet unknown and should still be investigated.

Table C.4: Potential mitigation measures and their impact on different criteria.

	Ponding volume	Beach water quality	Storm surge coping capability	Sociopolitical acceptability	Maintainability
Leave openings	+	-	-	+	0
Drains to beach	+	-	-	0	0
Divert runoff to bay	+	+	0	-	-
Divert runoff to San Luis	+	+	0	0	0
Dune infiltration system	+	+	u	u	0
Infiltration basins or trenches	+	+	0	0	-
Permeable pavement	+	+	0	0	-

Discharge related measures
Solutions that have a negative effect on storm surge coping capability were not considered to be a plausible option. Protection against storm surge is the primary function of the barrier, and a decrease in main functionality would put a lot of people at risk. Therefore, the dune system should be a closed line of defense without openings to let drainage water out. The same holds for application of horizontal drains, although in a less severe way. To prevent water penetrating the dunes due to a difference in hydraulic head during storm surge, a closing system for these drains might be considered. These open type of measures might be favorite for the local public, because of the resemblance with the current situation and the possibility to drain water away from the island, towards the beach. Therefore, the importance of a closed barrier in order to guarantee safety needs to be clearly addressed.

Diversion of stormwater runoff towards the Bay seems to solve a large part of the issue, but it is going to be a very costly and time consuming operation to implement. Natural elevation levels would have to be overcome and San Luis Pass Road would have to be crossed. The latter does not hold for a diversion of runoff towards San Luis Pass, but this would result in long pipes in an area with almost no slope, leading to difficulties in design. Due to the time, space and cost needed for construction, diversion is expected to receive some opposition from the public.

Infiltration related measures
In general, the storage capacity of the soil at Galveston Island is very low, with a maximum of $150mm$. These types of mitigation measures might therefore not be very effective for heavy rainfall events. Functionality for these type of measures would be to spread out runoff volumes over the area, instead of to direct all runoff towards one outlet point. This would allow to use a larger part of the infiltration capacity of the soil.

Implementation of infiltration basins or trenches and permeable pavement as a replacement for asphalt might help to lower runoff volumes. If properly designed, basins and trenches are equipped with storage capacity above the soil as well, reducing issues related to ponding water as this water can be stored at an appointed location. However, these measures require maintenance to operate properly. Infiltration basins or trenches seem most profitable just on the inner side of a dune, such that all stormwater runoff is first directed towards the beach and can be captured in these systems. These systems are already present, and are therefore not expected to lead to sociopolitical opposition.

Implementation of a dune infiltration system (DIS) might be a solution. This measure would provide both a storage possibility within the dune, and an effective way to increase runoff quality by filtration (Figlus and Song, 2019)(Burchell et al., 2013). As can be seen in Appendix A.5, these systems have already performed well for smaller catchment areas. In addition, the system is mostly covered by the dune and therefore beneficial for aesthetics, but sociopolitical acceptability should still be investigated. There however is a downside to the DIS: a rapidly permeable layer of several feet above the groundwater table is advised in order to allow the water to infiltrate rapidly (Burchell et al., 2013). This is not the case at Galveston Island. A solution might be to enlarge the infiltration area by increasing the number of chambers, but this comes

with unknowns regarding exact soil properties and system function, especially for larger catchments and combination with the core of a hybrid dune. Based on the scores, it seems useful to analyze this option more in depth, mostly into effectiveness of the system to deal with large volumes of rainwater and the effects it is going to have on storm surge coping capability of the system. As mentioned before, a negative effect on the main protective function of the barrier would mean that this measure could not be implemented.

Mitigation measures for seepage
Seepage was not analyzed in this research. However, the process can cause nuisance due to occurring water, and therefore some possible measures are discussed here. In the current situation, seepage is caught in wetlands on the inner side of the dune. Residents reported that these wetlands function well. This might be considered to implement in the final design of the land barrier as well. These wetlands might even offer storage possibilities for runoff. Furthermore, an analysis into the function of toe and chimney drains might contribute to a better control of seepage through the dune, in both directions.

Five cross sections on Galveston Island West End

Five different cross sections were taken on West End to determine the fitting of the dune system alternatives on the current coastal morphology of Galveston Island. The specifications are discussed in this appendix.

D.1. Average broadening of current dune morphology

The dunes cross sections were projected by taking the back dune foot and placing it on the back dune foot of the currently existing dune systems, thus where property boundaries starts. In Table D.1 a summary is given of the width by which the current dune system is going to be broadened per alternative. Here the existing dune width average (Google (2020)) of the cross section was subtracted from the width of the dune system alternative. The outcome was an amount in m by which the dune system and thus the coastal line would diverge seawards.

Table D.1: Broadening of coastal line.

Cross section	Alt. 1	Alt. 2	Alt. 3 & 4 (min)*	Alt. 3 & 4 (max)*	Alt. 3 & 4 (median)*
A: Kahala Beach	$31m$	$75m$	$-20m$	$35m$	$7.5m$
B: Jamaica Beach	$36m$	$80m$	$-15m$	$40m$	$12.5m$
C: Palm Beach	$36m$	$80m$	$-15m$	$40m$	$12.5m$
D: Pirate Beach	$41m$	$85m$	$-10m$	$45m$	17.5
E: Sunbather Ln.	$41m$	$85m$	$-10m$	$45m$	17.5

The minimum, maximum and median values have been used to determine the average influence of alternative 3 and 4. Dune systems with a dune width between $5m$ and $15m$ led to a narrowing of the current dune base width or, in case of the Pirate- and Sunbather Beach, kept the current dune base width in place. Dune widths ranging from $15m$ to $25m$ are going to cause broadening of current dune systems in four out of five cross sections, but is going to lead to a dune base width equal to the current situation at Kahala Beach. The dune base widths exceeding $25m$ all led to broadening of the current dune system. A maximum dune base width of $60m$ causes the beach to disappear under the proposed dune solution and would thus mean a movement of the coastline in seaward direction in order to maintain a beach of any size.

Alternative 2 has the largest footprint of all alternatives and is going to cause the coastal line to move $75m$ seawards minimally. Alternative 1 has an average value compared to the other alternatives and is going to cause the coastal line to move a minimum of $31m$ seawards if implemented. As stated in the section above, alternatives 3 and 4 propose small dune systems that are going to cause the current dune sections to be retracted with a minimum of $10m$ and a maximum of $20m$. The coastal line should not be moved in this case, and natural erosion of the coast can be left to lead its course. These smallest dimensions are not able to withstand storm surge events with a 50 year storm event. The maximum dimensions of alternatives 3 and 4 causes the current dune systems to be expanded seawards with a minimum of $35m$.

D.2. Locations of cross sections

In Figure D.1 the locations of the cross sections have been highlighted. Appendix D.3 till Appendix D.7 show areal photos (imaging, 2020) from these cross sections on the Galveston Island West End in order to give an impression of the location. Table D.2 includes an overview of location coordinates per cross section.

Table D.2: Location coordinates.

Cross section	Longitude	Latitude
A: Kahala Beach	95.0004625°W	29.1661737°N
B: Jamaica Beach	94.9727617°W	29.1829943°N
C: Palm Beach	94.9453375°W	29.1992039°N
D: Pirate Beach	94.9361493°W	29.2043119°N
E: Sunbathers Ln.	94.8996516°W	29.2256774°N
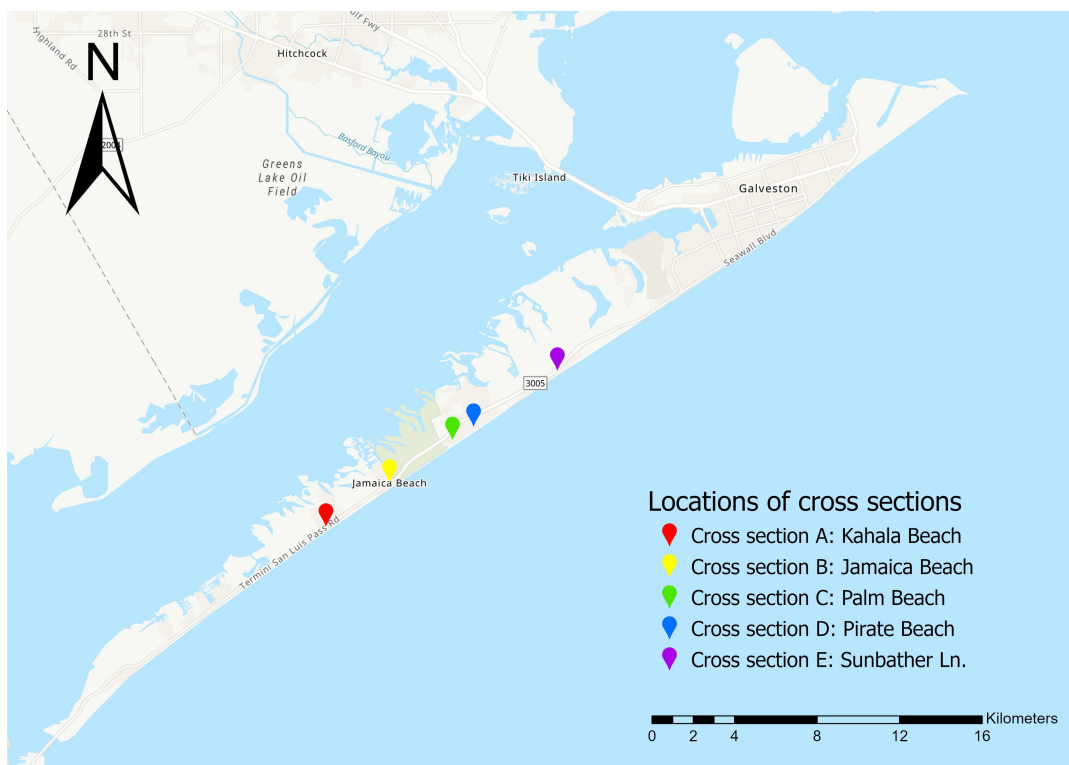
Figure D.1: Locations of cross sections on Galveston Island West End.

D.3. Cross section A: Kahala Beach

Figure D.2: Cross section A: Kahala Beach.

D.4. Cross section B: Jamaica Beach

Figure D.3: Cross section B: Jamaica Beach.

D.5. Cross section C: Palm Beach

Figure D.4: Cross section C: Palm Beach.

D.6. Cross section D: Pirate Beach

Figure D.5: Cross section D: Pirate Beach.

D.7. Cross section E: Sunbather Ln.

Figure D.6: Cross section E: Sunbather Ln.

E
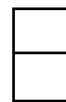
Neighborhood demographics

E.1. Property values

Property values were retrieved from Galveston Central Appraisal District (2020). From each cross section five to ten houses in east and westward direction from the cross section were analyzed. A distinction was made between property parcels directly next to the dune line (1st row) and property parcels in the 2nd row after the dune line, in order to determine the difference in property values. Property value maxima, minima, averages, values after Hurricane Ike and the overall change in property value from the pre Ike years to 2019 are given in Table E.3.

E.2. Origin property owners

Data from the register of Galveston Central Appraisal District (2020) was used. Along with the property values the county where property owners are registered is given. From each cross section 5 to 10 houses in east and westward direction from the cross section were analyzed. Percentages projected in Table E.1 were based on a "n" ranging from 10 to 20 subjects per cross section. The solutions project the percentage of home owners being registered in a certain city or state. If another city or state is given, this means that the home owner is not originally registered in Galveston. The selection of states in Table E.1 reflects the various locations in which property owners were registered. The rows of Galveston and Houston have been specifically added to reflect where the majority from Texas registered home owners come from. A conclusion of this assessment is presented in percentages in Table E.1.

Table E.1: Origin property owners.

State	City	Kahala Beach	Jamaica Beach	Palm Beach	Pirate Beach	Sunbather Ln.
Texas	*Total*	97%	80%	100%	100%	80%
	Galveston	4%	7%	13%	10%	0%
	Houston	47%	27%	50%	60%	30%
California		0%	0%	0%	0%	20%
Louisiana		0%	7%	0%	0%	0%
Ohio		0%	1%	0%	0%	0%
Oklahoma		3%	0%	0%	0%	0%
Washington		0%	7%	0%	0%	0%

E.3. Risk score

All datasets for creating the Risk indices have been acquired from best available non-proprietary data sources available. All risks are scored on a relative scale of 1-5: that is, a parcel with a score of 5 is estimated to be at five times more risk from the specific hazard than a parcel with a risk score of 1 for the same hazard. A risk score of 0 implies absence of any known threat from the specific hazard to the selected parcel. The overall score is the mean of all the specific hazard risk scores that have been selected and displayed in Table E.2 Texas Coastal Atlas (2020).

Table E.2: Specific Hazard Risks.

Risk	Scoring description
Hurricanes	Hurricane risk zones are presented on a relative scale of 1-5. This layer is derived from (Texas A&M / DEM Risk Area maps, 2020). Risk area zones 915) are identified by hurricane categories. Area 1 corresponds to a category 1 Hurricane.
Floods	Risk of flooding is presented on a relative scale of 1-5. Parcels within the 100 year floodplain are scored the highest (5), parcels within 500 year floodplains are considered to be at medium risk (3) (Texas A&M / DEM Risk Area maps, 2020).
Flood claim score	Parcels within block groups rated on flooding frequency. Parcels with a score of 1, are located within a block group without any paid claims since 2000. Scores between 1 and 2 indicate the property is located in an area with a relatively low frequency of flooding. A parcel with a score of 2-3 is located in an area that experiences moderate flooding. A score between 4-5 can be interpreted as being a parcel located within group with high amount of flooding. Any parcel with a score of 5 would be within a block group that experiences a very high amount of flooding. This scale offers insight into the frequency at which parcels within a block group are flooded, regardless of whether they are located within a flood zone (Texas A&M / DEM Risk Area maps, 2020).

E.4. Summation of values

Table E.3 represents a conclusion of the property values and the risk scores of properties found in the location of the cross sections. In column 'Characteristic', the individual data characteristics are specified, column 'Row', distinguishes if the property value represents properties that are either situated directly behind the dunes (1st), or properties that are situated in the second row of properties behind the dunes (2nd). The third until the seventh column represent the values found for the individual cross sections.

Table E.3: Demographic data per cross section.

Characteristic	Row	Kahala Beach	Jamaica Beach	Palm Beach	Pirate Beach	Sunbather Ln.
Property value average	1st	$654.580	$484.560	$965.640	$568.540	$733.180
	2nd	$596.210	$341.810	$701.640	$379.220	n.a.
Property value maximum	1st	$906.130	$733.710	$1.085.500	$640.000	$909.210
	2nd	$679.200	$504.740	$839.500	$455.600	n.a.
Property value minimum	1st	$499.320	$390.720	$800.000	$498.940	$593.710
	2nd	$495.530	$241.800	$565.000	$312.000	n.a.
P.V. after Ike	1st	−34%	−42%	-28%	−44%	−58%
	2nd	−10%	−15%	−4%	−17%	n.a.
P.V. between 2007 & 2019	1st	+18%	+23%	+53%	+18%	+19%
	2nd	+52%	+49%	+39%	+24%	n.a.
Risk score	1st	4	3*	4	4	3**
	2nd	4	3*	4	4	n.a.

* Hurricanes was graded a 1, unlike the other properties along the same Galveston West End Coastal line, that was graded a score of 2.

** The flood claim score for the neighborhood at Sunbather Ln., was valued a 4 rather than a 5, as the other neighborhoods that were assessed along the Galveston West End coast. An explanation could be, that dunes in-front of the houses in this section are indeed larger than in other parts, with dunes being brother around $5-10m$ in comparison with other dune locations. This is not a scientific deduction.
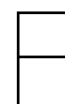
Stakeholder identification and response

F.1. Stakeholder identification

This section provides an extensive description of the main stakeholders with regard to the study and their interests and activities on Galveston Island. As can be seen, the stakeholders are divided into political stakeholders, economical stakeholders, residential stakeholders, environmental stakeholders and educational stakeholders.

Political stakeholders

Political stakeholders are responsible for creation and execution of laws, rules and regulations. Their aim is to protect residents against threats and assist them during natural occurring hazards. These stakeholders perform tasks that contribute to improvement and sustainable development of relations between residents, businesses and the natural environment.

- **Federal Government** is the nationwide government of the United States. It is the overall governmental administration responsible for setting boundaries in which local governments can operate.

- **Texas State Government** is the government on state level. The Texas State Government has the jurisdiction to implement their own laws within the boundaries of the Federal Government and approves plans and designs beyond the boundaries of the City of Galveston.

- **Texas General Land Office (GLO)** is a department within the Texas State Government. It can be seen as an independent agency of the United States Government. Its core mission is the management of state lands and mineral-right properties totaling 13 million acres (The Texas General Land Office, n.d.). Included in that portfolio are the beaches, bays, estuaries and other 'submerged lands' out to 10.3 miles in the Gulf of Mexico, and public domain lands on Galveston Island.

- **Galveston City Council** performs the organization and administration of public work in Galveston. They consider the interest of as many local stakeholders and try to avoid public upheaval and conflicts.

- **Federal Emergency Management Agency (FEMA)** is responsible for financial support when a disaster occurs. In case the local authorities do not have the resources to deal with an emergency or the Governor of the State has initiated 'a state of emergency', they coordinate assistance.

- **United States Army Corps of Engineers (USACE)** is a federal agency under the Department of Defense. They are the main party regarding the design and construction of the coastal defense. They are responsible for maintaining coastlines, inland waterways and flood risk measures in the USA.

- **US Environmental Protection Agency (USEPA)** is an organization within the Federal Government. The agency is responsible for the protection of human health and the environment. They assist with preparation and recovery for natural disasters and performs research to environmental quality for all states.

- **Texas Commission on Environmental Quality (TCEQ)** 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 (GCCPRD)** is an organization (not a governmental department) that is addressing the risks of storm surge during hurricanes. They support the State Government with research on storm surge and protection measures and works closely with Texas GLO.

- **The Park Board of Trustees** is a governmental entity for the purpose of directing all tourism efforts of Galveston. This entity is responsible for maintenance of the beaches on the island as well.

Economical stakeholders

The main interest of economical stakeholders is to make profit by selling goods and services or facilitating recreation, with the aim to strengthen the market position in the state, country or worldwide.

- **The Port of Galveston** is managed by the Board of Trustees of the Galveston Wharves and is non-federal funded. It is owned by the municipality and consists of the northern embankment of the Island of Galveston, the southern embankment of Pelican Island and the Galveston Ship Channel. The Port of Galveston has a strong position in the city as it is responsible for jobs and income. The cruise terminal is the 4th busiest terminal of North America and is able to handle various types of cargo including dry bulk and liquid bulk. The Port of Galveston is important for both the mainland and offshore activities (Port of Galveston, n.d.).

- **City & Port of Houston** Houston is the largest city near Galveston and therefore has strong economic bonds with the Port of Galveston.

- **Galveston Scholes Airport** is currently used for private flights and recreational activities. It used to be a military base.

- **Pleasure Pier Galveston** houses a lot of attractions and is highly valued by the city and tourists. It is located at 25th street and is partly constructed on the beach and above the sea.

- **Moody Gardens Theme Park** attracts thousands of people every year. It is located near the airport and owned by the Moody Foundation, a large institution on the island.

Residential stakeholders

Residential stakeholders are involved in the sense that the land barrier has a major impact on the surrounding and the way they live in Galveston City.

- **Galveston Association of Island Neighborhoods (GAIN)** represents the residents of Downtown Galveston. This is the lowest part of the city and located East from 31st street.

- **East End Historical District Association (EEHDA)** represents the residents on the East End of Galveston Island. Their mission is to preserve, restore and protect its cultural and architectural integrity by promoting community advocacy, education, cultural tourism and neighborhood awareness.

- **West Galveston Island Property Owners Association (WGIPOA)** represents the residents on the West End of Galveston Island. This part is not protected by the seawall or any dunes.

- **Offatts Bayou, Teichman Residents** represents the residents of the northwestern part of the City of Galveston. This area is located along the bay. It is sensitive for flooding as it is barely above sea level and surrounded by water.

- **Galveston Flood Defense Coalition (GFDC)** is an organization that aims to raise the awareness about the need for flood protection of Galveston. It consists of former Galveston City Council members, former engineering managers and a member of Galveston Alliance of Island Neighborhoods.

Environmental stakeholders

Environmental stakeholders aim to protect and improve the ecosystem for people fish and wildlife (Perrone, 2019), The ecosystem and human health depends on preservation of an intact, continuous mosaic of diverse habitats. This concerns the bay circulation and salinity, as well as the impact to oyster fishery.

- **The Nature Conservancy** is primarily addressing the importance of preserving habitat in the Galveston Bay, protecting freshwater basins, and improving health within the Gulf of Mexico.

- **Galveston Bay Foundation** strives to improve the environmental quality (biodiversity and health) of the Galveston bay.

- **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.

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

Educational stakeholders

Educational stakeholders aim to enlarge the body of knowledge. To reach this, they conduct research and spread knowledge by teaching people about various disciplines.

- **Texas A&M University at Galveston (TAMUG)** is the source for all ocean-oriented topics at Texas A&M University. It offers a unique blend of maritime and marine program, including engineering, transportation, majors in science, business and liberal arts. Their aim is to set the standard as the world-class university of the future by combining innovation, research and knowledge to create solutions that few institutions have the depth and breadth to achieve (Texas A&M at Galveston, n.d.).

- **Galveston College** is a comprehensive community college located on Galveston Island and opened its doors in September 1967. It provides the citizens of Galveston Island and the surrounding region with continuing education, academic, community service programs and academic.

- **University of Texas for the Medical Branch (UTMB)** is established in 1891 as the University of Texas Medical Department. It is the oldest medical school in Texas and is part of the University of Texas System (The University of Texas Medical Branch, n.d.). It focuses on health sciences education, health care services and medical research.

F.2. Stakeholder responses

This section provides a summary of the responses of the stakeholders relevant for the design and construction process of the land barrier. A distinction is made between local and professional knowledge.

Local knowledge

The perspectives of residents on flooding in the City of Galveston were gained during the Public Open House at Galveston Island on the 12th of February and from interviews with representatives of the following organizations:

- **The West Galveston Island Property Owners Association (WGIPOA)** represents the residents of the western part of Galveston Island. The representatives of WGIPOA perceived the (hybrid) dune systems positively, since it tends to be a natural intervention to improve flood resilience. However, for some house owners protection is not always desired. They argue that they are aware of the fact they live in a flood prone area and accept this risk. In case flooding occurs, most people evacuate. Besides this, they say most houses on the Island are already built on elevated parcels or stilts to mitigate flood damage. The main reason for these residents of living on the Galveston Island is proximity to the coast. For them it is extremely important that any form of protection does not obstruct the view toward and public pedestrian access of the beach on Galveston Island. They are also afraid that the construction of a land barrier is going to degrade the ecosystem and is going to negatively impact the beach circulation, salinity and oyster fishery.

- **The Galveston Association of Island Neighborhoods (GAIN)** represents the residents of downtown Galveston. For representatives of GAIN it is important that any form of protection in the form of dunes does not impede the local (industrial) businesses.

- **The East End Historical District Association (EEHDA)** represents the residents on the East End of Galveston Island. In their opinion it is extremely important that any form of protection does not influence the cultural tourism and architectural integrity of the beaches in a negative manner.

Professional knowledge
The professional insights were provided by representatives of private consulting firms, non-profit organizations, academic and research institutions and governmental agencies.

- **The United States Army Corps of Engineers (USACE)** is a federal agency under the Department of Defense. This organization can be seen as the most important party with relation to the flood measures in Galveston, since the construction of the coastal and inland flood protection falls under the USACE. After the construction is completed, the USACE provides guidelines concerning the maintenance of the beach and the dune system. According to them it is extremely important to investigate the impact of a land barrier on the ecology.

- **Texas General Land Office (GLO)** is an independent governmental agency of the United States Government within the Texas State Government. The GLO is responsible for managing public domain lands and directing all tourism efforts of Galveston Island. On top of that, the Texas GLO works together with USACE and is the official regulator who provides the final permits for construction. According to Texas GLO it is important that the land barrier is affordable and maintainable. On top of that, the responsible party for the maintenance of the project is still unknown.

- **The Park Board of Trustees** is a governmental entity for the purpose of directing all tourism efforts of Galveston Island (Tourism Economics, 2018). The Park Board of Trustees works together with Texas GLO in maintaining the beaches. The Park Board maintains the restoration of the beaches according to the Galveston Island Sand Dunes Maintenance Manual by (Howard et al., 2013). For them, it is also important that a land barrier on the beaches of Galveston Island West End does not negatively influence the architectural integrity or the cultural tourism of the beaches.

- **The Galveston Flood Defense Coalition (GFDC)** is an organization that aims to raise awareness for the need of flood protection for Galveston Island. In the opinion of GFDC, governance agencies should provide immediate benefits for the residents of Galveston Island. An example is the reduction of Galveston's flood insurance premiums and non-hurricane problem flooding.

G

Forms of governance

This appendix combines interview responses with literature study to examine how the governance priorities in flood risk management vary between the Netherlands and the United States of America (USA). This comparison is done to provide a recommendation on the form of governance with relation to the study. Governance can be described as the rules of the political system to solve conflicts and define responsibility and partnerships among the government, agencies, non-governmental, non-profit organizations and private firms and businesses (de Ridder, 2009).

G.1. Form of governance in the Netherlands

The flooding in 1953 initiated the importance of collaboration within flood risk management due to the damages and amount of people died. To provide a solution, the Delta Plan was launched in 1962 by the Delta Committee (1962). The measures to protect the land against future flood risk are combined in the Delta Works (Deltacommissie, 2008). The Dutch hazard management can be described as an advanced system that prioritizes permanent safety measures against flooding.

Rijkswaterstaat (RWS), the executive organization of the ministry of Infrastructure and Water Management, is responsible for the design, construction, management and maintenance of the water- and highways and the environment in the Netherlands. RWS is responsible for approximately 65% of all publicly awarded projects larger than ten million euros each year (Rijkswaterstaat, 2019). This makes RWS the main client in civil engineering in the Netherlands.

In practice, RWS delivers a preliminary design and a program of requirements, after which an external party is responsible for the final design and construction process. This can be described as a Public Private Partnership (PPP), where public administrations work closely together with the market sector to be able to build, manage, operate and maintain large moveable storm surge barriers (de Ridder, 2009). A typical structure of a PPP contract is visualized in Figure G.1. The further and earlier involvement of market parties in the process is initiated in accordance to the Parliamentary Construction Survey by Rijkswaterstaat (2019).
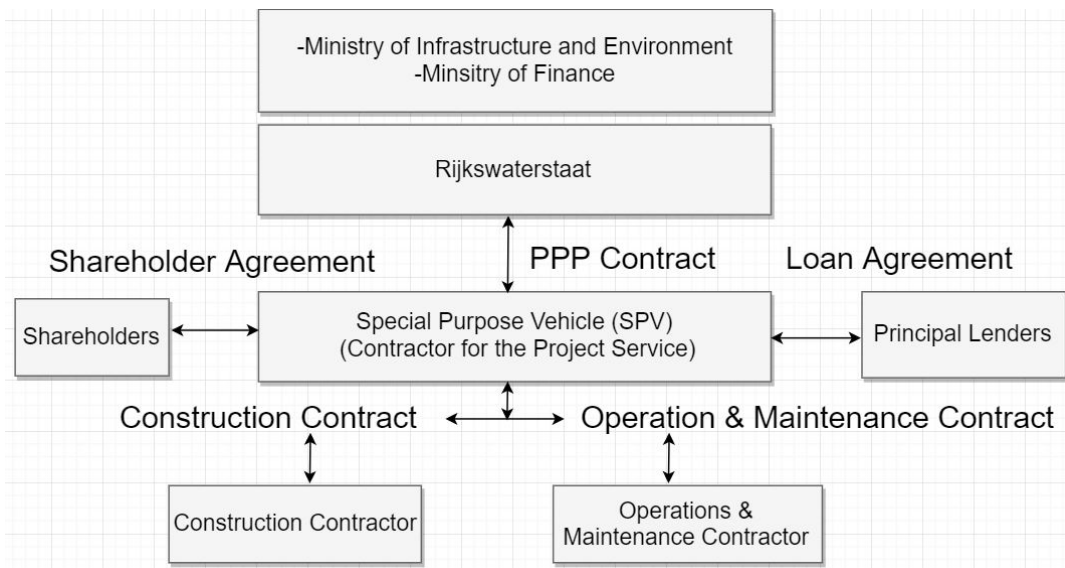
Figure G.1: The typical organization of a PPP contract (own illustration).

Another important subject is how to control a project. The question is not only how to control, but also who is managing what. According to the Senior Advisor of Storm Surge Barriers at RWS, Marc Walraven, the lack of control was felt as a major problem within RWS. For that reason the focus has shifted from working with procedures to a higher tendency for collaboration. To make the interface between RWS and market parties more manageable, RWS provided an Interface Management guideline. The integrated approach to flood risk management is visualized in Figure G.2 and can be roughly divided into protection, land use planning and disaster management (Perrone, 2019). A good example of this is The Room of the River Program. This program used nine nature-based solutions to lower water levels and lower flood risk within the Netherlands (Rijke et al., 2012). It was a large success due to its strong institutional cooperation and public support.
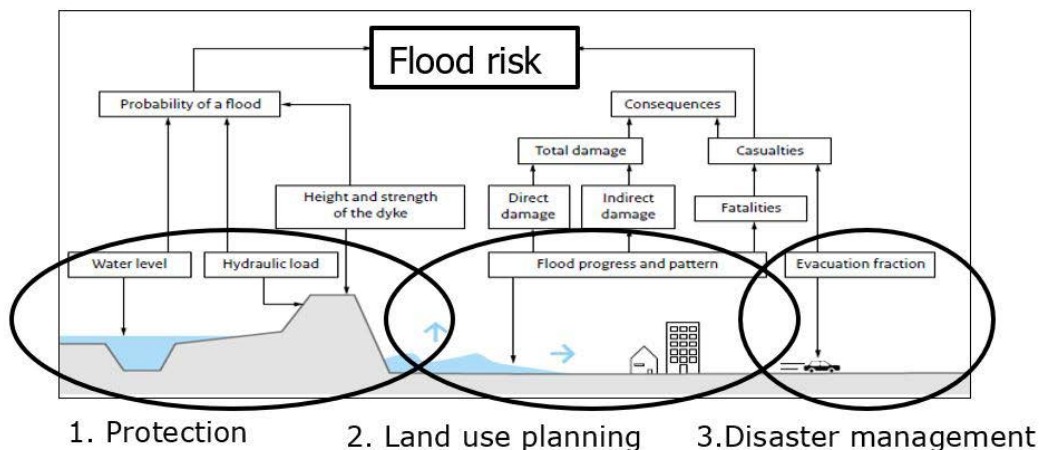
Figure G.2:
The integrated approach of RWS to manage regional plans, legislation and Project decision implementation (own illustration).

Moreover, the applicability of maintenance and durability in contracts in the Netherlands has become more prominent (de Ridder, 2009). According to Rijkswaterstaat (2016), the value of a project should be based on

best practices and performances rather than construction cost alone. Focusing on the lowest construction costs is not preferred. Instead, projects should introduce incentives that significantly improve operating performance and alignment not at trade or package level, but at the project-outcome level. RWS provided the so called 'Werkwijzer Aanleg Onderhoud (WWAO)' work guide to describe the project implementation process in construction and maintenance contracts. This guide elaborates on the project implementation process in contracts (Perrone, 2019). The standards with frameworks and process steps are mandatory, but in specific project situations deviations are allowed.

G.2. Form of governance in the USA

The form of governance in the United States of America (USA) on how to design, construct and operate a flood defense projects is not uniform. Reasons for this are the major variations between states and the political short-sighted decision-making. Therefore, this section focuses on two important parts of governance in case of flood risk management. Firstly the way of funding of flood defense projects, followed by the National Flood Insurance Program.

G.2.1. Funding of Flood defense projects

In the USA, there is no 'standard federal budget' for flood protection projects. Several studies have argued this lack of standards and guidelines in the federal flood protection system (Scata, 2018) Kousky and Shabman (2017) Scata (2018). There can be made a distinction between the following two ways of funding; Federal Funding and Local Funding.

Federal funding
Federal funding is often budgeted through emergency supplemental appropriations and targeted almost exclusively at the affected area (NOAA, 2020c). The USACE only receives mission from Federal Emergency Management Agency (FEMA) after a federal disaster declaration. Figure G.3 shows where FEMA allocates funds to and presents the total federal spending obligations, related to natural hazards in the 50 states. As can be seen, FEMA's funding programs also differ in the way they are awarded and designed.

- **The Hazard Mitigation Grant Program** provides funding to local and state governments for mitigation projects after a major disaster declaration. It focuses on reducing loss of life and property damage from future natural disasters.

- **Pre-Disaster Mitigation Grant Program** makes money available to local and state governments to reduce overall risk to individuals and property from future disasters. Through this program, all states receive some federal funding annually.

- **Flood Mitigation Assistance Grant program** provides competitive grants to local and state governments to undertake and develop projects to address flood risks. If states want extra money above the annual federal funding they must submit a proposal to a competitive review process. These competitive grants aim to reduce or eliminate claims under the NFIP.
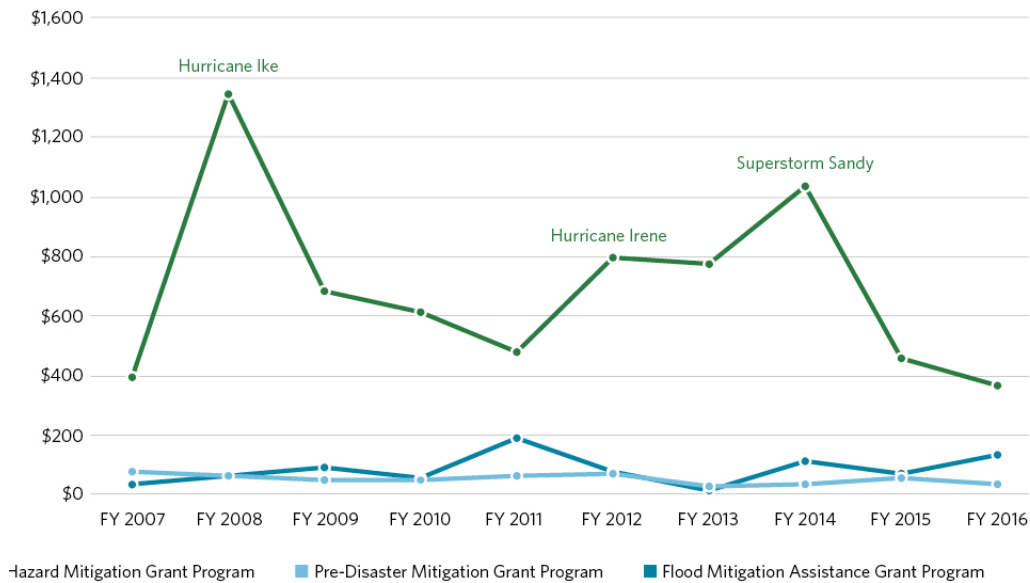
Figure G.3: Total federal funding by FEMA's grant programs.

Besides the financial support, FEMA is responsible to coordinate assistance to the USACE in the reconstruction of infrastructure and properties. FEMA prepares for disasters according to the National Incident Management System (FEMA, 2017b) and the National Disaster Framework (FEMA, 2016) . Between 1998 and 2014, FEMA has spent 48.6 billion US$ in the wake to repair for floods and coastal storm (Scata, 2018). According to NOAA (2020c), FEMA's flood mapping program is falling short in protecting people and property from flooding in its depiction of flood risk, For example, FEMA is not authorized to advice people on property insurance. It is necessary to perform mandatory surveys to make sure the USACE receives federal funding from FEMA. The Park Board of Trustees runs these survey programs every 6 months. To finance these programs, the Park Board of Trustees receives taxes from tourism.

Local funding

This way of 'non-federal funding' is applicable in case of typical flood defense measures. The USACE is financed by the Texas GLO, The Park Board of Trustees and local congress appropriate money. This approach is roughly comparable with the 'Public Private Partnerships', as described in the Section G.1. The difference lays in the need of sociopolitical acceptance to receive local funding, Instead of market parties, 'the public' owns and is in charge of the maintenance of flood defense projects. The challenge that arises is the disconnection between technical knowledge and social political decision-making and the amount of time it takes to receive the required support of public and private citizens (van Kerkhoff and Pilbeam, 2017).

G.2.2. National Flood Insurance Program

This National Flood Insurance Program (NFIP) offers business and home owners the opportunity to purchase coverage for water damage. The program is established in 1968 as a partnership between local communities and federal government (Clark, 1995). It delineates flood zones for local communities and specifies the Base Flood Elevation (BFE) for Special Flood Hazard Areas (SFHA). The BFE characterizes the 100-year flood level, so the elevation that has a 1% probability of being equaled or exceeded by the flood level in any given year. The relationship between BFE, still water elevations, flood hazard zones and wave effects are shown in Figure G.4.

The Flood Disaster Protection Act of 1973 was the first act in the NFIP that made flood insurance mandatory within Special Flood Hazard Areas (SFHA) (Penn and Pennix, 2017). The act was amended by the Coastal
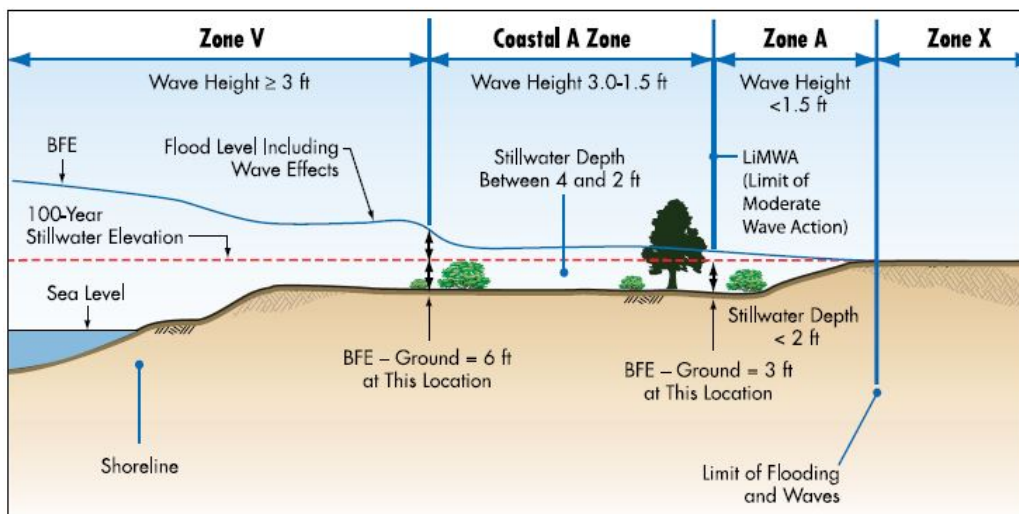
Figure G.4: Relationship between BFE, still water elevations, flood hazard zones and wave effects (L.Tanner et al., 2013).

Barrier Resources Act (CBRA) in 1982, which stated federal flood insurance was only available for new or significantly improved structures according to the minimal federal requirements. The reason for FEMA to obligate a minimum house elevation standard, to make sure the reconstruction of private infrastructure is more resilient against future flood conditions and reduce future flood damage through community.

In practice this means that a homeowner within a SFHA should build their houses on stilts according to a minimal federal elevation height (Atreya and Czajkowski, 2019). The higher the risks for flooding at that approximately area, the higher the minimal required height of house elevation. On top of that, to make it attractive to build your construction on stilts as high as possible, the higher the elevation the lower the flood insurance.

The coastal houses on Galveston West End are located within a coastal high hazard area, the so-called Zone V of a SFHA. These buildings also need to meet the NFIP's minimum floodplain management standards (L.Tanner et al., 2013). The NFIP minimum requirements for buildings built in Zone V are as follows:

1. Building must be elevated on pile, post, pier, or column foundations.
2. Building must be adequately anchored to foundation.
3. Building must have the bottom of the have the bottom of the lowest horizontal structural member supporting the lowest floor at or above the BFE. This is shown in Figure G.5.
4. Building design and method of construction must be certified by a design professional.
5. The area blow the BFE must be either free of obstructions or have breakaway construction.

For buildings in a community that participated in the NFIP when its initial FIRM was issues, post-FIRM buildings are the same as new construction.

The report by Galveston County (2017) provides the regulations of Galveston County to the Floodplain Management. In 2005, the Houston – Galveston Area Council's (H-GAC)'s Board of Directors created the Regional Flood Management Council (RFMC). Through their handbook, the RFMC's aims to advise and assist elected officials in their decision-making responsibilities on issues related to all aspects of flood
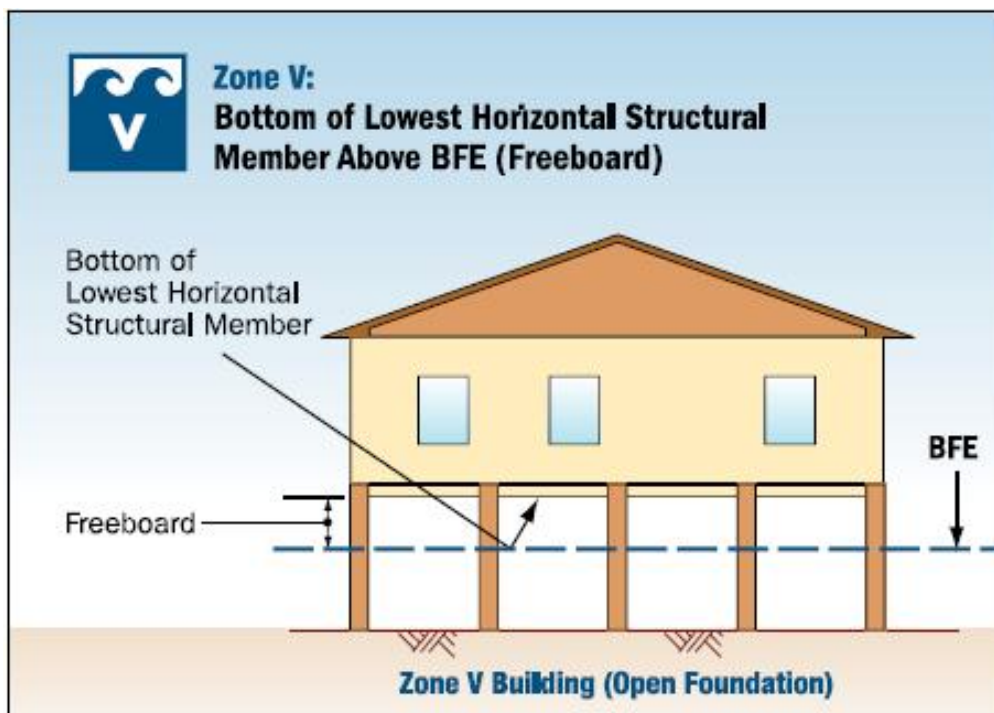
Figure G.5: In Zone V, elevation of residential structures to the BFE
is required. The Mitigation Assessment Team (MAT) recommends elevation higher, or adding freeboard (L.Tanner et al., 2013).

management in the Gulf Coast Planning Region. Research by Texas Floodplain Management Association (TFMA) in 2008 has indicated 77% of the coastal houses on the West End of Galveston Island require freeboard of 0.3 to $0.6m$ for new construction (L.Tanner et al., 2013).

For the last 20 years, the minimal federal requirement to the elevation of houses on Galveston West End rises frequently. To get a better view on the general heights of the houses, this reports highlights the following minimum house elevation standards;

- In the report of 2001, FEMA requires houses in coastal flood zones to be elevated at least $0.3m$ above the BFE and $3.5m$ +MSL (C. Jones, 2001). After Ike, observations on the West End of Galveston Island noted that many of the coastal houses constructed pre-Flood Insurance Rate Map (FIRM) were constructed at or within $3.5m$ +MSL of the mapped BFE (L.Tanner et al., 2013). All the houses constructed post-FIRM were sited above the BFE.

- The changed regulations after Ike requires all coastal houses on Galveston West End to be elevated $3.7m$ +MSL above the mapped BFE. (L.Tanner et al., 2013)

- FEMA's current guide lines with regard to house elevation heights of coastal houses consist of a minimum of $4.3m$ +MSL (Xian et al., 2017). The house insurance per year is approximately \$883 to \$1.198, which comes down to about \$73 to \$99 per month (Penn and Pennix, 2017).

G.3. Advice on governance strategy

The conclusion that results from this chapter provides a clear distinction between the priorities set with regard to the forms of governance in the USA and the Netherlands. Therefore, an advise is formed in the emphasis on future flood defense projects in the USA.

Firstly, the adaption of a flood protection standard for federally-funded infrastructure projects should be part of the solution. The Federal Flood Risk Management Standard provides a well-developed example

of such a standard (NOAA, 2020c). This standard requires Federal Emergency Management Agency (FEMA) to rebuild public infrastructure to be stronger than the structure that was damaged because of a hurricane. Such action would reduce the likelihood taxpayers pay to rebuild the same infrastructure after future floods and construct the project to be more resilient against future flood conditions. Unfortunately, President Trump revoked the Federal Flood Risk Management Standard in August 2019.

Secondly, a solution to connect the federal and local funding, which could consist on the use of 'special district funding'. Since investing early is going to be more beneficial than the reparation costs in the long run. On top of that, with the evasion of future payments come benefits: preservation of coastal flood plains and the safeguard of people and property can be seen as key benefits. In order to convince the state of such a similar way of funding, the state of Louisiana's proposed a Coastal Master Plan. This plan consist of a coordinated framework to simultaneously reduce flood risk to communities and infrastructure.

Thirdly, approach of flood defense in the USA need to move away from a primarily process-driven project system to a more holistic project-operating system in order to improve the performance on predictability and maintenance. The foundations of institutional co-operation currently exists, but cooperation is hindered by a lack of resources and political friction. Doing so could lead to flood risk management being treated with collaborative transparency across the project and among stakeholders. An example of such an approach is the I-STORM organization, which initiated a global development with collaborative and maintainable flood risk management. The I-STORM network unites public administration of countries that build, manage and maintain movable storm surge barriers I-STORM (2020). More information about this project can be found in Appendix A.3.

To end with, the USA can benefit by a change in mindset and behavior, and seeing flood protection as essential. The question remains whether the various players, who have different challenges and incentives, will indeed leave behind the status quo and embrace the change that leads to a long-term flood defense strategy.

Method: Storm surge coping capability

As mentioned in Section 5.3.1, the capability to cope with storm surges is inherently the leading criterium when evaluating different alternatives, due to the nature of the project. It can be described as a boundary condition to be met by the alternatives, in order to function as a barrier at all. The alternatives were modeled using a XBeach model in order to obtain an overview of the erosion rates of the alternatives. In addition, analytical calculations were made to obtain overtopping rates.

H.1. Erosion rate during normative event

First parameter was the erosion rate during a normative event. This parameter concerned the amount of sand that is lost due to a storm event, and was modeled using XBeach.

H.1.1. Application of XBeach

In this study the model programme XBeach was used to simulate dune and beach erosion in the cross shore at a specific location along Galveston Island.

XBeach is an open-source model, which has been developed with major funding from the USACE, RWS and the EU (Deltares, n.d.). The original idea of the model was to simulate hydro- and morphodynamic processes and to see their impacts on sandy coasts. The domain is intended ,in contrast to other models, to have a maximum in the order of five to ten kilometers, and the model is intended to do simulations on the time scale of storms.

The model resolves the hydrodynamic processes, mentioned in Appendix B.1. Thus, the model is able to resolve short wave processes such as refraction, shoaling and breaking. Next to that, the generation, propagation and dissipation of long waves (infragravity waves) are also included in the model. Other processes, such as wave induced setup, overwash and inundation are taken into account as well. The morphodynamic processes consist of bed load and sediment transport, avalanching and a bed update. The XBeach programme was validated with a series of tests, both analytical and in the laboratory. Furthermore, along the European coastline the model has been validated on different beaches (Hoonhout, B., 2015).

The model originally was developed so that it averages short waves but resolves wave groups. The short wave variations on the wave group scale are resolved. After a few years, a number of model options were added to the model, whereas nowadays one can choose which time-scales to resolve: stationary model (short wave averaging, neglecting long waves), instationary model (short wave variations on wave group scale and associated long waves) and non-hydrostatic model (solves all processes, including short wave motions).

The stationary wave mode was selected for implementation in this research, because it efficiently solves wave-averaged equations but neglects infragravity waves. In the case of the stationary wave mode, the wave breaking formula from Baldock has to be applied (Hoonhout, B., 2015).

First, the model input is described. Next, the model process is elaborated. Finally, the output of the model is discussed as well as the method to process the output.

H.1.2. Input parameters

To keep the model as simple as possible and subsequently save computational time, a 1D model was set up. The model input parameters are described in the following sections.

Location

One cross section (Figure H.1), at the height of Kahala Beach (29°9'46.9548"N ,95°0'19.9216"W), was used as the location to test all the alternatives. This location is a good representation of the West End, with an average beach width and small dunes behind it. A point six kilometers offshore was used as the offshore boundary of the model. There, a line was drawn perpendicular to the coast, six kilometers offshore from a point close to the beach, which resulted in a x-grid and associated bathymetry data (see Figure H.1). This data was obtained via NOAA (2007b).

Figure H.1: Location of cross-shore profile, from Google (2020).

Bathymetry & grid

The bathymetry data used in the model is derived from the coastal elevation models of NOAA (2007b). The data is formed trough surveys carried out by institutions including but not limited to the USACE and FEMA, and has a resolution ranging between $1/3$ and $3\ arc\text{-}second$. The following procedures where carried out using ArcGIS Pro. The NetCDF file obtained from NOAA was transformed to a raster layer and transformed to a 1D cross-section profile of the bathymetry. As the resolution of the data is equal to $1/3\ arc\text{-}second$, the horizontal spatial step in the cross-shore profiles is equal to $\sim 10m$. For both the SWAN model (see Section M) and the XBeach model, a 1D cross-shore profile of the bathymetry was generated at the location of interest (Kahala beach). The cross-shore profiles for the XBeach- and SWAN models extend $6km$ and $32km$ offshore respectively. Note that due to a difference in utility, the cross-shore profile used in the XBeach model extends up to the existing dune line, whereas the cross-shore profile used in the SWAN model only extends to the shoreline.

For every alternative a specific bathymetry profile was created. The levels of elevation for the points on land were based on existing characteristics of the different design. These characteristics were found in (Muller et al., 2018), (Galvez, 2019) and USACE and GLO (2018). The concrete core, in Alternative 3, was modeled by including a non-erodible structure with an elevation of $4.3m$. Due to the fact that it is not

possible to model a clay core in XBeach, it was assumed that alternative 4 performs the same under all conditions as Alternative 3. An overview of the four different cross-shore profiles are given in Figure H.2.

(a) 0-option.

(b) Alt. 1, USACE.

(c) Alt. 2, High single dune.

(d) Alt. 3, Concrete core.
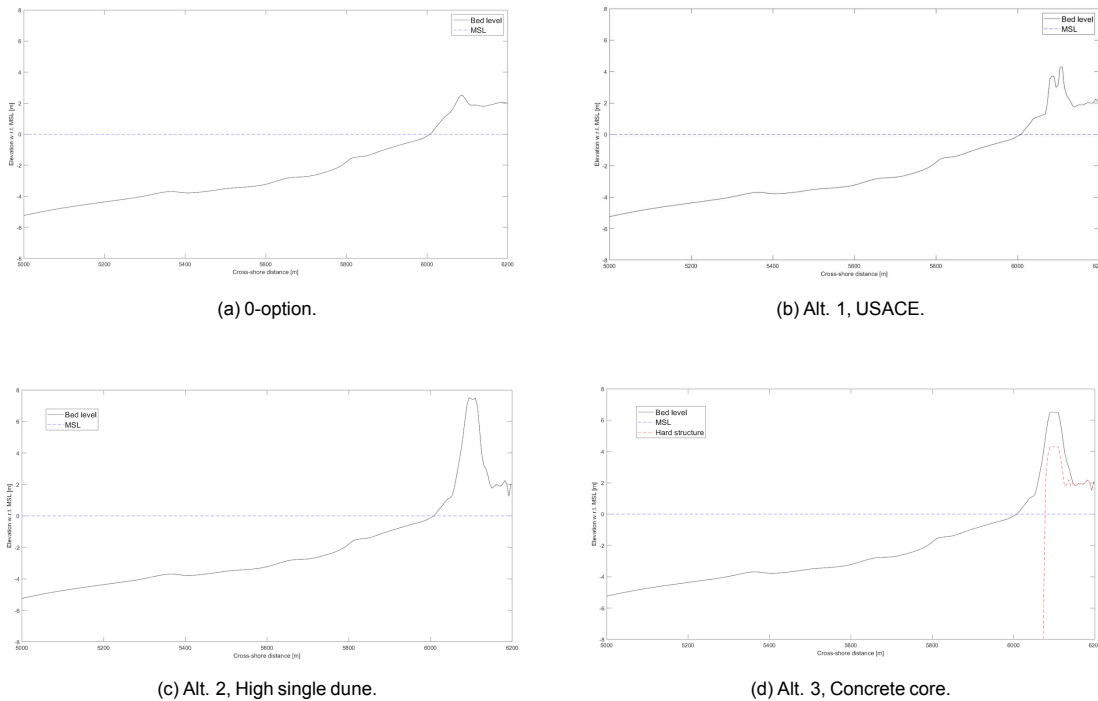
Figure H.2: Cross sections of the alternatives.

The grid must be accurate in order to be able to model all the nearshore processes. However, a too accurate grid requires too much computational time. So, a trade off has to be made between accuracy and computational time. For this model a 1D grid is used, which therefore only consists of coordinates in the x-direction. The grid is based on the slope of the bed, the Courant number and manual parameters. A grid size of $dx = 5.13m$ was used.

Tidal data
The retrieved water level and wave height data was converted into values with respect to mean sea level by using Figure H.3
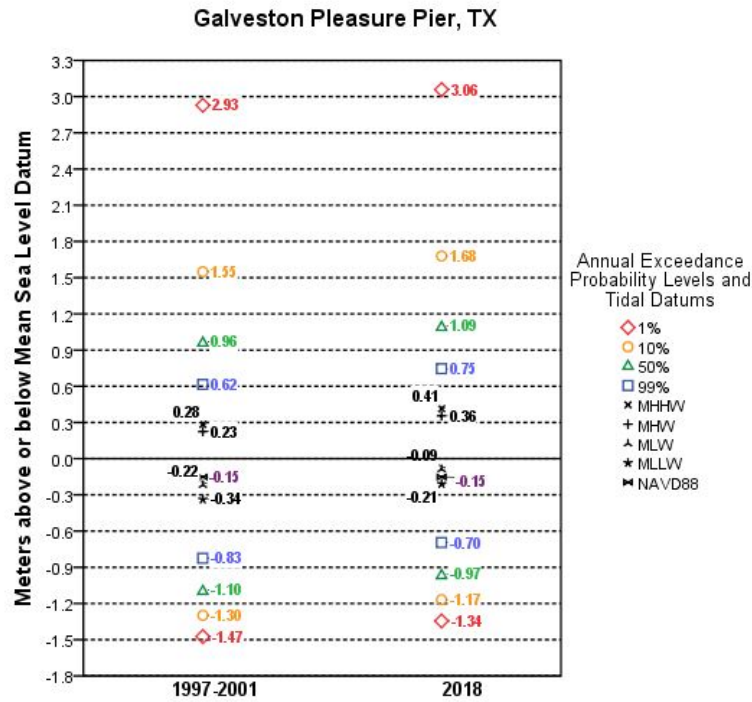
Figure H.3: Tidal data at location pleasure pier.

Design storms

As mentioned in the preceding paragraph, design storms were created to test the different alternatives. A storm is characterized by three different parameters: the wave height, the storm surge and the wave period. Every storm is unique, with each having a different chance of occurrence. For example, Hurricane Ike is characterized by a wave height that statistically occur 50 year storm and a storm surge level that occur once every 50 years (NOAA, 2020a). Five different storms were set up to simulate the performance of the alternatives under different storm conditions: a 10 year storm, a 50 year storm (short, medium and long duration) and a 100 year storm storm for wave height, storm surge level and wave period. In order to investigate the impact of storm duration on the alternatives, three different storm durations have been chosen. The return periods were chosen such that the barrier is not only assessed on a single big storm event, but also on smaller storm events. This performance review was needed to assess whether the barrier can still function without excessive maintenance after such a relatively small event.

The storm surge levels and the wave heights were derived from an analysis by Almarshed (2015), who determined the offshore wave heights, wave periods, and surge levels for different return periods at buoy 42035. By using SwanOne, these offshore wave heights, wave periods and surge levels were transformed into nearshore heights and levels. Since there are no buoys in front of the West End, for simplicity, it was assumed that buoy '42035' is located $32km$ offshore at the height of Kahala Beach. A more detailed explanation of the use of SwanOne can be found in Appendix M. An overview of the different design storms including their surge, wave height levels and wave periods is given in Table H.1. Figure M.1 represents the cross-shore profile of the bathymetry used in the SwanOne model.

Table H.1: Design storms.

Design storms (6 km offshore)	Wave height [m]	Storm surge [m]	Peak period [s]	Storm duration [h]
Storm 1 ($10year$)	4.74	0.64	11.16	40
Storm 2 ($50year$)	6.10	3.62	8.03	20, 40 & 60
Storm 3 ($100year$)	6.58	4.64	8.03	40

Surge

As explained in Section 2.2, storm surge of Hurricane Ike consisted of a forerunner followed by a primary

surge. The maximum values for the storm surge with relation to the probability are plotted in this section. The shape of the data points is compared with the shape of Hurricane Ike. The same duration is plotted for the different probabilities and the 50 year storm has been generated with a shorter, medium and longer storm duration.

The height of the forerunner and the primary surge have an empiric relation with each other and can be described by Equation H.1, based on real Ike data:

$$H_{forerunner} = \frac{3}{4.71} \cdot H_{primary} \tag{H.1}$$

Two horizontal lines were plotted with the primary surge and the forerunner height according to Table H.1 and Equation H.1, in order to find the correct graph indicating the storm surge height. For both wave patterns a uniform distribution was assumed. Finally, both profiles were added, together with the projected Relative Sea Level Rise (RSLR) in 50 years, which is $0.5m$.

10 year storm probability
The height of the storm surge for 10 year storm probability of exceedance is $0.64m$ +MSL and thus the forerunner has an exceedance of $0.41m$ +MSL, excluding relative sea level rise.
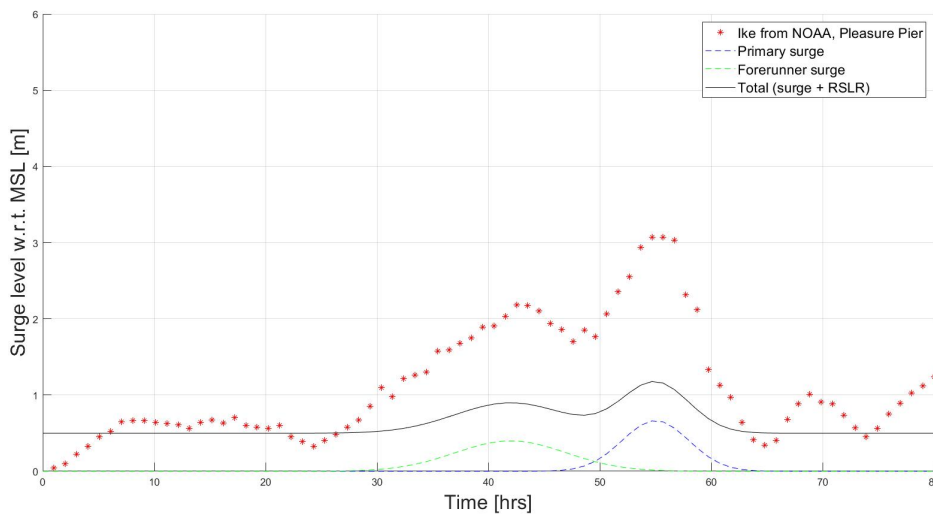
Figure H.4: Storm surge for 10 year storm probability of exceedance.

50 year storm probability
The 50 year storm probability of exceedance has been modeled in three different waves of duration. The height of all three graphs is $3.62m$ +MSL and thus the forerunner has an exceedance of $2.31m$ +MSL, excluding the relative sea level rise. The different figures for a 50 year storm surge of respectively a short, medium and long storm are illustrated in Figure H.5a , Figure H.5b ,Figure H.5c.
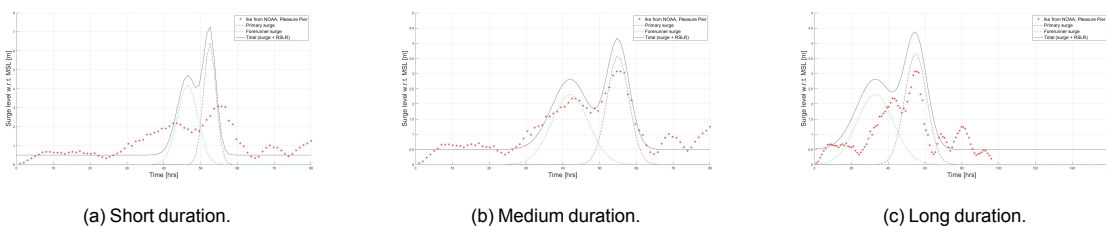
(a) Short duration.　　　　(b) Medium duration.　　　　(c) Long duration.

Figure H.5: The storm surge profiles of 50 year storm probability of exceedance for different durations.

100 year probability

The height of the combined storm surge for 100 year storm probability of exceedance is $4.64m$ +MSL and thus $2.95m$ +MSL for the forerunner, excluding the relative sea level rise. A fit for the graph is indicated in Figure H.6
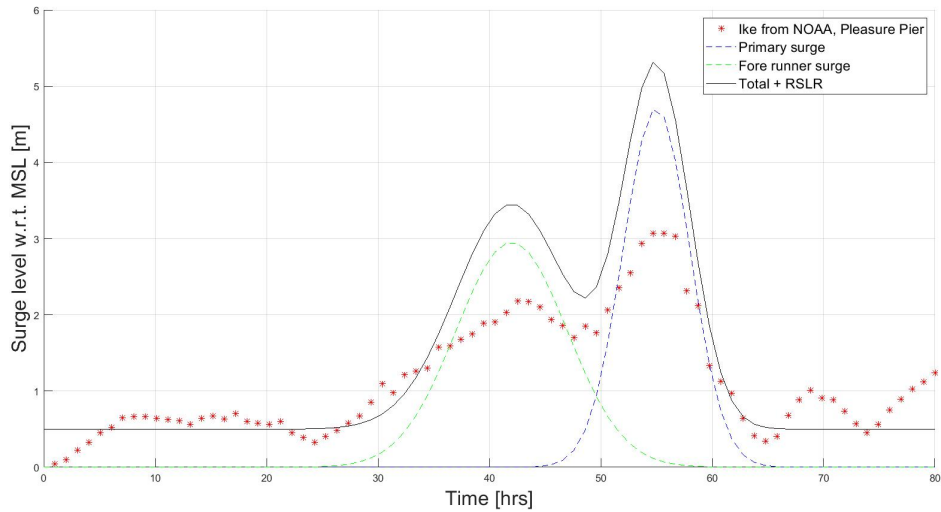
Figure H.6: Storm surge for 100 year storm probability of exceedance.

Wave height

A wave height plot for different probabilities was created, which can be seen in the following figures. The maximum value of these wave heights is given in Table H.1. The 'shape' of the wave height profile was based on real Ike data, obtained by (Kennedy et al., 2011a), which is also plotted in the different illustrations.
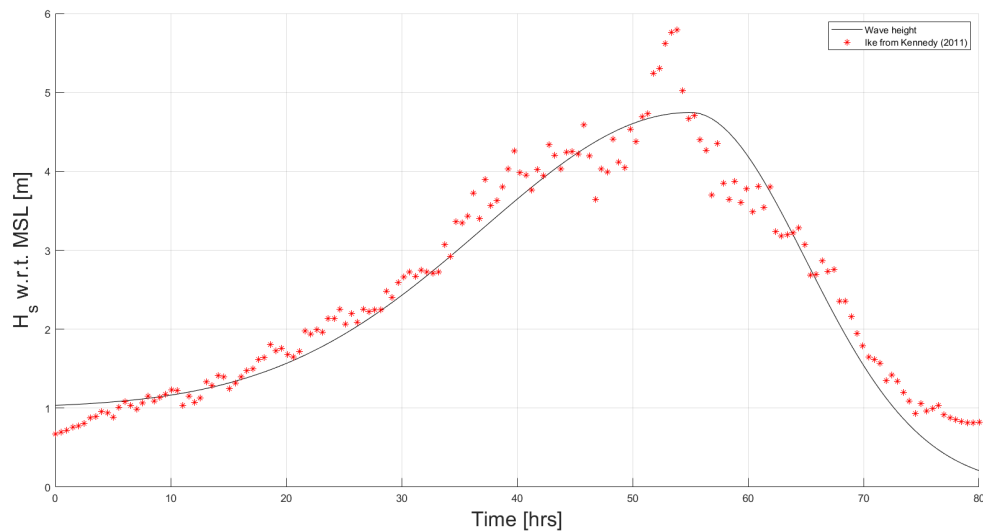
Figure H.7: Wave height for 10 year storm probability of exceedance.

(a) Short duration. (b) Medium duration. (c) Long duration.
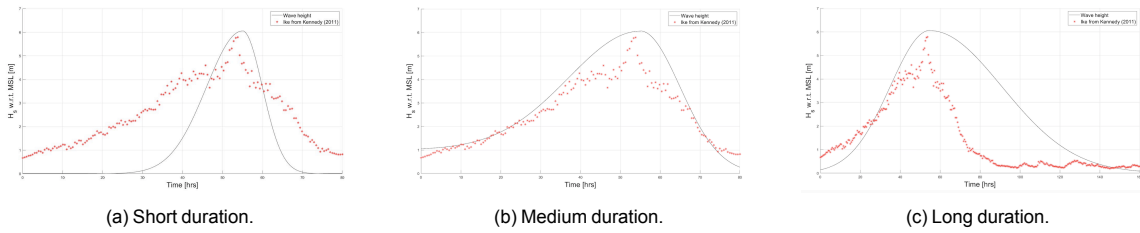
Figure H.8: The wave height profiles of 50 year storm probability of exceedance for different durations.
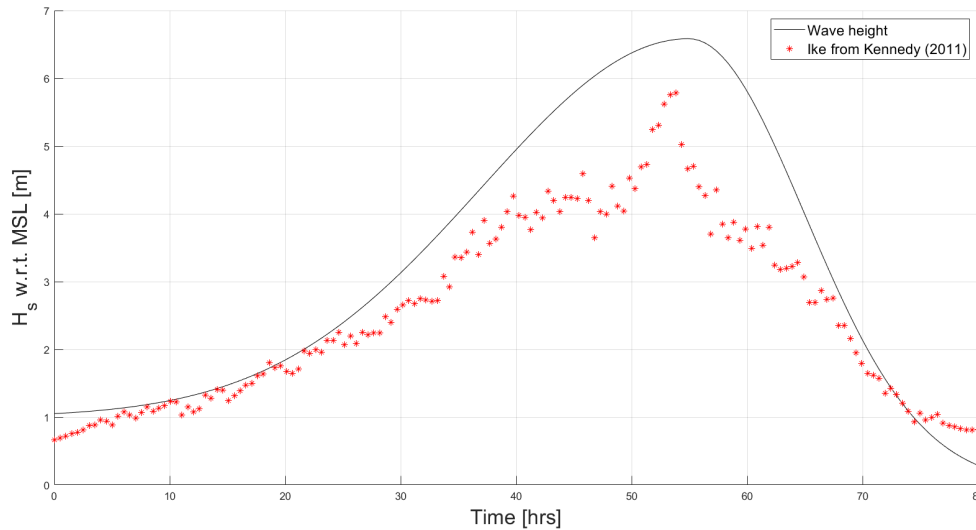
Figure H.9: Wave height for 100 year storm probability of exceedance.

Wave period

The wave period has also been generated for the different probabilities, which are given in Table H.1. For 10 year storm probability of exceedance this is $11.16s$. For the probabilities of both 50 year -, and 100 year storms of exceedance a peak wave period of $8.03s$ is given. A shallow water wave period of $4s$ is assumed, thus both figures run towards $4s$. These different fitted curves are illustrated in Appendix H.1.2.
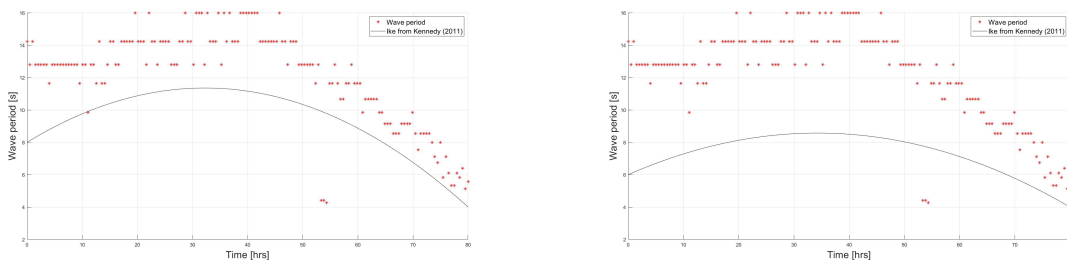
(a) For 10 year storm probability of exceedance. (b) For 50 year-, and 100 year storm probability of exceedance.

Figure H.10: Peak wave periods for different types of storm

Boundaries

The offshore wave boundary consists of imposed wave and surge conditions. A weakly reflective-absorbing type of boundary was included, to let waves and currents exit the domain. For the boundaries perpendicular to the coastline, a Neumann boundary was chosen, which allows flow to exit the domain.

Sediment distribution

Looking at its history, Galveston Island was mainly created through the sediment supply of rivers flowing into the ocean. However, not only rivers contributed to the sediment composition of the island. It is mainly composed by three different sources(The University of Texas at Austin, 2017):

- inorganic mud and sand eroded from the continent;

- organic mud;

- sand and gravel from shells.

Studies showed that most parts of the island are made up of a big mud substrate with a small sand layer on top of it. The whole area is sand limited, with minimal supply entering the system. The sand available on the beach has a typical median grain size of $150\mu m$, which can be considered as very fine sand (Frey et al., 2016). A uniform sediment distribution is assumed to simplify the model. As an input for the model a D_{50} value of $150\mu m$ is chosen, whereas the D_{90} value is based on Harter et al. (2015), who used a D_{90} of $187\mu m$.

Relative sea level rise and subsidence

According to the USACE, the different designs should at least have a lifetime of 50 years. Therefore, it was assumed that the design storms take place in the year 2070. The current mean sea level rise is determined to be $6.62mm/year$ (NOAA, 2007c). Together with a subsidence rate of $2.3mm/year$ (Paine, 1993), this gives a relative sea level rise of approximately $0.5m$ in the year 2070.

Flow

This study only focuses on developments in the cross-shore profile during a storm. Therefore only a single storm is simulated with a relatively short term. No astronomical constituents or other currents are taken into account in the model. The potential flows that have been created in the model can leave the model, due the its open boundaries.

Other input parameters

In the params.txt input file (as can be seen in the figures H.11, H.12, and H.13) several other parameters, such as the morfac, Courant number, Chezy value, breaker index γ and bottom friction, could be adjusted to further fine-tune the model. Values for these parameters were based on the validated model of Muller et al. (2018).

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%
%%% XBeach parameter settings input file
%%%
%%%
%%%
%%% date:      18-Mar-2020 06:02:32
%%%
%%% function: xb_write_params
%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%

%%% Physical processes %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%

_

%%% Grid parameters %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%

depfile     = bed.dep
posdwn      = 0
nx          = 1207
ny          = 0
alfa        = 0
vardx       = 1
xfile       = xnew.grd
yfile       = ynew.grd
thetamin    = -90
thetamax    = 90
dtheta      = 15
thetanaut   = 0

%%% Time management %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%

tstart      = 0
tstop       = 288000
tintp       = 60
tintg       = 600
CFL         = 0.7

%%% Wave breaking parameters %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%

break       = baldock
gamma       = 0.7
n           = 10

%%% Wave boundary condition parameters %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%

instat      = stat_table
```

Figure H.11: Input file params.txt (1/3).

```
bcfile      = medium_50waves.txt
rt          = 288000
dtbc        = 1

%%% Flow parameters %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%

C           = 55

%%% Flow boundary condition %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%

front       = abs_1d
back        = abs_1d

%%% Tide boundary conditions %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%

zs0file     = medium_50surge.txt
tideloc     = 2
paulrevere  = 0

%%% Limiters %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%

gammax

%%% Sediment transport parameters %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%

rhos        = 2650
D50         = 0.000150
D90         = 0.000187
struct      = 1
ne_layer    = nebed.dep

%%% Morphology parameters %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%

morfac      = 10
morstart    = 3600

%%% MPI Parameters %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%

mpiboundary     = x

%%% Output variables %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%

outputformat = netcdf
tunits       = seconds since 2016-12-01 +0
nglobalvar   = 14
H
```

Figure H.12: Input file params.txt (2/3).

```
hh
zs
zb
u
DR
D
Dc
E
Fx
Hrunup
Subg
Susg
Sutot
```

Figure H.13: Input file params.txt (3/3).

H.1.3. Process

The alternatives were tested by running the model with the specific bathymetry and the different design storms. Twenty runs were executed. Vegetation, wind and groundwater flows were not included in these runs.

In order to use the model with a level of certainty, a validation was executed before testing all the different alternatives. For this, historical erosion/accretion and elevation data before and after Hurricane Ike was used. Aim of this validation was to analyze the capability of the model to reproduce the hydrodynamic and morphodynamic effects of Hurricane Ike for three different transects at Kahala Beach. Where needed, parameters were calibrated. The results of this validation are given in Appendix L.

H.1.4. Output parameters

By testing the different alternatives upon different design storms, post storm cross-shore profiles were obtained. With the obtained cross-shore profiles the eroded amount of sand was calculated, as well as the final height of the dune profile.

H.2. Wave overtopping

The dune alternatives were tested on wave overtopping besides determining the profile with the XBeach models. More information on the data and the determination of the overtopping rates are explained in Appendix B.7.2.

H.2.1. Input parameters

Necessary data used in the simulation for the analytical model are from Table H.1, besides the slope of the dune. The necessary input parameters are:

- The significant wave height in deep water of the given storms;
- The peak wave period;
- The median grain size;
- The height of the storm surge level;
- The maximum height of the dune alternative;
- The slope of the dune alternative.

H.2.2. Process

The overtopping discharge can be calculated from the given parameters. The order of the analytical steps that have to be taken have been calculated in Appendix B.3.

The resulting overtopping discharge has been calculated for the different dune alternatives and for the three different probabilities of exceedance.

H.2.3. Output parameters

The output parameters are the resulting wave overtopping rates for the different surge and wave height probabilities. This is calculated for every alternative.

Method: Stormwater drainage impact

Quantification of the drainage impact parameter consists of multiple steps. Firstly, the relevant volume of runoff was determined based on the Modified Rational Method. Secondly, the drainage potential through the different dune types was quantified by means of Darcy's equation, in order to evaluate the quantitative impact of the dunes on stormwater drainage. Thirdly, the potential effects of the different alternatives on the quality of the runoff onto the beach was assessed.

I.1. Obstructive impact

The 0-option was analyzed first in order to quantify the impact of the various alternatives on the water volumes. Afterwards, these outlet points were assumed to be closed by the specific barrier alternatives (see Figure I.1), and the potential discharge through the systems was calculated.

I.1.1. Input

The input for this part of the research consists of the daily volumes calculated by the MRM and the characteristics of the different alternatives as described in Section 3.5.

I.1.2. Process

Firstly, the 0-option was assumed, with 71 open stormwater outlet points onto the beach. This allowed to come up with an estimate for the water depths in the current outlets through the dunes onto the beach, using a rewritten version of the Manning-Strickler equation:

(a) The 0-option.

(b) Alt. 1-4: Closure of the outlet.
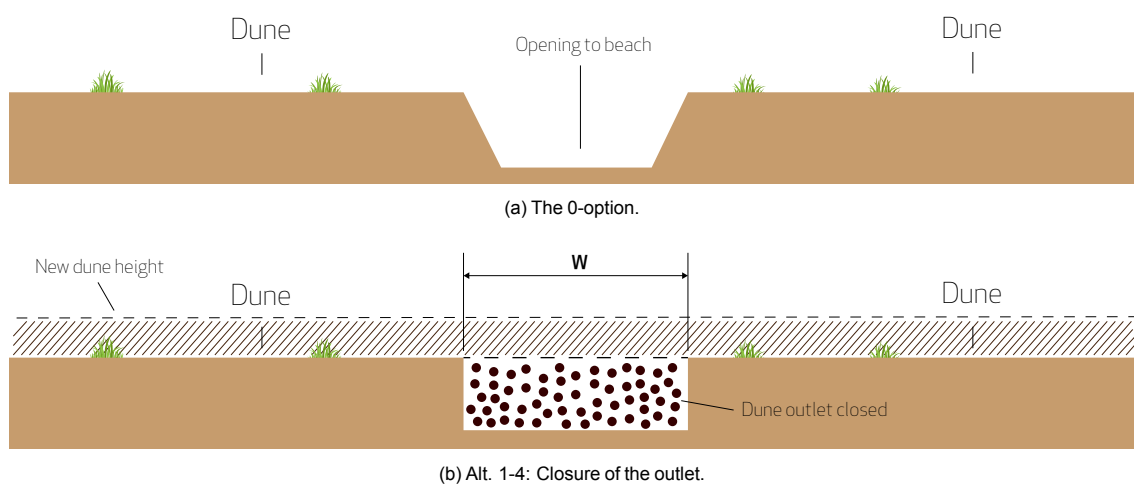
Figure I.1: Schematic overview of a drainage outlet before and after closure, observed from the beach.

$$d = \left(\frac{Qn}{W\sqrt{S}} \right)^{3/5} \tag{I.1}$$

In which:

d is the water depth at location of the outlet point $[m]$

Q is the discharge through the outlet $[m^3/s]$

n is Manning's roughness coefficient $[s/m^{1/3}]$

W is the width of the outlet $[m]$

S is the slope of the outlet $[-]$

The original Manning-Strickler's equation was used to calculate discharges in drainage channels. This equation uses the hydraulic radius R. R was assumed to be approximately equal to d, based on the relative low height compared to the width of the channel. The value for n depends on the material and state of the channel: smoother materials have a lower value for n and the n-value increases for increasing roughness. Typical Manning's roughness coefficients are defined by Chow (1959) and can be found in various design guides. The slope S was calculated in ArcGIS Pro, as an average of the slope of each individual cell within a catchment area.

Some important assumptions were made in this approach:

• Firstly, the total volumes obtained from application of the MRM were assumed to completely flow onto the beach through the corresponding outlet point. This means that the calculated daily volumes are directly used in Equation I.1;

• Secondly, the width was estimated to be equal to 10m for all outlet points. Thirdly, the average slopes for the entire catchment areas were calculated using ArcGIS and were used in Equation I.1;

• Lastly, a value of 0.02 was assumed for Manning's coefficient, based on Arcement Jr and Schneider (1989).

Secondly, the outlet points were assumed to be closed of by the different alternatives. For the characteristics of the alternatives see Section 3.5. Darcy's equation was applied to come up with a potential flow of water through each dune alternative. In this way, the dunes were modeled as aquifers with different hydraulic conductivities. Darcy's equation is shown in Equation I.2.

$$Q_{dune} = -kA\frac{\Delta h}{L} \tag{I.2}$$

In which:

Q_{dune} is the discharge through the dune $[m^3/d]$

k is the hydraulic conductivity $[m/d]$

A is the cross sectional area of flow through the dune $[m^2]$

Δh is the drop in hydraulic head over the length of the dune $[m]$

L is the length of the dune base $[m]$

Values for k are specific for each soil type. Table I.1 shows typical values for k.

Table I.1: Hydraulic conductivity ranges for different materials (Bakker, 2018).

Material	$k[m/day]$
Clay	<0.0001
Sandy clays	0.0001 - 0.001
Silt	0.001 - 0.01
Very fine sands	0.1 - 1
Fine sands	1 - 10
Course sands	10 - 100
Sands with gravel	100 - 1000
Gravels	>1000

Some important assumptions were made in this method. First, the cross sectional area of flow was assumed to remain equal to the 0-option. This implies that the values for W and d were assumed to be equal to the 0-option, which means a value of $10m$ for W. d varied for each different runoff volume, but followed from Equation I.1. Secondly, only 1D-flow in the direction of the beach was considered, as horizontal conductivity is generally lower than vertical conductivity of soils. Thirdly, the water depth at the outflow location was assumed to be negligible. Lastly, the pores of the soil were assumed to be completely filled, hence no infiltration was possible and equal in slope to the 0-option. The last assumption implies that Δh can be calculated as follows:

$$\Delta h = \Delta z + d$$
$$\Delta z = SL \tag{I.3}$$

In which:

Δh is the difference in hydraulic head $[m]$

Δz is the difference in elevation $[m]$

d is the water depth at the inner side of the dune $[m]$

S is the slope $[-]$

L is the length of the dune $[m]$

The discharge Q_{dune} calculated in Equation I.2 can be subtracted from the daily volumes Q calculated with the MRM in order to obtain an indication of the impact on the drainage conditions at the West End. Excessive water was assumed to pond, which can be explained as unwanted pooling of water.

I.1.3. Output

The output of these steps is the difference in ponding volume $V_{pond}[m^3]$.

I.2. Quality impact

The quality impact of the land barrier on the drainage conditions is expressed in one unit:

- The expected change in quality of the beach water.

I.2.1. Input

The input for this qualitative analysis were the used material and the discharges onto the beach, calculated by Equation I.2.

I.2.2. Process

The potential impact of the alternatives on the beach water quality was analyzed in two ways. First way of impact is a change in runoff discharge into the beach waters. A decrease in runoff discharge with a low quality would imply a decrease in pollutants reaching the beach water. Second way of impact is a change in pollutant concentration of the runoff, due to filtering functionality of the dune. If concentrations are reduced, beach water quality will increase. If the presence of a particular alternative generally led to a increase in beach water quality, the alternative was awarded a '+'. If an increase in pollutants was expected, the alternative was awarded a '-'. If no significant effect was expected, the alternative received a '0'.

I.2.3. Output

The output is the expected change in quality of the beach water.

J

Method: Maintainability

The human presence along the sandy shores of Galveston Island West End make conservation activities and restoration efforts relevant in order to sustain coastal systems, human activities and keep its function as a storm surge barrier.

Different characteristics and guidelines for the maintenance of the dunes were considered in order to identify notable differences between the proposed alternatives. This criterion was based on the outcome of conducted interviews and meetings were held in the course of the research. In accordance with the superiors at the Texas A&M University Galveston Campus, the identified criterion answers the research questions proposed and helps define guidelines that should be considered for the criterion of maintainability of the dune system. This criterion is discussed in Appendix J.1.

J.1. Maintenance approach

Regardless of the dune system alternative assessed, the alternative is going to have to cope with two different types of maintenance, which are post storm dune recovery and regular maintenance. Beach and dune nourishment fall under regular maintenance. Maintenance is necessary in order to preserve the integrity of the dune system, the beach line and the dune ecosystem in everyday conditions throughout the year. However, with the occurrence of a storm event a dune system might be damaged and is in need of post-storm maintenance.

Input parameters and processing
The material composition served as a basis for the maintenance approaches applicable for the different dune system alternatives. A literature review of dune system maintenance strategies served as the basis for conclusions and guidelines mentioned in this report. A distinction is made between beach and dune nourishment and post-storm maintenance. The approach led to a result of different maintenance requirements for different specified materials and the functions of the (hybrid) dune after a storm event.

Output parameters
Guidelines were set in the form of recommendations for the different dune system alternatives, budgeting of maintenance activities have not been considered in this research. In Section 6.1.3, each dune system was graded upon this criterion. Dune systems that require regular sand nourishment and unable to cope with multiple storm events were valued with a '0' symbol. Dune systems that require regular sand nourishment, but have a good post-storm resilient design (meaning that the dune remains some storm protection after a first storm event) were valued with a '+' symbol. Dune systems that require sand and clay nourishment and are not able to cope with multiple storm events, were valued with a '-' symbol.

Method: Sociopolitical acceptability

The process of designing a land barrier is a large undertaking and requires cooperation of many groups of diverse experts. The challenge that arises is to connect technical knowledge with sociopolitical decision making. This chapter shows the approach to quantify the sociopolitical acceptance with regard to the proposed alternatives.

The sociopolitical criterion was tested on these parameters: "Fitting of the dune", "Effect on the line of sight", and "Accessibility" in order to determine the wishes of residential and recreational stakeholders. The identified parameters allowed to give a measure for the requirements for sociopolitical acceptance of the land barrier. These parameters are further elaborated in Appendix K.2 up to Appendix K.4. The parameters were determined by combining findings of the literature study and interviews with the public and professionals, that were held during the course of the research.

K.1. Sociopolitical acceptability assessment

Five cross sections were made on the Galveston Island West End, all showing dominant differences in morphology along the coast. Consequently, a projection of the dune alternatives upon these cross sections was made in order to value the sociopolitical parameters. These cross sections consider various locations from west to east, starting from the West at Kahala Beach, Jamaica Beach, Palm Beach, Pirate Beach, Sunbather Ln., with symbols from A to E respectively. Each cross section differs in beach width, dune base width, dune crest height, distance of rear dune foot till first property and property heights. Because of a lack of exact property heights, elevations were derived by FEMA property height preconditions for the various construction years of analyzed properties.

K.2. Fitting of the dune

An evaluation of the dune footprints upon the current coastal morphology of Galveston Island West End was conducted to see what the morphological consequences are in regard to the coastal line.

K.2.1. Input parameters

The fitting of the dunes along the Galveston Island West End was considered by an evaluation of 5 cross sections of the West End and projecting the cross section of each dune alternative on it. Alternatives 3 and 4 both use a reduction or enlargement of a dune base widths, which correlates with various dune crest heights and storm coping capacities. A difference in these parameters was not considered in this section.

K.2.2. Process

The aim of the projection of the dune cross section on the Galveston Island West End was to determine the projected shift of the coastal line in the direction of the Mexican Gulf and to determine guidelines and actions that should be considered, for example regarding the adjustment of current coast to the new situation. One precondition agreed upon by the USACE for the placement of a dune is that no properties need to be moved or removed. The starting point for the projection of any dune alternative is the dune foot on the property side, and moving in the direction of the Gulf of Mexico.

K.2.3. Output parameters

One precondition for the evaluation of the alternatives is that the current coastline should be kept in place. The alternative was valued with a '+' if the current beach line could be kept in place, even if the beach width was reduced. A value of '-' was applied if the alternative moved the beach line offshore a value of '0' was applied if the alternative proposed a range of dune system dimensions that resulted in either retraction or expansion of the coast line.

K.3. Effect on the line of sight

The different alternatives come with different dune heights. These heights can block the line of sight to the beach of the home owners at the West End. An evaluation of the effect on the line of sight was undertaken.

K.3.1. Input parameters

The degree of visibility is determined by an evaluation of the cross sections on 5 differing locations on Galveston Island West End. The following three elevation standards heights were assumed in order to define the height of the first floor of the properties: $3.5m$ +MSL , $3.7m$ +MSL and $4.3m$ +MSL. Research has shown that these standards were most frequently used for the last 20 years. These heights were recommended as a mitigation guide by local engineering companies who provide home elevation services. Appendix G.2.2 further elaborates on the local policy of Galveston Island West End and the different elevation standard heights.

K.3.2. Process

The height of the dune alternatives were compared with the height of the first floor of the different homes. The distance of the inner side of the dune to the height of the first floor of the properties were also measured.

K.3.3. Output parameters

One condition for the evaluation of the alternatives is to not block the visual landscape of the homeowners. The alternative was valued with a '+' if the line of sight was not blocked. A value of '-' was applied if the alternative blocked the visual landscape of the property on the first line after the dune.

K.4. Accessibility

An evaluation on the accessibility to the beaches of Galveston Island West End was conducted to examine the consequences of the dune alternative with regard to the public coastal access.

K.4.1. Input parameters

The Beach Accessibility Guide of Texas provided by Texas General Land Office (2011) consists of guidelines on how dune walkovers must be constructed. This guidance document consists of both the Beach/Dune Rules and GLO's Dune Protection Manual. Requirements relevant for this project are summarized as follows:

- The deck of the dune walkover needs to be constructed at a minimum of $0.9m$ above the dunes;

- The running slopes of the dune walkovers may not exceed 5%;

- The dune walkovers need to comply with the portions of Texas Accessibility Standards (TAS);

- The design needs to be able to construct the appropriate amount of resting intervals/ level landings with regard to the running slope.

The total list of requirements of the Texas Beach Accessibility Guide is further elaborated in Appendix N.

K.4.2. Process

The accessibility is valuated in accordance to the Beach Accessibility Guide of Texas to determine if the dune alternative allows full beach access to the public. Temporary interruption of the beach access was not considered as disruption of the public beach access. This indicated minor transportation impacts, resulting from increased vehicular congestion along streets, roads and highways. However, construction and operational measures should minimize impacts on the accessibility of the beach and be addressed in engineering plans.

K.4.3. Output parameters

One precondition for the evaluation of the alternatives is that the public of Galveston Island West End should be afforded full and fair access to beaches and existing public coastal access. The alternative is valued with a '+' if the proposed shape do not indicate any problems to meet the requirements as set by the Texas Beach Accessibility Guide, so the access of the beach is not blocked. A value of '-' is applied if the alternative does indicate problems to meet the requirements set by the Texas Beach Accessibility Guide.

Validation XBeach model

This appendix describes the validation process of XBeach.

L.1. Method

Pre and post Ike bed elevation data were compared to the model output values to validate the model. The validation focused on three different transects at the height of Kahala Beach. These transects were made perpendicular to the coastline. The middle transect, transect B, is the one which is used as a base on which the five different alternatives have been tested. Transect A is located 100 meters west of this point, transect C 100 meters east of this point. The transects at the height of Kahala Beach were chosen in such a way that houses or other hard structures were not included in the cross section. The exact location of these transects can be seen in Figure L.1. The area behind the dune, containing vegetation and asphalt, was modeled as if it is completely non erodible.

Figure L.1: Location of transects for validation.

The input storm for this validation process was set up with data based on measurements during Hurricane Ike. The other boundary conditions are described in Appendix L. At the different cross sections, bed elevation data from LiDAR surveys have been obtained, one dataset from 2007 and one from 2009. This data was plotted against pre and post Ike bed level data from the XBeach model. The next section presents the results of the validation process.

L.1.1. Results

In Figure L.2a, Figure L.2b and Figure L.2c it can be seen that the post Ike profiles from the measurements and the XBeach model match quite well. However, there is a clear difference, about half a meter, between the predicted bed level and the 2009 measurements. This indicates that the XBeach model overestimated the erosion rate at all transects. This can be explained by various factors:

- The post Ike LiDAR measurements were obtained from November 2009, one year after Hurricane Ike has hit the American coastline. Within this year, the dune system could have already restored itself partially or artificial nourishments could have taken place.

- Vegetation, which normally inhibits erosion, has not been taken into account in the model. Areas with vegetation have much higher resistance against flow. It is possible to model this in XBeach but this is not taken into account.

- The model assumes everything to be sand. Less erosive materials and hard structures are not taken into account, causing erosion to be overestimated.

(a) Validation result transect A.

(b) Validation result transect B.

(c) Validation result transect C.
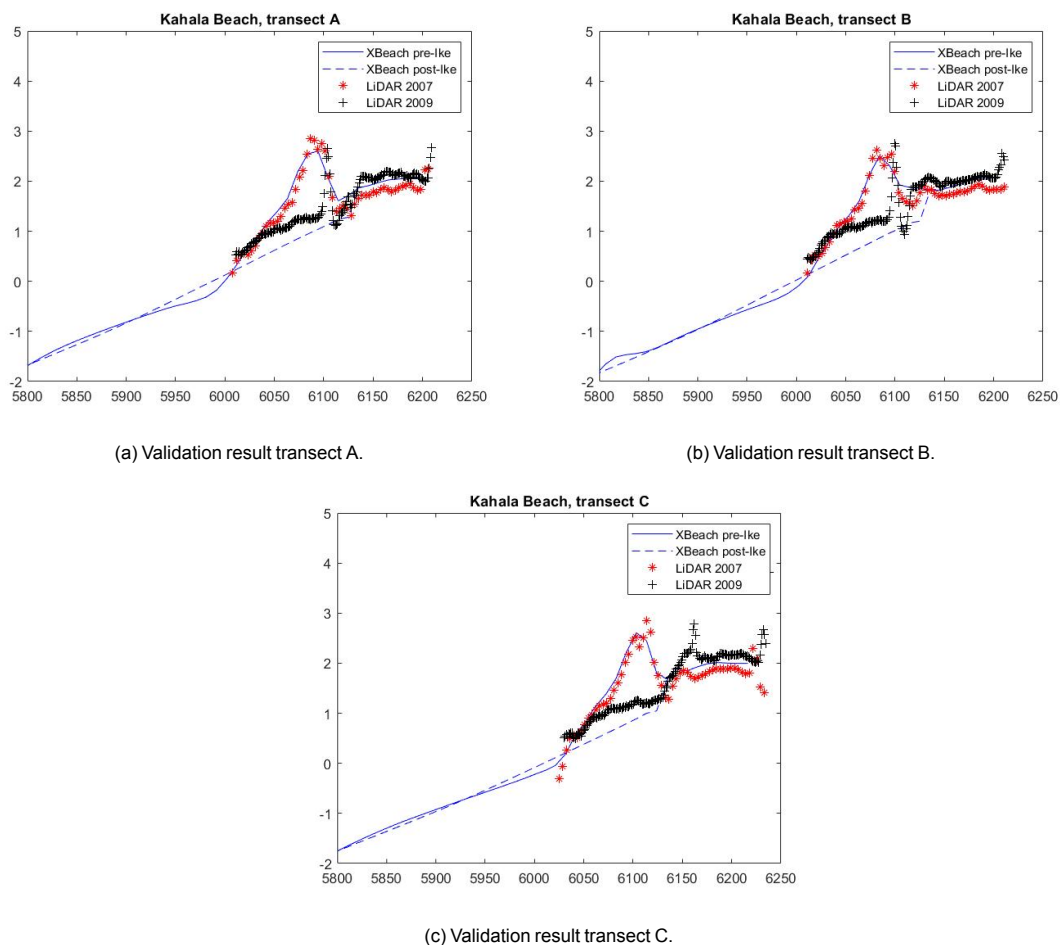
Figure L.2: Validation cross sections A, B & C.

L.1.2. Performance

In order to be able to use the model as a manner to test the different alternatives a assessment of the overall performance has to be made. The model performance is assessed by plotting the modeled bed level change against the measured bed level change for all the transects, which can be seen in Figure L.3. Most points are located close to the dashed line, which means the modeled bed level changes match with

the measured bed level changes. However, there is large deviation of points at the right side of the plot, which means overestimation of modeled bed level changes.
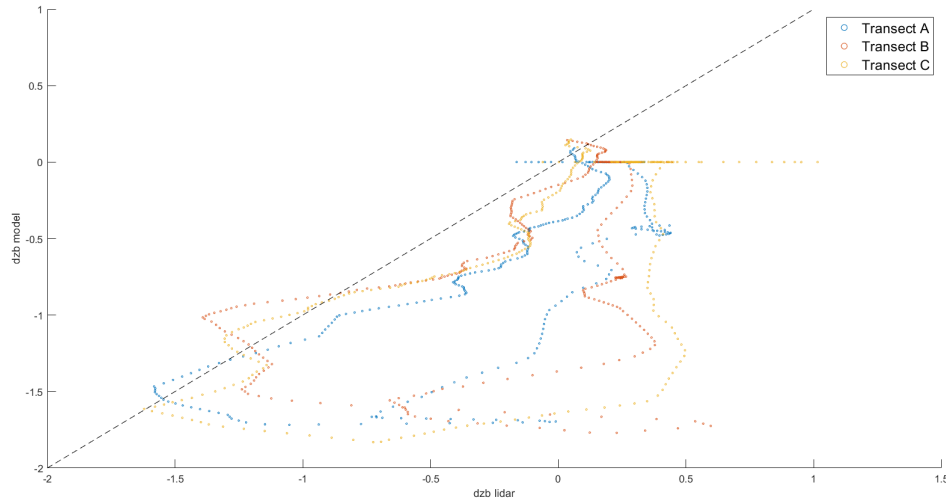
Figure L.3: Validation accuracy.

The performance is qualified by calculating its skill. It compares the simulated error in bed level change with the variance of the measured bed level change:

$$Skill = 1 - \frac{\sum_{N}^{i}(d_{zb,Measured,i} - d_{zb,Modeled,i})^2}{\sum_{N}^{i=1}(d_{zb,Measured,i})^2} \qquad (L.1)$$

In which:

N is total number of measured points from the LiDAR data

$d_{zb,Measured,i}$ is the measured bed level change according to the LiDAR data at location i

$d_{zb,Modeled,i}$ is the modeled bed level change according to XBeach at location i

$Skill = 1$ means an one-to-one correlation with the reality. $Skill = 0$ indicates that the simulation is no better than simulating no bed level change. $Skill < 0$ means that the simulation is worse than predicting zero bed level change.

Table L.1: Skill results.

Transect	Skill
A	−0.1115
B	−0.9268
C	−0.1288

The results from the skill calculations suggest that the model is worse than predicting zero bed level change for all transects. However, the XBeach model predicts on average half a meter lower bed level than was measured from the LiDAR data. For the purpose of this research this result is deemed sufficient enough to test the different alternatives.

M

SwanOne

The design wave height for the different storms is based on data obtained from an offshore wave buoy, NOAA's buoy '42035', which is located $32km$ offshore at the height of the Bolivar Channel. Almarshed (2015) analyzed time series with an extreme value analysis, based on a Weibull distribution. The offshore wave heights are transformed into nearshore heights for three different return periods using Swan. The bathymetry obtained via NOAA (2007a) was used an input. 'Swan' stands for "Simulating WAves Nearshore". As an 1D XBeach model is deemed sufficient, a 1D wave climate nearshore was generated. Thus SwanOne was used, which is a subset of Swan was made specifically to generate 1D wave profiles.
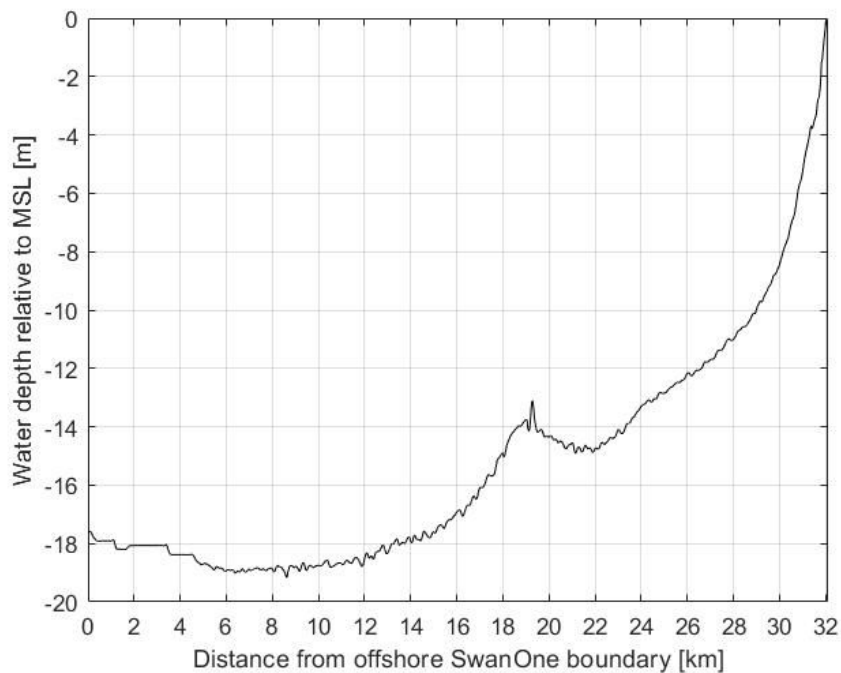
Figure M.1: Bathymetry ranging up from the offshore SwanOne boundary up to Kahala Beach.

SwanOne requires boundary conditions at the deep sea boundary, thus at 32km offshore (see Figure M.1). The following boundary conditions were used:

- **Water depth**
  In SwanOne, the water depth is the additional depth added to MSL. Thus, the storm surge level relative to MSL is entered here. The different storm surge for the storms are obtained from Almarshed (2015).

- **Wave setup**
  As the waves enter the breaker zone, wave set up occurs for all storms (Bosboom and Stive, 2015, p=200). Thus, this function is enabled for all storms.

- **Wind velocity**
  The wind speeds for all storms are based on the return periods for hurricanes in the Galveston Bay area Keim et al. (2007). SwanOne can only model wind speed in a single direction. Therefore, The wind is modeled as acting perpendicular to the shore. As this is the most unfavorable situation, for each of the normative storms the lowest bound of wind speed is chosen as input. The chosen wind speeds of storms with a return periods of 10 years, 50 years and 100 years correspond with the low bounds of the wind speeds of category 1, category 3 and category 5 respectively. Note that the wind speed of Hurricane Ike corresponded to the low bound of a category 3 hurricane.

- **Spectral significant wave height**
  Similar to the storm surge level, the spectral significant wave height for all storms is obtained from Almarshed (2015). The extreme values of the significant wave height where determined with a Gumbel distribution.

- **Peak period**
  Similarly to the significant wave height and the storm surge level, the peak period was obtained from Almarshed (2015). A joint probability distribution was formulated of the values for the peak period and the corresponding extreme values of the significant wave height to determine extreme values of the peak period.

- γ- **and** cos^m-**factor**
  These factors govern the spreading and the amount of energy transmitted into the system TU Delft (2018). Due to the limited data available the decision was made to leave these values at the default value for all storms. Thus, for all SwanOne runs: $\gamma = 3.3 \, [-]$ and $cos^m = 1 \, [-]$.

An overview of the boundary conditions used in the SwanOne model for all storms is given in Table M.1.

Table M.1: Overview of the boundary conditions of the SwanOne model.

Return period storm [$year$]	10	50	100
Water depth [m]	0.60	3.58	4.71
Wind velocity [m/s]	33.08	49.17	58.06
Spectral significant wave height [m]	4.80	5.96	6.54
Peak period [s]	11.50	12.85	12.91

Texas Beach Accessibility Guide, dune walkovers

The Texas Open beaches Act states the public should be afforded full and fair access to beaches and existing public coastal access. The purpose of the Texas Beach accessibility Guide is to provide guidance for local governments implementing and adopting beach accessibility measures (Texas General Land Office, 2011). This document has been developed in cooperation with the Texas Department of Licensing and Regulating (TDLR). Specifications and standards are based on the Texas Accessibility Standards (TAS). When implementing these measures, local government must coordinate the Texas GLO and TDLR.

Accessible public beach may include permanent pathways such as dune walkovers. Dune walkers must be constructed to provide a smooth transition of joining surfaces landward to seaward. Figure N.1 shows the construction of a dune walkover (Texas General Land Office, 2011). In accordance to the Texas Beach accessibility Guide, the GLO's Dune Protection Manual and Dune Rules, dune walkers must be constructed in accordance to the following requirements:

- Dune walkovers should minimize dune damages and maintain accessibility without creating obstruction and hazards on the public beach;

- Dune protection and beach access plan must comply with TAS and any other locally adopted building code to provide for public safety;

- Dune walkovers should commence landward of the back dunes and extend into the beach beyond the foredune ridge and coppice mounds.

- Walkovers with running slopes that exceed 5% must comply with the portions of TAS;

- The deck of a dune walkover should be constructed at a $0.9m$ minimum above the dunes. This includes adjacent dunes, equal to the width of the walkovers. This is to accommodate dune migration and allow sunlight and rain to reach underlying dune vegetation;

- To prevent hindering access sand accumulating, the seaward terminus should be oriented at an angle away from the prevailing wind directions;

- Slats that form the deck of a walkover must run perpendicular to the direction of travel and must be spaced $0.01m$ apart.

- Support posts should be implemented at least $1.5m$ in the ground to ensure stability and to allow for erosion during storm events;

- The sea side of a dune walkover should be located far enough landward to prevent regular destruction from wave action;

- Opening along the surfaces of footpaths must run perpendicular to the direction of travel and not exceed $0.01m$ in width. In order to accommodate one-way passage for a single wheelchair, a minimum clear width of $0.91m$ is required. If the natural conditions not allow this, the clear width may be reduced to $0.8m$ for a distance no greater than $0.6m$. However, it is highly recommended to provide a two-way passing for a single wheelchair. If the width of a beach route is less than $1.5m$, a $1.5m$ by $1.5m$ passing space should be provided every $61m$;
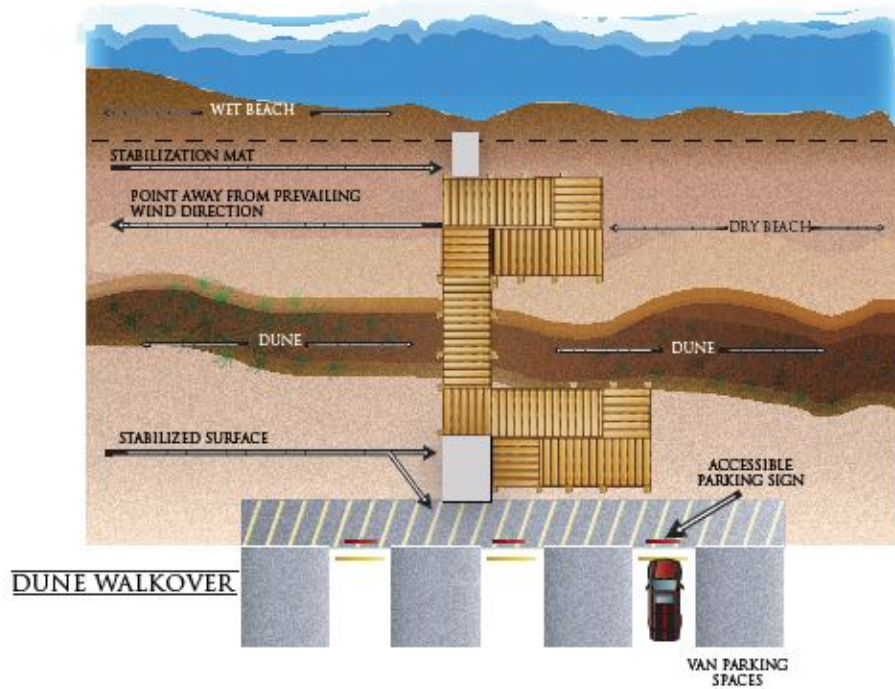
Figure N.1: Schematic design of a dune walkover (L.Tanner et al., 2013).

- The cross slope of the footpath on the public pedestrian beach access shall not exceed 5%. Resting interval should be at least as wide as the public beach access way and $1.5m$ long. These resting intervals/level landings must be provided at least every $15m$ for running slopes up to 10% and at least every $9m$ for running slopes of 8.33%;

- Edge protection for beach access routes should be constructed to prevent sand accumulation and minimize interference with natural sand distribution. For beach access routes with drop-offs greater than $0.025m$ but less than $0.15m$, the vertical edge of the drop-off must be beveled with a slope of 50%;

- Beach access routes shall provide a vertical clearance of at least $2m$;

- Beach access routes shall be designed to prevent water accumulation along the pathway.

N.1. Dune walkovers

Dune walkovers are commonly built to provide public access from off-beach parking areas to beaches in areas where dune vegetation and dunes can be destroyed or damaged by the construction of footpaths. Besides this, the dunes need to maintain its natural defense system for the coastline. As a result, the seaward terminus of a dune walkover is located far enough landward and the deck is constructed at a proper height above the dunes Texas General Land Office (2011). This is necessary to avoid regular destruction from accommodate project shoreline changes or wave action and to prevent sand accumulating on the deck.

Dune walkovers must ensure smooth transition of joining surfaces from the landward to the seaward. Local governments must decide on how to balance the protection and needs of the natural beach environment while providing access to as many people as possible. The public of Galveston Island West End is afforded access to beaches by dune walkovers on the locations as visualized in Figure N.2. These public pedestrian accesses vary in design and sizes. An example of a dune walkover on Galveston Island West End is shown in Figure N.3.

Figure N.2: The locations of dune walkovers on Galveston Island West End (own illustration).

Figure N.3: Front side of a Dune walkover on Galveston Island West End at Kahala Beach.

$$\bigcirc$$

Results

This appendix provides an overview of the results of the parameters of the criteria.

## O.1. Storm surge coping capability

The quantitative results obtained from the XBeach model runs are summarized in Table O.1, Table O.2, Table O.3, Table O.4 and Table O.5, grouped by the intensity of the storm. For the 50 year storm, results are grouped by the duration of the storm. The initial height is the highest point in the cross shore profile before running the model. The final height is the height of the point with the same x-coordinate as the initial height, after doing the simulation. All heights are listed with respect to Mean Sea Level. The associated figures give both a visualization of the cross shore profiles after a storm event and the wave height and water level during the peak of a storm. It is important to keep in mind that the model gives a higher erosion rate than in reality, which was found during the validation process.

O.1.1. Results 10 year storm

Running the model with the lowest intensity storm results in profiles Figure O.1a, Figure O.1b, Figure O.1c and Figure O.1d. It can be seen that the final height of every profile remains the same, which indicates that there is no threat for the underlying area. According to the model, the four alternatives are all able to withstand the storm. The eroded volume is in all cases approximately the same and is low enough for the dune to be able to restore itself (Doody, 2012).

Table O.1: Results 10 year storm.

10 year storm	0-option	Alt. 1	Alt. 2	Alt. 3
Volume eroded away $[m^2/m]$	9.39	9.40	9.55	9.46
Initial height $[m]$	2.51	4.30	7.50	6.50
Final height $[m]$	2.51	4.30	7.50	6.50
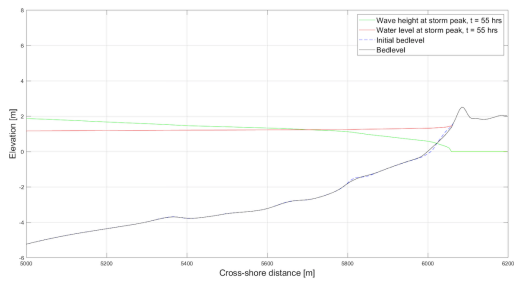
(a) 0-option.
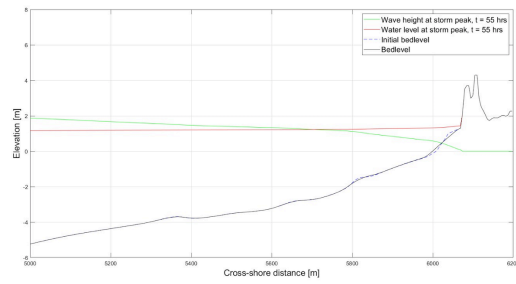
(b) Alt. 1.
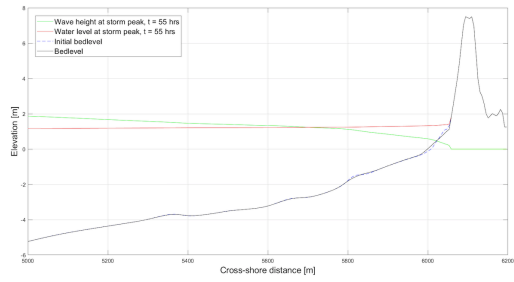
(c) Alt. 2.
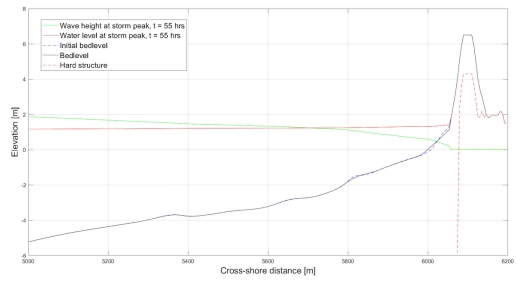
(d) Alt. 3.

Figure O.1: Behavior of different alternatives under 10 year storm conditions.

O.1.2. Results 50 year storm, short duration

The resulting profiles for the runs with a short duration 50 year storm can be seen in Figure O.2a, Figure O.2b, Figure O.2c and Figure O.2d. Both the 0-option and alternative 1 show large amounts of eroded sand. The profiles are completely flattened, which means that the underlying area faces large overtopping rates and inundation time. Alternative 2 and 3 are able to withstand the storm and show self restorable amounts of eroded sand. The concrete core, in the case of alternative 3, is not exposed.

Table O.2: Results 50 year storm, short duration.

50 year storm (short duration)	0-option	Alt. 1	Alt. 2	Alt. 3
Volume eroded away $[m^2/m]$	832.04	430.58	39.22	39.10
Initial height $[m]$	2.51	4.30	7.50	6.50
Final height $[m]$	−1.36	−0.02	7.50	6.50
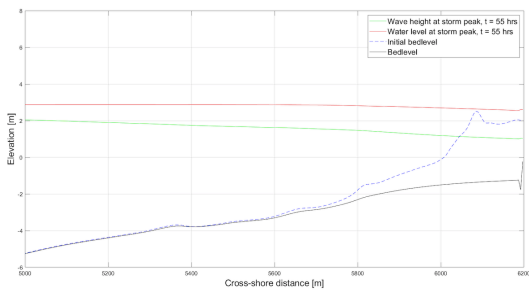

(a) 0-option.

(b) Alt. 1.
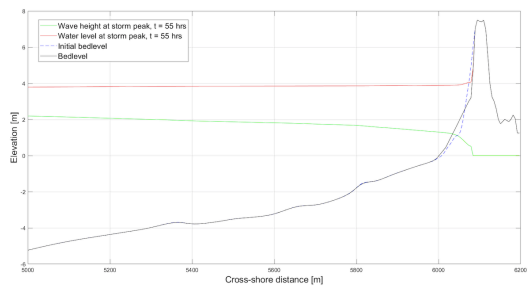
(c) Alt. 2.
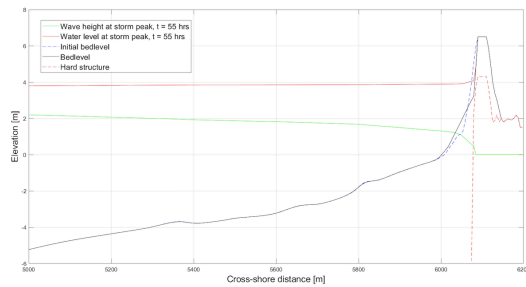
(d) Alt. 3.

Figure O.2: Behaviour of different alternatives under 50 year storm conditions (short duration).

O.1.3. Results 50 year storm, medium duration

Increasing the duration of the storm results in larger eroded volumes, in the case of the 0-option and alternative 1. With alternative 2 and 3, the eroded amount of sand decreased. It can be seen in Figure O.3a, Figure O.3b, Figure O.3c and Figure O.3d. Again, the profiles of the 0-option and alternative 1 are flattened, with a final height below Mean Sea Level. According to the model, alternative 2 and 3 keep the same height after this storm has hit the coast.

Table O.3: Results 50 year storm, medium duration

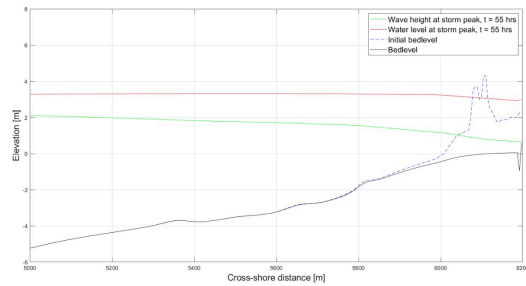| 50 year storm (medium duration)	0-option	Alt. 1	Alt. 2	Alt. 3
Volume eroded away $[m^2/m]$	1221.95	608.18	34.91	34.84
Initial height $[m]$	2.51	4.30	7.50	6.50
Final height $[m]$	−2.09	−0.64	7.50	6.50

(a) 0-option.
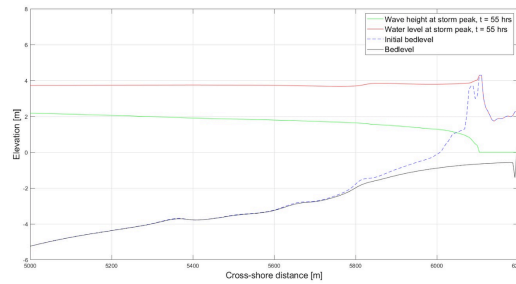
(b) Alt. 1.
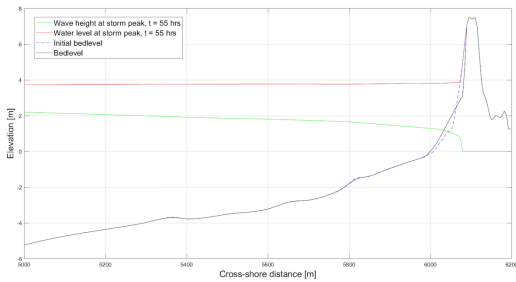
(c) Alt. 2.

(d) Alt. 3.

Figure O.3: Behaviour of different alternatives under 1/50 year per year storm conditions (medium duration).

O.1.4. Results 50 year storm, long duration

The 50 year storm with the longest duration gives results Figure O.4a, Figure O.4b, Figure O.4c and Figure O.4d. The final heights, associated with the 0-option and alternative 1, are both less than two meters below Mean Sea Level. This means very large amounts of overtopping and a complete destruction of Galveston Island. Alternative 2 and 3 are again able to withstand the storm and show reasonable eroding rates. The dunes might need an artificial nourishment after the storm has hit the coast but can mostly restore themselves.

Table O.4: Results 50 year storm, long duration.

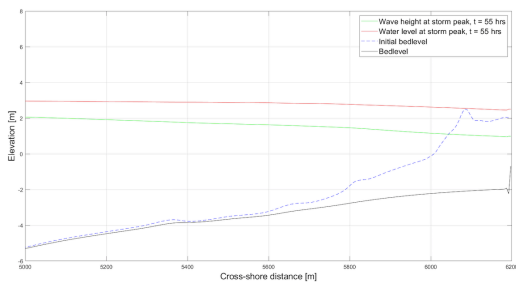| 50 year storm (long duration)	0-option	Alt. 1	Alt. 2	Alt. 3
Volume eroded away $[m^2/m]$	2134.68	1358.12	59.94	54.97
Initial height $[m]$	2.51	4.30	7.50	6.50
Final height $[m]$	-3.23	-2.15	7.50	6.50

(a) 0-option.
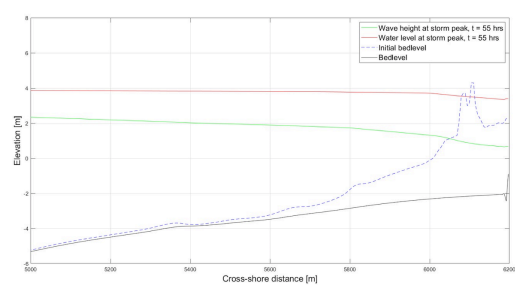
(b) Alt. 1.
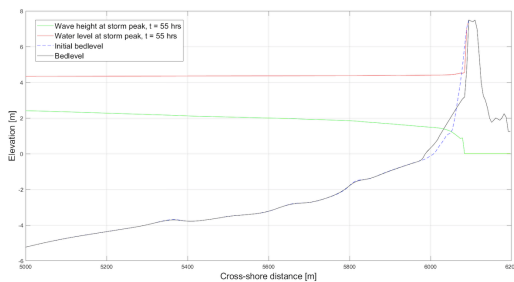
(c) Alt. 2.
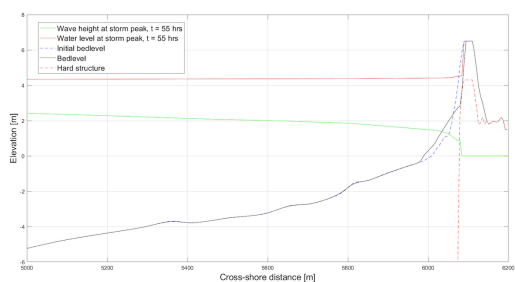
(d) Alt. 3.

Figure O.4: Behaviour of different alternatives under 50 year storm conditions (long duration).

O.1.5. Results 100 year storm

The storm with the highest intensity gives post storm profiles, which can be seen in Figure O.5a, Figure O.5b, Figure O.5c and Figure O.5d. As expected, the 0-option and alternative 1 show destructive results. Alternative 2 and 3 remain standing during this storm. The concrete core, at alternative 3, is exposed, which means extensive restoration works has to be executed after this storm has hit the coast.

Table O.5: Results 100 year storm.

100 year storm	0-option	Alt. 1	Alt. 2	Alt. 3
Volume eroded away $[m^2/m]$	1885.16	1235.20	62.31	55.92
Initial height $[m]$	2.51	4.30	7.50	6.50
Final height $[m]$	-2.98	-1.96	7.49	6.50
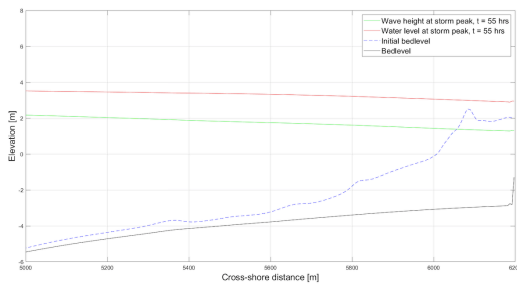
(a) 0-option.
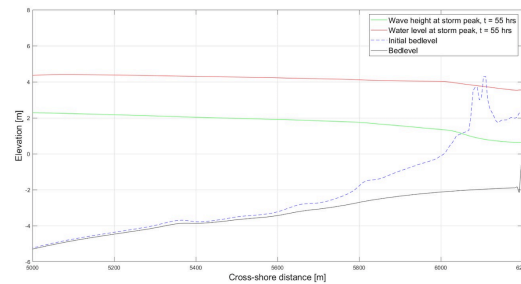
(b) Alt. 1.
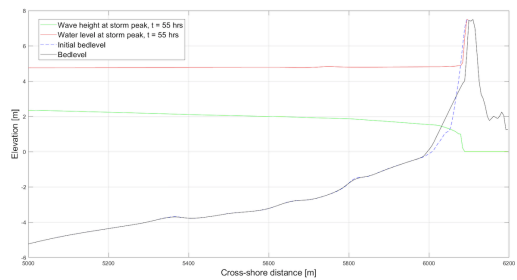
(c) Alt. 2.
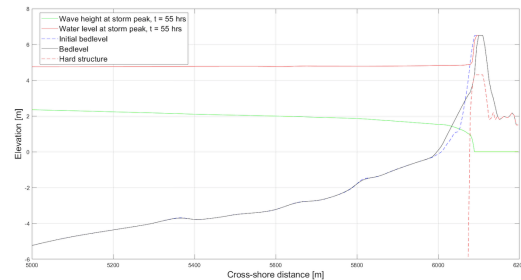
(d) Alt. 3.

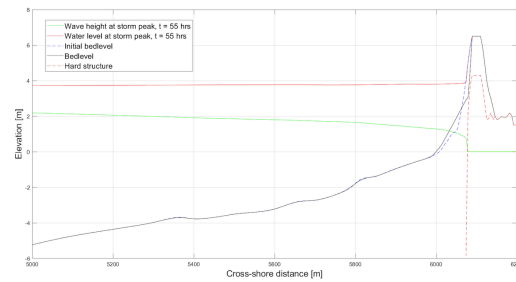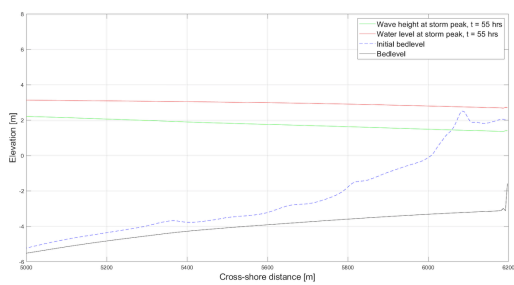Figure O.5: Behaviour of different alternatives under 100 year storm conditions.

O.1.6. Results erosion events

It can be concluded that the 0-option and alternative 1 do not perform well under conditions with a lower return period than 10 year storm. According to the model results, the profiles of these alternatives are flattened after high intensity storms have hit the coast. Therefore these alternatives have both been rated with a '-'. Alternative 2, 3 and 4 (it is assumed that, in the model, alternative 4 performs the same as alternative 3) have been rated with a '+', since these alternatives are able to withstand the heavier storms. Dune erosion is visible but the dune can restore itself or minimum restoration work is required. The grades of the results are given in Table O.6.

Table O.6: Results for erosion during normative event.

Parameter	0-option	Alt. 1	Alt. 2	Alt. 3	Alt. 4
Erosion during normative event	-	-	+	+	+

O.1.7. Results overtopping

Comparison of the results from the wave overtopping shows that the different options all do not suffice for the maximum allowable overtopping rate of 1 l/s per m stated in the Section 4.1. The low elevation with relation to MSL for the 0-option caused the largest overtopping rates. Because of this, a '-' has been rated for this option. Alternative 1 follows in decreasing order of wave overtopping. The elevation is higher than the 0-option, but not as high as the other alternatives. '0' as a grade is deemed fair for alternative 1, due to the wide design of the dune the overtopping could have not too damaging consequences. The hybrid dune option can withstand the overtopping of a 10 year storm. The complete results of the wave overtopping capability have been worked out in Appendix B.7.2.

Table O.7: Results for wave overtopping capability.

Parameter	0-option	Alt. 1	Alt. 2	Alt. 3	Alt. 4
Wave overtopping capability	-	0	+	+	+

O.2. Stormwater drainage impact

This section discusses the results for the parameters "Obstructive impact" and "Quality impact". These are shown in Table O.8 and Table O.12 respectively.

Table O.8: Result for stormwater drainage impact parameter 'Obstructive impact'.

Parameters	0-option	Alt. 1	Alt. 2	Alt. 3	Alt. 4
ΔV_{pond}	0	-	-	-	-

O.2.1. Quantitative impact

An indication of the quantitative impact of the different alternatives on the drainage through the outlets can be seen in Table O.9, showing the results for the different return periods for outlet point $P2$. As can be seen, discharges through the dunes are very small compared to the generated volumes, or equal to zero. As can be seen, the impact of the dune fully depends on the k-value assigned to the material, but in general the outflow through the dunes is negligible compared to the runoff volume V. That is shown in Table O.10 and O.11.

Table O.9: Results for P2, demonstrating Q_{dune} in m^3/s (Q_{outlet} in m^3/s for the 0-option).

$T[year]$	$V[*10^4 m^3]$	0-option $[*10^4]$	Alt. 1 $[*10^{-2}]$	Alt. 2 $[*10^{-2}]$	Alt. 3	Alt. 4 $[*10^{-2}]$
2	4.4	4.4	0.8	0.8	0	0.01
10	7.6	7.6	1.2	1.1	0	0.01
25	10.1	10.1	1.4	1.3	0	0.01
100	15.0	15.0	1.8	1.7	0	0.02

The 0-option

Table O.10: Results for the 0-option. V_{pond} in m^3, Q_{beach} in m^3/s.

ID	$T=$	$2year$	$T=$	$10year$	$T=$	$25year$	$T=$	$100year$
	V_{pond}	$Q_{beach}*10^4$	V_{pond}	$Q_{beach}*10^4$	V_{pond}	$Q_{beach}*10^4$	V_{pond}	$Q_{beach}*10^4$
P1	0	1.3	0	2.3	0	3.1	0	4.5
P2	0	4.4	0	7.6	0	10.1	0	15.0
P17	0	1.6	0	2.7	0	3.6	0	5.4
P27	0	1.9	0	3.3	0	4.4	0	6.5
P29	0	1.3	0	2.2	0	2.9	0	4.3

Alt. 1, 2, 3, and 4

Table O.11: Results for alt. 1, 2, 3 and 4. They are all similar. V_{pond} in m^3, Q_{beach} in m^3/s.

ID	$T=$ 2year		$T=$ 10year		$T=$ 25year		$T=$ 100year	
	$V_{pond}*10^4$	Q_{beach}	$V_{pond}*10^4$	Q_{beach}	$V_{pond}*10^4$	Q_{beach}	$V_{pond}*10^4$	Q_{beach}
P1	1.3	0	2.3	0	3.0	0	4.5	0
P2	4.4	0	7.6	0	10.1	0	15.0	0
P17	1.6	0	2.7	0	3.6	0	5.4	0
P27	1.9	0	3.3	0	4.4	0	6.5	0
P29	1.3	0	2.2	0	3.0	0	4.3	0

O.2.2. Quality impact

The 0-option
No change is applied in the 0-option, which means that there will be no change in runoff quality. Based on Appendix C.2.2, heavy rainfall in this situation can lead to higher levels of enterococcus, which indicates a low water quality and potential health risks. Therefore, a '-' is rewarded.

Alternatives 1, 2 and 4
Sand dunes have a positive impact on water quality due to a filtering function. Pathogens, microorganisms and other pollutants are removed from runoff directed towards the beach. Therefore, a '+' is awarded.

Alternative 3
The concrete core does not provide a filtering function. However, under the assumptions in this research alternative 3 does not let any stormwater reach the beach. This means an improvement on the water quality at the beach, and therefore a '+'.

Table O.12: Results for stormwater drainage impact parameter 'Quality impact'.

Parameters	0-option	Alt. 1	Alt. 2	Alt. 3	Alt. 4
ΔQI_Q	-	+	+	+	+

O.3. Maintainability

This section provides the basis upon which the criterion "Maintenance approach" has been graded in Table O.14. The final output of the results of Maintainability is given in Table O.13.

Regardless of the dune system alternative that is assessed, it will have to cope with two types of maintenance: post-storm dune recovery and maintenance (or beach and dune nourishment). Dune systems need to be maintained in order to preserve the integrity of the dune system, the beach line and the dune ecosystem in everyday conditions throughout the year. But, after a storm event, a dune system might be damaged and is in need of post-storm maintenance. The dune system alternatives are valued based on a combination between required dune maintenance and remaining storm surge capacity after a storm surge event.

O.3.1. Post-storm dune recovery

All alternatives are sand based, with an exception of alternative 3 and 4 which have either a concrete or clay base core. Every dune system is subject to natural erosion by the elements, though the dune systems that have been proposed along the Galveston Island West End will be having the function of a storm surge barrier. Erosion can occur at different rates depending on weather and storm events Appendix O.1. The eroding ability of the dune system can be seen as its resistance in the sense that, the more erosion it can hold, the longer the storm can be without failure or breaching (Galvez, 2019).

The result in erosion of a storm event determines the amount of maintenance or dune recovery that takes place after a storm event in order to keep the defense structure ready for when another event takes place. Following the modeling of the erosion rates of the dune system alternatives in Appendix O.1, it is possible to determine to what extend a dune system remains intact for its storm surge coping capabilities. Sand quantities for recovery have not been modeled, because this research has only evaluated the erosion in a 1D setup. In Table O.13 a summary of dune system erosion rates (discussed in Appendix O.1) have been given and have been differentiated with the terms:

- Intact: The dune system is intact, little or no erosion has taken place, the dune system can recover naturally, the storm surge capacity is intact.

- Needs restoration: The dune system has partly eroded and cannot naturally recover, the storm surge capacity is compromised, but can still withstand storms of lower intensity.

- Core exposed: The (concrete or clay) core from alternative 3 and 4 has been exposed and cannot naturally recover, the storm surge capacity is compromised, but can still withstand storms of lower intensity.

- Flattened: The dune system has fully eroded (to a level below MSL), no storm surge capacity is left, the dune system needs to be rebuild.

Table O.13: Post-storm state.

Return period storm	0-option	Alt. 1	Alt. 2	Alt. 3	Alt. 4
$10year$	intact	intact	intact	intact	intact
$50year$ (short)	flattened	flattened	intact	intact	intact
$50year$ (long)	flattened	flattened	intact	intact	intact
$50year$ (long)	flattened	flattened	needs restoration	needs restoration	needs restoration
$100year$	flattened	flattened	needs restoration	core exposed	core exposed

The 0-option
The dune system can withstand a 10 year storm and remains intact, the storm surge capacity remains intact. The erosion rates are small enough for the dune to recover naturally. A short 50 year storm or worse, completely flattens the dune system. No storm surge capability is left, the dune cannot recover naturally. A full reconstruction of the dune is required. Appendix O.1 leads to a positive conclusion for the maintenance and reconstruction of the dune, most of the eroded sediment from the dune front is deposited in the active coastal zone, relatively near the coast. This makes recovery actions easier and cheaper to perform, since most of the sediment can be found within the first $200m$ of the coast. The storm surge capability is totally vanished after 50 year storms and the dune system needs to be fully reconstructed, it cannot withstand any other storms. Storms that are of the magnitude of 10 year events cause little to no erosion, the dune system can recover naturally. In total this is not a positive outcome for a storm surge barrier dune system, but only with 50 year storms full recovery is needed, thus it is valued with a '0' symbol.

Alt. 1: Twin dunes proposed by the USACE
The dune system can withstand a 10 year storm and remains intact, the storm surge capacity remains intact. The erosion rates are small enough for the dune to recover naturally. A short 50 year storm or worse, completely flattens the dune system. No storm surge capability is left, the dune cannot recover naturally. A full reconstruction of the dune is required. Appendix O.1 leads to a positive conclusion for the maintenance and reconstruction of the dune, most of the eroded sediment from the dune front is deposited in the active coastal zone, relatively near the coast. This makes recovery actions easier and cheaper to perform, since most of the sediment can be found within the first $200m$ of the coast. The storm surge capability is totally vanished after 50 year storms and the dune system needs to be fully reconstructed, it cannot withstand any other storms. Storms that are of the magnitude of 10 year events cause little to no erosion, the dune system can recover naturally. In total this is not a positive outcome for a storm surge barrier dune system, but only with 50 year storms full recovery is needed, thus it is valued with a '0' symbol.

Alt. 2: Single dune proposed by Luis Galvez

The dune system can withstand a 10 year, 50 year and 100 year storm events storm and remains intact. The storm surge capacity remains intact. The erosion rates are relatively small for the dune to recover naturally most of the time. Only with 100 year storms artificial maintenance is required Appendix O.1. A positive conclusion for the maintenance and reconstruction of the dune is that most of the eroded sediment from the dune front is deposited in the active coastal zone, relatively near the coast. This makes recovery actions easier and cheaper to perform, since most of the sediment can be found within the first $250m$ of the coast Galvez (2019). In total this is not a positive outcome for a storm surge barrier dune system, thus it is valued with a '+' symbol.

Alt. 3: Dune with concrete core

The dune system can withstand a 10 year and 50 year storm events storm and remains intact. The storm surge capacity remains intact. The erosion rates are relatively small for the dune to recover naturally most of the time. Only with 100 year storm events the concrete core is exposed, artificial maintenance and reconstruction of the dune system is required Appendix O.1. The concrete core can withstand 10 year storm events. When comparing the results of wave overtopping, the core by itself can withstand approximately the same amount of overtopping discharge for both the 10 and 50 year storm events and is obsolete for 100 year storm events, see Table B.3. For a monochromatic wave of $1.47m$ the concrete core can withstand 3000 of these waves before showing initial damage.A positive conclusion for the maintenance and reconstruction of the dune is that most of the eroded sediment from the dune front is deposited in the active coastal zone, relatively near the coast, and that the base of the hybrid dune (concrete core) remains in place. This makes recovery actions easier and cheaper to perform, since most of the sediment can be found within the first $200m$ of the coast. In total this is not a positive outcome for a storm surge barrier dune system, thus it is valued with a '+' symbol.

Alt. 4: Dune with clay core

The dune system can withstand a 10 year and 50 year storm events storm and remains intact and thus the storm surge capability. The erosion rates are relatively small for the dune to recover naturally most of the time. Only with 100 year storm events the clay core is exposed, artificial maintenance and reconstruction of the dune system is required Appendix O.1. When comparing the results of wave overtopping, the core by itself can withstand approximately the same amount of overtopping discharge for both the 10 year -, and 50 year storm events and is obsolete for 100 year storm events, see Table B.3. For a monochromatic wave of $1.07m$ the clay can withstand 3000 of these waves before showing initial damage. A positive conclusion for the maintenance and reconstruction of the dune is that most of the eroded sediment from the dune front is deposited in the active coastal zone, relatively near the coast, and that the base of the hybrid dune (concrete core) remains in place. This makes recovery actions easier and cheaper to perform, since most of the sediment can be found within the first $200m$ of the coast. In total this is not a positive outcome for a storm surge barrier dune system, but due to the fact that an assumption has been made for the reaction of a clay core, thus it is valued with a '0' symbol, since it is not possible to determine the exact reaction of a clay core based dune system.

O.3.2. Regular maintenance

In the previous section the consequences on post-storm dune maintenance have been mentioned. However, maintenance due to minor storms or excessive erosion also plays an important role in order to keep in check the integrity of the dune system. A dune system not only degrades when (design)storm events hit the dune system, but also due to weathering and natural erosion. When and if a 50 year -, or 100 year storm event takes place, the impact on the dune system is catastrophic, so in order to retain a storm surge capacity of the dune system, the dune must be kept in good conditions during its lifetime to ensure its expected performance during storm events Martínez et al. (2013).

Any of the alternative dune systems is expected to be exposed to hydraulic conditions that can lead to a certain amount of erosion. Erosion of the dune system takes place whenever the water reaches the foot of the dune. This condition is met when the surge- and wave run-up effects combined result in hydraulic conditions that reach the bottom of the dune. The morphological impact of along-shore erosion on Galveston Island was not part of this research, the impact of vegetation on the dune systems was also not

considered, because it could not be modeled in the XBeach program that was used in this research. Due to the duration period of this research, no conclusions were made regarding the regular maintenance of the dune alternatives. Multiple dune restoration manuals and reports were evaluated for the grading of Appendix O.3.1. These include (Martínez et al., 2013), (GLO, 2016-2017) and (USACE, 2016).

O.3.3. Maintenance approach

The results of the maintainability of the dune system alternatives are valued in Table O.14. An explanation of these values is given in Appendix K.

Table O.14: Results for maintainability parameter Maintenance Approach.

Parameter	0-option	Alt. 1	Alt. 2	Alt. 3	Alt. 4
Maintenance approach	0	0	+	+	0

O.4. Sociopolitical acceptability

This section describes the results obtained from the test on the parameters: "Fitting of the dune", "Effect on the line of sight" and "Accessibility" are summarized in Table O.15, Table O.16. and Table O.17,

O.4.1. Fitting of the dune

The 0-option
The 0-option reflects the current coastal morphology with semi-naturally varying beach widths and dune widths. Semi-naturally means in this case that the coastal area is nourished where needed by the USACE. Since this is the natural or current coastal morphology, this parameter was valued with a '+' symbol because it 'fits' naturally.

Alt. 1: Twin dunes proposed by the USACE
With a proposed dune width of $56m$, the coastal line would have to move in a range from $31m$ to $41m$ towards the Gulf of Mexico. This range is based on the USACE alternative that was projected upon the five cross sections along the West End coast (Appendix D). The twin dunes proposed by the USACE are valued with a '-' symbol because the beach line needs to move a significant amount seawards in order to keep the current beach width.

Alt. 2: Single dune proposed by Luis Galvez
The proposed dune width is $100m$. The dune width would cover the current beach and beyond seawards if this option is implemented. The current beach would totally cease to exist and thus a significant movement of the coastline in seaward direction would be needed in order to maintain a beach of any size on the Galveston Island West End (Appendix D). Hence, alternative 2 was valued with a '+' symbol.

Alt. 3 and 4: Dune with concrete- and clay core
Dune systems with a dune width between $5m$ and $15m$ led to a narrowing of the current dune base width or, in case of the Pirate- and Sunbather Beach, kept the current dune base width in place. Dune widths ranging from $15m$ to $25m$ are going to cause broadening of current dune systems in four out of five cross sections, but led to a dune base width equal to the current situation at Kahala Beach. The dune base widths that exceed $25m$ all led to broadening of current dune systems. A maximum dune base width of $60m$ causes the beach to disappear under the proposed dune solution, and would thus mean a movement of the coastline in seaward direction in order to maintain a beach of any size. Alternative 3 consists of multiple proposed dune solutions, varying in consequence for the movement of the beach line, but also varying in dimensions and storm surge coping capabilities (Appendix D). Due to the fact that multiple options were considered, with multiple outcomes as a result, this alternative was valued with a '0' symbol.

Alternative 4 was based on the same design as alternative 3, only using a different core. The evaluation of alternative 4 follows the same argumentation as mentioned in alternative 3 and consequently were valued

with a '0' symbol.

Table O.15: Results for sociopolitical acceptance parameter Fitting of the dune.

Parameter	0-option	Alt. 1	Alt. 2	Alt. 3	Alt. 4
Fitting of the dune	+	-	-	0	0

O.4.2. Effect on the line of sight

The 0-option
The cross sections show that the heights of the existing dunes fluctuate from $1m$ +MSL to $3m$ +MSL. As a result, there is not going to be any visual obstruction for the homeowners, so the parameter Effect on line of sight was valued with a '+' symbol.

Alt. 1: Twin dunes proposed by the USACE
The proposed heights of the twin dunes are $3.7m$ +MSL and $4.3m$ +MSL. The results demonstrate that the USACE has used the two latest heights as standard height for their dunes. As a result, the twin dunes does not block the view of the houses and alternative 1 met the requirements and was valued with a '+' symbol.

Alt. 2: Single dune proposed by Luis Galvez
The proposed height of the single dune is $7.5m$ +MSL. Apparently, the single dune as proposed by Luis Galvez blocks the landscape view of properties on the first line after the dune. Thus Alternative 2 does not meet the requirements on the effect on the line of sight and was valued with a '-' symbol.

Alt. 3 and 4: Dune with concrete- and clay core
The proposed height of the dune indicate $6.5m$ +MSL. The results indicate both the proposed alternatives provide visual block to the homeowners of the first line after the dune. Accordingly, the parameter Effect on line of sight of alternative 3 was valued with a '-' symbol.

Alternative 4 is based on the same design as Alternative 3, only using a different core. The evaluation of alternative 4 follows the same argumentation as mentioned in alternative 3 and consequently was valued with a '-' symbol.

Table O.16: Results for sociopolitical acceptance parameter Effect on the line of sight.

Parameter	0-option	Alt. 1	Alt. 2	Alt. 3	Alt. 4
Effect on the line of sight	+	+	-	-	-

O.4.3. Accessibility

The 0-option
The so called 'dry sandy area' that extends from the beach to the natural line of vegetation is in most cases privately owned. However, it is subject to the public beach easement at some locations. The design and locations of the current dune walkovers are visualized in Figure N.1. The current dune walkovers are in line with the requirement as set by the Texas Beach Accessibility Guide, so was valued with a '+' symbol.

Alt. 1: Twin dune proposed by the USACE
The proposed design of the twin dunes does not provide difficulties with the requirements as set by the Texas Beach Accessibility Guide. The exact design and positioning of the dune walkovers would be optimized during future planning and design phases. Despite this, preliminary design shows it meet the requirements as set by the Texas Beach Accessibility Guide, so was valued with a '+' symbol.

Alt. 2: Single dune proposed by Luis Galvez
The main problem that arises results from the total required height of the dune walkover to fulfill the guidelines. As mentioned before in Appendix K.4, the deck of a dune walkover need to be constructed at a minimum of 0.9 m above the dunes. This results in a total height for the dune walkover of 8.4 m +MSL.

However, there is not enough area available to reach this height without running slopes that exceed the 5% or comply with the portions of TAS. On top of that, it is not possible to construct the appropriate amount of resting intervals/level landings. As a result, Alternative 2 does not meet the requirements as set by the Texas Beach Accessibility Guide, so was valued with a '-' symbol.

Alt. 3 and 4: Dune with concrete- and clay core
The proposed shape and parameters of the dunes with concrete core is similar to the alternative with the clay core. The results of alternative 3 and 4 does not indicate any problems to meet the requirements as set by the Texas Beach Accessibility Guide, thus they were both valued with a '+' symbol.

Alternative 4 is based on the same design as alternative 3, only using a different core. The evaluation of alternative 4 follows the same argumentation as mentioned in alternative 3 and consequently were valued with a '0' symbol.

Table O.17: Results for sociopolitical acceptance parameter Accessibility.

Parameter	0-option	Alt. 1	Alt. 2	Alt. 3	Alt. 4
Accessibility	+	+	-	+	+

Limitations per criterion

P.1. Limitations 'Storm surge coping capability'

- Only one location at the West End has been tested in the model runs. In practice, the bathymetry probably differs a lot along the entire West End. Moreover, for simplicity, a 1D model was set up, instead of a more detailed 2D model.

- The alternatives have only been tested upon five different design storms, which means that the results only corresponds with these storms. In practice, there are unlimited combinations of storm intensity, duration and location of landfall.

- The surge level and wave conditions that have been used as an offshore input for the XBeach model were based on buoy '42035'. This buoy is not located at the height of Kahala Beach, which is the location at which the input bathymetry was obtained. Therefore real wave and surge data for this location could differ from the used data.

- Not much research has been done about how dunes with a concrete core behave under storm conditions. XBeach models with hybrid core dunes have not been validated yet.

- The validation of the used XBeach model showed an overestimation of the erosion rate. The results for the different alternative might have this as well. This is due to the absence of the vegetation on these dunes.

- The equations for wave overtopping rates have not been widely applied on soft structures and the results could be under- or overestimated because of this. More research should be done on scale models in a wave flume to get to more accurate results on wave overtopping outcomes.

- The slopes of the dunes have been estimated from the grid of the XBeach input. The slope of the dune can vary over time and when constructing the dune, the slope is going to vary alongshore. More tests need to be done on the different slope angles of the options in order to get to more data on overtopping rates for alongshore locations on different alternatives.

- The dune width has not been assessed on with overtopping calculations. The width can be favorable for draining the overtopping rates back to the beach.

- The material properties of clay and concrete have not been taken into account when calculating the stability of waves. The cohesion of clay and the durability of concrete can lead to a too conservative value of the critical significant wave height.

P.2. Limitations 'Stormwater drainage impact'

- Only models and existing data were used in this research to calculate runoff volumes. No on site validation was performed to check the obtained volumes.

- The application of the MRM is a simplification of reality. A distributed model would probably have given more accurate results, however a lack of data did not allow to perform this kind of research. Processes such as interception, infiltration and percolation that would have been taken into account separately in a distributed model were caught in the runoff coefficient used in the MRM. Furthermore, rainfall was assumed to be uniformly distributed in both time and space, while a distributed model would be able to generate more time specific runoff data.

- The used model to calculate obstructive effects of the alternatives on drainage is an extreme simplification of reality. For simplicity, the 0-option was adjusted towards a system with a land barrier, disregarding the effects of these changes on spreading and accumulation of stormwater on the inner side. Furthermore, infiltration was assumed to be negligible, and only 1D-flow was analyzed.

- Seepage was not extensively analyzed in this research due to time constraints. The impact of seepage on stability of the dune system should be assessed and incorporated in the design if necessary.

P.3. Limitations 'Sociopolitical acceptability' and 'Maintainability'

- The stakeholder analysis is incomplete. It was not in the scope of this study to connect the stakeholders to the main issues of the project. This would have resulted in an overview of all stakeholders with their relationships and issues, which creates opportunities to establish a solution that satisfies more stakeholders.

- This research used a qualitative research methodology, not a quantitative approach. The parameters provided to quantify the criteria sociopolitical acceptability, for example, are partly based on interviews.

- The research was conducted from an 'outsider' perspective, this could be considered as a limitation of the research. The research aimed at providing an analysis of the proposed alternatives and its changes when the research is done with a more local perspective on the situation.

- The findings of the social political acceptability of the alternatives were based on a limited number of cross sections.

- In this study standard elevation heights instead of the exact property heights has been used. As a result, it is likely that some properties have a height above or below this standard level. This could result in other values of the final outcome.

- There is chosen to value the parameter Accessibility in accordance with the requirements of the Beach Accessibility Guide of Texas. The final plans can give another outcome.

- The study on the form of governance was conducted from a Dutch perspective, this could be considered as a limitation of the research.

- In this study alongshore erosion rates and the influence of vegetation on the dune system alternatives were not evaluated, resulting in a limitation in the evaluation of the maintenance criterion.

- Due to the quantitative nature of this research, construction costs and maintenance costs of the dune alternatives have not been considered.

- Only five cross sections were considered along the Galveston Island West End in order to determine sociopolitical results. These cross sections do merely represent an average view of the island.

- This research was only based upon the influence of a dune system on the stakeholders on the Galveston West End.